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THESIS

FACILITIES REQUIREMENTS FOR A FLASH X-RAY MACHINE

by

Edward Charles Zurey, Jr.

June 1985

Thesis Advisor: X. K. Maruyama

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This study discusses the impact and benefits of installing a 1.5 MeV flash X-ray machine at the Naval Postgraduate School. It reviews the specifications and applications of the 100 MeV linear accelerator currently in operation at NPS and compares it with the performance of the proposed equipment. Estimates of radiation production and area dosages from the flash X-ray machine, as well as proposals for equipment location and sheilding design, are presented. Laboratory requipments for electrical power, space, rediation monitoring, equipment interlocks and (continued)-

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Facilities Requirements for a Flash X-Ray Machine

by

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B.S., The Pennsylvania State University, 1978

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN PHYSICS

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ABSTRACT

This study discusses the impact and benefits of installing a 1.5 MeV flash X-ray machine at the Naval Postgraduate School. It reviews the specifications and applications of the 100 MeV linear accelerator currently in operation at NPS and compares it with the performance of the proposed equipment. Estimates of radiation production and area dosages from the flash X-ray machine, as well as proposals for equipment location and shielding design, are presented. Laboratory requirements for electrical power, space, radiation monitoring, equipment interlocks and safety awareness, as well as federal regulations applicable to an installation of this type, are considered.

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ACKNOWLEDGEMENT

I. INTRODUCTION

Past research at the Naval Postgraduate School Accelerator Laboratory has been conducted using the 100 MeV electron linear accelerator (LINAC), which became operational in September of 1966. Initially designed for use in radiation damage and nuclear structure studies, the LINAC's role has evolved to include research in various areas such as inelastic electron scattering, stimulated Cerenkov microwave and X-ray radiation, and scintillation analysis of gamma radiation. Some examples of this work, which represent a sample of the large volume and scope of thesis research accomplished with the LINAC over the past twenty years, can be found in the bibliography.

Travelling wave linear accelerators, such as the LINAC and the 2 mile long, 20 GeV machine at the Stanford Linear Accelerator Center (SLAC), are designed for elementary particle research involving high energy and low current beams. Induction linear accelerators, on the other hand, are able to produce large current particle beams at low to medium energies. Some design improvements in the induction linac have occured in the past several years involving pulsed power networks consisting of electrical components capable of delivering short pulses of high voltage, high

current electrical power many times per second. Pulsed power technology of this type is partially responsible for the capabilities of the 50 MeV Advanced Test Accelerator (ATA), which is able to generate a 10 kA beam with a burst rate of 1 kHz and a pulse length of 70 usec.

Not all pulsed electron accelerators are as colossal and complex as the ATA. A small pulsed electron beam machine with experimentally useful performance characteristics could be installed at the Naval Postgraduate School for relatively low cost and minimal impact on surrounding areas. A machine of this type could be used in either the flash X-ray or beam mode, expanding the capability of the accelerator laboratory and presenting vastly expanded and interdisciplinary experimental opportunities in modern pulsed power technology.

However, as in any research facility, machine location and shielding design are critical factors. Space limitations in the LINAC end station, for instance, have per)dically impacted on the scope and depth of possible experiments. The purpose cf this study, therefore, is to present several installation options and a sampling of resultant applications for a pulsed electron beam machine. Recommendations will attempt to strike a reasonable balance between the confines imposed by the physical plant, federal regulations, and the flexibility required by the broad spectrum of experimental applications.

II. PULSED ELECTRON BEAM SYSTEM

A pulsed electron beam/flash X-ray system is a high power, low maintenance, high reliability, and low cost controlled radiation and particle beam source. It is easily adapted to applications as diverse as laser pumping, flash radiography, materials testing, prompt gamma radiation generation, beam physics, and even thermonuclear fusion in the case of larger machines.

A block diagram of a pulse charged system is shown in Figure 1. The charging source is usually a bank of low inductance Marx generators although pulse transformers are occasionally used for this purpose. The pulse forming line can also consist of several types of devices, however, Blumlein transmission lines are more popular than the common transmission line because they can deliver the full charge voltage to a matched load. A fast output switch is used to rapidly transfer the energy to the field emission diode. In addition to this main output switch, a secondary switch is frequently installed to contain the prepulse and sharpen the risetime of the output pulse.

The entire body of the pulsed electron machine is immersed in a dielectric energy storage medium, usually transformer oil or deionized water. The diode is insulated

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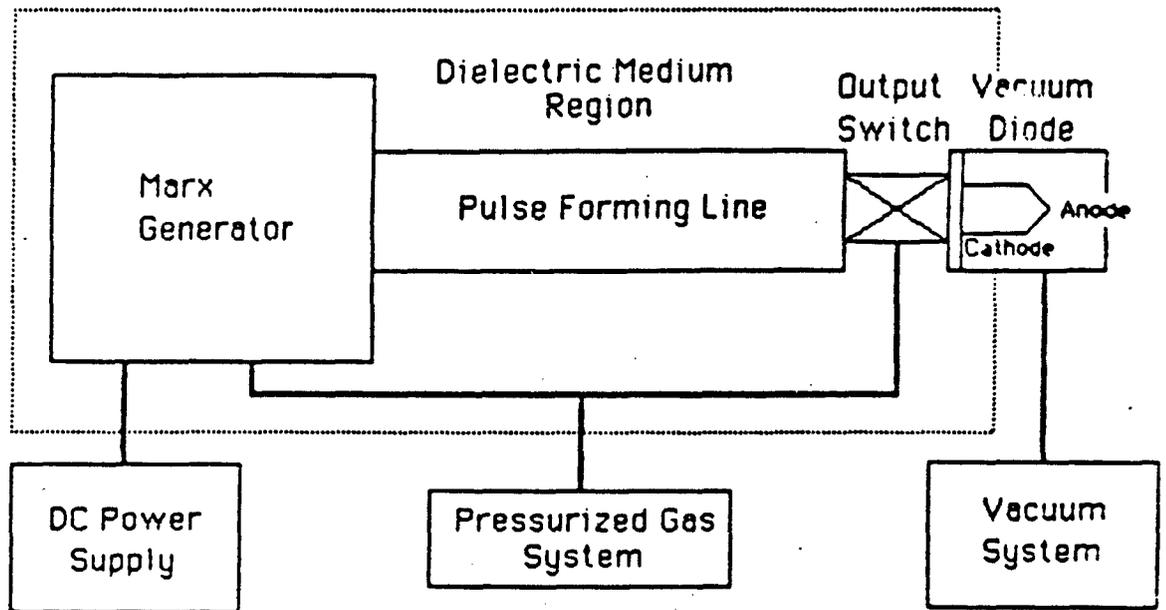
Figure 1: A Block Diagram of a Pulse Charged System

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from the fluid by a solid dielectric to maintain a vacuum in the beam generation region. We will now describe the most standard components of a pulsed charge system in more detail.

A. MARX GENERATOR

A Marx generator system is characterized by a bank of capacitors being charged in parallel, then discharged in series by a number of switches. The Marx system will produce a high voltage pulse due to its short rise time, low output impedance, and high energy. Figure 2 illustrates the charge and pulse cycle of a three stage Marx generator. The capacitors are charged by a DC power supply to voltage V_o. The spark gaps are triggered, causing the network to "erect" by connecting the capacitors in series, producing an output voltage of $3V_o$.

In systems of many capacitors, after triggering the early gaps the remaining banks will erect with voltages of down to about one third of the self-breakdown voltage of the individual gaps. The Marx configurations with numerous banks are relatively free from self-breakdown problems, but tend to erect more slowly than less complex configurations. Self erecting Marx generators are not always employed. In some cases it is preferable to trigger all the spark gaps simultaneously. [Ref. 1: p 3]

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A) Full Circuit Schematic

B) Effective Charging Circuit

C) Effective Pulse Discharge Circuit
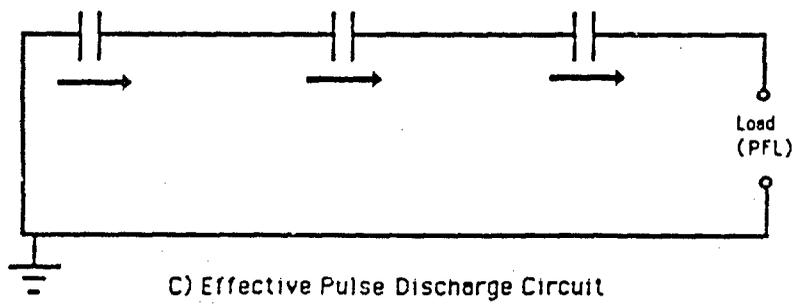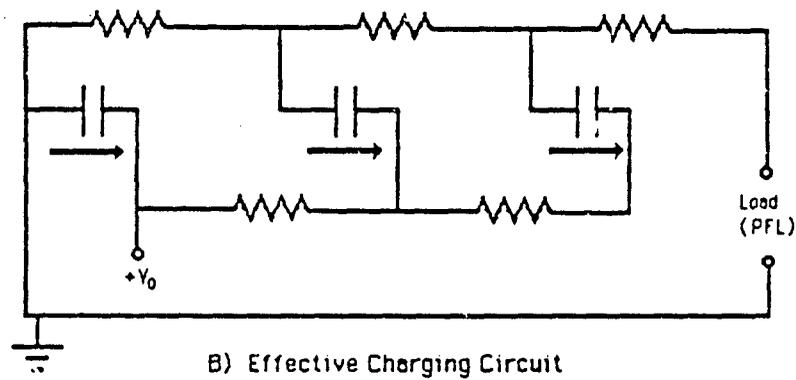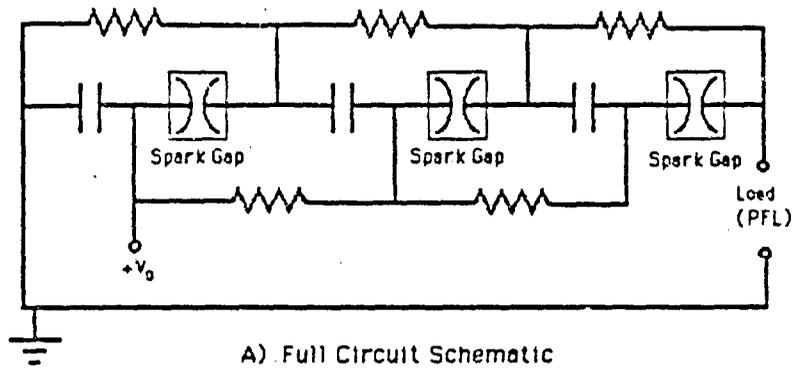
Figure 2: Operating Cycle of a Marx Generator

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Marx capacitors are usually immersed in transformer oil, which in this component serves to store energy and prevent flashover. The switches in the Marx generators are typically gas filled spark gaps. Since their dimensions are fixed, the operating ranges are varied by changing the pressure of the synthetic air or Sulfur-Hexaflouride(SF_6). For the lower voltage range from 60 to 100 kV/bank, synthetic air, which is dry air with a dew point of $-60oC$, is used. With SF6 the operating range may be extended to 120kV. The greater the gas pressure in the spark gap, the greater the static breakdown voltage, thereby providing a wider range of operating voltages. Figure 3 shows the static breakdown curves for both types of gases.
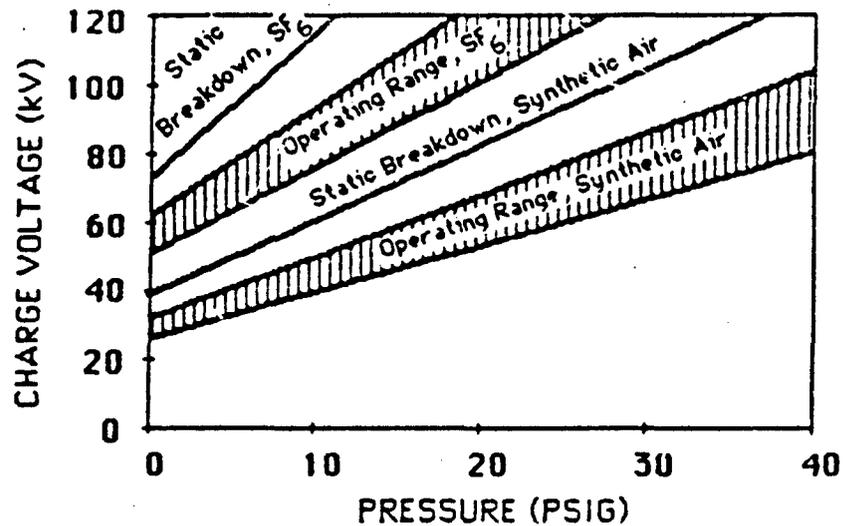
Figure 3: Static Breakdown Curves for SF_6 and Synthetic Air

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In certain applications, the Marx generator pulse has been directly fed into the vacuum diode to produce a long duration particle beam. Beam durations of a few microseconds have been obtained in this manner, which is useful for microwave generation and for electron and ion beam production for plasma heating and containment. The beam rise time in this mode is much slower than with pulse forming lines and the high generator impedance, compared to the Blumlein, limits the current. However, flash X-ray production requires a fast pulse risetime on the order of 10 nanoseconds with reproducable beam duration. In view of these rigid standards, the need for a pulse forming line as an intermediate component in a pulsed electron beam system becomes clear.

B. PULSE FORMING LINE

As mentioned earlier, there are several different designs for a PFL. However, they are usually only used in two types of circuits - the common coaxial transmission line and the double line, or Blumlein, an abbreviated name honoring its inventor. The Blumlein is capable of producing an output pulse that equals the charge voltage into a matched load. This is not possible with a coaxial transmission line because the line capacitance and inductance in series with the Marx capacitance causes a circuit ringing loss. With a perfectly matched load across the coaxial line, the

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output voltage will be half the charge voltage. Figure 4 shows a schematic diagram for the cylindrical Blumlein circuit. The intermediate cylinder is charged by the Marx system in a time of less than 1 microsecond. The center cylinder is connected to the outer grounded cylinder through an inductor. During the charge cycle, the inductor acts as a short, permitting the inner and outer cylinder to maintain the same potential level. But when the Marx generator erects, the inductor will act as a high impedance load. Both PFL circuit types generate a diode prepulse during this charging phase due to the unequal charging rates of the two halves of the Blumlein or coaxial cable. Depending on the diode design, this prepulse can produce a plasma which may effect the main output pulse. For a Blumlein, this prepulse can be reduced to acceptable levels by installing a prepulse switch prior to the diode.

The switching of a charged Blumlein into a load requires the reliable firing of a normally insulating gap. The controlled failure of the insulation properties of the dielectric at a controlled time and voltage can be accomplished using self-breakdown or deliberate triggering. When the output switch triggers, shorting the inner and intermediate cylinders, a reverse polarity wave will propagate from the output switch end forward to the prepulse switch end in time τ and will abruptly change the voltage across the prepulse switch from near ground potential to

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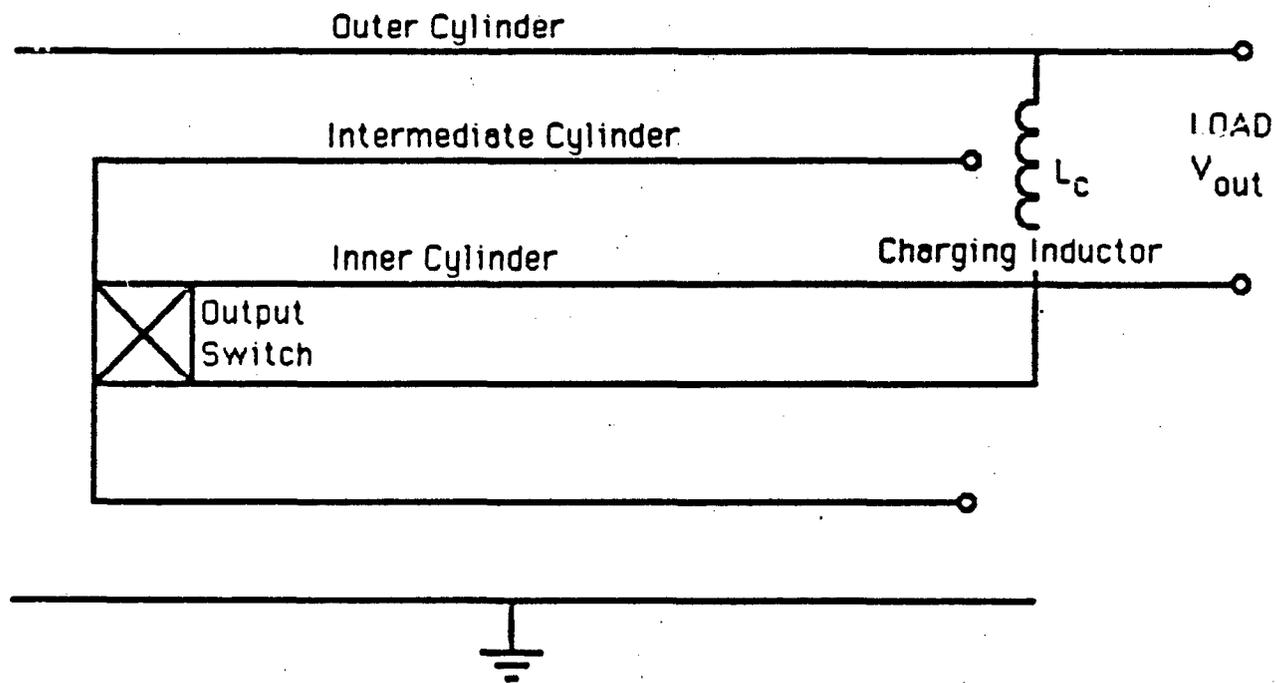
Figure 4: Schematic Diagram of a Pulse Forming Blumlein

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twice the pulse charge voltage. When this pulse reaches the prepulse switch end at time τ, the inductor becomes a high impedance load, forming a matched impedance switched across the output circuit. This impedance is matched for the known diode load, so the output voltage drops by one half to Vo. However, all the energy can be extracted in time 2τ, which defines the real pulse length. Miller [Ref. 2: p. 11] introduces an expression used to determine the pulse length for either a Blumlein or coaxial cable by:

$$\tau_J = \frac{2\ell\sqrt{\epsilon}}{c} \tag{2-1}$$

where ϵ is the dielectric constant and ℓ is the length of the line. For water, $\epsilon = 80$ and for transformer oil $\epsilon = 2.4$. Using Eqn 1-1, we can estimate typical Blumlein lengths for a machine of our specifications. Table 1 summarizes these calculations. In practice, a water dielectric is used for low impedance (4 - 10 ohms), moderate voltage (0.5 - 5 MeV) applications while oil is preferred for high voltage use in the 1 - 15 MeV range. The oil blumlein used in the Pulserad model 112A machine manufactured by the Physics International Company of San Leandro, Ca., for example, has an impedance of 43 ohms. A comparison of both dielectrics will be made in Chapter III after the pulsed electron beam machine's operating characteristics have been defined.

Table 1: BLUMLEIN LENGTHS FOR TYPICAL PULSE LENGTHS

Dielectric Type	ϵ	Pulse Length (nsec)	PFL Length (cm)	(ft)
Transformer Oil	2.4	30	290	9.5
Transformer Oil	2.4	20	194	6.4
Deionized Water	80.0	30	50	1.6
Deionized Water	80.0	20	34	1.1

C. VACUUM DIODE

The vacuum diode converts the short duration high power pulses into useful particle beams. It consists of a field emission cathode and a selectable anode designed for the appropriate machine mode. The entire assembly is usually pumped down to the 10^{-4} to 10^{-5} Torr vacuum range. The vacuum and diode separation is maintained by a standard multi-insulator utilizing stacked metallic gradient rings between lucite insulator stages. The insulators are usually cut at $30°$ to the axis of the diode and arranged so the electrons leaving the surface of the dielectric through thermionic emission do not hit the plastic, causing undesirable secondary emissions and beam breakdown. The metallic disks serve as grading rings, distributing the diode voltage uniformly along the length of the insulator. Figure 5 shows a schematic diagram of a vacuum diode used for beam propagation.

The anode consists of an interchangeable aluminum disk which determines the machine mode. A disk with a window of

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low absorption material cut into its center allows beam propagation outside of the diode. Different window sizes and shapes, when used with appropriate confining magnetic fields, result in varied beam propagation characteristics and can be used to tailor the beam for specific experiments. With a tungsten or tantalum foil placed inside the anode disk as a bremsstrahlung target, the machine produces flash X-rays. I_0, the total intensity of the continuous spectrum, is dependant on the atomic number Z of the bremsstrahlung target, on the accelerator voltage across the diode V and on the current i of electrons and is given by [Ref. 3: p. 3]:

$$I_0 = kiZV^2 \qquad (2-2)$$

where k is denotes a coefficient. Equation 2-2 shows that dose production is linear with current and squared with diode voltage. Efficiency, η, of the electron conversion of beam energy into the continuous bremspectra of X-ray energy can be estimated by [Ref. 3: p. 3 and Ref. 4: p. 10]:

$$\eta = 10^{-3}ZV \qquad (2-3)$$

where V is in MeV. So, to optimize dose when designing systems, it is practical for efficiency and yield to improve the diode voltage at the cost of current.

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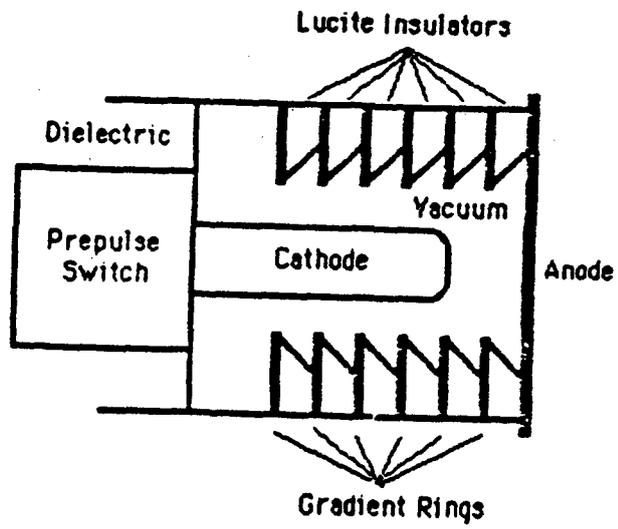
Figure 5: Schematic Diagram of a Vacuum Diode

III. PROPOSED NPS FACILITIES

A. MACHINE SPECIFICATIONS

The primary factors in machine selection are ease of operation, shot to shot reliability and reproducability, routine maintenance requirements, and a high mean time to failure factor. Table 2 summarizes the system operating characteristics which were obtained from input from the Naval Postgraduate School faculty and resulted in the contract specifications [Ref. 5]. A machine of this type used in the flash X-ray mode will produce a radiation dose of 250 Rads(Si) on axis, 10 cm from the X-ray target in a single 30 nsec pulse. Electrical radiated noise from the machine while in this mode will not exceed 100 mV at 1 MHz in the immediate vicinity of the machine outside of the forward X-ray field.

Table 2: PULSED ELECTRON SYSTEM OPERATING CHARACTERISTICS

Minimum Peak Electron Beam Voltage	1.5 MV
Minimum Peak Electron Beam Current	35 Kiloamperes
Minimum Electron Beam Energy	800 Joules
Current Pulse Width	30 nsec $\pm$ 5 nsec (FWHM)
Maximum Pulse Risetime	15 nsec (10%-90% peak)
Maximum Trigger Jitter	50 nsec (rms)

Note: Pulses demonstrating various peak levels and duration are measured by their full width at half the pulse maximum (FWHM) and is the parameter used for current pulse width.

Peripheral equipment to the basic machine described earlier is numerous. The dielectric material requires an extensive support system including storage tanks, pumps, filters, piping and valves. If the machine chosen has a deionized water Blumlein, a separate but similar system including deionizing equipment will be required. The Marx generators will have a transformer oil dielectric in any case.

Vacuum pumps, gauges and tubing are all required for the field emission diode. Pressurized lines, gauges and valves will also be required to control the numerous SF_6 switches. The electrical power supply for charging the banks and serving all ancillary equipment will operate on a 120 V, 60 Hz source. It is intended that the operator will be able to control and monitor the entire machine at one location from one or two electrical and mechanical equipment racks.

With the operating characteristics defined, some anaylsis of the optimum Blumlein dielectric is in order. As discussed in Chapter II, the short length of a water Blumlein producing a 30 nsec pulse is attractive for machine location, installation and maintenance considerations. The lower impedance of a water Blumlein, with the same diode voltage producing the same pulse length, will generate a current an order of magnitude greater than the operating characteristics require at the bremsstrahlung target. Also, the prepulse is suppressed more in a water Blumlein because

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the areas of the inner and outer cylinders are more nearly equal. This brings the charging rates of the two sections closer together. From a safety standpoint, a water dielectric will not create a fire hazard. However, these advantages are obtained at increased expense and complexity due to the related water ancillary equipment. Finally, to meet the design specifications of a 35 kiloampere beam current, the impedance of a water Blumlein would need to be increased with some sort of high power series resistance, returning us to the performance of an unmodified oil dielectric Blumlein. In summary, the key specifications of a 35 kiloampere beam current, 1.5 MV diode voltage and 30 nsec pulse length combine to make an oil Blumlein the ideal pulse forming component. Facilities analysis in Chapter IV will be directed solely towards a machine of this type.

Research at Maxwell Laboratories in San Diego, Ca. and Physics International has identified several likely models and custom design systems which fit the operating specifications. All of these machines employ the physical concepts and major system components discussed in the previous chapter. For purposes of discussion and general planning in this study, a representative generic machine will be addressed having the dimensions listed below in Table 3. These values take the largest dimensions resulting when system components from the different manufacturers are compared.

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Table 3: GENERIC MACHINE DIMENSIONS

Marx Tank	8' h X 4' w X 9' 1
PFL (30 nsec pulse length)	10' 1 (oil dielectric)
	1' 1 (water dielectric)
PFL Diode Assembly	5' off floor
Approximate Weight (30 nsec)	12000 lbs
Overall Size	
30 nsec Oil Blumlein	8' h X 4' w X 19' 1
20 nsec Water Blumlein	8' h X 4' w X 9' 1

B. X-RAY SPECTRUM AND RADIATION OUTPUT

The flash X-ray system of interest in this study is classified as a moderate X-ray source by the Defense Nuclear Agency, which is the controlling authority for several large X-ray facilities. [Ref. 6] This group contains all high current electron beam machines with energies in the 0.5 to 20 MV range. These sources create moderate energy X-rays with the preponderance of the source output ranging between the spectral limits of 50 to 300 keV. The curve in Figure 6 is a representative of a typical X-ray spectra for a 1.5 MeV beam striking a bremsstrahlung source and was constructed from information in Whyte [Ref. 7] and from DNA [Ref. 6]. The continuous, broad distribution of energy is interrupted by the characteristic K and L lines. These lines are shown in Figure 6 for a Tungsten bremsstrahlung target whose K line occurs at 70 KeV and L line at 9 KeV. X-ray yield is a function of the cube of the beam energy. The peak of this X-ray bremsspectra normally occurs at a value of approximately $E_o/5$.

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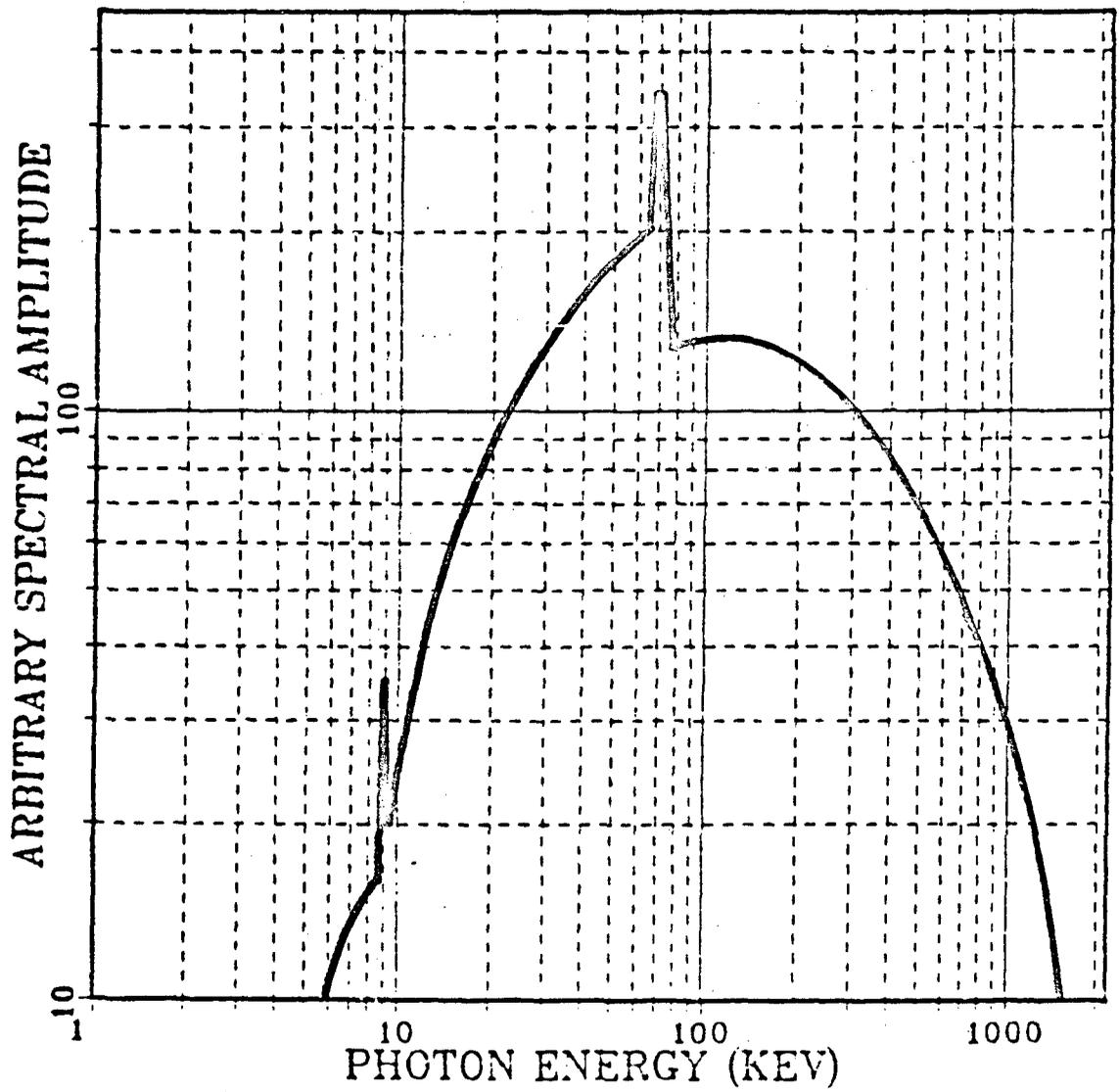
Figure 6:   Characteristic X-Ray Spectrum for a 1.5 MeV Beam

The dose map in Figure 7 represents actual dose readings taken from a Pulserad 112A machine. The operating characteristics of this device generally meet the required machine specifications [Ref. 8]. The beam pulse width was 30 nsec. The map demonstrates the $1/r^2$ attenuation trend in the expected exposure profile.

Other representative curves for the flash X-ray machine are presented in Figures 8 and 9. Figure 8 again shows the $1/r^2$ attenuation of exposure, this time on the axis containing the diode, high Z bremsstrahlung target and free space when the radiation dose is 250 Rad(Si) at 10 cm from the target. This attenuation will be of prime interest when designing shielding plans for various location sites in the Chapter IV. Figure 9 illustrates the angular distribution of X-ray intensity at 50 cm. Of principal concern here is the forward radiation nature of the distribution. This will also be a principal characteristic in shielding considerations.

1. Other Sources

Electron or X-ray energies below the photodesintegration threshhold for Beryllium (1.67 MeV) are insufficient to produce nuclear reactions requiring radiation protection. The beam electrons or X-rays emerging from the field emission diode constitute the only radiation hazards from the system. [Ref. 4: p. 14 and Ref. 9: p. 31]

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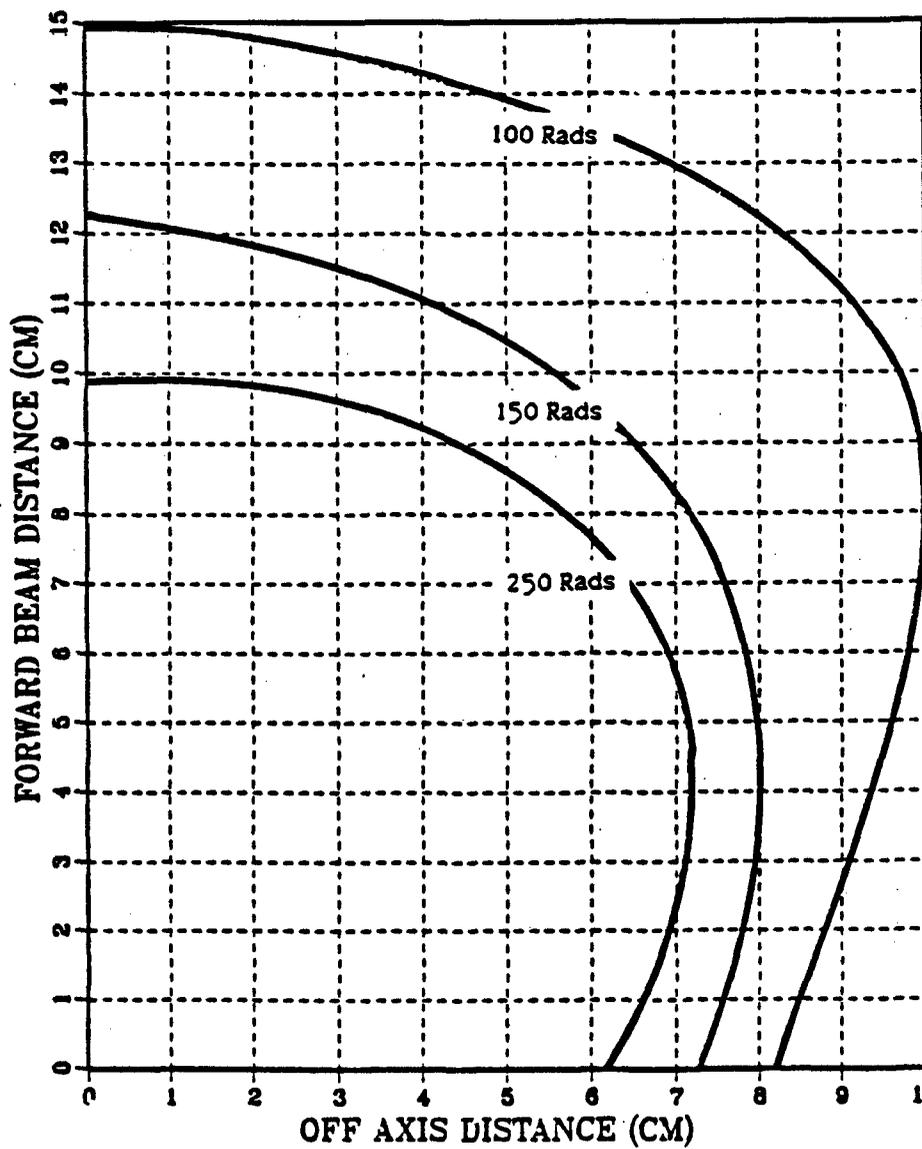
Figure 7: Dose Map for Pulserad 112A

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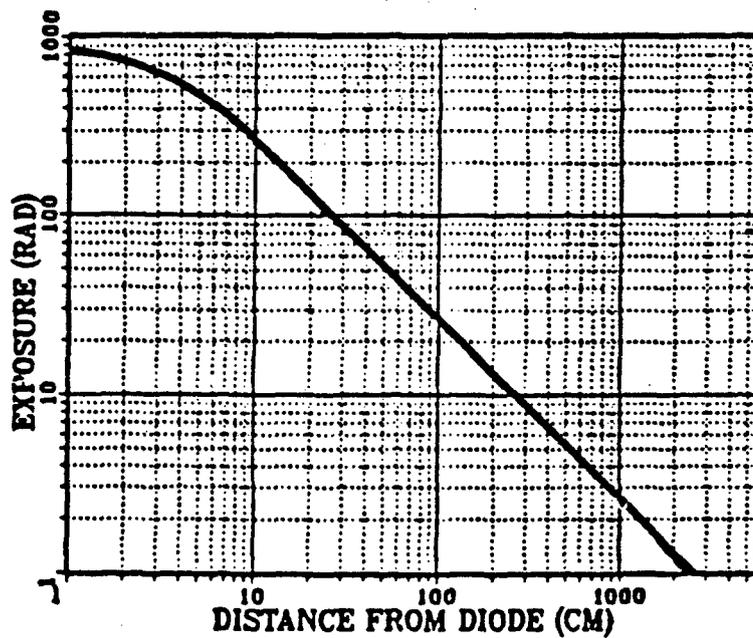
Figure 8: Calculated On-Axis Exposure
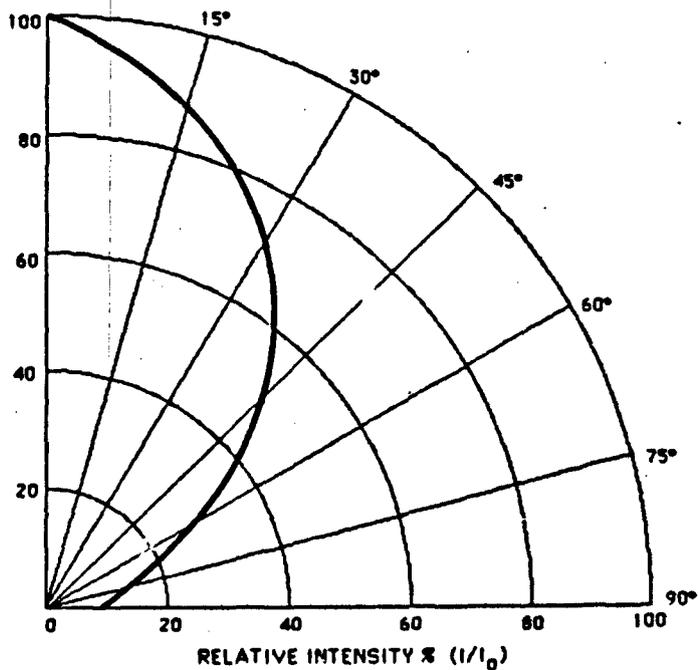
Figure 9: Angular Distrubution of X-Ray Intensity at 50 cm

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IV. INSTALLATION PROPOSALS

A. GENERAL SITE DISCUSSION

In this chapter, we will examine the feasibility of several locations available for machine installation, calculate unshielded radiation doses throughout the area, and design radiation protection designs based on those doses. Our area of discussion will be limited solely to the basement of Halligan Hall, which would afford the machine central location on campus, proximity to accelerator laboratory personnel and experimental equipment, and the natural shielding of unexcavated earth and reinforced concrete construction.

Practical considerations of installation start with space. Aside from the machine dimensions, room must be available for construction of surrounding shielding, a control room, and an experimental area. An ideal experimental area site would afford the opportunity for expansion to accomodate the needs of future experiments. Used in the flash X-ray mode, an area the size of a table top is adequate for radiating electronic components and hardware. Additionally, lead shielding hoods could be used to great advantage in an area this small. In the beam mode, however, a 1.5 MeV electron would travel at 0.94c in a

vacuum and in 30 nsec would form a pulse 27.8 ft (8.5 m) in length. This gives an idea of the distances to be considered in beam propagation experiments.

Another space issue to be considered is maintenance. Although individual capacitor modules in a Marx generator are reliable to the order of 104 unit shots, corrective maintenance for other reasons will eventually require opening the Marx tank. Capacitor trays in a Maxwell produced machine can be vertically removed from the top of the tank if necessary and suspended over an adjacent drip pan. Physics International and Febetron machines have removable doors in the rear of the machine requiring draining of the transformer oil followed by horizontal removal of the trays from the machine casing.

Closely related is the availabilty of a heavy lift capability to deliver the machine to the site, easily arrange shielding, and conduct maintenance. Halligan Hall contains a 9 ton travelling overhead crane which serves the central area of the basement numbered 021 in Figure 10. Selecting a site not within range of this crane would incur the additional expense of a 2 - 3 ton overhead hoist at the site. To put this into perspective, each 1' X 1.67' X 7.5' ordinary concrete roofing beam used over the accelerator section of the LINAC weighs close to 1 ton.

Floor loading is also an important consideration as the shielding surrounding the system could weigh over 20 times

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the weight of the machine itself. Depending on design, this could be in the range of 20 to 120 tons, or 270 to 1650 cubic feet of concrete. Ordinary concrete has a density of 146 lb/cu ft. Most of the basement floor in Halligan Hall is 6" thick reinforced concrete slab with a gravel foundation. These areas have a safe load rating of 500 lb/square foot with a 70% safety factor. This is a minimum value as each of the sites discussed have loading factors considerably better than this.

With electron beam currents in the range of kiloamperes, care must be taken with respect to noxious gases produced by ionizing radiation. The National Bureau of Standards [Ref. 4], the National Council on Radiation Protection and Monitoring [Ref. 9] and the International Atomic Energy Agency [Ref. 10] all treat toxic gas production in considerable detail. Ozone, along with the several nitrous oxides, may be produced in sufficient quantities to cause a health hazard in the experimental area. Even if the experimental area will not be entered between shots, the room should still be routinely ventilated to prevent gradual corrosive damage to electronic equipment. This is a good housekeeping practice although the decomposition time of ozone is fifty minutes for a typical facility.

The threshold limit value for ozone, which is the maximum safe concentration averaged over one 8 hour work day in

a forty hour work week, is 0.1 ppm. Ozone can be lethal at these low concentrations in an exposure time of a few hours [Ref. 9: p. 135]. Ozone yield can be quickly calculated by knowing that maximum production in air is 10.3 molecules per 100 MeV. A 1.5 MV, 35 kiloampere electron beam of 30 nsec duration would experience a collision stopping power of 2.2 keV cm^{-1} in air. A small experimental enclosure of 1 cubic meter, a reasonable setup for electronics testing experiments, would produce 1.49×10^{20} O_3 molecules per pulse. Knowing there are 1.16×10^{25} total molecules at standard temperature and pressure in a cubic meter, we can calculate an ozone concentration of 1.29 ppm, a hazardous level. Ozone calculations provide the limiting values since NO and NO_2 have lesser yields and greater toxic thresholds.

The volume in a small experimental room of 13 cubic meters would dilute the concentration down to acceptable levels. A more practical method would be to design ventilation into each shielding plan. The time to completely remove the ozone from any site can be computed by:

$$ T = \frac{T_v \times T_d}{T_v + T_d} \qquad (4-1) $$

where T is the total time required to make the experimental station Ozone free, T_v is the ventilation time, the room volume divided by the flow rate, and T_d is the decomposition time, taken to be 50 minutes. The smell of ozone can be

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detected at 0.1 ppm or below so any experimental area free of this characteristic odour can be considered safe.

Power requirements for the installation will include the power supply drawing a load from 2 - 5 kWatts and several pieces of electronic ancillary equipment used for machine diagnostics or to record experimental data. The power requirements compared to the LINAC, for instance, can be considered light. Electric load center 1 and load center 2 serve the southern and northern halves of Halligan Hall's basement, respectively. Both centers have several spare circuits which would be available to serve the machine site when location is determined. The active circuit loaus in these load centers range from 0.3 to 783 kWatts.

Each of the three potential sites will be examined for feasibility to recieve a pulsed electron laboratory and then compared to reach a recommendation. The sites are marked in Figure 10 and discussed in detail below.

1. Site 1: Test Machine Foundation

In the dead center of the basement floor in Halligan Hall lies the foundation pit for a 600,000 lb test machine removed years ago. Strongly reinforced, the foundation is 12' deep and measures 16' X 38'. It is currently used as an Aeronautics Department study room and small laser laboratory.

The advantages offered by this site are numerous. One is the availability of the travelling crane mentioned

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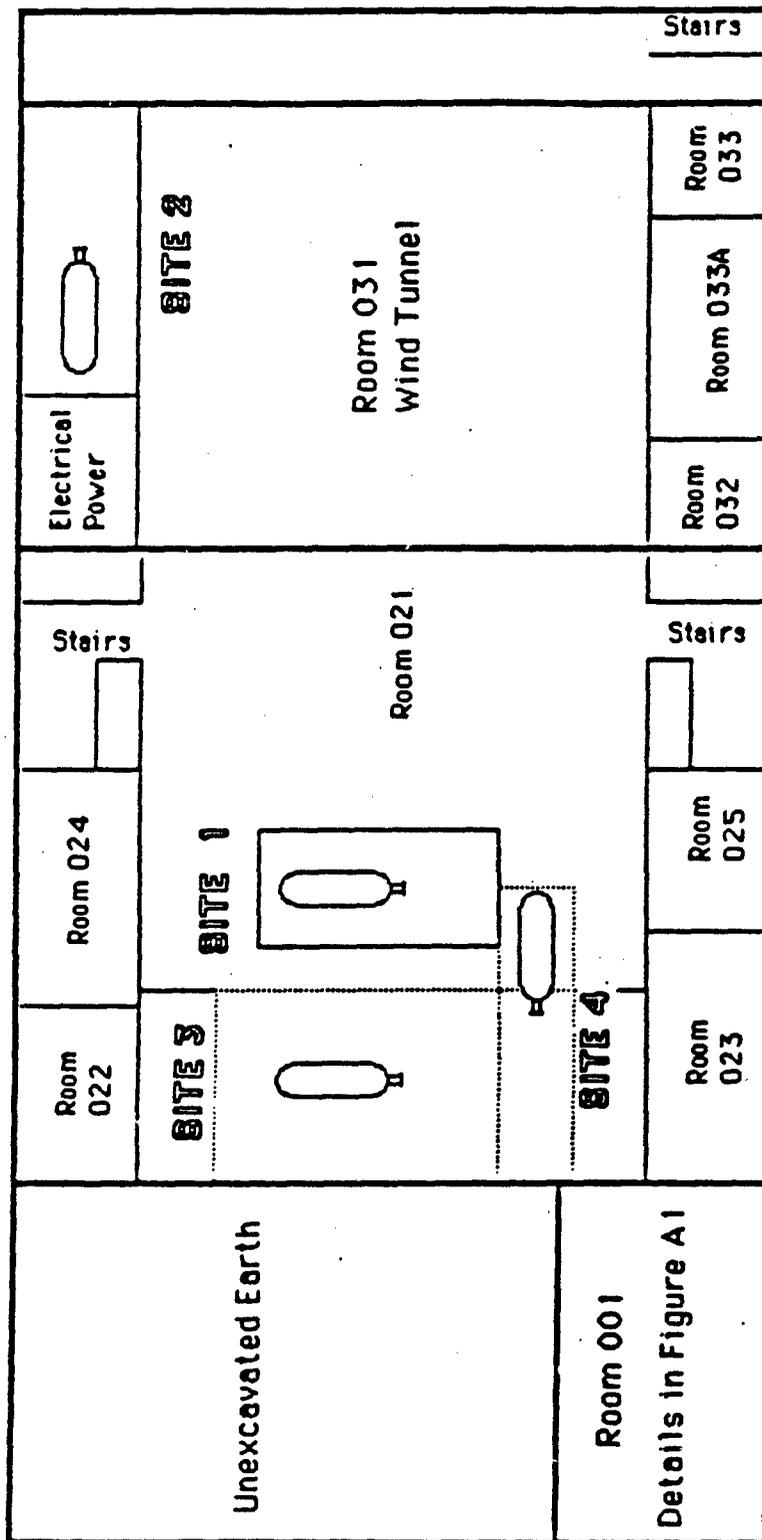
Figure 10: Basement Plan of Halligan Hall

earlier. Also, the efficient and inexpensive natural shielding provided by existing earth fill on five of six sides and ease of oil containment in the event of a dielectric plumbing accident are attractive points for this site. An estimated 1100 gallons of transformer oil (147 ft3) is required for a machine with an oil Blumlein. Also, a sufficient ventilation fan is already installed.

However, the disadvantages inherent to the foundation pit are considerable. Expansion of the experimental area could be accomplished only by considerable expense, as is currently a limiting case with the LINAC end station. Also, creating maintenance space for the Marx banks would require removing the roof shielding and lifting the capacitor up to the basement floor.

2. Site 2: Wind Tunnel

The western wing of the wind tunnel facility in Halligan Hall contains a power distribution bank and three areas of inactive storage. The floor is the basic 6" slab with an additional 6" padding and provides 18' of headroom.

Aside from the space available for beam propagation in this site, most other characteristics are disadvantages. For instance, the travelling crane does not serve this area. Additionally, the IBM Series 1 computer in room 132 directly overhead, although installed with sufficient RF filters and an isolation power transformer, may require special RF shielding on the machine. Finally, consultation with the

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Engineering Department of the Naval Postgraduate School Public Works Office has revealed that the floor loading of this area will be marginally capable to withstand the weight of the shielding designs proposed later in this chapter.

3. Site 3: Structural Static Test Display, East

The southern end of the basement is occupied by an inactive laboratory area containing a load floor used for static testing of aircraft wings. This floor is composed of concrete graded from 3' to 6' deep and formed over a network of reinforced bars. The area is surrounded by hydraulic line trenches which are 20" deep, without drains, and would serve as oil spill containment in the event of a dielectric plumbing accident. The total trench volume is over twice the projected volume of the transformer oil.

The test load floor offers many other advantages. There are also numerous power sources in this area to serve test equipment. The 27' X 49' floor area is entirely within the coverage of the overhead crane and provides ample room for maintenance and expansion of the experimental area to meet the demands of special experiments. The beam direction would be towards the east and the control area could be co-located near the existing accelerator laboratory.

4. Site 4: Structural Static Test Display, South

An alternative to site 3 is to orient the machine on the static test display floor to maximize co-location of the

flash X-ray machine with other spaces in the accelerator lab. With the machine placed along the entrance to the laboratory facing south, the advantage of unexcavated earth as shielding in the forward beam direction is realized. With an area 57' long X 15' wide, this site offers the longest possible propagation path for a beam. The overhead crane, ventilation and power supplies are all advantages.

Although site 4 offers many of the advantages of site 3, there are some disadvantages to consider. The cable trenches of site 3 would not be available for oil containment. This will require the installation of gutters to protect the test machine foundation pit. Additionally, although this site orientation does not interfere with the structural static test laboratory, in order to provide access to the accelerator laboratory for personnel and freight requiring the overhead crane, the supply cage in front of room 025 would have to be relocated.

Table 4: COMPARISON OF SITE CHARACTERISTICS

Criteria	Site 1 Test Machine	Site 2 Wind Tunnel	Site 3 Load Floor East	Site 4 Load Floor South
Space/Expansion	No	Yes	Yes	Yes
Floor Loading	Yes	No*	Yes	Yes
Power Sources	Yes	Yes	Yes	Yes
Heavy Lift	Yes	No*	Yes	Yes
Ventilation Potential	Yes	Yes	Yes	Yes
Oil Containment	Yes	No*	Yes	No*

Note: "*" denotes a correctable site deficiency.

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In summary, site 3 provides the best overall location in terms of radiation and industrial safety (i.e. remoteness, ability to accept additional shielding, and availability of heavy duty lift equipment), convenience to LINAC personnel and equipment, and for expansion in future years. Site 4 offers many of these advantages but to a lesser degree, and are gained by impact on other areas such as the storage cage. Site 1 offers inexpensive and effective shielding, already in place, as well as the potential for rapid instal- lation when the machine is delivered. However, researchers must accept the constraints on experimental flexibility caused by limited space. Site 2 presents several drawbacks which will inhibit installation, operation, and maintenance. Lack of readily available overhead heavy lift capability and the permanently installed computer system located in the room above are serious considerations.

B. UNSHIELDED DOSE ESTIMATES

After having defined the boundaries of the restricted areas surrounding each site, unshielded radiation doses will be calculated for those areas and several other sites of interest in Halligan Hall.

Propagation of radiation through air is effected by two processes, $1/r^2$ spherical spreading and absorption of energy in the medium. The first problem will be treated as a spherical shell surrounding a point source since our

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machine dose is specified for 10 cm from the bremsstrahlung target. Absorption attenuates the dose exponentially. Equation 4-2 summarizes these properties and will be used for dose calculations [Ref. 5: p. 36 and Ref. 3: p. 56].

$$I = I_o \left(\frac{r_o}{r}\right)^2 e^{-\mu x} \qquad (4-2)$$

where I_o is the initial dose or energy; r_o is the initial spherical shell radius, 10 cm in the unshielded problem; r is the total distance from the anode in cm; x is the absorber thickness in cm; and μ is the linear absorption coefficient for the medium in cm^{-1}. μ is actually a function of photon energy but a conservative approximation routinely used in shielding design to determine μ is to assume the entire dose is concentrated in a step function centered at energy $E_o/3$ [Ref. 4: p. 13]. Peak X-ray yield can be obtained by dividing beam energy by five. Figure 6 represents a more realistic approximation for the bremsstrahlung spectra. For 0.5 MeV X-rays, therefore, μ for air can be taken as a constant of 1.05 X 10^{-4} cm^{-1}. Figures for this and other values can be obtained from the International Atomic Energy Agency [Ref. 10; Table B-IV] or from Grodstein [Ref. 11].

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1. <u>Site 1</u>

The test machine pit is already surrounded by rails on its perimeter which can be used to control access to the restricted area of the flash X-ray machine. With the bremsstrahlung target placed in the center of this area, minimum and maximum distances up to the edge of the restricted area are 10.6' and 20.9', respectively. Using equation 4-2, we see that radiation doses at this restricted boundary will fall between 58 and 232 mrem/pulse. Doses for several benchmarks located throughout Halligan Hall are calculated in Table 5. Benchmarks for the sites in room 021 will be the closest points on the ground floor and mezzanine balconies in the forward beam direction. Also, doses at the ground floor balcony rail outside the Aeronautics Department lounge, room 131, will also be calculated.

2. <u>Site 2</u>

The site in the wings of room 031, although permitting sufficient room in the forward radiation direction, is only 18' wide and does not provide excessive space on either side to take advantage of spherical spreading. There is a walkway along the edge of the reinforced floor so the restricted area boundary should start there. The maximum dose rates along this one sided perimeter will range from 35 to 363 mrem/pulse. Benchmarks of interest differ with this site from the other two in room 021. We will study doses in the computer room, room 132 and

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the Aeronautics Department lounge across the building in room 131, which is currently undergoing remodeling which will increase the occupancy of that area.

3. Site 3

The inner perimeter of the hydraulic line trench provides a convenient boundary for the restricted area. Limited access could be achieved with a fence or simply the outside of the shielding wall, depending on the size of the design. With the bremsstrahlung target in the center of the floor, dose ranges around the perimeter fall between 32 and 142 mrem/pulse. Table 5 demonstrates how the spherical spreading attenuation is more appreciable for this site, which is more remote from routinely occupied areas of the building.

4. Site 4

In order not to interfere with the operation of the structural static test display, the perimeter of the restricted area would only be 18' wide and would require fencing close to the bremsstrahlung target. On the southern side facing the accelerator laboratory area, fencing would not be required. The outside of the concrete structure itself would provide adequate perimeter protection. Here, access to the experimental area would be next to the control station and would be closely supervised by laboratory personnel. Unshielded radiation doses in this perimeter

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range from 19 to 323 mrems/pulse. The ground floor and mezzanine balconies to the south are close to this site so care must be taken to sufficiently shield the roof as well. Other benchmarks of interest in this site are the same as in Site 3.

Table 5: SUMMARY OF UNSHIELDED DOSE CALCULATIONS

Benchmarks	Site 1 (mrem/pulse)	Site 2 (mrem/pulse)	Site 3 (mrem/pulse)	Site 4 (mrem/pulse)
Restricted Perimeter	58-230	35-362	32-142	19-323
1) Ground Floor Balcony	17.7	---	27.2	103
2) Mezzanine Balcony	7.9	---	11.0	22.5
3) Aero Lounge Balcony	7.7	---	2.9	3.2
4) Aero Lounge Room 131	---	2.3	---	---
5) Computer Lab Room 132	---	2.1	---	---

Note: " --- " denotes no direct path.

C. RADIATION PROTECTION DESIGNS

1. Preliminaries

This section will present several shielding designs to attenuate the doses of Table 5 to acceptable levels while permitting a reasonable operating rate for the machine. The maximum dose level, taken from Appendix B, will be the standard dose for non-occupational individuals allowing a predicted workload of 8 shots per work day. This workload

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schedule, totalling 2080 shots per year is an extremely conservative estimate of experimental use of the machine. A successful shielding plan, therefore, must achieve a dose of 0.24 mrems/pulse or less at the perimeter of the restricted area. For calculation purposes, the assumption used in the previous section concerning concentration of radiation intensity within a step function centered at 0.5 MeV will be continued. Ordinary concrete will be used as the shielding material but lead can be substituted in the results knowing that at 0.5 MeV, 1.0" of lead has the equivalent attenuation properties as 8.7" of concrete. As an example, Table 6 shows the concrete thickness required for different distances from the bremsstrahlung target which would produce the standard safe dose at the other side of the wall. Iterations of Equation 4-2 were used for each absorption medium in the path, in this case air and concrete. It can be seen that a 1' 5" thick concrete structure of dimensions 6' X 6' X 6' would attenuate the machine output to the standard dose.

Table 6: ABSORBER THICKNESS PRODUCING STANDARD DOSE (1.5MeV)

Distance From Bremsstrahlung Target	Concrete $(\mu = 0.205 \text{ cm}^{-1})$	Lead $(\mu = 1.80 \text{ cm}^{-1})$
3'	1' 5"	2.0"
6'	1' 3"	1.8"
9'	1' 1"	1.6"
12'	1' 0"	1.5"

As a worst case example for this approach, take the extreme assumption that a 250 Rad delta function is concentrated at 1.5 MeV rather than 0.5 MeV. Differences in absorption coefficients at this energy would cause the dose outside the 1' 3" concrete wall constructed 6' from the target would be 5.7 mrem per pulse, a value safely within dose standards. Permanently installed radiation monitor systems presented in Chapter V would quickly detect this discrepancy and result in additional shielding installation.

2. Shielding Plans

Although a concrete structure built to thicknesses selected in Table 6 will sufficiently shield the public areas of Halligan Hall, standard experimental practices at the accelerator laboratory and at other facilities is to shield as close to the target as possible. Use of standard (2" X 4" X 8") lead bricks and pieces to support and enclose the sample will not only shield out reflections and secondary radiation, but will have a substantial effect on the radiation dose leaving the controlled area. With this in mind, the following shielding calculations compare the safe standard doses emitting from the permanent concrete structures with the estimated doses obtained when lead is added close to the sample. Tables 7 and 8 rework the data of Table 5: The Summary Of Unshielded Dose Calculations, taking into consideration the attenuation resulting from the shielding plans described below. Table 7 addresses the

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plans for Site 1, and the plans for Sites 2, 3 and 4 using 12" of shielding concrete for the vertical walls. For comparison, Table 8 shows the results for the last three sites when the vertical wall thicknesses are increased to 13.5".

Site 1, Plan A: Cover the pit ceiling with concrete beams 8.5" thick. Using the specifications of the generic machine, this will place the beams 7' above the X-ray target. In addition, a concrete wall with an access door maze on one end will be required to separate the experimental end of the pit from the control area and laboratory personnel in the site. A proposed layout is illustrated in Figure 11. Tables 7 and 8 show the calculated results.

Site 1, Plan B: In addition to the permanent structure of Plan A, use portable lead hoods, bricks and pieces to add 1" of lead absorption close to the target.

Site 2, Plan A: With the machine centerline placed in the middle of the work space, construct a concrete wall and roof within the restricted perimeter. The roof will be 10' off the floor and will remain 12" thick in both Tables 7 and 8. The suggestion is made to build a roof rather than extend the wall up 18' to the cieling because additional overhead shielding is required to supplement the absorption of the 8" floor above the X-ray target, as demonstrated in Table 5, and to protect the unrestricted catwalks leading to
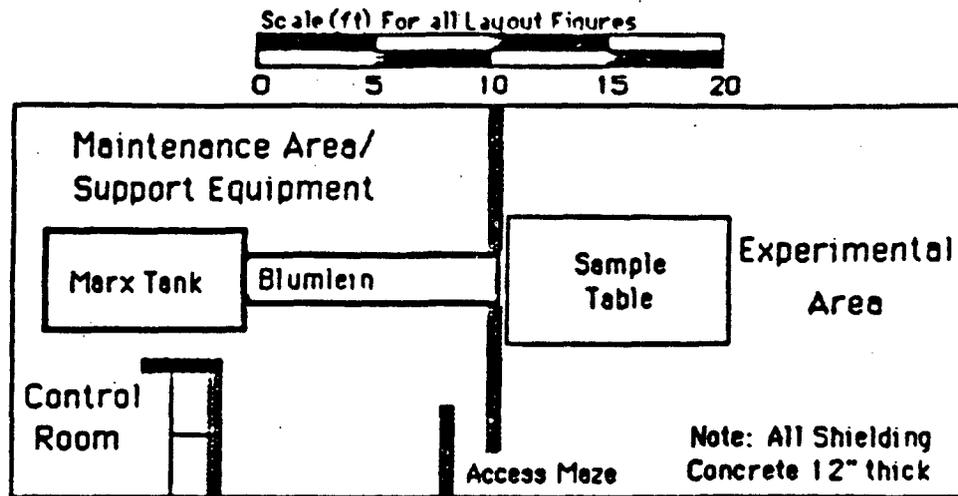
Figure 11: Layout for Site 1 – Test Machine Foundation Pit
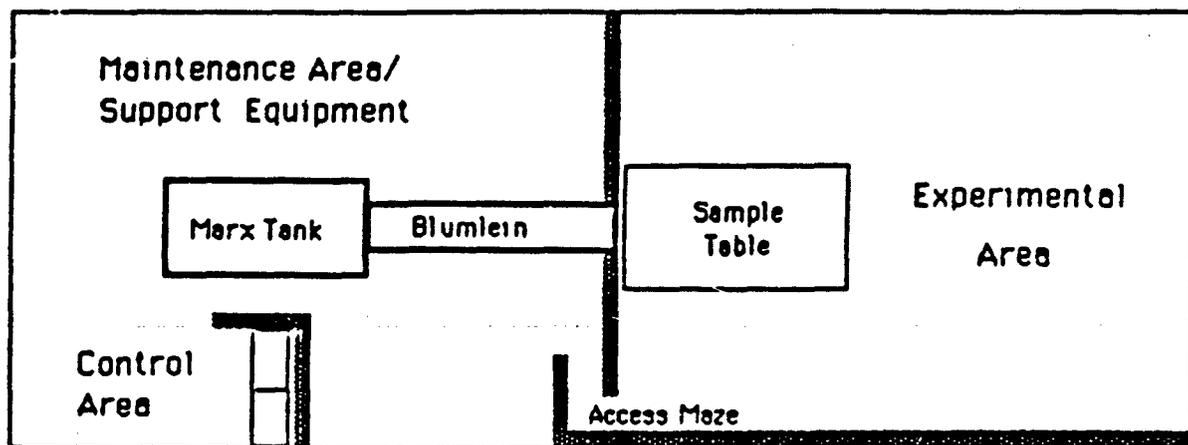
Figure 12: Layout for Site 2 – Wind Tunnel Wing

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the offices above the site. Also, a smaller structure will be easier to screen against the electro-magnetic pulse generated by the machine. It may be determined during machine trials that the site will require a Faraday cage or screen room constructed of standard mesh within the concrete structure or under the computer room floor. This site layout is illustrated in Figure 12.

Site 2, Plan B: In addition to the concrete structure and screen proposed above, place 1" of lead around the sample as standard experimental procedure.

Site 3, Plan A: With the bremsstrahlung target in the center of the floor area, construct a block house whose walls are 6' out from the target. The roof will be 10' high and 6" thick.

Site 3, Plan B: In addition to the permanent structure of Plan A, include 1" of lead in the sample area as standard experimental procedure.

Site 3, Plan C: Taking advantage of available space on the static load test floor, double the area of the experimental room by extending the walls to 9' from the X-ray target. The roof specifications of Plan A will be retained. This plan is illustrated in Figure 13.

Site 3, Plan D: Again, in addition to the structure of Plan C, include 1" of lead in the sample area as standard experimental procedure.
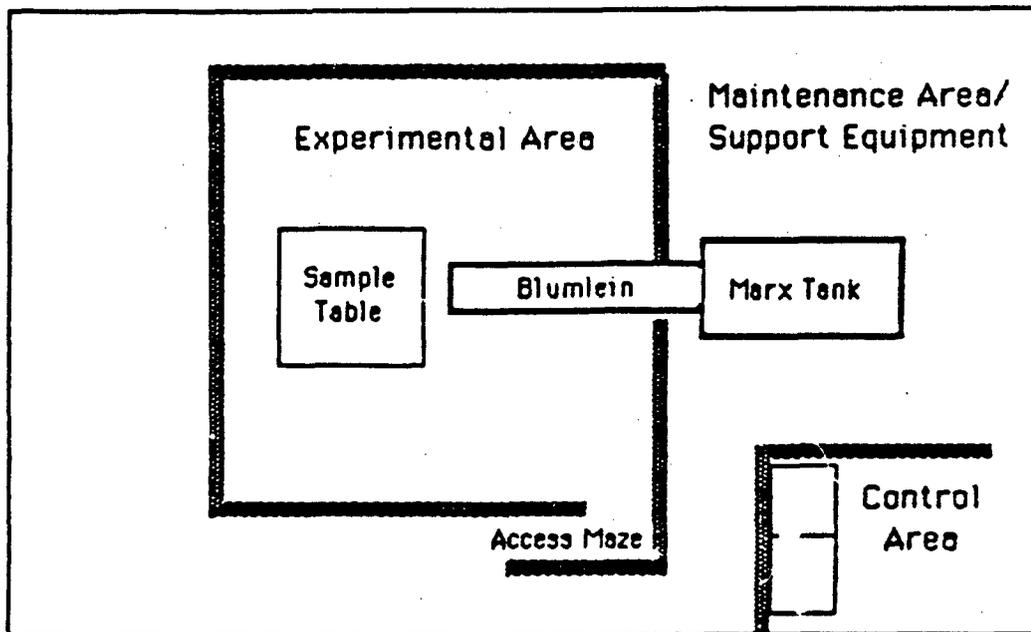
Figure 13:   Layout for Site 3 - Structural Static Test Floor
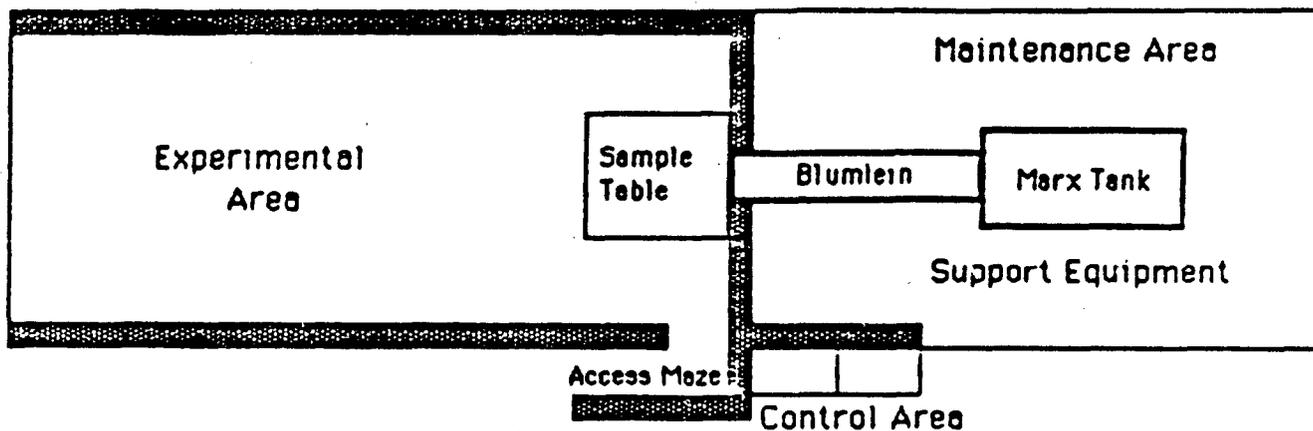
Figure 14:   Layout for Site 4 - Structural Static Test Floor

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Table 7: SUMMARY OF SHIELDED DOSE CALCULATIONS: VERTICAL WALLS 12" THICK

Site/Plan	Perimeter (mrems/pulse)	Benchmarks (mrems/pulse)				
		#1	#2	#3	#4	#5
1/A	$0.20 - 8.6 \times 10^{-5}$	0.026	0.015	1.2×10^{-11}	---	---
1/B	$5.2 \times 10^{-4} - 6.5 \times 10^{-7}$	4.9×10^{-5}	2.3×10^{-5}	6.8×10^{-14}	---	---
2/A	$0.55 - 7.8 \times 10^{-7}$	---	---	---	4.1×10^{-3}	4.0×10^{-3}
2/B	$5.6 \times 10^{-3} - 7.9 \times 10^{-9}$	---	---	---	4.1×10^{-5}	4.1×10^{-5}
3/A	$0.27 - 0.025$	0.026	5.8×10^{-3}	3.7×10^{-3}	---	---
3/B	$2.7 \times 10^{-3} - 3.1 \times 10^{-4}$	1.6×10^{-4}	2.2×10^{-5}	3.6×10^{-5}	---	---
3/C	$0.27 - 0.025$	0.026	0.044	3.7×10^{-3}	---	---
3/D	$2.7 \times 10^{-3} - 3.1 \times 10^{-4}$	1.6×10^{-4}	1.7×10^{-4}	3.6×10^{-3}	---	---
4/A	$0.49 - 4.8 \times 10^{-10}$	0.18	0.013	9.6×10^{-3}	---	---
4/B	$5.1 \times 10^{-3} - 4.9 \times 10^{-12}$	6.0×10^{-5}	1.7×10^{-5}	8.5×10^{-5}	---	---

Notes: 1) "---" denotes no direct path.
2) The effect of oblique transmission through the shielding material provides enhanced absorption and is included in these figures.

Table 8: SUMMARY OF SHIELDED DOSE CALCULATIONS: VERTICAL WALLS 13.5" THICK

Site/Plan	Perimeter (mrems/pulse)	Benchmarks (mrems/pulse) #1	#2	#3	#4	#5
2/A	$0.24 - 8.1 \times 10^{-8}$	---	---	---	1.9×10^{-3}	4.0×10^{-3}
2/B	$2.6 \times 10^{-3} - 8.3 \times 10^{-10}$	---	---	---	1.8×10^{-5}	4.1×10^{-5}
3/A	$0.12 - 0.010$	0.011	2.3×10^{-3}	1.6×10^{-3}	---	---
3/B	$1.3 \times 10^{-3} - 1.1 \times 10^{-4}$	6.7×10^{-5}	8.2×10^{-6}	1.6×10^{-5}	---	---
3/C	$0.12 - 0.010$	0.011	0.044	1.6×10^{-3}	---	---
3/D	$1.3 \times 10^{-3} - 1.1 \times 10^{-4}$	6.7×10^{-5}	1.7×10^{-4}	1.6×10^{-5}	---	---
4/A	$0.22 - 2.1 \times 10^{-11}$	0.18	0.013	4.3×10^{-3}	---	---
4/B	$2.3 \times 10^{-3} - 2.1 \times 10^{-13}$	6.0×10^{-5}	1.7×10^{-5}	3.8×10^{-5}	---	---

Notes: 1) "---" denotes no direct path.
2) The effect of oblique transmission through the shielding material provides enhanced absorption and is included in these figures.
3) Site 1 does not require vertical wall construction and is not included in this Table for comparative purposes.

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Site 4, Plan A: With the bremsstrahlung target over the hydraulic line trench and centered in the width of the area, construct concrete walls 10' high flanking the beam path. A wall in the forward beam direction is unnecessary as the walls of Halligan Hall at this site are 12" thick. The roof concrete will be 10" thick for both Tables 7 and 8. This plan is illustrated in Figure 14.

Site 4, Plan B: In addition to the permanent structure of the previous plan, include 1" of lead shielding in the sample area as standard experimental procedure.

3. Discussion of Tables 7 and 8

Table 7 shows the calculated effects of these shielding plans on the radiation leaving the restricted areas of each site using 12" thick vertical walls. Using permanent concrete shielding alone, the maximum radiation doses at the perimeters range from 0.55 to 0.20 mrems, near our workload goal of 0.24 mrems permitting eight pulses per work day. The effects of using 13.5" on the vertical walls is examined in Table 8. Here the maximum perimeter dose for each site ranges from 0.24 to 0.12 mrem/pulse. Use of 1" of Lead as a shield for the experimental sample provides additional attenuation on the order of 10^{-2}. Regardless of the site selected, therefore, planners can expect to require at least 1' of ordinary concrete to sufficiently shield the occupied areas of Halligan Hall.

4. Furthur Considerations

The calculations and shielding methods of this chapter represent a first approximation approach, appropriate until knowledge of the machine model and site location is available. Several standard shielding considerations were intentionally omitted which must be included in the second order calculations.

One such consideration is the assumption that the radiation from the bremsstrahlung target propagates spherically from a point source. The theoretical curve of Figure 9 and the experimental dose map of Figure 7 clearly show that perfectly spherical spreading is a most conservative estimate. These figures demonstrate that the forward radiation path is spherical but falls off to about $I_0/2$ at 45^0 from the forward axis and becomes $I_0/10$ at 90^0.

Another additional consideration is the area occupancy factor, T, which assumes that areas surrounding the immediate vicinity of the accelerator facility are occupied by the general public for only a fraction of the total weekly period. In the calculations shown in Tables 7 and 8, a 100% occupancy factor was assumed. This means that in order to absorb the non-occupational annual dose, that individual must stand at the closest point to the source, usually 90^0 off the bremsstrahlung target for each of 2080 pulses. This assumes the machine workload does reach this

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value and the angular distribution is spherical. Occupancy
factors range from 1 for full occupancy to 1/16 for
occasional occupancy (stairways, outside walkways, closets,
etc.) [Ref 9: p. 90]. For instance, traffic in the southern
half of the Halligan Hall basement is usually very light and
the perimeter of the restricted area can safely be assigned
an occupancy factor of 1/16. When the actual site is
selected, traffic surveys can be made to determine the
specific needs of the laboratory. The occupancy factor is
included in Equation 4-3.

In shielding design, the Compton scattering
experienced by absorbed radiation complicates the
calculation. Usually the radiation leaving the shield is
higher than the dose calculated with Equation 4-2. The
source of this radiation is scattering from other areas of
the shield. This radiation enhancement can be taken into
account by including a "build up factor" in Equation 4-2 as
is done below in Equation 4-3.

$$I = I_o BT \left(\frac{r_o}{r}\right)^2 e^{-\mu x} \qquad (4\text{-}3)$$

where B is the buildup factor and T is the occupancy factor
discussed earlier. This multiplication factor for build up
increases to higher values as the shielding thickness
increases. Build up factors vary for different materials.
It also depends on the geometry of the source, shield and
observer. For a plane, monodirectional source at a photon

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energy of 0.5 MeV penetrating a 2" lead shield, the build up factor would be 1.96 [Ref 13: p. 77]. Build up factors for other source geometries, materials, photon energies and path lengths are available from the National Bureau of Standards in Reference 13.

The shielding calculations of Tables 7 and 8, therefore, represent an extremely conservative, worst case treatment of the requirements of a 1.5 MeV pulsed power machine. Factors ignored in this first approximation were occupancy, build up, angular distribution and supplementary shielding. The designs for the final site shielding must incorporate these for the sake of construction constraints, economy, and space. The final determination of safety must rely on experimental data. Suggestions for a validation approach are made in Chapter VI: Proposed Applications.

D. SUMMARY

Sites 1, 3 and 4 are easily capable of enduring the floor loading of the proposed shielding, flash X-ray machine, and ancillary equipment. An initial review with the Engineering Department at the Naval Postgraduate School Public Works Office has revealed doubts about Site 2. The 6" concrete slab at the perimeter is marginally capable of supporting the combined weight of half of the overhead and the edge wall. Additional problems are anticipated in anchoring the concrete overhead to the opposite wall.

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In view of the radiation shielding conclusions, the driving considerations in the choice of machine location revert to three specific considerations detailed earlier in the general site discussion: Space, both experimental and maintenance, heavy lift access, and floor loading.

Site 3 provides each of these necessities and is the most acceptable location by the criteria established earlier in this chapter. Site 4 also provides these advantages but involves compromises in space, specifically that the supply cage outside room 025 must be removed to permit access to the accelerator laboratory. Site 1 is naturally shielded and possesses exceptional floor loading and heavy lift capability. However, it fails to provide space necessary for the pulsed electron beam machine for any applications outside the flash X-ray mode. Lastly, site 2 offers sufficient space, although requiring removal of another inactive storage area, but fails to provide adequate floor loading and heavy lift services.

V. SAFETY PROGRAM

This discussion of a proposed safety program at the Naval Postgraduate School Accelerator Laboratory will be divided into two major areas of interest: occupational safety, in the specific areas of radiation measurement and safety; and industrial safety. The accelerator laboratory already maintains a comprehensive radiation safety and personnel monitoring program designed for the 100 MeV electron linear accelerator facility. Most of the equipment and procedures recommended for the flash X-ray machine site are available from the accelerator laboratory. A brief description of the permanent and portable radiation monitoring equipment used in the LINAC is presented in Appendix A.

A. RADIATION MONITORING AND SAFETY

In addition to fixed monitors located throughout the restricted area, portable survey meters are useful as a different independant monitor method. This redundancy is important in order to localize potential hot spots detected by the fixed monitors as well as identify malfunctioning equipment. Recommendations for minimum instrumentation for a 1.5 MeV accelerator facility are made by the International Atomic Energy Agency in Reference 9 and are summarized below.

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The linear accelerator laboratory has been a participant in the lithium flouride thermoluminescent device personnel dosimetry program under the guidance of the National Naval Medical Center at Bethesda, MD since 1977. Consequently, the first recommendation is to employ LiF TLD film dosimetry badges for both personnel and fixed area monitors. Ionization chamber survey meters with regular and thin windows are recommended to detect low energy X-ray sources. Portable ionization survey meters are sensitive to photons of a b.oad energy range and are easy to interpret. Additional permanently installed ionization chambers should be considered as area monitors connected to readouts at the control station. These will provide the desired redundancy to the area film monitor badges and real time determination of radiation levels. It is not anticipated that radiation due to induced radionuclide activity will be generated by the pulse electron machine. Geiger-Muller or scintillation counters, therefore, will not be required.

B. INDUSTRIAL SAFETY

1. Warning System

Regardless of location, the flash X-ray machine site will be relatively exposed to non-radiation workers and the general public. Conspicuously posted signs on the perimeter of the restricted area are recommended to warn individuals of the dangers of the facility. In addition to the obvious

radiation hazards, possible future experiments in microwaves will make the site a special hazard to personnel with pacemakers and should be posted accordingly. Details of the standard purple and magenta radiation warning symbol are drawn by the National Bureau of Standards in Reference 12.

In addition to fences and radiation warning signs, stripes outlining a walkway should be painted on the floor in radiation warning colors to emphasize the routes leading into the occupied and public areas of the laboratory. This will help to prevent unescorted guests from entering the radiation areas.

To warn laboratory personnel of flash X-ray machine operation, the site should be equipped with centrally placed rotating or flashing police lights. As used in the LINAC, radiation warning lights should be colored red, and start up conditions should be designated by a yellow light. Signs explaining the significance of the color codes should be posted at several locations throughout the laboratory.

Since the accelerator laboratory area is small with a relatively low ambient noise level, it is not recommended that audible warnings such as sirens, horns or buzzers be used to forewarn radiation production. This procedure will be redundant, unnecessary and annoying to other occupants of Halligan Hall not affected by laboratory operations.

2. Interlocks

As a standard design practice, each site plan presented in the previous chapter had only one means of access into the experimental area. These access mazes should be provided with a door and interlock switch which will prevent radiation production if its circuit is opened. The contract specifications [Ref. 4] for the pulsed electron system include an interlock connector in the rear of the control console whose circuit must be closed in order to charge and fire the machine. All safety devices such as the closed access door and warning lights can be placed in a series circuit connected to the interlock. Malfunctions or openings in the circuit will immediately ground the machine. Although each control station was designed so the operator has visual contact and direct control of access to the experimental area, these interlocks must never be bypassed or used to actually operate the machine.

3. Fire Hazards

Material bombarded by the intense electron beam of the flash X-ray machine presents special fire hazard problems. Almost all of the energy absorbed by the sample will appear as local heating. If the sample is a poor conductor of heat, high internal temperatures will appear quickly. For this reason, it is recommended that support equipment and material placed inside the experimental area be fireproof and kept to a minimum. Adequate fire

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extinguishers should continue to be maintained in the accelerator laboratory and an additional one should be installed conveniently near the access door.

Outside the experimental area, transformer oil in the Marx bank and Blumlein presents a highly flammable hazard when inevitable spills or leaks are absorbed in sawdust or dehydrated clay. Fire safety and good housekeeping, therefore, dictate safe removal of all spills and proper disposal of used absorbing material.

4. Noxious Gas

The formation of ozone and nitrous oxides is treated in detail in Chapter IV. After a shielding design for the experimental station is selected, Equation 4-2 should be used to determine the necessary pump rate of the ventillation fan.

VI. PROPOSED APPLICATIONS

The principal application of the flash X-ray machine at
the Naval Postgraduate School will be in the area of
radiation effects on electronic components.   This is an
interdisciplinary concern and involves specialties from
nuclear weapons effects to satellite survivability in the
space environment.   In support of this emphasis, Section A
of this chapter discusses dosimetry, an essential research
area which must be thoroughly addressed before useful
experimental data can be obtained from the machine.
Additional experiments dealing with beam propagation, laser
excitation, and flash radiography will also be discussed
in brief to illustrate the flexibility of the high energy
pulsed electron apparatus and the improved capability of the
accelerator laboratory.

A. DOSIMETRY STUDIES

Immediately after installation of the flash X-ray
machine, reliable dosimetry practices must be established.
Probable systems deserving serious study will be lithuium
flouride thermoluminescent devices and p-i-n diode
detectors.   Lithium flouride thermoluminescent devices (LiF
TLDs), whose radiation response is discussed in Chapter V,
will require installation of reading equipment in the

laboratory if used for experimental dosimetry. They will provide timely dose readings, a capability not presently available in the accelerator laboratory.

P-i-n diodes composed of silicon doped with lithium (Si(Li) detectors) are able to detect low energy gamma or X-rays and are used extensively for this purpose. As electrical charges are created at the semiconductor boundary by the machine radiation, steady state leakage currents are formed and can be read indirectly to determine radiation dose. Si(Li) p-i-n diodes, and semiconductor detectors in general, are treated in detail by Knoll [Ref. 14].

Regardless of the detection system being tested, vital information can be obtained. For instance, while varying the operational parameters of the machine, sufficient data should be collected in order to plot the X-ray dose map of the experimental area. This study will facilitate easy estimation of expected doses samples will receive when located throughout the restricted area. Dose verification around the site perimeter and at benchmarks throughout Halligan Hall, as well as searches for radiation hot spots should also be included in the operational testing phase of the flash X-ray ma. 'ne installation.

B. BEAM PROPAGATION ST DIES

Kawai [Ref. 15] has done extensive research ' ..e characteristics of an intense relativistic electron beam

using a Pulserad model 110A with a diode voltage of 0.89 MV, beam current of 25 kA and pulse width of 30 nsec at FWHM. Experiments of this nature would be possible with a machine of our specifications.

The experimental apparatus for the beam propagation mode requires several alterations from the standard flash X-ray mode. As discussed in Chapter II, the anode must contain an aperture for beam propagation and the bremsstrahlung target is removed. A graphite rod replaces the cathode normally used in the flash X-ray mode.

Beam diagnostics in this particular experimental setup are very similar to that in the LINAC. A Faraday cup is used to monitor the beam current waveform and a spectrometer is used to analyze the energy spectrum of the beam.

C. LASER EXCITATION

Once beam propagation becomes routine in the accelerator laboratory, the electron energy can be used to drive other technologies and fields of research. Excimer lasers and free-electron lasers are two such technologies.

1. Excimer Lasers

The noble gas - halide laser is unusual because of the molecule, the excimer, which is excited by the electron beam. An excimer is composed of a pair of atoms that are bound together when the molecule is in an excited state. The best known excimers contain one halogen such as chlorine

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or flourine and an "inert" gas such as xenon, argon or krypton. When the energy level drops to its lowest state, the bonds are broken and the molecule falls apart. The population inversion required to generate the laser is achieved by forming these excimers. This is done when a mixture containing the laser gases under high pressure is excited by electrons from the beam. The lasing condition produces high power pulses at ultraviolet wavelengths.

Hoffman et al [Ref. 16] succeeded in exciting several different mixtures using a 2 MV, 6 kJ machine. The beam current in these experiments was 55 kA with a pulse width of 55 nsec at FWHM. The beam propagates 61 cm from the anode in a drift region composed of an externally applied axial magnetic field. After this confinement, the beam passes through a stainless steel foil and enters a steering magnetic field 180 cm in length. The beam then enters the laser excitation region.

2. Free-Electron Laser

The free-electron laser is different from other lasers in that a medium gas is not excited to create a population inversion. In a free-electron laser, a highly energetic beam of electrons is passed through a special transverse magnetic field region which is composed of a series of magnets arranged on axis but alternating in polarity. The electrons transiting this "wiggler" or pump

magnet region experience the influence of one magnet at a time, which bends their path, causing the electron to emit or absorb light. Proper design of the wiggler field will cause the electrons to emit more energy than they absorb. Efficient placement of the laser mirrors completes the vital components of a free-electron laser.

Experiments in free-electron lasers have been done at the Naval Research Laboratory in Washington, D. C. using a machine operating at a 1.35 MV diode voltage with a 1.5 kA electron beam. Details of the experimental apparatus and theoretical discussions are available in Parker [Ref. 17].

D. FLASH X-RAY RADIOGRAPHY

Flash X-ray radiography is useful in studies of macroscopic properties during extremely short time intervals. It is essentially the X-ray equivalent of optical strobe photography. The fact that the pulse length of our flash X-ray system is 30 nsec makes it ideally suited to the task of examining material that is changing or moving very rapidly through opaque material.

A typical radiograph setup consists of the object or event to be studied placed as far as possible from the flash X-ray machine diode. The X-ray photographic plate is then placed closely behind the specimen. The distance is necessary to approximate an incident X-ray plane wave as closely as possible to avoid edge effects. These detector

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systems can become more complex by using intensifying screens or optical image intensifiers prior to the X-ray film. Also, if the event under study is explosive in nature, special protection boxes must be designed to prevent damage to the detection system and concrete walls are usually built to deflect the blast wave away from the flash X-ray machine. Useful discussions on X-ray detection systems and event timing are available in Burke and Weiss [Ref.18: pp. 117-150] and Jamet and Thomer [Ref. 3: p. 101].

E. BETAGRAPHY

Similar to flash X-ray radiography, high speed electron beam shadow photography (betagraphy) is useful to image small particles moving at high speed. By changing the pulsed power machine mode from flash X-ray to beam propagation, betagraphy can be used on low density materials as flash X-ray radiography is used on high density subjects. The two methods, therefore, are complementary.

With the entire apparatus in a vacuum, the event to be studied can be recorded easily on high resolution film Prior to reaching the anode, the beam can be concentrated to a small area with a confining magnetic field, essentially creating the equivalent aperture used in an optical pinhole camera system. Details on proposed betagraph laboratory setups and further references are available in Jamet and Thomer [Ref. 3: p. 90].

APPENDIX A: PRESENT NPS FACILITIES

A. LINAC DESCRIPTION

The LINAC at the Naval Postgraduate School is a travelling wave type accelerator which is essentially a constant velocity device. Injected electrons are captured by the electro-magnetic wave and travel near the speed of light throughout the length of the machine. The increase in velocity of the electrons through the acceleration section is small so increases in beam energy take on the form of mass increase. In mathematical terms where:

$$E = \gamma mc^2 \tag{A-1}$$

$$\gamma = \frac{1}{\sqrt{1 - \beta^2}} \tag{A-2}$$

and

$$\beta = \frac{v_e}{c} \tag{A-3}$$

for a 100 Mev electron beam, γ = 195 and β = 0.9999985, which is almost equivalent to unity. This is accomplished in three major accelerator subsystems briefly described below.

1. Accelerator Section

The accelerator section consists of an electron injector, three ten-foot circular wave guides and a microwave generator source, along with associated beam monitoring

equipment, a vacuum system, and a water cooling system. Each one of the sub-accelerator sections are powered by a klystron amplifier delivering up to 21 Megawatts of peak power. The ten foot sections were originally used in Stanford's Mark III research accelerator, a prototype of the 2-mile long accelerator at the Stanford Linear Accelerator Center (SLAC). The sub-accelerators were obtained by NPS after the Mark III was dismantled for improvements in 1963.

Electrons are injected at 80 keV with a velocity close to half the speed of light, ride down the wave guide synchronized with the traveling wave, and emerge from the accelerator at energies up to 100 MeV with an average electron current of 0.1 microamperes. Detailed operating data is available in Table A1.

2. Beam Optics

The beam optics system is required to provide a well defined beam to a selected point in the target area. Major components include: one collimator, which serves as a source point for the magnetic deflection system; one pair of energy defining slits, which are required to tailor the energy spread to the limits established by experimental require-ments; two deflection magnets; and two quadrupole magnets. Deflection of the beam is desirable in order to place instrumentation out of the line of the forward radiation produced by the accelerated electron.

3. Monitoring and Instrumentation

The end station provides the monitoring, beam utilization, experimental instrumentation, and beam disposal functions. The target table takes up the majority of the space in the end station. Most of the shielding of radiation not caused by the beam optics system is done by the construction of the end station walls and ceiling.

Table A1: LINAC OPERATING CHARACTERISTICS

Maximum Beam Energy	100 MeV
Maximum Average Current	0.3 microamperes
Pulse Frequency	60 per second
Maximum Pulse Length	2 microseconds
Klystron Peak Power	21 Megawatts
Klystron Frequency	2.856 GHz

B. LINAC LOCATION

The LINAC is located in the basement of Halligan Hall, Building 234, on the main grounds of the Naval Postgraduate School. Halligan Hall is a two story concrete and glass building with numerous laboratory spaces, classrooms and offices. The structure itself contains reinforced concrete load bearing pillars, floors and basement walls as shown in Figure 10. The earthquake hardened construction of Halligan Hall lended itself readily to radiation shielding design for the LINAC. The accelerator is located in Room 001 and is colocated with several public works systems. The relative location and layout of the LINAC is shown in Figure A1. It
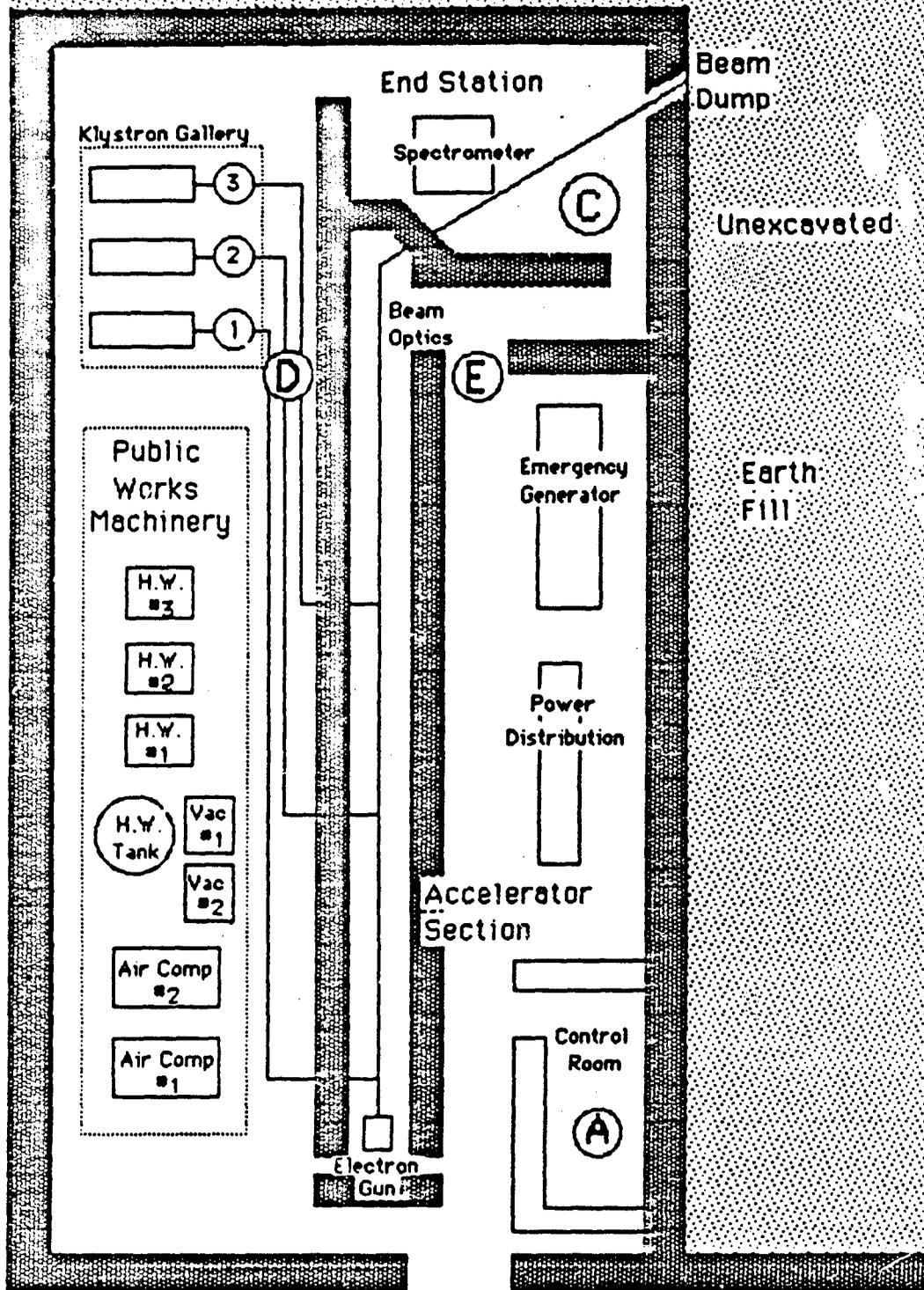
Figure A1: Layout of Room 001 - Halligan Hall

is instructive to note that the natural shielding of unexcavated earth was utilized on two sides of the accelerator to a maxim.m degree. The forward beam path end wall, end station side wall, beam dump and floor are all backed by earth fill.

There are several public areas of interest which were considered in the installation of the LINAC. Immediately above the beam optics system and end station is a large open laboratory, another enclosed laboratory, a small library, a hallway, and a moderately trafficked foyer leading to the Mechanical Engineering Department offices. These are all very public and uncontrolled. Additionally, outside the northeast face of Halligan Hall is a walkway running parallel to the LINAC. Other decision factors in the installation project were total floor space required to permit colocation of major components, radiation sources, and control equipment racks, as well as load bearing capacity of the floor. Since each 1' X 1' X 2' concrete block weighs 296 pounds and each 1' X 1.5' X 8' beam roofing the accelerator section weighs 1750 pounds, floor loading prevented direct construction of concrete block houses around the radiation components until a reinforced slab was added to the area. This consideration is pursued in Chapter IV of this study where flash X-ray shielding proposals are presented.

C. RADIATION MONITORING

The LINAC site is equipped with several permanent and portable systems which provide the redundancy discussed in Chapter IV. Remote area monitors include five Victoreen 716A ionization chambers located throughout room 001 and the Mechanical Engineering spaces upstairs. There is an additional lithium flouride thermoluminescient device (LiF TLD) located in the control room which serves as an environmental monitor against neutrons and ionizing radiation.

Portable survey meters used in the LINAC include: 1) the AN/PDR-70 radiac set, which has an operating range of 0-2000 mrem/hour for neutron detection; 2) the AN/PDR-27 radiac set, which has a range of 0-500 mrem/hour for gamma and beta radiation detection; and 3) the Victoreen 440, which has a response similar to the PDR-27 but is designed specifically to operate in the high RF fields of the LINAC environment. Both radiacs are maintained by participation in a calibration program.

The Naval Postgraduate School Accelerator Laboratory has participated in the LiF TLD personnel dosimetry program since its implementation in 1977. The LiF TLD badge is capable of detecting gamma, X-ray and neutron radiation. The issue period per TLD is usually 6 weeks and never exceeds 60 days.

D. LINAC SHIELDING STUDIES

In 1967, Soper [Ref. 19] conducted a radiation survey during the first experiments on the then newly completed LINAC. The highest levels of radiation are located in the beam optics area, end station, and power supply area, although the klystrons are equipped with their own shielding. The survey discovered one high radiation zone on the first floor of Halligan Hall immediately above the optics system and identified the pronounced radiation contributions of the Faraday cup and variations of the accelerator parameters. Table A2 shows the survey levels determined by Soper prior to the installation of supplementary lead and borated paraffin shielding on the tunnel roof, compared to readings taken recently.

Table A2: SURVEY OF LINAC RADIATION LEVELS

Site	Initial Readings 1967 (mrem/hr)	Recent Readings 1985 (mrem/hr)
A. Control Room	3.5	0.5
B. First Floor	10.0	1.2
C. End Station	100.0+	100.0+
D. Rear Door	50.0	45.0
E. Access Door	40.0	55.0

NOTE: Site locations taken from Figure A1

APPENDIX B: STANDARD DOSE LIMITS

Radiation exposure can be obtained from many sources in everyday life. The average individual in the United States absorbs a dose of 1 rem every 12 years from natural background sources. An average chest X-ray will expose a patient to an average of 27 mrem/pulse.

Compared to these common radiation doses, the occupational exposure levels are set conservatively and represent a very low risk. The annual exposure limits established by the Nuclear Regulatory Commission represent the safe doses which an adult can work within repeatedly for a lifetime. Table B1, assembled from the Code of Federal Regulations [Ref. 20], shows these exposures limits calculated for annual, quarterly and daily periods. The Code of Federal Regulations specifies occupational dose on a quarterly basis while general public doses are specified for a calender year. All other values are calculated from these and are not strictly applicable, as long as the annual and quarterly mandated limits are met.

Special care should be taken by pregnant women who are radiation workers at the accelerator laboratory. Risk of damaging radiation effects to an unborn child are greater than that for adults. The recommended radiation exposure

limit to a developing embryo and fetus has been establishe.
to be 0.5 rem or less during the gestation per⁴ ... The
shielding plans in Chapter IV, Section C a designed to
meet the exposure limits for individuals of the general
public, which is 0.5 mrems per year. Female radiation
workers in th. faculty or student body, therefore, are
protected from biological risk to unborn children. However,
women determined to be pregnant must follow the
administrative procedures detailed by the Chief of Naval
Operations [Ref. 21].

Table B1: Standard Dose Limits

Occupational Exposure

Annual Limit (Total Dose)	5.00 rems
Quarterly Limit	1.25 rems
Daily Limit	19.2 mrems

General Exposure

Individuals or Occasional	0.50 rems in any one year
Quarterly Limit	0.125 rems
Daily Limit	1.92 mrems
Students (< 18 years old)	0.10 rems in any one year
Quarterly Limit	25.0 mrems
Daily Limit	0.38 mrem

Note: Daily Limits based on 65 work days per quarter.

The maximum daily dose rate, therefore, is set by the
individual limit at 1.92 mrem or 0.24 mrem per hour. Addi-
tionally, absorption quality factors are assumed to be
unity. So, for X-rays, 1 Roentgen (unit of exposure) is
equivalent to 1 rad (unit of absorbed dose in tissue), which

equivalent to 1 rem (unit of dose equivalent). For electrons, 1 rad in tissue is also numerically equal to 1 rem [Ref. 9: p. 86].

APPENDIX C: DESCRIPTION OF PULSERAD MODEL 112A

In April 1985, the contract for the high power pulsed electron beam machine was let to Pulsar Products, Inc. of San Leandro, CA, a subsidiary of Physics International Co., for a Pulserad model 112A. The machine is very similar to the representative machine of Chapter III which was developed for purposes of discussion during the procurement process. However, there are differences between the generic machine and the Pulserad model 112A in several important areas which will be the subject of this appendix.

The Pulserad model 112A is a 30 nsec, transformer oil Blumlein machine with twelve 100 kV capacitor stages in the Marx generator. Only the first SF_6 pressurized spark gap in the Mark generator is triggered by the operator. All other gas switches, including the prepulse and output switches are self closing. Table C1 summarizes the model 112A operating characteristics. The main difference between this information and Table 2 is the doubling of energy available in the electron beam and a slight increase in the peak diode voltage. At the machine acceptance trials at the manufacturer on 30 May 1985, the pulse width, peak electron beam current, peak electron beam voltage and specified dose

of 250 Rads(Si) on axis 10 cm from the bremsstrahlung target were successfully demonstrated.

Table C1: PULSERAD MODEL 112A OPERATING CHARACTERISTICS

Minimum Peak Electron Beam Voltage	1.75 MV
Minimum Peak Electron Beam Current	35 kiloamperes
Minimum Electron Beam Energy	1.6 kilojoules
Current Pulse Width	30 nsec +5 nsec (FWHM)
Maximum Pulse Risetime	15 nsec (10-90% peak)
Maximum Trigger Jitter	50 nsec (rms)

The dimensions of the Pulserad model 112A are summarized in Table C2 and represent a slightly longer machine compared to the parameters chosen for Table 3.   The difference is only a 7" length increase, 2' less in height, and 300 lbs less in weight and does not require reconsideration of the site recommendations of Chapter IV.

Table C2: PULSERAD MODEL 112A DIMENSIONS

Marx Tank, Blumlein Casing	6' h X 4.3' w X 19' 1
Diode Assembly Centerline	3.5' off floor
Approximate Weight (with oil)	11,700 lbs
Overall Size	6' h X 4.3' w X 19.7' 1

The parameters which do require adjustment in view of the actual machine operating characteristics are the absorption coefficients.   The increase in the diode voltage from 1.5 to 1.75 MV shifts the $E_0/3$ energy from 0.5 to 0.58 MeV.   This causes a drop in absorption efficiency for most materials and approximately translates to an additional inch

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of ordinary concrete to the 13.5" calculated in Table 8 of Chapter IV. For comparison, the thicknesses of Table 6: Absorber Thickness Producing Standard Dose (1.5 MV) are recalculated for the same distances for 1.75 MV in Table C3.

Table C3: ABSORBER THICKNESS PRODUCING STANDARD DOSE (1.75MV)

Distance From Bremsstrahlung Target	Concrete ($\mu = 0.1929$ cm^{-1})	Lead ($\mu = 1.464$ cm^{-1})
3'	1' 06"	2.5"
6'	1' 04"	2.2"
9'	1' 02"	1.9"
12'	1' 01"	1.8"

In summary, the Pulserad model 112A meets or exceeds all of the specifications detailed in Chapter III. The enhanced diode voltage of 1.75 MV will require additional shielding as demonstrated in Table C3. The recommendations of Chapters IV and V remain valid since overall weight of the shielding was dismissed as a consideration due to the exceptional floor loading of sites 3, 4 and 1, favored in that order.

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