Chapter 13

Environment, Safety and Health Considerations

13.1 Introduction

The Neutrino Factory presents a number of challenges in the general area of environment, safety, and health. Here we identify these challenges and make a preliminary assessment of how they might be addressed and of their potential impact on the project. Many of these issues are very similar to those that have been encountered and solved during the construction and operation of other accelerator facilities at BNL and elsewhere, while others are novel. The novel ones will require particular attention as the project proceeds to ensure their timely resolution in a cost-effective manner that meets the approval of the Laboratory, the Department of Energy and the public. With adequate planning in the design stages, these problems can be adequately addressed in a manner that merits their support.

13.2 Procedural/Regulatory Matters

The actual design, construction, and operation of the Neutrino Factory will have to meet a number of procedural/regulatory milestones in the area of environment, safety, and health to ensure its success. Devoting early attention to these issues is likely the best way to enhance public support of the project. Design, analytical and operational requirements are currently provided in the BNL Standards Based Management System (SBMS) Accelerator Safety and Hazard Analysis Subject Areas, as well as the applicable SBMS Subject Areas on environmental protection [1].

13.2.1 Environmental Protection

All new DOE projects are subject to the National Environmental Policy Act (NEPA). In accordance with NEPA and the Cultural Resources Evaluations Subject Area [1], the project will generate an Environmental Evaluation Notification Form and request the funding agencies (DOE and/or NSF), to make a determination on the level of documentation needed to comply with NEPA. Based on the proposed design and past determinations on other accelerator projects, an Environmental Assessment (EA) should be sufficient and would be the expectation of the determination that the funding agencies will make. The decision making process and content of the EA is prescribed in NEPA, along with the requirement to seek public comment. The conclusion of the EA process is either a Finding of No Significant Impact (FONSI) or a determination of need to prepare an Environmental Impact Statement (EIS). The NEPA process is rigorous, but one that BNL has the expertise to conduct and complete. This task must be completed, customarily by using external resources, prior to expenditure of project funds. Other procedural requirements apply in the arena of environmental protection in the form of environmental permits that will be needed for construction. This was the case for the previous RHIC Project. Any permits that apply to operations will be identified if and when the EA identifies regulated effluents. Topics covered by such permits include stormwater water discharges, discharges of cooling water, wetlands mitigation, releases of air pollutants for both non-radioactive pollutants and for radionuclides, and construction permits. Historical sites have previously been identified on the BNL site that will be reviewed in the NEPA process.

13.2.2 Environment, Safety and Health Procedural and Regulatory Compliance

The Laboratory will be required to prepare an assessment of the environment, safety, and health issues associated with this project in the form of a Safety Assessment Document (SAD). Since the project will be a Major System Acquisition, the preparation of a Preliminary Safety Assessment Document (PSAD) is required as a scooping document for the hazards involved in construction and operation. The PSAR will also be the basis for the EA and must be completed and reviewed by the funding agencies before funding is approved to start construction. The main purpose of the PSAD is to identify the relevant ES&H issues at an early stage and propose how they might be mitigated. The SAD will later document their resolution in the final detailed design of the architecture and components of the machine. It is customary for the funding agencies to review these safety documents by utilizing an external independent review team throughout the preliminary and final design stages. DOE is presently "self-regulating" in the areas of industrial safety and occupational radiation protection. This situation could change at some future time if external regulation is applied to DOE facilities. Related developments are being monitored closely to identify new requirements or procedures that might apply to new projects such as the Neutrino Factory.

13.3 Occupational Safety During Construction of the Facility

The beamlines all would be located at or just below grade, but above the water table. At this level, construction is likely to proceed by the standard "cut and fill" method. The Occupational Safety and Health Administration regulations (OSHA) in 29 CFR 1926 apply to the construction activities. These rules are delegated down to BNL staff and contractors through SBMS and general conditions specified in contracts, as appropriate. There are no unconventional occupational safety issues expected to be associated with the construction work. The beamlines and target station will be heavily shielded to reduce onsite and offsite exposure from prompt radiation. The shielding will typically be constructed with a sand berm as has been employed by other accelerators at BNL. The production target will require a more dense and complex shield matrix to reduce prompt radiation and protect the groundwater in the vicinity, but the design will not present any special problems with respect to conventional construction.

13.4 Environmental Protection During the Construction of the Facility

The Laboratory as an institution is registered to the ISO 14001 Environmental Management System (EMS) [1], which will be used as the platform to identify Environmental Aspects and Impacts during construction. The EMS process will identify Operational Controls to ensure that legal and other requirements are maintained to protect the environment and provide the framework to manage the environmental aspects.

Based on past experience with the conventional construction at RHIC, environmental protection must be addressed during the conceptual design phase. With respect to the restoration of the forested area that will be disturbed to build the beamlines, only the area of the beam enclosure will be cleared to minimize this impact. If additional fill material is needed to construct sand berms for shielding, clean fill will be brought in from off-site without disturbing any existing vegetated land. A plan to restore the environment will be required to facilitate regrowth of the vegetation on the disturbed land and over the newly constructed beamlines.

13.4.1 Ordinary Operational Occupational Safety Hazards

The operational occupational safety hazards typically encountered at BNL and other large particle accelerator facilities will be found in this facility. These have been successfully addressed by well-known techniques and are simply listed below:

- High current electrical circuits will be used in the magnets on a large scale.
- High power radio-frequency (rf) generation and distribution equipment will be used extensively.
- Large numbers of cables will be installed in cable trays, with associated fire protection implications.
- Long tunnels will be present, with corresponding egress and fire protection issues to be addressed.
- Large, heavy components will have to be moved and aligned.

13.5 Novel Occupational Safety Hazards

13.5.1 Use of Nonflammable Cryogens

The extensive use of large amounts of nonflammable cryogenics in both magnets and rf structures presents special problems, but similar to those solved at RHIC and other accelerator facilities. Portions of these cryogenic systems will reside in machine enclosures and present oxygen deficiency hazards (ODH). As was done for the cryogenic components in RHIC, the ASME Boiler Code will be used in design, as previously described in the RHIC SAD. The Oxygen Deficiency Hazards Subject Area [1] will be followed to implement worker controls in operations.

13.5.2 Use of Flammable Cryogens

The use of ionization cooling in a liquid-hydrogen (LH_2) medium presents significant fire and explosion hazards. Also, the LH_2 cells will be interleaved with RF structures and magnets that handle a great deal of electrical energy. In the past, BNL has successfully used stringent review procedures involving an internal Cryogenic Safety Committee, as well as external review committees of experienced individuals, to provide advice on the design basis and management of cryogenic systems. Because of the high level of hazard nature and expected large volume of LH_2 an intensive process of safety review will begin at the earliest reasonable stage in the design process.

13.5.3 Muon Storage Ring Life Safety (Egress) Considerations

The Muon Storage Ring (MuSR), as defined for this study, constitutes a long above-grade tunnel sloped at 13.1° with respect to the horizontal. The fire protection/egress considerations of this configuration will need to be evaluated for life safety by a fire protection professional, and others, for adequacy. Plans will need to be made for the evacuation of any injured or ill personnel through the sloped arcs.

13.5.4 Muon Storage Ring Slope Hazards

The relatively steep slope of the MuSR presents unique hazards during operation as well as during construction. There will be safety engineering considerations involved with moving heavy machine components and equipment to support installation and maintenance. The surface of the finished floor should be made sufficiently rough to provide good traction to individuals wearing ordinary shoes. Gutters should be provided to direct water flowing into the tunnel toward the large sump pits at the lower end. They might also be designed to retard the unwanted downhill movement of large items, particularly that of any portable pieces of equipment on wheels. An idea that might address this, and other considerations, is to arrange the gutters in a spiral fashion, regularly crossing the tunnel to direct such items toward one of the walls. Regular tie-down points for heavy items of equipment could be provided. These problems can be solved if they are addressed early in the design process.

13.6 Prompt and Residual Radiation Safety During Operation of the Facility

13.6.1 Proton Driver

13.6.1.1 Production Target and Prompt Radiation Shielding

The conceptual target design is a 5 mm radius liquid mercury jet with a velocity of 30 m/s. The jet is tilted vertically downward at an angle of 100 mrad with respect to a 20 T solenoidal field. A 24 GeV proton beam with an rms radius of 1.5 mm, tilted vertically downward at an angle of 67 mrad with respect to that same solenoidal field, collides with the mercury jet 45 cm from the jet nozzle. That 45 cm distance is to the intersection of the jet and beam centers; due to the finite diameter of the jet and the beam, they interact over a range of 15 cm to 75 cm from the nozzle. The nozzle is embedded in an iron pole face which helps control the uniformity of the solenoidal field, and the proton beam enters through that same pole face. Every 400 ms, 6 bunches of 1.7×10^{13} protons each, separated by 20 ms, will hit the mercury jet target.

The Proton Driver and the Neutrino Factory Target Station will require massive amounts of hadron shielding, similar in scale and type to that of other proton accelerators in this energy and intensity regime. Detailed calculations made using MARS have already been performed to assess the prompt radiation inside the target hall to determine the amount of shielding required for a similar proposal made by Fermilab [2]. The transport of beam from the synchrotron to the Target Station poses no unusual problems with respect to prompt radiation shielding, although a deployment of a Design Basis Accident (DBA) and Beam Loss Scenario, as was done for the RHIC Project, is needed to complete the detailed design of shielding for the various regions of the beamline [3]. This is also needed for analysis of the existing AGS ring, to model the current infrastructure to asses the need for additional or upgraded shielding and penetrations.

The Proton Driver, under maximal operation, will handle an expected 7-14 times the beam power of the present AGS complex. Since the impacts to the AGS ring would scale roughly with the beam power, modifications to handle such a large upgrade are planned. Direct injection to AGS from a new 1200 MeV Linac instead of the existing Booster, coupled with the improved transition crossing jump, should lead to lesser beam losses during the acceleration and ejection of beams. Therefore, it is assumed that the normal beam loss per second in the AGS will remain at, or less than, the current level. The handling of this large beam power has already received, and merits, careful attention. Efforts should continue to better control such losses of beam both from the standpoint of component activation and also with respect to soil and groundwater impacts.

Because BNL resides on a Sole Source Aquifer, activation of soil and contamination of groundwater are both considerations near the target station. The amount of high density shielding, *i.e.* steel and tungsten, must be optimized to mitigate production of ^{3}H and ^{22}Na along with moisture barriers to prevent migration of these isotopes to the water table.

A study to assess shielding of prompt radiation from the storage ring was performed using MARS. [15] For a muon beam momentum of 20 GeV/c, 2×10^{20} muons per year decay in the storage ring. The straight section is 126 m long, and the arcs are each 53 m, for 180^o of rotation, (16.87 m radius). The BNL administrative design criteria for control of off-site radiation dose equivalent is 5 mrem/yr, and the drinking water standard in DOE Order 5400.5 requires less than 1 pCi/mL tritium and 0.2 pCi/mL ^{22}Na. For shielding calculations, the Fermilab wet soil properties were used with the density of 2.24 g/cm^3 and scaled to the BNL value of 1.9 g/cm^3. For neutrino-induced radiation, the soil density is negligible; therefore the results are transferable to BNL soil. Using the above assumptions the required soil thicknesses scaled to the BNL soil density of 1.9 g/cm^3 are listed below [15]:

- During normal operation, and with a design criterion of 0.25 mrem/h for occupancy in the underground facilities (electronics rooms, etc.), there must be at least 8.3 m of shielding outward from the arc tunnel enclosure, and 3 m of shielding on all other sides of the tunnel. The radiation that is being shielded from this source is due to electron showers.

- For groundwater protection from radiation due to electron showers, a geomembrane is required to prevent water flow within 1.8 m of the tunnel in all directions. In addition, there must be a geomembrane preventing water flow through a region extending 3.5 m from the end of each straight section in the downstream beam direction of those straight sections. As for neutrino-induced activation, it results in radionuclide concentrations a factor of 800 below BNL-imposed limits for tritium, and even lower for ^{22}Na.

- To meet the off-site radiation requirement of 5 mrem/yr due to neutrino-induced radiation, a plane extending 30 m from the outside of the arc tunnel enclosure, within a band ± 10 cm from the orbit plane, must be kept on-site (see Fig. 13.1). In addition, an ellipsoid of 2 m half-width, 1300 m long, the long axis extending in the direction of the production straight, must be kept within the site (see Fig. 13.2 and discussion in Section 13.6.3.1).

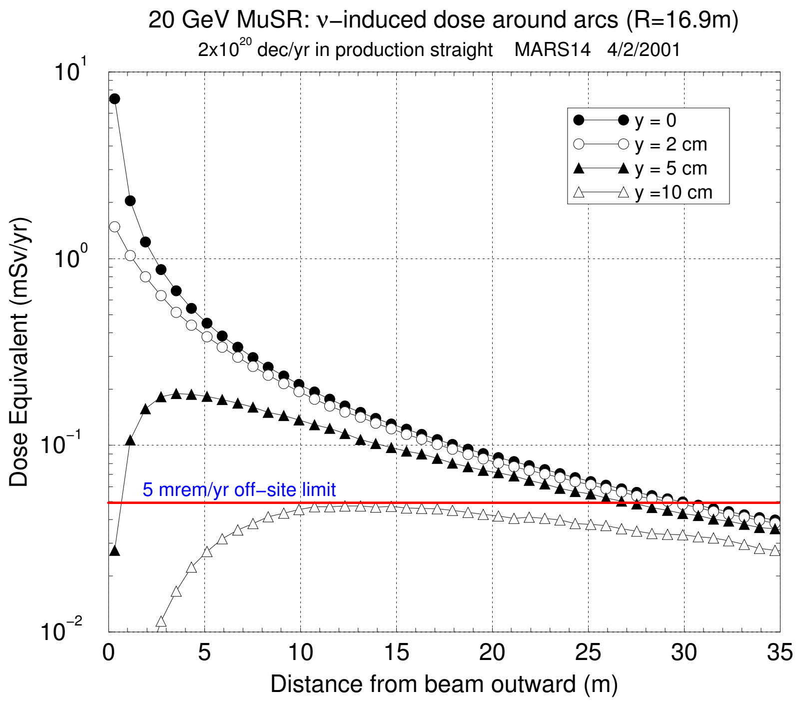

Figure 13.1: Neutrino-induced dose around the arcs as a function of the distance from the arc.

13.6.1.2 Residual Radioactivity at the Target Station

Given the high beam power, the residual activation of the Target Station merits special attention. The residual absorbed dose rates to be found in the Target Station are not presently known in detail, but will be large, of the order of krads h^{-1} (tens of Sv h^{-1}). There will also be significant activation of water used to cool the non-cryogenic components. Remote handling capabilities of the style used by other facilities, such as the Los Alamos Neutron Science Center (LANSCE) and those planned for the Spallation Neutron Source (SNS) at the Oak Ridge National Laboratory, will be needed.

Fission products will be produced from the primary interactions of protons on elemental mercury, resulting in a source term of volatile and non-volatile radionuclides. Air activation will be enhanced by the neutrons that will be produced from (p, Hg) interactions. Some of the isotopes produced in the target will exceed the thresholds for a

Non-reactor Nuclear Facility. Therefore, the target will require compliance with 10 CFR 830 Nuclear Safety Management and a funding agency approved Safety Analysis Report. Nuclear Facilities are subject to levels of safety analysis, quality assurance, and training requirements that are significantly more stringent than those normally applied to accelerator facilities. The present DOE definition of a Nonreactor Nuclear Facility excludes accelerators, such that the balance of the complex will remain regulated under the Accelerator Safety Order, DOE 420.2. Definition of the facility as a nuclear facility needs to be resolved. The target station, from a regulatory standpoint, should be segregated from the rest of the facility to the extent possible. The Laboratory continues to monitor the ongoing development of federal requirements on this topic.

13.6.1.3 Airborne Radioactivity

The production of airborne radioactivity in the vicinity of the Target Station will constitute the dominant source of airborne radioactivity emissions for the Neutrino Factory. At this early stage, a comparison with the work already done by Fermilab on the NuMI Target Station [6] may be useful, since the beam powers of the two facilities are comparable, although the source term for the Hg target is likely to exceed that from the Fermilab analysis of a carbon target and the site boundary distance may be different. The NuMI Target Station in the Fermilab proposal will operate at a beam power of 0.404 MW. It will release a total of about 15 Ci (555 GBq) annually. This is dominated by 5 Ci (185 GBq) of ^{11}C (half-life = 20.3 min.) and 9.8 Ci (363 GBq) of ^{41}Ar (half-life = 1.83 hours). Such releases will result in an annual dose equivalent of about 0.009 mrem (0.09 μSv) at the Fermilab site boundary. An evaluation of the offsite dose equivalent from airborne releases from the BNL design is required to assess whether 0.1 mrem (1 μSv) in one year may occur. If reaching that threshold is possible at the site boundary from the new beamlines at BNL, then a NESHPS Permit must be submitted. A continuous monitoring program and other requirements are specified by U. S. Environmental Protection Agency Regulations. [7] The monitoring program will have to be designed to demonstrate that the regulatory limit of 10 mrem (100 μSv) in one year is not exceeded. The design of the beam enclosure ventilation system will have to maximize the decay in transit and/or filtration from the point of production to the point(s) of release.

13.6.1.4 Radioactivity in Soil and Groundwater

The calculation of the radioactivity produced in the soil for the entire facility can be accomplished using current versions of Monte-Carlo shielding codes. As stated above, the Target Station is the most significant source. The impact of the beam loss on soil and ground water will be reassessed for new beamlines, as well as the AGS Complex, as part of the design process.

13.6.2 Cooling Stages and Muon Acceleration Stages

In the cooling stages, the collected muons from pion decays will deposit considerable energy in the LH_2 cells in the course of being "cooled." This energy will end up largely in the form of heat transferred to the hydrogen and dispersed by the refrigeration equipment. Given the low energy of the muons at this stage, only energy loss by ionization is important. It is straightforward to design shielding appropriate to ranging out "stray" muons that might miss the cooling apparatus as well as the electromagnetic cascades induced by their decay electrons. Present Monte-Carlo codes are adequate to provide accurate calculations of this effect. The forward-peaked nature of the muon decay field should minimize the lateral extent of the shielding necessary. The production of induced radioactivity in these stages is also severely limited by the energy, and the fact that leptons are the only particles present. At the higher energy stages, the scale of the muon shielding required will increase, but even the final muon energy is still relatively low since the mean range of a 50 GeV muon in soil is only about 109 m. Likewise the size and importance of the electromagnetic cascades produced by the decay electrons will grow as the energy increases. Radioactivation could be expected, but at levels much smaller than those to be experienced in the Proton Driver and Target Station.

13.6.3 Muon Storage Ring

13.6.3.1 Control of Radiation Dose Due to Neutrinos

The most unusual radiation consideration pertaining to the Muon Storage Ring is that due to the neutrinos produced by the decaying muons. Obviously, the design of the entire facility is optimized toward the production of a high fluence of neutrinos in the intended direction downward (westward). This also results, unavoidably, in a similar stream of neutrinos in the upward direction. The methods for calculating radiation dose equivalent from the neutrino fluence have been described elsewhere[9],[10]. The Department of Energy has specified annual limits on the radiation dose equivalent that can be received by occupational workers and members of the public [11]. These limits rather clearly refer to the dose equivalent that could plausibly be delivered to actual people. For individual members of the public, the limit in DOE Order 5400.5 is 100 mrem (1 mSv) in a year, not including man-made, medical, or enhanced natural radioactivity. Special reporting requirements apply when the annual dose equivalent received by an individual

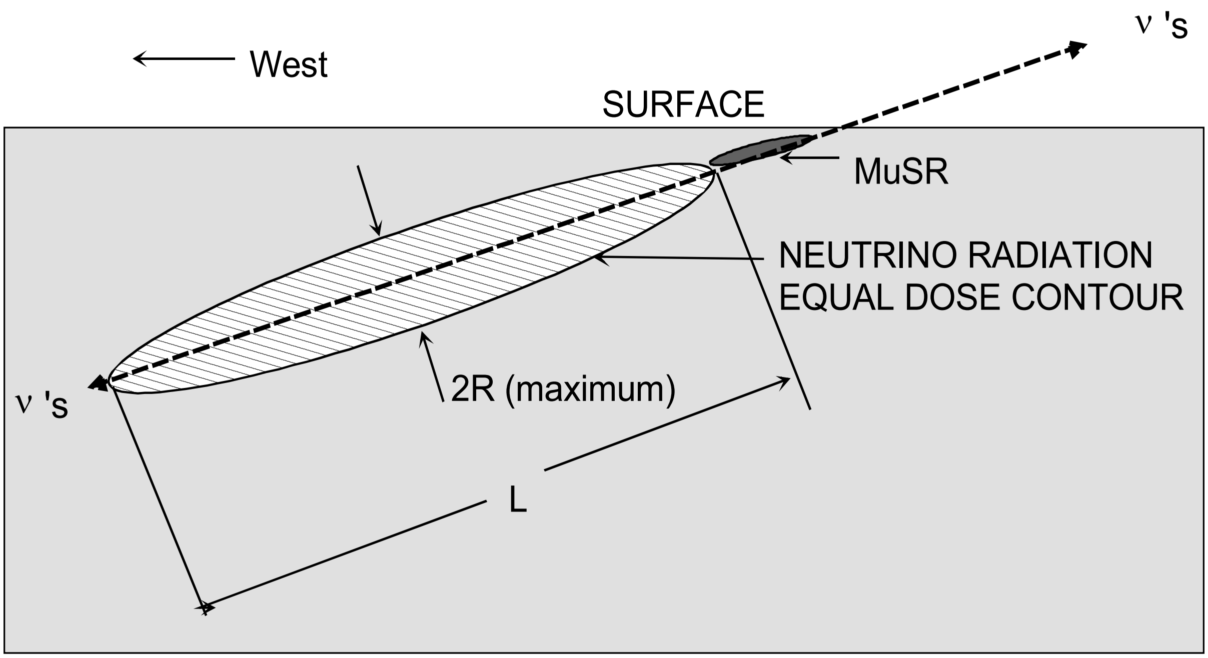

Figure 13.2: Schematic representation of the neutrino radiation fields due to muon decays in the MuSR. The gray region is the earth while the cross-hatched region is a schematic representation of the region inside of a selected contour of equal dose equivalent due to the neutrinos resulting from downward muon decays. A similar neutrino radiation lobe is to be found in the upward direction due to upward muon decays in the other straight section of the ring. The parameter L describes the intersection of this isodose contour with the centerline of the neutrino beam trajectory, while R is its maximum radial extent. The actual contours are more forward-peaked, and narrower than this symbolic ellipse. Symmetry about the centerline of the neutrino trajectories is expected.

exceeds 10 mrem (0.1 mSv) in a year. For comparison, the average annual radiation dose equivalent received by individuals living in the United States from natural sources of radiation, including exposure to radon indoors, is about 300 mrem (3000 μSv) [12]. Figure 13.2 schematically shows the "lobe" of neutrino radiation due to neutrinos produced by muon decays in the downward (westward) production straight section of the MuSR. The parameters L and R describe the length and maximum radius of a chosen contour of equal annual dose equivalent. L is measured from the end of the MuSR straight section along the centerline of the neutrino trajectory, while R is measured perpendicular to the neutrino trajectory. Cylindrical symmetry should hold about this axis for this radiation field. Due the extreme forward peaking, the dose equivalent at the surface due to these neutrinos is zero. A similar radiation field will penetrate the surface due to muon decays in the upward (eastward) return straight section of the MuSR centered about the axis of the return straight section. Mokhov has calculated these radiation fields and has plotted the results for two different contours of annual dose equivalent, 1 mSv (100 mrem) and 0.1 mSv (10 mrem) [13]. As stated in Section 13.6.1.1 and as applied to BNL, to meet the off-site radiation requirement of 5 mrem/yr due to neutrino-induced radiation, a plane extending 30 m from the outside of the arc tunnel enclosure, within a band ± 10 cm from the orbit plane, must be kept on-site (see Fig. 13.1). In addition, an ellipsoid of 2 m half-width, 1300 m long, the long axis extending in the direction of the production straight, must be kept within the site. In that regard, because the eastern site boundary is 2200 m away, the required distance of 1300 m to the east of the proposed location for the storage ring is well within the BNL site boundary. At the BNL site boundary the trajectory of the neutrino cone puts it at an elevation of 335 m. It can reasonably be assumed that a high-rise building that large will not be built, and no occupancy will occur in that aperture.

13.6.3.2 Other Radiation Sources

The bombardment of the walls of the MuSR components will involve a nearly uniform irradiation by electrons. Calculations of both the energy deposition in the superconducting magnets and the induced radioactivity due to these electromagnetic cascades were performed by Mokhov [14]. Residual dose equivalent rates due to these cascades will be small, less than about 1 mrem h^{-1} ($10\,\mu$Sv h^{-1}) after a 30 day irradiation and a 1 day cooldown. It is conceivable for the muons stored in the MuSR to be catastrophically lost in the event of a sudden power outage or some other failure of the magnets. However, given the orbit time of 6 μs, and the likely inductive time constants of the magnets, the loss of the muons during such an event would be distributed over many turns and large portions of the ring. Only a tiny fraction of them would be directed in a manner such that they penetrate the surface. Further calculations should be made to demonstrate this. It is certain that the near detector halls will be exclusion areas during operations due to neutrinos as well as the other background sources that are unavoidably present.

13.7 Non Radiological Environmental Protection Issues During Operation

13.7.1 Proton Driver, Target Station, Cooling Region, and Muon Acceleration Linacs

The issues are straightforward ones related to the control of non-radioactive wastes. Efforts should be made to prevent the creation of regulated mixed or hazardous wastes and to control environmental spills. Surface-water discharges should be managed in accordance with current Laboratory policies and any New York State SPDES permits already in place. In general, management of regulated materials will be via the ISO 14001 EMS.

13.7.2 Muon Storage Ring

The location of the MuSR over a Sole Source Aquifer demands especially stringent protection against spills. Careful attention to these problems and employment of EMS elements during the design and construction phases, should lead to their successful solution.

13.8 Summary

The Neutrino Factory provides a number of challenges in the area of environment, safety, and health. Many of these have been encountered, and effectively addressed, at BNL and other accelerator laboratories. Some of the problems are common to technological advancements in other accelerators worldwide. For these, collaborative efforts should continue to develop and improve the solutions that are needed. This project raises a few new issues that must be addressed. Continued attention to these issues is anticipated as the project proceeds.

13.8. Summary

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