DESIGN OF A FACILITY TO UTILIZE 600 Ci OF Cs-137

A Thesis

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of

Master of Science

in

Nuclear Engineering

by
Mohammed Abu-Shehadeh
B.S., Al-Fateh University, 1980
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Dedicated to

my mother, brothers, and sisters

ACKNOWLEDGEMENT

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ABSTRACT

Although many of the older irradiation facilities have been dismantled, renewed interest in the possibilities of radiation processing makes new facilities worth investigating. The existence of an unused shielded facility formerly used for Californium-252 studies, and an unused 600-Curie Cesium-137 source in the Nuclear Science Center at Louisiana State University prompted a study to determine if the two could be combined and made into a useful experimental gamma facility. The original 8-foot by 4-foot by 6.5-foot deep water tank, shielded on three sides by 3 feet of light concrete, was found to yield exposure rates below 2.5 mR/hr at all exterior points when the 600 Curies was placed in a vertical right-annular array with its central axis 2 feet from the shielded tank end and 2 feet from each wall, and 6 inches from the bottom. A variable dose-rate mechanism based on sliding cams can position the nine source pencils reproducibly and selectively at any radius from 2 inches to 12 inches from the array axis, and vary the dose rate by a ratio of 43/1. The initial maximum dose rate in a 4-inch-diameter canister was calculated to be approximately 65,000 rads/hr. By adding a 3-cm-thick lead shroud, the maximum/minimum dose-rate ratio can be 1000/1. An external beam with a maximum

intensity of 25 R/hr can be generated by an empty 4-inch-diameter tube from the source to the unshielded end of the tank; the tube can be flooded for safety. Several gamma shielding demonstrations can be provided for student laboratories, and both in-tank and external-beam shielding research will be possible. A 150-pound lead cask can be used to transfer the cesium one pencil at a time without risk of personnel over-exposure.

CHAPTER 1

Introduction

Gamma sources have found their applications in almost every industry and branch of scientific research. Applications have included level gaging, thickness gaging, density measurements, composition analysis, treatment for cancer, pasturization of foods, inhibition of sprouting in vegetables, curing of elastomers, bonding of dissimilar plastics, inspection of internal structures, and solutions to many other unusual problems.

A detailed knowledge of the properties and interactions of gamma radiation is required for development of each of these applications, and for the design of radiation shields. Every gamma source must be shielded, including accelerators, isotopic sources, and nuclear reactors. Although much theoretical knowledge already exists, many shielding problems can be solved only through computer codes utilizing empirical data derived from experimental facilities.

Both highly collimated and broad-beam facilities have been used to develop the necessary empirical data. In general, a well defined source is placed in a predetermined geometrical relationship with a specific shield, and the fields on one or both sides of the shield, and sometimes even within the shield, are carefully mapped. A classic example is the Bulk Shielding Reactor at Oak Ridge National Laboratory. This is a pool-type facility in which the reactor core is a nominal 42-cm x 42-cm x 61-cm parallelopiped, but is treated as a spherical source of gamma radiation. Much of the currently used empirical data for water and other shielding materials is directly traceable to the Bulk Shielding facility. Although there is a considerable body of data available, new facilities designed specifically for determining shielding parameters can produce useful information.

In the general time span of 1950-1970, a large number of studies were conducted with foods to determine economic benefits from treatment with gamma radiation. One of the major contributors was the irradiation pool at Fort Nattick, Massachusetts, where sterilization of food products for long-term storage without refrigeration was evaluated. The Departments of Food Science and Entomology investigated gamma radiation effects on the shelf life and quality of foods important to Louisiana, including shrimp, shellfish, strawberries, and sweet potatoes. These studies were done with the cobalt-60 sources in the Nuclear Science Center, and with portable relaxation of restrictions by the Food and Drug Administration have encouraged new research with foods.

Although, the pool in the basement of the Nuclear Science Center was originally designed for a single central source array containing up to 100,000 curies of cobalt-60, the Center has acquired additional cobalt-60 and cesium-137 sources which are stored in the pool. There is a strong desire to restrict the pool to cobalt-60, which will require the current inventory of 600 curies of cesium-137 to be removed. Since the Department of Energy discontinued its Californium-252 Demonstration Center program in 1970's, the other major radiation facility at the Nuclear Science Center has not been used. Conversion of this unused installation to a cesium-137 pool source is one of the possible means by which the basement pool can be returned to an exclusive cobalt-60 facility.

The purpose of this thesis is to evaluate the suitability of utilizing the former californium-252 tank and shield for a multiservice cesium-137 facility. In addition to determining the shielding adequacy as a preliminary qualification, two uses will be considered. These are for irradiation of small-volume samples, and for demonstration of shielding parameters. The irradiator is to be designed as a variable-geometry, variable dose-rate source, which can be adjusted reproducibly to pre-calibrated dose rates. A series of beam collimators, curved tubes, and source-positioning mechanism are required to emulate the Bulk Shielding Reactor gamma source in small scale, and to allow demonstration of streaming through ducts, forward-scatter buildup, and other gamma shielding aspects. The facility is to be considered as a general-purpose teaching and research installation for use in Nuclear Science and Nuclear Engineering courses and by the University at large.

CHAPTER 2

Shielding Calculations

In order to evaluate the possibility of utilizing the former Californium-252 Demonstration Facility for the currently available cesium-137, it will be necessary to describe both the source and the design of the facility.

The cesium-137 is in the form of nine "pencil" sources containing a total of approximately 600 curies. Each source is 12 inches long by 1 inch in diameter for the external double stainless-steel encapsulation; the inner source material is desiccated CsCl powder compacted into the first capsule. These sources were obtained by the University from Continental Oil Company (Ponca City, Oklahoma); they were encapsulated originally by Oak Ridge National Laboratory as described in ORNL Drawing B-RD-1430, and were exhaustively tested before being released to Continental Oil. These sources have not been inspected nor tested since leaving Oak Ridge National Laboratory.

Detailed drawings for the Californium-252 Demonstration Facility may be found in Appendix 1. Briefly, the facility consists of a half-inch thick stainless-steel tank approximately 4 feet wide by 8 feet long and 6.5 feet deep embedded in an external shield. The tank is open and accessible from the top; the bottom, rear, and two long side walls are shielded with dry-stacked concrete blocks and the front face is unshielded and accessible for experimental procedures. There is an open area at the front end of the tank to house experimental equipment within lightly shielded walls. The concrete-block shielding for the rear end and side walls is approximately 3 feet thick, with standard-dimension light-aggregate concrete block (97 lb/cu. ft) stacked in a fashion to limit streaming through cracks; fine sand was brushed into all cracks to limit streaming further. Because the facility was designed originally to provide shielding for up to 100 mg of Cf-252, which emits both fission and decay gamma radiation and fission neutrons, there is a 4-inch thick pocket of compacted boric acid between the tank wall and the concrete-block shield at the rear end and both sides. A top view of the arrangement is shown in Figure 2.1.

The Californium Demonstration Facility had not been used since the program was discontinued by the Department of Energy several years ago. However, the long residence of Cf-252 sources totalling up to 60 mg at the bottom of the tank has resulted in persistent cobalt-60 activity induced in the steel. For this reason the tank cannot be dismantled and used in other places. The intensity of the Co-60 gamma radiation is not sufficient to contaminate

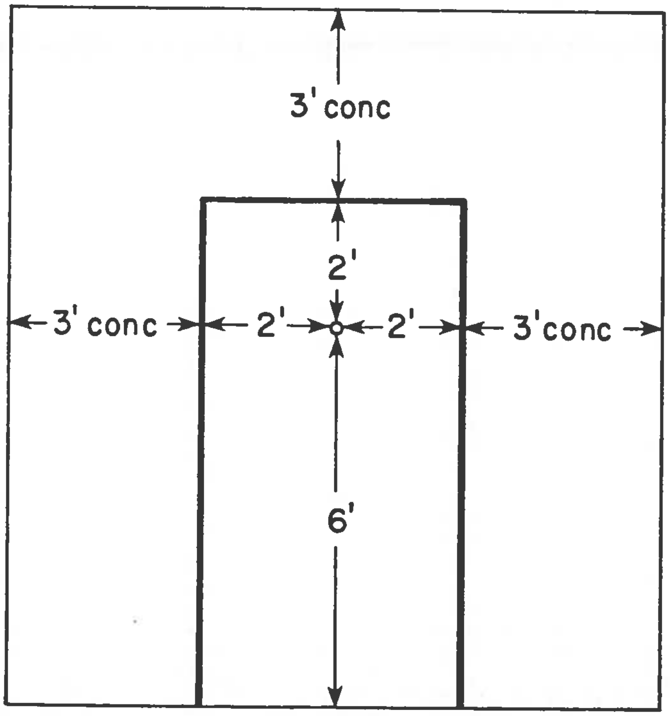


Fig. 2-1. Top View of the Californium-252 Tank.

the Cs-137 radiation significantly, nor even to be considered in the shielding calculations.

The source will be placed 6 inches above the bottom and 2 feet from each of the walls surrounded by concrete. This means that the source is 6 feet away from the unshielded front end of the tank. The tank will be filled with water, which has advantages as a shielding material.

The dose rate at the outer surface of the concrete shield should not exceed 2 mr/hr in an occupied area. There are three regions outside the tank for which the shielding calculations must be done; these three regions are:

1. The three sides of the tank where there is a concrete layer; in this case there is two feet of water (from the source to the steel wall of the tank) and three feet of concrete (from the steel wall to the outside).
2. The front end of the tank where there is no concrete layer; in this case there is only six feet of water from the source to the steel wall of the tank.
3. The surface of the water above the source, in this case there is also only six feet of water to shield the source.

To do the shielding calculations, the program "CASK"(4) was used. This program estimates the thickness of a slab shield necessary to attenuate monoenergetic radiation from a spherical surface. Some idealization of the actual physical arrangement of source and shield is inevitable. "CASK" uses three methods of approximation to estimate the shield thickness; these three methods used are, in increasing order of accuracy:

1) Point source approximation: Here the volume source is approximated by a point isotropic source of equivalent strength situated at the centre of a sphere of the same material as the shield. The program calculates the radius of this sphere (the shield thickness) necessary to attenuate the dose rates to the required level (Fig. 2.2).

2) Non-absorbing source approximation: In this method the source shape is treated correctly, but the material of the source is considered transparent to radiation; this assumption of course considerably simplifies the concommitant analysis (Fig. 2.3).

3) Absorbing sphere replaced by equivalent disc source approximation: In this method, which is expected to be the most accurate of the three used (unless the material of the source happens to be a weak absorber of the particular radiation being considered), the absorbing sphere is replaced by a disc source of the same radius.

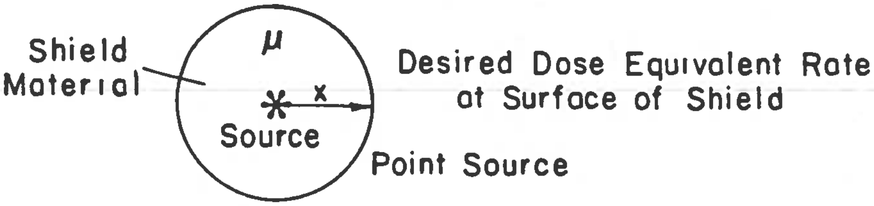


Fig. 2.2. Configuration Assumed in Point Source Approximation.

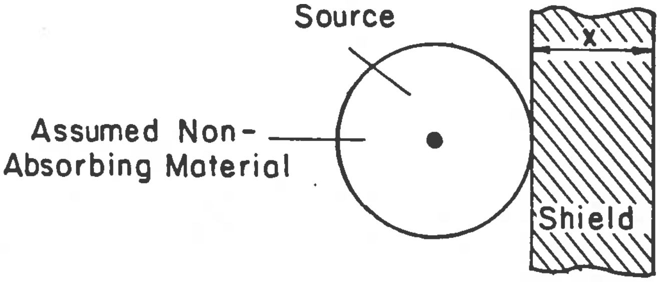


Fig. 2.3. Configuration Assumed in Spherical Source Approximation.

The following is a description and an order of the data required by "CASK".

(1) The source strength in Curies (Ci).

(2) The energy in MeV of the source gammas.

(3) The attenuation coefficient, μ_s, of the source material (cm^{-1}).

(4) The maximum permissible dose limit at the shield surface (mrem/hr).

(5) The radius of the sources (cm).

(6) The mass energy transfer coefficient, μ_{tr}/P for air or tissue ($cm^2 g^{-1}$).

(7) Taylor's build up factor coefficients, A1, A2, A3.

(8) The attenuation coefficient, μ, for the shield material (cm^{-1}).

(9) Initial estimate of the shield thickness (cm).

As mentioned above, "CASK" calculates the shield thickness required to reduce the dose rate to any desired value. This means that "CASK" is not ideal for this problem because the shield already exists. To make the program applicable to this case the following modifications can be made.

First, introduce the data (including the desired dose rate) to "CASK", then look at the shield thickness obtained. If the shield thickness obtained by "CASK" is equal to or less than the existing shield thickness then this means that the shield is sufficient to bring the dose rate down to the desired dose rate.

There is one more disadvantage of "CASK". It is unable to handle more than one shielding material at any one time. Therefore, when using "CASK", it is necessary to deal with the water layer and the concrete layer separately.

Actual dose rate calculations were made for the three worst case situations, above, to the side, and at the naked front of the tank with the minimum line-of-sight distances from the source center to the tank or water surface. The results are presented in Tables 2.1-2.3 for various gamma ray exit points, shield composites, and source geometries.

If the tank is considered alone, the three points of closest approach to a source 6 inches from the bottom and 2 feet from the two side walls and rear wall may be calculated. These three points will be the side wall (2 feet), the open front end (6 feet), and directly above the source at the water surface (6 feet). Because the line-of-sight distance for the tank front and water surface can be considered the same, only one calculation at 6 feet is required to cover both positions. The results for these two points are listed in Table 2.1. Table 2.2

lists the results for the rear wall and two side walls at 2 feet from the source. The minimum dose rate which can be achieved with water only is for the greatest-distance point at the top corner of the front (naked) wall; these results are presented in Table 2.3.

Because CASK calculates the shield thickness required for the input dose rate, if the physical distance for the case under consideration is greater than CASK requires, then the case provides adequate shielding. The measured dose rate therefore would be less than 2.5 mR/hr for such a case.

It is important to note that the actual source configuration was chosen to be a vertical array of the 9 pencils on the outside of a 4-inch diameter cylinder. The radius of this cylinder (5.08 cm) was entered into CASK, which used this for the radius of the spherical and disc sources. An additional approximation was made for the spherical source by assuming the cesium-137 to be distributed in water for calculating the self absorption.

As may be seen from an examination of Tables 2.1, the thickness of water to achieve a dose rate of 2.5 mR/hr is predicted by "CASK" to be a maximum 178.78 cm for a point source approximation. This is less than the 6 feet (182.88 cm) of water available at the top and front end of the tank. Hence, according to this prediction, 600 Ci of Cs-137 can be accomodated safely in the

Table 2.1. CASK Results for Three Source Approximations Water Shield Only (Top and Front of Tank where there is only six feet of water to shield the source).

DATA USED(1)

SRC = 6.00E 02 ENERGY MEV = 0.66

MU SHIELD (cm^{-1}) = 0.0840

DOSE LEVEL AT SHIELD SURFACE (MILLIREM/H) = 2.5000

MUA TISS (cm**2/G) = 0.029(3)

TAYLORS CONSTANTS = 81.0 0.11 -0.085

SOURCE RADIUS = 5.08 cm

POINT SOURCE APPROXIMATION

SHIELD THICKNESS = 178.78 cm BUF = 135.85

NONABSORBING SPHERICAL SOURCE APPROXIMATION

SHIELD THICKNESS = 178.27 cm BUF = 134.90

EQUIVALENT DISC SOURCE APPROXIMATION

SHIELD THICKNESS = 174.53 BUF = 128.16

Table 2.2. CASK Results for a Two-foot-water Shield.

DATA USED (1)

SRC = 6.00E 02 ENERGY MEV = 0.66

MU SHIELD (cm^{-1}) = 0.0840

DOSE LEVEL AT SHIELD SURFACE (MILLIREM/H) = 70,000.00

MU TISS (cm**2) = 0.0290 (3)

TAYLORS CONSTANTS = 81.00 0.110 -0.0850

SOURCE RADIUS = 5.08 cm MU SOURCE (cm^{-1}) = 0.0840

POINT SOURCE APPROXIMATION

SHIELD THICKNESS = 59.07 cm BUF = 17.83

NONABSORBING SPHERICAL SOURCE APPROXIMATION

SHIELD THICKNESS = 57.29 cm BUF = 17.09

EQUIVALENT DISC SOURCE APPROXIMATION

SHIELD THICKNESS = 54.45 cm BUF = 15.95

Table 2.3. CASK Results for the Farthest Point from the Source to the Top Corner at the Front End of the Tank (there is 192 cm of water to shield the source).

DATA USED(1)

SRC = 6.00E 02   ENERGY MEV = 0.66

MU SHIELD (cm^{-1}) = 0.0840

DOSE LEVEL AT SHIELD SURFACE (MILLIREM/H) = 1.9

MUA TISS (cm**2) = 0.029(3)

TAYLORS CONSTANTS = 81.00   0.110   -0.0850

POINT SOURCE APPROXIMATION

SHIELD THICKNESS = 182.14 cm   BUF = 142.23

NONABSORBING SPHERICAL SOURCE APPROXIMATION

SHIELD THICKNESS = 181.59 cm   BUF = 141.17

EQUIVALENT DISC SOURCE APPROXIMATION

SHIELD THICKNESS = 177.9 cm   BUF = 134.23

Californium Demonstration Facility without additional shielding in the two direct water paths.

In order to determine the shielding achieved by the water-plus-concrete path through the side and rear walls, the problem must be handled in two parts by "CASK". First, an approximation to the dose rate at the inside surface of the concrete was calculated, assuming only 2 feet of water, with the Taylor four-factor formula. Also, the dose rate through the maximum water path to the top front corner of the tank (192 cm) was estimated. These two estimates were 70,000 mR/hr and 1.9 mR/hr respectively. CASK was then employed to calculate the thicknesses of water required to achieve these two dose rates as a check on the original approximations. The results are given in Table 2.2 and 2.3 respectively. For the 70,000 mR/hr point "CASK" required 59.07 cm (worst case) of water, which is less than the 2 feet (60.96 cm) available, and for the 1.9 mR/hr point CASK calculated 182.14 cm rather than the 192 cm used in the Taylor estimation. "CASK" therefore was considered as yielding conservative values of required shield thickness when the point-source approximation is chosen.

CASK requires that the source must be in the shielding medium. Therefore, for the concrete shielding calculation, an equivalent source at the inner concrete surface must be estimated. The two points at 70,000 mR/hr and 1.9 mR/hr, which represent the maximum and minimum dose rates on the side wall provide the necessary data. From these, the required equivalent disc source may be approximated. The dose rate must be converted into its equivalent number of Curies. To do so, the two extreme dose rates will be considered:

a. The dose rate at the nearest point (2 feet)

D.R. = 70,000 mrem/hr

$$\phi_1 (\frac{\text{MeV}}{\text{cm}^2\text{sec}} = 70{,}000(\text{mrem/hr}) * 570 (\frac{\text{MeV/cm}^2\text{-sec}}{\text{mrem/hr}})$$

$$= 3.99 \times 10^7 \text{ MeV/cm}^2\text{-sec.}$$

b. The dose rate at the farthest point (upper corner)

D.R. = 1.9 mrem/hr

$$\phi_2 (\frac{\text{MeV}}{\text{cm}^2\text{-sec}}) = 1.9 \times 570$$

$$= 1.08 \times 10^3 \text{ MeV/cm}^2\text{-sec.}$$

$$\text{Average Flux} = \overline{\phi} = \frac{\phi_1 + \phi_2}{2} = \frac{3.99 \times 10^7 + 1.08 \times 10^3}{2}$$

$\overline{\phi} = 1.99 * 10^7$ MeV/cm^2-sec. Av. Energy Flux

$\overline{\phi} = 1.99 \times 10^7$ MeV/cm^3-sec * 1γ/0.662 MeV

$\overline{\phi} = 3.01 \times 10^7$ γ/cm^2-sec. Av. Number Flux

The number flux is 3.01×10^7 γ/cm^2-sec. This means that the average number of gammas falling at one cm^2 on the inner surface of the concrete is 3.01×10^7 gammas. To find the total number of gammas falling at the whole wall surface, the surface area of the wall is required.

Area = Depth x Length

$A = 6.5$ ft. x 8 ft.

$A = 52 \text{ ft}^2$

$A = 4.83 \times 10^4 \text{ cm}^2$

Total number of gammas arriving at the wall = A x $\overline{\phi}$

$= 4.83 \times 10^4 \text{ cm}^2 \times 3.01 \times 10^7 \ \gamma/\text{cm}^2\text{-sec.}$

$= 1.45 \times 10^{12} \ \gamma/\text{sec.}$

$$\text{Equivalent strength (in Ci)} = \frac{1.45 \times 10^{12} \ \gamma/\text{s}}{3.7 \times 10^{10} \ \gamma/\text{s-Ci}}$$

$$= 39.18 \text{ Ci}$$

This number of Curies represents the source strength for "CASK", but to be more conservative 40 Ci was used instead. The source radius is also one of the inputs required by "CASK". The radius was obtained by considering the rectangular wall as a circular wall with the same area:

$$A = \pi r^2$$

$$4.83 \times 10^4 \text{ cm}^2 = \pi r^2$$

$$r = \sqrt{\frac{4.83 \times 10^4}{\pi}} = 124 \text{ cm}$$

For the particular worst-case consideration at the side wall outside the concrete nearest the student class room, an allowable dose rate of 2 mR/hr was assumed to assure that no students in this classroom would receive in excess of 170 mR in a year (3 hours per week, 2 semesters per year). Hence, with the input data of 2 mR/hr, 40 Ci equivalent of Cs-137, and an equivalent disc source radius of 124 cm, CASK predicts the required thickness of light-aggregate concrete to be 73.08 cm instead of the actual 91.5 cm (see Table 2.4). Even the worst-case point source yields 92.44 cm, which is close to the actual value. Again, "CASK" calculation indicates that the existing Californium Demonstration Facility is capable of providing adequate shielding for 600 Ci of cesium-137.

There is an inherent conservative factor in all of the calculations presented here because of the cesium-137 decay modes. Throughout each disintegration was assumed to yield one 0.661-MeV gamma while in actuality only approximately 85% of the disintegrations yield this gamma.

For the special case of calculating the dose rate through the side with the water/concrete path, there is an additional conservative assumption. The average dose rate over the entire wall was assumed to the linear

Table 2.4. CASK Results for the Three Feet of Concrete

DATA USED(1)

SRC = 4.00E 01 ENERGY MEV = 0.66

MU SHIELD (cm^{-1}) = 0.137

DOSE LEVEL AT SHIELD SURFACE (MILLIREM/H) = 2.0

MUA TISS = 0.029(3)

TAYLORS CONSTANTS = 58.00 0.081 -0.059

SOURCE RADIUS = 124.0 cm

MU SOURCE (cm^{-1}) = 0.00

POINT SOURCE APPROXIMATION

SHIELD THICKNESS = 92.44 cm BUF = 41.45

NONABSORBING SPHERICAL SOURCE APPROXIMATION

SHIELD THICKNESS = 79.61 cm BUF = 31.84

EQUIVALENT DISC SOURCE APPROXIMATION

SHIELD THICKNESS = 73.08 cm BUF = 27.6

combination of the maximum and minimum dose rates. However, as is apparent from Figure 2.4, the linear combination severely over estimates the average dose rate. The actual dose rates to be expected outside the shield wall therefore will be much less than that predicted by the worst-case assumption.

The calculated dose rates for the shielding available at the sides and end of the tank are considered to be sufficiently low that more refined treatment is not warranted. However, the dose rate at the surface of the water above the source with 6 feet of shielding might be marginal for the design criteria. An alternate calculational approach therefore was used to obtain another estimate. For this, the source was assumed to consist of a single 600-Ci ^{137}Cs rod 12-in. high with its lower end 6 inches above the bottom of the tank. This then was divided into three 4-inch long segments containing 200 Ci each, and the shielding for each was taken as thickness of water between the top of each segment and the surface of the pool; hence, the topmost segment was assumed to have only 5 feet of water shielding. Each segment was then treated as an individual line source, and the dose rate at the pool surface was calculated for a point on the surface 5° away from the vertical source axis. No credit was taken for the 4 inches of water actually surrounding the source segment. This segmented line source approximation yielded the following results:

Segment	Assumed Water thickness, in.	Calculated Dose Rate, mR/hr
Top	60	0.873
Middle	64	0.331
Bottom	68	0.153
	TOTAL	1.357

On the basis of this approximation, the dose rate in the working area above the tank for the planned source arrangement will be low enough to permit unrestricted access and unlimited access time.

Because of the divergence among the various calculations, checks on the actual dose rates for a pencil-by-pencil loading will have to be made when the ^{137}Cs is brought up from the basement pool.

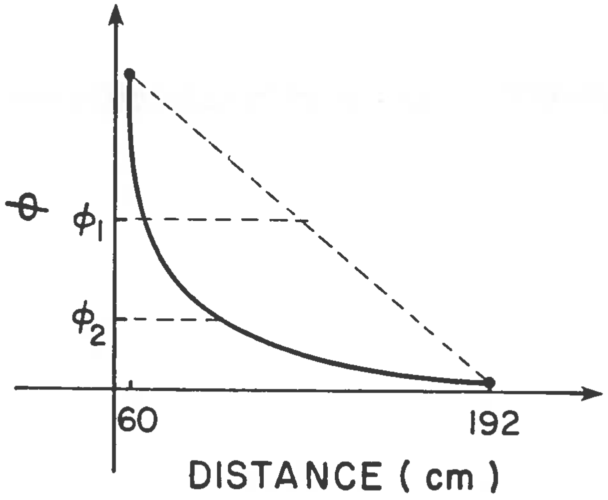


Fig. 2.4. A Plot of the Flux vs. the Distance.

CHAPTER 3

Irradiator Design

Verification that the available 600 Ci of Cesium-137 can be placed in the former Californium Demonstration Facility establishes the opportunity for detailed consideration of designs for experimental uses of this gamma source. The proposed new facility will be designated in the remainder of this thesis as the Cesium Experimental Radiation Facility (CERF). Two distinct possible uses for this new facility are as an irradiator similar to the existing cobalt-60 sources in the basement of the Nuclear Science Center, and for laboratory demonstration of gamma shielding problems and experimental gamma shielding projects. These uses will be discussed in this and the following chapter, and radiation-safety considerations will be described in Chapter 5.

Cesium-137 is different from cobalt-60 in several important ways. The dose rate per curie from ^{137}Cs (0.33 R/hr at 1 m)(3) is significantly less than that of ^{60}Co (1.32 R/hr at 1 m)(3), and the gamma energy of 0.661 MeV for ^{137}Cs is approximately one half of the 1.25 MeV average from ^{60}Co on the other hand, the ^{137}Cs gamma is monoenergetic, and the half life of ^{137}Cs is 30 years compared to the 5.21-year half life of ^{60}Co. The ^{137}Cs source therefore will not require recalibration as frequently as the ^{60}Co sources, and the ^{137}Cs source can be more accessible than the ^{60}Co because the water required for shielding is much less. For shielding studies, proper design can yield an almost purely monoenergetic beam from ^{137}Cs, which cannot be accomplished readily for ^{60}Co. The ease of shielding ^{137}Cs also offers the possibility for designing a variable dose-rate irradiator which can cover several orders of magnitude in available dose rates.

Dose Rate Calculations

Because the ^{137}Cs is available in double-encapsulated pencils, the conceptual design for an irradiator will be analogous to that for the existing ^{60}Co irradiators in the Nuclear Science Center. All calculations and mechanical arrangements therefore will be predicted on an array of nine pencils standing vertically to approximate a right-circular annulus which will receive a cylindrical irradiation canister lowered through the water shield from the top of the tank. A minimum canister diameter of 4 inches will be used for dose rate calculations and as a design criterion.

Since the pencils are arranged in a circle that is 2 in. radius, this means that the highest dose rate is obtained when they are located at the circumference of this circle. This configuration may be considered as an array of individual line sources. The following formula gives the flux from an unshielded line source.

$$\phi\left(\frac{\gamma}{cm^2\text{-}s}\right) = \frac{Q_\ell(\gamma/cm\text{-}s)}{4\pi\ a(cm)}\ (\theta_1+\theta_2) \qquad (3.1)$$

This is equation (6.4-19) in Reactor Shielding for Nuclear Engineers,(2) where Q_ℓ is the source strength of the line source expressed in γ/cm-s, a is the shortest distance between the point of interest and the source in cm, and θ_1 and θ_2 are the angles shown in Fig. 3.1 expressed in radians.

In this particular case, a = 2 in. (radius of the circle), and the source length = 12 in; if the point of interest (P) lies at the line that is normal to the axis of the source and divides the source into two equal parts, then $\theta_1=\theta_2$ (71.56° = 1.249 rad.). The source strength per unit length will be given by

$$Q = \frac{(600\ Ci/a\ pencils)(3.7\text{x}10^{10}\gamma/sec\text{-}Ci)(0.85\ \gamma/dis)}{(30.48\ cm/pencil)}$$

$$= 6.879\ \text{x}\ 10^{10}\ \gamma/cm\text{-}sec$$

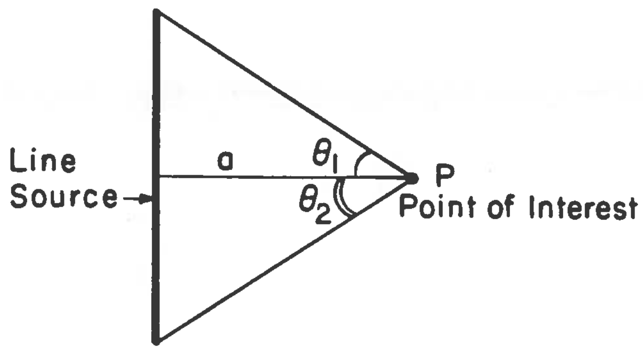


Fig. 3.1. Unshielded Line Source.

Now, substituting these data into Eq. (3.1) gives the flux:

$$\phi(\frac{\gamma}{cm^2\text{-}s}) = \frac{6.879 \times 10^{10}(\gamma/cm\text{-}s)}{4\pi\ (5.08\ cm)}\ (1.249 + 1.249)$$

$$\phi = 2.691 \times 10^9\ \gamma/cm^2\text{-sec.}$$

$$\text{Dose rate} = 2.691 \times 10^9\ (\frac{\gamma}{cm^2\text{-}s}) * 1.442 \times 10^{-3}\ (\frac{mrem/hr}{\gamma/cm^2\text{-}s})$$

$$D.R. = 3.881 \times 10^6\ mrem/hr$$

This is the dose rate from one pencil, the dose rate from the nine pencils is:

$$D.R. = 9(3.881 \times 10^6) = 3.492 \times 10^7\ mrem/hr.$$

This is the dose rate from the direct beam. The dose rate from the scattered gamma must also be considered. The major contribution of scattered gamma is from gammas scattered at 180° (back scatter). To simplify the problem all pencils are assumed to be located at the center of the circle as one pencil, Fig. 3.2(a) shows the actual arrangement, and Fig. 3.2(b) shows the assumed arrangement.

The following formula was used to calculate the dose rate from scattered gamma:(1)

$$D.R. = D.R_o \frac{A}{r^2} \alpha(E_o, \theta_o, \theta, \phi) \qquad (3.2)$$

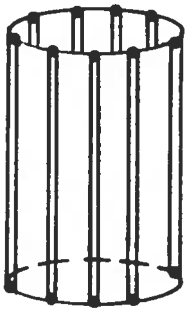


Fig. 3.2(a)

Actual Source Arrangement

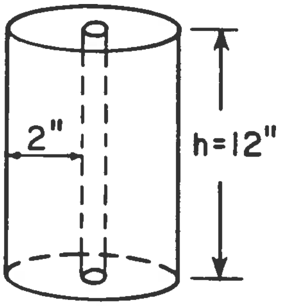


Fig. 3.2(b)

Assumed Source Arrangement

A Handbook of Radiation Shielding Data is the reference to Equation (3.2). In this equation:

D.R. = Reflected dose rate

$D.R._o$ = Dose incident on surface at angle (θ_o)

A = Reflecting area in (cm^2)

r = Distance from center of reflecting area to receptor in (cm).

To calculate the reflecting area A, the surface area of the cylinder shown in Fig. 3.2(b) must be calculated.

a_1 = area of top circle = area of bottom circle

$a_1 = \pi r^2 = \pi\ (5.08\ cm)^2 = 81.07\ cm^2$

Hence, the area of top and bottom = $2a_1 = 162.14\ cm^2$

The surface area of the wall of the cylinder

$$= 2\pi\ r\ h$$

$$= 2\pi(5.08)\ 30.48$$

$$= 972.87\ cm^2$$

Total area = $162.14 + 972.87 = 1135\ cm^2 = A$

$\alpha(E_o,\theta_o,\theta,\phi)$ is the gamma albedo, its value can be obtained from tables (1) if the arguments E_o,θ_o,θ, and ϕ are known. In this case $E_o = 0.662$ MeV, $\theta_o = 0$ (incidence angle), $\theta = 180°$ (scattering angle), and $\phi = 0$ (azimuthal angle).

$$\alpha(0.662\ MeV,\ 0°,\ 180°,\ 0°) = 0.0919553$$

Now, substituting these data into Equation (3.2) gives the dose rate from reflected gammas:

$$\text{D.R.} = 3.492 \times 10^7 \frac{1135}{(5.08)^2} \times 0.019553$$

$$\text{D.R.} = 3.00 \times 10^7 \text{ mrem/hr}$$

The total dose rate D.R_T is the sum of the dose rate from the direct beam and the dose rate from the reflected gammas.

$$\text{D.R}_T = 3.492 \times 10^7 + 3.00 \times 10^7$$

$$\text{D.R}_T = 6.492 \times 10^7 \text{ mrem/hr}$$

D.R_T is the maximum dose rate obtainable from the 600 Ci of Cs-137. Because of the large contribution of backscattered gammas, the dose in the canister will not be primarily from the 0.661-MeV ^{137}Cs direct radiation, but will be mixed with lower energies. Experimental estimation of the weighted average energy for scattered Compton radiation from ^{137}Cs in water (see Chapter 4) leads to 0.175 MeV, with the dominant 180° backscatter peak (0.165 MeV) accounting for a large part of the continuum. Weighted combination of these two components yields an effective energy of approximately 0.44 MeV for the radiation energy which delivers the total dose rate of 6.49×10^7 mrem/hr.

The dose rate can be varied by moving the sources away from the canister wall. To a first approximation the dose rate could be reduced by a factor of 10 by introducing one tenth-value layer of water, or 18.5 inches. However, this ignores both buildup and geometry changes. The following calculation illustrates the method for finding dose rate as a function of distance for a 12-inch source circle:

$$\phi\left(\frac{\gamma}{cm^2-s}\right) = \frac{B\ Q_\ell(\gamma/cm\text{-}s)}{4\ \pi\ a}\ [2\ F(\theta,b)]^{(1)} \qquad (3.3)$$

In which, B is the build up factor, Q_ℓ is the source strength, a is the distance from the source to the point of interest (P) and F(θ,b) is the Sievert integral. To evaluate F the values of the arguments θ and b are required. To find θ refer to Fig. 3.3.

$$\tan\theta = \frac{1/2\ \ell}{a} = \frac{6}{12} = 0.5$$

$$\theta = 26.56° = 0.464\ \text{rad.}$$

The linear attenuation coefficient of water $\mu_\ell = 0.084\ cm^{-1}$.

$$b = \mu_\ell X \quad \text{but } X = 10\ \text{in} = 26.4\ \text{cm}$$

$$b = 0.084\ (cm^{-1}) \times 25.4\ cm$$

$$b = 2.13 = \text{relaxation length}$$

Now from the graph of Sievert integral:(1)

$$F(26.5,\ 2.13) = 5.0 \times 10^{-2}.$$

To evaluate B, Taylor's formula will be used. The following data are required for water at 0.662 MeV. Taylor's coefficients:(1) $A = 81$, $\alpha_1 = -0.11$, $\alpha_2 = -0.085$. Taylor's formula(1) is:

$$B = Ae^{-\alpha_1 b} + (1-A)e^{-\alpha_2 b}$$

$$B = 81^{-(-0.11)2.13}e + (1-81)^{-(-0.085)2.13}e$$

$$B = 6.5$$

Now, all the data required to evaluate the flux using Equation 3.3 are available.

$$\phi\left(\frac{\gamma}{cm^2\text{-}s}\right) = \frac{6.5 \times 6.879 \times 10^{10}}{4\pi(30.48)}\ (2 \times 5 \times 10^{-2})$$

$$\phi = 1.167 \times 10^{8}\ \frac{\gamma}{cm^2\text{-}s}$$

$D.R = \phi \times \text{conversion factor}$

$D.R = (1.167 \times 10^{8})\ (1.442 \times 10^{-3})$

$D.R = 1.683 \times 10^{5}$ mrem/hr; this is the minimum dose rate obtained from one pencil. The minimum dose rate from all pencils is:

$D.R_m = (1.683 \times 10^{5}) \times 9$

$D.R_m = 1.515 \times 10^{6}$ mrem/hr

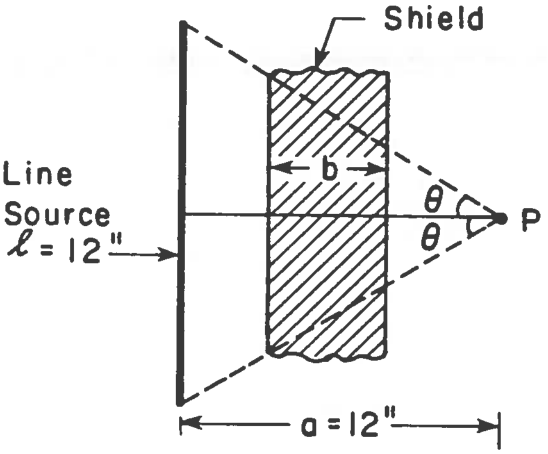


Fig. 3.3. Shielded Line Source

Intermediate points between the minimum of 2 inches and maximum of 12 inches are listed in Table 3.1. The ratio of the maximum to the minimum dose rate is:

$$\frac{D.R_T}{D.R_m} = \frac{6.492 \times 10^7}{1.515 \times 10^6} = 43$$

This means that by moving the pencils to the 12-inch-radial circle the dose rate was reduced by a factor of 43. If a smaller dose rate is still required a lead shroud can be used to surround the canister. The tenth value layer of lead at 0.662 MeV is 2.1 cm. This means that if the canister is surrounded by 2.1 cm of lead the dose rate will be reduced by a factor 10, or a total maximum/minimum ratio of 430.

Mechanical Design

Now, the mechanical design of the source arrangement must be developed. Two concepts for the design were developed and analyzed. The first concept is the gear concept, the other is the cam concept. These two concepts are discussed below:

Gear Concept

The basic idea for this concept is to mount each source vertically at a point on the outer circumference

Table 3.1. Expected Dose Rates for Various Source Positions.

Radius of Source Circle, inches	Water Thickness, inches	Dose Rate mRem/hr
2	0	6.49×10^7
4	2	1.59×10^7
6	4	8.24×10^6
8	6	4.32×10^6
10	8	2.62×10^6
12	10	1.52×10^6

of a gear such that the source pencil is moved from its point of closest approach to the canister out to the maximum distance away by rotating the gear through 180°. In this concept the following four sets of gears are required.

a. Sun gear or central gear (one gear is required)
b. Planet gears (nine gears are required)
c. External gear (one gear is required)
d. Driving gear (one gear is required)

These four sets of gears should be arranged in the following manner: the Sun Gear which is 2 inches in radius is placed at the center and the nine planet gears are arranged around it in such a way that none of the planet gears comes in contact with another planet gear. The external gear holds all the planet gears tight to the central gear, and the driving gear is placed on the outer side of the external gear. The whole assembly is placed on a mounting bed. A shaft that passes through the center of the driving gear extends up to the top of the tank where it can be connected to a motor located above the tank. Each of the nine Cs-137 pencils is inserted into a hole made at the edges of each planet gear. When the motor rotates the driving gear, say clockwise, the external gear rotates counterclockwise and the planet gears rotate clockwise. Consequently, the pencils rotate with the planet gears and they become closer to or far away from the center of the sun gear. As the pencils move away from the center, the dose rate to the canister is reduced. The maximum dose rate is obtained when the pencils are at the edges that are in contact with the central gear. Fig. 3.4 shows the whole assembly and the way the gears should be arranged.

Since the pencils are to be arranged in a circle that is 2 inches in radius, the sun gear has to have a radius of 2 inches. Since the system is limited to the size of the sun gear, the planet gears should also have a limited size so that they will not come in contact with one another. The circle passing through the centers of the planet gears will have a circumference given by

$$C = 2\pi\ (R + r),$$

in which R is the radius of the sun gear and r is the radius of a planet gear. In order to accomodate the nine sources, the circumference must be greater than 9 x 2r°, hence

$$18r < 2\pi\ (R + r)$$

This inequality can be manipulated to give

$$r < R/(\frac{9}{\pi} - 1)$$

$$< 0.536 \cdot R$$

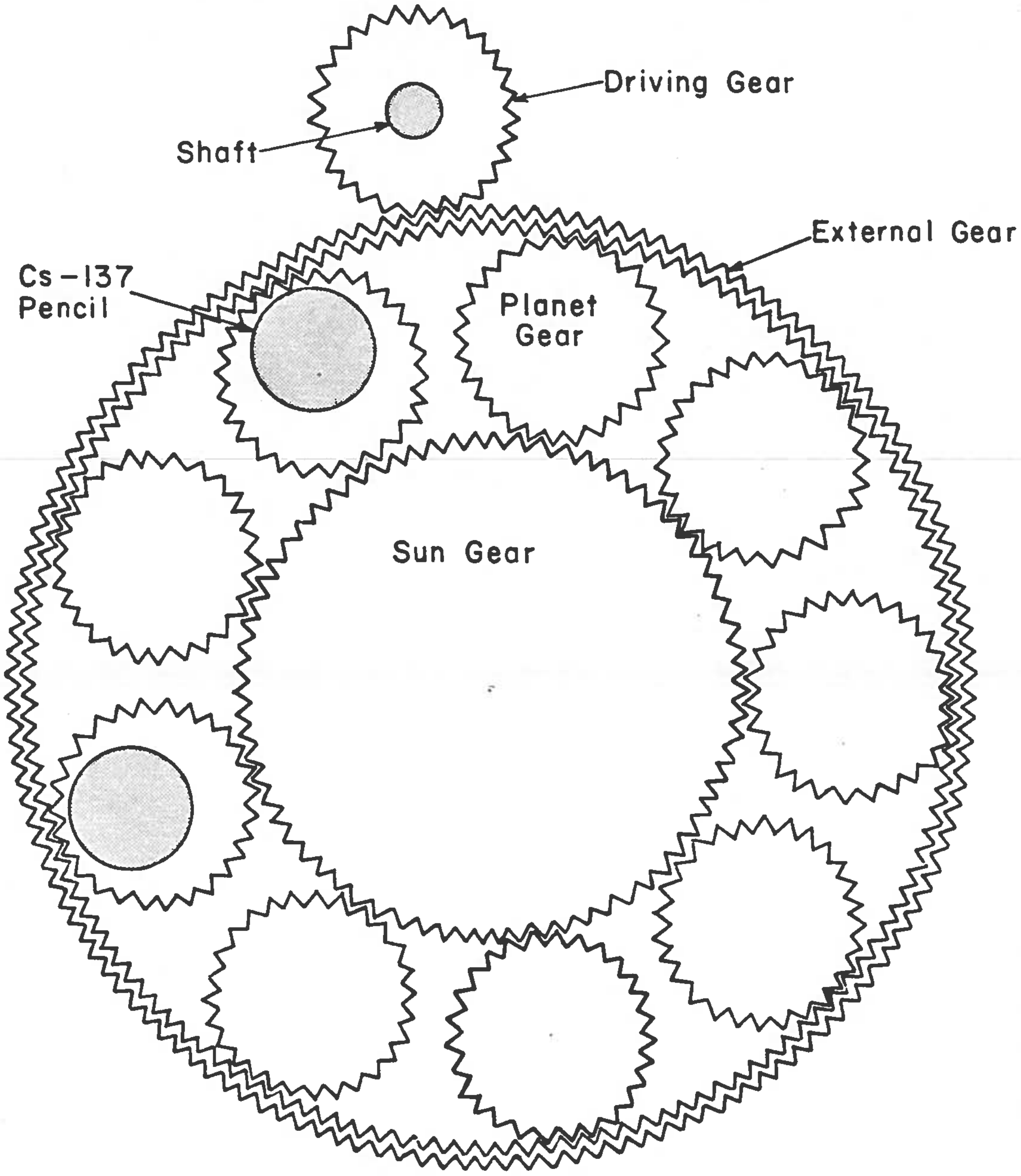


Fig. 3.4. The Arrangement of Gears for the Gear Concept.

For R = 2 inches, r must be less than 1.07 inch; in practice, however, the radius of planet gears must be reduced to approximately 0.9 inch.

As mentioned before, the diameter of the Cs-137 pencil is one inch. When this pencil is placed in a hole in the planet gear there will be only 0.8 inch of the planet gear left unoccupied by the pencil. These 0.8-inch distance is the maximum distance we can move the pencils away from the edge of the sun gear. Unfortunately, this distance can only reduce the dose rate to 95% of the maximum value. Because the goal is to reduce the dose rate to 1% of the maximum, the gear concept was abandoned and the cam concept was adopted instead.

Cam Concept

The basic idea for this concept is to mount each source pencil vertically in a holder which moves in a pair of matching guide slots in two cam plates, one of which is stationary and the other rotated by an external gear. For the cam concept, the following are required:

1. One 25-inch square metal plate with legs at each corner to be attached to the bottom of the tank. Nine linear radial slots are to be machined into the plate with their inner ends tangent to a 4-inch diameter circle inscribed at the center of the plate; and their outer ends tangent to a

24-inch diameter concentric circle. The nine 10-inch-long slots are to be equally spaced around the circles, with the angle between slots being 40°.

2. One circular plate 12.7 inches in radius to be mounted on an axle through the center of the fixed plate, with gear teeth machined on the perimeter for approximately 105° of arc. Nine curved slots are to be machined into the plate with their inner ends centered on a 4-inch diameter inscribed circle and their outer ends centered on a 10-inch radius inscribed circle. Each slot is constructed such that the chord of its centerline is 10 inches, and the radius of the centerline is 7.65 inches. The centers of radii for the nine slots are on a construction circle 6 inches in radius concentric with the inner and outer inscribed terminal circles. This plate is to be machined with central and periferal bearing surfaces which mate with bearing surfaces machined into the fixed plate.
3. One external gear to mate with the toothed section of the circular plate. This gear is to have its axle mounted on the fixed plate, and will be driven by a shaft extending to the top of the tank.

4. Nine source carriers which pass through the matching pairs of slots in the rotating and fixed plates, acting as individual cam followers. These carriers are to be mounted such that they cannot be disengaged from the assembly without removing it from the tank. The sources will be free-standing in the carriers, but will be contrained to inhibit accidental removal.

A schematic plan of the gear and cam slots is shown in Figure 3.5, and Figure 3.6 is the arrangement of slots in the fixed plate. Geometric construction details for the cam slots and gear sector may be found in Figures 3.7 and 3.8. Figure 3.9 is a generalized drawing of the source carrier indicating the relationship of the fixed and moving parts. The top part of the carrier which holds the source pencil will be at least 5 inches deep to assure that the pencil will be held vertically.

When the top plate is rotated, the lateral force applied to the carrier axle will force the carrier to move away from the applied force. The direction of motion of the plate therefore will determine whether the carriers move away from the center or toward it. Coordinating the relative positions of the top and bottom plates with an indicator at the top of the tank where the driving gear is controlled will allow accurate and reproducible source location. The indicator actually could be calibrated in terms of dose rate, so that an experimenter would be able to dial in any desired dose rate between the current maximum and minimum values. A choice of lead shrouds which could be attached to the outside of the canister would add to the low-dose-rate range.

Discussion of detailed machining and construction details is considered to be beyond the scope of this thesis. However, the importance of friction is recognized as a potential limitation for translating this design into practice. Strategic incorporation of ball- and roller-bearing relief into the final design is considered essential for success.

Irradiator Use

Throughout the preceding discussion the assumption has been made that the Cesium Experimental Radiation Facility would be used in a manner analogous to current practice for the ^{60}Co irradiator, with the source maintained in a water-shielded state and the experimental material being moved through the water into the source array.

A simple solution to lowering an irradiation canister to the source is to use a hoist. The canister assumed for the previous dose rate calculations is 4 inches in diameter by 12 inches high, with a volume of approximately 2.5 liters. In order for this to sink, a lead weight of 3 Kg would be attached to the bottom, which could be accomplished by a 4-inch diameter by 1.25-inch thick disk; in actuality, this could be placed inside the canister with little loss in useful volume. The weight of such a canister machined from aluminum would be less than 10 lb, which could be handled easily by a manual hoist. However, if the tenth-value-layer shroud described earlier were to be used, an additional weight of 66 lb would be required, and the total weight of 76 lb would be beyond simple manual handling. A slightly thicker shroud would allow attenuation of the source gammas such that a total dose rate range from maximum to maximum/1000 could be achieved by shroud and source positioning. The required thickness is 3.0 cm, which would add approximately 101 lb, or a total canister weight of slightly over 110 lb. These estimates suggest that a hoist capable of handling up to 500 lb would be more than adequate for manipulating the canister.

For reasons which will become apparent in later chapters, the hoist will be required to move the full length of the tank with accurate positioning, and must be capable of lifting through approximately 15 feet.

Automatic Closed Loop Positioning System

To focus the canister in the center of the source circle the idea of an Automatic Closed Loop Positioning System (ACLPS) was found reasonable. The advantages of this system appear in the following manner. First, since the tank is full of water, it is difficult to center the canister in the middle of the source circle. The ACLPS guarantees the positioning of the canister. Second, when dealing with a heavy canister, manual handling will be extremely difficult, and more than one person is required. For these two important factors the Automatic Closed Loop Positioning System (ACLPS) is adopted. The basic idea for this system is to attach the canister to a removable plate centered in the middle of the source circle. This plate is to be connected from the back side to a steel cable (say 1/4 in. in dia.) passing through the centers of the two source carrier plates, where it turns around a pulley and continues to the side of the tank where it turns around another pulley and extends to the top of the tank. Above the tank, the cable turns around a third pulley making its direction horizontal till it turns around a fourth pulley making its axle vertical, then it is connected to the canister from the other end. Figure 3.10 shows the above description.

The cable must be rolled around a drum that is driven by a reversible motor. As the motor is turned on, the drum rotates, in place, allowing the cable to move back and forth. Fully lowered and fully raised positions can be set by limit switches.

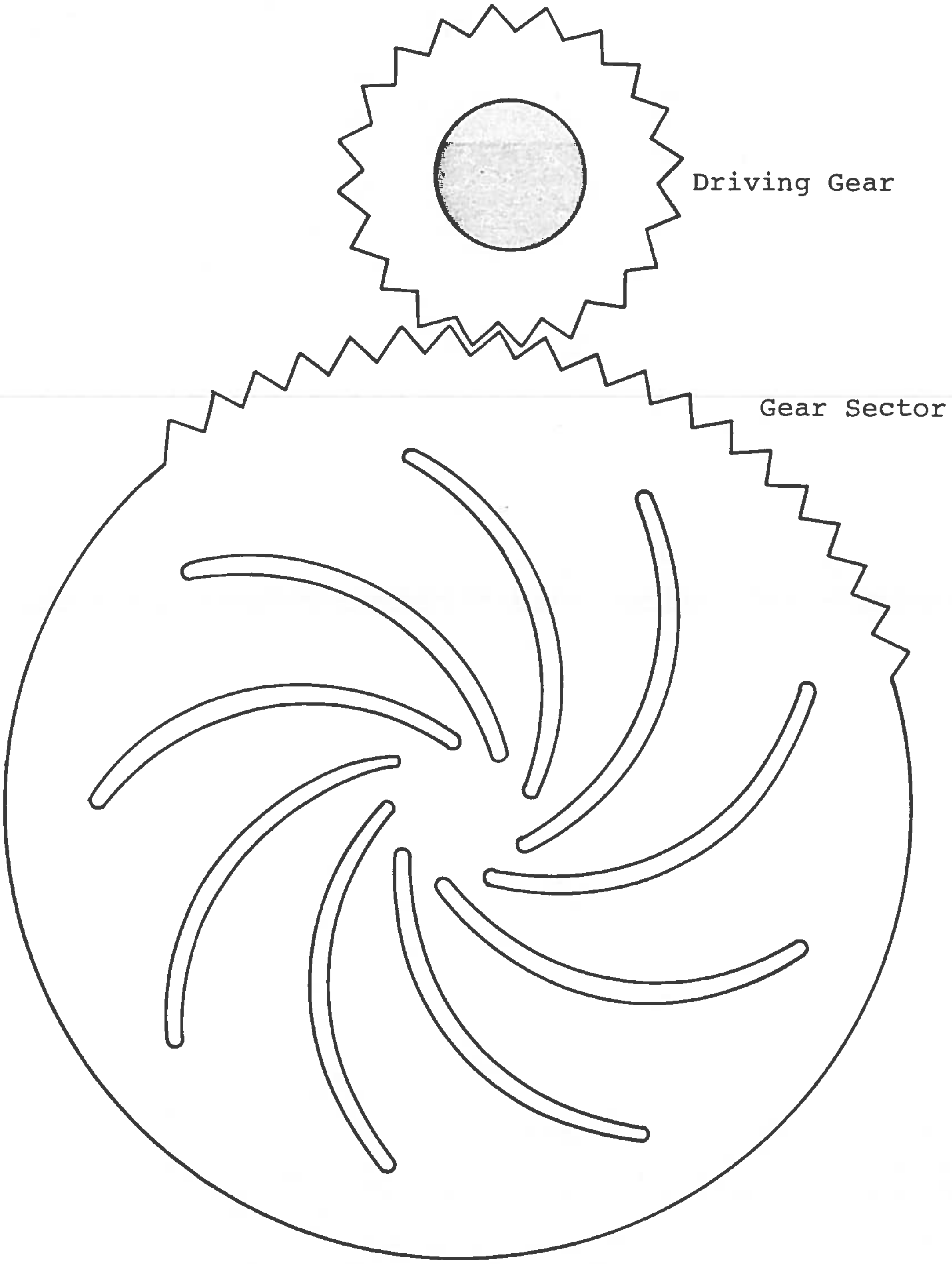


Fig. 3.5. Schematic Plan of the Driving Gear and the Cam Slots on the Movable Cam Plate.

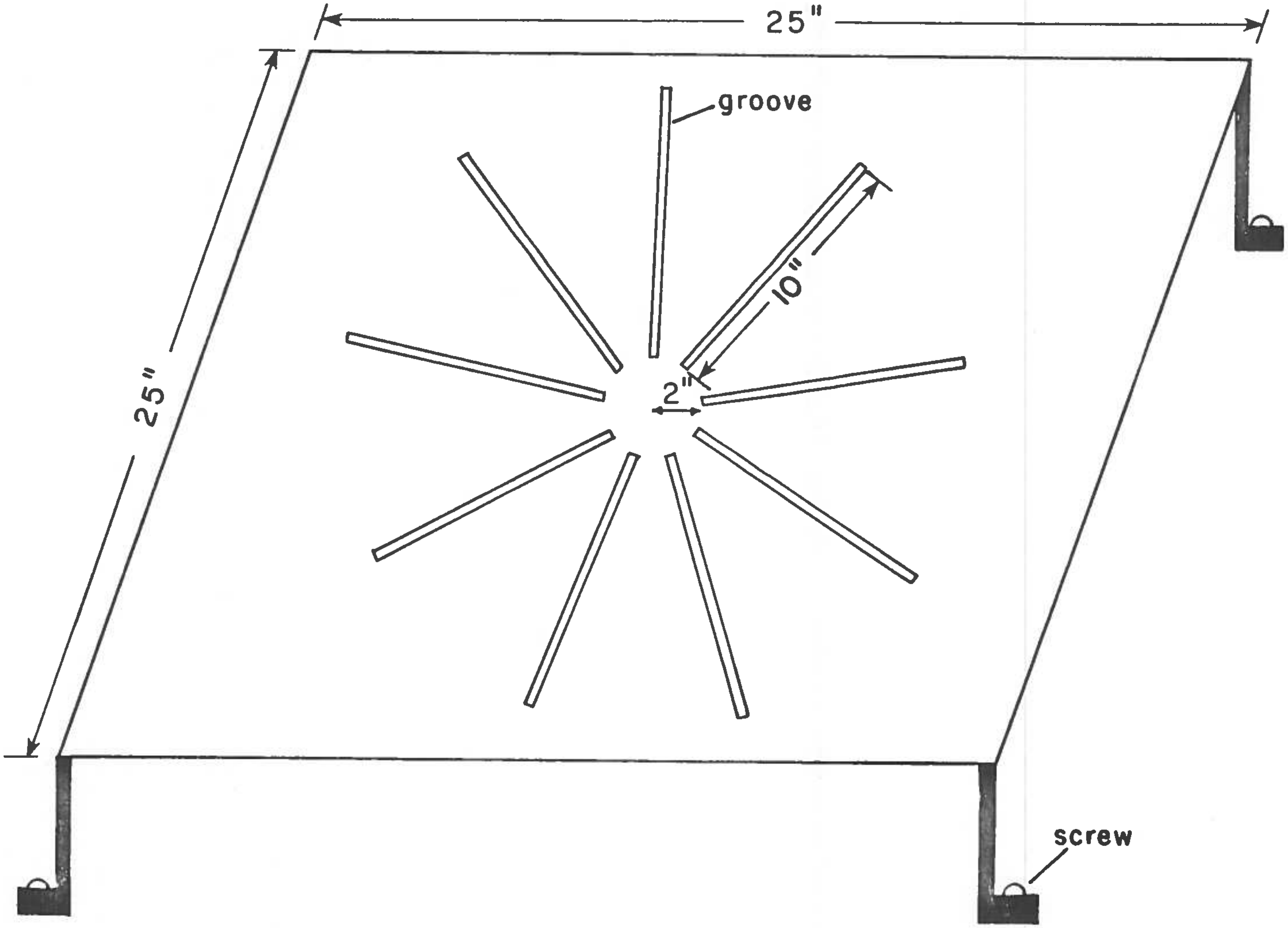


Fig. 3.6. Schematic Plan of the Cam Slots on the Stationary Cam Plate.

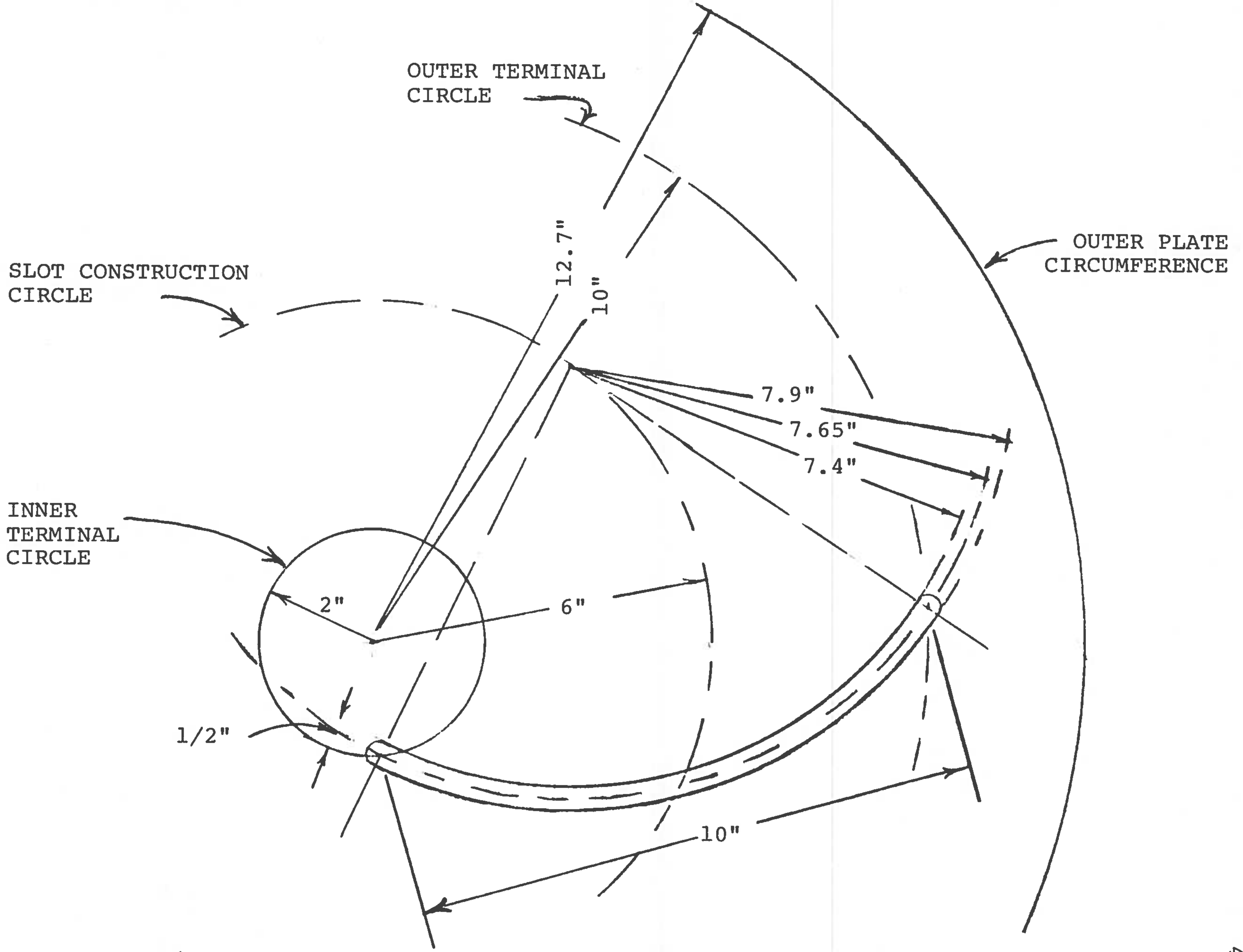


Fig. 3.7. The Detailed Dimensions of a Curved Slot.

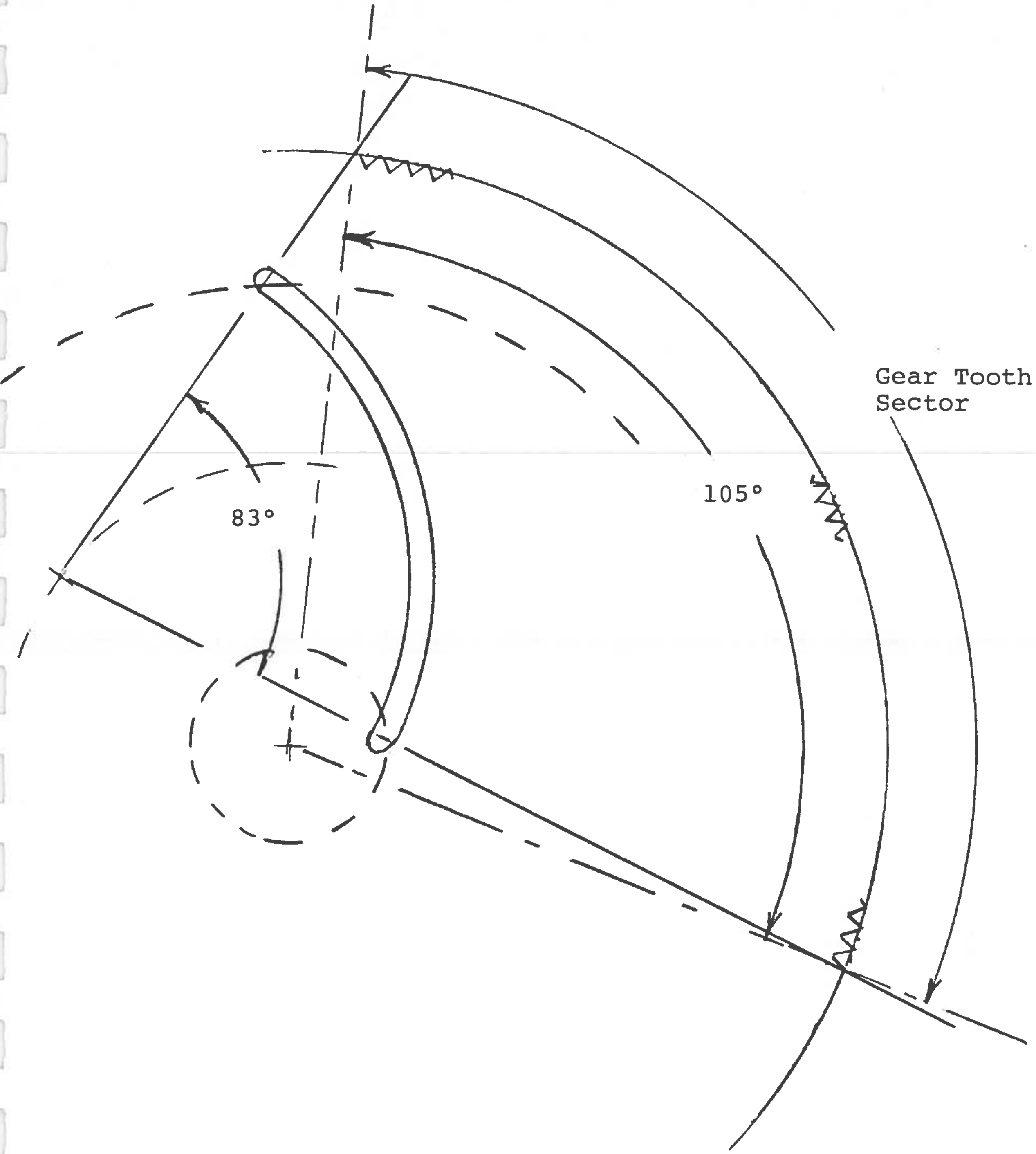


Fig. 3.8. The Gear Sector of the Moving Cam Plate.

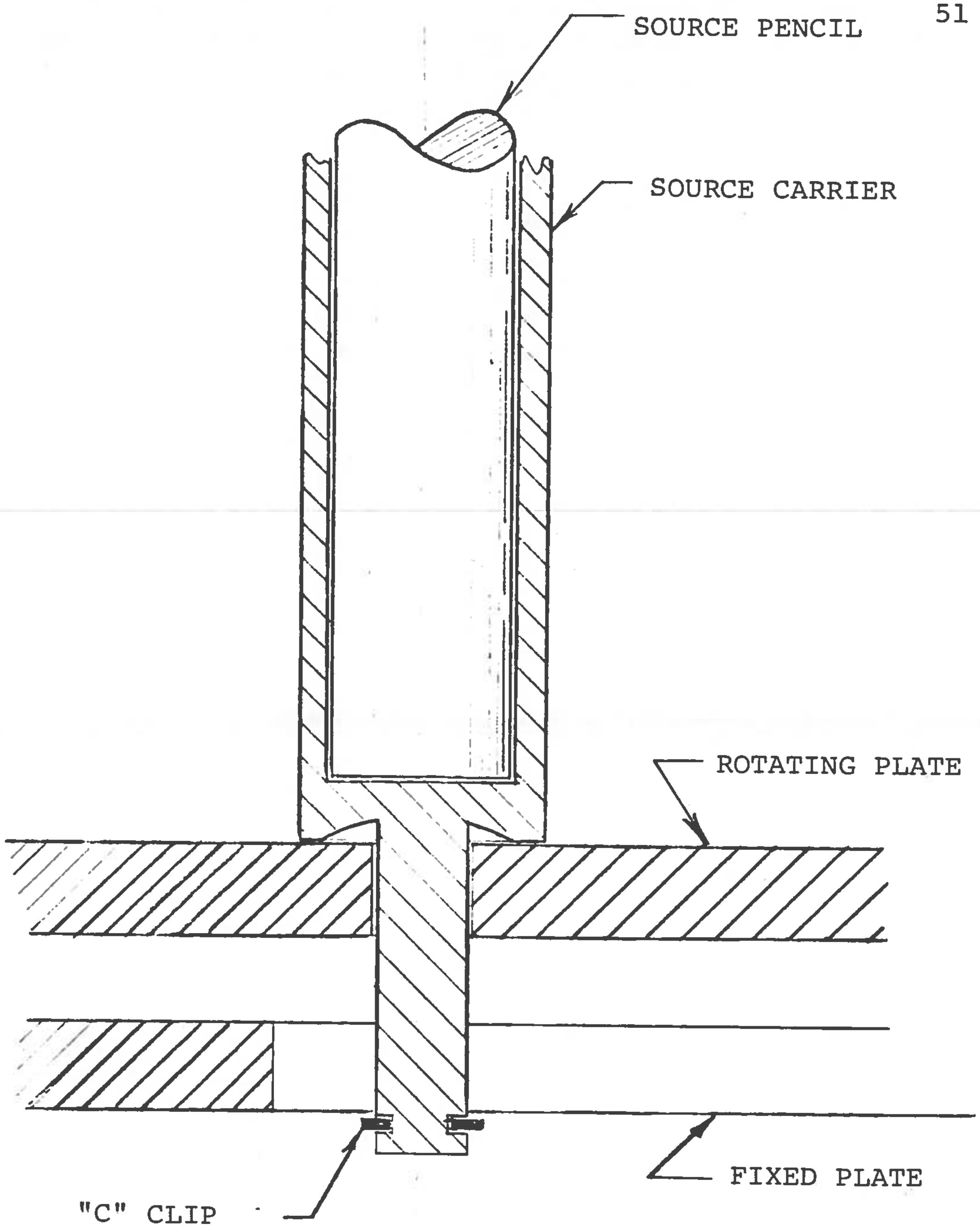


Fig. 3.9. The Source Carrier Arrangement on the Moving and Fixed Plates.

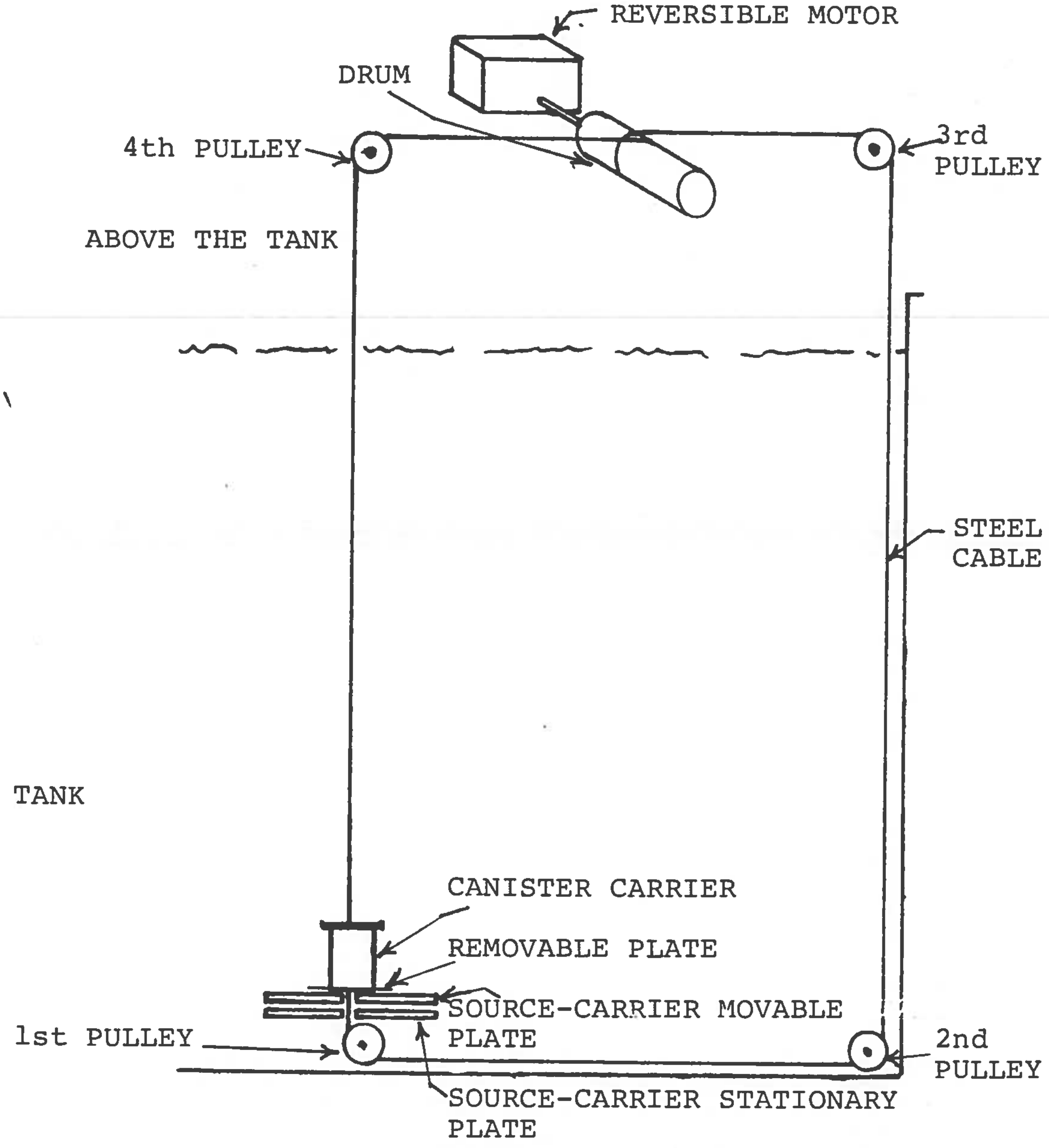


Fig. 3.10. Automatic Closed-Loop Positioning System (ACLPS).

CHAPTER 4

General Considerations for Gamma Shielding Demonstration and Experiments

Installation of the 600-Ci ^{137}Cs source in the Cesium Experimental Radiation Facility offers opportunities for uses other than irradiation of specimens. These opportunities include both demonstration of established gamma shielding techniques and experimental studies of new problems in gamma shielding. The unique configuration and location of the facility permits demonstrations and experiments not previously possible at the Nuclear Science Center. Specifically, the almost unlimited open working space above the tank with little likelihood for accidental personnel exposure, and the experimental bay at the unshielded end of the tank are the keys to these opportunities.

"Gun-Barrel" Source

A configuration of particular interest is a "gun-barrel" system consisting of an empty tube extending from the immediate vicinity of the source array out to the front, unshielded face of the tank, as shown in Figure 4.1. The first two feet of the tube nearest the source array would be heavily shielded with lead to inhibit scattered radiation from the surrounding water from

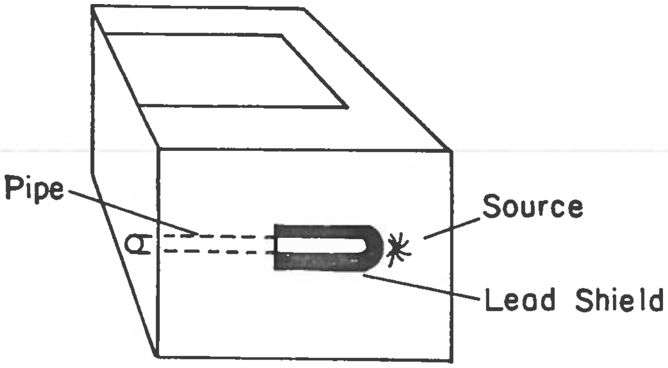


Fig. 4.1. "Gun-barrel" Source Configuration.

contaminating the primary monoenergetic radiation; a heavy lead plate behind the source array may also reduce scattered-radiation contamination.

In this concept, the tube would be lowered into position while filled with water, and carefully aligned between the source array and tank face. The source array would be made as compact as possible to attain maximum intensity at the exit end of the tube. Once the tube has been positioned, aligned, and secured, and the experimental bay prepared, the water in the tube could be forced out with compressed air to create the "gun barrel".

A tube 4 inches in diameter could deliver a beam which is reasonably well collimated and rich in the 0.661-MeV primary source gammas. Further collimating could be achieved by devices external to the tank in the experimental bay. Although exact prediction of the beam intensity is difficult, a dose rate approaching 25 R/hr at the tank face may be possible.

Uses for an external beam source include gamma scattering experiments, radiographic inspections, exposure of personnel dosimeters for calibration purposes, production of fairly intense low-energy anisotropic radiation fields with backscattered radiation, transmission of gamma radiation through novel materials, irradiation of specimens in low-intensity gamma fields, and validation of one-dimensional transport codes. The general arrangement for external transmission and scatter experiments is shown in Figure 4.2.

A point of concern for the external-beam projects is to assure adequate shielding around the experimental bay. Scattered radiation can be handled adequately by two thicknesses of concrete block, but the direct beam will require additional shielding. A large-area (2 ft x 2 ft) lead beam trap mounted on a dolly moving on a track in line with the beam is considered as a convenient extra shield. This could be placed flush against the tank face to allow access to the experimental bay without flooding the source tube, or rolled to the back of the experimental bay while work is in progress and assure that exposure rates outside the shield wall are low. Estimates of available dose rates from the "gun-barrel" source lead to a beam-trap thickness of 2.5 inches of lead to provide a working dose rate level of 10 mR/hr inside the experimental bay, and less than 1 mR/hr at the exterior of the shield wall.

Demonstration Experiments

The "gun-barrel" configuration described in the previous section is only one of the ways in which the CERF could be used. Another important use is the demonstration of shielding principles for configurations placed in the

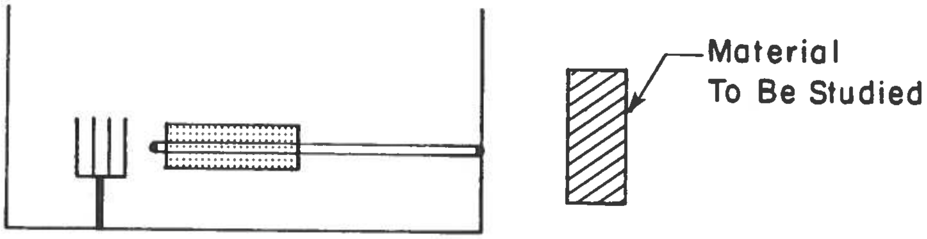


Fig. 4.2. General Arrangement for External Transmission and Scatter Experiments.

water, and for demonstration of shield effects. Some of these possible uses are:

1. Bulk shielding facility: the CERF can be used to simulate the bulk shielding facility at Oak Ridge National Laboratory. Different shielding materials can be placed in the tank and their attenuation coefficients can be studied by measuring the flux behind the shielding material (Fig. 4.3).
2. Buildup factor determination: For a thin shield and narrow beam (Fig. 4.4), the buildup factor is unity, B=1, because scattering events deflect the gamma rays out of the beam and thus away from the detector. For the geometry of Fig. (4.5), as the thickness of the shield is increased so that multiple scatters become more prevalent or as the width of the beam is increased so that single scatters may reach the detector, the buildup factor increases to values greater than unity.
3. Estimation of void perturbation: An irregularity that increases the radiation penetration through a shield but does not extend to either surface is called a void. An air bubble in a water shield or concrete pour is a void. Estimation of void effects on the flux is extremely important in restoring a shield integrity. To estimate the

void effect, we need to measure the increase in flux density at the shield surface. This can be done by determining the flux intensities with and without the void (Fig. 4.6).

4. Duct streaming study: Duct streaming study is extremely important because in almost every facility where radioactive materials are involved there are ducts that extend from the inside of the facility to the outside. For example, in a nuclear reactor, controls and instruments must have mechanical or electrical conduits leading outside. The shield designer is faced with the problem of maintaining the integrity of the shield while providing workable means for the necessary communicating pathways to the outside world. Design and analysis of a straight duct is relatively uncomplicated. The line-of-sight component, i.e., the direct beam is obviously the most important. A more complicated situation is faced when treating ducts with one or more bends where the scattered component predominates (Fig. 4.7).
5. Spectrum purity: The CERF can be used to show the effect of different materials placed near the source on the gamma spectrum. The procedure is as follows:

a. A sodium iodide detector connected with a multichannel analyzer can be used to obtain the γ-spectrum when air is in front of and in the back of the source. Fig. 4.8(a), shows this arrangement, and Fig. 4.9 shows the spectrum.

b. Water is placed behind the source, Fig. 4.8(b), and again the γ-spectrum is obtained. Fig. 4.10 shows this spectrum. A comparison between spectrum 4.9 and 4.10 shows that the area under the curve from Compton scattering has been increased. This shows that water is a better scattering material than air.

c. A lead brick is placed behind the source, Fig. 4.8(c), the γ-spectrum is again obtained for this arrangement. Fig. 4.11 shows this spectrum. A comparison between spectrum 4.10 and spectrum 4.11 shows that the Compton scattering area has been reduced. This indicates that lead is not as good a γ-backscatter as water.

d. Finally, the source is moved back allowing water to be in front of and behind the source, Fig. 4.8(d). The γ-spectrum is again obtained. Fig. 4.12 shows this γ-spectrum. As can be seen in the spectrum the Compton scattering area as well as the peak due to the direct beam are both reduced by a great amount.

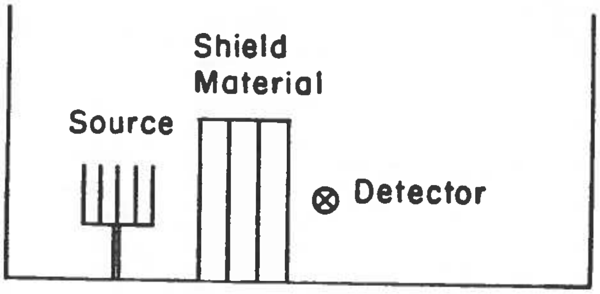


Fig. 4.3. General Arrangement for the Source, Detector and Shield Material to be Studied.

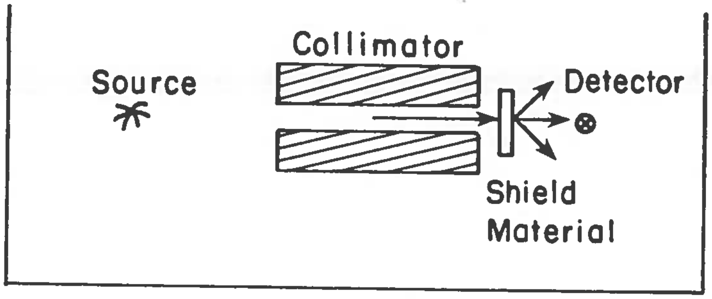


Fig. 4.4. Narrow-beam Geometry.

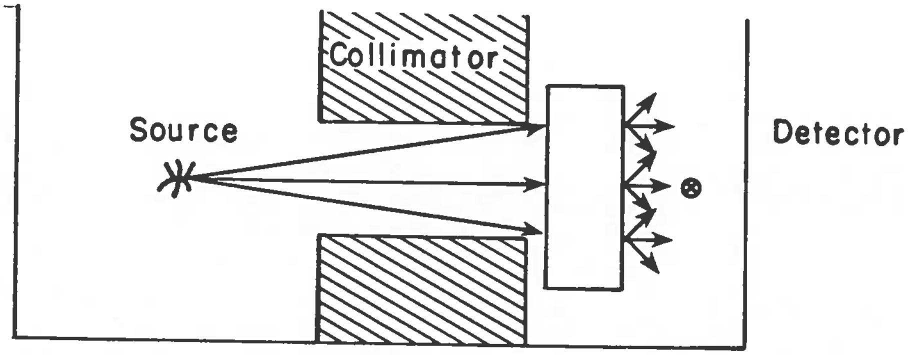


Fig. 4.5. Wide-beam Geometry.

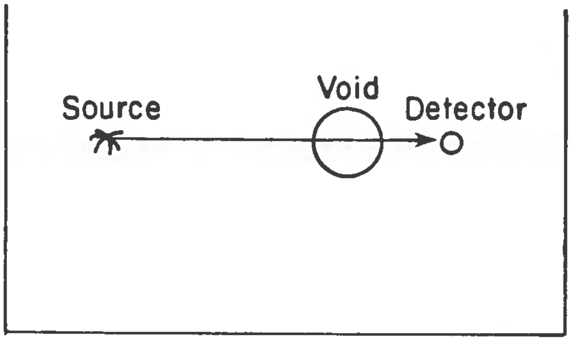


Fig. 4.6. Geometry for the Estimation of Void Perturbation.

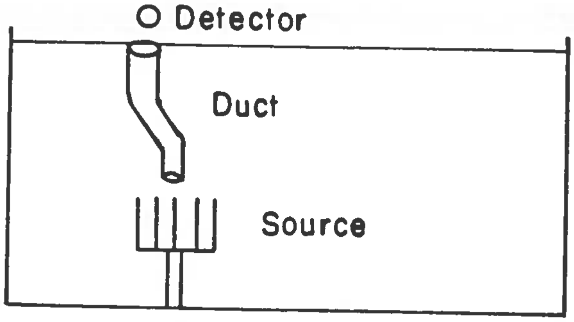


Fig. 4.7. Geometry for the Duct Streaming Study.

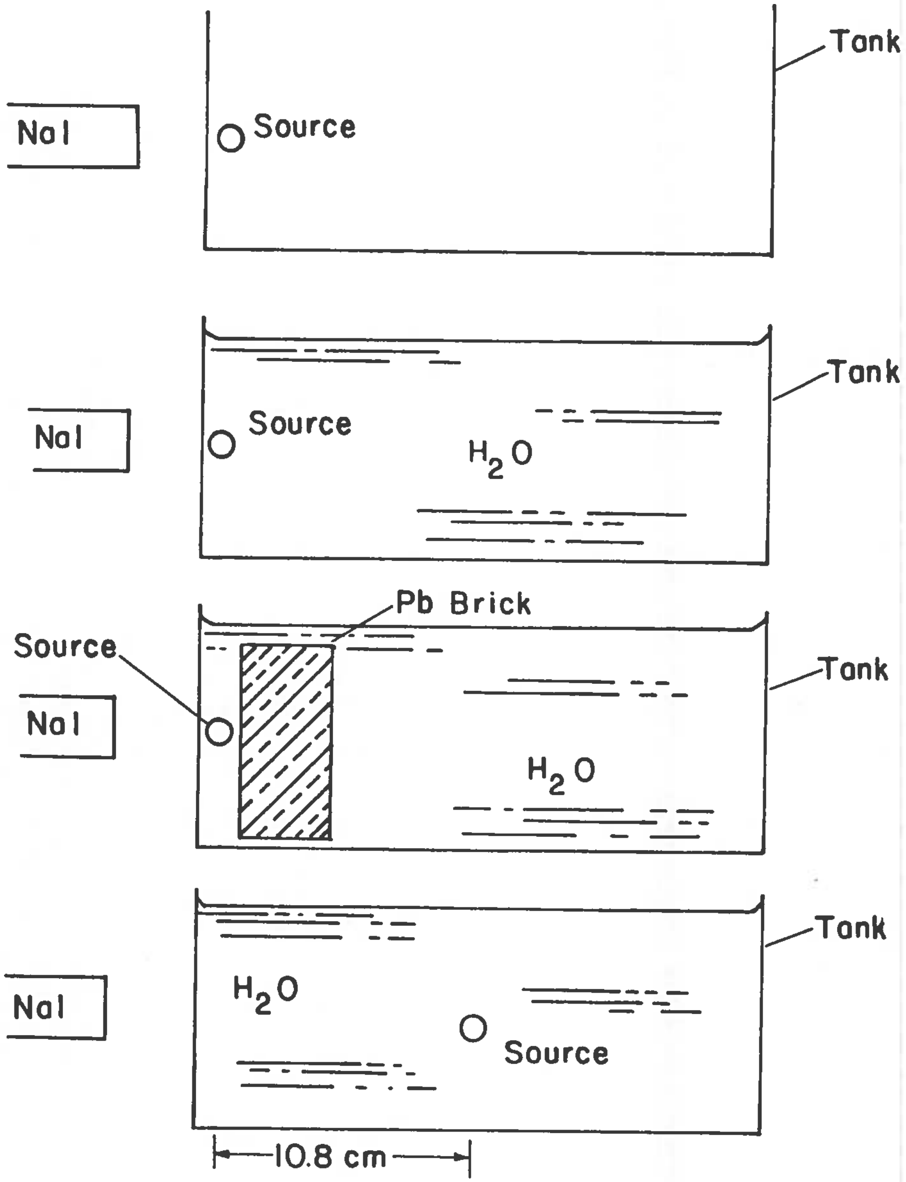


Fig. 4.8

(a) Air is in the front and behind the source

(b) Air is in the front and water is behind the source

(c) Air is in the front and lead is behind

(d) Water is in the front and behind the source

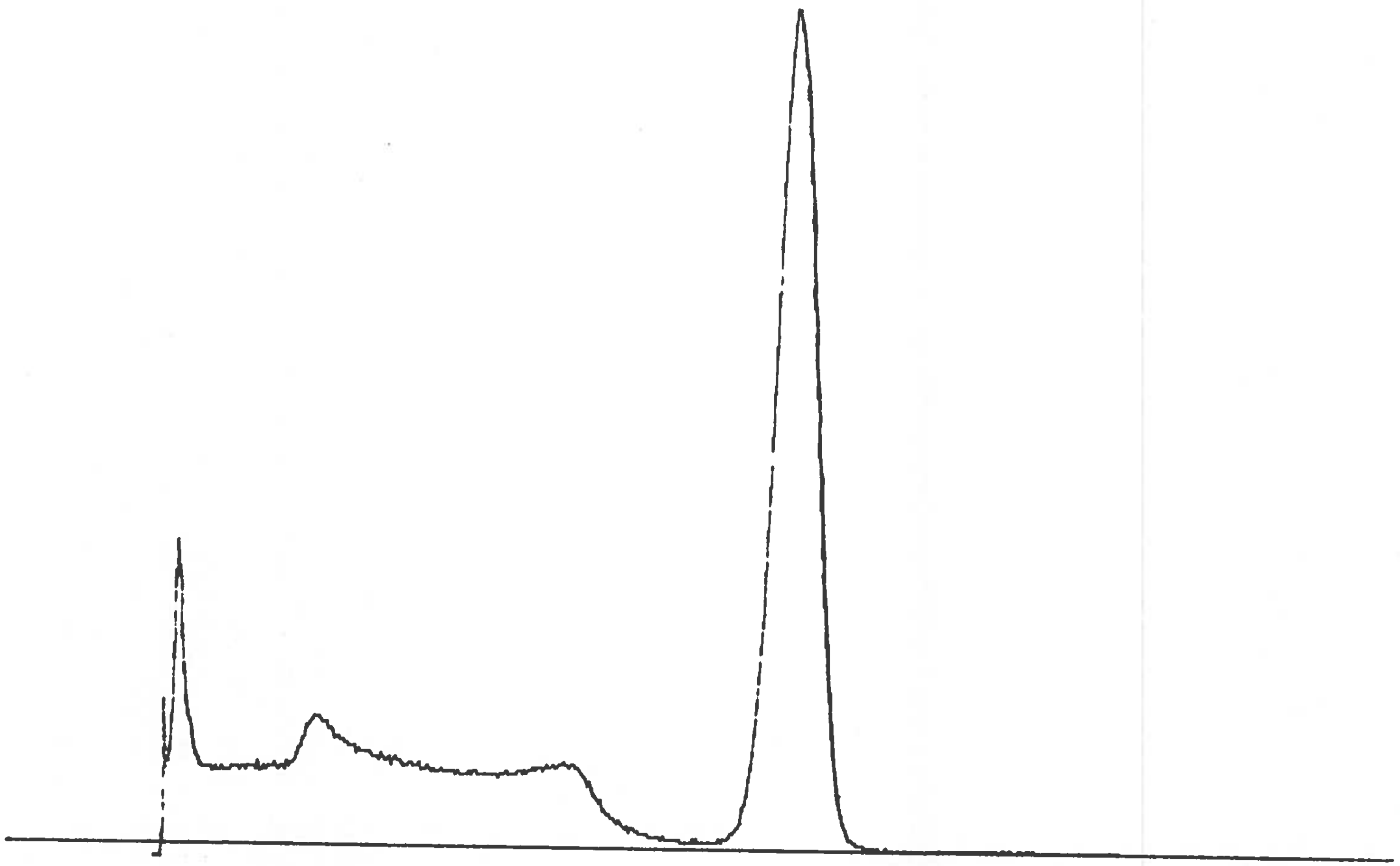


Fig. 4.9. Gamma spectrum of Cs-137 for the source arrangement in Fig. 4.8(a).

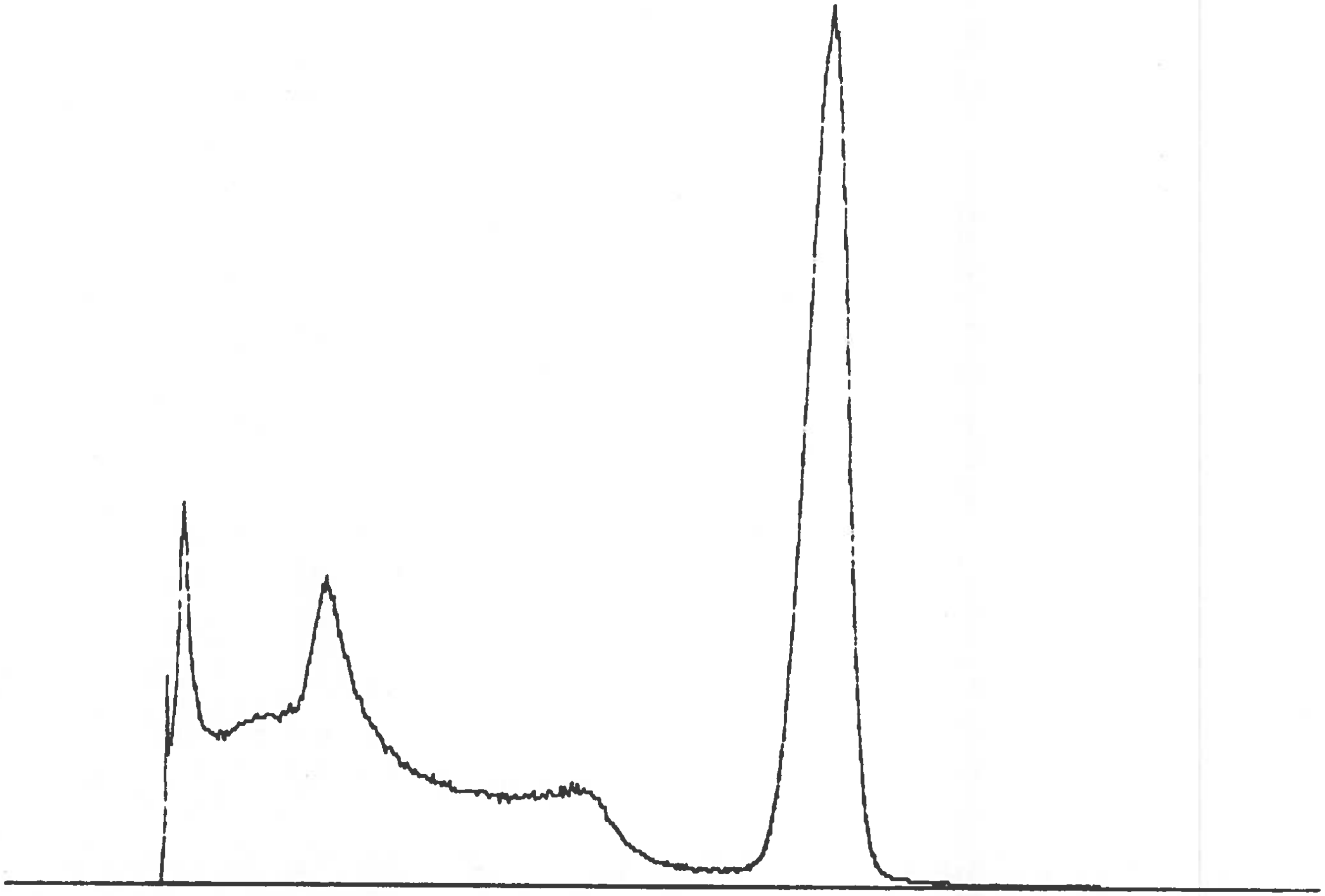


Fig. 4.10. Gamma spectrum of Cs-137 for the source arrangement in Fig. 4.8(b).

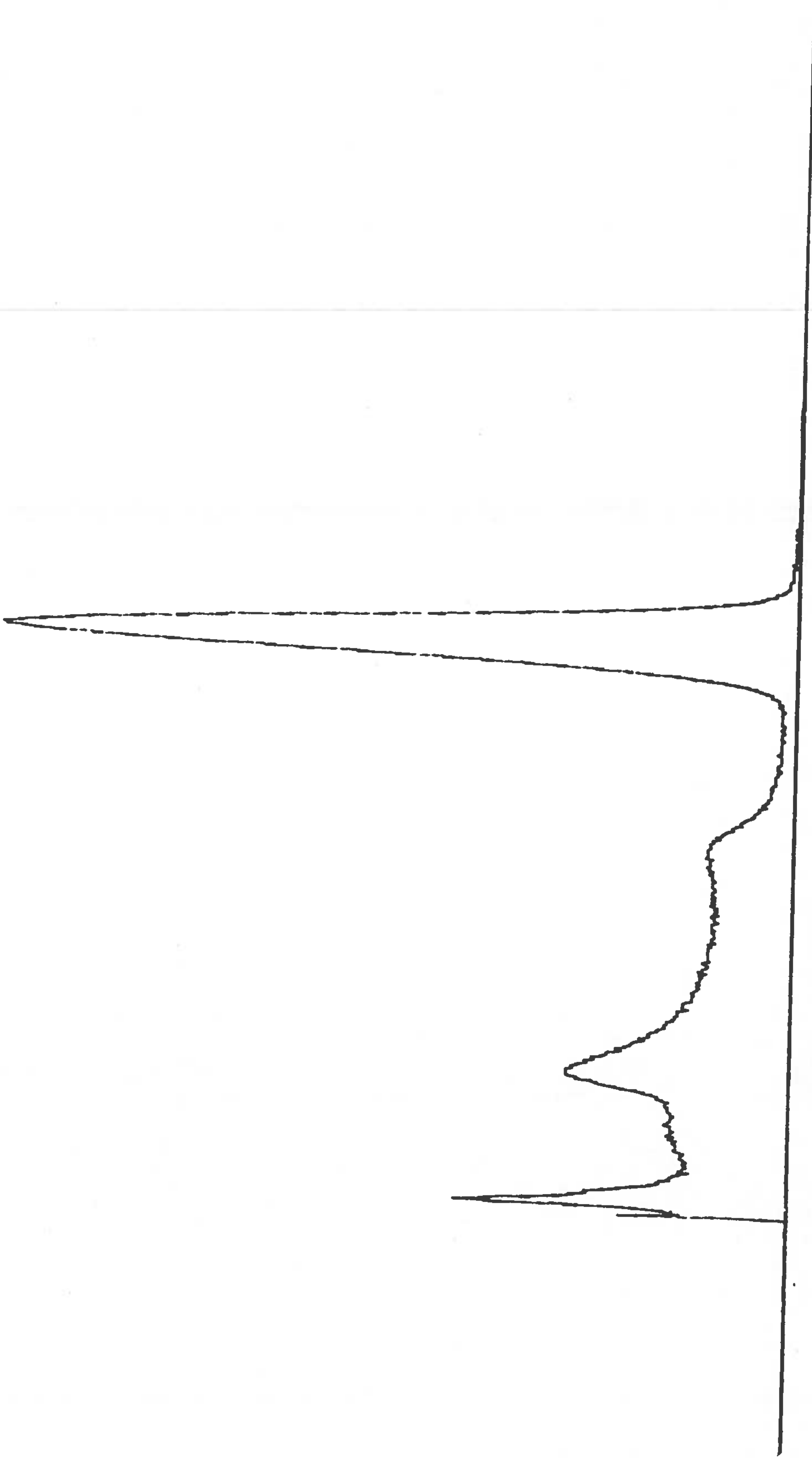


Fig. 4.11. Gamma spectrum of Cs-137 for the source arrangement in Fig. 4.8(c).

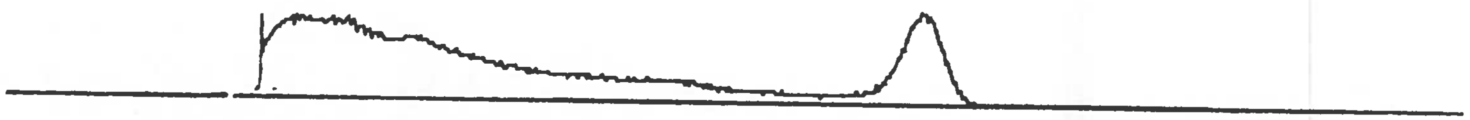


Fig. 4.12. Gamma spectrum of Cs-137 for the source arrangement in Fig. 4.8(d).

CHAPTER 5

Radiation Safety Considerations

Because the ^{137}Cs is currently in the pool in the basement of the Nuclear Science Center and the Cesium Experimental Radiation Facility is on the main floor, a safe transfer procedure must be established. Additional radiation safety procedures must be developed for routine and experimental uses of the CERF. These two problems are discussed separately in this chapter.

Cesium Transfer

There are two aspects of the transfer which must be addressed, namely, a transport cask and the transfer protocol. As in the usual practice for pool-type sources, the general transfer procedure will be to lower the empty transfer cask into the basement pool with the top open, place a source pencil into the cask, fit the top into position, retrieve the cask from the pool, and place it on a transfer dolly. The dolly and cask will be rolled out to the stairwell, lifted to the main-floor level with the outside hoist, and lowered onto an extension ramp built even with the top step of the outside landing. After the dolly and cask have been rolled into the experimental bay at the end of the CERF tank, the cask will be lifted with the CERF hoist and lowered into the tank. The cask top will then be removed, and the source pencil will be transferred into a source carrier or storage rack. Finally, the cask will be retrieved from the tank and placed back on the dolly to be returned to the basement for another cycle.

Mock trials of the transfer protocol have led to time estimates of 2 minutes to manipulate a loaded cask in the basement, and 3.5 minutes to manipulate the cask on the main floor, for a total of 5.5 minutes of personnel exposure close to the loaded cask. The total exposure time for the nine source pencils is therefore estimated to be approximately 50 minutes. If one person did all transfers, the dose would not exceed 100 mrem, roughly one week's dose commitment. Assuming that the average distance the individual would be from the cask during the procedure is approximately 2 feet, a cask-design criterion of 120 mrem/hr at two feet from the surface will be allowable. Personnel positions above and below the cask during hoisting can be controlled, so a design dose rate of 500 mrem/hr at one foot from the top and bottom can be assumed safely for the cask. These estimates provide the necessary data for calculation of shield dimensions to allow transfer of a 1-foot-long source rod 1 inch in diameter.

Cask Dimensions

The following formula is used to calculate the gamma flux at distance a from a line source at any point on the line perpendicular to the source and passing through the center of the source: where B is the dose buildup factor, Q is the source strength expressed in the number of gammas emitted by one cm per sec, a is the distance from the source to the point of interest in cm, and F(θ,b) is Sievert's Integral as a function of the angle (θ) and the relaxation length (b). Taylor's formula$^{(1)}$ has been used to calculate the buildup factor:

$$B = Ae^{-\alpha_1 b} + (1-A)e^{-\alpha_2 b}$$

where A, α_1, and α_2 are called Taylor buildup factor coefficients. Their values can be obtained from tables. The value of Sievert's function can be obtained from graphs, and the value of θ can be obtained from the source geometry and length. Since lead is an excellent gamma shield, it has been chosen for the cask.

The following data were obtained from the Radiological Health Handbook$^{(3)}$ and a A Handbook of Radiation Shielding Data:$^{(1)}$ Taylor buildup factor coefficients for lead at 0.662 MeV are $A = 1.847$, $\alpha_1 = -0.0339$, $\alpha_2 = 0.243$

Mass attenuation coefficient (μ_m) = 0.116 cm^2/g

Once the value of θ_3 has been set at 5°, θ_2 can be calculated to be 10°. The buildup (B) requires the number of mean free paths (b) to be known, hence the shield thickness must be set in advance. By guessing at shield thicknesses and performing the required calculations, a wall thickness of 6 cm and end thickness of 4 cm were selected. These lead to the following external dose rates:

a. Thickness of the wall = 6 cm. The number mean free paths (b) = $\mu_\ell t = 1.23\ (\text{cm}^{-1}) \times 6\ (\text{cm}) =$ 7.38 cm. The buildup factor has been calculated using Taylor's formula

$$B = A\ e^{-\alpha_1 b} + (1-A)e^{-\alpha_2 b} \quad \text{at 0.66 MeV for lead}$$

$$B = 1.847e^{-(-0.0339)7.38} + (1-1.847)e^{-0.243*7.38}$$

$$A = 1.847,\ \alpha_1 = -0.0339,\ \alpha_2 = 0.243$$

$$B = 2.23$$

The value of $F(15°, 7.38) = 1.5 \times 10^{-4}$ (from the graph)

Now, at 2 ft on the side of the container:

$$\phi\left(\frac{\gamma}{\text{cm}^2\text{-s}}\right) = \frac{B\ Q_\ell(\gamma/\text{cm-s})}{4\pi\ a}\ [2F(\theta,b)]$$

$$= \frac{2.23 \times 8.117 \times 10^{10}}{4\pi\ (60.94)} = 7.202 \times 10^4\ \frac{\gamma}{\text{cm}^2\text{-s}}$$

Using Table 7.3 in A Handbook of Radiation Shielding Data,(1) the following conversion factor was found for 0.66 MeV photon: conversion factor = 1.442×10^{-3} mrem/hr per photon/cm^2-sec. Multiplying the flux by the conversion factor gives the dose rate

$$\text{D.R.} = 7.202 \times 10^{-4} \times 1.442 \times 10^{-3} = 108 \text{ mrem/hr}$$

b. Thickness of the bottom and the top of the container = 4 cm.

Mean free path (b)

$b = \mu_\ell t = 1.23\ (\text{cm}^{-1}) \times 4 \text{ cm} = 4.92$

Buildup factor (B)

$$B = 1.847e^{-(-0.0339)*4.92} + (1-1.847)e^{-0.243*4.92}$$

$B = 1.92$

Sievert's functions values at θ_2 and θ_3

$F(\theta_2,b) = F(10°,4.92) = 1.4 \times 10^{-3}$

$F(\theta_3,b) = F(5°, 4.92) = 6.0 \times 10^{-4}$

Flux at a = 30.48 cm = 1 ft

$$\phi\left(\frac{\gamma}{\text{cm}^2\text{-s}}\right) = \frac{B\ Q(\gamma/\text{cm-1})}{4\pi a}\ [F(\theta_2,b) - F(\theta_3,b)]$$

$$\phi\left(\frac{\gamma}{\text{cm}^2\text{-s}}\right) = \frac{(1.92)(8.117\text{x}10^{10}\ \gamma/\text{cm-s})}{4\pi a\ (30.48 \text{ cm})}\ [1.4 \times 10^{-3} - 6.0 \times 10^{-4}] = 3.255 \times 10^{5}\ \gamma/\text{cm}^2\text{-s}$$

Dose-rate = conversion factor x flux (1)

$$\text{D.R.} = 1.442 \times 10^{-3} \left(\frac{\text{mrem/hr}}{\gamma/\text{cm}^2\text{-s}}\right) \times 3.255 \times 10^{5} (\gamma/\text{cm}^2\text{-s})$$

$$\text{D.R.} = 469.3 \text{ mrem/hr}$$

Once the wall and end thicknesses have been established, the shield dimensions and weight can be determined. A general cross section of the transfer cask with 6-cm thick walls, a 4-cm thick bottom, and a 3-cm thick top is shown in Figure 5.2. The outer diameter is 15 cm to allow for a 3-cm diameter cavity to receive a source pencil, and the shield height is approximately 34.5 cm. In order to prevent radiation streaming, the top will mate into a 2-cm deep recess in the shield, and a 2-cm deep cavity will be machined into the top to accomodate the end of the source pencil. The total cask weight, including the top can be calculated as follows:

Volume of the shallow hole = ν_1

$$\nu_1 = \pi(3)^2 \times 2 = 56.54 \text{ cm}^3$$

Volume of the deep hole = ν_2

$$\nu_2 = \pi(1.5)^2 \times 28.48 = 201.31 \text{ cm}^3$$

Volume of the whole cylinder = ν_3

$$\nu_3 = \pi(7.5)^2 \times 34.48 = 6093.11 \text{ cm}^3$$

Volume of lead material after holes have been made = V.

$$V = \nu_1 - \nu_1 - \nu_2$$

$$= 6093.11 - 201.31 - 56.54$$

$$= 5835.26 \text{ cm}^3$$

Net weight of lead in the cylinder = $V\rho = \omega_1$

$$\omega_1 = 5835.26 \text{ cm}^3 \times 11.35 \text{ g/cm}^3$$

$$= 66230.2 \quad \text{g} = 66.23 \quad \text{Kg} = 146.0 \text{ lb}$$

The weight of the top can be calculated in the following manner:

Volume of the part above the surface = ν_4

$$\nu_4 = \pi(5)^2\ 3 = 235.6 \text{ cm}^3$$

Volume of the part that fills the cavity of the shallow hole = ν_5

$$\nu_5 = \pi(3)^2 \times 2 = 56.54 \text{ cm}^3$$

Volume of the hole in the top = V_c

$$V_c = \nu_4 + \nu_5 - \nu_6$$

$$V_c = 235.6 + 56.54 - 14.13$$

$$V_c = 278.01 \text{ cm}^3$$

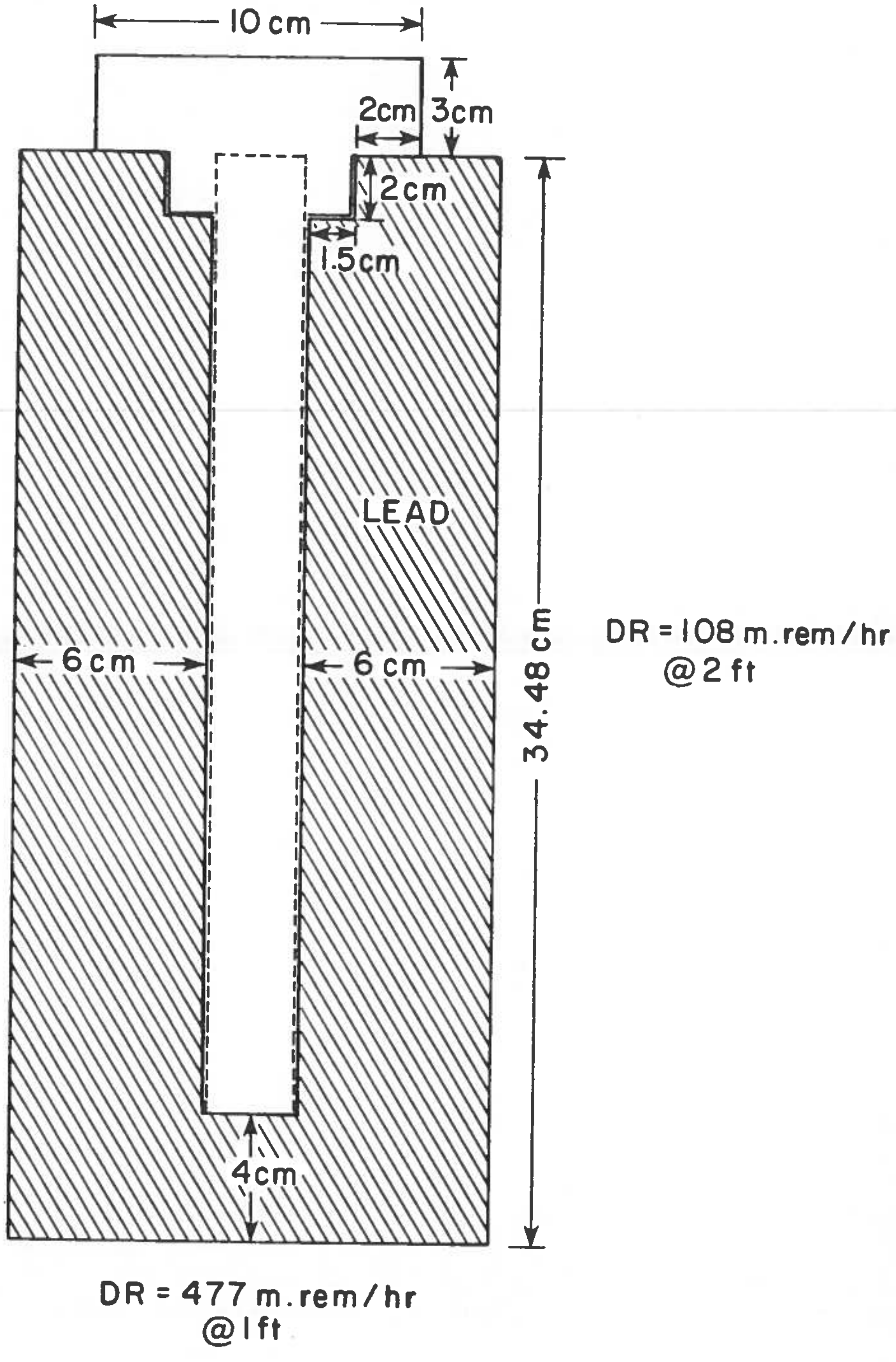


Fig. 5.2. General Cross-section of the Transfer Cask.

Weight of the top = $\omega_2 = V_c \rho$

$$\omega_2 = 278.01\ \text{cm}^3 \times 11.35\ \text{g/cm}^3$$

$$\omega_2 = 3121.3\ \text{g}$$

$$\omega_2 = 3.12\ \text{Kg}$$

$$\omega_2 = 6.88\ \text{lb}$$

The total weight of the transfer cask then is $\omega_1 + \omega_2$:

$$W = 146.0 + 6.88 = 152.88\ \text{lb}$$

Figure 5.2 must be modified to allow for a drain hole at the bottom so that water can escape when the cask is lifted out of the pool or tank. Two lifting eyes on the cask body and one on the top also are needed. Finally, provisions must be made to lock the transfer cask to its dolly for safety.

Operational Radiation Safety

General considerations for operational radiation safety include restricting access to areas in the CERF where dose rates may be higher than 2.5 mrem/hr, proper training of authorized users, and formal pre-operational approval of all new projects.

A locked door at the top of the steps leading to the working area around the tank at the top of the facility, and a wall in place of the railing above the subcritical assembly area will limit access to the main work area. A door also must be provided to limit access to the experimental bay at the front face of the tank, particularly when projects involving the external-beam tube are underway. Both doors must lock, and key access must be limited to authorized users. Emergency escape must be available, however.

Area monitors which can provide visual indications of dose rates in the work area at the top of the facility and in the experimental bay through the doors will be required. The monitors will need to have alarms also to signal unexpected radiation fields.

Persons who will use the CERF must be familiar with general operating procedures and emergency response actions. Each project should be reviewed carefully to prevent accidental exposures from occurring.

CHAPTER 6

Summary and Conclusions

Gamma irradiators have found considerable use in the past for a variety of research applications, and currently find use in several important industrial areas. Renewed interest in radiation food processing, and continued interest in finding new uses of gamma radiation justify the development of new, low-cost irradiation facilities. The availability of both an unused well-shielded facility and a modest Cesium-137 source in the Nuclear Science Center at Louisiana State University affords the opportunity to establish such an irradiation facility. At the same time, a potential problem with having both Cesium-137 and Cobalt-60 in the same pool-irradiation facility in the basement of the Center can be solved. The new facility also would provide the basic needs for both gamma shielding research and laboratory demonstrations of shielding principles.

As an initial consideration, the former Californium Demonstration Facility was evaluated to determine if additional shielding would be required for it to house the 600 Ci of Cesium-137 available. The anticipated placement of the nine one-foot long source pencils is as a vertical right-annular array located 6 inches above the bottom of the 8-foot long by 4-foot wide by 6.5-foot deep tank which is the central unit of the facility; the central axis of the array would be 6 feet from the unshielded end of the tank, and two feet from each side wall. In this position, the source array would be shielded from the two sides and rear end of the tank with 2 feet of water and three feet of light-aggregate concrete, from the open end of the tank by 6 feet of water, and from above by an average of 5.5 feet of water.

Shielding calculations using CASK, a general-purpose shielding code, and point- and line-source approximations yield maximum dose rate of 2 mR/hr at the sides and shielded end of the tank, 2.5 mR/hr at the open end of the tank, and 8.5 mR/hr at the surface of the water in the tank. Refined shielding estimates using a segmented line-source approximation for the dose rate at the surface of the water above the source array indicate that the dose rate may be much lower than the worst-case point-source calculation, and that there may be no need to restrict access or access time to the work area on top of the facility.

The feasibility of loading all 600 Ci of Cesium-137 into the tank has prompted renaming this facility the Cesium Experimental Radiation Facility (CERF). An important capability for CERF will be its variable-dose-rate irradiator which will give a maximum dose rate of approximately 65,000 rads per hour for the nine source pencils on a 4-inch-diameter circle. Through a remotely actuated cam system, the source pencils can be moved to larger distances under controlled conditions to select specific dose rates; at the maximum source radius of 12 inches, the dose rate in the 4-inch-diameter irradiation canister would be reduced by a factor of 43, or to approximately 1,500 rads per hour. By adding a 3-cm-thick lead shroud around the 4-inch-diameter canister, the dose rate range is increased to cover a factor of 1,000 from maximum to minimum. The mechanism which moves the source pencils consists of a fixed plate machined with nine radial slots, a rotating plate with nine curved slots, a drive gear to rotate the second plate through approximately 105 degrees, and nine pencil carriers which ride in the two matching slots of the bottom fixed plate and top rotating plate. Because the curved slots in the top plate are arcs of a circle, machining this plate should not be difficult.

Another feature of the irradiation arrangement is the Automatic Closed-Loop Positioning System (ACLPS), which will assure that the irradiation canister will be centered exactly and reproducibly in the source array. This will be particularly important when the source pencils are at the minimum radius to prevent damage to the source array, and when the sources have been moved to a larger diameter and reproducible positioning cannot be controlled visually. ACLPS also should permit rapid source transit with automatic limit-switch controls to stop downward and upward motion.

The Cesium Experimental Radiation Facility also is planned to provide an external beam "gun-barrel" source for low-dose-rate irradiations and shielding experiments in the experimental bay area at the unshielded end of the tank. A maximum dose rate of nearly 25 rads/hr has been estimated for the external-source beam at the face of the tank. With carefully placed lead shielding, it should be possible to limit large-angle radiation scatter into the beam tube, and to make the beam spectrum rich in the primary monoenergetic 0.661-MeV radiation. The beam tube would be flooded with water for general safety, and the water would be blown out to activate the beam. A beam stop consisting of a 24-inch square lead plate 3 inches thick riding on a rail-guided dolly would provide permanent protection for personnel outside the experimental bay. Additional concrete blocks in the walls of the bay may be required for some scattering experiments.

Other experimental arrangements also have been developed for CERF. These would permit demonstration of streaming through shield-penetration ducts, scattering around shields in homogeneous media, and void perturbations in shield by introducing controlled volumes of various shapes which would be rigidly positioned and then blown free of water. Another planned arrangement emulates the well-known Bulk Shielding Facility at Oak Ridge National Laboratory where much of the earlier work was done to determine gamma shielding parameters.

Transfer of the cesium from the basement of the Nuclear Science Center up to CERF on the main floor of the building has also been examined. The transfer will be accomplished one pencil at a time in a cask that has been calculated to weigh approximately 150 pounds and have exposure rates of 108 mR/hr at 2 feet from the side and 480 mR/hr at 1 foot from the bottom and top surfaces. Under these conditions, one individual could do all the cask handling necessary to transfer all nine sources without exceeding the weekly radiation protection guide of 100 mrem.

Other radiation safety features would include restricting access to high-radiation areas by means of physical barriers, permanently located area monitors, thorough training of operators, and review of planned experiments to establish proper precautions to limit high radiation fields.

Conclusions

Conclusions and recommendations which are apparent from the work presented here to establish the Cesium Experimental Radiation Facility are:

1. The existing Californium Demonstration Facility is sufficiently well shielded that the available 600 Curies of Cesium-137 in the source pool at the Nuclear Science Center can be accomodated safely.
2. A variable dose-rate-irradiator can be established with a remotely actuated cam mechanism to provide pre-selected dose rates.
3. The maximum irradiator dose rate attainable in a 4-inch-diameter canister is approximately 65,000 rads per hour. The cam mechanism alone can reduce this by a factor of 43, or down to 1,500 rad/hr, and a 3-cm-thick lead shroud could reduce the maximum dose rate by an additional amount to achieve a factor of 1,000, or down to 65 rads/hr.
4. Gamma shielding experiments and demonstrations are possible through an external-beam source or other apparatus installed in the CERF tank.

5. Safe transfer of the Cesium-137 source pencils can be accomplished easily with a relatively light lead cask (150 pounds) mounted on a dolly. The maximum radiation exposure for any individual, even if one person manipulates the cask for all nine sources, should not exceed 100 mrem.

On the basis of the calculations and conclusions described in this work, it is recommended that serious consideration should be given to establishing the Cesium Experimental Radiation Facility. It is recommended that a prototype of the variable-dose-rate irradiator should be fabricated and tested, and that detailed calculation and design of the "gun-barrel" external-beam tube should be undertaken. Prior to actual source transfer, it is recommended that the individual cesium pencils should be examined visually and their dose rates established by means of an experimental apparatus installed in the current irradiator pool. The experimental dose rates then can provide basic data needed for final transfer-cask design and other factors for loading and activating CERF.

REFERENCES

(1) A Handbook of Radiation Shielding Data, J. C. Courtney, Editor. Published by LSU Printing Office, 1976.

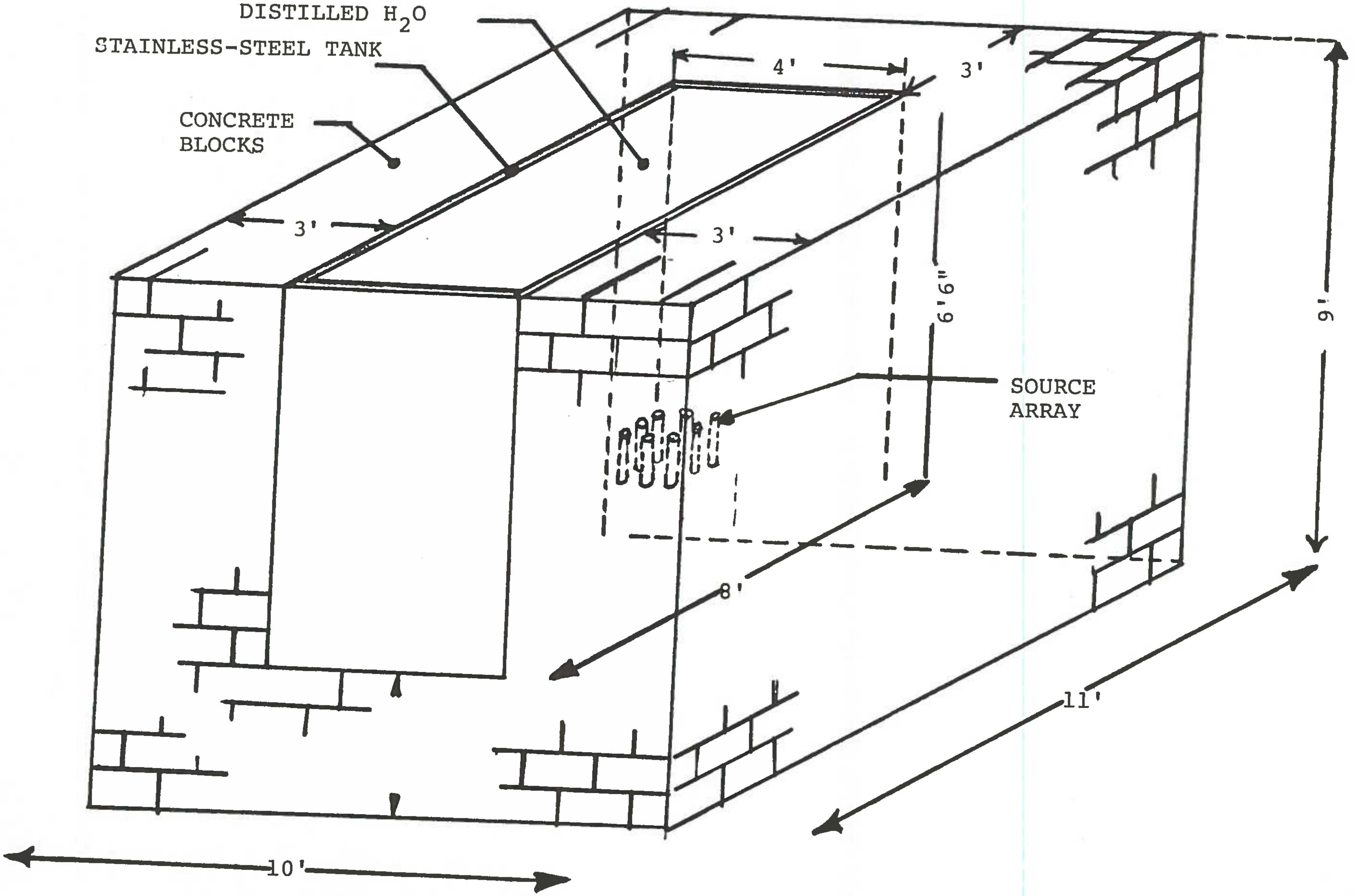
(2) Reactor Shielding for Nuclear Engineering, N. M. Shaeffer, First Edition. Published by U.S. Atomic Energy Commission Office of Information Service, 1973.

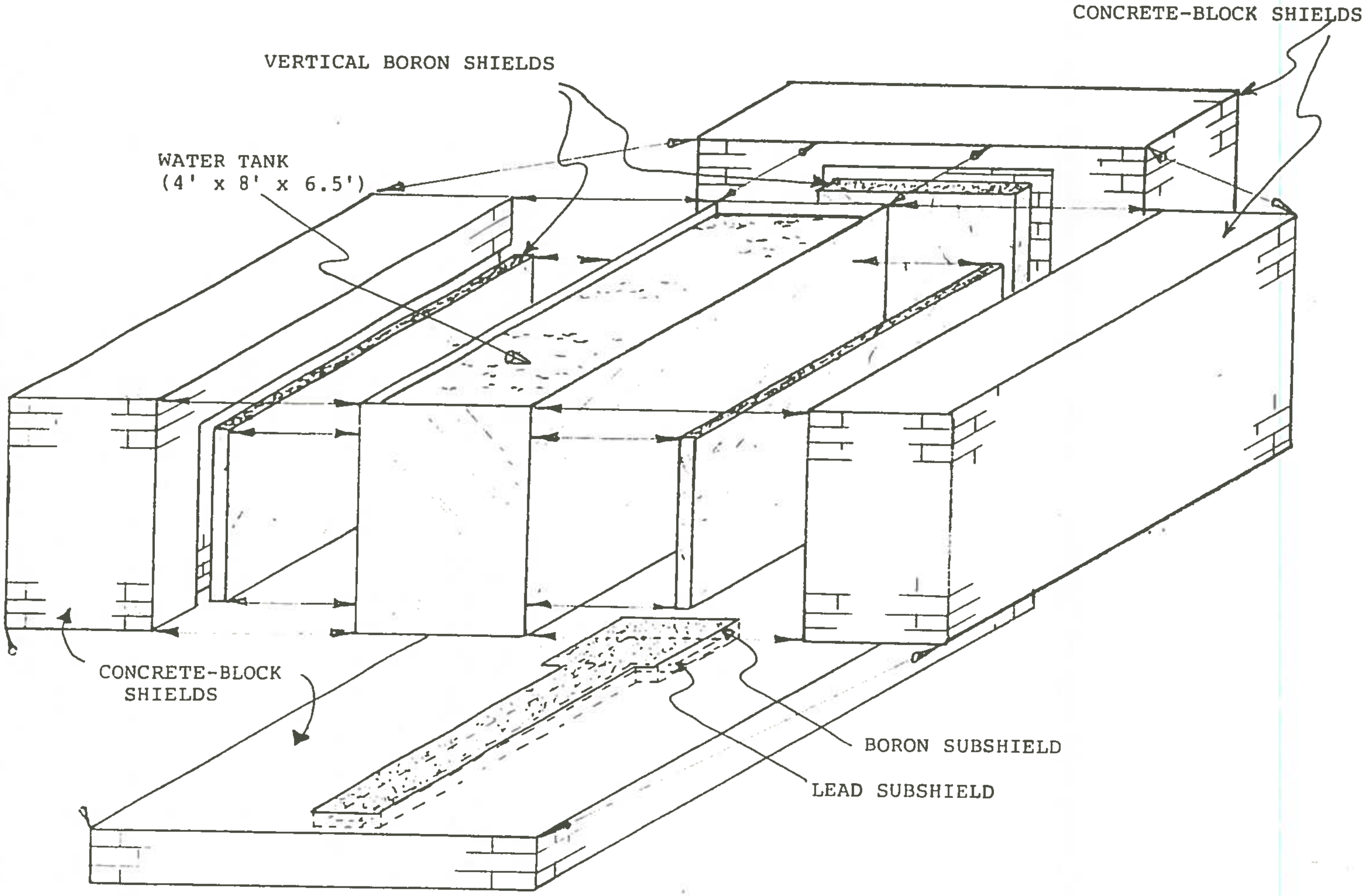
(3) Radiological Health Handbook, Public Health Service. Revised Edition, January 1970.

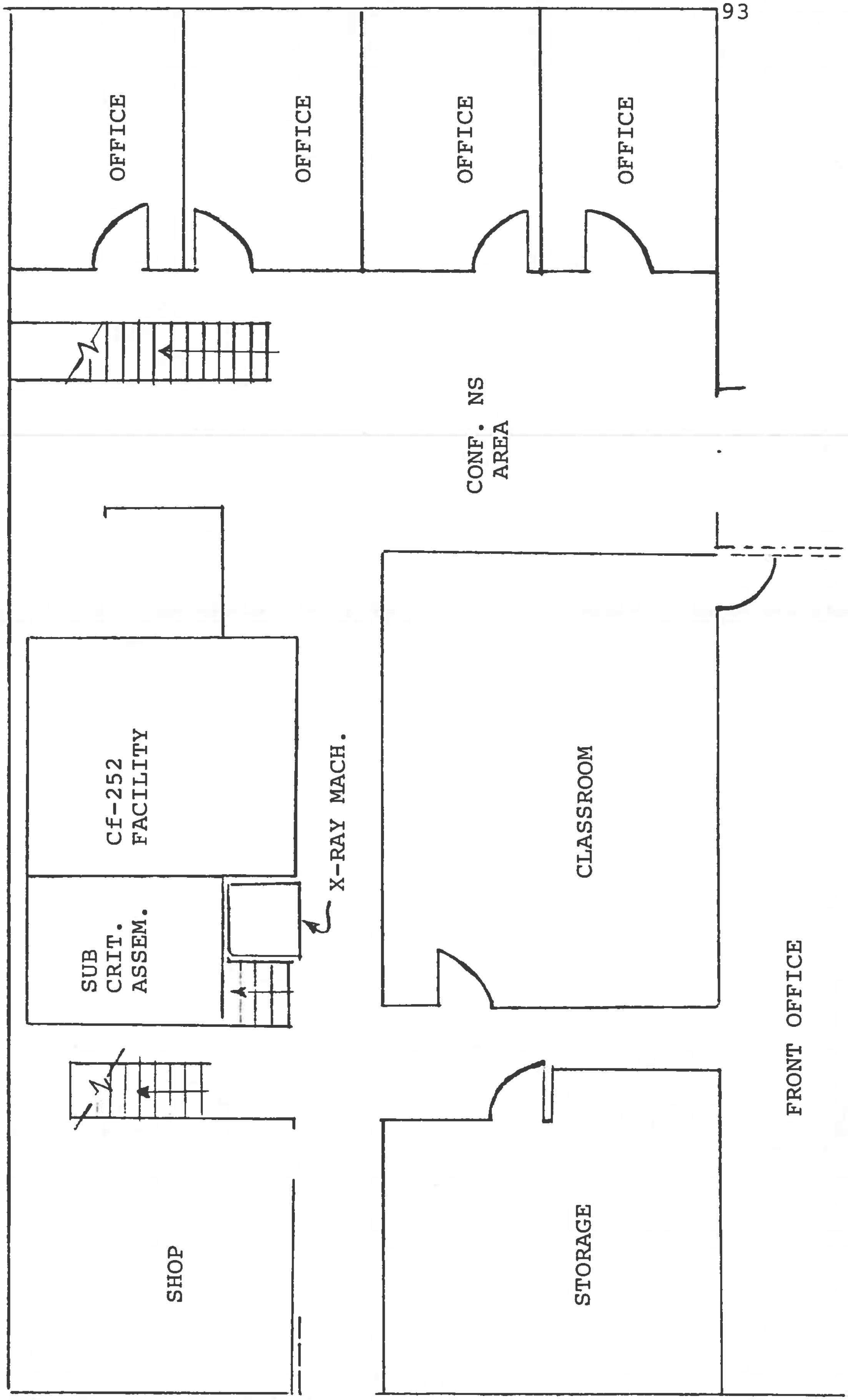
(4) Computational Methods in Reactor Shielding, James Wood, First Edition. Published by Pergamon Press, 1982.

Appendix 1

Detailed Drawings of the Shield Arrangement for the Californium Demonstration Facility and Physical Layout.


DISTILLED H_2O
STAINLESS-STEEL TANK
CONCRETE BLOCKS
4'
3'
3'
3'
6'6"
9'
SOURCE ARRAY
8'
11'
10'


CONCRETE-BLOCK SHIELDS
VERTICAL BORON SHIELDS
WATER TANK
(4' x 8' x 6.5')
CONCRETE-BLOCK SHIELDS
BORON SUBSHIELD
LEAD SUBSHIELD


OFFICE
OFFICE
OFFICE
OFFICE
CONF. NS AREA
Cf-252 FACILITY
X-RAY MACH.
SUB CRIT. ASSEM.
CLASSROOM
FRONT OFFICE
SHOP
STORAGE

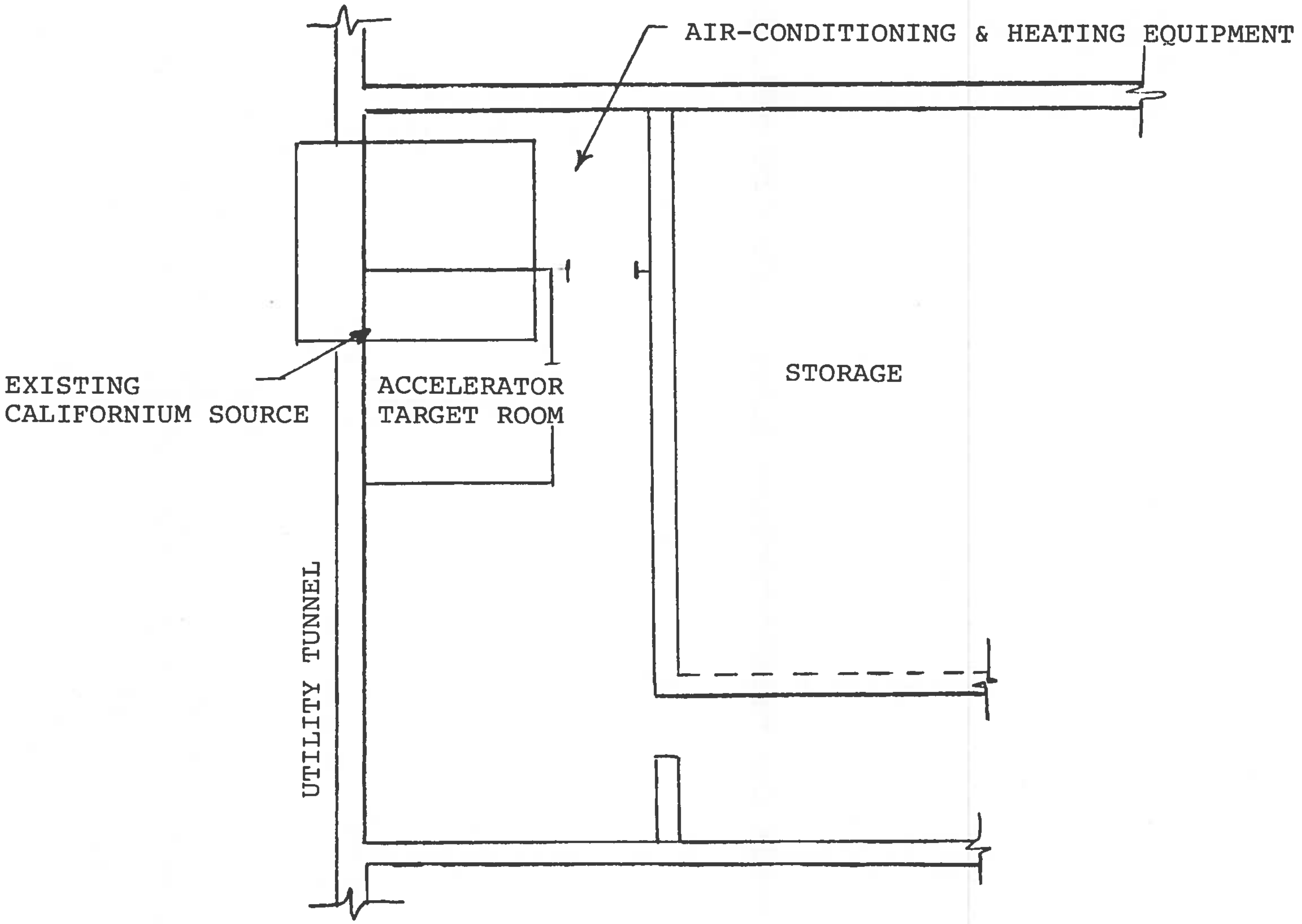


Fig. 4. Basement Area of the Nuclear Science Center

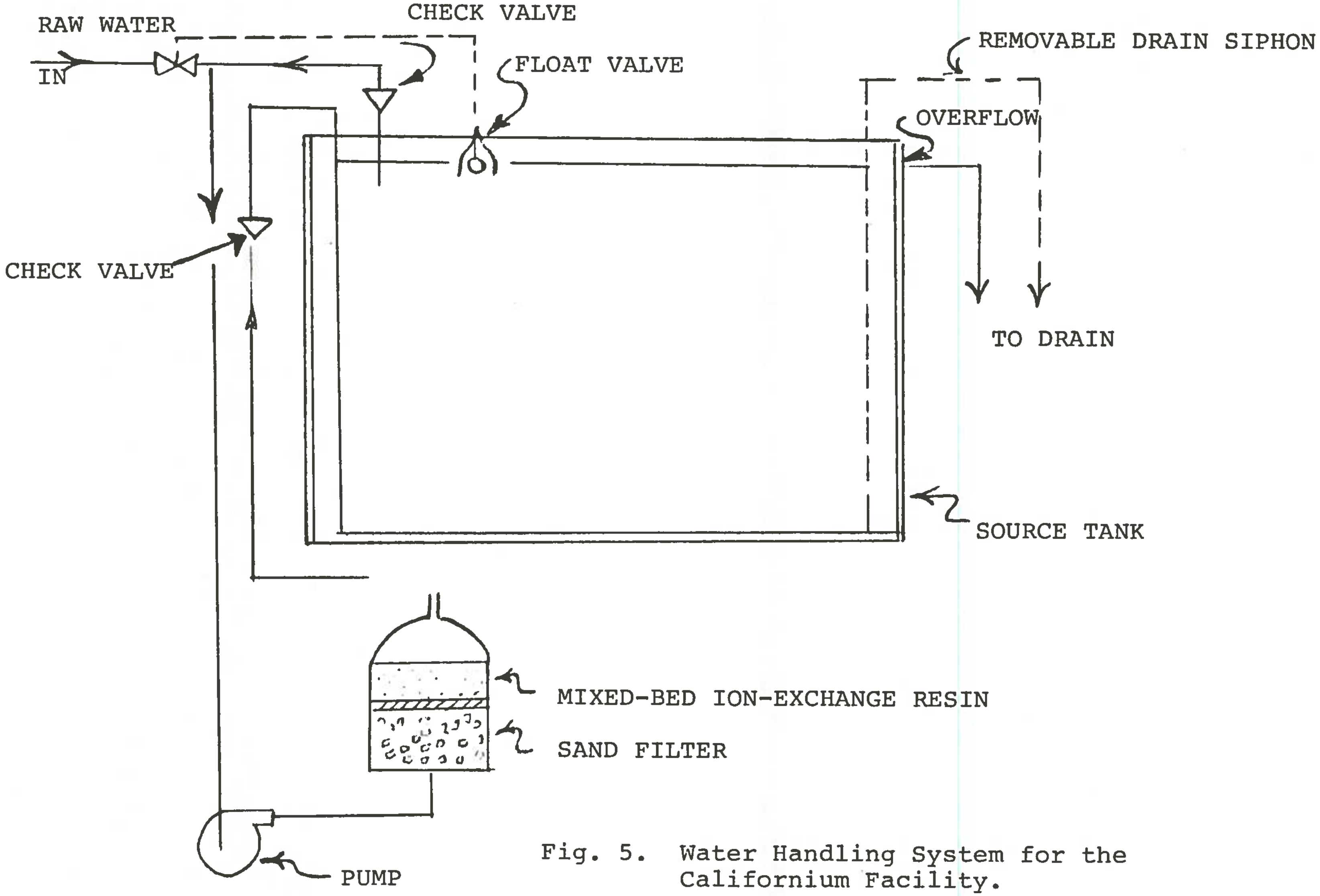


Fig. 5. Water Handling System for the Californium Facility.

Appendix 2

Instructions for Using CASK

"CASK"

It is a simple shielding program for spherical source of nuclear radiation. It was written at the University of London by James Wood. A complete description of the program can be found in Computational Methods in Reactor Shielding, Chapter (5), Section (4). Only three data cards are required to run this program. The following is the input instructions for "CASK".

INPUT INSTRUCTIONS FOR "CASK"

Card No.	FORMAT	VARIABLE	DESCRIPTION
1	E15.3	SCI	Source strength in Curies
1	F10.3	EMAX	Energy of gamma in "MeV"
1	F10.3	XMUSO	Linear attenuation coefficient for source material(cm^{-1})
1	F10.3	DMWL	Maximum dose rate desired at shield surface in mrem/hr
1	F10.3	RAD	Radius of spherical source (cm)
2	F10.3	XAB	Mass energy transfer coefficient for air or tissue at source energy in cm^2/g
2	3F10.3	A1,A2, A3	Taylor's dose buildup factors A2 has sign changed in the program
2	F10.3	XMU	Linear attenuation coefficient for shield material μ_ℓ(cm^{-1})
3	F10.3	XO	Initial "crude" guess for shield thickness (cm)
3	I6	KPRIN	KPRIN=-1, Index for controlling detailed printout: to suppress printout

VITA

Name - Mohammed Abu-Shehadeh

Date of Birth - December 25, 1957

Place of Birth - Gazza, Palestine

Education - Elementary School (Gazza, Palestine)
- Preparatory and Secondary School (Zerka, Jordan) - 1975
- B.Sc. in Chemistry at Al-Fateh University, Tripoli, Libya, started September 1976 Graduated June 1980 with 4 point average and honor certificate was given.
- M.S. in Nuclear Engineering at Louisiana State University, started January 1982 Graduated August 1984.