1 of 1

SEP 07 1993
OSTI

PRELIMINARY SAFETY ANALYSIS REPORT (PSAR)

The NSLS 200 MeV Linear Electron Accelerator

L.N. Biumberg, A.I. Ackerman, T. Dickinson, R.N. Heese, R.A. Larson,
C.W. Neuls, S. Pjerov and J.F. Sheehan
National Synchrotron Light Source
Brookhaven National Laboratory

June, 1993

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

PREFACE

This report has been categorized as a Draft PSAR by the BNL ES&H Committee to serve as a guidance document for the initial commissioning and acceptance tests of the 200-MeV NSLS electron linac. It is recognized that this document will be revised when the intended purpose of the Linac - an injector into a synchrotron radiation research facility - is fully defined and the new operating parameters are well characterized. In the interim, the reader should be cautioned that the dose rates and occupancy times cited in this report and in summary Table IV reflect the BNL administrative action level of 1250 mrem per year for a radiation worker rather than the radiological control design criteria of 500 mrem per year for a new facility as stated in the most recent DOE Radiological Control Manual (DOE N5480.6, June, 1992) and the BNL Radiological Control Manual (Dec. 1992). Administrative action levels and design criteria for non-radiation workers and the general public remain at 25 mrem per year. Moreover, the neutron dose rates as evaluated from National Council on Radiation Protection Document NCRP-51 (1977) utilize a neutron quality factor $Q = 9$ for the 2-2.5-MeV neutrons used in the present calculations, whereas the Radiation Control Manuals cited above recommend a quality factor of $Q = 20$ for new facility design. Finally, we omit in the present report the appendices attached to the original document which are essentially administrative background material.

June 15, 1993

PRELIMINARY SAFETY ANALYSIS REPORT (PSAR)

The NSLS 200 MeV Linear Electron Accelerator

L.N. Blumberg, A.I. Ackerman, T. Dickinson, R.N. Heese, R.A. Larson,
C.W. Neuls, S. Pjerov and J.F. Sheehan
National Synchrotron Light Source,
Brookhaven National Laboratory

June, 1993

Executive Summary

1. Introductory Description of the Facility in Building 729
2. Safety Policy
  - 2.1 Introduction
  - 2.2 Project Safety
  - 2.3 Laboratory Safety Committee
  - 2.4 Safety Training
3. Building 729 Systems
  - 3.1 Introduction
  - 3.2 Building Equipment Services
    - 3.2.1 Electrical Power Distribution System
    - 3.2.2 Air System
    - 3.2.3 Water System
    - 3.2.4 Communications Systems
  - 3.3 Building Access and Egress
  - 3.4 Hazards and Controls
    - 3.4.1 Fire Hazards and Controls
    - 3.4.2 Linac Area Security System
    - 3.4.3 Occupational Health Hazards
    - 3.4.4 Building Hazards Risk Assessment
4. Linear Accelerator Systems
  - 4.1 General Description of the Linac
  - 4.2 Accelerator Operations
  - 4.3 Hazards and Controls
    - 4.3.1 Radiation Hazards and Shielding
      - 4.3.1.1 Electron Gun Radiation Hazards
      - 4.3.1.2 Electron Backstreaming in the Linac
      - 4.3.1.3 Linac and Transport Line Prompt Radiation Hazards (Faults)

June 15, 1993

- 4.3.1.3.1 Accidental Dump at 200 MeV End of Linac
  - 4.3.1.3.1.1 Maximum Credible Accident
  - 4.3.1.3.1.2 Dump of Straight-Through 200 MeV Beam
  - 4.3.1.3.1.3 Levels in Uncontrolled Area Outside 4-Ft. Wall
  - 4.3.1.3.1.4 The Vault Entry Maze at Security Gate 1
  - 4.3.1.3.1.5 Skyshine in Uncontrolled Areas Adjacent to Bldg. 729
  - 4.3.1.3.1.6 Skyshine within Bldg. 729 from Accidents
- 4.3.1.3.2 Accidental Dumps at Intermediate Points Along Linac
  - 4.3.1.3.2.1 Dose Levels Outside 4-Ft. North Wall
  - 4.3.1.3.2.2 Dose Levels Outside 3-Ft. Wall within Bldg. 729
  - 4.3.1.3.2.3 Skyshine within Bldg. 729 and Adjacent Areas
- 4.3.1.4 Beam Dump and Momentum Slits Radiation and Shielding
  - 4.3.1.4.1 Levels within Bldg. 729 from Beam Dump
  - 4.3.1.4.2 Skyshine from Beam Dump in Bldg. 729 and Adjacent Structures
  - 4.3.1.4.3 Levels within Bldg. 729 from slits
  - 4.3.1.4.4 Skyshine from Slits in Bldg. 729 and Adjacent Structures
  - 4.3.1.4.5 Levels on Bldg. 729 Roof from Beam Dump
- 4.3.1.5 Activation Hazards
- 4.3.2 Electrical Hazards from Electron Gun and Linac
- 4.3.3 Occupational Health Hazards
  - 4.3.3.1 Non-Ionizing Radiation Hazard
  - 4.3.3.2 Magnetic Fields
  - 4.3.3.3 Lasers
- 4.3.4 Accident Assessment and Fault Studies

5. References

6. Figures and Captions

- Fig. 1 BNL site plan in vicinity of Building 729.
- Fig. 2 Plan view of Building 729 and Adjacent Structures.
- Fig. 3 Building 729 with 200-MeV Linac and Shielding Walls.
- Fig. 4 Elevation view of Building 729 and Shielding Walls.
- Fig. 5 NSLS Department Organizational Chart.
- Fig. 6 X-Ray source dose equivalent index vs. electron energy.
- Fig. 7 X-Ray transmission factor B_x vs. lead thickness
- Fig. 8 Cross-section of transport line H-type bending Magnet B1,2
- Fig. 9 X-Ray transmission factor B_x vs. concrete thickness.
- Fig. 10 Total photoneutron yield Y vs. incident electron energy.
- Fig. 11 Forward and 90° neutron yields for various reactions.
- Fig. 12 Neutron dose-equivalent index transmission B_n vs. concrete thickness.
- Fig. 13 Neutron evaporation energy spectrum from statistical model.

- Fig. 14 Average neutron energy in evaporation spectrum vs. maximum energy.
 Fig. 15 Number of electrons in electromagnetic shower vs. absorber depth.
 Fig. 16 Detail of downstream (200-MeV) end of linac.
 Fig. 17 Reflection coefficients of X-Rays from concrete and iron.
 Fig. 18 Linear absorption coefficient of X-Rays vs. X-Ray energy in Al, Cu, Sn, Pb
 Fig. 19 Transmission coefficient of neutrons B_{nm} through concrete maze.
 Fig. 20 Tenth value layer (TVL) for neutrons in concrete vs. neutron energy.
 Fig. 21 Equivalent 90° X-Ray energy for thick target bremsstrahlung vs. incident electron energy.
 Fig. 22 Bremsstrahlung attenuation factor B_x vs. Pb thickness.
 Fig. 23 Bremsstrahlung attenuation factor B_x vs. steel thickness.
 Fig. 24 Bremsstrahlung attenuation factor B_x vs. concrete thickness.
 Fig. 25 Average X-Ray energy in bremsstrahlung spectrum vs. incident electron energy.
 Fig. 26 Block diagram of the 200-MeV electron linear accelerator.
 Fig. 27 Enlarged plan view of the transport line vault of Bldg. 729.
 Fig. 28 Attenuation of fission spectrum neutrons in 5% Boron-polyethylene.

7. Appendices

Appendix I	Section NS1.2.0 of NSLS SEAPPM Manual
Appendix II	Area Safety Representative
Appendix III	NEPA Document and Approval
Appendix IV	NESHAPS Evaluation for 200 MeV Linac
Appendix V	Waiver of PSAR for Construction of Building 729
Appendix VI	Plant Engineering Specifications of Building Systems
Appendix VII	Fire Hazard Analysis

EXECUTIVE SUMMARY

The radiological, fire and electrical hazards posed by a 200 MeV electron Linear Accelerator, which the NSLS Department will install and commission within a newly assembled structure designated as Building 729, are addressed in this Preliminary Safety Analysis Report. Although it is clear that this accelerator is intended to be the injector for a future experimental facility, we address only the Linac in the present PSAR since neither the final design nor the operating characteristics of the experimental facility are known at the present time. The fire detection and control system to be installed in the building is judged to be completely adequate in terms of the marginal hazard presented - no combustible materials other than the usual cabling associated with such a facility have been identified. Likewise, electrical hazards associated with power supplies for the beam transport magnets and accelerator components such as the accelerator klystrons and electron gun are classified as marginal in terms of potential personnel injury, cost of equipment lost, program downtime and public impact perceptions as defined in the BNL Environmental Safety and Health Manual and the probability of occurrence is deemed to be remote. No unusual features have been identified for the power supplies or electrical distribution system, and normal and customary electrical safety standards as practiced throughout the NSLS complex and the Laboratory are specified in this report. The radiation safety hazards are similarly judged to be marginal in terms of probability of occurrence and potential injury consequences since, for the low intensity operation proposed - a factor of 25 less than the maximum Linac capability specified by the vendor - the average beam power is only 0.4 watts. The shielding specifications given in this report will give adequate protection to both the general public and nonradiation workers in areas adjacent to the building as well as radiation workers within the controlled access building. The specified vault shielding thickness covers the contingency of possible future full intensity operation, whereas the specified skyshine shielding over the linac area is designed for the low intensity operation mode only. No general roof shielding over the linac or experimental vault is included in the present design, although the construction of such a roof is not precluded if required in the future. The present shielding design identifies radiation hazards in both the normal operating mode and in accident situations and specifies local shielding around the beam dump locations to contain the X-Ray and neutron radiation. BNL Environmental Safety and Health standards of annual radiation doses not to exceed 25 mrem for members of the public and nonradiation workers, and 1250 mrem for radiation workers are adhered to in the shielding design. The overall facility is categorized as low risk, as per DOE Order 5481.1B. This PSAR meets the requirements of DOE Order 5480.25, "Safety of Accelerator Facilities".

1. Introductory Description of the Facility in Building 729

The 200-MeV electron linac described herein is presently in the final phase of its 4-year design and fabrication by an outside vendor, Beta Development Corporation [1], and will be assembled and commissioned on the BNL site within a pre-fabricated structure designated as Building 729. The building has been assembled and conventional power, water, fire protection, heat and ventilation have been installed; the structure has successfully passed an Occupational Readiness Review. The facility is located northeast of the intersection of Brookhaven Ave. and Railroad Street and east of the existing NSLS Building 725 complex as shown in the site plan of Fig. 1. The new building is, in effect, a 40-ft. x 120-ft. addition to the existing Building 726 which is currently used as a machine shop by the NSLS, and is in proximity to an existing modular Building 728 which contains offices for NSLS personnel and the existing Building 727 which serves as an NSLS assembly and magnetic measurements area as shown in Fig. 2.

The accelerator, a conventional S-Band (2856 MHz) RF electron linac of overall length (including electron gun) of 60-ft, will be located along the north wall of Building 729 as shown in Fig. 3 and in the elevation view Fig. 4. The linac is ultimately intended to serve as an injector for an electron experimental facility, also to be assembled in Building 729 within the vault shown in Fig. 3, which will provide a source of far ultra-violet photons for a prototype projection lithography or FEL facility. However, the details of this facility have not yet been fully defined; therefore, the present PSAR addresses only the 200-MeV linac facility.

The salient features of the radiation shielding layout for the linac include (1) a 4-ft. thick, 8-ft. high ordinary concrete wall along the north side of the machine and outside of the building wall, (2) a 3-ft. thick, 8-ft. high concrete wall within the building to provide the south side of the machine enclosure, (3) an entry through the shielding wall at the low energy east end of the machine to provide access to the electron gun area, (4) a maze entry into the high energy west end of the linac cave/ring vault area, and (5) no roof shielding over the linac/ring vault. We justify the elimination of roof shielding with skyshine calculations which show that annual dose levels to non-radiation workers in adjacent structures will be below BNL tolerance levels for the planned operating conditions of the linac - a factor of 25 lower than the maximum intensity capability specified by the vendor - when additional local shielding is added above points where accidental beam dumps can occur. The additional shielding includes a canopy supporting shielding over the entire Linac. With the planned operating parameters of 2 Hz repetition rate, 1 nsec pulse duration and 1A peak current, the average linac current is $I = 2$ nAmps and the average beam power at 200 MeV electron energy is $P = 0.4$ watts. For these very low intensity conditions we characterize the linac with the specified shielding as a low risk facility.

2. Safety Policy

2.1 Introduction

The 200-MeV linac project is administratively a part of the NSLS Department and, as such, is under the umbrella of the existing NSLS safety organization and its area safety representatives. The Department has a strong commitment to safety in the operation of its accelerators and beamlines as evidenced by the central position of the safety group in the

organizational chart given in Fig. 5; NSLS Environmental Safety and Health (ES&H) Coordinator, K. Batchelor and NSLS Project Safety Officer, T. Dickinson, report directly to the Department Chairman, D. McWhan, and are assisted by two full time safety engineers and three representatives of the Safety and Environmental Protection Division. In addition, the Department maintains a Safety Committee which reviews both the accelerator operations and the experimental facilities in an advisory capacity to the Safety Coordinator. The present composition of this committee is given in Appendix II.

The NSLS safety policies and procedures are detailed in the Department's Safety and Environmental Administrative Policy and Procedures Manual (SEAPPM) document [2] which specifies the responsibilities and procedures of the NSLS safety organization.

2.2 Project Safety

The project safety committee is the NSLS Department ES & H Committee and, as such, will review the present PSAR and subsequent SAR for the 200-MeV Linac Project. In addition, the Department conducts quarterly safety inspections of the facility as outlined in the NSLS SEAPPM manual, and a portion of this document relating to the inspection procedures to be implemented for the 200-MeV Linac is reproduced herein as Appendix I.

Within the project the designated safety officer will be Project Head, R. Heese, who bears primary responsibility for the safe conduct of operations of the accelerator and the associated building support facilities. In this context it should be noted that Dr. Heese is also Head of NSLS Operations and, as such, is thoroughly familiar with electron Linacs and storage rings. He will be assisted in these duties by the NSLS Safety organization and S&EP representatives as noted on the NSLS Organizational Chart, Fig. 5. In addition to input from the project technical staff and advice from the NSLS ES & H Committee, the Project Safety Officer will be informed and act upon safety concerns conveyed by the NSLS area safety representative appointed by the Department ES & H Coordinator. The designated representative for Building 729 is T. White of the NSLS Mechanical Engineering Section as noted in Appendix II. The area representative has direct responsibility for monitoring both radiation and safety hazards and bringing safety concerns to the attention of the Project Safety Officer and the NSLS ES & H Coordinator.

Approval for this project was required from the Environmental Protection Agency (EPA) under the terms of the National Environmental Policy Act (NEPA). Consequently, an Environmental Assessment (EA) report was prepared by the Brookhaven Area Office of the DOE and is included herein as Appendix III. The conclusion of this EA was a finding of no significant impact, and therefore no need for preparation of an Environmental Impact Statement. Approval of this conclusion by the EPA is also included in Appendix III.

The subject of air activation and subsequent possible radiation at the site boundary from this project, as well as discharge of contaminants to the ground water was discussed in the NEPA request and regarded therein as a negligible hazard. The electron beam will not traverse an air path anywhere in the system under normal operating conditions. Concurrence with this conclusion by the BNL S&EP Division, the DOE Brookhaven Area Office and responsible officials of the U.S. DOE Office of Energy Research are cited in Appendix III. However, since

the scope of the project was changed since the NEPA Environmental Assessment was executed, a separate NESHAPS (National Emissions Standards for Hazardous Air Pollutants) evaluation for the 200-MeV linac alone has been prepared by G. Schroeder of the BNL S&EP Division and is included here as Appendix IV.

2.3 Laboratory Environmental Safety and Health Committee

The Laboratory Environmental, Safety and Health (ES&H) Committee is required by regulations published in the BNL Environment, Safety and Health Standards Manual [3] to review this PSAR and make a recommendation to the Associate Director for Reactor, Safety and Security. The Associate Director's approval is required before construction can begin. In view of the cancellation of the project (SXLS) for which the 200-MeV Linac was originally intended, and the imminent arrival of the Linac from the vendor, we requested a waiver of the requirement for construction of Building 729. This request, and the subsequent approval of the request, are included herein as Appendix V. Building 729 has since been completed, and the Linac components are now on site. Authorization to assemble the components to establish vacuum integrity in the drift tubes and electron gun has been granted by the Associate Director and is also included in Appendix V.

The BNL ES & H Manual also directs the S&EP Division to assist the Department in developing the PSAR and conduct an independent review of the document prior to its submission to the ES&H committee. In addition, S&EP Division personnel assist the Department in implementing the Laboratory safety program and in training NSLS personnel in safety matters.

2.4 Safety Training

The S&EP Division regularly schedules training programs in non-technical areas such as respirator training, crane operation, materials handling, film badge usage, etc. as may be requested by personnel to perform their job assignments. However, there are several topics related to the 200-MeV Linac facility which will require specialized training such as electrical, radiation and radiofrequency safety. Written procedures for securing radiation areas are provided in Section 3.4.2 and written instructions on safe operation of high voltage power supplies are required for the electron gun, klystron modulators, and vacuum pumps as well as potentially hazardous high current power supplies for the DC magnets in the beam transport line downstream of the Linac and will be provided to operations and maintenance personnel by cognizant project engineers. Training to carry out these procedures will also be provided to the operations staff by project engineers.

3. Building 729 Systems

3.1 Introduction

The building is a modular-type structure acquired from an outside vendor. The plan view of Fig. 3 shows an L-shaped structure of approximately 118-foot length and 39.4-foot width with the west end extended an additional 40-feet to join the existing Building 726. The elevation

view of Fig. 4 shows a minimum inside building height of about 14.7-feet on the north side of the Linac enclosure, sloping up to a maximum inside height of about 22.4-feet at the building center. Thus, the interior dimensions of the building are adequate to contain any foreseeable increase in the present 8-foot shielding wall height or additional roof shielding over the Linac or experimental vault. No crane coverage is provided or anticipated.

The electric power distribution for the building has been outlined below, first in terms of the low (120/208-volt) voltage system for building sources such as lighting, heating and ventilation pumps, water system pumps and other small equipment needs such as control console components, fire safety monitors and alarms and communications equipment. A 480-volt, 3-phase system will also be employed for the high power needs such as Linac klystron modulators, electron gun power supplies, and transport magnet power supplies. Relevant safety codes as employed throughout the NSLS complex at the Laboratory are cited and will be implemented. The electrical system contains no unusual features when compared to similar Laboratory facilities such as the NSLS and ATF Linacs and, as such, hazards appear to be marginal in terms of occurrence probability and potential consequences as defined in the BNL ES & H Manual.

Heat and cooling systems are presented as specified by BNL Plant Engineering in Appendix VI. They comprise a forced air system with conventional, closed loop, ethylene glycol/water heat exchangers. Discharge of contaminants to the ground and sewers is neither planned nor expected. Heat exchangers for the deionized and ethylene glycol cooling systems will be mounted on a metal base with angle iron sides to contain any spill. On this basis we regard safety hazards associated with the air and water systems as of negligible consequence and of routine risk. A communications system within the building will be installed, both for safety and information transfer functions.

The access and egress doors and gates are described and indicated on building plan view Fig. 3. Six doors were constructed; however Door 6 on the west side of the building and Door 3 on the east side are intended for egress only and will therefore have no entry knobs. Roll-up door 4 is intended only for equipment access and will otherwise be padlocked closed. The main doors and only designated personnel access entry is door 1 on the west side of 729, door 2 near the control console and door 5 to Bldg. 726. Standard outdoor lighting is provided for doors 1-4 and 6, and asphalt paving leading to door 2 will be provided. Additional exterior flood lights will be installed on the east, west and south building walls to illuminate the access route to doors 1 and 2. Radiation signs will be posted at these access doors indicating that Bldg. 729 is a controlled area in accordance with the regulations specified in the BNL Radiological Control Manual [28]. Doors 1, 2, and 5 will be provided with the Standard controlled access entry system in effect throughout the NSLS, with entry enabled by a BNL ID card reader. Special provisions for access/egress via Kirk key through radiation gates 1 and 2 are described under Linear Accelerator Area Security System, Section 3.4.2, below.

3.2 Building Equipment Services

3.2.1 Electrical Power Distribution System

The electrical power to operate the gun and linac is distributed at 480 volts, 3 phase with a grounded wye system. Power for smaller equipment is distributed by a similar

system at the 120/208 volt level. The installation and operation of this distribution equipment is according to standard industrial practice for this type of equipment and conforms to applicable ANSI National Safety Codes including ANSI spec #39.5 (electrical and electrical measurement and controlling instrument safety requirements), the National Electric Code, Department of Energy General Design Criteria DOE order 6430.1a, DOE/EV-0051-1 electrical safety criteria for research and development activities, and BNL Environment, Health and Safety Standards 1.5.0 and 1.5.2.

All equipment is enclosed in grounded dead front cabinets. All systems operating at voltages above 30 volts RMS are contained inside secured enclosures with locked or interlock protection, or bolted access according to the serviceability of the equipment and the potential hazard.

In equipment where stored electrical energy may be present, a system of discharge bleeders, automatic shorting bars and manual grounding sticks are provided.

The major sources of electrical hazard in the system are:

- A.C. Power Distribution
- Electron Gun System
- Klystron/modulator System
- Magnet Systems
- Controls and miscellaneous equipment

The A.C. Power Distribution System uses conventional design practice and provides for lockout and tagging of all equipment for which these rules are applicable.

3.2.2 Air System

The Heat, Ventilation and Air Conditioning system has been specified by BNL Plant Engineering and is summarized in the attached memo from G. Leskody (Appendix VI). Two independent air handling units are to be provided, each connected to a closed loop ethylene glycol/water heat exchanger. The system provides for a minimum fresh air intake rate of 600 CFM. Air Handling Unit #1 will provide both heating (70°F setpoint) and cooling (74°F setpoint) and will be tied into the sitewide Energy Management Control System (EMCS). A compressed air system at 100 psi is also specified for operating pneumatic valves; the air compressor for this system will supply 43 SCFM from a 120 gallon storage tank. The piping will be designed and tested in accordance with ANSI B31.1 and identified in accordance with BNL ES & H Standard 1.14.0.

3.2.3 Water System

Plant Engineering has also specified (Appendix VI) two closed loop water cooling systems for the facility. The first, an ethylene glycol/water system for building heating/cooling, noted above, provides 575 GPM of water to the two chillers for the two independent air handling units. The glycol system has a total capacity of 80 gallons. In addition, a 55 gallon barrel of glycol will be stored at the facility. This quantity is less than the 250 gallon limit which, if

exceeded, would require a special storage area in accordance with Suffolk County Sanitary Code, Article 12. All potable water connections are protected with backflow prevention devices. The second closed loop system provides deionized (2 M Ω -cm resistivity) cooled water at 71.6°F and a 93 GPM rate for machine components such as the beam transport magnets. Note that the linac vendor will provide a separate, additional deionized water cooling system for the Linac components such as the klystrons, drift tubes and electron gun.

3.2.4 Communication System

The PA system for Building 729 announcements will be made from the console. Speakers will be located throughout the building to keep personnel informed of any occurrence and status within the building. A "plectron" receiver will be installed at the console to alert personnel to any lab-wide emergency.

3.3 Building Access and Egress

Primary access and egress for Personnel will be through doors 1, 2 & 5; door 1 located on the west side, door 2 on the south side and door 5 to Bldg. 726 as shown in Fig 3. Roll-up door 4, located on the west side will be for delivery of materials. Additional egress can be made through door 3 on the east side of Building 729. Door 6 is an emergency exit from the Machine Room only. Doors 3 and 6 will not permit entry into the Building. Doors comply with Chapter 4.1.2 BNL Environmental Safety and Health Standards. Nowhere can anyone be more than 60' from an exit. Emergency lighting is provided by battery pack units. Exits are marked with self-illuminating exit signs, and additional exterior flood lighting will be provided in the area near doors 1 and 2.

3.4 Hazards and Controls

3.4.1 Fire Hazards and Controls

The fire control system has been specified by BNL Plant Engineering in their memo of March 19, 1992, included here as Appendix VI. They specify an extension of the existing wet-pipe system of Building 726 to Building 729 which will provide 63 sprinkler heads in 729 activated by thermo sensitive elements as well as smoke detectors in the air handling system. The Building 729 alarm circuit is monitored at the BNL Fire Station, and two fire hose valves are provided at either end of 729. It is noted that the building is constructed of non-combustible materials. Equipment within the building contains combustible wire insulation as well as interconnecting power and signal cables. No combustible gases or fluids are anticipated. We judge the risk probability of a cable fire to be occasional, and the consequences for personnel injury, equipment loss and program downtime to be marginal as defined in the BNL ES & H Manual. An independent Fire Hazards Analysis has been performed by J. Eckroth of the BNL S&EP Division and is appended as Appendix VII.

3.4.2 Linac Area Security System

Potential radiation levels inside the linac enclosure while the linac is operating qualify the area as a High Hazard Radiation Area as defined in section 3.4.0 of the BNL

Environment Safety and Health Standards, and the interlock system designed for this area meets the requirements set forth in that section.

Design of the interlock system was done by an electrical engineer on the NSLS staff. Advice and concurrence with the design was provided by the NSLS Interlock Working Group, and an independent technical review was done by a committee of NSLS staff members appointed for this purpose. Several changes were implemented during this process, and agreed to by all parties. The departmental review is recorded in the Q.A. documentation maintained by the NSLS. When installed, this system will become part of the inventory of personnel protection systems at the NSLS, with responsibility for testing and configuration control resting with the NSLS Safety Officer. Tests are done by written procedure after any maintenance work, and at least every six calendar months, and records are maintained in an auditable form. This process is periodically audited by the S&EP Representative to the NSLS.

The interlock is a simplified version of a standard NSLS hutch interlock, using the perimeter control, search sequence, emergency stop, and warning provisions of that design. Protection is provided by turning off the linac modulators and gun. There are no interlocked beam stops in the system. There are two independent interlock chains, A and B, comprising switches on doors, contact modules on stop buttons, and linac shutdown devices. These two chains have no common electrical connections and the circuits are implemented differently to minimize the opportunity for common cause failures. Chain A also includes the search sequence and warning circuits, with check station latch-ups, search time-out, and warning interval. This serves as an electromechanical backup to a proper and diligent area search by the linac operator, and is not redundant in hardware. The design calls for chain A to act through the modulator and gun interlock connections in the linac control ladder provided by the vendor. Chain B will operate a dedicated, NSLS-installed contactor in the primary power to the modulator high voltage supply. A lock-out key provided by the vendor will be controlled by the operator-in-charge to prevent unauthorized operation. The two entrance doors will have mechanical locks with the keys administratively controlled by the operator.

The search of the area can be done by one person since the long narrow configuration makes it easy to "sweep". The search is started at check station 1, inside near the downstream door. This door must remain closed and the emergency stop buttons armed from this point on, otherwise the system is returned to the inactive state. The searcher moves through the area, insuring that anyone inside moves out through the exit door ahead of the searcher. After exiting through the upstream door and closing it, the searcher completes the search by pressing check station 2 outside the door. This must be done within two minutes of starting, otherwise the search will trip and must be redone. Completing the search starts the 30 second warning interval with flashing beacons and siren. At the end of the warning interval, permits are provided from the interlock system to the linac. The flashing beacons continue as long as the area is secured, and status lights and signs are provided at the doors and at the control console.

3.4.3 Occupational Health Hazards

The 200 MeV Linac will be housed in a new structure designated Building 729. The occupational health hazards anticipated at this location are associated with the Linac equipment and are addressed in Section 4.3.3 of this document.

3.4.4 Building Hazards Risk Assessment

The building hazards are identified as electrical and fire. Electrical hazards from the building power distribution system are regarded as of remote probability and negligible consequence. The probability of fire, judging from experience with similar installations, is regarded as occasional, with injury to personnel, equipment cost and program downtime of marginal consequence. There are no unusual electrical or fire hazards identifiable in this facility compared to similar facilities elsewhere. Further evaluation of fire hazards is included in the Fire Hazards Analysis of Appendix VII.

4. Linear Accelerator Systems

4.1 General Description of the Linac

The Linac is a commercially built [1] (Beta Development Corp., Dublin, CA) RF electron linear accelerator of nominal maximum energy $E_0 = 200$ MeV, energy range 40-200 MeV, containing four 3-m SLAC iris-loaded drift tubes powered by three 45-MW peak power pulsed Thomson-CSF TH-2128 klystrons operating at the standard S-band frequency of $f_r = 2856$ -MHz. The vendor's block diagram of the complete system is reproduced here for convenience as Fig. 26. The overall length, including electron gun is given on Fig. 3 as 60-feet and the diameter of the vacuum enclosure around the drift tubes is about 85-cm. The beam elevation above the building floor has been fixed at $h=1.4$ -m. The vendor's stated maximum energy performance capability is [1] 222-MeV + buncher energy, and the nominal performance specifications for the machine relating to this report are given by the vendor as [1]:

Beam Energy:	Variable from 40 to 200-MeV
Beam Pulse Width:	1-10 nsec in 1 nsec steps
Pulse Repetition Rate:	1-10 Hz in 1 Hz Steps
Energy Spread at 200-MeV:	$\pm 1\%$
Peak Beam Current:	2A at 1 nsec 1A at 2-10 nsec
Vacuum pressure:	10^{-8} Torr at vacion pumps
RF pulse width:	1.2- μ sec flattop
Klystron Peak Power:	45 MW x 3 tubes
H.V. Pulse Flattop:	2.6- μ sec
Gun peak pulse current:	7A
Gun anode voltage:	120-kV nominal, 150-kV peak
Klystron Modulator Voltage:	48-kV
Klystron Modulator Peak Current:	13.0 - kA

As described in Section 4.2 the peak beam current specs have since been modified to lower values. We intend to operate the Linac in a reduced intensity mode for the intended storage ring application whereby the beam pulse width will be limited to ≤ 1 -nsec and the repetition rate limited to ≤ 2 -Hz. We will operate the gun current at the performance specs of ≤ 7.0 -Amp. These reduced intensity conditions lead to an average current of $\langle I \rangle = 2$ -nAmps and the average power at 200-MeV of $\langle P \rangle = 0.4$ -Watt.

In Section 4.3 we examine the adequacy of the concrete shielding shown in Fig. 3 for radiation hazards from X-Rays generated by electron bremsstrahlung and photoneutrons generated by these photons, both in normal operation and for accidents which we can anticipate. We show that, in the horizontal plane, the shielding thickness is adequate with several exceptions: (1) at the end of the external beam transport line, additional lead and concrete shielding are needed around the Faraday cup to protect radiation workers within Bldg. 729 with an assumed 2000 hour/yr occupancy, (2) additional forward direction and side shielding is needed at several potential accident points in the external line, both to protect personnel within Bldg. 729 and members of the general public outside the 4-foot north shielding wall, (3) at the momentum-selection slits during normal operation, (4) along and at the end of the Linac in accident situations to protect the general public outside the north wall and to protect workers within Bldg. 729 near the maze (gate 1) entry to the Linac cave. For X-Ray and neutron skyshine, we find that the absence of a shielding roof compels us to add lead and concrete shielding above normal beam dump points as well as accident points. For the vault portion of the facility we have specified shielding thicknesses adequate for full intensity (50 nA) Linac operation. In the Linac cave, we specify overhead skyshine shielding only for the reduced intensity (2 nA) mode. An assessment of the accident risks is given in Section 4.3.4.

In Section 4.3.1.5 it is concluded that activation of air from photon and neutron reactions on N^{14} and O^{16} do not pose a radiation problem at the site boundary. The reason for these low activation levels is that we have designed a beam transport system with no air path for the primary electron beam.

In Section 4.3.2 it is concluded that no unusual electrical safety hazards associated with the Linac or beam transport power supplies exists. These supplies are enclosed in grounded, dead-front cabinets with interlocked, locked, or bolted doors according to the serviceability requirements and hazard potential. The NSLS has considerable applicable experience in safe operation of similar power supplies and interconnecting cabling to transport magnets, the electron gun, and klystron modulators of the NSLS Linac.

The occupational health hazards associated with the Linac are identified in Section 4.3.3 as RF power flux greater than 10 mW/cm^2 originating from the klystrons, stray magnetic fields in excess of 10-Gauss from the klystron permanent magnet or the electromagnets of the beam transport system, and conventional lasers used by surveyors to align the Linac tanks and external beam line. No significant health hazards are expected from these sources for the present facility.

We conclude the description of the Linac with an assessment of the numerous accident possibilities and associated risks identified in Sections 4.3.1.1, 4.3.1.2 and 4.3.1.3, evaluated in accordance with the Hazard Assessment Matrix of the BNL ES & H Manual. We

conclude that the most serious radiation risk is a failure of the hard wired radiation monitor interlocks which we propose to implement in order to maintain less than dose limits outside the Linac cave. Such a failure is computed to be non-life-threatening and indeed of marginal potential consequence. Clearly, such accidents will be simulated in fault studies during the commissioning of the facility to validate the predictions of this report. Redundant radiation monitors will be deployed to minimize failure possibility.

4.2 Accelerator Operations

The linear accelerator (LINAC) is a 200 MeV electron machine capable of operating within the following parameters:

Repetition Rate:	1 - 10 Hz
Macro Bunch Length:	1 - 10 nsec
Peak Current over Macrobunch:	1A at 1 nsec 0.75 A at 2 nsec 0.5A at 3 - 10 nsec
Output electron energy:	40 - 200 MeV
Max. accelerated charge capability	3.12×10^{11} e/sec (10 Hz/10 nsec/.5A)
Constrained operating conditions	1.25×10^{10} e/sec (2 Hz/1 nsec/1A)

Due to shielding considerations, the initial operation of the LINAC will be constrained administratively to a maximum accelerated beam current of 1A with a hardwired maximum bunch length and repetition rate of 1 nsec and 2 Hz, respectively, as considered elsewhere in this PSAR and as indicated in the table above. The intended use for the LINAC was to serve as an injector for a compact synchrotron, and these operating parameters were all that was required as a synchrotron injector. However, this PSAR only covers the LINAC and its commissioning, during which the output of the machine will be guided through a beam transport line for analysis and then to a heavily shielded vacuum Faraday cup/beam dump. An Operational Readiness Report is being prepared for this commissioning phase of the LINAC; an Accelerator Safety Envelope containing Operational Safety Limits as required by DOE Orders 5481.1B and 5480.25 as well as BNL ES & H Standards 1.3.3 and 1.3.4 will be prepared based on results of fault studies conducted during the commissioning. Once the LINAC has been commissioned and the acceptance tests performed, there will be no routine operation of the machine. It is envisioned to install a compact synchrotron or an FEL in the facility in the near future to perform experiments; at that time this SAR will be upgraded.

4.3.1 Radiation Hazards and Shielding

4.3.1.1. Electron Gun Radiation Hazards

The electron gun for this linac is similar to, and from the same vendor (Hermosa Electronic, Inc.), as the gun already in use on the NSLS 70-MeV injection Linac. The vendors specifications [1] are 120-kV anode voltage and peak cathode current of 7-amperes with a maximum pulse length capability of 10-nsec and maximum repetition rate of 10-Hz. Under normal operating conditions most of this beam (8-12% loss on the grid of the triode gun) will be transmitted through the gun anode aperture and through the low energy beam transport line into the first linac drift tube, with 30-50% of the beam (vendor's specs, Sect. 4.1) captured

and accelerated to 200-MeV. Thus we expect negligible radiation problems in the gun area. This is the observed situation for the NSLS Linac gun where no special provisions are needed for X-ray shielding, i.e. the vacuum pipe flanges near the gun anode plus the ~ 0.5 -m distance from the anode to the outside of the gun containment cabinet are adequate to attenuate bremsstrahlung from normal anode losses. Under worst fault conditions where the entire gun beam targets on the anode we have a 120-keV electron beam of average current $\langle I \rangle = 7$ Amps $\times (10 \times 10^{-9} \text{ sec}) \times 10 \text{ pulses/sec} = 0.7\text{-}\mu\text{A}$. The radiation source function at 90° to the beam direction for a beam of this energy striking a high-Z target is given in report NCRP-51[4], Appendix E.1, reproduced here for convenience as Fig. 6, as $\dot{D}_{10}I^{-1}(90^\circ, \text{high Z}) = 0.08 \text{ rad-m}^2/\text{mA-min}$. Thus the source strength at $d = 1$ -meter is $\dot{D}_{10}(90^\circ, \text{high Z}, d=1) = 5.6 \times 10^{-5} \text{ rad/min}$ and, using the additional reduction factor of 0.5 specified in NCRP-51 [4], Appendix E.3, for the low-Z (stainless steel) anode, we obtain the 1-meter rate of $\dot{D}_0(90^\circ, \text{Fe}) = 1.7 \text{ mrem/hr}$. This rate would be excessive for radiation workers who may be required to work on the gun within the controlled area where the gun is operated with a "reasonable" assumption of $T \approx 50$ hrs/year occupancy; it would constitute an appreciable fraction of the maximum allowable dose for radiation workers of 1250 mrem/year BNL administrative action levels quoted in the BNL Radiological Control Manual [28], Chapter 2, p. 2-3. Thus, we recommend that the vacuum pipe in the vicinity of the gun anode/grid structure as well as the pipe around the isolation valve and the collimating slits in the low energy beam transport line (see [1], Fig. 2.9, p. 24) be wrapped with the equivalent of 1-mm of lead (Pb) sheet which will attenuate the X-rays by a factor of about 100 as stated in NCRP-51 [4], Appendix E.10, included here for convenience as Fig. 7.

It should also be noted that under our proposed reduced operating conditions for the electron gun referred to in Section 1 of this PSAR, we will reduce the rep rate from 10 Hz to 2 Hz, the pulse duration from 10-nsec to 1-nsec; the gun current will be maintained at 7.0 Amps, thus gaining an additional factor of 50 reduction in radiation levels at the gun from the values cited above. We propose to accomplish these reductions by a combination of administrative controls in the form of instructions to machine operators on these maximum gun operating parameters, hardwired modifications of the rep rate and pulse duration circuits, and pre-set radiation monitors which will shut off the gun anode voltage and concurrently alert operations personnel to a radiation fault condition. The hardware modifications to reduce the gun rep rate and pulse duration will be documented and reviewed by the NSLS Interlock Working Group, together with the interlock from the radiation monitors to the gun high voltage power supply. Maintenance and calibration of the monitors will be performed in a manner similar to other NSLS radiation monitors, presently by the AGS instrumentation group. The relevant monitor for the electron gun is designated as M20 on Fig. 3. Radiation levels at full and reduced intensity operation as well as tests of the interlock are outlined in Section 4.3.4 under Fault Studies.

4.3.1.2 Electron Backstreaming in the Linac

Under normal conditions, electrons generated at any point within the Linac accelerating column (drift tubes) by the primary beam in such processes as secondary emission, residual gas ionization, etc. or by non-beam related phenomena such as arcing can be accelerated backward in the linac and target at the upstream end of the first drift tube. Radiation from these electrons has been observed and measured at the NSLS 70-MeV Linac [5], although the energy

spectrum and intensity has not been measured and is likely variable, dependent on the amount of primary beam loss and the position of origin of the secondaries. Consequently we are unable to estimate a source function for the resultant Bremsstrahlung; however, the radiation shielding necessary to reduce X-ray dose rates to BNL ES & H Standards has been empirically established, and a 4-inch thick lead wall has been constructed around the low energy beam transport pipe of the NSLS Linac immediately upstream of the first drift tube. Accordingly, we will construct a similar shielding wall for the 200-MeV Linac and perform studies under varying Linac operating conditions to insure the adequacy of this shielding with our higher energy machine. It should also be noted that it was not found necessary to build a concrete neutron shield immediately upstream of the lead wall at the NSLS Linac; however, that facility is within a controlled area of the NSLS, whereas for the 200-MeV Linac we are adjacent to the uncontrolled area outside of Building 729. We have therefore extended the external shielding wall southward along the east side of the building, as shown in Fig. 3, to provide 3-feet of concrete neutron shielding. There is no direct line-of-sight through security gate 2 to the point where the low energy beam transport line enters drift tube #1.

4.3.1.3 Linac and Transport Line Prompt Radiation Hazards (Faults)

Under normal conditions the beam will be entirely contained within the vacuum system and we expect negligible losses in the Linac and transport line to the beam dump, except at the momentum slits, labelled point S in Fig. 3, where approximately 50% of the beam [5] will normally be lost. Consequently, all other loss situations considered in this report are faults.

4.3.1.3.1 Accidental Dump at 200-MeV End of Linac

4.3.1.3.1.1 Maximum Credible Accident

The worst accident we can envision is the beam emerging through the vacuum chamber wall at point M, Fig. 3 and impinging directly on the shielding wall. This situation could occur most readily from a steering error in the external H-type bending magnet B1 and emerging through the 1/16" stainless steel (S.S.) vacuum pipe wall at the downstream end of B1 in the direction labelled "B" in Fig. 3. A similar situation could occur at the downstream end of magnet B2 since B1 and B2 are powered by the same power supply; however, in this case, the external beam would be stopped within the beam dump. The beam "B" would then strike the 4-foot thick concrete west shielding wall of the vault at approximately 45° , giving a slant thickness in the concrete of $t_s = 172.4\text{-cm}$. The beam emerging from the vacuum chamber at B1 would be 13.5-cm outside the normal beam axis of this 72.34° bending magnet with normal radius of curvature $\rho = 792\text{-mm}$, as shown in the magnet cross-section view of Fig. 8, and would therefore be making an angle of $\theta = 0.135\text{-rad} = 7.735^\circ$ with respect to the chamber wall. The slant thickness through the $1/16" = 1.5875\text{-mm}$ wall is then $t_w = 11.795\text{-mm} = 9.28\text{ gm/cm}^2$, using a density $\rho_{\text{Fe}} = 7.87\text{ gm/cm}^3$ for iron. The average rate of electron energy loss through the wall can be inferred from the tables of Berger and Seltzer [6] as $\langle dE/dx \rangle = 11.8\text{-MeV/gm/cm}^2$. Thus the energy loss through the 1.18-cm S.S. is $\Delta E = 109.5\text{-MeV}$ and we thus have an $E = 90.5\text{-MeV}$, 2-nAmp electron beam impinging on the concrete shield wall. Berger and Seltzer do not tabulate ranges in concrete, but the ranges for all of the light elements are similar, and we use for concrete the range for 90-

MeV electrons in Aluminum which they give [6] as $R(\text{Al}, E_e = 90\text{-MeV}) \approx 30 \text{ gm/cm}^2$. For the density of shielding concrete we use the value given in NCRP-51, Appendix H.1 of $\rho = 2.35 \text{ gm/cm}^3 = 147\text{-lbs/ft}^3$; this density is quite close to the measured [7] value of $\approx 150\text{-lbs./ft.}^3$ for our concrete. Thus, the 90.5-MeV electrons are stopped in the first 12.77-cm of the concrete, and the remaining thickness of $t = 159.65\text{-cm}$ attenuates the resulting electromagnetic cascade shower.

The X-ray dose rate outside the concrete wall can then be calculated first by using the 0° X-ray source function value from Fig. 6 (NCRP-51, App. E.1) of $\dot{D}_{10}I^1 = 4 \times 10^6 \text{ rad-m}^2/\text{mA-min}$ for high Z targets and reducing this by the factor 0.5 cited in NCRP-51, App. E.3 for concrete. The source dose rate index for the $2 \times 10^{-6}\text{-mA}$ beam is then $\dot{D}_{10} = 4 \text{ rad-m}^2/\text{min}$. The X-ray dose-equivalent index rate is then evaluated from the expression of NCRP-51, Sect. 4.3.2, p. 50, Eq. (2):

$$\dot{H}_{1dx} = \frac{\dot{D}_{10}B_x T}{1.67 \times 10^{-5} d^2} \quad (1)$$

where d is the distance in meters from the source point 0 to the observation point 1, B_x is the shielding transmission ratio, and the factor 1.67×10^{-5} converts the dose rate of Eq. (1) to mrem/hr. T is the occupancy factor at point 1 which we set to unity here. The transmission factor B_x for 90-MeV electrons through the remaining 160-cm of concrete is obtained from NCRP-51, App. E.8, reproduced here as Fig. 9, as $B_x = 9 \times 10^{-4}$. The dose rate from Eq. (1) is then

$$\dot{H}_{1dx} = 84.2 \text{ mrem/hr.} \quad (2)$$

We must also add the dose rate at point 1 (M7 of Fig. 3) from the bremsstrahlung produced by the 200-MeV beam incident on the 1.18-cm slant thickness steel vacuum chamber wall at magnet B1 (pt M). The dose rate index from the 2-nAmp beam on a thick, high Z target at this point is $\dot{D}_{10} = 40 \text{ rad-m}^2/\text{min}$. We must diminish this high-Z source strength by the factor 0.7 cited in NCRP-51, App. E.3 for an iron target, and further reduce $\dot{D}_{10}$ because the $t = 1.18\text{-cm}$ steel thickness does not constitute a range-thick target; the range of 200-MeV electrons in iron is [6] $R(\text{Fe}, 200\text{-MeV}) = 35.0 \text{ gm/cm}^2 = 4.45\text{-cm}$. The reduction factor we adopt here is the fraction of the incident electron energy lost in the steel, $f = .55$. Thus, the source dose rate is reduced to $\dot{D}_{10} = 15.4 \text{ rad-m}^2/\text{min}$. The transmission factor B_x through the 172.4-cm concrete is given by Fig. 9 as $B_x \approx 5 \times 10^{-4}$, and the distance from the source point at magnet B1 to the outer surface of the concrete shield is, from Fig. 3, $d \approx 6.77 \text{ m}$. Then the X-ray dose rate from Eq. (1) is

$$\dot{H}_{1dx} = 10.1 \text{ mrem/hr.} \quad (3)$$

Finally, we can show that the neutron dose rate outside the shield wall due to this accident is negligibly small. For the photoneutron source from the 2-nAmp, 90-MeV beam stopped in 12.77-cm of concrete, the neutron yield from NCRP-51, App.

F.3, reproduced here for convenience as Fig. 10, gives $Y = 1.5 \cdot 10^{10}$ neutrons/sec/ μ A from extrapolation of the Ta(γ ,n) curve. Then, from NCRP-51, App. F.4 reproduced here as Fig. 11, the forward yield per steradian for all (γ ,n) reactions is

$$Y_{sr-1}(0^\circ) = Y_{sr-1}(90^\circ) = .5Y = 7.5 \cdot 10^9 \text{ neut/sec}/\mu\text{A} \quad (4)$$

and the forward neutron fluence from Fig. 11 for a $2 \times 10^3 \mu\text{A}$ beam is

$$\phi_o(0^\circ) = \frac{Y_{sr-1}(0^\circ) \times 10^{-4}}{d^2} = 1.5 \cdot 10^3 \text{ neut/cm}^2\text{-sec} \quad (5)$$

at $d = 1\text{-meter}$. Then, the neutron dose-equivalent index rate is given by NCRP-51, Section 4.33, p. 55, Eq. (10) as

$$\dot{H}_{1dn} = \frac{\phi_o B_n T}{2.8 \cdot 10^{-7} d^2} \quad (6)$$

with $\dot{H}_{1dn}$ the dose rate in mrem/hr with the neutron fluence ϕ_o in neut/cm²-sec, B_n the neutron transmission shielding ratio in rem-cm², d the distance in meters from the source point O to the observation point I and T again the occupancy factor which we again set to unity. The factor $2.8 \cdot 10^{-7}$ is a conversion factor from rem/sec to mrem/hr. To obtain the transmission ratio B_n we have to know the average neutron energy in the evaporation spectrum produced by the photonuclear process. We follow the formulation of Blatt and Weisskopf [8] where it is shown that the photoneutron spectrum $n(\epsilon)$ is in the form of the evaporation spectrum of molecules from a gas in a Maxwell-Boltzmann distribution

$$n(\epsilon) d\epsilon = K \sigma_c(\epsilon) \epsilon e^{-\epsilon/kT} d\epsilon \quad (7)$$

where σ_c is the cross section for formation of the compound nucleus C at excitation energy E_c^* , $\epsilon = E_n$ is the kinetic energy of the emitted neutron, and T is the temperature of the residual nucleus Y at excitation energy E_y^* after the neutron has been emitted. The cross section σ_c is a slowly varying function of the excitation energy and is assumed to be constant for present purposes and incorporated into the proportionality constant K . The neutron energy is related to the compound nucleus excitation $E_n = E_M - E_c^*$ where E_M is the maximum neutron energy, attained when the residual nucleus is left in its ground state $E_y^* = 0$. The average neutron energy $\langle E_n \rangle$ in the spectrum of Eq. (7) is readily obtained by elementary integration as [29]

$$\begin{aligned} \langle E_n \rangle &= \frac{\int_0^{E_M} E_n n(E_n) dE_n}{\int_0^{E_M} n(E_n) dE_n} \\ &= kT \left[\frac{2 - e^{-x} (x^2 + 2x + 2)}{1 - e^{-x} (x + 1)} \right] \end{aligned} \quad (8)$$

where $x = E_M/kT$. Eqs. (7) and (8) are shown [9] in Figs. 13 and 14 in the interval $X = 0$ to

10. The spectrum of Fig. 13 shows that the most probable neutron energy is kT ; however, from Fig. 14 we see that the average neutron energy is generally greater than kT since the spectrum has an extensive high energy tail. To evaluate $\langle E_n \rangle$ we need E_M and kT for the particular photoneuclear reaction. For E_M we have

$$E_M = E_{\gamma 0} - E_n \quad (9)$$

where $E_{\gamma 0}$ is the energy of the absorbed gamma ray and E_n is the binding energy of the emitted neutron to the parent compound nucleus. For heavy nuclei ($A > 100$) such as Pb, Hayward [10] notes that the peak of the photoneuclear absorption cross section (the giant resonance) occurs at an energy $E_{\gamma 0}$ which can be approximated as $E_{\gamma 0} = 80/A^{1/3}$ MeV. For Pb this expression gives $E_{\gamma 0} = 13.52$ MeV $= E_{\gamma}^*$. The experimental photoneutron peak energies for the most abundant isotopes of the elements normally used in shielding have been tabulated by Fuller [11] and Berman [12] and are given below together with neutron binding energies for these isotopes computed from atomic mass data [13]. The calculation of E_M assumes only (γ, n) reactions and not $(\gamma, 2n)$, etc.

TABLE I

Isotope	$E_{\gamma 0}$ (MeV)	E_n (MeV)	E_M (MeV)	kT (MeV)	$\langle E_n \rangle$
C ¹²	22.9	18.72	4.2		
O ¹⁶	22.3, 24.2	15.66	7.1	6.5	~ 8
A ²⁷	21.3	13.06	8.2	9.0	~ 10
Si ²⁸	19.8, 20.8	17.18	3.1	4.0	~ 10
Ca ⁴⁰	19.9	15.64	4.3	3.0	5.9
Fe ⁵⁶	16.9	11.20	5.7	1.6	2.6
Cu ⁶³	16.8	1.54	15.3	1.0	2.0
Pb ²⁰⁸	13.5	7.37	6.1	1.0	1.9

For the temperatures in Table I, the values have been taken as the energy at the peak of the measured neutron spectra [11] since the statistical theory result of Blatt and Weisskopf [8] giving $kT = (E_{\gamma}^*/a)^{1/2}$ with values of the factor a obtained by them appears to be only in rough agreement with the data on light nuclei. Also, the values of $\langle E_n \rangle$ from Eq. (8) are too small for $X = E_M/kT < 1$ and we have used estimates from the experimental data for Ca⁴⁰ and lighter elements. For Fe⁵⁶ and heavier elements, the results of Eq. (8) given in Fig. 14 are in excellent agreement with the data.

Finally, given the value of $\langle E_n \rangle$ we can estimate the neutron transmission shielding ratio B_n for neutrons emanating from the 12.8-cm concrete thickness in which the electron beam stops. Since the composition of shielding concrete given in the Particle Properties Compilation [14] is: O₂ = 52%, Si = 32.5%, Ca = 6%, Al = 4%, Fe = 2% and Na = 1.5%, we consider only O¹⁶ and Si²⁸ contributions and an average neutron energy $\langle E_n \rangle$

≈ 9 -MeV. Then Fig. (12) gives for the remaining $t = 159.6$ -cm (375 -gm/cm²) of concrete, $B_0 \approx 3 \cdot 10^{-13}$ rem-cm². Then Eq. (6) gives for the negligible neutron dose outside the shielding wall

$$\dot{H}_{14n} = \frac{(1.5 \cdot 10^3)(3 \cdot 10^{-13})}{2.8 \cdot 10^{-7}(1.596)^2} = 6.3 \cdot 10^{-4} \text{ mrem/hr.} \quad (10)$$

Thus, the sum of Eqs. (2) and (3) give $\dot{H} = 94.3$ mrem/hr. for the maximum credible accident with the reduced intensity (2-nA) beam. Even the factor of 25 from the maximum Linac capability would not produce a lethal dose for any reasonable assumption of occupancy for a radiation worker with this fault condition. We will nonetheless put lead shielding at the downstream end of magnet B1 to stop the primary electron beam and attenuate the resultant electromagnetic cascade. The range [6] of the emerging 90-MeV electrons in Pb is 17.8 gms/cm² $= 1.57$ -cm. The cascade can be estimated from Heisenberg's approximation [15] as quoted by Rossi [16] for the number of electrons $N(\tau)$ with energy greater than E at depth τ (in radiation lengths X_0) in the absorber initiated by an incident electron of energy E_0 .

$$N(\tau) = \left[\frac{y-B}{\tau(\tau-A)} \right]^{1/2} \exp[-\tau + 2(y-B)(\tau-A)^{1/2}] \quad (11)$$

where A and B are empirical constants $A = 1.4$, $B = .56$ and $y = \ln(E_0/E)$. Eq. 11 is shown out to $\tau = 60 X_0$ in Fig. (15); we see that the 200-MeV shower peaks at $\tau_{\text{peak}} = 6.6 X_0$ with $N(6.6 X_0) = 111$ electron/incident electron and then decreases exponentially. We are down to 10^3 electrons/incident electron at $\tau = 35 X_0$. In passing through the $t = 1.18$ -cm. steel vacuum chamber wall with $X_0(\text{Fe}) = 1.75$ -cm [14] we have only gone through $.67 X_0$. For lead, $X_0(\text{Pb}) = 0.56$ -cm so we need $t_{\text{Pb}} = 19.6$ -cm. Actually, we will reduce the X-ray dose rate with this lead thickness by more than the factor of 10^3 decrease in electron beam intensity because the electron energy has clearly been reduced to less than the 1-MeV needed to generate bremsstrahlung which can create e^+e^- pairs and thus increase $N(\tau)$ when we are beyond τ_{peak} . The lead will also reduce the gamma-ray component of the shower by the factor $e^{-11.76} = 7.8 \cdot 10^{-6}$ assuming that the average γ -energy in the shower is $E_\gamma \approx 21$ -MeV (See Eq. 15 and Fig. 25) and using the total linear absorption coefficient $\mu_\gamma = 0.6$ cm⁻¹ [17].

4.3.1.3.1.2 Dump of Straight-Through 200-MeV Beam

Another possible accident with the external bending magnets is complete loss of power in magnet B1. The straight-through beam will then pass through the 1/16" steel vacuum chamber wall and the 6 cm steel backleg yoke of magnet B1 (an H-magnet) at a slant angle of $\phi = 58.7^\circ$ relative to the normal as computed from the radii of curvature of the beam and yoke wall of $\rho_b = 792$ -mm and $\rho_{yoke} = 927$ -mm in Fig. 8. The effective steel thickness is then $t = 11.85$ -cm, which is considerably larger than the 4.45-cm range of 200-MeV electrons in steel. This thickness, with $X_0 = 1.76$ -cm [14] is $\tau = 6.73 X_0$ and we can then refer to the cascade calculation of Fig. 15 to obtain the number of electrons in the beam as $N_e \approx 111$ /incident electron, i.e. the effective beam impinging on the 4-ft. concrete west wall of the vault is 222-nA. However, we are beyond the peak of the cascade and the average

electron energy is therefore not greater than 1-MeV. For the present calculation we assume that the remaining electrons in the cascade are produced mainly by the 0.511-MeV gammas from positron annihilation interacting with the electrons of the Fe atoms via either photoelectric absorption or Compton scattering, giving $E_e = 0.5$ -MeV. Use of Fig. 6 gives the X-ray source function at the concrete surface of $\dot{D}_{10} I^{-1} = 0.9$ rad-m²/mA-min. This value decreases by a factor of 0.5 as cited in NCRP-51, App. E.3. The source dose rate index is then $\dot{D}_{10} = 1.0 \cdot 10^{-4}$ rad-m²/min. The transmission factor B_s in Eq. (1) through the $d = 121.9$ -cm concrete is estimated by extrapolation of the $E_e = .5$ MeV curve of Fig. 9 to be $B_s = 3 \cdot 10^{-9}$ and Eq. (1) gives a dose rate in the controlled area outside the 4-ft. wall as $\dot{H}_{14.4} = 1.2 \cdot 10^{-8}$ mrem/hr, completely negligible. A larger dose rate is incurred from the primary bremsstrahlung originating in the first 4.45-cm of the steel yoke. The 0° X-ray source strength from this target is given in Fig. 6 as $\dot{D}_{10} I^{-1} = 2 \cdot 10^7$ rad-m²/mA-min and, for our $I = 2 \cdot 10^{-4}$ mA beam and diminishing the source strength by the factor 0.7 for Fe as given in NCRP-51, App. E.3, we have $\dot{D}_{10} = 28$ rad-m²/min. This dose rate is attenuated exponentially by the remaining $t = 7.4$ -cm of Fe with the linear absorption coefficient at 21-MeV (actually, for Cu) of $\mu_a = .28$ cm⁻¹ given by Bethe and Ashkin [17] to $\dot{D}_{10} = 3.53$ rad-m²/min. After passing through 121.9-cm of concrete at a distance of $d = 4.91$ -m the X-ray transmission factor from Fig. 9 is $B_s = 6 \cdot 10^{-3}$ and Eq. 1 gives a dose rate $\dot{H}_{14.4} = 52.6$ mrem/hr, a value not much lower than the maximum credible accident discussed in the preceding section. Again, it would be prudent to provide sufficient shielding to reduce the highest attainable dose rate (the factor of 25 in beam intensity) by a factor of about 1000 to limit the maximum dose rate for this fault in the controlled area to 2.5 mrem/hr. Using an attenuation factor of 0.6 cm⁻¹ in Pb [17], we required $t = 10.7$ -cm of Pb in the 0°-direction downstream of magnet B1.

The neutron dose from this $I=2$ nA accident can again be estimated by the preceding discussion. The yield given in Fig. 10 from linear extrapolation of the $Ta(\gamma, n)$ curve to $E_\gamma = 200$ -MeV is $Y = 3 \cdot 10^{10}$ neu/sec/ μ A and the forward yield per steradian from NCRP-51, App. F.4 is $Y_{s,0}(0^\circ) = 1.5 \cdot 10^{10}$ and the 0° fluence from Eq. 5 is $\phi_0(0^\circ) = 3 \cdot 10^3$ neu/cm²-sec at 1-meter. The average photoneutron energy from neutrons produced in the 4.45 cm Fe target and required to evaluate the transmission ratio B_n is $\langle E_n \rangle = 2.6$ -MeV from Table I and, from Fig. 12, we get for $\tau_{concrete} = 286.5$ gm/cm², $B_n = 1.5 \cdot 10^{-12}$ rem-cm². Then, at $d = 4.91$ -m, Eq. 6 given $\dot{H}_{14.4} = 6.7 \cdot 10^{-4}$ mrem/hr. So the neutron dose is also negligible here. Note that no credit was taken for neutron attenuation in the remaining 7.4 cm of Fe and 10.7 cm of Pb.

4.3.1.3.1.3 Levels in Uncontrolled Area Outside 4-Ft. Wall

The dose levels along the 200-MeV beamline outside the 4-foot north wall are of particular concern since this is an uncontrolled, general public area for which we take a maximum permissible dose rate of 0.25 mrem/hr to keep annual doses below 25 mrem with reasonable assumptions for occupation times during the fault conditions described below. For the full 200-MeV beam dump fault into the yoke of magnet B1 described above, we take the 90° X-ray source function for high-Z from Fig. 6 as $\dot{D}_{10} I^{-1} = 6 \cdot 10^3$ rad-m²/mA-min, and for $I = 2$ -nA, obtain the source strength $\dot{D}_{10}(Fe, 90^\circ) = 1.2 \cdot 10^3$ rad-m²/min. The sidewise thickness of the 6-cm iron yoke of B1 is $t = 5.7$ -cm and the attenuation of X-rays in this thickness, from the effective electron energy of 100-MeV of Fig. 21 and using the absorption coefficient $\mu_a = .28$ cm⁻¹ [1], from Fig. 18 for Cu and mean X-Ray energy of $\langle E_\gamma \rangle = 12$

MeV in Fig. 25, is 0.203 which reduces the source strength to $\dot{D}_{10} = 2.43 \cdot 10^{-3}$ rad-m²/min. At a source to field point distance $d = 2.88$ -m, and a transmission ratio from Fig. 9 of $B_x = 5 \cdot 10^{-3}$ through 121.9-cm of concrete, for $E_e = 100$ MeV we obtain the dose rate from Eq. (1) of $\dot{H}_{1d,x} = .088$ mrem/hr. Thus, we require no additional side shielding other than the yoke of magnet B1. For the worst case scenarios with full (factor of 25) Linac intensity, we would require a factor of 8.76 additional attenuation which is accomplished with 3.4-cm of Pb. Thus, the total Pb shielding in the 0° direction downstream of B1 is 10.7 cm long and 6.8 cm wide. The neutron dose outside the 4-ft. north wall is, from the preceding discussion, negligible.

In addition to an accidental 200-MeV beam dump at magnet B1, other points upstream of this location could be targeted. In Fig. 16 we show an expanded view of the region immediately downstream of the end of the Linac (tank 4). The beam emerges through a 1-cm diameter hole in a 1-inch thick copper flange at the end of tank 4 and passes through a 1-inch diameter pneumatic valve (valve V1 of Fig. 3) of gate thickness 1/4-inch stainless steel approximately 62-cm downstream of the flange. Both the Cu flange and valve gate could be accidentally targeted. The vendor will provide an interlock to turn off the beam when the valve is closed; failure of the interlock will result in 200-MeV beam passing through the 6.35-mm gate, which is thin compared to the 4.45-cm range in Fe, and the resulting 141-MeV beam either targeting on the yoke of the B1 magnet if the magnet is off as discussed in the preceding section or targeting along the inner vacuum chamber wall of magnet B1. The resulting cascade will be attenuated by the shielding downstream of B1 as discussed in 4.3.1.3.1.1. X-rays and neutrons generated in the 6.35-mm steel gate would then be a potential hazard only in the 90° direction through the 4-foot north concrete wall. The X-ray source strength of $\dot{D}_{10}(\text{Fe}, 90^\circ) = 1.2 \cdot 10^{-2}$ rad-m²/min used in 4.3.1.3.1.3 is then applicable here, but we reduce this value to $\dot{D}_{10}(\text{Fe}, 90^\circ) = 3.54 \cdot 10^{-3}$ since only 29.5% of the beam energy is deposited in the valve gate. Taking no credit for additional attenuation provided by the steel of the valve, the transmission ratio through the 121.9-cm north wall from Fig. 9 is again $B_x = 5 \cdot 10^{-3}$ and Eq. (1) gives the dose rate outside the wall at distance $d = 2.88$ -m of $\dot{H}_{1d,x} = .128$ mrem/hr. Thus, we again require no additional shielding here to protect the uncontrolled area outside the north shielding wall, although again it would be prudent to add 3.9-cm of Pb along the north side of the gate valve to obtain the additional factor of 12.8 attenuation required to reduce the dose rate to 0.25 mrem/hr for full intensity (50 nA) Linac operation. The neutron dose rates outside the 4-foot wall are again negligible here.

A more serious radiation problem would result from a mis-steering accident where the 200-MeV beam targets on the 1-inch thick Cu flange at the end of tank 4. Using $\rho = 8.96$ -gm/cm³ [14] the Cu thickness of 22.76-gm/cm² is less than the $R = 33.88$ -gm/cm² range of 200-MeV electrons in Cu; however, the resulting scattered electrons emerging from the flange would target appreciably on the 1-inch diameter vacuum pipe between the flange and the gate valve, or on the valve body itself. So it seems reasonable here to assume in the dose calculation that the entire beam targets on the flange, and use the full X-ray source strength of $\dot{D}_{10}(\text{Cu}, 90^\circ) = 1.2 \cdot 10^{-2}$ rad-m²/min of 4.3.1.3.1.3. Again taking no credit for shielding provided by the ~ 3-inch thickness of the Cu flange, the X-ray dose rate outside the 4-ft. north wall from Eq. (1) at $d = 2.88$ -m and again with $B_x = 5 \cdot 10^{-3}$ is $\dot{H}_{1d,x} = .43$ mrem/hr. Thus, we again would require no additional shielding with the $I = 2$ -nA beam, but a prudent approach would be to add an additional 5.8-cm of Pb shielding along the north side of the exit flange and 62-cm of vacuum pipe between the flange and gate valve to accommodate the possible

accidental operation of the Linac at full (factor of 25) intensity.

4.3.1.3.1.4 The Vault Entry Maze at Security Gate 1

The accident discussed in 4.3.1.3.1.3 for which the entire 200-MeV beam targets on the 1-inch Cu exit flange of the Linac presents the most serious problem for the entry maze at Gate 1 on Fig. 3. The formulation for the X-ray dose rate at the outside aperture of the maze is given in NCRP-51 [18] as

$$\dot{H}_{1,n} = \frac{\dot{D}_0 \alpha_1 A_1 (\alpha_2 A_2)^{n-1}}{(d_1 d_2 d_3 \dots d_n)^2} \quad (12)$$

where $\dot{D}_0$ is the previously defined source absorbed dose rate index at 1-meter (rad-m²/min), α_1 is the reflection coefficient of the material at the first reflection point, α_2 is the reflection coefficient at the 2nd and subsequent reflections, A_1 is the surface area irradiated by X-rays at the first reflection (m²), A_2 is the cross-sectional area of the maze, i.e. H x W (m²), d_1 is the distance from the source to the first reflecting wall (m), d_2 the distance from the 1st to 2nd wall (m), etc. The reflection coefficient is given in NCRP-51, App. E.15, and reproduced here for convenience as Fig. 17.

The worst case in terms of X-rays entering the maze appears to be a total 200-MeV beam dump at the end of the Linac on the Cu exit flange as discussed above in 4.3.1.3.1.3. The X-ray source strength at 90° to the electron beam direction was estimated there as $\dot{D}_0 = 1.2 \cdot 10^{-2}$ rad-m²/min for $I = 2$ nA. To evaluate the reflection coefficient we need the incident gamma-ray energy, which we take here to be the average photon energy at 90° in the Bremsstrahlung spectrum from incident $E_0 = 200$ -MeV electrons, which was obtained by Blumberg and Perlman [19] from integration of the Bremsstrahlung cross-section given by Bethe and Ashkin [17]. The photon energy spectrum is

$$n(E_\gamma) = \frac{1}{E_\gamma} \left[\frac{4}{3} - \frac{4}{3} \left(\frac{E_\gamma}{E_0} \right) + \left(\frac{E_\gamma}{E_0} \right)^2 \right] \quad (13)$$

and the average photon energy in the spectrum is

$$\langle E_\gamma \rangle = \frac{\int_{E_{\min}}^{E_0} E_\gamma n(E_\gamma) dE_\gamma}{\int_{E_{\min}}^{E_0} n(E_\gamma) dE_\gamma} \quad (14)$$

which is easily evaluated to give

$$\langle E_\gamma \rangle = E_0 \left[\frac{4(1-y) - 2(1-y^2) + (1-y^3)}{-4(\ln y) - 4(1-y) + 3/2(1-y^2)} \right] \quad (15)$$

with $y = E_{\min}/E_0$. It is necessary to provide a low energy cut-off $E_{\min}$ in the integration since Eq. (13) exhibits the well-known "infrared catastrophe" as $E_\gamma \rightarrow 0$. The value of $\langle E_\gamma \rangle$ is

somewhat sensitive to the choice of $E_{\min}$. For present purposes we look at the absorption coefficients μ_x at low photon energy given by Bethe and Ashkin [17] and reproduced here as Fig. 18. For Cu the coefficient is rising rapidly below $E_\gamma \approx .5$ (mc²) and it seems reasonable to take $E_{\min} \approx 0.2$ (mc²) ≈ 0.1 -MeV where the photons will be appreciably attenuated in the 0.11-cm steel vacuum pipe wall. Eq. 15 is evaluated in Fig. 25 for this choice of $E_{\min}$ [27] and, for an effective electron energy of 100-MeV as given in Fig. 21 for 90° bremsstrahlung, results in an average photon energy of $\langle E_\gamma \rangle \approx 12$ MeV. This energy is beyond the range of Fig. 17 and we make an extrapolation to obtain $\alpha_1 \sim 2.3 \cdot 10^{-3}$ for normal incidence on concrete. The area A_1 of the south wall of the maze is given approximately by the four foot width of the entry door and the eight foot height of the wall as $A_1 \sim 2.97$ m². The distance d_i from the source to the south maze wall from Fig. 3 is $d_i = 4.23$ m and the average distance from the wall to the north corner of gate 1 is $d_i \sim 3.56$ m. Then Eq. 12 gives

$$\dot{H}_{1,r1} = 1.2 \cdot 10^{-2} \frac{\text{rad-m}^2}{\text{min}} \frac{(2.3 \cdot 10^{-3})(2.97)\text{m}^2}{(4.23)^2 \text{m}^2 (3.56)^2 \text{m}^2} = 3.61 \cdot 10^{-7} \frac{\text{rem}}{\text{min}} = .022 \frac{\text{mrem}}{\text{hr}} \quad (16)$$

This is a negligible dose rate for radiation workers in the controlled area outside gate 1 and thus no additional shielding is needed for X-Rays on the south side of the Linac exit flange, one inch pipe and gate valve. We have also evaluated the case of a double reflection from the maze east wall and south wall and find the X-Ray dose rate outside the maze to be negligible.

Neutrons leaking through the maze can also pose a radiation hazard. In NCRP-51 the dose rate $\dot{H}_M$ (mrem/hr) is given in terms of the neutron flux ϕ_m (neutrons/cm²-sec) incident on the entrance aperture of the maze as [18]

$$\dot{H}_M = \frac{K\phi_m B_{nm}}{270} \quad (17)$$

where $K=8$ for a two-legged maze, $K = 4$ for a 3-legged maze, etc. and the factor of 270 is the neutron fluence rate per unit dose - equivalent index rate for thermal neutrons. The neutron flux ϕ_m can be evaluated from the source fluence for the 200 MeV 2-nA beam dump into the range thick Fe of Section 4.3.1.3.1.2 of $\phi_o(0^\circ) = \phi_o(90^\circ) = 3 \cdot 10^3$ neut/cm²-sec and, at a distance of $d = 1.52$ m from the source to the maze entrance, we have $\phi_m = \phi_o/d^2 = 1.3 \cdot 10^3$ neutrons/cm² sec. The neutron transmission ratio B_{nm} through the maze is evaluated from NCRP-51, App. F.11, reproduced here as Fig. 19. For a maze of width $W = 4$ feet, height $H = 8$ feet, the centerline distance through the maze in units of $\sqrt{HW}$ is 2.8 and Fig. 19 gives $B_{nm} \sim 7.5 \cdot 10^{-2}$. Then, with $K = 8$, Eq. 17 gives $\dot{H}_M = 2.9$ mrem/hr which is sufficiently close to the dose limit for radiation workers that it would be prudent to position concrete shielding along the south side of the Linac exit flange, one inch vacuum pipe and exit valve. For the average neutron energy from a Cu target in Table I of $\langle E_n \rangle = 2$ MeV it is seen from Swanson [20] that the tenth value layer thickness (TVL) for neutrons in concrete, reproduced here as Fig. 20, is $\text{TVL} \sim 73$ gm/cm² = 31 cm. Since the neutron attenuation from thickness t is $10^{-t/\text{TVL}}$, and Fig. 20 gives the 2nd tenth value layer thickness $\text{TVL}_2 \sim 80$ gm/cm² = 34 cm, we would need $t = 1.46 \text{ TVL} = 45.3$ cm of concrete to reduce the full Linac intensity (factor of 25) dose rate to < 2.5 mrem/hr. We see from Fig. 16 that it will be cumbersome to provide that much concrete along the flange-to-valve region downstream of the end of the Linac; however other light elements tabulated by Swanson [20] are not a significant improvement over

concrete (vz TVL of H₂O = 22 cm). Even borated polyethylene would not provide a significant improvement over concrete; the TVL for 30% Boron-poly is, for example 27-cm as seen in Fig. 28 [21]. Note also that it would be possible to design a more complex labyrinth at gate 1 but this would further crowd an already congested and limited area. We will, however, be able to get most of the desired 45-cm concrete on the south side of the flange-to-valve region and the equivalent of the entire amount if heavy concrete is available. [30]

4.3.1.3.1.5 Skyshine in Uncontrolled Areas Adjacent to Bldg. 729

Skyshine radiation to nonproject associated workers in Buildings 726, 727 and 728 as well as the general public in uncontrolled areas adjacent to Bldg. 729 poses a particularly serious problem for this facility since we do not plan to use roof shielding over the Linac or transport line - beam stop vault. NCRP-51 gives an expression [22] for absorbed X-Ray dose index rate $\dot{D}_{1s,d_s}$ (rad/min) as

$$\dot{D}_{1s,d_s} = 2.5 \cdot 10^{-2} \dot{D}_{10} \Omega^{1.3} / d_s^2 \quad (18)$$

where Ω (sr) is the solid angle subtended at the source by the periphery of the shielding walls, $\dot{D}_{10}$ is the source dose index rate previously defined (rad-m²/min) and d_s is the straight line distance (m) between the source and point where the dose rate is to be evaluated. In section 4.3.1.4 we consider skyshine doses during normal operation from the beam stop and momentum slits. Here we address accident situations. Clearly, one of the most serious such dumps is the maximum credible accident situation at point M of Fig. 3. The 200 MeV, I = 2 nA beam will be stopped in the $t_v = 1.18$ cm slant distance of the vacuum chamber wall and the first $t_{pb} = 1.57$ cm of the 19.6 cm of Pb we will install at this point. Following the procedure of Section 4.3.1.3.1.1 we obtain the X-Ray dose rate index at 90° for high Z targets from Fig. 6 as $\dot{D}_{10} = .012$ rad m²/min and reduce that rate by a factor of $f = .55$ since the steel is not range thick, to obtain $\dot{D}_{10} = 6.6 \cdot 10^{-3}$ rad-m²/min. The solid angle Ω subtended at a point within an enclosure bounded by shielding in the form of a polygon of L lines at height H above the point has been evaluated [23] by numerical integration of the solid angle increment $d\Omega = \sin\theta d\theta d\phi$ and is summarized for the various points of interest given in Fig. 3 in Table II.

Table II. Solid Angles Subtended by Points Within Bldg. 729 Shielding

<u>Point</u>	<u>Ω(Sr)</u>	<u>Point</u>	<u>Ω(Sr)</u>
Beam Dump D	4.73789	After tank 3, pt. 3	4.06915
Momentum Slit S	4.74401	After tank 2, pt. 4	4.02967
Maximum Accident M	4.66934	After tank 1, pt. 5	4.00142
Straight Thru, pt. 1	4.50809	After elect. gun, pt. 6	3.91011
End of Linac, pt. 2	4.18204		

The height of the eight foot shielding above the 1.4 m beam elevation is $H = 1.038$ m for Table II. Using the value of Ω at point M and the distance $d_s = 3.387$ m to the outside of the four foot north wall, the nearest distance to an uncontrolled area, we obtain from Eq. 18 the X-Ray skyshine dose rate $\dot{D}_{1s,d_s}$ (Fe,M) = 6.4 mrem/hr. Next, we

add to this rate the dose rate from the remaining 90 MeV beam penetrating the downstream Pb. Figure 6 gives $\dot{D}_{10}(90^\circ, \text{Pb}) \sim 8 \cdot 10^{-3} \text{ rad m}^2/\text{min}$ which contributes an additional X-Ray dose rate $\dot{D}_{1s,da}(\text{Pb}, \text{M}) \sim 7.8 \text{ mrem/hr}$. Thus, the total X-Ray dose outside the north wall is $\dot{D}_{1s,da}(\text{tot}) = 14.2 \text{ mrem/hr}$, which far exceeds the dose limit of 0.25 mrem/hr used herein. We can attenuate the X-Rays by the required factor of 56.8 using the absorption coefficient for Pb of $\mu_x = .65 \text{ cm}^{-1}$ from Fig. 18 for an equivalent electron energy on Fe of 100 MeV from Fig. 21 and an average bremsstrahlung energy of $\langle E_\gamma \rangle = 12 \text{ MeV}$ from Fig. 25. The corresponding absorption coefficient for 90° bremsstrahlung for 90 MeV electrons incident on the 1.57 cm of Pb is obtained from an effective electron energy of 50 MeV from Fig. 21 and a mean photon energy of $\langle E_\gamma \rangle = 6.67 \text{ MeV}$ from Fig. 25, giving $\mu_x(\text{Pb}) = 0.5 \text{ cm}^{-1}$ in Fig. 18. The resulting transcendental equation to reduce the dose rate to 0.25 mr/hr is solved to give the required lead thickness of $t_{\text{pb}} = 7.37 \text{ cm}$. For full intensity (factor of 25) a similar iteration procedure gives a total of $t_{\text{pb}}(\text{tot}) = 13.52 \text{ cm}$. It would be prudent to use this thicker value above the exit pipe and 19.6 cm long Pb shower attenuator at point M.

For neutron skyshine from point M, NCRP-51 [22] gives the neutron flux rate at any point S at distance d, < 20 m from the source point as

$$\phi_{s,d} = 5.4 \cdot 10^{-4} \phi_o \frac{\Omega}{2\pi} \text{ neutrons/cm}^2\text{-sec} \quad (19)$$

where ϕ_o is the previously defined source fluence at $d = 1 \text{ m}$ in $\text{neutron/cm}^2 \text{ sec}$. To obtain the fluence from the 2 nA, 200 MeV beam in the 1.18 cm of steel pipe wall, we again use the procedure of Section 4.3.1.3.1.1 to obtain, from Fig. 10, the yield $Y \approx 3 \cdot 10^{10} \text{ neutrons/sec-}\mu\text{A}$ and, from Fig. 11, the 90° yield per unit solid angle $Y_{sr,1}(90^\circ) = .5Y = 1.5 \cdot 10^{10} \text{ neut/sec } \mu\text{A}$.

For the 90° fluence, Eq. (5) with $I = 2 \cdot 10^{-3} \mu\text{A}$ gives

$$\phi_o(90^\circ) = Y_{sr,1}(90^\circ) \times 10^{-4} I / d^2 = 3 \cdot 10^3 \text{ neut/cm}^2\text{-sec} \quad (20)$$

at $d = 1 \text{ m}$. Further reduction by the factor of $f = .55$ to account for the fact that the steel wall is not range thick gives $\phi_o(90^\circ, \text{Fe}) = 1.65 \cdot 10^3$. Substituting this fluence into Eq. 19 again with the Table II value of Ω for point M gives $\phi_{s,da} = 0.66 \text{ neutrons/cm}^2\text{-sec}$. Using the equivalent dose rate for a fission spectrum [24] of $7.5 \text{ neutrons/cm}^2\text{-sec} = > 1 \text{ mrem/hr}$, the neutron dose rate is only $\dot{D}_{n,s} \sim .09 \text{ mrem/hr}$. A similar calculation for the remaining 90 MeV electrons stopping in the lead downstream of the steel wall gives an additional 2/3 of the above neutron dose, for a total skyshine neutron dose rate of $\dot{D}_{n,s}(\text{tot}) \sim .15 \text{ mrem/hr}$. We have taken no credit for the attenuation of the photoneutrons in the 13.5 cm of Pb above point M. The additional dose rate from the neutrons is not entirely negligible compared to the .25 mrem/hr from the X-Rays which we achieved with the Pb shielding. Including the maximum intensity condition, it would be prudent to attenuate the neutron skyshine dose by a factor of about 15 which, from the discussion of Section 4.3.1.3.1.4, would require a thickness $t = 1.18 \times \text{TVL}$ where the tenth value layer thickness of concrete from Swanson's tabulation [20] is $\text{TVL}_{10} = 31 \text{ cm}$. Thus, we need $t = 36.6 \text{ cm}$ of concrete above the lead at point M, which is inconvenient.

A less severe accident from the point of view of skyshine would

result from the straight through (point 1 of Fig. 3) 200 MeV, $I=2\text{nA}$ beam stopping in the $t = 11.85\text{ cm}$ Fe slant distance of the transport magnet yoke because, from Fig. 8, it is seen that an additional 14.75 cm of steel yoke exists above the beam target point. From the above discussion of the accidental dump at point M, we see that the X-Ray source dose rate index is $\dot{D}_{10} = .012\text{ rad m}^2/\text{min}$, and with the solid angle at point 1 from Table II of $\Omega = 4.50809\text{ sr}$ and the distance $d_s = 2.879\text{ m}$ to the area outside the north wall, we have from Eq. 18 the dose rate index of $\dot{D}_{1s,da} = 15.38\text{ mrem/hr}$ without the 14.75 cm Fe yoke shielding. With the yoke, we can use the Fig. 18 linear absorption coefficient, again noting from Fig. 21 that the effective electron energy is 100-MeV for 90° bremsstrahlung and, from Fig. 25, the corresponding mean photon energy is $\langle E_\gamma \rangle = 12\text{ MeV}$ from Section 4.3.1.3.1.4 to obtain $\mu_x \sim 0.30\text{ cm}^{-1}$ for Fe (actually Cu) which decrease the dose rate by a factor of 83.5 to $\dot{D}_{1s,da} = .184\text{ mrem/hr}$. This level at the reduced Linac beam of 2 nA is well below the value of $.25\text{ mrem/hr}$ we have adopted for general public dose limit. However, we again believe it is prudent to accommodate the full (factor of 25) Linac intensity, which requires a factor of 18.4 reduction in X-Ray intensity. This is accomplished, using the absorption coefficient at $\langle E_\gamma \rangle = 12\text{ MeV}$ of $\mu_x = .65\text{ cm}^{-1}$ in Pb, with $t = 4.48\text{ cm}$ of Pb. For neutron skyshine from point 1 the source fluence from Eq. 20 of $\phi_o(90^\circ, \text{Fe}) = 3 \cdot 10^3\text{ neutron/cm}^2\text{-sec}$ pertains and Eq. (18) gives the flux outside the north wall as $\phi_{s,da} = 1.16\text{ neutrons/cm}^2\text{ sec}$ which is equivalent to the dose rate $\dot{D}_{n,s} \sim 0.15\text{ mrem/hr}$. Note that no credit for neutron shielding is taken here for the 14.75 cm steel or 4.5 cm Pb above the source point. Again, we would want to accommodate the maximum linac intensity condition and reduce the neutron dose rate under this condition to $\sim .10\text{ mrem/hr}$ with a concrete thickness of $1.53\text{ TVL} = 47.4\text{ cm}$ of concrete.

The worst accident in terms of skyshine dose to an adjacent uncontrolled area is the full 200 MeV beam dump on the exit flange at the end of the linac (point 2 of Fig. 3). Without overhead shielding the X-Ray dose outside the four foot north wall can be estimated from Eq. 18. The X-Ray dose rate index for the reduced linac beam operation of $I = 2\text{ nA}$ is the same value used above for point 1, $\dot{D}_{10}(90^\circ) = .012\text{ rad-m}^2/\text{min}$, as is the distance $d_s = 2.879\text{ m}$. The solid angle from Table II is $\Omega = 4.18204\text{ sr}$. But we do not have the benefit of existing overhead steel shielding as at point 1; thus the dose rate outside the north wall is $\dot{D}_{1s,da} = 13.96\text{-mrem/hr}$. We can reduce this rate to the $.25\text{ mrem/hr}$ general public/nonradiation worker tolerance with $t = 6.19\text{ cm}$ of Pb above point 2 if we use the average X-Ray energy from Fig. 25 of $\langle E_\gamma \rangle \approx 12\text{-MeV}$ from $E_o = 200\text{ MeV}$ incident electrons from Fig. 25 reduced to an effective electron energy of 100 MeV by Fig. 21, and the linear absorption coefficient $\mu_x \approx .65\text{ cm}^{-1}$ from Fig. 18. Again, we can readily accommodate the full Linac intensity operation by increasing the lead thickness to $t = 11.14\text{ cm}$ above this small region. For neutron skyshine from the accident at point 2, we obtain the same dose rate of $\dot{D}_{n,s} = 0.15\text{ mrem/hr}$ as pertained for point 1 outside the north wall, and the same $t_c = 47.4\text{ cm}$ of concrete to attenuate the dose rate for a maximum (factor of 25) Linac intensity accident to 0.10 mrem/hr . Again, no credit is taken for neutron attenuation by the 11 cm of Pb. As discussed below is section 4.3.1.3.2.3, the practicality of extending the 11 cm Pb plus 47 cm concrete above the entire Linac upstream of the exit flange must be considered, and our tolerance criteria for such possible extended source accidents and/or our operating procedures must be reexamined. It is clear from the foregoing discussion that if the skyshine rates are adequately small in the uncontrolled, general public area outside the north shielding wall from the identified full beam dump accident points, then dose rates in uncontrolled areas in adjacent buildings 726, 727 and 728 are even smaller.

4.3.1.3.1.6 Skyshine Within Building 729 From Accidents

It is clear that the above discussion has addressed the most stringent shielding requirements for accidental beam dumps since distances d , from dump points to the outside of the building are smaller than those to occupied areas within Bldg. 729. Moreover, dose limits are higher for workers within this controlled area.

4.3.1.3.2 Accidental Dump at Intermediate Points Along Linac

4.3.1.3.2.1 Dose Levels Outside Four-Foot North Wall

Upstream of the Linac exit flange, the most probable accident is assumed to be targeting of the full beam on a sectionalizing manual valve (valve V2 of Fig. 3) provided by the vendor between Linac tanks 2 and 3 (labelled point 4 in Fig. 3). Again, the vendor will provide an interlock to inhibit the Linac operation if this valve is closed and thus an accident there is failure of the interlock. The valve gate thickness is again 6.35 mm steel, but the Linac energy at this point is only 88 MeV [1]. The range of 88 MeV electrons in Fe is 24.7 gms/cm² [6] so the 5 gm/cm² valve gate is not range thick. The electrons lose about 31 MeV, and the transmitted 57 MeV electrons likely target at the end of the Linac and produce less radiation than the full dump at that location already considered. From Fig. 6 the 90° X-Ray source function is $\dot{D}_{10}I^{-1} = 4 \cdot 10^3$ rad-m²/mA-min which is .67 of the value at 200 MeV. We will further decrease that source strength by the fraction of beam energy deposited, 0.35 to obtain $\dot{D}_{10}I^{-1} = 1.40 \cdot 10^3$ rad-m²/mA-min. Thus, the X-Ray dose rate outside the four-foot north shielding wall is $\dot{H}_{1d,x} = .101$ mrem/hr for an $I = 2$ nA accident, about 0.3 of the value obtained previously from the similar value downstream of tank 4. Thus, no additional side shielding is needed at valve V2 for reduced intensity (2 nA). But it would be prudent to provide Pb shielding along the north surface of this valve to accommodate a full intensity (50 nA) accident; for this case the thickness of Pb required is 3.8 cm.

The only remaining potential targets within the Linac are the array of 1/8 inch thick Cu disks with 1 cm apertures which comprise the iris-loaded drift tube structure. These thin disks would comprise an extended source at the 200 MeV end of the Linac, with appreciable scattered beam from the aperture edges targeting on the one-inch exit flange and downstream vacuum pipe. We feel that this accident is no worse than already considered above. At the upstream end the disks could present a range-thick target to the low energy beam. Consider an example in which the beam targets on disks near the end of tank 1 where the electron energy is 38 MeV [1]. Each Cu disk is 2.85 gm/cm² thick and $R(38 \text{ MeV, Cu}) \approx 15.5$ gm/cm² [6]. Thus five disks constitute a range thick target. But the X-Ray source function at this energy is $\dot{D}_{10}I^{-1} = 3 \cdot 10^3$ rad-m²/mA-min, about three times larger than at the 1/4 inch valve at the tank 2-3 location. The resulting 2 nA X-Ray dose rate is $\dot{H}_{1d,x} \approx .117$ mrem/hr. Thus, we are below maximum dose limits outside the four-foot north wall for these extended source beam dumps within the Linac at the reduced, $I = 2$ -nA operations level. At the maximum (50 nA) Linac capability, we will exceed the 0.25 mrem/hr rate but do not feel at the present time that a full lead belt along the north side of the Linac length is justified.

4.3.1.3.2.2 Dose Levels Outside Three-Foot Wall Within Bldg. 729

For dose rates along the three-foot south wall from accidental dumps along the Linac, the worst situation would be a full beam dump distributed along an array of the Cu disks near the end of tank 3, where the electron energy is 155 MeV. The X-Ray dose rate index for the 2 nA beam is $\dot{D}_{10}I^{1/2}(90^\circ, \text{Fe}) \approx 5.5 \cdot 10^3 \text{ rad-m}^2/\text{mA-min}$. The X-Ray dose rate from Eq. 1 at $d = 2.37 \text{ m}$ through the 91.4 cm concrete wall is, from the $B_1 = 2.5 \cdot 10^{-2}$ of Fig. 9, $\dot{H}_{10,x} = 2.93 \text{ mrem/hr}$, near the 2.5 mrem/hr dose rate limit we are using in this report for 50 hr/year accidents to radiation workers. For neutrons, we use the source fluence $\phi_0(90^\circ, \text{Fe}) \approx 3 \cdot 10^3 \text{ neut/cm}^2\text{-sec}$ of Section 4.3.1.3.1.2 for the 2 nA beam and the transmission ratio of $B_n = 2.5 \cdot 10^{-11} \text{ rem cm}^2$ through the $t = 214.8 \text{ gm/cm}^2$ concrete wall for $\langle E_n \rangle = 2.0 \text{ MeV}$ neutrons to obtain the dose rate of $\dot{H}_{10,n} = .032 \text{ mrem/hr}$ from Eq. (6), also a negligible value. It is clear that other accidents upstream of this point will be at lower electron energy and, in the case of the valve between tank 2 and 3, a target that is less than range-thick. We do not feel that it would be justified to shield the south side of the Linac against failure of procedures given in Section 4.2 for limiting the Linac intensity to the value used above.

4.3.1.3.2.3 Skyshine Within Building 729 and Adjacent Areas

For accidents within the Linac upstream of the exit flange, the X-Ray and neutron source strengths are generally less than those from the external beam for the reasons cited above. As a worst case consider the dose rate outside the north wall for the full (2 nA) beam dump at the end of tank 3 where $E_e = 155 \text{ MeV}$. The X-Ray source dose rate index is, as above, $\dot{D}_{10}(90^\circ, \text{Cu}) = 0.011 \text{ rad-m}^2/\text{min}$ and the solid angle subtended by the shielding walls is, from Table II, $\Omega = 4.06915 \text{ Sr}$. At $d_s = 2.879 \text{ m}$, Eq. (18) gives the X-Ray skyshine dose rate $\dot{D}_{10,d_s} = 12.34 \text{ mrem/hr}$. For the neutron dose rate we obtain $\dot{D}_{n,d_s} = 0.14 \text{ mrem/hr}$, about the same as at the end of the Linac, point 2, in Section 4.3.1.3.1.5. We consider this accident much less likely than the full dump at the Linac exit discussed in that section, and therefore adopt an occupancy duration of 25 hours which requires a dose rate limit of 1 mrem/hr. A cost benefit argument leads us to the conclusion that a full (50 nA) Linac intensity accident is sufficiently unlikely in view of the operating precautions discussed in Section 4.2, and that a roof over the Linac enclosure is unjustified. The X-Ray dose can be reduced to 1 mrem/hr with a lead sheet of thickness $t_{pb} = 4.02 \text{ cm}$ on a canopy over the entire Linac. Here, we noted from NCRP-51, App. E.6, reproduced here as Fig. 21, that the X-Ray bremsstrahlung spectrum at 90° from thick, high Z targets for 155 MeV incident electrons is equivalent, for purposes of transmission calculations, to the spectrum at 0° produced by 85 MeV electrons. The mean gamma energy in such a spectrum as evaluated from Eq. 15 of Section 4.3.1.3.1.4 is about $\langle E_\gamma \rangle = 10.5 \text{ MeV}$ and the attenuation coefficient for Pb at this energy is $\mu_x \approx .62 \text{ cm}^{-1}$ from Fig. 18. No concrete is required on top of the lead.

For the upstream end of the Linac, for example, at the end of tank 1 with $E_e = 38 \text{ MeV}$, the X-Ray source strength for $I = 2 \text{ nA}$ is down by a factor of 2 from the 155 MeV value and the $\Omega^{1/2}$ factor of Eq. 18 is slightly reduced, resulting in a dose rate of $\dot{D}_{10}$, $d_s \approx 6.6 \text{ mrem/hr}$. However, the X-Ray attenuation coefficient for lead for the average Bremsstrahlung energy there, $\langle E_\gamma \rangle \approx 3.2 \text{ MeV}$, is near its minimum of $\mu_x = .45 \text{ cm}^{-1}$ so we need $t_{pb} = 4.19 \text{ cm}$ there. Use has also been made here of the equivalent electron energy for the 90° spectrum from Fig. 21.

Clearly, the accident rates within Bldg. 729 or in adjacent buildings is lower than the dose rate calculated above.

4.3.1.4 Beam Dump and Momentum Slits Radiation Shielding

The normal operating condition of the facility will involve negligible beam losses everywhere except the momentum-selection slits and beam dump (points S and D in Fig. 3). Typically we expect ~ 50% of the beam intercepted by the slits and the remainder stopped in the beam dump; however, the slits have a variable aperture so we calculate for 100% of the beam striking either point. The slits will be only 1/4" thick Cu and are thus not range-thick; therefore, the worst case is the beam dump D.

4.3.1.4.1 Radiation Levels from Beam Dump within Bldg. 729

The beam dump will be a range-thick ($t_{cu} = 34.88 \text{ gm/cm}^2 = 3.89 \text{ cm}$ at the maximum possible Linac energy of $E_e = 222 \text{ MeV}$ given by the vendor [1]) Faraday cup. It would be prudent here to calculate the required lead shielding thickness on the basis of the full intensity, $\langle I \rangle = 50 \text{ nA}$, Linac capability. It would furthermore be advisable to reduce the X-Ray dose to less than a radiation worker accident dose limit outside the lead shielding. The 0° X-Ray source dose rate index at $E_e = 222 \text{ MeV}$ on Cu is, from Fig. 6 and NCRP-51, App. E.3, about $\dot{D}_{10}(0^\circ, \text{Cu}) = 1 \cdot 10^3 \text{ rad-m}^2/\text{min} = 6 \cdot 10^7 \text{ mrem m}^2/\text{hr}$. For a bremsstrahlung attenuation factor for gammas in Pb of $B_x = 2 \cdot 10^{-6}$, Swanson's graph [26], reproduced here as Fig. 22, gives a Pb thickness of $t \sim 27 \text{ cm}$ to reduce the X-Ray dose rate to 120 mrem/hr at 1 meter. This estimate takes no credit for the subsequent four-foot concrete vault wall which has a slant thickness of about 172.4 cm in the 0° direction. If we take credit for the X-Ray attenuation in the concrete, then the attenuation factor from Fig. 9 is $B_x = 6 \cdot 10^{-4}$ and, with the distance $d = 6.265 \text{ m}$ from the Cu Faraday cup to outside the shielding wall (point M4 in Fig. 3), Eq. 1 gives $\dot{H}_{10,x} = 961 \text{ mrem/hr}$ without the lead. With the 27 cm Pb lead attenuation factor, the X-Ray dose at point M4 becomes $1.92 \cdot 10^{-3} \text{ mrem/hr}$. Thus, our Pb thickness estimate here is larger than the 19.6 cm of Pb for the maximum credible accident beam stop in Section 4.3.1.3.1.1 where we took credit for 160 cm of concrete and had only 90 MeV electrons incident on the Pb attenuator.

The thickness of lead side shielding at the beam stop can be calculated in a similar manner. At 90° to the 3.89 cm Cu target of the Faraday cup, we again use the X-Ray source dose rate index from Fig. 6 and NCRP-51, App. E.3 to obtain $\dot{D}_{10}(90^\circ, \text{Cu}) = 0.30 \text{ rad m}^2/\text{min} = 1.8 \cdot 10^4 \text{ mrem-m}^2/\text{hr}$ for 50 nA . We then use the equivalent electron energy of 100 MeV from Fig. 21 to estimate the lead thickness to obtain the required attenuation factor of $B_x = 6.67 \cdot 10^{-3}$ and resultant dose rate of $\dot{H}_x = 120 \text{ mrem/hr}$ at 1 meter. From Fig. 22, the lead thickness is $t = 10.9 \text{ cm}$. The X-Ray dose rate outside of the 4-ft. west wall with the 10.9 cm lead side shielding in place can be computed from the above source dose rate index modified by the lead attenuation to give $\dot{D}_{10}(90^\circ, \text{Cu} + \text{Pb}) = .002 \text{ rad-m}^2/\text{min}$, and use of the attenuation factor from 121.9 cm of concrete with 100-MeV equivalent incident electron energy of $B_x = 5.5 \cdot 10^{-3}$ from Fig. 9. Then Eq. 1 gives, for a distance of $d = 5.0 \text{ m}$ from the beam dump to the outside of the west wall, $\dot{H}_{10,x} = .0263 \text{ mr/hr}$. Without the 10.9 cm lead shielding, the X-Ray dose rate at the west wall would be $\dot{H}_{10,x}(\text{no Pb}) = 3.95 \text{ mr/hr}$ which would exceed the 2000 hr/yr BNL administrative dose limit for radiation workers.

For neutrons emanating from the Cu beam stop target, we take no credit for the neutron attenuation of the Pb. We have already shown in Section 4.3.1.3 that the four-foot concrete vault shielding walls are quite adequate to attenuate the neutron source fluence to less than dose limits. Taking the slant thickness into account, Eq. 6 gives, with a fluence $\phi_0 = 7.5 \cdot 10^4$ neut/cm²-sec for $\langle I \rangle = 50$ nA and attenuation factor $B_n = 3.0 \cdot 10^{-14}$ from Fig. 12, a neutron dose rate at point M4 of $\dot{H}_{14,n} = 2 \cdot 10^{-4}$ mrem/hr.

4.3.1.4.2 Skyshine from Beam Dump in Bldg. 729 and Adjacent Structures

The X-Ray and neutron skyshine problem differs from our previous discussion mainly with respect to the occupancy factor for this normal operating condition of 2000 hours/year for radiation workers within Building 729 or nonradiation workers (machinists, technicians) in Buildings 726, 727 and 728. The occupancy factor for the general public in the area outside the four-foot north wall is still assumed to be 50 hours/year. Both groups, the general public outside the building 729 facility and BNL non-radiation workers in Bldg. 726, 727 and 728 are subject to the same BNL administrative maximum dose limit of ≤ 25 mr/yr [3,25]. It is easy to show that the additional factor of 40 in occupancy factor for nonradiation workers in Bldgs. 726, 727 and 728 relative to the general public outside the north wall is more than compensated by the increased distance d_i to these work areas from beam dump point D, since the X-Ray dose rate varies as $1/d_i^2$ in Eq. 18. For example, the X-Ray skyshine dose rate calculated in Section 4.3.1.3.1.5 for the maximum credible accident at point M (Fig. 3), which is similar in dose rate to the beam dump D, was based on the distance $d_i = 3.382$ m to the outside of the north wall, whereas the corresponding distance d_i from point M (or the beam dump point D) to points in Bldg. 726 and 727 where workers might conceivably spend 2000 hrs/yr is about 24 m, a factor of 7 larger. Specifically, with the 50 nA, $E_0 = 222$ -MeV, 90° source dose rate index of $\dot{D}_{10} = .3$ rad-m²/min obtained above, and the solid angle of $\Omega = 4.73789$ sr at pt. D with $d_i = 24$ m from dump D to Bldg. 726, Eq. 18 gives the X-Ray dose rate of $\dot{D}_{u,d_i} = 9.838 \cdot 10^{-5}$ rad/min = 5.903 mr/hr. In a 2000 hr year the integrated dose without shielding above the beam dump is 11806 mr. If we use the same $t_{pb} = 13.52$ cm above pt. D as was used above accident dump pt. M in Sect. 4.3.1.3.1.5, then the Pb attenuation factor from Fig. 22 is $B_n = 1.9 \cdot 10^{-3}$ and the annual X-Ray dose in Bldg. 726 becomes $D_n = 22.4$ mrem, less than the 25 mrem BNL administrative dose limit for non-radiation workers. For neutrons, the skyshine dose rates were previously calculated from Eq. 19 which assumes $d_i < 20$ m and has no explicit d_i dependence; for the longer distances to adjacent buildings, NCRP-51 [22] gives the neutron flux (neutrons/cm²-sec)

$$\phi_{s,d_i} = \frac{6.5 \cdot 10^{-2} \phi_0 \Omega}{2\pi d_i^{1.6}} \quad (21)$$

which is identical to Eq. 19 at $d_i = 20$ m and smaller for larger values of d_i . The units of ϕ_0 , Ω and d_i of Eq. 21 are the same as Eq. 19. Thus, the neutron dose rate calculated for maximum Linac intensity (50 nA) from beam dump D, using Eq. 21 and $d_i = 24$ m becomes $\dot{D}_n = 3.03$ mrem/hr in Bldg. 726. However, we are required [25] to reduce the annual dose to workers in these buildings to ≤ 25 mrem/yr, and the 2000 hr/yr neutron dose rate cited above becomes an annual dose of $D_{n,i} = 6060$ mrem/yr without Pb or concrete shielding. We can reduce this dose by using the concrete thickness of 74.4 cm above beam dump D as needed below for doses at

pt. M4. The annual dose in Bldg. 726 from neutrons from pt. D then becomes $D_{n,1} = 32.1$ mrem/yr. No credit is taken here for neutron attenuation in the $t_{n,1} = 13.52$ cm above dump D. For $\langle E_n \rangle = 2$ -MeV this is not negligible; the total cross section for Pb(n,x) at this energy is $\sigma_T = 5.6$ barns [31] and the resultant attenuation length for these neutrons is $\lambda_T = A/N_0 \sigma_T \rho$ with $N_0 =$ Avogadro's number, $\rho = 11.35$ g/cm³ and $A = 207.2$. Then $\lambda_T = 5.41$ cm and the resultant attenuation factor from the lead is $\exp (1/\lambda_T) = 12.17$. The annual neutron dose in Bldg. 726 is then $D_n = 2.64$ mrem and the total dose become $D_T = D_1 + D_n = 25$ mrem, the BNL administrative limit for non-radiation workers. Alternatively, we can invoke the planned reduced intensity operation (1/25 of above rates) specified in Section 4.2. Since the area to be shielded here is relatively small, the increased shielding thickness appears reasonable.

Specifically, the skyshine from the beam dump D to Point M4 within Bldg. 729 along the south side of the 4-ft shield wall and in the 0° direction to the $\langle I \rangle = 50$ nA electron beam can be evaluated as follows. For X-Rays we have from Fig. 6 the source dose rate index of $\dot{D}_{10}(90^\circ, \text{Cu}) = 0.3$ rad-m²/min. The dose rate at M4 without the 74.4-cm of concrete is, from Eq. 18 with the solid angle of $\Omega = 4.73789$ sr from Table II and the distance $d_1 = 6.265$ m, $\dot{D}_{1,10} = 1.444 \cdot 10^{-3}$ rad/min = 86.62 mr/hr. Using Swanson's (Fig. 22) attenuation of $B_1 = 1.9 \cdot 10^{-3}$ for the 13.52-cm of Pb and Swanson's (Fig. 24) attenuation of $B_1 = 0.05$ for the 74.4-cm of concrete, the resultant dose rate is $\dot{D}_{1,10} = .0082$ mr/hr, an integrated dose of 16.4 mrem/2000 hrs. For neutrons, Fig. 11 gives a source fluence of $\phi_0 = 7.5 \cdot 10^4$ neut/cm²-sec and Eq. 19 then yields a neutron flux rate of $\phi_{1,10} = 30.54$ neut/cm²/sec which is a dose rate equivalent of $\dot{D}_n = 4.072$ mr/hr. Without credit from the 13.52-cm Pb, the attenuation from the 74.4 cm concrete is equivalent to 2.276 TVL's, i.e. an attenuation factor of 189 which reduces the neutron dose rate at M4 to $\dot{D}_n = .0215$ mr/hr, an integrated dose of 43 mrem/2000 hrs. This annual dose is well below the BNL administrative dose limit for workers in Bldg. 729 at M4. The skyshine doses at $\langle I \rangle = 50$ nA from the beam dump to the uncontrolled area outside the north wall (pt. M16) are larger than to pt. M4 for X-Rays since $d_1 = 5.588$ m is smaller. Eq. 18 gives $\dot{D}_{1,10} = .0103$ mr/hr at M16. For neutrons, Eq. 19 gives the same dose rate at M16 as at M4, namely $\dot{D}_n = .0215$ mr/hr, since Eq. 19 is independent of distance d_1 , but if we take credit for the Pb shielding, $\dot{D}_n \rightarrow .0018$ mr/hr at M4 and M16. Thus the total 50 hr/yr dose at M16, a general public area, from X-Rays and neutrons becomes .6 mrem which is negligible.

4.3.1.4.3 Radiation Levels within Bldg. 729 from Slits

Finally, for the momentum slits at point S (Fig. 3) we have noted that their thickness is only $t_{slit} = .635$ cm of Cu whereas the range of 222 MeV electrons in Cu [6] is $R = 3.90$ cm. The energy loss of the electrons in the slit is $\Delta E = 84.8$ MeV which is $f = .38$ of the total energy. We reduce the X-Ray and neutron source dose rates by this fraction. For the 0° direction, the $I = 50$ nA X-Ray source dose rate from Fig. 6 is $\dot{D}_{10}(0^\circ \text{Cu}) = 1.5 \cdot 10^3$ rad-m²/min and, modified by the Z factor of NCRP-51, App. E.3 and the above energy fraction f , becomes $\dot{D}_{10}(0^\circ, \text{Cu}, 50\text{nA}) = 399$ rad-m²/min = $2.39 \cdot 10^7$ mrem-m²/hr. The bremsstrahlung beam then impinges on the backleg yoke of bending magnet B2 of Fig. 3 which has a slant thickness of $t_e = 11.85$ cm. The X-Ray attenuation factor through the steel is taken from Swanson's graph [26], reproduced here as Fig. 23, as $B = 8 \cdot 10^{-2}$ giving an X-Ray dose rate of $1.91 \cdot 10^6$ mrem m²/hr. From Eq. 1 the X-Ray dose rate from this source strength at Point 7 of Fig. 3 to the point labelled M6 outside the vault 4-ft south shielding wall is, with a distance d_1 ,

$= 4.911\text{-m}$ and an attenuation factor from 130 cm concrete of $B_1 = 4 \cdot 10^{-3}$ from Fig. 9, $H_{1,1} = 317\text{ mrem/hr}$. To reduce this rate to a value well below the 1250 mrem annual tolerance level for 2000 hrs/yr, say 0.3 mr/hr , we require an attenuation factor of $9.46 \cdot 10^{-4}$ which, from Swanson's curve of Fig. 22 is given by 14.1 cm of Pb. This is a slant thickness along a line making a 58.7° angle with the normal to the iron yoke of magnet B2; the radial Pb thickness at pt. 7 is then 7.3 cm. In addition, the electron beam which passed through the slits impinges on the 11.85 cm (slant distance) iron yoke of magnet B2 at Pt. 8 of Fig. 3 with an energy of $E_0 = 137.2\text{ MeV}$ and stops in the first 3.75 cm. The X-Ray source dose rate index at 0° for this secondary source is again obtained from Fig. 6 and NCRP-51 App. E.3 as $\dot{D}_{10}(0^\circ, \text{Fe}, I = 50\text{ nA}, E_0 = 137\text{ MeV}) = 2.1 \cdot 10^7\text{ mrem-m}^2/\text{hr}$, essentially the same source strength as from the Cu slit. This dose rate is decreased by the attenuation factor from the remaining 8.1 cm of steel yoke, given by Fig. 23 as $B = .2$ to obtain an X-Ray dose rate from the secondary source of $\dot{D}_{10}(0^\circ, \text{Fe}, I = 50\text{ nA}) = 4.2 \cdot 10^6\text{ mrem-m}^2/\text{hr}$. It is clear from Swanson's graph [26] of attenuation in concrete, given here as Fig. 24, that we could not attenuate this dose rate in the four-foot vault south shielding wall to $.62\text{ mrem/hr}$ which would be required within the controlled Bldg. 729 to adhere to the BNL administrative dose limit of 1250 mrem/year for a 2000 working hour year. The slant thickness of the concrete wall is about 170 cm in the 0° direction from pt. 8. The dose rate from Eq. 1 and the source strength index rate $\dot{D}_{10}$ given above is evaluated with a distance $d = 6.61\text{ m}$ from pt. 8 to pt. M4 of Fig. 3 and an attenuation factor of $B_1 = 5 \cdot 10^{-4}$ from Fig. 9 to be $H_{1,1} = 48\text{ mr/hr}$. The required lead thickness, from Fig. 22, to reduce the dose rate to $.3\text{ mrem/hr}$ (attenuation factor $B = 6.24 \cdot 10^{-3}$) is $t_{\text{Pb}} = 10.8\text{ cm}$ along a slant length at an angle of 58.7° relative to the normal to the magnet yoke surface. Thus, the radial Pb thickness along the magnet outer surface is 5.6 cm. It is worthwhile to point out here that the method previously used to estimate required Pb shielding thicknesses by use of the attenuation coefficients of Fig. 18 would, for incident $E_0 = 137\text{ MeV}$ electrons, give an average bremsstrahlung energy from Fig. 25 of $\langle E_\gamma \rangle = 15.56\text{ MeV}$ [27] which leads to an average attenuation coefficient for Pb of $\mu_x \sim 0.7$ from Fig. 18 and a Pb thickness of only $t = 8.28\text{ cm}$ to achieve the $B = 6.24 \cdot 10^{-3}$ attenuation. However, it should be noted that the expression for $\langle E_\gamma \rangle$, Eq. 15, is for monoenergetic incident electrons, whereas in the thick target we are producing bremsstrahlung from electrons of all energies from E_0 to zero. It would be more reasonable to assume some average electron energy, say 68.6 MeV which gives from Fig. 25 an average bremsstrahlung energy of $\langle E_\gamma \rangle = 8.69\text{ MeV}$ and, from Fig. 18, an attenuation coefficient $\mu_x \sim .55\text{ cm}^{-1}$ and a Pb thickness $t = 9.24\text{ cm}$ to achieve the desired attenuation, in better agreement with t_{Pb} obtained from Swanson's Fig. 22.

X-Ray side shielding at the Cu slits at $E_0 = 222\text{ MeV}$ electron energy is obtained from the source dose rate index of Fig. 6 for 90° , and the additional factor of 0.38 since the target is not range-thick, to get the source dose rate $\dot{D}_{10}(\text{Cu}, 90^\circ, I = 50\text{ nA}) = .114\text{ rad-m}^2/\text{min}$. To determine whether the four-foot concrete west wall of the vault is adequate without further X-Ray shielding, use Eq. (1) with the wall slant thickness of $t_c = 1.32\text{ m}$ giving the attenuation factor from Fig. 9 of $B_1 = 4 \cdot 10^{-3}$. At distance $d = 4.74\text{ m}$, Eq. (1) gives $H_{1,1} = 1.21\text{ mrem/hr}$ which is higher than the 2000 hr/yr dose limit for radiation workers in this controlled area. To attenuate the annual dose by a factor of 4 to $\sim 600\text{ mr}$, the thickness of Pb for the 90° bremsstrahlung from the effective electron energy of 100-MeV in Fig. 21 and the resulting $\langle E_\gamma \rangle = 12\text{ MeV}$ from Fig. 25 is obtained from the absorption coefficient μ_x (Pb) $= .65\text{ cm}^{-1}$ of Fig. 18. We get $t_{\text{Pb}} = 2.2\text{ cm}$ required. A similar argument shows that we do not need Pb side shielding for the dump of the $E_0 = 137\text{ MeV}$ beam transmitted through the

slits and stopped in the iron yoke of magnet B2; the 6 cm iron yoke radial thickness more than compensates for the absence of the factor of 0.38 we took at the slits due to a less-than-range-thick target.

More quantitatively, the 137-MeV electrons striking the yoke of magnet B2 at point 8 of Figs. 3 and 27 and stopped in the first 3.75 cm of the iron [6]. The electron path makes an angle of 58.7° relative to the normal to the magnet yoke. Thus, the mean thickness of iron from the beam to the side of the yoke is $t_{Fe} = 5.03$ -cm. The mean bremsstrahlung energy emitted at 90° by the 137-MeV electrons with effective energy of 75 MeV from Fig. 21 is given from Fig. 25 as $\langle E_\gamma \rangle = 9.5$ MeV and the linear absorption coefficient corresponding to this photon energy is given in Fig. 18 for Cu (closest to Fe) as $\mu_a = .28 \text{ cm}^{-1}$. Thus we will attenuate the source dose rate index $\dot{D}_{10}$ by $\exp(.28 \times 5.03) = 4.09$. To obtain the source dose rate index, note first that for X-Ray shielding at 90° , the effective electron energy from Fig. 21 is 75 MeV. Then, from Fig. 6, we have $\dot{D}_{10} I^{-1} = 5000 \text{ rad-m}^2/\text{mA-min}$ and, for $\langle I \rangle = 50 \text{ nA}$, the dose rate index $\dot{D}_{10}(90^\circ, \text{Fe}, E_{e, \text{eff}} = 75 \text{ MeV}, 50 \text{ nA}) = .25 \text{ rad-m}^2/\text{min}$. This dose rate is then attenuated by the 5-cm of iron yoke to obtain $\dot{D}_{10} \rightarrow .0611 \text{ rad-m}^2/\text{min}$. Then refer to Fig. 27 to obtain a distance of $d = 8.656 \text{ m}$ from point 8 to the outside of vault gate 1 (point M3 in Fig. 3) through the 4-ft = 121.9 cm concrete shielding wall. Use Fig. 9 with $E_{e, \text{eff}} = 75 \text{ MeV}$ to obtain an X-Ray transmission ratio of $B_s = 4.5 \cdot 10^{-3}$. Then Eq.(1) gives the X-Ray dose rate of $\dot{H}_{10, s} = 0.220 \text{ mr/hr}$. The annual 2000 hr/yr dose to a radiation worker at point M3 is thus well below the 1250 mrem administrative dose limit and no further X-Ray side shielding is needed at point 8 of Fig. 3, as stated previously.

4.3.1.4.4 Skyshine from Momentum Slits in Bldg. 729 and Adjacent Structures

For X-Ray and neutron skyshine from the slits and iron of magnet B2, first consider the X-Rays from the slits. We can use the source dose rate index obtained previously, $\dot{D}_{10}(\text{Cu}, 90^\circ, I = 50 \text{ mA}) = .114 \text{ rad m}^2/\text{min}$, and substitute into Eq. 18 the solid angle $\Omega = 4.744 \text{ sr}$ and the distance $d_s = 4.064 \text{ m}$ to the outside of the four-foot north wall to get $\dot{D}_{10, s} = 1.31 \cdot 10^{-3} \text{ rad/min} = 78.4 \text{ mrem/hr}$. We clearly need Pb shielding above the slits. We need an attenuation factor of $B = 3.2 \cdot 10^{-3}$ which, from Swanson's curve of Fig. 22 gives $t_{Pb} = 12.2 \text{ cm}$, where use is made of the 60-100 MeV curve since, from Fig. 21, NCRP-51, E.6 recommends use of an effective electron energy of 100 MeV for 90° transmission of bremsstrahlung from incident 222 MeV electrons. The attenuation factor used above reduces the dose rate to .25 mrem/hr which we take as the dose limit for a 50 hr/year occupancy of this general public area. The X-Ray dose rate to a nonradiation worker in Bldgs. 726 and 727 would be still lower due to the $1/d_s^2$ factor of Eq. (18); at $d_s = 24 \text{ m}$ and using the above $B = 3.2 \cdot 10^{-3}$ attenuation factor, from the 12.2 cm of Pb, the skyshine dose rate there is $\dot{D}_{10, s} = 7.17 \cdot 10^{-3} \text{ mrem/hr}$ which is less than the dose limit for these 2000 hr/year workers.

For neutron skyshine from the slits to the uncontrolled area outside the north wall for $I = 50 \text{ nA}$ operation we can scale up the source fluence of Eq. (20) to give $\phi_s(90^\circ, \text{Cu}, 50 \text{ nA}) = 7.5 \cdot 10^4 \text{ neut/cm}^2\text{-sec}$. Reducing this value by the factor of 0.38 for the less-than-range-thick Cu slits and Eq. (19) with the solid angle $\Omega = 4.744 \text{ Sr}$ gives the flux outside the north wall of $\phi_{1, s} = 11.6 \text{ neutrons/cm}^2\text{-sec}$ which is equivalent to a dose rate, $\dot{D}_{n, s} = 1.55 \text{ mrem/hr}$. To reduce this rate to a value $< .25 \text{ mrem/hr}$, say .03 mrem/hr we need an attenuation factor of $B = 1.94 \cdot 10^{-2}$ which requires 1.71 TVL at 31 cm/TVL, or $t_{\text{concrete}} \approx 53$

cm for 2 MeV neutrons. No credit is taken here for the neutron attenuation of the $t_p = 12.2$ cm above the slits as noted above. For neutron skyshine from the slits to Bldg. 726 we can still use the same source fluence as above, $\phi_s = 7.5 \cdot 10^{-4} \times .38$ neut/cm²-sec, and solid angle $\Omega = 4.744$ sr but with distance $d_s = 24$ cm to obtain the flux from Eq. 21 of $\phi_{s,d} = 8.66$ neut/cm²-sec and dose rate $\dot{D}_s = 1.154$ mr/hr without the lead or concrete shielding above the slits. For 2000 hr/yr occupancy in Bldg. 726 the integrated dose without shielding would then be $D_s = 2309$ mr/yr, much larger than the 25 mr/yr dose limit for non-radiation workers. The annual dose is reduced to the negligible value of $D_s = 4.7$ mr when the attenuation factor of $B_s = 1.94 \cdot 10^{-2}$ from the 53 cm of concrete and $B_{tp} = \exp(-12.2/5.41) = .105$ from the 12.2 cm of Pb.

Finally, for the skyshine problem from the secondary beam dump at pt. 8 for the $E_e = 137$ MeV emerging from the slits, we refer back to the similar dump into the magnet yoke discussed in Section 4.3.1.3.1.5 for an accident at point 1. The X-Ray source dose rate at that point, scaled up to a 50 nA beam, is $\dot{D}_{10}(90^\circ, \text{Fe}, 50\text{nA}) = .25$ rad-m²/min with small changes to the solid angle Ω and distance d_s to the outside of the north shield wall from point 8 relative to the values we needed at point 1, we get $d_s = 5.08$ m and $\Omega = 4.738$ Sr (we use the value of Ω for point D in Table II to approximate the solid angle subtended at point 8). Again using the X-Ray attenuation from the 14.75 cm of iron yoke above this point, we decrease the x-Ray dose rate by a factor of 25 obtained by use of an effective electron energy of $E_{eff} = 75$ -MeV for 90° bremsstrahlung from Fig. 21 and Swanson's attenuation curve of Fig. 23 for Fe which yields an X-Ray attenuation of $B_t = .04$, and obtain the X-Ray dose rate outside the north wall from Eq. 18 as $\dot{D}_{t,d} = 4.39$ mrem/hr. We can reduce this value to well below the .25 mrem/hr for this uncontrolled area with assumed 50 hr/year occupancy with only $t_p = 2.8$ cm on the top of magnet B2 and the 66 cm of concrete required below for neutron shielding. The resulting attenuation coefficients for lead and concrete from Swanson's curves, Figs. 22 and 24 respectively, give $B_t(\text{Pb}) = .28$ and $B_t(\text{conc.}) = .07$ which reduce the X-Ray dose outside the north wall to .086 mrem/hr, a 50 hr/yr annual dose of $D_t = 4.3$ mrem. For neutron skyshine from point 8, we again scale the calculations for point 1 up to $I = 50$ nA to obtain the source fluence of $\phi_s(90^\circ, \text{Fe}, 50 \text{ nA}) = 6.25 \cdot 10^4$ neutron/cm²-sec to obtain the neutron flux rate outside the north wall from Eq. 19 as $\phi_{s,d} = 30.54$ neutrons/cm²-sec which is equivalent to a neutron dose rate $\dot{D}_{n,s} = 4.07$ mrem/hr. Reducing this value to $\sim .03$ mrem/hr requires a concrete thickness of 2.13 TVL = 66 cm. The X-Ray and neutron skyshine rates in Bldgs. 726 and 727, where the occupancy factor is 20 times larger, are reduced to less than dose limit by the $1/d_s^2$ X-Ray dose dependence of Eq. 18 and the $1/d_s^{1.6}$ neutron dose dependence in Eq. (21).

A quantitative discussion of the X-Ray and neutron skyshine doses in Bldg. 726 for the 137 MeV electron beam dump into magnet B2, at point 8 of Fig. 3, is as follows. For X-Ray production at pt. 8 we use the source dose rate index at 90° from Fig. 6 to obtain $\dot{D}_{10}I^{-1} = 5000$ rad -m²/mA-min, and, for a $\langle I \rangle = 50$ nA beam, $\dot{D}_{10}(90^\circ, \text{Fe}, 50 \text{ nA}) = .25$ rad-m²/min. At a distance of $d_s = 24$ m from pt. 8 to Bldg. 726 and the solid angle Ω subtended at pt. 8 by the shielding vault walls of $\Omega = 4.738$ Sr (actually the value from Table II at nearby point D), we obtain the Bldg. 726 unshielded dose rate from Eq. 18 of $\dot{D}_{t,d} = 8.198 \cdot 10^{-3}$ rad/min = 4.919 mrem/hr. For the $t = 14.75$ cm of Fe and $t = 2.0$ cm of Pb above point 8, we use the average bremsstrahlung energy from Fig. 25 of $\langle E_e \rangle = 15.8$ -MeV and Bethe's [17] linear absorption coefficients from Fig. 18 of $\mu_a(\text{Cu}) = .28$ cm⁻¹ and $\mu_a(\text{Pb}) = .7$ cm⁻¹ to obtain attenuation factors $\exp(\mu_a t) = 62.18$ and 4.055 for the iron and Pb respectively. For the $t = 66$ cm of concrete specified above pt. 8 we use the effective electron energy of E_{eff}

= 75-MeV from NCRP-51, E. 6 (Fig. 21) for 90° bremsstrahlung and Swanson's [26] attenuation factor from Fig. 24 of $1/.07 = 14.286$ to get an attenuated X-Ray dose rate in Bldg. 726 of $\dot{D}_{b,d} = .00136$ mrem/hr and an annual 2000 hr/yr integrated dose of $D_{b,d} = 2.72$ mrem for the non-radiation workers there. The neutron skyshine dose from pt. 8 to Bldg. 726 can be obtained from the total (4π) neutron yield from 137 MeV electrons of $Y = 2.5 \cdot 10^{10}$ neut/sec/ μ A given by Fig. 10 (NCRP-51, F.3). From NCRP-51, F. 4 the yield per unit solid angle at 90° is $Y_{90^\circ} = .5Y = 1.25 \cdot 10^{10}$ and, for an $\langle I \rangle = 50$ nA beam, $Y_{90^\circ} = 6.25 \cdot 10^8$ neut/sec. The neutron fluence from NCRP-51, F.4 is then $\phi_0 = Y_{90^\circ} \times 10^{-4} = 6.25 \cdot 10^4$ neut/cm²/sec at $d = 1$ meter. At $d_s = 24$ m from pt. 8 to Bldg. 726 and again using the subtended solid angle $\Omega = 4.738$ sr at pt. 8, we obtain the flux in Bldg. 729, without credit for the shielding above pt. 8, of $\phi_{b,d} = 18.96$ neut/cm²/sec. The attenuation factors for the $t_p = 14.75$ cm plus $t_b = 2.8$ cm plus $t_{concrete} = 66$ -cm concrete above pt. 8 must be evaluated individually. For iron, the total cross section for 2.6-MeV neutrons originating from the $\langle E_n \rangle$ of the Fe⁵⁶ evaporation spectrum of Table I is $\sigma_T = 3.25b$ [31] which gives an interaction length of $\lambda_T = A/N_0\sigma_T\rho = 3.626$ cm and thus an attenuation factor of $\exp(-t_p/\lambda_T) = 58.445$. For Pb the total cross section at $E_n = 2.6$ MeV is $\sigma_T = 7.0b$ [31] and thus $\lambda_T = 4.33$ cm. The attenuation factor from the 2.8 cm of Pb is then $\exp(-t_b/\lambda_T) = 1.909$. For the 66-cm concrete we use the tenth value layer from Swanson's report [20], reproduced in Fig. 20, as TVL = 31 cm and thus we have $t_{concrete} = 2.129$ TVLs and an attenuation factor of $10^{2.129} = 134.59$. The overall attenuation factor is then $f_A(Pb)f_A(Fe)f_A(concrete) = 1.5016 \cdot 10^4$. The attenuated neutron skyshine in Bldg. 726 is then $\phi_{b,d} = 1.26 \cdot 10^{-3}$ n/cm²/sec and, using the flux conversion factor of 7.5 n/cm²/sec = 1 mr/hr [24] we have a dose rate of $\dot{D}_{b,d} = 1.68 \cdot 10^{-4}$ mr/hr or an annual integrated 2000 hr/yr dose of $D_{b,d} = 0.4$ mr. The total annual skyshine dose (X-Ray + neut) from pt. 8 to Bldg. 726 is then 3.1 mr.

4.3.1.4.5 Radiation Levels on Bldg. 729 Roof from beam Dump

Access to the roof will not normally be needed for either NSLS operations personnel or Laboratory maintenance workers during the operation of the Linac; no building services are located on the roof and we have not provided any stairway or ladder to access this area, nor provided any barriers to prevent such access. In the remote instance where workers may be required to be on the roof, the same requirements and procedures for prior approval by S&EP Dept representatives as pertains for access to the NSLS Bldg. 725 roof will be used. All maintenance work on this project now requires written S&EP approval before start of the job. The roof will be included in the "Safety Instructions Required" binder issued by the maintenance management center of BNL Plant Engineering. Radiation levels expected on the roof during normal machine operation can be estimated by our previous methods and shown to be well below dose limits for non-radiation workers for reasonable occupancy times of, say, 100 hrs/year. For example, the X-Ray dose rates on the roof immediately above beam dump D can be calculated from the 90° source dose rate index from $E_e = 222$ -MeV electrons given in Sect. 4.3.1.4.2 as $\dot{D}_{10}I^{-1} = 6 \cdot 10^1$ rad-m²/mA-min. Even for an $\langle I \rangle = 50$ -nA beam, the dose rate index is $\dot{D}_{10}(90^\circ, Cu) = .3$ rad-m²/min. The transmission index B_t though the 74.4 cm of concrete above the dump is obtained from Fig. 9 at the effective electron energy $(E_e)_{eff} \approx 100$ -MeV from Fig. 21 to be $B_t \approx 5 \cdot 10^{-2}$. Then the X-Ray dose rate at distance $d_s = 4.924$ m above the dump from Fig. 4 is given by Eq. 1 as $\dot{H}_{b,d} = 37.05$ mr/hr. But we also have lead thickness $t_p = 13.52$ cm above the dump; the attenuation factor for this thickness is given by Swanson's curve, Fig. 22, as $f_A \approx 3 \cdot 10^{-3}$. The X-Ray dose rate on the roof then becomes $\dot{H}_{b,d}$

= 0.11 mr/hr. For neutrons from the dump we can again use the fluence from Sect. 4.3.1.4.2 of $\phi_n = 7.5 \cdot 10^4$ neut/cm²-sec and the neutron transmission index B_n through the 74.4 cm (174.8 g/cm²) concrete, assuming $\langle E_n \rangle = 2$ -MeV from Table I, of $B_n = 3.5 \cdot 10^{-11}$ rem-cm² from Fig. 12. Then Eq. 6 gives the neutron dose rate at distance $d_n = 4.924$ m of $\dot{H}_{n,d_n} = 0.387$ mr/hr. The additional attenuation of neutrons through the $t_n = 13.52$ cm can be estimated from the total interaction length $\lambda_T = 4.33$ cm obtained in Sect. 4.3.1.4.4 as $\exp(13.52/4.33) = 22.7$ which reduces the neutron dose rate to $\dot{H}_{n,d_n} = 0.017$ mr/hr. The total X-Ray plus neutron dose rate is then $\dot{H}_{t,d_n} = .13$ mr/hr which is below the non-radiation worker dose limit of 25 mr/yr for 100 hr/yr occupancy.

4.3.1.5 Activation Hazards

The beam losses (both accidental and intentional) described in the preceding sections will activate both machine components (vacuum chamber, magnets, accelerating sections and beam dumps) as well as the surrounding lead and concrete shielding and air, principally via photoneutron reactions. During normal operations the major losses are expected on the momentum analyzing slits and the beam dump as well as small losses due to low energy stray electrons along the LINAC accelerating sections. The expected loss regions are locally shielded for prompt radiation, and that shielding will also serve as protection from residual activity. Experience with similar losses, i.e. momentum slits and beam dump on the NSLS components justifies these shielding expectations.

In normal operations, the beam path is entirely within vacuum, thus the cascade resulting from electron losses is initiated by interactions at grazing incidence at the inside edges of the 3/4 in. size holes in the copper irises comprising the accelerating structure of the LINAC on the periphery of the stainless steel vacuum chamber in the drift regions - generally non-elastic electron scattering events accompanied by bremsstrahlung. The scattered electrons will then exit from the vacuum chamber and interact with the external shielding abutting the chamber which is sized to contain the cascade or, with essentially equal probability, reenter the vacuum chamber and interact with some downstream point on the wall. In case of the LINAC, the cascade will interact with the downstream 1/4 in. thick irises spaced at approximately 1 1/2 in. intervals. The whole structure is contained inside a 1/2 in. thick copper vacuum envelope. This structure provides considerable shielding, especially in a downstream direction, allowing only gammas and neutrons to escape to the outside.

The situation with regard to accidental losses is similar except that with component failure we can expect the electron beam to impact the vacuum chamber at larger angles relative to the surface and interact principally with the external shielding. Thus, assuming that the loss points have been properly identified in section 4.3.1.3, it seems reasonable that no more than 50% of the electron loss will lead to cascades in the surrounding air.

The activation problem in air has been discussed by K. Batchelor (SAR for the BNL-ATF, 1989). He identifies ¹³N ($T_{1/2} = 10$ min., β^+) and ¹³O ($T_{1/2} = 2$ min., β^+) as the principal isotope hazards and based on the formulation of W.P. Swanson [20] (IAEA, Vienna, 1979, Technical Report Series #188), he estimates the saturation activities of these nuclides as 5.6 μ Ci and 0.6 μ Ci respectively from the ATF LINAC at 50 MeV and a beam power of 8

watts. We can scale from these results by noting first that the ELF LINAC beam at 200 MeV, 1.25×10^{10} electrons/sec at 2 Hz (200 MeV, 3.12×10^{11} electrons/sec, at 10 Hz) has a beam power of 0.4 watts (10 watts). If we further consider that all of the ELF cascades will be initiated by electrons of >10 MeV, whereas Batchelor estimates that only 5% of the ATF electrons will be above that energy, and further note that about 50% of the ELF electrons could generate air activation, then we obtain saturation activities of $2.8 \mu\text{Ci } ^{13}\text{N}$ and $0.3 \mu\text{Ci } ^{15}\text{O}$ ($70 \mu\text{Ci } ^{13}\text{N}$ and $7.5 \mu\text{Ci } ^{15}\text{O}$). If we assume that the activity is distributed uniformly throughout the ELF building (due to the open structure of the shielding walls) we obtain a saturation activity density of $1.1 \times 10^{-9} \mu\text{Ci/cm}^3$ of ^{13}N and $1.17 \times 10^{-10} \mu\text{Ci/cm}^3$ of ^{15}O , ($2.75 \times 10^{-8} \mu\text{Ci/cm}^3$ of ^{13}N and $2.92 \times 10^{-9} \mu\text{Ci/cm}^3$ of ^{15}O), well below the quoted MPC tolerance level of $2 \times 10^{-6} \mu\text{Ci/cm}^3$, even for the operation of the LINAC at maximum capability (in brackets) and a fault condition existing long enough for the saturation activity to be established.

4.3.2 Electrical Hazards from the Electron Gun and Linear Accelerator

The Electron Gun System uses a 150 kilovolt high voltage power supply in an enclosed interlocked compartment. This power supply is constructed with a limited short circuit output capability of less than 5 milliamperes such that the power supply does not present a safety hazard. The stored energy in the electron gun assembly is limited to as low a value as consistent with system performance requirements and is protected by door interlocks, bleeder resistors, and automatic shorting bars, which disable the power supply and remove the stored energy.

The Klystron/Modulator System is used to provide the high power pulsed radio frequency energy to the accelerating structures. The modulator consists of a high voltage DC power supply used to charge a pulse forming network (PFN) to about 40 kilovolts. A thyratron tube is used to discharge this PFN into a high voltage stepup transformer to deliver a pulse of power to the klystron.

Several small power supply and support functions are provided to the klystron by the modulator assembly. The modulator, stepup transformer, and klystron are bolted together to form a single enclosure. Three identical klystron systems are used.

All of the Modulator/klystron assemblies are locked and interlocked to allow both supervisory control and interlock protection. These assemblies should only be serviced by trained certified personnel.

Several electromagnets are powered by low voltage direct current power supplies and are interlocked because of the large possible short circuit currents, and because of the primary power distribution system in the power supply enclosures.

The control system is operated at low voltage wherever feasible (<30 volts). Control of plant and accelerator security as well as operational control of the accelerator is performed by these systems. No exposed voltages or hazards are present in this equipment. Several low power enclosures are also present to control and monitor the accelerators vacuum integrity, environmental levels, and provide communications within the facility. These systems all use conventional equipment and do not create any unusual hazards. All of this equipment will conform to the existing codes and regulations.

4.3.3 Linear Accelerator Occupational Health Hazards

4.3.3.1 Control of Non-Ionizing Radiation

The emission of non-ionizing radiation is to prevent the radio frequency power generated by the klystron system from interfering with low level instrumentation or providing a source of personnel hazard. Each klystron is capable of producing about 45 Megawatts of pulsed power at a frequency of 2.856 GHz. Normally the requirements for not causing interference with sensitive monitoring equipment is much more restrictive than that required for personnel protection. The klystron(s) output power is confined to the vacuum enclosure of the klystron, feed waveguides, and accelerator structures which provides a redundant safety protection system. A break in the vacuum integrity of any of these systems would immediately interlock the systems off, and the loss of vacuum would also remove the insulation the system requires to continue generating this power. Thus, the high power radiofrequency fields are contained within the system's vacuum waveguide or accelerating cavities and should not present a significant health risk. Measurements will be made to define any detectable fields and to assure that their measured power density is below the 10 mW/cm² limit defined by the American Conference of Governmental Industrial Hygienists(ACGIH).

4.3.3.2 Magnetic Fields

The ACGIH recommendation for people with cardiac pacemakers is that they not be exposed to magnetic fields exceeding 10 Gauss (1.0 milliTesla). Magnetic fields in excess of that limit are expected near the permanent magnets of the klystrons and near the electromagnets used to bend the electron beam from the transport line to the beam stop. Field measurements will be made, and regions above 10 Gauss will be posted as dangerous to persons with pacemakers.

4.3.3.3 Lasers

Conventional laser systems may be used for alignment purposes. These systems are subject to the controls described in the BNL Environmental Safety and Health Standards Manual Section 2.3.1 and the NSLS Safety and Environmental Administrative Policy and Procedures Manual (SEAPPM) Section NS 2.3.1.

4.3.4 Accident Assessment and Fault Studies

The accidents identified in Section 4.3.1 and the calculated radiation dose rates at selected points for the case of full Linac intensity ($I=50$ nA) and no additional lead shielding added are summarized below in Table III. In addition, we summarize in Table IV the dose rates at the reduced 2-nA intensity with and without additional local shielding. We have reduced the hazard risk for all identified dumps within the vault by local lead and concrete shielding to levels below BNL tolerances for the full intensity operation mode. At points in the Linac cave upstream of the exit flange, we provide side shielding adjacent to the sectionalizing valve V2 to accommodate a full intensity dump, but no side shielding along the remainder of the linac. This choice requires that we operate the Linac only at reduced ($I=2$ -mA) intensity. Even at the reduced intensity, the X-Ray skyshine dose rate is the uncontrolled area outside the 4-foot north

shielding wall is 6.2-mrem/hr, which exceeds the general public tolerance dose for the 25 hr/year occupancy time we assume at this point. Thus, we are required to add lead shielding above the Linac even for the reduced intensity case. The accident risk probability category and associated hazard consequence given in the BNL Hazard/Risk Assessment Matrix and also listed in Table III for these radiation accidents. It is seen that we regard no accident probability as being greater than occasional, or any consequence more serious than marginal. The assessment assumes that the added shielding specified in this report is in place and properly stacked. No assessment of the risk of human failure to provide these safeguards is made.

The radiation monitoring system, required as the machine shut-off part of our safety system to enforce the low intensity operation mode, consists of an array of "chipmunk" detectors inside and outside of the shielding enclosure, each independently capable of turning off the Linac via the electron gun high voltage. The position of these monitors are indicated in Fig. 3 and in the enlarged view of the transport line vault given in Fig. 27. During commissioning of the facility, we will simulate the accidents discussed in this report with the monitors outside the shielding walls pre-set at the appropriate tolerance levels. Specifically, we will make measurements both for the normal operating condition and with simulated faults at the 2-nA intensity level at the locations listed below. We will also perform an acceptance test at full 50-nA intensity during off-hours and with the electron gun high voltage on/off Switch remotored to the south end of Bldg. 726.

- (1) With valve V2 closed and radiation monitors at positions M18 and M22.
- (2) Valve V1 closed and beam missteered to hit exit flange at point 2, make measurements at monitor M17 and M3 outside gate 1.
- (3) Missteer beam to target near point 3 and measure at monitor M3.
- (4) With magnet B1 power off, make measurements at monitor positions M16, M10, and M15.
- (5) With magnet B1 powered at less than full excitation, simulate maximum credible accident at point M and measure dose rates at monitors M7 and M16.
- (6) With magnets B1 and B2 powered at full excitation and slits closed, measure at points M4, M6, M10 and M16 and monitor M23 in Bldg. 726.
- (7) With magnets B1 and B2 energized and slits open, measure with monitors M4, M6, M10, M16 and M23.

**Table III. Dose Rates from full intensity, 50-nA
accidents at indicated points (no additional shielding)**

Point of Accident	Type of Area/Worker	Dose Rates (mrem/hr)			Probability	Hazard
		X-Ray	Neutrons	Total		
Electron Gun pt.6 (90°)	Controlled/Radiation	1.7		1.7	occasional	negligible
Upstream End, Tank 1 (pt. 6)	Controlled/Radiation	to be measured			occasional	negligible
Magnet B1, pt. M	Controlled/Radiation	2357	.016	2357	occasional	marginal
	Uncontrolled General Public/Skyshine outside north wall	355	3.75	358.7		
Magnet B1, pt. 1	Controlled/Radiation	1315	.017	1315	remote	marginal
	Uncontrolled/General public/outside north wall	2.2	---	2.2		
	Uncontrolled/General Public/skyshine outside north wall	4.6	3.75	8.35		
Valve 1	Uncontrolled/general public/outside north wall	3.2	---	3.2	remote	negligible
Linac Exit Flange, pt. 2	Uncontrolled/general public/outside north wall	10.75	---	10.75	remote	marginal
	Controlled/Radiation/ Gate 1	.55	72.5	73.0		
	Uncontrolled/General Public/Skyshine outside north wall	349	3.75	352.7		
Upstream End, Tank 4, pt. 3	Controlled/Radiation/ outside south wall in Bldg. 729	52.75	.8	53.5	occasional	marginal
	Uncontrolled general public/skyshine outside north wall	308.5	3.5	312		
Upstream End, Tank 3, pt. 4 (Valve 2)	Uncontrolled/general public/outside north wall	2.52	---	2.52	remote	negligible
Upstream End, Tank 2, pt. 5	Uncontrolled/general public/outside north wall	2.92	---	2.92	occasional	marginal

**Table IV. Dose Rates at Reduced Intensity (2-nA)
for Accidents and Normal Operations, With and Without Additional Local Shielding**

Source Point	Person Location	Dose Rates (X-Ray + neut mrem/hr)		Max. Occupancy (hrs/yr)	
		No local Shielding	With Local Shielding	2-nA	50-nA
Gun (pt.6)	pt. 6 + 1m	1.7	.017	> 2000	
Mag. B1, pt. M	M6	94.3	$7.4 \cdot 10^{-4}$	> 2000	
pt. M Skyshine	M16	14.35	.002	> 2000	500
Mag. B1, pt. 1	M10	52.6	.053	> 2000	943
Mag. B1, pt. 1	M16	.088	.010	> 2000	100
pt. 1 Skyshine	M16	.334	.014	1786	71
Valve V1	M17	.128	.010	> 2000	100
End Linac, pt. 2	M17	.43	.010	> 2000	100
pt. 2 Skyshine	M17	14.11	.014	1786	71
pt. 2	Gate 1	2.9	.10	> 2000	500
Linac pt. 4	M18	.101	.010	> 2000	100
Linac pt. 5 direct + skyshine	north wall	6.72	1.03	24.3	1
Linac pt. 3	M3	2.14	2.14	584	23
pt. 3 Skyshine	north wall	12.48	1.14	22	.9
Beam Dump D	M4	38.44	$1.176 \cdot 10^{-4}$	> 2000	
pt. D Skyshine	M4	3.628	$1.19 \cdot 10^{-3}$	> 2000	
pt. D Skyshine	M16	----	$1.02 \cdot 10^{-3}$	> 2000	980
pt. D Skyshine	Bldg. 726	.357	$3.062 \cdot 10^{-4}$	> 2000	3266

References

- [1] Linear Electron Accelerator Assembly - Technical Proposal BP-080-201, April 18, 1990, Beta Development Corp., Dublin, CA 94568
- [2] NSLS Safety and Environmental Administrative Policy and Procedures Manual (SEAPPM), BNL Controlled Document, ed. D. McWhan, September 15, 1991.
- [3] BNL Environment, Safety and Health Standards Manual, Rev. 1, BNL Internal Document, N. Samios, April 18, 1991.
- [4] Radiation Protection Design Guidelines for 0.1-100 MeV Particle Accelerator Facilities, National Council on Radiation Protection and Measurements Document NCRP No. 51, Eds. E. Murrill, J. Beyster, G. Brownell, A. Chilton, J. Haimson, C. Karymark, W. Kreger, J. Wyckoff and D. Grace, Washington, DC (1977).
- [5] K. Batchelor and J. Sheehan, private communication (September 1992).
- [6] M.J. Berger and S.M. Seltzer, Tables of Energy Losses and Ranges of Electrons and Positrons, NASA Report SP-3012 (1964).
- [7] W. Jordan, private communication (1992).
- [8] J. M. Blatt and V.F. Weisskopf, Theoretical Nuclear Physics, J. Wiley & Sons, New York (1952), p. 368.
- [9] L. Blumberg, Program *EVAPORATE*, March 1992 (unpublished).
- [10] E. Hayward, Photonuclear Reactions, in Encyclopedia of Physics, eds. R.G. Lerner and G.L. Trigg, VCH Publishers, Inc., New York (2nd edition, 1990), p. 916.
- [11] E.G. Fuller and H. Gerstenberg, Photonuclear Data-Abstract Sheets 1955-1982, Vols. I-XIV, National Bureau of Standards Document NBSIR-83-2742 (Aug. 1985).
- [12] B.L. Berman, Atlas of Photoneutron Cross Sections Obtained with Monoenergetic Photons, Atomic Data and Nuclear Data Tables 15, 319 (1975) ed. K. Way, Academic Press, Inc. (1975).
- [13] R.L. Heath, Tables of Isotopes, CRC Handbook of Chemistry and Physics, ed. R.C. Weast, 67th Edition, CRC Press, Inc. (1989), pp. B219-B440.
- [14] G.P. Yost, R.M. Barnett, I. Hinchliffe, G.R. Lynch, A. Rittenberg, R.R. Ross, M. Suzuki, T.G. Trippe, C.G. Wohl, B. Armstrong, G.S. Wagman, F.C. Porter, L. Montanet, M. Aguilar-Benitez, J.J. Hernandez, G. Conforto, R.L. Crawford, K.R. Schubert and M. Roos, Review of Particle Properties, LBL Particle Data Group, Phys. Letters B, Vol. 204, 1 (1988).
- [15] W. Heisenberg, Cosmic Radiation, Dover Publications, New York (1946), p. 11.
- [16] B. Rossi, High Energy Particles, Prentice-Hall, Inc., Englewood Cliffs, NJ (1952) P. 251.
- [17] H.A. Bethe and J. Ashkin, Passage of Radiations Through Matter, in Experimental Nuclear Physics, Vol. 1, Part II, p. 309, ed. E. Segre, J. Wiley & Sons, Inc. (1953).
- [18] Ibid. Ref. 4, Section 4.4.2.
- [19] L. Blumberg and M. Perlman, Maximum Credible Radiation Accident, BNL Memo to K. Batchelor, May 15, 1980.
- [20] W.P. Swanson, Radiological Safety Aspects of the Operation of Electron Linear Accelerators, Tech. Rep. Series No. 188, Int. At. Energy Agency, Vienna, 1979, p. 189.
- [21] Private communication, D. White, Reactor Experiments, Inc., 1275 Hammerwood ave., Sunnyvale, CA 94089.
- [22] Ibid., Ref. 4, Section 4.5.1, p. 69, Eq. (18).
- [23] L. Blumberg, Program *OMEGA*, unpublished (1992).
- [24] H. Kahnhauser, private communication (1992).

- [25] W.R. Casey, BNL memo to M. Brooks, Chairman, BNL Safety Committee, Feb. 4, 1988.
- [26] Ibid, Ref. 20, p. 176.
- [27] L. Blumberg, Program *EBARBREM*, unpublished (1992).
- [28] BNL Radiological Control Manual, Environment, Safety and Health Standards, Safety and Environment Protection Division (December 1, 1992).
- [29] J. Preisig, private communication (March 1993). We are grateful to Dr. Preisig for pointing out an error in the originally presented integral.
- [30] M. Woodle, private communication (March, 1993).
- [31] D. J. Hughes and R. B. Schwartz, Neutron Cross Sections - 2nd ed., BNL-325 (July 1, 1958).

Fig. 1 BNL site plan in vicinity of Building 729.

Fig.3 BLDG. 729
200-MeV LINAC AND SHIELDING LAYOUT
● RADIATION MONITOR POSITIONS

Fig.4 BLDG. 729
BUILDING ELEVATION AND SHIELDING WALLS

NATIONAL SHOCKSTATION LIGHT SOURCE

• Temporary
on Report to John
Holt, Jr. for Basic Energy Sciences

July 6, 1993

Signature
John Holt, Jr.

X Rays and Gamma Ray

E.1 X-Ray Emission Rates from High-Z Targets

Fig. 6 X-Ray source dose equivalent index vs. electron energy.

f X Rays

E.10 Broad-Beam Transmission Through Lead of X Rays
Produced by 0.1- to 0.4-MeV Electrons

Transmission through lead (density 11.3 g cm^{-3}) of x rays produced by 0.1- to 0.4 MeV electrons, under broad-beam conditions. Electron energies designated by asterisk (*) were accelerated by voltages with pulsed wave form; unmarked electron energies were accelerated by a constant potential generator. Curves represent transmission in dose-equivalent index ratio. (See Appendix E-14 for basis for interpolation between curves.) Curves were derived from NCRP Report No. 34 (NCRP, 1970a).

Fig. 7 X-Ray transmission factor B_x vs. lead thickness.

E.8 Broad-Beam Transmission Through Concrete of X Rays Produced by 0.5- to 176-MeV Electrons

Transmission of thick-target x rays through ordinary concrete (density 2.35 g cm^{-3}), under broad-beam conditions. Energy designations on each curve (0.5 to 176 MeV) refer to the monoenergetic electron energy incident on the thick x-ray producing target. Curves represent transmission in dose-equivalent index ratio. (See Appendix E-12 for basis for interpolating between curves.) Curves derived from: (1) Miller and Kennedy (1956); (2) Kirn and Kennedy (1954); (3) Karzmark and Capone (1968); and (4) NCRP Report No. 34 (NCRP, 1970a) and NCRP Report No. 49 (NCRP, 1976).

F.3 Thick-Target Neutron Yields for (γ, n) Reactions

Fig. 10 Total photoneutron yield Y vs. incident electron energy.

Thick-target neutron yields (in 4π solid angle) per microampere of target current from several photonuclear reactions, as a function of incident electron energy on the thick-target x-ray source. In the case of the $^9\text{Be}(\gamma, n)$ yields, a mass of Be was placed around the x-ray source. The ^{181}Tl target thickness was 6.3 g cm^{-2} , serving as x-ray source as well as neutron source. The ^{238}U target was 5.9 g cm^{-2} thick; the yields include the neutrons from the photofission of ^{238}U . The curves were empirically derived from the following references: (1) Gozani and Kull (1969); (2) MacGregor (1959); and (3) Berger and Seltzer (1970). Neutron fluence rates can be estimated, for purposes of calculating shielding thickness, from Appendix F-4.

Fig. 11 Forward and 90 degree neutron yields for various reactions.

F.4 Typical Angular Distributions in Neutron Yield Ratios^a from Several Neutron-Producing Reactions

Reaction	Energy MeV	A	B	Ref.
		$Y \text{ sr}^{-1} (90^\circ)/Y \text{ sr}^{-1} (0^\circ)^b$	$Y \text{ sr}^{-1} (0^\circ)/Y \text{ sr}^{-1} \text{ etc.}^c$	
$^3\text{H}(p,n)^3\text{He}$	$\geq 1.02 (E_{th})^a$	0.25	0.25	1
	2.5	0.5	0.15	1
$^7\text{Li}(p,n)^7\text{Be}$	$\geq 1.88 (E_{th})$	0.25	0.25	1
	2.5	0.5	0.15	1
$^9\text{Be}(p,n)^9\text{B}$	$\geq 2.05 (E_{th})$	0.25	0.25	1
	2.5	0.67	0.10	1
	14	<0.1	>0.5	2
$^3\text{H}(d,n)^3\text{He}$	0.5	0.3	0.2	1
	2.5	0.15	0.35	1
$^3\text{H}(d,n)^4\text{He}$	0.2	~ 1	~ 0.1	1
$^9\text{Be}(d,n)^{10}\text{B}$	<2	~ 1	~ 0.1	1
	7.5	0.1	0.5	2
$^9\text{Be}(^3\text{He},n)^{11}\text{C}$	20	0.1	0.5	2
$\text{Ta}(^4\text{He},n)$	40	<0.1	>0.5	3
All (p,n), (d,n) ($^3\text{He},n$), ($^4\text{He},n$)	>5	≤ 0.1	≥ 0.5	—
All (γ,n)	$\gg E_{th}$	~ 2	$\sim 0.5^d$	—

^a E_{th} : threshold energy.

^b Ratios of yields per steradian are estimates only, and are useful mainly for purposes of calculating shielding thicknesses.

^c Yield per steradian in all other directions is assumed to be equal to $Y \text{ sr}^{-1} (90^\circ)$.

^d $Y \text{ sr}^{-1} (90^\circ)/Y$.

^e Neutron fluence rates, ϕ , at distance d from the target can be approximated by $(Y \text{ sr}^{-1} \times 10^{-1})/d^2$, when d is measured in meters. Where total (4π) yield is given (Appendices F-2, F-3), $Y \text{ sr}^{-1} (0^\circ)$ is obtained from Column B. $Y \text{ sr}^{-1} (90^\circ)$ is then obtainable from Column A. Note: for (γ,n) reactions, Column B provides the value for $Y \text{ sr}^{-1} (90^\circ)$ directly.

References: (1) Burrill (1963); (2) Bruninx and Crombeen (1969); and (3) Stephens and Miller (1969).

Fig. 12 Neutron dose-equivalent index transmission B_n vs. concrete thickness.

F.6 Dose-Equivalent Index Transmission Through Concrete of Monoenergetic Neutrons

Dose-equivalent index transmission per unit fluence (rem cm^2) of monoenergetic neutrons incident normally on slabs of ordinary concrete (TSF-5.5, see Appendix H-2). Multi-collision dose-equivalent index per unit fluence is calculated to include the dose-equivalent index contribution by capture gamma rays produced within the slab. Energies noted on the curves refer to the average energies of neutrons in the energy bins chosen for the discrete-ordinate calculations, as follows:

Fig. 13 Neutron evaporation energy spectrum from statistical model.

Fig. 14 Average neutron energy in evaporation spectrum vs. maximum energy.

Fig. 16 Detail of downstream (200-MeV) end of Linac.

E.15 Reflection Coefficients for Monoenergetic X Rays in Concrete, Iron and Lead

Reflection coefficients, α_r , for monoenergetic x rays on ordinary concrete, iron, and lead as a function of incident monoenergetic photon energy, for several angles of reflection assuming normal incidence and equal angles of incidence and reflection. Values are given for ordinary concrete and iron, based on existing available information, both theoretical and experimental, with particular emphasis on the following references: (1) Chilton and Huddleston (1963); (2) Chilton (1962); (3) Chilton (1965); and (4) Chilton *et al.* (1965). For photon energies higher than 10 MeV, the use of the 10-MeV values of α_r is expected to be safe.

Values of α_r for photons incident on lead are not as readily calculable, but a conservative upper limit is 5×10^{-3} for any energy and scattering angle.

The values of α_r for $\theta_r = 180^\circ$ in Curve A are the same as for $\theta_r = 180^\circ$ in Curve B.

Fig. 18 Linear absorption coefficient of X-Rays vs. X-Ray energy in Al, Cu, Sn and Pb.

Fig. 32. Total absorption coefficient for gamma-rays, per centimeter, in various materials, as a function of the gamma-ray energy. For lead, the separate contributions of photoelectric effect, Compton scattering, and pair production are shown by the dotted curves. Circles represent measurement made in 1934. From *The Quantum Theory of Radiation* by W. Heitler. Used by permission of the Clarendon Press, Oxford.

F.11 Thermal-Neutron Transmission Through Mazes and Ducts

Transmission of thermal-neutron fluence rates through multi-legged concrete mazes or large ducts, as a function of the summed centerline distances from the inner duct entrance to the duct exit, divided by the square root of the product of the height and width of the duct aperture ($\sqrt{hw}$ ft). The curves for each leg are essentially similar in shape, with discontinuities in the transmission factor at the intersections between legs. The curve for the second leg intersects the first-leg curve at a distance equal to the centerline length of the first leg; the curve for the third leg intersects similarly on the second-leg curve. These curves are adapted from Maerker *et al.* (1968), and are illustrative of a specific maze configuration. Intersects of curves for other configurations would occur at dimensions corresponding to the particular maze design in question.

Fig. 20 Tenth value layer (TVL) for neutrons in concrete vs. neutron energy

FIG. 20. Dose-equivalent tenth-value layer, TVL, for broad beams of monoenergetic, unidirectional neutrons incident on ordinary concrete, as a function of neutron energy E_n . The dashed curve represents TVL₁ (the 'first' TVL) and the solid curve is for TVL_e, corresponding to the nearly exponential attenuation of subsequent layers. The dose equivalent from n-capture gamma rays is implicitly taken into account. The curves are based on discrete-ordinate calculations of Roussin and Schmidt [44], Roussin et al. [45], and Alsmiller et al. [46], using in part the smoothed data of Wyckoff and Chilton [43]. The low-energy limit is to indicate that the TVL_e does not vary greatly below the energy range shown. The high-energy limit is based on semi-empirical considerations (see Section 3.5.2).

Fig. 21 Equivalent 90 degree X-Ray energy for thick target bremsstrahlung vs. incident electron energy.

E.6 Equivalent Incident Electron Energies

Equivalent electron energy for analysis of transmission of x rays emitted in the 90° direction from very thick high-Z targets, as a function of the incident electron energy. The x-ray spectrum at 90° is lower in energy than the spectrum at 0°. This lower-energy radiation can be described in terms of an incident electron energy that would in effect produce x rays with similar transmission characteristics in the 0° direction. Transmission curves or tenth-value layer curves applicable to the lower energy selected from this graph may be used in the calculation of shielding thicknesses for the 90° beam. The same procedure would be a conservative approach for x rays from low-Z targets, and for x rays emitted in the 180° direction.

References: (1) Burrill (1968); (2) Berger and Seltzer (1970); (3) McCall and Nelson (1974); and (4) Saxon (1964).

Fig. 22 Bremsstrahlung attenuation factor B_x vs. Pb thickness.

Fig. 23 Bremsstrahlung attenuation factor B_x vs. steel thickness.

Fig. 24 Bremsstrahlung attenuation factor B_x vs. concrete thickness.

Fig. 25 Average X-Ray energy in bremsstrahlung spectrum vs. incident electron energy.

Fig. 26 Block diagram of the 200-MeV electron linear accelerator.

Figure 2.1 R.F. SYSTEM SCHEMATIC

Attenuation of Cf-252 Radiation by R/X Type 201 (5% Boron-Polyethylene)

**DATE
FILMED**

10 / 19 / 93

END