1. INTRODUCTION

This report contains a description of the design of the technical components of the Neutrino at Main Inject (NuMI) project at Fermilab as well as a summary of radiation safety considerations. The technical baselines for the NuMI Project have already been established and can be found in the NuMI Facility Technical Design Report, issued in October 1998. The NuMI Project was baselined in November 1998. In October 2001, revised cost and schedule of the NuMI Project were submitted as NuMI Baseline Change Proposal. This baseline Change Proposal was approved in January 2002. This report updates and expands upon the scope and the design of technical components in the NuMI Facility after the Baseline Change Proposal.

The NuMI Facility Project produces an intense beam of neutrinos to enable a new generation of experiments whose primary scientific goal is to definitively detect and study neutrino oscillations. The beam is of sufficient intensity and energy so that experiments capable of identifying muon neutrino (ν_μ) to tau neutrino (ν_τ) oscillations, as well as other possibilities, are feasible. Although not a primary goal, the intense NuMI beam could also support a strong program of neutrino scattering physics of interest to both the Elementary Particle Physics and Nuclear Physics communities.

The first step in the production of the NuMI neutrino beam is to direct a beam of protons from Fermilab's Main Injector onto a production target. Interactions of the proton beam in the target produce mesons, which are focused toward the beam axis by two magnetic horns. The mesons then decay into muons and neutrinos during their flight through a long decay tunnel. A hadron absorber downstream of the decay tunnel removes the remaining protons and mesons from the beam. The muons are absorbed by the subsequent earth shield, while the neutrinos continue through it to a "near" detector (in a new experimental hall at Fermilab) and beyond, to the "far" detector in Soudan, Minnesota. The Fermilab and Soudan experimental halls house massive detectors specially designed to detect the small fraction of the NuMI beam neutrinos that interact in them. This experiment is called MINOS (Main Injector Neutrino Oscillation Search).

The NuMI Facility includes the underground enclosures (tunnels and halls) as well as two service buildings located on the surface. The NuMI beamline and experimental facility at Fermilab are fully described in the NuMI Facility Technical Design Report. The layout of the NuMI Facility underground enclosures is illustrated in **Figure 1-1.** An aerial photograph of the

Fermilab site with the beamline superimposed is shown in **Figure 1-2** and the trajectory of the neutrino beam between Fermilab and Soudan is shown in **Figure 1-3**.

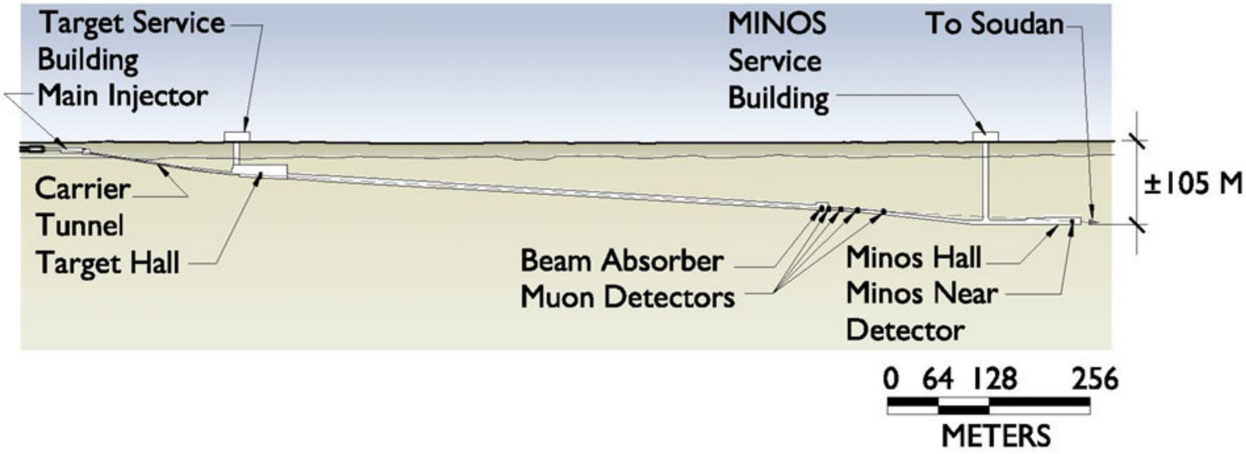

Figure 1-1 Layout of the NuMI Facility.

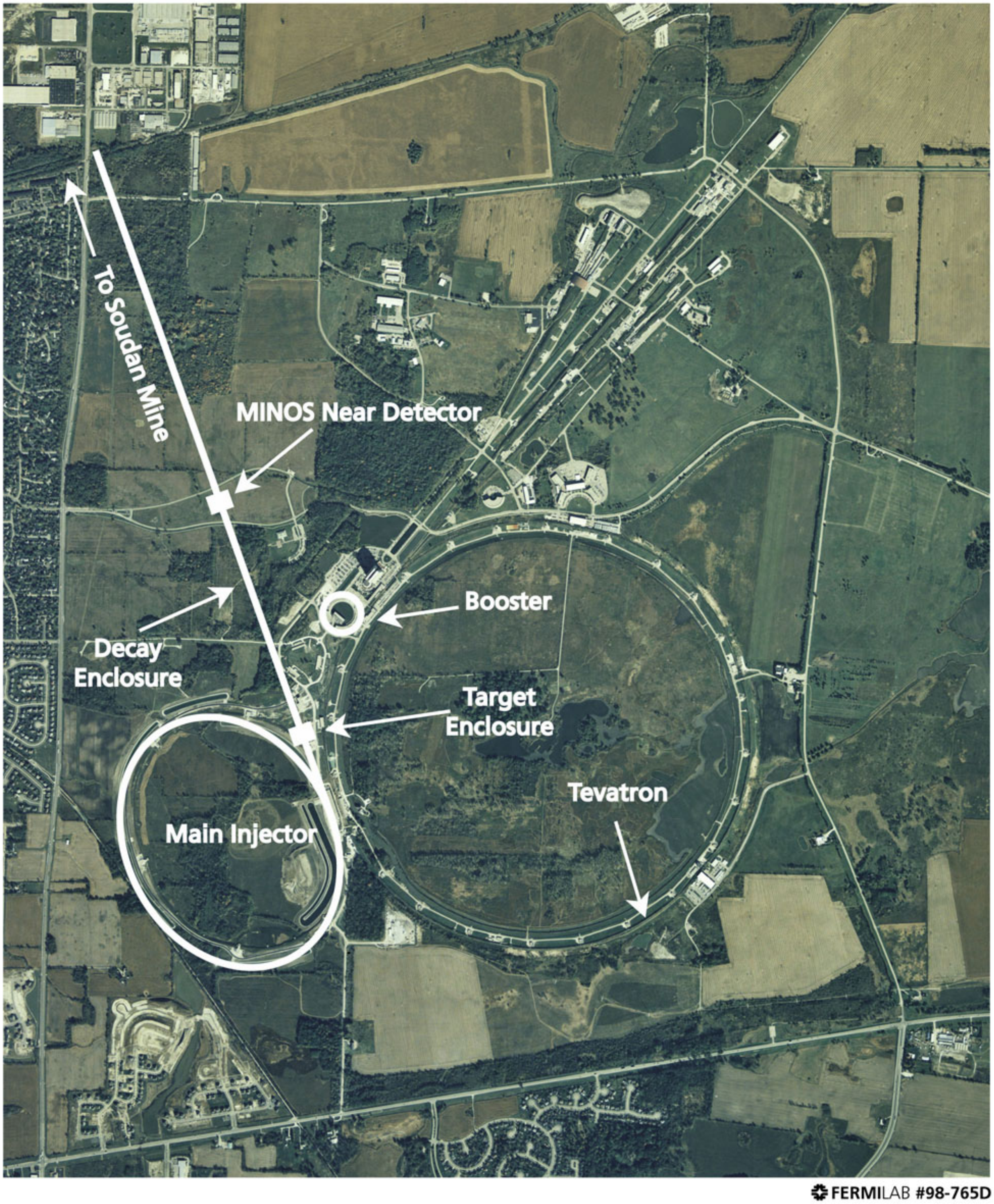

Figure 1-2 Aerial view of the Fermilab site and the NuMI beamline.

Figure 1-3 Trajectory of the neutrino beam between Fermilab and Soudan, Minnesota.

1.1 Scope and parameters

The scope of the NuMI Technical Components is laid out in **Table 1-1** and described in more detail in Chapter 2. Key parameters of the beamline are listed in **Table 1-2.**

Subsystem	Description
Primary Beam	Extraction and transport of 120 GeV proton beam from the Main Injector to the NuMI Target
Neutrino Beam Devices	Production and focusing the secondary beam from the NuMI target through the focusing horns
Power Supply Systems	Power supplies, cables and connections for NuMI beamline elements
Decay Region & Hadron Absorber	Decay pipe for neutrino-producing decays of mesons, absorber for non-decaying particles, and associated radiation shielding
Neutrino Beam Monitoring	Measurement of flux and profiles of secondary beam and muons
Survey, Alignment & Geodesy	Accurate determination of the neutrino beam centerline at Fermilab and Soudan. Accurate positioning of the neutrino beamline elements
Beamline Utilities	Water, vacuum and gas
Controls, Cables & Interlocks	Controls systems, cable specifications and installation, interlocks methodology and locations

Table 1-1 Technical components of the NuMI beamline

Downward slope of ν beam		58 mr (3.3°)
Proton intensity		2.5×10^{13} p/1.9 sec
Spill length		8 μsec
Protons on target per year		2.5×10^{20}
Target material		Graphite
Pion focusing		Wide band, 2 horn
Neutrino Energy Options		
Baseline	Low Energy	1 - 3 GeV
Option 1	Medium energy	3 - 8 GeV
Option 2	High energy	8 -16 GeV
Decay pipe		1 m radius × 675 m long
Downstream hadron monitoring		Ion chambers upstream of absorber
Muon absorber		240 m of dolomite
Muon monitoring		Ion chambers in absorber enclosure and alcoves in the dolomite shield

Table 1-2 Parameters for the NuMI beamline

1.2 Performance and Operational Goals

The Main Injector is a very high intensity proton accelerator that can provide an adequate neutrino event rate even in a detector 735 km away. Furthermore, the anticipated mode of operation of the Main Injector during the next decade is well suited to the NuMI Project. The accelerator must operate a significant fraction of the time to produce antiprotons for $\overline{p}-p$ collisions in the Tevatron. However, only one of six bunches are to be used for antiproton production, the other five being available for stationary target experiments such as MINOS. Furthermore, the Main Injector has adequate design margin and scope for upgrades in key subsystems so there is a good possibility that its intensity will increase with time and thus experiments with higher statistics and better sensitivity will be possible in the future.

The production of the neutrino beam occurs in two stages. First the 120 GeV proton beam from the Main Injector is directed by single-turn extraction into the NuMI beamline. In the NuMI beamline, the protons are focused onto a segmented target, producing secondary mesons, both pions and kaons. Because the neutrino beam must be aimed at the Soudan Underground Laboratory, the proton beam is directed downward at 58 mrad before it strikes the target. Subsequently, forward-going particles (mesons) in the energy range of interest are focused and allowed to decay, producing neutrinos. The focusing is performed by a set of two magnetic horns. These devices are shaped in such a way that, when a pulse of current passes through them, a magnetic field is generated which focuses particles in the desired momentum range over a wide range of production angles. The average meson energy is selected by adjusting the locations of the second horn and target with respect to the first horn. Thus, this “zoom” beam optics design allows the energy of the meson beam (and therefore of the neutrino beam) to be varied during the course of the experiment.

The particles selected by the focusing horns (mainly pions with a small component of kaons and uninteracting protons) are then allowed to propagate down an evacuated beam pipe (decay tunnel) 1 m in radius and 675 m long, placed in a tunnel, pointing downward towards Soudan. While traversing the beam pipe, a fraction of mesons decay, yielding forward-going neutrinos. By adjusting the energy of the parent meson beam, a neutrino beam in the desired energy range can be obtained. As mentioned above, this feature is crucial to our ability to experimentally explore a wide range of possible oscillation parameters and to minimize the errors associated with these measurements. A hadron absorber is placed at the end of the decay pipe to remove the residual flux of protons and mesons, followed by a set of beam monitoring detectors.

The neutrino beam line has the following design objectives:

- Potentially cover the energy range 1 to 20 GeV. This is accomplished by a hadron focusing system that can be optimized to 1-3 GeV, 3-8 GeV or 8-20 GeV in neutrino energy.
- Predict the neutrino energy spectrum in the MINOS far detector to 2 or 3%, if neutrino oscillations are absent, given a measurement of the spectrum at the MINOS near detector.
- Center the neutrino beam at the detectors and to keep the effect of mis-steering to less than 2% anywhere in the neutrino spectrum.
- Long term reliability, stability and reparability such that the facility is usable for a minimum of 10 years while assuring personnel safety and allowing for future modifications and upgrades.

The integrated technical goals of the NuMI facility and MINOS experiment are listed in Table 1-3 and 1-4. The commissioning goals are the parameter values that must be achieved for approval to start operations (Critical Decision 4) and are given in Table 1-3. The operational goals, which are needed for the NuMI project to accomplish its scientific objectives, are expected to be reached after several years of operation and are given in Table 1-4. Although the NuMI Project will have sensitivity to a wide range of parameter space to search for neutrino oscillations, recent scientific results from Japan strongly indicate the most promising area to search within this parameter space. Thus the project begins in its “Low Energy” beam configuration. The commissioning goals are to be met with cosmic rays and atmospheric neutrinos to demonstrate the effectiveness of the far neutrino detector. Measurements made with the beamline monitoring instrumentation assure that the neutrino beam is aimed correctly at the MINOS far detector.

Parameter	Measurement	Commissioning Goal
Cosmic ray muons detected in the MINOS Near Detector	Near Detector data read out through DAQ system	Majority of the 153 Near Detector planes sensitive to muons
Cosmic ray muons detected in each of the two MINOS Far Detector Super Modules	Far Detector data read out through DAQ system	Majority of the 484 planes of the Far Detector sensitive to muons. Atmospheric neutrinos detected in the Far Detector.
Proton intensity in target hall	Toroid (or equivalent) beam intensity monitor at entrance to the Target Hall	Greater than $1\mathrm{x}10^{12}$ 120 GeV protons/spill
Beam alignment	Transverse distributions of the proton beam and secondary beam.	Proton direction established to within 1 mr of the known direction to Soudan.
Near detector neutrino flux	Charged current event rate in 15 ton fiducial region	Observe neutrinos in the Near Detector produced by the NuMI beam

Table 1-3 NuMI Technical Commissioning Goals

Parameter	Measurement	Operational Goal
Proton intensity in target hall	Toroid (or equivalent) beam intensity monitor at entrance to the Target Hall	2.5 x10^{13}/spill 2.5 x10^{20}/year
Beam alignment	Transverse distributions of the proton beam and secondary beam	Neutrino Beam centered at Soudan to +/-0.2mr
Near detector neutrino flux	Charged current event rate in 15 ton fiducial region	1.2x10^{-14} events/proton
Far detector neutrino flux*	Charged current event rate	4x10^{-18} events/proton
Muon momentum resolution +	Curvature vs. range in magnetic overlap region	14%
Hadron energy resolution +	Test beam	$\Delta E/E = 70\%/E^{1/2} + 8\%$
Detection efficiency for charged current events +	Event length distribution	90% with <4% neutral current contamination

*Assuming 50% reduction from neutrino oscillations

+Applies to both near and far detectors

Table 1-4 NuMI Operational Technical Goals

1.3 Organization of This Report

This report is organized into five chapters with several appendices. Chapter 1 is the Introduction. Chapter 2 is the overview description of the NuMI beamline including neutrino beam fundamentals, neutrino oscillation experiments, and conceptual design of neutrino beam. Chapter 3 summarizes the design parameters of the NuMI beam as well as the design drivers and basis. Chapter 4 contains a description of the technical component subsystems as well as design specifications. Discussion and descriptions of the technical component subsystems are organized to follow the Work Breakdown Structure (WBS) of the project. Chapter 5 summarizes the radiation safety.

WBS Organization

Chapter 4 is organized according to the Work Breakdown Structure (WBS) that has been adopted for the NuMI Project. All technical components are contained in WBS category 1.1. The third digit of the WBS describes the component type. and serve to number the sections of chapter 4.