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CONSTRUCTION OF THE NUMI UNDERGROUND LABORATORY FACILITIES

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ABSTRACT

At Fermilab, a 4000-ft long underground complex has recently been constructed for a high-energy physics experiment. The complex is sited up to 350 ft, below grade principally in bedrock. The rock excavations were mined by TBM and drill and blast methods and supported by a combination of rock bolts, dowels and shotcrete. Water control was achieved using a combination of pre- and post-excavation grouting, drainage systems, drip shielding and air desiccation measures.

INTRODUCTION

At Fermi National Accelerator Laboratory (Fermilab), located in Batavia, Illinois, a 4,000-foot long underground complex has been constructed on a decline varying from six to sixteen percent. The underground complex houses the technical components that will be used to generate a beam of neutrino particles for an experiment scheduled to begin in 2005. The neutrino beam will be aligned to intersect two detectors, one located on the Fermilab site and one located 430 miles away, at the base of the Soudan Iron Mine, in northern Minnesota. The beam components, detectors and their associated underground housings form the US Department of Energy's NuMI-MINOS (Neutrinos at Main Injector-Minnesota Illinois Neutrino Oscillation Search) Project.

At Fermilab, the underground facilities are sited close to operating high-energy particle accelerators. During construction, care was exercised to ensure that there was no disruption to the on-going accelerator operations. The neutrino beam line requirements were met without the use of cast-in-place linings in the rock tunnel sections and caverns. A combination of rock bolts, dowels and shotcrete provided permanent rock support in all excavated structures. Permanent water control was achieved using a combination of pre- and post-excavation grouting, drainage systems, drip shielding and air desiccation measures.

The creation of these underground laboratory facilities presented the design and construction team with a variety of challenges, including the satisfaction of strict alignment, stability, water control and radiation shielding criteria.

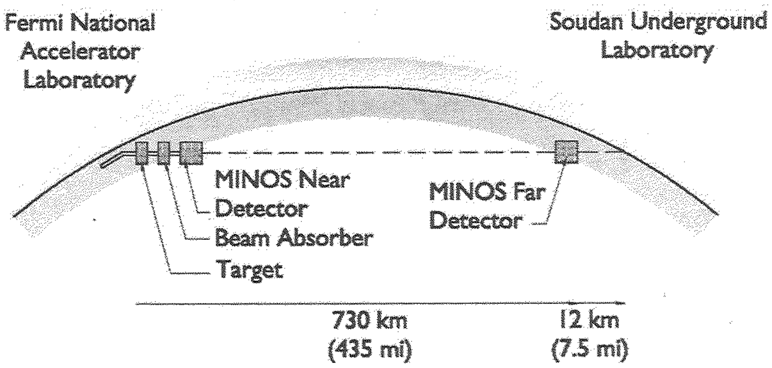


Figure 1. **Schematic of the NuMI-MINOS experimental facilities**

OVERVIEW OF THE NEUTRINO EXPERIMENT

The NuMI-MINOS Project is one of a number of neutrino experiments currently being built worldwide to investigate the properties and behavior of the neutrino. The neutrino is a small, elemental particle that was descriptively named by Enrico Fermi as the little neutral one ("neutrino"). Owing largely to its size and electrical neutrality, the neutrino has historically proven difficult to study. However, the advent of new, more powerful and prolific accelerators such as Fermilab's Main Injector provides the physicists with a new facility that will have the dense flux of neutrinos needed to conduct frontier research in the United States.

For the NuMI-MINOS Project, the neutrino beam generated at Fermilab will be monitored by two detectors; one located on the Fermilab site and the other located at the Soudan Underground Laboratory, in northern Minnesota. Between the two detectors, the neutrino beam will pass through the earth's crust at depths of over 10 km (Figure 1). Being so small and electrically neutral, neutrinos can pass through the earth without any significant loss in beam flux or intensity.

It is anticipated that the research from this experiment will have profound ramifications for the worldwide high-energy physics community and could help resolve some key issues related to the "Standard Model," the cornerstone of modern physics theory.

Soudan Mine Site

The far detector is currently being assembled in a 50-foot wide chamber, which lies at a depth of over two thousand feet, at the base of an existing mine shaft (Figure 2). The shaft is maintained to provide access to the Soudan Iron Ore Mine Park facility, located in Tower, Minnesota. This "park" is maintained by the Minnesota Department of Natural Resources. This chamber is the twin of an existing chamber that was excavated in the same greenstone rock mass in the early 1980s. Both detector chambers were designed as bolted and shotcreted openings.

Fermi National Accelerator Laboratory (Fermilab) Site

At Fermilab, the beamline components and near detector are to be housed in a series of tunnels and chambers, collectively referred to as Neutrinos at Main Injector (NuMI). This underground complex is sited in the glacial tills and bedrock, typical of the Chicagoland region.

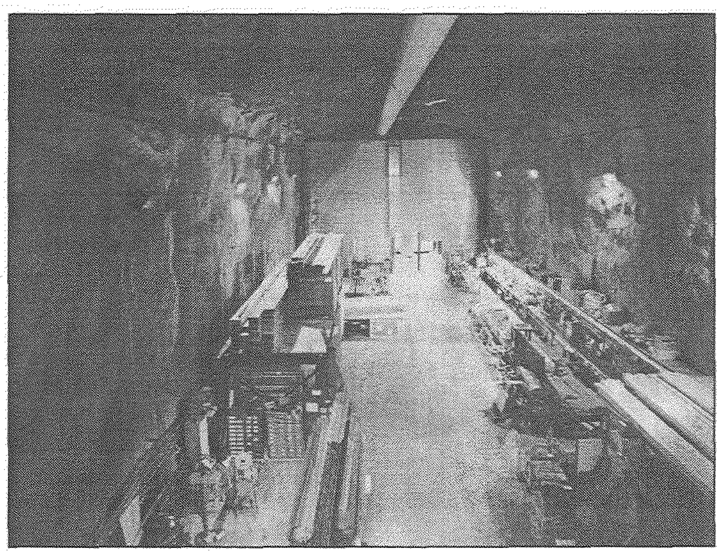


Figure 2. The Soudan 2 mine chamber with the detector in the background

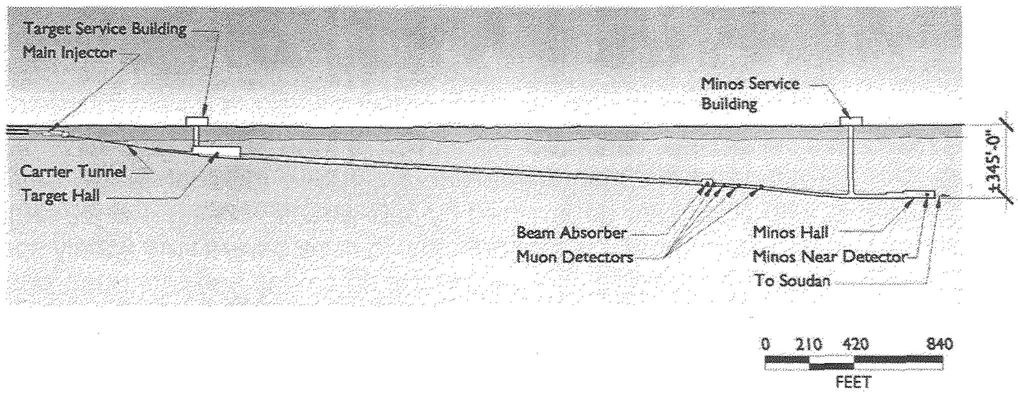


Figure 3. Longitudinal profile of the NuMI underground facilities

The complex is laid-out to allow for the transportation, installation, and maintenance of the laboratory components needed to create and study the beam of neutrinos. The facilities also provide for the safe refuge and emergency egress of underground personnel and for radiation protection of the groundwater in the surrounding rock mass.

The alignment allows for a proton beam transfer from the Main Injector to the "Target," housed at a depth of some 120 feet below ground level. The neutrinos are created by the decay of a proton beam products in the section of tunnel downstream of the Target Hall, the Decay Tunnel, located between the Target and Beam Absorber Halls or caverns. Upstream of the Target Hall, the charged protons can be guided within a magnetic field and the beam elements were aligned to allow for a rapid decline into bedrock and the Target Hall, excavated as a low cover chamber rather than a deep cut-and-cover structure, as originally planned. The neutrinos created by the facility cannot be guided and precise alignment of the proton beam impinging on the "Target" need to be correctly aligned to intersect the detector in northern Minnesota.

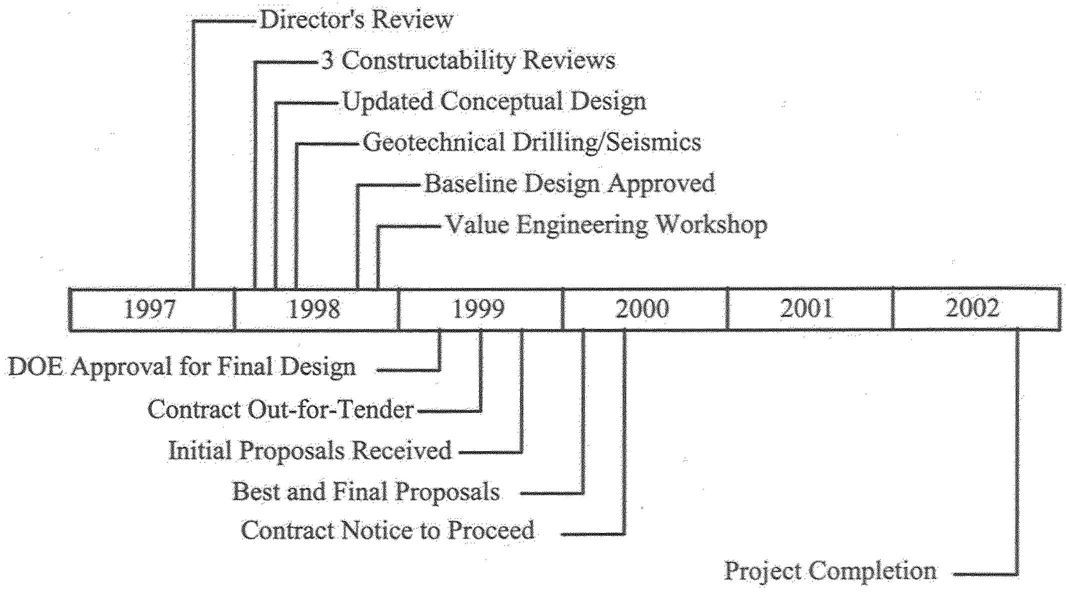


Figure 4. Timeline of the NuMI underground design process

ROCK MASS CONDITIONS AT THE FERMILAB SITE

Three main sedimentary rock units were identified for design purposes; they were dolomites (Silurian), siltstones (Brainard Formation of the Maquoketa Group) and shales (Scales Formation of the Maquoketa Group). These rocks units are basically blocky to massive, with block size determined by sub-vertical, orthogonal jointing and sub-horizontal bedding. In general, the two principal joint sets were very widely spaced (10 to 100 ft spacing), while bedding thickness in the dolomites and siltstones was thin to thickly bedded (0.3 to 3 ft). In the more argillaceous materials, notably the Scales shale, jointing and bedding were not always readily discernible and the shales would have been perhaps more appropriately described locally as a mudstone or claystone as it exhibits little or none of the fissile characteristics associated with shale materials.

Pattern bolts and dowels were used to mitigate these blocky conditions. In the lower Maquoketa unit (Scales), where slaking and swelling was a concern, the timely placement of shotcrete was added as a design requirement.

The rock excavations are largely sited within the upper bedrock aquifer. However, the deeper portions of the excavations, principally from the base of the MINOS shaft to the MINOS Hall are sited in an aquitard, the Scales Formation.

DESIGN OF THE FERMILAB UNDERGROUND FACILITIES

As with many physics experiments, the NuMI-MINOS Project has taken over a decade to become a reality. Initial speculation on the viability and physics merits of such a project began in the late 1980s. In the early 1990s, a series of engineering studies and reports were generated, and culminated in a conceptual design review in late 1997. The final design commenced, after the neutrino experiment was approved by the Department of Energy. From this point, it took some eighteen months to complete the design and tender for proposal. A "design timeline" from late 1997 through 2002 is shown in Figure 4.

The design process followed the recommendations of the International Tunnelling Association. Early emphasis was placed on defining the end-user's space, excavation stability and dryness requirements (Bruen et al., 2000). Once these requirements had been established, existing geotechnical information was reviewed and additional, alignment-specific site investigations were performed. Special design provisions were needed to ensure a dry environment in the absence of cast-in-place tunnel linings in the rock tunnels. Cast-in-place linings had been eliminated during the concept design phase, as they were unnecessary to ensure the long-term stability of the openings. Typical to most of the excavations was the installation of a thin shotcrete lining. Water control provisions included pre- and post-excavation grouting, drainage sheeting, metal roofing over sensitive experimental equipment, and the use of dry ventilation air (below 10% relative humidity).

In the Decay Tunnel, special design provisions were made to maintain a minimum level of residual water inflow. In this region of the excavations, there was a concern that slow-moving groundwater would become slightly radioactive during the experiment operation. Accordingly, a full peripheral geotextile drainage sheeting will be required to control and direct groundwater infiltration.

At the beginning of the final design, constructability meetings were held with active underground contractors (Frontier Kemper, Kenny Construction and J.F.Shea). All three contractors provided valuable input on underground layout and methods and means selection. Later in the design process, after a comprehensive cost estimate had been developed, a Value Engineering (VE) Workshop was held. At this workshop, an outside engineering agency (USACE) was invited to brainstorm and formulate alternate engineering solutions to various aspects of the project. Alternate solutions or proposals identified at the workshop were roughly scoped and their costs estimated and presented to NuMI management for approval or rejection. Minutes from the constructability meetings and VE Workshop were made available to proposing contractors during the tender period.

CONSTRUCTION OF THE UNDERGROUND NEUTRINO BEAM FACILITY

General

Although the excavation scope of the NuMI underground facility was small, involving less than a mile of tunnel and approximately one hundred thousand cubic yards of soil and rock material, the contractor, S.A. Healy, encountered a variety of ground materials (soils, dolomite, siltstone and shale) and needed to employ a variety of mining means and methods to excavate a wide range of tunnel cross-sections, a number of short length drifts, and caverns.

Shaft and Tunnel Construction in the Glacial Soils

In the glacial soils the contractor used mechanical equipment to excavate and a combination of steel arching, shotcrete and lagging to support the excavation. In the Carrier Tunnel, that connected the existing Main Injector and Target Hall facilities, air spades and a "Bobcat" were used to excavate an eight-foot horseshoe tunnel approximately 260 ft through soils. Prior to mining through the saturated section of glacial till just above bedrock, the contractor dewatered the area by drilling probe holes upward from the excavated rock tunnel section of the alignment. During dewatering, the water table and surface elevations were carefully monitored to ensure that the adjacent accelerator structures were not impacted by any consolidation settlement. The soils at this location were primarily overconsolidated and no noticeable settlement was recorded.

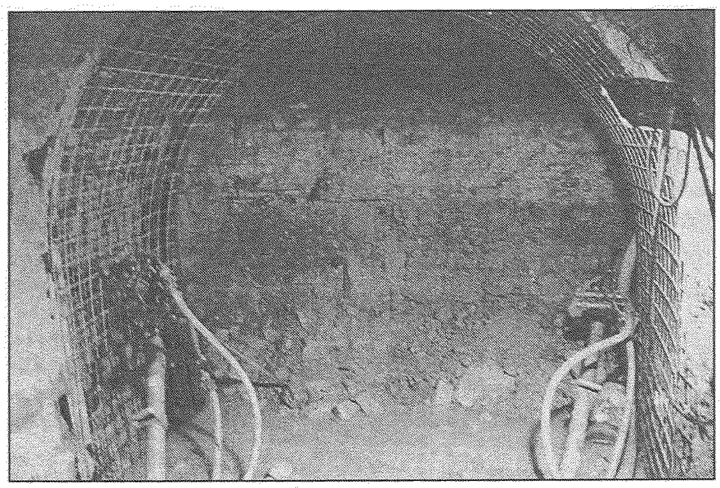


Figure 5. Carrier tunnel excavation of the mixed-face

In the soil and mixed face portions of the Carrier Tunnel the contractor selected a temporary ground support system consisting of steel arches, wire mesh and shotcrete. Steel ribs and reinforced shotcrete were placed every four feet as the heading advanced. Only a small depth of weathering was observed in to the underlying bedrock. Blasting was typically required to excavate the rock section of the mixed face—blast-holes are visible in the Figure 5.

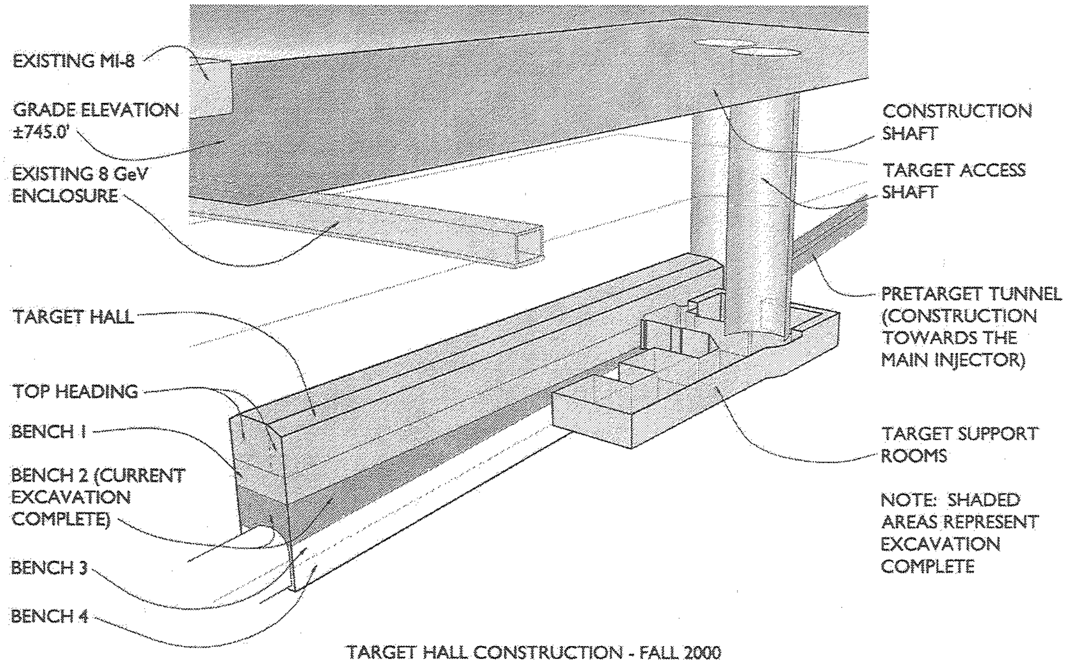
Construction of the Target Hall Complex In Dolomite

The underground openings designed to house the "Target" facilities underlie beamline housings that are essential to the operation of Fermilab's existing accelerators. The housed equipment, allows for the acceleration and sustained orbiting of subatomic particles to follow micron-aligned trajectories. Not surprisingly this equipment is highly sensitive to any differential floor displacements or ground vibration. The "8 GeV" particle beamline is located within about 60 ft of the crown of the Target Hall excavation and at this location, the designer and contractor paid close attention to the movement of the ground mass and housings using extensometers and tilt-beam sensors. Accelerometers were used to measure the blast vibration parameters.

Although a large number of blasts for the excavation of the shafts, tunnels and hall were executed in close proximity to the 8 GeV accelerator structure, the peak particle velocity (ppv) were typically well below one inch per second and there were no interruptions to the accelerators. Extensometers recorded Target Hall crown movements as the top heading pilot drift came into and under the instrument locations. The magnitude of the rock displacement was as anticipated (Thapa et al., 2001.

Construction of the Decay and Absorber Tunnels in Dolomite, Siltstones and Shales

During the early stages of construction, the contractor submitted a value engineering proposal to excavate the Decay Tunnel and Absorber Access Tunnel to the MINOS Shaft, approximately 2900 lineal feet using a 21´-6˝ diameter hard rock TBM rather than the contract required conventional drill and blast excavation method (Figure 7). This scheme would necessitate an initial drive with the TBM on a 6% decline through dolomite and siltstone, followed by a second pass drill and blast operation to enlarge the Decay Tunnel for the walkway and complete the lower section



TARGET HALL CONSTRUCTION - FALL 2000

Figure 6. 3-D layout of the target hall complex and overlying accelerator structure

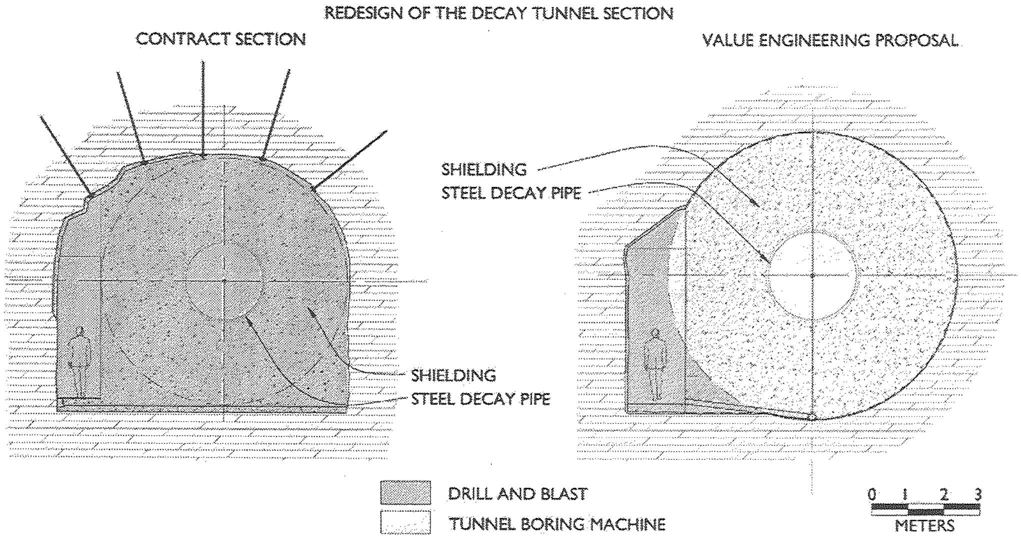


Figure 7. Decay tunnel section value engineering change

of the tunnel to the Absorber Hall. With the TBM method, a tunnel segment was added (250 L.F.) to provide a transition to the Absorber Access Tunnel and completion of the TBM drive. The Absorber Access Tunnel was excavated on a 10% decline through siltstone and shale.

A combination of rock dowels, tensar fabric, steel channels and interlocking wire mesh provided rock support in the TBM excavation. In the Absorber Access Tunnel, the siltstone and shale were covered and protected by a shotcrete lining.

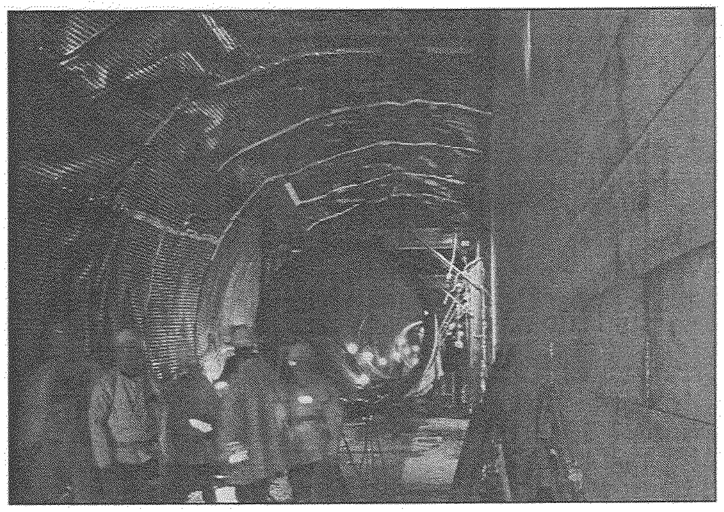


Figure 8. Decay Tunnel drainage membrane and decay pipe

The Decay Tunnel houses a 6-ft diameter vacuum pipe through which the beamline will pass, encased in 3.3 ft to 7.1 ft thick controlled low strength cementitious material for shielding, to contain radiation emitted during the decay of the beam particles. In addition, a continuous, full-peripheral dimpled drainage liner/membrane was installed between the shielding fill and rock to control groundwater infiltration and prevent contamination (Figure 8).

The 2252-ft long vacuum pipe was installed within required tolerances of ±0.75-inch. Once secured, the pipe was embedded within approximately 25,000 cy of the low strength shielding material.

CONSTRUCTION OF THE NEAR DETECTOR HALL IN SHALES

The MINOS Hall underground opening will house the near detector. The 28 ft wide and 150-ft long cavern was constructed using a combination of excavation methods, drill and blast excavation of the top heading, TBM mining, and drill and blast excavation to slash out the side walls to its full width. Rock support in the shale consisted of rock bolts and shotcrete. Both rock support elements were installed immediately after each blast round in the crown and walls.

Close attention was paid to movements of the rock mass constructed in shale. Extensometers installed in the crown indicated that rock movements were within acceptable limits predicted in model studies and the stable conditions were achieved.

Although the shale was dry material, a drip ceiling of metal corrugated roofing was installed in that portion of the cavern where the near detector would be installed.

CONCLUSION

The tunneling contract was completed in November 2002 and work has now commenced on the underground installation of the electrical and mechanical systems and the construction of shaft head-houses. The contractor mined through various soil and rock materials using a variety of excavation and support techniques, and delivered a first-rate facility that will allow the United States to conduct experiments at the frontier of neutrino physics. The various excavations that comprise the NuMI facility will also serve as prototype structures for use in the

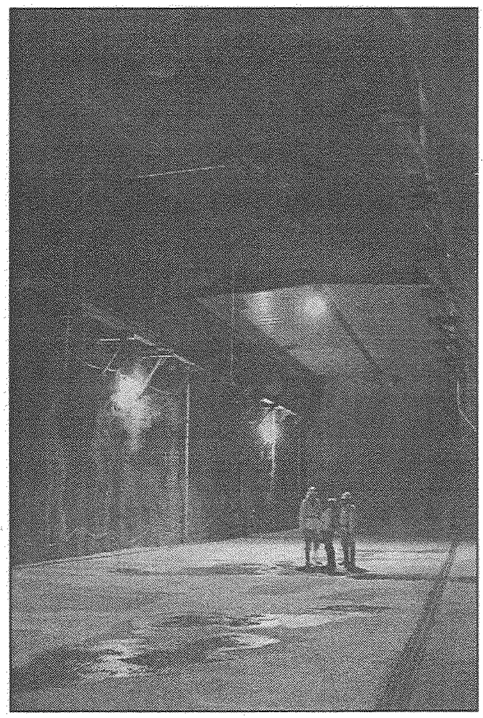


Figure 9. MINOS Hall shotcrete lining and drip ceiling.

development of other underground high-energy physics facilities that may be constructed in the United States in the near future.

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