

BENCHMARK SKYSHINE EXPOSURE RATES

by

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1.0 INTRODUCTION

Public concern about long term exposure effects due to all types and levels of radiation is demanding increased accuracy in computing low level exposure rates. One source of low level radiation exposure is atmospheric reflection (skyshine) of upwardly directed gamma radiation originating from a radionuclide source on the ground. Since most nuclear facility roofs are only lightly shielded, if shielded at all, then facilities such as BWR turbine buildings, radioactive waste storage structures, and post accident reactor containment buildings can produce potentially significant skyshine exposure rates in areas near these facilities. Since overly massive roof shielding would require substantial structural material and extensive structural support, accurate calculation of skyshine exposure rate is important to the economic design of such nuclear facilities.

Computer codes based on multi-energy group, multi-dimensional, transport theory are the most accurate skyshine calculational methods presently available. However, these gamma photon transport computer codes are very complex and require large computers. Therefore use of these photon transport codes for routine analysis of skyshine exposure rate problems is prohibitively expensive. Since these photon transport codes are so costly, development of a simplified approximate skyshine exposure rate model would be useful. The most popular simplified skyshine exposure rate models are point kernel techniques which calculate single scattered photon distributions in the air above the gamma radiation source. The angular source distribution is pre-

dicted by using the incoherent differential scattering cross section and multiple photon scattering is accounted for by using buildup factors.

Although point kernel exposure rate models are inexpensive to use compared to transport theory computer codes, the accuracy of point kernel models is generally unknown. The accuracy of the more sophisticated transport theory codes has also been questioned. Therefore, the Study Committee on Air-Scattered Gamma Rays in Nuclear Facilities of the Japanese Nuclear Safety Research Association (NSRA) conceived a benchmark skyshine experiment to obtain accurately measured skyshine data from an experiment with easily modelled geometry. These benchmark skyshine experimental results can then serve as a simple standard with which the accuracy of various calculation techniques can be tested. To accomplish this goal, the experiment itself should be easily modelled by point kernel techniques or other calculation methods. Therefore, the benchmark skyshine experiment was based on a cylindrically collimated primary radiation field due to an isotropic point source. Skyshine exposure rate measurements were to be taken at several radial distances from the source. These measurements were to be taken over flat terrain and at the same elevation as the source. The source radiation was to be collimated into 150° cone (unshielded configuration) and to be shielded vertically by concrete slabs 20 cm and 40 cm thick (the two shielded configurations) see Figs. 1-1 and 1-2.

Point kernel calculations of the skyshine exposure rates for these various source configurations were performed by various members of

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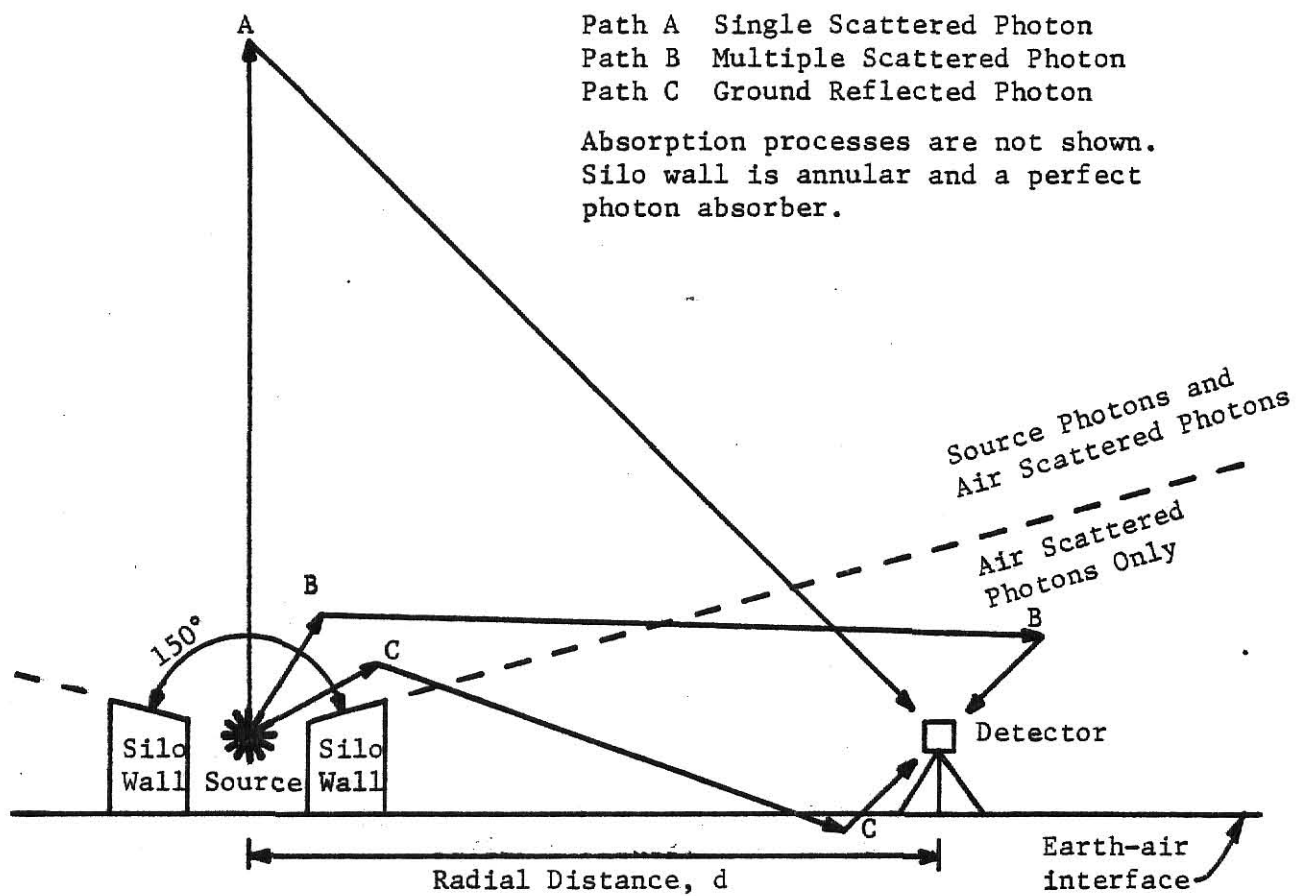


Fig. 1-1. Ideal unshielded source configuration.

Path A Single Air Scattered Photon
 Path B Single Concrete Scattered Photon
 Singly Scattered in Air

Absorption processes are not shown.
 Silo wall is annular and a perfect
 photon absorber. Multiple air scattering
 and multiple concrete scattering of photons
 is not shown.

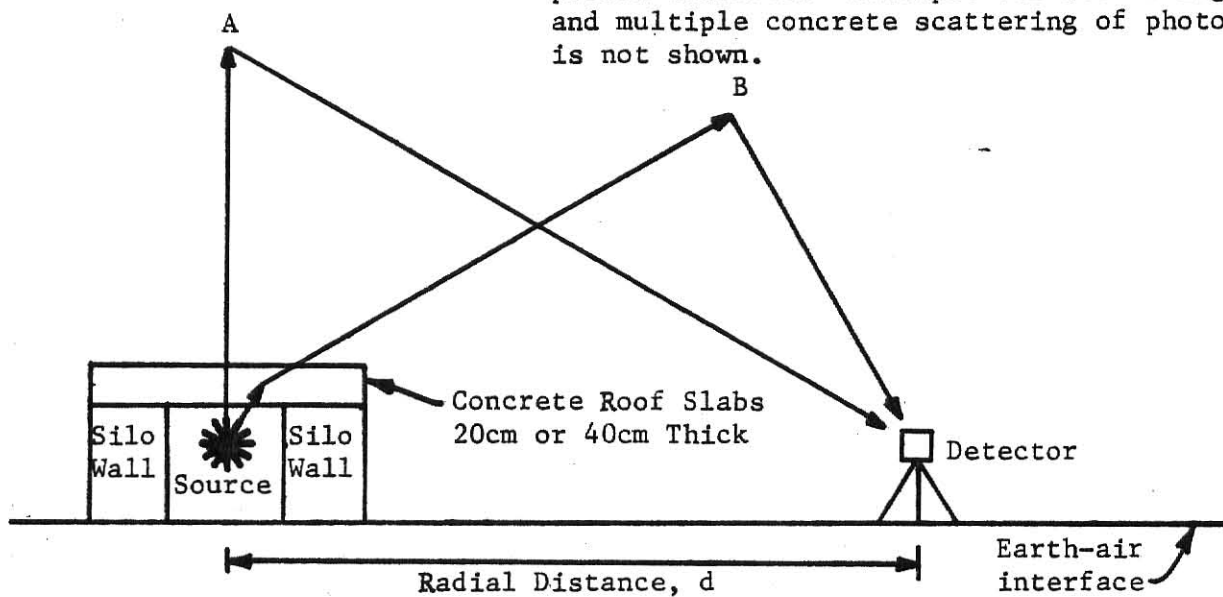


Fig. 1-2. Ideal shielded source configuration.

the NSRA committee. The results of these calculations varied by a factor of nearly seventy at some calculation points. The large disagreement in these results prompted the committee to sponsor and design this experiment to provide experimental data to compare with calculated predictions. The results of the benchmark skyshine experiment can be used to check the accuracy of a calculational method, to correct a calculational method, or to serve directly as design data for skyshine exposure rate problems similar to the experiment.

This benchmark skyshine experiment, designed and sponsored by NRSA, was performed at the Kansas State University Nuclear Engineering Shielding Facility (KSUNESF) from May through November 1977. The KSUNESF site is approximately 175 acres of Flint Hills prairie located approximately five miles west of the Kansas State University campus in Manhattan, Kansas. To obtain a long reasonably level measurement baseline, the skyshine source silo was positioned at the western site boundary adjacent to the Fort Riley Military Reservation. The anticipated positions at which skyshine measurements were to be taken were surveyed and staked off in an east-northeasterly direction from the source. The skyshine measurement positions at every 100 m from the source are shown on Fig. 1-3. Plate 1-1 depicts the terrain details from the source silo toward the measurement locations.

Three ^{60}Co sources with nominal strengths of 10, 250, and 5000 Ci were employed to obtain skyshine radiation fields significantly above background over the entire 700 meter measurement baseline. An approximately cylindrical concrete silo was built with sufficiently thick

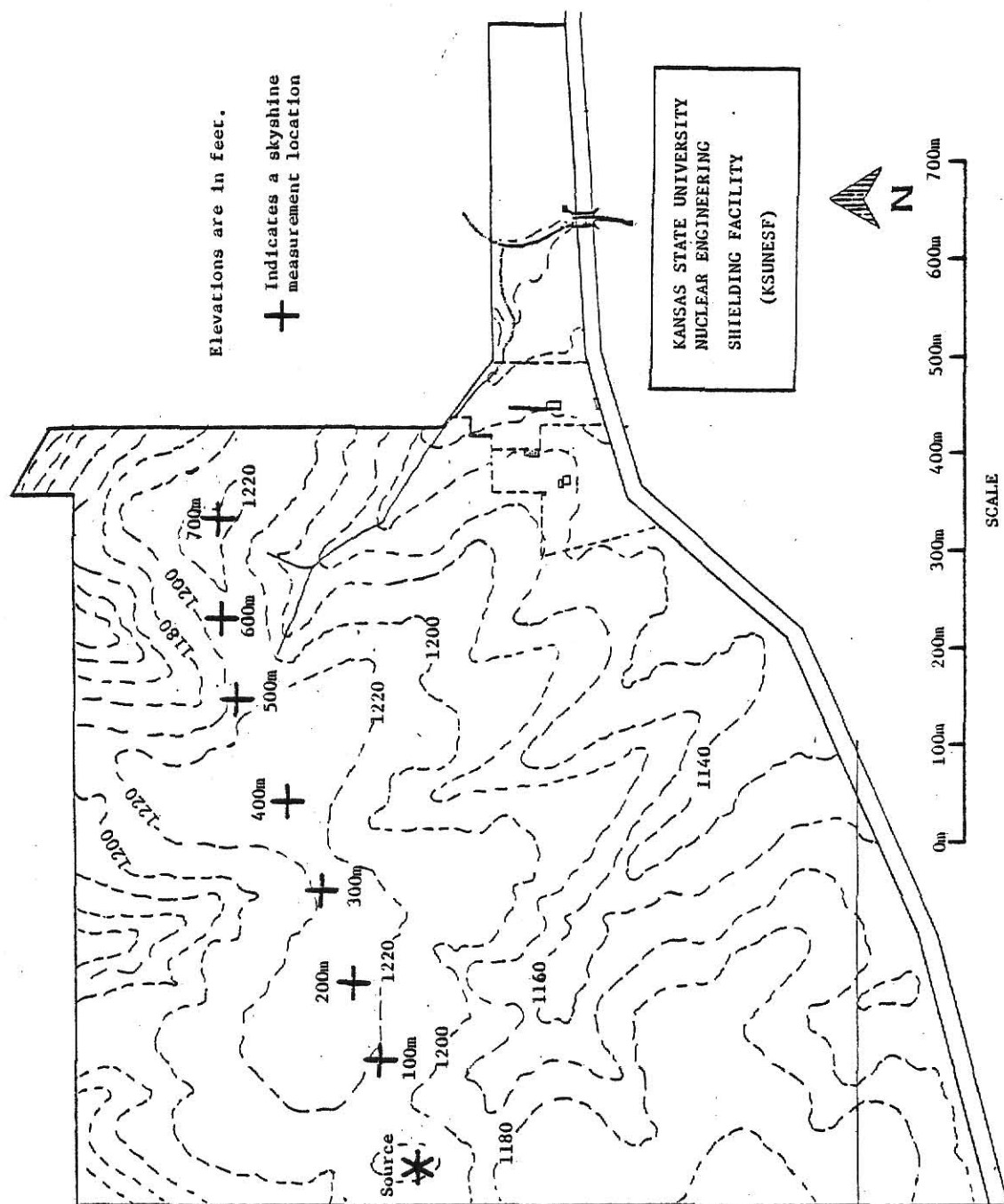


Fig. 1-3. Map of the shielding facility

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Plate 1-1. The Kansas State University Nuclear Engineering Shielding Facility Site photographed from the silo location toward the 100 m detector location (easterly).

walls to reduce the direct penetration component to negligible levels. Skyshine radiation measurements were made with the sources collimated into a 150.5° upwardly directed conical beam and with the sources shielded vertically by 21.0 cm and 42.8 cm of concrete.

Total skyshine exposure rate measurements were taken over source-to-detector distances ranging from 30 m to 700 m for the unshielded configuration (150.5° cone) and the 21.0 cm shielded configuration. For the 42.8 cm shielded silo configuration, the total skyshine exposure rate measurements were taken over source to detector distances of 30 m to 400 m. These measurements were taken with a 25.4 cm spherical high pressure ionization chamber (HPIC). The HPIC was tripod mounted with the supporting electronics housed in a separate container. The HPIC was tested for proper calibration, directional sensitivity, and energy sensitivity. Concurrently, with the HPIC measurements spectral measurements of the skyshine radiation were made with a collimated NaI spectrometer system. For details of this system and the subsequent results see Reference 2.

This work first reviews and examines, in Chapter 2, the experimental facilities designed and constructed for this experiment, the experimental methods used, and the skyshine exposure rate results. The author assisted in the design and supervised the construction of the source silo. The author also assisted in the calibration, sensitivity determinations, and exposure rate data acquisition with the HPIC.

Chapter 3 presents the derivation of a point kernel calculational model based on singly scattered photons for the geometry of this experi-

ment. A constant scattering angle geometry was used to simplify the point kernel model and the numerical analysis of the point kernel. A computer program based on this point kernel was developed and this computer model's sensitivity to the number of mesh points was explored. The computer model also limited integration over photon path lengths up to 10 mfp in air and 15 mfp in concrete. The effects of changing these limits were also explored in Chapter 3.

In Chapter 4, the HPIC skyshine exposure rate results are utilized to determine the proper method of correcting for multiply scattered photons in the point kernel model. Discrete ordinates transport theory (DOT 3.5) calculations performed by Radiation Research Associates, Inc., of Fort Worth, Texas¹; point kernel exposure rate calculations performed by Kadotani, of Century Research Center Corporation in Tokyo, Japan¹⁶; and the point kernel exposure rate calculations performed by the author are compared to HPIC skyshine exposure rate results in Chapter 4. Also in Chapter 4, predictions of the skyshine exposure rate behavior with respect to source collimation, source shielding, and source photon energy are made based on the point kernel model developed in this work.

2.0. EXPERIMENTAL FACILITIES, METHODS AND RESULTS

The objectives of the experimental phase of this work were the measurement of atmospherically scattered gamma radiation from an upwardly collimated 150° conical radiation field and the measurement of atmospherically scattered gamma radiation from a point source shielded vertically by a 20 cm. and a 40 cm. thick concrete slab. Two separate experiments were ran concurrently. Spectral measurements of the skyshine radiation were taken with a 12.7 cm. (5 in.) diameter by 10.2 cm. (4 in.) deep cylindrical NaI crystal in a truck-mounted collimator. Details of the NaI spectrometer system and NaI spectral analysis can be found in Reference 2. High pressure ionization chamber (HPIC) exposure rate measurements were taken along a 700 m radial baseline for the two shielded silo configurations (0.210 m and 0.428 m concrete roofed silos) and for an unshielded silo configuration (150° upwardly collimated conical radiation field). In this chapter, summaries are presented of the design and construction of the source silo, the calibration and sensitivity tests of the HPIC, and the experimental skyshine exposure rate measurements.

2.1 Skyshine Source Silo Design and Construction

Design of the concrete source silo and associated components was based on the following criteria³:

- 1) The gamma sources used should produce a skyshine radiation field significantly above background radiation levels.
- 2) The source silo should be a vertical annulus to simplify numerical modelling.

- 3) The open silo radiation cone should be well defined to simplify numerical analysis.
- 4) The shielded silo roof should be mobile, easily stacked, flat concrete sections with a minimum of reinforcing steel.
- 5) The silo walls must be thick enough to reduce direct penetration of source gamma photons to negligible levels.

All of these design criteria were given due consideration in the construction of the source silo.

2.1.1. Source Silo and Equipment Base Pads

To support the silo walls and the source irradiator casks, a 4.6 m (15 ft.) square 0.23 m (9 in.) thick concrete base pad was fabricated. Radially placed reinforcing steel and wire mesh were used to distribute the expected loads. Figure 2-1 and Plate 2-1 show details of the silo base pad. A steel plate distributed the concentrated source cask load and the source cask guide rails were welded to this plate. Around the base pad, 0.102 m (4 in.) thick concrete pads were poured to support handling equipment for the roof sections (see Fig. 2-2).

2.1.2. Silo Wall

Ideally the silo wall should have had an annular cross section; however, construction of accurate circular concrete forms is both time consuming and expensive. Therefore, the ideal circular shape was approximated by an annular dodecagon (twelve side annulus) as shown in Fig. 2-3. The 0.92 m (3 ft.) thick silo walls reduce the direct penetration exposure rate by a factor of 9000.³ The silo wall was poured in two sections, the lower 1.22 m (4') high section and then the upper 1.07 m (3'-6") high section. The wall sections and the base pad

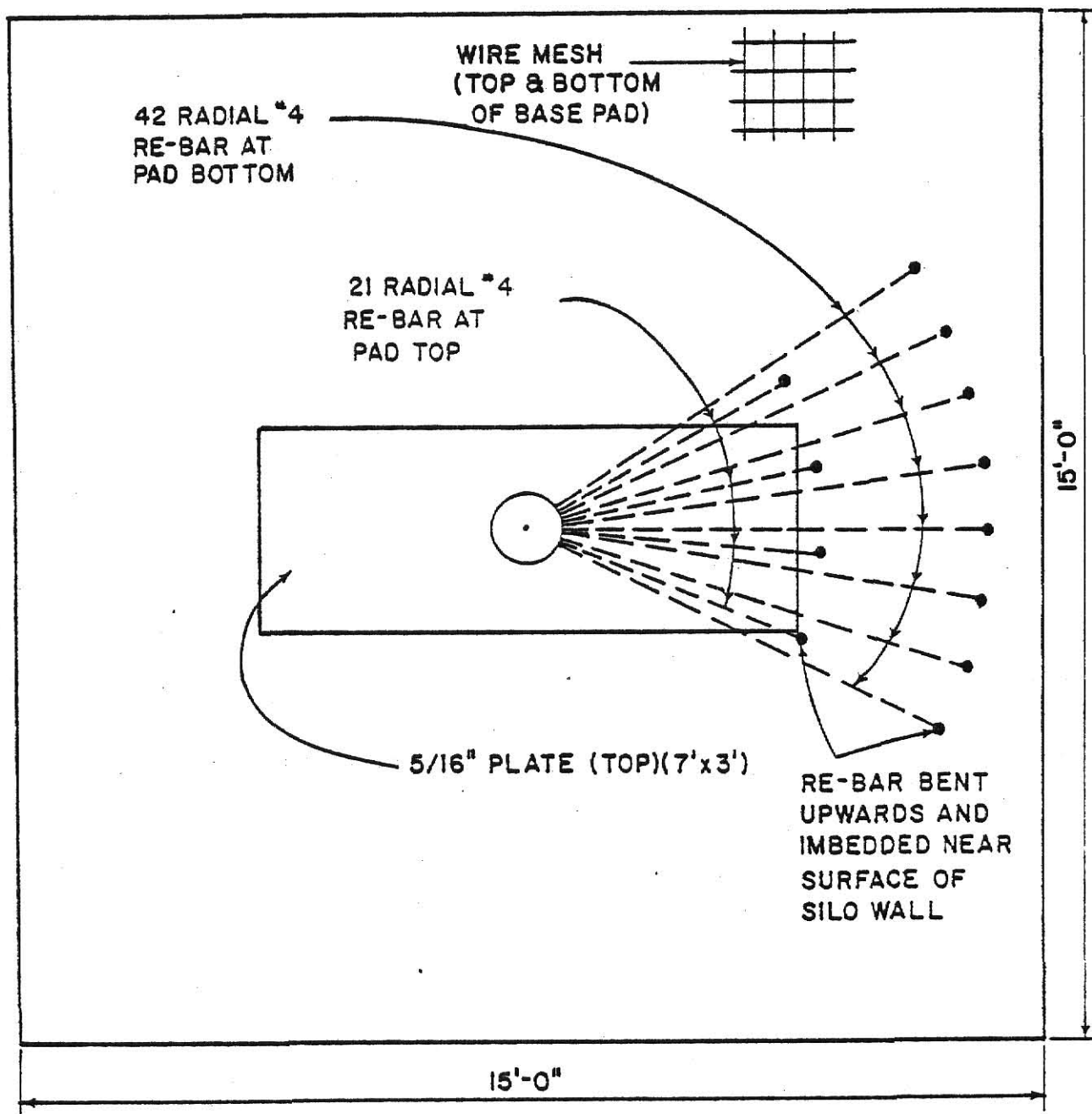


Fig. 2-1. Silo base pad and source cask load distribution plate.



Plate 2-1. The construction of the silo base pad.

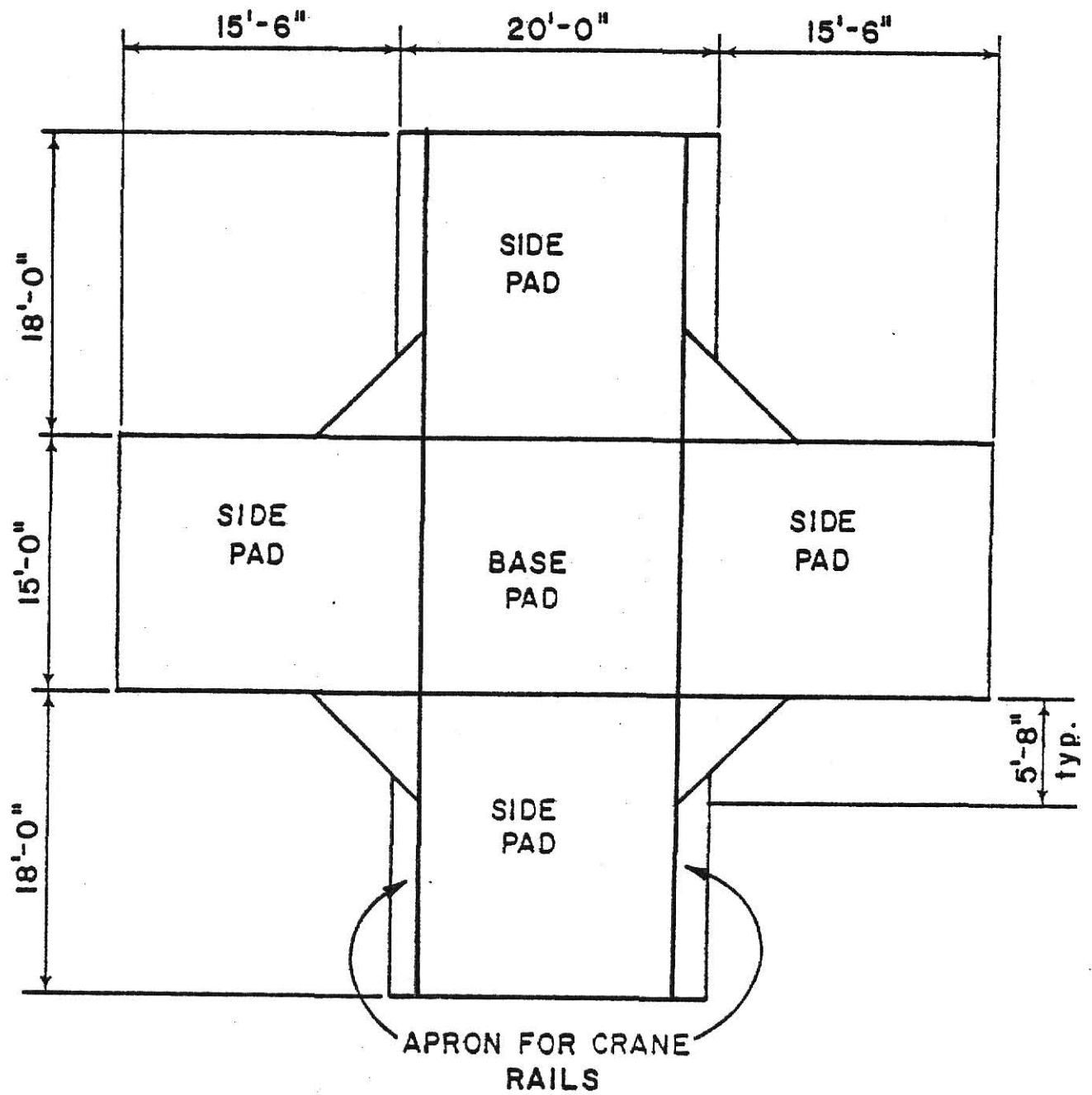


Fig. 2-2. Equipment support pads surrounding the silo.

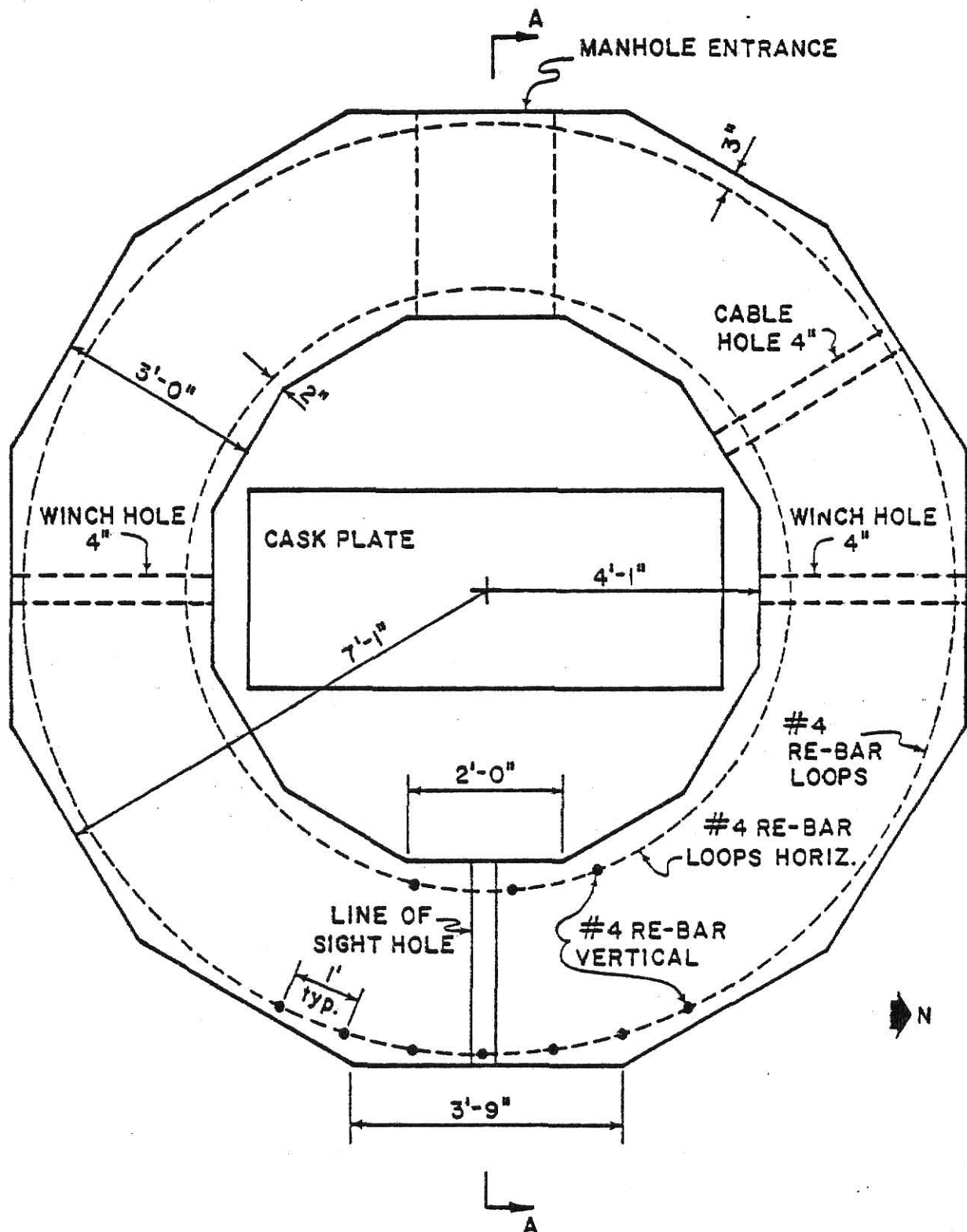


Fig. 2-3. Cross sectional view of the silo walls perpendicular to the silo axis.

were all joined by stepped construction joints and the wall concrete was mechanically vibrated to eliminate voids. The silo wall height was the most critical silo dimension because the source collimator wedges were to be placed on top the silo wall. The silo wall height was carefully maintained at 2.286 ± 0.003 m above the cask base plate.

Several penetrations through the lower section of the silo wall were made to allow personnel access, control cable penetration, and water drainage. A "line-of-sight" penetration was placed on the east side (toward the measurement baseline) so that the gamma irradiator sources could be directly viewed (necessary during the source calibration phase of this experiment). During all skyshine measurements, this line of sight penetration was filled with solid concrete blocks. Figure 2-4 shows the major penetrations in the silo wall.

2.1.3. Collimator Wedges

For the unshielded skyshine measurements, an upwardly directed gamma photon beam of 150° conical collimation was specified. Wedge shaped, solid concrete blocks were made which when placed atop the silo wall defined the required 150° cone when the ^{60}Co source was raised to the cone's apex. These collimator wedges, when positioned on top of the silo wall, defined the apex of the collimation cone on the silo axis at 1.98 m (6.5 ft.) above the cask plate. The collimated beam strength was easily changed by moving the appropriate source cask to the silo center and raising the source to the required height.

Collimator wedge dimensions, shown in Fig. 2-5, were selected so that 48 wedges formed an annulus with an inside diameter of 2.49 m

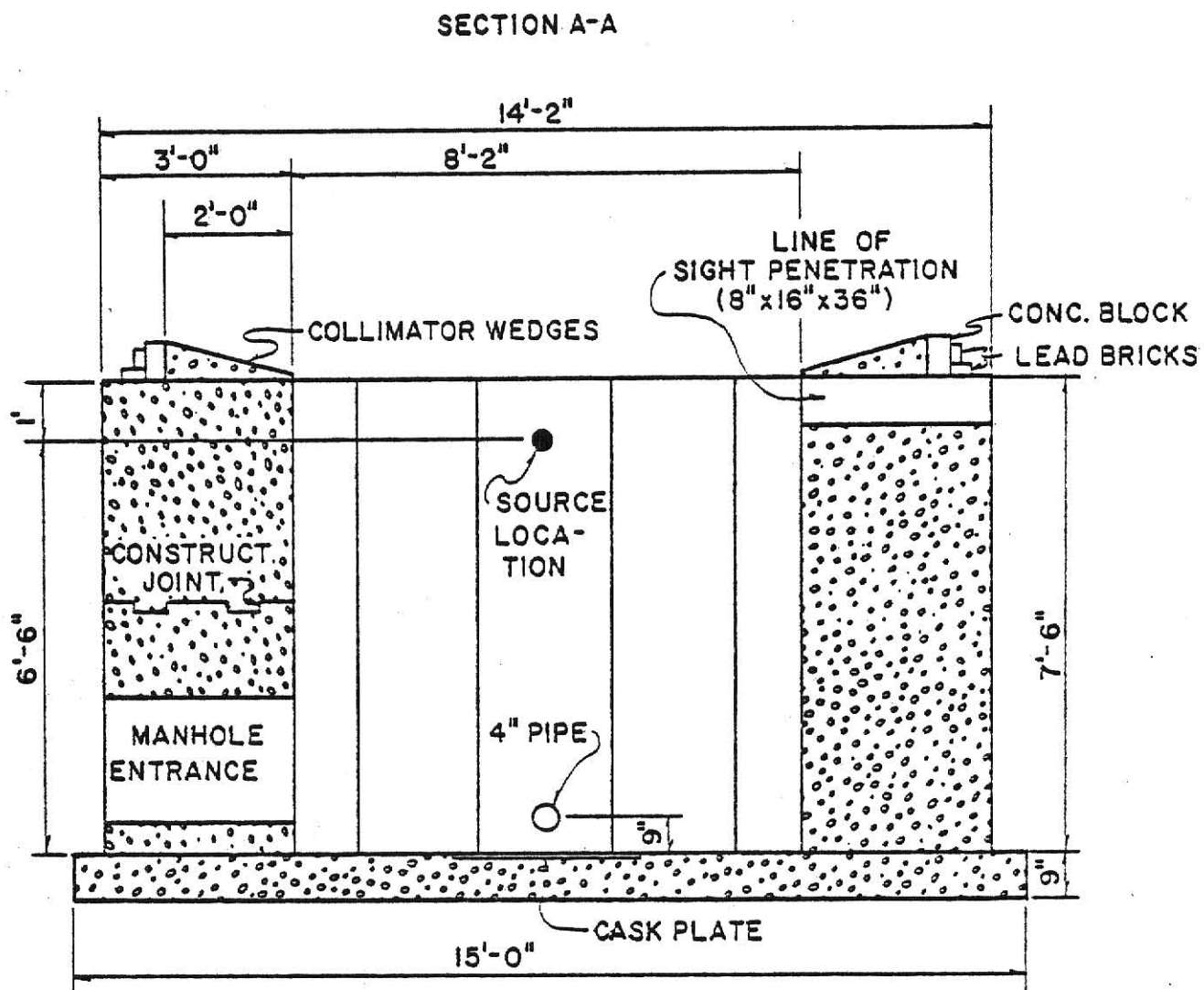


Fig. 2-4. Cross sectional view of the silo walls parallel to the silo axis.

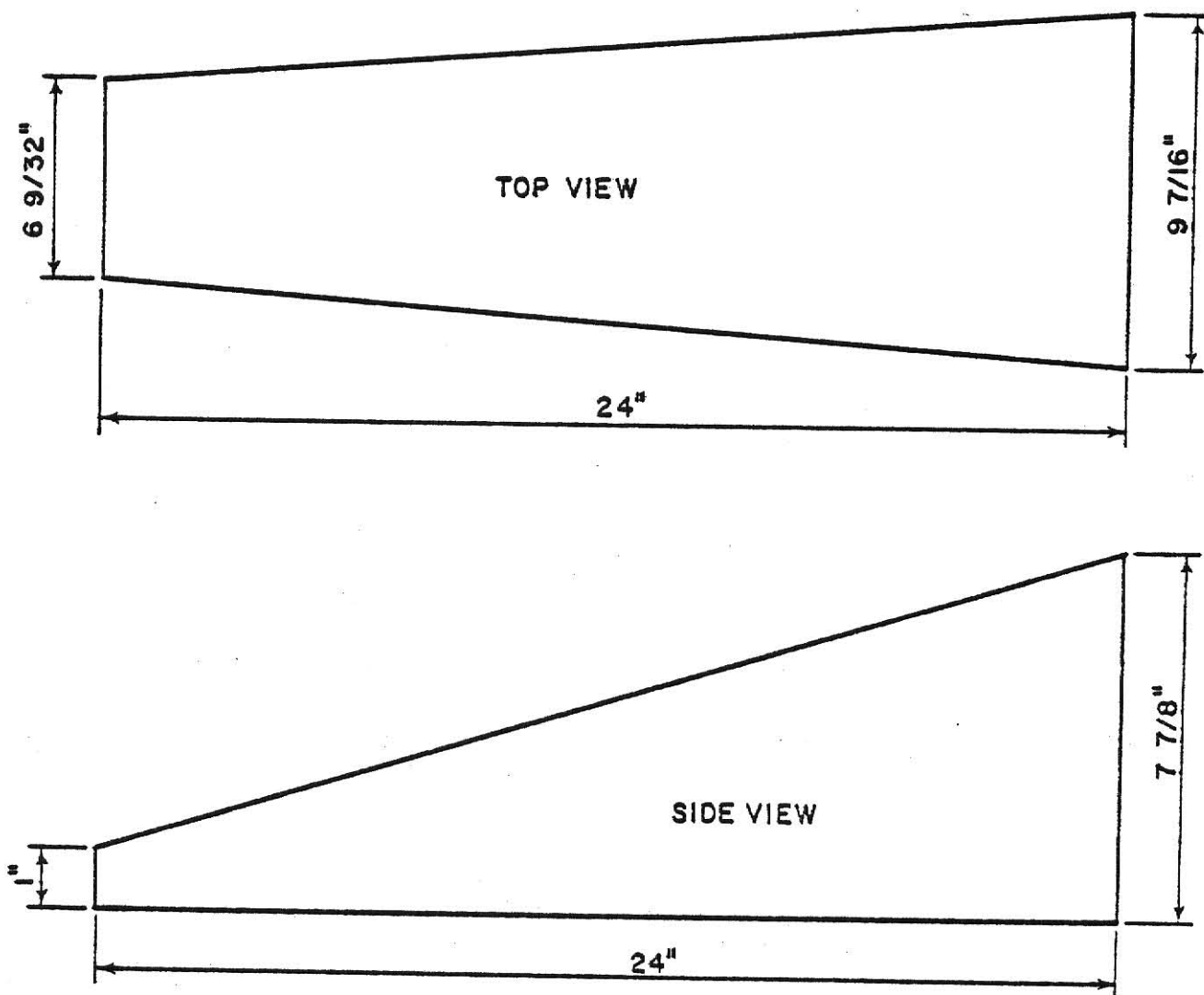


Fig. 2-5. Dimensions of the collimator wedges used to define the 150° source collimation cone.

(8.17 ft.). After completion of the silo wall, the collimator wedges were arranged and the collimator angle was measured at $150.5^\circ \pm 0.2^\circ$. Concrete and lead bricks were placed around the outside of the collimator to minimize further any radiation streaming between or through the collimator blocks. None of the outside bricks were allowed to affect the collimated radiation field by keeping this additional shielding below the lip of the collimator blocks. Plate 2-2 shows the collimator wedges in place.

2.1.4 Silo Roof Slabs

For the shielded skyshine measurements, concrete roof slabs $1.2 \times 3.6 \text{ m} \times 0.10 \text{ m}$ (4 ft. x 12 ft. x 4 in.) were made by pouring concrete into specially constructed steel frames. The steel frame not only served as a form, but also minimized the possibility of breaking the 5.08 cm. (2") stepped sides of the slab. To insure the structural integrity of the roof slabs during movement with a forklift or with the A-frame crane, a small amount of reinforcing steel and wire mesh was imbedded in the concrete slabs. The dimensions and other details of the roof slabs are shown in Fig. 2-6. The thickness of each slab was measured at six locations with a specially constructed long armed caliper. Average thicknesses for each slab are given in Table 2-1.

Concrete sample densities of the silo wall, collimator wedges, and roof slabs were determined by faculty members of the Civil Engineering Department at Kansas State University. These densities are tabulated in Table 2-2, where no correction has been made to account for structural steel.



Plate 2-2. The concrete collimator blocks in position on top of silo wall.

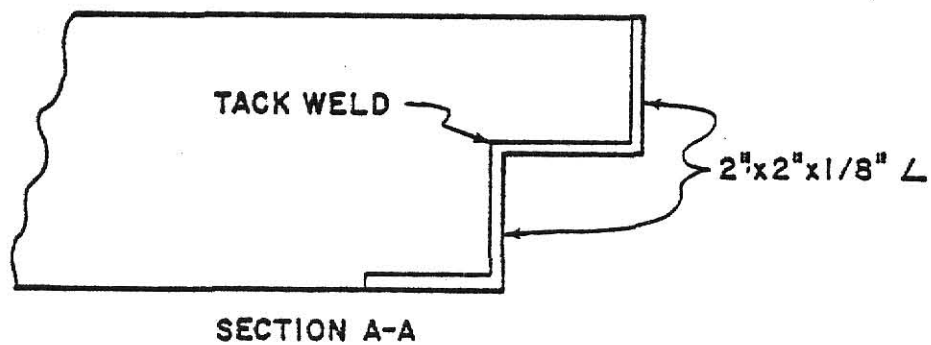
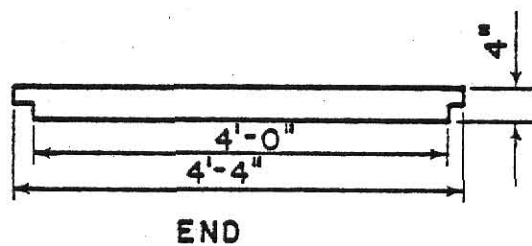
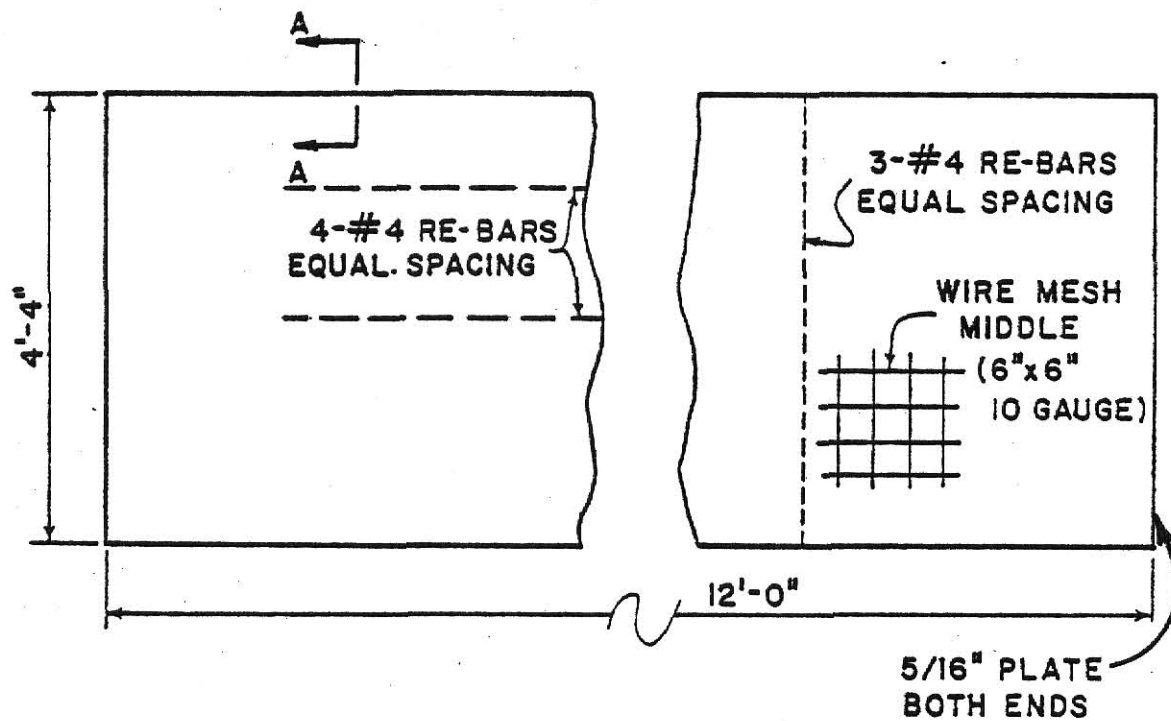


Fig. 2-6. Details of the silo roof slabs used in the shielded source configuration.

Table 2-1. Mean Thicknesses of Silo Roof Shields

Slab No.	Thickness (cm)
1	10.77 $\pm$ 0.29
2	10.90 $\pm$ 0.48
3	10.72 $\pm$ 0.19
4	10.40 $\pm$ 0.16
5	10.34 $\pm$ 0.21
6	11.03 $\pm$ 0.34
7	10.45 $\pm$ 0.25
8	10.53 $\pm$ 0.19
9	10.45 $\pm$ 0.16
10	10.40 $\pm$ 0.22
11	10.58 $\pm$ 0.16
12	10.58 $\pm$ 0.24
Center, 9 + 12	21.03 $\pm$ 0.29
Center, 1 + 6 + 9 + 12	42.83 $\pm$ 0.53

Table 2-2. Measured Concrete Densities for Various Source Silo Structures³

Structure	Density (g cm ⁻³)
Silo	2.17 ± 0.02
Roof Shields	2.13 ± 0.02
Collimator Wedges	1.93 ± 0.02

After completion of the open silo skyshine measurements, the first layer of roof slabs were mortared on top of the silo wall. This mortar eliminated the possibility of radiation streaming between the lowest roof slabs and the top of the silo wall. Matching the stepped sides on the roof slabs prevented radiation streaming vertically. The roof slabs were numbered and always stacked in the same pattern as shown in Fig. 2-7. To minimize the effect of the steel frames, the slabs were positioned with their long axis parallel to the skyshine measurement baseline. In this configuration, the steel frames would have a maximum (although small) effect on the radiation leaving the silo perpendicularly to the source detector axis. Radiation leaving towards the detector encountered a minimum of steel. Plate 2-3 shows the source silo in the 0.428 m shielded configuration.

2.1.5 ⁶⁰Co Gamma Irradiators

The ⁶⁰Co gamma irradiators were designed and manufactured by J. L. Shephard and Associates, Inc., especially for this experiment. Two source casks were mounted on a V-wheeled cart. The V-wheels rode on an inverted angle iron welded to the base pad cask plate. Wheel chocks were attached to both ends of the angle iron guide rail. When

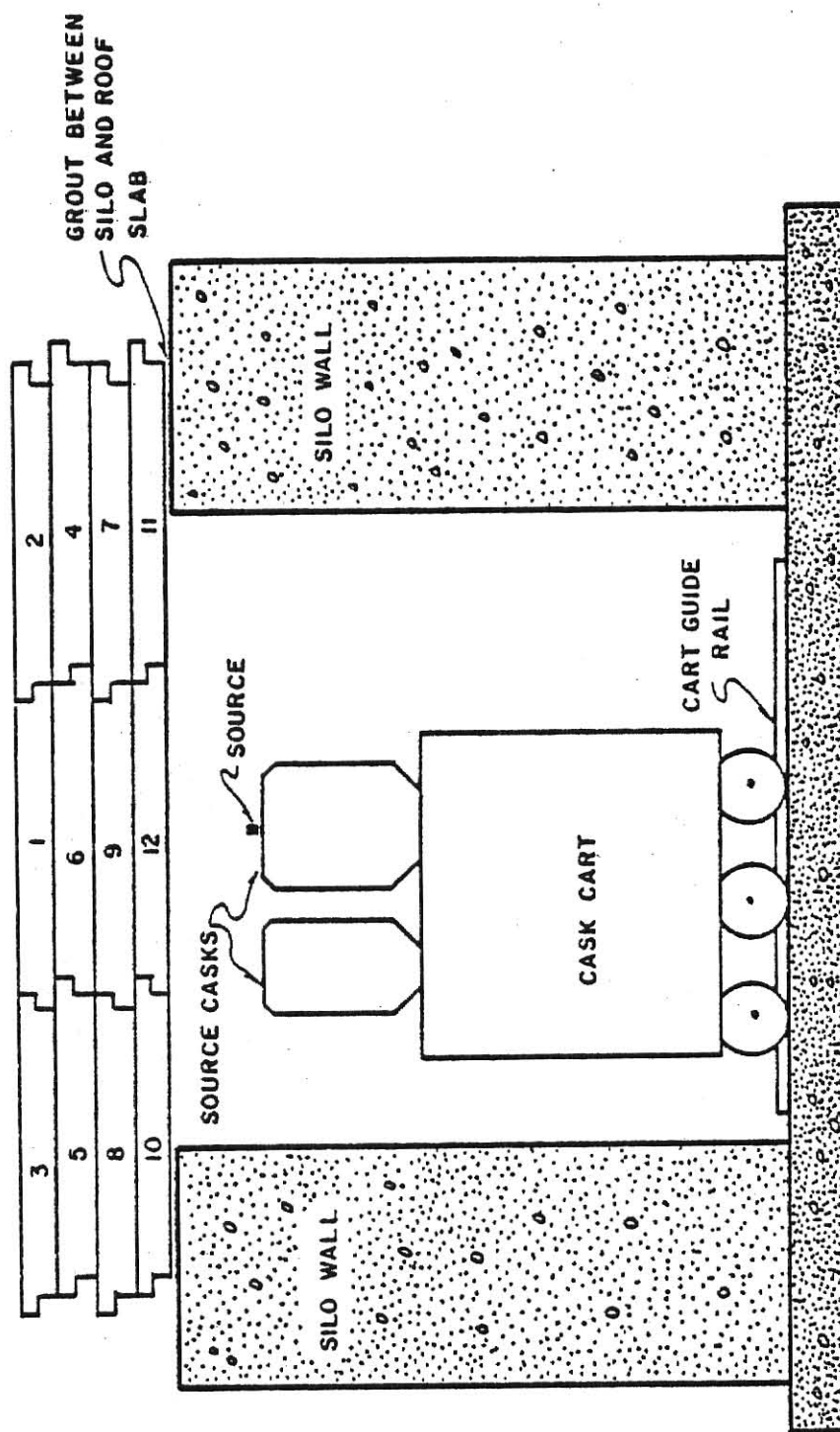


Fig. 2-7. View of the source silo showing the roof slabs in position for the shielded source configuration.



Plate 2-3. Source silo in the 0.428 m shielded configuration.

the cart was at either end of the guide rail, one of the casks was positioned along the axis of the source silo. Plates 2-4 and 2-5 show installation of the two irradiator units and Fig. 2-8 gives the dimensions of the irradiator assemblies.

The smaller cask contains both the nominal 10 Ci and 25.0 Ci ^{60}Co sources. While the larger cask contains a nominal 5000 Ci ^{60}Co source. The 10 Ci source was 2" from the apex of the collimator core when exposed. The mid-points of the larger sources were at the apex of the collimator core when these sources were properly positioned and raised.

In order to minimize personnel dosages, the irradiators were operated from a remote console at the 100 m skyshine measurement position. The remote console is pictured in Plate 2-6. Irradiator operation started with the pneumatic positioning of the sliding source attenuator, which was mounted on top of the source cask, until a vertical hole in the attenuator was positioned over the source (refer to Fig. 2-8). After the attenuator was positioned, the selected source was pneumatically raised out of the irradiator to a height of 1.98 m (6'-6") above the silo base pad. The positioning of the sources and attenuators were confirmed by status lights on the remote console. Microswitches on the irradiator assembly prevented inappropriate movement of the attenuator and the source.

A cubical sheet metal weather housing fitted over both source casks to protect the irradiator casks and associated components from

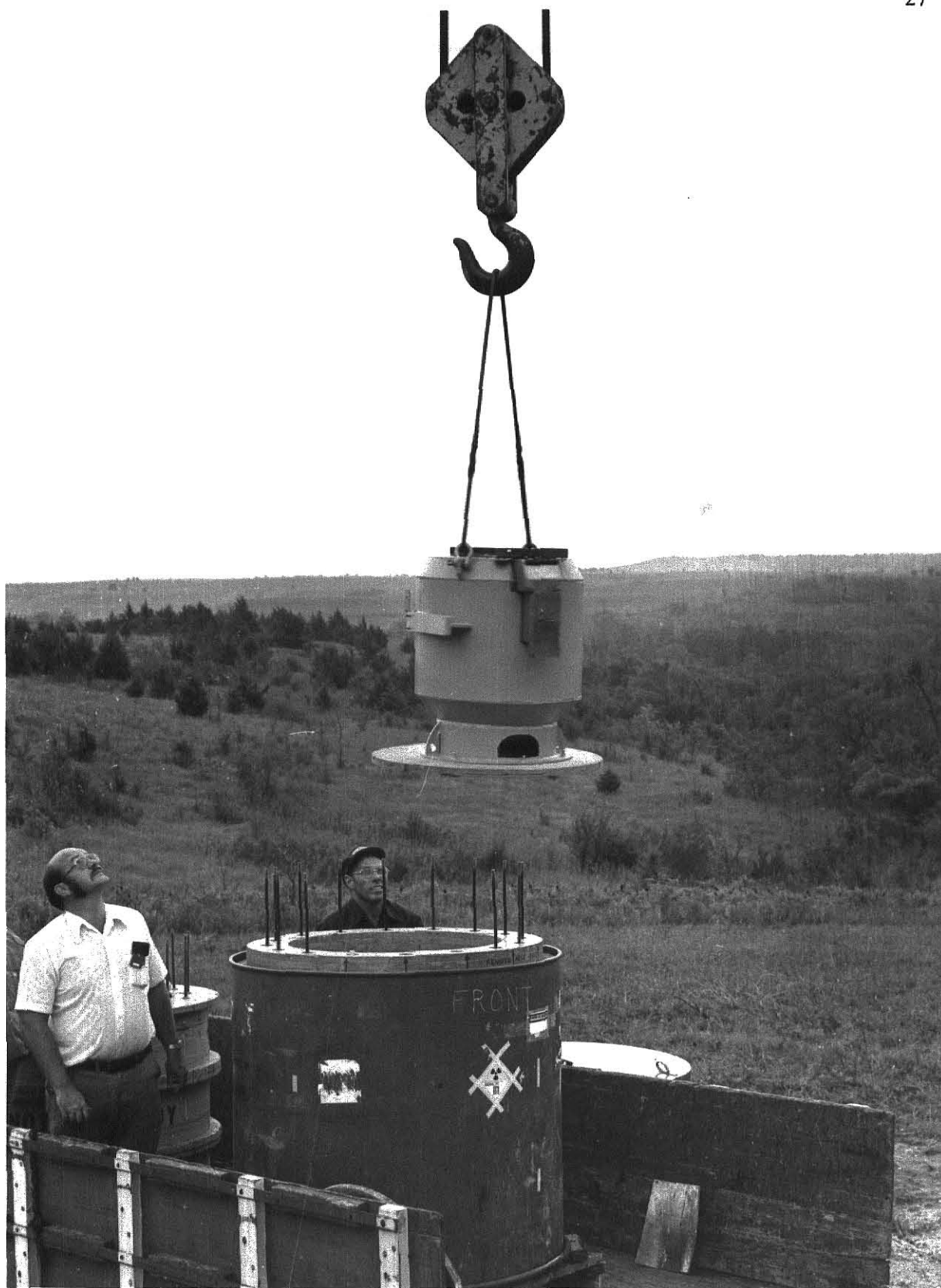


Plate 2-4. Source irradiator prior to placement in source silo.

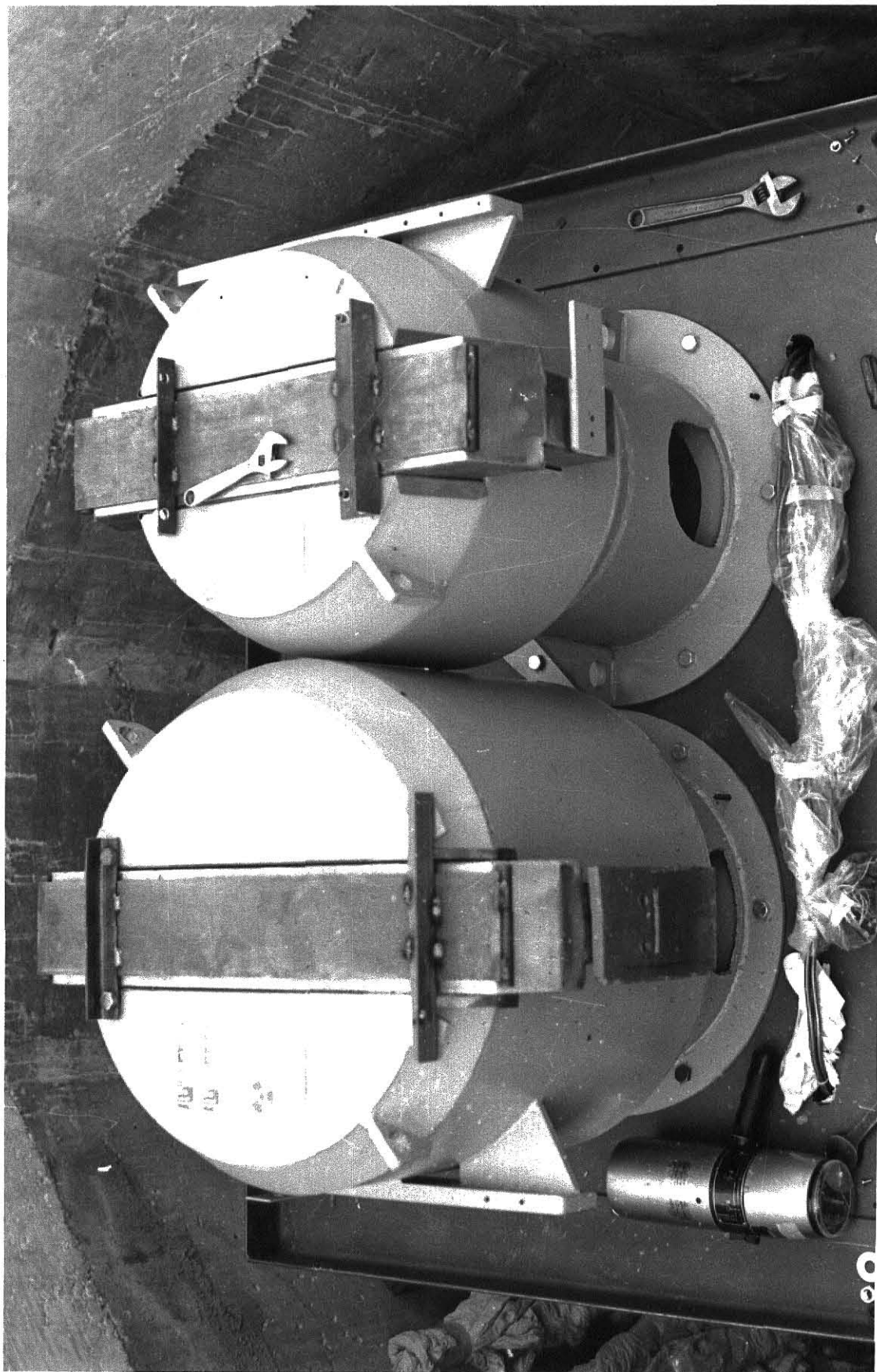


Plate 2-5. Source irradiators being installed on movable platform.

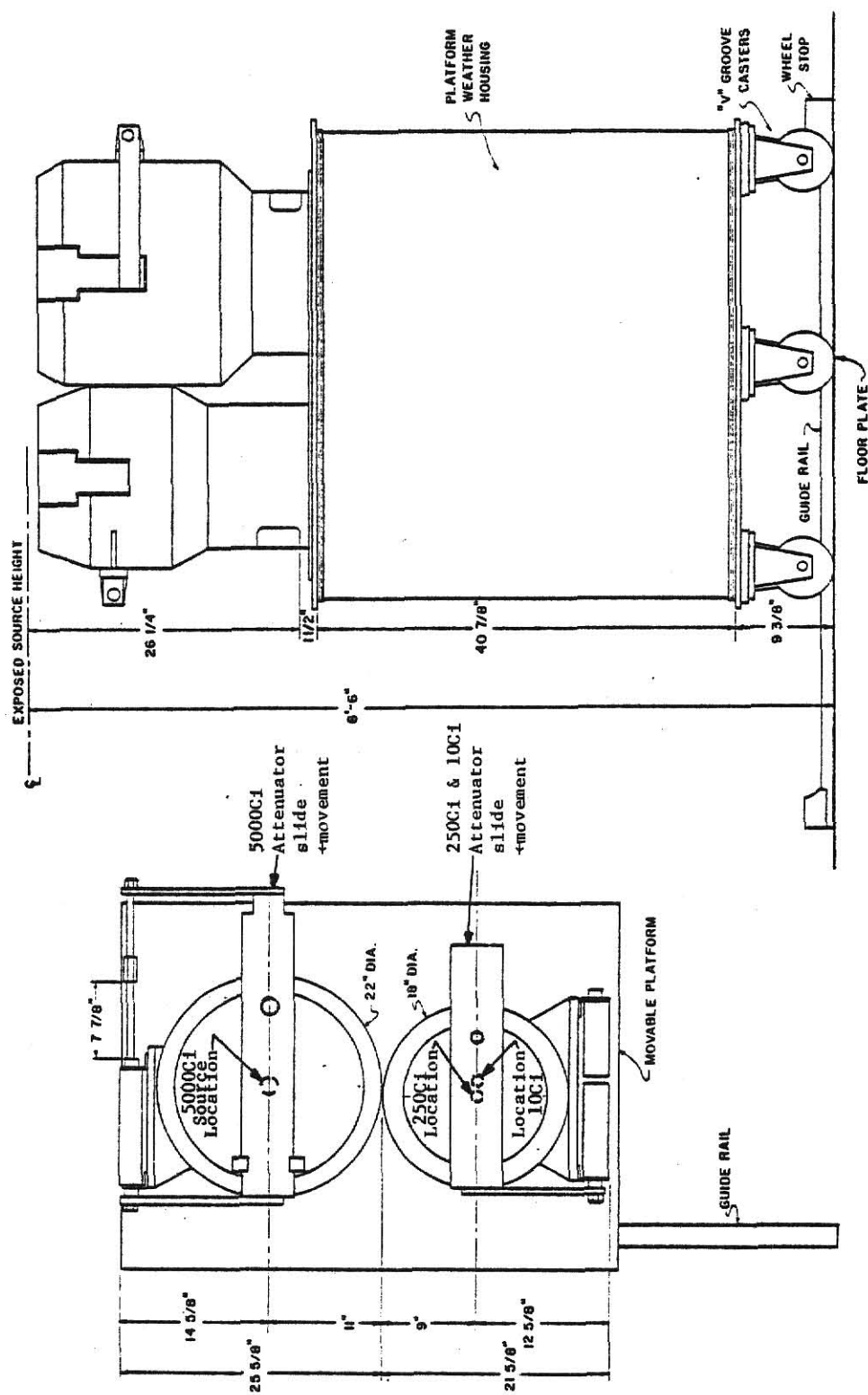


Fig. 2-8. Diagram of the ^{60}Co irradiator.

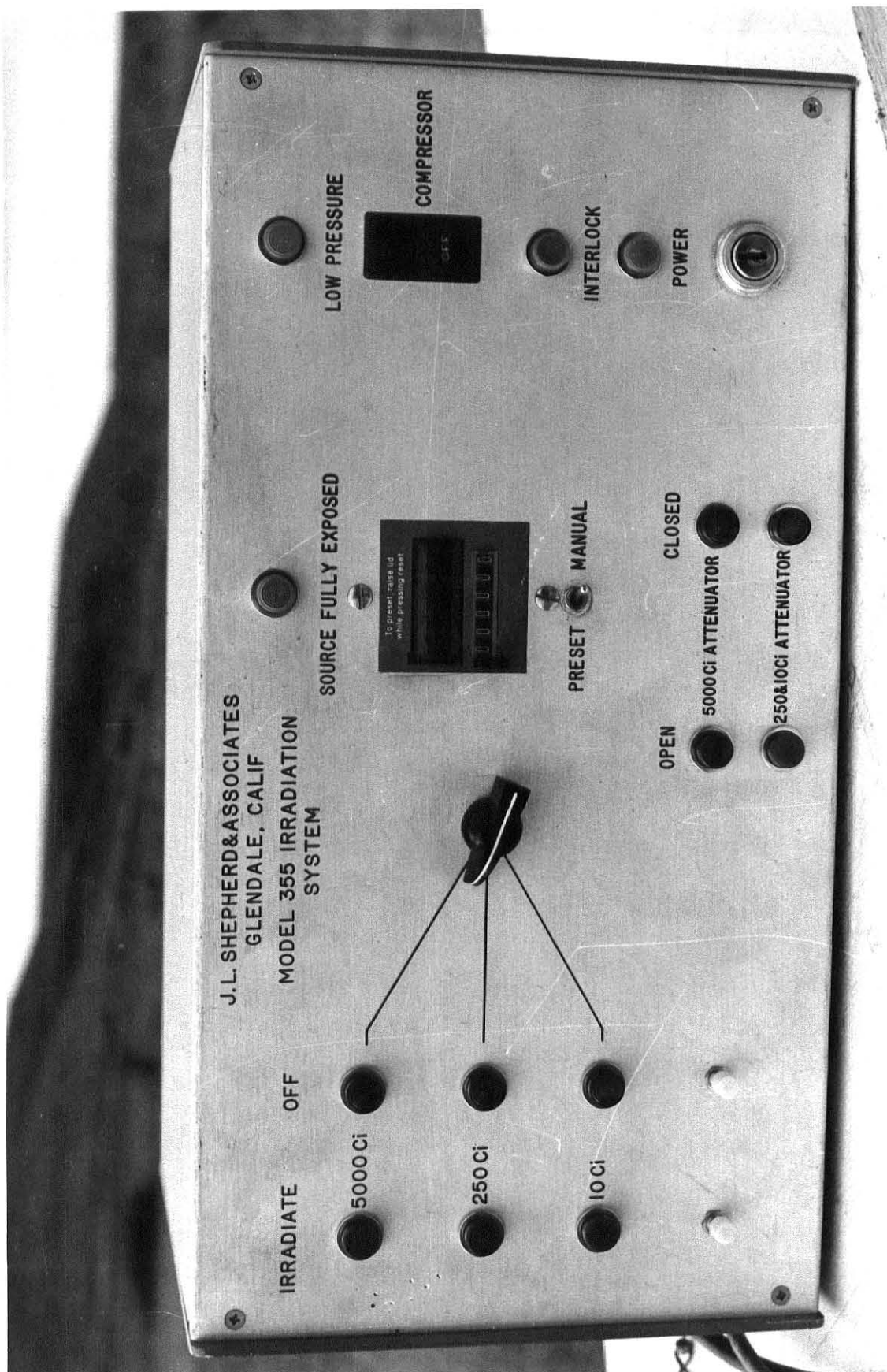


Plate 2-6. Source irradiators remote console.

moisture and dust. Thin walled steel hemispherical domes were built into the top of this weather housing directly over the sources. These hemispherical domes presented all upward directed photons from the raised source with identical mass thicknesses, thereby assuring all portions of the upward collimated photon beam would be attenuated equally.

The ^{60}Co sources stored in the irradiators were right cylinders doubly encapsulated in stainless steel and manufactured by Atomic Energy of Canada, Ltd. The 5000 Ci ^{60}Co source was dimensionally the largest of the three sources, 2.86 cm (1.125 in.) in diameter and 3.49 cm (1.375 in.) long. Therefore, all three sources were considered point sources when compared to source to detector distances involved.

However, since these sources were encapsulated and some self-absorption of emitted photons took place, the effective source strengths were determined experimentally to be 10.37, 228.7, and 3797 Ci, effective October 1, 1977.⁴ The overall uncertainty (standard deviation) in these source strengths was estimated to be 5.0 percent. These calibration experiments were based on absolute measurements by the NaI spectrometer of the uncollided source photons which passed through a known distance and mass thicknesses of attenuating material (air and iron slabs). The geometry used is depicted in Fig. 2-9. After a suitable spectrum was taken, the table at the 120 m position was stacked with 4" thick lead bricks and another spectrum was taken. Subtracting the spectrum with the lead brick attenuator from the first spectrum yielded a spectrum without small angle scattering contributing to the

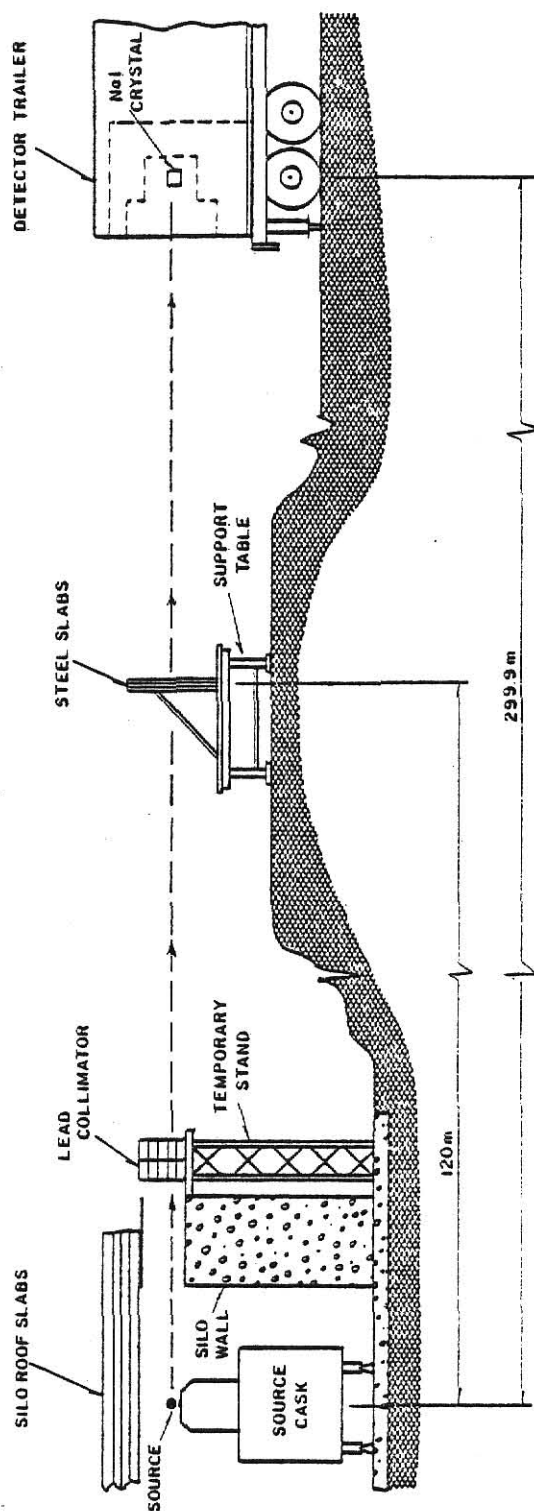


Fig. 2-9. Geometry used in the skyline source calibration experiment.

photopeaks. Comparison of this spectrum with a spectrum from an National Bureau of Standards (NBS) calibrated source yielded an effective source strength. Using effective source strengths calculated in this manner and the relative source strengths calculated from skyshine spectra at 300 m and 600 m, the effective source strengths, quoted above, were determined, for additional details on the source calibrations, see Reference 4.

2.2 High Pressure Ionization Chamber

The exposure rate measurements were obtained with a Reuter Stokes RSS-111 Area Monitor System. The basic detector of this system was a 25.4 cm. (10 in.) spherical ion chamber constructed of 3.05 mm (0.120 in.) thick 304 stainless steel.⁵ The steel shell of this ion chamber was filled with high purity argon at 2.5 MPa (25 atmospheres).⁶ The central electrode of the ion chamber was a 5 cm (2 in.) aluminum sphere. The ion chamber was protected from moisture and dust by a 2.4 mm (0.093 in.) thick aluminum cubical housing.⁵ A solid state electrometer with a strip chart recorder and a LED readout was connected to the ion chamber by a 6.1 m (20 ft.) coaxial cable. This electrometer and its readouts were enclosed with a battery pack and battery charger in a second aluminum cubical weather housing. Plate 2-7 shows the high pressure ionization chamber HPIC ready to take measurements. Plate 2-8 shows the control and readout panel for the HPIC.

The area monitor system was calibrated by the manufacturer on 24 March 1977. The HPIC was calibrated to read directly in μRh^{-1} . The HPIC system had automatic range switching with ranges of 1-50



Plate 2-7. High pressure ionization chamber set up at a 100 m measurement location.

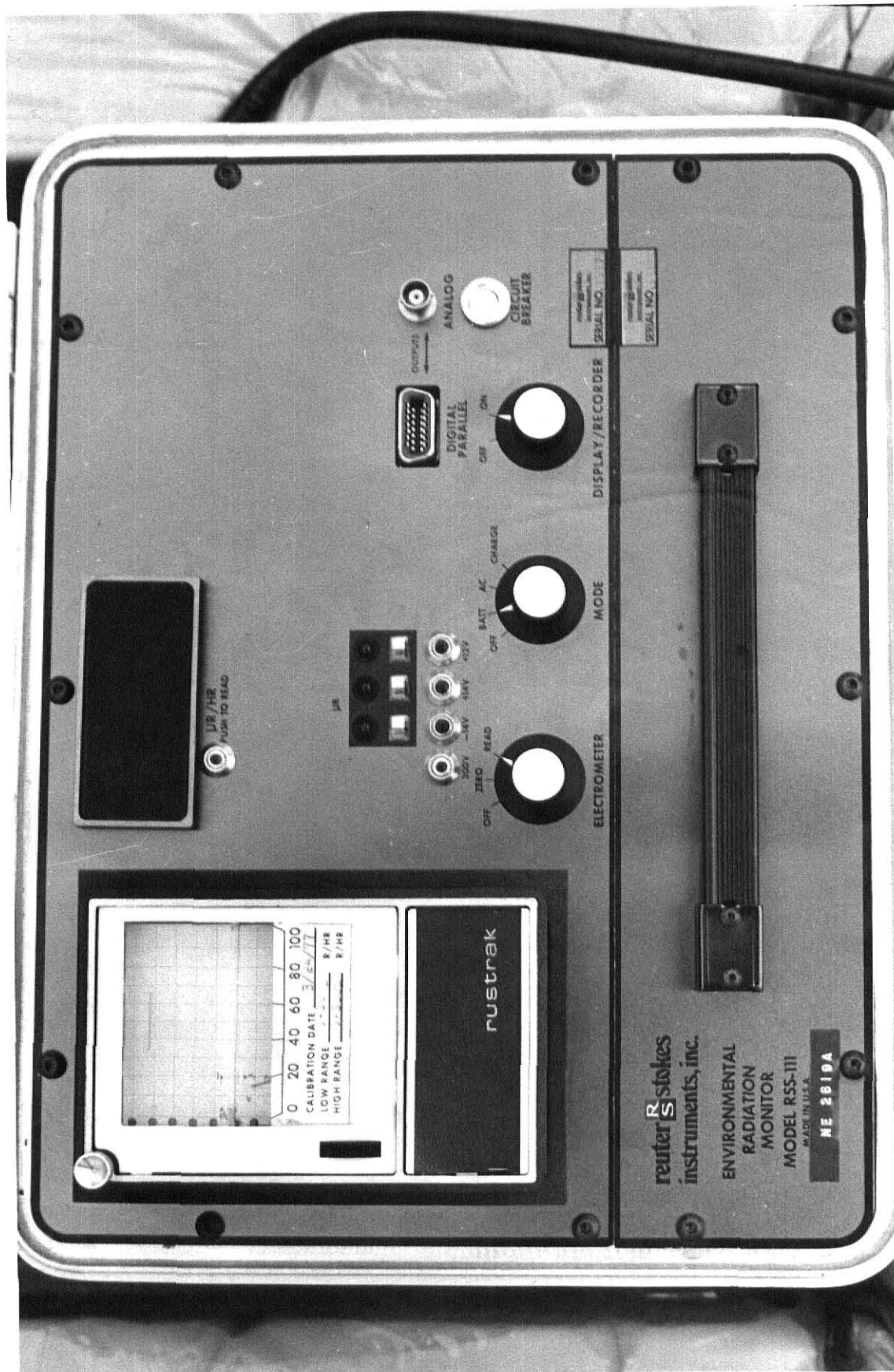


Plate 2-8. High pressure ionization chamber control console.

and 50-500 μRh^{-1} . Before skyshine exposure rate measurements were attempted, the directional sensitivity, the calibration, and the energy sensitivity of the HPIC system were verified. These pre-operational tests are described in the following subsections.

2.2.1 Directional Sensitivity

Directional sensitivity was determined by measurements of exposure rates with each of the six faces of the cubical detector housing, containing the HPIC, sequentially illuminated by the same intensity of ^{137}Cs photons. In these measurements, the center of the cubical detector housing and a 3.38 mCi ^{137}Cs source were placed 2 m apart with both 1 m above a concrete floor. This simple test showed that the HPIC readings varied only $\pm 1.4\%$ when the detector was illuminated from the four sides or the top.⁵ This variation was well within the uncertainties due to positioning errors. However, when the detector was illuminated from the bottom, HPIC response was 8.8% lower than the average response obtained with the other five faces illuminated.⁵ A low response was expected due to the tripod mounting plate attached to the base of the HPIC. Since less than 10% of the skyshine radiation¹ would intersect the detector bottom, this small directional sensitivity of the HPIC was considered negligible.

2.2.2 Calibration Tests

In the calibration tests, the manufacturer's calibration was verified over radiation intensities ranging from 10 to 330 $\mu\text{R h}^{-1}$. The cubical detector housing was centered 0.914 m (3 ft.) above a large concrete pad at the KSU Nuclear Engineering Shielding Facility.

A 3.1 ± 0.1 mCi or a 14.2 ± 0.5 mCi ^{137}Cs source was positioned 5.08 cm (2 in.) above the concrete pad and 2 to 18 m from the vertical axis of the detector housing. Figure 2-10 depicts the source-detector geometry used in the verification of the HPIC calibration.

An exposure rate calculational method which includes scattered radiation components specifically applicable to this geometry has been reported by Chilton.⁷ This method was based on the calculation of the unscattered gamma flux ϕ_0 by the equation

$$\phi_0 = \frac{3.7 \times 10^6 \text{ Sf}}{4\pi x^2} \exp[-100 (\mu/\rho) \rho x] \{\text{cm}^{-2} \text{ s}^{-1}\}, \quad (2-1)$$

in which S is the point source strength in curies, f the fraction of decay in which a gamma photon of energy E_0 is emitted, μ/ρ the mass attenuation coefficient for air in $\text{cm}^2 \text{ g}^{-1}$, and ρ the air density in g cm^{-3} . The source-detector distance x for this calibration experiment is given by the equation (see Fig. 2-10)

$$x = (r^2 + 0.8636^2)^{1/2} \{\text{m}\}. \quad (2-2)$$

For ^{137}Cs gamma photons of energy 0.6616 MeV, γ is 0.846 and μ/ρ is $0.0771 \text{ cm}^2 \text{ g}^{-1}$ according to Reference 5. Air density was approximated by

$$\rho = 0.001293 \times 273 \text{ p/T} \{\text{mg cm}^{-3}\}, \quad (2-3)$$

in which T is the absolute temperature in degrees K and p is the atmospheric pressure in bars. The total exposure rate $\dot{X}$ in mR h^{-1} is then computed as⁵

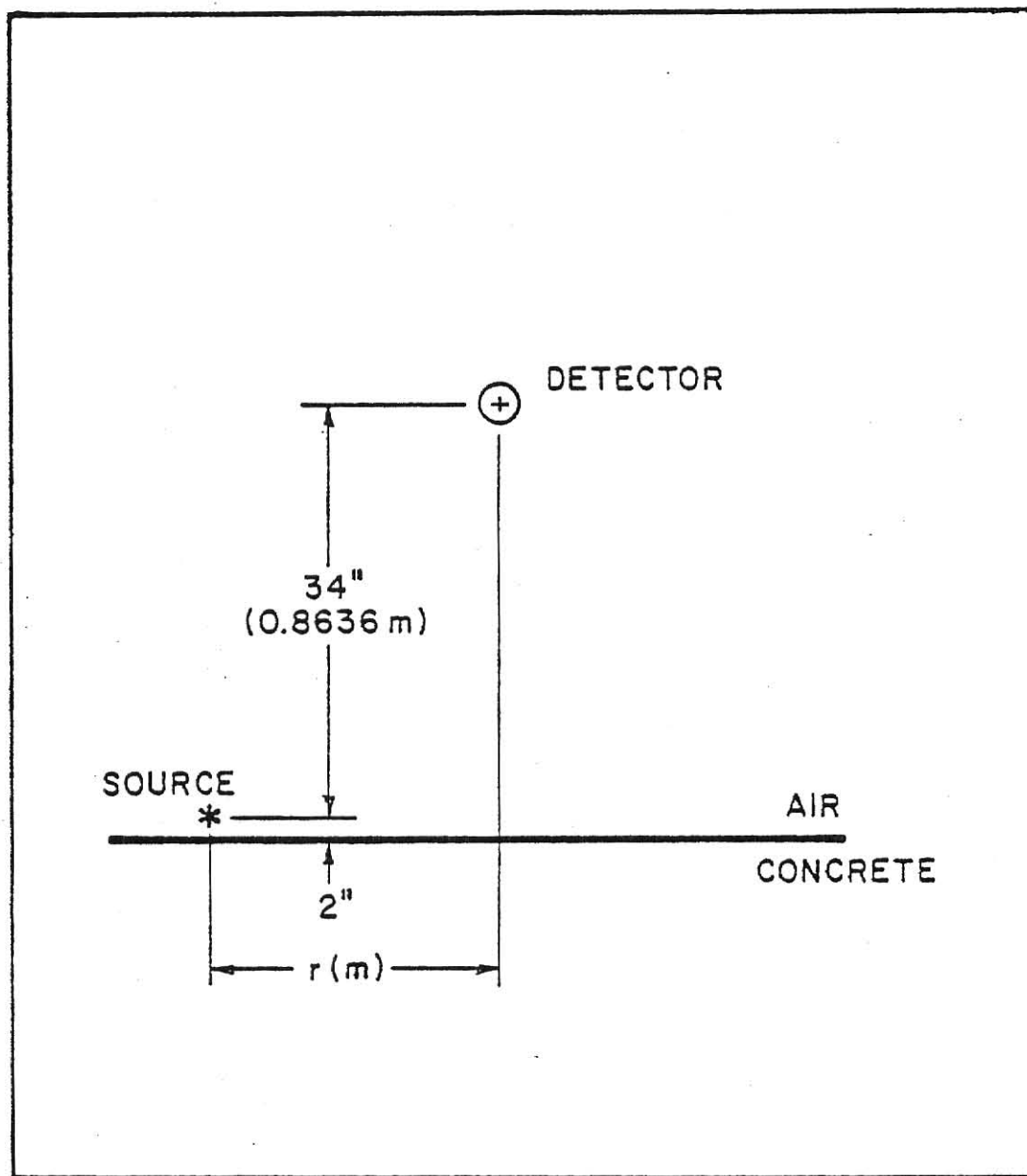


Fig. 2-10. Source-detector geometry for calibration of the HPIC.

$$\dot{X} = 0.0658 E_o \phi_o (\mu_{en}/\rho) B_{\infty} K \{mR h^{-1}\}, \quad (2-4)$$

in which μ_{en}/ρ is the air mass absorption coefficient, $0.0295 \text{ cm}^2 \text{ g}^{-1}$ for ^{137}Cs gamma photons and E_o is the source photon energy in MeV.

The quantity B_{∞} is the infinite medium exposure buildup factor for air. The Berger form of the buildup factor, used in the Chilton method, can be written for the $0.6616 \text{ MeV } ^{137}\text{Cs}$ gamma photons as

$$B_{\infty} = 1 + 0.92 (100 \mu x) + 0.36 (100 \mu x)^2. \quad (2-5)$$

The factor K , developed by Chilton, is included in Eq. (2-4) to correct for the reflection of gamma photons from the concrete pad. For the geometry of Fig. 10, the appropriate K factors can be found from Fig. 2-11.

Calibration exposure rates, corrected for background, are presented in Table 2-3 and illustrated in Fig. 2-12. These calibration results indicated that the HPIC response was linear over a wide range of exposure rates. A linear least squares fit of the data yielded

$$C = 0.951 M, \quad (2-6)$$

in which M is the measured HPIC reading and C is the calculated exposure rate. Statistical analysis of the least squares fit yielded an estimated standard deviation of 0.5% for an individual HPIC response. This uncertainty was completely overshadowed by the 3.5% uncertainties of both source activities. The coefficient 0.951 in Eq. (2-6) was a result of the HPIC variable sensitivity to different photon energies

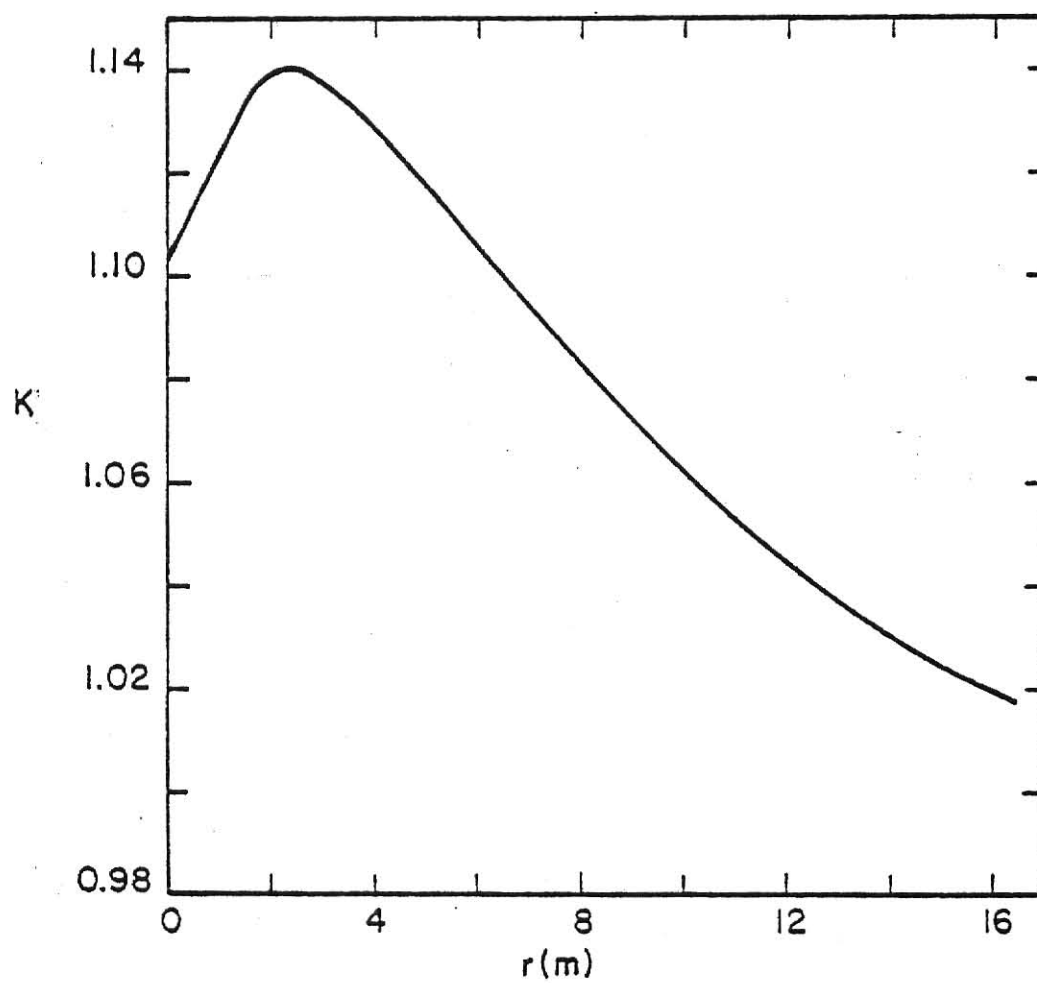


Fig. 2-11. Correction factor for reflection of ^{137}Cs gamma photons for the geometry of Fig. 2-10.⁷

Table 2-3. Calibration Check for the Reuter-Stokes Area Radiation Monitor Using ^{137}Cs Gamma Ray Sources.

S(mCi)	ρ (mg cm $^{-3}$)	r(m)	Calculated $\bar{X}$ ($\mu\text{R/h}$)	Instrument Reading ($\mu\text{R/h}$)
14.23	1.197	4	305.7	333.4 $\pm$ 1.1
		5	196.7	205.6 $\pm$ 1.0
		7	99.5	106.3 $\pm$ 0.9
		7	99.5	106.9 $\pm$ 0.9
		8	75.5	82.7 $\pm$ 0.7
		10	47.6	49.4 $\pm$ 0.8
		12	32.5	35.6 $\pm$ 0.6
		14	23.5	26.4 $\pm$ 0.9
		18	14.0	14.8 $\pm$ 0.6
14.23	1.159	4	306.0	321.5 $\pm$ 0.3
		7	99.7	107.5 $\pm$ 0.4
		7	99.7	107.0 $\pm$ 0.5
		10	47.7	53.5 $\pm$ 1.3
		14	23.6	25.3 $\pm$ 0.4
3.096	1.159	2	237.4	237.0 $\pm$ 0.9
		4	66.6	60.0 $\pm$ 0.5
3.094	1.142	2	237.3	246.8 $\pm$ 0.8
		4	66.6	69.8 $\pm$ 0.6
14.22	1.142	4	306.0	320.3 $\pm$ 0.7
		5	196.8	208.8 $\pm$ 0.8
		7	99.7	105.8 $\pm$ 0.8
		8	75.8	79.8 $\pm$ 0.6
		10	47.8	53.8 $\pm$ 0.8
		12	32.6	35.3 $\pm$ 0.6
		14	23.7	25.7 $\pm$ 0.6
		18	14.1	15.2 $\pm$ 0.6
3.094	1.159	2	237.3	248.8 $\pm$ 0.7
		4	66.6	66.8 $\pm$ 0.6
14.22	1.159	5	196.8	209.8 $\pm$ 0.7
		8	75.7	82.8 $\pm$ 0.8
		12	32.6	35.2 $\pm$ 0.6
		18	14.1	13.9 $\pm$ 0.6
3.093	1.218	3	115.0	108.2 $\pm$ 0.7
	1.210	5	42.7	48.3 $\pm$ 0.7
	1.210	6	29.6	32.0 $\pm$ 0.8
	1.205	7	21.6	23.0 $\pm$ 0.7
	1.205	8	16.4	17.4 $\pm$ 0.6
	1.201	9	12.9	13.7 $\pm$ 0.6
	1.201	10	10.3	10.2 $\pm$ 0.5
3.093	1.154	3	115.1	118.8 $\pm$ 0.6
	1.157	5	42.8	46.3 $\pm$ 0.7
	1.157	6	29.7	30.2 $\pm$ 0.7
	1.157	7	21.7	21.4 $\pm$ 0.6
	1.165	8	16.5	16.3 $\pm$ 0.6
	1.165	9	12.9	12.8 $\pm$ 0.6
	1.165	10	10.4	9.8 $\pm$ 0.6

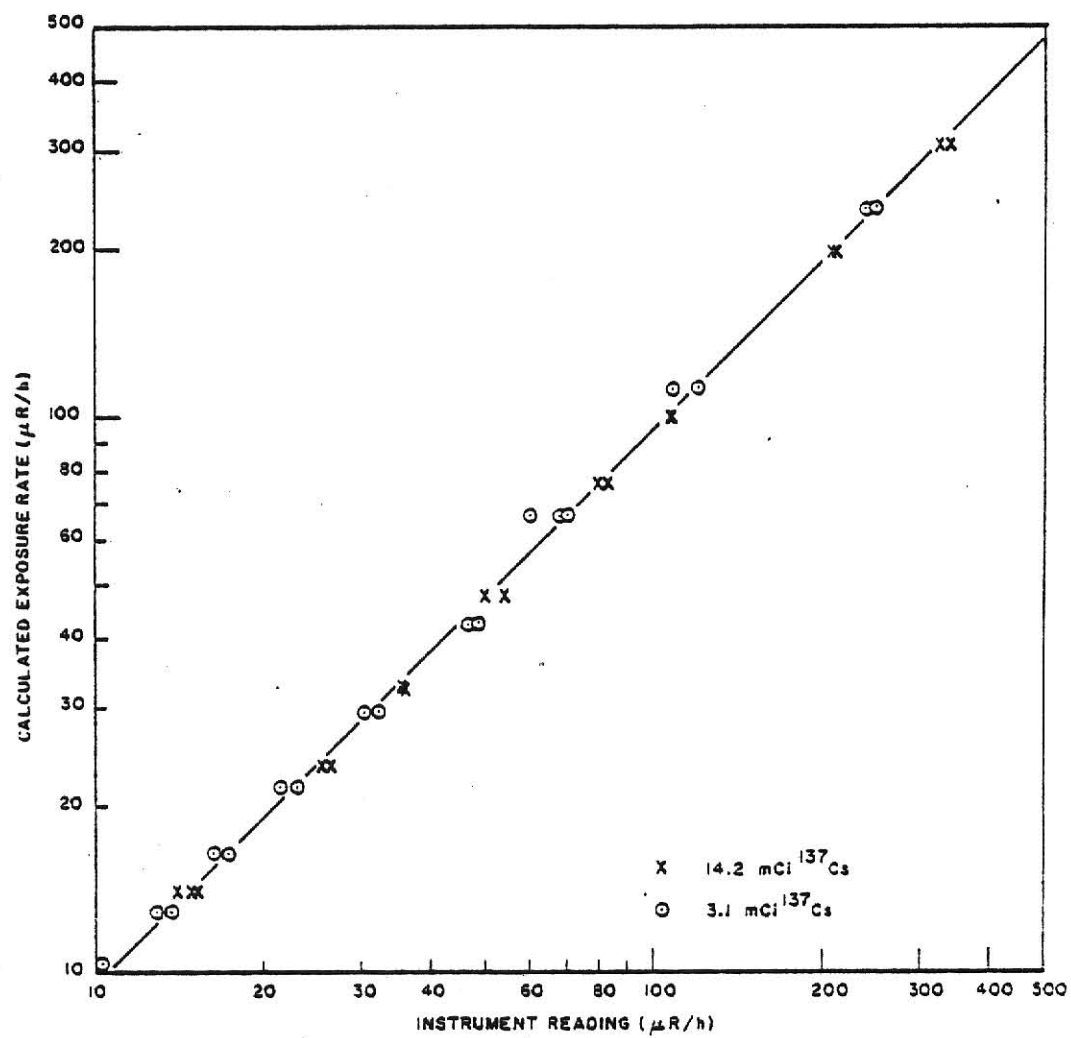


Fig. 2-12. Calibration data for the HPIC

(see Fig. 2-13 and the next subsection). The relative response $R(E)$ is the HPIC response to a calibration source of energy E divided by the HPIC response to any source for which the true exposure rates at the HPIC are the same for both sources. Then from Eq. (2-6), the relative response of the HPIC to ^{137}Cs based on the calculated exposure rate is

$$R(E) = c/M = 0.951. \quad (2-7)$$

From the manufacturer's data in Table 2-4, the relative response for a bare HPIC calibrated with a ^{60}Co source responding to a ^{137}Cs source is 0.96 or the manufacturer's relative response for ^{60}Co divided by the manufacturer's relative response for ^{137}Cs . The experimental relative response of 0.95 compared well after considering the possible error in the experimental result due to the 3.5% uncertainty in the source activities.

2.2.3 Energy Sensitivity

Energy sensitivity measurements were made by exposure of the HPIC to known intensities of gamma and x ray photons emitted from ^{60}Co , ^{137}Cs , ^{203}Hg , and ^{241}Am calibrated sources. Some characteristics of these sources are presented in Table 2-5. For the energy sensitivity measurements, the tripod mounted detector surrounded by its protective weather housing was positioned 1 m above a concrete floor. A calibrated radiation source was then positioned 1 m from a side face of the detector at the same height. Measured exposure rates, corrected for background, and the corresponding calculated exposure rates for this geometry are presented in Table 2-6. The "measured sensitivity" listed in this table is the ratio of the measured to the calculated exposure

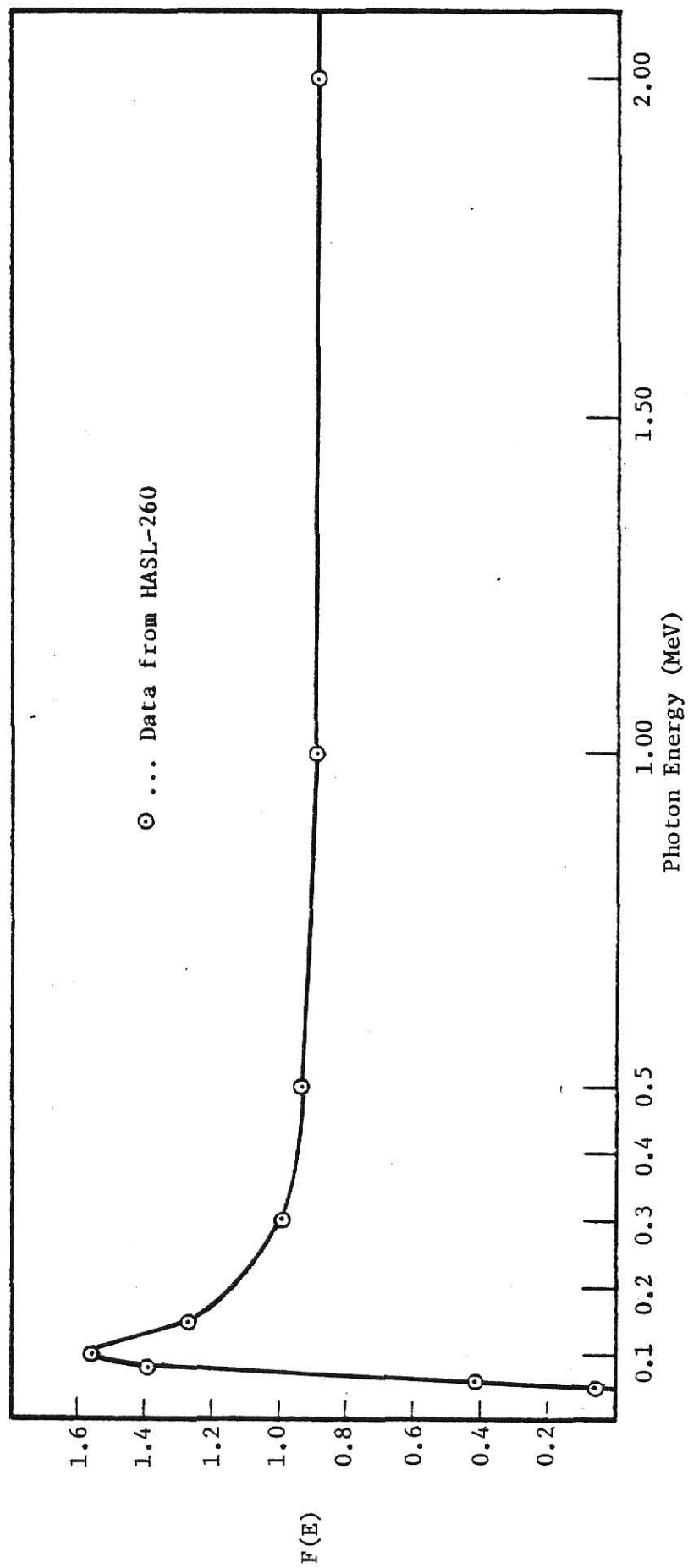


Fig. 2-13. Energy sensitivity of the high pressure ionization chamber.⁸

Table 2-4. Relative Sensitivities for the Bare 10 Inch Diameter Ion Chamber as Reported by the Manufacturer.

Isotope	Energy (keV)	Relative Response ^a
²⁴¹ Am	60	0.46
Pb-X rays	74-78	1.20
¹⁴¹ Ce	145	1.35
¹³⁷ Cs	662	0.93
⁶⁰ Co	1173 & 1333	0.89
²²⁶ Ra	...	0.91

^aRelative response based on 4000 keV relative response = 1.00.

Table 2-5. Characteristics of Calibration Sources.

Isotope	Half-Life	Activity (μCi)	Date	Energy (keV)	Efficiency ^a	/s
^{60}Co	5.26y	94.7 ± 3.1	6/1/77	1332	1.000	3.50×10^6
				1173	1.000	3.50×10^6
^{137}Cs	30.0 y	98.7 ± 3.5	6/1/77	661.6	0.846	3.09×10^6
				22.9	0.0688	2.51×10^5
^{203}Hg	46.59d	199.5 ± 1.5	5/4/77 (1200 EST)	279.2	0.815	6.02×10^6
				74.6	0.128	9.45×10^5
				(10.3) ^b	(0.0563)	(4.16×10^5)
^{241}Am	433y	98.4 ± 2.9	-	59.54	0.353	1.29×10^6
				(13.94) ^b	(0.290)	(1.06×10^6)

^aNumber of X or gamma rays per disintegration.^bNot included in estimate of exposure rate because of sensitivity of ion chamber.

Table 2-6. Energy Sensitivity of the Reuter Stokes Area Monitor.

Isotope	Principal Gamma-Ray Energy (keV)	Calculated Exposure Rate ($\mu\text{R/h}$) ^a	Measured Exposure Rate ($\mu\text{R/h}$) ^b	Measured Sensitivity	Calculated Sensitivity
⁶⁰ Co	1173 and 1333	117 ± 3.6	126.1 ± 1.4	1.08 ± 0.03	1.00
¹³⁷ Cs	661.6	30.9 ± 1.1	33.3 ± 1.2	1.08 ± 0.05	1.05
²⁰³ Hg	279.2	3.67 ± 0.4	5.9 ± 0.9	1.26 ± 0.19	1.13
²⁴¹ Am	59.5	1.20 ± 0.04	1.2 ± 0.9	1.0 ± 1.0	0.52

^aCorrected for radioactive decay to data of experiment; not corrected for scattered radiation.^bUncertainties are estimated.

rate, and the "calculated sensitivity" is the energy sensitivity $F(E)$ presented in Fig. 2-13 when $F(E)$ is normalized to unity for ^{60}Co gamma photons. The results of these energy sensitivity measurements were inconclusive because of the small selection of suitably active sources available to the experimenters. However, the energy sensitivity results did show general agreement with expected trends.

Since the HPIC response had variable sensitivity to the energy of the incident gamma radiation, particularly for low energies (see Fig. 2-13), a system energy correction factor $\bar{f}$ was used to correct the measured response. This correction factor $\bar{f}$ required knowledge of both the system energy sensitivity, $F(E)$, and the incident energy spectra, $\phi(E)$. Two different sets of values were developed for $\bar{f}$ dependent upon the source of $F(E)$ and $\phi(E)$.

The energy system correction factor $\bar{f}$ developed by Nason² was based on

$$\bar{f} = \frac{F_c e^{\mu_a t'}}{\bar{F}} \quad (2-8)$$

in which F_c is the energy sensitivity of the HPIC to the calibration source of energy E_c (in this case ^{60}Co), t' is the wall thickness of the aluminum protective shell, and μ_a the linear attenuation coefficient for aluminum and gamma energy E_c . The average system sensitivity $\bar{F}$ was defined as

$$\bar{F} = \frac{\int_0^{E_{\max}} dE F(E) E \phi(E) (\mu_{\text{en}}/\rho)}{\int_0^{E_{\max}} dE E \phi(E) (\mu_{\text{en}}/\rho)}, \quad (2-9)$$

in which $\phi(E)$ is the incident photon flux for gamma photons of energy E , $F(E)$ is the measured energy sensitivity of the HPIC system, $E_{\max}$ is the maximum photon energy in the spectrum, and μ_{en}/ρ is the mass absorption coefficient for air.

Tables 2-7 thru 2-9 present the energy system correction factors $\bar{f}$ developed by Radiation Research Associates (RRA)¹ and Nason². RRA's values of $\bar{f}$ were calculated by using AEC Health and Safety Laboratory (HASL) data⁸ for $F(E)$, NBS cross sections, and discrete ordinates transport (DOT 3.5) calculated skyshine fluxes. Little else is known about the RRA method for calculating values of $\bar{f}$. Nason's $\bar{f}$ values for the unshielded source configuration used Gaussian smoothed, 39 group, 4π geometry, DOT calculated fluxes and a system energy sensitivity $F(E)$ based on exponential fitting of HASL's data.⁸ His $\bar{f}$ values for shielded source configurations used unfolded collimated NaI spectra for $\phi(E)$ and the same exponentially fitted $F(E)$. Nason compared the effects on $\bar{f}$ of using collimated and uncollimated 4π geometry photon fluxes and concluded that no significant difference existed. For other details on the calculation of $\bar{f}$ see References 1 and 2.

2.3 High Pressure Ionization Chamber Measurements of Skyshine Exposure Rates

Skyshine exposure rates were measured at radial distances varying from 30 to 700 m using the Reuter-Stokes high pressure ionization chamber HPIC described in the previous section. Three source silo configurations were used a 150.5° upward collimated cone, a 21.0 cm concrete roofed silo, and a 42.8 cm concrete roofed silo. Three ^{60}Co sources with

Table 2-7. Reported Unshielded $\bar{f}$ Values.

Radial Distance (meters)	RRA ¹	Nason ²
50	0.885	...
100	0.905	0.881
200	0.901	0.892
300	0.895	0.902
400	0.890	0.909
500	0.887	0.913
600	0.883	0.916
700	0.883	0.918

Table 2-8. Reported $\bar{f}$ Values for the 21 cm Shielded Source Configuration.

Radial Distance (meters)	RRA ¹	Nason ²
30	0.88	...
50	0.89	...
70	0.89	...
100	0.89	0.845
150	0.89	...
200	0.89	0.884
300	0.89	0.914
400	0.89	0.912
500	0.89	0.922
600	0.89	0.936
700	0.89	0.958

Table 2-9. Reported $\bar{f}$ Values for the 42.8 cm Shielded Source Configuration.

Radial Distance	RRA ¹	Nason ²
30	0.875	...
50	0.880	...
70	0.880	...
100	0.885	0.855
150	0.885	...
200	0.885	0.883
300	0.885	0.908
400	0.885	0.912
500	...	0.918

effective strengths of 10.37, 228.7, and 3797 Ci on October 1, 1977 were used to provide radiation fields measurably above background levels.

2.3.1 High Pressure Ionization Chamber Measurement Procedures

Before any skyshine measurements were attempted, the source-to-detector distances were surveyed and stacked. Surveyed detector positions at 100, 200, 300, 400, 500, 600, and 700 m are plotted on Fig. 1-3. Detector positions at 30, 50, 70, and 150 m were stacked on a line between the source silo and the 200 m position. Elevations relative to the source were also measured and reported since any large change in elevation could affect the measured exposure rate by changing the source detector geometry and by changing the amount of ground reflected radiation. Elevations and estimated positioning errors for the detector positions are listed in Table 2-10.

HPIC skyshine measurements were started on the 7 September 1977 and completed the 28 October 1977. Data were taken at various times of the day and no more than 13 skyshine measurements were taken in any one day. For each measurement recorded, the HPIC was positioned at each measurement location and at a nominal height of 1 m from the ground. Nine unshielded skyshine exposure rate measurements were made with the detector at 0.72 m above the grade, however, comparison with the remaining skyshine exposure rate measurements showed no significant difference between the 0.72 m data and the 1.0 m data.

For each measurement, the HPIC was allowed to record data for at least five minutes with the source exposed and at least five minutes

Table 2-10. Surveyed Detector Elevations
Relative to the Source Elevation.

Location (m)	Elevation (m)
source	0.00
30 $\pm$ 0.5 ^a	- 2.07
50 $\pm$ 0.5	- 1.82
70 $\pm$ 0.5	- 1.33
100 $\pm$ 0.5	0.33
150 $\pm$ 0.5	1.69
200 $\pm$ 0.5	2.15
300 $\pm$ 1.0	1.44
400 $\pm$ 1.0	2.51
500 $\pm$ 1.0	.22
600 $\pm$ 1.0	.51
700 $\pm$ 1.0	2.28

^a Estimated detector positioning error.

with the source stored. The skyshine exposure rates and background exposure rates were then read directly from the strip chart recorder. The exposure rate uncertainties were estimated on the HPIC strip chart by taking one-sixth of the spread between extrema. Periodically, single point calibration checks were made. No evidence was seen of any calibration changes.

Since the skyshine exposure rate was expected to vary with air density ρ , the air temperature T and the air pressure p were recorded for each skyshine measurement or set of measurements. Air densities were calculated using

$$\rho = 1.2929 (273.13/T) (p/1013.25 - 4.98 \times 10^{-6} R P_s), \quad (2-10)$$

in which ρ is the air density in mg cm^{-3} , T the absolute temperature in degrees K, p the atmospheric pressure in mill-bars, R the percent relative humidity and p_s the water saturation vapor pressure in mm Hg at temperature T .^{9,10} Relative humidity data on campus, five miles from the experimental site, was obtained from Kansas State University Department of Physics Weather Reports. For the range of air temperatures experienced during the experiment, the last term of Eq. (2-10), the humidity term could have had a maximum value of only 0.018 (evaluated at 305 °K and 100% relative humidity). Therefore, the maximum effect on the air density using campus relative humidity values could only be 1.8%. The range of air densities during the experiment was 1.089 to 1.213 mg cm^{-3} .

The sensitivity of open silo skyshine exposure rate measurements to terrain features was investigated at 100 m radial distances from

the source. Detector locations are illustrated in Fig. 2-14, along with approximate topographical contours. The central detector location was the normal 100 m measurement location. Other detector positions were at azimuthal angles $\pm 12.75^\circ$ and $\pm 25.50^\circ$. Position L2 was on the edge of a gully. Position R2 was on the edge of a rise. The exposure rate data, adjusted for background, presented in Table 2-11 confirms the expected insensitivity of the exposure rate to terrain features. This result allowed the use of a flat plane to represent the air-earth interface during numerical modeling.

2.3.2. Skyshine Exposure Rates

The exposure rate data presented in Tables 2-12 thru 2-14 are the high pressure ionization chamber instrument readings corrected for background radiation, but not corrected for the HPIC's energy sensitivity. The uncertainties given for the exposure rates were developed from the uncertainties obtained for the background and gross exposure rates by the method given in the previous subsection. The source strengths given were corrected for radioactive decay and the estimated error on the source strengths was 5%. The estimated error for the unshielded configuration air densities was 2% and the estimated error for the shielded configuration air densities was 1%. The detector positioning errors were given in Table 2-10. The 42.8 cm concrete shielded HPIC skyshine exposure rate was approaching background levels at 400 m with the 5000 Ci source exposed. Therefore, the 42.8 cm concrete shielded HPIC data was not extended beyond 400 m.

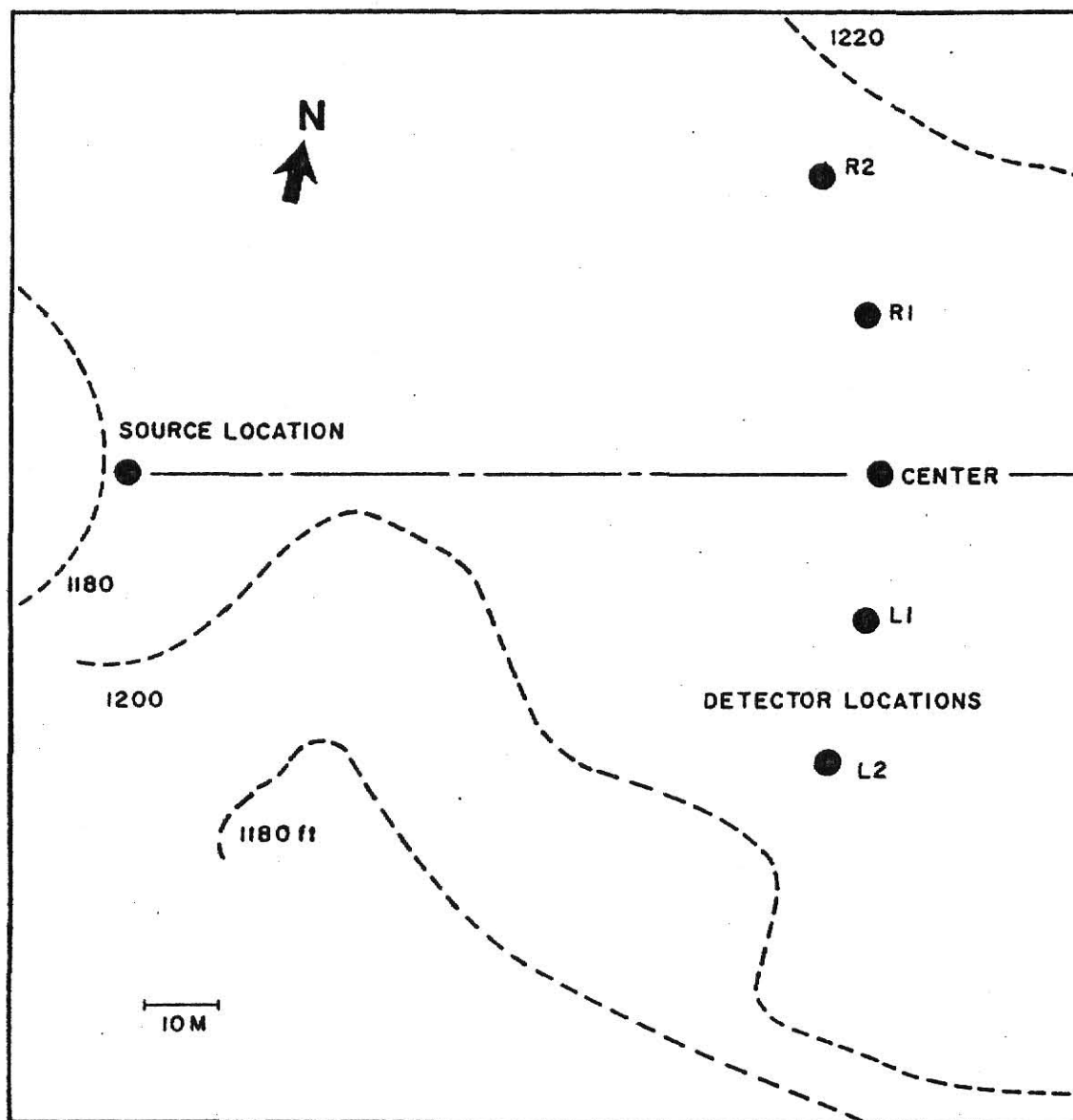


Fig. 2-14. Source and detector locations for measurement of skyshine sensitivity to topography.

Table 2-11. Sensitivity of Skyshine Exposure Rate to Terrain Features.

Source (Ci)	Distance (m)	Position	Relative Elevation (m)	Exposure ₁ Rate (μRh^{-1})
10.32	100	L2	-1.31	115.5 ± 0.8
	100	L1	-0.58	117.5 ± 0.6
	100	Center	0.00	116.7 ± 0.8
	100	R1	-0.04	115.3 ± 0.7
	100	R2	+0.23	115.0 ± 0.9

Table 2-12. Experimental Data for Skyshine Measurements Using the Reuter-Stokes Area Radiation Monitor. Source is Collimated to a Vertical Cone of 150.5° Full Angle.

r (m)	ρ (mg cm ⁻³)	ρr (g cm ⁻²)	Source (Ci)	Exposure Rate (μ Rh ⁻¹)
50	1.144	5.72	10.39	281.0 $\pm$ 0.9
50	1.096	5.48	10.33	284.0 $\pm$ 0.4
100	1.158	11.58	10.40	109.5 $\pm$ 1.4
100	1.144	11.44	10.39	109.6 $\pm$ 0.8
100	1.119	11.19	10.32	116.7 $\pm$ 0.8
100	1.096	10.96	10.33	113.3 $\pm$ 0.7
100	1.089	10.89	10.38	109.5 $\pm$ 0.6
100	1.089	10.89	10.38	107.5 $\pm$ 3.0
200	1.144	22.88	10.39	28.5 $\pm$ 0.6
200	1.096	21.92	10.33	28.1 $\pm$ 0.4
300	1.144	34.32	10.39	8.9 $\pm$ 0.4
300	1.144	34.32	230.5	186.4 $\pm$ 0.6
300	1.096	32.88	10.33	8.5 $\pm$ 0.4
300	1.096	32.88	229.1	193.0 $\pm$ 0.9
400	1.144	45.76	230.5	69.6 $\pm$ 0.7
400	1.096	43.84	229.1	78.0 $\pm$ 0.4
500	1.144	57.20	230.5	25.9 $\pm$ 0.5
500	1.096	54.80	229.1	29.3 $\pm$ 0.6
600	1.124	67.44	229.4	12.0 $\pm$ 0.6
600	1.124	67.44	3809	210.7 $\pm$ 0.8
600	1.096	65.76	3804	225.0 $\pm$ 0.4
700	1.111	77.77	3811	101.7 $\pm$ 0.6
700	1.096	76.72	3804	101.0 $\pm$ 0.9

Table 2-13. Experimental Data for Skyshine Measurements Using the Reuter-Stokes Area Radiation Monitor. Source is Covered by 21.0 cm of Concrete of Density 2.13 g/cm³.

r (m)	ρ (mg cm ⁻³)	ρr (g cm ⁻²)	Source (Ci)	Exposure Rate (μRh^{-1})
30	1.209	3.629	10.27	54.5 $\pm$ 0.6
30	1.166	3.499	10.22	51.9 $\pm$ 0.5
30	1.120	3.360	10.24	50.2 $\pm$ 0.4
50	1.205	6.025	10.27	28.2 $\pm$ 0.5
50	1.166	5.831	10.22	28.1 $\pm$ 0.5
50	1.116	5.581	10.24	25.9 $\pm$ 0.4
70	1.201	8.404	10.27	16.7 $\pm$ 0.4
70	1.201	8.404	227.8	348.7 $\pm$ 0.6
70	1.158	8.103	226.7	342.2 $\pm$ 0.5
70	1.112	7.786	227.1	328.2 $\pm$ 0.5
100	1.213	12.13	10.27	9.3 $\pm$ 0.5
100	1.213	12.13	227.8	195.6 $\pm$ 1.0
100	1.162	11.62	226.7	186.1 $\pm$ 0.7
100	1.108	11.08	227.1	182.4 $\pm$ 0.5
150	1.196	17.94	227.8	78.7 $\pm$ 0.5
150	1.161	17.42	226.7	79.0 $\pm$ 0.6
150	1.124	16.86	227.1	79.0 $\pm$ 0.5
200	1.196	23.92	227.8	37.1 $\pm$ 0.5
200	1.157	23.14	226.7	37.1 $\pm$ 0.6
200	1.112	22.24	227.1	37.3 $\pm$ 0.5
300	1.191	35.74	227.8	9.5 $\pm$ 0.4
300	1.191	35.74	3782	162.3 $\pm$ 0.6
300	1.152	34.57	3764	168.6 $\pm$ 0.5
300	1.116	33.49	3770	166.9 $\pm$ 0.5
400	1.191	47.64	3782	49.2 $\pm$ 0.6
400	1.152	46.08	3764	51.9 $\pm$ 0.7
400	1.116	44.64	3770	60.0 $\pm$ 0.4
500	1.186	59.31	3782	15.7 $\pm$ 0.6
500	1.144	57.20	3764	17.2 $\pm$ 0.4
500	1.113	55.63	3770	18.8 $\pm$ 0.4
600	1.186	71.13	3782	5.8 $\pm$ 0.4
600	1.152	69.15	3764	6.0 $\pm$ 0.6
600	1.109	66.51	3770	6.7 $\pm$ 0.4
700	1.148	80.35	3764	2.5 $\pm$ 0.5
700	1.116	78.14	3770	2.5 $\pm$ 0.5

Table 2-14. Experimental Data for Skyshine Measurements Using the Reuter-Stokes Area Radiation Monitor Source is Covered by 42.8 cm of Concrete of Density 2.13 g/cm³.

r (m)	ρ (mg cm ⁻³)	ρr (g cm ⁻²)	Source (Ci)	Exposure Rate (μRh^{-1})
30	1.127	3.380	226.5	94.7 $\pm$ 0.5
30	1.126	3.378	226.6	93.0 $\pm$ 0.5
30	1.114	3.343	226.6	93.4 $\pm$ 0.5
50	1.131	5.653	226.5	49.6 $\pm$ 0.7
50	1.122	5.611	226.6	50.3 $\pm$ 0.5
50	1.114	5.572	226.6	50.6 $\pm$ 0.4
70	1.139	7.971	226.5	27.8 $\pm$ 0.5
70	1.118	7.828	226.6	28.0 $\pm$ 0.5
70	1.110	7.772	226.6	26.4 $\pm$ 0.6
100	1.142	11.42	226.5	14.8 $\pm$ 0.5
100	1.118	11.18	226.6	14.7 $\pm$ 0.4
100	1.110	11.10	226.6	15.4 $\pm$ 0.5
150	1.146	17.20	3760	110.8 $\pm$ 0.6
150	1.118	16.76	3762	109.0 $\pm$ 0.5
150	1.110	16.65	3763	110.1 $\pm$ 0.6
200	1.150	23.01	3760	49.7 $\pm$ 0.4
200	1.117	22.35	3762	49.3 $\pm$ 0.5
200	1.110	22.19	3763	50.2 $\pm$ 0.5
300	1.154	34.61	3760	11.6 $\pm$ 0.5
300	1.121	33.64	3762	11.9 $\pm$ 0.4
300	1.110	33.29	3763	12.6 $\pm$ 0.4
400	1.154	46.15	3760	3.3 $\pm$ 0.4
400	1.121	44.83	3762	3.8 $\pm$ 0.5
400	1.113	44.52	3763	4.1 $\pm$ 0.5

Presented in Tables 2-15 thru 2-17 and Figs. 2-15 thru 2-17 are the energy corrected high pressure ionization chamber exposure rates obtained in this phase of the skyshine experiment as well as Nason's NaI inferred exposure rates.^{1,2} All these data were normalized by dividing by the appropriate source strength. Also in order to produce a more slowly varying quantity, the normalized exposure rates were multiplied by the square of the source to detector distance. The exposure rates inferred from the collimated NaI spectra were obtained from

$$\dot{X} = \frac{65.664}{C} \sum_{i=1}^{NC} E_i \phi_i (\mu_{en}/\rho)_i \{ \mu R/h \}, \quad (2-11)$$

in which NC represents the number of components in the collimated unfolded spectrum, E_i in MeV and $(\mu_{en}/\rho)_i$ in $\text{cm}^2 \text{g}^{-1}$ are appropriately averaged values for the i -th energy interval in the spectrum, and ϕ_i in $\text{cm}^{-2} \text{sec}^{-1}$ is the energy-integrated flux over the i -th energy interval. The factor C was defined as

$$C = \dot{X}_{\text{col}} / \dot{X}_{4\pi}, \quad (2-12)$$

in which $\dot{X}_{\text{col}}$ was the collimated geometry exposure rate and $\dot{X}_{4\pi}$ was the 4π geometry exposure rate as computed from results of discrete ordinates calculations (DOT) by RRA. For further details on NaI 4π exposure rates see Reference 2. The skyshine exposure rates calculated by RRA¹ from the discrete ordinates results are also plotted on Figs. 2-15 thru 2-17.

Figures 2-15 thru 2-17 summarize the measured normalized skyshine exposure rates versus air mass thickness for the three source silo

Table 2-15. Comparison of Energy Corrected Reuter-Stokes Measurements with Nason's NaI Exposure Rates for the Unshielded Source Configuration.

Air Mass Thickness (g cm ⁻²)	Energy Corrected Exposure Rate ^a Using RRA f ¹ (mR m ² h ⁻¹ Ci ⁻¹)	Energy Corrected Exposure Rate ^a Using 39 group ₂ DOT weighted f ² (mR m ² h ⁻¹ Ci ⁻¹)	NaI Spectral Measurement Reduced to 4π Exposure ₂ Rates ^a by Nason ² (mR m ² h ⁻¹ Ci ⁻¹)
5.48	60.8		
5.72	59.8		
10.89	93.8	91.2	
10.89	95.5	92.9	
10.96	99.3	96.6	
11.19	102	99.7	
11.34			98.6
11.38			102.
11.44	95.5	93.0	
11.58	95.3	92.8	
21.92	98.0	97.0	
22.00			105.
22.88	98.8	97.9	
32.88	63.3	66.8	
32.88	67.9	68.3	
33.74			75.4
33.75			76.8
34.32	65.2	65.7	
34.32	68.9	69.6	
43.84	48.5	49.5	
45.76	43.0	43.9	
46.22			48.7
54.80	28.3	29.2	
57.20	24.9	25.7	
58.87			27.9
65.76	18.8	19.5	
67.21			20.3
67.44	17.6	18.2	
67.44	16.6	17.2	
67.62			18.9
75.99			13.8
76.72	11.5	11.9	
77.77	11.6	12.0	

^aExposure rates are normalized with respect to source strength and multiplied by the square of the source to detector distance.

Table 2-16. Comparison of Energy Corrected Reuter-Stokes Measurements with Nason's NaI Exposure Rates for the 21.0 cm Shielded Source Configuration.

Air Mass Thickness (g cm ⁻²)	Energy Corrected Exposure Rate ^a Using RRA's $\bar{f}^1$ (mR m ² h ⁻¹ Ci ⁻¹)	Energy Corrected Exposure Rate ^a Using NaI Spectra Weighted $\bar{f}^2$ (mR m ² h ⁻¹ Ci ⁻¹)	NaI Spectral Measurements Reduced to 4 π Exposure Rates ^a by Nason ² (mR m ² h ⁻¹ Ci ⁻¹)
3.36	3.88		
3.50	4.02		
3.63	4.20		
5.58	5.73		
5.83	6.13		
6.03	6.10		
7.79	6.32		
8.10	6.57		
8.40	6.66		
8.40	7.11		
11.08	7.15	6.85	
11.46			7.92
11.57			8.25
11.62	7.31	7.02	
11.68			7.70
12.13	7.67	7.35	
12.13	8.09	7.75	
16.86	6.97		
17.42	6.97		
17.94	6.91		
22.24	5.84	5.80	
23.14	5.84	5.79	
23.71			6.01
23.92	5.80	5.78	
33.49	3.55	3.64	
34.57	3.59	3.69	
34.88			3.44
35.08			3.73
35.28			3.70
35.74	3.34	3.44	
35.74	3.44	3.54	

Table 2-16 continued.

Air Mass Thickness (g cm ⁻²)	Energy Corrected Exposure Rate ^a Using RRA's $\frac{f_1}{f_2}$ (mR m ² h ⁻¹ Ci ⁻¹)	Energy Corrected Exposure Rate ^a Using NaI Spectra Weighted $\frac{f_2}{f_1}$ (mR m ² h ⁻¹ Ci ⁻¹)	NaI Spectral Measurements Reduced to 4 π Exposure Rates ^a by Nason ² (mR m ² h ⁻¹ Ci ⁻¹)
44.64	2.27	2.32	
45.73			2.18
46.08	1.97	2.01	
47.64	1.86	1.89	
55.63	1.11	1.15	
57.20	1.02	1.05	
57.67			1.26
59.31	0.923	0.959	
66.51	0.569	0.597	
68.60			0.759
68.68			0.699
69.15	0.511	0.538	
71.13	0.490		
78.14	0.289	0.310	
78.59			0.472
80.35	0.290	0.312	

^aExposure rates are normalized with respect to source strength and multiplied by the square of the source to detector distance.

Table 2-17. Comparison of Energy Corrected Reuter-Stokes Measurements with Nason's NaI Exposure Rates for the 42.8 cm Shielded Source Configuration.

Air Mass Thickness (g cm ⁻²)	Energy Corrected Exposure Rate ^a Using RRA f_1^1 (m ² μ Rh ⁻¹ Ci ⁻¹)	Energy Corrected Exposure Rate ^a Xd ² Using NaI Spectra Weighted f_2^2 (m ² μ R h ⁻¹ Ci ⁻¹)	NaI Spectral Measurement Reduced to 4 π Exposure ² Rates ^a by Nason ² (m ² μ R h ⁻¹ Ci ⁻¹)
3.34	325		
3.38	323		
3.38	329		
5.57	493		
5.61	488		
5.65	483		
7.77	500		
7.83	529		
7.97	529		
10.99			714
11.06			645
11.10	601	581	
11.18	572	554	
11.42	574	559	
11.95			633
11.96			693
16.65	583		
16.76	576		
17.20	587		
22.19	472	470	
22.35	464	462	
23.01	468	467	
23.67			477
33.29	266	273	
33.64	252	258	
34.61	246	252	
34.83			282
35.09			299
44.52	154	159	
44.83	143	147	
46.15	124	128	
46.34			160
56.71			77.0
56.74			78.1
57.21			77.5

^a Exposure rates are normalized with respect to source strength and multiplied by the square of the source to detector distance.

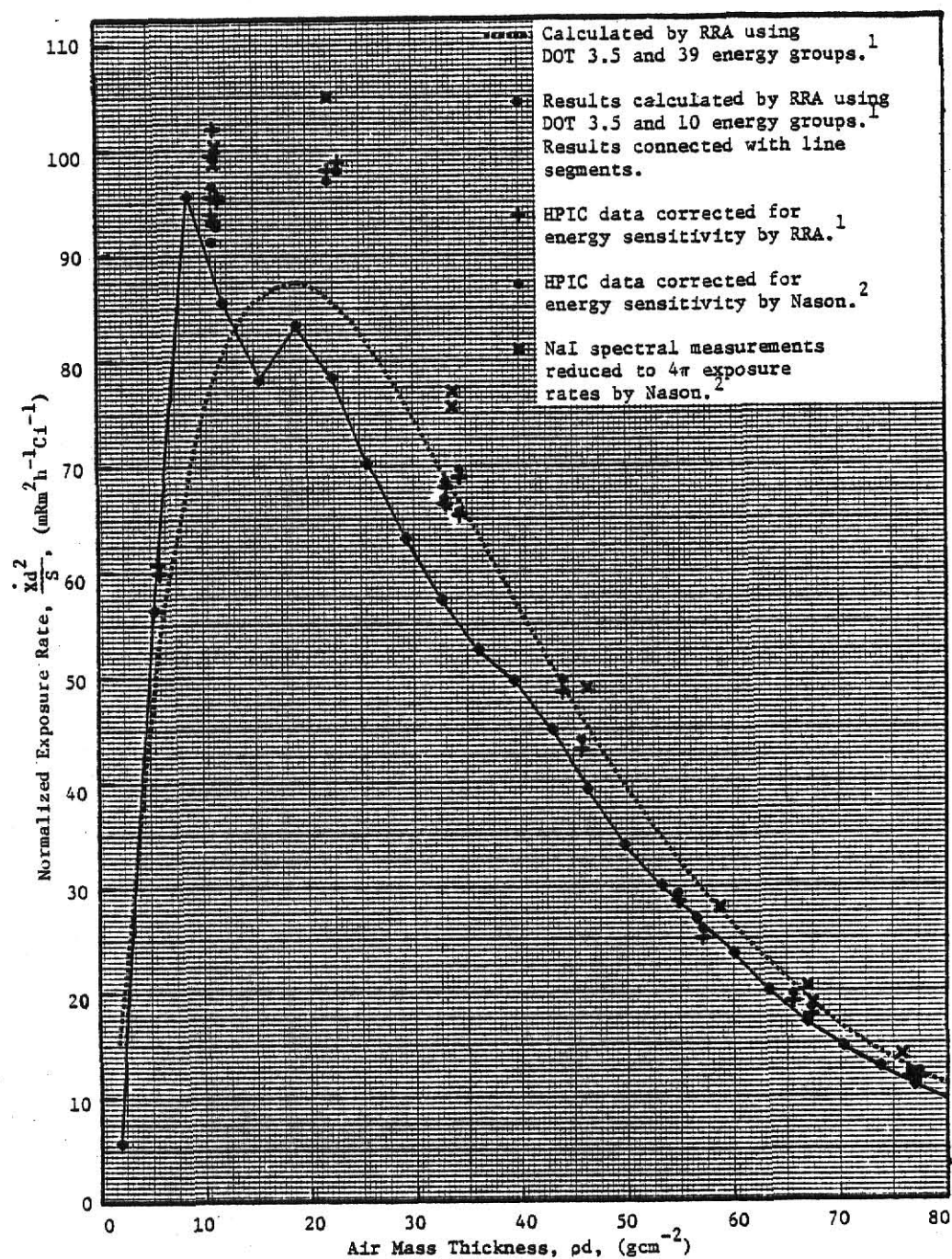


Fig. 2-15. Comparison of energy corrected HPIC exposure rates to NaI inferred exposure rates for the unshielded source silo configuration

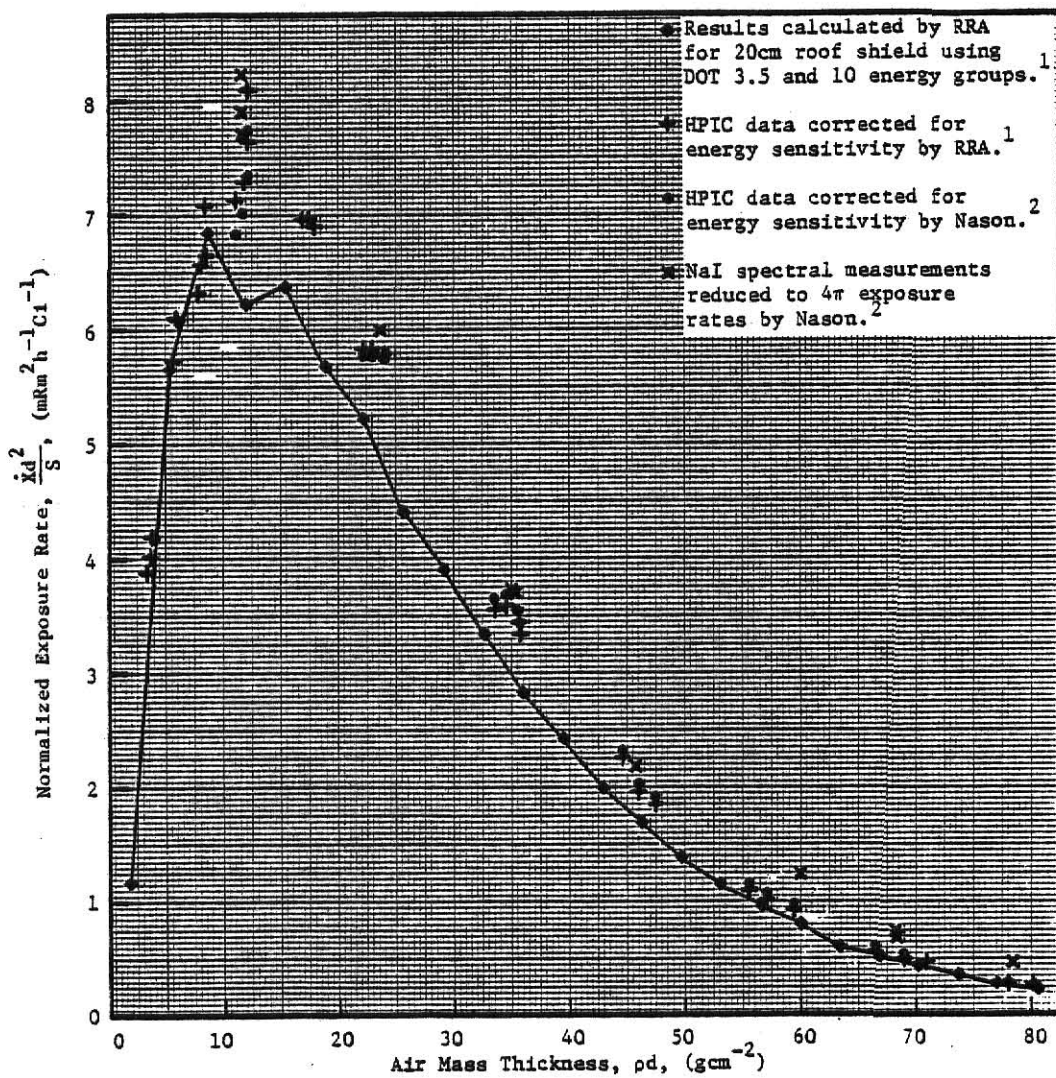


Fig. 2-16. Comparison of energy corrected HPIC exposure rates to NaI inferred exposure rates for the 21.0 cm shielded source configuration.

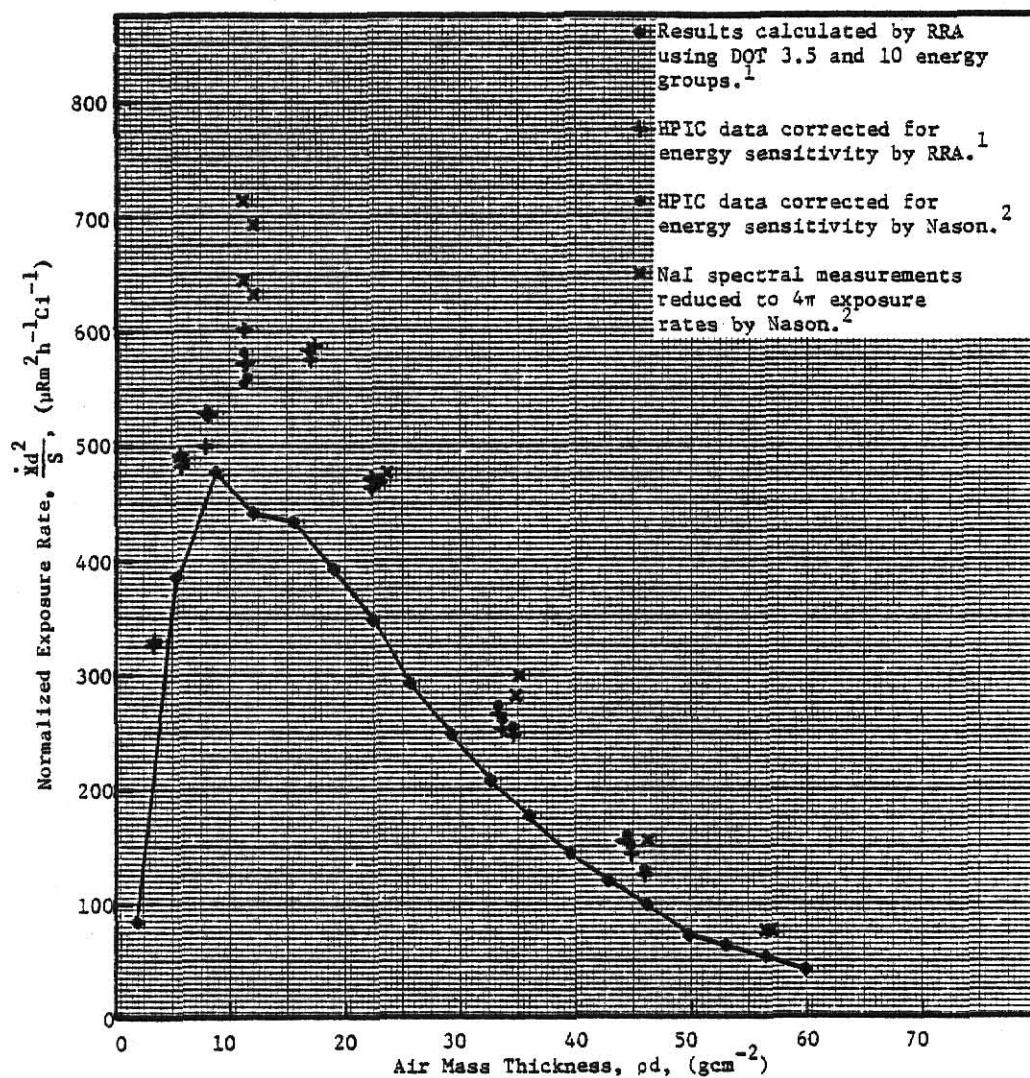


Fig. 2-17. Comparison of energy corrected HPIC exposure rates to NaI inferred exposure rates for the 42.8 cm shielded source configuration.

configurations. The normalized exposure rates multiplied by the square of the source to detector distance, $\dot{X}d^2$, tend to peak between 10 and 15 g/cm². These $\dot{X}d^2$ values also show an exponential-like tail after about 30 g/cm² and 20 g/cm² for the unshielded and shielded source silo cases, respectively. Since the graphs on Figs. 2-15 thru 2-17 are linear, the differences between RRA's and Nason's energy corrected HPIC exposure rates can be seen to be small, with a possible exception in the results at ~ 12 g/cm² (~ 100 m). Figures 2-15 thru 2-17 indicate that some of the experimental scatter noted in Tables 2-15 thru 2-17 is due to differences in the air mass thickness and not experimental error. Also presented on Figs. 2-15 thru 2-17, RRA's discrete ordinate transport calculations (DOT) were based on the DOT 3.5 code developed by ORNL.¹ The 39 energy group DOT used for the unshielded silo configuration exposure rate calculation agrees well with the HPIC results except near the 100 and 200 m measurement locations. The 10 energy group DOT showed a lack of smoothness and consistently underestimated the energy corrected HPIC exposure rates.

3.0 CALCULATION OF SKYSHINE EXPOSURE RATES

As discussed in the introduction to this work, calculation of skyshine exposure rates is becoming increasingly important in the design of nuclear facilities. The most popular and simplified (although approximate) calculational methods are based on point kernel techniques in which a first collision source distribution in the atmosphere is first calculated. The angular distribution of this distributed source is based on the incoherent photon scattering cross section. Buildup factors are then used to account for multiple scattering between the location of the first interaction and the location at which the exposure rate is to be calculated. This chapter describes the development of such a point kernel calculation method especially suited to skyshine exposure rate determinations.

3.1 Singly Scattered Photon Exposure Rate Integral Equation

A simplified representation of the skyshine experiment is shown in Fig. 3-1. The detector is located at a radial distance d from the source, and both the detector and source are assumed to be at the same elevation. The radiation field produced by the isotropic gamma photon source is collimated vertically by the source silo. The gamma radiation leaving the silo thus must scatter in the air to reach the detector. Compton air scattering is assumed to be the primary mode of gamma photon scattering for photons of energy less than 2.0 MeV.

If the silo is covered with a concrete roof, the unscattered gamma flux ϕ^0 at the differential scattering volume dV is simply

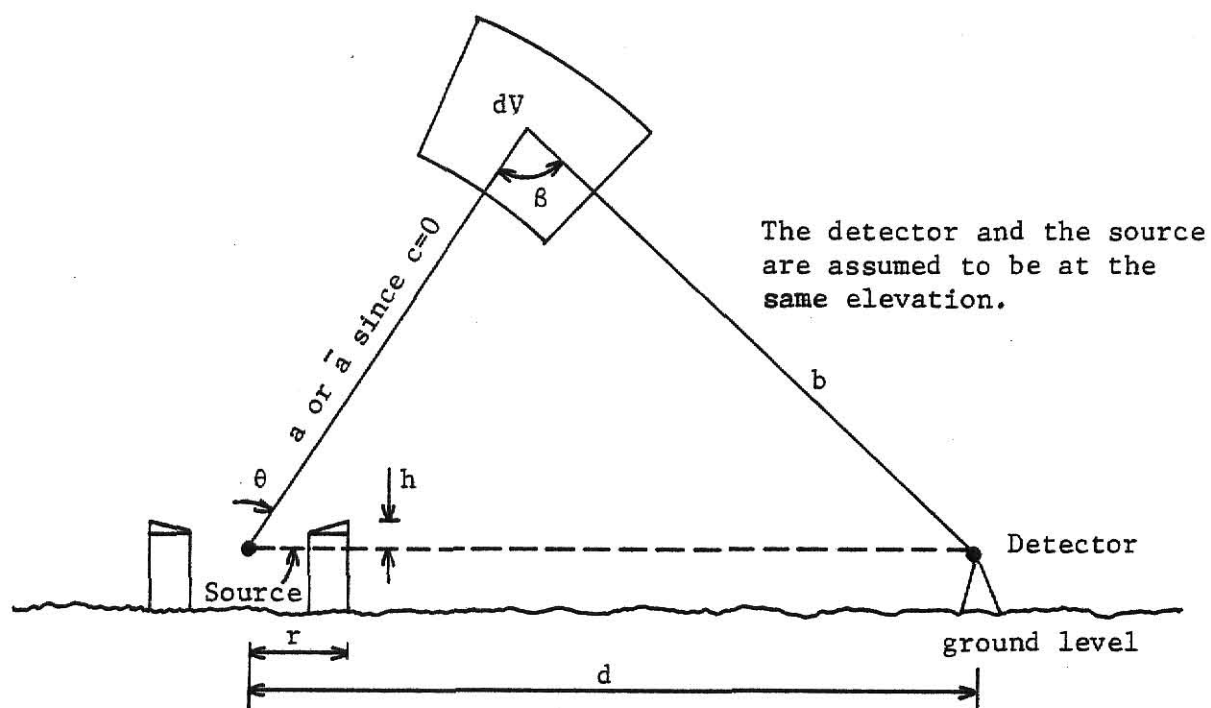


Fig. 3-1. Simplified calculational geometry.

$$\phi^0 = \frac{S}{4\pi (a+c)^2} \exp(-\mu a - \bar{\mu} c), \quad (3-1)$$

in which S is the source strength, a is the distance in air from the source to the scattering volume dV (i.e., the "first air leg") c is the distance through the concrete roof along a line segment from the source to dV , μ is the air linear attenuation coefficient for photons of energy E , and $\bar{\mu}$ is the concrete linear attenuation coefficient for photons of energy E . When no roof shield covers the source, Eq. (3-1) reduces to

$$\phi^0 = \frac{S}{4\pi a^2} \exp(-\mu a). \quad (3-2)$$

The number of photons per unit time scattered at dV through the angle β into a steradian towards the detector can be written as

$$S_v = \phi^0 N \sigma \, dV = \frac{S N \sigma}{4\pi (a+c)^2} \exp(-\mu a - \bar{\mu} c) \, dV, \quad (3-3)$$

in which N is the electron density at dV and σ is the differential scattering cross section as a function of the angle β and incident photon energy E . It should be noted that the actual photon scattering angle is $\pi - \beta$ (see Fig. 3.1). For photon scattering on free electrons, the scattered photon energy $\hat{E}$ can be related to β and the incident photon energy E by¹¹

$$\hat{E} = \frac{E m_e c^2}{m_e c^2 + E (1 + \cos \beta)}, \quad (3-4)$$

in which $m_e c^2$ is the rest mass energy of an electron. The corresponding differential scattering cross section for incident photons of energy E scattering from free electrons into a steradian around the scattering

angle $\pi - \beta$ with scattered photon energy $\hat{E}$ can be written explicitly as¹¹

$$\sigma = \frac{r_e^2}{2} \frac{\lambda^2}{(1 + \lambda + \cos\beta)^2} \left(\frac{\lambda}{1 + \lambda + \cos\beta} + \frac{1 + \lambda + \cos\beta}{\lambda} - \sin^2\beta \right), \quad (3-5)$$

in which the classical electron radius $r_e = 2.818 \times 10^{-15}$ m and the Compton wavelength λ is given by $\lambda = m_e c^2 / E$.

The differential exposure rate $d\dot{X}_s$ at the detector due to singly scattered photons from dV can be written as

$$d\dot{X}_s = \frac{S_v}{b^2} \frac{\mu_{en}}{\rho} \hat{E} K \exp(-\hat{\mu}b), \quad (3-6)$$

in which the second air leg, b , is the scattering volume-to-detector distance, $\frac{\mu_{en}}{\rho}$ is the mass energy absorption coefficient in air for scattered photons of energy $\hat{E}$, $\hat{\mu}$ is the air linear attenuation coefficient for scattered photons of energy $\hat{E}$, and K is the energy-flux-to-exposure-rate conversion factor equal to $0.01842 \mu R \text{ g MeV}^{-1}$.¹² Substitution for S_v from Eq. (3-3) then yields

$$d\dot{X}_s = \frac{SKN}{4\pi(a+c)^2 b^2} \frac{\mu_{en}}{\rho} \sigma \hat{E} \exp(-\mu_a - \hat{\mu}b - \mu_c) dV. \quad (3-7)$$

Equation (3-7) represents the differential skyshine exposure rate at the detector from singly scattered photons originating from a monoenergetic isotropic source located in the source silo. Actually several factors degrade the monoenergetic source spectrum before the radiation arrives at the differential scattering volume. Most of these first leg spectrum degradation factors are photon scattering interactions in the source, in the source silo walls, in the silo concrete roof, and in the air around dV . However, the spectrum reaching dV is unknown unless transport theory results are used. Similarly, scattering will

also alter the spectrum of photons starting from dV and which eventually reach the detector. Several assumptions were made in this study which corrected for the multiple photon scattering effects. These assumptions were as follows:

- 1) A buildup factor $\hat{B}$ was used to correct for multiple scattering along the scattering-volume-to-detector air path (the second air leg). The exposure buildup factor used was for infinite air medium with an isotopic point source. The errors resulting from the use of this buildup factor in a finite case and with anisotropic sources will be discussed in the next chapter of this work.
- 2) The Compton (free electron) differential scattering cross section for monoenergetic photons of source energy E was used instead of a spectrum weighted scattering cross section, since the spectra arriving at dV from the source was unknown. Because the air mass relatively close to the source silo scatters the majority of the radiation which eventually reaches the detector, the distances from the source to those scattering volumes that contribute the majority of the exposure rate at the detector are relatively short. The gamma photon spectrum from the source would not be seriously degraded over these short distances. Since the lower energy components of the source spectrum will be absorbed before they contribute significantly to the exposure rate at the detector, the use of a monoenergetic scattering cross section would be justifiable.
- 3) A second buildup factor B was used to account for multiple scattering on the first leg. This buildup factor was defined as the correction factor necessary to obtain the true exposure rate at the detector from the singly scattered exposure rate (including the second air leg buildup factor and the monoenergetic scattering cross section). This buildup factor B has the same effect as artificially increasing the number of source energy photons arriving at dV . Approximations for B are discussed in the next chapter of this work.

The differential exposure rate $d\dot{X}$, corrected for multiple scattering, can now be expressed as

$$d\dot{X} = \frac{SKNB\hat{B}}{4\pi (a+c)^2 b^2} \frac{\mu_{en}}{\rho} \sigma \hat{E} \exp(-\mu a - \hat{\mu} b - \bar{\mu} c) dV. \quad (3-8)$$

Integration of Eq. (3-8) over all space V yields the total exposure rate $\dot{X}$ at the detector

$$\dot{X} = \int_V \frac{SKNB\hat{B}}{4\pi (a+c)^2 b^2} \frac{\mu_{en}}{\rho} \sigma \hat{E} \exp(-\mu a - \hat{\mu} b - \bar{\mu} c) dV. \quad (3-9)$$

Of course, as with any integral expression, the selection of an appropriate geometry can greatly simplify the evaluation of the equation.

3.2 Skyshine Geometry

Parameters $\bar{a} \equiv a + c$, ϵ , and θ in Fig. 3-2 define a spherical coordinate system. Since nearly every variable in the integrand of Eq. (3-9) depends on β or $\hat{E}(\beta)$ (see Table 3-1) and β is dependent upon $\bar{a}$ in cylindrical geometry, then numerical integration over $\bar{a}$ would be excessively complex. However, a geometry in which the angle β is the independent variable would simplify the evaluation of the exposure rate equation. Since three direction vectors or angles (such as β , θ and ϵ in Fig. 3-2) do not alone define a position in space, another variable must be specified. If β is defined such that β , θ , and the line d between the source and the detector form a triangle, then for a fixed distance d , the angles β , θ , and ϵ define a unique point in space. For a fixed source-to-detector distance d , the surface produced by a fixed angle β is the surface produced by rotating a circular line segment with end points at the detector and the source

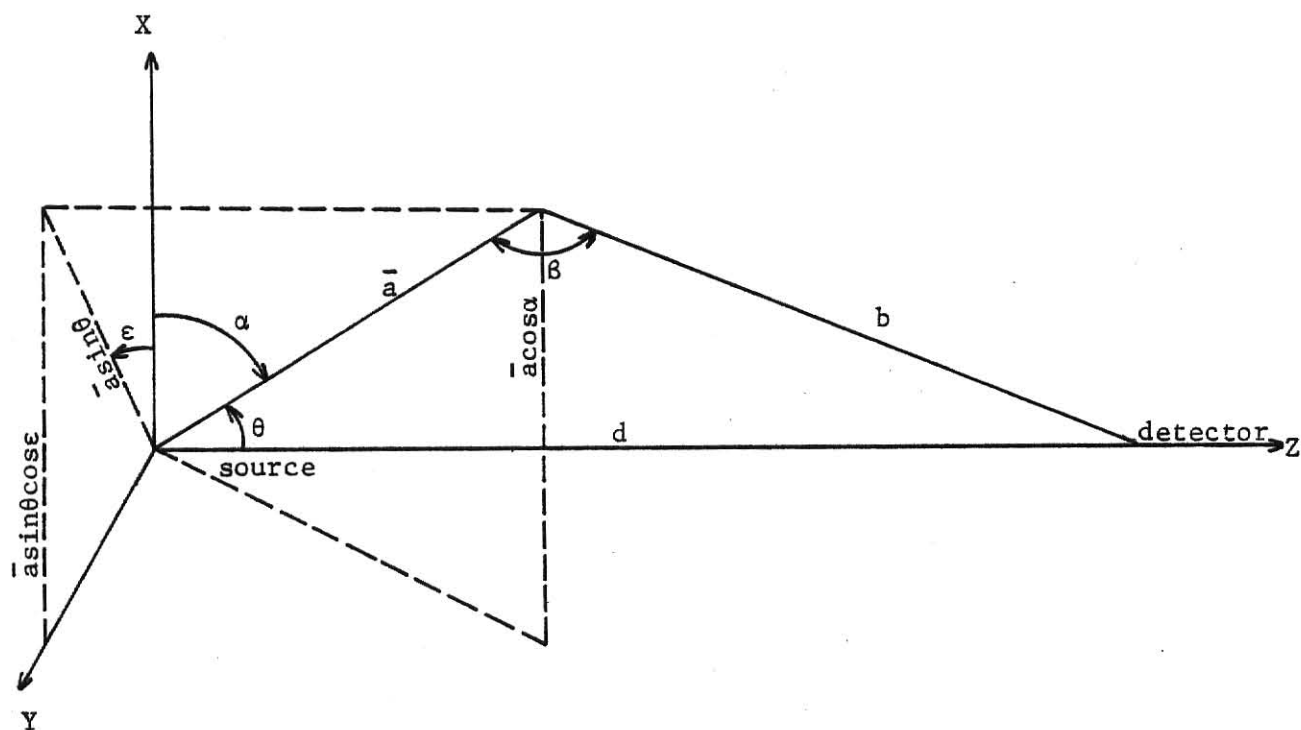


Fig. 3-2. Skyshine geometry.

Table 3-1. Functions^a Used in Derivation of Skyshine Exposure Rate Point Kernel Equations.

Function	Dependent Upon	Defining Equation	Trapezoidal Approximation Notation Eq. (3-35) or (4-3)	Comments
$\theta_{\max}$	β	Eq. (3-21) or Eq. (3-22)	$\theta_{\max, i} = \theta_{\max}(\beta_{\max} - i\Delta\beta)$	Maximum value for θ
ϵ_m	β	Eq. (3-32)	$\Delta\theta_i = (\theta_{\max, i} - \theta_{\min})/m$	θ trapezoidal integration increment
ϵ	θ	Eq. (3-25) or Eq. (3-39)	$\epsilon_{m, ij} = \epsilon(\theta_{\min} + j\Delta\theta_i)$	Limit for ϵ
$\bar{a}$	θ	Eq. (3-34)	$\Delta\epsilon_{ij} = \epsilon_{m, ij}/\ell$	ϵ trapezoidal integration increment
a	β, θ	Eq. (3-12)	$a_{ij} = \bar{a}(\beta_{\max} - i\Delta\beta, \theta_{\min} + j\Delta\theta_i)$	Source-to-scattering volume distance in air assumed to be equal to a
b	β, θ	Eq. (3-13)	$b_{ij} = b(\beta_{\max} - i\Delta\beta, \theta_{\min} + j\Delta\theta_i)$	Scattering-volume-to-detector distance
c	θ, ϵ	Eq. (3-14)	$c_{ijk} = c(\theta_{\min} + j\Delta\theta_i, k\Delta\epsilon_{ij})$	Photon path length in the concrete roof in the direction of θ and ϵ
$\hat{E}$	β	Eq. (3-4)	$\hat{E}_i = \hat{E}(\beta_{\max} - i\Delta\theta)$	Singly scattered photon energy
$\frac{\mu_{en}}{\rho}$	$\hat{E}(\beta)$	$\dots^b$	$\left(\frac{\mu_{en}}{\rho}\right)_i = \frac{\mu_{en}}{\rho}(\hat{E}_i)$	Mass energy absorption coefficient for air
$\hat{\mu}$	$\hat{E}(\beta)$	$\dots^b$	$\hat{\mu}_i = \hat{\mu}(\hat{E}_i)$	Air linear attenuation coefficient for single scattered photons
σ	β	Eq. (3-5)	$\sigma_i = (\beta_{\max} - i\Delta\beta)$	Differential scattering cross section
$\hat{B}$	$\hat{\mu}(E(\beta)),$ $b(\beta, \theta)$	$\dots^c$	$\hat{B}_{ij} = \hat{B}(\hat{E}_i, \hat{\mu}_i, b_{ij})$	Second leg buildup factor

Table 3-1 - continued

Function	Dependent Upon	Defining Equation	Trapezoidal Approximation Notation Eq. (3-35) or (4-3)	Comments
B	$E, a(\beta, \theta)$ or $c(\theta, \epsilon)$	...		First leg buildup factor
	$E, a(\beta, \theta)$	...	$B_{ij} = B(E, \mu a_{ij})^d$	First leg air buildup factor
	$E, c(\theta, \epsilon)$	...	$B_{ijk} = B(E, \mu c_{ijk})$	First leg concrete buildup factor

^aFunctions with respect to β , θ , and ϵ .

^bThese values are interpolated from values listed in Appendix B.

^cThese values are from Berger Buildup factors, see Chapter 4 for details.

^dSet equal to 1 in Eq. (3-35), used in Eq. (4-3).

around the source-to-detector axis. The radius of curvature of this circular segment is $d/(2\sin\beta)$. Figure 3-3 shows the intersection of the constant scattering angle surfaces with the positive x-z half plane.

Since the triangle $\overline{abd}$ is rotationally invariant about the source-to-detector axis d (i.e., $\overline{a}$ and b are not functions of ϵ), then the derivation of the source-to-differential-scattering volume distance $\overline{a}$ in terms of θ , β , and d begins with the law of cosines,

$$d^2 = \overline{a}^2 + b^2 - 2\overline{a}b \cos\beta \quad (3-10)$$

and

$$b^2 = \overline{a}^2 + d^2 - 2\overline{a}d \cos\theta. \quad (3-11)$$

Equation (3-11) is substituted into Eq. (3-10) to eliminate b^2 and b . Trigonometric identities ($d^2 = d^2 \sin^2\theta + d^2 \cos^2\theta$ and $\tan^2\beta = \sec^2\beta - 1$) are then used to reduce the result to

$$\overline{a} = d (\cos\theta + \sin\theta \cot\beta). \quad (3-12)$$

Equations (3-11) and (3-12) are then solved for the differential scattering volume-to-detector distance. The result is

$$b = d \sin\theta \csc\beta. \quad (3-13)$$

The concrete silo roof path length c is determined geometrically from Fig. 3-4. Since triangle ABE is a right triangle and the line DC, the projection of AE on plane x-y, is equal to AE in length then AB must be related to the roof thickness t by

$$c \equiv |AB| = t \sec\epsilon \csc\theta. \quad (3-14)$$

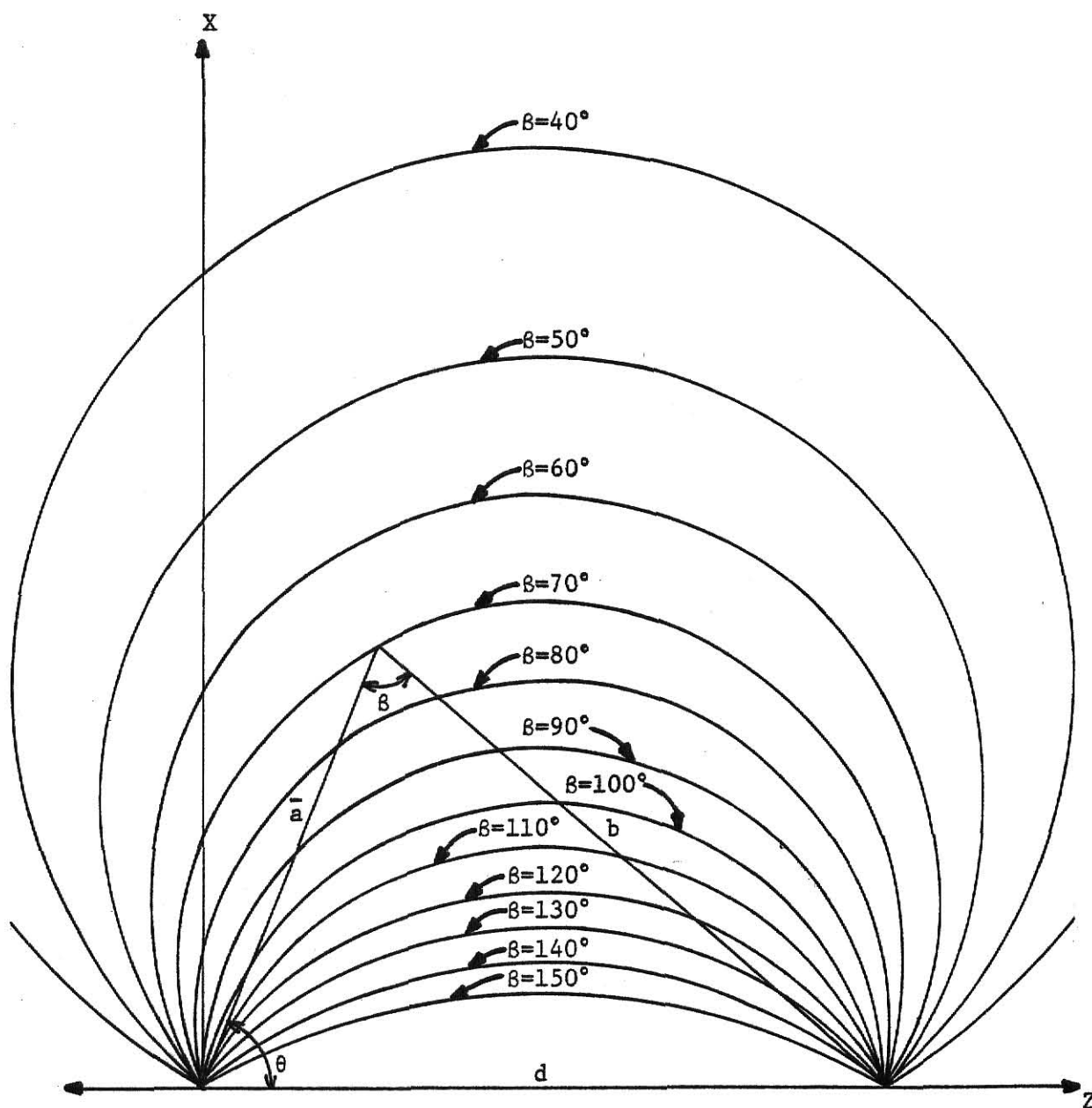


Fig. 3-3. Intersections of constant energy surfaces for singly scattered photons.

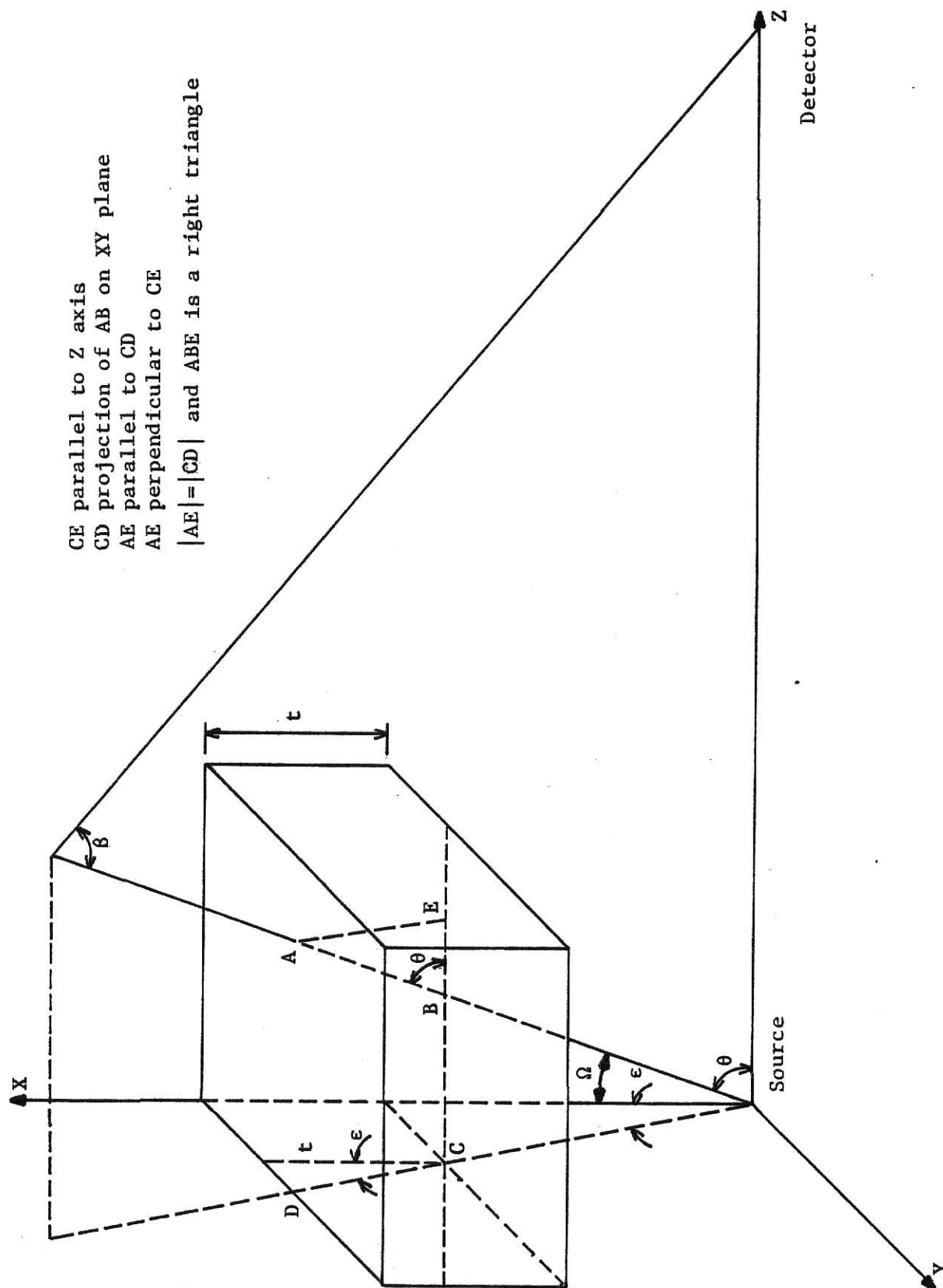


Fig. 3-4. Determination of silo roof path length.

The differential scattering volume dV as a function of d , β , ϵ , and θ is derived from

$$dV = \bar{a}^2 \sin\theta \frac{\partial \bar{a}}{\partial \beta} d\beta d\theta d\epsilon. \quad (3-15)$$

which is the differential volume element in spherical geometry.

Equation (3-12) differentiated with respect to β yields

$$\frac{\partial \bar{a}}{\partial \beta} = -\sin\theta \csc^2\beta. \quad (3-16)$$

Equation (3-16) substituted into Eq. (3-15) yields the differential scattering volume

$$dV = \bar{a}^2 d\sin^2\theta \csc^2\beta d\beta d\theta d\epsilon, \quad (3-17)$$

as a function of d , β , ϵ , and θ . Since $\bar{a} \equiv a+c$, then substitution of b , from Eq. (3-13), into Eq. (3-17) yields

$$dV = \frac{-(a+c)^2 b^2}{d} d\beta d\theta d\epsilon. \quad (3-18)$$

3.3 Single Scattered Gamma Exposure Rate Numerical Evaluation

The exposure rate integral equation, Eq. (3-9), rewritten in the geometry of the preceding section thus becomes

$$\dot{X} = \int_0^{\beta_{\max}} \int_{\theta_{\min}}^{\theta_{\max}} \int_{-\epsilon_m}^{\epsilon_m} \frac{SKNBB}{4\pi d} \frac{\mu_{en}}{\rho} \sigma \hat{E} \exp(-\mu_a - \mu_b - \mu_c) d\epsilon d\theta d\beta, \quad (3-19)$$

in which the limits of integration $\beta_{\max}$, $\theta_{\max}$, ϵ_m and $\theta_{\min}$ are determined by the silo detector geometry. Derivation of these limits of integration is discussed below.

The lower limit $\theta_{\min}$ on the variable θ is deduced from Fig. 3-1 as

$$\theta_{\min} = \arctan(h/r), \quad (3-20)$$

in which h is the height of the outer collimator relative to the source elevation and r is the silo collimator outer radius. The upper limit $\theta_{\max}$ on the integration variable θ must meet two conditions. The first condition imposed was that θ , β , and d must form a triangle. Therefore

$$\theta_{\max} = \pi - \beta - \arctan\left(\frac{h}{d-r}\right), \quad (3-21)$$

This last statement is derived from the fact that the sum of the angles in a triangle equals π . The second imposed condition is

$$\theta_{\max} \leq \pi - \theta_{\min} \quad (3-22)$$

which is required by the collimator geometry. Therefore, the smaller of the two $\theta_{\max}$ values gives the limiting condition.

The limit ϵ_m on ϵ is deduced from the maximum collimator cone angle α depicted in Fig. 3-2. The distance from a scattering point on the edge of the collimation cone to the y - z plane is equal to the height of the projection of the abd triangle on the x - y plane or

$$a \cos \alpha = a \sin \theta \cos \epsilon_m. \quad (3-23)$$

Since by definition

$$\alpha = \pi/2 - \theta_{\min}, \quad (3-24)$$

then solution of these last two equations for ϵ_m yields

$$\epsilon_m = \arccos(\sin \theta_{\min} / \sin \theta). \quad (3-25)$$

The angle β is limited by the outer lip of the silo collimator.

Therefore, the maximum angle $\beta_{\max}$ is related to the silo dimensions by

$$\beta_{\max} = \pi - \theta_{\min} - \arctan\left(\frac{h}{d-r}\right). \quad (3-26)$$

Of course when the silo is covered with a concrete roof, no well defined collimation exists, i.e., there is no sharp cutoff. However, as α increases less radiation penetrates the roof and thus one may think of an effective collimation angle defined in terms of the longest photon path through the concrete that significantly contributes to the radiation field. Further discussion of the concrete-roofed silo limits will be presented at the end of this section.

The exposure rate equation, Eq. (3-19), can be rewritten as

$$\dot{X} = \frac{SKN}{2\pi d} \int_0^{\beta_{\max}} \sigma \hat{E} \frac{\mu_{en}}{\rho} \int_{\theta_{\min}}^{\theta_{\max}} \hat{B} \exp(-\mu a - \hat{\mu} b) \int_0^{\epsilon_m} B \exp(-\bar{\mu} c) d\epsilon d\theta d\beta, \quad (3-27)$$

since $\int B \exp(-\bar{\mu} t \sec \epsilon \csc \theta) d\epsilon$ is symmetric about zero. Table 3-1 lists the functions which depend upon β , θ , and ϵ . Table 3-2 lists the functions which are constant with respect to β , θ , and ϵ . The exposure rate equation, Eq. (3-27), rewritten for semi-infinite air (i.e., no silo or 2π collimation) yielded the same equation as reported by Kitazume.¹³ Appendix A shows the extension to the semi-infinite air case.

The exposure rate given by Eq. (3-27) can be normalized by dividing by the source strength and multiplying by the square of the source-to-detector distance, i.e.,

$$\frac{\dot{X}d^2}{S} = \frac{CKNd}{2\pi} \int_0^{\beta_{\max}} \sigma \hat{E} \frac{\mu_{en}}{\rho} \int_{\theta_{\min}}^{\theta_{\max}} \hat{B} \exp(-\mu a - \hat{\mu} b) \int_0^{\epsilon_m} B \exp(-\bar{\mu} c) d\epsilon d\theta d\beta, \quad (3-28)$$

in which C represents the number of gamma photons of energy E emitted per curie of source activity. This last equation can be numerically integrated by using triple trapezoidal integration. The result of the

Table 3-2. Constants^a used in derivation of skyshine exposure rate point kernel equations.

Constant	Dependent Upon	Comments	Source
E	Source	Source photon energy	Input
f	Source	Fraction of source photons emitted per disintegration	Input
t	Geometry	Silo concrete roof thickness	Input
r	Geometry	Silo collimator outside radius	Input
h	Geometry	Silo collimator elevation relative to the source	Input
d	Geometry	Source-to-detector radial distance	Input
ρ_c	Material	Silo roof concrete density	Input
ρ	Material	Air density	Input
C	f	$C=f(1.332 \times 10^{14})$ photons $\text{h}^{-1} \text{Ci}^{-1}$	By definition
K		$K=0.01842 \mu\text{R g MeV}^{-1}$	Ref. 12
N	ρ	$\frac{N}{\rho} = 3.007 \times 10^{23}$ electrons g^{-1}	Appendix B
μ	E, ρ	Air linear attenuation coefficient	Appendix B
$\bar{\mu}$	E, ρ_c	Concrete linear attenuation coefficient	Appendix B
$\theta_{\min}$	r,h	Minimum value for θ	Eq. (3-20)
$\beta_{\max}$	r,h,d	Maximum value for β	Eq. (3-26)
$\beta_{\min}$	see text	Minimum value for β	Eq. (3-37)
$\Delta\beta$	$\beta_{\max}, \beta_{\min}$	β trapeziodal integration increment	Eq. (3-30)

^aConstants with respect to θ , β , and ϵ .

triple trapezoidal integration of Eq. (3-28) is

$$\frac{\dot{X}_d^2}{S} \approx \frac{CKNd\Delta\beta}{4\pi} \sum_{i=0}^n w_i \sigma_i \left[\frac{\mu_{en}}{\rho} \right]_i \hat{E}_i I_i, \quad (3-29)$$

where

$$\Delta\beta = (\beta_{\max} - \beta_{\min})/n, \quad (3-30)$$

$$I_i = \frac{\Delta\theta_i}{2} \sum_{j=0}^m w_j \hat{B}_{ij} \exp(-\mu a_{ij} - \hat{\mu}_i b_{ij}) \hat{I}_{ij}, \quad (3-31)$$

$$\Delta\theta_i = (\theta_{\max,i} - \theta_{\min})/m, \quad (3-32)$$

$$\hat{I}_{ij} = \frac{\Delta\epsilon_{ij}}{2} \sum_{k=0}^l w_k B_{ijk} \exp(-\bar{\mu} c_{ijk}), \quad (3-33)$$

and

$$\Delta\epsilon_{ij} = \epsilon_{m,ij}/l. \quad (3-34)$$

The weights w are equal to two except for those at the end points

(w_0, w_n, w_m and w_l) which are equal to one.

Equations (3-31) and (3-33) are the trapezoidal approximations of the double integration over ϵ and θ and the single integration over ϵ , respectively, in Eq. (3-27). Equations (3-29) and (3-31) can be simplified since $\theta_{\max} = \theta_{\min}$ at $\beta_{\max}$ ($\hat{I}_0 = 0$) and $\epsilon_m = 0$ at $\theta_{\min}$ ($I_{10} = 0$) (see Eqs. (3-32), (3-26) (3-21), and (3-25)). The resultant simplified exposure rate equation thus becomes

$$\begin{aligned} \frac{\dot{X}_d^2}{S} \approx & \frac{CKNd\Delta\beta}{16\pi} \sum_{i=1}^n w_i \sigma_i \left[\frac{\mu_{en}}{\rho} \right]_i \hat{E}_i \Delta\theta_i \sum_{j=1}^m w_j \hat{B}_{ij} \exp(-\mu a_{ij} - \hat{\mu}_i b_{ij}) \Delta\epsilon_{ij} \\ & \times \sum_{k=0}^l w_k B_{ijk} \exp(-\bar{\mu} c_{ijk}). \end{aligned} \quad (3-35)$$

The notations used for various functions are defined in Table 3-1.

This result was programmed and used to predict the skyshine exposure rates expected in this study. The "standard computer code" used 1100 mesh points ($n=10$, $m=10$, $l=10$), a total air mean free path limit of 10 mfp, a total concrete mean free path limit of 15 mfp, and Berger infinite medium exposure buildup factors for the concrete silo roof and the second air leg. To justify the choice of 1100 mesh points and the photon path limits, each of these conditions was studied without changing the others. The distance from the source to the differential scattering volume was assumed to be equal to the photon air path length ($a=\bar{a}$) for all computer runs. Also, the ^{60}Co emission spectrum was approximated by two 1.25 MeV photons emitted per disintegration. The result of this energy spectrum approximation will be discussed in the next chapter.

The effect of changing the number of trapezoid mesh points on the standard exposure rate program was explored by setting n , m , and l to 10, 20, and 40 in sequential computer runs. Table 3-3 indicates that changing the number of mesh points from 1100 to 65600 resulted in a change of less than 1.1%. The 65600 mesh point run used almost 35 times as much computer time as the 1100 mesh point run. Therefore, for skyshine calculation the standard computer program was set to run with n , m , and l of Eq. (3-35) equal to 10.

Another approximation arose from the fact that the air legs a and b become infinite as the scattering angle approached zero. Therefore, a total air path limit L was imposed such that

$$\mu_a + \mu_b \leq L \quad (3-36)$$

Table 3-3. Stability of the Normalized Exposure Rate, $\frac{\dot{X}_d^2}{S}$, calculation for the 0.428 m shielded silo configuration.

Source-to-Detector Mass Distance (g/m^2)	1100 Mesh points exposure rate ($\mu\text{Rm}^2/\text{hCi}$)	8400 Mesh points exposure rate ($\mu\text{Rm}^2/\text{hCi}$)	65600 Mesh points exposure rate ($\mu\text{Rm}^2/\text{hCi}$)
11.10	493.8	493.7	493.7
22.20	468.3	467.2	466.8
33.30	310.7	309.0	308.5
44.52	177.4	175.9	175.5

Geometrically, a and b cannot be greater than the diameter of the circular segment used to generate the constant scattering angle surface. Since the scattered photon linear attenuation coefficient $\hat{\mu}$ is always greater than the source photon linear attenuation coefficient μ , then $\mu a + \hat{\mu} b$ is assumed to have a maximum value when b is at its maximum value. The distance between the differential scattering volume and the detector, b , is a maximum at θ equal to $\pi/2$ for angles β less than $\pi/2$. Equations (3-12) and (3-13) substituted into Eq. (3-36) and the result evaluated at $\theta = \pi/2$ yields

$$d\mu \cot\beta + d\hat{\mu} \csc\beta \leq L. \quad (3-37)$$

The minimum scattering angle $\beta_{\min}$ is numerically approximated by evaluating the left side of Eq. (3-37) at one degree intervals until the left side is less than L . Then one degree is added to this value and the result is considered $\beta_{\min}$. Different total air path limits were evaluated to determine the effect on the calculated open silo skyshine exposure rate. As can be seen in Table 3-4, increasing the total air path limit beyond 10 mfp changes the skyshine exposure rate by less than 0.4%. Therefore, for detector-to-source distances equal to or less than 700 m the total air path limit of 10 mfp is adequate.

Addition of the concrete roof to the silo requires another approximation to be made. Obviously as photons travel through the concrete roof at larger Ω angles (see Fig. 3-4), the path length the photon travels through the roof increases. For computation purposes,

Table 3-4. Effects of Various Total Air Mean Free Path Limits on the Calculated Normalized Open Silo Exposure Rates, $\frac{X_d^2}{S}$. Air density is 1.200 gcm^{-3} .

Source to Detector Distance d (m)	Total Air Mean Free Path Computer Cutoff Limits						
	5 mfp	7.5 mfp	10.0 mfp	12.5 mfp	15.0 mfp	17.5 mfp	20.0 mfp
50	64.16 ^a	64.46 ^a	64.60 ^a	64.76 ^a	64.76 ^a	64.84 ^a	64.84 ^a
100	101.33	102.32	102.44	102.59	102.63	102.67	102.70
200	106.73	109.28	109.90	110.08	110.08	109.99	110.00
300	78.96	82.17	82.80	82.97	83.01	83.01	82.99
400	50.61	53.82	54.35	54.46	54.47	54.44	54.40
500	25.08	32.72	33.18	33.24	33.23	33.21	33.16
600	8.08	19.00	19.36	19.42	19.40	19.38	19.35
700	... ^b	10.21	10.98	11.01	11.01	10.98	10.96

^aUnits are $\text{mR}^2 \text{ m}^2 \text{ h}^{-1} \text{ Ci}^{-1}$

^bThe source to detector air mean free path length is greater than 5 mfp.

some limit L_c on the concrete path length c needs to be set. This limit was determined by multiplying Eq. (3-14) by the concrete linear attenuation coefficient $\bar{\mu}$, setting the result equal to L_c and solving for ϵ_m . In other words,

$$\bar{\mu}c = L_c = \bar{\mu}t \sec\epsilon_m \csc\theta, \quad (3-38)$$

solved for ϵ_m becomes

$$\epsilon_m = \arccos \left(\frac{\bar{\mu}t}{L_c} \csc\theta \right), \quad (3-39)$$

in which t is the concrete roof thickness. As calculated skyshine exposure rate results listed in Table 3-5 indicate, increasing the concrete path length beyond 15 mfp changes the calculated exposure rates by less than 0.1%. Thus Eq. (3-39) with $L_c = 15$ mfp replaces Eq. (3-25) as the limit on ϵ for concrete covered silos whenever ϵ_m as calculated by Eq. (3-39) is less than ϵ_m calculated by Eq. (3-25).

The effect of different buildup factors will be discussed in the next chapter. A computer program SKY based on Eq. (3-35) was developed by the author. This computer program SKY is presented in Appendix B.

Table 3-5. Effects of Various Total Concrete Mean Free Path Limits on the Normalized Exposure Rates, $\frac{X_d^2}{S^{23}}$ for the 0.428 m Concrete Roofed Silo Configuration. Air Density is 1.200 g cm⁻³.

Source to Detector Distance d (m)	Total Concrete Mean Free Path Computer Cutoff Limits						
	7.5 mfp	10.0 mfp	12.5 mfp	15.0 mfp	17.5 mfp	20.0 mfp	22.5 mfp
50	306.48 ^a	344.20 ^a	347.58 ^a	347.93 ^a	347.96 ^a	347.96 ^a	347.96 ^a
100	439.74	498.98	504.33	504.89	504.95	504.95	504.95
200	377.80	437.59	443.82	444.46	444.52	444.53	444.53
300	229.00	269.13	273.48	273.99	274.04	274.04	274.04
400	118.30	143.22	146.14	146.49	146.52	146.53	146.53
500	56.34	70.46	72.32	72.53	72.55	72.56	72.56
600	25.43	33.00	34.06	34.18	34.20	34.20	34.20
700	11.18	14.96	15.56	15.63	15.63	15.63	15.63

^aUnits are $\mu R \text{ m}^2 \text{ h}^{-1} \text{ Ci}^{-1}$.

4.0 SKYSHINE EXPOSURE RATE ANALYSIS

The usefulness of any numerical analysis program is based on two factors, the program's accuracy and the program's complexity. Analysis based on transport theory is capable of yielding the most accurate results for the prediction of skyshine exposure rates. However, programs based on transport theory are typically complex and require large computers and extensive computational effort. On the other hand, point kernel techniques are considerably simpler but not always as accurate. In this chapter, the accuracy of the point kernel technique developed in Chapter 3 is discussed and the results of using this model for different source energies and source shielding thicknesses are presented.

4.1 The Unshielded Source Silo Buildup Factors

In Section 3.1 of this work, two buildup factors B and $\hat{B}$ for the first and second streaming legs were introduced. These buildup factors, as defined in Chapter 3, produce the exact correction necessary for the exposure rate equation (Eq. 3-9) to equal the actual exposure rate. Since both of these buildup factors require complex geometry and anisotropic photon distributions, neither of these buildup factors have been calculated. Therefore, infinite medium buildup factors for point isotropic sources are traditionally used to approximate B and $\hat{B}$.

The use of the isotropic point source buildup factors for infinite mediums requires recognition of the following limitations.

- 1) The skyshine experiments were performed near the air-ground interface and not in an infinite air medium. Therefore use of an infinite medium buildup factor for the second leg could be expected to overestimate slightly the actual exposure rate, since the probability that a photon will be scattered into the detector is decreased by the proximity of the higher z material in the ground. This decrease in the scattering probability for the higher z material is due to the increased photoelectric absorption cross section in the soil.
- 2) The angular distribution of photons scattered from a point is not isotropic, since Compton scattering is preferentially forward at photon energies above 100 keV. Therefore, use of an isotropic point source buildup factor in the second leg is inappropriate.
- 3) The actual silo source is a collimated point source not a 4π isotropic source. Therefore use of an isotropic source buildup factor in the first leg would overestimate the exposure rate in the scattering volumes near the edges of the collimated radiation field. The isotropic source buildup factor overestimates the buildup in this case because no unscattered source photons may be scattered into the collimated region from outside of the collimated cone.

The buildup factor in the first leg has another theoretical inconsistency besides the collimated source problem discussed above. This problem is that the buildup factor in the first leg artificially increases the number of source energy photons which arrive at the scattering volume dV and are subsequently scattered. Therefore, this buildup factor together with the assumption of no spectrum degradation leads to an overestimation of the exposure rate at the detector.

All the buildup factors in this work were represented by the Berger buildup factor equation,

$$B(E, \mu z) = 1 + C_1(E) \mu z \exp(C_2(E) \mu z) \quad (4-1)$$

in which μz is the medium mean free path length along the appropriate path to or from the scattering volume dV and the constants $C_1(E)$ and $C_2(E)$ are linearly interpolated from either Table 4-1 or 4-2 as appropriate.^{14,1}

Experimental factors did contribute to the differences between the calculated exposure rates and the experimental exposure rates. Some direct penetration of source photons through the silo was present. However in the open silo case, the direct penetration component was several orders of magnitude less than the skyshine component. Near the silo, photon scattering within the silo, within the source, and from the steel top of the source cask can increase the unshielded experimental exposure rate by increasing the number of low energy photons which reach the detector. At larger distances, photons scattered within the silo or within the source are absorbed before affecting the detector. Since these photons have lost energy in at least two scattering interactions and the photoelectric absorption cross section increases with decreasing energy then the probability that these twice scattered photons will reach the detector is less than the probability that singly scattered photons will reach the detector.

Since the roof thickness is zero ($c=0$) for the unshielded source silo, the integral over ϵ in Eq. (3-28) can be evaluated to yield

$$\frac{\dot{X}_d^2}{s} = \frac{CKNd}{2\pi} \int_0^{\beta_{\max}} \sigma \hat{E} \frac{\mu_{en}}{\rho} \int_{\theta_{\min}}^{\theta_{\max}} \hat{B} \hat{B} \exp(-\mu_a - \mu_b) \epsilon_m d\theta d\beta. \quad (4-2)$$

Table 4-1. Berger Parameters for Point Source Buildup Factors in Infinite Air, Air Kerma Response Function.¹⁴

E (MeV)	C ₁	C ₂	Maximum Deviation (%)
0.2	3.94	0.113	40.8
0.3	3.10	0.094	37.0
0.4	2.61	0.079	32.5
0.5	2.29	0.067	29.2
0.6	2.05	0.058	25.7
0.8	1.71	0.045	20.8
1	1.50	0.035	17.2
1.5	1.16	0.021	10.7
2	0.97	0.013	6.6

Table 4-2. Berger Parameters for Point Source Buildup Factors in Infinite Concrete, Exposure Rate Response Function.¹⁵

E (MeV)	C ₁	C ₂	Maximum Deviation (%)
0.2	2.20	0.065	19.2
0.3	2.03	0.067	21.3
0.4	1.87	0.061	21.7
0.5	1.73	0.055	20.7
0.6	1.60	0.049	19.7
0.8	1.41	0.040	16.9
1	1.27	0.032	14.6
1.5	1.02	0.021	9.7
2	0.89	0.014	6.8

Trapezoidal integration of Eq. (4-2) produces

$$\frac{\dot{X}_d^2}{S} \approx \frac{CKNd\Delta\beta}{16\pi} \sum_{i=1}^n w_i \sigma_i \left(\frac{\mu_{en}}{\rho} \right)_i \hat{E}_i \Delta\theta_i \sum_{j=1}^m w_j \hat{B}_{ij} B_{ij} \exp(-\mu a_{ij} - \hat{\mu}_i b_{ij}) \epsilon_{m,ij} \quad (4-3)$$

in which all the functions in Eqs. (4-2) and (4-3) are defined in Tables 3-1 and 3-2.

In order to decide whether both first and second air leg buildup factors should be used in the point kernel model given by Eq. (4-3) the unshielded skyshine exposure rates were calculated with three different buildup conditions. These calculations were made using the standard computer code SKY ($n, m, l, = 10, a = \bar{a}$, etc.) with $\hat{B}_{ij}$ and B_{ij} set equal unity, with B_{ij} set equal unity and $\hat{B}_{ij}$ evaluated by Eq. (4-1), and with $\hat{B}_{ij}$ and B_{ij} both evaluated by Eq. (4-1). The results of these calculations are presented in Fig. 4-1 along with the measured results obtained by averaging the energy corrected exposure rate data of Table 2-15. If the air mass thicknesses were within 1.00 g cm^{-2} or the exposure rates were indistinguishable when plotted, then the average exposure rate was determined by averaging both the exposure rates and their respective air mass thicknesses to obtain the average exposure rate and the average air mass thickness.

As would be expected, use of both air leg buildup factors overestimated the skyshine exposure rate. When both buildup factors were set to unity, the skyshine exposure rate was underestimated. However, use of the second air leg buildup factor alone produced skyshine exposure rates ranging from 3% low at 11.20 g cm^{-2} to 50% high at 57.2 g cm^{-2} when compared to HPIC measured exposure rates corrected with

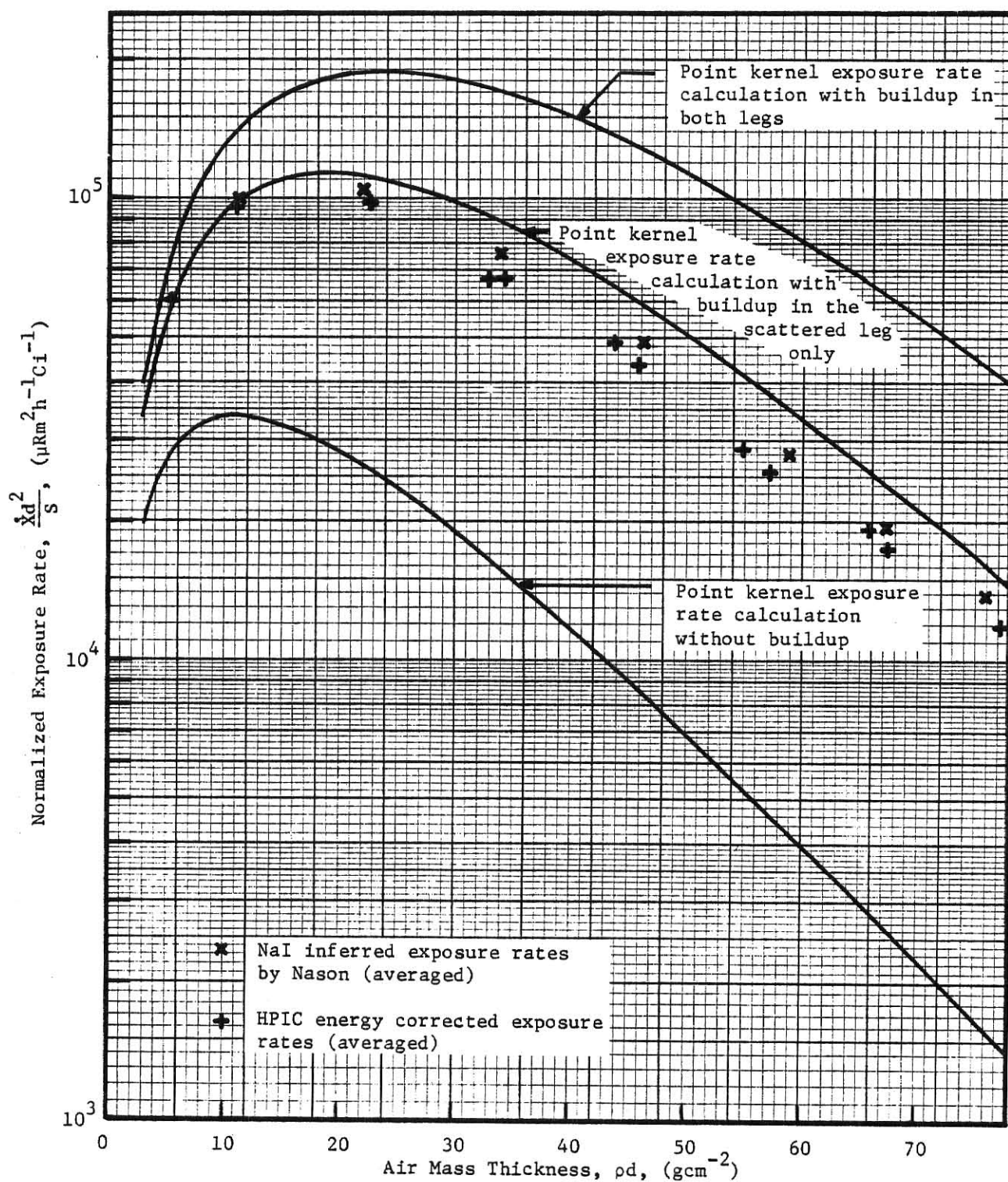


Fig. 4-1. Skyshine exposure rates calculated using different air buildup techniques. The source silo is in the unshielded configuration.

RRA's energy correction factors (from Table 2-15). Calculated skyshine exposure rates ranged from 0.4% low at 11.20 g cm^{-2} to 45.8% high at 57.2 g cm^{-2} when compared to HPIC measured exposure rates corrected with Nason's energy correction factors (from Table 2-15). The overall average percent error $\overline{\%E}$ was 22.5%.

The absolute average percent error, $\overline{\%E}$, is calculated by

$$\overline{\%E} = \frac{1}{N} \sum_{n=1}^N |\%E|_n, \quad (4-4)$$

in which N is the number of HPIC data points or the number of calculated data points whichever is smaller and $\%E$ is given by

$$\%E = \left(\frac{\dot{X}_{\text{cal}}}{\dot{X}_{\text{HPIC}}} - 1 \right) 100, \quad (4-5)$$

in which $\dot{X}_{\text{cal}}$ is the numerically calculated exposure rate and $\dot{X}_{\text{HPIC}}$ is the HPIC energy corrected exposure rate.

The second air leg buildup factor was retained in Eq. (4-3) and Eq. (3-35) and the first air leg buildup factor was discarded as a result of these calculations. The use of the second air leg buildup factor with the point kernel technique is widely accepted in unshielded skyshine exposure rate calculations.^{2,13,18} Theoretically, the first air leg buildup is not needed because any first leg multiply scattered photons are less energetic than source energy photons and therefore more easily absorbed before reaching the detector.

The average first air leg path length for the unshielded source case was calculated by

$$\bar{a}_\mu = \frac{16\pi \sum_{i=1} w_i \sigma_i \left(\frac{\mu_{en}}{\rho} \right)_i \hat{E}_i \Delta\theta_i \sum_{j=1} w_j \hat{B}_{ij} \exp(-\mu_{a_{ij}} - \hat{\mu}_i b_{ij}) \mu_{a_{ij}} \epsilon_{m,ij}}{CKNd\Delta\beta \left(\frac{\dot{X}d^2}{S} \right)} \quad (4-6)$$

in which the functions are defined in Tables 3-1 and 3-2. The average first air leg path length varied from 0.12 mfp at a source-to-detector mass thickness of 3.0 g cm^{-2} to 1.277 mfp at 84 g cm^{-2} . This short path length supports the assumption that the source photon energy would not be significantly degraded at the scattering volumes which contribute to the calculated exposure rates. Therefore, the use of a monoenergetic scattering cross section can be supported for measurement locations out to 700 m.

4.2 The Shielded Source Silo Buildup Factor

The concrete buildup factor B_{ijk} was used to correct for multiple scattering of source energy photons within the concrete roof. To determine the need for this correction to the point kernel model given by Eq. (3-35), the shielded skyshine exposure rates were calculated with two silo concrete roof thickness (0.210 m and 0.428 m) and two different buildup conditions. These calculations were made using the standard computer code SKY ($n, m, \ell = 10$, etc.) redefined to include air buildup in the second leg only (see Eq. (3-35)). The shielded skyshine exposure rates were then calculated for both shielded configurations, with the concrete buildup factor B_{ijk} set equal to one (no concrete buildup) and with B_{ijk} given by Eq. (4-1) in which $\mu z = \bar{\mu}c$. The results

of these calculations are presented in Figs. 4-2 and 4-3 along with the averaged, energy-corrected, measured exposure rate data.

As would be expected, the exposure rates calculated without the concrete roof buildup factor were considerably low. However, the exposure rates corrected for concrete roof buildup were in good agreement with the HPIC, energy-corrected, experimental values as can be seen in Table 4-3.

Justification of the use of the concrete roof buildup factor can be based on the following statements. Since the concrete roof shielding is comparatively thick, a significant number of source photons undergo small deflection scatters in the roof. However, these photons after scattering in the air are still energetic enough to reach the detector and affect the exposure rate. The concrete roof buildup factor corrects for these photons slightly deflected by the roof.

The last assumption in the evaluation of the point kernel model of Eq. (3-35) to be considered is the use of two 1.25 MeV source photons to approximate the 1.332 MeV and 1.173 MeV source photons from a ^{60}Co skyshine source.¹⁷ The use of two 1.25 MeV photons instead of the actual photon energies induces a difference of less than 1.7% between the calculated exposure rates over all experimental silo configurations and measurement locations. This result was obtained by computing the exposure rates for two 1.25 MeV photons and the exposure rates for the actual ^{60}Co photon energies and comparing the results. Therefore, two 1.25 MeV photons per disintegration of ^{60}Co are used in any subsequent analysis.

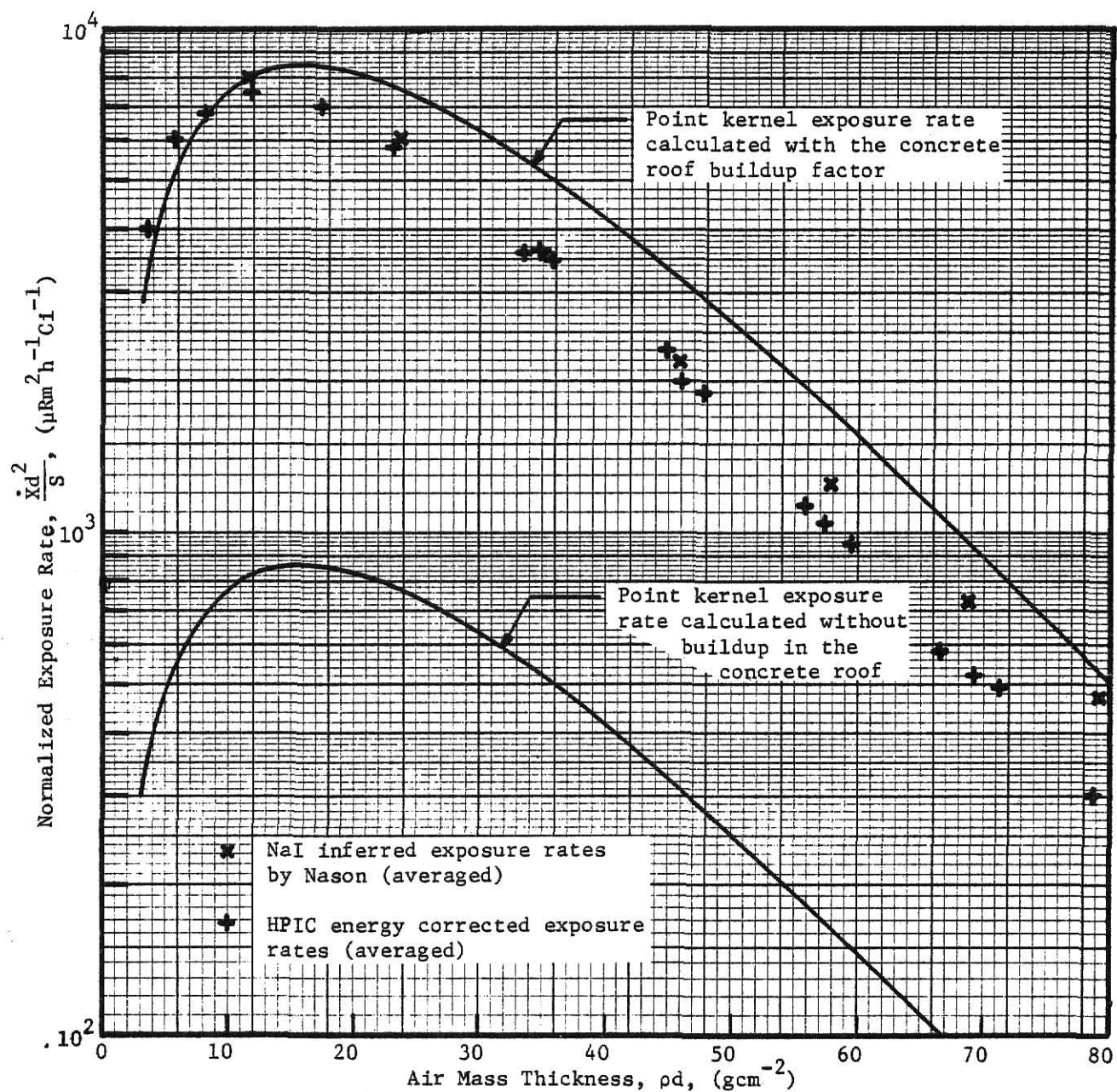


Fig. 4-2. Exposure rates calculated using different concrete roof buildup techniques. The source silo is in the 21.0 cm shielded configuration.

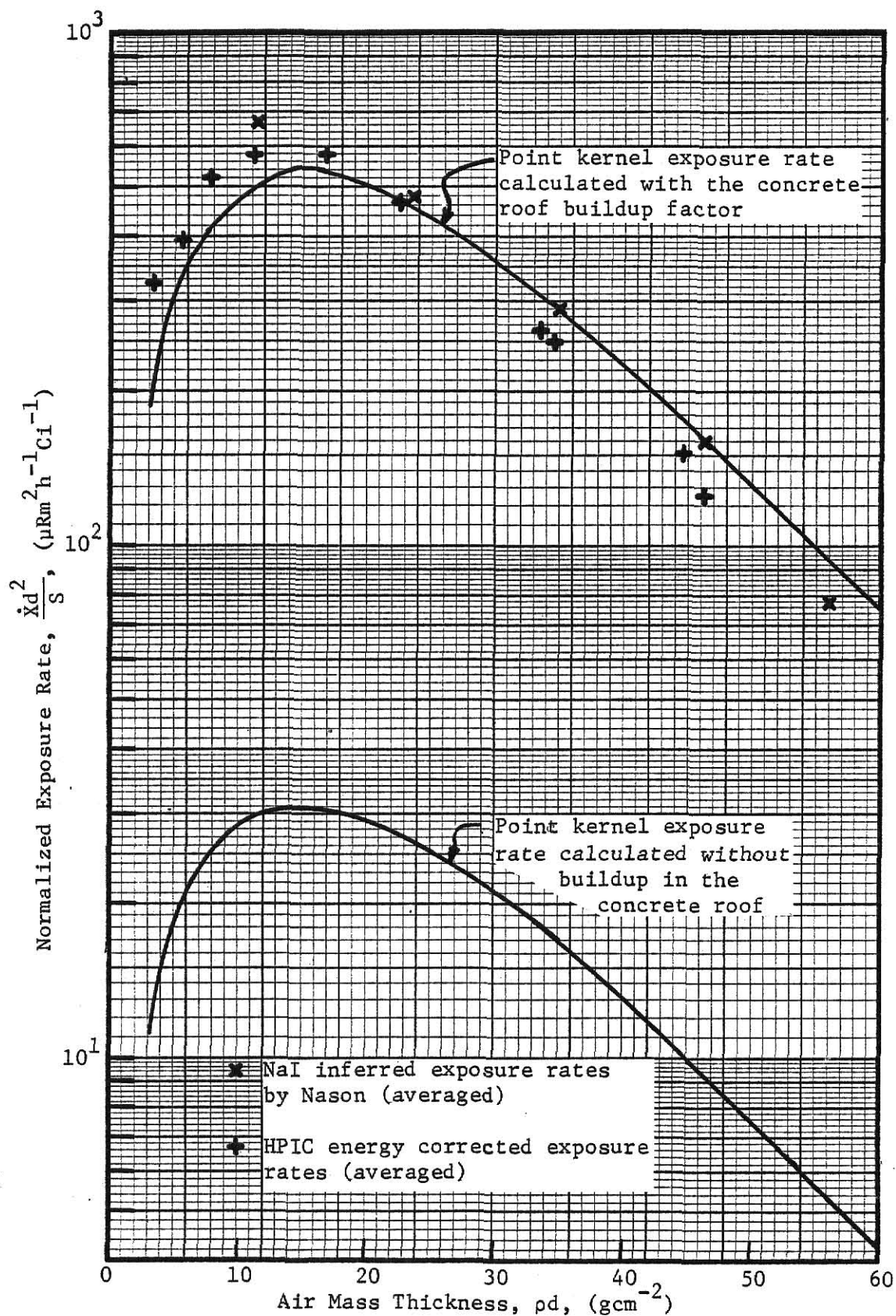


Fig. 4-3. Exposure rates calculated using different concrete roof buildup techniques. The source silo is in the 42.8 cm shielded configuration.

Table 4-3. % Error Ranges and Average % Errors for SKY Calculated Exposure Rates Compared to Energy Corrected HPIC Experimental Exposure Rates.

Silo Concrete Roof Thickness (m)	Maximum % Error %E	Minimum % Error %E	Average % Error %E
0.210	94.7% (78.12) ^a	-17.2% (3.63) ^a	42.6%
0.428	30.6% (46.16)	-36.1% (3.38)	17.0%

^aValues in parenthesis are the air mass thicknesses in g cm^{-2} at which the maximum % error or the minimum % error occurred.

4.3 Comparison of Calculated and Experimental Skyshine Exposure Rates

Various unshielded skyshine exposure rate calculations and the measured exposure rate data are compared in Fig. 4-4. The 10 energy group and the 39 energy group discrete ordinates transport calculations (made with DOT 3.5) presented on Fig. 4-4, were calculated by RRA especially for the unshielded source configuration.¹ The 39-group DOT exposure rate calculation underestimated the corrected HPIC exposure rate by 17.2% at 11.4 g cm^{-2} and overestimated the HPIC exposure rate by 17.6% at 57.2 g cm^{-2} . The average absolute percent error calculated for the 39 energy group DOT calculation is 10.5% (using Eq. (4-4)). The average percent error calculation was limited to 12 points since the DOT calculations were not performed for all the mass thicknesses in Table 2-15. The 10 group DOT calculations could not be compared directly to experimental data since the mass thicknesses at which these calculations were made do not directly correspond to the experimental data. However, Nason noted that the 10 group results underestimated the HPIC experimental results by approximately 10% at all measurement locations.²

Point kernel calculations by Kadotani of Century Research Center Corporation in Tokyo, Japan are also depicted on Fig. 4-4.¹⁶ These calculations use Taylor's buildup factor equation on the second air leg and cartesian coordinates.¹⁸ Taylor's formula for buildup is given by

$$B_T(\hat{\mu}x) = Ae^{-\alpha\hat{\mu}x} + (1-A)e^{-v\hat{\mu}x} \quad (4-7)$$

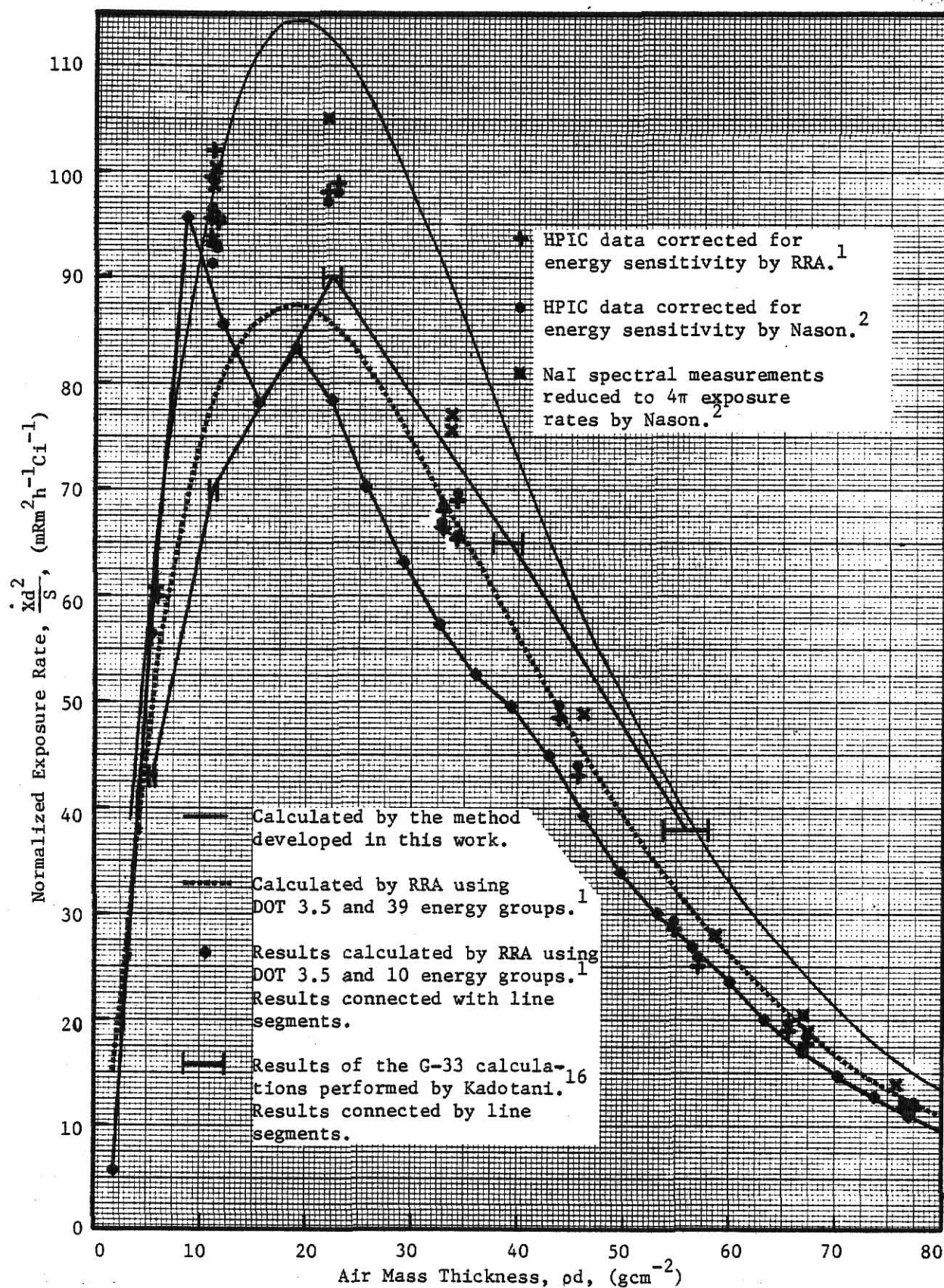


Fig. 4-4. Comparison of point kernel models and discrete ordinates calculated exposure rates for the unshielded source configuration.

in which A , α , and ν are constants for a given photon energy.¹¹

These G-33 skyshine exposure rate results are approximately 30% low at the 50 meter location and approximately 40% high at the 500 meter location. The average absolute percent error of the G-33 calculation based on 50 m, 100 m, 200 m, and 500 m G-33 data compared to HPIC experimental data is approximately 25%. All G-33 calculated values from Kadotani were obtained from his hand drawn graphs. Also, the air density at which these G-33 calculations were made is unknown. Therefore, all % errors for the G-33 calculations are approximate and the horizontal error bars on Fig. 4-4 indicate approximate mass thickness ranges of Kadotani's G-33 calculations.

Until reaching the 200 m measurement location, the G-33 calculations underestimated the unshielded skyshine exposure rates. After the 200 m location the G-33 calculation overestimated the skyshine exposure rates. The DOT (39 group) calculation underestimated the skyshine exposure rate at the 100 m and 200 m location and closely approximated the HPIC skyshine measurements elsewhere. The DOT (10 group) calculation approximated the skyshine measurement until about 100 m then the DOT (10 group) calculation underestimated the skyshine exposure rate. The point kernel model developed in this work matched the skyshine data near the source (until 200 m). Beyond 200 m, the SKY calculated exposure rate overestimated the skyshine exposure rate.

Kadotani investigated the concept of no first leg buildup in the concrete roof and the exposure rates produced seriously underestimated

the experimental exposure rates.¹⁶ The G-33 program was then modified by Kadotani to account for the concrete roof shield. This modification was the inclusion of a first leg concrete buildup factor of Taylor's form. This Taylor's form buildup factor was evaluated with $A = 51.5$, $\alpha = -0.04307$, and $\nu = -0.020715$.¹⁶ The distance x in Eq. (4-7) was set equal either to the concrete roof thickness t or to the photon path length c . The concrete linear attenuation coefficient $\bar{\mu}$ was also substituted for $\hat{\mu}$ in Eq. (4-7). The G-33 calculations using second air leg buildup and concrete roof buildup with $x=t$ are identified with the horizontal error bars on Figs. 4-5 and 4-6. The G-33 calculations using second air leg buildup and concrete roof buildup with $x=c$ are identified with the horizontal error bars with triangles on each end in Figs. 4-5 and 4-6. The type of buildup factor (i.e., slab, point source, etc.) was not reported by Kadotani.

Figures 4-5 and 4-6 compare DOT (10 group) calculations, G-33 calculations, and calculations using the point kernel model developed in this work to the shielded skyshine exposure rate experimental data. For the 21.0 cm shielded source configuration, the DOT calculations were mistakenly performed with a 20 cm thick shield and therefore the DOT calculated values need to be decreased by 13% (see Section 4.4). The % error reported by RRA for the DOT calculation was 20% at the 700 m location¹. The G-33 calculations using $B_T(\bar{\mu}t)$ when compared to HPIC skyshine data have a percent error range of approximately 65% low at the 50 m location to 25% high at the 500 m location. These G33 calculations have an average percent error of 40% when compared to the HPIC skyshine

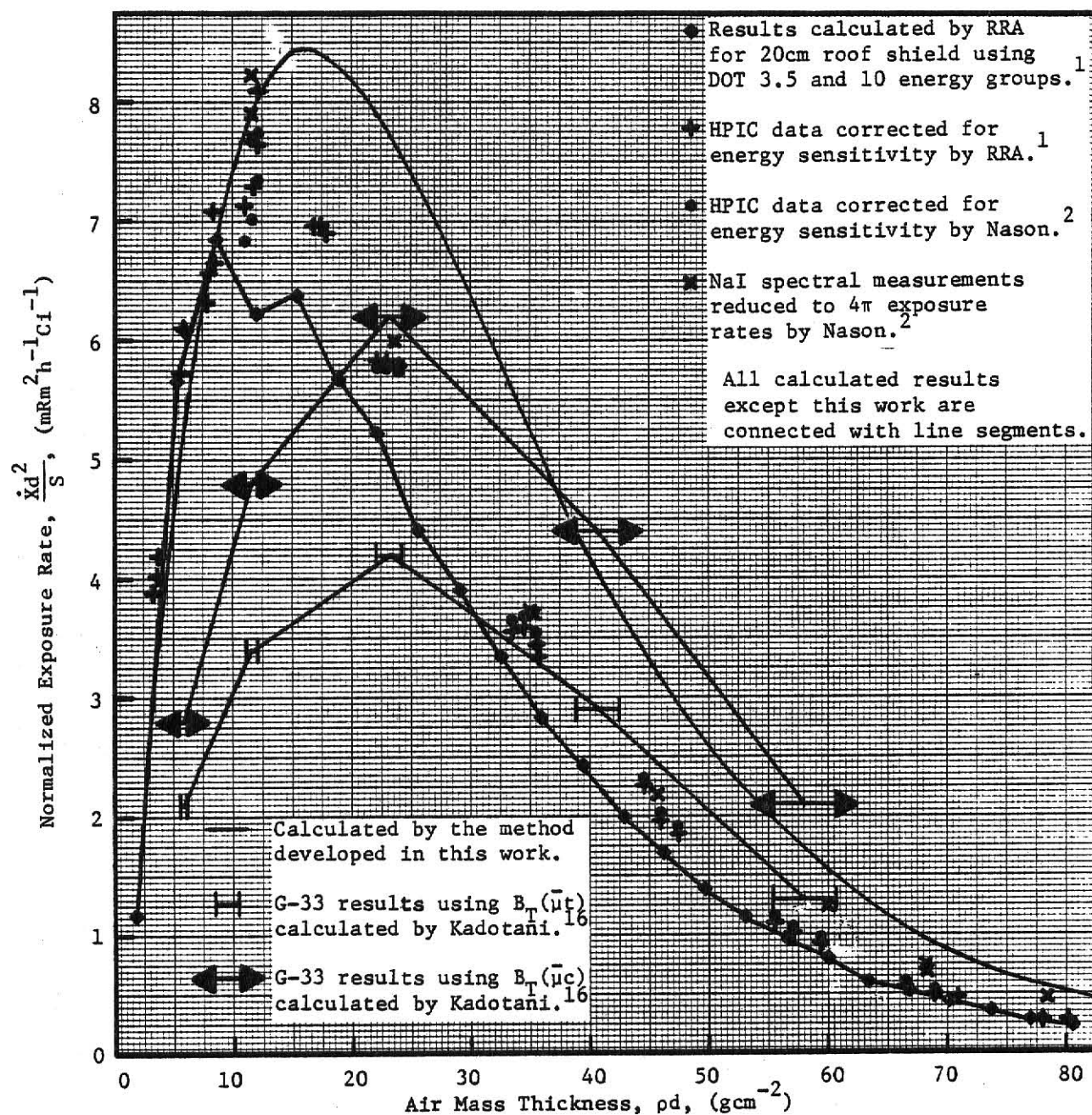


Fig. 4-5. Comparison of point kernel models and discrete ordinates calculated exposure rates for the 21.0 cm shielded source configuration.

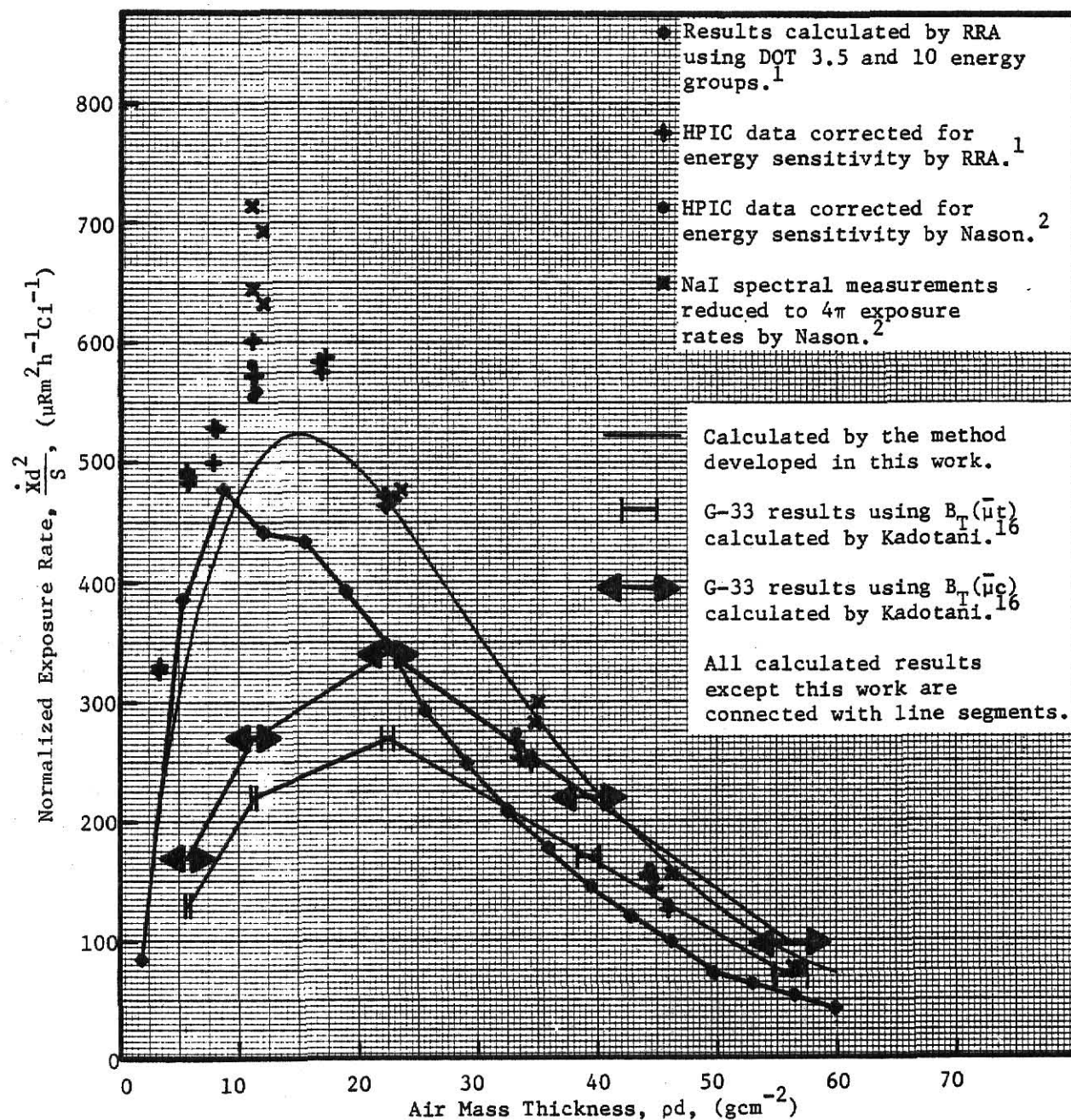


Fig. 4-6. Comparison of point kernel models and discrete ordinates calculated exposure rates for the 42.8 cm shielded source configuration.

data. The G-33 calculations using $B_T(\bar{\mu}c)$ compared to HPIC skyshine data have an approximation percent error range of 50% low at the 50 m location to 100% high at the 500 m location and an approximate average percent error of 45%.

In general the DOT (10 group) calculation underestimates the HPIC skyshine data for the 21.0 cm shielded case. The G-33 calculations using $B_T(\bar{\mu}t)$ produces a slightly better fit to the HPIC 21.0 cm shielded skyshine data than the G-33 calculations using $B_T(\bar{\mu}c)$. The point kernel calculation developed in this work overestimated the skyshine exposure rates for the 21.0 cm shielded case beyond the 150 m location.

Figure 4-6 compares the calculated skyshine exposure rate results with the experimental skyshine data for the 42.8 cm shielded source configuration. The DOT (10 group) calculations were reported as being within 25% of the HPIC skyshine data without the DOT calculations correcting for direct penetration of source photons.¹ Direct penetration accounts for more of the HPIC exposure rates as the roof thickness is increased since the source strengths must be increased in order to produce significant instrument responses above background levels. The DOT (10 group) calculations are underestimating the skyshine data over the entire measurement range of 30 m to 400 m. The G-33 calculation using $B_T(\bar{\mu}t)$ had an approximate percent error range of 70% low at 50 m compared to HPIC skyshine data to 10% low at 500 m compared to Nason's NaI inferred 4π exposure rates (see Table 2-17). The G-33 calculation using $B_T(\bar{\mu}t)$ had an approximate average percent error of 45% when compared to the skyshine data. The G-33 calculation using

$B_T(\bar{\mu}c)$ had an approximate percent error range of 65% low at the 50 m location compared to HPIC skyshine data to 25% high at the 500 m location compared to Nason's NaI inferred 4π exposure rates. These G-33 calculations have an approximate average percent error of 40% when compared to experimental data. The NaI data at the 500 m location were used since the HPIC could not distinguish the skyshine exposure rates from background exposure rates beyond 400 m. Both G-33 calculations underestimate the skyshine exposure rate over nearly the entire measurement range. The calculated exposure rates using the model developed in this work underestimated the skyshine exposure rate after the 200 m location. Since the point kernel model does not correct for direct penetration, underestimation of the exposure rate near the silo could be expected. Tables 4-4, 4-5, and 4-6, summarize the percent error ranges and averages for the various calculational methods.

4.4 Prediction of Skyshine Exposure Rates

The point kernel model, once shown to give reasonable agreement with measured values, can then be used to determine the sensitivity of the skyshine experiment to various experimental parameters. For example, the sensitivity of the open silo skyshine exposure rate to collimation angle can be seen in Fig. 4-7. The effect of a five degree change in collimation angle from 150.5° would make about a 20% change in skyshine exposure rates. The general behavior of the skyshine exposure rate is as would be expected, i.e., a decrease in collimation angle yields a decrease in overall exposure rate. Also the exposure rates beyond 30 g cm^{-2} drop off more quickly for the smaller collimation

Table 4-4. Summary of Percent Error Ranges and Average Percent Errors for Various Skyshine Exposure Rate Calculation Methods. The Source Silo is in the Unshielded Configuration.

Calculational Method	Maximum % Error	Minimum % Error ^a	% Error Range	Average % Error ^b
SKY ^c	50 (500 m) ^d	- 3 (100 m) ^d	53	22.5
DOT 3.5 ¹ (39 group)	18 (500 m)	-17 (100 m)	25	10.5
DOT 3.5 ¹ (10 group)	...	...	...	10 ²
G-33) ¹⁶	40 (500 m)	-30 (50 m)	70	25

^aNegative signs indicate underestimation of the HPIC data.

^bAverage % errors with decimal points were calculated by Eq. (4-4). All other average % errors are estimated.

^cSKY is the point kernel skyshine exposure rate program developed in this work (see Appendix B).

^dFigures in parenthesis are detector locations at which the maximum or minimum occurred.

Table 4-5. Summary of Percent Error Ranges and Average Percent Errors for Various Skyshine Exposure Rate Calculation Methods. The Source Silo is in the 21.0 cm Shielded Configuration.

Calculational Method	Maximum % Error	Minimum % Error ^a	% Error Range	Average % Error ^b
SKY ^c	95 (700 m) ^d	-17 (30 m) ^d	112	42.6
DOT 3.5 ¹ (10 group)	...	...		20 ¹
G-33 ¹⁶ (B _T (μt))	25 (500 m)	-65 (50 m)	90	40
G-33 ¹⁶ (B _T (μc))	100 (500 m)	-50 (50 m)	150	45

^aNegative signs indicate underestimation of the HPIC data.

^bAverage % errors with decimal points were calculated by Eq. (4-4). All other average % errors are estimated.

^cSKY is the point kernel skyshine exposure rate program developed in this work (see Appendix B).

^dFigures in parenthesis are detector locations at which the maximum or minimum occurred.

Table 4-6. Summary of Percent Error Ranges and Average Percent Errors for Various Skyshine Exposure Rate Computational Methods. The Source Silo is in the 42.8 cm Shielded Configuration.

Computational Method	Maximum % Error ^a	Minimum % Error ^a	% Error Range	Average % Error ^b
SKY ^c	31 (400 m) ^d	-36 (30 m) ^d	67	17.0
DOT 3.5 ¹ (10 group)	...	...		25 ¹
G-33 ¹⁶ (B _T (μt))	-10 (500 m)	-70 (50 m)	80	45
G-33 ¹⁶ (B _T (μc))	25 (500 m)	-65 (50 m)	90	40

^a Negative signs indicate underestimation of the HPIC data.

^b Average % errors with decimal points were calculated by Eq. (4-4). All other average % errors are estimated.

^c SKY is the point kernel skyshine exposure rate program developed in this work (see Appendix B).

^d Figures in parenthesis are detector locations at which the maximum or minimum occurred.

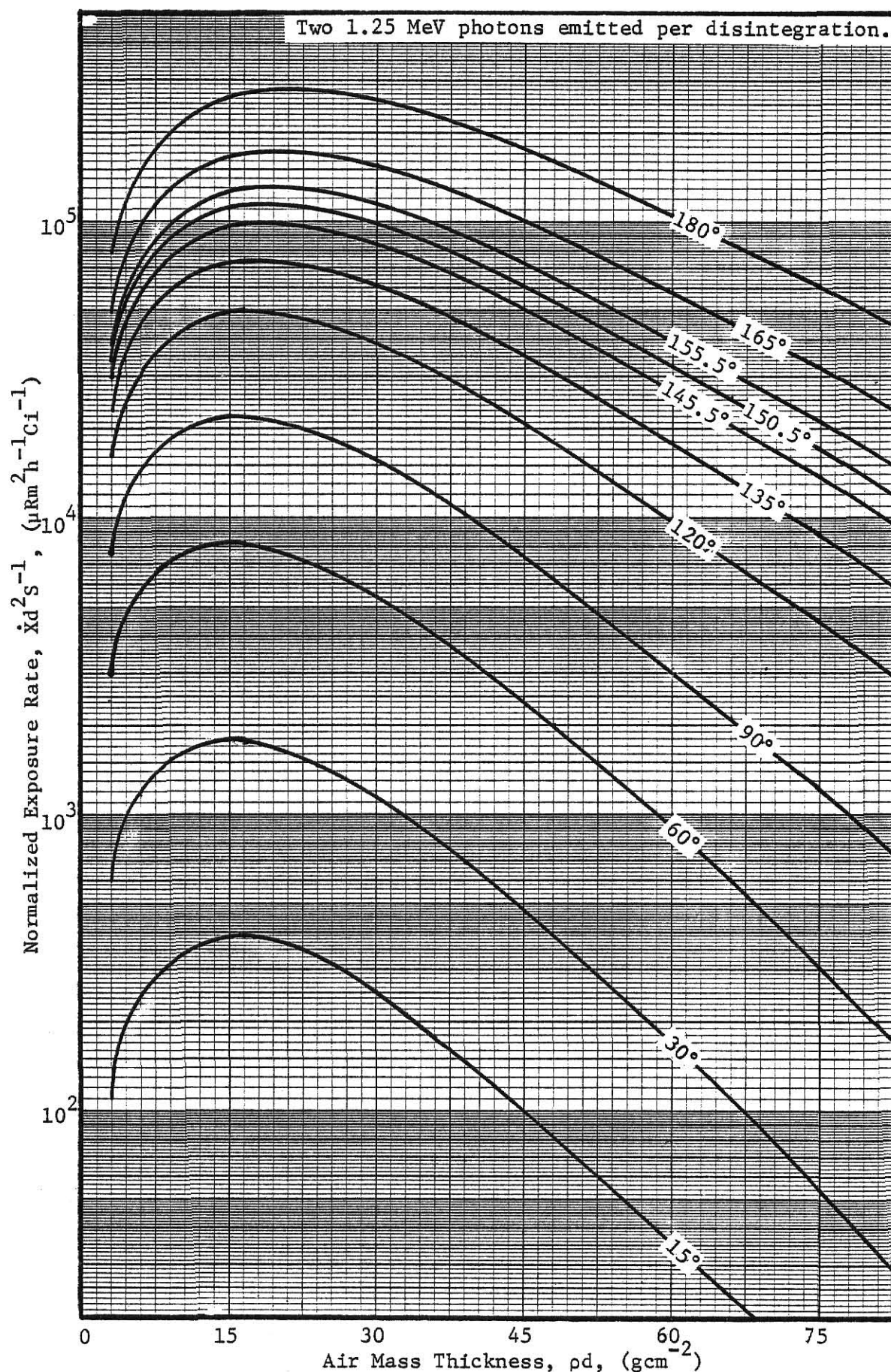


Fig. 4-7. Calculated skyshine exposure rates for various collimator angles with the source unshielded.

angles. This would be expected since a photon which reaches the detector must on the average make a larger angle scatter for smaller collimation angles. Therefore, the photons scattered toward the detector from a smaller collimation angle are less energetic than the photons scattered toward the detector from a larger collimation angle and the lower energy photons are absorbed more easily in the intervening air between the scattering point and the detector.

Figure 4-8 depicts the skyshine exposure rate behavior with increasing silo roof shielding. The general decrease in skyshine exposure rate with increasing roof thickness is as would be expected. The exposure rates beyond 30 g cm^{-2} drop off more quickly for the thicker shielded cases. This steeper slope for the thicker roof shields is due to the overall decrease in the energy of the photon spectrum leaving the top of source silo.

The skyshine exposure rates for both 20 cm and 21 cm thick shields were calculated in order to determine the correction factor necessary for the DOT calculation done by RRA. This point kernel calculation indicates that the DOT calculation for the 20 cm shielded case should be decreased by about 13% to approximate the 21 cm shielded results. This correction to the DOT calculations produces worse agreement between the DOT calculations and the experimental results.

The unshielded skyshine exposure rate calculations for various source photon energies are presented in Fig. 4-9. In general, the maximum normalized skyshine exposure rate did not decrease much with decreasing energy, in fact the maximum $\frac{\dot{X}_d}{S}$ for 0.5 MeV source photons is

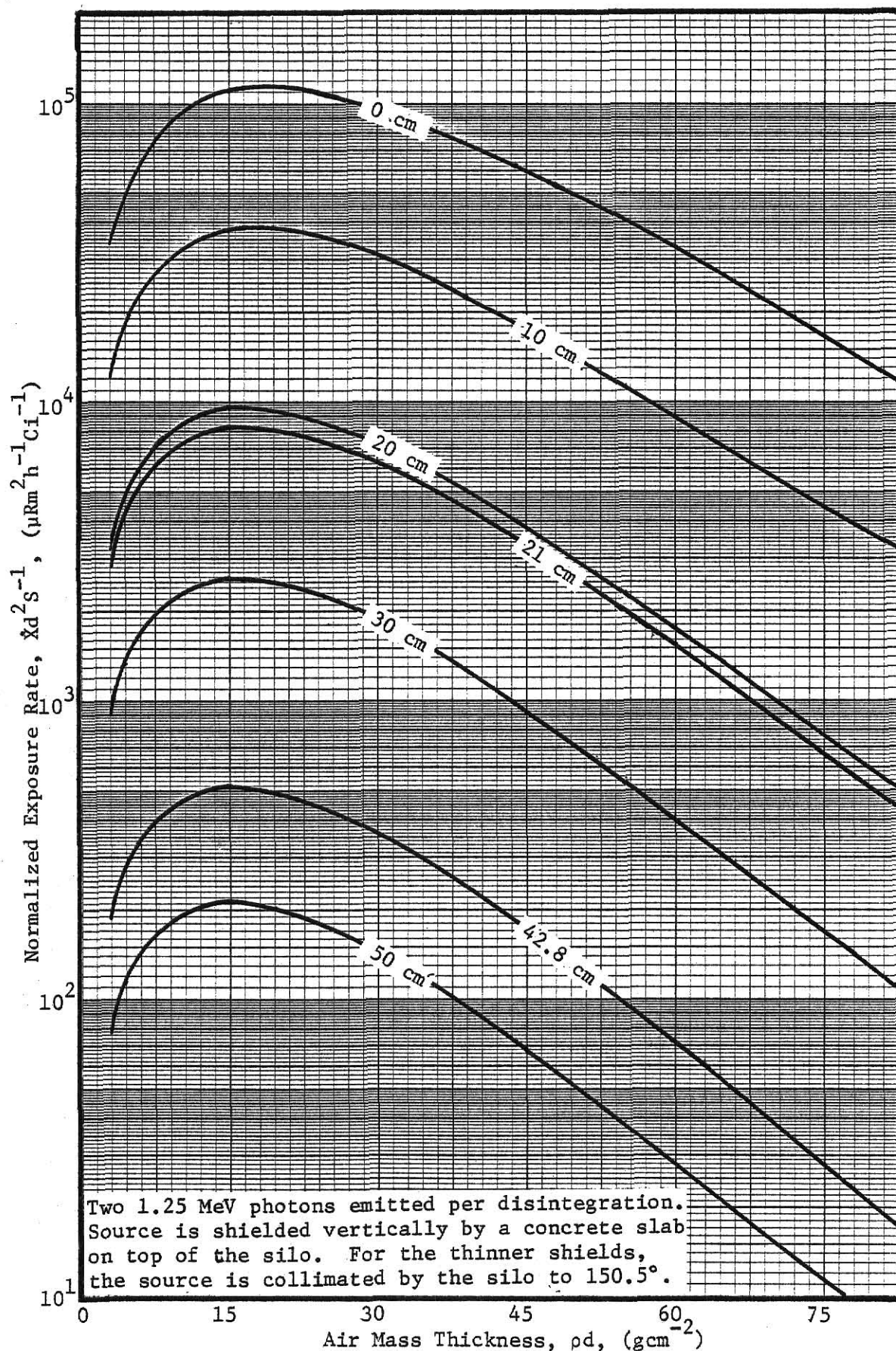


Fig. 4-8. Calculated skyshine exposure rates for various silo roof shield thicknesses.

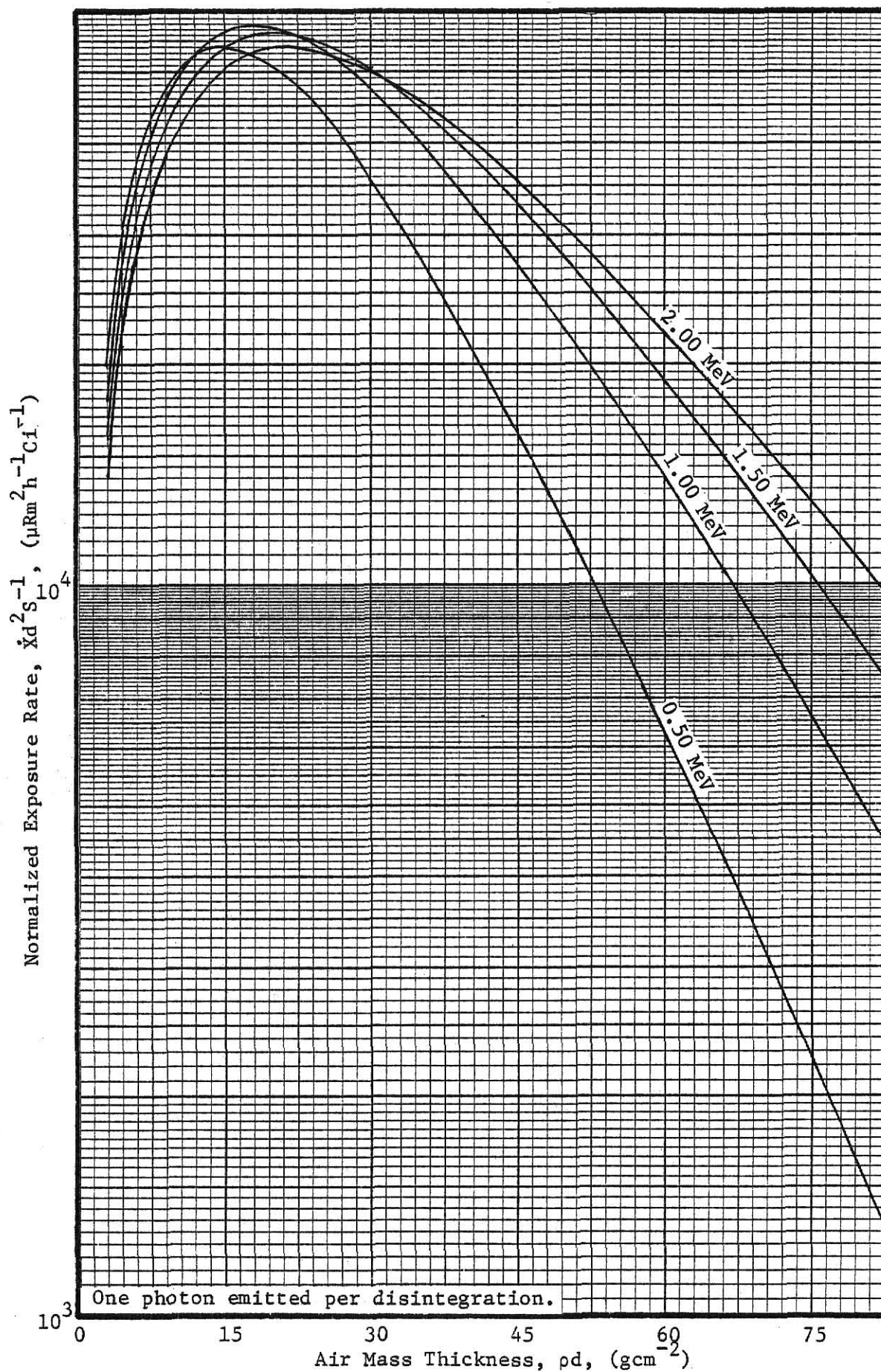


Fig. 4-9. Calculated skyshine exposure rates for various monoenergetic photon sources with source collimated into a 150.5° cone.

greater than the maximum $\frac{\dot{x}_d^2}{S}$ for the 2.0 MeV source. This behavior can be explained by the anisotropic nature of the Compton scattering cross section.

Since Compton scattering becomes increasingly forwardly oriented with increasing photon energy, the number of photons which scatter toward the detector decreases with increasing photon energy. Therefore, the photon flux at the detector decreases. Far from the source, the skyshine exposure rates for lower energy photon sources are more rapidly decreasing than the skyshine exposure rates for higher energy photon sources because the photoelectric absorption cross section increases with decreasing energy.

Figures 4-10 and 4-11 depict the calculated skyshine exposure rates for the 21.0 cm and 42.8 cm shielded source silo configurations and various photon energy sources. In both cases, the 1.5 MeV and 2.0 MeV sources produce exposure rates within 30% of each other over the whole range of mass thicknesses (3.0 to 80.0 g cm⁻²). The maximum normalized exposure rates for the 1.0 MeV and 0.5 MeV sources are respectively 82% and 42% of the 2.0 MeV maximum in the 21.0 cm shielded case. For the 42.8 cm shielded case, the maximum normalized exposure rates for the 1.0 MeV and 0.5 MeV sources are respectively 49% and 10% of the 2.0 MeV maximum.

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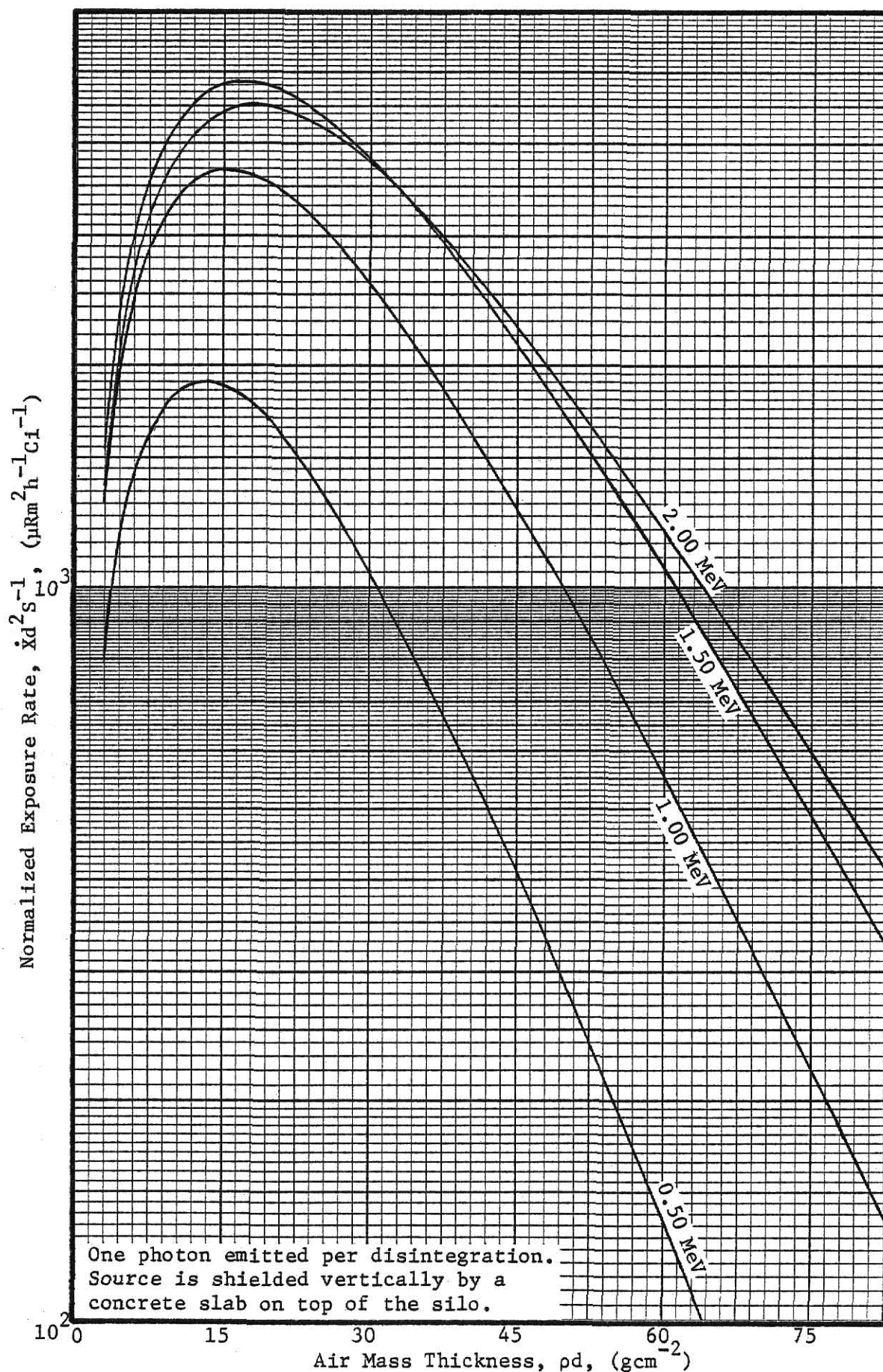


Fig. 4-10. Calculated skyshine exposure rates for various monoenergetic photon sources with the source shielded by 21.0cm of concrete.

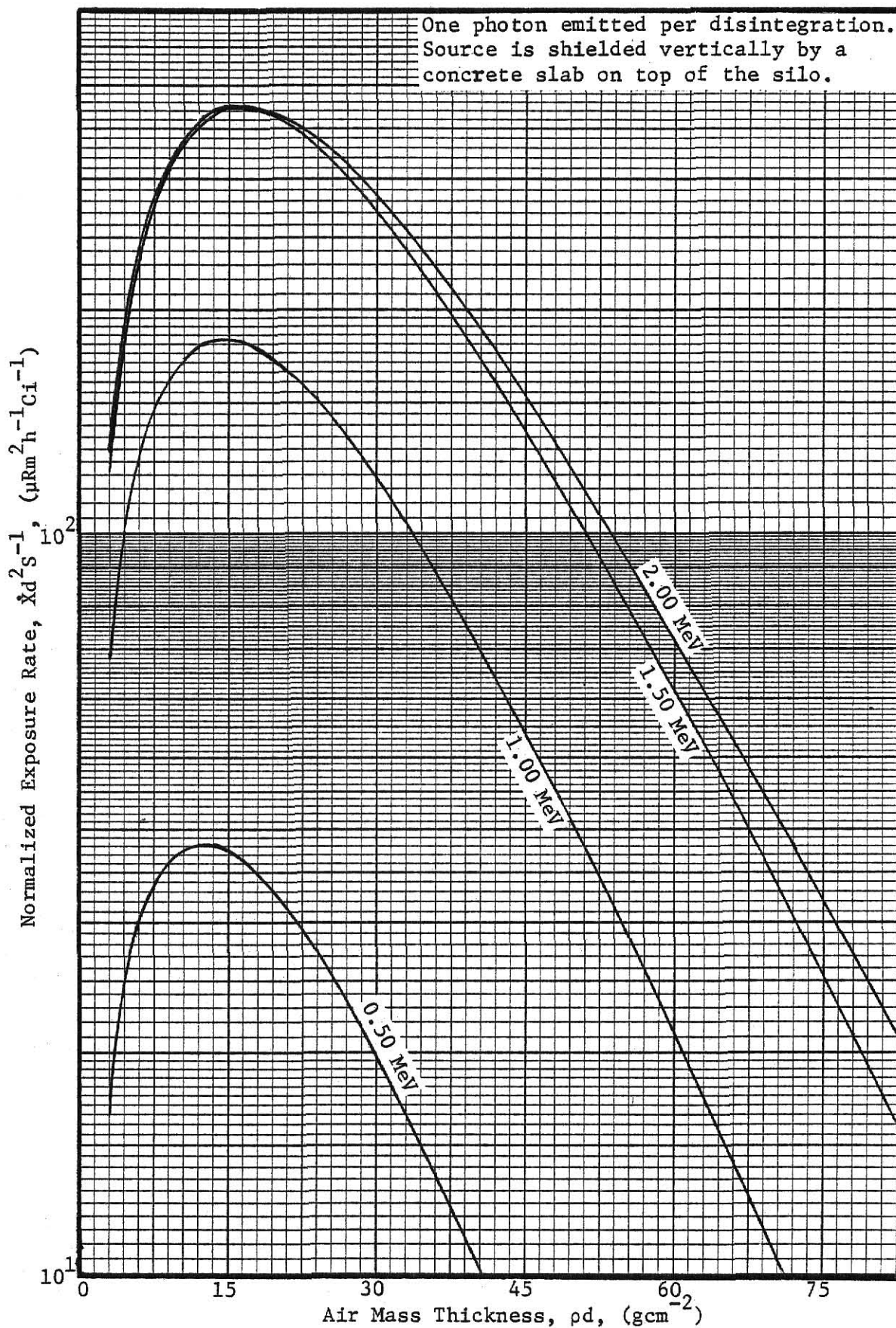


Fig. 4-11. Calculated skyshine exposure rates for various monoenergetic photon sources with the source shielded by 42.8cm of concrete.

5.0 CONCLUSIONS AND SUGGESTIONS FOR FURTHER STUDY

The overall objectives of the benchmark skyshine experiment were to provide experimental skyshine data for comparison with analytical calculations, for direct use on nuclear facility shielding design, and for use in the correction of calculational methods. In order to achieve these objectives, this benchmark skyshine experiment was designed using easily analyzed geometry (i.e., cylindrical source silo, isotropic point sources, and well defined silo configurations).

The normalized skyshine exposure rate data obtained with the HPIC and with a ^{60}Co source collimated into $150.5^\circ \pm 0.2^\circ$ cone, varied from $27.5 \mu\text{R h}^{-1} \text{Ci}^{-1}$ at an air mass thickness (from the source to the detector) of 5.48 g cm^{-2} (50 m measurement location) to $0.0266 \mu\text{R h}^{-1} \text{Ci}^{-1}$ at 76.7 g cm^{-2} (700 m measurement location). The average percent error for the HPIC exposure rate measurements with this source configuration was 1.4% (calculated by averaging the errors given in Table 2-12). The normalized skyshine exposure rate data obtained with the HPIC for ^{60}Co sources vertically shielded by a 21.0 ± 0.3 cm thick concrete slab varied from $5.31 \mu\text{R h}^{-1} \text{Ci}^{-1}$ at 3.63 g cm^{-2} (30 m measurement location) to $663 \text{ pR h}^{-1} \text{Ci}^{-1}$ at 78.1 g cm^{-2} (700 m measurement location). The average percent error for the HPIC exposure rate measurements with the 21.0 cm shielded source configuration was 3.0% (calculated from Table 2-13). The normalized skyshine exposure rate data obtained with the HPIC for ^{60}Co sources vertically shielded by a 42.8 ± 0.5 cm thick concrete slab varied from 418 nR h^{-1}

Ci^{-1} at 3.38 g cm^{-2} (30 m location) to $878 \text{ pR h}^{-1} \text{ Ci}^{-1}$ at 46.2 g cm^{-2} (400 m location). For the 42.8 cm shielded configuration, the HPIC exposure rate measurements were not extended beyond 400 m because of low skyshine exposure rate to background exposure rate ratios. The average percent error for the HPIC measured exposure rates with the source shielded by 42.8 cm of concrete was 3.0% (calculated from Table 2-14). These low average percent errors on the HPIC skyshine measurements indicate the high precision at which this experiment was performed.

However, before the HPIC data may be used, the data must be normalized with respect to the source strength used in the experiment and the data must be corrected for the energy sensitivity of the HPIC. A source calibration experiment was performed by the experimenters and the effective source strengths of the nominal 10, 250, and 5000 Ci ^{60}Co sources were respectively found to be 10.37, 228.7 and 3797 Ci as of October 1, 1977.⁴ The estimated uncertainty of the source strengths was 5%. The energy sensitivity correction factor $\bar{f}$ could be a source of error for the energy corrected exposure rate data. The $\bar{f}$'s reported by RRA and Nason differ in value up to 4% in the unshielded source configuration, up to 8% in the 21.0 cm shielded source configuration, and up to 3% in the 42.8 cm shielded source configuration.

Therefore, the possible error in the HPIC skyshine exposure rates, corrected for HPIC energy sensitivity and normalized with respect to source strength, could be 7% in the unshielded source configuration,

10% in the 21.0 cm shielded source configuration, and 7% in the 42.8 cm shielded source configuration. This author estimates the actual error in the normalized HPIC skyshine exposure rates using the energy correction factor developed by Nason to be 7% for all source configurations. The excellent agreement between the HPIC skyshine exposure rate measurements corrected for the energy sensitivity of the HPIC and the NaI-inferred 4π exposure rate measurements derived by Nason lends support to the accuracy of this experiment.

One may conclude from this error analysis of the skyshine experiment and from consideration of the general characteristics of the skyshine experiment (i.e., simple geometry, etc.) that the skyshine benchmark experimental data will prove to be very useful in the determination of the accuracy of various methods for calculating skyshine exposure rates. In fact, the benchmark experimental data were used in the latter part of this work to determine the accuracy of several skyshine calculation methods and to determine the correct use of buildup factors in a point kernel model. The usefulness of the skyshine benchmark data as design data will have to be determined by application.

The discrete ordinates calculations of the skyshine exposure rates using 10 energy groups were within only 20% and 25% of the measured skyshine exposure rates for the 21.0 cm and 42.8 cm shielded source configurations. The discrete ordinates calculations performed by RRA for the unshielded source configuration were within 10% of the skyshine benchmark experiment data. This author believes that the accuracy of the discrete ordinates calculation could be improved in all cases,

however the cost of this improvement is perhaps not justifiable.

Both the G-33 calculations of Kadotani and the point kernel model developed in this work were compared to the benchmark skyshine measurements. For the unshielded silo configuration, the G-33 calculations had an average absolute percent error of 25% and the point kernel model of this work had an average absolute percent error of 23% when compared to the experimental skyshine exposure rate data. All the percent errors reported for point kernel calculations (G-33 and this work) are based on the average absolute percent error calculated by Eq. (4-4). For the 21.0 cm shielded silo, the G-33 calculations had an average absolute percent error from 40% to 45% and point kernel model of this work had an average absolute percent error of 43% when compared to benchmark skyshine data. For the 42.8 cm shielded silo, the G-33 calculations had an average absolute percent error from 45% to 40% and the point kernel model of this work had an average absolute percent error of 17% when compared to benchmark skyshine data. G-33 data were not reported beyond 500 m from the source. However, the increasing difference between the G-33 calculated exposure rates and the HPIC measured exposure rates up to the 500 m location indicates that the error between the G-33 calculations beyond 500 m and the HPIC data is increasing. Thus one may conclude that the model of this work is more accurate than the G-33 model for the geometries of the benchmark experiment.

For measurement locations beyond 200 m, the point kernel model of this work overestimates the HPIC skyshine exposure rate by a

nearly constant factor in each silo configuration (see Figs. 4-1, 4-2, and 4-3). This behavior tempts one to conclude that the experimental source calibration (see Chapter 2) is high. However, the point kernel model is theoretically expected to overpredict the skyshine exposure rate in the unshielded case and the discrete ordinates calculations are nearly always lower than the HPIC data for the measurement locations beyond 200 m which indicates that the source calibration may be too low. The author concluded that the overestimation of the skyshine exposure rates beyond 200 m by the point kernel model of this work is due to errors inherent in the use of the infinite medium buildup factors for an isotropic point source on the second air leg. Two possible methods of correcting the point kernel model are the development and use of a buildup factor for the geometry of incoherent scattering cross section or the point kernel model could be fitted to the experimental data. Since nearly every point kernel model uses a second air leg buildup factor, transport theory development of such a buildup factor for an air infinite medium with an annular conical source distribution and the detector positioned within the direct path of the source photons may be worthwhile (but beyond the scope of this work). The simpler solution, the fitting of point kernel model to the experimental data, is an example of using the experimental data to improve a point kernel technique. However, such empirical fits give no assurance of being applicable to other geometries or source energies.

The skyshine exposure rate predictions made in the latter part of Chapter 4 should be used with caution. The accuracy of these pre-

dictions (or any other point kernel predictions and some photon transport calculations) becomes suspect with increasing extrapolation.

Therefore, other skyshine experiments with different silo collimation angles, source photon energies, and roof shield thicknesses would prove useful to confirm these predictions.

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APPENDIX A

2 π Source Collimation

The equivalency of Eq. (3-27) to Kitazume's equation for a source near an air and ground interface (Eq. 10 in Ref. 13) is presented in this appendix. Equation (3-27) is rewritten here as

$$\dot{X} = \frac{SKN}{2\pi d} \int_0^{\beta_{\max}} \sigma \frac{\mu_{en}}{\rho} \hat{E} \int_{\theta_{\min}}^{\theta_{\max}} \hat{B} \exp(-\mu_a - \hat{\mu}b) \int_0^{\epsilon_m} B \exp(-\bar{\mu}c) d\epsilon d\theta d\beta, \quad (A-1)$$

in which all the constants and functions are defined in Tables 3-1 and 3-2. For open silo skyshine ($c=0$ and $B=1$), the integral over $d\epsilon$ can be simplified to

$$\int_0^{\epsilon_m} B \exp(-\bar{\mu}c) d\epsilon = \int_0^{\pi/2} d\epsilon = \pi/2$$

and Eq. (A-1) becomes

$$\dot{X} = \frac{SKN}{4d} \int_0^{\beta_{\max}} \sigma \frac{\mu_{en}}{\rho} \hat{E} \int_{\theta_{\min}}^{\theta_{\max}} \hat{B} \exp(-\mu_a - \hat{\mu}b) d\theta d\beta. \quad (A-2)$$

For 2 π source collimation, $\beta_{\max}$ and $\theta_{\min}$ are not limited by the silo geometry therefore $\beta_{\max} = \pi$ and $\theta_{\min} = 0$. Since θ , β , and d must form a triangle, $\theta_{\max}$ is limited to $\pi - \beta$. Therefore, Eq. (A-2) can be written as

$$\dot{X} = \frac{SKN}{4d} \int_0^{\pi} \sigma \frac{\mu_{en}}{\rho} \hat{E} \int_0^{\pi-\beta} \hat{B} \exp(-\mu_a - \hat{\mu}b) d\theta d\beta. \quad (A-3)$$

If $\psi \equiv \pi - \beta$, then Eq. (A-3) becomes

$$\dot{X} = \frac{SKN}{4d} \int_0^{\pi} \sigma \frac{\mu_{en}}{\rho} \hat{E} \int_0^{\psi} \hat{B} \exp(-\mu_a - \hat{\mu}b) d\theta d\psi. \quad (A-4)$$

Equation (A-4) with the order of integration reversed can be shown to be

$$\dot{X} = \frac{SKN}{4d} \int_0^\pi \int_\theta^\pi \sigma \frac{\mu en}{\rho} \hat{E} \hat{B} \exp(-\mu a - \hat{\mu} b) d\psi d\theta, \quad (A-5)$$

in which the limits on ψ are developed from the fact that β , θ , and d must form a triangle. Substitution of $\beta = \pi - \psi$ into Eqs. 3-12 and 3-13 yields

$$b = d \frac{\sin \theta}{\sin(\pi - \psi)} = d \frac{\sin \theta}{\sin \psi} \quad (A-6)$$

and

$$\begin{aligned} a &= d (\cos \theta + \sin \theta \cot(\pi - \psi)) = \frac{d}{\sin \psi} (\cos \theta \sin \psi - \sin \theta \cos \psi) \\ &= \frac{d \sin(\psi - \theta)}{\sin \psi} \end{aligned} \quad (A-7)$$

since $a = \bar{a}$ for the unshielded case, $\sin(\pi - \psi) = \sin \psi$ and $\cos(\pi - \psi) = -\cos \psi$. Equations (A-6) and (A-7) substituted into Eq. (A-5) and the result rearranged yields

$$\dot{X} = \frac{1}{4d} \int_0^\pi d\theta \int_\theta^\pi d\psi (S) (K \frac{\mu en}{\rho} \hat{E}) (\sigma N) \exp(-\mu d \frac{\sin(\psi - \theta)}{\sin \psi}) \exp(-\hat{\mu} d \frac{\sin \theta}{\sin \psi}) \hat{B} \quad (A-8)$$

which is exactly equal to Kitazume's equation,¹³

$$\begin{aligned} D &= \frac{1}{4b} \int_0^\pi d\delta \int_\delta^\pi d\hat{\theta} S_p(E_1) Q(E_2) \Sigma(\hat{\theta}; E_1, E_2) \exp(-\mu_1 \hat{b} \frac{\sin(\hat{\theta} - \delta)}{\sin \hat{\theta}}) \\ &\quad \times \exp(-\mu_2 \hat{b} \frac{\sin \delta}{\sin \hat{\theta}}) B_T \end{aligned} \quad (A-9)$$

where

$D \equiv \dot{X} \equiv$ Exposure rate at the detector

$S_p(E_1) \equiv S \equiv$ Point isotropic source strength

$Q(E_2) \equiv K \frac{\mu_{en}}{\rho} \hat{E} \equiv$ Conversion coefficient from flux to exposure rate

for scattered γ rays of energy E_2

$\Sigma(\hat{\theta}; E_1, E_2) \equiv N_c \frac{d\sigma(\hat{\theta}; E_1, E_2)}{d\Omega} \equiv N\sigma$

$N_c \equiv N \equiv$ Number of electron per unit volume of air

$\frac{d\sigma(\hat{\theta}; E_1, E_2)}{d\Omega} \equiv \sigma \equiv$ Differential Compton scattering cross section
per electron, dependent on θ .

$\mu_1 \equiv \mu \equiv$ Linear attenuation coefficient for emitted γ rays
of energy E_1

$\mu_2 \equiv \hat{\mu} \equiv$ Linear attenuation coefficient for scattered γ rays
of energy E_2

$\delta \equiv \theta \equiv$ The angle as defined in Fig. 3-1

$\hat{\theta} \equiv \Psi \equiv$ Photon scattering angle

$\hat{b} \equiv d \equiv$ Distance between the detector and the source

$B_T \equiv \hat{B} \equiv$ Scattered leg buildup factor

$E_1 \equiv E \equiv$ The energy of the emitted photon

$E_2 \equiv \hat{E} \equiv$ The energy of the scattered photon.

APPENDIX B

The Program Sky Used to Evaluate the Point Kernel Model
Developed in this Work

A computer program SKY was written to calculate both unshielded and shielded skyshine exposure rates. SKY is written in G level Fortran IV compatible with the Kansas State University's CMS remote terminals. Input instructions are given at the beginning of the program.

The program SKY calculates the unshielded skyshine exposure rate based on Eq. (4-3) while the shielded skyshine exposure rate is calculated from Eq. (3-35). For the unshielded calculations, only the buildup in the second leg air is included. For the shielded calculations, the buildup in air along the second leg and in the concrete roof along the first leg are used. Photon buildup in air on the first leg (i.e., before scattering) is not incorporated in either calculation.

SKY uses 11 subroutines, 9 of which are functions. These subroutines and their characteristics are listed in Table B-1. Table B-2 lists the mass attenuation coefficients for air and concrete. These coefficients were used to obtain the linear attenuation coefficients used in SKY. Table B-3 lists the mass energy absorption coefficients used in SKY.

The remainder of this appendix is a program listing of SKY and two typical outputs.

Table B-1. Subroutines Used in the Computer Program SKY.

Subroutine Name	Purpose	Defining Equations or Data Set
FUNCTION TING2	Trapezoidal integration over the angle θ	Uses Eq. (3-31) and Eq. (3-32) with $m=10$
FUNCTION TING1	Trapezoidal integration over the angle ϵ . For unshielded cases, this function returns the value of the limit on ϵ .	Uses Eq. (3-33) and Eq. (3-34) with $l=10$
FUNCTION EPF	Calculates the values of the limit on ϵ in the unshielded cases and limits the value of ϵ such that the concrete path length for the shielded cases does not exceed 15 mfp	Uses Eq. (3-25) for unshielded cases and when the path length in the roof does not exceed 15 mfp. Otherwise, Eq. (3-39) is used.
FUNCTION CONMU	Determines the concrete linear attenuation coefficient	Linearly interpolates the data in Table B-2.
FUNCTION ATTENF	Determines the air linear attenuation coefficient	Linearly interpolates the data in Table B-2
FUNCTION ENGABS	Determines the mass energy absorption coefficient for air	Linearly interpolates the data in Table B-3
FUNCTION SCATEN	Calculates the energy of the scattered photon	Uses Eq. (3-4)
FUNCTION SIGMA	Calculates the incoherent photon scattering cross section	Uses Eq. (3-5)
FUNCTION BMIN	Estimates the angle β necessary to limit the total air path length to 10 mfp	Uses Eq. (3-37)

Table B-1 continued -

Subroutine Name	Purpose	Defining Equations or Data Set
SUBROUTINE BERAIR	Determines the coefficients for the Berger form of the air buildup factor	Linearly interpolates the data in Table 4-1
SUBROUTINE BERCON	Determines the coefficients for the Berger form of the concrete buildup factor	Linearly interpolates the data in Table 4-2

Table B-2. Values of the Air and Concrete Mass Attenuation Coefficient μ/ρ , Less Rayleigh (Coherent) Scattering and the Photonuclear Effect.¹⁹

Photon Energy (MeV)	Air (cm^2/g)	Concrete (cm^2/g)
0.01	4.82	26.5000
0.015	1.45	8.0100
0.02	0.691	3.44
0.03	0.318	1.12
0.04	0.229	0.559
0.05	0.196	0.361
0.06	0.179	0.273
0.08	0.162	0.201
0.10	0.151	0.171
0.15	0.134	0.140
0.20	0.123	0.125
0.30	0.106	0.107
0.40	0.0954	0.0957
0.50	0.0868	0.0872
0.60	0.0804	0.0806
0.80	0.0706	0.0708
1.00	0.0635	0.0637
1.50	0.0517	0.0519
2.00	0.0444	0.0493
3.00	0.0358	0.0365
4.00	0.0308	0.0319
5.00	0.0276	0.0290
6.00	0.0252	0.0270
8.00	0.0223	0.0245

Table B-3. Values of the Air Mass Energy
Absorption Coefficient.²⁰

Photon Energy (MeV)	μ_{en} (cm ² /g)
0.15	0.0251
0.20	0.0268
0.30	0.0288
0.40	0.0296
0.50	0.0297
0.60	0.0296
0.80	0.0289
1.0	0.0280
1.5	0.0255
2.0	0.0234

ILLEGIBLE DOCUMENT

**THE FOLLOWING
DOCUMENT(S) IS OF
POOR LEGIBILITY IN
THE ORIGINAL**

**THIS IS THE BEST
COPY AVAILABLE**

```

C SKY FORTRAN CALCULATES THE EXPOSURE RATE DUE TO A POINT
C ISOTROPIC SOURCE COLLIMATED INTO A CONICAL RADIATION BEAM
C OR SHIELDED VERTICALLY BY A CONCRETE SLAB.
C
C SKY INTEGRATES THE SINGLY SCATTERED GAMMA FLUXES OVER A TOTAL PATH
C LENGTH OF 10 MEAN FREE PATHS. BERGER BUILDUP FACTORS ARE USED ON
C THE CONCRETE ROOF PATHS AND THE SCATTERED PHOTON AIR PATHS TO CORRECT
C FOR MULTIPLE SCATTERING. SKY USES TRIPLE TRAPEZOIDAL INTEGRATION.
C
C SKY IS WRITTEN IN G LEVEL FORTRAN COMPATIBLE WITH KANSAS STATE
C UNIVERSITY'S CMS TERMINALS. INPUT DATA IS FORMATTED AS FOLLOWS:
C
C FIRST CARD - FORMAT 3D15.6
C
C CONCRETE DENSITY IN G CM**-3
C GAMMA PHOTON ENERGY IN MEV
C FRACTION OF PHOTONS EMITTED PER DISINTEGRATION
C
C SECOND CARD - FORMAT 3D15.6
C
C CONCRETE SLAB THICKNESS IN METERS
C COLLIMATOR OUTSIDE RADIUS OR
C RADIUS OF THE RADIATION ILLUMINATED AREA ON THE
C SOURCE SIDE OF THE SLAB IN METERS
C COLLIMATOR HEIGHT RELATIVE TO THE SOURCE OR
C DISTANCE FROM THE SOURCE TO THE SHIELDING
C SLAB IN METERS
C
C FOLLOWING CARDS - FORMAT 3D15.6
C
C SOURCE TO DETECTOR DISTANCE IN METERS
C AIR DENSITY IN MG CM**-3
C EXPERIMENTAL EXPOSURE RATE IN UR*M**2/(H*C1)
C
C THE LIMITS ON THE SOURCE PHOTON ENERGY ARE 0.5MEV TO 2.0MEV
C IF EXPERIMENTAL DATA IS UNAVAILABLE, ENTER 1.000.
C
0001 IMPLICIT REAL*8 (A-H,O-Z)
0002 DIMENSION EN(10),X(10)
0003 COMMON/S1/T,CMU,E/S2/THS,D,US,ES,U/S5/AB1,A82/S3/N1,N2
0004 PI=0.4712389
0005 INDEX=0
0006 NEXP=0
0007 IX=0
0008 ISET=19
0009 SUM=0.000
0010 N1=10
0011 N2=10
0012 N3=10
C INPUT SOURCE PARAMETERS AND INITIALIZE
0013 READ (5,5) RC,E,F
0014 5 FORMAT (3D15.6)

```



```

0015      READ (5,5) T,R,H
0016      CALL BERGUN (E)
0017      WRITE (6,10) RC,T,E,F,R,H
0018      10 FORMAT ('1'.33X,'SKY - CALCULATED SKYSHINE',/
A .33X,'USING BERGER BUILDUP FACTORS',/,/,7X,80('*')
B /,7X,'*',31X,'INPUT PARAMETERS',31X,'*'
C /,7X,'* CONCRETE DENSITY =',F10.5,' G/CC',10X,
D 'ROOF THICKNESS =',F10.5,' M *',
E /,7X,'* SOURCE PHOTON ENERGY =',F10.5,' MEV',11X,
F 'GAMMA FRACTION =',F10.5,' *',
G /,7X,'* SILO RADIUS =',F10.5,' M ',12X,
H 'SILO HEIGHT =',F10.5,' M *',/,7X,
I 80('*'),/)
0019      RC=RC*1.00 06
0020      15 FORMAT (/,8X,79('*'),/,
A 8X,'+ SOURCE + + SOURCE- + CALCULATED +',
B ' ENERGY + PERCENT +',/,
C 8X,'+ TO + AIR + DETECTOR + NORMALIZED +',
D ' COMPENSATED + ERROR +',/,
E 8X,'+ DETECTOR + DENSITY + AIR MASS + EXPOSURE RATE +',
F ' EXPERIMENTAL + +',/,
G 8X,'+ DISTANCE +(MG/CM**3)+ THICKNESS+ (UR*M**2/(HCI))+',
H ' EXPOSURE RATE + +',/,
I 8X,'+ (M) + + (G/CM**2)+ (NOTE 1) +',
J '(UR*M**2/(HCI))+ (NOTE 2) +',/,
K 8X,79('*'),/,8X,'+',3(10X,'+'),2(15X,'+'),12X,'+')
0021      16 FORMAT (/,22X,50('*'),/,
A 22X,'+ SOURCE + + SOURCE- + CALCULATED +',/,
B 22X,'+ TO + AIR + DETECTOR + NORMALIZED +',/,
C 22X,'+ DETECTOR + DENSITY + AIR MASS + EXPOSURE RATE +',/,
D 22X,'+ DISTANCE +(MG/CM**3)+ THICKNESS+ (UR*M**2/(HCI))+',/,
E 22X,'+ (M) + + (G/CM**2)+ (NOTE 1) +',/,
F 22X,50('*'),/,22X,'+',3(10X,'+'),15X,'+')
0022      CMU=CONMU(E,RC)
0023      THS=DATAN(H/R)
C      INPUT DETECTOR PARAMETERS AND INITIALIZE
0024      20 READ (5,5,END=11) D,RAA,XEXP
0025      RA=RAA*1.00 03
0026      IF (XEXP.EQ.1.000) NEXP=1
0027      U=ATTENF(E,RA)
0028      BMAX=PI-THS-DATAN(H/(D-R))
0029      EMAX=SCATEN(E,BMAX)
0030      BMN=BMIN(RA)
0031      CON=5.9330 34*U*RA*F
0032      DB=(BMAX-BMN)/N3
0033      PARTO=0.000
C      INTEGRATION OVER SCATTERING ANGLE
0034      DO 30 I=1,N3
0035      AUG=BMAX-I*DB
0036      EN(I)=SCATEN(E,AUG)
0037      ES=EN(I)
0038      CALL BEAIR (ES)

```

```

0039      UEN=ENGABS(ES)
0040      US=ATTENF(ES,RA)
0041      SIG=SIGMA(E,AUG)
0042      THL=PI-THS
0043      IF (THL.GT.(PI-AUG-DATAN(H/(D-R)))) THL=PI-AUG-DATAN(H/(D-R))
0044      PARTN=SIG*UEN*ESTING2(THL,AUG)
0045      X(I)=CON*DB/2.000*(PARTN+PARTO)
0046      PARTO=PARTN
0047 30 CONTINUE
0048      XSUM=X(I)
0049      DO 40 I=2,N3
0050 40 XSUM=XSUM+X(I)
0051      IF (NEXP.EQ.1) XEXP=XSUM
0052      INDEX=INDEX+1
0053      IF (NEXP.NE.1.AND.INDEX.EQ.1) WRITE (6,15)
0054      IF (NEXP.EQ.1.AND.INDEX.EQ.1) WRITE (6,16)
0055      IX=IX+1
0056      CE=(XSUM/XEXP-1.000)*1.00 02
0057      SUM=SUM+DAUS(CE)
0058      DM=D*RA/1.00 04
      C      OUTPUT
0059      IF (IX.NE.ISET) GO TO 85
0060      IX=0
0061      ISET=22
0062      IF (NEXP.NE.1) WRITE (6,70)
0063      IF (NEXP.EQ.1) WRITE (6,71)
0064 70 FORMAT (8X,79(' '))
0065 71 FORMAT (22X,50(' '))
0066      WRITE (6,72)
0067 72 FORMAT ('1',/,/,/,/)
0068      IF (NEXP.NE.1) WRITE (6,15)
0069      IF (NEXP.EQ.1) WRITE (6,16)
0070 85 IF (NEXP.EQ.1) WRITE (6,91) D,RAA,DM,XSUM
0071      IF (NEXP.NE.1) WRITE (6,90) D,RAA,DM,XSUM,XEXP,CE
0072 90 FORMAT (8X,'+ ',3(F8.4,' + '),2(1X,F10.3,' + '),
      A 1X,F8.3,' + ',/,8X,'+ ',3(10X,'+ '),2(15X,'+ '),12X,'+ ')
0073 91 FORMAT (22X,'+ ',3(F8.4,' + '),1X,F10.3,' + ',
      A /,22X,'+ ',3(10X,'+ '),15X,'+ ')
      GO TO 20
0074
0075 11 VAR=SUM/INDEX
0076      CONE=(PI-2.000*THS)*180.000/PI
0077      IF (T.NE.0.00) CONE=EPF(PI/2.000)*3.60 02/PI
0078      IF (NEXP.NE.1) WRITE (6,95) VAR,CONE
0079      IF (NEXP.EQ.1) WRITE (6,96) CONE
0080 95 FORMAT (8X,79(' '),/,/,3X,'NOTE 1 - EXPOSURE RATES ARE ',
      A 'NORMALIZED TO ONE CURIE AND MULTIPLIED BY THE SQUARE '
      B 'OF THE',/,7X,'SOURCE TO DETECTOR DISTANCE',/,3X,
      C 'NOTE 2 - THESE VALUES ARE THE PERCENT ERRORS IN THE CALCULATED',
      D ' EXPOSURE RATE BASED ON THE',/,7X,'EXPERIMENTAL EXPOSURE RATES.',
      E '/,3X,'AVERAGE OF THE ABSOLUTE VALUES OF THE PERCENT ERRORS IS',
      F F7.3,/,7X,'THE SOURCE SILD COLLIMATION ANGLE IS ',F12.5,
      G ' DEGREES')

```

```

0081      96 FORMAT (22X,50('+'),/,/,3X,'NOTE 1 - EXPOSURE RATES ARE ',
      A 'NORMALIZED TO ONE CURIE AND MULTIPLIED BY THE SQUARE '
      B 'OF THE',/,7X,'SOURCE TO DETECTOR DISTANCE.',/,3X,
      C 'THE SOURCE SILO COLLIMATION ANGLE IS ',F12.5,' DEGREES')
0082      STOP
0083      END

```

```

C
C      FUNCTION TING2 INTEGRATES THE THETA INTEGRAL BY THE TRAPEZOID RULE
C      THAL = UPPER LIMIT OF INTEGRATION
C      B    = THE SCATTERING ANGLE IN RADIAN
C
0001      FUNCTION TING2 (THAL,B)
0002      IMPLICIT REAL*8 (A-H,O-Z)
0003      COMMON/S1/T,CMU,E/S2/THAS,D,US,ES,U/S5/AB1,AB2/S3/W1,N2
0004      DTHA=(THAL-THAS)/N2
0005      AR=D*(DCOS(THAL)+DSIN(THAL)*DCOTAN(B))*U
0006      BR=D*DSIN(THAL)/DSIN(B)*US
0007      EP=EPF(THAL)
0008      TING2=(1.00+AB1*BR*DEXP(AB2*BR))*DEXP(-AR-BR)*TING1(EP,THAL)/2.00
0009      N=N2-1
0010      DO 10 J=1,N
0011      A=THAS+J*DTHA
0012      AR=D*(DCOS(A)+DSIN(A)*DCUTAN(B))*U
0013      BR=D*DSIN(A)/DSIN(B)*US
0014      EP=EPF(A)
0015      TING2=TING2+(1.00+AB1*BR*DEXP(AB2*BR))*DEXP(-AR-BR)*TING1(EP,A)
0016      10 CONTINUE
0017      TING2=TING2*DTHA
0018      RETURN
0019      END

```

```

C
C FUNCTION TING1 INTEGRATES THE EPSILON INTEGRAL BY THE TRAPEZOID RULE.
C     EP = UPPER LIMIT OF INTEGRATION
C     THA = THETA AS DEFINED BY THE GEOMETRY IN RADIANS
C
0001 FUNCTION TING1 (EP,THA)
0002 IMPLICIT REAL*8 (A-H,O-Z)
0003 COMMON/S1/T,CMU,E/S6/A3,A4/S3/N1,N2
0004 IF (EP.EQ.0.000) GO TO 15
0005 IF (T.NE.0.000) GO TO 5
0006 TING1=2.000*EP
0007 RETURN
0008 5 DEP=EP/N1
0009 AG=T*CMU/DSIN(THA)
0010 TING1=(1.000+AG*A3*DEXP(AG*A4))*DEXP(-AG)/2.000
0011 A=AG/DCOS(EP)
0012 TING1=TING1+(1.000+A*A3*DEXP(A*A4))*DEXP(-A)/2.000
0013 M=N1-1
0014 DO 10 K=1,M
0015 A=AG/DCOS(K*DEP)
0016 TING1=TING1+(1.000+A*A3*DEXP(A*A4))*DEXP(-A)
0017 10 CONTINUE
0018 TING1=2.000*DEP*TING1
0019 RETURN
0020 15 TING1=0.000
0021 RETURN
0022 END

```

```

C
C FUNCTION EPF(THA) CALCULATES THE UPPER LIMIT ON THE EPSILON INTEGRAL
C     THA = THETA VALUE IN RADIANS
C     FUNCTION EPF LIMITS EPF SUCH THAT THE CONCRETE PATH LENGTH <OR= 15
C
0001 FUNCTION EPF(THA)
0002 IMPLICIT REAL*8 (A-H,O-Z)
0003 COMMON/S1/T,SMU,E/S2/THSM,U,US,ES,U
0004 A=DSIN(THSM)/DSIN(THA)
0005 IF (A.GE.1.000) GO TO 10
0006 EP=DARCCOS(A)
0007 TEST=T*SMU/DCOS(EP)/DSIN(THA)
0008 IF (TEST.LE.15.000) GO TO 15
0009 A=TEST*DCOS(EP)/15.000
0010 IF (A.GE.1.000) GO TO 10
0011 EP=DARCCOS(A)
0012 GO TO 15
0013 10 EP=0.000
0014 15 EPF=EP
0015 RETURN
0016 END

```

```

C
C FUNCTION CONMU(E,R) EVALUATES THE CONCRETE LINEAR ATTENUATION
C COEFFICIENT IN M-1
C E = GAMMA ENERGY IN MEV
C R = CONCRETE DENSITY IN G/CM**3
C
0001 FUNCTION CONMU(E,R)
0002 IMPLICIT REAL*8 (A-H,O-Z)
0003 DIMENSION EN(6),C(6)
0004 DATA C / .087200,.080600,.070800,.063700,.051900,.049300/
0005 DATA EN / .500,.600,.800,1.00,1.500,2.00/
0006 IF (1.500.GT.E.OR.E.GT.2.000) WRITE (6,10) E
0007 10 FORMAT (5X,'GAMMA ENERGY OUT OF CONCRETE ATTENUATION FUNCTION ',
A 'RANGE. GAMMA ENERGY =',F6.3)
0008 DO 20 I=2,6
0009 IF (EN(I).GE.E) GO TO 30
0010 20 CONTINUE
0011 30 N=I-1
0012 CONMU=(C(N)+(C(N)-C(I))/(EN(N)-EN(I))*(E-EN(N)))*R*1.00-04
0013 RETURN
0014 END

```

```

C
C FUNCTION ATTENF(E,R) EVALUATES THE AIR LINEAR ATTENUATION
C COEFFICIENT IN M-1
C E = GAMMA ENERGY IN MEV
C R = AIR DENSITY IN G/CM**3
C
0001 FUNCTION ATTENF(E,R)
0002 IMPLICIT REAL*8 (A-H,O-Z)
0003 DIMENSION EN(10),C(10)
0004 DATA EN / .1500,.200,.300,.400,.500,.600,.800,1.00,1.500,2.00/
0005 DATA C / .13400,.12300,.10600,.095400,.086800,.080400,.070600,
A .063500,.051700,.044400/
0006 IF (1.1500.GT.E.OR.E.GT.2.000) WRITE (6,10) E
0007 10 FORMAT (5X,'GAMMA ENERGY OUT OF AIR ATTENUATION FUNCTION ',
A 'RANGE. GAMMA ENERGY =',F6.3)
0008 DO 20 I=2,10
0009 IF (EN(I).GE.E) GO TO 30
0010 20 CONTINUE
0011 30 N=I-1
0012 ATTENF=(C(N)+(C(N)-C(I))/(EN(N)-EN(I))*(E-EN(N)))*R*1.00-04
0013 RETURN
0014 END

```

```

C
C      FUNCTION ENGABS(E) EVALUATES THE AIR MASS ENERGY ABSORPTION
C      COEFFICIENT IN G/M**2
C      E = GAMMA ENERGY IN MEV
C
0001      FUNCTION ENGABS(E)
0002      IMPLICIT REAL*8 (A-H,O-Z)
0003      DIMENSION EN(10),C(10)
0004      DATA EN / .1500,.200,.300,.400,.500,.600,.800,1.00,1.500,2.00 /
0005      DATA C / .025100,.026800,.028800,.029600,.029700,.029600,.028900,
0006      A .028000,.025500,.023400 /
0007      IF (.1500.GT.E.OR.E.GT.2.000) WRITE (6,10) E
0008      10 FORMAT (5X,'GAMMA ENERGY OUT OF ENERGY ABSORPTION COEFFICIENT ',
0009      A 'RANGE. GAMMA ENERGY =',F6.3)
0010      DO 20 I=2,10
0011      20 CONTINUE
0012      IF (EN(I).GE.E) GO TO 30
0013      30 N=I-1
0014      ENGABS=(C(N)+(C(N)-C(I))/(EN(N)-EN(I))*(E-EN(N)))*1.00-04
0015      RETURN
0016      END

```

```

C
C      FUNCTION SCATEN(E,B) CALCULATES THE SCATTERED GAMMA ENERGY
C      IN MEV AFTER A SINGLE SCATTER.
C      E = THE UNSCATTERED GAMMA ENERGY IN MEV
C      B = THE SCATTERING ANGLE WITH RESPECT TO THE INCIDENT
C      PHOTON DIRECTION IN RADIANS
C
0001      FUNCTION SCATEN (E,B)
0002      IMPLICIT REAL*8 (A-H,O-Z)
0003      SCATEN=E/(1.000+E/.51100*(1.000+DCOS(B)))
0004      RETURN
0005      END

```

```

C
C
C
C
C
FUNCTION BMIN(R) ESTIMATES THE VALUE OF THE SCATTERING ANGLE FOR
      WHICH THE TOTAL AIR PATH LENGTH IS 10 MFP
      R = AIR DENSITY IN G/M**3

0001      FUNCTION BMIN(R)
0002      IMPLICIT REAL*8 (A-H,O-Z)
0003      COMMON/S1/T,CMU,E/S2/THSM,O,US,ES,U
0004      PI=0.3141592653589793
0005      DB=PI/180.000
0006      B=2.000*DB
0007      DO 10 I=1.89
0008      AG=SCATEN(E,B)
0009      TEST=0*(DCOTAN(B)*U+ATTENF(AG,R)/DSIN(B))
0010      IF (TEST.LE.10.00) GO TO 20
0011      B=B+DB
0012 10 CONTINUE
0013      DO 15 I=1.75
0014      AG=SCATEN(E,B)
0015      TEST=0*ATTENF(AG,R)
0016      IF (TEST.LE.10.00) GO TO 20
0017      B=B+DB
0018 15 CONTINUE
0019      WRITE (6.5) O,E
0020      5 FORMAT (5X,'THE FUNCTION TO FIND THE MINIMUM VALUE OF BETA',
      A ' FAILED. DETECTOR - SOURCE DISTANCE IS',F7.2,' SOURCE',
      B ' GAMMA ENERGY IS',F6.3)

0021 20 BMIN=B-DB
0022      RETURN
0023      END

C
C
C
C
C
FUNCTION SIGMA(E,B) CALCULATES THE KLEIN-NISHINA CROSS-
      SECTION IN M**2
      E = THE UNSCATTERED GAMMA ENERGY IN MEV
      B = THE SCATTERING ANGLE WITH RESPECT TO THE INCIDENT
      PHOTON DIRECTION IN RADIANS

0001      FUNCTION SIGMA (E,B)
0002      IMPLICIT REAL*8 (A-H,O-Z)
0003      AL=.51100/E
0004      P=1.000+AL+DCOS(B)
0005      SIGMA=3.9710-30*AL**2/P**2*(AL/P+P/AL-DSIN(B)**2)
0006      RETURN
0007      END

```

```

C
C
C
C
C
SUBROUTINE BERAIR PRODUCES THE COEFFICIENTS FOR THE AIR BERGER
BUILDUP FACTOR
ES = GAMMA ENERGY IN MEV

0001 SUBROUTINE BERAIR(ES)
0002 IMPLICIT REAL*8 (A-H,O-Z)
0003 DIMENSION EN(9),AA(9),AB(9)
0004 COMMON/S5/AB1,AB2
0005 DATA EN/.200,.300,.400,.500,.600,.800,1.00,1.500,2.00/
0006 DATA AA/3.9400,3.100,2.6100,2.2900,
A 2.0500,1.7100,1.500,1.1600,.9700/
0007 DATA AB/.11300,.09400,.07900,.06700,
A .05800,.04500,.03500,.02100,.01300/
0008 DO 10 I=2,9
0009 IF (ES.LE.EN(I)) GO TO 15
0010 10 CONTINUE
0011 15 N=I-1
0012 AB1=AA(N)+(AA(N)-AA(I))/(EN(N)-EN(I))*(ES-EN(N))
0013 AB2=AB(N)+(AB(N)-AB(I))/(EN(N)-EN(I))*(ES-EN(N))
0014 RETURN
0015 END

```

```

C
C
C
C
C
SUBROUTINE BERCON PRODUCES THE COEFFICIENTS FOR THE CONCRETE BERGER
BUILDUP FACTOR
ES = GAMMA ENERGY IN MEV

0001 SUBROUTINE BERCON(ES)
0002 IMPLICIT REAL*8 (A-H,O-Z)
0003 DIMENSION EN(9),AA(9),AB(9)
0004 COMMON/S6/AB1,AB2
0005 DATA EN/.200,.300,.400,.500,.600,.800,1.00,1.500,2.00/
0006 DATA AA/2.200,2.0300,1.8700,1.7300,
A 1.600,1.4100,1.2700,1.0200,.8900/
0007 DATA AB/.06500,.06700,.06100,.05500,
A .04900,.0400,.03200,.02100,.01400/
0008 DO 10 I=2,9
0009 IF (ES.LE.EN(I)) GO TO 15
0010 10 CONTINUE
0011 15 N=I-1
0012 AB1=AA(N)+(AA(N)-AA(I))/(EN(N)-EN(I))*(ES-EN(N))
0013 AB2=AB(N)+(AB(N)-AB(I))/(EN(N)-EN(I))*(ES-EN(N))
0014 RETURN
0015 END

```


SKY - CALCULATED SKYSHINE
USING BERGER BUILDUP FACTORS

```
*****
*                               INPUT PARAMETERS                               *
*  CONCRETE DENSITY  =  2.13000 G/CC      ROOF THICKNESS =  0.42000 M *
*  SOURCE PHOTON ENERGY =  1.25000 MEV    GAMMA FRACTION =  2.00000 *
*  SILO RADIUS       =  1.85400 M          SILO HEIGHT   =  0.48000 M *
*****
```

```
*****
+ SOURCE + SOURCE- + CALCULATED + ENERGY + PERCENT +
+ TO + AIR + DETECTOR + NORMALIZED + COMPENSATED + ERROR +
+ DETECTOR + DENSITY + AIR MASS + EXPOSURE RATE + EXPERIMENTAL +
+ DISTANCE + (MG/CM**3) + THICKNESS + (UR*M**2/(HCI)) + EXPOSURE RATE +
+ (M) + (G/CM**2) + (NOTE 1) + (UR*M**2/(HCI)) + (NOTE 2) +
*****
+ 30.0000 + 1.1260 + 3.3780 + 210.418 + 323.100 + -34.875 +
+ 30.0000 + 1.1140 + 3.3420 + 208.252 + 324.900 + -35.903 +
+ 30.0000 + 1.1270 + 3.3810 + 210.599 + 329.400 + -36.066 +
+ 50.0000 + 1.1220 + 5.6100 + 310.954 + 487.500 + -32.112 +
+ 50.0000 + 1.1140 + 5.5700 + 329.107 + 492.500 + -33.176 +
+ 50.0000 + 1.1300 + 5.6500 + 332.790 + 482.500 + -31.028 +
+ 70.0000 + 1.1180 + 7.8260 + 418.200 + 529.200 + -20.975 +
+ 70.0000 + 1.1390 + 7.9730 + 422.512 + 529.200 + -20.160 +
+ 70.0000 + 1.1100 + 7.7700 + 416.405 + 499.800 + -16.686 +
+ 100.0000 + 1.1100 + 11.1000 + 493.814 + 601.000 + -17.835 +
+ 100.0000 + 1.1180 + 11.1800 + 494.961 + 572.000 + -13.468 +
+ 100.0000 + 1.1420 + 11.4200 + 498.225 + 574.000 + -13.201 +
+ 100.0000 + 1.1100 + 11.1000 + 493.814 + 580.700 + -14.962 +
+ 100.0000 + 1.1180 + 11.1800 + 494.961 + 554.400 + -10.721 +
+ 100.0000 + 1.1420 + 11.4200 + 498.225 + 558.300 + -10.840 +
+ 150.0000 + 1.1100 + 16.6500 + 517.912 + 582.800 + -11.134 +
+ 150.0000 + 1.1180 + 16.7700 + 517.265 + 576.000 + -10.197 +
+ 150.0000 + 1.1420 + 17.1300 + 515.522 + 587.300 + -12.222 +
*****
```

SOURCE	AIR	SOURCE- DETECTOR	CALCULATED	ENERGY	PERCENT
TO	DENSITY	AIR MASS	NORMALIZED	COMPENSATED	ERROR
DETECTOR	(MG/CM**3)	THICKNESS	EXPOSURE RATE	EXPERIMENTAL	
DISTANCE	(M)	(G/CM**2)	(UR*M**2/(HCI))	EXPOSURE RATE	(NOTE 2)
(M)			(NOTE 1)	+(UR*M**2/(HCI))	
200.0000	1.1100	22.2000	468.340	472.000	-0.775
200.0000	1.1170	22.3400	466.587	464.000	0.557
200.0000	1.1500	23.0000	457.980	463.000	-2.141
200.0000	1.1100	22.2000	468.340	470.200	-0.396
200.0000	1.1170	22.3400	466.587	462.100	0.971
200.0000	1.1500	23.0000	457.980	466.900	-1.910
300.0000	1.1100	33.3000	310.738	266.400	16.643
300.0000	1.1210	33.6300	306.187	252.000	21.503
300.0000	1.1540	34.6200	292.580	245.700	19.080
300.0000	1.1100	33.3000	310.738	273.200	13.740
300.0000	1.1210	33.6300	306.187	258.300	18.533
300.0000	1.1540	34.6200	292.580	252.300	15.965
400.0000	1.1130	44.5200	177.372	154.200	15.027
400.0000	1.1210	44.8400	174.381	143.000	21.945
400.0000	1.1540	46.1600	162.289	124.300	30.563
400.0000	1.1130	44.5200	177.372	158.900	11.625
400.0000	1.1210	44.8400	174.381	147.300	18.365
400.0000	1.1540	46.1600	162.289	128.100	26.690

NOTE 1 - EXPOSURE RATES ARE NORMALIZED TO ONE CURIE AND MULTIPLIED BY THE SQUARE OF THE SOURCE TO DETECTOR DISTANCE.

NOTE 2 - THESE VALUES ARE THE PERCENT ERRORS IN THE CALCULATED EXPOSURE RATE BASED ON THE EXPERIMENTAL EXPOSURE RATES.

AVERAGE OF THE ABSOLUTE VALUES OF THE PERCENT ERRORS IS 17.000
THE SOURCE SILO COLLIMATION ANGLE IS 138.86810 DEGREES

SKY - CALCULATED SKYSHINE
USING BERGER BUILDUP FACTORS

```
*****
*                               INPUT PARAMETERS                               *
* CONCRETE DENSITY   = 2.13000 G/CC      ROOF THICKNESS = 0.0      M *
* SOURCE PHOTON ENERGY = 1.25000 MEV    GAMMA FRACTION = 2.00000 *
* SILO RADIUS        = 1.85400 M         SILO HEIGHT   = 0.43800 M *
*****
```

```
*****
+ SOURCE +          + SOURCE- + CALCULATED +
+ TO     + AIR     + DETECTOR + NORMALIZED +
+ DETECTOR + DENSITY + AIR MASS + EXPOSURE RATE +
+ DISTANCE + (MG/CM**3) + THICKNESS+ (UR*M**2/(HC1)+
+ (M)      +      + (G/CM**2) + (NOTE 1)  +
*****
+ 25.0000 + 1.2000 + 3.0000 + 33533.964 +
+ 37.5000 + 1.2000 + 4.5000 + 50079.030 +
+ 50.0000 + 1.2000 + 6.0000 + 64603.070 +
+ 62.5000 + 1.2000 + 7.5000 + 77105.031 +
+ 75.0000 + 1.2000 + 9.0000 + 87453.161 +
+ 87.5000 + 1.2000 + 10.5000 + 95887.553 +
+ 100.0000 + 1.2000 + 12.0000 + 102440.157 +
+ 112.5000 + 1.2000 + 13.5000 + 107398.189 +
+ 125.0000 + 1.2000 + 15.0000 + 110921.336 +
+ 137.5000 + 1.2000 + 16.5000 + 113153.020 +
+ 150.0000 + 1.2000 + 18.0000 + 114194.759 +
+ 162.5000 + 1.2000 + 19.5000 + 114272.295 +
+ 175.0000 + 1.2000 + 21.0000 + 113466.248 +
+ 187.5000 + 1.2000 + 22.5000 + 112000.574 +
+ 200.0000 + 1.2000 + 24.0000 + 107900.711 +
+ 225.0000 + 1.2000 + 27.0000 + 104416.663 +
+ 250.0000 + 1.2000 + 30.0000 + 97737.954 +
+ 275.0000 + 1.2000 + 33.0000 + 90407.292 +
*****
```

```

*****
+ SOURCE +          + SOURCE- + CALCULATED +
+ TO     + AIR     + DETECTOR + NORMALIZED +
+ DETECTOR + DENSITY + AIR MASS + EXPOSURE RATE +
+ DISTANCE +(MG/CM**3)+ THICKNESS+ (UR*M**2/(HC1)+
+ (M)      + (G/CM**2)+ (NOTE 1) +
*****
+ 300.0000 + 1.2000 + 36.0000 + 82799.069 +
+          +      +      +          +
+ 350.0000 + 1.2000 + 42.0000 + 67856.582 +
+          +      +      +          +
+ 400.0000 + 1.2000 + 48.0000 + 54345.438 +
+          +      +      +          +
+ 450.0000 + 1.2000 + 54.0000 + 42747.428 +
+          +      +      +          +
+ 500.0000 + 1.2000 + 60.0000 + 33176.677 +
+          +      +      +          +
+ 550.0000 + 1.2000 + 66.0000 + 25468.043 +
+          +      +      +          +
+ 600.0000 + 1.2000 + 72.0000 + 19363.179 +
+          +      +      +          +
+ 650.0000 + 1.2000 + 78.0000 + 14617.726 +
+          +      +      +          +
+ 700.0000 + 1.2000 + 84.0000 + 10977.385 +
+          +      +      +          +
*****

```

NOTE 1 - EXPOSURE RATES ARE NORMALIZED TO ONE CURIE AND MULTIPLIED BY THE SQUARE OF THE
 SOURCE TO DETECTOR DISTANCE.
 THE SOURCE SILO COLLIMATION ANGLE IS 150.50679 DEGREES

BENCHMARK SKYSHINE EXPOSURE RATES

by

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B.S., Kansas State University, 1977

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the
requirements for the degree

MASTER OF SCIENCE

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1980

ABSTRACT

A benchmark gamma-ray skyshine experiment was performed to obtain skyshine exposure rate data against which point kernel models and discrete ordinates transport theory models were compared. Skyshine radiation fields were measured over radial distances to 700 meters using ^{60}Co sources with nominal strengths of 10, 250, and 5000 Ci. Skyshine exposure rate data was obtained from three source configurations, a 150° vertically collimated conical radiation field and two collimated radiation fields shielded vertically by 21 cm and 43 cm of concrete.

Total exposure rate measurements were made with a 25 cm spherical high pressure ionization chamber (HPIC) filled with 2.5 MPa of high purity argon. These exposure rate measurements were normalized with respect to effective source activity and corrected for the energy sensitivity of the HPIC. Skyshine exposure rates measured with the HPIC and independently measured skyshine exposure rates inferred from a collimated NaI detector agree to within 5-10%.

A point kernel model developed in this work and a point kernel model based on the G-33 computer code were compared to the skyshine exposure rates measured with the HPIC and were found to agree within a factor of two. The point kernel model developed in this work was the more accurate of the two models.

The skyshine exposure rates measured with the HPIC were also compared to discrete ordinates transport theory calculations (DOT 3.5) and the DOT calculations were found to be within 25% of the measured exposure rates.

Predictions of skyshine exposure rates for different source photon energies, source collimation angles, and source shield thicknesses were also reported.