15 RADIATION SAFETY AND SHIELDING

15.1 SHIELDING OBJECTIVES

NSLS-II is subject to the DOE radiation protection standards. The primary document that defines the DOE radiation protection standards is the Code of Federal Regulations 10 CFR 835. In addition, the accelerator-specific safety requirements are set by DOE Order 420.2B, Safety of Accelerator Facilities. All radiation protection policies and guidelines at NSLS-II must be in compliance with these regulations along with the BNL Radiation Control Manual and other pertinent documents in the BNL Standards Based Management System.

The maximum annual exposure to radiation workers and members of the public is limited in 10 CFR Part 835 to 5,000 mrem and 100 mrem, respectively. To keep radiation exposures well below regulatory limits, BNL maintains an annual administrative control level of 1,250 mrem for its workers and 5 mrem per year from any single facility to the public off-site. An additional control level of 25 mrem/year from NSLS-II operations is established for personnel working in non-NSLS-II facilities on site.

The dose to workers and to the members of the public from NSLS-II operations will be kept well below federal limits and within BNL administrative levels through shielding, operational procedures, and review of all experiments and other use of radioactive materials. In accordance with 10 CFR 835.1001, measures will be taken to maintain radiation exposure as low as reasonably achievable (ALARA) through shielding design and administrative controls. The primary method of radiation control will be through physical design features such as shielding and barriers to radiological areas. Administrative controls will only be employed as supplemental to control radiation exposure. An internal control level for the facility will be to keep the annual dose equivalent, as the result of NSLS-II operations, <100 mrem/year for all NSLS guests, users and staff members working at the facility.

Shielding for the accelerators and the storage ring will be provided through a combination of various materials (e.g. concrete, lead, polyethylene, and soil) and will be designed for normal operations using conservative beam loss assumptions to limit the maximum dose to 500 mrem when in contact with the shield for 2,000 hours per year. Occupational exposure of personnel is most likely to occur in the vicinity of experimental hutches along the beam lines. Shielding of these areas will be designed to maintain exposures when in contact with the hutch wall to <100 mrem/year for 2,000 hours of exposure per year.

The adequacy of the shielding for abnormal conditions, including a maximum credible incident (MCI) will be evaluated. The MCI is defined as a credible fault condition with the maximum or worst-case radiological consequences. Depending upon the severity of the radiological conditions created during the MCI, additional shielding or other engineering controls (e.g. interlocked radiation monitors) may be needed. The likelihood of an incident creating a dose to an individual exceeding the administrative control level must be determined to be low and any exposure exceeding the annual limit because of inadequate shielding will be prevented.

Effectiveness of the shielding will be actively monitored by radiation instruments located on the experimental floor and by frequent area-surveys performed by the health physics personnel. Additional local shielding will be provided to reduce the radiation field as needed. Passive area monitors will also be used to integrate doses in various areas. The results will be analyzed for trends, and shielding will be improved as appropriate.

15.2 SHIELDING ESTIMATES FOR THE ACCELERATOR ENCLOSURES

Radiological conditions for the design and operation of the NSLS-II linac, storage ring, and booster synchrotron have been analyzed using the currently available design parameters. The booster synchrotron will be housed in the same tunnel as the storage ring at NSLS-II. Calculations of the resulting radiation fields and required shielding have been made for normal loss of stored beam and loss of beam during injection at the septum/extraction magnets. The shielding estimates are based on conservative assumptions, including several modes of operations that involve normal beam loss mechanisms as well as certain abnormal beam loss scenarios. These situations are drawn from experiences and assumptions used at existing accelerator and synchrotron radiation facilities. Shielding requirements for the storage ring and booster synchrotron are based on maintaining exposure to personnel to less than 500 mrem/year assuming a occupancy of 2,000 hours per year for a worker at NSLS-II. The calculated shielding for the occupiable regions during operation is for a dose rate of <0.25 mrem/h, at the exterior of the accelerator enclosures on contact. Sufficiently conservative factors are included in these estimates to provide additional margin of safety.

15.2.1 Sources of Radiation Hazard

For the radiological analysis of NSLS-II accelerator enclosures, the following radiation components were considered:

- bremsstrahlung radiation created during electron beam loss
- neutron production by high-energy bremsstrahlung
- synchrotron radiation from the insertion devices

High-energy electrons produce bremsstrahlung [15.1] when intercepted by the accelerator components or residual gas molecules in the vacuum chamber. Bremsstrahlung, or “breaking radiation,” is emitted by a high-energy electron as it decelerates due to inelastic radiative interaction with the coulomb field of atomic nuclei of the medium it traverses. Subsequent pair production and bremsstrahlung production can generate an electromagnetic shower. The radiation originating in the shower is highly forward-peaked in the forward direction of the electron beam. However the transverse component is significant and cannot be ignored. The lateral shielding for the accelerator enclosures is designed to protect personnel from the transverse component of the electromagnetic shower. In addition to bremsstrahlung radiation, two other radiation components need to be considered. These are Giant Resonance Neutrons and High Energy Neutrons originating from the interaction of bremsstrahlung with heavy metals [15.2]. GRN are produced by photonuclear interactions when the photon energy is above the threshold energy of 7 to 20 MeV. This component has an average effective energy of about 2 MeV and is emitted isotropically. If the photon energy is above 50 MeV, high-energy neutrons (>25 MeV) are also emitted. The high-energy neutron component is not isotropic. To estimate the shielding and other requirements for the NSLS-II accelerator enclosures, these sources of radiation have been considered, across a range of possible conditions.

15.2.2 Shielding Design Methodology for the Accelerators

15.2.2.1 Radiation Attenuation Factors for the Shielding Materials

The radiation attenuation factors used for the materials in the current shielding calculations are given in Table 15.2.1. These data have been obtained from various sources in the literature [15.3–15.6]. A number of references which discuss these attenuation factors have been reviewed. We have chosen conservative values for these factors to provide an additional safety margin for the shielding calculations.

Table 15.2.1 Radiation Attenuation Factors of Shielding Materials.

Radiation Component	Shielding Material	Density [g/cm^3]	Attenuation Length [g/cm^2]
Bremsstrahlung	Concrete	2.35	49
	Heavy Concrete	3.70	50
	Lead	11.34	25
	Iron	7.80	37
	Earth	1.60	70
	Polyethylene	1.01	70
Giant Resonance Neutrons (E <25 MeV)	Concrete	2.35	40
	Heavy Concrete	3.70	45
	Lead	11.34	161
	Iron	7.80	100
	Earth	1.60	33
	Polyethylene	1.01	6.3
High-Energy Neutrons	Concrete	2.35	65 (<100 MeV) 115(>100 MeV)
	Heavy Concrete	3.70	125(>100 MeV)
	Lead	11.34	191
	Iron	7.80	138
	Earth	1.60	90
	Polyethylene	1.01	62

15.2.2.2 Dose Equivalent Factors of Radiation Components

Effective Dose Equivalent factors for the unshielded source terms at 1 meter in the transverse direction from a 3.0 GeV electron beam interaction on a thick copper or iron target are given in Table 15.2.2. The data are taken from Sullivan [15.7]. Note that the dose equivalent factors in the transverse direction (90 degrees) are independent of the electron beam energy, but dependent on the beam power.

Table 15.2.2 Dose Equivalent Factors (Fi) Used for Shielding Calculations.

Radiation Component	Dose Equivalent Factor [mrem-m^2/Joule]
Bremsstrahlung	1.39
Giant Resonance Neutrons	0.27
High-Energy Neutrons	0.043

In the absence of any shielding, the bremsstrahlung component will include low-energy particle component (e^- and e^+), which can be disregarded, since shielding for bremsstrahlung will ensure attenuation of the particle component. In the forward direction with respect to the electron beam (zero degrees), the dose equivalent factor for bremsstrahlung [15.8] is 8.3 × E mrem-m^2/J, where E is the electron energy in MeV. The bremsstrahlung dose rate at 1 m near zero degrees, but not within the forward spike [15.8], is taken as 850 mrem-m^2/J. The GRN component is assumed to be isotropic from the loss point. These forward dose equivalent components are important for the design of ratchet wall shielding of the storage ring.

15.2.2.3 Shielding Calculations for NSLS-II Accelerator Enclosures

The bulk shielding for the accelerator enclosures has been calculated using the following expression [15.9]:

$$H = \sum_i \frac{F_i J}{R^2} e^{-t/\lambda_i} \qquad (15\text{-}1)$$

where H = Dose Equivalent Rate summed over all components, in mrem/h, F_i = Radiation Dose Equivalent Factors for the corresponding radiation component (i^{th} component), J = electron energy dissipation in joules/hour, R = total distance of the dose point from the source in meters, t = thickness of bulk shielding in g/cm^2, and λ_i = attenuation length of the i^{th} radiation component in g/cm^2.

The equation is solved using a parameter search for the thickness of the bulk shielding (concrete), such that H <0.25 mrem/h. The shielding strategy employed is to use concrete as bulk shielding, to provide global shielding of accelerator enclosures for distributed losses in the system. This shielding needs to be supplemented by additional local shielding, employing lead for bremsstrahlung or polyethylene for neutrons, to reduce radiation fields from the high loss points to acceptable limits of <0.25 mrem/h (500 mrem/2,000-hour work year).

15.2.3. Shielding Estimates for the Linac Enclosure

15.2.3.1 Linac Parameters

For NSLS-II, a linac will be providing 200 MeV electrons into the booster synchrotron. In the current calculations the linac tunnel is assumed to be 60 meters long, 4 meters wide, and 3 meters high. The salient features of the linac system are as follows:

- beam energy ■ 200 MeV
- beam current ■ 20 nA
- bunch pattern ■ 500 pC/ 40 bunches
- frequency ■ 1 Hz
- tunnel length ■ 60 m
- tunnel width x height ■ 4 m x 3 m
- position of beam from floor ■ 1 m
- power ■ 4 W

15.2.3.2 Bulk Shielding for the Linac Tunnel

For the linac system, the bulk shielding computations are based upon normal operation beam losses of certain fractions of beam power. Table 15.2.3 gives the estimated losses of beam energy in the linac system components.

Table 15.2.3 Estimated Losses in the Linac System Components.

Component	Charge [nC/s]	Loss [%]	Energy [MeV]	Power Loss [W]
Accelerator system	20	1 % distributed	200	0.04
Injection septum	0.25	50 %	200	0.05
Linac beam stop	20	100 %	200	4.0

To estimate the bulk shielding for the linac tunnel, a distributed loss of 1% of the beam energy is assumed along the length of the tunnel. The shielding requirement for the lateral walls and the roof of the linac tunnel is calculated based upon this beam loss scenario. The occupiable regions are shielded for a dose rate of 0.25 mrem/h (500 mrem for 2,000 work hours per year). The roof is considered as a fully occupiable region in the current calculations. The distance of the lateral walls and the roof is taken as 2 m from the beam.

The bulk shielding estimates of the concrete thickness for the linac tunnel is given in Table 15.2.4. 90cm-thick standard concrete with a density of 2.35 g/cm^3 will limit the dose rate to <0.25 mrem/h at the exterior of the lateral wall and the roof, for an assumed 1% distributed beam loss scenario.

The injection septum for the linac injection to the booster synchrotron is in the storage ring enclosure.

Table 15.2.4 Bulk Shielding Estimates for the Linac Tunnel.

Component	Lateral wall Concrete Equivalent[1] Thickness [cm]	Roof Concrete Equivalent[1] Thickness [cm]
Non-injection region	90	90
Linac downstream wall	220 100 cm + 15 cm (Pb)	100

[1] A density 2.35 g/cm^3 is considered standard for concrete.

The bulk shielding estimates in the forward direction of the linac should be estimated if an occupiable region exists in the forward direction of the extraction magnet. The calculations are based on the forward direction bremsstrahlung dose equivalent rates provided by Sullivan [15.7]. These estimates are given in Table 15.2.4. The estimated concrete equivalent thickness for bulk shielding is 220 cm. Local shielding of lead in the forward direction can be provided to save on the concrete bulk shielding. A factor of 8 with respect to standard concrete can be applied to calculate the equivalent thickness of lead. Local shielding by the equivalent thickness of lead may replace concrete in the forward direction at the extraction region of the linac.

15.2.4 Design of the Linac Beam Stop

When the linac is not injecting into the booster, the beam is dumped at the linac beam stop. This beam stop will be located at the end of the linac accelerator tunnel closer to the extraction region. Since the detailed layout of the building is not currently available, it is assumed that the concrete bulk shield, which separates the occupiable regions, is 2 m away in all directions from the beam stop. 100% of the 4-W electron beam is dissipated on the beam stop. The shielding strategy in this case will be to shield the stop locally in addition to the linac concrete bulk shielding available at the injection/extraction region.

When 200-MeV electrons interact with the material of the beam stop, an electromagnetic shower will be generated within the material, due to successive bremsstrahlung and pair-production interactions. A shower is developed in the material when the primary electron energy is much greater than the critical energy of the material. The critical energy, E_c, is the electron energy for a given element at which the average energy loss from bremsstrahlung production is equal that from ionization. The lateral and longitudinal shower dimensions within the material are determined by the Moliere radius and the radiation length of the material [15.10] Table 15.2.5 gives the shower parameters for various shielding materials that are also used for beam stops.

Table 15.2.5 Electromagnetic Shower Parameters for Various Materials.

Material	Density [gm/cm^3]	Critical Energy [MeV]	Radiation Length [cm]	Moliere Radius [cm]
Aluminum	2.70	51.0	8.89	3.70
Iron	7.87	27.4	1.76	1.40
Copper	8.96	24.8	1.43	1.22
Tungsten	19.3	10.2	0.33	0.73
Lead	11.35	9.5	0.56	1.25
Concrete	2.35	51.0	10.9	4.5

The material considered for the linac stop is iron, for various qualities such as sturdiness, thermal stability, conductivity, and relative compactness of shower dimensions. Iron being a low Z material, the photo-neutron yield and the resulting activation will also be minimal.

The theory of electromagnetic showers stipulates that material of dimensions of approximately 20 radiation lengths in longitudinal and 3 Moliere radii in transverse will contain 99.99% of the electromagnetic shower [15.10]. Thus, an iron cylinder of 35 cm length and 8.5 cm diameter will be sufficient to effectively contain the electromagnetic shower in the linac stop. The scattered low-energy photon radiation will require additional lead shielding, but will be well below the critical energy and photo-spallation reaction threshold. The neutrons created in the shower will escape isotropically from the stop and require additional shielding.

Table 15.2.6 shows the dose rate due to various radiation components around the linac beam stop at the exterior of the 1m concrete shield wall without local shielding. Since the exact layout of the storage ring-linac tunnel is not available at present, the concrete shield wall is assumed to be 2 m away from the iron beam stop. Table 15.2.6 also provides the dose rates on the exterior of the concrete shield wall with a local shielding of 15 cm of Pb and 25 cm of polyethylene (density = 1 g/cm^3). The local shielding limits the dose rate at the exterior of the concrete bulk shielding to <0.25 mrem/h. The stop will be in the linac enclosure; personnel will have no access to the enclosure when there is the potential for beam acceleration.

Table 15.2.6 Dose Rates at the Exterior of the Concrete Shield Wall around the Linac Beam Stop.

Radiation Component	Unshielded Dose Rates [mrem/h]	Dose Rates with 15 cm Pb and 20 cm Poly [mrem/h]
Bremsstrahlung	18.37	0.0142
Giant Resonance Neutrons	1.21	0.0079
High Energy Neutrons	1.85	0.2172
Total Dose Rate	21.43	0.2393

15.2.5 Shielding Estimates for Booster and Storage Ring

15.2.5.1 Storage Ring Parameters

The operations goal for the NSLS-II storage ring is to store a 500 mA current of 3.0 GeV electrons injected by the booster synchrotron. However, it may be desirable to increase either the electron energy or the stored current in the future if the user program requires it. Since it is very difficult and costly to increase the shielding after construction, the initial shielding will be sized to enable safe operation for a 500 mA current stored at an electron energy of 3.5 GeV. The estimated lifetime of the beam in the storage ring is 2 hours. In the current calculations the storage ring tunnel is assumed to be 780 meters in circumference. The maximum assumed operating parameters of the storage ring system are thus:

- beam energy ■ 3.5 GeV
- beam current ■ 500 mA
- beam lifetime ■ 2 hr
- tunnel circumference ■ 780 m
- stored charge ■ 1.3 μC
- stored electrons ■ 8.1×10^{12}
- stored energy ■ 4,540 J

15.2.5.2 Bulk Shielding for the Storage Ring Enclosure

With two hours of beam lifetime in the storage ring, ~ 50% stored beam loss occurs in one hour. 10% of this beam loss is assumed to occur at any one location of the storage ring. The shielding requirements for the storage ring at regions other than the injection/extraction region are calculated based on this beam loss scenario. Table 15.2.7 summarizes the various beam loss scenarios considered.

Table 15.2.7 Estimated Beam Losses in the Storage Ring - Booster Components.

Accelerator component	Loss [%]	Energy [MeV]	Power Loss [W]
SR Accelerator System	10%	3,500	0.075
Booster Accelerator system	2%	3,500	0.0175
Injection/Extraction, booster to storage ring	50%	3,500	0.82
Injection/Extraction linac to booster	50%	200	0.05
Booster beam stop	100%	3,500	0.874

The lateral wall of the storage ring on the experimental floor side is assumed to be 1 meter from the storage ring vacuum chamber. The roof and the inboard walls are assumed to be 2.5 meters from the vacuum chamber. The ratchet wall in the forward direction is assumed to be 20 meters from the middle of the insertion device straight section. The ratchet wall shielding thickness is calculated using the forward-peaking component of the Dose Equivalent Factors available in the literature [15.8]. The occupied regions on the experimental floor side of the storage ring are shielded for a dose limit of <0.25 mrem/h for 2,000 hours of occupancy per year. The roof and inboard wall are also considered as fully occupied regions in the current calculations.

The bulk shielding estimates in terms of concrete thickness for the storage ring and booster synchrotron system are given in Table 15.2.8. Shielding wall thickness in standard concrete equivalent is given for the lateral wall and roof. The standard concrete can be replaced by a high density concrete. Shielding thickness is also given in terms of heavy concrete of density 3.7 g/cm^3. However, if concrete of a different density is used, shielding thickness will need to be scaled accordingly.

The ratchet wall shielding thicknesses at the first optics enclosure side of the beamlines are also given in Table 15.2.8. These walls are assumed to be 20 meters from the center of the straight section of the insertion devices. These walls are thicker (160 cm standard and 102 cm high-density concrete) due to the bremsstrahlung forward component that needs to be shielded.

15.2.5.3 Bulk Shielding: Booster-to-Storage Ring Injection/Extraction Region

Injection from the booster synchrotron to the storage ring takes place approximately every 1 minute. Taking into account the storage ring lifetime as 2 hours, 0.83% of the beam is lost in 1 minute. In 1 hour, 49.77% of the beam is lost and an equivalent amount is injected into the storage ring to keep the ring current at 500 mA—an operation known as “top-off.” During injection, 50% injection efficiency is assumed. Therefore, twice the amount of charge is injected into the storage ring and half as much of the injected charge is lost on the injection/extraction septum magnets. The shielding requirement at the injection/extraction region is calculated taking into account this beam loss scenario. There may be a higher rate of injection during other modes of operation, such as accelerator performance evaluation or during injection to fill the storage ring from zero current. Assuming that top-off is the prevailing mode of operation in the long run, shielding calculations are performed for an average injection frequency of once every minute and 50% of the injected beam energy being dissipated at the injection/extraction septum region. The lateral wall on the experimental floor side and the roof is assumed to be 1 meter from the septum.

The bulk shielding estimates in terms of concrete thickness for the storage ring enclosure at the booster-to-storage-ring injection/extraction region are also given in Table 15.2.8. 160cm-thick standard concrete with a density of 2.35 g/cm^3 will limit the dose rate to <0.25 mrem/h at the exterior of the lateral wall of the storage ring. 150 cm of concrete on the roof will limit the dose rate to the same level at the exterior on contact. Part of the concrete can be replaced with an equivalent thickness of lead as additional local shielding, if needed. A factor of 8 with respect to standard concrete can be applied to calculate the equivalent thickness of lead required. The extraction region can be shielded locally with an additional 10 cm of lead all around to maintain uniformity of the storage ring roof thickness around the ring. A berm (of earth) with a density of 1.6 g/cm^3 may be used as shielding to partially replace the inboard concrete wall. A berm/standard concrete factor of 2.1 can be applied to estimate the necessary thickness for this berm.

15.2.6 Bulk Shielding Estimates for the Booster Enclosure

At NSLS-II, the booster synchrotron will be housed in the storage ring enclosure. A top-off injection from the linac to the booster synchrotron will take place approximately every minute. The injected beam energy is 200 MeV and the injected charge is 15 nC. These electrons are accelerated to 3.5 GeV and injected into the storage ring. There may be a higher rate of injection during other modes of operation, such as accelerator performance evaluation or during injection to fill the storage ring from zero current. Assuming that top-off is the prevailing mode of operation, shielding calculations are performed for an average injection frequency of one in every minute and 2% of the beam energy being dissipated at any single point in the booster synchrotron during acceleration. The salient features of the booster synchrotron are given below.

- beam energy ▪ 3.5 GeV
- repetition rate ▪ 1 Hz
- ring circumference ▪ 780 m
- accelerated charge ▪ 15 nC
- no of electrons per fill ▪ 9.36×10^{10}
- total energy in the booster ▪ 52.5 J

In the current design, the booster system will be suspended from the roof of the storage ring. The roof and lateral wall are each assumed to be 1 meter from the booster vacuum chamber. Bulk shielding for the booster synchrotron is calculated based on the algorithm given in Section 15.2.2.3. The results are given in Table 15.2.5.2. Storage ring shielding estimates are also given in the same table. The bulk shielding thickness for both standard concrete and high density concrete are given. Note that the required shielding in all directions is less than the shielding of the storage ring enclosure. Therefore, the booster synchrotron can be safely housed inside the storage ring enclosure with the current configuration without any additional radiological consequences. It must be emphasized that the distance from the source to the bulk shielding is critical in determining dose rates outside the shielding. The stated distances in the current calculations need to be maintained in the civil construction design, and any change warrants rescaling of the bulk shielding thickness.

15.2.6.1 Bulk Shielding for the Linac-to-Booster Injection/Extraction Region

Injection to the booster from the linac takes place once per minute during top-off mode. This injection frequency can be temporarily higher during machine studies periods. Assuming that top-off is the prevailing mode of operation, shielding calculations are carried out for an average injection frequency of once per minute. 15 nC of charge is injected to the booster in every minute. During the injection, 50% injection efficiency is assumed. This results in 50% of the injected beam energy being dissipated at the injection/extraction region and twice the quantity of charge being injected into the booster to achieve filling.

The linac injection septum to the booster is housed in the storage ring injection region. The bulk shielding estimates of the concrete thickness for the linac to booster injection region are also given in Table 15.2.8. 115 cm-thick standard concrete with a density of 2.35 g/cm^3 will limit the dose rate to <0.25 mrem/h at the exterior of the bulk shielding on contact for the lateral wall and the roof for the assumed 50% injection loss. In the current calculations, the distance from the loss points to the lateral walls and the roof is assumed to be 1 meter. The distance from the septum to the inboard wall is assumed to be 2 meters. These assumptions can be modified when a more detailed layout of the tunnels is available. If the septum is located at the booster to storage ring injection region, the available bulk shielding of the storage ring at the injection region will limit dose rates to <0.25 mrem/h. Additional local shielding can replace concrete, if bulk shielding is deficient.

Table 15.2.8 Bulk Shielding Estimates for the Storage Ring and Booster Synchrotron Enclosures.

Component	Expt. Floor Wall Concrete Equivalent Thickness [cm]	Roof Concrete Equivalent Thickness [cm]	Inboard Wall Concrete Equivalent Thickness [cm]
Storage ring non-injection region	120[a] or 76[b]	100[a]	100[a]
Booster to storage ring Injection/Extraction	160[a] or 102[b]	150[a] or (100[b] + 8 Pb)	150a or (100b + 8 Pb)
Storage ring ratchet wall (forward direction)	160[a] or 102[b]	100[a]	---
Booster non-injection region	95[a] or 60[b]	95[a]	80[a]
Linac to booster Injection region	115[a]	115[a]	100[a]

[a]Concrete of density 2.35 g/cm^3 is taken as standard concrete.

[b]Corresponding thickness with concrete of density 3.7 g/cm^3.

15.2.7 Booster Beam Stop Design Calculations

15.2.7.1 Booster Beam Stop

When the booster is not injecting into the storage ring, the beam is dumped at the booster beam stop. This beam stop will be located on the floor of the storage ring enclosure closer to the extraction/injection region. As the detailed layout of the building is currently not available, it is assumed that the concrete bulk shield, which separates the occupiable regions, is 1 m away at the experimental floor side and 3 meters away from the roof. The lateral wall of the storage ring at the injection region of the storage ring is assumed to be 160 cm of standard concrete equivalent and the roof is 100 cm of concrete equivalent without any additional local shielding. 100% of the 0.87 W electron beam is dissipated on the beam stop. The shielding strategy in this case will be to shield the stop locally in addition to the concrete bulk shielding available at the injection extraction region.

The electromagnetic shower parameters for various materials considered for the booster beam stop are given in Table 15.2.5. Iron is the preferred material for the stop, due to various qualities such as sturdiness, thermal stability, conductivity, and relative compactness of shower dimensions. As iron is a relatively low-Z material, the photo-neutron yield and the resulting activation will also be minimal.

The theory of electromagnetic showers (Table 15.2.5) stipulates that material approximately 20 radiation lengths long and 3 Moliere radii in transverse will contain 99.99% of the electromagnetic shower [15.10]. Thus, an iron cylinder 35 cm long and 8.5 cm in diameter will be sufficient to effectively contain the electromagnetic shower in the booster beam stop. The scattered low-energy photon radiation will require additional lead shielding, but will be well below the critical energy to further propagate the shower and the photo-spallation reaction threshold. The neutrons created in the shower will escape isotropically from the stop and require additional shielding.

Table 15.2.9 shows the dose rates due to various radiation components around the booster beam stop with no local shielding in place. This table also provides the dose rates on the exterior of the concrete shield wall with a local shielding of 10 cm of Pb and 10 cm of polyethylene (1g/cm3). As the exact layout of the storage ring injection region is not currently available, the distance from the iron beam stop to a) the concrete shield wall at the floor side, b) the roof, and c) the inboard wall is assumed to be 1 meter, 3 meters, and 2 meters, respectively. It can be seen that the dose rates after local shielding are primarily due to high-energy neutrons. With the proposed local shielding, the dose rates come down to <0.25 mrem/h on contact at the exterior of the concrete shield walls. (The possible effect of neutrons slowing in polyethylene is neglected in the current calculations.) The stop is inside the storage ring enclosure, and personnel have no access when the beam is in the storage ring.

Table 15.2.9 Dose Rates on Contact : Exterior Concrete Shield Walls near the Booster Beam Stop.

Radiation Component	Dose Rate on Lateral wall [mrem/h]		Dose Rate on Roof [mrem/h]		Dose Rate on Inboard Wall [mrem/h]	
	No local shielding	Pb+Poly 10+10 cm	No local shielding	Pb+Poly 10+10 cm	No local shielding	Pb+Poly 10+10 cm
Bremsstrahlung	0.3011	0.0028	2.2600	0.0208	4.0189	0.0369
Giant Resonance Neutrons	0.0104	0.0010	0.1493	0.0151	0.2653	0.0268
High Energy Neutrons	0.0616	0.0178	0.2277	0.0660	0.4048	0.1174
Total Dose Rate	0.3731	0.0216	2.6370	0.1019	4.6890	0.1811

15.3 Shielding Estimates for Beamlines and Front Ends

NSLS-II is subject to DOE radiation protection rules established in 10 CFR 835. Operating with an administrative control level of 100 mrem per year, NSLS-II will be well within the legal limits established in 10 CFR 835. Shielding for NSLS-II beamlines will be designed to maintain levels through the shielding to less than 0.05 mrem/hr. A worker could work immediately adjacent to the shielded enclosure along the beamline for 2,000 hours per year and not exceed 100 mrem/year, such that the individual beamline scientist dose will be ALARA.

15.3.1 Sources of Radiation Hazard in the Beamlines

The radiation present on the experimental floor can be separated into sources that come through the ratchet wall penetration and those that come through the ratchet wall itself.

15.3.1.1 Radiation through the Ratchet Wall

In the process of operating the storage ring, as well as producing the desired synchrotron radiation [15.11], there is considerable generation of other radiation behind the storage ring wall. The shielding for this parasitic radiation is achieved by the concrete shield wall and the local shielding at various locations inside the storage ring. During the commissioning of the storage ring, surveys will be made to determine if any "hot spots" exist and, if so, additional local shielding will be employed to reduce the dose rates on the experimental floor to acceptable levels.

15.3.1.2 Radiation through the Ratchet Wall Penetration

The radiation through the ratchet wall penetration falls into the following categories:

- radiation from electron beam hitting storage ring components
- gas bremsstrahlung created from electron interaction with the residual gas molecules in the vacuum chamber
- synchrotron radiation created by the bending magnets and the insertion devices [15.11]

To estimate the shielding and other requirements for NSLS-II beamlines, these sources of radiation have been considered across a range of possible conditions. The neutron dose estimates done by the PICA neutron shield program [15.12] and confirmed by the measurements in other synchrotron radiation facilities [15.13] determined that the neutron dose hazard on the experiment floor is insignificant for all credible scenarios. Therefore, neutron shielding on the experiment floor for the beamlines has not been recommended other than for specific instances.

15.3.1.3 Interaction of Stored Beam with Storage Ring Components

If the stored electron beam collides with any storage ring component, a bremsstrahlung shower will be produced. Only a small portion of this radiation makes it through the synchrotron radiation apertures. In addition, bremsstrahlung collimators in the front end will severely limit the line of sight through the ratchet wall penetration. These collimators allow only radiation scattered in small angles to the beam path to exit onto the experimental floor. The beamline shielding present to account for other radiation sources will be more than sufficient to stop the radiation from beam losses inside the storage ring components.

Initial operations at NSLS-II will require that the beamline safety shutters (located inside the ratchet wall) be closed during injection. The closed shutters will keep any radiation that might come through the ratchet wall penetration. When NSLS-II begins operating in the top-off mode, in which the safety shutters are left open, the additional radiation due to this mode of operation needs to be addressed. Preliminary analysis and experience at the other facilities indicates that it is not expected to be a problem [15.14].

15.3.2 Shielding Design Simulations

15.3.3.1 Simulation Tools

Bremsstrahlung dose scattering calculations for NSLS-II ID beamlines were carried out using the EGS4 electron-gamma shower simulation program [15.15]. This implementation is part of the CALOR program package distributed by the Radiation Shielding Information Center (RSIC) of the Oak Ridge National Laboratory. EGS4 simulates the coupled interactions of photons and electrons with materials over an energy range from a few keV to several TeV. It also includes a standalone program, PEGS4, which creates parameterized cross sections to be used by EGS4. Physical processes simulated by this program include bremsstrahlung production, positron annihilation at rest and in flight, Moliere multiple scattering, Moller and Bhabha scattering, Compton scattering, pair production, photoelectric effect, and continuous energy loss by Bethe-Bloch formalism. The photoneutron production and transport is not simulated by EGS4, but measurements at the other third-generation light source facilities have confirmed that photoneutrons are not a radiation hazard at the synchrotron radiation beamlines.

The synchrotron radiation scattering calculations for NSLS-II beamlines have been performed using the STAC8 program [15.16]. STAC8 was developed at the Spring8 facility and has been used extensively at other third-generation synchrotron radiation facilities during design and operation. STAC8 generates insertion device radiation spectra and monochromatic beams with a fixed band width. The program simulates photon transport by Compton scattering (with anisotropy), Rayleigh scattering, and photo-absorption. It calculates scattered photon flux as a function of energy and angle, and converts photon flux to dose rates. Build-up factors in the shielding materials are taken into account, but the effect of polarization has not been considered.

15.3.3 Bremsstrahlung Source Estimates in the ID Beamlines

Gas bremsstrahlung is produced by interaction of the storage ring electron beam with residual gas molecules in the ring vacuum chamber. Such interactions are sources of stored beam loss, which results in beam decay and occurs continuously during storage ring operation. Gas bremsstrahlung interactions take place all around the storage ring, but are a particular problem in the straight sections for the insertion devices. Gas bremsstrahlung is produced in a very narrow beam in the straight path and sums up for the entire straight path in the line of sight of the beamlines. The NSLS-II straight beam paths are 16 m long. (The straight beam path length is longer than the insertion device straight section length.)

The total beam integrated bremsstrahlung dose rate D (rem/h) from the straight particle trajectory in the vacuum chamber of the storage ring at a distance L from the straight path is usually approximated by semi-empirical equations. Three common empirical relations have been in use historically. The semi-empirical equation proposed by Frank [15.17] had been successfully utilized at the Advanced Photon Source and other similar facilities. Using the equation developed by Frank, the dose rate due to primary bremsstrahlung is described as at a distance L from the end of the straight path is

$$\text{dose rate (rem/h)} = \frac{3.0\times10^{-4}}{\pi\times X_0}\,\frac{E^2}{0.511^2}\,\frac{l\times I}{L(L+l)}\,, \qquad (15\text{-}2)$$

where X_0 = radiation length of air at 10^{-9} Torr = 2.34×10^{16} cm, l = effective length of the straight path (16 meters), I = beam current in e/s (3.1×10^{18} electrons/s for 500 mA), and E = electron beam energy in MeV. L is nominally taken as 20 meters. This equation yields a primary bremsstrahlung dose rate of 240 rem/hour.

Another analysis developed by Ferrari [15.18], et al., gives the following expression for dose rate produced by the primary bremsstrahlung in the ID beamlines at a distance of L from the straight path.

$$\text{dose rate (rem/hour)} = 2.5 \times 10^{-25} \frac{E^{2.67}}{0.511^{2.67}} \frac{l \times I}{L(L+l)} \frac{P}{P_0}, \qquad (15\text{-}3)$$

where l = effective length of the straight path (16 meters), I = beam current in e/s (3.1×10^{18} electrons/s for 500 mA), E = electron beam energy in MeV, P = operating pressure in the vacuum chamber in nTorr, and P_0 = 1 nTorr. L is nominally taken as 20 meters. This equation yields a primary bremsstrahlung dose rate of 280 rem/hour.

Chronologically, the first expression developed in this regard is by Rindi and Tromba [15.19]. This simple expression provides the dose rate at 10 meters from the straight path as

$$\text{dose rate (rem/hour at 10 m)} = 1.7 \times 10^{-14}\, E^{2.43} \frac{P}{P_{atm}}\, I\, l, \qquad (15\text{-}4)$$

where l = effective length of the straight path (16 meters), I = beam current in e/s (3.1×10^{18} electrons/s for 500 mA), E = electron beam energy in MeV, P = operating pressure in the vacuum chamber, and P_{atm} = atmospheric pressure. This expression yields a primary bremsstrahlung dose rate of 450 rem/h at 10 meters and 112 rem/h at 20 meters.

Table 15.3.1 gives the estimated primary bremsstrahlung dose rates in the NSLS-II beamlines calculated by the three semi-empirical expressions at 20 meters from the straight path for a straight path length of 16 meters and vacuum chamber pressure of 1 nTorr. Methods 1 and 2 give similar results, in contrast to method 3. Being conservative, methods 1 and 2 are used to estimate the primary bremsstrahlung dose rates for the NSLS-II insertion device beamlines.

Table 15.3.1 Primary Bremsstrahlung Dose Rates at the NSLS-II ID Beamlines.

	Bremsstrahlung Dose Rate [rem/h]	Notes:
Method 1 (Lure-APS)	240	Beam Energy = 3.5 GeV
Method 2 (Ferrari)	280	Beam Current = 500 mA
Method 3 (Rindi-Tromba)	112	Straight section Path Length = 16 m
		Distance to the dose point = 20 m
		Straight section vacuum = 10^{-9} Torr

15.3.4 Design of Shutters/Stops

15.3.4.1 Geometry Used for the Calculations

The primary bremsstrahlung dose rates at the insertion device beamlines determine the thickness of bremsstrahlung shutters, stops, and collimators in the beamlines and front ends. Figure 15.3.4.1 shows the geometry used in the EGS4 simulations to calculate the thickness of lead and tungsten required to attenuate the dose rate <0.25 mrem/h at the downstream side of the stop/shutter on contact. These shutters will be located inside the shielded enclosures. The primary bremsstrahlung source term was estimated using the empirical formulae from Table 15.3.1 to scale the dose rate results. The bremsstrahlung beam from the NSLS-II straight section is incident on a lead or tungsten block with transverse dimensions of 20 x 20 cm^2. The heavy metal is followed by the ICRU tissue [15.20] of 30 cm thick to score the dose at the downstream side of the shutter/stop. The ICRU tissue is binned into 1 cm^3 bins for scoring the dose, and the maximum dose is taken as the dose index.

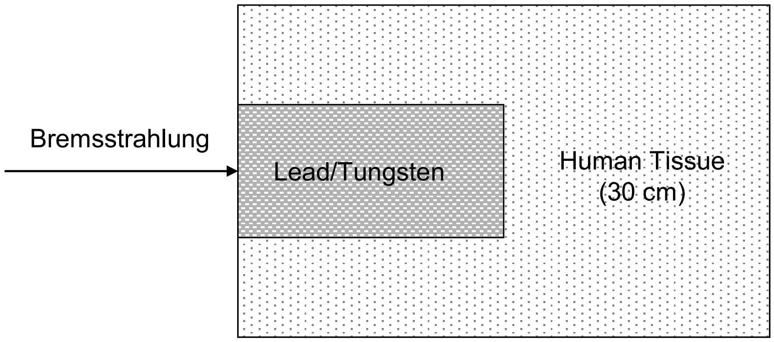

Figure 15.3.1 Simulated EGS4 geometry of the NSLS-II safety shutters.

15.3.4.2 Thickness of Shutters/Stops

Table 15.3.2 shows the primary bremsstrahlung dose rates predicted by the two conservative methods, and the thickness of lead or tungsten required to reduce the radiation dose rate at the back of the shutter/collimator to less than 0.25 mrem/h (<2.5 μSv/h). The dose rates at the downstream surface in the ICRU tissue were calculated as a function of lead or tungsten thickness and fitted using an effective exponential attenuation factor. The results are also plotted in Figure 15.3.2 for source calculated by method 1. Note that a lead thickness of > 30 cm or a tungsten thickness of >20 cm are required as stops/shutters at NSLS-II beamlines to reduce the dose rate to less than 0.25 mrem/h (<2.5 μSv/h), taking into account the conservative primary bremsstrahlung source term.

Table 15.3.2 Shutter/Collimator Thickness for NSLS-II Insertion Device Beamlines.

	Method 1 (LURE-APS)	Method 2 (Ferrari-CERN)
Bremsstrahlung dose rate [rem/h]	240	280
Lead thickness required [cm]	28.9	29.2
Tungsten thickness required [cm]	19.6	19.8
Dose rate behind the stop/shutter [mrem/h]	0.25	0.25

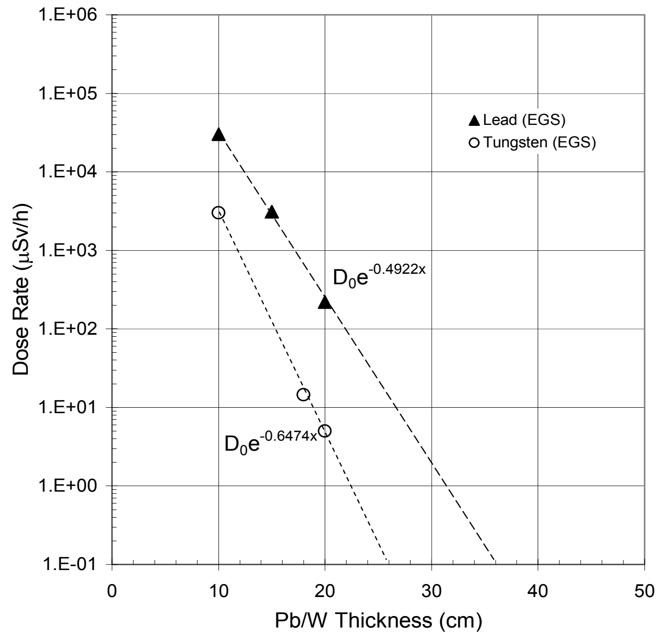

Figure 15.3.2
Contact dose rates at the downstream surface of the shutters/stops. Bremsstrahlung source was calculated by method 1.

15.3.5 Shielding Estimates for Experimental Stations

15.3.5.1 Computation for Bremsstrahlung and Synchrotron Radiation Scattering

The synchrotron radiation and bremsstrahlung can be scattered from any potential component in the beamlines and front ends. Such components include windows, slits, monochromators, mirrors, and so forth, and vary from beamline to beamline. Therefore, calculations were performed with a worst-case potential scatterer upstream of the first optics enclosure (Figure 15.3.3), of typical dimensions (2.0 m wide, 3 m high, and 10 m long). Figure 15.3.4 shows the results of the calcuations. The worst-case potential scatterer for bremsstrahlung is 3 cm thick copper, and for synchrotron radiation is 0.1 cm thick aluminum with small transverse dimensions. In addition to this, 10 meter air in the station is also a potential scatterer for synchrotron radiation. The EGS4 calculations were performed for bremsstrahlung, and STAC8 calculations were performed for synchrotron radiation.

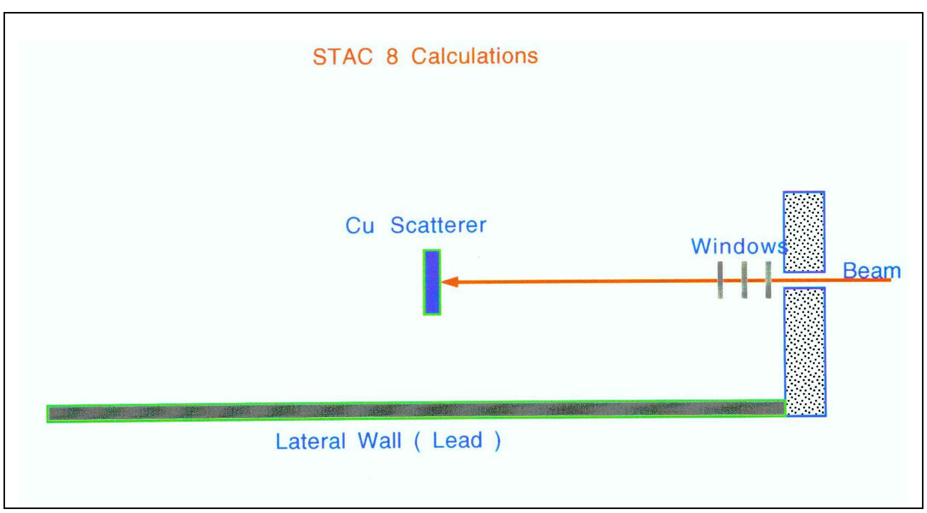

Figure 15.3.3 EGS4 and STAC8 geometry for bremsstrahlung and synchrotron radiation scattering calculations.

15.3.5.2 Shielding Estimates for the First Optics Enclosures

Preliminary shielding estimates for the NSLS-II First Optics Enclosures are calculated using the available beamline and insertion device parameters. For each shielding situation, the synchrotron and bremsstrahlung shielding have been calculated for the representative station geometry. The shielding simulations for bremsstrahlung were done using the EGS4 program and for synchrotron radiation using the STAC8 program. In most cases, one of the sources (bremsstrahlung or synchrotron radiation) dominates for the shielding requirement and the contribution of the other becomes negligible; thus, the calculated shielding for the dominant source can be implemented. All bremsstrahlung and synchrotron radiation calculations were done at 500 mA of beam current, at 3.5 GeV electron beam energy. Also, all the doses are scored in the ICRU tissue on contact unless otherwise mentioned, instead of at a distance of 30 cm from the dose point. Occupational exposure of personnel is most likely to occur in the vicinity of experimental stations along the beamlines. Shielding of these areas is designed to maintain individual exposures when in contact with the hutch wall as <100 mrem/year for 2,000 hours of exposure per year. Thus, the experimental station shielding is designed to meet or exceed this criterion to ensure that occupational radiation doses are ALARA.

15.3.5.3 Shielding Estimates for Secondary Bremsstrahlung

Bremsstrahlung scattering calculations for the representative geometry of the NSLS-II FOE were performed using EGS4. The computational geometry given in Figure 15.3.1 was used. EGS4 calculates integral energy deposition per particle at various regions of the geometry. The radiation dose (energy deposited per unit mass) at any given location per particle was calculated from the 3D energy deposition profile in the standard ICRU tissue placed at the location, taking the maximum energy deposition per unit mass**.** Once energy deposition per particle at each region is available, the absolute dose rate at any region can be scaled, using the primary bremsstrahlung dose rate provided by the empirical formulae.

Figure 15.3.4 gives the scattered bremsstrahlung dose rates 1 meter away from a 3 cm thick copper scatterer in terms of μSv/h (× 0.1 mrem/h). The bremsstrahlung forward-beam direction in this figure is 90 degrees. The transverse directions are 0 degrees and 180 degrees. Calculations are for a 240 rem/h primary bremsstrahlung dose rate. Note that the scattered bremsstrahlung beam is highly forward peaked.

To calculate the shielding requirements for the downstream wall of the FOE, the calculated dose rates (DR) from Figure 15.3.4 were used. The minimum distance from the copper scattering target to the downstream wall is taken as 10 meters. For small angles, a constant distance of 10 m to the wall is assumed, and the distance-adjusted dose factor is taken as 10^2. The required lead thickness for the downstream wall of the FOE, as a function of the scattering angle to achieve the design dose limit of <0.05 mrem/h, is calculated using the expression

$$\text{lead thickness (cm)} = [\ln(0.01 \times DR) - \ln 0.05\,] / 0.473. \qquad (15\text{-}5)$$

The minimum attenuation coefficient of 0.473 cm^{-1} for lead has been used in these calculations for bremsstrahlung attenuation.

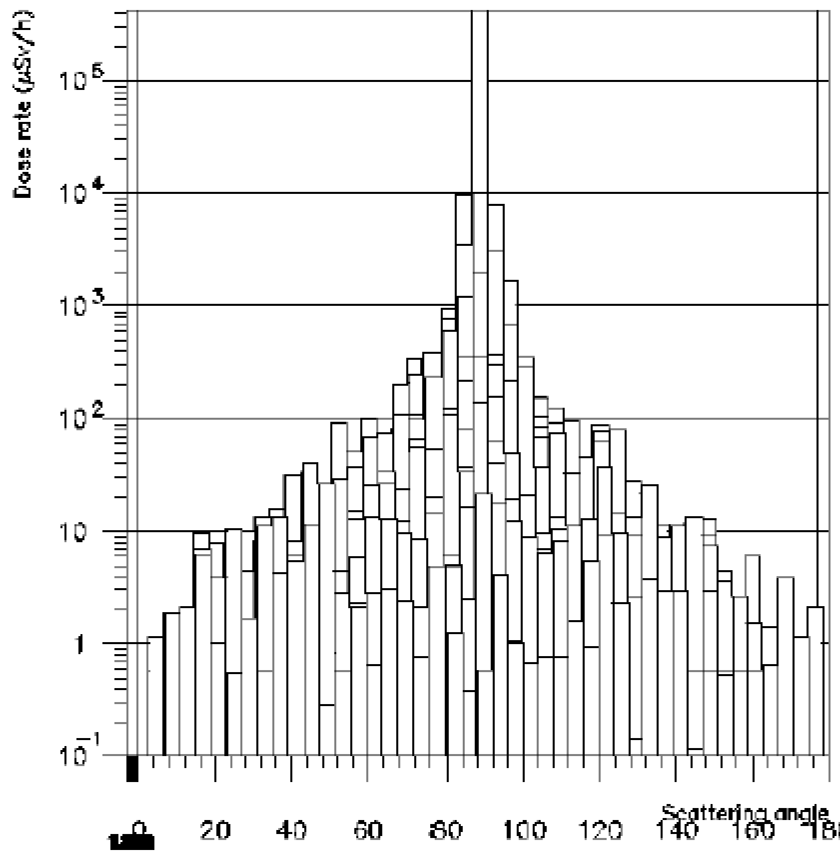

Figure 15.3.4
Scattered bremsstrahlung dose rates for the NSLS-II beamlines. (Primary bremsstrahlung scattered from a Cu target of 3 cm thickness with small transverse dimensions.)

Table 15.3.3 provides the calculated lead thickness for the panels of the FOE as a function of the scattering angle to achieve the design dose limit of <0.05 mrem/h. Because of the forward-peaking nature of the high-energy bremsstrahlung scattering, the lead shielding thickness required at small angles along the beam direction is large. In practice, this will be satisfied by the presence of collimators or bremsstrahlung stops approximately from 0 to 2 degrees. Considering a uniform downstream wall thickness of 5 cm, additional shielding will be required for scattering angles <4 degrees. This can be satisfied by placing the appropriate lead local shielding around the beam transport pipes. The exact transverse dimensions of these local shields can be calculated once the station dimensions are available. Currently, a uniform downstream wall thickness of 50 mm is recommended.

Table 15.3.3 Shielding Estimates for the FOE for Bremsstrahlung Scattering[a].

Angle [deg]	Dose Rate [$mrem/m^2$-h]	Lead Thickness Back Wall [cm][b]	Lead Thickness Side Wall [cm]	Lead Thickness Roof [cm]	Half Width of Local Shielding Required [cm]
1	5.0×10^3	14.6	2.3	0.4	17
2	1.5×10^3	8.65	2.3	0.4	34
3	7.0×10^2	7.04	2.3	0.4	52
4	4.0×10^2	5.86	2.3	0.4	69
5	2.2×10^2	4.59	2.3	0.4	87
6	1.5×10^2	3.78	2.3	0.4	100
8	1.0×10^2	2.93	2.3	0.4	140
10	7.0×10^1	2.17	2.3	0.4	170

[a] Lead thickness required to reduce the dose rate to <0.05 mrem/h for bremsstrahlung scattering from a 5 x 5 x 3 cm^3 Cu scatterer at the upstream of the experimental station, beam current 500 mA, beam energy 3.5 GeV. Experiment station is 10 meters long.

[b] A uniform thickness of 5.0 cm is recommended. Additional shielding in the forward direction can be achieved by the stop/collimator and local shielding.

The lateral wall (side wall) shielding for the FOE can be calculated using the same equation:

$$\text{lead thickness (cm)} = [\ln DR - \ln 0.05] / 0.473. \quad (15\text{-}6$$

Because of the relatively large statistical fluctuation of calculated DR at 180 degrees and 0 degrees in Figure 15.3.4, an average DR of 0.15 mrem/h (1.5 μSv/h) has been used to calculate the required lead thickness for the side wall to achieve the design dose limit of <0.05 mrem/h. This gives a lead thickness of

$$\text{lead thickness (cm)} = [\ln 0.15 - \ln 0.05] / 0.473 = 2.3 \text{ cm}. \quad (15\text{-}7)$$

A side wall thickness of 23 mm is recommended for the insertion device beamlines. The roof of the experimental stations is assumed to be at distance of 1.5 m from the beam. The distance adjustment factor for DR in this case is $1/1.5^2$. The shielding thickness for the roof can be calculated by the expression

$$\text{lead thickness for roof (cm)} = [\ln (DR \times 0.4) - \ln 0.05] / 0.473. \quad (15\text{-}8)$$

Taking an average transverse DR of 0.15 mrem/h, the expression yields a roof thickness of 4 mm for the insertion device experiment stations. This thickness is less than the lead thickness required for synchrotron radiation shielding, in most cases.

It must also be emphasized that the bremsstrahlung production is linear with respect to the pressure in the vacuum chamber. In the current calculations for primary bremsstrahlung source term, a vacuum chamber pressure of 1 nTorr is assumed. It is imperative to maintain a vacuum of <1 nTorr in the storage ring to minimize bremsstrahlung production during the storage ring operation.

15.3.5.4 Synchrotron Radiation Scattering Calculations with STAC8

Synchrotron radiation scattering calculations to estimate the shielding requirements for the NSLS-II FOE were performed using the STAC8 shield program. The worst-case scatterer, 0.1 cm aluminum, is used as the potential scatterer upstream of the station. In addition to this, 10 meters of air along the length of the station were also considered as a potential scatterer of the synchrotron radiation in the station.

The source spectrum for the NSLS-II insertion devices for this calculation was generated by the STAC8 program. Four kinds of IDs were considered for the NSLS-II beamline station shielding design. The salient features of these insertion devices, calculated by the STAC* program, are given in Table 15.3.4.

Table 15.3.4 NSLS-II Insertion Device Parameters for Beamline Shielding Calculations.

Device Type	No. of Poles	B_{eff} [Tesla]	Period [mm]	Power at 500 mA [kW]	Critical Energy [keV]	Aperture in FOE [mm]
DW	120	1.8	100	75.25	14.66	4 x 10
U19	316	1.0	19	11.64	6.26	4 x 4
U14	286	1.4	14	15.46	8.75	4 x 4
SCW	10	3.5	150	35.57	28.47	4 x 8

Station dimensions of 2 x 3 x 10 meters are assumed. All calculations for 3.5 GeV beam energy at 500 mA.

The lateral walls of the experimental stations were assumed to be 1 meter distant and the roof was 1.5 meter. Shielding for these areas was calculated to maintain individual exposures, when in contact with the experimental station wall, at less than100 mrem/year for 2,000 hours of exposure per year. This converts to an effective dose rate of <0.05 mrem/h at the occupiable areas.

Table 15.3.5 gives the preliminary shielding estimates for the FOE at NSLS-II for four insertion device beamlines. Required shielding estimates for the side panel, roof, and the upstream panel are given only for calculations of synchrotron radiation scattering.

Table 15.3.5 Preliminary Shielding Estimates for NSLS-II White Beam Stations (SR Only).

	Lead Thickness [mm]		
Insertion Device	Side Panel	Roof	Upstream Panel
U19	8	7	8
U14	10	9	10
SCW	16	14	16
DW	14	12	14

SR = Synchrotron radiation. All calculations are done for Beam Energy of 3.5 GeV at 500 mA. Insertion Device parameters are used from Table 15.3.5.2. Station dimensions are assumed to be 2.0 x 3.0 x 10.0 m^3. Side panels are at a distance of 1 m and roof at 1.5 m away from the beamline.

15.3.5.5 Shielding Recommendations for NSLS-II First Optics Enclosures and White Beam Stations

Table 15.3.3 provides the shielding estimates for the FOE and white beam stations for NSLS-II from bremsstrahlung scattering calculations. Table 15.3.5 provides the shielding estimates from scattering calculations of synchrotron radiation. In each case, the shielding requirement for the dominant source must be implemented.

To summarize, bremsstrahlung shielding dominates for the back wall and side wall, and synchrotron radiation dominates for the roof and upstream wall. Table 15.3.6 compiles the shielding requirements for the NSLS-II FOE and white beam stations. Shielding requirements for the four kinds of ID beamlines are given. Lead shielding of 50 mm is needed for the entire downstream wall of all ID beamlines to shield the forward-peaking bremsstrahlung scattering source. An additional 50 mm of lead (100 mm total) is needed for the central portion around the beam penetration. This lead shielding can be achieved by the appropriate design of the local shielding around the beam pipe. It is also desirable to design bremsstrahlung collimators at appropriate locations upstream of the FOE, near the potential scattering components.

Table 15.3.6 Summary Shielding Requirements for NSLS-II First Optics Enclosures.

Insertion Device	Side Panel [mm]	Roof [mm]	Upstream Panel [mm]	Downstream Panel[a] [mm]
U19	23	7	8	50
U14	23	9	10	50
SCW	23	14	16	50
DW	23	12	14	50

[a] An additional 50 mm of lead locally around the beam pipe penetration.

15.4 RADIOLOGICAL CONSEQUENCES OF ACCIDENTAL BEAM LOSS

15.4.1 Consequences of Accidental Linac Beam Losses

Shielding calculations for the linac enclosure have been carried out assuming a 1% distributed beam loss during beam acceleration (0.66% at any given point). Shielding thickness has been calculated for a dose rate of <0.25 mrem/h, at the exterior of the concrete bulk shielding. In the unlikely event of 100% linac beam loss during beam acceleration at any given point of the accelerator system, the dose rate on contact at the exterior shielding wall will be ~150 times more than the limiting value. The dose rate will be <37.8 mrem/h at the exterior of the concrete bulk shielding of the enclosure due to this beam loss event.

15.4.2 Consequences of Linac-to-Booster Injection Losses

The shielding calculations for the storage ring and the booster assume an average injection frequency from the linac into the booster of once per minute. An unlikely situation was conceived where 20 nC/s, which is the capacity of the linac, would be injected into the booster continuously and all of it be lost at the injection septum. The total charge lost at the septum in this case in an hour would be 7.2×10^4 nC/h. Assuming 50% loss of injected beam at the injection/extraction region (15 nC every minute), 900 nC/h would be lost at the region for which the shielding design calculations were carried out. The shielding is designed for a dose rate of <0.25 mrem/h at the occupiable regions. Therefore, the dose rate during this accident scenario at the exterior of the concrete bulk shielding on contact near the injection region would be less than 0.25 (7.2×10^4/900) = 20 mrem/h.

15.4.3 Consequences of Booster-to-Storage Ring Injection Losses

The shielding calculations for the booster to storage ring injection assume an average injection frequency of once per minute. A scenario was developed where 20 nC/s, the capacity of the linac, was injected continuously into the booster and the storage ring, and all of it was lost at the injection septum. The total charge lost in this case in an hour would be 7.2×10^4 nC/h. Assuming a 50% loss of injected beam at the injection/extraction region, 750 nC/h would be lost at the region for which the shielding design calculations were carried out. The shielding for the accelerators is designed for a dose rate of <0.25 mrem/h at the occupiable regions, on the exterior of the bulk shielding. Therefore, the dose rate at the occupiable regions during this accident scenario would be less than 0.25 (7.2×10^4/750) = 24 mrem/h at the exterior of the shield wall.

15.4.4 Maximum Credible Incident Analysis

In the shielding estimates of NSLS-II injection losses, the average injection frequency from the booster into the storage ring is assumed to be once per minute. A highly unlikely scenario would be if 20 nC/s, the capacity of the linac, were injected into the storage ring continuously and 100% were lost at the septum. This scenario was considered for the radiological consequences of injector loss at the booster septum.

In addition to the scenario described above, a situation was conceived where a dipole magnet downstream of the injection septum shorts and the 100% injected beam proceeds along the direction of one of the beamlines. However, the mis-steered electron beam would generally be unable to proceed farther than a collimator or a front end shutter, where it would create an electromagnetic shower. If this accidental scenario were to persist, it would result in higher dose rates in the first optics enclosure of the beamlines. The shielding wall of the storage ring is designed for a beam loss charge of 77.5 nC/h, 10% of the stored beam loss at any given location. The shielding for the storage ring is designed for a dose rate of <0.25 mrem/h at the occupiable regions. Dose rates during this particular accident scenario would be a factor of 929 greater than the limiting dose rates. The dose rates would be <$(7.2\times10^4/77.5)$ 0.25 = 232 mrem/h at the exterior of the shield wall of the storage ring on contact near the optics enclosure regions.

Loss of vacuum in the insertion device straight path is another credible incident that can cause higher dose rates around the FOE of the beamlines. In the bremsstrahlung source calculations in Section 15.3.3, a straight section pressure of 10^{-9} Torr is assumed. A sudden loss of vacuum to 1 Torr in the straight section would increase bremsstrahlung production by a factor of 10^9. We further assumed that this scenario would last for <1 millisecond (approximately 1,000 revolutions of the beam) before the beam would be completely absorbed. No credit was given to the engineering controls that trip the beam at vacuum loss. The FOEs are designed for a dose rate of <0.05 mrem/h on contact at the exterior of the shield panels. The dose rate during this accident scenario would be higher by a factor of 10^9, but would last for only a millisecond. The total dose commitment to an individual beamline scientist due to one such incident can be estimated as $<(0.05\times10^9)/(3.6\times10^6) = 14$ mrem.

The probability of these failure scenarios to occur simultaneously is extremely small and the radiological consequences of these incidents are insignificant. In addition, sufficiently conservative factors are included in the shielding estimates to provide additional margins of safety. Dose rates in the current estimates are calculated on contact at the exterior of the bulk shielding, which is conservative. It is also prudent to assume a time period for each event duration, such that the total dose commitment to personnel during such an unlikely scenario can be estimated. Continuous injection for prolonged periods can also be limited by the engineering controls.

15.5 Activation Analysis of Accelerator Components

Bremsstrahlung is generated in accelerator systems of synchrotron radiation facilities by the radiative interaction of the circulating electron beam with accelerator components and with residual gas molecules in the vacuum chamber. The photoneutron interaction of bremsstrahlung with materials leads to the radioactivation of accelerator components through neutron emission and the production of radioisotopes. However, this activation interaction is a second-order effect, because it involves the intermediate process of bremsstrahlung production. Photoneutron interaction takes place above the threshold bremsstrahlung energy of 7–20 MeV; the cross section for photoneutron interactions is in millibarns. Therefore the electron beam activation of materials is not as abundant as the proton beam activation, because electrons do not cause direct spallation interaction with the nuclei.

Photospallation is another process (with comparable cross sections) by which radioisotopes are produced. The particular radionuclides produced in a material will depend on (γ, n), (γ, 2n), and photospallation cross sections of the material. These interactions can potentially activate various accelerator components. Isotopes and their saturation activities are listed in IAEA 188 [15.21]. The materials of interest for NSLS-II operations are aluminum, iron (in steel), copper, tungsten, and lead.

Radioactivity builds up during the operation of accelerator systems. When operations cease, there is an initial rapid decay of shorter-lived isotopes; after a waiting period, only the longer-lived isotopes remain. For routine operations of NSLS-II, short-lived isotopes will be of interest, because residual activity in the accelerator components and beam stops may be high enough to limit access time to the area.

15.5.1 Residual Activity Estimates of Accelerator Components

15.5.1.1 Methodology for Estimating Activation in Materials

The methodology of estimating activity of a radionuclide formed by (γ,n) reaction is to assume that the yield of neutrons is also the yield of radionuclide atoms [15.9]. The neutron yield in the accelerator components and in the beam stops is based on the equation from Swanson:

$$Y^1 = 1.21 \times 10^8 \, Z_1^{0.66} \text{ neutrons/joule,} \tag{15-9}$$

where Z_1 = atomic number of the element. The equation can be modified for a given isotope as

$$Y = F(1.21 \times 10^8 \, Z^{0.66}) \;\; \text{n/J,} \tag{15-10}$$

where F is the fractional abundance of a given isotope with atomic number Z. Therefore, the change in the number of radioactive nuclides (N) due to (γ,n) interactions per unit time is given by

$$dN/dt = WYf - \lambda_R N \;\; \text{atoms/sec,} \tag{15-11}$$

where W = dissipated electron beam power in watts, f = fraction of electron beam power which converts to bremsstrahlung, and λ_R = radioactive decay constant of the radionuclide in s^{-1}. By solving the equation and applying the initial boundary condition N = 0 for t = 0,

$$N = \frac{WYf}{\lambda_R} \left(1 - e^{-\lambda_R t}\right) \text{ atoms.} \tag{15-12}$$

Since the activity is $\lambda_R N$

$$\text{Activity} = WYf\,(1 - e^{-\lambda_R t})\ \text{disintegrations/sec}, \tag{15-13}$$

the saturation activity of the radionuclide, as t tends to be large, is

$$A = WYf\ \text{disintegrations/sec} \tag{15-14}$$

This is the saturation activity of a radionuclide with a given half life if the continuous operation time of the accelerator system is about three times the half life of the radionuclide formed. For each of the potential activated materials, Swanson (IAEA 188) has prepared tables listing the saturation activities of the (γ,n), (γ,2n) and photospallation products in (Ci/kW), and the exposure rate in (R/h) at 1 meter from the saturation activity.

The data in these tables have been used to estimate the saturation activity and the radiation fields following certain operation periods and the residual radiation field after shutdown.

15.5.1.2 Radioactivation of the Linac Iron Beam Stop

Approximately 4 watts of electron beam power are dissipated in the linac beam stop during the continuous beam dump on the stop. The radioactive materials formed in the iron beam stop have a range of half lives from a few seconds to a few years. Continuous operation for 1 hour of the iron beam stop results in about 90% of the saturation exposure rate. The main activities are due to ^{52}Mn(m), ^{56}Mn, ^{54}Mn, ^{52}Fe, and ^{53}Fe. The estimated combined exposure rate at 1 meter from the beam stop for a power dissipation of 4 watts is about 2.21 mR/h, contributed mainly by ^{52}Mn (m) (half life 21.1 min) and ^{53}Fe (half life 8.51 min). After about an hour of shutdown, the exposure rate would be ~0.046 mR/h at 1 meter. ^{54}Mn, the long-living isotope formed in the iron beam stop with a half life of 303 days, will not attain saturation activity until about three years of continuous operation. After 200 hours of continuous operation of the beam stop, the activity due to ^{54}Mn in iron would be 0.05 mR/h. ^{55}Fe, produced from ^{54}Fe, will not pose any substantial exposure hazard, due to the low-energy x-ray emission of 5.95 keV. Activation of the linac beam stop during NSLS-II operations is not a serious radiological hazard.

15.5.1.3 Radioactivation of the Booster Iron Beam Stop

Approximately 0.87 watts of electron beam power is dissipated in the booster beam stop during the continuous beam dump on the stop. Continuous operation of 1 hour of the iron beam stop results in about 90% of the saturation exposure rate. The main activities are due to ^{52}Mn(m), ^{56}Mn, ^{54}Mn, ^{52}Fe, and ^{53}Fe. The estimated combined exposure rate at 1 meter from the beam stop is about 0.48 mR/h, contributed mainly by ^{52}Mn(m) (half life 21.1 min) and ^{53}Fe (half life 8.51 min). After about an hour the exposure rate would be ~0.01 mR/h at 1 meter. ^{54}Mn, the long-living isotope formed in the iron beam stop with a half life of 303 days, will not attain saturation activity until about three years of continuous operation. After 200 hours of continuous operation of the beam stop, the activity due to ^{54}Mn in iron would be 0.01 mR/h. ^{55}Fe, produced from ^{54}Fe, will not pose any substantial exposure hazard, due to the low-energy x-ray emission of 5.95 keV. Activation of the booster beam stop during NSLS-II operations is not a serious radiological hazard.

Saturation activity and the resulting radiation field, due to the activation of iron in the septum magnet from injection losses, will be comparable to or less than at the booster beam stop.

15.5.1.4 Radioactivation of the Tungsten Injection Stop

There is a stop between the linac and booster, made of tungsten. This stop will not normally see any beam, but should an incident occur, the entire 4-watt electron beam would be directed to it. Tungsten has four isotopes that can be activated: ^{182}W [0.264], ^{183}W [0.144], ^{184}W [0.306], and ^{186}W [0.284] (the fractions in brackets indicate isotopic abundance). Only ^{182}W and ^{183}W contribute the relatively long-lived radionuclides of ^{181}W (half life 140 days) and ^{182}Ta (half life 115 days). These isotopes contribute residual activity after prolonged operation. Because this stop normally will not see beam, a generous 1-hour operation time was used in calculations of radioactivation: This scenario would produce the activities $^{180}Ta(m)$, $^{182}Ta(m)$, ^{184}Ta, ^{185}Ta, $^{183}W(m)$, and $^{185}W(m)$. The essential exposure rate at 1 meter is 4.9 mR/h (IAEA188), mainly from $^{183}W(m)$ (half life 5.3 s), and $^{185}W(m)$ (half life 1.62 min). After a decay of 1 hour, the estimated exposure rate will be 0.05 mR/h. The short-term radiation field for this material is not a radiation hazard.

The front end safety shutters and the beamline bremsstrahlung stops will also be made up of tungsten. These shutters/stops intercept the bremsstrahlung beam from the straight section coming along the beamlines. The bremsstrahlung power incident on these stops/shutters is a few microwatts and will not create any detectable activation of the beamline and front end safety shutters and stops.

15.5.1.5 Radioactivation of Copper at the Injection Septum

The injection septum consists of copper conductor with iron. As the septum is a high beam-loss point, the copper in the injection septum can become activated during continuous operation, as happens during top-off. Most of the isotopes formed during this process are short-lived except ^{60}Co (half life 5.26 years) and ^{63}Ni (half life 93 years). Other short-lived isotopes produced are ^{58}Co (half life 71.3 days), $^{58}Co(m)$ (half life 9.2 h), ^{61}Cu (half life 3.32 h), ^{62}Cu (half life 9 min), and ^{64}Cu (half life 12.8 h). After 100 hours of continuous operation, these isotopes will attain saturation activity. After shutdown, the initial activity will be mainly due to ^{62}Cu. The initial combined activity after 100 hours of continuous operation is estimated <5.8 mR/h at 1 m from the septum. After 200 hours of operation, ^{60}Co will achieve only 0.3% of the saturation value. The radiation field attributable to this isotope will be negligible. After about an hour of waiting time, the activity from short-lived isotopes will decay and the corresponding radiation field will be <0.09 mR/h.at 1 meter from the septum.

15.5.1.6 Radioactivation of Lead at the Injection Septum

The injection septum is a high beam-loss point. This region is heavily shielded with lead, which becomes activated and results in the production of ^{206}Tl, ^{207}Tl, $^{207}Tl(m)$, $^{202}Pb(m)$, $^{203}Pb(m)$, and $^{204}Pb(m)$. Most of these isotopes are relatively short lived and attain saturation activity in a few hours of continuous operation of the septum. After prolonged operation of the septum, the estimated initial radiation field from lead activation at 1 meter from the septum shielding will be 1.6 mR/h. After a few minutes of waiting time, the activity will be 0.36 mR/h, mainly from $^{204}Pb(m)$, which has a half life of 67 minutes.

Lead is also used as bremsstrahlung beam stops and collimators in the beamlines and front ends. These stops and collimators intercept the bremsstrahlung beam from the straight section coming along the beamlines. The bremsstrahlung power incident on these stops/collimators consists of a few microwatts. This bremsstrahlung energy will not create any detectable activation of the safety stops and collimators in the beamlines and front ends.

15.5.1.7 Radioactivation of the Aluminum Vacuum Chambers

The vacuum chambers of the accelerator system are made of aluminum. Stored beam loss occurs continuously during storage ring operations. For shielding calculations of the storage ring, a stored beam loss of 10% is assumed to take place at any given location of the storage ring. Part of his beam loss energy will dissipate on the aluminum vacuum chamber, possibly activating it. The main activation products are ^{11}C, ^{13}N, ^{15}O, ^{24}Ne, ^{25}Al, and $^{26}Al(m)$. The isotopes will attain saturation activity after a few hours of operation. ^{22}Na, the long-living isotope produced by activation, will not attain saturation activity until about seven years. After a few hours of operation, the combined exposure rate due to saturation activity is estimated as <0.2 mR/h, at 1 meter from the vacuum chamber. The major contribution is from $^{26}Al(m)$ (half life 6.37 s). After a few minutes, the exposure rate will come down to less than 0.02 mR/h at 1 meter from the vacuum chamber. After 200 hours of continuous operation, ^{22}Na will attain only 0.5% of the saturation value and the corresponding radiation field will be <0.1 mR/h at 1 m from the vacuum chamber.

Table 15.5.1 summarizes the results of the activation analysis for various accelerator components that can be potentially activated at NSLS-II. For each component, activity and the resulting exposure rates have been calculated for the assumed beam loss scenario.

Table 15.5.1 Activation Results for Various Accelerator Components at NSLS-II.

Accelerator Components	Activity after 200 hours of operation [mCi]	Immediately after shutdown, exposure rate at 1 m [mR/h]	1 hour after shutdown, exposure rate at 1 m [mR/h]
Linac iron beam stop	3.45	2.21	0.05
Booster iron beam stop	0.75	0.48	0.01
Linac tungsten injection stopper	17.7	4.9	0.05
Copper at injection septum	11.0	5.8	0.09
Lead at the septum shielding	4.28	1.6	0.44
Storage ring aluminum vacuum chamber	0.56	0.20	0.05

The foregoing analysis shows that the activation of accelerator and beamline components is not a serious radiation hazard during NSLS-II operations, although it is good practice to conduct a complete radiation survey of each accelerator enclosure prior to permitting access after prolonged operation. Based on this survey, access requirements are to be specified at various locations inside the accelerator enclosures.

15.5.2 Activation of the Soil

The potential for soil activation is limited at the electron accelerators, since the main radiation component, bremsstrahlung, is mainly in the forward direction of the electron beam and gets absorbed by machine components such as magnets, absorbers, and so forth. The soil berms are generally at very large angles (almost at right angles) to the forward direction of the electron beam. However, there exists a potential for the high-energy neutron component to penetrate through the transverse concrete shield and produce radioisotopes in the soil. These isotopes can migrate to the groundwater systems. Therefore, it is desirable to assess this risk in detail at a large installation like NSLS-II to reassure the staff and the public.

The soil activation analysis for the NSLS-II design has been carried out at three distinct locations of the accelerator enclosures where the probability for beam loss is significant. These are at the linac beam stop, booster beam stop, and booster-to-storage-ring injection septum.

15.5.2.1 Results of Soil Activation Calculations for NSLS-II

Table 15.5.2 gives the activity in the soil created by ^{3}H and ^{22}Na at various beam-loss locations, for 5,000 hours of NSLS-II operation. The potential activity created by leachables in the groundwater is also shown. Leachability rates of 100% and 7.5% are assumed for ^{3}H and ^{22}Na, respectively. A water concentration factor of 1.1 is used. Although the average annual local rainfall is 55 cm, the soil beneath the concrete floor is not exposed to rainfall and the potential leachability of radioactive isotopes from the soil to the water table at these locations is minimal.

Table 15.5.2 Activity in the Soil Created by ^{3}H and ^{22}Na at Various Beam Loss Locations.

Beam loss Location	Average HEN Flux in soil [Φ_{av}]	^{3}H Soil Activity [Ci/cm^3]	^{3}H Leachable to water [pCi/liter]	^{22}Na Soil Activity [Ci/cm^3]	^{22}Na Leachable to water [pCi/liter]
Linac beam stop (floor)	0.22×10^{2}	2.77×10^{-15}	2.97	2.47×10^{-14}	2.04
Linac beam stop (inboard)	0.39×10^{2}	4.91×10^{-15}	5.40	4.38×10^{-14}	3.61
Booster beam stop (floor)	0.05×10^{2}	0.62×10^{-15}	0.68	0.56×10^{-14}	0.46
Booster beam stop (inboard)	0.08×10^{2}	1.00×10^{-15}	1.10	0.90×10^{-14}	0.74
Storage ring septum (floor)	0.04×10^{2}	0.50×10^{-15}	0.55	0.45×10^{-14}	0.37
Storage ring septum (inboard)	0.06×10^{2}	0.76×10^{-15}	0.84	0.67×10^{-14}	0.55

15.5.3 Activation of Air in the Accelerator Enclosures

Routine accelerator operations at NSLS-II would generate small amounts of air activation at high beam-loss locations, due to photoneutron reactions of bremsstrahlung in air. The isotopes produced by air activation are ^{13}N (half life 10 min), ^{11}C (half life 20 min), and ^{15}O (half life 2.1 min). These isotopes would be produced within the accelerator enclosure and would attain saturation activity within hours of operation, but would decay quickly because of their short half lives and would remain primarily within the confines of the enclosure.

The air activation analysis for NSLS-II has been carried out at three distinct locations of the accelerator enclosures where the probability for beam loss is significant. These are at the linac beam stop, booster beam stop, and booster-to-storage-ring injection septum.

15.5.3.1 Results of Air Activation Calculations for the Accelerator Enclosures

Table 15.5.3 gives the activity in air at various beam-loss locations inside the accelerator enclosures of NSLS-II. For the linac tunnel, an effective bremsstrahlung straight path of 30 m is assumed. The linac tunnel volume is taken as $3\times3\times60 = 540$ m^3. A half chord of length 23 meters from the source inside the storage ring tunnel is considered as the maximum bremsstrahlung path length inside the tunnel. For the purpose of calculating activity per unit volume, a corresponding volume of air $3\times3\times 46$ m^3 = 414 m^3 is assumed inside the storage ring.

Table 15.5.3 Saturation Activity in Air at Various Beam Loss Locations.

Beam loss location	Beam loss [Watts]	Volume of air [m^3]	^{13}N [pCi/cm^3]	^{15}O [pCi/cm^3]	^{11}C [pCi/cm^3]
Linac beam stop	4.0	540	0.083	0.009	0.002
Booster Beam stop	0.87	414	0.019	0.002	0.0004
Storage ring septum	0.63	414	0.484	0.052	0.010

The computed concentration of radionuclides in air at various beam loss locations inside the accelerator enclosures is orders of magnitude smaller than the derived air concentration for environmental exposure in DOE Order 5400.5. Once the operation is shut down, this concentration will rapidly decrease, due to both radioactive decay and air ventilation.

15.5.4 Activation of Cooling Water

Activation of water for cooling the magnets and the other accelerator components may be estimated by the similar method as the estimation of air activation inside the accelerator enclosures. The primary reactions leading to the activation of cooling water are the bremsstrahlung interactions with ^{16}O in water. The most abundant of the radionuclide produced by this process is ^{15}O. Other activation products that are formed include ^{11}C (4.4 % of ^{15}O), ^{3}H (at saturation, 2.2 % of ^{15}O) and ^{13}N (about 1% of ^{15}O). ^{15}O has a radioactive half life of 2.05 minutes and attains saturation during a short period of operation. ^{3}H will not attain saturation until several decades of accelerator operation.

15.5.4.1 Results of Cooling Water Activation Estimates

Among the accelerator components which require cooling, the storage ring septum is a maximum beam loss location. The saturation activity of radionuclides in the cooling water is estimated at the storage ring septum. A closed-loop inventory of 100,000 gallons (3.785×10^8 cm^3) of water is assumed in the system. Table 15.5.4 provides the saturation concentrations of the radionuclides in the cooling water of the storage ring septum. As mentioned earlier, ^{3}H will attain saturation only after decades of operation. After 5,000 hours of continuous operation, the concentration of ^{3}H will be only 3% of the saturation value.

Table 15.5.4 Saturation Activities of Radionuclides in the Cooling Water at the Storage Ring Septum.

Beam loss [Watts]	^{15}O [pCi/cm^3]	^{11}C [pCi/cm^3]	^{13}N [pCi/cm^3]	^{3}H [pCi/cm^3]
0.63	0.24	0.01	0.002	0.005

The computed concentration of radionuclides in cooling water of the storage ring septum is orders of magnitude smaller than the derived concentration for environmental discharge limits in the DOE Order 5400.5. Once the operation is shut down, concentration of all nuclides, except that of ^{3}H, will rapidly decrease, due to radioactive decay of the short-lived isotopes.

15.6 SKYSHINE ESTIMATES AND SITE BOUNDARY DOSES

The term skyshine refers to the radiation that is initially directed skyward from a source but, due to scattering reactions with air nuclei, then is directed back to the earth. The neutron component of the radiation will be the major contributing factor to the skyshine dose. Any location in the accelerator where there is a probability for potential beam loss can be a source of skyshine. However, the potential beam loss and the resultant photo-neutron production at any given location in the accelerator system is small. The neutron component is well shielded at NSLS-II for personnel protection. Therefore, most beam losses do not cause significant skyshine.

15.6.1 Estimates of Skyshine Created at the Linac Beam Stop

Some skyshine radiation will be produced at the linac beam stop, where four watts of electron power will be dissipated. For the skyshine calculations, it is assumed that the linac beam stop is completely unshielded locally, aside from the 1 meter of concrete shielding on the roof.

The skyshine dose rates due to neutron radiation are calculated using the method developed by Rindi and Thomas [15.22]. The unshielded neutron dose at the concrete roof is taken as the source term. The skyshine at a given distance is calculated by the following algorithm.

$$\text{skyshine dose rate} = (a \times H / r^2)\, e^{-r/\lambda} \qquad (15\text{-}15)$$

Where a = 7 (constant), H = unshielded dose rate on the concrete roof (source term), r = distance of the dose point from the source in meters, and λ = 3300 meters, effective air attenuation factor.

Table 15.6.1 gives the calculated skyshine estimates for the linac beam stop at 100 meters and 1 mile (1,600 meters) from the linac stop. For a conservative operational period of the linac, 5,000 hours a year, the annual skyshine dose estimates are well within the acceptable limits. With the additional local shielding of the linac stop, the skyshine doses will be comparable to background levels.

Table 15.6.1 Estimates of Skyshine Created at the NSLS-II Linac Beam Stop.

Neutron source component	Skyshine Dose at 100 m		Skyshine Dose at 1 mile	
	[mrem/h]	[mrem/year]	[mrem/h]	[mrem/year]
Giant resonance neutrons	8.2×10^{-4}	4.1	2.0×10^{-6}	0.010
High-energy neutrons	1.3×10^{-3}	6.3	3.0×10^{-6}	0.015
Total skyshine dose	2.1×10^{-3}	10.4	5.0×10^{-6}	0.025

15.6.2 Estimates of Skyshine Created at the Booster Beam Stop

Some skyshine radiation will be created at the booster beam stop. However, these dose rates will be lower than the skyshine dose rates produced at the linac beam stop because only 0.874 watts of electron power are dissipated at the booster beam stop, versus 4 watts at the linac beam stop. For the booster beam stop skyshine calculations, it was assumed to be unshielded locally, except for the 1-meter concrete bulk shielding.

Table 15.6.2 gives the calculated skyshine estimates for the booster beam stop using the same algorithm as in the previous section. The skyshine estimates at 100 meters and 1 mile (1,600 meters) from the beam stop have been calculated. For a conservative operational period of 5,000 hours a year, the annual skyshine dose estimates are well within the acceptable limits. With the additional local shielding of the booster beam stop, the skyshine doses will be comparable to background levels.

All other skyshine dose rates that result from beam losses in the accelerator systems will be comparable to background dose rates.

Table 15.6.2 Estimates of Skyshine Created at the NSLS-II Booster Beam Stop.

	Skyshine Dose at 100 m		Skyshine Dose at 1 mile	
Neutron Source component	[mrem/h]	[mrem/year]	[mrem/h]	[mrem/year]
Giant Resonance Neutrons	1.0×10^{-4}	0.5	2.5×10^{-7}	0.001
High Energy Neutrons	1.6×10^{-4}	0.8	3.7×10^{-7}	0.002
Total Skyshine Dose	2.6×10^{-4}	1.3	6.2×10^{-7}	0.003

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