# Conceptual Engineering Designs for a Mechanical Shutter, a Medical Room Door, and a Water Shutter for a Fission Converter-Based Boron Neutron Capture Therapy Medical Facility

By

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Submitted to the Department of Mechanical Engineering on May 8, 1999 in
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**Abstract**

The conceptual designs for a mechanical shutter, a medical room door, and, a water shutter for use in a new fission converter-based boron neutron capture therapy medical facility were developed. In the design of the mechanical shutter and the medical room door, several alternatives were introduced. Design methodology and engineering judgment yielded the overall best -- conceptually speaking -- alternatives to pursue. These were a horizontally-moving mechanical shutter (perpendicular to the fission converter beamline) and a sliding medical room door (parallel to the fission converter beamline). For the water shutter, engineering judgment and simplification were used to scale back the water shutter design from the initial two-tank idea to the final one-tank design.

Thesis Supervisor: Otto K. Harling

Title: Professor of Nuclear Engineering

Thesis Supervisor: Peter Griffith

Title: Professor of Mechanical Engineering

## Acknowledgments

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# Table of Contents

## List of Figures

## Medical Room Door

## List of Tables

# Chapter 1

# Introduction

## 1.1 Boron Neutron Capture Therapy (BNCT)

Boron Neutron Capture Therapy (BNCT) has been around since 1936 when it was suggested by Gordon L. Locher at the Franklin Institute in Swarthmore, Pa. (Barth, et al, 1990). Clinical studies of brain cancer (glioblastoma multiforme) began in the 1950s; however, some patients died due to excessive radiation to microvasculature. Subsequently, studies in the USA tapered off and stopped in the early 1960s.

Nevertheless, with recent advancements in the development of effective boron compounds, improved neutron beams, and dosimetry, interest in BNCT has increased for the possible treatment of the glioblastoma multiforme and metastatic melanoma types of cancer.

BNCT involves the infusion of a boron-10 ($B^{10}$) containing compound into the patient. This $B^{10}$ compound has been engineered such that it concentrates preferentially within the patient's tumor cells. The area of the tumor is then irradiated with epithermal neutrons (neutrons in the energy range of 1 electronvolt (eV) to 10 keV). These neutrons are thermalized (thermal neutrons have energies around .025 eV) as they pass through bone and tissue to arrive at the cancerous cells. The $B^{10}$ atoms, having a high cross-section for the absorption of thermal neutrons, then undergo $B^{10}(n,\alpha)Li^7$ reactions whereby the thermal neutron captured by the $B^{10}$ atom excites the $B^{10}$ to an unstable $B^{11}$ state. This $B^{11}$ atom then decays, or 'fissions,' releasing a Lithium-7 ion ($Li^7$), an alpha particle and 2.3 MeV of kinetic energy. The highly energized $Li^7$ and alpha particles deposit all of their energy within a range of less than 13 $\mu$m (the approximate diameter of a normal cell), thereby minimizing the potential for adjacent healthy tissues to be deleteriously affected.

The Nuclear Reactor Lab (NRL) at MIT is currently funded by the Department of Energy in order to construct a facility whereby MIT and the Beth Israel-Deaconess Hospital can perform BNCT clinical trials with an improved epithermal neutron irradiation facility. This new facility, called the fission converter beam (FCB), will provide medical and nuclear engineering personnel a state of the art setting and a cleaner, more intense neutron beam than is currently employed.

### 1.2 Fission Converter Beam (FCB)

The main components of the fission converter beam facility are shown schematically in Figure 1.1. These components are usually massive pieces of equipment (on the order of several tons apiece).

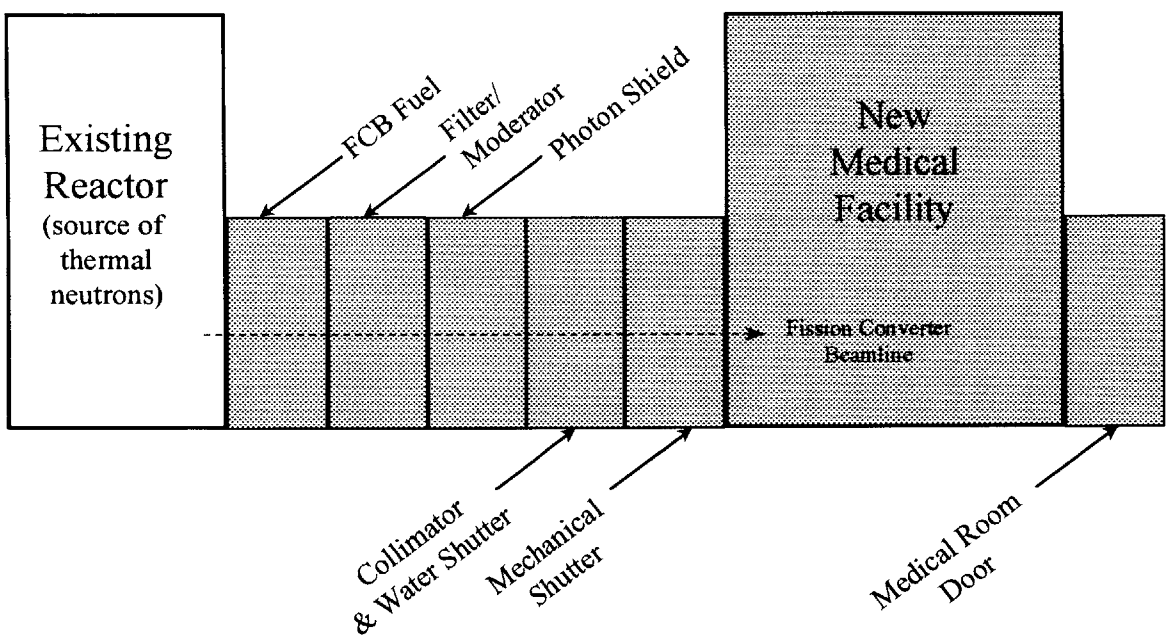


**Figure 1.1.** Block Diagram of the FCB system.

When the FCB system is in operation, most neutrons from the reactor, upon entering the FCB fuel elements, interact with Uranium-235 ($U^{235}$) atoms and each reaction produces 2 to 3 more neutrons. With many of these reactions occurring each second (approximately $2*10^{16}$ per second) a source of neutrons for the patient treatment beam in the medical room is established. On their way to the patient, the neutrons are partially moderated, filtered, and collimated.

When they pass through the filter/moderator, the neutrons, which are still 'fast' (neutrons in the energy range of 100 keV to 10 MeV) are slowed down to the epithermal range; most of the remaining fast neutrons are scattered out of the beamline. In the photon shield, harmful gamma rays (photons) are heavily attenuated. As a result, the photon shield, in front of the collimator, removes most of the unwanted gamma rays, leaving a neutron beam with low photon contamination. The neutrons are then collimated, or 'funnelled,' in the collimator module, producing a compact, high-intensity beam. Inside the collimator module is an aluminum tank, which can be filled with water. This tank is known as the water shutter. It is emptied to allow for neutron beam transmission; filled to help attenuate the beam. Following the collimator module, the mechanical shutter then acts as a heavy, movable slab, which controls the supply of neutrons to the patient. The medical room, or shielded irradiation room, is where the patient is placed to receive an irradiation treatment, having entered via the medical room door; see Figure 1.2, a simplified isometric figure of the reactor and the FCB components.

Staff in the Nuclear Reactor Laboratory (NRL) and the Nuclear Engineering Department (NED) are designing the FCB facility and students from the Mechanical Engineering (ME) Department have been assisting in the design of the mechanical shutter, the FCB cooling system, and the door to the medical room. This thesis will explain the steps taken in the initial design of the mechanical shutter, the medical room door, and the fluidic design of the water shutter, as outlined in section 1.3.

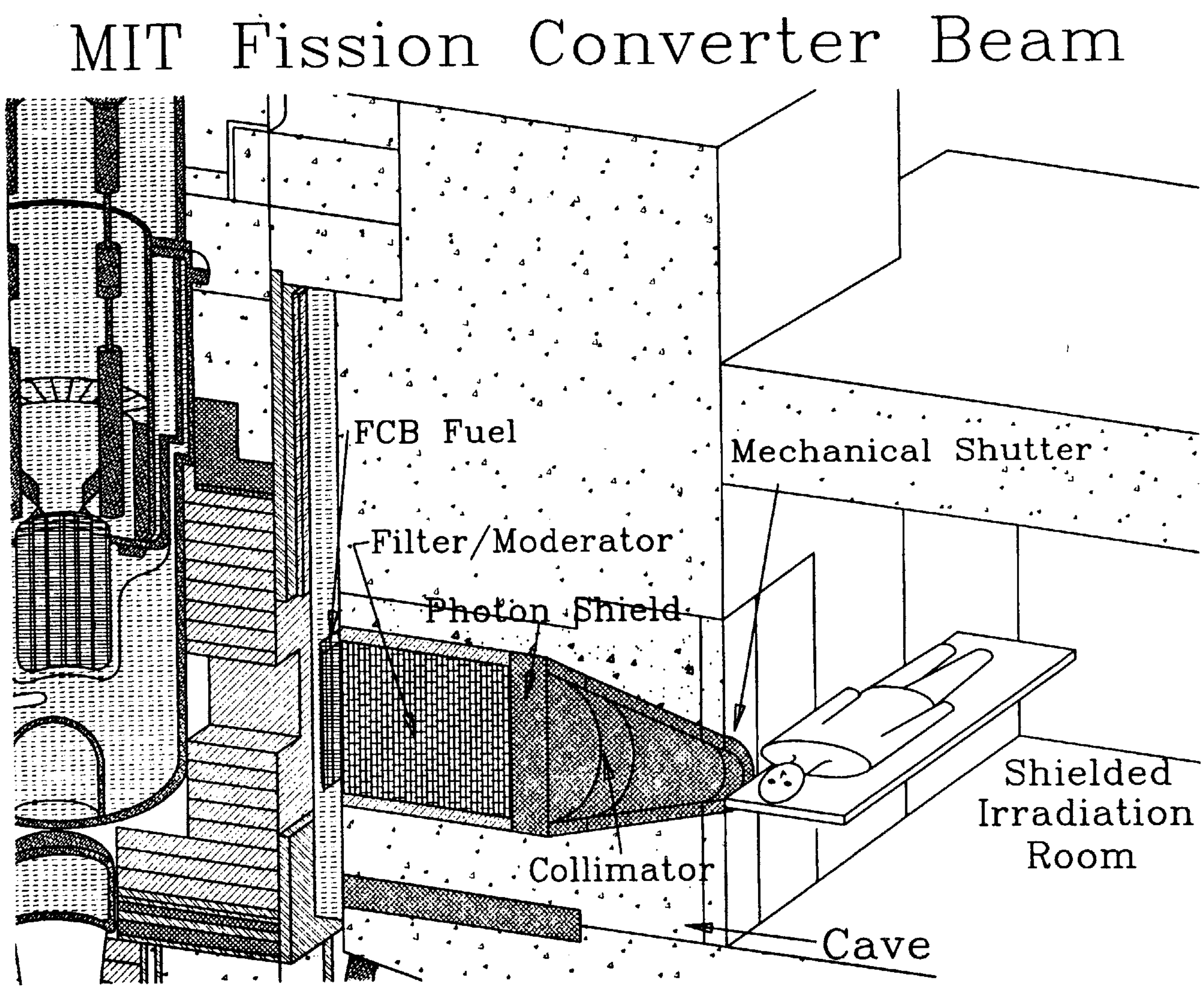


**Figure 1.2.** Reactor and FCB Components.

## 1.3 Thesis Objective

The objective is to design a mechanical shutter, a shielding door to the new medical room, and a water shutter for use in a fission converter-based boron neutron capture therapy medical irradiation facility. To complete this objective, the following tasks will be undertaken:

1. Perform mechanical engineering design work on the three fission converter based components.

2. Utilize previous shutter and medical room door design work done by Sutharshan and Ledesma, respectively, and further develop these designs.

3. Construct conceptual designs and drawings of the three fission converter based components.

4. Optimize the locations of the three fission converter based components.

# Chapter 2 FCB Shutters

## 2.1 Introduction

A shutter is an FCB component that controls the transmission of the neutron beam to the patient and hence, the dose rates inside the medical room.

Within the FCB there are three shutters: a cadmium shutter, a water shutter, and a mechanical shutter. The function of these shutters, in their closed positions, is to attenuate the neutron dose and the gamma ray dose by factors of $2.5*10^7$ and $6*10^6$, respectively, such that the dose rate at the patient position can be reduced to ≅ one mrem/hr when all shutters are closed (Sutharshan, 1998). Conversely, in their open positions, the shutters must not affect the neutron beam performance in any way. In addition, for reasons of safety, there must be provisions in place to manually close the shutters in case of an emergency (for example, loss of power during an irradiation treatment). The subsections to follow describe the three shutters and their functions.

### 2.1.1 Cadmium Shutter

The cadmium shutter is situated between the reactor and the FCB fuel tank. It resembles a curtain, which is raised and lowered to control the fission converter's output power. When the cadmium shutter is closed (lowered), it reduces both neutron and gamma ray dose rates by two orders of magnitude by reducing the thermal neutrons incident upon the converter fuel.

### 2.1.2 Water Shutter

The water shutter (in actuality, an aluminum water tank) is positioned inside the funnel-shape of the collimator. When the water shutter is closed (water tank full), it reduces the neutron dose rate by several orders of magnitude and the gamma dose rate by about one order of magnitude.

### 2.1.3 Mechanical (Fast) Shutter

The mechanical shutter, placed right before the patient position in the beamline of the FCB, is really a large slab of lead and polyethylene, about 20 centimeters each, with a cut-out in one portion that acts as a continuance of the funnel-shape of the collimator. Therefore, in the shutter open position, the mechanical shutter's cutout portion is lined up with the collimator module and the neutron beam is transmitted and further collimated down to the area desired at the patient position.

The major function of the mechanical shutter is to transmit the treatment beam in the shutter open position and to attenuate it in the shutter closed position. Specifically, when the mechanical shutter is closed, it must reduce both neutron and gamma ray dose rates by four orders of magnitude to reach the desired level of ≅ one mrem/hr inside the medical room.

Because irradiation treatment times can be as short as several minutes, the mechanical shutter, in order to accurately quantify the dose that the patient receives, must be opened and closed quickly. Since the operation of this shutter is necessarily much faster than both the cadmium and water shutters, it will henceforth be referred to as the 'fast' shutter.

Of the three shutters just described in this brief introduction, the fast shutter is the one that will be the focus of the remainder of this chapter.

## 2.2 Fast Shutter Function

As mentioned previously, the fast shutter provides a fast-acting method of controlling the transmission of the neutron beam to the patient during an irradiation treatment. It also controls the dose rate inside the medical room during the treatment. In this capacity, the fast shutter's shielding effect is very important. In the shutter open position, the shutter must provide adequate shielding such that any radiation not incident upon the cancerous region of the patient is minimized. Likewise, in the shutter-closed position, the shutter must attenuate neutrons and gamma rays each by about four orders of magnitude. Thus, in the closed position, the shutter shields the patient and medical personnel in the medical room.

Another function of the fast shutter is that it reconstitutes the shape of the collimator when it is in the shutter-open position. This produces a compact, high-intensity neutron beam for the cancerous region under irradiation.

### 2.3 Fast Shutter Design Goals and Requirements

In the construction and placement of the fast shutter, any major modifications to the reactor biological shield must be avoided.

Additional design goals and requirements are that the fast shutter uses materials that: are readily available, are relatively inexpensive, have good engineering properties, and possess good radiation shielding properties. Furthermore, the fast shutter must have a manual-closing feature in the event of a medical emergency or power failure during the irradiation treatment.

Also, since irradiation treatment times can be on the order of several minutes, it is imperative to control the transmission of the neutron beam as quickly as possible. This means that the fast shutter must open and close rather rapidly so as to minimize the amount of dose delivered during shutter opening and closing times. This will insure that the non-quantifiable dose delivered during the opening and closing of the shutter is small in comparison to the intended, targeted dose, which is administered when the shutter is fully open.

It has been shown that the types and thicknesses of shutter materials needed to attenuate the neutrons and gamma rays sufficiently (in the fast shutter closed position) are twenty centimeters of polyethylene and twenty centimeters of lead. The hydrogen content of the polyethylene will attenuate the neutrons by four orders of magnitude whereas the high-Z content of the lead will attenuate the gamma rays by the same amount. These materials and thicknesses will not vary, regardless of the form or type of movement that the fast shutter possesses. The remainder of the fast shutter material will be of high-density concrete (250 lb./cu.ft.).

## 2.4 Horizontal Fast Shutter Design Choice

Several fast shutter design alternatives were investigated. The shutter that was chosen to be the overall best, conceptually speaking, was a horizontal shutter. The horizontal shutter is so named because it is situated horizontally -- and moves parallel -- to the reactor floor, as shown in Figure 2.1 (in all figures in this thesis, when dimensions are given, the units are inches). The biggest advantage to this type of shutter is that shielding is plentiful and does not pose a problem in either the open or closed positions.

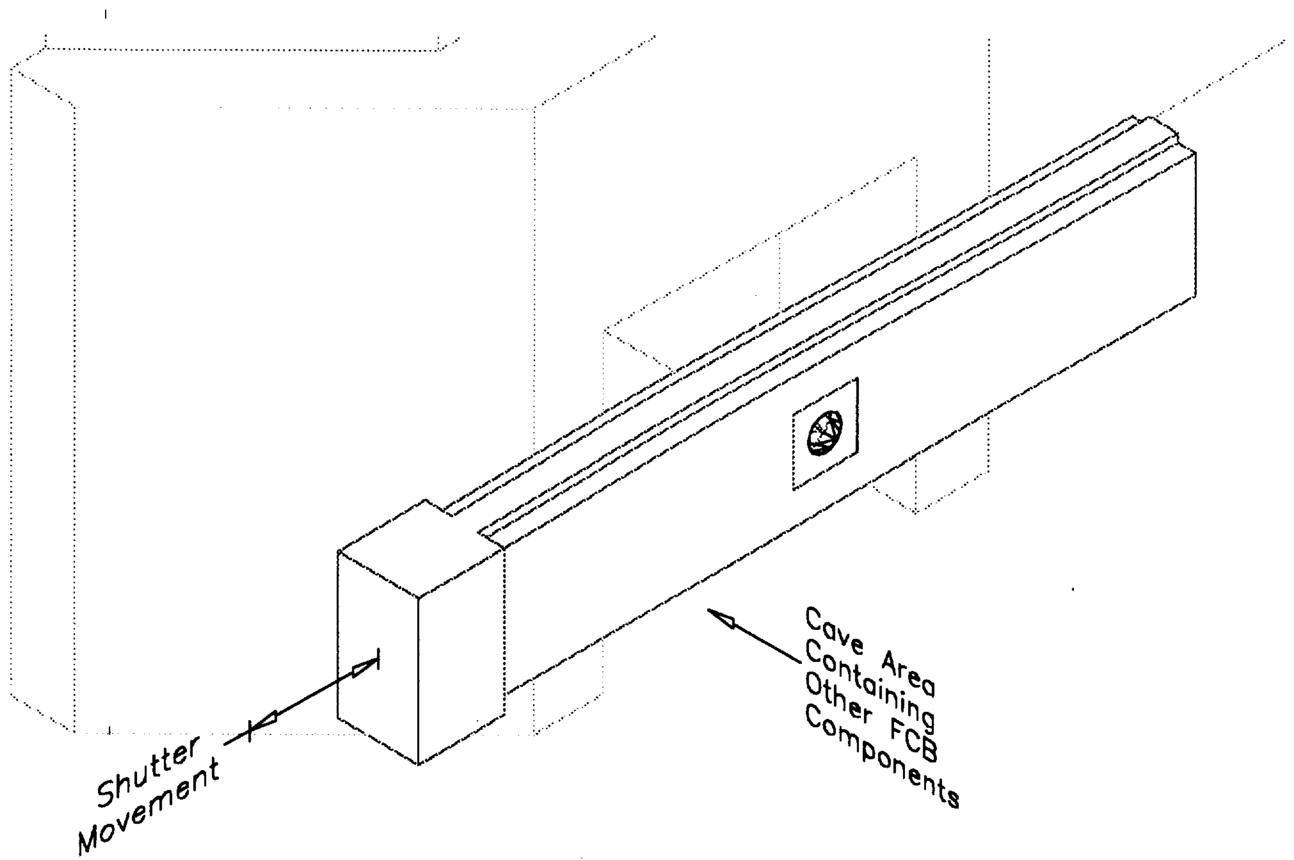


**Figure 2.1.** Horizontal Shutter.

The other fast shutter designs investigated (but not chosen to be pursued into the development phase) were a vertical fast shutter, two circular fast shutters, and a slanted (with respect to the reactor floor) fast shutter. Full descriptions and drawings of these turned-down design alternatives can be found in Appendix A, Fast Shutter Design Alternatives. A brief summary of why these particular fast shutter design alternatives were not chosen is as follows: for the vertical fast shutter, a sufficient amount of shielding material for the shutter would have necessitated a hole being mined out of the reactor floor. This hole would have reduced the load-carrying capacity of the reactor floor in the area where most of the tonnage of the new medical room walls are to be located. For the circular fast shutters and the slanted fast shutter, disadvantages outweighed the advantages of having these designs constructed. For example, two disadvantages common to both of these types of fast shutters were exotically shaped side blocks and difficulties in mounting the power sources.

For the horizontal shutter, advantages outweighed the disadvantages. There is room enough on both ends of the horizontal shutter for shielding material to be added to prevent radiation streaming in both the open and closed positions. Without a doubt, this type of shutter provides the best shielding of all fast shutter alternatives considered.

Other advantages to this horizontal shutter are that a power source can be unobtrusively mounted. Also, an emergency-closing feature, such as a mechanical winch, could be added as well. This would take the place of the fail-safe feature that the vertical shutter had.

Since advantages outweigh disadvantages for the horizontal shutter -- which is just the opposite for the other fast shutter alternative designs -- and since shielding is one of the most important design requirements for a fast shutter conceptual design, the horizontal shutter proves to be the best fast shutter alternative design to pursue into the conceptual phase.

What needs to be mentioned is that since an extensive amount of time and effort was spent in trying to realize the vertical fast shutter, there was not enough time left to go through a formal design methodology approach (as shown in Appendix B for the vertical and circular fast shutters) with the slanted and horizontal shutters, whose designs were considered (chronologically speaking) after the vertical and circular fast shutters. Therefore, the formal Pahl and Beitz approach used in Appendix B (utilizing decision criteria and a decision matrix) was bypassed. In its place was discussion and input from NRL staff at weekly FCB meetings and at specially held fast shutter meetings. It was from these discussions and meetings that the decision was made to go with the horizontal shutter.

## 2.5 Horizontal Shutter Conceptual Design

There are three main components that need to be designed with regard to the horizontal shutter: the shutter's bottom support and shield block, the horizontal shutter itself, and the shutter's top shield block. In addition, the shutter will be evaluated for excessive bending stresses and deflections. These stress and deflection evaluations are shown in Appendix C.

The bottom support and shield block (made of concrete, see Figure 2.2), will sit on the reactor floor and will be notched lengthwise. This notch will provide guidance for the shutter, which will also be notched, but in the opposite direction so that it can slide in the bottom block's notch, or groove. Another feature to the bottom block is the rectangularly shaped hole cut out of its front (medical room-side) plate. This hole is for the purpose of creating space for a delimiter which may be added to the horizontal shutter and extend outward, toward the patient position. This delimiter would be attached at the collimator portion of the shutter and would have to travel along with the shutter as it moves between open and closed positions -- the reason for the long notch in the plate of the bottom block extending to the left (relative to looking into the beam).

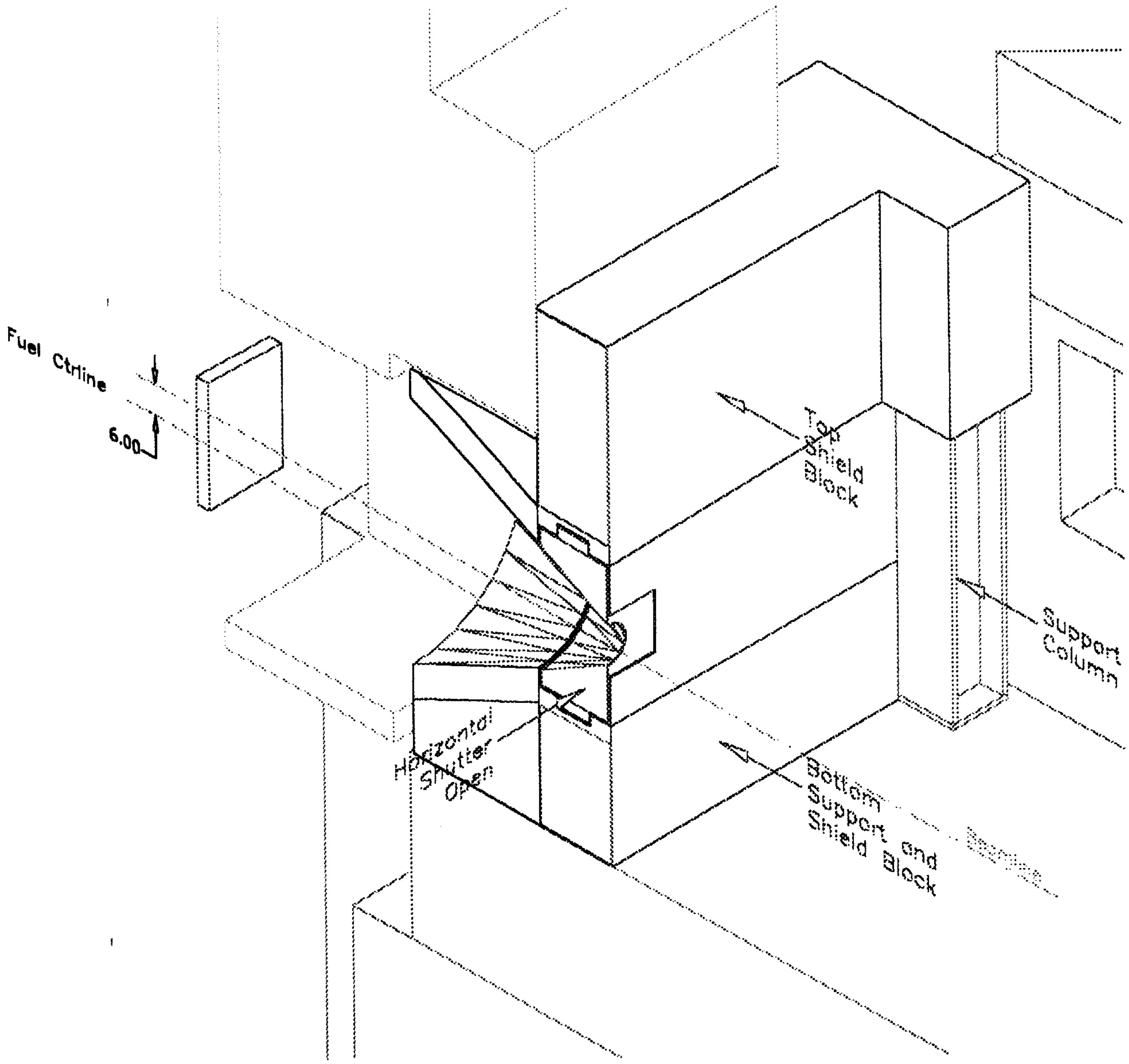


**Figure 2.2.** Shutter Support and Shield Blocks.

The horizontal shutter itself will travel to the right to open (facing the reactor) and will travel to the left to close (see Figure 2.3). In addition, the shutter may include the provision for a removable collimator – a removable and exchangeable extension of the FCB's collimator -- which is part of the shutter itself. This will provide the opportunity to increase or decrease the beam width at the patient position. The delimiter (mentioned above in the paragraph on the shutter's bottom block) would then be attached to the removable collimator, extending even further into the medical room. The delimiter and the removable collimators are shown in Figure 2.4.

The top shutter shield block will be above the horizontal shutter and will be supported by four beams -- one on each corner. This block is necessary to prevent excessive radiation doses from coming out over the top of the horizontal shutter (see Figure 2.1). This block, like the bottom block, will be constructed of concrete.

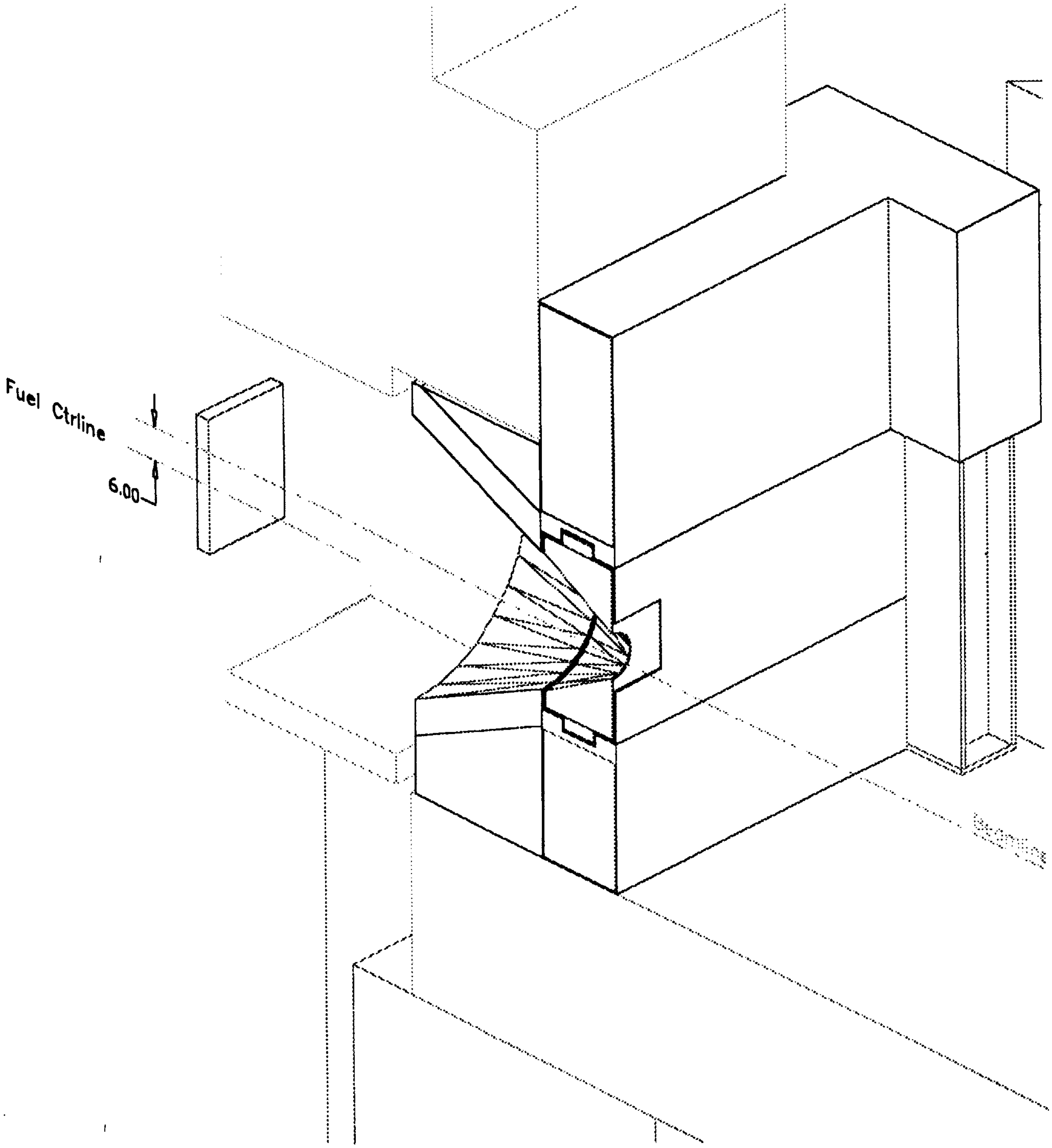


**Figure 2.3.** Horizontal Shutter in the Open Position.

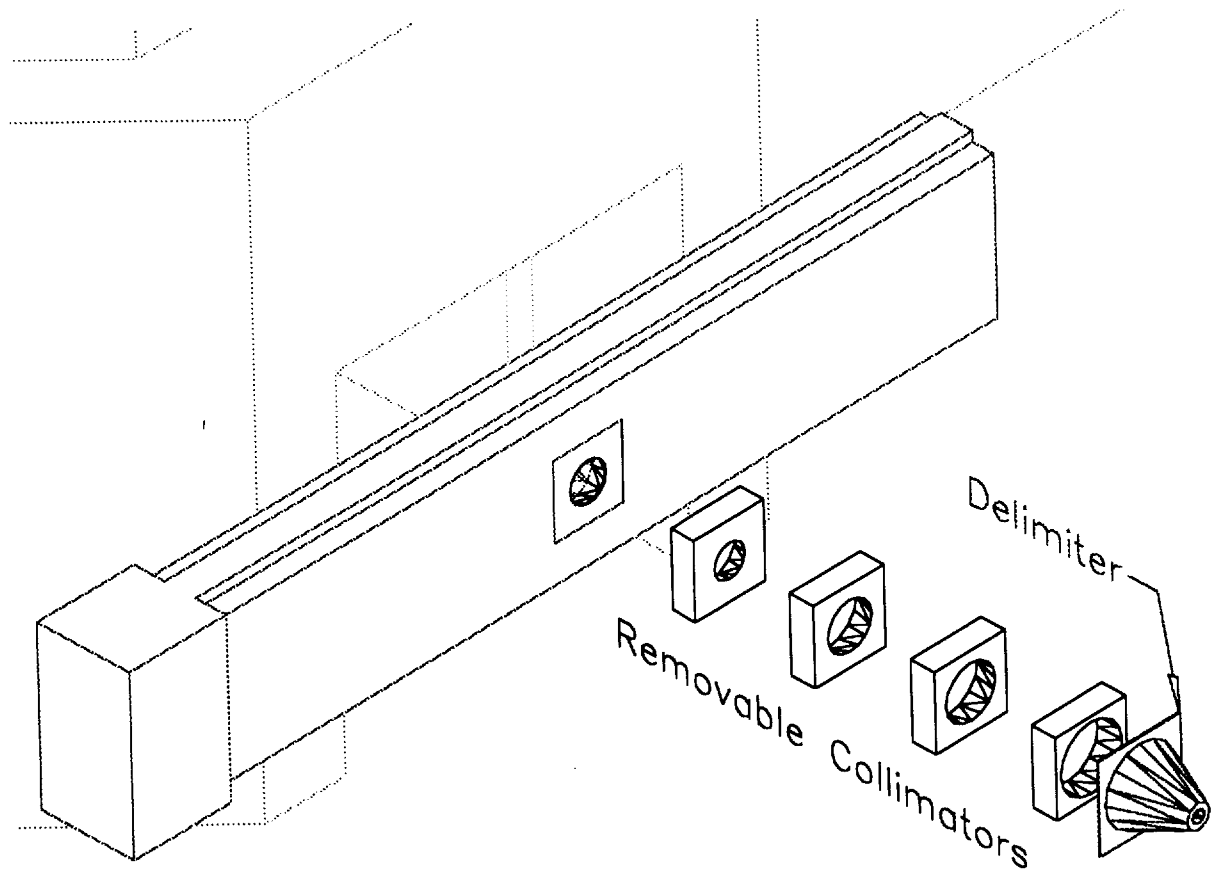


**Figure 2.4.** Shutter Delimiter and Removable Collimators.

# Chapter 3 Medical Room Door

## 3.1 Introduction

The new FCB medical room will need to be accessed repeatedly before, during, and after a patient irradiation session. Therefore, the medical room must include the provision for a safe, reliable, and dependable passageway for the patient and medical personnel. The entrance to this passageway will be a heavy, shielded door called the medical room door. This door is an integral feature of the medical room and is located in a back corner of the room (relative to the patient position) in order to minimize the dose rate at the door.

In the open position, the medical room door allows for access in and out of the medical room; in the closed position, it minimizes the radiation dose to the outside area (to ≅1 mrem/hr) where the medical personnel and NRL staff are situated during an irradiation treatment.

The medical room door is a heavy piece of equipment (on the order of ten to fifteen tons, depending on the density of the material or materials used) and has the rough dimensions of eight feet in height, four and one half feet in width, and one and a half to three feet in thickness -- again, depending on the materials used. This thickness is necessary in order to sufficiently attenuate the neutron and gamma ray dose levels that are present inside the medical room during an irradiation treatment.

### 3.2 Medical Room Door Function

The medical room door provides a quick and easy method for entering and exiting the medical room. This most basic function is of utmost importance, as safe and reliable passage should be taken for granted.

This passageway also needs to be proportioned such that the patient, medical personnel, NRL staff, and all other necessary equipment such as wheelchairs, stretchers, and so forth will have unobstructed movement in and out of the medical room. Even before the day of an irradiation treatment, maneuvers take place whereby the patient and staff make preparations for the actual treatment; the medical room door is an integral part of this pre-treatment maneuvering.

In addition to providing free and clear accommodations to movement, another function of the medical room door is to attenuate the radiation incident upon its inside surface. It must do this so that the neutron and gamma ray dose levels are reduced to $\cong$ one mrem/hr on the reactor floor outside the medical room door.

### 3.3 Medical Room Door Design Goals and Requirements

The location of the medical room door must be kept out of the direct line of the neutron beam to aid in minimizing, not only the radiation incident upon the door, but also the radiation dose levels outside the door during the irradiation treatment. Positioning the door's location in such a manner also helps to minimize the door thickness and, therefore, its overall weight.

The door geometry must be optimized with respect to its weight, the amount of floor space it occupies, and the amount of shielding it provides.

The door material, or materials, must have sufficient hydrogen content to attenuate neutrons and sufficient high-Z (or heavy element) content to attenuate gamma rays.

The door must have a quick and safe opening and closing mechanism and power source, as well as an emergency stop feature -- in case of inadvertent contact with someone or something.

The door must have a manual-opening feature, for safety reasons, in the event of a power failure during the irradiation treatment.

The door must weigh ≤ 20 tons, which is the limit of the reactor room's polar crane. This crane will be used to initially place the door in position and will also be used in case an emergency opening situation arises.

The door must be stepped at the bottom and lapped at the sides and top to prevent radiation streaming outside of the medical room onto the reactor floor.

### 3.4 Medical Room Door Options

M.N. Ledesma, in her M.S. Thesis, *Medical Room Design for a Fission Converter-Based Boron Neutron Capture Facility* (1998), studied the new medical room door in-depth. Part of her work was calculating how much door material (or materials) were needed to reduce the neutron and gamma ray dose levels to ≅ one mrem/hr on the reactor floor outside the medical room door. Her results are given in Table 3.1 -- properties of single composition door options, and in Table 3.2 -- properties of door options – combination of shielding materials.

The author took this work and showed, in Table 3.3, the estimated costs of the door options -- both single composition and combination of shielding materials doors. These estimated costs are purely materials costs. Table 3.3 shows that the least expensive -- materially speaking -- medical room door would be the all concrete door (high density concrete, 250 lb. per cubic foot.), while the most expensive would be the all polyethylene door.

Note (in Table 3.1) that thicknesses of more than ≈ 100 centimeters can be ruled out as impractical. For single component (material) doors, only concrete, lead, or steel are practical options. However, lead can be ruled out because its weight exceeds 20 tons, the limit of the polar crane.

**Table 3.1.** Properties of single composition door options (Courtesy of M.N. Ledesma).

| **Single Materials** | Gamma Dose (mrem/ hr) | Neutron Dose (mrem/ hr) | Amount of material needed to reduce gamma dose to 1 mrem/ hr **(cm)** | Amount of material needed to reduce neutron dose to 1 mrem/ hr **(cm)** | volume ($cm^3$) | Density ($g/cm^3$) | Total Weight assuming door 4.5 ft wide x 8 ft tall (tons) |
|---|---|---|---|---|---|---|---|
| **S1)** Concrete | 9.94E-01 | 1.04E+00 | 70 | 67 | 2.34E+06 | 3.94 | 10.16 |
| **S2)** Lead | 9.38E-01 | 9.85E-01 | 19 | 64 | 2.14E+06 | 11.34 | 26.74 |
| **S3)** Steel | 9.73E-01 | 9.17E-01 | 34 | 44 | 1.50E+06 | 7.8 | 12.90 |
| **S4)** Polyethylene | 1.00E+00 | 9.93E-01 | 258 | 68 | 8.62E+06 | 0.93 | 8.84 |
| **S4)** Masonite | 1.07 | 1.08 | 321 | 74 | 1.07E+07 | 1.4 | 16.56 |

**Table 3.2.** Properties of door options – combination of shielding materials (Courtesy of M.N. Ledesma).

| Combinations of Materials | Thickness of material 1 (cm) | Thickness of material 2 (cm) | Total thickness (cm) | Density of material 1 ($g/cm^3$) | Density of material 2 ($g/cm^3$) | Weight of material 1 assuming door 4.5 ft wide x 8 ft tall (tons) | Weight of material 2 assuming door 4.5 ft wide x 8 ft tall (tons) | Total Weight assuming door 4.5 ft wide x 8 ft tall (tons) |
|---|---|---|---|---|---|---|---|---|
| C1) concrete/lead | 61 | 8 | 69 | 3.94 | 11.34 | 8.86 | 3.34 | 12.20 |
| C2) poly/lead | 50 | 19 | 69 | 0.93 | 11.34 | 1.71 | 7.94 | 9.65 |
| C4) concrete/steel | 33 | 25.4 | 58.4 | 3.94 | 7.8 | 4.79 | 7.30 | 12.09 |
| C5) poly/steel | 30.48 | 31.75 | 62.23 | 0.93 | 7.8 | 1.04 | 9.13 | 10.17 |
| C6) masonite/steel | 33 | 30.48 | 63.48 | 1.4 | 7.8 | 1.70 | 8.76 | 10.46 |

There are two reasons why the five particular door materials given in Tables 3.1 and 3.2 were chosen as door options: radiation shielding purposes and cost effectiveness (in a materials selection manner of speaking).

With regard to the radiation shielding purpose, the door material must sufficiently attenuate both gamma rays incident upon the door and the gamma rays produced by nuclear reactions occurring within the door. Additionally, the door material must sufficiently attenuate fast neutrons incident upon the door.

With regard to cost effectiveness, several factors contribute to the reasons behind the consideration of a sensible and probable choice for a particular door option to be designed. Those factors include cost and ease of door fabrication, cost, ease, and placement of the mechanical device that will be used to power the door, and finally, the door dimensions and weight of the door.

**Table 3.3.** Estimated costs of door options – both single composition and combination of shielding materials doors.

| **Material:** | **Poly** | **Lead** | **Steel** | **Concrete** | |
|---|---|---|---|---|---|
| **Quote:** | **McMaster-Carr:** High-Density Polyethylene (.949 gm/cc) Sheets; 12" by 24" by 1" thick: $37.03 each; ~$222/ft^3 | **APEC:** $1 per lb. to pour | **Thypin Steel:** hot rolled steel; 4 ft by 8 ft sheets, 3/8 in. thick: ~$.40 per lb. | **Boston Sand and Gravel :** approximately $100 per cu. yd. ($100 added for delivery) | |
| **Mat'l. Cost per Qty:** | [per cu. ft.] | [per lbm] | [per lbm] | [per cu. yd.] | |
| | $222.00 | $1.00 | $0.40 | $100.00 | |
| **Door: Mat'l. & Qty.** | | | | | **Material Cost Estimate** |
| **S1)** concrete | 0.00 | 0.00 | 0.00 | 3.02 | $302 |
| **S2)** lead | 0.00 | 54320.50 | 0.00 | 0.00 | $54,321 |
| **S3)** steel | 0.00 | 0.00 | 25866.90 | 0.00 | $10,347 |
| **S4)** poly | 302.17 | 0.00 | 0.00 | 0.00 | $67,083 |
| | | | | | |
| **C1)** concrete/lead | 0.00 | 6685.60 | 0.00 | 2.67 | $6,952 |
| **C2)** poly/lead | 59.02 | 15878.30 | 0.00 | 0.00 | $28,980 |
| **C3)** steel/lead | 0.00 | 1671.40 | 25292.08 | 0.00 | $11,788 |
| **C4)** concrete/steel | 0.00 | 0.00 | 14600.43 | 1.44 | $5,984 |
| **C5)** poly/steel | 35.98 | 0.00 | 18250.54 | 0.00 | $15,287 |
| **C6)** masonite/steel | 0.00 | 0.00 | 17520.52 | 0.00 | $7,008 |

It would be too time consuming to optimize the medical room door by taking into consideration all of the possible door movements and materials. Therefore, engineering judgment will be used and pertinent decision criteria will be formulated to aid in the decision-making process.

As shown in Figure 3.1 (courtesy of M.N. Ledesma), floor space is at a premium for the new medical room door. To the reactor side (left side in the figure) of the door, the medical control panel, the control console, and the staff are situated; to the opposite side is the containment wall. In the area directly parallel to the door (if it were to slide toward the containment wall) are located the heavy water ($D_2O$) pipes (not shown in the figure, but extending slightly outward from the containment wall). These pipes further restrict the amount of room for the door to move -- if it were to move toward the containment wall.

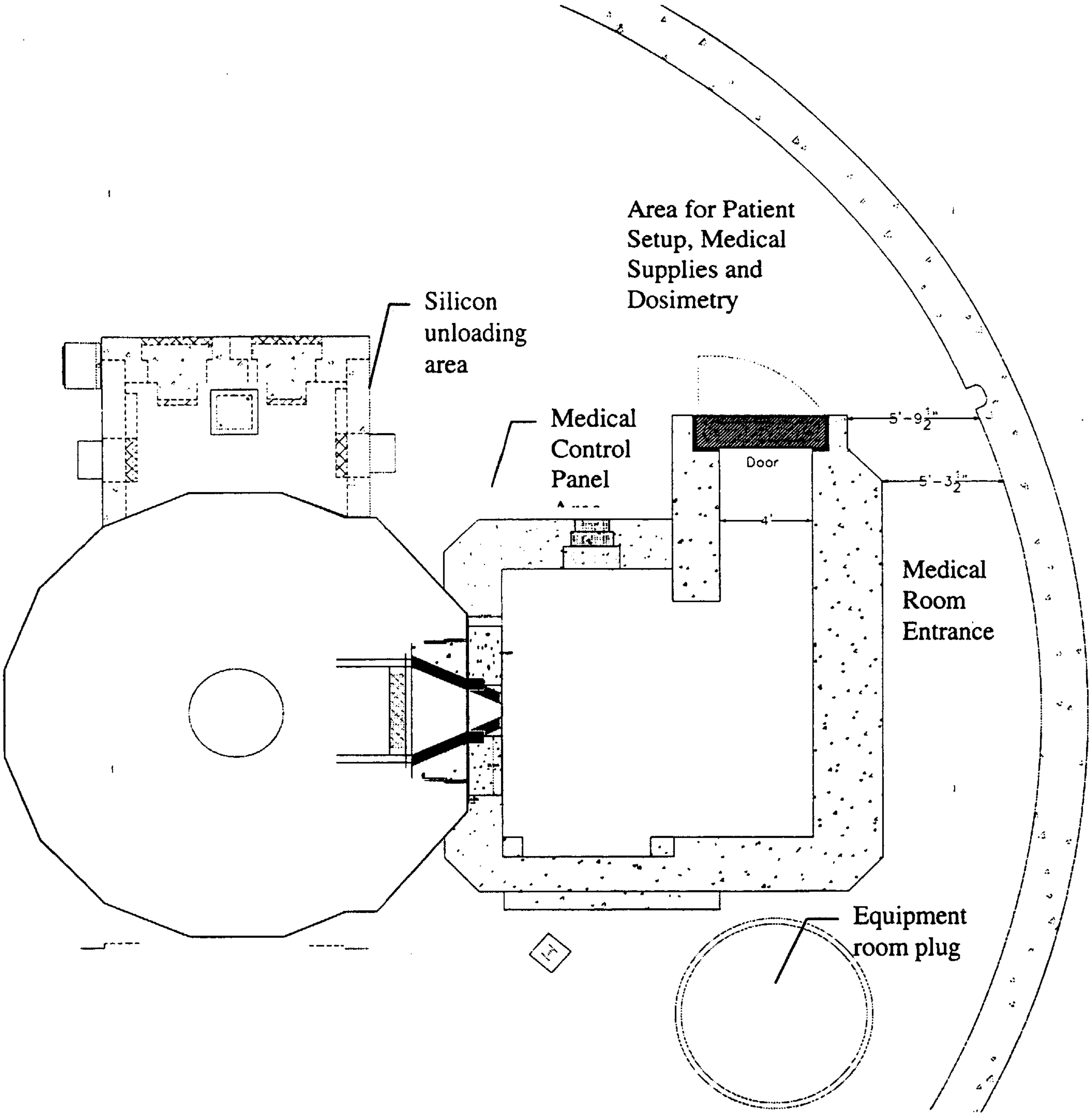


**Figure 3.1.** Plan View of the New Medical Room Layout. (Courtesy of M.N. Ledesma)

## 3.5 Chamfered Medical Room Door Design Choice

Several medical room door design alternatives were researched. The door that was chosen to be the overall best design, conceptually speaking, has an edge that is beveled, or chamfered -- thus, the name of chamfered medical room door. This conceptual design for a door to the medical room came as a result of investigating several other door design alternatives. Those door designs investigated but not pursued into the development phase were: a hinged and swinging door, a vertically moving door, a parallel-to-beam sliding door, a slanted sliding door, and a transverse-to-beam sliding door. Full and in-depth descriptions and drawings of these turned-down door alternative designs are found in Appendix D, Medical Room Door Alternative Designs.

There were several reasons why the turned-down door alternatives were not chosen. Among the reasons are that some alternatives would have taken up too much floor space (which is already severely limited, as indicated in Figure 3.1) -- particularly the parallel-to-beam sliding door and the transverse-to-beam sliding door. Other reasons were that the alternative design would have had negative effects on access to the medical room passageway -- in particular, the hinged and swinging door and the transverse-to-beam sliding door. Finally, for the reason of safety (actually, lack of safety) the vertically moving door alternative was turned down.

### 3.6 Chamfered Door -- Conceptual Design

As in the case of choosing the horizontal shutter as the fast shutter alternative to pursue, engineering judgment, many FCB meetings, and many special medical room door working group meetings were held to decide which medical room door alternative to pursue. The advantages and disadvantages were weighed for each alternative. The result was that the parallel-to-beam sliding door alternative and the slanted sliding door alternative were combined, as shown in Figure 3.2. The angled door edge, or chamfer, on the door's side facing the containment wall is, conceptually speaking, the most desirable alternative to pursue. This door alternative, nicknamed the chamfered door, is the overall best alternative such that it mimics the current medical room door with its sliding movement on the overhead track and trolleys. This approach is judged to combine the best design alternatives and compromises.

Another advantage to the chamfered door design is that, in its open position, it leaves enough space between the door edge (chamfer) and the $D_2O$ pipes for personnel and equipment to pass through (see Figure 3.3).

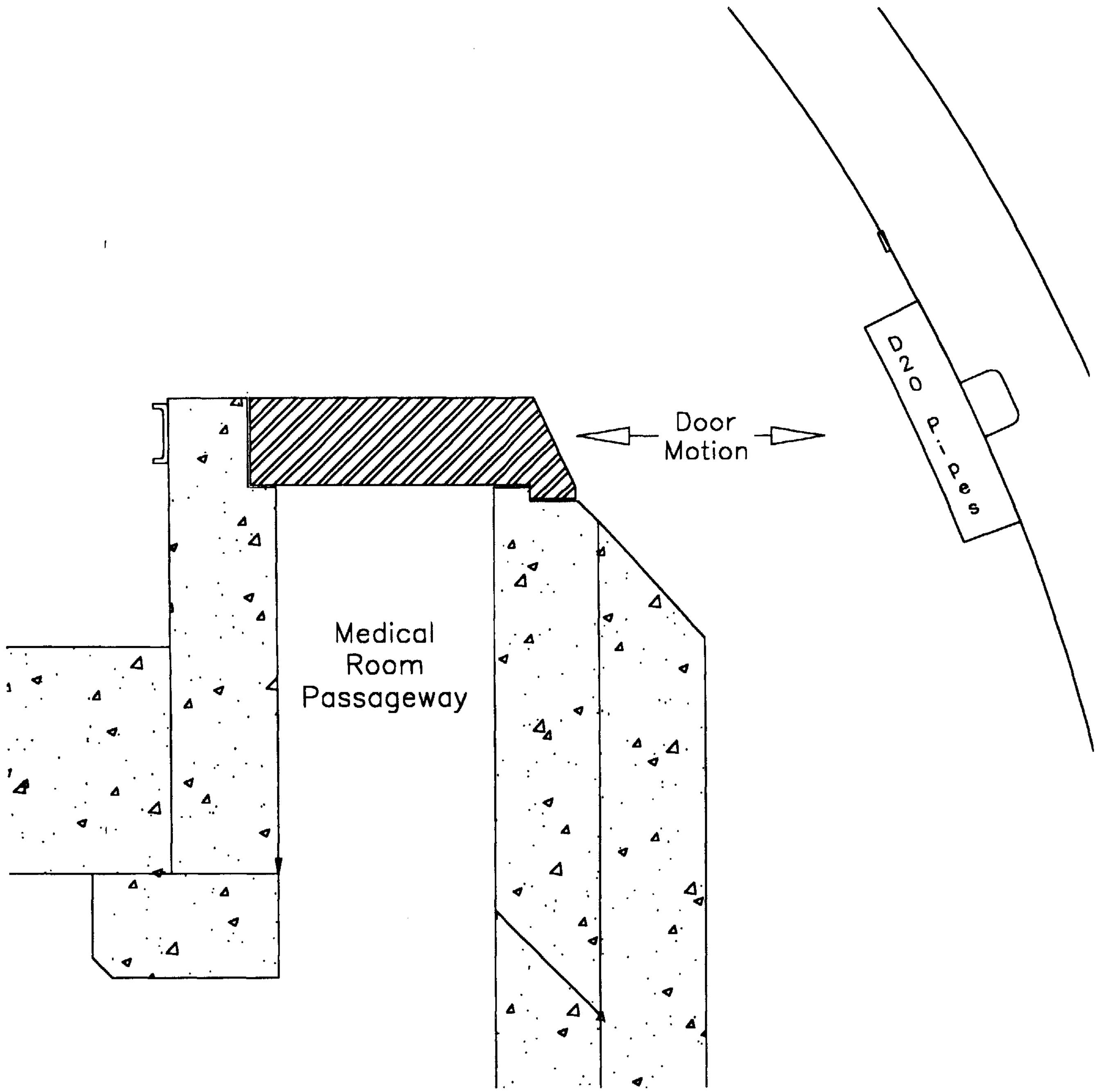


**Figure 3.2.** Chamfered Sliding Door -- Plan View, Closed Position (support structure for door not shown).

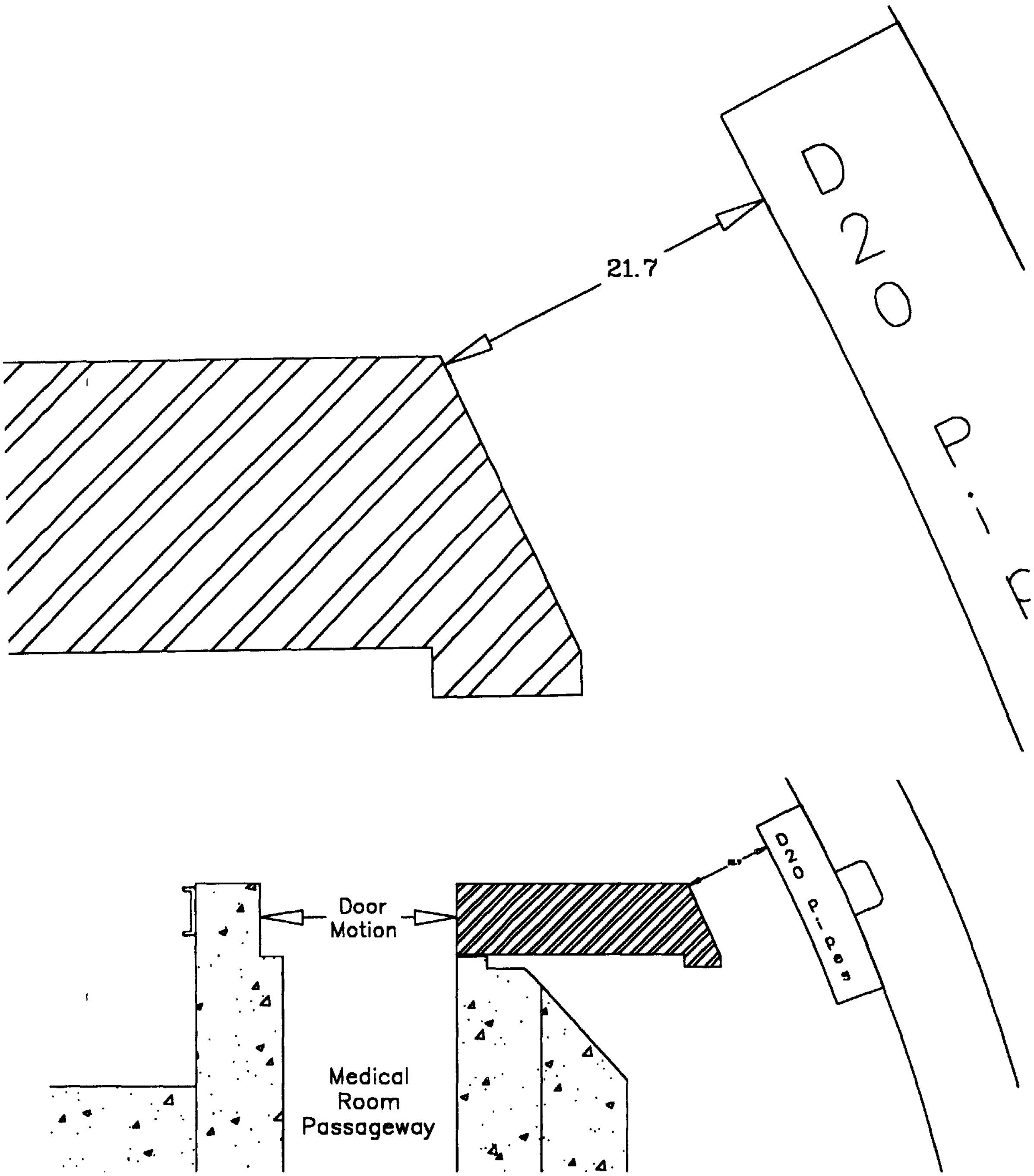


**Figure 3.3.** Chamfered Sliding Door – Plan View, Open Position (support structure for door not shown).

## Chapter 4 Water Shutter

### 4.1 Introduction

The water shutter is an aluminum tank, which can be filled with water. Its function is to aid the fast shutter in attenuating the neutron and gamma ray dose. It does this when it is full of water (closed position) as the hydrogen content of the water attenuates the neutron dose by several orders of magnitude and attenuates the gamma dose, primarily by photoelectric and Compton scattering interactions, by about one order of magnitude. When the water shutter is empty (open position), it allows for unimpeded transmission of the neutron beam to the patient.

The aluminum tank of the water shutter has a tapered, conical shape so that it fits inside the funnel-shape of the collimator module. The supply tank for the water shutter is mounted above the shutter on the medical room roof. Because the shutter is then filled by gravity, this implies a built-in fail-safe feature for neutron dose moderation; that is, in the event of a power failure or other emergency, the manual opening of a valve will fill the shutter. In addition, the supply pipe and the drainpipe are one and the same. This pipe enters the bottom of the shutter, as shown in Figure 4.1. This type of plumbing simplifies the fluidic design and helps to minimize the number of penetrations through the roof of the medical room.

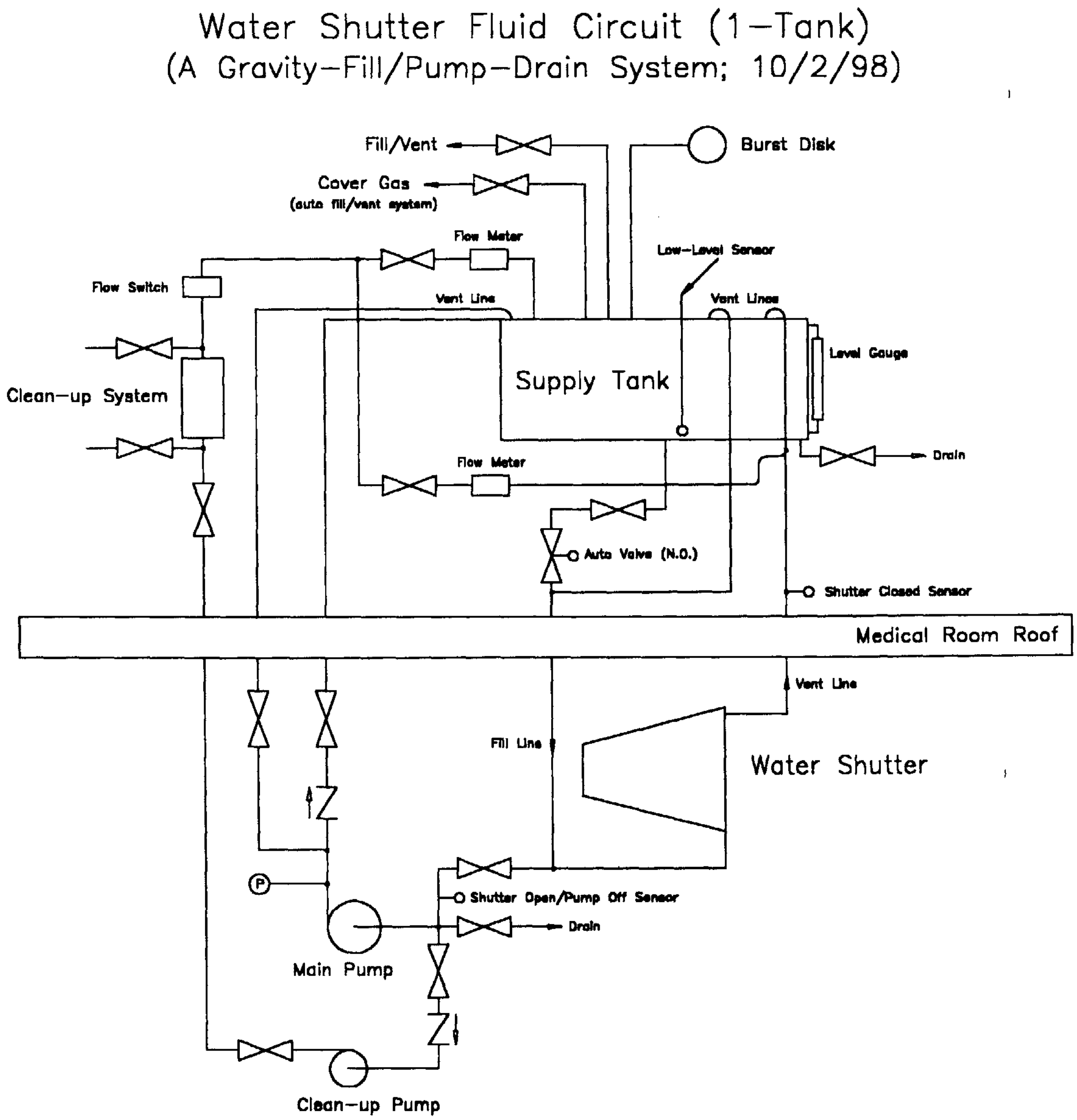


**Figure 4.1.** Water Shutter Fluid Circuit.

## 4.2 Design Goals and Requirements

In the design of the water shutter fluid circuit, one needs to place the various tanks, pumps, valves, sensors, gauges, and meters in the correct locations such that everything works together properly. Proper sizing of the aforementioned components is also an issue that is very important. The valves to be used are typically of similar size; however, due to the water shutter fluid circuit analysis to follow (in Appendix E), it will be shown that some pipes and vent tubes need to be larger than others. This will enable the water shutter to fill in a sufficiently quick time, for example. The same water shutter fluid circuit analysis will produce the size of the main pump needed to drain the water shutter in a given time.

The clean-up system for the water shutter circuit is a necessary feature since the circuit is a closed system; the clean-up pump will most likely be a gear pump which, although having a low volumetric flow rate, can pump against large heads. It will need to do this since the distance from where the clean-up pump will be placed -- the equipment room floor -- to the supply tank on the top of the medical room roof is approximately 25 feet.

## 4.3 Fluidic Design

A concise overview of the water shutter fluid circuit analysis is as follows: the horsepower needed for the main (drain) pump is found by first computing the losses due to pumping against gravity, imparting speed to the water, friction and bends in the pipes, and pumping against the cover gas in the supply tank. These losses are calculated as functions of shutter drain time; therefore, the horsepower of the main pump is also a function of shutter drain time.

The next step in the analysis of the water shutter fluid circuit is to compute the shutter fill time. This is first done by assuming a free discharge of water from the supply tank (minus the friction and pipe bend losses) to the water shutter. However, the water entering the shutter will have to force the gas out of the shutter through the vent line. This gas vent "back pressure" is an added loss and is calculated as a function of vent tube diameter and added to the friction and pipe bend losses to yield a "new" shutter fill time.

These calculations are done using both air and helium as the cover gas; as can be expected, due to the much lower density and viscosity of helium, the shutter fill times for helium as the cover gas are much lower than the shutter fill times for air as the cover gas. The water shutter fluid circuit analysis is shown in its entirety in Appendix E.

# Chapter 5 Summary and Suggestions for Future Work

## 5.1 Summary

Conceptual designs were performed for three components of the proposed medical facility for the fission converter neutron beam project. These components were a mechanical shutter, a shielded door for the medical room, and a water shutter. The two shutters, in their open positions, allow the neutron beam to reach the patient; in their closed positions, they attenuate the neutron beam, lowering the radiation levels at the patient position to ≅ one mrem/hr. The shielded door to the medical room allows passage for the patient, medical staff, and NRL personnel into and out of the medical room. In its closed position, it attenuates radiation levels outside the door to ≅ one mrem/hr even when the medical beam is on or open.

The mechanical shutter will be constructed of concrete, lead, and polyethylene -- encased in a steel wrap -- and move horizontally, with respect to the reactor floor. It has been shown that twenty centimeters of lead and twenty centimeters of polyethylene will be sufficient to attenuate the neutron beam to ≅ one mrem/hr at the patient position (with the other shutters closed).

The shielded medical room door will move parallel to the fission converter beamline. This door has an edge (on the containment wall side of the door) that is chamfered, or beveled, to provide the maximum amount of room for personnel to pass through on that side when the door is in the open position. In addition, the new medical room door mimics the current medical room door in that it will move by overhead track and trolleys.

The water shutter will be a tapered, conical, aluminum tank that will fit inside the collimator module of the fission converter system. The water shutter will be filled by gravity from a supply tank mounted overhead. Pumping the water out of the shutter and back up to the supply tank will drain it.

## 5.2 Suggestions for Future Work

Since this thesis was limited to the conceptual designs of the mechanical shutter, the medical room door, and the water shutter, there remains the need to have these designs finalized. This section of chapter five will attempt to address the final design work that remains to be accomplished.

### 5.2.1 Mechanical Shutter Suggestions

The final dimensions of the fast shutter have yet to be determined; this will impact the amounts of concrete, lead, polyethylene, and steel that will be needed. What is known, and has been proven to be sufficient, is that a thickness of 20 centimeters of polyethylene -- together with a thickness of 20 centimeters of lead -- will be enough to attenuate the neutron beam to ≅ one mrem/hr, with the other shutters closed, an FCB design requirement.

As shown in Figures 5.1 and 5.2, there are four support columns for an existing overhead platform (not shown) which are located to the left (facing the reactor) of the horizontal shutter. Figure 5.2 shows the shutter in a full extension to the left; although the shutter itself does not strike any of the four support columns, the prime mover, or power source for moving the shutter will be very difficult to place within these obstructions. The author agrees with M.N. Ledesma where she suggests in her M.S. thesis *Medical Room Design for a Fission Converter-Based Boron Neutron Capture Therapy Facility* (1998) that some of these support columns may have to be moved. The reason for the column movement is that two of the support columns (see Figure 5.2) are in direct conflict with one of the new medical room walls.

What also needs to be designed is an emergency-closing device for the fast shutter in the event of a power failure (or other emergency situation) with the shutter in the open position.

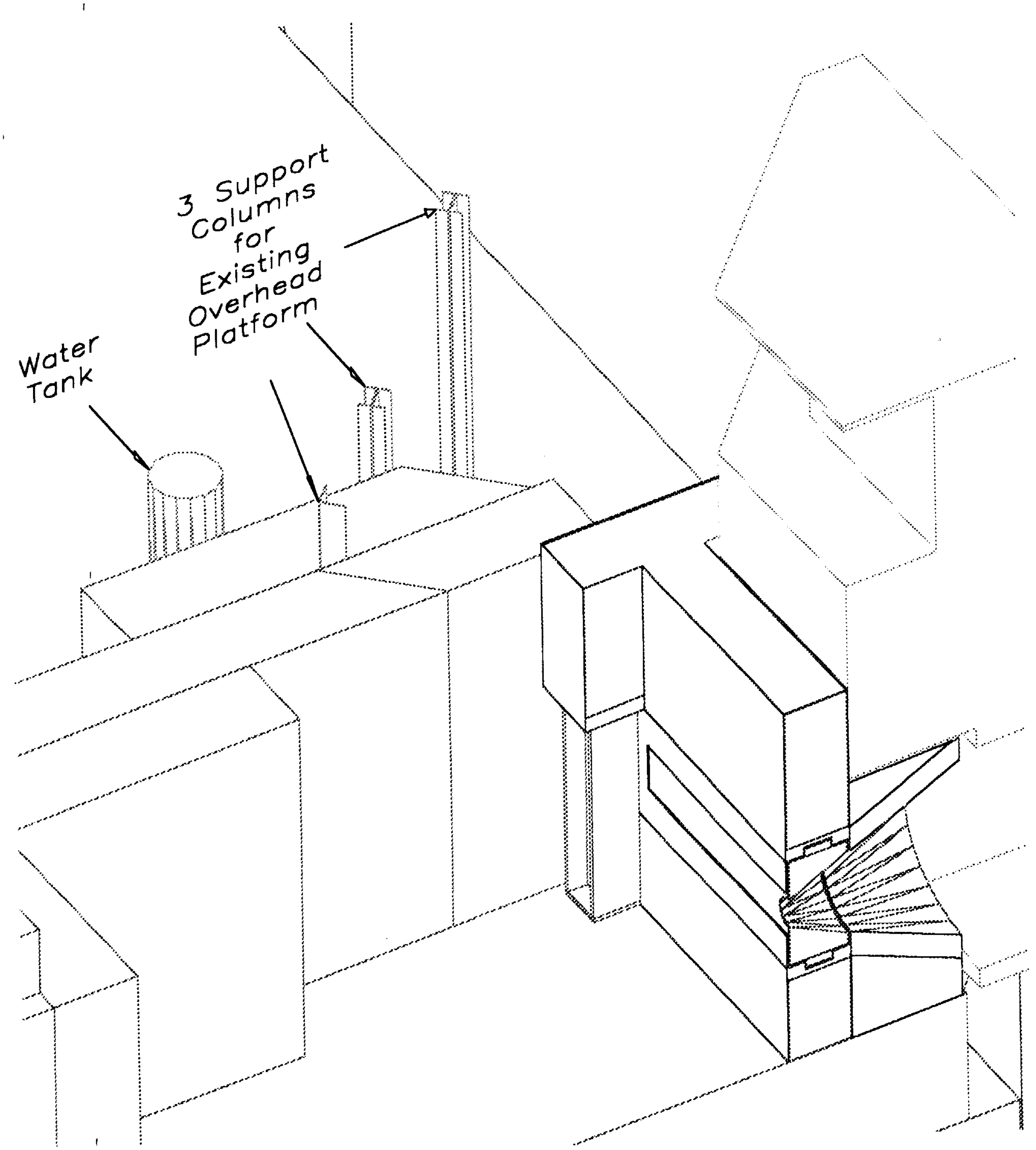


**Figure 5.1.** Isometric View of Sectioned Medical Room.

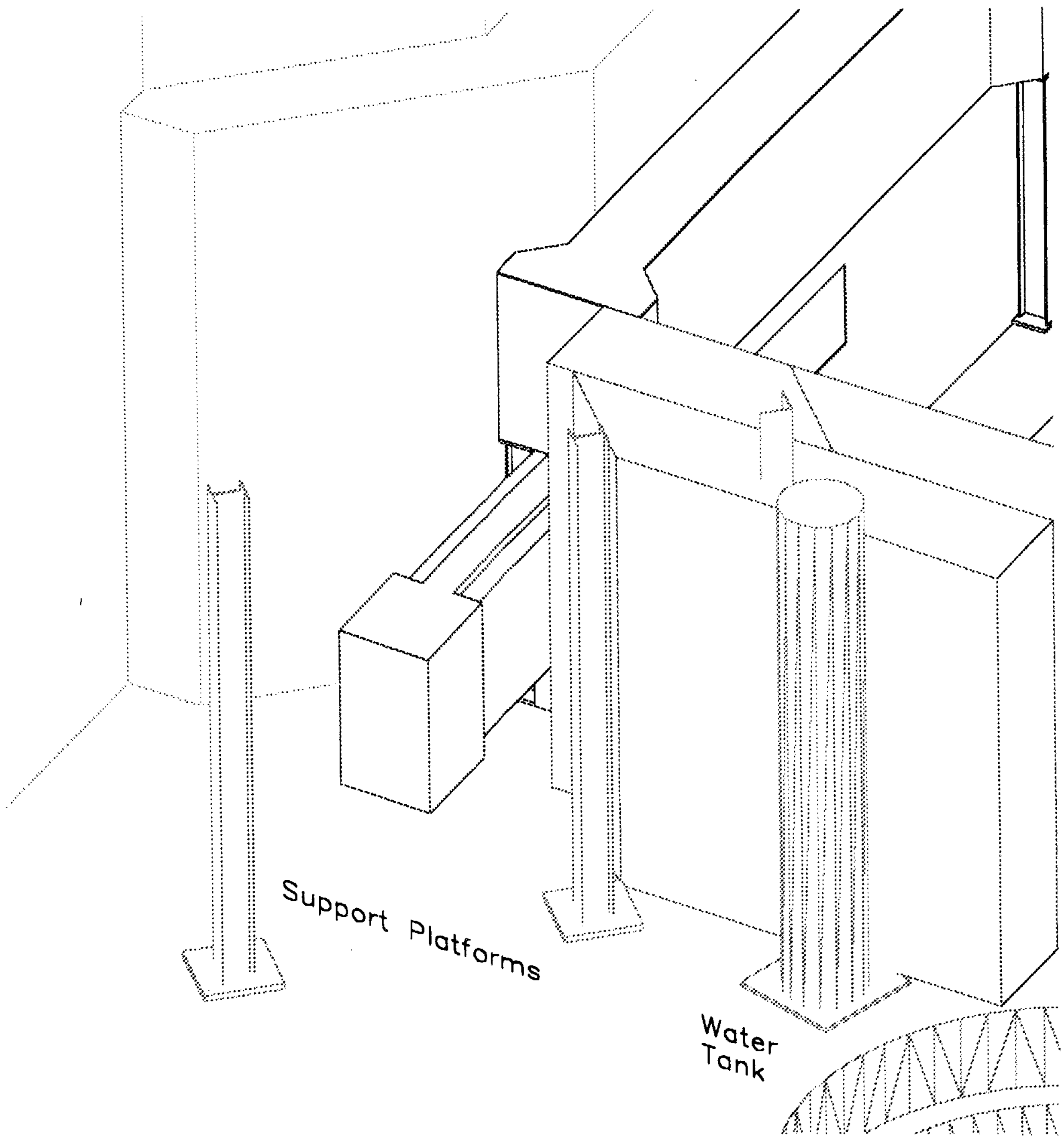


**Figure 5.2.** Isometric View of Extended Shutter.

### 5.2.2 Medical Room Door Suggestions

Although the overhead track and trolleys will be used to move the door, placement of the support columns for the overhead track has yet to be determined. This placement -- and size -- of the support columns depends on the total weight of the door, which is also an unknown, but is in the range of ten to fifteen tons. Door material, or materials, still need to be resolved, although the author believes that the all-steel door is the optimal medical room door design. There are three reasons for this choice: the all-steel door is the thinnest of all door options shown in Tables 3.1 and 3.2 (thereby using a minimum of floor space), it attenuates gamma rays and fast neutrons better than any other material considered (except for lead, which as a single door material was ruled out due to weight) and is of moderate weight, 12.9 tons ( M.N. Ledesma (in her M.S. thesis *Medical Room Design for a Fission Converter-Based Boron Neutron Capture Therapy Facility*, also believed the all-steel door to be the optimal design for a medical room door)

The weight of the all-steel door is well below the polar crane's weight limit of 20 tons; additionally, it should be a relatively straightforward matter in locating and installing a power source that will efficiently open and close the door.

### 5.2.3 Water Shutter Suggestions

The water shutter fluid circuit analysis (in Appendix E) provides insight on main pump size and tube and pipe diameter sizes, and Figure 4.1 displays the water shutter fluid circuit; however, what remains to be determined are the exact placements of both pumps (main and clean-up), the location of the runs of both piping and tubing, and the material that the supply tank will be made of. Also as yet undetermined is the placement of the supply tank in amongst the FCB's heat removal equipment on top of the new medical room.

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# Appendix A:

# Fast Shutter Design Alternatives

## A.1 Vertical Fast Shutter

A vertically moving shutter (similar vertical geometry to the cadmium shutter) was the first fast shutter alternative design considered. This shutter resembles a sluice gate in that it is raised to allow for the passage of neutrons and lowered to stop the flow of neutrons. In this respect, it has a gravity-driven fail-safe feature. In other words, upon loss of power (or other emergency), the shutter fails in the closed position. This feature automatically protects the patient and medical personnel from excessive radiation levels inside the medical room.

The initial concept for the vertically moving fast shutter placed it inside the reactor biological shield, in the thermal column area known as the 'cave.' Inside the cave, shutter travel length is constrained by the reactor floor and the roof of the cave. This initial location of the shutter provided inadequate shielding for the patient with the shutter in the open position.

With the fast shutter in its open position, undesirable radiation exposure would have been delivered to the patient due to radiation streaming under the shutter, as shown in Figure A.1.1.

Likewise, with the fast shutter in the closed position, inadequate shielding would have resulted with the shutter sitting on the reactor floor, as shown in Figure A.1.2. An unimpeded flow of radiation over the top of the shutter would have put dose rates inside the medical room at much greater than one mrem/hr.

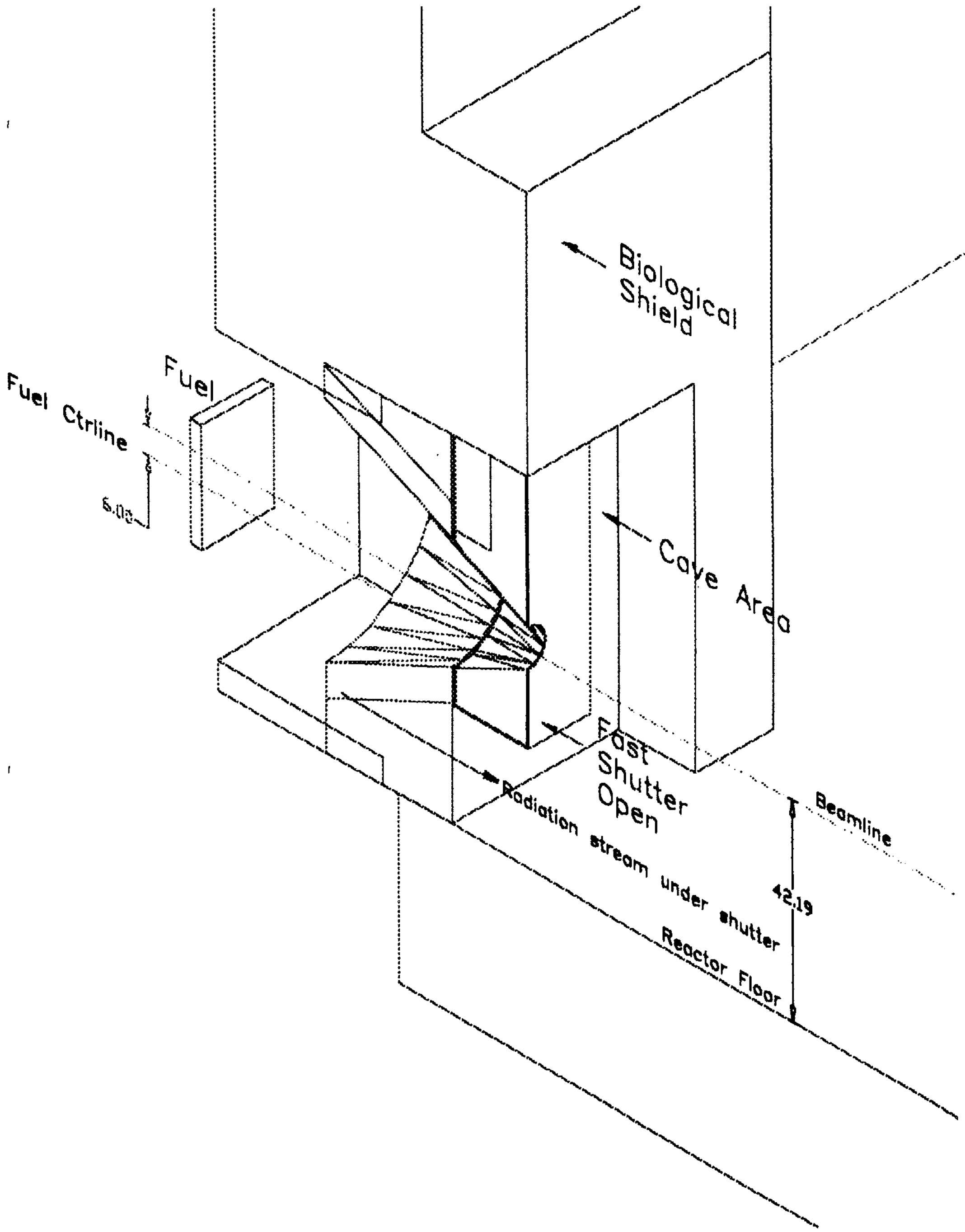



**Figure A.1.1.** Open Fast Shutter inside Cave.

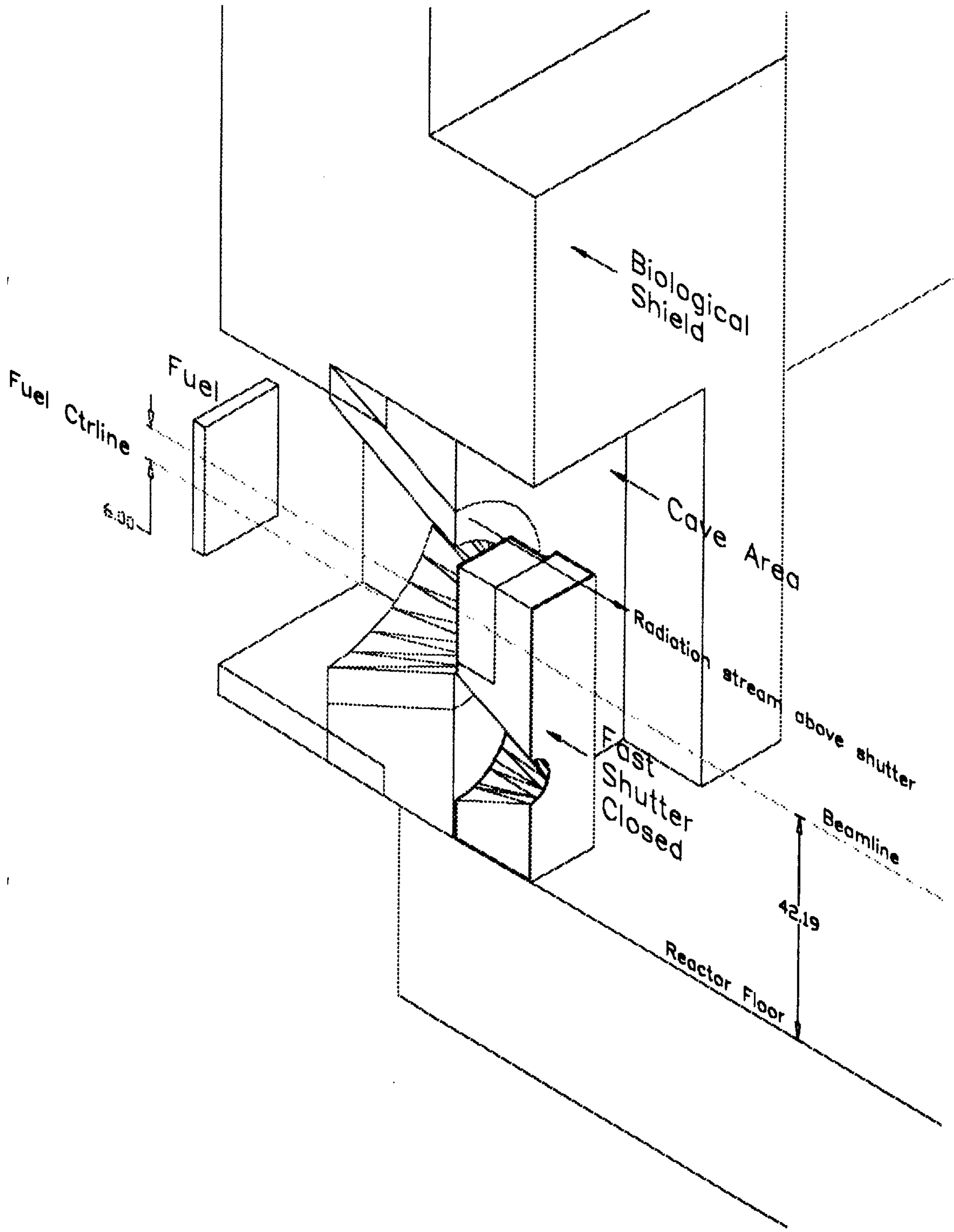



**Figure A.1.2.** Closed Fast Shutter inside Cave.

The solution to these shielding problems was to bring the fast shutter outside of the cave, placing the rear of the shutter flush with the face of the reactor biological shield. Monte Carlo N-particle (MCNP) calculations (using MCNP version 4.a) showed that this placement of the shutter and hence, the patient, further away from the source of the radiation had an acceptable effect on neutron beam intensity.

Outside the cave, an unlimited amount of material could be added to the top of the shutter, enhancing the shielding effect in the shutter closed position, as shown in Figure A.1.3. Nevertheless, the reactor floor still limited the shielding effect in the shutter open position. Radiation streaming under the shutter continued to be a problem (see Figure A.1.4). Also, radiation leakage through the edge of the shutter aperture and near the top of the aperture continued to be a problem.

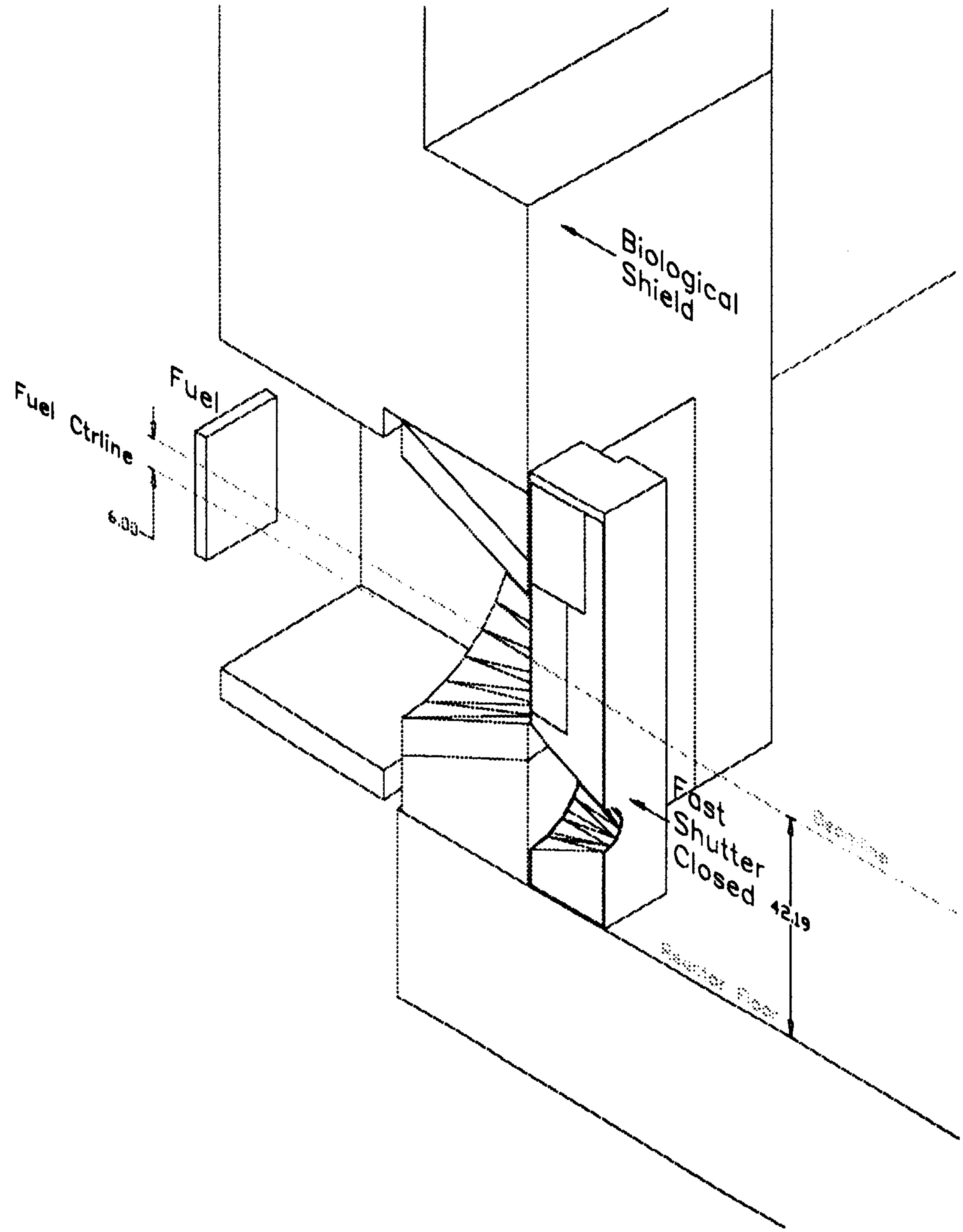



**Figure A.1.3.** Closed Fast Shutter outside Cave.

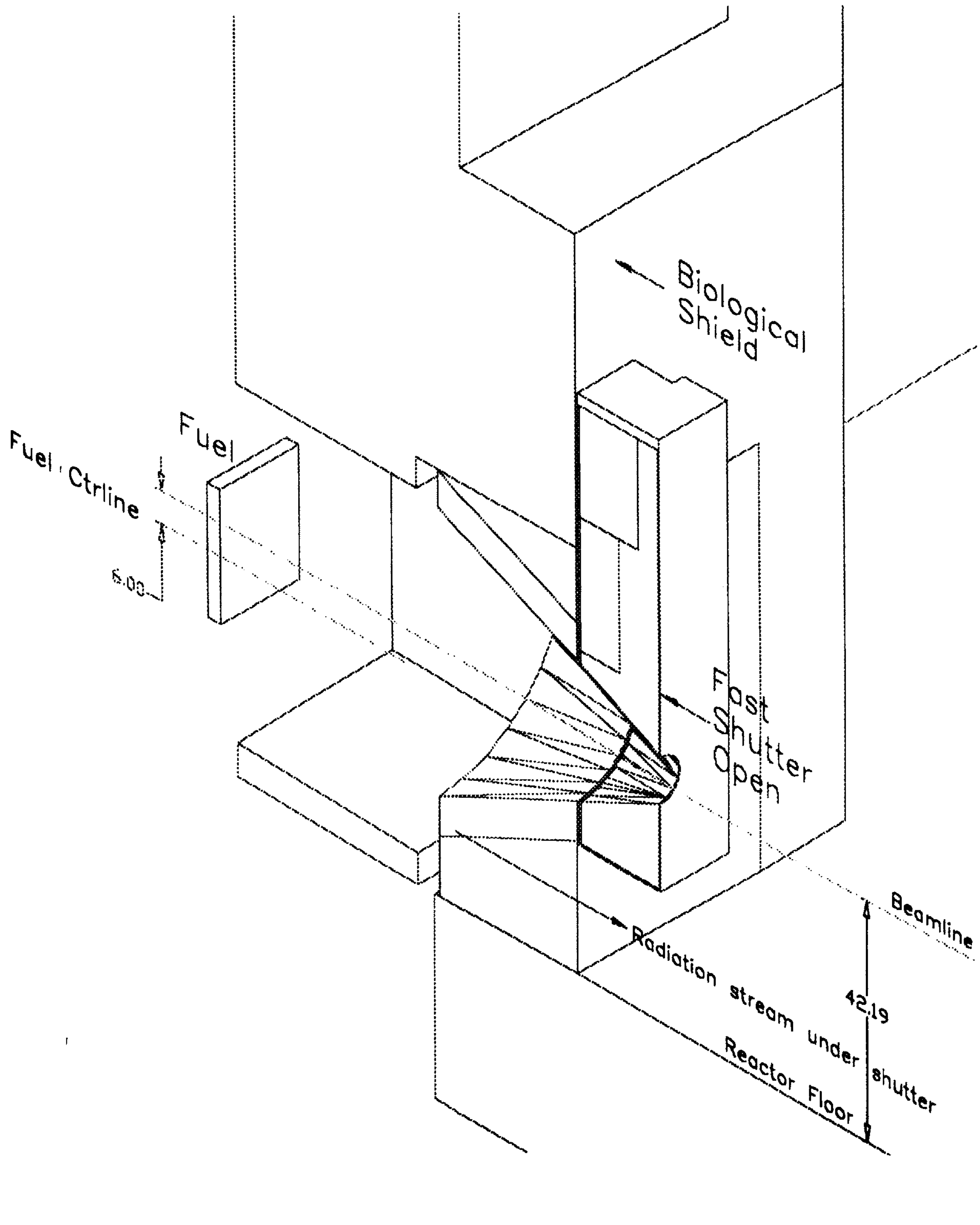



**Figure A.1.4.** Open Fast Shutter outside Cave.

One potential solution to this problem of radiation streaming under the shutter in the open position was to slide a temporary kneewall, or board, into place to block the radiation streaming into the medical room. However, this kneewall would necessarily interfere with the patient positioning system, making it an unlikely candidate to solve the shielding problem.

One other solution to the shielding problem, that of mining a hole into the reactor floor, was identified. This hole would enable lengthening the shutter, through the addition of shielding material placed at the shutter bottom; thereby, radiation streaming under the shutter in the open position would be minimized (see Figure A.1.5). The hole idea was considered to be a superior alternative to the temporary kneewall idea.

In addition to this vertically moving shutter, two circular shutters were identified as potential fast shutter alternative designs. These circular shutters are also mounted outside the cave and are flush with the reactor biological shield, like the vertical shutter. The circular fast shutter idea was first introduced in A. LeGal's and M. Ledieu's unpublished report *Beam Shutter Design and Medical Room Design*, MIT, September, 1995. Appendix A.2 goes into more detail of these circular shutters.

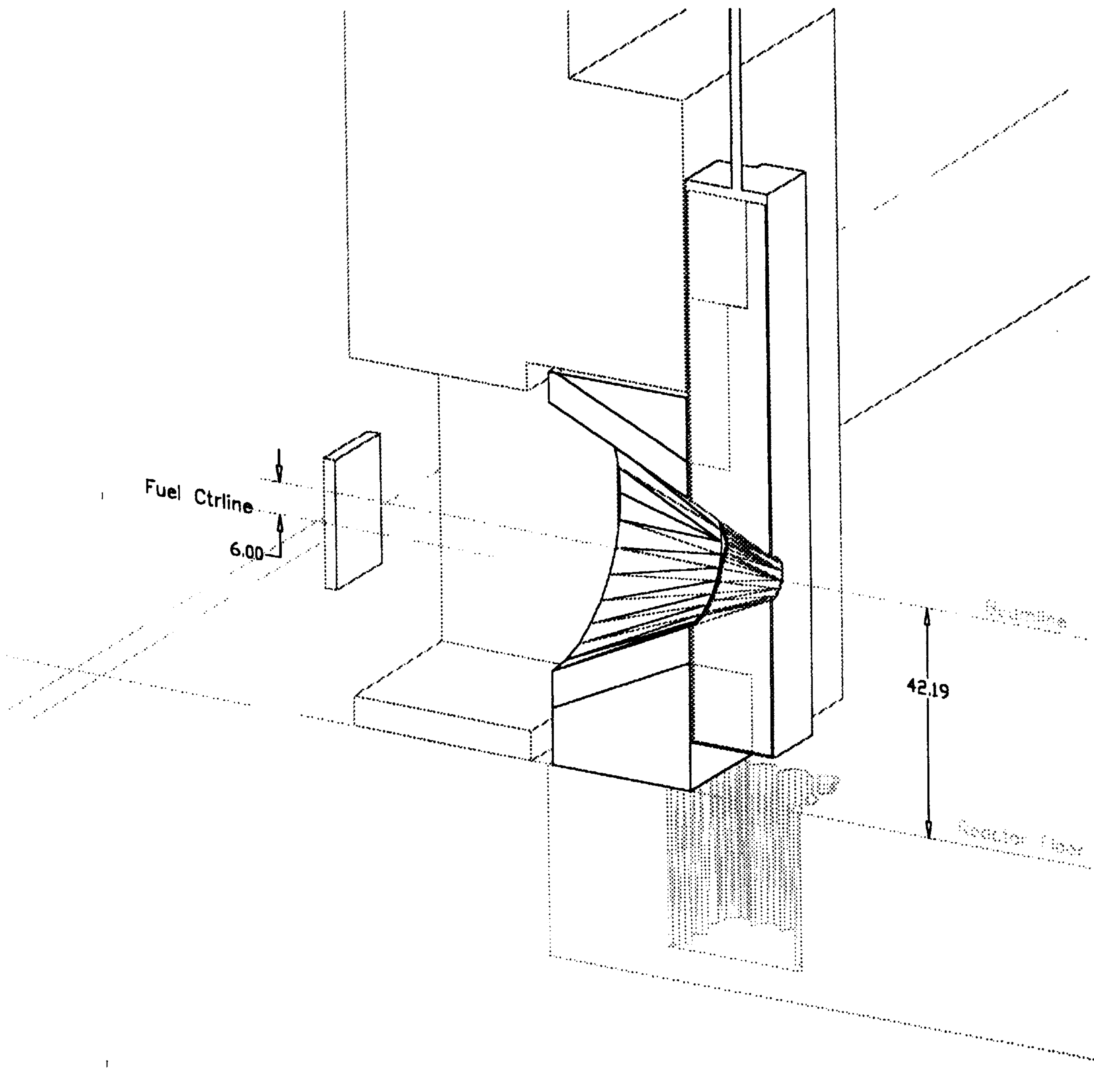



**Figure A.1.5.** Open Fast Shutter Showing Floor Hole.

## A.2 Circular Fast Shutters

One circular shutter, named the support wheel circular shutter (SWCS), is mounted on two support wheels which are themselves mounted by way of support stands to the reactor floor. One portion of the SWCS is of a higher-density material than the other. In other words, the SWCS is purposely unbalanced to maintain the gravity-driven fail-safe feature that the vertical shutter has.

The other circular shutter, named the center bearing circular shutter (CBCS), is mounted on a bearing situated at the axis of rotation. As with the SWCS, the CBCS is purposely unbalanced to provide the gravity-driven fail-safe feature.

Figures A.2.1 and A.2.2 show these two circular shutters and the remainder of Appendix A.2 contains the studies done on the two circular shutters, including their kinematics.

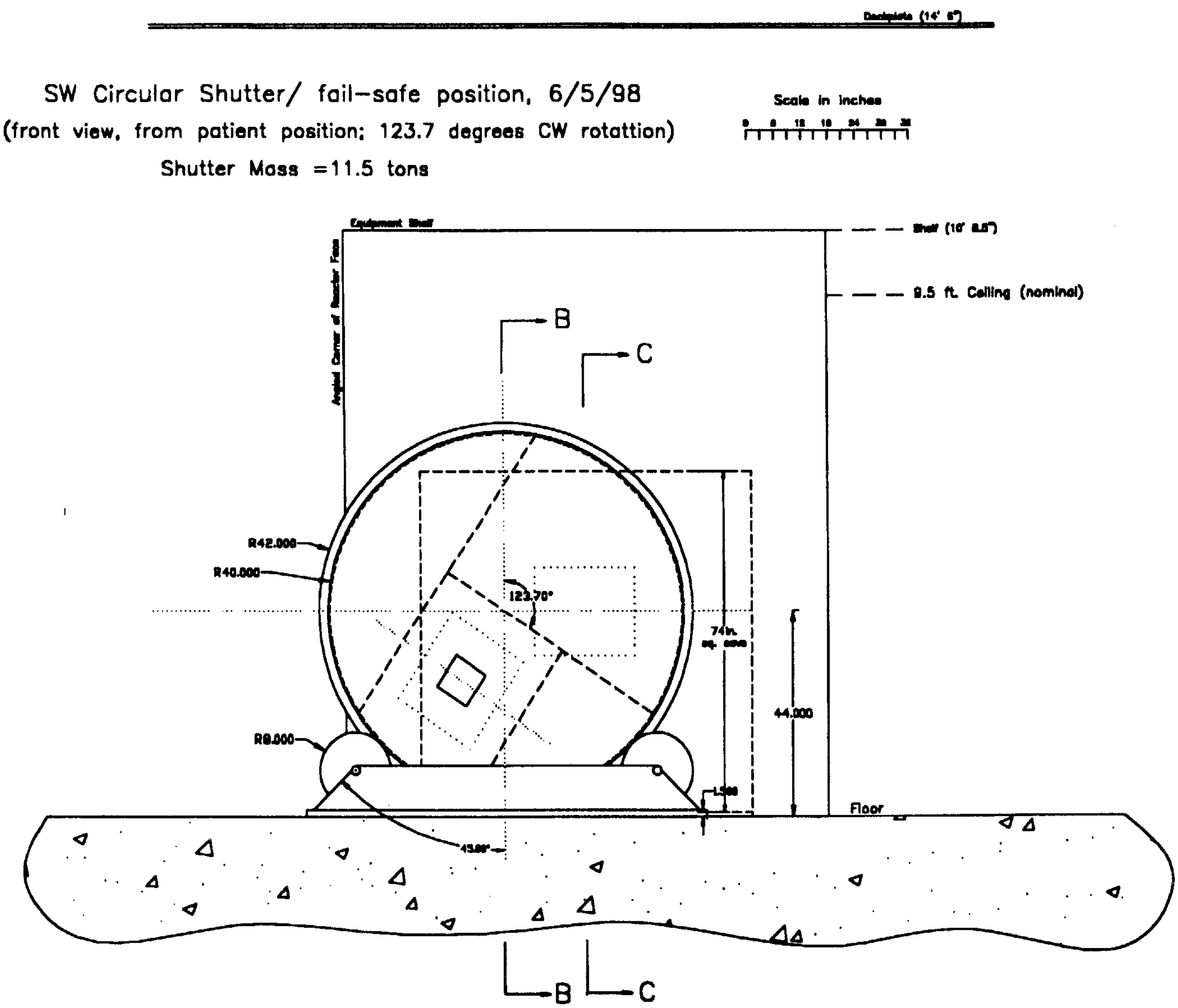



**Figure A.2.1.** Support Wheel Circular Shutter.

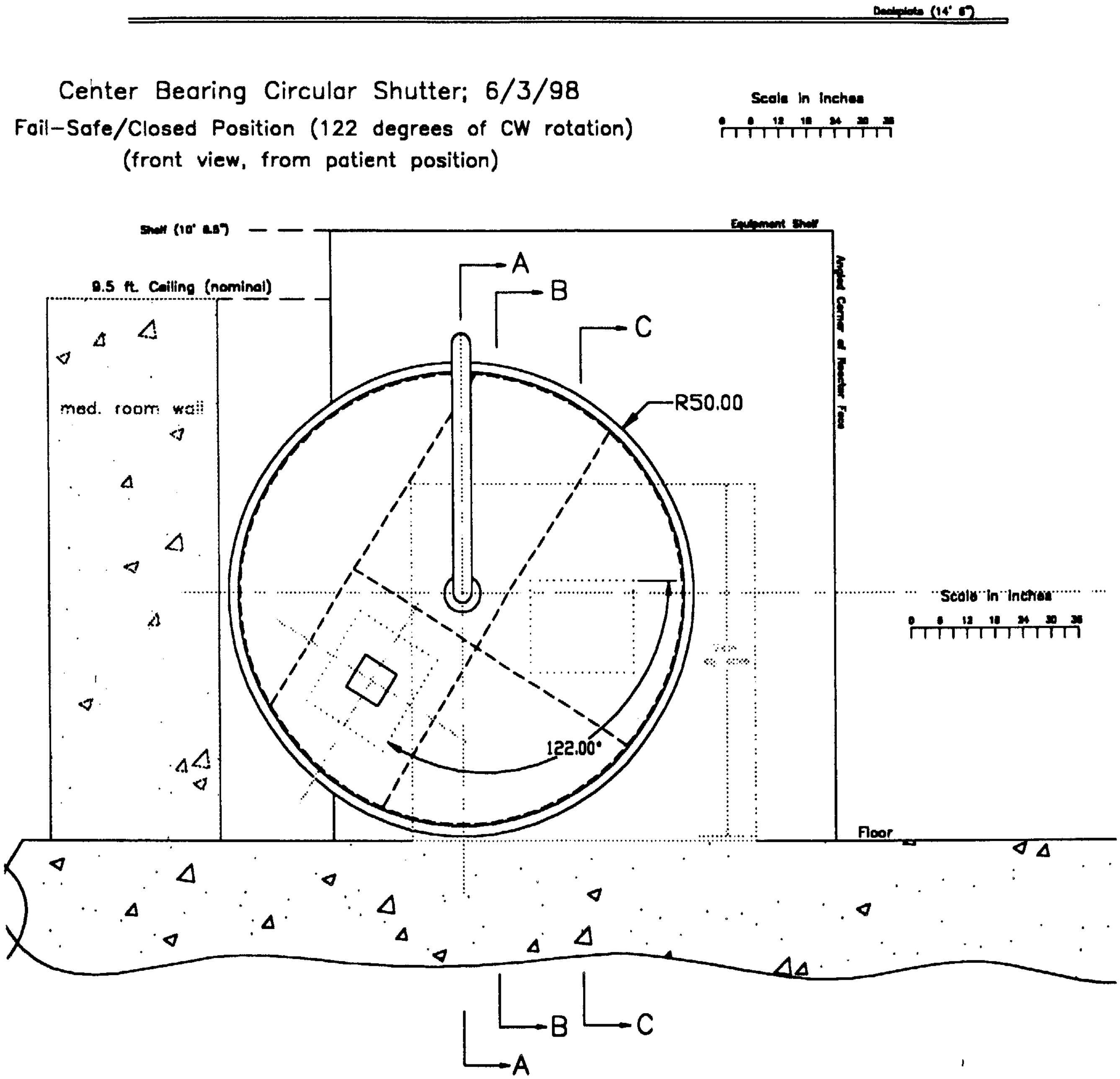



**Figure A.2.2.** Center Bearing Circular Shutter

## Support Wheel Circular Shutter Kinematics:

*(The following analysis is done only for the SWCS; it is similar for the center bearing circular shutter)*

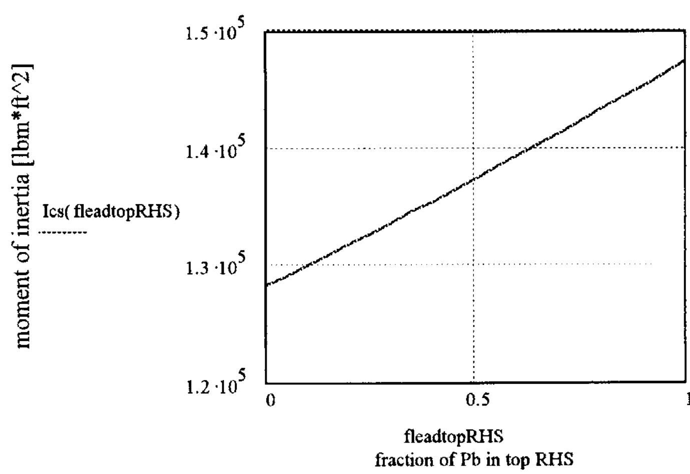
$\theta max := \pi$ rad : amount of rotation  $T := 10$ sec : time to travel

$g := 32.2 \ \frac{ft}{s^2}$  $rcm(fleadtopRHS) := \frac{rbarcs(fleadtopRHS)}{12}$ ft  $D := \frac{2 \cdot Rmax}{12}$ ft

$D = 7$ ft

$gc := 32.2 \ \frac{ft \cdot lbm}{lbf \cdot s^2}$

$$Ics(fleadtopRHS) := 2000 \cdot mcstotal(fleadtopRHS) \cdot \left(\frac{D^2}{8} + rcm(fleadtopRHS)^2\right) \quad lbm \cdot ft^2$$




$t1 := 0, .1 .. T$

$t2 := T, T + .01 .. 2 \cdot T$

$$\theta 1(t1) := \frac{\theta max}{2} \cdot \sin\left(\left(\frac{\pi}{T} \cdot t1 - \frac{\pi}{2}\right)\right) + \frac{\theta max}{2}$$

$$\theta 2(t2) := \frac{\theta max}{2} \cdot \cos\left[\left(\frac{\pi}{T}\right) \cdot (t2 - T)\right] + \frac{\theta max}{2}$$

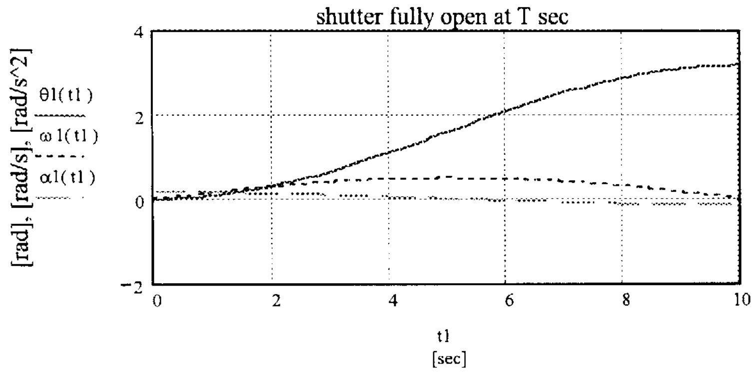
$$\omega 1(t1) := \left(\frac{\pi \cdot \theta max}{2 \cdot T}\right) \cdot \cos\left(\frac{\pi \cdot t1}{T} - \frac{\pi}{2}\right)$$

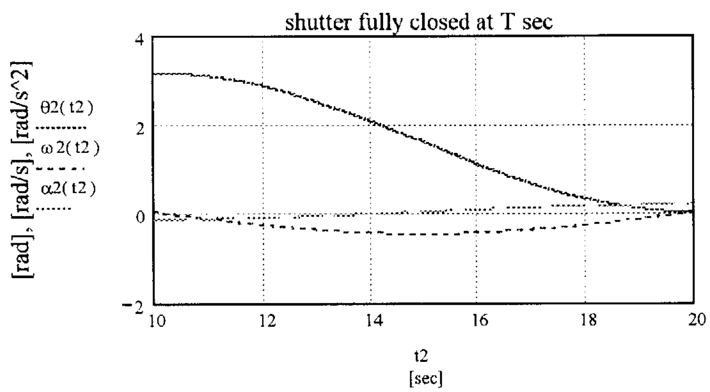
$$\omega 2(t2) := -\left(\frac{\pi \cdot \theta max}{2 \cdot T}\right) \cdot \sin\left[\left(\frac{\pi}{T}\right) \cdot (t2 - T)\right]$$

$$\alpha 1(t1) := -\left(\frac{\pi}{T}\right)^2 \cdot \left(\frac{\theta max}{2}\right) \cdot \sin\left(\frac{\pi \cdot t1}{T} - \frac{\pi}{2}\right)$$

$$\alpha 2(t2) := -\left(\frac{\pi}{T}\right)^2 \cdot \left(\frac{\theta max}{2}\right) \cdot \cos\left[\left(\frac{\pi}{T}\right) \cdot (t2 - T)\right]$$

## Angular Positions, Speeds, and Accelerations




**SW CS External Force Applied:**

Force Applied -- modeled as tension on LHS of shutter -- (a function of T and fraction of lead in top RHS segment -- flt):

$flt := .75$

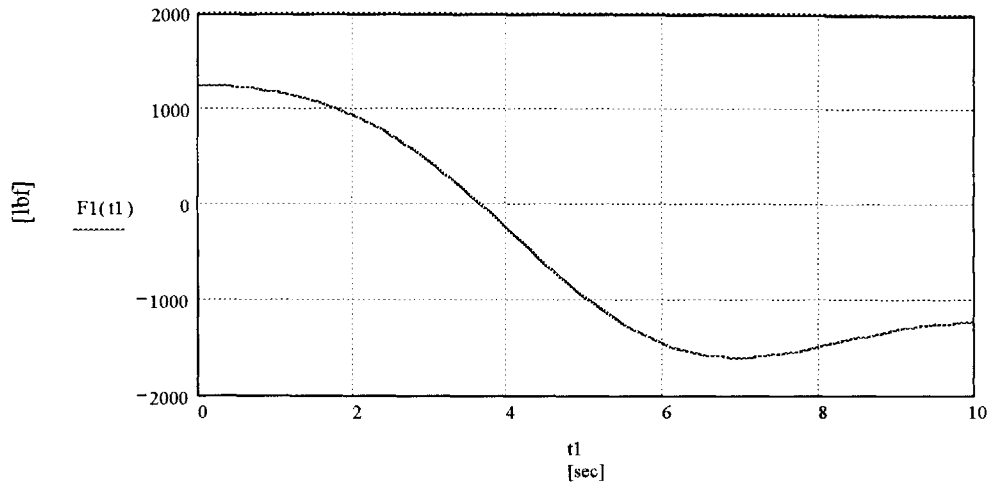
$\phi open := \phi barcs(flt) \cdot \frac{\pi}{180}$ $\quad rcmopen := \frac{rbarcs(flt)}{12}$ $\quad m := 2000 \cdot mcstotal(flt)$ $\quad I := Ics(flt)$

$\phi open = 0.588$ rad $\quad rcmopen = 0.264$ ft $\quad m = 2.296 \cdot 10^{4}$ lbm $\quad I = 1.422 \cdot 10^{5}$ $lbm \cdot ft^{2}$

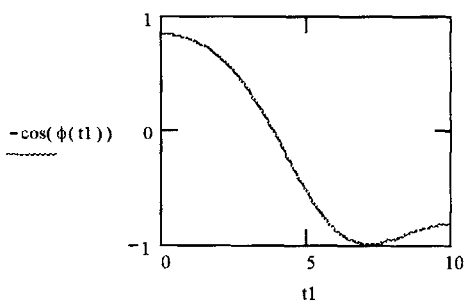
$\phi(t1) := \phi open - \pi + \theta 1(t1)$

$$F1(t1) := \frac{m \cdot g \cdot rcmopen \cdot (-\cos(\phi(t1))) - I \cdot \alpha 1(t1)}{\left(\frac{Rmax}{12}\right) \cdot gc}$$

## Force Applied as a Function of Time




$F1(0) = 1.245 \cdot 10^{3}$ $F1(.7 \cdot T) = -1.613 \cdot 10^{3}$ $F1(T) = -1.245 \cdot 10^{3}$




$$tFmax := \frac{\operatorname{asin}\left[-1 + \frac{\left[\operatorname{asin}\left[\frac{\left[-I \cdot \left(\frac{\pi}{T}\right)^{2}\right]}{m \cdot g \cdot rcmopen}\right] + \pi - \phi open\right]}{\frac{\theta max}{2}}\right] + \frac{\pi}{2}}{\frac{\pi}{T}}$$

$tFmax = 6.969$

$F1(tFmax) = -1.613 \cdot 10^{3}$ lbf

## Energy Approach to find max SWCS speed and time to close in a "free-fall" situation

(1st-order, linear distribution)

$\phi barcs(flt) = 33.674$ degrees

$$zmax := rcmopen \cdot \left[1 + \sin\left[(\phi barcs(flt)) \cdot \frac{\pi}{180}\right]\right]$$

$zmax = 0.41$ ft

$$Umax := \frac{m \cdot g \cdot zmax}{gc}$$

$Umax = 9.417 \cdot 10^{3}$ ft·lbf

$Kmax := Umax$

$$\omega max := \left(\frac{2 \cdot m \cdot g \cdot zmax}{I}\right)^{.5}$$

$\omega max = 2.065$ $\frac{rad}{s}$

$$vmax := \omega max \cdot \frac{D}{2}$$

$vmax = 7.227$ $\frac{D}{2} = 3.5$

$$x := \left(\frac{D}{2}\right) \cdot CW(.75) \cdot \left(\frac{\pi}{180}\right)$$

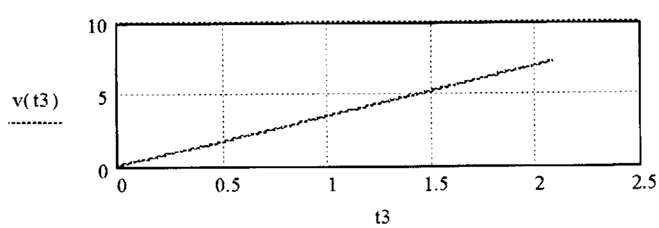
$x = 7.555$ ft

$$tmin := \frac{x}{(.5 \cdot vmax)}$$

$tmin = 2.091$ sec

$t3 := 0, .01 .. tmin$

$$v(t3) := \left(\frac{vmax}{tmin}\right) \cdot t3$$



## A.3 Slanted Fast Shutter

The design process, being an iterative one, does not always proceed in a straightforward fashion, yielding a clear-cut solution. This is true in the case of the fast shutter. What was originally intended to be a solution to the vertical fast shutter's shielding problem -- cutting a hole in the reactor floor -- turned out to have detrimental side effects (decreased floor strength). For this reason, additional alternative designs needed to be researched. An additional design requirement is that the new alternative design cannot penetrate the reactor floor by more than an inch. This requirement is necessary since the steel reinforcement bars are situated just an inch below the surface of the reactor floor. For this reason, a slanted shutter was investigated.

This type of shutter design is slanted on an angle of eighteen degrees with the reactor floor (see Figure A.3.1). At this angle, it would penetrate the reactor floor by $\approx$ three-fourths of an inch, missing the steel reinforcement bars by $\approx$ one-fourth of an inch.

An advantage to this slanted shutter is that it maintains part of the gravity-driven fail-safe feature that the vertical shutter had. However, a disadvantage to the slanted shutter is that it would introduce exotically shaped side, or end, blocks – similar to the situation with the circular shutters. Again, difficulties in manufacturing and installing the side blocks with any degree of precision would be encountered. Another disadvantage to this slanted shutter would be found in the mounting of its power source. If the power source were mounted on the left side, it would require a special platform, which would necessarily interfere with the existing platform on that side. If the power source were mounted on the right side, it would infringe upon the space for the control area.

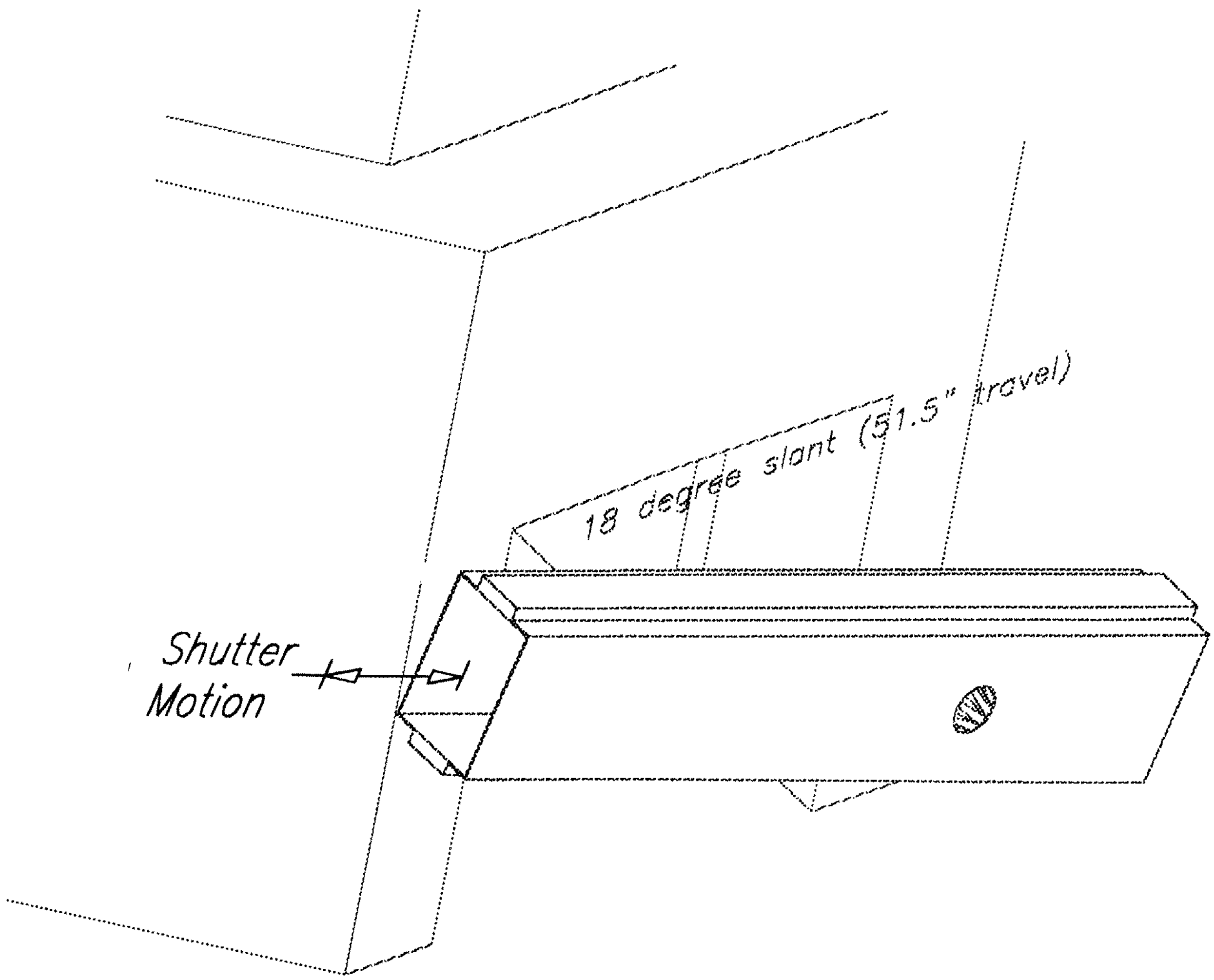



**Figure A.3.1.** 18 Degree Slanted Shutter.

# Appendix B:

# Fast Shutter Design Methodology,

# Decision Criteria,

# and Decision Matrix

## B.1 Fast Shutter Design Methodology

The methodology used in this phase of the design work, that phase being the decision-making process between the three fast shutter alternative designs, is adopted from a Pahl and Beitz approach. This approach involves the construction of a decision matrix. In the matrix, several decision criteria are formulated and assigned specific weights. Each alternative design is judged on how well, relatively speaking, it satisfies each decision criteria. Then each alternative design's specific weights and relative comparisons are multiplied to yield a given weight factor for each decision criteria. The weight factors are then summed to give an indication of how well each alternative design satisfies all the decision criteria. Appendix B.2, Decision Criteria, and Appendix B.3, Fast Shutter Decision Matrix, explain this process in greater detail.

## B.2 Fast Shutter Decision Criteria

To help facilitate a choice between the three fast shutters -- vertical, SWCS, and CBCS – decision criteria are identified. These criteria are chosen shutter features that most strongly satisfy the design goals and requirements. The criteria will aid in making the decision as to which of the three fast shutters alternative designs will be pursued into the conceptual design phase. The decision criteria are as follows: shielding, cost, reliability, safety of closure/emergency closing feature, ease of use, speed, and ease of installation/removal.

A formal decision matrix is then constructed. This decision matrix is shown in its entirety in Appendix B.3. The various weights designated to each decision criteria are formulated in a somewhat iterative process. This process involved independent research, but mainly was based on interviewing the various technicians involved in the construction, installation, operation, and maintenance of the fast shutter.

Based on the above input, the vertical shutter was identified as the most likely candidate to pursue into the conceptual design phase. As shown in Appendix B.3, this vertical shutter choice was driven by its superiority with the decision criteria of cost, ease of use, emergency closing capability, and ease of installation/ removal.

Before the vertical shutter could be conceptualized, however, it became apparent that the proposed hole to be mined out of the reactor floor would necessarily cut several important steel reinforcement bars (see Figures B.2.1 and B.2.2). An outside professional structural engineer (from Goldenberg Associates)

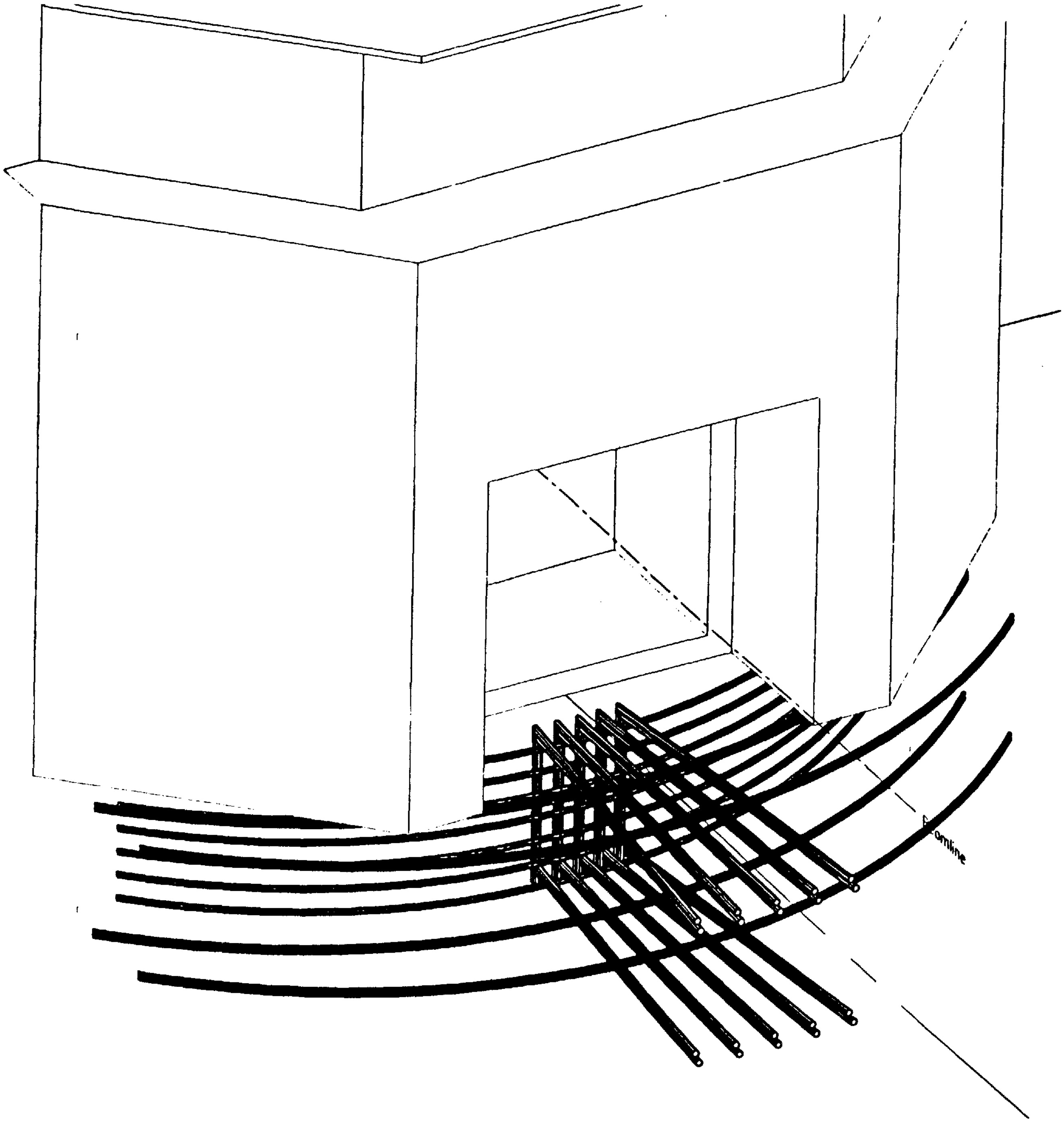


**Figure B.2.1.** Sections of Reactor Floor Steel Reinforcement Bars.

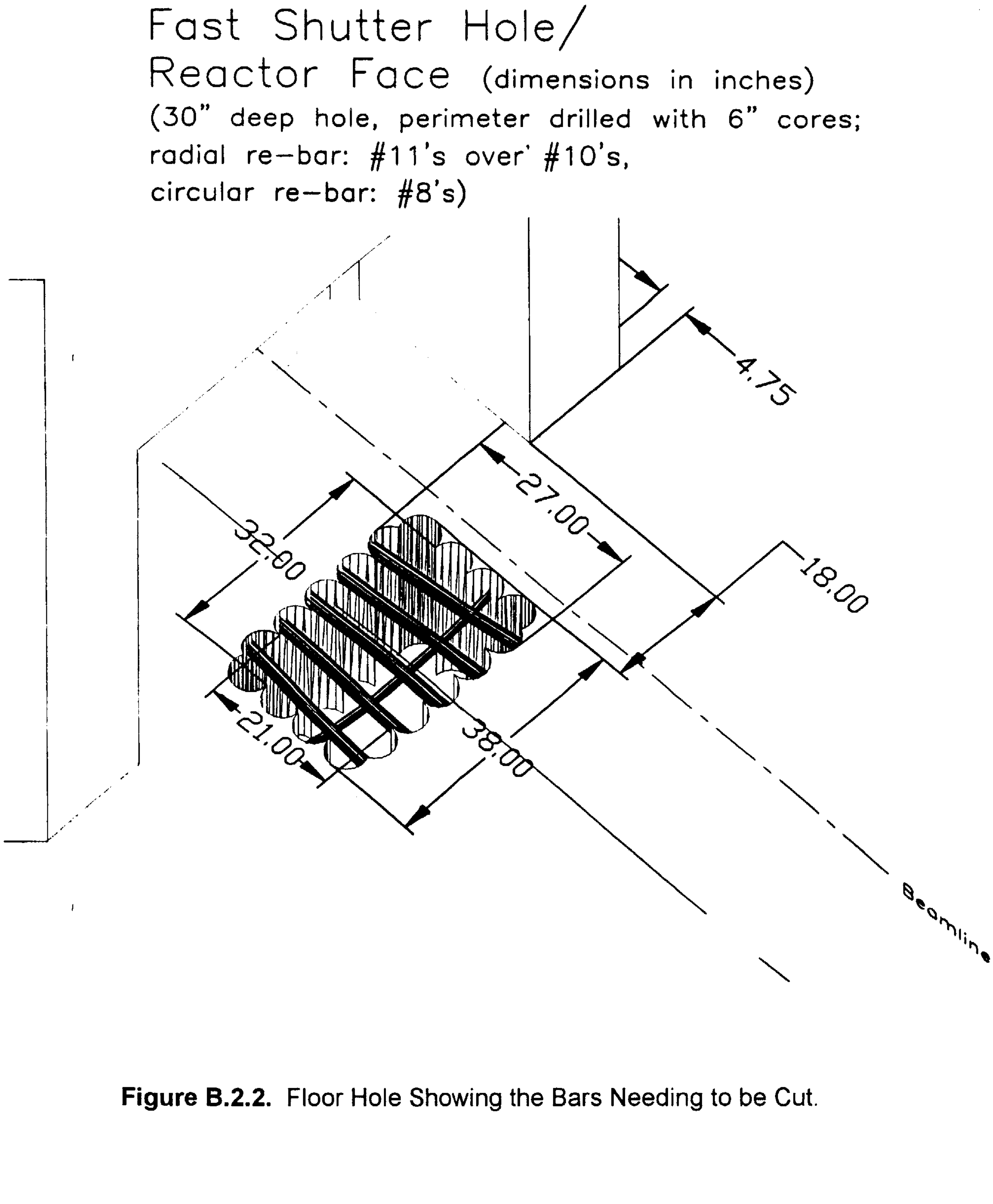



**Figure B.2.2.** Floor Hole Showing the Bars Needing to be Cut.

was hired to analyze this situation. His conclusions were that the proposed hole and sliced reinforcement bars would reduce the load carrying capacity of the reactor floor by 35 percent. Since this structural impairment would occur in the area where most of the tonnage of the medical room walls would be located, a decision was made to forgo digging the hole for the vertical shutter. Moreover, this decision was aided by the fact that the NRL Safeguards Committee would have had to approve such drastic floor rating modifications, and this would have used up precious time in the design and construction of the shutter.

Since the vertical shutter, without the extra length to be inserted into the floor, is shielding deficient in the open position, other possible alternative designs needed to be looked into. These designs included a slanted shutter and the horizontally moving shutter. The two circular shutters were not revisited for reasons of their overall massiveness and complexity. Moreover, the circular shutters would have required odd shaped side blocks, which would have been difficult to manufacture and install with any degree of precision.

## B.3 Fast Shutter Decision Matrix

## Fast Shutter Alternative Designs and Decision Criteria

| Shutter Design → <br> Decision Criteria ↓ | Vertical (VS) ~5.5 tons | Support Wheel Circular (SWCS) ~11.5 tons | Center Bearing Circular (CBCS) ~16 tons |
| --- | --- | --- | --- |
| 1. Shielding | -Still a question mark -- above the shutter in the closed position, below the shutter in the open position.<br>-May require a portable/flexible kickboard below the shutter in the open position, which may hinder patient positioning.<br>-Requires 2 side shield blocks; however, these also function as guides/constraints for VS travel. | -Relatively equivalent to VS shielding.<br>-Support wheels will need to be shielded and this may be awkward to accomplish, adversely affecting patient positioning.<br>-Would also require some type of side/ "circumference" block(s) -- of a more exotic geometry than VS's side blocks -- these would not function as guidance, but act as an emergency constraint in case of shutter unbalance/toppling towards the patient. | -Even better shielding than SWCS due to larger radius.<br>-The 'fail-safe' position could also be the 'closed' position because the beam port will be outside the cave (at 122 degrees CW rotation from the 'open' position).<br>-Like SWCS, would also require the "circumference" block. |

## 2. Ease of Use

### VS

-Electro-hydraulics system – push-button operation. Movement is straight up to open, straight down to close; limit switches determine the kinematics.

### SWCS

-Since 180 degrees of rotation (see Figure 1) is required, this demands that a force be applied in one direction (or on one side of the shutter) for part of the rotation and then in the other direction (or on the other side of the shutter) for the completion of the rotation.

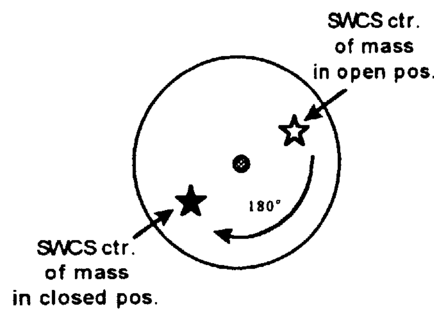



**Figure 1.** SWCS center of mass rotation.

-To accomplish the required kinematics, a hydraulics system comparable to VS's -- or

### CBCS

-122 degrees of rotation -- see Figure 2 -- implies that force needs to be exerted in only one direction (or on a single side of the shutter), as opposed to both directions (or both sides) for SWCS operation.

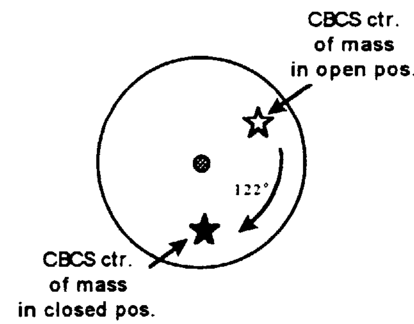



**Figure 2.** CBCS center of mass rotation.

-Pull up on RHS to open shutter, hold for treatment, and release tension to close shutter -- allowing the Prony (friction)

| 2. Ease of Use, cont'd. | VS | SWCS | CBCS |
| --- | --- | --- | --- |
| | | synchronized electric hoists on each side of the shutter -- would be needed. This implies a more complex (or equally expensive) power source than both VS and CBCS -- especially to deliver the 10-second shutter opening time. | brake to mechanically 'damp' the free-fall motion.<br>-To deliver the ten-second shutter opening time would necessitate a more expensive motive force than an 'off-the-shelf' (~$2K) electric hoist, i.e. a hydraulics system or an electric motor. |
| **3. Safety of Closure/Fail-Safe Feature** | -Malfunctions in the hydraulic valving would impede safe closing, as would obstructions in the hole mined out of the reactor floor.<br>-In case of emergencies, polar crane could be used to lift/ jar shutter out of its jammed position. | -Would require very reliable support wheels – a seized, broken, or flattened wheel would preclude safe shutter travel.<br>-Need the worm gear in the electric hoist to release ('kick out' of gear) upon loss of power (or other emergencies) to allow the fail-safe to activate (off-the-shelf electric hoists do not have this feature).<br>-The Prony (friction) brake can be used as an inexpensive mechanical | -Very dependable bearings would be needed; however, in the advent of a bearing failure, since the weight of the shutter bears on the shaft through the axis (as opposed to two support wheels on the rim of the shutter), this would make it easier than SWCS for a grip on the shutter rim to rotate the shutter out of its stuck position (i.e. brute force polar crane method --moment arm is greater |

| | VS | SWCS | CBCS |
| --- | --- | --- | --- |
| **3. Safety of Closure/Fail-Safe Feature, cont'd.** | | damping system for fail-safe operation. | for CBCS than for SWCS).<br>-Prony brake as an inexpensive damper for fail-safe mode.<br>-Required roller bearings will be more reliable and are more available than SWCS's support wheels. |
| **4. Reliability** | -"Sits" in its hole when not in use; hydraulics system is exposed for easy maintenance; cut-outs in steel plating of shield block allow for visual inspection of coupling between the shutter and the hydraulic cylinder shaft extension.<br>-Hydraulics system needs to deliver a max. force of 10,000 to 11,000 lbf. | -Since a full 180 degrees of rotation is required to open and close the shutter, force needs to be exerted to hold the shutter closed as well as open.<br>-Each support wheel would have to carry close to 6 tons at all times.<br>-Support wheels would need to be shielded (streaming concerns) – this would prevent visual inspection of the wheels.<br>-Maximum force needed would be ~1600 lbf. | -Since the 'fail-safe' position can double as the closed position, the only force exerted would be to open the shutter and to hold it open.<br>-Electric hoist (as with VS's hydraulics system) would need to be very reliable -- however, it could be mounted on the equipment shelf or the med. room roof; either way, it will be exposed for easy maintenance and inspection. |

| | VS | SWCS | CBCS |
|---|---|---|---|
| **4. Reliability, cont'd.** | | | -Maximum force needed would be ~2000 lbf. |
| **5. Ease of Installation and Removal** | -Requires mining a hole in the concrete of the reactor floor – 27" by 18" by 30" deep. There is some uncertainty involved with potential obstructions (pipes, re-bar) in this concrete and, therefore, the ease with which this hole can be dug is unknown.<br>-Polar crane is just right for vertical shutter installation and removal; VS can be dropped vertically into the steel "can" (shield block) and then covered with the top block, making future shutter access possible without ceiling removal. | -Eliminates the need for floor removal.<br>-Although SWCS can be installed and removed with the polar crane, the associated "circumference" block (or blocks) would need to be removed prior to shutter removal; moreover, shutter access would require ceiling removal. | -Same advantage (no floor removal) and disadvantage (circumference block and ceiling removal) as for SWCS.<br>-More complicated insertion and removal procedures than for VS and SWCS, since the shaft of the shutter is supported by both the collimator section and the biological shield.<br>-Communication between CBCS and the collimator section inside the cave is a disadvantage; in addition, shaft protrusion on the med. room side of CBCS may adversely affect patient positioning. |

| | VS | SWCS | CBCS |
|---|---|---|---|
| **6. Speed to Open and Closed Positions** | -Needs to move vertically 37.5" in 10 seconds or less – hydraulics system has already been specified. to deliver this requirement. | -Requires 180 degrees of rotation (~11 ft. tangential displacement), a distance that would be difficult to accomplish -- inexpensively -- in 10 seconds, but is possible.<br>-The 11 ft. linear translation distance could be decreased by applying force closer to the shutter axis; however, this would require the application of more force. | -Requires 122 degrees of rotation (~9 ft. tangential displacement) -- possible in 10 seconds.<br>-As with SWCS, we encounter the same trade-off between 'less time to open' and 'more force needed' (i.e. applying force closer to the axis of rotation lowers the linear translation of the power source -- hydraulics, electric motor -- but, at the same time, increases the power needed). |
| **7. Cost** | ~$6K for the hydraulics system; ~$3Kto $4K for the floor removal.<br>- See Table 1 for VS total cost estimate. | ~$5K to $6K for a hydraulic or a double-motor driven system.<br>~$5K for support wheels and base.<br>- See Table 1 for SWCS total cost estimate. | ~$5K for a custom-built electric hoist that will deliver the required speed and include an emergency release for fail-safe activation.<br>~$5K for bearings and shaft.<br>- See Table 1 for SWCS total cost estimate. |



**7. Cost, cont'd.**

# Shutter Cost Comparison

| Material: | Poly | Lead | Steel | Concrete | | | | |
|---|---|---|---|---|---|---|---|---|
| Quote: | **McMaster-Carr:** High-Density Polyethylene (.949 gm/cc) Sheets; 12" by 24" by 1" thick: $37.03 each; ~$222/ft^3 | **APEC:** $1 per lbm. to pour | **Thypin Steel:** hot rolled steel; 4 ft by 8 ft sheets, 3/8 in. thick: ~$.40 per lb. | **Boston Sand and Gravel :** approximately $100 per cu. yd. ($100 added for delivery) | | | | |
| | Poly [ft^3] | Lead [lbm] | Steel [lbm] | Concrete [cu. yd.] | **Material Cost Estimate:** | **Labor Cost Estimate** (APEC): | ***Total Cost Estimate:** | **Total Weight:** [tons] |
| **VS** mat'l qty: | 3.21 | 7965.8 | 1156 | 0.27 | | | | |
| price: | $713 | $7,966 | $462 | $127 | **$9,268** | **$19,500** | **$38,768** | **5.57** |
| % of total mat'l cost: | 7.7% | 86.0% | 5.0% | 1.4% | | | | |
| **SWCS** mat'l qty: | 8.33 | 16784 | 2122 | 0.36 | | | | |
| price: | $1,849 | $16,784 | $849 | $136 | **$19,618** | **$15,600** | **$45,218** | **10.93** |
| % of total mat'l cost: | 9.4% | 85.6% | 4.3% | 0.7% | | | | |
| **CBCS** mat'l qty: | 15.4 | 22328 | 2804 | 0.91 | | | | |
| price: | $3,419 | $22,328 | $1,122 | $191 | **$27,059** | **$20,800** | **$57,859** | **16.12** |
| % of total mat'l cost: | 12.6% | 82.5% | 4.1% | 0.7% | | | | |

*Excludes costs associated with the necessary side, shield, circumference, and/or top blocks.

# Decision Matrix

| Alternative Design: | Decision Criteria: / Decision Criteria Weight: | Shielding | Ease of Use | Safety of Closure/ Emerg. Closing Feature | Reliability | Ease of Install/ Remove | Speed | Cost | Total |
|---|---|---|---|---|---|---|---|---|---|
| | | 0.2 | 0.1 | 0.15 | 0.15 | 0.1 | 0.15 | 0.15 | 1 |
| **VS** | rc: | 0.85 | 1 | 1 | 1 | 1 | 1 | 1 | |
| (Vertical) | wf: | 0.17 | 0.1 | 0.15 | 0.15 | 0.1 | 0.15 | 0.15 | **0.970** |
| **SWCS** | rc: | 0.75 | 0.8 | 0.9 | 0.9 | 0.9 | 1 | 0.8 | |
| (Support Wheel Circular) | wf: | 0.15 | 0.08 | 0.135 | 0.135 | 0.09 | 0.15 | 0.12 | **0.860** |
| **CBCS** | rc: | 1 | 0.9 | 1 | 1 | 0.8 | 1 | 0.75 | |
| (Center Bearing Circular) | wf: | 0.2 | 0.09 | 0.15 | 0.15 | 0.08 | 0.15 | 0.1125 | **0.933** |

***key:***

**Decision Criteria Weight:** these values signify the importance, or contribution, of each decision criteria to the overall shutter design; they sum to 1.

**rc:** "relative comparison." For each decision criteria, one or more alternative shutter designs are designated as the standard in performance (rc=1); the remaining alternative designs are then rated comparatively, on a scale from 0 to 1.

**wf:** "weight factor." This is the product of respective decision criteria weights and relative comparisons for each alternative design. The wf are summed, for each alternative, to provide an indication of how well that design satisfies the overall design requirements.

The "**total**" column contains the sum of the pertinent rows; for the VS, $\Sigma$ wf=.97 -- indicating that it would be the optimal alternative design to pursue into the embodiment stage.

# Appendix C:

# Horizontal Shutter Stresses and Deflections

## Horizontal Shutter: Max Bending Moment, Max Bending Stresses, and Max Deflection

***Goal:*** *Find the minimum amount of steel to wrap the shutter in to prevent excessive bending stresses and deflections*

***Assumptions:*** **Model the shutter as a hollow steel beam with a gravity load inside (of lead, concrete, and poly)*
**Shutter height is 50 in. (this is the minimum, which will give conservative estimates for stress, $\sigma$ and deflection, $\delta$ )*
**Rectangular poly and lead segments, cylindrical hole of diameter Davg=(Dfront+Dback)/2*

***Shutter dimensions:***

$h := 50 \cdot in$

$L := 128 \cdot in$

$t := 15.75 in$

$davg := \dfrac{22.88 in + 20 \cdot cm}{2}$

$davg = 15.377 \cdot in$

$rc := \dfrac{davg}{2}$ $\quad rc = 7.689 \cdot in$

:average radius of the collimator portion of the shutter

$gc := 32.2 \cdot \dfrac{ft \cdot lb}{lbf \cdot sec^2}$

***Steel thicknesses:***

$ts := .25 \cdot in$ *ts is the thickness of the steel, sides and top of shutter*

$tb := .25 \cdot in, .3 \cdot in .. 1 \cdot in$ *tb is the thickness of the steel, bottom of the shutter*

***Segment lengths: The shutter is split into 5 segments, lengthwise; each segment is analyze separately***

$\Delta x1 := (39 \cdot in - rc)$ $\quad \Delta x1 = 31.311 \cdot in$

$\Delta x2 := 2 \cdot rc$ $\quad \Delta x2 = 15.377 \cdot in$

$\Delta x3 := (71.93 in - 39 \cdot in - rc)$ $\quad \Delta x3 = 25.241 \cdot in$

$\Delta x4 := 34.14 in$

$\Delta x5 := (128 in - 106.07 in)$ $\quad \Delta x5 = 21.93 \cdot in$

***Segment Volumes:***

$Vc1 := h\cdot .75\cdot t\cdot (39\cdot in - rc - 6\cdot in)$ :volume of concrete in segment 1

$Vpb1 := h\cdot t\cdot (39\cdot in - rc) - Vc1$ :volume of lead in segment 1

$Vst1(tb) := \Delta x1\cdot ((h + ts + tb)\cdot (t + 2\cdot ts) - h\cdot t)$ :volume of steel in segment 1

$Vcircle := \pi \cdot t\cdot (rc)^2$ :volume of the hole in segment 2

$Vpb2 := h\cdot t\cdot \Delta x2 - Vcircle$ :volume of lead in segment 2

$Vst2(tb) := \Delta x2\cdot ((h + ts + tb)\cdot (t + 2\cdot ts) - h\cdot t)$ :volume of steel in segment 2

$Vc3 := h\cdot .75\cdot t\cdot (\Delta x3 - 6\cdot in)$ :volume of concrete in segment 3

$Vst3(tb) := \Delta x3\cdot ((h + ts + tb)\cdot (t + 2\cdot ts) - h\cdot t)$ :volume of steel in segment 3

$Vpb3 := h\cdot t\cdot \Delta x3 - Vc3$ :volume of lead in segment 3

$Vpoly := h\cdot .25\cdot t\cdot \Delta x4$ :volume of polyethylene in segment 4

$Vpb4 := h\cdot t\cdot \Delta x4 - Vpoly$ :volume of lead in segment 4

$Vst4(tb) := \Delta x4\cdot ((h + ts + tb)\cdot (t + 2\cdot ts) - h\cdot t)$ :volume of steel in segment 4

$Vc5 := h\cdot .75\cdot t\cdot \Delta x5$ :volume of concrete in segment 5

$Vpb5 := h\cdot .25\cdot t\cdot \Delta x5$ :volume of lead in segment 5

$Vst5(tb) := \Delta x5\cdot ((h + ts + tb)\cdot (t + 2\cdot ts) - h\cdot t)$ :volume of steel in segment 5

***Densities:*** $\rho pb := 730\cdot \frac{lb}{ft^3}$ $\rho c := 250\cdot \frac{lb}{ft^3}$ $\rho poly := 62.4\cdot \frac{lb}{ft^3}$ $\rho st := 480\cdot \frac{lb}{ft^3}$

$$\rho 1(tb) := \frac{\rho c\cdot Vc1 + \rho pb\cdot Vpb1 + \rho st\cdot Vst1(tb)}{Vc1 + Vpb1 + Vst1(tb)}$$

$\rho 1(.5\cdot in) = 440.834\,lb\cdot ft^{-3}$

$$\rho 2(tb) := \frac{\rho pb\cdot Vpb2 + \rho st\cdot Vst2(tb)}{Vpb2 + Vst2(tb) + Vcircle}$$

$\rho 2(.5\cdot in) = 550.353\,lb\cdot ft^{-3}$

$Vcircle = 1.693\,ft^3$

$$\rho 3(tb) := \frac{\rho c \cdot Vc3 + \rho pb \cdot Vpb3 + \rho st \cdot Vst3(tb)}{Vc3 + Vpb3 + Vst3(tb)}$$

$$\rho 3(.5 \cdot in) = 456.675 lb \cdot ft^{-3}$$

$$\rho 4(tb) := \frac{\rho poly \cdot Vpoly + \rho pb \cdot Vpb4 + \rho st \cdot Vst4(tb)}{Vpoly + Vpb4 + Vst4(tb)}$$

$$\rho 4(.5 \cdot in) = 559.353 lb \cdot ft^{-3}$$

$$\rho 5(tb) := \frac{\rho c \cdot Vc5 + \rho pb \cdot Vpb5 + \rho st \cdot Vst5(tb)}{Vc5 + Vpb5 + Vst5(tb)}$$

$$\rho 5(.5 \cdot in) = 374.96 lb \cdot ft^{-3}$$

***Volumes, Masses:***

$V1(tb) := Vc1 + Vpb1 + Vst1(tb)$ :volume of segment 1

$V2(tb) := Vpb2 + Vst2(tb)$ :volume of segment 2

$V3(tb) := Vc3 + Vpb3 + Vst3(tb)$ :volume of segment 3

$V4(tb) := Vpoly + Vpb4 + Vst4(tb)$ :volume of segment 4

$V5(tb) := Vc5 + Vpb5 + Vst5(tb)$ :volume of segment 5

$m1(tb) := \rho 1(tb) \cdot V1(tb)$ :mass of segment 1

$m2(tb) := \rho 2(tb) \cdot V2(tb)$ :mass of segment 2

$m3(tb) := \rho 3(tb) \cdot V3(tb)$ :mass of segment 3

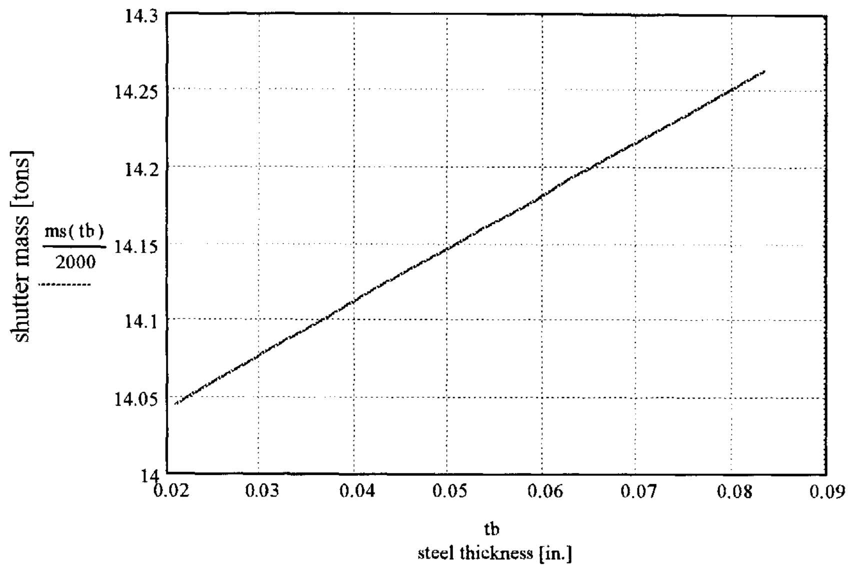
$m4(tb) := \rho 4(tb) \cdot V4(tb)$ :mass of segment 4

$m5(tb) := \rho 5(tb) \cdot V5(tb)$ :mass of segment 5

$ms(tb) := m1(tb) + m2(tb) + m3(tb) + m4(tb) + m5(tb)$

***Shutter mass as a function of the thickness of the steel on the bottom of the shutter:***

$ms(.5 \cdot in) = 14.117\,ton$




***Weight per unit length of the segments (q's):***

$q1(tb) := \frac{m1(tb)}{\Delta x1}$ $\qquad q1(.5 \cdot in) = 210.388\,\frac{lb}{in}$

$q2(tb) := \frac{m2(tb)}{\Delta x2}$ $\qquad q2(.5 \cdot in) = 202.074\,\frac{lb}{in}$

$q3(tb) := \frac{m3(tb)}{\Delta x3}$ $\qquad q3(.5 \cdot in) = 217.948\,\frac{lb}{in}$

$q4(tb) := \frac{m4(tb)}{\Delta x4}$ $\qquad q4(.5 \cdot in) = 266.951\,\frac{lb}{in}$

$q5(tb) := \frac{m5(tb)}{\Delta x5}$ $\qquad q5(.5 \cdot in) = 178.95\,\frac{lb}{in}$

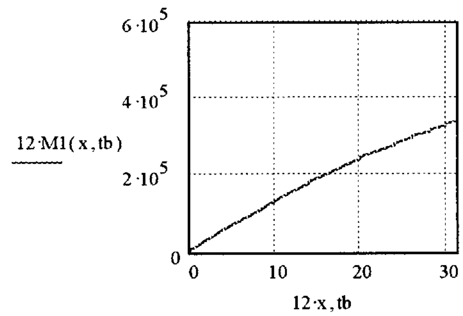
***Bending moments in each segment:***

$$x := 0\cdot in, 2\cdot in .. L$$

***for x<Δx1:***

$$M1(x, tb) := \left(\frac{ms(tb)}{2}\right)\cdot x - \frac{q1(tb)\cdot x^2}{2}$$

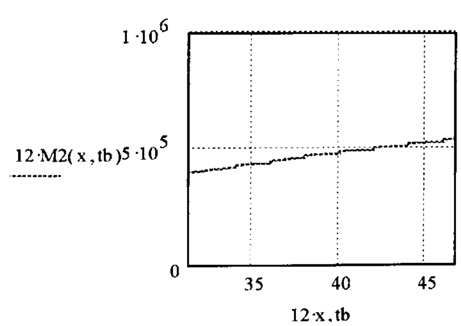
$$M1(15\cdot in, .5\cdot in) = 1.881\cdot 10^5 \cdot lb\cdot in$$




***for Δx1<x<Δx2:***

$$M2(x, tb) := \left(\frac{ms(tb)}{2}\right)\cdot x - \frac{q2(tb)\cdot(x - \Delta x1)^2}{2} - \frac{q1(tb)\cdot\Delta x1\cdot\left(x - \frac{\Delta x1}{2}\right)}{2}$$

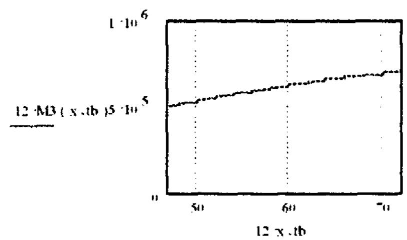
$$M2(46\cdot in, .5\cdot in) = 5.276\cdot 10^5 \cdot lb\cdot in$$



*for Δ x2 < x < Δ x3:*

$$M3(x,tb) := \frac{ms(tb)}{2}\cdot x - \left[\frac{q1(tb)\cdot\Delta x1\cdot\left(x - \frac{\Delta x1}{2}\right)}{2}\right] - \left[\frac{q3(tb)\cdot(x-(\Delta x1+\Delta x2))^2}{2}\right] - \frac{q2(tb)\cdot\Delta x2\cdot\left(\Delta x1 + \frac{\Delta x2}{2}\right)}{2}$$

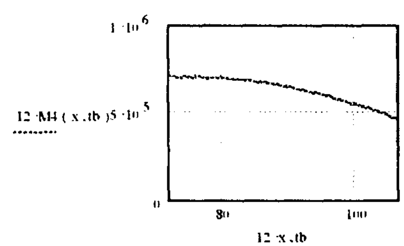
$$M3(71.9\cdot in, .5\cdot in) = 6.999\cdot 10^5 \cdot lb\cdot in$$




*for Δ x3 < x < Δ x4:*

$$M4(x,tb) := \frac{ms(tb)}{2}\cdot x - \left[\frac{q1(tb)\cdot\Delta x1\cdot\left(x - \frac{\Delta x1}{2}\right)}{2}\right] - \left[\frac{q3(tb)\cdot\left(x - \frac{\Delta x3}{2}\right)\cdot\left[x-(\Delta x1+\Delta x2+\Delta x3)+\frac{\Delta x3}{2}\right]}{2}\right] - \left[\frac{q2(tb)\cdot\Delta x2\cdot\left[x-(\Delta x1+\Delta x2)+\frac{\Delta x2}{2}\right]}{2}\right] - \frac{q4(tb)\cdot(x-(\Delta x1+\Delta x2+\Delta x3))^2}{2}$$

$$M4(75\cdot in, .5\cdot in) = 6.995\cdot 10^5 \cdot lb\cdot in$$

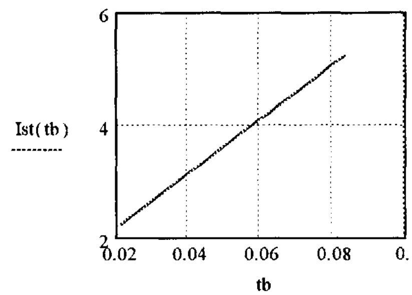


***The last 2 plots indicate that the max bending stress ocurrs at the junction of segments 3 and 4, where x = 71.93 inches, where the max bending moment is 70,000 lb*in.***

***Modulus of elasticity (E):*** $Est := 28 \cdot 10^6\ psi$

***Moment of inertia of the steel beam (I):*** $Ist(tb) := \frac{(L + 2 \cdot ts) \cdot (h + ts + tb)^3 - L \cdot h^3}{12}$

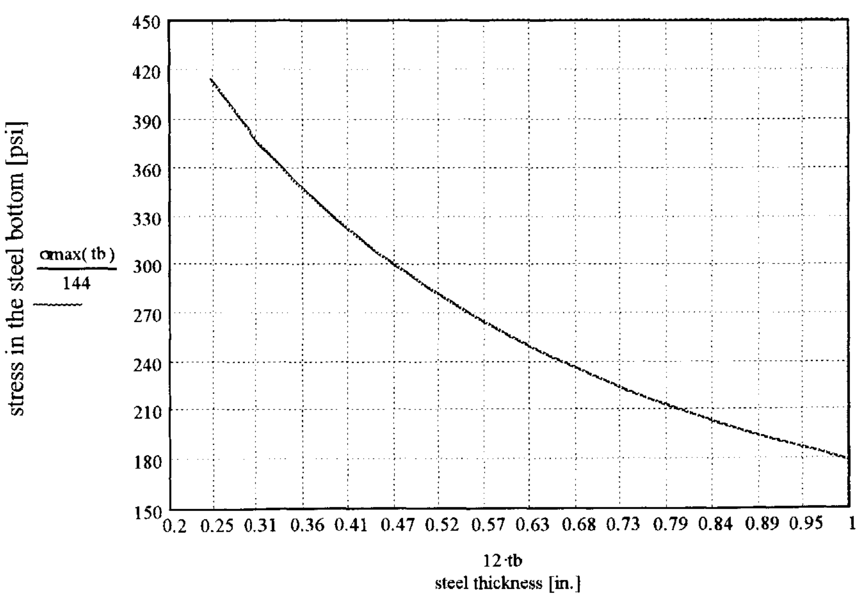
$Ist(.5 \cdot in) = 6.63510^4 \cdot in^4$




***Max bending stress (σ =Mc/I):***
*(assume the neutral axis is at h/2)*

$$\sigma max(tb) := \frac{(7.5 \cdot 10^5 \cdot lb \cdot in) \cdot \left(\frac{h + ts + tb}{2}\right)}{Ist(tb)}$$

***This plot shows the max bending stress occurs when the steel is thinnest (.25 inches); there the stress is ~400 psi.)***



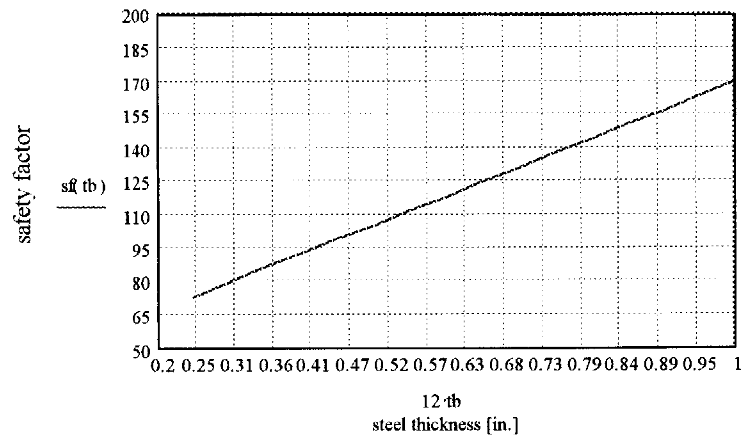

$\sigma max(.5 \cdot in) = 286.828 \frac{lb}{in^2}$

***Safety factor (sf):*** $\sigma yield := 30000 psi$ :the yield stress of the steel

$$sf(tb) := \left(\frac{\sigma yield}{\sigma max(tb)}\right)\cdot\frac{gc}{g}$$

***Safety factor as a function of steel thickness at the bottom of the shutter:***

$sf(.5\cdot in) = 104.677$

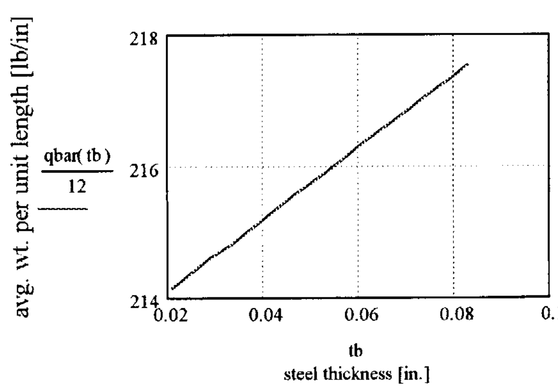



***Max deflection of the steel beam (δ ):***

*average weight per unit length (qbar):*

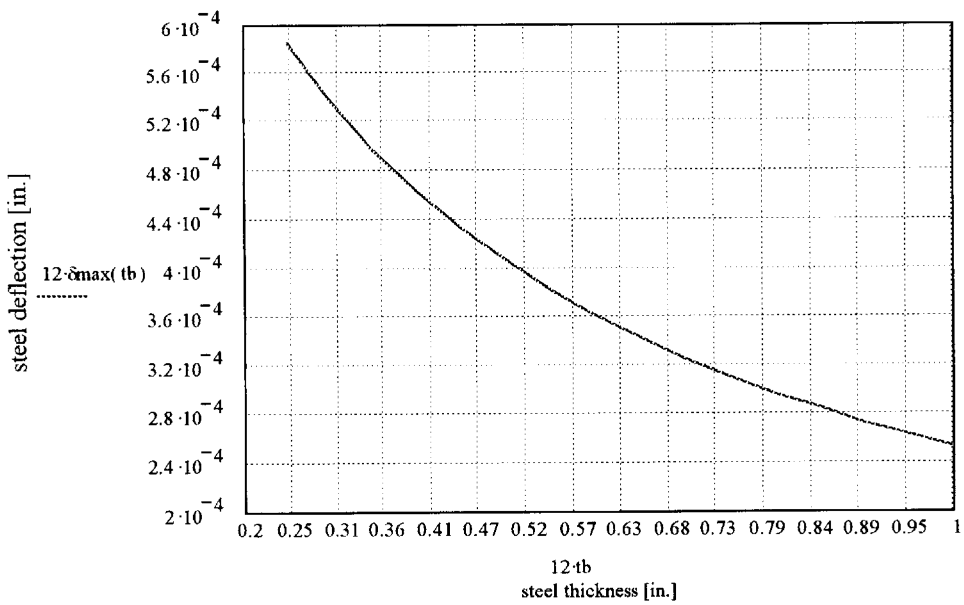
$$qbar(tb) := \frac{q1(tb) + q2(tb) + q3(tb) + q4(tb) + q5(tb)}{5}$$

$qbar(.5\cdot in) = 215.262\frac{lb}{in}$



$$\delta max(tb) := \left( \frac{5 \cdot qbar(tb) \cdot L^4}{384 \cdot Est \cdot Ist(tb)} \right) \cdot \frac{g}{gc}$$

***Deflection in the steel bottom as a function of steel thickness:***




$$\delta max(.5 \cdot in) = 4.047 \cdot 10^{-4} \circ in$$

**Results indicate that deflections are minimal, even if the thickness of the steel on the bottom of the shutter was .25 inches (~ .00058 inches of deflection)**

# Appendix D:

# Medical Room Door Alternative Designs

## D.1 One Hinged and Swinging Door

The hinged and swinging medical room door alternative is shown in Figure D.1.1. An abundance of time and effort went into trying to make this a workable alternative, from a conceptual standpoint of view. As shown at the end of Appendix D.1, kinematics studies were done to see just how great the reaction forces would be on the two hinges. Additionally, kinematics studies were done to analyze the starting force a person would have to apply to get the door to move from its closed (or open) position. These studies took into account the friction moment of the hinges and the desired time period needed to fully open (or close) the swinging door.

Disadvantages to this type of door are the overturning moment applied to the top hinge, the multi-ton reaction forces applied to the top and bottom hinges, and the starting force needed if a person were required to open the door very quickly. One idea for overcoming these disadvantages is for a wheel rolling on the floor, helping to carry the load of the door. This wheel would be located at the bottom of the free, swinging end of the door; however, this introduces the disadvantage of having something -- even the smallest piece of contaminant -- getting caught under the wheel, causing the wheel to stop rolling and jamming the entire door in place.

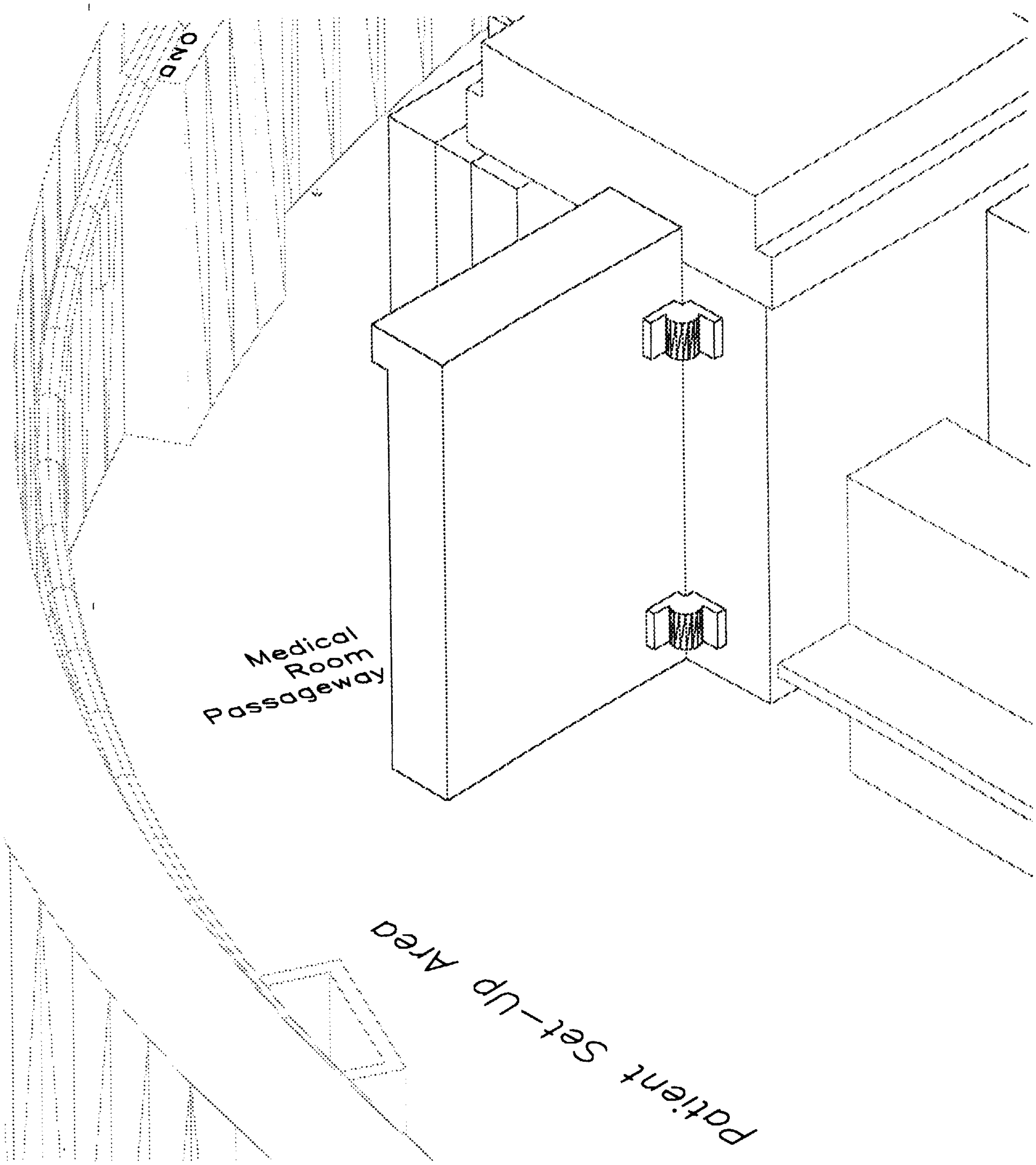



**Figure D.1.1.** One Hinged and Swinging Door (viewed from above the silicon unloading area in Figure 3.1).

## *Hinged Steel door of six 3" thick plates: Analyzing the Reactions at the Hinges and Starting Force Needed to Open (or Close) the Door*

***(origin of x-, y-, and z-axes is at the bottom corner of the door, hinge side, outside the med room)***
***x-dir.: Parallel to beamline***
***y-dir.: Toward the ceiling***
***z-dir.: Transverse to beamline***

$tp := 3\cdot in$ : plate thicknesses

$wmaze := 4\cdot ft$ : maze width

$hdoor := 8\cdot ft$ : door height

Hinges: $od := 3\cdot in$

$id := 1.5\cdot in$

$\mu s := .3$

$xstep := 2\cdot in$

$ystep := 2\cdot in$

$halfstep := .5\cdot in$

$bumpstep := .25\cdot in$

: steps in the plates

Opening Time: $T := 20\cdot sec$

***Analyzing the first plate (at the maze-side of the door):***

**Plate width, radius, height:**

$rhosteel := 480\cdot \frac{lb}{ft^3}$

$w11 := wmaze + 2\cdot xstep$

$w11 = 4.333\,ft$ : maze-side width of first plate

$r1 := \sqrt{(6\cdot tp)^2 + (w11 + xstep)^2}$

$r1 = 56.921\,in$ : radius of first plate's outer edge

$w12 := \sqrt{r1^2 - (5\cdot tp)^2} - xstep$

$w12 = 52.909\,in$ : out-side width of first plate

$h1 := hdoor - ystep - 5\cdot bumpstep$

$h1 = 92.75\,in$ : height of first plate

**Plate center-of-mass:**

$y1cm := \left(\frac{h1}{2}\right) + 5\cdot bumpstep$

$y1cm = 47.625\,in$

$x1cm := -\left(\frac{.5\cdot w11 + .5\cdot w12}{2}\right) + xstep$

$x1cm = -24.227\,in$

$z1cm := -\left[\left(\frac{tp}{2}\right) + 5\cdot tp\right]$

$z1cm = -16.5\,in$

**Plate volume, mass:**

$V1 := tp\cdot h1\cdot \left(\frac{w11 + w12}{2}\right)$

$V1 = 8.446\,ft^3$

$m1 := V1\cdot rhosteel$

$m1 = 2.027\,ton$

**Plate moment of inertia:**

** Assumtion here is that the plate is shaped rectangularly, with an average width of .5*(w11+w12); i.e. the wedge mass is insignificant to the slab mass (see calculation to the right)*
*This assumption allows us to use the the formula for the moment of inertia of a rectangular plate even though our plates are actually trapezoidal-shaped.*

$mslab1 := rhosteel\cdot h1\cdot tp\cdot w11$

$\frac{mslab1}{m1} = 0.991$

$I1 := \left(\frac{m1}{12}\right)\cdot\left[\left(\frac{w11 + w12}{2}\right)^2 + tp^2\right] + m1\cdot\left(x1cm^2 + z1cm^2\right)$

$I1 = 3.067\cdot 10^4\,lb\cdot ft^2$

***Similar analyses for the other 5 plates:***

$w21 := w12 + halfstep$

$w21 = 53.409 \cdot in$

$r2 := \sqrt{(5 \cdot tp)^2 + (w21 + xstep)^2}$

$r2 = 57.403 \cdot in$

$w22 := \sqrt{r2^2 - (4 \cdot tp)^2} - xstep$

$w22 = 54.135 \cdot in$

$h2 := hdoor - ystep - 4 \cdot bumpstep$

$h2 = 93 \cdot in$

$y2cm := \left(\frac{h2}{2}\right) + 4 \cdot bumpstep$

$y2cm = 47.5 \cdot in$

$x2cm := -\left(\frac{.5 \cdot w21 + .5 \cdot w22}{2}\right) + xstep$

$x2cm = -24.886 \cdot in$

$z2cm := -\left[\left(\frac{tp}{2}\right) + 4 \cdot tp\right]$

$z2cm = -13.5 \cdot in$

$V2 := tp \cdot h2 \cdot \left(\frac{w21 + w22}{2}\right)$

$V2 = 8.682\, ft^3$

$m2 := V2 \cdot rhosteel$

$m2 = 2.084 \cdot ton$

$$I2 := \left(\frac{m2}{12}\right) \cdot \left[\left(\frac{w21 + w22}{2}\right)^2 + tp^2\right] + m2 \cdot \left(x2cm^2 + z2cm^2\right)$$

$I2 = 3.019 \cdot 10^4\ lb \cdot ft^2$

$w31 := w22 + halfstep$

$w31 = 54.635 \cdot in$

$r3 := \sqrt{(4 \cdot tp)^2 + (w31 + xstep)^2}$

$r3 = 57.893 \cdot in$

$w32 := \sqrt{r3^2 - (3 \cdot tp)^2} - xstep$

$w32 = 55.189 \cdot in$

$h3 := hdoor - ystep - 3 \cdot bumpstep$

$h3 = 93.25 \cdot in$

$y3cm := \left(\frac{h3}{2}\right) + 3 \cdot bumpstep$

$y3cm = 47.375 \cdot in$

$x3cm := -\left(\frac{.5 \cdot w31 + .5 \cdot w32}{2}\right) + xstep$

$x3cm = -25.456 \cdot in$

$z3cm := -\left[\left(\frac{tp}{2}\right) + 3 \cdot tp\right]$

$z3cm = -10.5 \cdot in$

$V3 := tp \cdot h3 \cdot \left(\frac{w31 + w32}{2}\right)$

$V3 = 8.89\, ft^3$

$m3 := V3 \cdot rhosteel$

$m3 = 2.134 \cdot ton$

$$I3 := \left(\frac{m3}{12}\right) \cdot \left[\left(\frac{w31 + w32}{2}\right)^2 + tp^2\right] + m3 \cdot \left(x3cm^2 + z3cm^2\right)$$

$I3 = 2.994 \cdot 10^4\ lb \cdot ft^2$

$w41 := w32 + halfstep + xstep$

$w41 = 57.689 \cdot in$

$r4 := \sqrt{(3 \cdot tp)^2 + w41^2}$

$r4 = 58.386 \cdot in$

$w42 := \sqrt{r4^2 - (2 \cdot tp)^2}$

$w42 = 58.077 \cdot in$

$h4 := hdoor - 2 \cdot bumpstep$

$h4 = 95.5 \cdot in$

$x4cm := -\left(\frac{.5 \cdot w41 + .5 \cdot w42}{2}\right)$ $x4cm = -28.942 \cdot in$

$y4cm := \left(\frac{h4}{2}\right) + 2 \cdot bumpstep$

$y4cm = 48.25 \cdot in$

$z4cm := -\left[\left(\frac{tp}{2}\right) + 2 \cdot tp\right]$ $z4cm = -7.5 \cdot in$

$V4 := tp \cdot h4 \cdot \left(\frac{w41 + w42}{2}\right)$ $V4 = 9.597\,ft^3$

$m4 := V4 \cdot rhosteel$

$m4 = 2.303 \cdot ton$

$I4 := \left(\frac{m4}{12}\right) \cdot \left[\left(\frac{w41 + w42}{2}\right)^2 + tp^2\right] + m4 \cdot \left(x4cm^2 + z4cm^2\right)$

$I4 = 3.755 \cdot 10^4\ lb \cdot ft^2$

$w51 := w42 + halfstep$

$w51 = 58.577 \cdot in$

$r5 := \sqrt{(2 \cdot tp)^2 + w51^2}$

$r5 = 58.884 \cdot in$

$w52 := \sqrt{r5^2 - (1 \cdot tp)^2}$

$w52 = 58.807 \cdot in$

$h5 := hdoor - 1 \cdot bumpstep$

$h5 = 95.75 \cdot in$

$x5cm := -\left(\frac{.5 \cdot w51 + .5 \cdot w52}{2}\right)$ $x5cm = -29.346 \cdot in$

$y5cm := \left(\frac{h5}{2}\right) + 1 \cdot bumpstep$

$y5cm = 48.125 \cdot in$

$z5cm := -\left[\left(\frac{tp}{2}\right) + 1 \cdot tp\right]$ $z5cm = -4.5 \cdot in$

$V5 := tp \cdot h5 \cdot \left(\frac{w51 + w52}{2}\right)$ $V5 = 9.757\,ft^3$

$m5 := V5 \cdot rhosteel$

$m5 = 2.342 \cdot ton$

$I5 := \left(\frac{m5}{12}\right) \cdot \left[\left(\frac{w51 + w52}{2}\right)^2 + tp^2\right] + m5 \cdot \left(x5cm^2 + z5cm^2\right)$

$I5 = 3.803 \cdot 10^4\ lb \cdot ft^2$

$w61 := w52 + halfstep$

$w61 = 59.307 \cdot in$

$r6 := \sqrt{(1 \cdot tp)^2 + w61^2}$

$r6 = 59.383 \cdot in$

$w62 := \sqrt{r6^2 - (0 \cdot tp)^2}$

$w62 = 59.383 \cdot in$

$h6 := hdoor - 0 \cdot bumpstep$

$h6 = 96 \cdot in$

$y6cm := \left(\frac{h6}{2}\right) + 0 \cdot bumpstep$ $\qquad y6cm = 48 \cdot in$

$x6cm := -\left(\frac{.5 \cdot w61 + .5 \cdot w62}{2}\right)$ $\qquad x6cm = -29.673 \cdot in$

$z6cm := -\left[\left(\frac{tp}{2}\right) + 0 \cdot tp\right]$ $\qquad z6cm = -1.5 \cdot in$

$V6 := tp \cdot h6 \cdot \left(\frac{w61 + w62}{2}\right)$ $\qquad V6 = 9.891\,ft^3$

$m6 := V6 \cdot rhosteel$

$m6 = 2.374 \cdot ton$

$I6 := \left(\frac{m6}{12}\right) \cdot \left[\left(\frac{w61 + w62}{2}\right)^2 + tp^2\right] + m6 \cdot \left(x6cm^2 + z6cm^2\right)$

$I6 = 3.88 \cdot 10^4\ lb \cdot ft^2$

***Mass of the Door:***

$gc := 32.174 \frac{ft \cdot lb}{lbf \cdot sec^2}$

$mdoor := m1 + m2 + m3 + m4 + m5 + m6$

$mdoor = 13.263 \cdot ton$

***Moment of Inertia of the Door:***

$Idoor := I1 + I2 + I3 + I4 + I5 + I6$

$Idoor = 2.052 \cdot 10^5\ lb \cdot ft^2$

***Center of Mass of the Door:***

$xdoorcm := \frac{x1cm \cdot m1 + x2cm \cdot m2 + x3cm \cdot m3 + x4cm \cdot m4 + x5cm \cdot m5 + x6cm \cdot m6}{mdoor}$

$xdoorcm = -27.225 \cdot in$

$ydoorcm := \frac{y1cm \cdot m1 + y2cm \cdot m2 + y3cm \cdot m3 + y4cm \cdot m4 + y5cm \cdot m5 + y6cm \cdot m6}{mdoor}$

$ydoorcm = 47.829 \cdot in$

$zdoorcm := \frac{z1cm \cdot m1 + z2cm \cdot m2 + z3cm \cdot m3 + z4cm \cdot m4 + z5cm \cdot m5 + z6cm \cdot m6}{mdoor}$

$zdoorcm = -8.697 \cdot in$

***Hinge Placement:***

$\varepsilon := 12 \cdot in$ : distance from the top and bottom edges of the door to center of the top and bottom hinges, respectively

$\delta := hdoor - 2 \cdot \varepsilon$ : distance between the hinge centers

$\delta = 6\ ft$

***Hinge Inputs:***

$od := 3 \cdot in \qquad id := 1.5 \cdot in \qquad \mu s := .3$

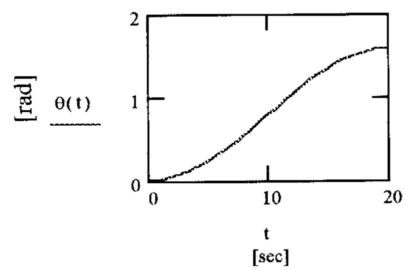
***Friction Moment of the Hinges:***

$$Mfric := \left(\frac{2}{3}\right)\cdot \mu s \cdot mdoor \cdot \frac{g}{gc} \cdot \left[\frac{\left(\frac{od}{2}\right)^3 - \left(\frac{id}{2}\right)^3}{\left(\frac{od}{2}\right)^2 - \left(\frac{id}{2}\right)^2}\right] \qquad Mfric = 773.677\,ft\cdot lbf$$

***Kinematics:***

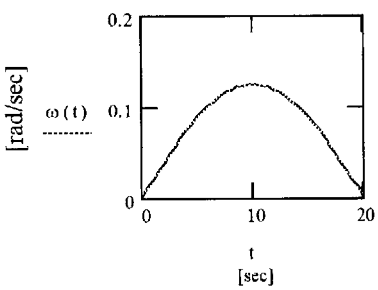
$T := 20\cdot sec \qquad t := 0\cdot sec, .5\cdot sec .. T$

$$\theta(t) := \left(\frac{\pi}{4}\right)\cdot\left[1 + \cos\left[\left(\frac{\pi}{T}\right)\cdot(t - T)\right]\right]$$



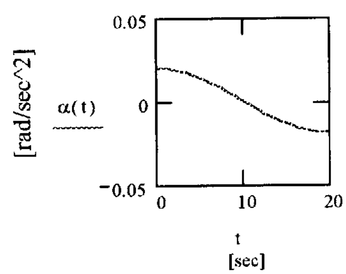

$$\theta\left(\frac{T}{2}\right) = 45\,deg$$

$$\omega(t) := \frac{d}{dt}\theta(t)$$




$$\omega\left(\frac{T}{2}\right) = 0.123\,sec^{-1}$$

$$\alpha(t) := \frac{d^2}{dt^2}\theta(t)$$




max velocity of the leading edge:

$rmax := r6$

$$vmax := rmax\cdot\omega\left(\frac{T}{2}\right)$$

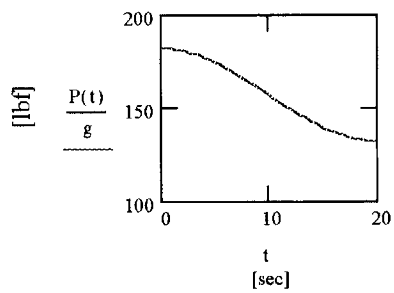
$$vmax = 7.326\,\frac{in}{sec}$$

## ***Handle Placement:***

$hhandle := 3.5 \cdot ft$ : distance from the bottom of the door to the door handle

$$P(t) := \frac{Idoor \cdot \alpha(t) + Mfric}{w62}$$ : Applied force needed to open the door

$P(0 \cdot sec) = 181.316 \cdot lbf$




$\frac{Mfric}{w62} = 156.342 \cdot lbf$

$P\left(\frac{T}{2}\right) = 156.342 \cdot lbf$

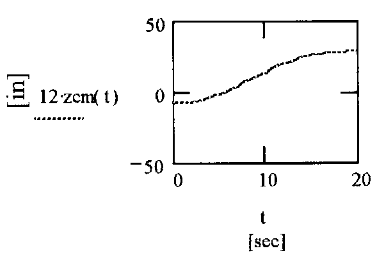
$$rcmxz := \sqrt{xdoorcm^2 + zdoorcm^2}$$

$rcmxz = 28.581 \cdot in$ : abs. value of the door's center of mass in the x-z plane, measured from the y-axis at a height of ydoorcm (a constant).

$$\gamma := atan\left(\frac{zdoorcm}{xdoorcm}\right)$$

$\gamma = 17.716 \cdot deg$ : angle the c of m makes with the x-axis

$zcm(t) := -rcmxz \cdot sin(\gamma - \theta(t))$

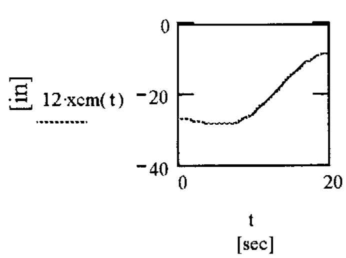



$zcm(0 \cdot sec) = -8.697 \cdot in$

$zcm(T) = 27.225 \cdot in$

$zcm(10 \cdot sec) = 1.092\, ft$

$xcm(t) := -rcmxz \cdot cos(\gamma - \theta(t))$

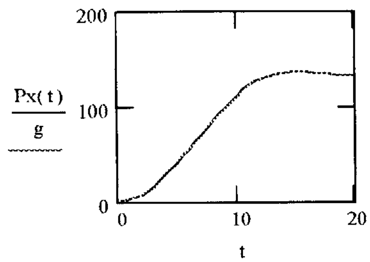



$xcm(0 \cdot sec) = -27.225 \cdot in$

$xcm(T) = -8.697 \cdot in$

$Px(t) := P(t)\cdot\sin(\theta(t))$

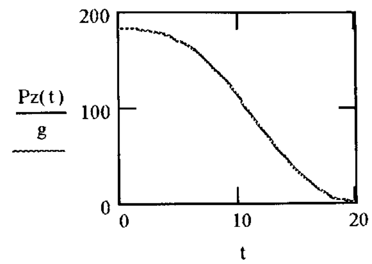
**Pulling force in the x-dir.**



$Px(15\cdot sec) = 135.031\cdot lbf$

$Pz(t) := P(t)\cdot\cos(\theta(t))$

**Pulling force in the z-dir.**



$Pz(0\cdot sec) = 181.316\cdot lbf$

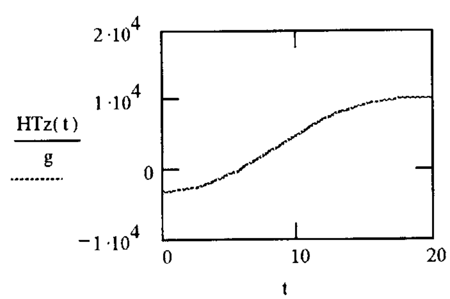
## ***Reactions on the door at the hinges:***

** Assumption here is that the top hinge carries the entire vertical thrust of the door, i.e. VT = mdoor * g and VB = 0)*

From a summation of moments about an x'-axis throught the bottom hinge:

$$HTz(t) := \frac{mdoor\cdot\frac{g}{gc}\cdot zcm(t) - Pz(t)\cdot(hhandle - \varepsilon)}{\delta}$$

**Reaction at the top hinge in the z-dir.**



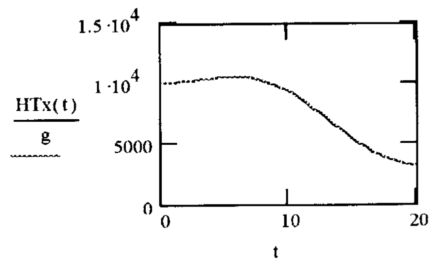
$HTz(T) = 1.003\cdot 10^{4}\cdot lbf$

$$\frac{HTz(T)}{g} = 1.003\cdot 10^{4}\cdot lb$$

From a summation of moments about a z"-axis throught the bottom hinge:

$$HTx(t) := \frac{mdoor \cdot \frac{g}{gc} \cdot \left| xcm(t) \right| - Px(t) \cdot (hhandle - \varepsilon)}{\delta}$$

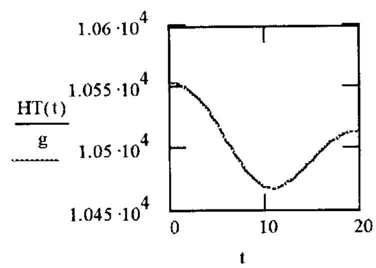
**Reaction at the top hinge in the x-dir.**




$$\frac{HTx(6 \cdot sec)}{g} = 5.253 \cdot ton$$

$$HT(t) := \sqrt{HTz(t)^2 + HTx(t)^2}$$

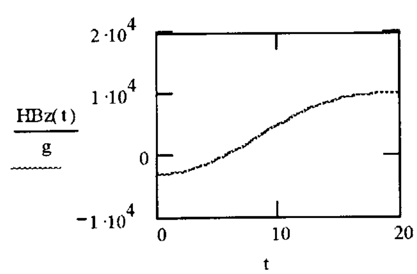
**Total reaction at the top hinge**




$$\frac{HT(0 \cdot sec)}{g} = 5.276 \cdot ton$$

$$HBz(t) := HTz(t) + Pz(t)$$

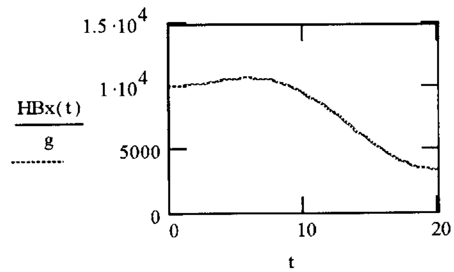
**Reaction at the bottom hinge in the z-dir.**




$$\frac{HBz(20 \cdot sec)}{g} = 5.015 \cdot ton$$

$HBx(t) := HTx(t) + Px(t)$

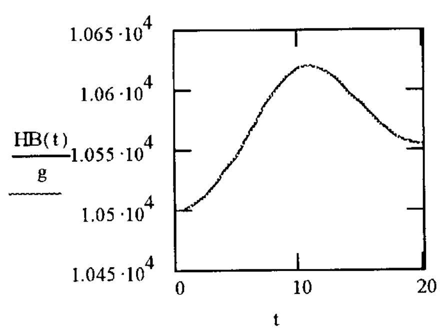
**Reaction at the bottom hinge in the x-dir.**




$$\frac{HBx(20\cdot sec)}{g} = 1.64 \cdot ton$$

$HB(t) := \sqrt{HBz(t)^2 + HBx(t)^2}$

**Total reaction at the bottom hinge**




$$\frac{HB(10\cdot sec)}{g} = 5.308 \cdot ton$$

## D.2 Vertically Moving Door

The vertically moving medical room door alternative is shown in Figure D.2.1. It essentially mimics the motion of a guillotine. The door is raised straight up to open and lowered straight down to close. Definite advantages to this door alternative are that it takes up a minimum of floor space and that the reactor's polar crane could be used to lift (or lower) the door in an emergency situation.

Nevertheless, there are serious disadvantages to this door alternative, beginning with safety. Having a multi-ton structure suspended overhead, as people walk underneath it, is not safe. Another disadvantage to this door alternative is that part of the structure to power, or move, the door would need to be mounted upon the roof blocks above the medical room door passageway. This structure -- in addition to the multi-ton weight of the door that the structure carries -- presents another serious drawback to this door alternative in that the weight may overload the roof blocks.

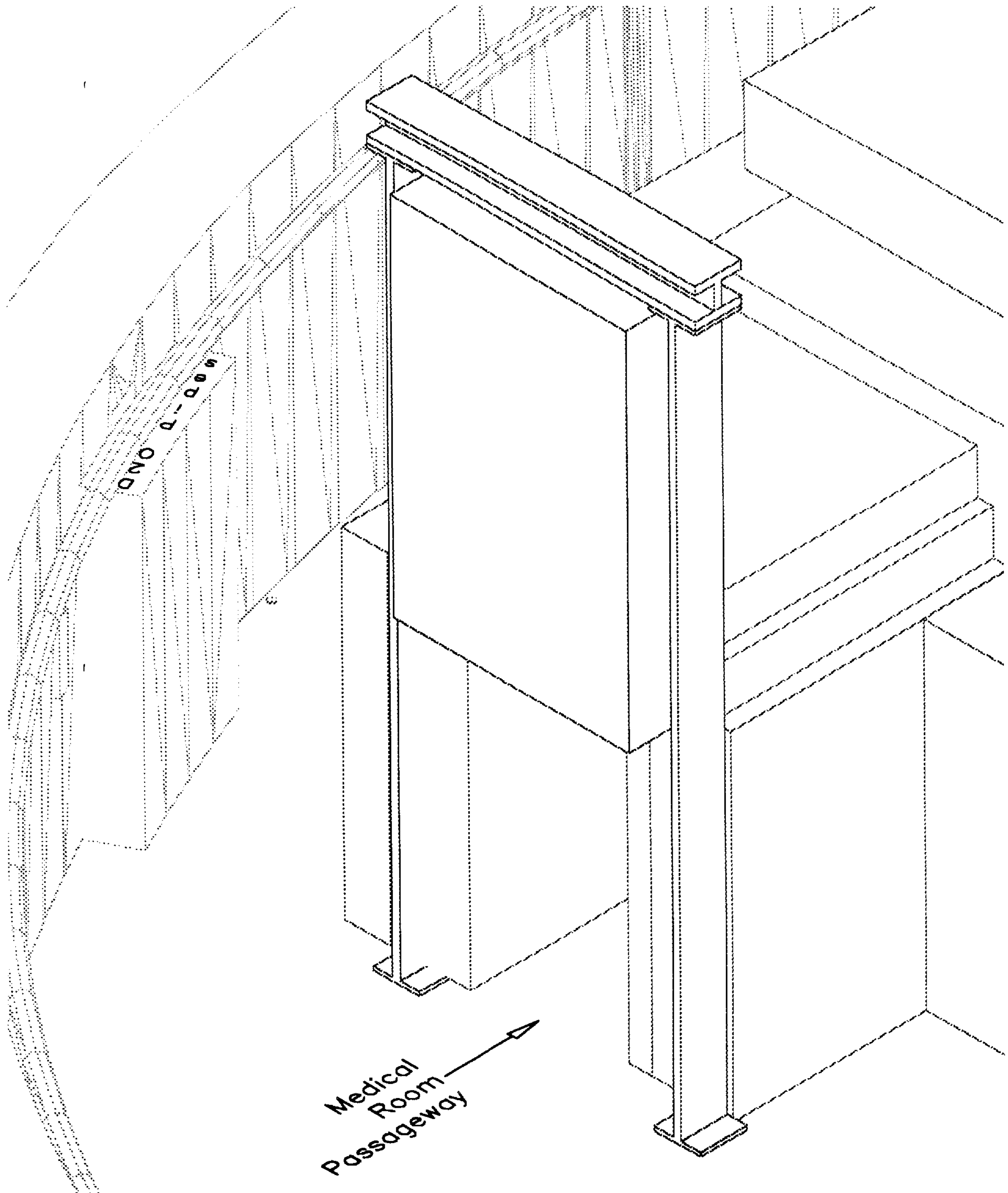



**Figure D.2.1.** Vertically Moving Door.

## D.3 Parallel-to-Beam Sliding Door

This medical room door alternative is shown in Figure D.3.1. A definite advantage to this type of door movement is that it mimics the current medical room door movement which has been proven to be reliable over many years of use. However, this door alternative cannot slide toward the reactor for the reason that the control console is located on that side. Furthermore, if this door alternative slides toward the containment wall, it would leave minimal space for personnel and equipment to pass between it and the $D_2O$ pipes located on that side. One method of bypassing the $D_2O$ pipe obstruction would be to slant the sliding door, with respect to the beamline, as discussed in the Appendix D.4.

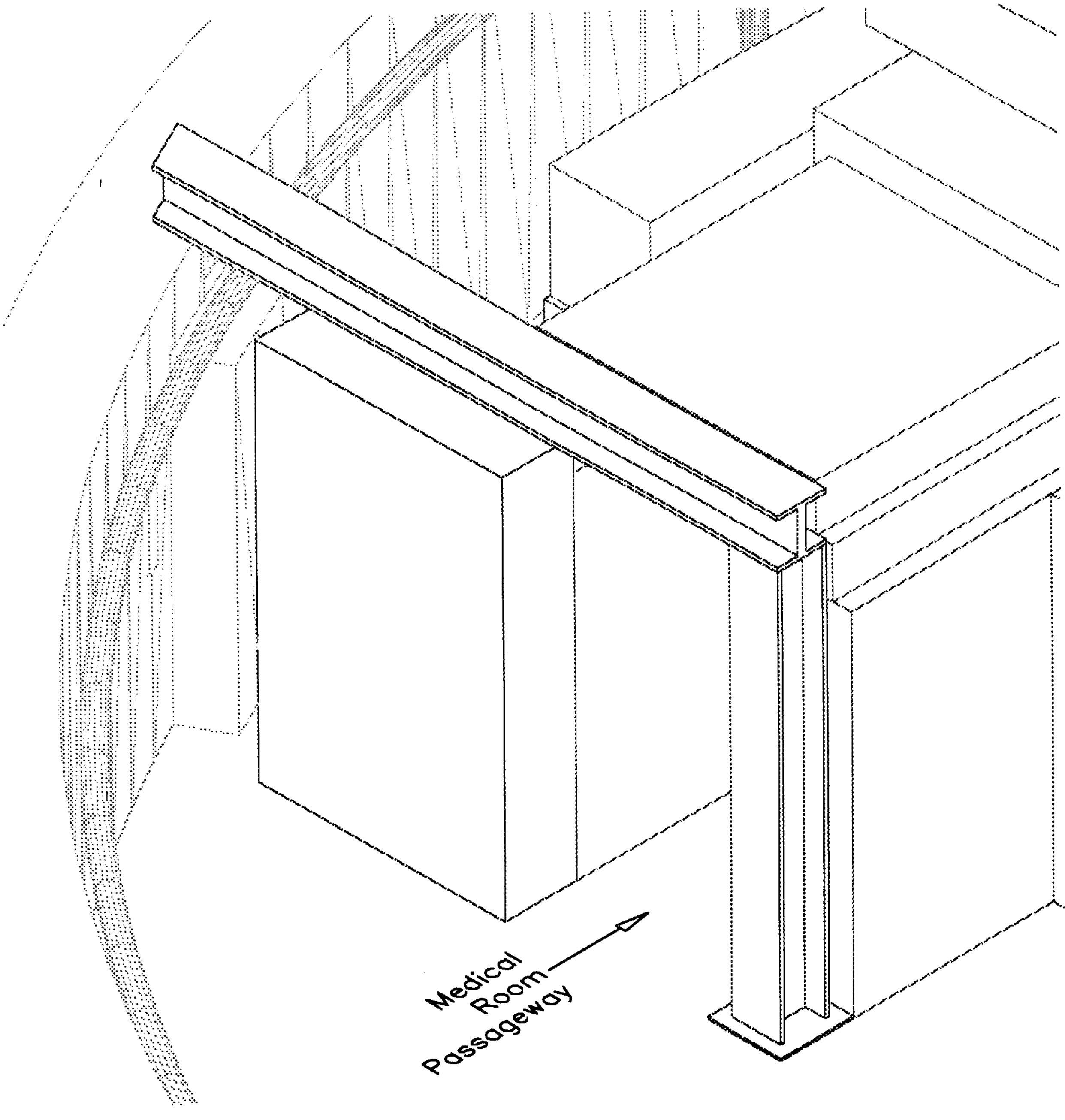



**Figure D.3.1.** Parallel-to-Beam Sliding Door (door will be suspended from horizontal I-beam by trolleys -- not shown).

## D.4 Slanted Sliding Door

The plan view of this medical room door alternative is shown in Figure D.4.1; its isometric view is displayed in Figure D.4.2. This door is situated at an angle of twenty degrees from the beamline, therefore, it does not move perpendicularly to the medical room passageway. Thus, the term 'slanted' is used to differentiate this door from the parallel-to-beam sliding door. At this angle, and in the fully open position, the door would miss the $D_2O$ pipes on the containment wall altogether. Nevertheless, this door alternative introduces two angled cuts in the two concrete blocks forming the medical room passageway. For this reason, problems arise with the tracking system. It becomes difficult to get the slanted door to mesh with any degree of precision with the two angled concrete blocks.

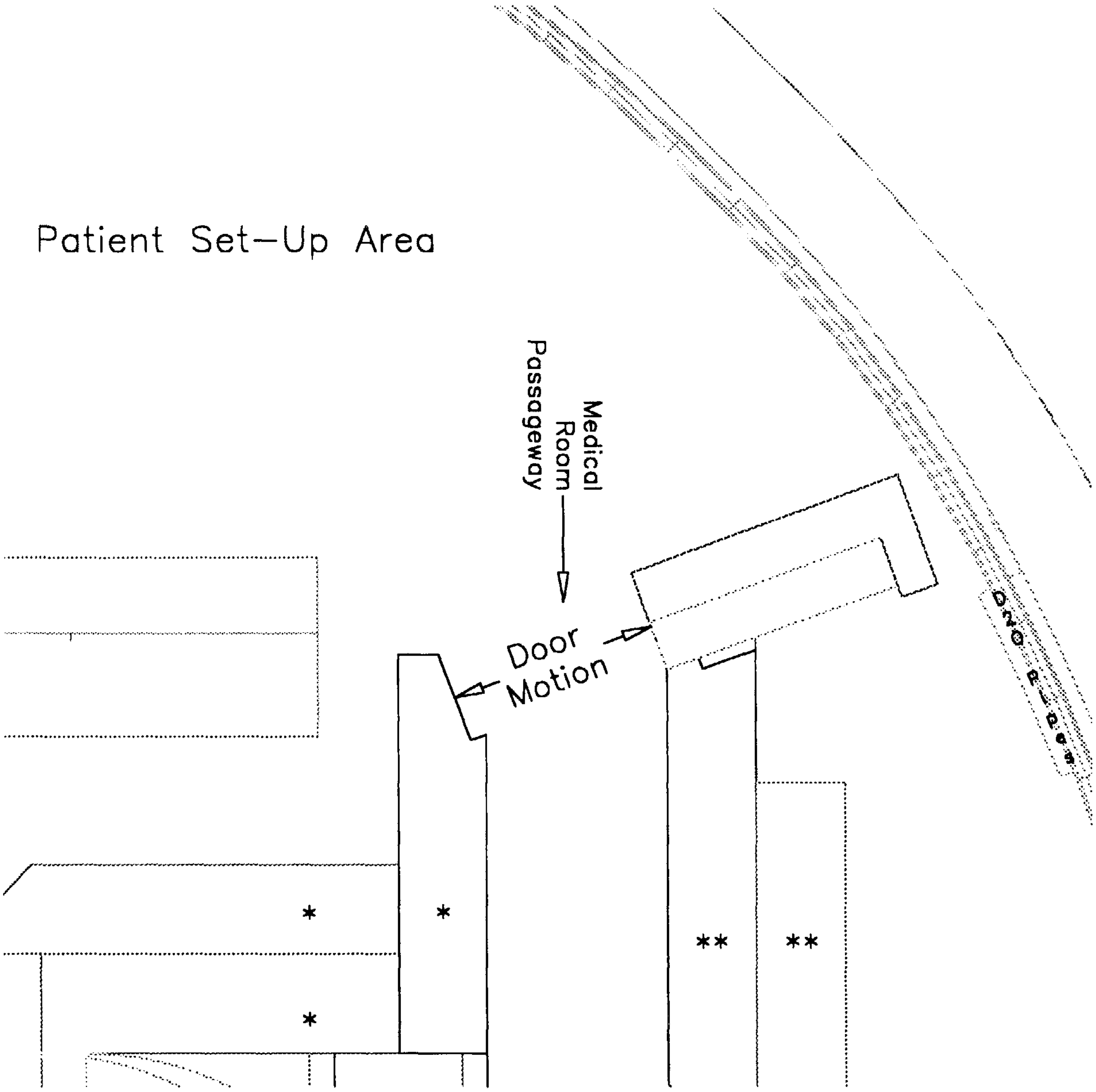



**Figure D.4.1.** Slanted Sliding Door -- Plan View (support structure for door not shown).

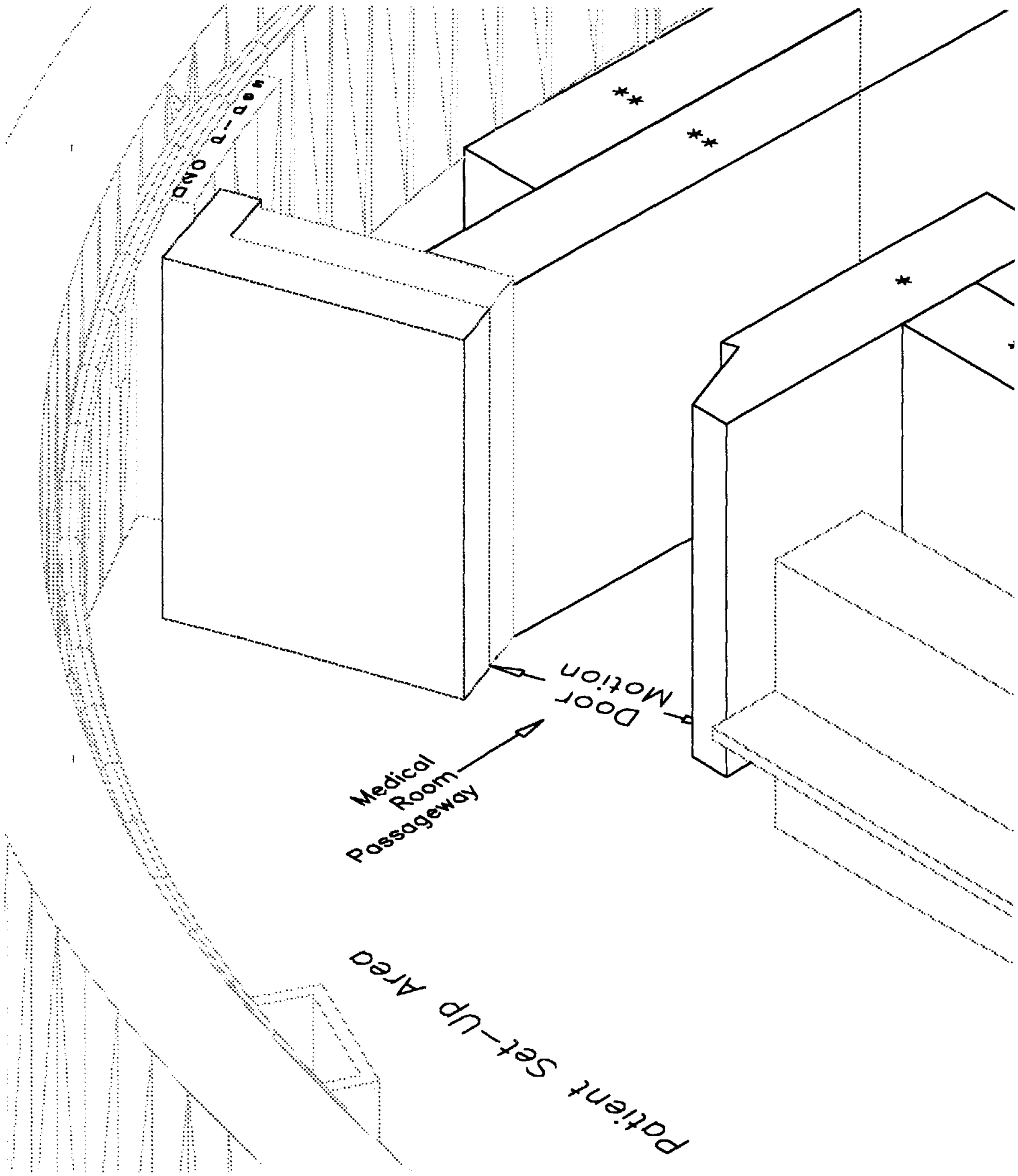



**Figure D.4.2.** Slanted Sliding Door -- Isometric View (support structure for door not shown).

## D.5 Transverse-to-Beam Sliding Door

This medical room door alternative is shown in Figure D.5.1. This door would slide straight out from the medical room passageway, perpendicular to the beamline, tracking on two overhead beams. As with the other two sliding medical room door alternatives, this overhead tracking has been proven to be a safe method for moving the door, since the current medical room door uses the same method.

However, as can be seen in the figure, floor space is limited with this alternative. The two support columns for the two overhead I-beam tracks use up quite a bit of reactor floor space. The floor space taken up not only infringes upon the medical personnel's and NRL staff's room to maneuver, but also upon everyday operations that take place in the reactor room. In addition, another disadvantage to this medical room door alternative is that the door barely opens wide enough to maneuver specially needed equipment, such as a six and a half foot stretcher, or gurney, into the medical room passageway.

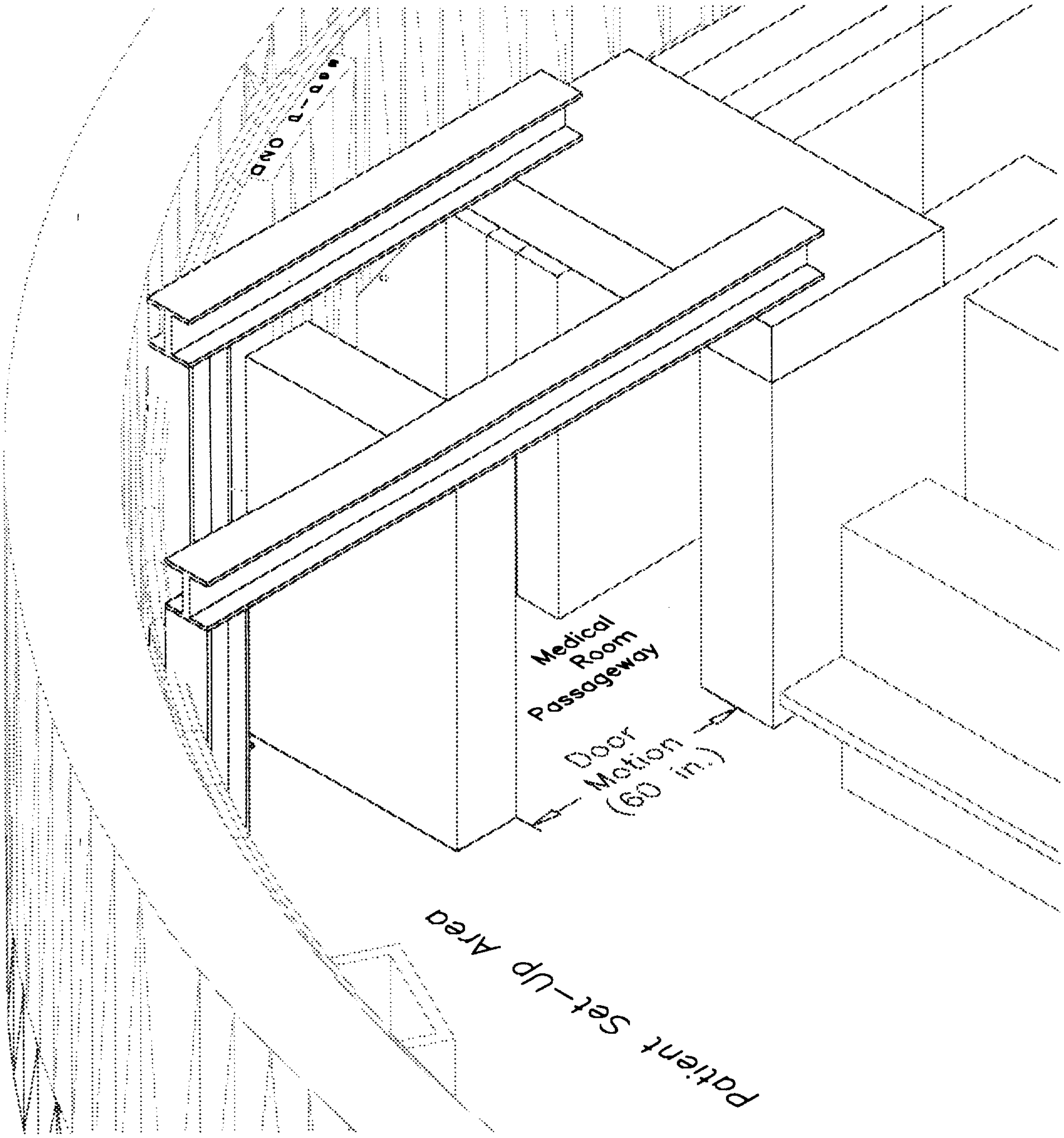



**Figure D.5.1.** Transverse-to-Beam Sliding Door (suspended from horizontal beams by trolleys -- not shown).

# Appendix E:

# Water Shutter Fluid Circuit Analysis

## Water Shutter Fluid Circuit Analysis:

***Constants/Water Properties, Shutter Volume:*** $Vshutter := 105 \cdot gal$ : water shutter volume

$Vshutter = 14.036 \, ft^3$

$1 \cdot ft^3 = 7.481 \, gal$

water properties evaluated at 300K and 1 atm;
sources: Fox and McDonald, Incropera and DeWitt:

$g = 32.174 \, \frac{ft}{sec^2}$ $\quad gc := 32.174 \frac{ft \cdot lb}{lbf \cdot sec^2}$

$\mu w := .85 \cdot 10^{-3} \cdot \frac{newton \cdot sec}{m^2}$ $\quad \rho w := 1000 \frac{kg}{m^3}$

$\rho w = 62.428 \, \frac{lb}{ft^3}$ : density of the water

$mgal := \rho w \cdot 1 \cdot gal$

$mgal = 8.345 \, lb$

***Supply Tank:*** $Dst := 2.5 \cdot ft$ $\quad hst := 4 \cdot ft$

$Vst := \left(\frac{\pi}{4}\right) \cdot Dst^2 \cdot hst$

$Vst = 146.88 \, gal$ : supply tank volume

$Vst = 19.635 \, ft^3$

$mst := \rho w \cdot Vst$

$mst = 1.226 \cdot 10^3 \, lb$

### Analyzing the Pump Size Needed to Drain the Shutter in a Given Time:

***Water Return Pipe:***

$Drpipe := 2 \cdot in$

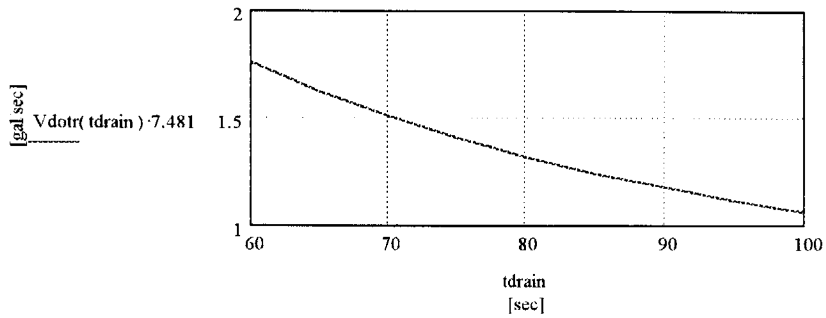
$Arpipe := \left(\frac{\pi}{4}\right) \cdot Drpipe^2$

***Water Return Flow Rate:*** $tdrain := 60 \cdot sec, 65 \cdot sec .. 100 \cdot sec$

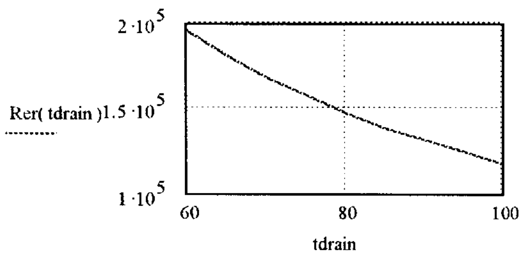
$Vdotr(tdrain) := \frac{Vshutter}{tdrain}$

$vr(tdrain) := \frac{Vdotr(tdrain)}{Arpipe}$ $\quad mdotr(tdrain) := \rho w \cdot Vdotr(tdrain)$

$Rer(tdrain) := \frac{\rho w \cdot vr(tdrain) \cdot Drpipe}{\mu w}$




$Vdotr(90 \cdot sec) = 1.167 \frac{gal}{sec}$ $\quad vr(90 \cdot sec) = 7.149\,ft \cdot sec^{-1}$ $\quad mdotr(90 \cdot sec) = 9.736\,lb \cdot sec^{-1}$




$fr := .025$

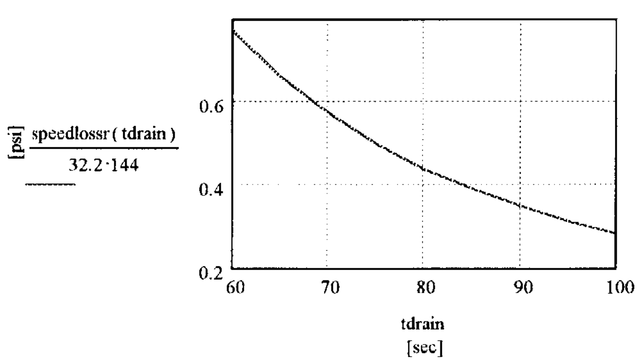
:using the conservative estimate of .001 for e/D -- relative roughness of the water drain pipe -- along with Figures 8.14 and 8.15, Fox and McDonald (pp.350-351)

***Water Return Head Loss:***

*Return losses due to imparting speed to the water (Δ **KE** term):*

$$speedlossr(tdrain) := \frac{\rho w \cdot vr(tdrain)^2}{2}$$

$$speedlossr(90 \cdot sec) = 0.344\,psi$$



*Return losses due to pumping against gravity ($\Delta$ **PE** term):*

$heqroom := 14 \cdot ft$ — heqroom: equip. room roof height plus the thickness of the reactor floor

$hmr := 11 \cdot ft$ — hmr: med. room roof height

$\Delta zr := heqroom + hmr + hst$ — $\Delta$zr: vertical distance from reactor floor to top of supply tank

$\Delta zr = 29 \circ ft$

$gravitylossr := \rho w \cdot g \cdot \Delta zr$

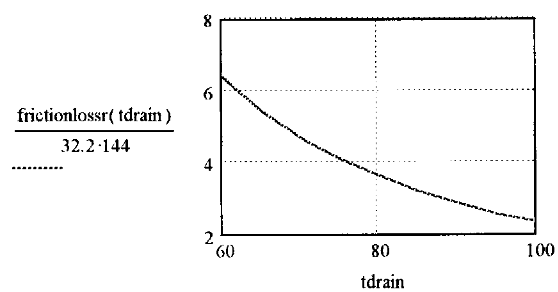
$gravitylossr = 12.572 \circ psi$

*return losses due to friction and bends in return piping:* $Lreturn := \Delta zr + 4 \cdot ft$

$\frac{Lreturn}{Drpipe} = 198$ $LeffD90 := 30$ $LeffD45 := 16$ $Ke := 1$

$$frictionlossr(tdrain) := (\rho w \cdot fr) \cdot \left(\frac{vr(tdrain)^2}{2}\right) \cdot \left(2 \cdot LeffD90 + 2 \cdot LeffD45 + \frac{Lreturn}{Drpipe}\right) + (\rho w) \cdot \left(\frac{vr(tdrain)^2}{2}\right) \cdot Ke$$

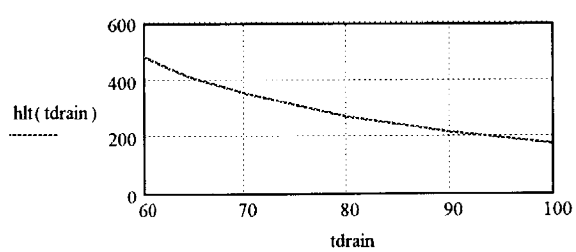
$frictionlossr(90 \cdot sec) = 2.84 \circ psi$




*friction/pipe bend head loss, hlt [ft^2/sec^2] :*

$$hlt(tdrain) := \left(\frac{vr(tdrain)^2}{2}\right) \cdot \left[Ke + fr \cdot \left(2 \cdot LeffD90 + 2 \cdot LeffD45 + \frac{Lreturn}{Drpipe}\right)\right]$$

$hlt(90 \cdot sec) = 210.804 \circ \frac{ft^2}{sec^2}$



$$hatm := \frac{1 \cdot atm}{\rho w \cdot g}$$

$hatm = 33.899 \, ft$

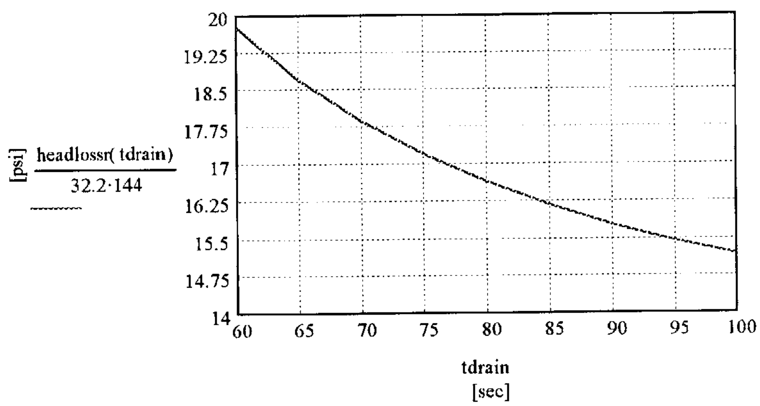
:height of water displaced by the pressure of one atmosphere

*Total Return Head Loss:*

$headlossr(tdrain) := speedlossr(tdrain) + gravitylossr + frictionlossr(tdrain)$

: Total return head loss in [psi] units

$headlossr(90 \cdot sec) = 15.757 \, psi$



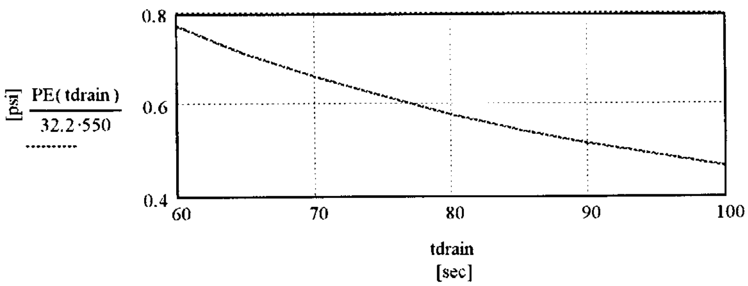

***First Law to find pump power needed (Wdot) to drain the water shutter:***

DE/DT = Wdot + mdot * [ (h1 + v1^2/ 2 + g * z1) - ( h2 + v2^2/ 2 + g * z2) - hlt ]
DE/DT = 0
assume h2 = h1, v1 =0

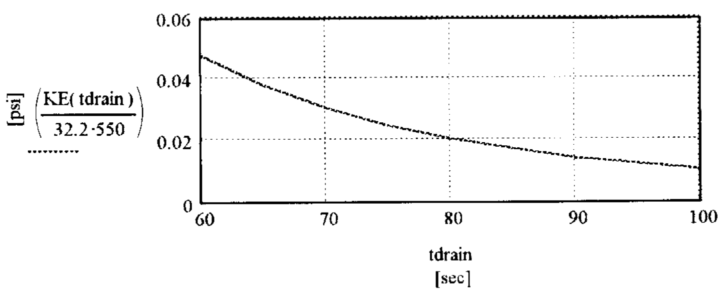
**Wdot = mdot * [ v2^2/ 2 + g * (Δzr) + hlt ]**

***Pump Horsepower required to overcome the 4 losses****(a function of shutter drain time):*
*(losses due to Δ PE, Δ KE, pipe friction & bends, and the cover gas pressure in the supply tank)*

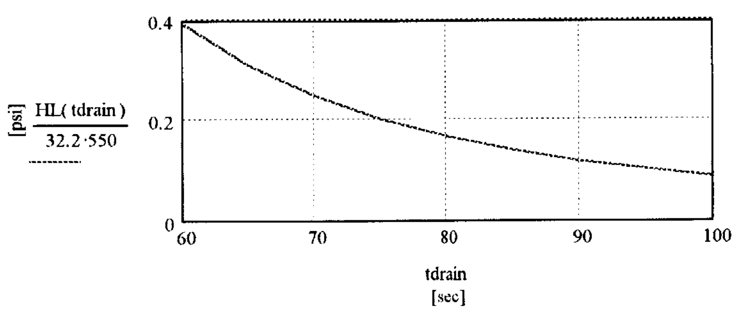
$$PE(tdrain) := mdotr(tdrain) \cdot g \cdot \Delta zr$$




$$KE(tdrain) := mdotr(tdrain) \cdot \left(\frac{vr(tdrain)^2}{2}\right)$$



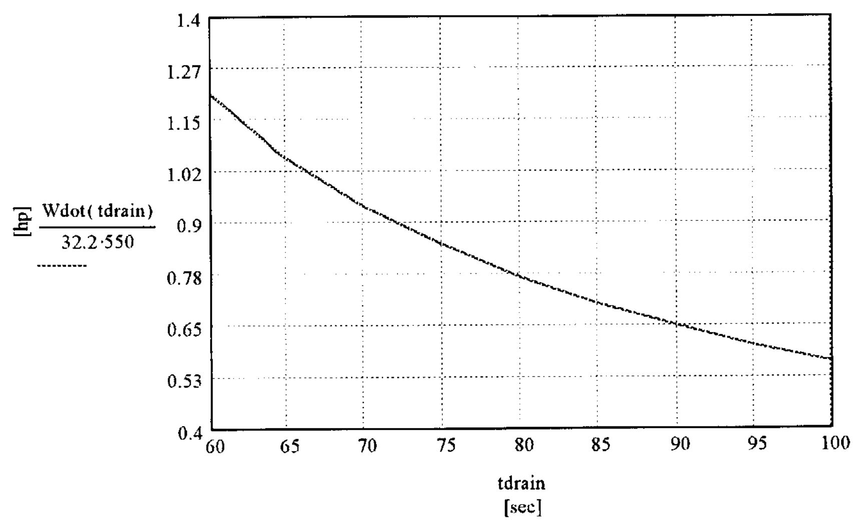

$$HL(tdrain) := mdotr(tdrain) \cdot hlt(tdrain)$$



***Total Horsepower Required :***
*(a function of shutter drain time)*

$$Wdot(tdrain) := PE(tdrain) + KE(tdrain) + HL(tdrain)$$

$$Wdot(75 \cdot sec) = 0.841 \circ hp$$



## Analyzing Shutter Fill Time:

***Water Supply Pipe:***

$hmr = 11\,ft$ hmr: height of the med room (from reactor floor)

$Dspipe := 2 \cdot in$

$Aspipe := \left(\frac{\pi}{4}\right) \cdot Dspipe^2$

$hcoll := 3.5 \cdot ft - 2 \cdot ft$ hcoll: min height of water shutter tank (from reactor floor)

$\Delta zs := hmr - hcoll$

$\Delta zs = 9.5 \circ ft$ $\Delta$zs: vertical distance from bottom of supply tank to bottom of water shutter, i.e. the inlet port

$\Delta zw := \frac{hst}{2}$ $\Delta zw = 2\,ft$ $\Delta$zw: avg. height of water in supply tank

$\Delta zt := 2 \cdot ft$

$Lsupply := \Delta zs + 6 \cdot ft$ : length of the supply water piping

$Lsupply = 15.5 \circ ft$

*losses due to friction and bends in supply piping:* *(2-90 degree bends, and 2-45 degree bends; iteration on water supply pipe friction factors)*

$Ke := 1$ $LeftD45 := 16$ $LeftD90 := 30$ $fs1 := .023$ :initial guess for friction factor of the supply water pipe

$\frac{Lsupply}{Dspipe} = 93$

$LeftDs := 2 \cdot LeftD90 + 2 \cdot LeftD45$

$LeftDs = 92$

***Water Supply Velocity, Flow Rate:***

$$vs := \sqrt{\frac{2 \cdot g \cdot (\Delta zs + \Delta zw - \Delta zt)}{fs1 \cdot \left(LeftDs + \frac{Lsupply}{Dspipe}\right) + Ke + 1}}$$

$vs = 9.886\,ft \cdot sec^{-1}$

$Res := \frac{\rho w \cdot vs \cdot Dspipe}{\mu w}$

$fs := .023$

$Res = 1.801 \cdot 10^5$

:uses the conservative estimate of.001 for e/D -- the relative roughness of the water supply pipe -- along with Figures 8.14 and 8.15, Fox and McDonald (pp.350-351)

$Vdots := vs \cdot Aspipe$

$Vdots = 0.216 ft^3 \cdot sec^{-1}$

$Vdots = 1.613 \cdot \frac{gal}{sec}$

$tfill := \frac{Vshutter}{Vdots}$

$tfill = 65.081 \cdot sec$

***<u>Gas Vent From Water Shutter -- Incompressible Gas Assumption:</u>***
*(solving for the $\Delta$ P needed to force the air out of the shutter -- i.e. the "back-pressure" exerted on the water-- letting the diameter of the tube range between 1/2" and 1")*

$eD := .001$ (conservative estimate for the relative roughness of the air tube)

$Kc := .5$ (contraction) $\alpha 1 := 1$ $\alpha 2 := 1$ (assumes turbulent flow)

$\rho air := 1.16 \frac{kg}{m^3}$ $\mu air := 184.6 \cdot 10^{-7} \cdot \frac{newton \cdot sec}{m^2}$ $\rho He := .1625 \frac{kg}{m^3}$ $\mu He := 199 \cdot 10^{-7} \cdot \frac{newton \cdot sec}{m^2}$

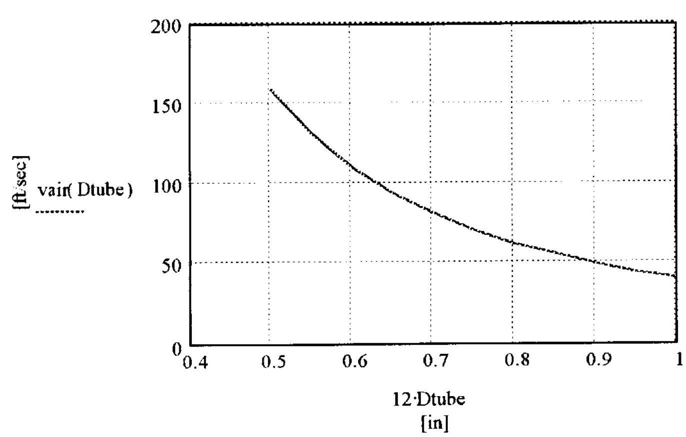
(gas properties evaluated at 300K and 1 atm; source: Incropera and DeWitt)

$Dtube := .5 \cdot in, .55 \cdot in .. 1 \cdot in$

$Atube(Dtube) := \left(\frac{\pi}{4}\right) \cdot Dtube^2$

$vair(Dtube) := \frac{Vdots}{Atube(Dtube)}$ (uses the rel'n. Vdotwater = Vdotair)

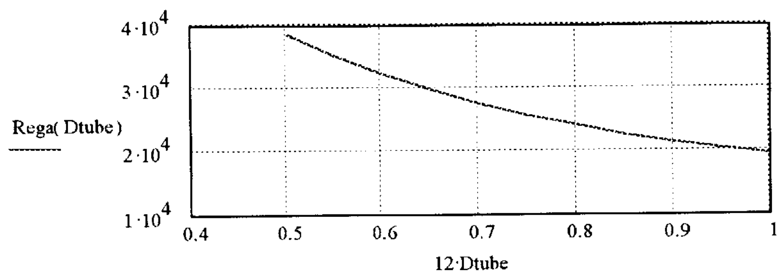
$vair(.75 \cdot in) = 70.3 ft \cdot sec^{-1}$



***Air as the "Incompressible" Gas:***

$\rho g := \rho air \qquad \mu g := \mu air$

$$Rega(Dtube) := \frac{\rho g \cdot vair(Dtube) \cdot Dtube}{\mu g}$$

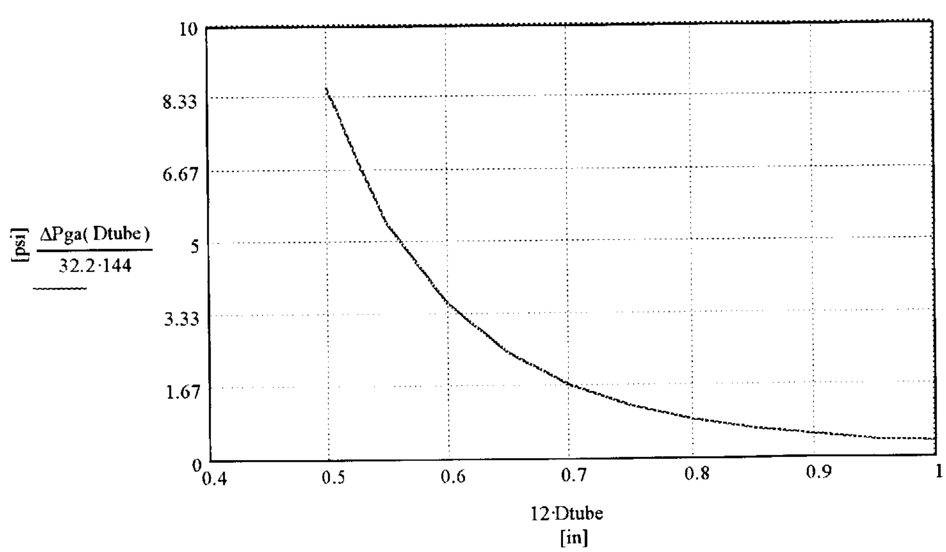



***Solving for Gas Vent "Back Pressure"*** *(a function of Dtube)* ***due to forcing the gas out of the water shutter as it fills:***

$Ltube := Lreturn - hcoll \qquad Kc := .5 \qquad Ke = 1$

$Ltube = 31.5\,ft$

$$\Delta Pga(Dtube) := \rho g \cdot \left(\frac{vair(Dtube)^2}{2}\right) \cdot \left[fga \cdot \left(2 \cdot LeffD90 + 2 \cdot LeffD45 + \frac{Ltube}{Dtube}\right) + (Kc + Ke)\right]$$



***This Gas Vent "Back Pressure" tends to slow down the shutter fill time; therefore, Bernoulli will again be applied to the water entering the shutter -- this time incorporating the back pressure loss term,$\Delta$ Pga; then, solving for a 'new' water supply velocity and flow rate:***

$$vsnewa(Dtube) := \sqrt{\frac{2\cdot\left[g\cdot(\Delta zs + \Delta zw - \Delta zt) - \frac{\Delta Pga(Dtube)}{\rho w}\right]}{fs1\cdot\left(LeffDs + \frac{Lsupply}{Dspipe}\right) + Ke + 1}}$$

$$Vdotsnewa(Dtube) := vsnewa(Dtube)\cdot Aspipe$$

$$\frac{\Delta Pga(.5\cdot in)}{\rho w} = 637.036 ft^2\cdot sec^{-2}$$

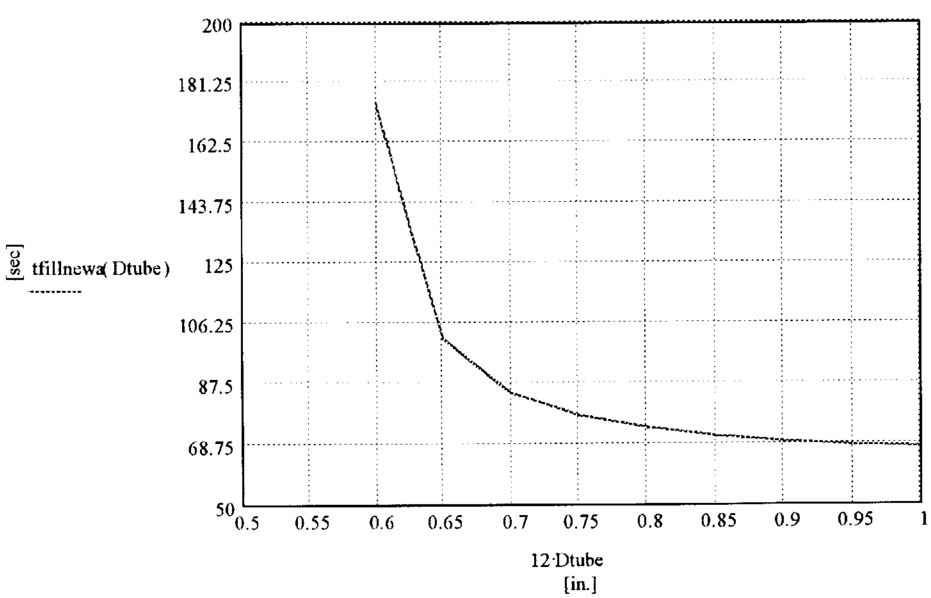
$$g\cdot(\Delta zs + \Delta zw - \Delta zt) = 305.653 ft^2\cdot sec^{-2}$$

$$vsnewa(.5\cdot in) = 10.294 ift\cdot sec^{-1}$$

$$Vdotsnewa(.5\cdot in) = 0.225 ift^3\cdot sec^{-1}$$

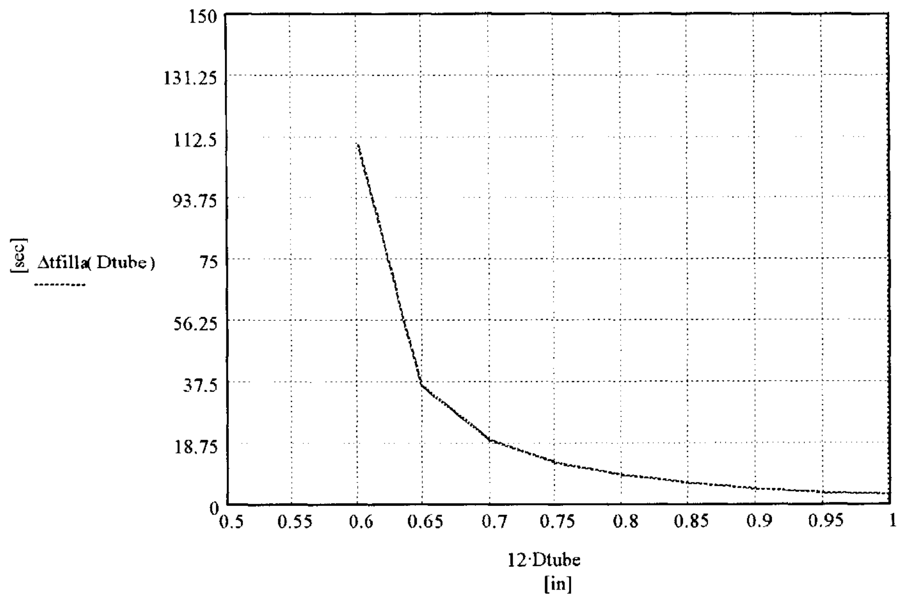
$$fs1\cdot\left(LeffDs + \frac{Lsupply}{Dspipe}\right) + Ke + 1 = 6.255$$

***yields a new, lengthened, shutter fill time:*** $tfillnewa(Dtube) := \frac{Vshutter}{Vdotsnewa(Dtube)}$



***and the $\Delta$ time in filling the shutter due to the gas vent back pressure is:***

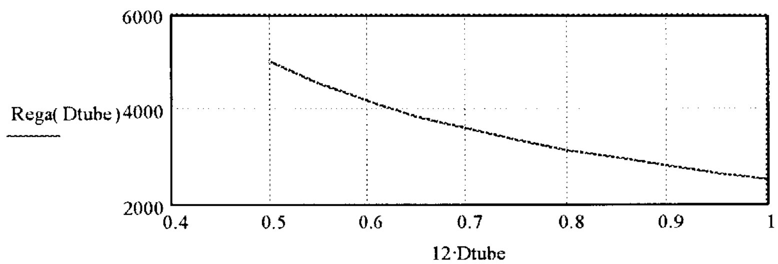
$\Delta\,\text{tfilla}(\text{Dtube}) := \text{tfillnewa}(\text{Dtube}) - \text{tfill}$



## ***Helium* as the "Incompressible" Gas:**

$\rho g := \rho He \qquad \mu g := \mu He$

$$Rega(Dtube) := \frac{\rho g \cdot vair(Dtube) \cdot Dtube}{\mu g}$$

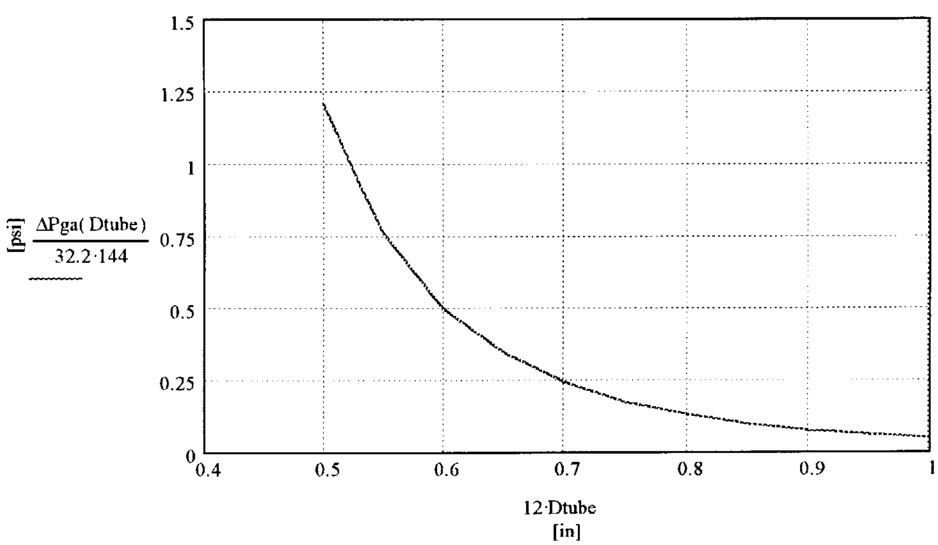



## **Solving for Gas Vent "Back Pressure"*(a function of Dtube)* due to forcing the gas out of the water shutter as it fills:**

$Ltube := Lreturn - hcoll \qquad Kc := .5 \qquad Ke = 1$

$Ltube = 31.5 ft$

$$\Delta Pga(Dtube) := \rho g \cdot \left(\frac{vair(Dtube)^2}{2}\right) \cdot \left[fga \cdot \left(2 \cdot LeffD90 + 2 \cdot LeffD45 + \frac{Ltube}{Dtube}\right) + (Kc + Ke)\right]$$



***This Gas Vent "Back Pressure" tends to slow down the shutter fill time; therefore, Bernoulli will again be applied to the water entering the shutter -- this time incorporating the back pressure loss term,Δ Pga; then, solving for a 'new' water supply velocity and flow rate:***

$$vsnewa(Dtube) := \sqrt{\frac{2\cdot\left[g\cdot(\Delta zs + \Delta zw - \Delta zt) - \frac{\Delta Pga(Dtube)}{\rho w}\right]}{fs1\cdot\left(LeffDs + \frac{Lsupply}{Dspipe}\right) + Ke + 1}}$$

$$Vdotsnewa(Dtube) := vsnewa(Dtube)\cdot Aspipe$$

$$\frac{\Delta Pga(.5\cdot in)}{\rho w} = 89.24\,ft^2\cdot sec^{-2}$$

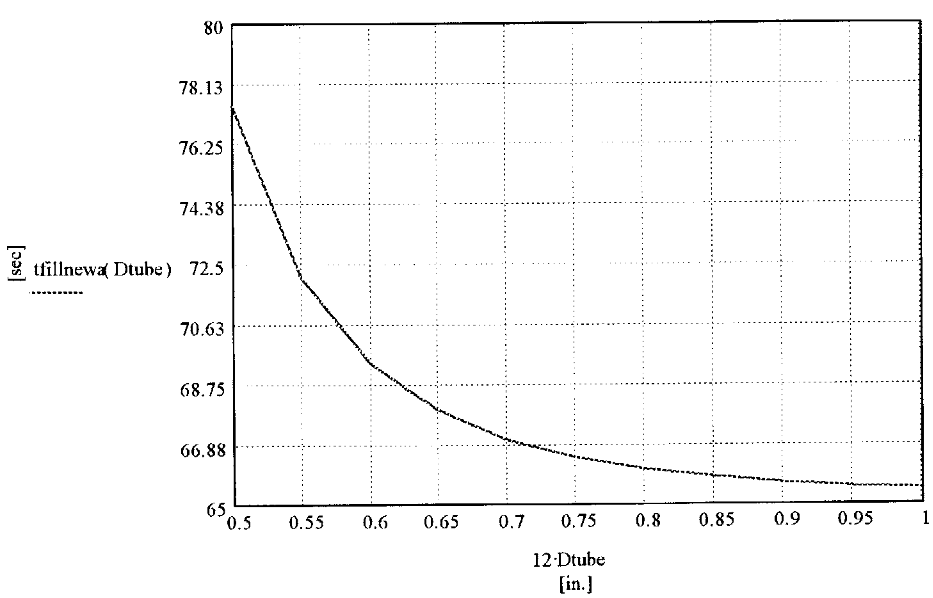
$$g\cdot(\Delta zs + \Delta zw - \Delta zt) = 305.653\,ft^2\cdot sec^{-2}$$

$$vsnewa(.5\cdot in) = 8.318\,ft\cdot sec^{-1}$$

$$Vdotsnewa(.5\cdot in) = 0.181\,ft^3\cdot sec^{-1}$$

$$fs1\cdot\left(LeffDs + \frac{Lsupply}{Dspipe}\right) + Ke + 1 = 6.255$$

***yields a new, lengthened, shutter fill time:*** $tfillnewa(Dtube) := \frac{Vshutter}{Vdotsnewa(Dtube)}$



***and the Δ time in filling the shutter due to the gas vent back pressure is:***

$$\Delta \text{tfilla}(\text{Dtube}) := \text{tfillnewa}(\text{Dtube}) - \text{tfill}$$