2 RADIATION SAFETY AND SHIELDING

2.1 SHIELDING OBJECTIVES

NSLS-II is subject to DOE radiation protection standards. The primary document that defines the DOE radiation protection standard 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 limits to radiation workers and members of the public are 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 and for visitors and minors within the NSLS-II building.

The dose to workers and beamline scientists from NSLS-II operations will be kept well below federal limits and within BNL administrative levels through shielding, operational procedures, and administrative controls. Shielding will be provided to reduce radiation levels during normal operation to less than 0.5 mrem/h and as low as reasonably achievable. Assuming an occupancy of 2,000 hours per year, this will reduce annual exposure to 1,000 mrem or less, in accordance with 10 CFR 835.1001. Because of higher occupancy compared to accelerator enclosure walls, beamline enclosures will be shielded during normal operations to 0.25 mrem/h or less.

Shielding will also be evaluated for abnormal operating conditions. Additional shielding or engineering controls will be provided to reduce the potential severity of an abnormal operating condition. The controls will be considered acceptable if exposures in excess of 100 mrem per incident are considered unlikely and exposures above 2,000 mrem are considered extremely remote. Based on the current experience at NSLS and other synchrotron radiation facilities, we expect annual radiation exposures <<100 mrem/year to NSLS-II staff and users.

Effectiveness of the shielding will be actively monitored by radiation instruments located on the experimental floor and other locations 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 in the form of supplementary shielding as appropriate.

2.2 SHIELDING ESTIMATES FOR THE ACCELERATOR ENCLOSURES

Radiological conditions for the design and operation of the NSLS-II linac, booster, and storage ring have been analyzed using the preliminary design parameters. The booster synchrotron will be housed in a separate tunnel from 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. The conservative factors used in the calculations are conservative beam loss assumptions, conservative radiation attenuation factors, storage ring beam life time of 2 hours, radiation dose equivalent factors derived from the thick target approximation and the dose rates calculated on contact at the shield walls.

The beam loss scenarios 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 1,000 mrem/year assuming an occupancy of 2,000 hours per year for a worker at NSLS-II. The calculated shielding for the occupied regions during operation is for a dose rate of <0.5 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.

2.2.1 Sources of Radiation Hazard at the Electron Accelerators

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 [2.1] 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 [2.2]. 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 slightly forward peaked and 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.

2.2.2 Shielding Design Methodology for the Accelerators

2.2.2.1 Radiation Attenuation Factors for the Shielding Materials

The radiation attenuation factors used for the materials in the current shielding calculations are given in Table 2.2.1. These data have been obtained from various sources in the literature [2.3–2.6]. 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 2.2.1 Radiation Attenuation Factors of Shielding Materials.

Radiation Component	Shielding Material	Density [g/cm³]	Attenuation Length [g/cm²]
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

2.2.2.2 Shielding Calculations for NSLS-II Accelerator Enclosures

The bulk shielding for the accelerator enclosures has been calculated using the following expression [2.9]:

$$H = \sum_i \frac{F_i J}{R^2} e^{-t/\lambda_i} \tag{5-1}$$

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 <0.5 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 <0.5 mrem/h (1,000 mrem per 2,000-hour work year).

2.2.2.3 Dose Equivalent Factors of Radiation Components

Effective Dose Equivalent factors for the unshielded source terms at 1 meter in the transverse direction (90 degrees) from a 3.0 GeV electron beam interaction on a thick copper or iron target are given in Table 2.2.2. The data are taken from Sullivan [2.7]. 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 2.2.2 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 [2.8] is $8.3 \times E$ 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 [2.8], 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 in the forward direction.

2.2.3. Shielding Estimates for the Linac Enclosure

2.2.3.1 Linac Parameters

For NSLS-II, a linac will be providing 200-MeV (injection energy) 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	15 nA
frequency	1 Hz
tunnel length	40 m
tunnel width x height	4 m x 3 m
position of beam from floor	1 m
power	2.96 W

2.2.3.2 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 2.2.3. gives the estimated losses of beam energy in the linac system components.

Table 2.2.3 Estimated Losses in the Linac System Components.

Component	Charge [nC/s]	Loss [%]	Energy [MeV]	Power Loss [W]
Accelerator system	15	10% distributed	200	0.30
Injection septum	7.5	50%	200	1.48
Linac beam stop	15	100%	200	2.96

To estimate the bulk shielding for the linac tunnel, a distributed loss of 10% of the beam energy is assumed along the length of the tunnel. The shielding requirements for the lateral walls and the roof of the linac tunnel are calculated based on this beam loss scenario and are shielded for a dose rate of 0.5 mrem/h.

The distance of the lateral wall at the klystron gallery side is at 3.0 m and the roof is taken as at 2 m from the beam center line.

The bulk shielding estimates of the concrete thickness for the linac tunnel are given in Table 2.2.4. 100 cm-thick standard concrete with a density of 2.35 g/cm^3 will limit the dose rate to <0.5 mrem/h at the exterior of the lateral wall, for an assumed 10% distributed beam loss scenario.

The injection septum for the linac injection to the booster synchrotron is covered in the next section.

Table 2.2.4 Bulk Shielding Estimates for the Linac Tunnel.

Component	Lateral wall Concrete Equivalent[1] Thickness [cm]	Roof Concrete Equivalent[1] Thickness [cm]
Non-injection region	100	110
Linac downstream wall	220 100 cm + 15 cm (Pb)	110

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

The bulk shielding estimates in the forward direction of the linac should be estimated, because an occupiable region exists in the forward direction of the bend magnet in the booster ring. The calculations are based on the forward direction bremsstrahlung and neutron dose equivalent rates provided by Sullivan [2.7]. These estimates are given in Table 2.2.4. The estimated concrete equivalent thickness for bulk shielding in the forward direction is 220 cm. Local shielding of lead in the forward direction can be provided to save on the concrete bulk shielding. A factor of 7 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.

2.2.4 Design of the Linac Beam Dump

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 bending magnet. 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 ~3-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 [2.10]. Table 2.2.5 gives the shower parameters for various shielding materials that are also used for beam stops.

Table 2.2.5 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 [2.10]. 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 photospallation reaction threshold. The neutrons created in the shower will escape isotropically from the stop and require additional shielding.

Table 2.2.6 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. This table also provides the dose rates on the exterior of the concrete shield wall with a local shielding of 15 cm of Pb and 20 cm of polyethylene (density = 1 g/cm^3). The local shielding limits the dose rate at the exterior of the concrete bulk shielding to <0.5 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 2.2.6 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

2.2.5 Bulk Shielding Estimates for the Booster Enclosure

At NSLS-II, the compact booster synchrotron will be housed in a separate 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 3.0 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 at 3.0 GeV being dissipated at any single point in the booster synchrotron during acceleration. A 50% beam loss at the booster injection septum at 200 MeV is assumed. The salient features of the booster synchrotron are given below.

beam energy	3.0 GeV
repetition rate	1 Hz
ring circumference	158.4 m
accelerated charge	15 nC
no of electrons per fill	9.36×10^{10}
total energy in the booster	43.75 J

The lateral wall at the occupied regions and the roof are each assumed to be 2 meters from the center line of the booster vacuum chamber. Bulk shielding for the booster synchrotron is calculated based on the algorithm given in Section 2.2.2.2 and given in Table 2.2.7. 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. No credit has been given to the shielding provided by the magnet iron in the booster ring. Supplementary shielding is also provided around the injection septum for possible higher injection rates. The area above the injection region is potentially occupiable and will be shielded with Pb supplementary shielding.

Table 2.2.7 Bulk Shielding Estimates of the Booster Enclosure.

	Lateral wall concrete equivalent (cm)	Roof concrete equivalent (cm)
Booster	70	70

2.2.6 Booster Beam Dump

When the booster is not injecting into the storage ring, the beam is dumped at the booster beam Dump. This beam dump will be located on the floor of the booster ring closer to the beam extraction region. It is assumed that the concrete bulk shield, which separates the occupiable regions, is 1 meter away at the storage ring side and 2 meters away from the roof.

The electromagnetic shower parameters for various materials considered for the booster beam stop are given in Table 2.2.5. Iron is the preferred material for the dump, 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 2.2.5) stipulates that material approximately 20 radiation lengths long and 3 Moliere radii in the transverse direction will contain 99.99% of the electromagnetic shower [2.10]. 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 photospallation reaction threshold. The neutrons created in the shower will escape isotropically from the stop and require additional shielding.

Table 2.2.8 shows the dose rates at the concrete bulk shielding wall due to various radiation components around the booster beam stop with no supplementary shielding in place other than the concrete bulk shielding. 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/cm^3). 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 <0.5 mrem/h on contact at the exterior of the concrete shield walls. The stop is inside the booster enclosure, and personnel have no access when the beam is in the storage ring. Additional supplementary shielding is required for possible higher rate of injection [2.11].

Table 2.2.8 Dose Rates on Contact : Exterior Concrete Shield Walls near the Booster Beam Stop.

	Dose Rate on Lateral wall [mrem/h]		Dose Rate on Roof [mrem/h]		Dose Rate on Inboard Wall [mrem/h]	
Radiation Component	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

2.3 Shielding Estimates for the Storage Ring

2.3.1 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. The conservatively estimated lifetime of the beam in the storage ring is 2 hours. In the current calculations, the storage ring tunnel is assumed to be 791 meters in circumference. The maximum assumed operating parameters of the storage ring system are shown below.

beam energy	3.0 GeV
beam current	500 mA
beam lifetime	2 hr
tunnel circumference	791 m
stored charge	1.3 μC
stored electrons	8.1×10^{12}
stored energy	3898 J

2.3.2 Storage Ring Beam Loss Assumptions

In the beam loss scenario perceived for these calculations, we considered the use of four scrapers in the injection region (two vertical and two horizontal), to intercept injected electrons that enter the storage ring at the wrong trajectory. The scrapers intercept incorrectly positioned electrons and prevent loss at other locations in the ring (e.g., at undulators). It is believed that it will be possible to intercept essentially all electrons that might be lost during injection on the scrapers and septum. The scrapers are likely to intercept a significant fraction of stored beam losses, as well. The bulk shielding calculations of the storage ring are performed with the following beam loss scenario. Assuming a conservative 2-hour lifetime and 80% injection efficiency, 18 nC of charge will be injected into the storage ring every minute to replenish the 14 nC of stored beam lost the previous minute (assuming 2 hours lifetime). Of the 18 nC injected, 4 nC (~20%) is lost during injection. We assume that 50% of the particles lost during injection (2 nC/min), will be lost at the injection septum and the remaining 50% will be intercepted at two horizontal injection scrapers (1 nC/min each) in the storage ring.

The 14 nC of stored beam will eventually be lost in the next minute. It is further assumed that out of ~14 nC/min lost from the stored beam:

- 30% is lost at the two horizontal scrapers (2.1 nC/min each)
- 15% is lost at the septum (2.8 nC/min)
- The remaining 55% is lost at vertical apertures, assumed to be at the two vertical scrapers and arbitrarily at five other limiting apertures (1.1 nC/min each)

Taking into account all the loss assumptions, in the present calculations, a 13 nC/min loss is assumed at any point in the injection region of the booster to storage ring injection (combined loss at the septum and the scrapers) and 1.1 nC/min loss is assumed at any given location in the non-injection region of the storage ring.

2.3.2.1 Bulk Shielding for the Storage Ring Enclosure

With two hours of beam lifetime in the storage ring, ~50% of the 1.3 μC of the stored beam loss occurs in one hour. 1.1 nC/min 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: The lateral wall of the storage ring on the experimental floor side is assumed to be 1 meter from the storage ring vacuum chamber center line. The roof and the inboard walls are assumed to be 2 meters from the vacuum chamber. The ratchet wall in the forward direction is assumed to be at 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 [2.8]. The occupied regions on the experimental floor side of the storage ring are shielded for a dose limit of <0.5 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 are given in Table 2.3.1. Shielding wall thickness in standard concrete equivalent is given for the lateral wall and roof. The ratchet wall shielding thicknesses at the FOE side of the beamlines are also given in that table. These walls are assumed to be 20 meters from the center of the straight section of the insertion devices.

Table 2.3.1 Bulk Shielding Estimates for the Storage Ring.

Component	Expt. Floor Wall Concrete Equivalent Thickness [cm]	Roof Concrete Equivalent Thickness [cm]	Inboard Wall Concrete Equivalent Thickness [cm]
Storage ring non-injection region	101	81.5	81.5
Booster to storage ring injection region	141	116	116
Storage ring ratchet wall (forward direction)	137	---	---

2.3.3 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. During injection, 20% injection efficiency is assumed. Also, beam loss takes place on the scrapers. The shielding requirements at the injection/extraction region are 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.

The bulk shielding estimates in terms of concrete thickness for the storage ring enclosure at the booster-to-storage-ring injection region are given in Table 2.3.1. 141 cm-thick standard concrete with a density of

2.35 g/cm^3 will limit the dose rate to <0.5 mrem/h at the exterior of the lateral wall of the storage ring. 116 cm of concrete on the roof will limit the dose rate to the same level at the exterior on contact. It may be possible to replace the additional concrete shielding by lead supplementary shielding at the roof and inboard wall side of the storage ring. Additional supplementary shielding is also required for possible higher point beam losses and higher rates of injection (greater than 1 injection per minute).

2.4 SHIELDING ESTIMATES FOR BEAMLINES AND FRONT ENDS

2.4.1 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.

2.4.1.1 Radiation through the Ratchet Wall

In the process of operating the storage ring, as well as producing the desired synchrotron radiation [2.11], 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.

2.4.1.2 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 straight section
- synchrotron radiation created by the bending magnets and the insertion devices [2.11]

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 [2.12] and confirmed by measurements in other synchrotron radiation facilities [2.13] determined that 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.

2.4.1.3 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 other facilities indicates that it is not expected to be a problem [2.14].

2.4.2 Shielding Design Simulations

Bremsstrahlung dose scattering calculations for NSLS-II ID, BM, and 3PW beamlines were carried out using the EGS4 electron-gamma shower simulation program [2.15]. This implementation is part of the CALOR program package distributed by the Radiation Shielding Information Center (RSIC) of 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 are not simulated by EGS4, but measurements at 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 [2.16]. 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.

2.4.3 Bremsstrahlung Source Estimates in the 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 concern 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 in the line of sight of the beamlines are 12.5 m for the insertion device straight sections and 6.6 meters for the BM/3PW beamlines.

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. The semi-empirical equation proposed by Frank [2.17] 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 at a distance L from the end of the straight path as

$$\text{dose rate (rem/h)} = \frac{3.0\times10^{-4}}{\pi\times X_0}\,\frac{E^2}{0.511^2}\,\frac{l\times I}{L(L+l)}\,, \tag{5-2}$$

where X_0 = radiation length of air at 10^{-9} Torr = 2.34×10^{16} cm, l = effective length of the straight path (15.5/6.6 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 for the insertion device beamlines and 100 rem/h for the BM/3PW beamlines.

2.4.4 Design of Bremsstrahlung Shutters/Stops

2.4.4.1 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 2.4.1 shows the geometry used in the EGS4 simulations to calculate the thickness of lead and tungsten required to attenuate the dose rate <0.5 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 2.4.1 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 [2.20] 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.

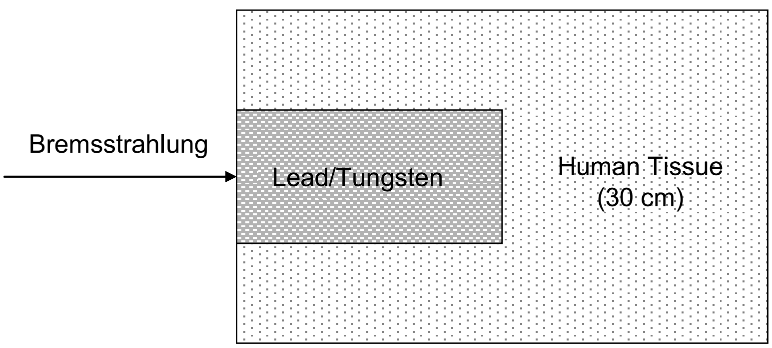

Figure 2.4.1 Simulated EGS4 geometry of the NSLS-II safety shutters.

2.4.4.2 Thickness of Shutters/Stops

Table 2.4.1 shows the primary bremsstrahlung dose rates predicted and the thickness of lead or tungsten required to reduce the radiation dose rate at the back of the shutter/collimator to less than 0.5 mrem/h (<5.0 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 2.4.2. 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 0.5 mrem/h (<5.0 μSv/h). Therefore a uniform lead thickness of 30 cm and a tungsten thickness of 20 cm are recommended for bremsstrahlung shutters or stops for insertion device and bending magnet beamlines.

Table 2.4.1 Calculated Thickness of Bremsstrahlung Shutters and Stops.

	Insertion Device Beamlines	3PW and BM Beamlines
Bremsstrahlung dose rate at 1 nT (rem/h)	240 rem/h	100 rem/h
Lead thickness required (cm)	28.9 cm	26.4
Tungsten thickness required (cm)	19.6 cm	17.8
Dose rate behind the stop/shutter (mrem/h)	0.5 mrem/h	0.5 mrem/h

For all beamlines, a lead thickness of 30 cm and tungsten thickness of 20 cm are recommended for the bremsstrahlung stops/shutters.

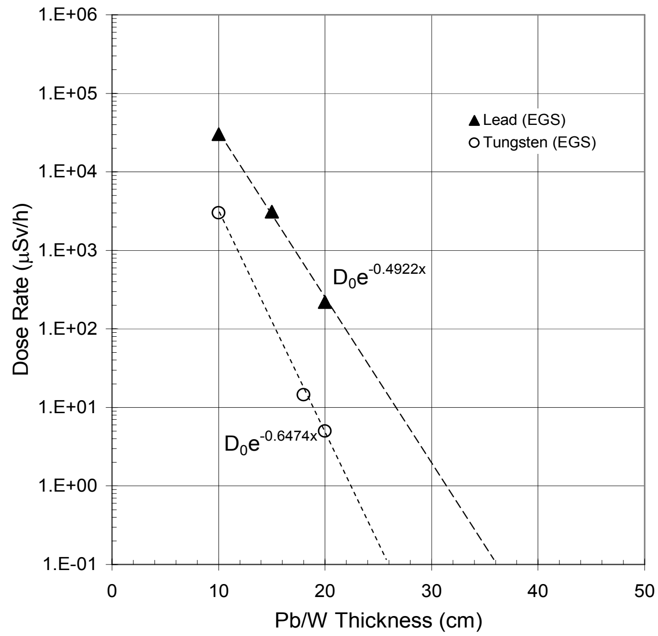

Figure 2.4.2
Contact dose rates at the downstream surface of the shutters/stops. Bremsstrahlung source was calculated by method 1.

2.4.5 Shielding Estimates for Experimental Stations

2.4.5.1 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 FOE (Figure 2.4.3), of typical dimensions (2.0 m wide, 3 m high, and 10 m long). Figure 2.4.4 shows the results of the calculations. Typically, the worst-case potential scatterer for bremsstrahlung is 3 cm-thick copper, and for synchrotron radiation is 1 cm-thick aluminum with small transverse dimensions. The EGS4 calculations were performed for bremsstrahlung, and STAC8 calculations were performed for synchrotron radiation.

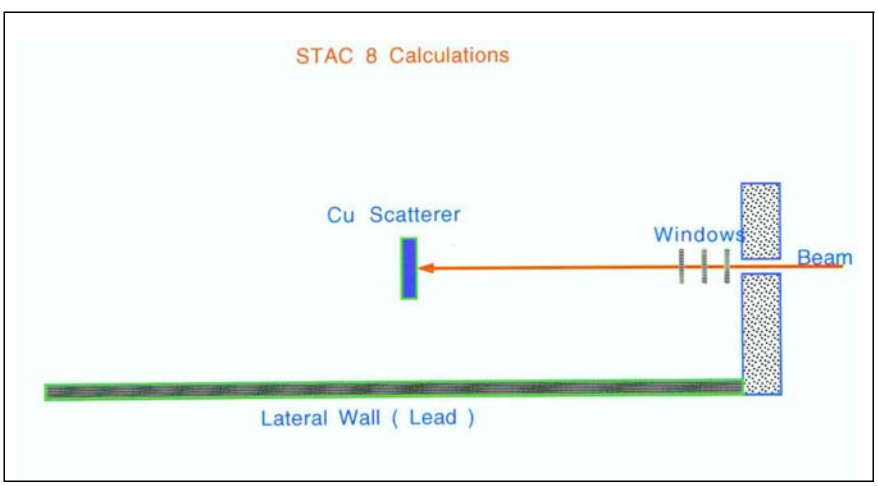

Figure 2.4.3 EGS4 and STAC8 geometry for bremsstrahlung and synchrotron radiation scattering calculations.

2.4.5.2 Shielding Estimates for the First Optics Enclosures

Preliminary shielding estimates for the NSLS-II First Optics Enclosures (FOEs) 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 for the beamlines were done at 500 mA of beam current, at 3.6 GeV electron beam energy. Also, all the doses are scored in the ICRU tissue on contact. Shielding of these areas is designed to maintain individual exposures when in contact with the hutch wall as <0.25 mrem/h for 2,000 hours of exposure per year. Station shielding is designed to meet this criterion to ensure that occupational radiation doses are ALARA.

2.4.5.3 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 2.4.1 was used. The EGS4 program 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 2.4.4 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) for the NSLS-II insertion device beamlines. 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 (2.4 Sv/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 insertion device FOE, the calculated dose rates (DR) from Figure 2.4.4 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 <0.25 mrem/h, is calculated using the expression

$$\text{lead thickness (cm)} = [\ln (0.01 \times DR) - \ln 0.25] / 0.473. \qquad (5\text{-}3)$$

The minimum attenuation coefficient of 0.473 cm^{-1} for lead, calculated by EGS4, has been used in these calculations for bremsstrahlung attenuation. The same methodology is also used for the Bending Magnet (BM) and 3-Pole Wiggler (3PW) beamlines.

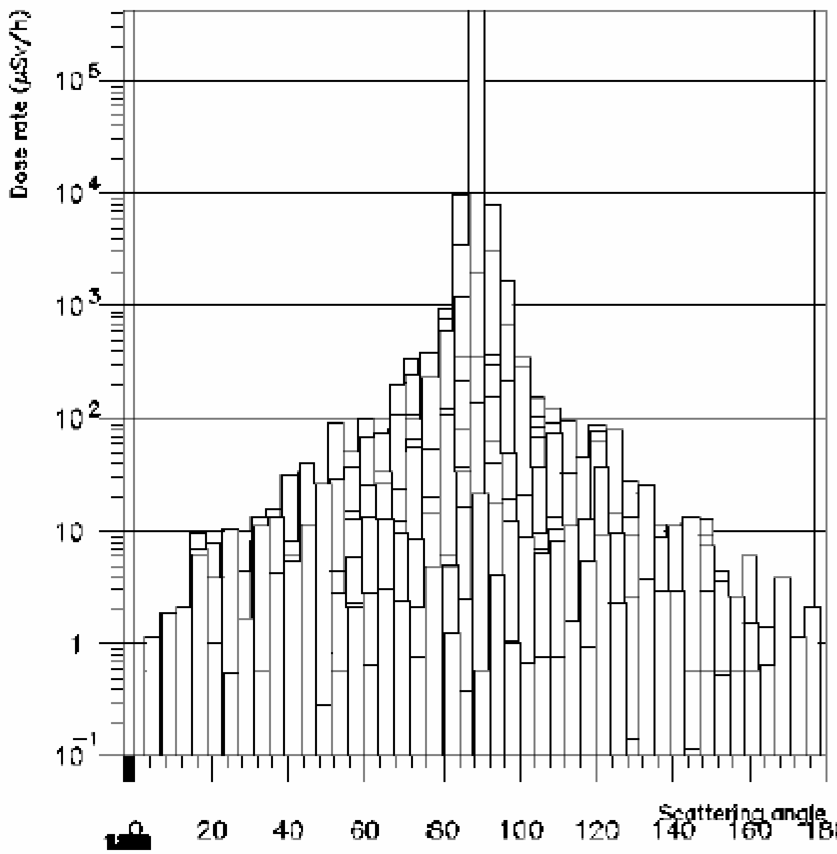

Figure 2.4.4
Scattered bremsstrahlung dose rates for the NSLS-II ID beamlines. (Primary bremsstrahlung scattered from a Cu target of 3 cm thickness with small transverse dimensions.)

Tables 2.4.2 and 2.4.3 provide the calculated lead thickness for the downstream panels of the FOE for ID and BM/3PW beamlines as a function of the scattering angle to achieve the design dose limit of <0.25 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 pipe penetrations. 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 of lead is recommended for the insertion device beamlines and 35 mm of lead is recommended for the BM/3PW beamlines.

Table 2.4.2 Bremsstrahlung Shielding for the Downstream Panel of the First Optics Enclosures of the Insertion Device Beamlines.

Angle [deg.]	Dose Rate [mrem/m^2·h]	Pb to shield < 0.25 mrem/h [mm]
1	5.0×10^3	108
2	1.5×10^3	84
3	7.0×10^2	68
4	4.0×10^2	56
5	2.2×10^2	44
6	1.5×10^2	37
8	1.0×10^2	28
10	7.0×10^1	21

Table 2.4.3 Bremsstrahlung Shielding for the Downstream Panel of the First Optics Enclosures of the BM and 3PW Beamlines.

Angle [deg.]	Dose Rate [mrem/m^2·h]	Pb to shield < 0.25 mrem/h [mm]
1	2.1×10^3	90
2	6.2×10^2	66
3	2.9×10^2	50
4	1.6×10^2	38
5	9.1×10^1	26
6	6.2×10^1	19
8	4.1×10^1	10
10	2.8×10^1	6

The lateral wall (side wall) and roof shielding for the FOE can also be calculated using the same equation. DR is designated as the scattered secondary bremsstrahlung dose rate in the transverse direction:

$$\text{lead thickness (cm)} = [\ln DR - \ln 0.25] / 0.473. \quad (5\text{-}4)$$

Tables 2.4.4 and 2.4.5 show the calculated lead thickness for the lateral panels of the FOE for ID and BM/3PW beamlines. For comparison, it also shows the thickness of Pb for lateral panels required to shield for the dose rates <0.05 mrem/h.

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. A higher vacuum chamber pressure might result in requirements for safety shutters to be closed until vacuum is restored.

Table 2.4.4 Bremsstrahlung Shielding for the Lateral Panel of the First Optics Enclosures of the Insertion Device Beamlines.

Angle [deg.]	Dose Rate [mrem/m²·h]	Pb to shield [<0.25 mrem/h]	Pb to shield [<0.05 mrem/h]
90	0.15	None	23

Table 2.4.5 Bremsstrahlung Shielding for the Lateral Panel of the First Optics Enclosures of the BM and 3PW Beamlines.

Angle [deg.]	Dose Rate [mrem/m²·h]	Pb to shield [<0.25 mrem/h]	Pb to shield [<0.05 mrem/h]
90	0.062	None	5

2.5 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, typically 10 mm aluminum, is used as the potential scatterer upstream of the station. The source spectrum for the NSLS-II insertion devices and BM for this calculation was generated by the STAC8 program. Five sources are considered for the NSLS-II beamline station shielding design. The salient features of these sources, calculated by the STAC8 program, are given in Table 2.5.1. The source parameters in this section are calculated for the beamlines at a beam energy of 3.6 GeV and a beam current of 500 mA.

The lateral walls of the experimental stations are assumed to be at a distance of 1 meter and the roof at 1.5 meter from the beam center line. Shielding for these areas was calculated to maintain individual exposures, when in contact with the experimental station wall, at less than 0.25 mrem/h at the occupiable areas.

Table 2.5.1 Source Parameters for the NSLS-II Beamlines.

Source	Source opening angle (mrad-Hori.) FOE Aperture	No. of Periods	B_{eff} [T]	Period [mm]	Length [m]	E_c [KeV]	Total Power [KW]
DW	3.0 mrad-H (60 x 5 mm²)	70	1.8	100	7 m	15.5	58.75
EPU45 L.Mode	1.0 mrad-H (14 x 4 mm²)	89	1.03	45	4 m	8.87	19.89
U19	1.0 mrad-H (4 x 4 mm²)	158	1.14	19	3 m	9.05	16.54
BM	10.0 mrad-H (200 x 5mm²)	1	0.4		2.6 m	3.44	0.321
3PW	4.0 mrad-H (80 x 5 mm²)	1	1.1		0.15 m	9.24	0.671

2.5.1 Shielding Recommendations for the First Optics Enclosures

Table 2.5.2 gives the combined results of the STAC8 and EGS4 calculations for the shielding requirements of the lateral panel and the roof for the five sources. The shielding requirements for the downstream panels of the FOEs are dominated by bremsstrahlung and therefore the recommendation in Section 2.4.5.3 applies. For comparison, shielding requirements for the annual dose rate of 0.05 mrem/h mrem are also given.

The station dimensions are taken as 2 m wide, 3 m high and 10 m long. The lateral panel is at a distance of 1 m and the roof is at a distance of 1.5 m from the beamline. If the stations are narrower, the shielding estimates need to be re-evaluated.

Table 2.5.2 Shielding Thickness in Pb for NSLS-II First Optics Enclosures.

Beamline Source	Lateral Panel Pb to shield <0.25 mrem/h [mm]	Lateral Panel Pb to shield <0.05 mrem/h [mm]	Roof Pb to shield <0.25 mrem/h [mm]	Roof Pb to shield <0.05 mrem/h [mm]
DW	12	23	11	11
EPU45	8	23	7	7
U19	9	23	8	8
BM	6 (Fe)	5	4(Fe)	4 (Fe)
3PW	5	5	5	5

2.5.2 Shielding Calculations for Monochromatic Experimental Enclosures

The shielding calculations for the monochromatic experimental stations are carried out by the STAC8 program. Since bremsstrahlung is stopped in the FOEs, no EGS4 simulations are necessary to estimate the shielding thickness of the side, roof and downstream panels. Five reflections (111, 333, 444, 555, and 777) with corresponding bandwidths are considered for these calculations. One of the energies (88 KeV) corresponds to the K-edge energy of lead. The five energies and their corresponding bandwidths used for the monochromatic experimental station shielding calculations are given in Table 2.5.3.

Table 2.5.3 Monochromatic Beam Energies and Bandwidths used for STAC8 Calculations.

Energy (KeV)	Band Width (%)
22	5×10^{-4}
66	4×10^{-5}
88	3×10^{-5}
110	6×10^{-6}
154	1.5×10^{-6}

All calculations are done for the beam energy of 3.6 GeV at 500 mA. The dimensions of monochromatic experimental station are assumed to be 2 m (W) x 3 m (H). Side panels are at a distance of 1.0 m from the roof and 1.5 m away from the beamline. Buildup factors for lead and iron are taken into account.

2.5.3 Shielding Thickness for the Monochromatic Experimental Enclosures

The results of these calculations are provided in Table 2.5.4. The recommended shielding thickness for the side panels, roof and upstream/downstream panels are given. In most cases thickness in Pb is given and in some cases the lead panels can be replaced by steel (Fe). An appropriate monochromatic stop can be provided in the line of sight of the beam in the monochromatic experimental station. The monochromatic experimental stations with a vicinity of higher occupancy by non-radiation workers is shielded for an annual dose rate of 100 mrem per year.

Table 2.5.4 Shielding Thickness for NSLS-II Monochromatic Experimental Stations.

Beamline Source	Lateral Panels Pb to shield <0.05 mrem/h [mm]	Roof Pb to shield <0.05 mrem/h [mm]	US & DS Panels Pb to shield <0.05 mrem/h [mm]
DW	6	5	6
EPU45	3 16 (Fe)	3 14 (Fe)	3 16 (Fe)
U19	4	3	4
BM	2 (Fe)	2 (Fe)	2 (Fe)
3PW	1.5 8 (Fe)	1.5 6 (Fe)	1.5 8 (Fe)

a. All calculations are done for beam energy of 3.6 GeV at 500 mA
b. Station dimensions are assumed to be 2 m (W) x 3 m (H)
c. Side panels are at a distance of 1.0 m and roof at 1.5 m away from the beamline

2.6 Shielding for the Pink Beam Experimental Enclosures

In most cases, the pink beam experimental stations (assuming 30 to 50 KeV cut-off) have the same shielding requirements as the monochromatic experimental stations because of the absence of higher energy synchrotron radiation component in the pink beam. However, bremsstrahlung needs to be completely stopped in the upstream station.

2.7 Radiological Consequences of Accidental Beam Loss

2.7.1 Consequences of Accidental Linac Beam Losses

Shielding calculations for the linac enclosure have been carried out assuming a 10% distributed beam loss during beam acceleration (6.6% at any given point). Shielding thickness has been calculated for a dose rate of <0.5 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 ~15 times more than the limiting value. The dose rate will be <7.5 mrem/h at the exterior of the concrete bulk shielding of the enclosure due to this beam loss event.

2.7.2 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 15 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 5.4×10^4 nC/h. Assuming 13 nC/min loss of injected beam at the injection/extraction region, 780 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 <0.5 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 35 mrem/h at the exterior of the shield wall on contact.

2.7.3 Consequences of Loss of Vacuum in the Straight Section

Loss of vacuum in the insertion device straight path is another credible incident that can cause higher dose rates around the beamline FOEs. In the bremsstrahlung source calculations in Section 2.4.3, a straight section pressure of 10 to 9 Torr is assumed. A sudden loss of vacuum to 1 Torr in the straight section would increase bremsstrahlung production by a factor of 109. 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 <0.25 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 109, 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 $<(0.25\times10^9) / (3.6\times10^6) = 70$ mrem.

2.7.4 Consequences of Linac-to-Booster Injection Losses

The shielding calculations for the booster enclosure assume an average charge of 15 nC/min injected to the booster system with a frequency of once per minute. A scenario is developed where 15 nC/s, the maximum capacity of the linac, is injected continuously into the booster, and all of it is lost at some location in the booster structure. The total charge lost in this case in an hour would be 5.4×10^4 nC/h. Assuming 2% (0.3 nC/min) loss of injected beam at any location in the booster system, 18 nC/h would be lost at the location for which the shielding design calculations are carried out. The shielding for the accelerators is designed for a dose rate of <0.5 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 <1,500 mrem/h at the exterior of the shield wall on contact.

2.8 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 [2.21]. 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.

2.8.1 Residual Activity Estimates of Accelerator Components

2.8.1.1 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 [5.9]. The neutron yield in the accelerator components and in the beam stops is based on the equation from Swanson:

$$Y^1 = 1.21 \times 10^8 Z_1^{0.66} \text{ neutrons/joule,} \tag{5-5}$$

where Z1 = atomic number of the element. The equation can be modified for a given isotope as

$$Y = F(1.21 \times 10^8 Z^{0.66}) \text{ n/J,} \tag{5-6}$$

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

$$dN/dt = WYf - \lambda_R N \text{ atoms/sec,} \tag{5-7}$$

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

$$N = \frac{WYf}{\lambda_R} (1 - e^{-\lambda_R t}) \text{ atoms.} \tag{5-8}$$

Since the activity is λRN

$$\text{Activity} = WYf (1 - e^{-\lambda_R t}) \text{ disintegrations/sec,} \tag{5-9}$$

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

$$A = WYf \text{ disintegrations/sec} \tag{5-10}$$

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.

2.8.1.2 Radioactivation of the Linac Iron Beam Stop

Approximately 3 watts of electron beam power at 200 MeV 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 52Mn(m), 56Mn, 54Mn, 52Fe, and 53Fe. 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 52Mn (m) (half life 21.1 min) and 53Fe (half life 8.51 min). After about an hour of shutdown, the exposure rate would be ~0.046 mR/h at 1 meter. 54Mn, 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 54Mn in iron would be 0.05 mR/h. 55Fe, produced from 54Fe, 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.

2.8.1.3 Radioactivation of the Booster Iron Beam Stop

Approximately 0.73 watts of electron beam power at 3.0 GeV is dissipated in the booster beam stop during a 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 52Mn(m), 56Mn, 54Mn, 52Fe, and 53Fe. The estimated combined exposure rate at 1 meter from the beam stop is about 0.48 mR/h, contributed mainly by 52Mn(m) (half life 21.1 min) and 53Fe (half life 8.51 min). After about an hour the exposure rate would be ~0.01 mR/h at 1 meter. 54Mn, 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 54Mn in iron would be 0.01 mR/h. 55Fe, produced from 54Fe, 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 storage ring septum magnet from injection losses, will be comparable to or less than at the booster beam stop.

2.8.1.4 Radioactivation of Copper at the Injection Septum

The injection septum in the storage ring also 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 60Co (half life 5.26 years) and 63Ni (half life 93 years). Other short-lived isotopes produced are 58Co (half life 71.3

days), 58Co(m) (half life 9.2 h), 61Cu (half life 3.32 h), 62Cu (half life 9 min), and 64Cu (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 62Cu. 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, 60Co 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.

2.8.1.5 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 206Tl, 207Tl, 207Tl(m), 202Pb(m), 203Pb(m), and 204Pb(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 204Pb(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.

2.8.1.6 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 1.1 nC/min 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 2.8.1 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 2.8.1 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
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.

2.8.2 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.

2.8.2.1 Results of Soil Activation Calculations for NSLS-II

Table 2.8.2 gives the activity in the soil created by 3H 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 3H 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 2.8.2 Activity in the Berm 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 berm)	0.22×10^2	2.77×10^{-15}	2.97	2.47×10^{-14}	2.04
Linac beam stop (inboard berm)	0.39×10^2	4.91×10^{-15}	5.40	4.38×10^{-14}	3.61
Booster beam stop (floor berm)	0.05×10^2	0.62×10^{-15}	0.68	0.56×10^{-14}	0.46
Booster beam stop (inboard berm)	0.08×10^2	1.00×10^{-15}	1.10	0.90×10^{-14}	0.74
Storage ring septum (floor berm)	0.04×10^2	0.50×10^{-15}	0.55	0.45×10^{-14}	0.37
Storage ring septum (inboard berm)	0.06×10^2	0.76×10^{-15}	0.84	0.67×10^{-14}	0.55

2.8.3 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 photospallation 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.

2.8.3.1 Results of Air Activation Calculations for the Accelerator Enclosures

Table 2.8.3 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 length of 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 $3\times3\times46$ m^3 = 414 m^3 is assumed inside the storage ring.

Table 2.8.3 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	3.0	540	0.083	0.009	0.002
Booster Beam stop	0.73	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.

2.8.4 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), 3H (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. 3H will not attain saturation until several decades of accelerator operation.

2.8.4.1 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 × 108 cm^3) of water is assumed in the system. Table 2.8.4 provides the saturation concentrations of the radionuclides in the cooling water of the storage ring septum. As mentioned earlier, 3H will attain saturation only after decades of operation. After 5,000 hours of continuous operation, the concentration of 3H will be only 3% of the saturation value.

Table 2.8.4 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]	3H [pCi/cm^3]
0.20	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 3H, will rapidly decrease, due to radioactive decay of the short-lived isotopes.

2.9 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.

2.9.1 Estimates of Skyshine Created at the Linac Beam Stop

Some skyshine radiation will be produced at the linac beam stop, where approximately 3 watts of electron beam 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 [2.22]. 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.

$$\text{skyshine dose rate} = (a \times H / r^2)\, e^{-r/\lambda} \qquad (5\text{-}11)$$

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 2.9.1 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 2.9.1 Estimates of Skyshine Created at the NSLS-II Linac 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	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

2.9.2 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 0.73 watts of electron power are dissipated routinely at the booster beam stop, versus 3 watts at the linac beam stop. For the booster beam stop skyshine calculations, it was assumed to be unshielded locally, except for the 70 cm concrete bulk shielding.

Table 2.9.2 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 2.9.2 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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