

SLAC-TN-91-11
SSRL M178 CODE 0900
September 1991
(TN)

Radiological Aspects of the SSRL 3 GeV Injector

By Nisy Ipe

Stanford Linear Accelerator Center
Stanford University, Stanford, CA 94309

*Work supported by the Department of Energy contact DE-AC03-76SF00515

RADIOLOGICAL ASPECTS OF THE SSRL 3 GeV INJECTOR

Nisy Ipe
September 24, 1991

CONTENTS

i.	Introduction	4
1.	Shield Design Criteria	6
2.	Shielding Methodology	7
	2-1. Electromagnetic Shower	7
	2-2. Neutron Production Mechanisms	9
	2-3. Shielding Codes	12
3.	Preliminary Shielding Analysis	19
	3-1. Assumed Beam Losses	20
	3-1-1. Linac	20
	3-1-2. Booster	20
4.	Final Shielding Analysis	25
	4-1. Linac	25
	4-1-1. Assumed Beam Operating Parameters and Losses	28
	4-1-2. Beam Containment Electronics	28
	4-1-3. Linac Housing	30
	4-1-4. LTD Beamline	31
	4-1-5. LTB Beamline	31
	4-1-6. Linac-Booster Port	33
	4-2. Booster	36
	4-3. Losses in the LTB (Linac to Booster)	41
	4-3-1. Quadrupole QF4	41
	4-3-2. Magnets B2 and B3	41
	4-3-3. Injection Septum	43

4-4. Losses in the Ring	46
4-4-1. Ring Magnets	46
4-4-2. Ring Quadrupoles	47
4-5. Losses in the Ejection and Booster to SPEAR Transport Lines	49
4-5-1. Ejection Kicker	49
4-5-2. Ejection Septum	50
4-5-3. B1V	52
4-5-4. BTS - General	52
4-5-5. BTS Quadrupoles	52
4-5-6. BTS B2-6	52
4-5-7. ST-17	59
4-5-8. Permissible Stand-by Modes for the Booster	61
4-6. Shielding of Penetrations and Thin Spots	62
4-6-1. Linac	62
4-6-2. Booster	62
5. Radiation Measurements	64
6. The Personnel Protection System/ Beam Containment Systems	70
6-1. The Personnel Protection System (PPS)	70
6-1-1. PPS Security Perimeters	70
6-1-2. Entry Modules	71
6-1-3. Annunciator/Status Panels	71
6-1-4. Warning Lights	71
6-1-5. Emergency Off Buttons	72
6-1-6. Flashing Lights and Audible Warning	72
6-1-7. Search Controls	72
6-1-8. Stoppers	73
6-2. The Beam Containment System (BCS)	74
6-2-1. Beam Containment Devices	74
6-2-2. Beam Shut Off Ionization Chambers	74
7. Area Monitoring	78

8.	Beam Authorization Sheets/Administrative Controls and Procedures	81
	8-1. Beam Authorization Sheets	81
	8-2. Procedures	83
9.	Operator Training	84
10.	Personnel Dosimetry	86
11.	Muons	88
12.	Air Activation	93
13.	Toxic Gases	100
14.	Induced Activity	104
	14-1. Activation of Copper	105
	14-2. Activation of Lead	107
	14-3. Activation of Stainless Steel	109
	14-4. Induced Activity Measurements	110
15.	Skyshine	113
	ACKNOWLEDGEMENTS	117
	REFERENCES	118
	APPENDIX A	126

RADIOLOGICAL ASPECTS OF THE SSRL 3 GeV INJECTOR

Nisy Ipe
September 24, 1991

INTRODUCTION

The Stanford Synchrotron Radiation Laboratory (SSRL) completed in 1990 the construction of an injector for the storage ring SPEAR from which they operate synchrotron beamlines. The injector is comprised of a linear accelerator (linac) capable of energies ≥ 120 MeV, a 3 GeV slow cycling synchrotron and a beam transport line for transporting and injecting the electrons into SPEAR.

The linac produces a string of electron bunches within a single pulse. The bunches are injected into the synchrotron and can be accelerated to 3 GeV by slowly ramping the synchrotron ring magnets to higher fields. At the final energy the bunches are transferred from the synchrotron to the transport line which carries them to SPEAR.

Responsibility for safety at SLAC is a line responsibility. The SLAC Radiation Physics Department (RPD) and the Operational Health Physics Department (OHP) act as advisory and oversight organizations in matters of radiation safety pertaining to the injector.

The shielding for the injector was completed over a period of three years. The injector was tested phase by phase, and prior to each phase, approval for the shielding, beam containment and personnel protection systems was obtained from the SLAC Radiation Safety Committee. The SSRL machine physicists and engineers provided the beam operating parameters, loss scenarios and ray traces. RPD performed calculations and specified the shielding and together with the SLAC Accelerator Department Safety Office (ADSO) provided the

authorization for beam operation at each phase. This authorization is referred to as Beam Authorization Sheet (BAS), and specifies the conditions under which the injector may be operated. Operators were trained to operate the machine safely. RPD performed radiation surveys initially to check the integrity of the shielding. Additional shielding was specified when required. Radiation areas were posted and roped off. Initially the immediate vicinity of the injector was restricted to radiation workers, and all workers wore pocket ionization chambers (PICs) and logged exposures daily. Administrative controls and procedures were instituted to ensure that the dose equivalent rates in occupied areas during injector operation were within acceptable limits. PICs were installed at strategic locations around the injector and read out by operators once every shift. Operators also performed radiation surveys once every shift.

A monitoring system consisting of discrete ion chambers known as Beam Shut Off Ionization Chambers (BSOICS) were installed at strategic locations to turn the beam off if undesirable radiation levels were encountered. A passive area monitoring program was instituted to determine integrated dose equivalents outside the shielding during long periods of injector operation. Warning lights were installed on the roof of the injector to indicate the status of the beam. RPD made frequent checks to ensure that procedures and administrative controls were followed.

This document describes the shielding of the injector, results of radiation measurements, the personnel protection system, the beam containment system, the area monitoring, administrative controls and procedures, operator training and personnel dosimetry. In addition, other radiological aspects of the injector such as muons, air activation, toxic gases, induced activity and skyshine are discussed.

1. SHIELD DESIGN CRITERIA

The shielding for the injector was specified by the SLAC Radiation Physics Department. The following two design criteria were mainly used⁽¹⁾:

According to the first criterion the integrated dose equivalent for a 2000 hour operating year should not exceed 1 rem (10 mSv) at the outer surface of the shield. This meets the D.O.E. requirements according to which the design criteria for any shielded facility within an area that can be controlled will be 1/5th of the nominal operating limit or 1 rem/y (10 mSv/y) for normal beam losses.

The second criterion is an internal guideline set by SLAC. This requires that the dose equivalent rate at the shield surface under the worst-case scenario should not exceed 25 rem/hour. Inherent in this is the assumption that this situation will not persist for more than ten minutes or so. An example of the worst case scenario could be the failure of two out of three protective devices such as PPS stoppers or beam containment devices. The loss of the maximum allowable beam at a point anywhere along the injector was initially also considered as a worst-case scenario.

For the booster another criterion was used for conditions of mis-steering. This limits the maximum dose equivalent rate to 400 mrem/h (4 mSv/h) at the shield surface, if the entire beam were to be lost at a point due to some extreme case of mis-steering.

2. SHIELDING METHODOLOGY

The shielding model used for thick targets is based on measurements made by Jenkins⁽²⁾ with subsequent modifications to photon terms based on further Monte Carlo calculations. The model uses an electron beam striking a thick target and considers radiation patterns outside the shielding.

2-1 Electromagnetic Shower

When a target is hit by a high energy electron only a small fraction of the energy is dissipated as a result of collision processes. A large fraction is spent in the production of high energy photons or bremsstrahlung. These photons interact through pair production or Compton collisions resulting in the production of electrons. These electrons radiate more photons which in turn interact to produce more electrons. At each new step the number of particles increases and the average energy decreases. This process continues until the electrons fall into the energy range where radiation losses can no longer compete with collision losses. Eventually the energy of the primary electron is completely dissipated in excitation and ionization of the atoms resulting in heat production. This entire process resulting in a cascade of photons, electrons and positrons is called an electromagnetic shower.

The average or characteristic angle of photons and electrons emitted by bremsstrahlung and pair production is given by:

$$\theta_c = m_e / E_0$$

where θ_c is in radians, m_e and E_0 are the rest mass and energy of the electron. This angle is so small that the shower is peaked in the forward direction. However, there is also a lateral spread in the shower due to Coulomb scattering of the electrons and Compton scattering of the photons.

An electromagnetic shower is produced when the primary beam energy greatly exceeds the critical energy of the target material⁽³⁾. The critical energy (E_c) is the energy of the electron at which the average energy loss due to radiation is equal to that due to ionization and is given by

$$E_c \text{ (MeV)} = 800 / (Z + 1.2)$$

where Z is the atomic number of the target material.

At the depth in the target at which the average electron energy is near the critical energy, the shower essentially reaches a maximum. After this the electron energy is so low that it can no longer propagate the shower. Photons are then the principal particles which propagate the shower. The photon energy at which the minimum attenuation coefficient occurs is called the Compton minimum and is typically $1/2$ to $1/3 E_c$ for all materials. The Compton minimum is reached at the photon energy at which the cross-sections for the Compton effect and electron-positron pair production are about equal. Below E_c the probability for Compton scattering increases. When Compton scattering occurs the electron and photon have energies well below E_c , thus the photons in the tail of the shower cannot effectively replenish the shower. In this region the attenuation coefficient of the shower is close to the minimum photon attenuation coefficient of the material.

At this point it is useful to define some additional quantities that are used to describe the interaction of high energy electrons with targets.

These definitions have been taken from reference 3.

"The radiation length X_0 is the distance an electron must travel so that its energy is reduced by an average factor of e by radiation at the high-energy limit:

$$X_0 = 716A[Z(Z + 1) \ln(183Z^{-1/3})]^{-1}$$

where A and Z are the mass number and atomic number of the medium, respectively, and X_0 is expressed in units of grams per centimeter squared."

Target widths or radii are expressed in terms of the Moliere length.

"The Molière length X_M is used to describe the transverse development of a shower:

$$X_M = X_0 (E_s/E_c)$$

where E_s is a constant equal to 21.2 MeV."

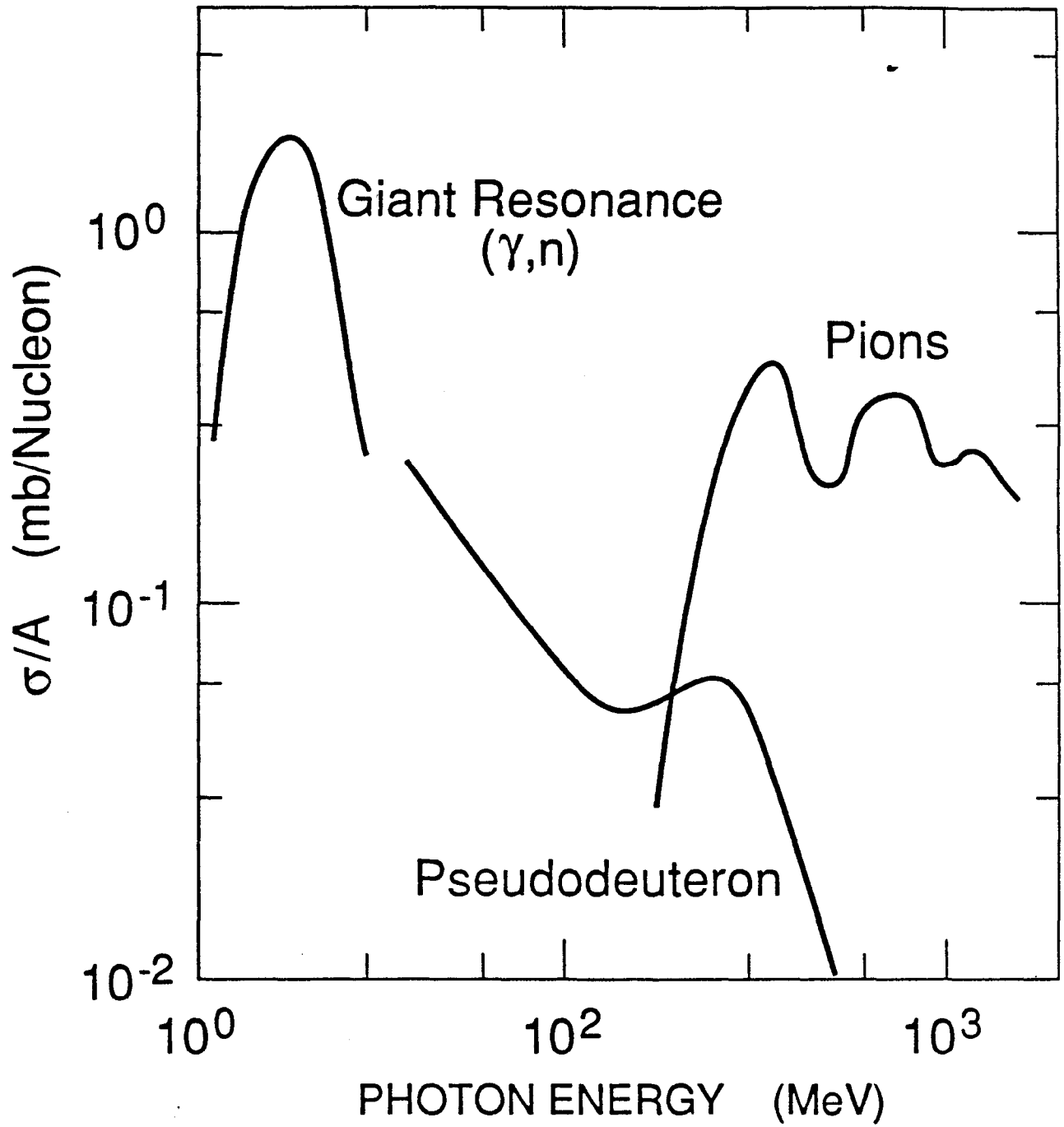
The photon field after passing through a target and any intervening shielding consists essentially of two components⁽³⁾: a broad photon field that is peaked in the forward direction, but extends to backward angles with decreasing intensity; and a very sharp forward spike which contains photons of the highest energy possible for that primary energy.

2-2 Neutron Production Mechanisms

A very small fraction of the bremsstrahlung energy in the shower goes into the production of hadrons including neutrons, protons and pions. There are three neutron production mechanisms, as shown in Figure 1.

Figure 1

Photonuclear Cross Section



(adapted from reference 4)

Neutrons will be produced in any material struck by the electron or bremsstrahlung beam above threshold energies which vary from 10-19 MeV for light nuclei and 4-6 MeV for heavy nuclei⁽⁵⁾. The threshold energy for deuterium is 2.2 MeV and 1.6 MeV for beryllium. For photon energies below 30 MeV neutron production results mainly from the giant photonuclear resonance.

The electric field of the photon transfers its energy to the nucleus by inducing an oscillation such that the protons as a group move in a direction opposite to the neutrons. The giant resonance cross-section reaches a maximum at photon energies of about 20-23 MeV for light nuclei ($A < 40$) and 13-18 MeV for heavier nuclei. Giant resonance neutrons are of low energy, with an average energy of the order of a few MeV.

The electromagnetic shower contains photons of all energies from zero up to the primary particle energy⁽³⁾. The photon spectrum exhibits a k^{-2} distribution where k is the energy of the photon. At low photon energies the giant resonance dominates because of the large numbers of low-energy photons and the large cross-sections at these low energies.

At energies between 30 and 300 MeV the photon interacts with a neutron-proton pair within the nucleus, instead of the nucleus as a whole⁽⁵⁾. This mechanism is called the "pseudodeuteron" or "quasi deuteron" effect.

The "pseudodeuteron" cross-section $\sigma_{QD}(k)$ is related to the deuteron photodisintegration cross-section $\sigma_D(k)$ as shown:

$$\sigma_{QD}(k) = \frac{LNZ\sigma_D(k)}{A}$$

where L is a dimensionless quantity, N is the number of neutrons, Z is the atomic number and A the mass number. The "pseudodeuteron" cross-section is about an order of magnitude below the giant resonance cross-section.

Above photon energies of 140 MeV the cross-section rises again due to photopion production and goes through a number of resonance peaks. These peaks are only a fraction of the giant resonance cross-sections, however the neutrons released as a product of photopion reactions are much higher in energy, and therefore much more penetrating than giant resonance neutrons. For shield thicknesses greater than about 2 m of concrete, these neutrons dominate and continually regenerate a field of lower energy neutrons and neutron capture gamma rays. Thus the dose equivalent outside the shield will have both neutron and photo components.

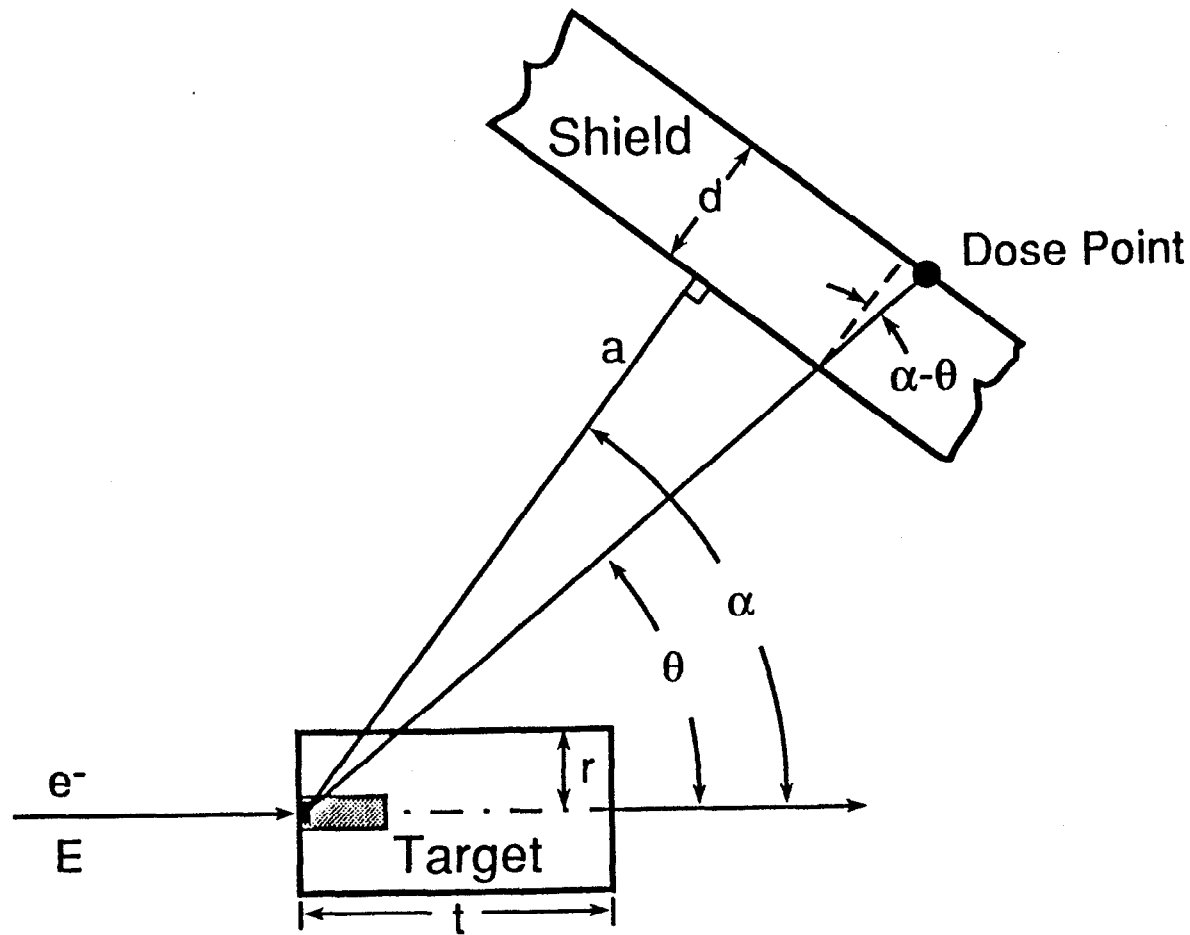
2-3 Shielding Codes

The shielding calculations were performed using a computer program which puts the two photon and three neutron components together to give the total dose-equivalent outside the shielding. The preliminary shielding analysis was done with SHIELDOO MORTRAN and subsequent analysis with modified versions (SHIELDO2, SHIELD10, SHIELD11) of this program⁽⁶⁾.

Figure 2 shows the typical shield geometry used in the program. The model uses a cylindrical target of radius r such that $r/\lambda_\gamma \geq 1.18$, where λ_γ is the minimum attenuation length for photons, in the target. The target length must be greater than $0.01X_0$ for photons and greater than $10X_0$ for neutrons. The target radius must be greater than $1 X_m$ for neutrons.

The photon components consist of a direct component from the electromagnetic cascade and from bremsstrahlung; and an indirect component which consists of photons in equilibrium with the hadronic cascade⁽⁷⁾. These photons originate in such processes as neutron capture and the decay of neutral pions. The assumption is that charged particles which are generated are stopped in the shielding. The direct component of the photon dose equivalent at large angles (from $\sim 5-10^\circ$ to 180°) is given by:

Typical Shield Geometry in Shield Program



13

Figure 2

8-91
6970A11

$$H_{\gamma L} = 10^{-11} E_0 \left(\frac{\cos \beta}{a+d} \right)^2 \times [1.26 \times 10^5 E_0 e^{-\mu_1 t_1} e^{-\theta^{0.6}} + 755 e^{-\left(\frac{\theta}{72}\right)} e^{-\left(\frac{r}{\lambda \gamma}\right)}] e^{-\left(\frac{\mu_2 d}{\cos \beta}\right)}$$

The direct component of the photon dose equivalent for forward directed photons ($\theta \leq 5^\circ$) is given by:

$$H_{\gamma F} = 10^{-11} E_0 \left(\frac{\cos \beta}{a+d} \right)^2 \times [1.26 \times 10^5 E_0 e^{-\mu_1 t_1} e^{-\theta^{0.6}}] e^{-\left(\frac{\mu_2 d}{\cos \beta}\right)}$$

where $H_{\gamma L}$ and $H_{\gamma F}$ are in rem/e⁻,

E_0 = energy of the primary electron beam in GeV

θ = production angle in degrees

$\beta = \alpha - \theta$

α = angle which normal to the shield makes with beam direction (in degrees)

μ_1 = attenuation coefficient of target at Compton minimum in cm⁻¹

t_1 = thickness of target in cm

u_2 = attenuation coefficient of shield at Compton minimum
in cm^{-1}

ρ = density of shield in g/cm^3

d = thickness of shield in cm

a = target to shield distance in cm

r = radius of target in cm

$\lambda\gamma$ = minimum attenuation length of photons in target in cm

The neutron dose equivalent components (H_n) are made up of a high energy (HEN), a mid energy (MID) and a giant resonance (GRN) term.

$$H_n = H_{\text{HEN}} + H_{\text{MID}} + H_{\text{GRN}}$$

where

$$H_{\text{HEN}} = 10^{-11} E_0 \left(\frac{\cos\beta}{a+d} \right)^2 \times \frac{13.69}{A^{0.65}} \frac{e^{-\left(\frac{d\rho}{\lambda_1 \cos\beta} \right)}}{(1-0.72 \cos\theta)^2}$$

$$H_{\text{MID}} = 10^{-11} E_0 \left(\frac{\cos\beta}{a+d} \right)^2 \times \frac{44.3 e^{-\left(\frac{d\rho}{\lambda_2 \cos\beta} \right)}}{A^{0.37} (1-0.75 \cos\theta)}$$

$$H_{\text{GRN}} = 10^{-11} E_0 \left(\frac{\cos\beta}{a+d} \right)^2 \times 4.94 Z^{0.66} e^{-\left(\frac{d\rho}{\lambda_3 \cos\beta} \right)}$$

where H_n is in rem/e,

A is the mass number of the target.

Z is the atomic number of the target.

λ_1 , λ_2 , and λ_3 are the attenuation lengths in g/cm^2 for high energy neutrons, mid energy neutrons and giant resonance neutrons in the shield. These expressions are used for $E_0 > 1$ GeV. Below 1 GeV the high energy and mid energy terms are modified in the program to fit existing measurements. According to this expression the giant resonance neutron yield is isotropic.

The indirect gamma dose equivalent $H_{I\gamma}$ from the hadronic cascade is

$$H_{I\gamma} = 0.27 H_{HEN}$$

In this expression only photons from the high energy neutrons are included because other terms are masked by direct photons until the shield becomes very thick.

The dose equivalent in rem/e can be converted to rem/Kw-h by using a multiplication factor of

$$\frac{2.25 \times 10^{16} \text{ e}^-}{E_0 \text{ Kw-h}}$$

where E_0 is in GeV.

The attenuation lengths used in this program are shown in Table 1.

Attenuation Length (g/cm ²)	Concrete	Iron	Lead
λ_1	120	145	200
λ_2	55	145	200
λ_3	30	47*	97*
λ_γ	42	33.6	24

* These values are based on measurements which assume that there is a certain amount of hydrogenous material (concrete, polyethylene) following the iron or lead.

The computer program allows one to easily change the various input variables such as source to shield distance, shield thickness, the angle which the shield normal makes with the beam direction, the electron beam energy, the production angle etc.

SHIELDOO MORTRAN and its modified versions were used to determine radiation levels from electron beams impinging on thick targets. For thin targets, the EGS4 code ⁽⁸⁾ was used. EGS4 is an electron-photon transport code that utilizes Monte Carlo techniques. The EGS program was designed to simulate electromagnetic showers in various materials with different geometries. The dynamic range of charged particles extends from a few tens of keV up to a few thousand GeV. For photons the lower limit is 1 keV.

Sections 3 and 4 describe the preliminary and final shielding analyses. During the preliminary shielding analysis the external shielding thicknesses were determined based on some initial beam loss scenarios. However, with time more

realistic beam loss scenarios were established, which allowed for addition of local shielding. The final shielding analysis take these into consideration. The side walls of the linac

were shielded for 0.5 mrem/h $\left(\frac{1 \text{ rem/y}}{2000 \text{ h/y}}\right)$ or 5 $\mu\text{Sv/h}$ in

occupiable areas under normal operating conditions. Since the roof was to be administratively controlled, higher levels were allowed on the roof.

The booster was shielded for 8 mrem/h $\left(\frac{1 \text{ rem/y}}{120 \text{ h/y}}\right)$ or 80 $\mu\text{Sv/h}$ in occupiable areas (excluding roof). Normal operating conditions and all possible beam loss scenarios are addressed in the section on final shielding analysis.

In keeping with the SLAC ALARA (As Low As Reasonably Achievable) policy, the immediate vicinity of the injector will be monitored on an ongoing basis and considerable efforts will be made to eliminate "hot spots" with local shielding. If radiation measurements indicate that there is a potential for exceeding the 1 rem/y (10 mSv/y) in occupiable areas or the personnel dose equivalent for radiation workers exceeds 100 mrem/quarter (1 mSv/quarter) or for non-radiation workers exceeds 100 mrem/year (1 mSv/year) additional measures will be taken. These additional measures could include limiting annual operating hours for the booster by administrative controls, addition of shielding, and/or restriction of access to areas with higher radiation levels.

3. PRELIMINARY SHIELDING ANALYSIS

The shielding for the linac housing was determined by SSRL and the shielding for the booster was determined by the SLAC Radiation Physics Department. Details of this can be found in reference 9.

Assumed Operating Parameters:

1. Maximum achievable electron intensity from linac
= $1 \times 10^{11} \text{ e}^-/\text{sec}$
2. Energy of beam injected from linac to booster = 150 MeV.
3. Energy of beam injected from booster into SPEAR = 3 GeV.

4. Current required in SPEAR/fill = 100 mA.

[Circumference of SPEAR = 234 m
Velocity of light = $3 \times 10^8 \text{ m/s}$]

$$\frac{100 \times 10^{-3} \text{ A/fill}}{1.6 \times 10^{-19} \text{ C/e}^-} \times \frac{1 \text{ C}}{\text{s-A}} \times \frac{234 \text{ m}}{3 \times 10^8 \text{ m/s}} = 4.9 \times 10^{11} \text{ e}^-/\text{fill}$$

5. Number of fills/year = 467.

$$[700 \text{ shifts/year} \times 8 \text{ h/shift} \times \frac{1}{12 \text{ h/fill}} = 467]$$

Note: The time between fills in SPEAR is typically about 12 hours.

6. Number of electrons stored per year in SPEAR =
= 467 fills $\times 4.9 \times 10^{11} \text{ e}^-/\text{fill}$
= $2.3 \times 10^{14} \text{ e}^-$

7. Overall efficiency of linac - booster for injection (and accumulation) into SPEAR = 4.5%.

3-1 ASSUMED BEAM LOSSES

Figure 3 shows a layout of the injector.

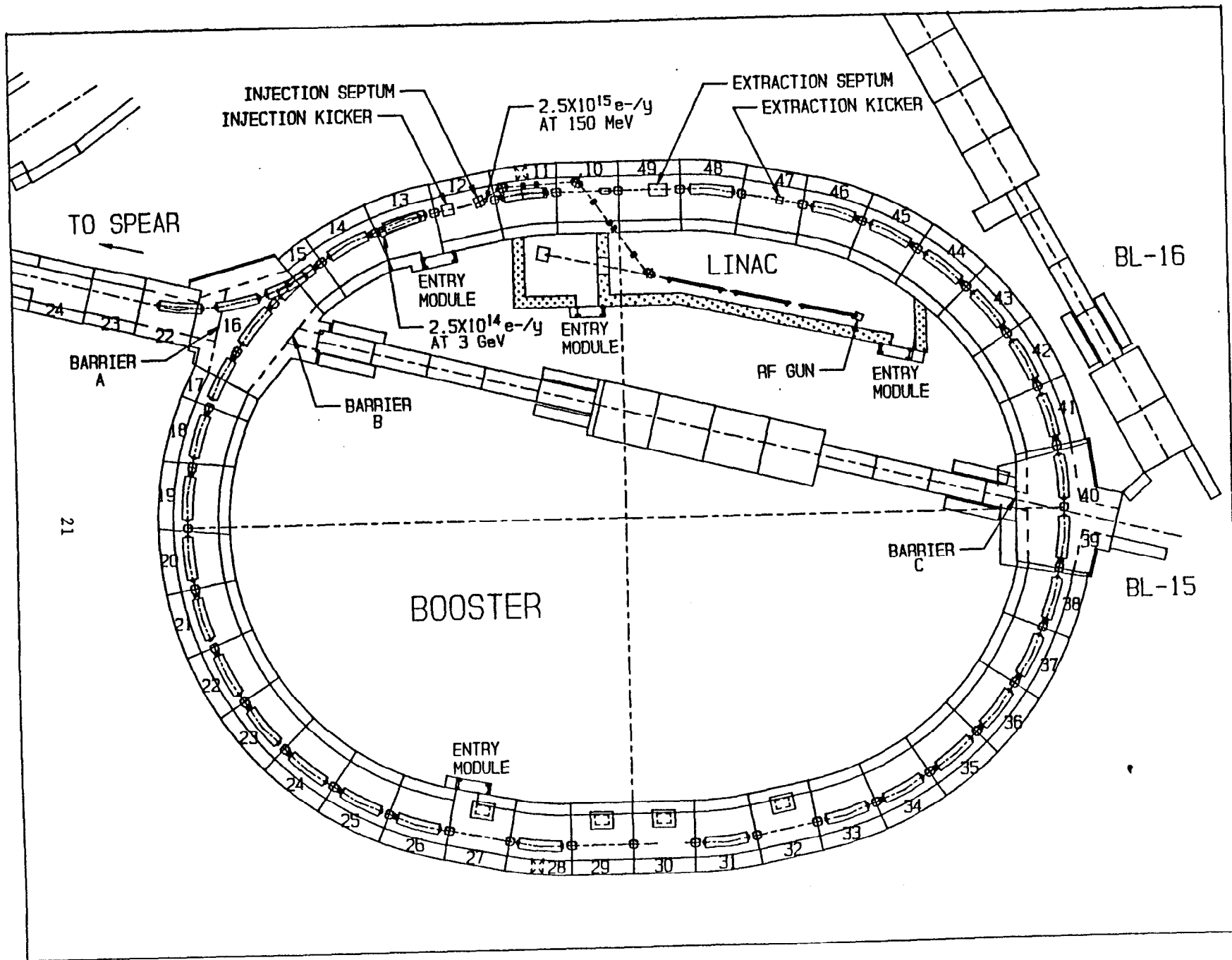
3-1-1 Linac

Due to various restraints SSRL had specified that the transverse walls of the linac housing would be two feet (~61 cm) thick and the roof one foot (~30 cm) thick. Some preliminary estimates were made of radiation levels outside the shielding. For normal operations the assumption was that 3% of the beam could be lost in a thick target anywhere along the linac at 150 MeV. Under these conditions the linac could operate for 500 hours so that the annual dose equivalent at the shield surface [source to shield distance = 4 feet (~122 cm)] would be less than 1 rem (10 mSv). This was derived using the computer program SHIELD00 in which the target is an iron cylinder of length $17.3X_0$ (12 inches or 30.48 cm) and radius $3.7 X_m$ (2 inches or 5.08 cm) ⁽¹⁰⁾. For a source-to-shield distance of 2 feet, additional local shielding (1.5 inches or 3.81 cm of lead) would be required.

3-1-2 Booster

It was expected that about 50% of the electrons delivered at 150 MeV from the linac will be accepted in the booster ⁽¹¹⁾. The losses may be local at the injection point and/or around the ring in the first few turns. Since the electrons gain only about 20 keV in the first few turns, for shielding purposes we assumed that $0.5N$ electrons, all of energy 150 MeV, are lost at a point in the booster ring (N is the number of electrons/year that are injected into the booster). $0.5N$ electrons are transmitted.

There is little loss during the acceleration in the booster but during the last 10 to 20 turns as much as 10% of the energy in the ring may be lost. Some of this loss can also



INJECTOR LAYOUT

Figure 3

occur locally during injection into SPEAR (i.e., in the booster ejection line). The shielding for these losses will be addressed in another section. Again for shielding purposes, we assumed that 10% of the electrons all of energy 3.0 GeV, are lost at a point in the ring. Thus, $0.1 \times 0.5N = 0.05N$ electrons of energy 3.0 GeV are lost and $0.9 \times 0.5N = 0.45N$ are transmitted at this stage.

There will also be accumulation losses in SPEAR of about 90% of the incoming beam. Thus the number of electrons per year that arrive at SPEAR is $0.1 \times 0.45N = 0.045N$. We know that the number of electrons to be stored in SPEAR per year is 2.3×10^{14} . Thus $N \approx 5 \times 10^{15}$ electrons have to be injected per year into the booster under this beam loss scenario in order to obtain 5×10^{11} electrons (100 mA) per fill in SPEAR.

To summarize, the following beam loss scenario was assumed:

1. 50% of $5 \times 10^{15} e^-$ /year of energy 150 MeV are lost at a point in the booster ring ($2.5 \times 10^{15} e^-$ /year).
2. 10% of the remainder i.e. $2.5 \times 10^{14} e^-$ /year of energy 3.0 GeV are also lost at a point in the booster ring.

Both point sources were added together in arriving at the shield thickness necessary to keep the annual integrated dose equivalent below 1 rem (10 mSv) at the outer surface of the shielding. The shielding thicknesses specified are shown in the following table:

TABLE 2

Transverse Walls	Source-to-Shield Distance (cm)	Shield Thickness (cm)	
		No Fe	Fe*
Outer Wall	61	76 (30")	64
Inner Wall	168	57 (22")	43
Roof	107	67 (26")	35

* 2.1 inches or ~ 5.3 cm (inner/outer walls), 5.9 inches or ~ 15 cm (roof). This is iron in the existing magnets.

The north and south arcs of the booster ring have a series of magnets and therefore in most of this area there is extra magnet iron in the vertical direction, which would provide some attenuation. Hence the specified roof thickness in these areas was 35 cm. Since there are very few magnets in the east and west straight sections, the specified roof thickness in these areas was 67 cm.

If the beam losses occurred such that they were uniformly distributed around the ring, the dose equivalent rates would be lower by a factor of 55 for the outer wall and a factor of 33 for the inner wall. These results were obtained using the computer program SHIELDO MORTRAN, which is a modified version of SHIELDOO MORTRAN⁽¹²⁾ that allows calculation of dose equivalent rates from distributed sources.

The linac and ring enclosures consist of poured in place concrete walls and precast concrete roof blocks. The roof is 1 foot (~30 cm) thick for the linac and for the north and south arcs of the booster ring tunnel. The roof is two feet (~61 cm) thick in the east and west straight sections of the booster ring. The

transverse walls of the linac are physically 2 feet (~61 cm) thick. The inner and outer walls of the booster are physically 24 (~61 cm) and 32 (~81 cm) inches thick, respectively.

The transverse walls of the linac and booster are made of two rows of light masonry blocks (specified density = 105 pcf or 1.68 g/cc) and the space between the two rows is filled with concrete (specified density = 150 pcf or 2.4 g/cc). However the measured density of the masonry block was only 89 pcf, or 1.42 g/cc, and therefore the concrete equivalent shielding of the inner and outer walls are about 21.5 (~55 cm) and 29.5 (~ 75 cm) inches respectively⁽¹³⁾. All further shielding calculations were done using the equivalent concrete thicknesses for the linac and booster walls of ~ 21.5 inches (~ 55cm) and 29.5 inches (~ 75cm), respectively.

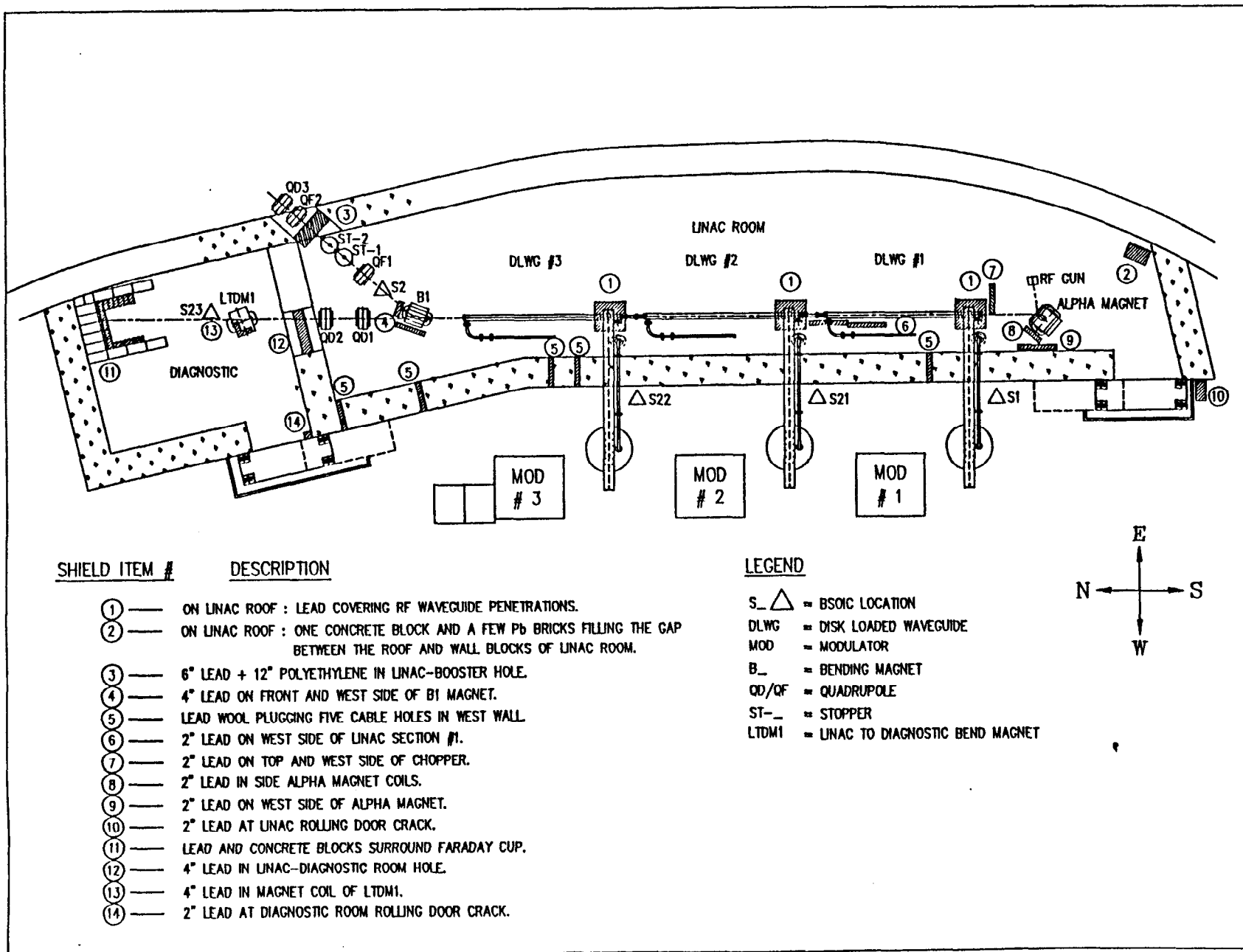
4. FINAL SHIELDING ANALYSIS

4-1 LINAC

Figure 4 shows a layout of the linac and diagnostic room. The linac is comprised of an electron gun, the Gun-To-Linac section (GTL), and three accelerating sections.

The gun is an RF gun with a thermionic cathode⁽¹⁴⁾. Electrons emitted from the cathode are quickly accelerated to relativistic energies because the cathode reaches directly into the high field of a microwave cavity. The operating frequency of the gun is 2856 MHz, which is the same as the linac. The gun produces a continuous train of bunches spread about 350 psec apart. Thus a 1.4 μ sec wide RF pulse will produce about 4,000 bunches. The gun is designed to produce a maximum of 1.5 A peak current during the RF pulse with about 2.5 MeV/c momentum for the electrons.

The section between the gun and the first accelerating section is known as the GTL section. This section includes an alpha magnet, five quadrupoles, four steering magnets and a beam chopper. The alpha magnet filters out the low energy electrons by means of slotted absorbers located within the gap of the magnet at the point of maximum dispersion⁽¹⁵⁾. In addition the alpha magnet compresses the bunch length. Electrons at the head of the bunch are more energetic than those at the tail. The alpha magnet causes the higher-energy electrons to travel longer paths than the lower-energy electrons, thus allowing the lower-energy electrons to catch up with the higher-energy ones. Compression of the bunch length results in a reduction in the spread in the linac, thus reducing losses in the linac-to-booster transport line.



LINAC AND DIAGNOSTIC ROOM LAYOUT

Figure 4

The booster RF bucket can only accept 3 - 5 bunches. Hence a beam chopper selects a triplet of consecutive bunches from the continuous train of bunches. The beam chopper also prevents injection of large currents into the booster. In order to prevent accidental injection of continuous current into the linac, the chopper has two permanent magnet deflectors and a 4 mm aperture through which the bunches pass in order to enter the linac. The chopper is a parallel plate transmission line. An electromagnetic wave is sent along the line in such a manner as to deflect the electron beam in a direction opposite to that caused by the permanent magnets. When the chopper is pulsed the beam is swept onto the slit/aperture to permit the 3 bunches to enter the first linac accelerating section. Each linac section is driven by a separate klystron, and is capable of accelerating the beam up to 58 MeV, provided there is no beam loading. The second klystron supplies RF power to both the second linac section and the RF gun. It can accelerate the electrons up to energies of 51 MeV. The nominal energy of the beam at the end of the three linac sections is about 150 MeV.

The two quadrupoles located between the first and second linac sections reduce beam losses downstream and help in matching the injected beam to the booster.

At the end of the third linac section, the beam can be directed straight ahead into the diagnostic room via the Linac-To-Diagnostic (LTD) line or be bent into the booster through the Linac-To-Booster (LTB) transport system.

The LTD line consists of two quadrupoles, a phosphorescent screen for emittance measurements, a bending magnet for energy measurements and a Faraday cup for measurement of total charge. The LTB transport system in the linac housing consists of a bending magnet, B1, a quadrupole, QF1, and two stoppers, ST-1 and ST-2.

4-1-1 Assumed Beam Operating Parameters and Losses

The assumed operating beam parameters and beam losses are as follows⁽¹⁶⁾:

Energy of electrons from RF gun = 2.5 MeV
Maximum intensity from RF gun = $1.4 \times 10^{14} e^-/\text{sec}$

Maximum intensity at exit of alpha magnet = $7.3 \times 10^{13} e^-/\text{sec}$ (~50%)
Maximum intensity through linac = $3.1 \times 10^{10} e^-/\text{sec}$
(Limited by two average current toroids.)

Loss in linac section 1 = 3%

Loss in linac section 2 = 0.25%

Loss in linac section 3 = 0.25%

Maximum beam power to diagnostic room dump at 150 MeV = 0.75 watt

Maximum beam power to booster at 150 MeV = 0.75 watt

Average occupancy time for workers = 2000 h/year

4-1-2 Beam Containment Electronics

The electron intensity in the linac sections is limited to $3.1 \times 10^{10} e^-/\text{sec}$ by two beam current monitoring toroids, LT1 located between linac sections 1 and 2, and LT2 located downstream of section 3⁽¹⁷⁾. The toroids are connected to SLAC-type Average Current Monitor Module (ACM). A beam containment trip caused by excessive current through either

toroid will interrupt the triggers to the three modulators as well as the triggers to the pulsed RF amplifier which feeds the RF gun. If the chopper fails, beam cannot be injected into the linac. However, if the amplitude of the chopper high voltage is too low, the unchopped beam may enter the linac. Hence a chopper high voltage interlock has been added to ensure that an unchopped beam does not enter the linac. Recently it has been demonstrated that certain steering and focussing configurations of the GTL section can result in too much beam going through even a properly functioning chopper^(76,77). Thus, more than 3 bunches could enter the linac sections. The beam could be lost in the first section without tripping the first toroid, or be lost after the first section after tripping the first toroid. It is also remotely possible that a large fraction of beam can pass through the chopper due to mis-steering of beam components upstream of the chopper. The transmitted fraction could be 10 percent or higher. Calculations by Benson indicate that if the entire beam (all 3000 bunches) were lost at a point in the first section (at 50 MeV) the dose equivalent rate outside the roof and west wall will be 64 rem/h (0.64 Sv/h) and 5 rem/h (50 mSv/h) respectively⁽⁷⁸⁾. For a loss of the entire beam (3000 bunches) at 150 MeV in the third linac section the corresponding dose equivalent rates are 194 rem/h (1.94 Sv/h) and 126 rem/h (1.26 Sv/h).

Hence, the addition of a third toroid between linac sections 1 and 2 has been proposed with the proviso that if the beam is lost in the first section before it can be detected by ACM1 (connected to LT1) and the new ACM (connected to new toroid), the maximum dose equivalent rate in occupiable areas cannot exceed 400 mrem/h (guideline for loss of entire beam during mis-steering). If the beam is lost after linac

section 1 without tripping the first two ACMS, the maximum dose equivalent rate in occupiable areas cannot exceed 25 rem/h (guideline for accident case in which two out of three beam containment devices fail).

In addition to radiation measurements already made, additional measurements will be made to analyze the failure modes of the beam containment electronics. Three Beam-Shut-Off-Ionization-Chambers (BSOICS) S1, S21 and S22 have been placed outside the linac west wall by modulators 1, 2 and 3, respectively, to detect the failure of any of these beam containment devices (Figure 17). These BSOICS are all set to trip at 10 mR/h (DR = 0.1 mGy/h, using 1 R = 1 rad and 1 rad = 0.01 Gy).

4-1-3 Linac Housing

In order to meet the 1 rem/year or 10 mSv/y (0.5 mrem/h or 5 μ Sv/h) criterion the following local shielding was specified (Figure 4) ⁽¹⁶⁾:

1. Two inches of lead inside the alpha magnet coils
2. Two inches of lead on west side of alpha magnet
3. Two inches of lead on top of and on the west side of the chopper
4. Two inches of lead on the west side (downstream half) of linac section 1

If the entire beam were to be lost at 150 MeV (0.75 watt), the maximum dose equivalent rate (DER) on the linac roof will be 194 mrem/h (1.94 mSv/h) and outside the west wall will be 125 mrem/h (1.25 mSv/h).

4-1-4 LTD Beamline

The beam will enter the LTD beamline when magnet B1 is off. The port, through which the beampipe enters the diagnostic room from the linac housing, is lined with 4 inches (10.16 cm) of lead. The walls of the diagnostic room are about 21.5 inches (~55 cm) thick. The roof is 1 foot (~30 cm) thick.

Any mis-steering of the beam will cause it to strike the 4 inches (10.16 cm) of lead in the coil of magnet LTDM1⁽¹⁸⁾. This will result in a dose equivalent rate (DER) of 58 mrem/h or 0.58 mSv/h (at 0.75 watt) outside the west wall. If the beam is mis-steered slightly so that it is stopped by a flange or the magnet steel, the highest radiation level outside the roof will be 280 mrem/h (2.8 mSv/h). If LTDM1 is in reverse polarity the beam will strike the magnet iron and the maximum DER will occur outside the east wall (i.e. inside the booster tunnel). This DER will be 2.5 rem/h (25 mSv/h).

The maximum angle an LTD quad could bend a 150 MeV beam is 4.8°. Any mis-steered beam would strike the 4-inch (10.16 cm) thick lead wall in the linac-diagnostic room port. The DER outside the north wall of the diagnostic room would be 53 mrem/h (0.53 mSv/h).

The Faraday cup in the diagnostic room was shielded with a combination of lead and concrete to ensure that the DER outside the walls of the diagnostic room were less than 0.5 mrem/h (5 μ Sv/h) for a beam power of 0.75 watt⁽¹⁹⁾.

4-1-5 LTB Beamline

When magnet B1 is on, the beam is bent into the LTB line. The 4 inches (10.16 cm) of lead in front of the magnet ensures that any mis-steered beam strikes the lead, thus producing a

shower in the proximity of the beampipe. If the lead was not in place the beam could strike the beampipe, which is a thin target. Electrons from the shower (produced in the thin target) in the forward direction may be energetic enough to propagate the shower in the concrete shielding walls. Thus the lead acts as a thick target. The lead wall in the linac-diagnostic room port and the north wall of the diagnostic room will provide the necessary shielding. If B1 is in reverse polarity the beam will strike the 4 inches (10.16 cm) of lead on the west side of the magnet. The west walls of the linac housing and the diagnostic room will provide the required shielding. Any mis-steering along the LTB line up to the two stoppers will cause the beam to hit the magnets downstream or the wall in the linac-booster port. A BSOIC, S2, (Figure 17) is located on the roof so that it can respond to radiation losses along the LTB and a BSOIC S23 is located on the roof above the LTD line to detect losses in this line. These BSOICs are set to trip at 50 mR/h (0.5 mGy/h).

The magnet B1, and stoppers ST-1 and ST-2 are considered to be the "LTB stoppers." An accident situation is defined as one in which two out of three stoppers fail. In such an event the maximum dose equivalent rate in the nearest occupied area can not exceed 25 rem/h (0.25 Sv/h). If the booster is in "Permitted Access", and there is a failure such that B1 is on when it should be off and ST-1 is out when it should be in the "IN" position, then the beam will strike ST-2. The DER in the booster tunnel will be less than 25 rem/h (0.25 Sv/h). Stoppers ST-1 and ST-2 have been designed to meet this criterion and consist of 5.91 inches or 15 cm (10.42 X₀) of copper and 1 inch or 2.54 cm (7.26 X₀) of tungsten (20). The depth at which shower maximum occurs is given by:

$$L = \frac{2.0 - Z/340 + (0.664 - Z/340) \ln E}{0.634 - (0.0021 \times Z)}$$

where E is the beam energy (GeV) and Z is the atomic number of the material.

For $Z = 29$ and $E = 0.15$ GeV
 $L = 1.425$ cm

Assuming a target of $10.42 X_0$ of copper and $7.26 X_0$ of tungsten, the DER in the forward direction at a distance of about 1 m from ST-2, for 0.75 watt (using SHIELD11) is less than 15 rem/h (0.15 Sv/h)⁽²¹⁾. A BSOIC, S3, (Figure 17) has been placed inside the booster tunnel to detect radiation in the event that any two of the LTB stoppers fail. This BSOIC is set to trip at 10 mR/h (DR = 0.1 mGy/h) and is automatically bypassed when the booster is in a "NO ACCESS" state. If B1 is on and ST-1 is in the "IN" position and ST-2 in the "OUT" position, the DER in the booster tunnel will be less than 15 rem/h (0.15 Sv/h) because the distance from ST-1 to the tunnel is greater than from ST-2 to the tunnel.

4-1-6 Linac-Booster Port

The linac booster port is shielded with 6 inches (15.24 cm) of lead followed by 12 inches (30.48 cm) of concrete. Since photons and giant resonance neutrons are the major contributors to the dose equivalent rate outside the shielding, this combination of shielding is more than the equivalent of 21.5 inches (~55 cm) of concrete, as can be seen from the following calculation.

The attenuation provided by X inches of a material of density ρ (g/cc) and attenuation length λ (g/cm²) is:

$$e^{-\frac{X(\text{in}) \times 2.54 (\text{cm/in}) \times \rho (\text{g/cc})}{\lambda (\text{g/cm}^2)}}$$

Hence the thickness of lead X (inches) required to provide the same photon attenuation as 21.5 inches (~55 cm) of concrete can be obtained from the following equation:

$$e^{-\frac{X \times 2.54 \text{cm/in} \times 11.35 \text{ g/cc}}{24 \text{g/cm}^2}} = e^{-\frac{21.5 \text{ in} \times 2.54 \text{ cm/in} \times 2.35 \text{ g/cc}}{42 \text{ g/cm}^2}}$$

$$X = 2.54 \text{ in (6.45 cm)}$$

The thickness of polyethylene required to provide the same attenuation as 21.5 inches (~55 cm) of concrete can be determined as follows:

The attenuation length λ for giant resonance neutrons in concrete is 30 g/cm^2 or 12.77 cm. The half-value layer (HVL) and the tenth-value layer (TVL) are the thicknesses which attenuate the radiation intensity by one-half and one-tenth, respectively.

$$1 \text{ HVL} = 0.693 \lambda$$

$$1 \text{ TVL} = 3.32 \text{ HVL}$$

$$\begin{aligned} \text{TVL for concrete} &= 3.32 \times 0.693 \times 12.77 \text{ cm} \\ &= 29.4 \text{ cm (11.57 in)} \end{aligned}$$

The energy of the neutrons will be degraded after passing through lead and the average energy is given by⁽²²⁾

$$\bar{E} = E_{\text{av}} \left(\frac{1}{2} \right) \frac{X}{\text{HEL}}$$

where E_{av} is the average energy before passing through lead, X is the thickness of the lead and HEL is the half energy layer for neutrons in lead.

For $E_{av} = 2.5$ MeV, HEL = 18 cm (7.09 in)

For $X = 6$ inches

$$\bar{E} = 2.5 \left(\frac{1}{2} \right) \frac{6 \times 2.54}{18}$$

$$\bar{E} = 1.4 \text{ MeV}$$

The TVL for neutrons ($E = 1.4$ MeV) is 12 cm (4.72 in).

Therefore thickness of polyethylene Y (cm) required to produce the same attenuation as 21.5 inches (~55 cm) of concrete is given by

$$\frac{Y(\text{cm})}{12(\text{cm})} = \frac{21.5 \text{ in} \times 2.54 \text{ cm/in}}{29.4 \text{ cm}}$$

$$\text{Number of TVLs} = \frac{Y(\text{cm})}{12(\text{cm})} = 1.86$$

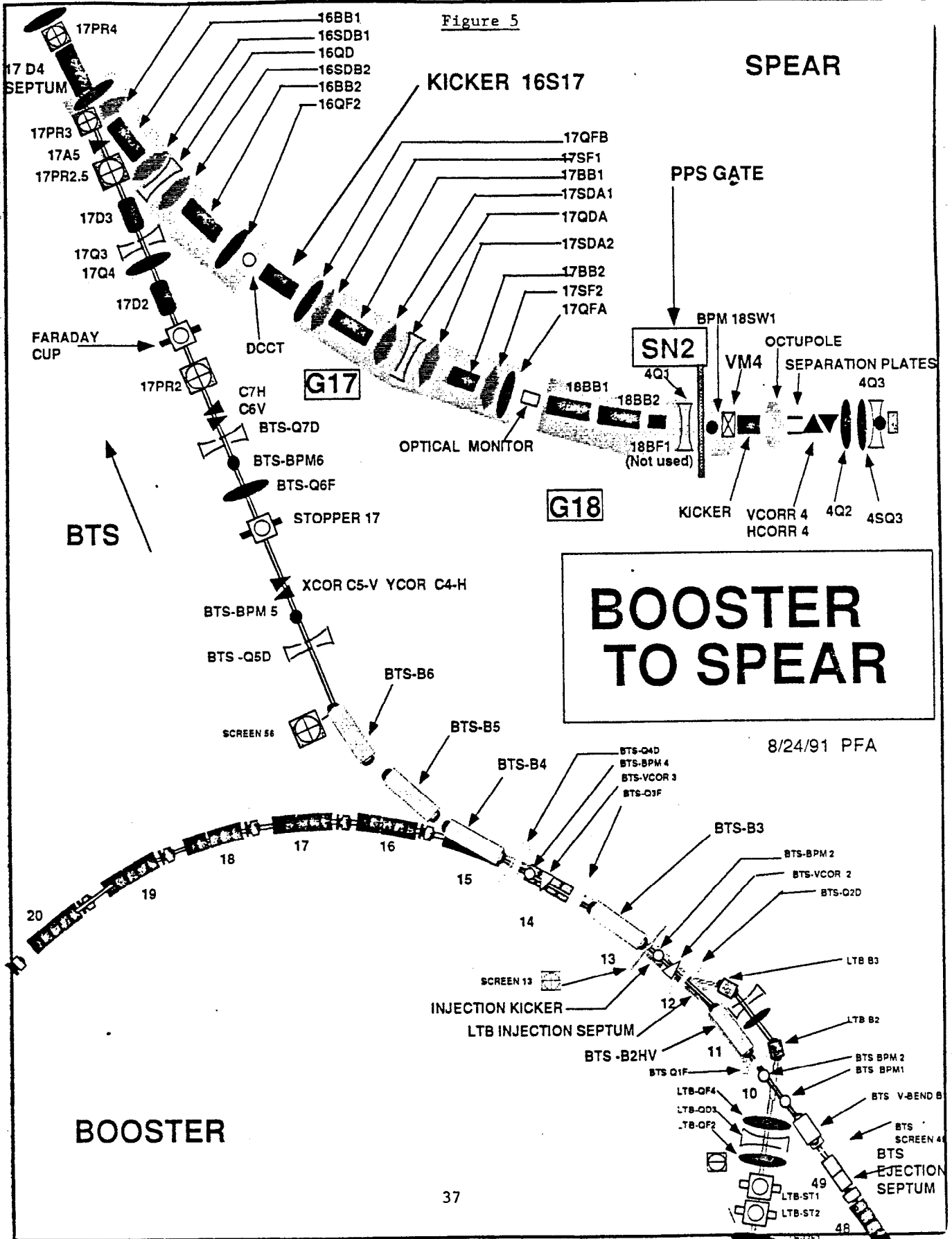
Therefore, $Y = 22$ cm (8.66 in)

Thus the required shielding combination is 2.54 inches (6.45 cm) of lead followed by 8.66 inches (22 cm) of polyethylene. The actual shielding combination that was used was 6 inches (15.24 cm) of lead followed by 12 inches (30.48 cm) of polyethylene.

After construction of the booster the shielding was re-analyzed due to more realistic beam loss scenarios⁽²³⁾. The linac to booster (LTB) beam transport system consisting of magnets and quadrupoles guides the beam from the linac into the booster where it is injected by means of a septum and a kicker magnet into the booster (Figure 5)⁽²³⁾. The septum magnet is strong enough to accommodate a large deflection angle such that the incoming beam need not pass through a ring magnet. A pulsed magnetic field from the kicker magnet in the booster deflects the incoming beam into the booster orbit. The kicker magnet must be turned off before the first injected particle arrives again at the kicker location after one turn in the booster. The kicker is therefore on for a very short period and is synchronized with the injector bunch. The injected beam is matched to the optical parameters of the booster at the injection point by means of bending and focusing magnets.

Injection of the beam into the booster occurs near the low point of the sinusoidal 10 Hz cycling of the booster magnets⁽¹⁴⁾. As the currents to the magnets increase, the magnets reach higher fields. At the same time the RF drive to the booster klystron is increased, thus increasing the energy of the electron bunches, while keeping the effective strength of the magnets constant. In other words, as the energy of the bunches increases the magnetic fields increase so as to keep the bending radius constant. The three injected bunches coalesce into a single bunch (due to radiation damping) as they circulate into the booster. A kicker magnet kicks the booster bunch into the BTS (Booster-to SPEAR) transport line, at the peak of the cycle. Therefore at 3 GeV only one pulse (composed of one bunch) can be lost since the magnets are cycling at 10 Hz.

Figure 5



8/24/91 PFA

Tables 3, 4, and 5 list the booster ring shielding, operating parameters and design criteria. The maximum allowable beam injected into the booster from the linac is 0.75 watts (3.12×10^{10} e⁻/sec at 150 MeV). The maximum electron intensity is limited by a pair of average current toroids in the linac. The worst case scenario occurs when all of the 0.75 watt are lost at a point in the booster during injection. At 3 GeV, only one pulse can be lost at a point. This corresponds to 1.5 watt-sec/pulse (3.12×10^9 e⁻/pulse at 3 GeV).

During normal operating conditions it was expected that 50% of the 150 MeV electron beam is likely to be lost in the LTB at the septum during injection. The remaining 50% will be accelerated to 3 GeV and 10% of this was expected to be lost during ejection. Most of these losses will occur in the ejection area. Very little loss was expected during acceleration in the booster. For shielding purposes we assumed that a 1% loss is likely at any location in the LTB during normal operating conditions, except at the injection septum where a 50% loss is expected. Unless otherwise stated all dose equivalent rates are for the worst case (0.75 watt).

The differences between the preliminary shielding analysis and the final shielding analysis are found in Table 6. The next section describes all possible beam loss scenarios in the LTB line. Radiation levels have been calculated for the worst case which assumes that all 3.1×10^{10} e/sec. are accelerated to 150 MeV and lost at a point. This is a very conservative approach since normally losses do not take place at a point, but are distributed. In addition, the next section describes the beam containment which consists essentially of local lead shielding. The local lead shielding will ensure that the beam will initiate an electromagnetic shower in a thick target close to the beam pipe, thus preventing the propagation of the shower in the concrete shielding walls.

TABLE 3

BOOSTER RING SHIELDING

	<u>Equivalent Thickness of Concrete (inches)</u>	<u>Thickness (cm)</u>
Outer Wall	29.5	~75
Inner Wall	21.5	~55
Roof (Straight Sections)	24.0	~61
Roof (Arcs)	12.0	~30

TABLE 4

OPERATING PARAMETERS

	<u>Maximum No. of Electrons/Pulse</u>	<u>Pulse Rate</u>	<u>Energy</u>
Linac	3.12×10^9	10 Pulses/sec	150 MeV
Booster	3.12×10^9	10 Pulses/sec	3 GeV

TABLE 5

SHIELDING DESIGN CRITERIA

	<u>Dose Equivalent Rate</u>
Worst Case*	< 25 rem/h
Normal Operating Conditions	< 1 rem/y or < 8 mrem/h**

*Losing the maximum allowable beam at a point.

**Annual operating hours = 467 fills/y x 15 min/fill,
approximately 120 h.

TABLE 6

Differences Between Preliminary and
Final Shielding Analyses

	PRELIMINARY	FINAL	RELATIVE DECREASE
Maximum electron intensity	$1 \times 10^{11} e^-/s$	$3.12 \times 10^{10} e^-/s$	$\sim 1/3$
Losses for shielding	Always in a thick target (Fe cylinder, L=30 cm, R=2 cm)	Thin targets were also considered	—
Worst case loss (at a point)	$1 \times 10^{11} e^-/s$ at 3 GeV \Rightarrow 50 watts	$3.12 \times 10^{10} e^-/s$ at 150 MeV \Rightarrow 0.75 watts	$\sim 1/60$. Can only lose 1 pulse at 3 GeV at a point
Normal losses	a) Based on injecting $5 \times 10^{15} e^-/y$ into booster	Based on injecting $3.12 \times 10^{10} e^-/s$ into booster	—
	b) 50% loss at 150 MeV at a point in the ring ($2.5 \times 10^{15} e^-/y$)	50% loss at 150 MeV at injection septum	—
	c) 10% of remainder at 3 GeV lost at same point in the ring ($2.5 \times 10^{14} e^-/y$)	10% of remainder at 3 GeV lost at ejection	—
	d) ———	1% loss at any location in LTB	—
Booster operating time	$(5 \times 10^{15} e^-/y)/(10^{11} e^-/s)$ $\Rightarrow \sim 14hr$	15 min/fill \times 467 fills/y $\Rightarrow \sim 120 hr$	—

4-3 LOSSES IN THE LTB (LINAC TO BOOSTER)

4-3-1 Quadrupole QF4

It is likely, that due to mis-steering, the beam could hit the beam pipe in the focussing quad QF4⁽²⁴⁾. The beam pipe in this area is 0.05 inches (0.127 cm) thick. In order to prevent any forward directed thin target bremsstrahlung from showering in the concrete wall downstream, local lead shielding has been added as shown in Figure 6. The dose equivalent rate (DER) at K' for this instance will be less than 130 mrem/h^a (1.3 mSv/h) in the worst case. The lead shielding is one inch (2.54 cm) thick in the vertical direction. The DER outside the 2-foot (~61 cm) thick roof will be less than 25 mrem/h^a, or 0.25 mSv/h, (0.75 watt) for losses in the lead.

If, due to mis-steering, the beam can hit the beam pipe between QD3 and QF4, the DER outside the roof will be less than 300 mrem/h^b, or 3 mSv/h (0.75 watt).

4-3-2 Magnets B2 and B3

Magnets B2 and B3 are both shielded with lead such that if the magnets are on, off or in reverse polarity, the DER in the worst case will be significantly less than 25 rem/h, or 0.25 Sv/h (Figure 6).

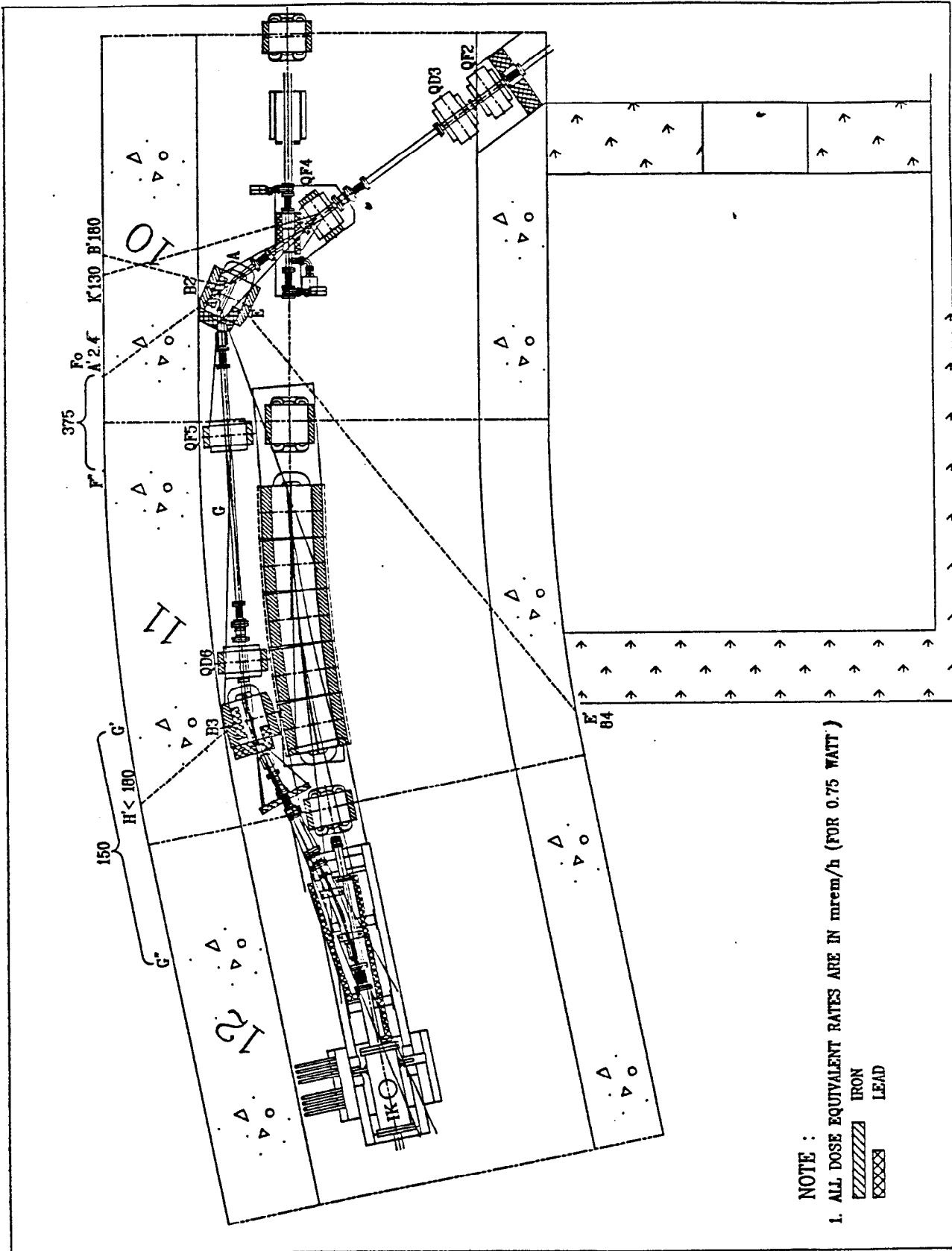
B2-reverse, maximum bend, AB', DER = 180 mrem/h^a (1.8 mSv/h)

B2-off, AA', DER = 2.4 mrem/h^a (24 μ Sv/h)

B2-on, maximum bend, EE', DER = 84 mrem/h^a (0.84 mSv/h)

B3-reverse, maximum bend, H', DER = 180^a mrem/h (1.8 mSv/h)

Figure 6



NOTE :
 1. ALL DOSE EQUIVALENT RATES ARE IN mrem/h (FOR 0.75 WATT)
 IRON
 LEAD

If B2 is in reverse polarity and the beam hits the trimmer magnet steel downstream of B2 the maximum photon DER outside the outer wall between FO and F" will be 375 mrem/h^c or 3.75 mSv/h (0.75 watt). A BSOIC, S4, (Figure 17) has been mounted outside the outer wall to detect radiation losses during injection. This BSOIC is set to trip at 50 mR/h (DR = 0.5 mGy/h). If the entire beam were to hit the beam pipe at point G the maximum photon DER between G' and G" will be less than 150 mrem/h^c (1.5 mSv/h). Any beam that escapes the lead around B3 is intercepted by a lead collimator downstream of B3.

4-3-3 Injection Septum

The energy of the beam injected from the linac is 150 MeV. If the septum is set to the wrong energy the beam will hit the vacuum chamber. Under normal operating conditions about 50% loss is expected in the injection septum. Since the septum magnet iron is very thin (0.5 inch or 1.27 cm), the septum is enclosed on the sides and on the top with 2 inches (5.08 cm) of lead (Figure 7). The photon DER at N' will be approximately 55mrem/h^c (0.55 mSv/h) for a 50% less loss and 110 mrem/h^c (1.1 mSv/h) in the worst case. The photon DER at N'' will be 37 mrem/h^c (0.37 mSv/h) in the worst case, and 38 mrem/h (0.38 mSv/h) at N'''.

FOOTNOTES:

- a Using SHIELD10 MORTRAN
- b Using results from reference 25
- c Using results from computer code EGS4.

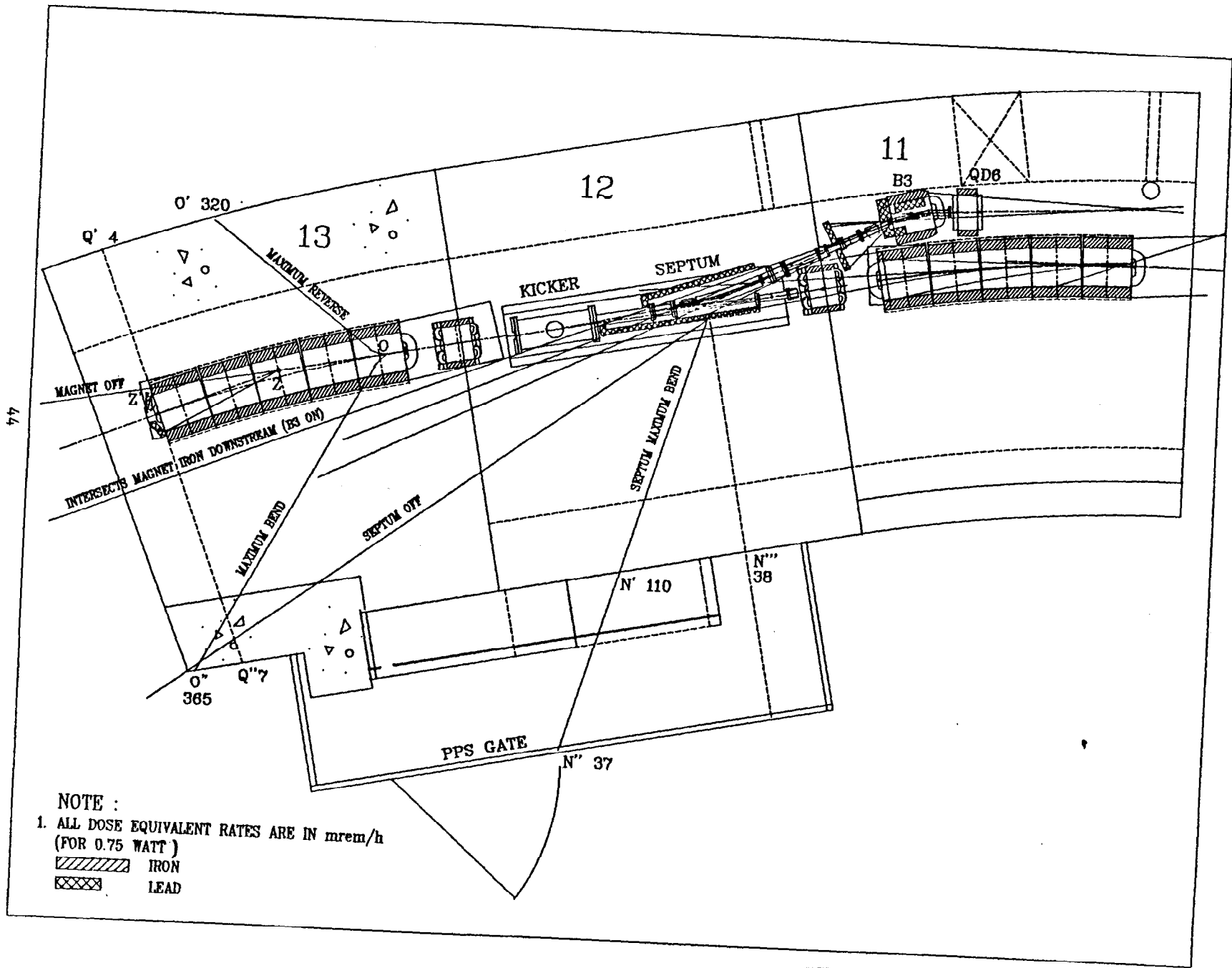
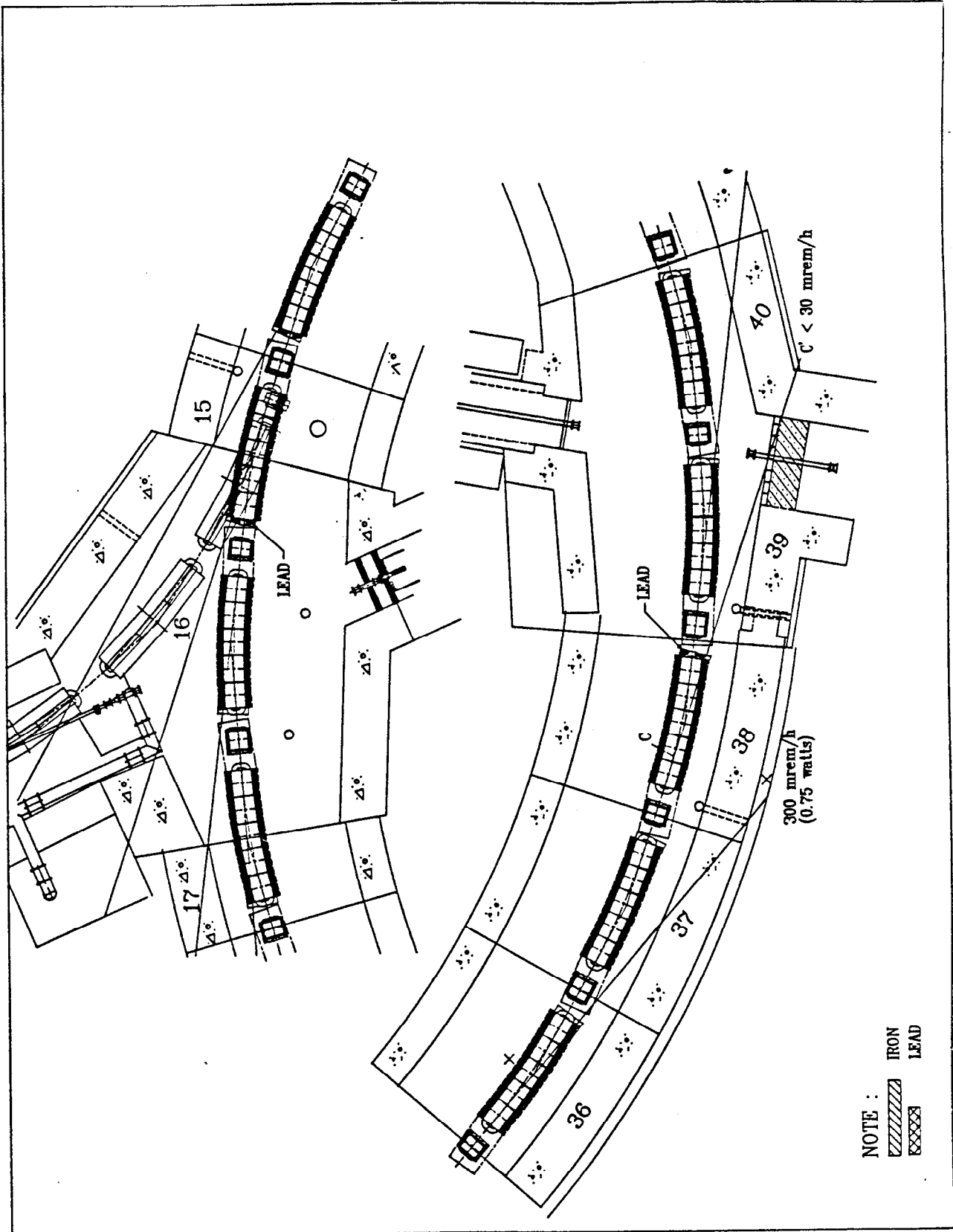


Figure 7

Figure 8



4-4 LOSSES IN THE RING

This section addresses losses in the ring. Since the arrangement of magnets in the booster is symmetrical, only general cases are considered except in a few special cases. Again, a very conservative approach of loss at a point has been taken. In addition, the worst case assumes all 3.1×10^{10} e/sec are accelerated to 3 GeV and injected into the booster. However, there will be losses during injection so in practice, the worst case is never achieved.

4-4-1 Ring Magnets

Due to timing errors, a 150 MeV beam entering the first ring magnet could experience a B field set for the wrong energy. This could happen continuously during injection. The worst timing error would result in a 150 MeV beam experiencing a field set for 3 GeV. In addition, if the first ring magnet is in reverse polarity, the ray would be bent as shown (OO' in Figure 7) ⁽²⁴⁾. The DER at O' will be about 320 mrem/h^a or 3.2 mSv/h (0.75 watt). If the beam was bent in the opposite direction, the DER outside the inner wall (O") will be approximately 365 mrem/h^a (3.65 mSv/h).

If there is a small mismatch between the B field and the incoming beam energy, it is likely that the beam can follow the extreme ray ZZ' (which is not intercepted by magnet iron) as shown in Figure 7. Since this scenario could happen only in the first few ring magnets, these magnets have been locally shielded with lead on the outside as shown in Figures 7 and 8. The DER at the outer wall from the extreme ray hitting the lead is approximately 4 mrem/h or 40 μ Sv/h (Q')^a and on the exit side approximately 7 mrem/h or 70 μ Sv/h (Q")^a at the inner wall. The beam pipe in the ring is 0.012 inches (.03 cm) thick. Once the beam has been accelerated to 3 GeV, if one or all the magnets

trip, 3.1×10^9 electrons (i.e. 1 pulse) are lost. If this was assumed to take place at a point, the integrated photon dose equivalent outside the shield due to an extreme ray XX' (Figure 8) will be about 1 mrem (10 μ Sv). At 150 MeV all 10 pulses could be lost at a point (extreme ray XX'). This will result in a photon DER of about 300 mrem/h (3 mSv/h) outside the outer wall. The DER outside the roof (1 foot or ~30 cm thick) for an extreme ray which produces thin target bremsstrahlung will be less than 1.8 rem/h^b (18 mSv/h) in the worst case. A BSOIC, S5, (Figure 17) has been placed on the booster roof where the roof is one foot (~30 cm) thick. This is set to trip at 50 mR/h (DR ~ 0.5 mGy/h). Under normal operating conditions no losses are expected during acceleration in the booster.

All the ring magnets are connected in series to one power supply⁽²³⁾. If the power supply trips the stored energy in the magnets or capacitor banks will discharge in about one second. The beam will be lost over thousand of revolutions in the focussing quadrupoles where beam size is a maximum. Only one pulse will be lost at 3 GeV. The remaining pulses will be lost at 150 MeV since the magnet fields are decaying or are off.

Since an extreme ray from the ring magnet in section 38 will go through less concrete shielding (point C) than those from other ring magnets, this magnet has also been locally shielded with lead. The DER at C' for the worst case will be less than 30 mrem/h^a (0.3 mSv/h).

4-4-2 Ring Quadrupoles

If the linac and booster are misadjusted by more than 2% compared to each other, the beam will not be captured in the booster. In such a case the beam will be lost in one of the 20 focussing quadrupoles in the booster, because the dispersion function reaches its largest value in the focussing quadrupole⁽²³⁾.

If the beam is lost in one of the quadrupoles due to energy mismatch between the linac and the booster, the DER outside the outer wall will be about 10 mrem/h^a (0.1 mSv/h) in the worst case. If the RF system is too low or off when the beam is captured in the booster orbit, the beam spirals horizontally inwards over tens of thousands of turns. This is because of the long damping times at 150 MeV. The electrons will get scraped off in the focussing quadrupoles where the beam size is a maximum. This will result in a distributed loss around the booster, and this is what would be expected under normal operating conditions. However, due to poor orbit correction, the beam can be lost in a single quadrupole. The DER outside the inner wall will be about 9 mrem/h^a ($90 \text{ } \mu\text{Sv/h}$) in the worst case.

During normal operating conditions, the RF system could trip at any energy up to 3 GeV. If this happens, the beam will spiral inwards and be lost in the focusing quadrupoles. The distribution of losses will again depend upon the orbit distortions. However in this case, only 1 pulse will be lost at that energy. The remaining pulses will be lost at 150 MeV because the RF is off.

FOOTNOTES:

a Using SHIELDO MORTRAN

b Using results from reference 25

c Using results from EGS4

4-5 LOSSES IN THE EJECTION AND BOOSTER TO SPEAR TRANSPORT LINES

In this section losses in the ejection and BTS lines are considered. Again, a conservative approach of losing the maximum possible beam at a point is taken.

After the beam is accelerated to the storage ring energy (3 GeV) it is ejected and deflected into a transport system which guides the beam into SPEAR (Figure 5)⁽¹⁵⁾. A fast full aperture kicker magnet in the booster deflects the beam into the magnetic aperture of the lambertson septum magnet. The septum deflects the beam vertically out and away from the booster components into the BTS (booster to SPEAR transport line). The BTS consists of a system of quadrupoles and bending magnets which steer the beam into SPEAR. The beam containment system, consisting of local lead shielding has been designed to ensure that any mis-steered beam will hit the lead close to the beam pipe, thus preventing the propagation of shower in the concrete shielding walls. The beam loss mechanisms for the ejection and BTS system are described in reference 26. All the following calculations assume the loss of 14.4 watts (3.12×10^{10} e⁻/sec at 3 GeV) unless otherwise stated.

4-5-1 Ejection Kicker

Due to a timing error, the beam could be ejected at the wrong energy, in which case it would strike the quadrupole or bending magnet downstream of it. If the kicker is set for 3 GeV and the incoming beam energy is 0.12 GeV, the beam (0.56 watt) will hit the magnet at A as shown in Figure 9⁽²⁷⁾. The DER outside the shielding at A' will be less than 10 mrem/h (0.1 mSv/h).

If the kicker is set for 3 GeV and the beam energy is 1 GeV the beam (4.4 watts) will hit the lead at C. The DER at C' outside the shielding will be 54 mrem/h^a (0.54 mSv/h). Above the 2 foot (~61 cm) roof at C", the DER will be 67 mrem/h (0.67 mSv/h). If there is no timing error and the magnet is off the beam (14.4 watts) will hit the magnet at B. The DER at B will be 105 mrem/h^a (1.05 mSv/h).

4-5-2 Ejection Septum

If the septum were set at too low a field or at reverse polarity the beam would strike the ring magnets downstream of the septum. If the septum were set too high the beam would strike the lead collimator downstream of the septum for angles of mis-steering that are 1.2° greater than the design angle. For a beam mis-steered by less than 1.2°, the beam strikes the quadrupole or BIV downstream. If the beam (14.4 watts) hits the quadrupole at D, the DER on the roof at D" will be 600 mrem/h or 6 mSv/h (Figure 9). A BSOIC, S6, (Figure 17) has been placed in this location and is set to trip at 50 mR/h (DR = 0.5 mGy/h).

FOOTNOTES:

- a Using SHIELDO MORTRAN
- b Using results from reference 25
- c Using results from EGS4

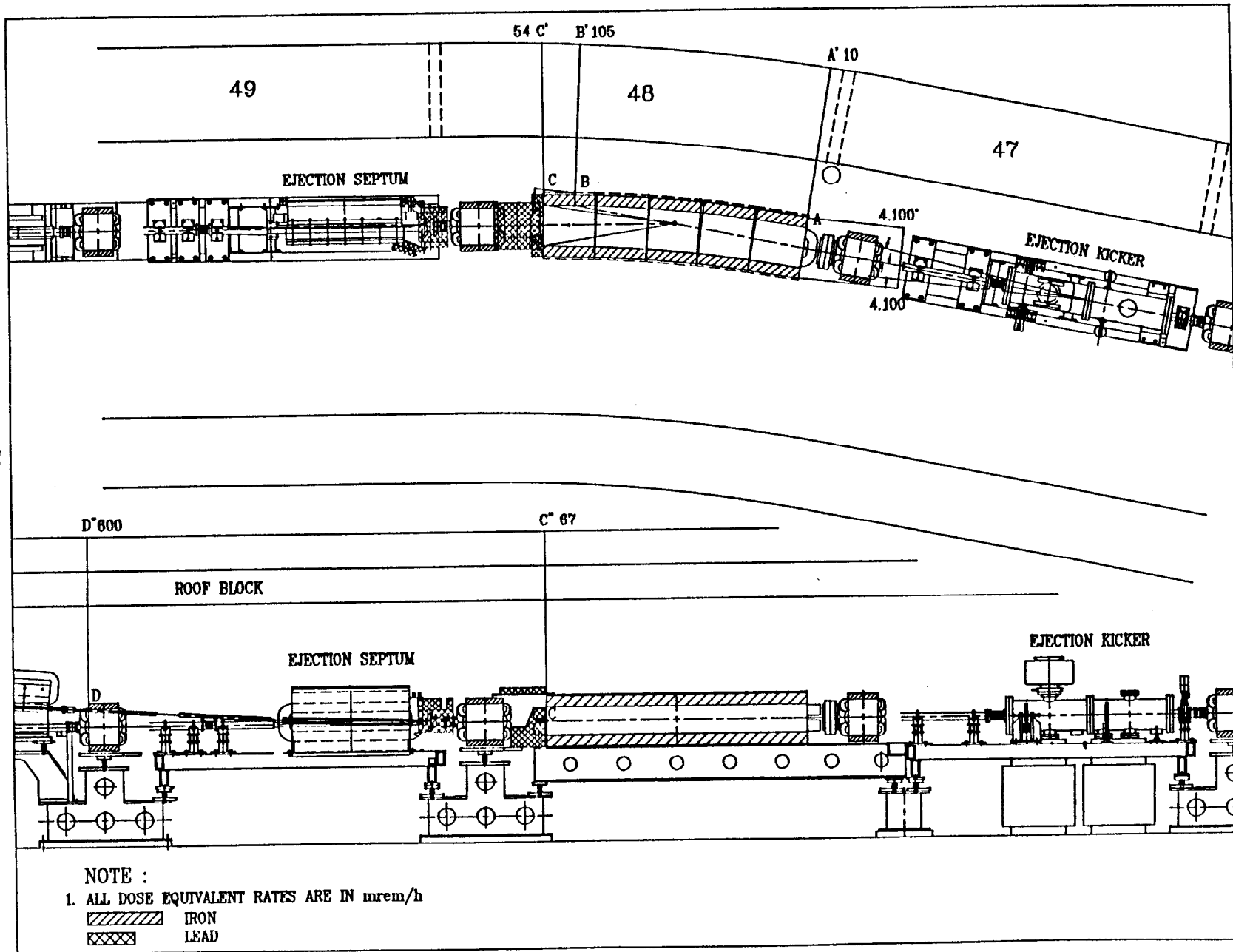


Figure 9

4-5-3 B1V

If B1V was set for 3 GeV and the ejected beam energy was 1 GeV the beam would be deflected by 2.7° and strike QIF downstream (Figure 10). At ejected energies lower than 1 GeV the beam would never reach B1V.

4-5-4 BTS - General

Along the BTS there are several sections where the beam pipe (stainless steel) is 60 mils (0.15 cm) thick. The beam can hit the beam pipe at any one of these locations due to energy mismatch or mis-steering. If the beam (14.4 watts) hits the beam pipe at an angle of 1° at E (Figure 10) the DER at E' (90°) will be 7.5 mrem/h (75 μ Sv/h) and the maximum DER will be 75 mrem/h (0.75 mSv/h) at E' (max).

The DER above the 2 foot (~61 cm) roof will be 36 mrem/h (0.36 mSv/h) at E'' (90°) and 250 mrem/h (2.5 mSv/h) at E'' (max).

4-5-5 BTS Quadrupoles

The maximum angle that the quadrupole could steer a 1 GeV beam is 2.2° . Mis-steering of Q2D could cause the beam (4.8 watts) to strike BTS-B3 at F. The DER at F' would be 362 mrem/h or 3.62 mSv/h (Figure 10). The DER above the 2 foot (~61 cm) roof at F'' would be 533 mrem/h (5.33 mSv/h).

4-5-6 BTS B2-6

Lead collimators at the exit side of magnets B2 - B6 intercept any beam that is mis-steered by more than 2.2° . For mis-steered beams that miss the lead, the downstream magnets

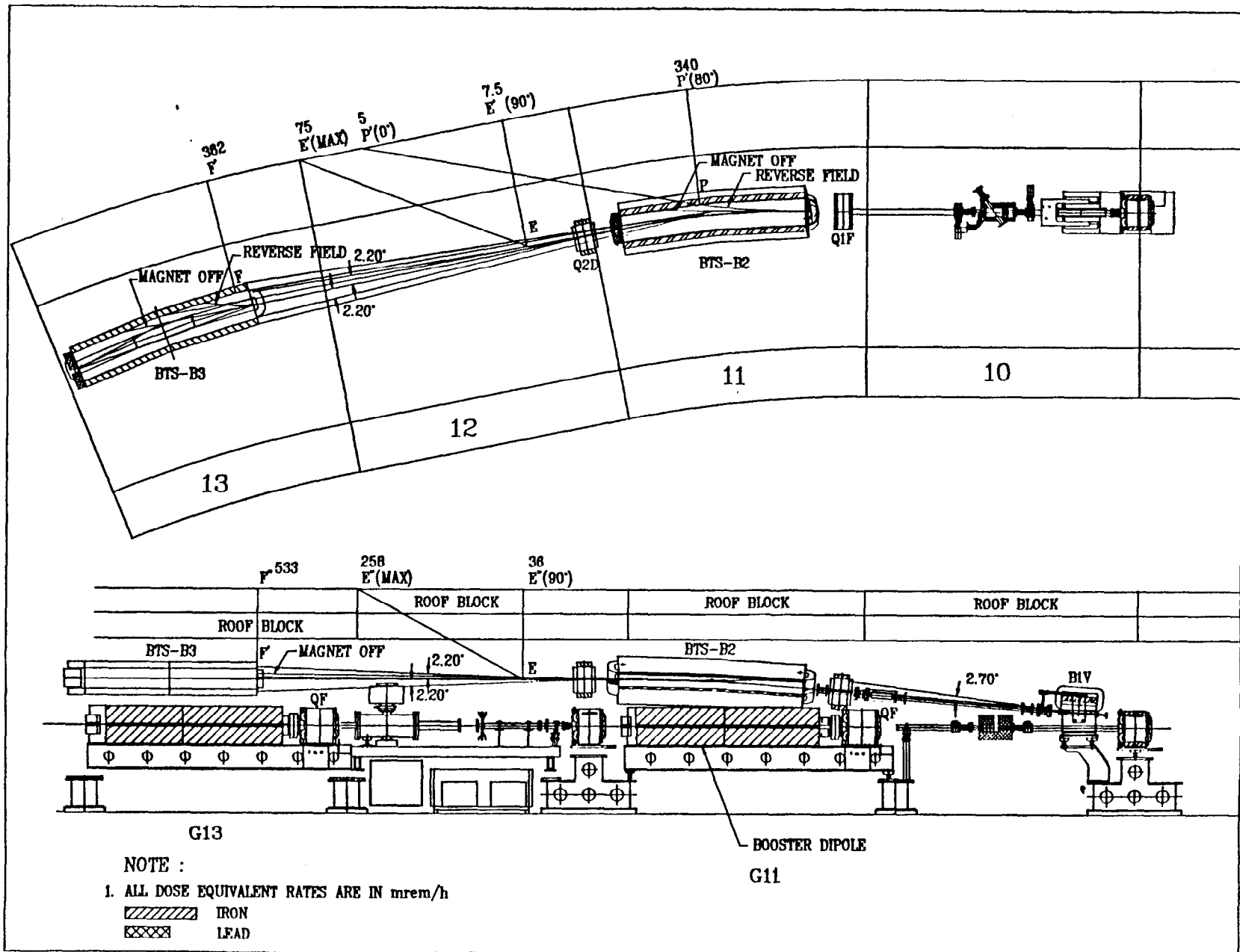


Figure 10

become the target or in the case of B6, the lead wall behind stopper 17 becomes the target.

If the beam hits the lead at the exit of magnet B6(M) the DER at M' will be 485 mrem/h (4.85 mSv/h).

If the beam hits the lead at the exit of B3H at G, the DER at G' will be 380 mrem/h or 3.8 mSv/h (Figure 11). The DER above the 2 foot (~61 cm) roof at G" will be 480 mrem/h (4.8 mSv/h).

If any of the magnets are off or in reverse polarity the beam (14.4 watts) will hit the magnet iron. The DERs produced as a result of this for some of these magnets are listed below:

B2 - reverse bend, PP' (0°), DER = 5 mrem/h (50 μ Sv/h),

Figure 10

PP' (80°), DER = 340 mrem/h (3.4 mSv/h),

Figure 10

B3 - reverse bend, HH' (0°), DER = 23 rem/h (0.23 Sv/h),

Figure 11

HH' (90°), DER = 300 mrem/h (3 mSv/h),

Figure 11

B5 - reverse bend, II', DER = 6.6 rem/h (66 mSv/h),

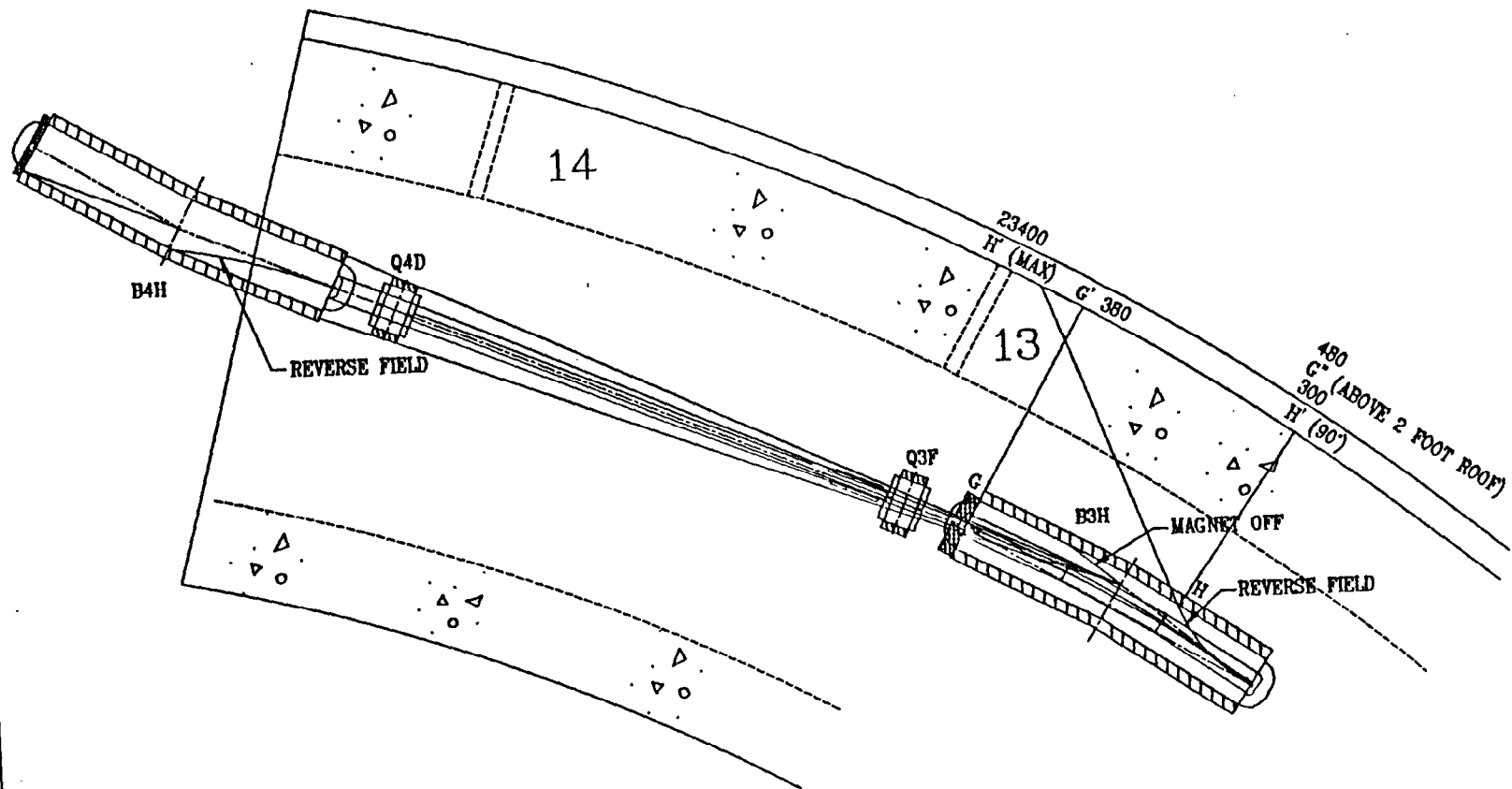
Figure 11

B5 - off, JJ', DER = 54 mrem/h (0.54 mSv/h),

Figure 12

B6 - reverse bend, KK', DER = 316 mrem/h (3.16 mSv/h),

Figure 13



NOTE :

1. ALL DOSE EQUIVALENT RATES ARE IN mrem/h

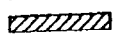

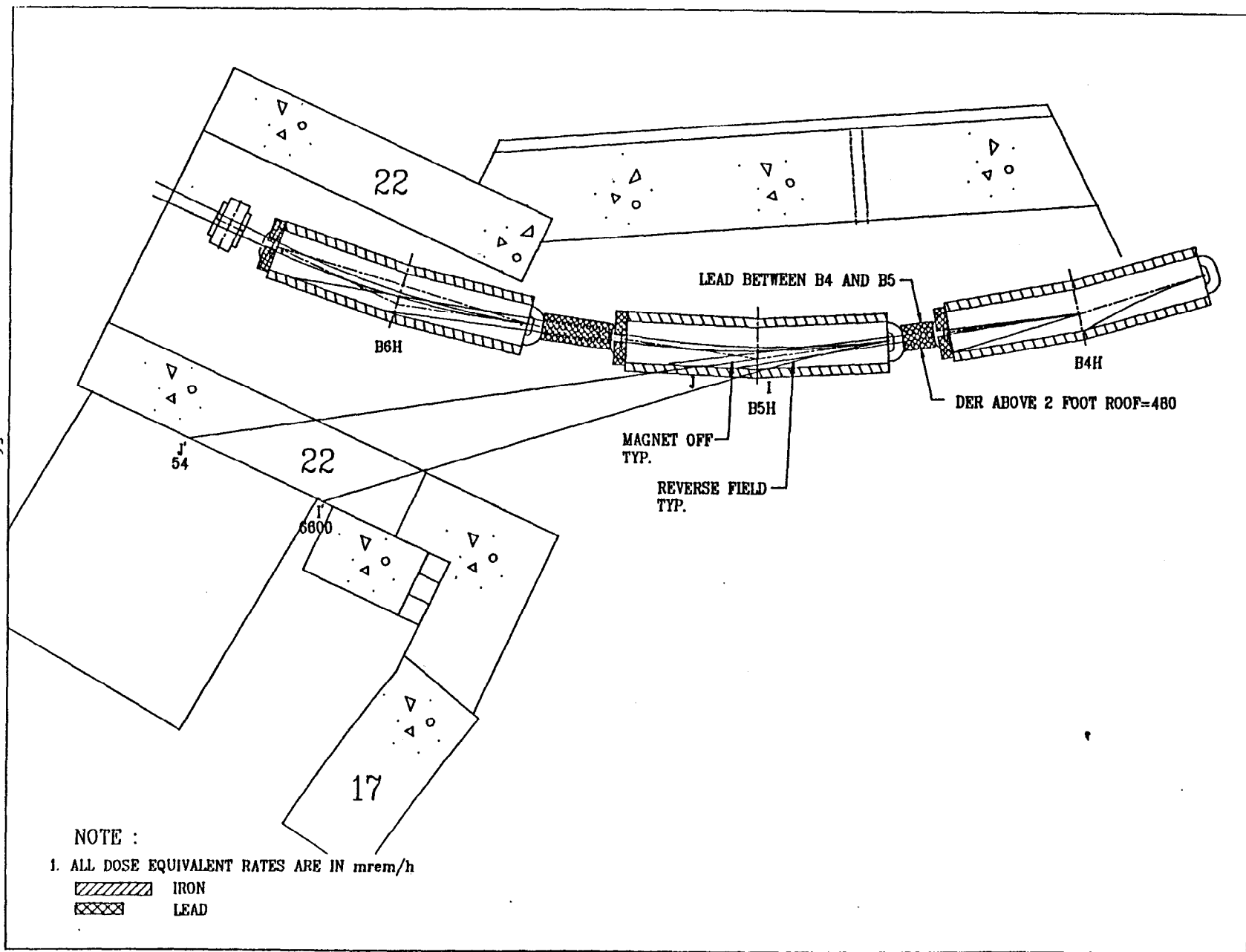
 IRON
 LEAD

Figure 11



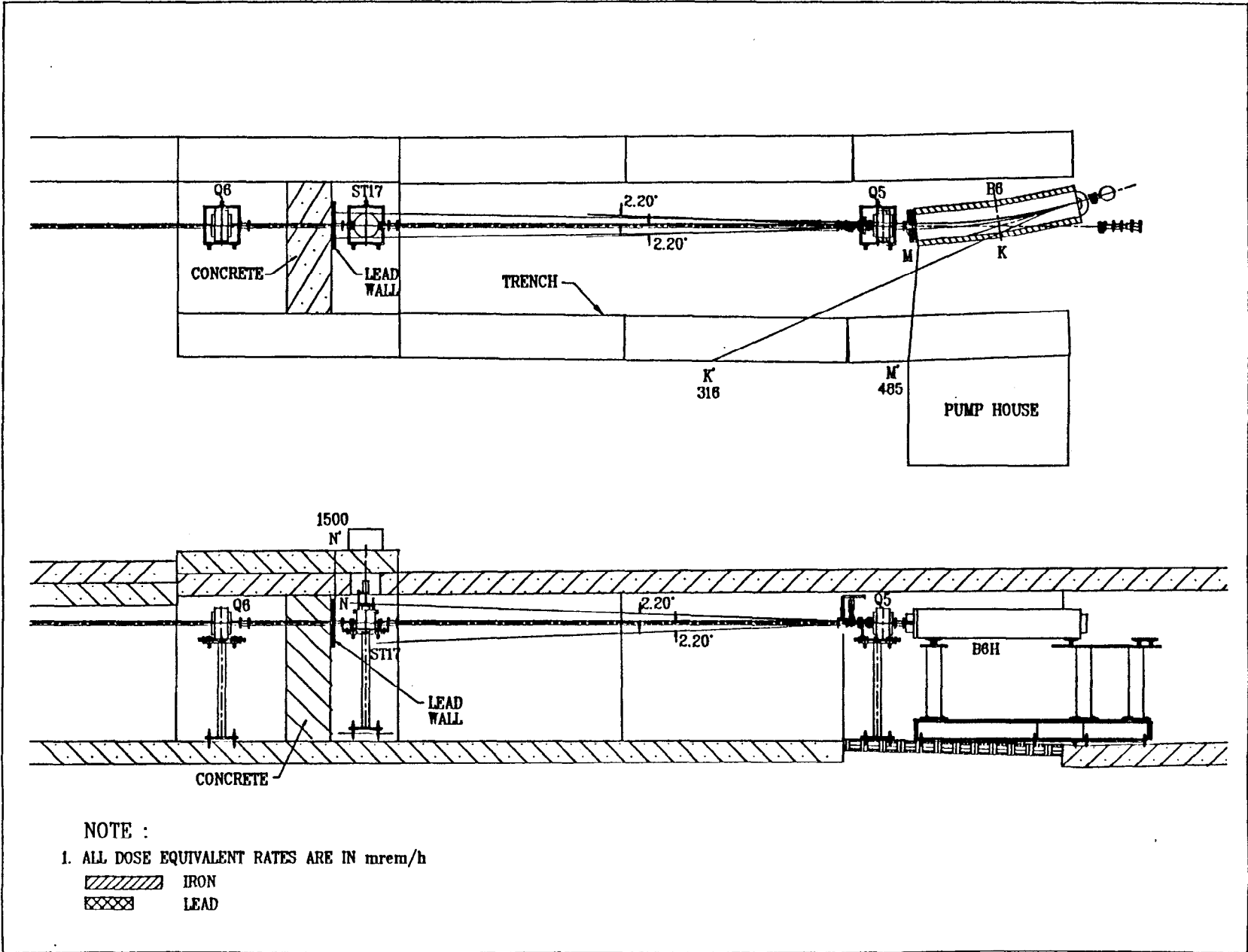


Figure 13

Magnets B2-B6 are connected in series with a solid buss. Once the magnets are connected it is extremely difficult to reconnect them. Hence the probability of these magnets being in reverse polarity is extremely small. Since these magnets are in series, if they are in reverse polarity, B2 being the first magnet in the series, will cause the beam to strike the magnet at P. The DER is only 340 mrem/h (3.4 mSv/h) at P' in this case. Hence if only B3 or B5 were in reverse polarity this could be considered an "accident" and the DER should be less than 25 rem/h in either of these cases. This criterion has been met. If the beam (14.4 watts) hits the lead between magnets B4 and B5 or B5 and B6, the DER above the 2 foot (~ 61 cm) concrete roof will be about 480 mrem/h or 4.8 mSv/h (Figure 12). A BSOIC, S20, has been placed on the roof in this area to detect losses in the BTS line (Figure 17). This BSOIC is set to trip at 50 mR/h (DR = 0.5 mGy/h). If the beam hits the lead at K at the exit of magnet B6, the DER at K' will be 316 mrem/h or 3.16 mSv/h (Figure 13). If the beam hits the beam pipe between B6 and ST-17, the levels are slightly higher than the DER at E' and E" (Figure 10) since the beam pipe is closer to the roof in this case.

While the booster is operating the PPS system allows access in SPEAR as long as the 3 BTS stoppers are in place. This means that the ejection septum and magnets B2-B6 should be off while the stopper (ST-17) is in the "IN" position. The nearest point of access is barrier gate E (Figure 14). A failure in the BTS transport system could result in the septum and magnets B2-B6 being "ON" when they are supposed to be "OFF". For radiation protection purposes the maximum dose equivalent rate in the nearest occupiable area should be less than 25 rem/h (0.25 Sv/h) when two out of three PPS stoppers fail. If the septum and B2-B6 were "ON" the beam would hit ST-17, in which case the DER at barrier gate E should be less than 25 rem/h (0.25 Sv/h). ST-17 was designed to keep the DER at barrier gate E below 25 rem/h (0.25 Sv/h), for a beam of 50 watts⁽²⁸⁾, because the initial beam loss scenarios were based on a maximum intensity of 1×10^{11} e⁻/sec from the linac. The maximum intensity in the linac, however, is limited to 3.1×10^{10} e⁻/sec.

ST-17 consists of 5.44 inches (9.6 X₀) of copper and 2 inches (14.5 X₀) of tungsten⁽²⁹⁾. Assuming a target of length 9.6 X₀ of copper and 14.5 X₀ of tungsten the DER in the forward direction at barrier gate E (at a distance ~ 9.5 m) is less than 11 rem/h (0.11 Sv/h) for 14.4 watts (using SHIELD11)⁽²¹⁾.

In the event that the magnets are "ON" and the beam is being badly mis-steered the beam could hit the lead (4 inches or 10.16 cm thick) mounted behind ST-17. The DER at O will be 4 rem/h or 40 mSv/h (14.4 watts) If the beam hits the lead at N, the DER at N' (above the 2-foot, or ~61 cm, concrete roof) will be 1.5 rem/h (15 mSv/h) (Figure 13). A BSOIC, S7, (Figure 17) has been placed in this location and is set to trip at 50 mR/h (DR = 0.5 mGy/h).

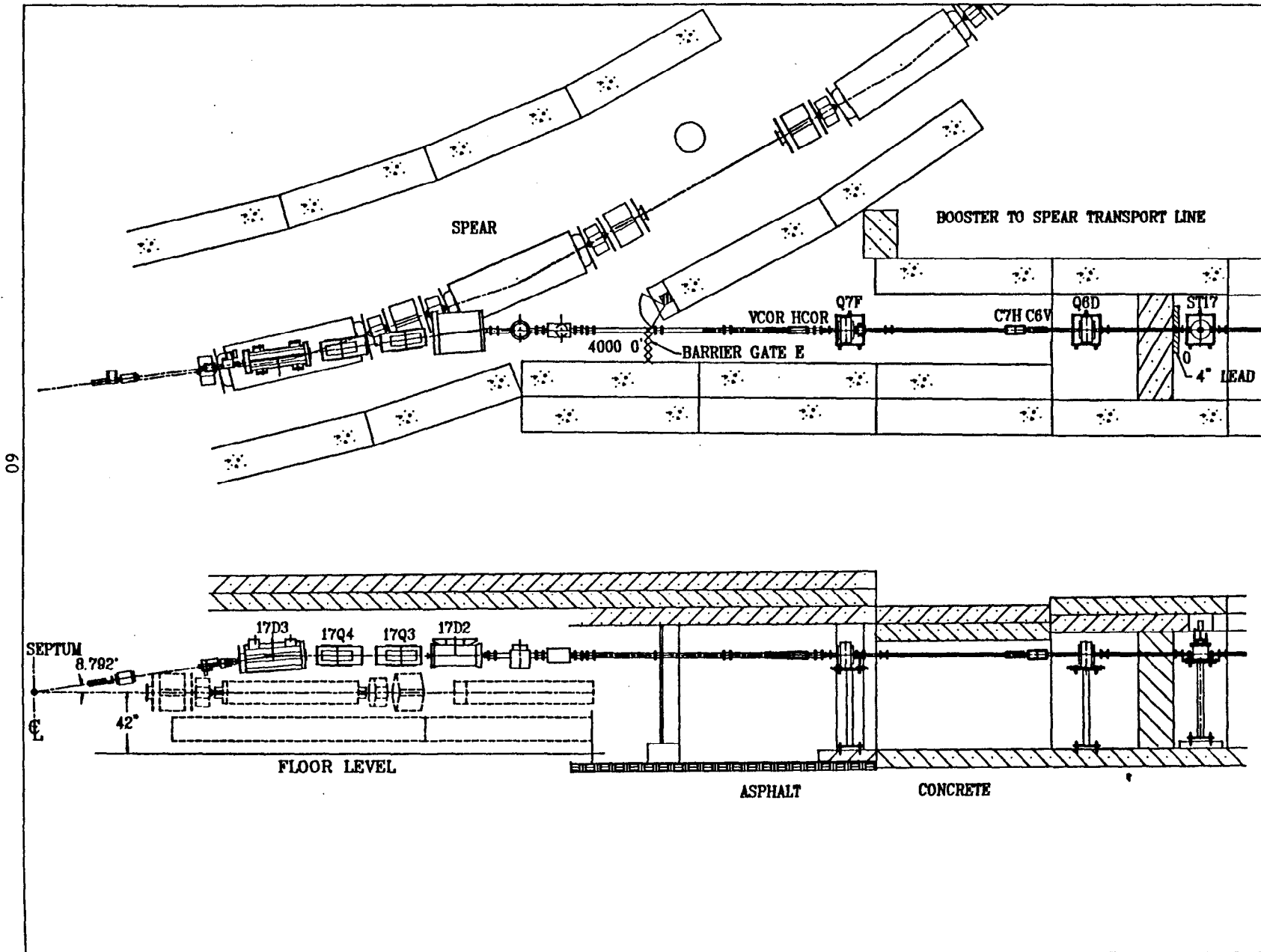


Figure 14

When the booster is not injecting into SPEAR, the beam from the linac is parked in the diagnostic room Faraday cup or is allowed to be lost over several thousands of turns in the booster, by turning the ejection kicker off⁽⁷⁹⁾. In the latter case, since the losses are distributed around the ring, the radiation levels outside the shielding are much lower than losing the entire beam locally.

4-6 SHIELDING OF PENETRATIONS AND THIN SPOTS

All penetrations and thin spots in the enclosures of the linac and booster have been supplemented with additional shielding. These shielding items are checked off on the BAS (Section 8).

4-6-1 Linac

All waveguide penetrations on the linac roof have been covered with lead bricks, so that the gaps between the waveguides and the roof are minimized.

The gap between the roof and wall blocks of the linac has been filled with concrete blocks and lead bricks.

All cable holes in the walls of the linac housing have been filled with lead wool. Cracks between the rolling doors and the walls for both the linac and diagnostic room have been filled with lead.

4-6-2 Booster

The shielding at the intersection of the booster tunnel and BL-17 (Barrier A in Figure 3) consists of 4 inches (10.16 cm) of lead followed by 20 inches (~51 cm) of concrete. This combination is about the equivalent of 29.5 inches (~75 cm) of concrete (thickness of outer wall)⁽³⁰⁾. Barriers B, C, and E (Figure 3) are just physical barriers. Barrier D consists of 2 feet (~61 cm) of concrete.

The portions of the BL-17 beam pipe that crossed the booster tunnel (perpendicular to the booster beam pipe) have been removed and the ends have been capped with solid aluminum plugs⁽³¹⁾.

The waveguide penetrations in the booster roof (sections 27, 29 and 32) have been blocked with concrete blocks, 2 feet (~61 cm) thick. These blocks are secured in place. The opening around the waveguide (in section 30) has been blocked with a combination of plywood (1/2 inch or 1.27 cm thick) followed by lead (1/4 inch or 0.63 cm thick), followed by plywood (1/2 inch or 1.27 cm thick)⁽³²⁾. This shielding is chained and locked in place. The 6 inch (15.24 cm) wide cable penetrations (sections 18-20, 36-44) in the booster roof have been covered with 2 inches (5.08 cm) of lead, followed by fiberglass, and caulked in place⁽³³⁾. The cable penetrations (sections 10, 45, 46 and 48) are blocked with 1/2 inch (1.27 cm) thick steel plates, which are bolted and welded in place.

The cable and pipe penetrations along the outer wall have been left unfilled because the holes are very small and do not provide a line-of-sight to the beam pipe. Shield blocks (10 x 1.5 x 1 ft) have been bolted and welded into place on the booster roof over sections 26 and 28 where there are thin spots in the shielding. A concrete block chained in place has been placed on the roof of BL-17 on top of ST-17 where there is a thin spot in the shielding.

5. RADIATION MEASUREMENTS

Since the injector was constructed phase by phase, radiation measurements were made at each phase for the linac (34, 35) and booster (36, 37, 38). Based on these measurements additional shielding was specified in some cases. In addition, SSRL operators performed radiation surveys once every shift. Records of these surveys are maintained in the booster control area. Once an optimum beam (for injection into SPEAR) had been established, Radiation Physics performed a comprehensive radiation survey under both normal operating conditions and mis-steering conditions⁽³⁸⁾.

Figure 15 shows the radiation levels around the linac under normal operating conditions⁽³⁸⁾. The beam parameters for this measurement are as follows:

Linac Energy = 126 MeV

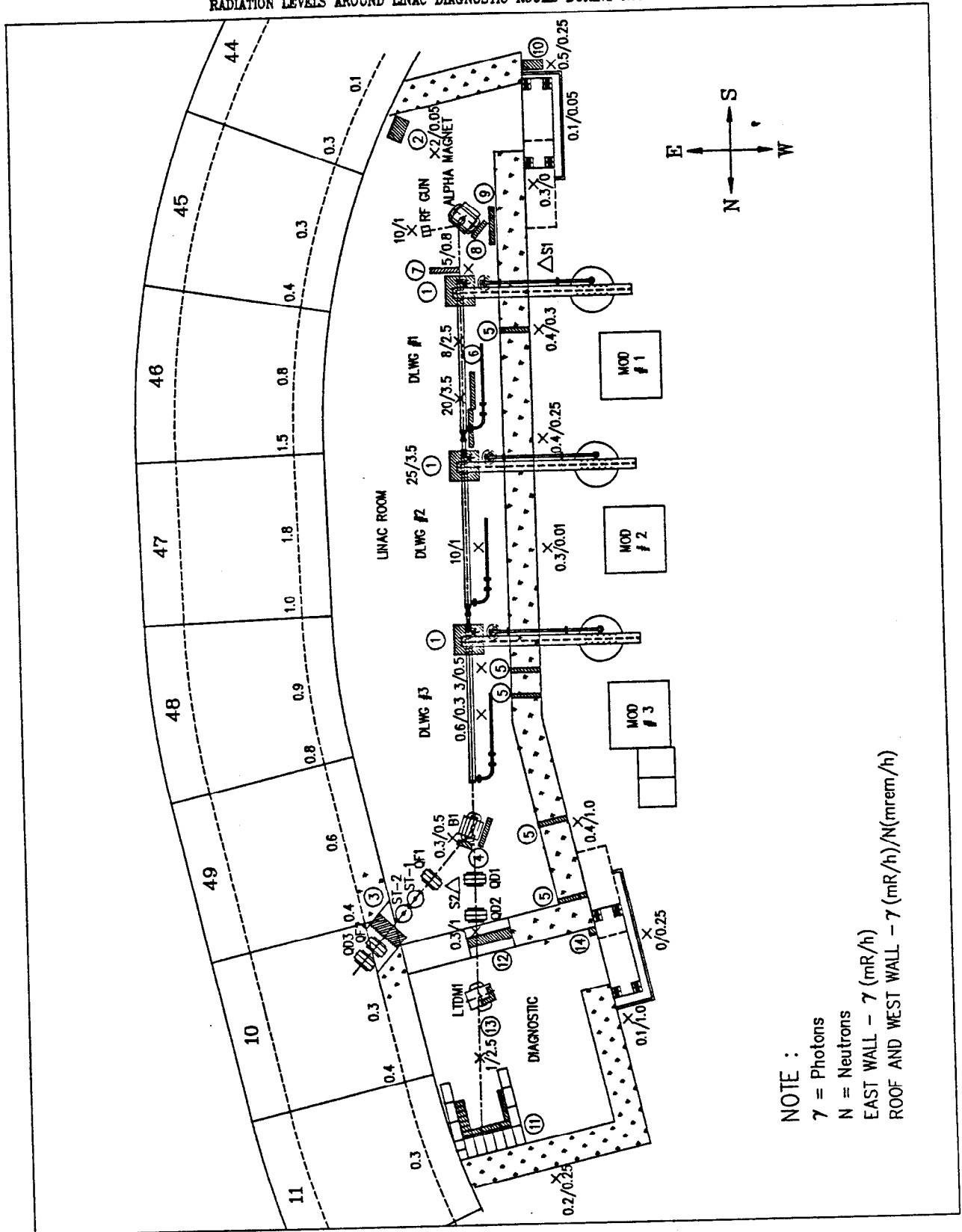
Linac Intensity = 2×10^{10} e⁻/s

The radiation levels outside the west wall range from 0.15 to 1.4 mrem/h (1.5 to 14 μ Sv/h). These measurements were made at about a few inches away from the wall. The occupiable areas are beyond the klystrons which are roped off.

Outside the east wall, in the booster tunnel, only photon measurements were made. These numbers range from 0.1 to 1.8 mR/h. Normally the booster tunnel is not occupied unless there is some maintenance work in the tunnel. The measurements on the roof range from 0.8 to about 29.5 mrem/h (8 μ Sv/h to 0.29 mSv/h). The linac roof is roped off and the access is restricted to radiation workers. The Victoreen 440 and 450P ionization survey meters were used for the photon measurements. The Victoreen 488 neutron survey meter was used for neutron measurements. This is a portable meter designed to measure neutrons below 10 MeV⁽³⁹⁾. The detector consists of a boron

Figure 15

RADIATION LEVELS AROUND LINAC DIAGNOSTIC ROOMS DURING NORMAL OPERATION



NOTE :
 7 = Photons
 N = Neutrons
 EAST WALL - 7 (mR/h)
 ROOF AND WEST WALL - 7 (mR/h)/N(mrem/h)

lined proportioned counter which is inserted into a cylindrical moderator. The moderator is only one inch thick and therefore the detector has an energy-dependent response. The reading in counts per minute was corrected to dose equivalent assuming a neutron spectrum outside the shielding with an average energy of 1 MeV.

The linac intensity is limited to 3×10^{10} e⁻/sec and the maximum linac energy is 150 MeV. Hence, the radiation levels around the linac should be scaled by a factor of

$$\frac{150}{126} \times \frac{3 \times 10^{10}}{2.3 \times 10^{10}} = 1.55$$

in order to compare the radiation measurements with the calculated values.

Figure 16 shows the radiation levels around the injector under normal operating conditions⁽³⁸⁾. The radiation levels in most areas around the booster were less than 0.5 mrem/h (5 μSv/h). Only radiation levels greater than 0.5 mrem/h (5 μSv/h) are shown in Figure 16.

The radiation levels around the booster should be scaled by

$$\frac{3}{2.3} \times \frac{3 \times 10^{10}}{2.3 \times 10^{10}} = 1.70$$

in order to compare them with calculated values, except at injection where the energy is 150 MeV. Table 7 summarizes the radiation measurement performed under various beam conditions. The maximum radiation levels for each condition are listed in the table. The first condition is the normal operating condition. The other conditions are cases of mis-steering. In general, the radiation levels around the booster during normal operating conditions are less than 5 mrem/h or 50 μSv/h (design

Figure 16
 RADIATION MEASUREMENTS AROUND THE INJECTOR UNDER NORMAL OPERATING CONDITIONS

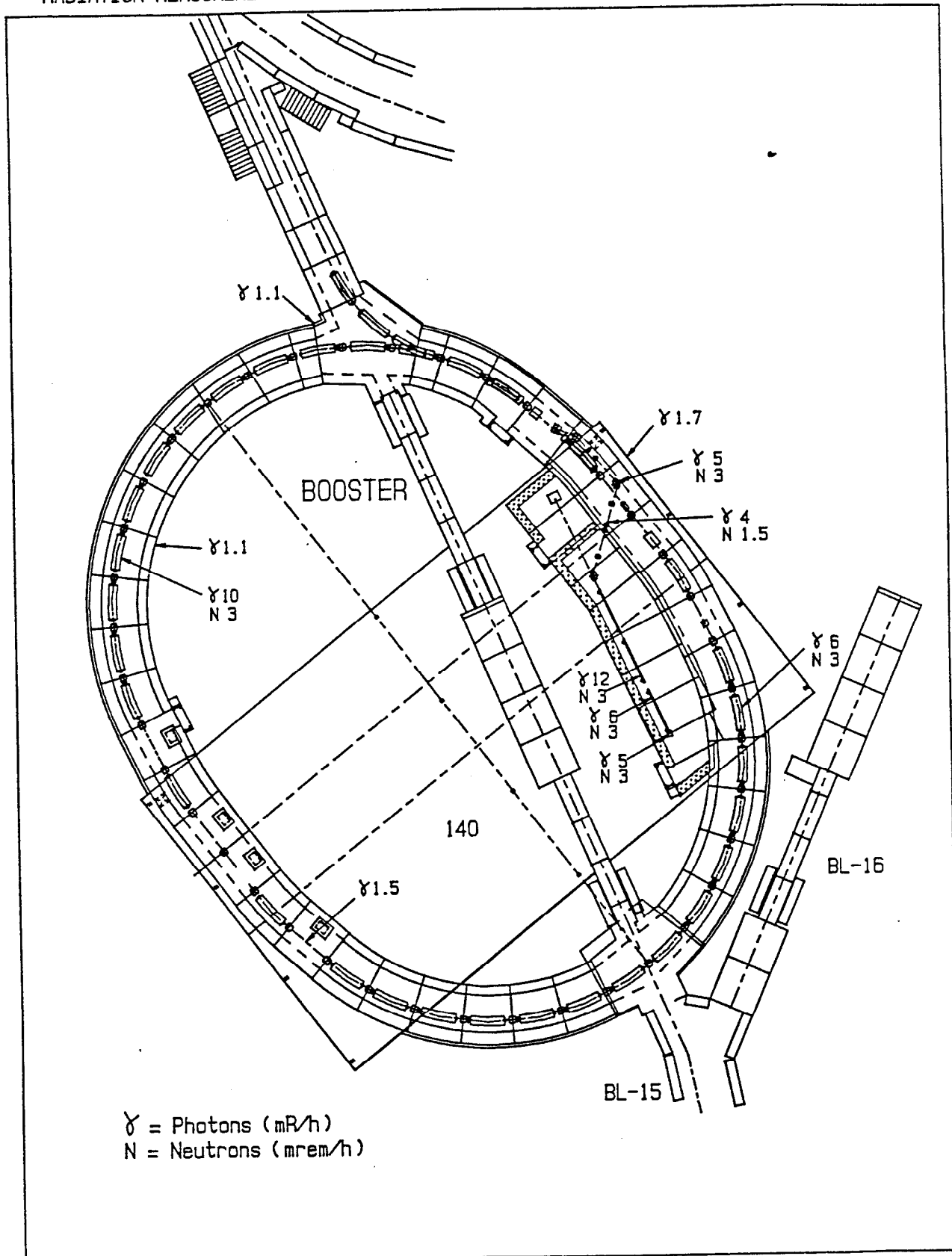


TABLE 7

Radiation Measurements For Booster Under Different Beam Conditions
normalized to a Linac intensity of 2×10^{10} e/s

Beam Condition	Maximum Dose Equivalent Rate H_m (mrem/h)		Remarks
	γ	n	
Normal Operation and beam ejected to SPEAR	10	3	H_m is on roof between blocks 22 and 23. The other radiation area is on roof block 10 (~ 8 mrem/h) (All other areas < 5 mrem/h)
BTS B2 Max 800 A BTS B2 Min 300 A	26 45	- 4.5	H_m is in the inner ring of block 11. H_m is on the roof between blocks 11 and 12.
Ejection Septum Max 260 V Ejection Septum Min 100 V	13 19	4 5	H_m is on the roof block 10. H_m is between roof blocks 49 & 10.
Ejection Kicker Max 24 kV Ejection Kicker Min 0 V	20 8	4 2	H_m is between roof blocks 49 & 48. H_m is between roof blocks 49 & 10.
Injection Kicker Min 0 V	-	-	All less than 1 mrem/h.
Injection Septum Max 300 A Injection Septum Min 0 A	1.8 1	0.5 -	H_m is on roof block 12. H_m is around East Entry Gate.
LTB B2 Max 250 A LTB B2 Min 0 A	2 1	0.4 -	H_m is on the roof block 11. H_m is in the outer ring, opposite to LTB B2.

Note: The energy is 126 MeV for the Linac and 2.3 GeV for the Booster.

level = 8 mrem/h or 80 μ Sv/h at 3 GeV and 3.1×10^{10} e^-/s). Higher levels were allowed on the roof and the highest levels observed were 13 rem/h (0.13 mSv/h). Since then local shielding consisting of 2 inches of lead has reduced the photon component to 2 mR/h (DR = 20 μ Gy/h).

Under conditions of mis-steering the maximum levels observed were below 50 mrem/h (0.5 mSv/h). These levels were measured on the roof. There is good agreement between these radiation measurements under normal operating conditions and those performed by operations once every shift.

The Victoreen 450P pressurized ionization survey meter was used for the photon measurements and the SLAC neutron remmeter was used for the neutron measurements. The SLAC remmeter is similar to the commercially available SNOOPY remmeter⁽³⁹⁾ and is calibrated to read the dose equivalent directly. The energy response of the remmeter is very similar to the Anderson-Braun remmeter. The Radiation Physics Department is currently analyzing the data from the measurements and will eventually provide a document which compares the measured values to the calculated ones.

6. THE PERSONNEL PROTECTION SYSTEM/BEAM CONTAINMENT SYSTEMS

While the machine is operating the radiation levels inside the beam housing can be extremely high. For instance, if 14.4 watts at 3 GeV were to be lost in an iron target of radius and length, 2 inches (5.08 cm), the DER at 90°, at 2 inches (5.08 cm) from the target would be 1.4×10^4 rem/h (140 Sv/h). The DER at 0° at 2 inches (5.08 cm) from the target will be 1.4×10^8 rem/h (1.4×10^6 Sv/h). An acute whole body dose of about 450-500 rads (4.5 - 5 Gy) could be fatal to about fifty percent of the persons exposed. Fatalities could occur within thirty days.)

In addition to shielding, the personnel protection system (PPS) and beam containment system (BCS) protect people from radiation exposure. The PPS and BCS for the injector are described in reference 40.

6-1 THE PERSONNEL PROTECTION SYSTEM (PPS)

The PPS consists mainly of an access control system which prevents accidental or unauthorized entry into the beam housing. This includes the following elements⁽⁴¹⁾:

PPS security perimeter, entry modules, annunuator/status panels, warning lights, emergency off buttons, flashing lights and audible warning, search controls, and stoppers.

The PPS design includes complete redundancy, high reliability components and fail-safe circuits.

6-1-1 PPS Security Perimeter

This is essentially an enclosure for the beam delivery area and includes shielding. All moveable shielding blocks are interlocked.

6-1-2 Entry Modules

These are remotely controlled entry facilities into a PPS area. An entry module consists typically of two interlocked and remotely controlled doors or gates. These doors or gates have emergency exit functions, local door controls, controlled keybank, and audio and video communication with the injector control console area. There are four entry modules for the injector, one each at the entrance to the linac and diagnostic room, one each at the east and west access to the booster (Figure 3).

6-1-3 Annunerator/Status Panels

These are display panels usually located at the entry module that show local PPS access status and other status information.

6-1-4 Warning Lights

Warning lights are also located at the entry modules and indicate the status of the beam as follows:

Yellow - no beam, but possible residual radiation levels
Steady Magenta - beam ready to operate
Flashing Magenta - beam on

The implications of the status lights are as follows⁽⁴²⁾:

Linac/Diagnostic Rooms

Yellow = Linac modulators 1, 2 and 3 high voltage and triggers off.

Steady Magenta = Modulator 1 and/or 3 on.

Flashing Magenta = Modulator 2 on.

Booster

Yellow = Booster ring RF off and LTB stoppers in or linac RF off.

Steady Magenta = Booster ring RF permitted but not on and LTB stoppers in or linac RF off.

Flashing Magenta = LTB stoppers off or booster ring RF on.

Warning lights are also located on top of the linac roof and on top of the booster roof to indicate the status of the beam.

6-1-5 Emergency Off Buttons

These are wall mounted redundant switches which are primarily used if one finds oneself in an area which is ready for beam. Activating the emergency off button will turn the beam off, or inhibit the beam from turning on. Emergency off buttons are also located in SPEAR, booster and linac control areas, to turn the beam off in case of an emergency.

6-1-6 Flashing Lights and Audible Warning

These are used to indicate that an area is ready to beam.

6-1-7 Search Controls

All areas have to be searched prior to delivering a beam. Search controls are located throughout the beam housing so as to require a prescribed search route by the search team.

Stoppers are devices which absorb beam power for short periods of time, or change direction of beam delivery when required. The LTB stoppers are magnets B1 and stoppers, ST-1 and ST-2. The LTB stoppers are required to be "IN" and the booster RF "OFF" when the booster is in permitted, controlled or restricted access. Stoppers St-1 and ST-2 are equipped with disaster monitors. However, these disaster monitors are not connected to the PPS.

The BTS stoppers are the ejection septum, magnets B2-B6 and a stopper ST-17. The BTS stoppers are required to be "IN" when SPEAR is in a permitted, controlled or restricted access. Stopper ST-17 is equipped with a disaster monitor which is interlocked to the PPS. A burn-through detected by the disaster monitor will put the LTB stoppers in and turn the booster RF off. All stoppers are PPS interlocked.

6-2 THE BEAM CONTAINMENT SYSTEM (BCS)

The BCS has two major components:

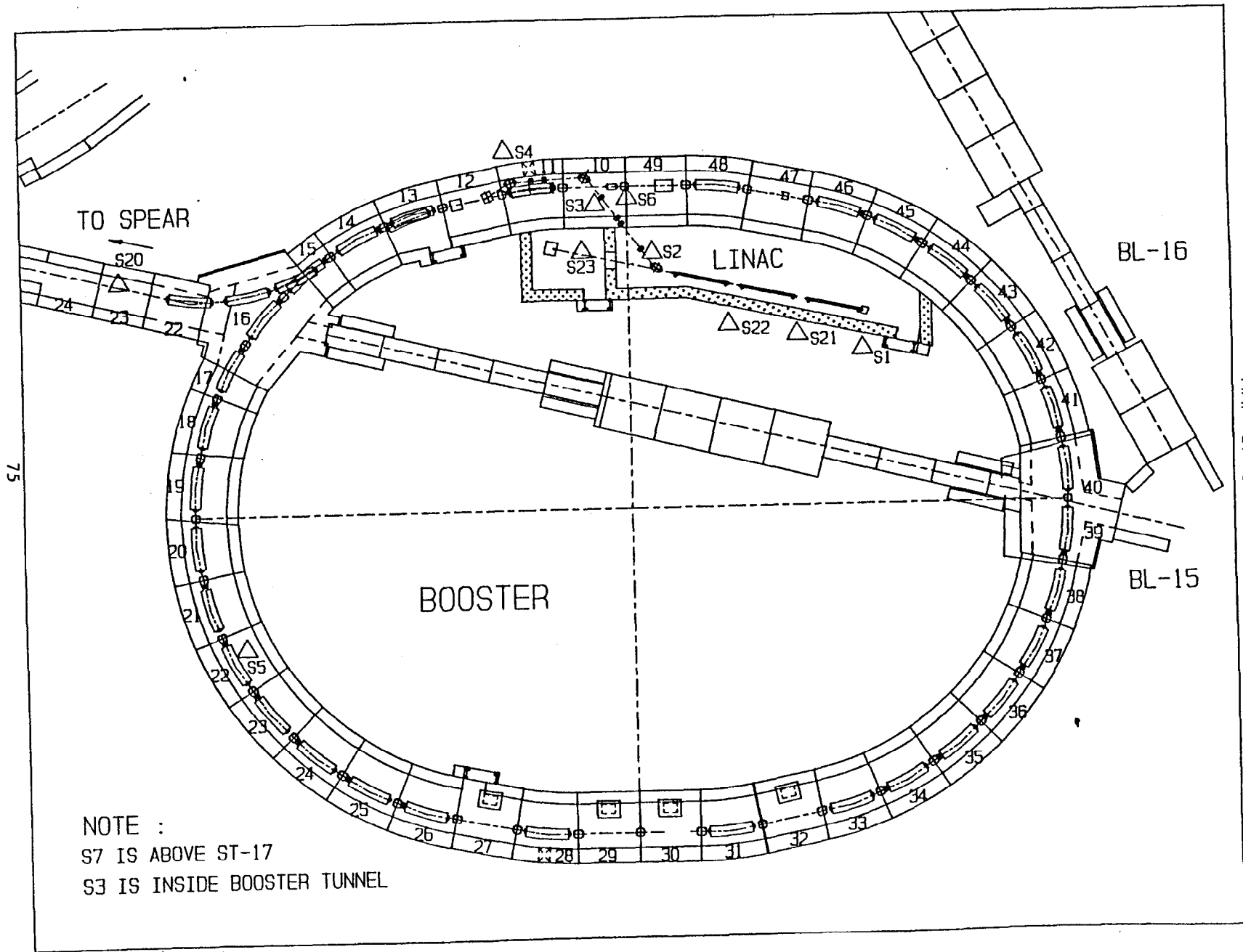
- 1) Beam containment devices limit the current.
- 2) Beam Shut-Off Ionization Chambers (BSOICS) prevent excessive beam loss by detecting radiation in occupied areas.

6-2-1 Beam Containment Devices

There are three beam containment devices in the linac, a beam chopper and two average current toroids, which limit the electron intensity into the booster to 3.1×10^{10} e⁻/sec. The beam chopper is interlocked such that if the high voltage pulse applied to the chopper is too high, the RF power to the three linac sections is removed by interrupting trigger signals to the linac modulators and RF amplifiers⁽⁴⁰⁾. A trip caused by excessive current through either toroid will also turn the beam off in the same way. As stated in section 4-1-2, the addition of a third toroid has been proposed.

6-2-2 Beam Shut Off Ionization Chambers (BSOICS)

Beam Shut Off Ionization Chambers (BSOICS) are interlocked such that if radiation levels exceed a pre-set level the beam is turned off. BSOICS have been placed at strategic locations (Figure 17) where beam losses are expected, either due to normal operating conditions, cases of mis-steering, or failure of PPS stoppers or BCS devices. The BSOICS S1-S3, and S21-S23 trip the beam by turning off the klystron high voltage power supply and removing the triggers to the modulators. BSOICS S4-S7 and S20-S23 trip the beam by removing triggers to the modulators and removing the low level RF drive to the modulators.



NOTE :
 S7 IS ABOVE ST-17
 S3 IS INSIDE BOOSTER TUNNEL

Figure 17
 MAP OF BSOICS

75

Table 8 summarizes the BSOIC locations, trip level and trip mechanism. All BSOICS are set to produce an alarm if radiation levels exceed 10 mR/h (DR = 0.1 mGy/h) and in most cases (except S1, S3 and S21-S23) turn the beam off if radiation levels exceed 50 mR/h (DR = 0.5 mGy/h). All BSOIC faults are latched and can be reset locally or via the injector computer. BSOICs turn the beam off within 50-100 milliseconds depending upon the relay system used.

A BSOIC consists of an ionization chamber and a three decade electrometer (1 mR/h to 1R/h) enclosed in a weather-tight container⁽⁴³⁾. The aluminum-walled ionization chamber is filled with ethane at 1 atmosphere. The volume of the chamber is 10 liters. A small ⁹⁰Sr source, mounted inside the chamber provides a constant current to the electrometer, this acting as a continuous internal check. Because of this the BSOIC will always show a readout of 1-3 mR/h. Unplugging the BSOICs will result in a beam trip.

The ethane in the chamber enhances the response to fast neutrons. The BSOIC responds on an equal dose basis to both photons and neutrons. However, on a dose-equivalent basis the neutron response is about 10% to 30% of the photon response depending upon the incident neutron spectrum⁽³⁹⁾.

TABLE 8

BSOIC #	LOCATION	TRIP LEVEL	TRIP MECHANISM
S1	Outside linac west wall by modulator #1	10 mR/h	a) Removes triggers to modulators b) Turns off klystron high voltage
S2	On linac roof downstream of LTBB1	50 mR/h	Same as S1
S3	Inside booster tunnel adjacent to LTB Line	10 mR/h	Same as S1 (Bypassed when booster tunnel is in "No Access")
S4	East wall	50 mR/h	a) Removes triggers to modulators b) Removes low level RF drive to modulators
S5	North arc, between booster roof blocks 22 and 23	50 mR/h	Same as S4
S6	Between booster roof blocks 10 and 49	50 mR/h	Same as S4
S7	Above ST-17 on on roof block 25	50 mR/h	Same as S4
S20	Roof of BTS Section	50 mR/h	Same as S4
S21	Outside linac west wall by modulator #2	10 mR/h	Same as S1
S22	Outside linac west wall by modulator #3	10 mR/h	Same as S1
S23	On diagnostic roof above LTD beamline downstream of LTDM1	50 mR/h	Same as S1

7. AREA MONITORING

Area monitors consisting of bare and moderated thermoluminescent dosimeters have been placed at strategic locations around the injector, where beam losses are expected and in areas which are occupiable. The thermoluminescent dosimeters used at SLAC are lithium fluoride (LiF) phosphors. When these phosphors are irradiated with ionizing radiation, free electrons are transferred from the conduction band to the valence band⁽⁴⁴⁾. These electrons migrate about until they are trapped by lattice defects in the material. Free positive holes are also produced when the electrons are transferred from the valence band. These free positive holes may also migrate and be trapped by lattice defects. The trapped electrons will remain in their traps as long as they are not provided with sufficient energy to escape the traps. If the material is heated, the trapped electrons may acquire sufficient energy to be released. The released electrons may then recombine with trapped holes radiating visible or ultraviolet photons. The amount of light released is a measure of the radiation dose.

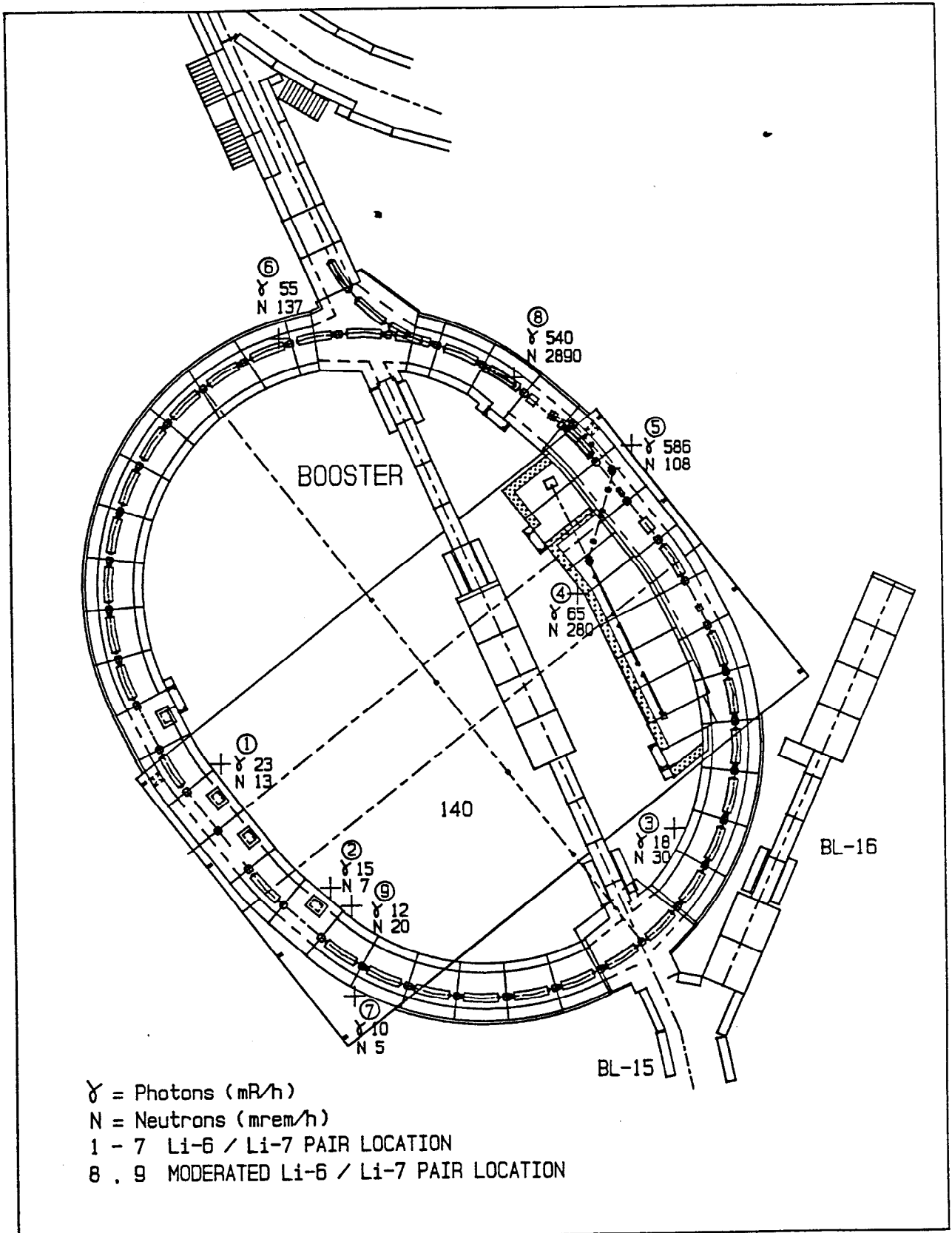
A pair of thermoluminescent dosimeters, consisting of Li-7 (99.9% Li-7) and Li-6 (96.5% Li-6) is used to determine the photon and neutron components of the dose. LiF has a photon effective atomic number Z_{eff} of 2 compared with Z_{eff} of 7.6 for tissue. For most practical applications, LiF can be considered tissue equivalent. The Li-7 responds mainly to photons while the Li-6 responds to both photons and thermal neutrons. The Li-7 and Li-6 have a similar response to photons. However, the Li-6 thermal neutron sensitivity is orders of magnitude greater than that of Li-7. Thus the Li-7 response gives a measure of the photon dose, while the difference in response between Li-6 and Li-7 gives a measure of the thermal neutron dose.

If the TLDs are moderated (surrounded by a hydrogenous material such as polyethylene), fast neutrons incident on the moderator are thermalized in the moderator and the thermal neutrons are then registered by Li-6. A cylindrical cadmium covered polyethylene moderator is used to moderate the fast neutrons⁽⁴⁵⁾. The cadmium lining absorbs the incident thermal neutrons. Thus moderated TLDs can be used to measure the fast neutron dose. The moderated TLDs have a fluence response fairly independent of energy between a few KeV and 10 MeV. Usually the photon component is much greater than the neutrons produced by the injector. Since the Li-7 reading is subtracted from the Li-6, a large number must be subtracted from the total reading. This introduces a large uncertainty and so the minimum detection limits for photons and neutrons are about 30 mrad and 40 mrem respectively.

Figure 18 shows the location of the TLDs placed around the injector and the accumulated doses (after background subtraction) for the time period of 7/30/90 to 11/30/90⁽⁴⁶⁾. Since the actual number of operating hours nor the integrated currents during this operating period are not well known, it is not possible to project future doses based on this data. However, this time period was the commissioning period, hence the normal hours of operation should be much less than that during this time period. Area monitoring at the injector will continue and area monitors will be read out at the end of each run.

Figure 18

RESULTS OF AREA MONITORING. 7/30/90 - 11/30/90



8. BEAM AUTHORIZATION SHEETS/ADMINISTRATIVE
CONTROLS AND PROCEDURES

8-1 BEAM AUTHORIZATION SHEETS

In order to ensure radiation safety at the injector, authorization sheets, administrative controls and procedures are used. The SLAC Radiation Physics Department (RPD) and the Accelerator Department Safety Office (ADSO) jointly issue Beam Authorization Sheets (BAS) for operation of the injector. A separate BAS is issued for both the linac and the booster. The BAS specifies the time period and the experiments for which the authorization is valid. Only the specific individuals from RPD and ADSO, listed on the front page of the BAS, can issue and approve the BAS. The BAS becomes official only when these individuals sign the front page of the BAS. The official copy of the BAS is located at the injector. Copies of the BAS are kept by RPD, SPEAR, Operational Health Physics (OHP) and Main Control Center (M.C.C.).

Only the official copy is signed by individuals from RPD and ADSO, and initialled by operators. The operators for the injector have been approved by the SSRL Accelerator Research and Operations Division (AROD). The names of these individuals appear in the relevant appendices of the SLAC Radiation Rule Book (47).

The BAS consists of check-off boxes, changes or additions, running conditions, initial checkout, pre-running conditions, and verification of safety checklist completion. The operators initial the check-off boxes when they come in on shift, thus acknowledging that they have read the BAS, are familiar with its contents, and that all running conditions have been met. The operators are required to read the "changes or additions" page daily.

If changes or additions are needed (such as extension of time, changes in operating conditions, additional administrative controls), the individuals from RPD and ADSO must agree on the change. This agreement may be reached by phone. The change or addition is then entered on the relevant page of the BAS, dated and initialed by RPD, ADSO and the operator. The change or addition is not valid until all three individuals have initialed the respective columns.

The running conditions list all conditions which need to be in effect while the machine is operating. The operators are responsible for ensuring that all running conditions have been met.

The initial check-out items include special check-out items which need to be carried out when the machine is first turned on. These items are usually completed and signed off when the machine is first turned on. An example of an initial check-out item would be the radiation measurements performed by Radiation Physics to check the integrity of the shielding, when the beam is first delivered.

Pre-running conditions include all the requirements that need to be met prior to first operating the machine. This includes shielding items, areas being roped off, posting of warning signs, calibration and check-out of BSOICS and PPS certification.

In addition, whenever the booster has been in the "Permitted Access" state, operators are required to fill out a safety checklist prior to beam operation which includes critical shielding items. The operators are then required to initial a page in the BAS entitled "Verification of Safety Checklist Completion."

8-2 PROCEDURES

All areas have to be searched prior to beam delivery. Operators follow written search procedures. These procedures are written, and maintained, by the SSRL Accelerator Research and Operations Division. Copies of search procedures for the linac and booster can be found in the SLAC Radiation Safety Procedures Manual (48).

9. OPERATOR TRAINING

The SSRL AROD is responsible for approving individuals as operators and providing the necessary training. The SLAC Radiation Rule Book requires that an operator must be a radiation worker. DOE Order 5480.11 defines a radiation worker as follows:

"An occupational worker whose job assignment requires work on, with, or in proximity of radiation producing machines or radioactive materials, and/or who has the potential of being routinely exposed above 0.1 rem (0.001 sievert) per year, which is the sum of the annual effective dose equivalent from external irradiation and the committed dose equivalent from internal radiation."

At SLAC, radiation workers are badged on a quarterly basis and are required to undergo Radiation Worker Training (RWT). This training is provided by the Operational Health Physics Group (OHP). Individuals are required to take a test at the end of the training. Upon successful completion of the training, the individual receives a certificate of completion and is then eligible to receive a quarterly badge.

In addition to being radiation workers, the Radiation Rule Book also requires that the operator must be certified by the Radiation Safety Officer (or his designate) as being familiar with the radiation rules. This certification includes testing of the individual's knowledge of the SLAC Radiation Rulebook (except items that are SLAC-specific and hence not related to SSRL). This testing is done by a member of the Radiation Physics Department (RPD). The RPD notifies the SSRL AROD once the individual has successfully completed this certification. The individual's name is then listed in Appendix A-1 of the

Radiation Rule Book. The SSRL AROD maintains an injector operator qualifications checklist for radiation safety which includes:

1. Radiation Worker Training
2. Survey Meter Training
3. Search Procedure Training (Linac and Booster)
4. Radiation Survey Training (Linac and Booster)
5. BAS Orientation (Linac and Booster)
6. Injector PPS Training
7. Operator Radiation Certification.

A description of each item on this list can be found in the SSRL Injector Operator Qualification Checklist. Each of these items are signed off and dated by the responsible person after completion of training on the checklist. Upon completion of the injector operator qualification program (this includes items besides radiation safety), the AROD notifies Radiation Physics and the individual's name then appears in Appendix E/F in the SLAC Radiation Rule Book.

10. PERSONNEL DOSIMETRY

Initially all workers in the immediate vicinity of the injector were classified as radiation workers. The DOE annual limit for radiation workers is 5 rem (50 mSv), however the SLAC internal guideline is 1.5 rem (15 mSv). The DOE annual limit for non-radiation workers is 100 mrem/y (0.1 mSv/y). The SLAC OHP group provides the dosimetry service for SSRL. The personnel dosimeters are typically carried in the wallet or worn somewhere on the upper torso. Pairs of TLDs composed of Li-7 and Li-6 teflon loaded discs are wrapped in black plastic (to protect them from light) and sealed in a plastic badge holder. The badge indicates the name, social security number, group number, and mail stop of the individual. In addition, the date of the badge exchange and level of training, RWT (Radiation Worker Training) or GET (General Employee Training) are indicated on the badge. Since radiation workers are badged on a quarterly basis, their badge is marked with a "Q". Annual badge holders at SSRL have badges marked with an "S".

As described in section 7, the Li-7 detects photons and the Li-6 detects photons and thermal neutrons. Thus the responses of the Li-7 is a measure of the photon dose while the difference in response between the Li-7 and Li-6 is a measure of the thermal neutron dose. In order to obtain the fast neutron dose equivalent, the assumption is made that there is a correlation between thermal neutron fluences and fast neutron fluences in the immediate vicinity of the injector. Based on measurements at locations 8 and 9 (Figure 18) the ratio of the fast to the thermal neutrons ranges from 2.2 - 2.7⁽⁴⁹⁾. This would correspond to a fast neutron sensitivity of 3.4 - 6 mV/mrem. However at SLAC, a conservative value of 1 mV/mrem⁽⁴⁵⁾ has been used. This same level of conservatism is also used for determining the neutron dose equivalent for the

SSRL personnel. The personnel dosimetry records for the last two quarters of 1990 and the first quarter of 1991, indicate that out of the 62 radiation workers, only 15 had a positive dose equivalent (i.e. above background). The cumulative dose equivalent for three quarters was less than 100 millirem (1 mSv) for each of these 15 workers. However, since the actual number of operating hours and the integrated current for this time period are not known, it is not possible to correlate these doses with beam operating parameters, or to project doses for future operation. Future personnel doses will be monitored and correlated with beam operating conditions.

11. MUONS

Muon pair production (μ^+ , μ^-) by photons becomes possible at energies greater than about 211 MeV (2×105.66 MeV)⁽⁵⁾. This process is very similar to the electron positron pair production, except that the cross-sections scale by the ratio of the particle masses [$(m_e/m_\mu)^2 = 40,000$]. Thus the cross-section for muon pair production is orders of magnitude smaller than electron-positron pair production. The dominant process is the coherent production, in which the nucleus remains intact as it recoils from the interaction of the photons with the target nucleus.

Muons are also produced during the decay of Π^\pm and K^\pm mesons (photo produced) but depending on the decay path, these fluences are much smaller than those from direct muon pair production⁽³⁾. The muon fluence is very highly peaked in the forward direction. The typical beam diameters outside thick shielding are about 10-20 cm.

Because of their large masses, muons do not readily radiate energy by bremsstrahlung except at very high energies (> 50 GeV)⁽⁵⁰⁾. Muons with energies below about 50 GeV mainly lose their energy by ionization, and hence have a fairly well-defined range associated with each energy.

For most accelerator facilities which are well shielded, muons do not pose a problem until the beam energy exceeds 1 GeV. Since the muons are very highly peaked in the forward direction, they are rarely a problem for transverse shielding. However because of their weakly interacting nature, they are a problem in the forward direction.

Under normal operating conditions, losses in the booster are distributed around the ring, unless there is an RF trip in which case the beam could be lost in the focussing quadrupoles. Since muons are strongly peaked in the forward direction, they are not of a concern for the transverse shielding of the booster.

In the event of a ring magnet trip, only one pulse could be lost at 3 GeV, the remaining pulses would be lost at 150 MeV. So, in the case of the extreme ray XX' (Figure 8), muons would not be a concern. However, in the BTS line all 10 pulses at 3 GeV could be lost. Consider the worst case scenario when the BTS magnet B3H is in reverse polarity (ray HH' in Figure 11). This ray goes through 12.7 cm of iron, 81 cm of air and 117 cm of concrete. The following two methods are used to estimate the dose equivalent rates:

METHOD 1

Using the method of Swanson⁽⁵⁾ the muon DER at 3 GeV is

$$\frac{5 \text{ rem-m}^2}{h-kw} \text{ for iron (from Figure 43, reference 5)}$$

Maximum beam power = 14.4 watts

Distance to point X' = 12.7 cm + 81 cm + 117 cm = 211 cm

Total density thickness = 12.7 cm x 7.87 g/cm² + 117 cm x 2.35 g/cm²

$$= 375 \text{ g/cm}^2$$

$$\begin{aligned} \text{Iron equivalent thickness} &= \frac{375 \text{ g/cm}^2}{7.87 \text{ g/cc}} \quad (p = 7.87 \text{ g/cc for iron}) \\ &= 47.6 \text{ cm} \end{aligned}$$

Therefore the unshielded DER is:

$$\begin{aligned} \dot{H}_u &= \frac{5 \text{ rem-m}^2}{h-kw} \times \frac{14.4 \times 10^{-3} kw}{(2.11m)^2} \times \frac{10^3 \text{ mrem}}{\text{rem}} \\ &= 16 \text{ mrem/h (0.16 mSv/h)} \end{aligned}$$

Swanson suggests the use of a correction factor (to take into account the scattering effect of an existing shield of thickness X (cm)) to be applied to the unshielded DER. Therefore, the corrected DER is:

$$\dot{H} = \left(\frac{25}{25 + X/X_0} \right) \times \left(\frac{X(E_0) - X}{X(E_0)} \right) \times \dot{H}_u$$

$X = 47.6 \text{ cm}$ (shield thickness)

$X_0(\text{Fe}) = 1.76 \text{ cm}$

$X(E_0) = 230 \text{ cm}$ (Figure 41, reference 5)

$X(E_0)$ is the maximum possible muon range at the primary energy E_0 .

$E_0 = 3 \text{ GeV.}$

The first factor in the correction accounts for multiple Coulomb scattering of muons in the shield. The second factor accounts for the fraction of muons which is stopped. This correction is usually applied in cases where the shield is very close to the target, and the distance to the point at which the DER is to be determined is much greater than the shield thickness. It must be pointed out that this is really not the case for ray XX'.

$$\begin{aligned} \dot{H} &= \left(\frac{25}{25 + 230/1.76} \right) \times \left(\frac{230-47.6}{230} \right) \times 16 \text{ mrem/h} \\ &= 2 \text{ mrem/h (20 } \mu\text{Sv/h)} \end{aligned}$$

METHOD 2

Muon 89 is a computer program used to calculate the production and transport of muons produced by a high-energy electron beam striking a beam dump. This program is based on work done by Nelson et al⁽⁵¹⁾.

Using the equivalent iron thickness of 47.6 cm the muon fluence rate is

$$\begin{aligned} & \frac{1.23 \times 10^4 \mu}{\text{cm}^2 - \text{s} - \text{kw}} \text{ at 1 m} \\ \dot{H} &= \frac{1.23 \times 10^4 \mu}{\text{cm}^2 - \text{s} - \text{kw}} \times \frac{14.4 \times 10^{-3} \text{kw}}{10 \mu/\text{cm}^2 - \text{s}} \times \frac{11 \text{ mrem/h} \times (1 \text{ m})^2}{(2.11 \text{ m})^2} \\ &= 4 \text{ mrem/h (40 } \mu\text{Sv/h)} \end{aligned}$$

Method 2 yields a higher dose equivalent rate (by a factor of 2) than method 1. Based on these results it is clear that muons are not a concern in this case.

Another area where muons could be of concern is at barrier gate E, when the BTS stoppers fail (section 4-5-7). ST-17 consists of 13.82 cm of copper ($\rho=8.96$ g/cc) and 5.08 cm of tungsten ($\rho=19.3$ g/cc). The iron equivalent thickness is

$$= \frac{13.82\text{cm} \times 8.96 \text{ g/cc} + 5.08\text{cm} \times 19.3\text{g/cc}}{7.87 \text{ g/cc}}$$

$$= 28 \text{ cm}$$

$$H = \frac{5 \text{ rem} \cdot \text{m}^2}{\text{h} \cdot \text{kw}} \times \frac{14.4 \times 10^{-3} \text{ kW}}{(9.5 \text{ m})^2} \times \frac{10^3 \text{ mrem}}{\text{rem}}$$

$$= 0.8 \text{ mrem/h (8 } \mu\text{Sv/h)}$$

Using Method 2 (52):

$$H = 0.28 \text{ mrem/h (2.8 } \mu\text{Sv/h)}$$

In this case, Method 1 yields a higher dose equivalent rate. Based on these results muons are not of concern at barrier gate E. Thus it has been demonstrated that muons are not of concern for the injector shielding.

12. AIR ACTIVATION

Air activation becomes a concern when the energy of the primary beam (E_0) exceeds the production threshold of 10.55 MeV in air⁽⁵⁾. Radioactive gases are produced mainly by the interaction of electrons and photons with nitrogen, oxygen, argon and carbon nuclei that are present in the air⁽⁵⁰⁾. An electron beam without bremsstrahlung will not cause significant air activation because the nuclear cross-section of electrons are 1/137 of those of photons. It is a common experience at accelerator facilities that external exposure from activated machine components is the limiting factor as opposed to air activation. The reason is that the total amount of activation in solids is much greater than in air. The air mass absorbs much less beam energy than the many radiation lengths of solid beamline components.

Air activation is reduced by a factor of the order of X/X_0 where X is the bremsstrahlung pathlength in air and X_0 is the radiation length of air ($X_0 = 30.38$ cm). Since the activated air mixes rapidly with the inert air, and coupled with the fact that radioactive decay takes place, radioactive concentrations decay away rapidly. Activated air products with half lives of less than one minute are of negligible concern, as they away decay rapidly before personnel enter the beam housing.

Initial air activation estimations were made by Donahue⁽⁵³⁾. Since then, the maximum intensity available from the linac has been reduced by a factor of 3. Table 9 summarizes the revised calculations.

The calculations for all radionuclides except ^{41}Ar were performed using the saturation activity per unit pathlength per unit beam power (A_s) from Swanson⁵.

TABLE 9

Radionuclide	Half Life	Reaction	Thresholds (MeV)	Saturation Activity $\mu\text{Ci}/\text{m}/\text{kw}$	Concentration			DAC $\mu\text{Ci}/\text{cc}$
					Linac	$\mu\text{Ci}/\text{cc}$ Diagnostic	Booster	
^3H	12.26 y	$^{14}\text{N}(\gamma, \text{sp})$	22.73	140	1.0×10^{-8}	1.2×10^{-8}	2.5×10^{-8}	$2 \times 10^{-5^a}$
		$^{16}\text{O}(\gamma, \text{sp})$	25.02	140	1.0×10^{-8}	1.2×10^{-8}	1.5×10^{-8}	0.5^b
^7Be	53.6 d	$^{14}\text{N}(\gamma, \text{sp})$	27.81	30	2.2×10^{-9}	2.5×10^{-9}	5.5×10^{-9}	$8.1 \times 10^{-6^c}$
		$^{16}\text{O}(\gamma, \text{sp})$	31.86	30	2.2×10^{-9}	2.5×10^{-9}	5.5×10^{-9}	
^{11}C	20.34 min	$^{12}\text{C}(\gamma, n)$	18.72	0.5	3.7×10^{-11}	4.2×10^{-11}	9.1×10^{-11}	$4 \times 10^{-6^d}$
		$^{14}\text{N}(\gamma, \text{sp})$	22.73	300	2.2×10^{-8}	2.5×10^{-8}	5.5×10^{-8}	
		$^{16}\text{O}(\gamma, \text{sp})$	25.88	300	2.2×10^{-8}	5.5×10^{-8}	5.5×10^{-8}	
^{13}N	9.96 min	$^{14}\text{N}(\gamma, n)$	10.55	2800	2.1×10^{-7}	2.3×10^{-7}	5.5×10^{-7}	$4 \times 10^{-6^d}$
^{15}O	123 s	$^{16}\text{O}(\gamma, n)$	15.67	1500	1.1×10^{-7}	1.2×10^{-7}	2.7×10^{-7}	$4 \times 10^{-6^d}$
^{16}N	7.14 s	$^{18}\text{O}(\gamma, np)$	21.81	0.5	3.7×10^{-11}	4.2×10^{-11}	9.1×10^{-11}	$7 \times 10^{-7^d}$
^{38}Cl	37.29 min	$^{40}\text{Ar}(\gamma, np)$	20.59	6	4.5×10^{-10}	4.8×10^{-10}	1.1×10^{-9}	$3 \times 10^{-6^d}$
^{39}Cl	55.5 min	$^{40}\text{Ar}(\gamma, p)$	12.52	40	3×10^{-9}	3.3×10^{-9}	7.3×10^{-9}	$2 \times 10^{-5^c}$
^{41}Ar	1.83 h	$^{40}(\text{n}_{th}, \gamma)$			1.5×10^{-9}	4.8×10^{-9}	6.2×10^{-9}	$3 \times 10^{-6^d}$

NOTE: sp = spallation
 n_{th} = thermal neutron
a = water
b = elemental
c = inhalation
d = submersion

$$\text{Concentration } (\mu\text{ci/cc}) = \frac{\text{Activity } (\mu\text{ci})}{\text{Volume (cc)}}$$

$$\text{Activity} = A_s \frac{\mu\text{ci}}{\text{m-kw}} P (\text{kw}) \times L (\text{m})$$

where P is the beam power and L is the bremsstrahlung pathlength.

Inherent in the calculations is the assumption that the injector is on for a sufficient time such that all radionuclides reach their saturation activities.

The following parameters were used:

Percentage of energy escaping beampipe = 100% (All this energy is assumed to be above the production threshold for the various radionuclides.)

Linac room volume = 3,560 ft.³ = 1.0 x 10⁸ cc (54)

Diagnostic room volume = 960 ft.³ = 2.7 x 10⁷ cc

Booster tunnel volume = 28,051 ft.³ = 7.9 x 10⁸ cc

Total surface area of linac room = 2.1 x 10⁶ cm² (55)

Total surface area of diagnostic room = 6.6 x 10⁵ cm²

Total surface area of booster tunnel = 9.8 x 10⁶ cm²

Maximum beam power in linac and diagnostic room = 0.75 watt

Maximum beam power in booster = 14.4 watts

Bremsstrahlung pathlength in linac = 10 m

Bremsstrahlung pathlength in diagnostic room = 3 m

Bremsstrahlung pathlength in booster = 10 m

(These pathlengths were chosen so that they were less than the maximum dimensions and more than the minimum dimension for the linac and diagnostic rooms. In the beam direction there are always sufficient beamline components which will absorb the bremsstrahlung.)

The data in columns 2, 3, 4 and 5 are taken from reference 5, except the saturation activity for ^{13}N , which is taken from reference 56. The last column lists the Derived Air Concentrations (DAC). According to ICRP30⁽⁵⁷⁾:

"The DAC for any radionuclide is defined as that concentration in air (Bq m^{-3}) which, if breathed by Reference Man for a working year of 2000 h (50 weeks at 40 h per week) under conditions of "light activity", would result in the ALI by inhalation.

$$\begin{aligned}\text{DAC} &= \text{ALI}/(2000 \times 60 \times 0.02) \\ &= \text{ALI}/(2.4 \times 10^3) \text{ Bq m}^{-3}\end{aligned}$$

where 0.02 m^3 is the volume of air breathed at work by Reference Man per minute under conditions of "light activity" (ICRP Publication 23)."

(Note: $1 \text{ Bq m}^{-3} = 2.7 \times 10^{-11} \text{ pCi/cc}$)

The annual limit on intake (ALI) of radionuclide is a secondary limit which has been designed to meet the basic limits for occupational exposure recommended by the ICRP.

For some of the radionuclides such as ^{11}C , ^{13}N , ^{15}O , and ^{41}Ar the contribution to dose equivalent from external exposure is greater than inhalation. Hence for these radionuclides the DACs for submersion being more restrictive are listed, while for the others the DACs for inhalation are listed. The DACs (listed in the last column) have been taken from DOE Order 5480-11⁽⁵⁸⁾. However, it should be pointed out that the DACs for submersion are based on a semi-infinite cloud.

These DAC values are valid only for gamma radiation and/or for the annihilation components which penetrate a body submerged in a large radioactive cloud. Höfert has suggested that for cloud radii of up to 10 m the DACs should be based on dose to the skin from β emitters, and these DACs would be much higher* (at least an order of magnitude) than those listed in Table 9⁽⁵⁹⁾.

Since ^{41}Ar is produced from a thermal neutron capture reaction, the thermal neutron fluence rate Φ_{th} must first be estimated. Neutrons produced from beam losses are moderated by the concrete shielding. The neutron yield as given by Swanson⁽⁵⁷⁾ is

$$Y(\text{n/s-kw}) = 1.21 \times 10^{11} z^{0.66}$$

For iron targets the yield is 1×10^{12} n/s-kw.

According to Patterson and Wallace⁽⁶⁰⁾ the thermal neutron fluence can be estimated knowing the fast neutron yield Q (n/s) and the surface area S (cm^2) of the beam housing.

$$Q = \frac{1.25 \times Q}{S}$$

For the linac and diagnostic rooms

$$Q = 10^{12} \frac{\text{n}}{\text{s-kw}} \times 0.75 \times 10^{-3} \text{ kw} = 7.5 \times 10^8 \frac{\text{n}}{\text{s}}$$

For the booster

$$Q = 10^{12} \frac{\text{n}}{\text{s-kw}} \times 14.4 \times 10^{-3} \text{ kw} = 1.44 \times 10^{10} \frac{\text{n}}{\text{s}}$$

Therefore,

$$\phi_{th} = \frac{1.25 \times 7.5 \times 10^8 \text{ n/s}}{2.1 \times 10^6 \text{ cm}^2} = 4.5 \times 10^2 \frac{\text{n}}{\text{cm}^2\text{-s}} \text{ (linac)}$$

$$\phi_{th} = \frac{1.25 \times 7.5 \times 10^8 \text{ n/s}}{6.6 \times 10^5 \text{ cm}^2} = 1.42 \times 10^3 \frac{\text{n}}{\text{cm}^2\text{-s}} \text{ (diagnostic)}$$

$$\phi_{th} = \frac{1.25 \times 1.44 \times 10^{10} \text{ n/s}}{9.8 \times 10^6 \text{ cm}^2} = 1.84 \times 10^3 \frac{\text{n}}{\text{cm}^2\text{-s}} \text{ (booster)}$$

The saturation activity

$$A_s = \phi_{th} \sigma N$$

σ = thermal neutron cross-section for $^{40}\text{Ar} = 0.53 \times 10^{-24} \text{ cm}^2/\text{atom}$

N = number of ^{40}Ar atoms in air

$$N = \frac{N_o \rho f}{A}$$

where

$$N_o = \text{Avogadro's Number} = 6.02 \times 10^{23} \frac{\text{atoms}}{\text{g-molecule}}$$

ρ = density of dry air = 1.205×10^{-3} g/cc

f = fraction by weight of ^{40}Ar in air = 0.013⁽⁵⁾

A = mass number of ^{40}Ar = 40

$$A_s = 5.6 \times 10^{-5} \frac{\text{atoms}}{\text{cc-s}} = 1.5 \times 10^{-9} \text{ } \mu\text{ci/cc (linac)}$$

$$A_s = 1.77 \times 10^{-4} \frac{\text{atoms}}{\text{cc-s}} = 4.8 \times 10^{-9} \text{ } \mu\text{ci/cc (diagnostic room)}$$

$$A_s = 2.3 \times 10^{-4} \frac{\text{atoms}}{\text{cc-s}} = 6.2 \times 10^{-9} \text{ } \mu\text{ci/cc (booster)}$$

These calculations are extremely conservative as they assume that 100 percent of the beam energy escapes the beampipe at the maximum possible beam power, and that all energy escaping is above the threshold for the production of the various radionuclides. In reality only a few percent of the beam energy will escape the beampipe during beam losses. Hence, these concentrations are conservative at least by two orders of magnitude. These concentrations are at least one to three orders of magnitude lower than the DACS.

In addition, the calculated values are concentrations in the beam housing while the machine is on. When the machine is off the concentrations will decay with time. No one is allowed to be in the beam housing during machine operation. Thus air activation is not a concern for the injector.

13. TOXIC GASES

Toxic gases can be produced by the interaction of ionizing radiation with air^(5, 61). These gases are ozone, nitric oxide, nitrogen dioxide, nitrogen trioxide, nitrogen tetroxide, nitric anhydride, and nitrous oxide. Ozone and nitric acid formed by the interaction of nitrogen oxides and water vapor present in the atmosphere may cause gradual corrosion of beamline equipment.

Toxic gas production occurs by a chemical transformation, whose reaction rate is almost proportional to the integral dose to the air. Hence an electron beam without bremsstrahlung can cause significant toxic gas production. Among all the toxic gases, ozone production is the limiting factor because of its lower threshold limit value (TLV) of 0.1 ppm⁽⁶²⁾. Hence only ozone will be discussed in this section.

The G value or radiolytic yield is defined as the number of molecules produced per unit energy deposited. The G value for ozone in pure oxygen is around 13 molecules per 100 ev. However, in air, because of an efficient charge transfer mechanism of positive charge transfer from N_2^+ ions to oxygen, the ozone yield is enhanced, and the G value ranges from about 7.4 - 10. Since the W value for air is about 34 ev per ion pair formed, more than one ozone molecule is formed for every ion pair formed. The yields for other toxic gases are smaller.

Ozone decomposes spontaneously and is decomposed by radiation. It reacts chemically with air impurities and other materials. The effective decomposition time will therefore depend on room size, wall material, temperature, impurities and the ozone concentration itself. The effective decomposition time for ozone is about 50 minutes. Since ozone can be detected by smell at concentration levels of about 0.02 - 0.05 ppm, any room that is free of its characteristic odor may be regarded as safe from toxic gases.

Ozone calculations were done using the EGS4 code (63, 64, 65) to determine the energy deposition in air. ESG4 calculations were done for 3 GeV electrons ($3.1 \times 10^{10} \text{ e}^-/\text{s}$) striking the inside of a 6-cm diameter, 0.3 mm thick iron beam pipe in the middle of a tunnel (133m x 3m x 2.5m).

Fraction of energy deposited in air = 0.021 (from EGS)

Maximum beam intensity = $3.1 \times 10^{10} \text{ e}^-/\text{s}$

Total energy deposition rate =

$$= 0.021 \times 3.1 \times 10^{10} \frac{\text{e}^-}{\text{s}} \times \frac{3\text{GeV}}{\text{e}^-} \times \frac{1000 \text{ MeV}}{\text{GeV}}$$

$$= 1.95 \times 10^{12} \frac{\text{MeV}}{\text{s}}$$

Ozone production rate =

$$p = 1.95 \times 10^{12} \frac{\text{MeV}}{\text{s}} \times 10.3 \frac{\text{molecules}}{100 \text{ eV}} \times 10^6 \frac{\text{eV}}{\text{MeV}} \times 60 \frac{\text{sec}}{\text{min}}$$

$$= 1.2 \times 10^{19} \frac{\text{molecules}}{\text{min}}$$

The saturation concentration

$$C_s = p \frac{\bar{T}}{V}$$

where $\bar{T} = 50 \text{ min}$

$$V = 133 \times 3 \times 2.5 \text{ m}^3 = 1 \times 10^9 \text{ c}$$

$$C_s = \frac{1.2 \times 10^{19} \text{ molecules/min}}{1 \times 10^9 \text{ cc}} \times 50 \text{ min}$$

$$= 6 \times 10^{11} \frac{\text{molecules}}{\text{cc}}$$

Therefore the ozone concentration =

$$= \frac{6 \times 10^{11} \text{ molecules}}{\text{cc}} \times \frac{2.4 \times 10^4 \text{ cc}}{6.02 \times 10^{23} \text{ molecules}}$$

$$= 0.024 \text{ ppm}$$

(At NTP 6.02×10^{23} molecules occupy 24 liters.)

This concentration is much less than the TLV of 0.1 ppm. Under normal operating conditions the entire beam at 3 GeV is not lost. These calculations are very conservative since they assume that the entire beam at 3 GeV is lost at a point. However they also indicate that ozone production and therefore toxic gas production is not a problem for the booster.

Similar calculations can be carried out for the linac and diagnostic rooms where the energy deposition at 150 MeV is 2.8% (from EGS).

Ozone concentration for linac (volume = 1.0×10^8 cc)

$$= 0.028 \times 150 \frac{\text{MeV}}{e^-} \times 3.1 \times 10^{10} \frac{e^-}{s} \times 10.3 \frac{\text{molecules}}{100 \text{ ev}} \times \frac{10^6 \text{ ev}}{\text{MeV}}$$

$$\times 60 \frac{s}{\text{min}} \times 50 \text{ min} \times \frac{1}{1.0 \times 10^8 \text{ cc}} \times \frac{2.4 \times 10^4 \text{ cc}}{6.02 \times 10^{23} \text{ molecules}}$$

$$= 1.6 \times 10^{-8}$$

$$= 0.016 \text{ ppm}$$

For the diagnostic room (volume = 3.2×10^7 cc)

$$\text{Ozone concentration} = \frac{1.6 \times 10^{-8} \times 1.0 \times 10^8 \text{ cc}}{3.2 \times 10^7 \text{ cc}}$$

$$= 5 \times 10^{-8}$$

$$= .05 \text{ ppm}$$

These concentrations are below the TLV (0.1 ppm), and since the calculations assume loss of the entire beam, these values are very conservative. Thus ozone production, and hence toxic gas production is not a problem for the linac or diagnostic rooms.

14. INDUCED ACTIVITY

As described in section 2-1, when a high energy electron interacts with a material, an electromagnetic shower consisting of electrons, positrons and photons is developed. The development of the shower continues until the energy of the photons falls below the Compton minimum.

When a high energy photon (> 10 MeV) interacts with a nucleus, the photon is absorbed, with the subsequent emission of one or more nucleons by the excited nucleus⁽⁶⁶⁾. Thus the element is changed to a different isotope. This new isotope may be radioactive, and it is the production of these types of isotopes which result in induced or residual radioactivity in electron accelerators. In addition, photonuclear reactions will result in the production of high energy particles which may interact with other nuclei producing radioactive isotopes. Very high energy particles are also capable of initiating nuclear cascades.

Thus radioactivity may be induced in beamline components by an electron or bremsstrahlung beam. The amount of activity will depend on the energy, beam power and type of material⁽⁵⁾.

Most of the activity is produced by the photon-induced reactions, namely the giant photonuclear resonance, the pseudo-deuteron effect and high-energy photospallation reactions. The beamline components that are most susceptible to activation are beam dumps, and components in areas where beam losses are normally expected. If the beam power is sufficiently high to produce large neutron fluences, then neutron activation becomes possible.

Materials which are highly susceptible to activation are stainless steel, tungsten, tantalum, zinc, gold, manganese, cobalt and nickel. Materials which are moderately susceptible to activation are iron and copper. Materials which are relatively insusceptible to activation are lead (antimony-free), ordinary concrete, aluminum, wood and plastics.

The linac waveguides are made of copper and losses along the linac can cause activation. Since the Faraday cup in the diagnostic room acts as a dump for the linac when the booster is not operating, it will also be activated. However because it is made of lead, the activation will not be of much concern. The vacuum chambers of the linac and booster transport lines are made of stainless steel (#304). Some estimation of induced activity can be made assuming that the machine has been operating steadily for time periods which are long compared with the half-lives of the produced radionuclides (typically 2-3 half-lives), so that the radionuclides have built up to saturation activity.

14-1 ACTIVATION OF COPPER

Pure copper is composed of ^{63}Cu (69.1%) and ^{65}Cu (30.9%). Table 10 lists the reactions producing the radionuclides, the half-lives, the threshold, and the saturation exposure rate obtained from Swanson⁽⁵⁾. For ^{58}Co and ^{63}Cu the exposure rates from McCall⁽⁶⁷⁾ were used to obtain saturation exposure rates. Since half-lives for ^{60}Co and ^{63}Ni are very large, these will not build up to saturation during normal machine operation, so they will be neglected in the calculations. Exposure rates have been converted to dose rates (DR) using 1 R ~ 1 rad (actually 1 R = 0.95 rads in tissue) and 1 rad = 0.01 Gy.

TABLE 10

Reaction	Half Life	Threshold (MeV)	Saturation exposure rate $X_s [(R\text{-m}^2)/(h\text{-kw})]$
$^{63}\text{Cu}(\gamma, sp)^{58}\text{Co}$	71.3 d	41.75	0.18 ^a
$^{63}\text{Cu}(\gamma, sp)^{58m}\text{Co}$	9.2 h	41.75	0.21
$^{63}\text{Cu}(\gamma, n2p)^{60}\text{Co}$	5.263 y	9.05	0.83
$^{65}\text{Cu}(\gamma, np)^{63}\text{Ni}$	92 y	17.11	no γ
$^{63}\text{Cu}(\gamma, 2n)^{61}\text{Cu}$	3.32 h	19.73	0.61
$^{63}\text{Cu}(\gamma, n)^{62}\text{Cu}$	9.76 min	10.84	6.5
$^{65}\text{Cu}(\gamma, n)^{64}\text{Cu}$	12.8 h	9.91	0.6 ^b
$^{65}\text{Cu}(n, \gamma)^{66}\text{Cu}$	5.10 min	—	—

a) using $\Gamma = 0.55 [(R\text{-m}^2)/(h\text{-Ci})]$

b) using $\Gamma = 0.12 [(R\text{-m}^2)/(h\text{-Ci})]$

Typically during normal operations there may be about 3% loss along linac section 1. Assuming this is all at 50 MeV, the beam power will be:

$$\frac{3}{100} \times 3.1 \times 10^{10} \frac{e^-}{s} \times 50 \text{ MeV} \times 10^6 \text{ eV} \times 1.6 \times 10^{-19} \frac{C}{e^-}$$

$$= 7.44 \times 10^{-3} \frac{VC}{s} = 7.44 \times 10^{-3} \text{ watt}$$

The exposure rate from activation of linac section 1 immediately after shutdown at time $t = 0$ will be

$$8.1 \frac{R\text{-m}^2}{h\text{-kW}} \times 7.44 \times 10^{-6} \text{ kW} = 6 \times 10^{-5} \frac{R\text{-m}^2}{h}$$

Exposure rate at 1 foot (~ 30 cm) from linac section = 0.65 mR/h (D.R. = 6.5 μ Gy/h).

After approximately one hour ^{62}Cu would have decayed away and the exposure rate would be about 10 μ R/h (0.1 μ Sv/h).

14-2 ACTIVATION OF LEAD

Pure lead is composed of ^{204}Pb (1.4%), ^{206}Pb (25.1%), ^{207}Pb (21.7%) and ^{208}Pb (52.3%).

Table 11 lists the various reactions producing the radionuclides, the half-life, threshold and saturation rate for each radionuclide(5).

TABLE 11

Reaction	Half Life	Threshold (MeV)	Saturation exposure rate X_s [(R-m ²)/(h-kw)]
$^{206}\text{Pb}(\gamma, np)^{204}\text{Tl}$	3.81 y	14.83	no γ
$^{207}\text{Pb}(\gamma, p)^{206}\text{Tl}$	4.19 min	7.46	no γ
$^{208}\text{Pb}(\gamma, p)^{207m}\text{Tl}$	1.3 s	8.04	0.91
$^{208}\text{Pb}(\gamma, p)^{207}\text{Tl}$	4.79 min	8.04	0.001
$^{204}\text{Pb}(\gamma, 2n)^{202m}\text{Pb}$	3.62	15.32	0.03
$^{204}\text{Pb}(\gamma, 2n)^{202}\text{Pb}$	3.0×10^5 y	15.32	—
$^{204}\text{Pb}(\gamma, n)^{203m}\text{Pb}$	6.1 s	8.38	0.13
$^{204}\text{Pb}(\gamma, n)^{203}\text{Pb}$	52.1 h	8.38	0.07
$^{206}\text{Pb}(\gamma, 2n)^{204m}\text{Pb}$	66.9 min	14.85	1.4
$^{206}\text{Pb}(\gamma, 2n)^{204}\text{Pb}$	stable	14.85	—

The major contribution to the exposure rate from induced activity are ^{207m}Tl , ^{202m}Pb , ^{203m}Pb , ^{203}Pb and ^{204m}Pb . If the entire beam at 150 MeV (0.75 watt) were dumped in the diagnostic room Faraday cup, the external exposure rate immediately after shut down (at time $t = 0$) would be:

$$2.5 \frac{R\text{-m}^2}{h\text{-kw}} \times 0.75 \times 10^{-3} \text{ kw} = 1.9 \text{ mR/h at 1 m (D.R. = 19 } \mu\text{Gy/h)}$$

The exposure rate at one foot (~ 30 cm) would be 20 mR/h (D.R. = 0.2 mGy/h).

After one hour only ^{202m}Pb , ^{203}Pb and ^{204m}Pb will remain.

The exposure rate after one hour will be

$$0.85 \frac{R\text{-m}^2}{h\text{-kw}} \times 0.75 \times 10^{-3} = 0.6 \text{ mR/h at 1 m}$$

The exposure rate at one foot (~ 30 cm) = 6.8 mR/h (68 $\mu\text{Gy/h}$).

14-3 ACTIVATION OF STAINLESS STEEL

Stainless steel (#304) is composed of iron (68%), carbon (0.08%), manganese (2%), phosphorous (0.04%), sulphur (0.030%), silicon (1%), chromium (18-20%) and nickel (8-12%). Stainless steel is highly susceptible to activation. Calculations are currently being performed to provide an estimate of induced radioactivity in stainless steel.

Tables 12 and 13 show the result of induced activity measurements (at one foot [\sim 30 cm] away from the beam pipe) in the booster. These results indicate that there is loss along the LTB transport line and along the BTS transport lines. This is to be expected as there are losses at injection and ejection. The vacuum chamber in both the LTB and BTS transport lines is made of stainless steel.

TABLE 12

Induced Radiation Survey - 5/29/91

Booster Shutdown at 2041

Time	Reading (mR/h)	Location
2105	0.115	G45
2105	0.240	G46
2106	0.520	G49 - BTS Septum
2107	11.0	G10 - BTS B1
2108	0.440	G11
2109	0.280	G12 Injection Septum
2110	0.014	G14

Less than 0.010 mR/h elsewhere.

G = Girder

TABLE 13

Induced Radiation Survey - 5/31/91

Booster Shutdown at 1304

Time	Reading (mR/h)	Location
1324	1.0	PED 47
1330	0.9	BTS Kicker
1331	0.9	Between G11 and G46
1331	0.6	G48
1335	3.0	BTS Septum (downstream end)
1336	1.5	PED 10 - Quad
1336	1.5	BTS B1
1338	0.6	LTB Q4
1338	5.0	Between LTB B2 and LTB Q5
1339	0.6	G11
1341	1.8	PED 23 - BPM #11

G = Girder

PED = Pedestal

BPM = Beam Profile Monitor

15. SKYSHINE

Skyshine refers to secondary radiation which first proceeds upwards and then is scattered back to the earth's surface after one or more collisions with air nuclei. In a broad sense, skyshine includes all radiation reaching some point in the vicinity of an accelerator facility. This radiation includes direct as well as scattered radiation, radiation scattered by the air, ground and neighboring buildings⁽⁶⁹⁾. Usually the point of interest is far away such that the radiation reaching it is dominated by particles that have undergone elastic and inelastic scattering with air nuclei. At large distances neutrons are the dominant contribution. Several studies have been done to formulate expressions for skyshine dose. A summary of these studies can be found in reference 69.

Jenkins has written a program called "Skyshine Mortran" which is based on theoretical work and measurements^(70,71). This program can be used for points of interest within 200 to 300 m of the accelerator facility.

The dose equivalent (in rem/electron) in this program is given by

$$H = \frac{E_o \omega e^{-(R/140)}}{R} Y_{GRN} e^{-(\rho x/30)} + Y_{MID} e^{-(\rho x/55)} + Y_{HEN} e^{-(\rho x/120)} \\ + \frac{E_o e^{-(R/140)}}{R} Y_{sc} e^{-(\rho x/20)}$$

where

E_o = energy of primary electron beam in GeV

ω = solid angle subtended by the roof

R = distance to point of interest (in m)

x = thickness of roof shield in cm

ρ = density of roof shield in g/cc

Y_{GRN} = yield of giant resonance neutrons (GRN)
 $= 1.48 \times 10^{-17} E_0 Z^{0.66}$

The attenuation length for GRN is 30 g/cm^2

Y_{MID} = yield of mid energy neutrons (MID) = $1.33 \times 10^{-16} E_0/A^{0.37}$

The attenuation length for MIDN is 55 g/cm^2

Y_{HEN} = yield of high energy neutrons (HEN) = $4.49 \times 10^{-17} E_0/A^{0.65}$

The attenuation length of HEN is 120 g/cm^2

Y_{MID} and Y_{HEN} are the 90° yields. Angular dependence has been neglected.

Y_{SC} = yield of scattered neutrons (SCN)

The attenuation length for SCN is 20 g/cm^2

The assumptions made in this program are:

- 1) Scattered dose is twice the GRN dose.
- 2) All non-scattered doses vary according to solid angle.
- 3) MIDN yields are 1/4 of GRN yields.
- 4) HEN yields are 1/20th of MIDN yields. (This is a factor of 2 lower than in the SHIELD program.)
- 5) HEN produce 1 evaporation neutron each.
- 6) All neutrons vary as $\exp(-R/140)$.
- 7) Roof shield thickness is at least 1 foot.

Using $R = 3.0 \text{ m}$ for the boundary and using a roof shield thickness of 2 feet ($\sim 61 \text{ cm}$), calculations for the boundary dose from skyshine were performed using the computer program. If all $3.1 \times 10^{10} \text{ e}^-/\text{s}$ at 150 MeV are lost at a point (in a thick target) in the booster, the annual dose equivalent (for 120 hours of operation) will be 4 μrem ($0.04 \mu\text{Sv}$)⁽⁷²⁾. If all $3.1 \times 10^{10} \text{ e}^-/\text{s}$ at 3 GeV are lost in the booster the annual boundary dose equivalent will be 82 μrem ($0.82 \mu\text{Sv}$). This represents an upper bound on the boundary dose equivalent for 120 hours of operation.

Operational experience indicates that there is about 10-20% loss in the LTB line and also 30% loss during injection at 150 MeV. The injection losses take place at the septum and during the first three turns in the booster. Losses in the BTS line during ejection vary from about 30% to higher levels. A typical loss may be about 50% in the BTS line. These losses would correspond to a boundary dose equivalent of about 40 μrem or 0.4 μSv (for 120 hours of operation).

SLAC has peripheral monitoring stations along its boundary which continuously measure the boundary dose^(71,73). Each station consists of a neutron monitor (moderated BF_3 counter) and a gamma monitor (Geiger counter), and their associated electronics enclosed inside a wooden enclosure. The moderated BF_3 counter measures the neutron fluence rate. The outputs from these monitors are computerized.

The monitoring station closest to the SSRL injector is PRM#1, which is located about 3.6 m away from the center of the booster. The typical neutron background is about 6-11 mrem/y (60-110 $\mu\text{Sv/y}$). Measurements indicate that SPEAR injection (6 hours/day for 365 days/year) contributes an increase of 0.2 mrem/y (2 $\mu\text{Sv/y}$)⁽⁷⁴⁾.

The booster can be operated in the booster stand-by mode, i.e., the ejection kicker is turned off, so that the beam is lost around the booster ring. Measurements indicate that this mode of operation (18 hours/day for 365 days/year) contributes an additional 0.1 mrem/y (1 $\mu\text{Sv/y}$). The linac parameters for these measurements were:

$$\text{Intensity} = 2 \times 10^{10} \text{e}^-/\text{s}$$

$$\text{Linac energy} = 126 \text{ MeV}$$

$$\text{Booster energy} = 2.3 \text{ GeV}$$

Calculations indicate that under these conditions the boundary dose equivalent would be about 2.3 mrem/year (23 μ Sv/y). At SLAC each machine has been shielded so that its contribution to the boundary dose equivalent does not exceed 5 mrem/y (50 μ Sv/y). These calculations are very conservative and assume that in the stand-by mode all the electrons are lost at 2.3 GeV at a point. In reality the energy at which the electrons may be lost may be more like 1 GeV. While the booster magnets are cycling at 10 H_z , they are re-energized, and the instability caused by this re-energizing causes the electrons to be lost over several thousands of turns. Since these losses are distributed, local shielding in several locations around the booster will cause further reduction, thus the measured boundary doses will be always less than the calculated values.

ACKNOWLEDGMENTS

The author is deeply indebted to Terry Mellinger of SSRL for her patience in typing this entire document. Acknowledgment are also due to Digna Lacey, the SSRL Engineering and Technical Services Group and the SLAC Publications Department for their help with the tables and figures.

The author is grateful to members of the Radiation Physics Department - Ed Benson, Ted Jenkins, James Liu, Dick McCall and Ralph Nelson, and members of the Accelerator Department Safety Office, Ken Crook and Gerri Nelson, for their involvement and contribution at the various stages of the injector project. Gratitude is also expressed to the various SSRL staff members for their contributions to the completion of this document.

REFERENCES

1. SLAC Radiation Safety Procedures, Shield Design Criteria, - RP Proc. #1.
2. Jenkins, T.M., 1979, "Neutron and Photon Measurements Through Concrete from a 15 GeV Electron Beam on a Target - Comparison with Models and Calculations", Nuclear Instruments and Methods 159, pp. 265-268.
3. Swanson, W.P. and Thomas, R.H., 1990, "Dosimetry for Radiological Protection at High-Energy Particle Accelerators", The Dosimetry of Ionizing Radiation, Volume III, (Academic Press, Inc.).
4. Patterson, W.H. and Thomas, R.H., 1973, Accelerator Health Physics, p. 115, (Academic Press, New York).
5. International Atomic Energy Agency, 1979, Radiological Safety Aspects of the Operation of Electron Linear Accelerators, Technical Report Series No. 188 (written by W.P. Swanson), (IAEA, Vienna).
6. Jenkins, T.M., 1990, SHIELDO2 MORTRAN, Memo to File, SLAC Radiation Physics Department.
7. Nelson, W.R., Hirayama, H. and Rogers, D.W.O., 1985, "The EGS4 Code System", SLAC Report 265. Stanford Linear Accelerator Center, Stanford, California.
8. Jenkins, T.M., 1991, Private Communication.
9. Final Safety Analysis Document (FSAD) for 3 GeV SPEAR Injector Project, Revision 2, April 1991, Stanford Synchrotron Radiation Laboratory, Stanford, California.

10. Ipe Notebook, 1987-1988, Booster 1, page 91.
11. Wiedemann, H., January 24, 1988, "Radiation Shielding for the 3 GeV SPEAR Injector", SSRL Injector Memo to SLAC Radiation Physics Group.
12. Ipe Notebook, 1987-1988, Booster 1, p. 43.
13. Ipe Notebook, 1987-1988, Booster 1, p. 78.
14. Borland, M., May 17, 1990, "Overview of Booster Operating Cycle - SSRL 3 GeV Injector Project", in proposal submitted to Radiation Safety Committee.
15. 3 GeV SPEAR Injector, July 1988, Conceptual Design Report, Stanford Synchrotron Radiation Laboratory, Stanford, California.
16. Benson, E., May 21, 1990, "Radiation Safety Items for 150 MeV SSRL Booster Linac Operation", Memo to J. Cerino.
17. Nelson, G., June 28, 1990, Minutes of Radiation Safety Committee Meeting, May 29, 1990.
18. Safranek, J., May 18, 1990, "Shielding and Beam Containment, LTD and LTB to the stoppers (revision 1)", in proposal submitted to Radiation Safety Committee.
19. Benson, E. and Nelson, W.R., April 20, 1990, "Energy Diagnostic and Faraday Cup Dump Shields", memo to J. Weaver.
20. Cerino, J. and Baritchi, L., March 1989, "SSRL Injector Project Beam Stopper and Linac Actuator and Blank", DWG# PF-44-194-03 CO.

21. Ipe Notebook, 1991, Booster 5, pp. 45-51.
22. NCRP, 1984, Neutron Contamination from Medical Electron Accelerators, NCRP Report No. 79, National Council on Radiation Protection and Measurements, (Bethesda, Maryland).
23. Wiedemann, H., May 12, 1990, "Beam Loss Scenarios in the Injector Booster", Memo to N. Ipe.
24. Ipe Notebook, 1990, Booster 4, pp. 50-67.
25. Dinter, H. and Tesch, K., 1977, "Dose and Shielding Parameters of Electron-Photon Stray Radiation from a High-Energy Electron Beam", Nuclear Instruments and Methods 143, pp. 349-355.
26. Ipe Notebook, 1990, Booster 4, pp. 105-123.
27. Safranek, J., October 11, 1990, "Beam Loss Mechanisms in the BTS Transport System (rev. 1)", Memo to N. Ipe.
28. Ipe Notebook, 1989, Booster 2, pp. 46-56.
29. Cerino, J. and Baritchi, L., March 1989, "SSRL Injector Project Beam Stopper and Disaster Monitor BL-17, ACT. and Blank", DWG # PF 44-194-01-CO.
30. Ipe Notebook, 1990, Booster 3, pp. 54-57.
31. Morales, H., October 25, 1990, "BL-17 Drift Chamber Removal", Memo to N. Ipe.
32. Day, D., February 1991, Private Communication.
33. Golde, A., February 1991, Private Communication.

34. Ipe Notebook, 1990, Booster 3, p. 105.
35. SSRL Linac Notebook, 1990-1991, pp. 33, 62, 69, 75-81, 90-91.
36. Ipe Notebook, 1990, Booster 4, pp. 43-47, 127-132, 139-140, 151.
37. Ipe Notebook, 1991, Booster 5, pp. 55-56, 70.
38. Injector/SPEAR Radiation Measurements, 1991.
39. Liu, J.C., et al, May 1991, "Neutron Dosimetry at SLAC: Neutron Sources and Instrumentation", SLAC-TN-91-3 (DRAFT).
40. Yotam, R. et al, May 1991, "Personnel Protection and Beam Containment Systems for the 3 GeV Injector", in Proceedings of IEEE 1991 Particle Accelerator Conference, May 6-9, 1991, San Francisco, California.
41. Walz, H.V., January 1991, "Personnel Protection System - Technical Introduction", presented at Operations Training, SLAC, 7 January 1991.
42. Smith, H., October 25, 1990, "Yellow/Magenta Warning Lights Status for the SSRL Linac and Booster", Memo to distribution.
43. Babcock, G., Warren, G., MacDonald, B. and Leeman, R., "Accelerator Area Monitoring System", SLAC Internal Note (unpublished).

44. McKinley, A.F., 1981, Thermoluminescence Dosimetry, Medical Physics Handbook 5, pp. 10-14 (Adam Hilgar, Bristol).
45. Jenkins, T.M., and Busick, D.D., March 1987, "Personnel Dose Equivalent Monitoring at SLAC Using Lithium-Fluoride TLDs", SLAC TN 87-2.
46. Liu, J.C., February 6, 1991, "Field Radiation Measurements Results for the Booster Ring during 7/30/91 to 11/30/90", Memo to George Brown.
47. SLAC Radiation Rule Book, Internal Document, Radiation Physics Department.
48. SLAC Radiation Safety Procedures, Internal Document, Radiation Physics Department.
49. Ipe Notebook, 1991, Booster 5, p. 95.
50. ICRU 1978, Basic Aspects of High Energy Particle Interactions and Radiation Dosimetry, ICRU Report 28, (International Commission on Radiation Units and Measurements, Washington, D.C.).
51. Nelson, W.R., and Kase, K.R., 1974, "Muon Shielding Around High-Energy Electron Accelerators: Part I Theory", Nuclear Instruments and Methods 120, p. 401.
52. Ipe Notebook, 1991, Booster 5, pp. 104-105.
53. Donahue, R.J., 1987, "3 GeV Booster Synchrotron Air Activation Estimates", Memo to Radiation Physics Group File.

54. Boyce, R., 1991, "Volume of Booster Tunnel and Linac Vault", SSRL Engineering Note M171.
55. Montgomery, J., 1991, Private Communication.
56. Huntzinger, C.J., and Holmes, J.A., 1987, "Production and Control of Activation Products at an Electron Linear Accelerator Complex", in Health Physics of Radiation Generating Machines, Proceedings of the Twentieth Midyear Topical Symposium, February 8-12, 1987, Reno, Nevada.
57. ICRP 1979, "Limits for Intakes of Radionuclides by Workers", ICRP Publication 30, Part I, Annuals of the ICRP, pp. 8 - 9, (Pergamon Press, New York).
58. DOE, 1988, "Radiation Protection for Occupational Workers", DOE Order 5480.11 (U.S. Department of Energy, Washington, D.C.).
59. Hofert, M., 1969, "Radiation Hazard of Induced Activity in Air as Produced by High Energy Accelerators", in the Second International Conference on Accelerator Dosimetry and Experience, November 5-7, 1969, Stanford Linear Accelerator Center, Stanford, California.
60. Patterson, H.W., and Wallace, R., "A Method of Calibrating Slow Neutron Detectors", UCRL 8359.
61. Swanson, W.P., 1980, "Toxic Gas Production at Electron Linear Accelerators", SLAC PUB-2470.
62. American Conference of Governmental Industrial Hygienists (AGGIH), 1990-1991, Threshold Limit Values for Chemical Substances and Physical Agents and Biological Exposure Indices.

63. Nelson, W.R., and Ipe, N., August 21, 1990, "Improved Ozone Calculations for the SSRL Booster Synchrotron", Memo to Radiation Physics Group File.
64. Ipe, N., April 11, 1991, "Revised Ozone Calculations", Memo to John Cerino.
65. Ipe Notebook, 1991, Booster 4, pp. 74-79.
66. Barbier, M., 1969, Induced Activity, pp. 214-249, (John Wiley, New York).
67. McCall, Dick, March 24, 1987, "Specific Gamma Ray Constants in IAEA Report 188", Memo to File, Radiation Physics Department, SLAC.
68. CRC 1982-83, Handbook of Chemistry, 63rd Edition, p. 120.
69. International Atomic Energy Agency, 1988, Radiological Safety, 1988, Radiological Safety Aspects of the Operation of Proton Accelerators, Technical Report Series No. 283 (written by Ralph H. Thomas and Graham R. Stevenson), (IAEA, Vienna).
70. Jenkins, T.M., "Skyshine Morfran", On Disc PUB 222, Radiation Physics Deptment, SLAC.
71. Jenkins, T.M., 1973, "Accelerator Boundary Doses and Skyshine - A Review", SLAC PUB-1332.
72. Ipe Notebook, 1989, Booster 2, pp. 94-95.
73. Neal, R.B., 1968, The Stanford Two Mile Accelerator, Stanford Linear Accelerator Center, Stanford, California, pp. 798-802.

74. Liu, J.C., July 19, 1991, "Boundary Dose from SSRL Injector Operation," Memo to H. Winick.
75. Liu, J.C., August 23, 1991, "Radiation Levels During Normal Injector Operation and Its Implication to the Injector Operation", Memo to H. Winick.
76. Hettel, R., August 2, 1991, "Minutes of SSRL Linac Beam Containment Safety Review - 7/31/91", Memo to SAFE and Ipe.
77. Liu, J.C., August 29, 1991, "Summary of the Measurements for SSRL Linac BCS Test", Memo to H. Winick.
78. SSRL Linac Notebook, 1990-1991, p. 55.
79. Liu, J.C., June 27, 1991, "Permissible Mode for Parking the Booster Beam", Memo to H. Winick.

APPENDIX A

RADIATION SAFETY COMMITTEE Proposals/Memos/Minutes

1. H. Wiedemann, May 2, 1988, "SSRL Booster Synchrotron - Request for Approval of Tunnel Shielding".
2. W.R. Nelson, May 6, 1988, "SSRL Booster Synchrotron - Dose Equivalent Rates Under Continuous Injection". Memo to Adam Boyarski.
3. G. Nelson, May 27, 1988, "Minutes of Radiation Safety Committee of May 5, 1988".
4. J.A. Cerino and R.O. Hettel, February 7, 1989, "SPEAR Injector Project Interim Personnel Protection System".
5. G. Nelson, February 28, 1989, "Minutes of the Radiation Safety Committee Meeting, 2/7/89", SM 160.
6. R. Hettel, July 19, 1989, "PPS for Linac and Diagnostic Room Shielding Areas Phase I".
7. G. Nelson, August 10, 1989, "Minutes of Radiation Safety Committee Meeting - July 27, 1989", SM 221.
8. R. Hettel and J. Cerino, "SSRL 3 GeV Injector Project Interim Personnel Protection System".
9. G. Nelson, February 23, 1990, "Radiation Safety Committee Meeting - February 14, 1990", SM 327.

10. J. Cerino, R. Hettel and R. Yotam, March 8, 1990, "Design Proposal for the SSRL Injector Project Booster Personnel Protection System (rev. 1a)".
11. G. Nelson, March 20, 1990, "Radiation Safety Committee Meeting: March 13, 1990", SM 340.
12. H. Wiedemann, May 18, 1990, "Beam Containment Proposal to Operate SSRL Injector into Linac to Booster Stoppers and Linac to Diagnostic Dump".
13. J. Cerino, June 7, 1990, "SSRL Injector Booster Beam Containment", Memo to G. Nelson.
14. G. Nelson, June 28, 1990, "Radiation Safety Committee Meeting - May 29, 1990", SM 382, Revision 1.
15. G. Nelson, July 17, 1990, "Radiation Safety Committee Meeting - June 14, 1990", SM 391.
16. N. Ipe, December 18, 1990, "Update on SSRL Injector".
17. N. Ipe, December 19, 1990, "Results of Radiation Survey".
18. H. Smith and R. Yotam, January 15, 1991, "Design Proposal to Rebuild the SPEAR Personnel Protection System".
19. G. Nelson, January 15, 1991, "Radiation Safety Committee Meeting - January 9, 1991", SM 486.
20. J. Liu, May 23, 1991, "Request for Approval of the Commissioning of SSRL Synchrotron Beamlines".
21. G. Nelson, July 30, 1991, "Radiation Safety Committee Meeting - July 19, 1991", SM 603.