Chapter 7

Far detector installation

7.1 Overview

This Chapter describes the installation of the MINOS far detector and its associated infrastructure in the new underground laboratory at Soudan. It includes the checkout and validation of completed sections of the detector and the transition to routine data acquisition operation. Much of the laboratory infrastructure needed for detector installation and operation has been designed as part of the MINOS cavern construction and outfitting tasks described in the MINOS Far Detector Laboratory Technical Design Report and Basis of Estimate documents[1, 2]. The transfer of control from the cavern construction and outfitting task to the far detector installation task will occur when beneficial occupancy of the new underground laboratory begins.

The detector installation procedures described in this Chapter were developed by MINOS Collaboration physicists and engineers during the preparation for the active detector technology choice, as described in the Report of the MINOS Installation Committee (MIC)[3]. Much of the material in this Chapter is described in more detail in the Basis of Estimate document for the far detector installation[4], which has evolved along with the MINOS detector design since it was started as part of the MIC process. The far detector installation task must be closely coordinated with the fabrication of detector components: the magnet steel and coils (Chapter 4), the scintillator detector (Chapter 5) and the electronics systems (Chapter 6). In general, the transfer of control from these tasks to the far detector installation task occurs when fabricated components arrive at the Soudan mine headframe.

An overview of the design of the far detector has already been given in Chapter 3 and the details of its construction have been discussed in the three Chapters preceeding this one. The main parameters of the detector, laboratory infrastructure and installation are summarized in Table 7.1.

7.1.1 Far detector facilities

The facilities required to install and operate the MINOS far detector consist of the underground laboratories (the MINOS and Soudan 2 caverns), the surface building and receiving areas, and the equipment needed to move, assemble and install detector components. In somewhat more detail, the following facilities are included:

System	Parameters
MINOS cavern	82.3 m $\times$ 13.8 m $\times$ 11.6 m (height)
Supermodules	2 supermodules, each 2.7 metric kt, 14.4 m long $\times$ 8 m wide
Planes/supermodule	243 steel planes and 242 scintillator planes (5.94 cm pitch)
Detector units/plane	192 scintillator strips packaged in 8 modules
Readout	2-ended, with 8 $\times$ multiplexing
Channel count	484 planes $\times$ 192 strips $\times$ 2 $\div$ 8 = 23,232 channels
Photodetectors	1452 16-channel PMTs in 484 MUX boxes
Installation rate	1 plane/1.85 shifts or 24 planes/month (maximum)
Installation time	12 months for first supermodule, 22.5 months for two
Magnetic field	1.5 T at 2 m radius in steel octagon planes
Magnet coils	15 kA-turns, water-cooled copper wire, 58 kW total
Total cavern cooling	257 kW maximum (at the end of the installation period)

Table 7.1: Summary of some of the major parameters of the far detector and its requirements on the infrastructure systems of the MINOS cavern in the Soudan mine.

- MINOS cavern infrastructure: utilities (electrical and lighting systems, magnet coil cooling system, compressed air, fire protection), environmental control equipment, large steel structures such as the detector support, overhead bridge crane, observation deck.
- Soudan 2 cavern facilities: counting house (upgraded for MINOS), elevated platform for scintillator testing and storage.
- Surface facilities: a new building, provided by the State of Minnesota, for receiving, materials staging, offices.
- Soudan mine hoisting facilities: shaft station and cages (upgraded for MINOS), and equipment for loading and unloading large components from the shaft cages.
- Equipment needed to assemble and install the far detector: fixtures, tooling and procedures for handling, assembling and testing the large planes of steel and scintillator.
- Associated work space, storage and office areas, and facilities for the workers who will assemble and install the far detector.

7.1.2 Soudan infrastructure

Most of the infrastructure needed to install and operate the MINOS far detector is provided as part of the cavern construction and outfitting task[1]. These systems (described in Section 7.3.2) include the underground cavern itself, the 25-ton overhead bridge crane and detector support structure, devices for handling the large steel plates of the MINOS magnet, electrical power and other utilities, most safety systems (summarized in Chapter 12) and the surface receiving building. Far detector safety systems, which are described in Reference [5], are very similar to those for the near detector[6]. Although some office facilities will be provided in the new MINOS cavern, most computers, terminals, office areas and lunchroom will be located in the existing Soudan 2 counting house. The existing lunchroom and sanitary facilities in the Soudan 2 cavern will be substantially expanded.

The electrical power required to operate the completed MINOS detector along with the other experiments located in the MINOS and Soudan 2 caverns will average about 250 kW, which is well within the capacity of the Soudan mine electrical system. About 25% of the total heat energy produced underground is from the MINOS magnet coils. The heat generated by this electrical power will be removed from the underground laboratories by a heat exchange system which will transfer the heat to an air-cooled water chiller located on the surface (see Section 7.4.1.6 below).

Most of the underground infrastructure requirements of the MINOS far detector are similar to those of a typical fixed target experiment at Fermilab. MINOS has modest requirements for electrical power, compressed air, air circulation and conditioning, counting house and computer facilities. MINOS requires only standard fire protection systems: smoke detectors, automatic electrical power cutoffs, and sprinkler systems. The surface infrastructure required for MINOS installation is very similar to common commercial facilities; it consists of standard office areas and an enclosed receiving area near the mine headframe.

Although nearly all infrastructure will be provided by other tasks, the far detector installation task includes responsibility for maintaining and operating these facilities. A small MINOS "startup" crew is already working with the architect engineering firm (CNA Consulting Engineers) on infrastructure design. The startup crew will also work with the excavation and outfitting contractors to ensure that all infrastructure systems are operating satisfactorily when beneficial occupancy occurs.

7.1.3 Detector assembly

The MINOS far detector installation task includes the procedures used to move steel and scintillator detector components into the underground laboratory, to assemble the 8-m wide octagonal planes of steel and scintillator at two workstations, and to install these planes on the rails of the hanging-file detector support structure. Detector assembly techniques will be optimized at Fermilab during the trial assembly of prototype planes (see Section 7.5.1). The far detector installation "startup" crew will participate in this activity, beginning about one year prior to beneficial occupancy of the MINOS cavern at Soudan.

The 82.3-m long by 13.8-m wide by 11.6-m high MINOS cavern is designed to accommodate two identical 2.7 kt "supermodules," two assembly workstations, and a 10-m long area reserved for a possible future detector at the upstream (south) end of the cavern. In addition, the cavern is long enough for a third 2.7 kt supermodule, but the upstream workstation would have to be removed to provide room to install it. (The third supermodule and upstream detector are not part of the baseline experiment design.) Figure 7.1 shows a plan view of the new MINOS cavern and the existing Soudan 2 laboratory. The workstations are located at the downstream (north) end of the MINOS cavern, where the cavern width is increased to 15.9 m. Figures 7.2 and 7.3 show elevation views of the MINOS cavern at the location of the detector supermodules and the workstations, respectively. Detector assembly begins with the upstream supermodule, which will be ready to operate when the NuMI

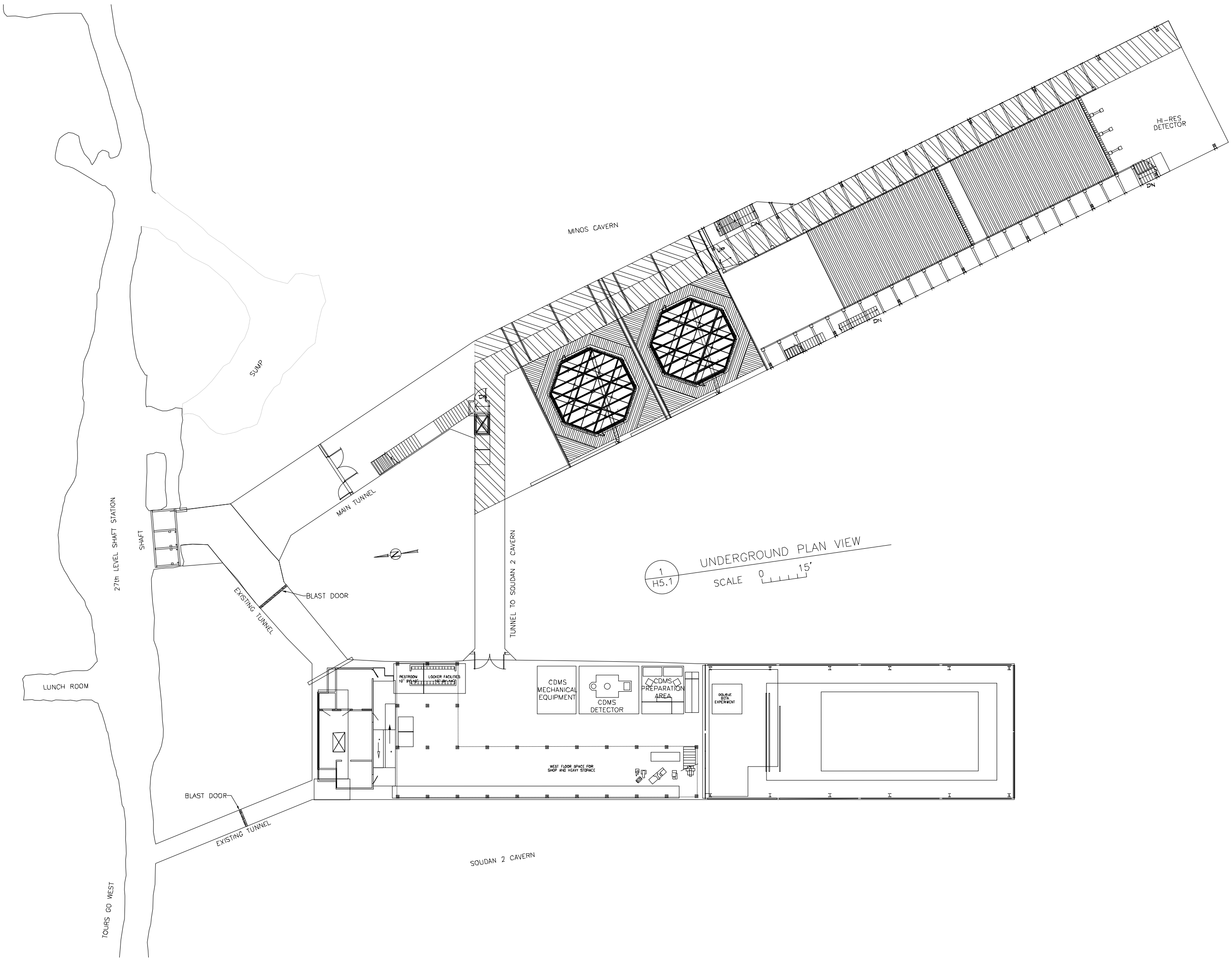

Figure 7.1: Plan view of the new MINOS cavern (top) and the existing Soudan 2 laboratory (bottom). The neutrino beam enters the MINOS cavern from the South (upper right) end, parallel to the cavern axis in this view. The two supermodules, separated by a 1.5 m gap, are shown as edge views of their steel planes, perpendicular to the cavern axis. The two octagonal workstations are shown at the North (left) end of the MINOS cavern. The 10-m long space at the upstream end of the MINOS cavern is reserved for a possible future detector.

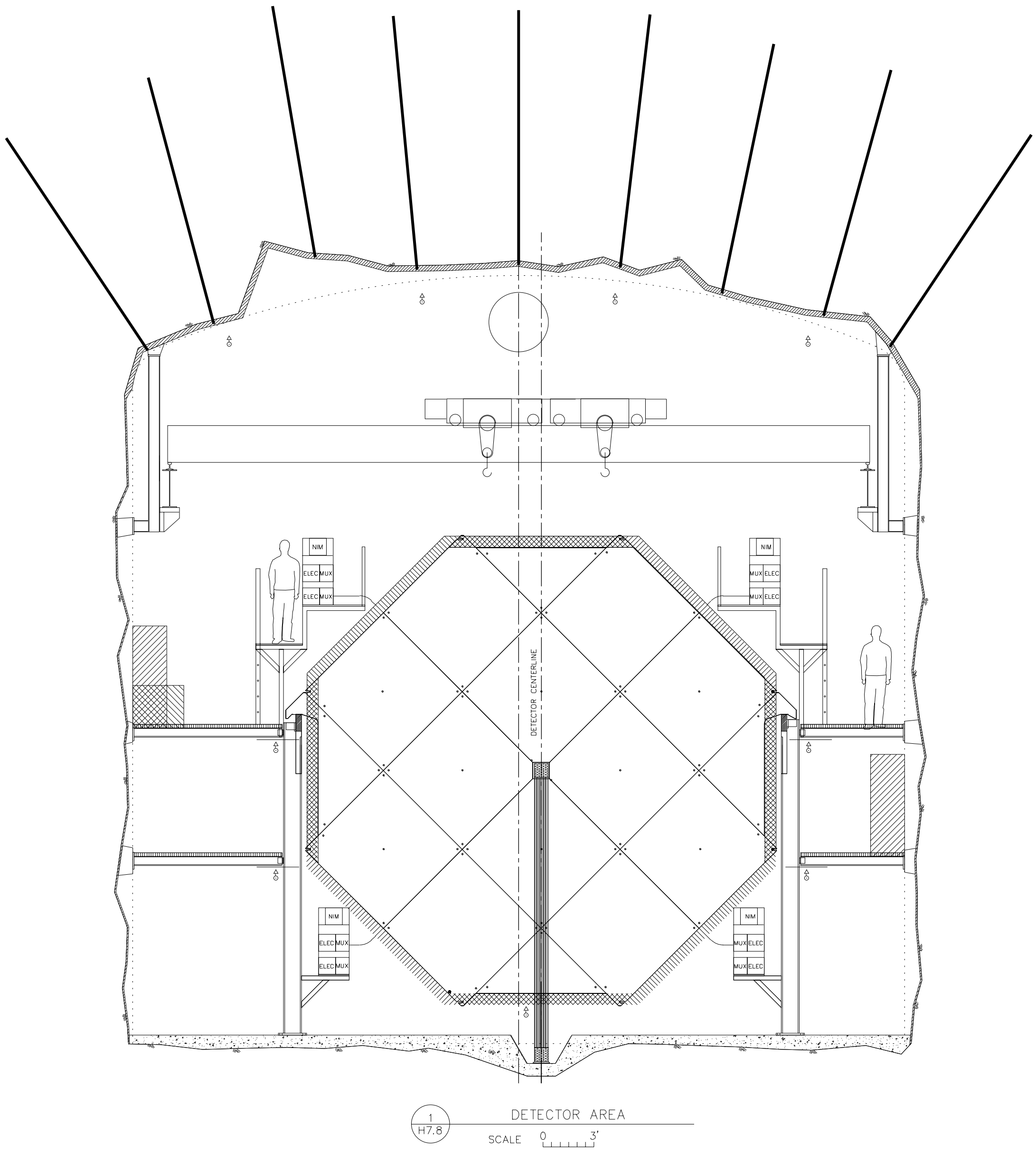

Figure 7.2: Elevation view of the MINOS cavern at the location of the first or second supermodule. The detector support rails, side walkways, electronics support platforms, magnet coil and overhead bridge crane are also shown.

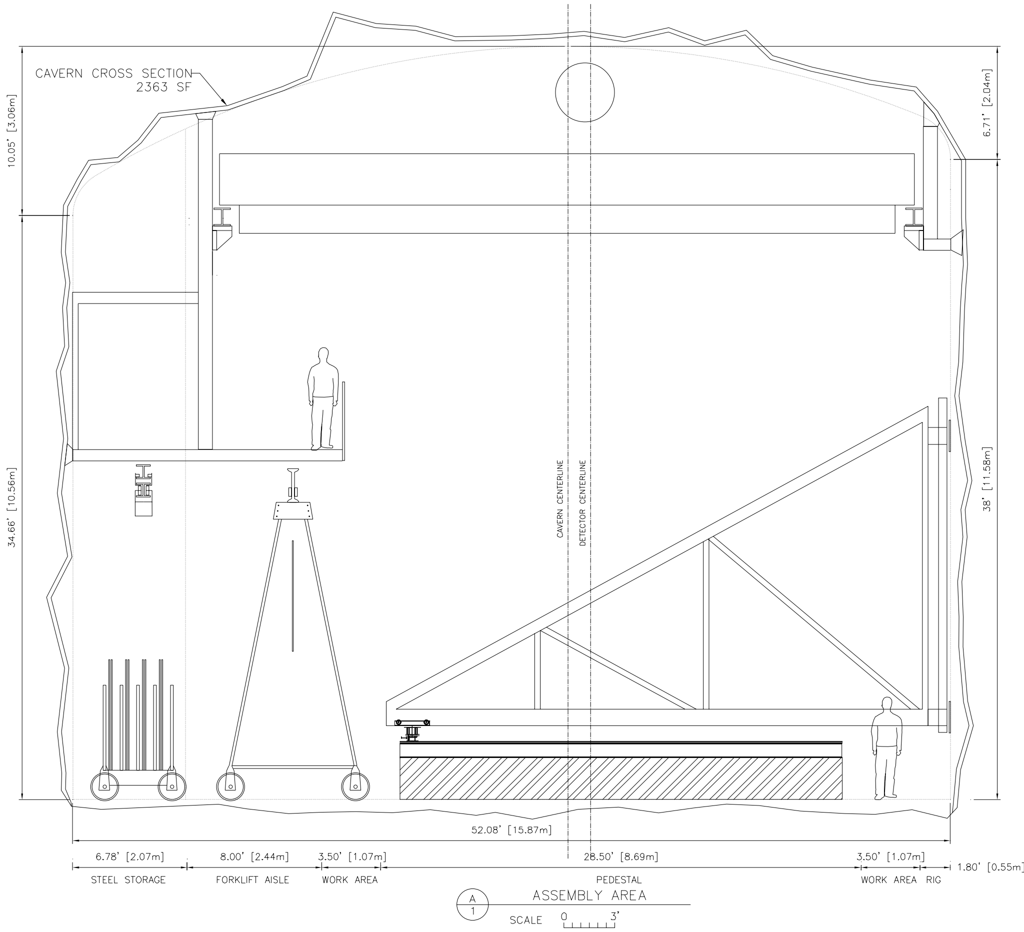

Figure 7.3: Elevation view of the MINOS cavern at the location of a detector assembly workstation. The cavern is 2 m wider at this location than at the supermodules to provide space for steel handling fixtures and for traffic to pass while plane assembly is in progress. The Figure shows (from left to right): the observation deck, the monorail, a steel storage cart, a gantry crane, a compression rig, and an assembly pedestal.

neutrino beam turns on in 2002. This first supermodule will be operated while the second supermodule is being assembled. Each supermodule coil is fabricated and installed after all the supermodule planes are mounted.

Assembly procedures are described in detail in Section 7.4 and in the far detector installation Basis of Estimate[4]. The far installation cost estimate is based on detailed installation plans and schedules developed by the MINOS Installation Committee (MIC). The technical effort for the labor-intensive installation process is the most costly component of the far-installation WBS task[7]; the effort requirements are described in detail in Section 7.4.3.

7.1.4 Testing of scintillator modules

Detector and infrastructure components which are delivered to the Soudan site will have already passed strict quality control inspections and performance tests before being shipped from commercial vendors (e.g., steel plates) or MINOS fabrication facilities (e.g., scintillator modules). Nevertheless it will be important to repeat some of these tests after arrival at Soudan to check for shipping damage. It is important to perform these checks before plane components are moved to the assembly workstations in order to maintain the required assembly rate of one plane per 3.7 shifts per workstation.

Performance tests of scintillator modules, preassembled panels of plastic scintillator strips which are 82 cm and 115 cm wide by up to 8 m long, are particularly important because internal damage may have been caused by mechanical shock or temperature stresses experienced during shipping and handling. Malfunctioning modules will delay the installation schedule if they have to be replaced after they are mounted on the steel planes. More serious delays will result if faults are detected on planes which have already been mounted vertically on the detector itself. It will be very difficult to remove a plane from the detector support structure after subsequent planes have been installed. Scintillator modules will be tested with the built-in WLS fiber light injection system and radioactive source tubes using a portable photodetector system which can be plugged directly into each module's fiber optics connectors. These tests, which are summarized in Section 7.4.5 and described in detail in Section 5.4.6, will be performed immediately after modules arrive at Soudan, after installation on the steel planes, and again after each plane is mounted vertically. The last set of tests will use the final detector-plane photodetectors and electronics, and will make use of cosmic ray muon tracks in addition to the light injection and radioactive source tubes.

7.1.5 Detector operational requirements

The MINOS detector must be able to acquire data from the first supermodule while the second supermodule is being assembled. Potential conflicts between construction and operation include the effects of electrical noise from steel plane welding, the overhead crane, and other large machines, as well as the effect of construction dirt and debris. None of these is expected to be a significant problem. The use of fiber optics for signal transmission will reduce sensitivity to noise pickup in ground loops. The design of the cavern infrastructure includes electrical power sources and grounds for the crane, welding machines, and other heavy equipment which are separate from the detector and electronics power supplies and grounds. A low-impedance ground grid will be imbedded in the concrete cavern floor for construction equipment which could generate electrical noise.

The noise, dust and dirt from some types of heavy construction could adversely affect operation of completed sections of the detector. The welding of the steel plane assemblies can be physically isolated from the completed detector sections.

Electronics will be installed on completed sections of the detector as soon as possible so that the performance of the scintillator, photodetectors and electronics can be evaluated and monitored continuously. Performance will be monitored using charge injection, light injection and cosmic ray muons, and will allow any system-level problems to be identified at the earliest possible time. The magnet coil of each supermodule will be installed and energized as soon as the supermodule is complete. The experiment-control and monitoring systems, described in Chapter 6, will be installed and brought into operation at the earliest possible time. Many data acquisition and electronics functions will be remotely controllable, so that some diagnostic and calibration studies can be performed from remote locations over computer networks. The occupancy of the underground laboratory is therefore not expected to increase as the operating detector mass increases. Routine operation of the completed detector will require only a small on-site crew of technical experts.

Electrical power consumption and the resulting heat generation will gradually increase as more of the detector comes into operation. As this occurs, cavern air heaters will be turned off and, eventually, cavern air cooling (see Section 7.4.1.6 below) will be turned on to maintain a constant air temperature of about 70° F. Experience with the Soudan 2 cavern shows that the dry-rock conditions prevailing at Soudan allow the relative humidity of the cavern air to fall as the air temperature is raised. (The ambient mine air temperature is 52° F with 100% humidity.)

7.2 Technical requirements

The goal of the far detector installation task is to assemble and install the MINOS far detector and data acquisition system, to verify that its performance meets physics requirements, and to provide the infrastructure needed to install, maintain and operate the detector and associated systems to record neutrino interactions and cosmic ray muons. The following sub-tasks are included in the far detector installation WBS element:

- **Infrastructure installation and maintenance tasks:**

  1. **Environmental conditions.** Maintain the laboratory air temperature around 70° F and relative humidity around 50%. Control electrical noise and airborne dirt and dust as required by the electronics.
  2. **Laboratory utilities.** Establish stable and reliable operation of the electrical power, air handling and heat removal systems, and supplies of laboratory water and compressed air. Provide operational support for safety systems and protocols for maintaining them, including fire alarms and fire suppression, and control of physical, electrical, magnetic, radioactive and chemical hazards.

3. **Worker facilities.** Maintain lunchroom and sanitary facilities, offices and office machines. Establish safety training protocols for the laboratory technical staff and for visiting scientists and engineers. Establish and maintain an appropriate inventory of laboratory supplies and chemicals for general use: screws, bolts, plumbing supplies and other mechanical hardware, electronics components, solvents and cleaning supplies.
4. **Communications.** Establish and maintain communication equipment including telephones, computers, terminals and computer network connections. Establish systems for coordination of detector operation with the neutrino beam and the near detector, including absolute time (GPS clock) and clock synchronization.
5. **Materials handling machinery.** Establish procedures for operating and maintaining materials handling equipment provided by the cavern outfitting task: steel plate handling between the mine shaft and the compression rig, steel plane welding and inspection equipment, overhead bridge cranes, fork lifts, machine shop tools and hand tools.
6. **Detector access.** Establish protocols and maintain hardware for safe use of detector access facilities including the top surfaces of the detector, the detector support structure, walkways, cable trays and electronics racks.

- **Installation tasks:**

7. **Materials receiving.** Design and operate facilities for receiving detector components (steel, scintillator modules, electronics, photodetectors and fiber optics connections). Design and set up work and storage areas required to perform this task efficiently. This task includes unloading delivery trucks, transporting material underground, providing intermediate storage facilities on the surface and underground, performing inspection, inventory and performance tests.
8. **Detector plane assembly.** Set up, operate and schedule the detector plane assembly workstations and associated equipment. Design and set up work and storage areas required to perform this task efficiently. Coordinate tasks involving the supply of components to the workstations, scheduling of workers and shared equipment including use of the overhead bridge cranes. Maintain a database of all detector elements which allows the history and past performance of all components to be determined after installation in the detector.
9. **Detector plane mounting.** Establish and schedule procedures for mounting the steel and scintillator planes on the body of the detector. This includes the installation of fiber optics connections to the scintillator modules.
10. **Electronics installation.** Establish and schedule procedures for installing multiplexing boxes (including photodetectors), front end electronics, and other electronics hardware and power supplies, including the hubs, central data system, trigger farm and data acquisition equipment.
11. **Detector performance tests.** Set up, operate and maintain test equipment and protocols for scintillator modules, fiber optics connections, photodetectors,

and electronics systems. Design and set up work and storage areas required to perform this task efficiently. Perform tests at specific stages of the detector assembly process to ensure that detector performance meets established criteria. Coordinate test procedures with those at the fabrication facilities, the test beam calibration setup, and the MINOS near detector laboratory to obtain reliable comparisons of performance criteria such as efficiencies, energy calibrations and resolutions, and neutrino event characterizations. Maintain an inventory of spare detector components and establish procedures for diagnosing and replacing faulty components during and after installation.

12. **Magnet coil.** Set up, operate and schedule the magnet coil fabrication and installation. Design and set up work and storage areas required to perform this task efficiently. Establish safe and stable operation of the coils, power supplies, and cooling systems.

13. **Alignment and survey.** Design procedures for measuring and recording the locations of all components within the assembled detector. Provide measurement tools and maintain the database required to manage this information. Provide procedures and alignment templates for locating scintillator modules, mounting hardware and other components on the steel detector planes.

14. **Transition to physics operation.** Establish operating procedures and performance criteria for installed sections of the detector and begin routine data acquisition of cosmic ray and neutrino events. Begin operation of the data recording and distribution system, and of the software systems for identifying and characterizing events of interest.

7.3 Interfaces to other MINOS systems

7.3.1 Soudan detector halls

The Technical Design Report for the Soudan site preparation[1] describes the excavation of the underground cavern for the MINOS far detector at Soudan (including the rockbolting and concreting of the floor, walls, and ceiling), the outfitting of this cavern with utilities (electrical systems, electronics grounding grid in the concrete floor, air handling and conditioning, lighting, fire protection systems), the 25-ton overhead bridge crane, the support structure for the 5.4 kt detector and other detector installation equipment. The outfitting also includes all materials handling equipment (e.g., the monorail system for moving steel plates), the preparation of work and storage areas in both the MINOS and Soudan 2 caverns, and surface facilities (e.g., office areas, storage areas and receiving facilities for large detector components). The site preparation TDR includes compliance with State and Federal regulations, for example, the preparation of an Environmental Assessment Worksheet[8]. It also covers the upgrade of the hoist system and the fabrication of the new West shaft cage, which is needed for moving large detector components underground. Two existing shaft cages will be modified for rock removal during the MINOS cavern excavation.

7.3.2 Soudan steel structures

The MINOS far detector cavern construction and outfitting task[1] includes the design and fabrication of the following steel structures in the new MINOS cavern:

- **Utility deck.** This 240 m^2 steel-grating platform is suspended 7 m above the cavern floor at the downstream end of the MINOS cavern. It provides a large visitor observation area, a mechanical-electrical utility room, office areas and storage space.

- **Bridge cranes.** Two bridge cranes share the same set of rails and serve the entire underground cavern area including the most of the observation deck. The 25-ton bridge crane has two 15-ton hoists and is used mainly for mounting assembled steel and scintillator planes on the body of the detector. The 2-ton bridge crane, which is installed upstream of the 25-ton crane, has two 2-ton hoists and is used mainly to provide personnel access to the upper surfaces of the detector.

- **Shaft cage.** A new, custom-built MINOS shaft cage will be used in the West Soudan mine shaft during the outfitting and installation phases of the experiment. This 3-deck cage can be configured to transport personnel (e.g., tourists and MINOS technicians), 2 m by 8 m steel plane components, scintillator module shipping crates, and other materials between the surface and the underground laboratory shaft station. The cage can carry a 6-ton load and is equipped with a 7-ton electric hoist to aid in loading and unloading heavy objects. The underground shaft station will be modified to permit loading and unloading of plane components. Both steel and scintillator plane components will be specially packaged to fit into the new cage and for handling by special rigging equipment.

- **Monorail steel transport.** The ceiling-mounted monorail system is used to move steel plates and other equipment from the shaft station to the workstation storage areas.

- **Detector support structure.** This steel-beam structure supports the rails on which the 8-m wide octagonal detector planes rest and also provides elevated access and work areas on steel-grating decks adjacent to the detector planes. The structure supports the platforms and walkways which give access to the four 45° sides of the octagonal detector, where the photodetectors and associated electronics are mounted. The structure includes the "bookend" supports to which the first steel plane of each supermodule is attached. Electronics support platforms will be permanently installed only after the planes which they serve are in place.

- **Assembly pedestals.** Each of the two assembly workstations is built around a central assembly pedestal. The pedestals are steel and concrete structures which support the strongbacks on which the octagonal steel and scintillator detector planes are assembled.

- **Strongbacks.** A strongback is used at each assembly workstation as a rigid support upon which the eight steel plates of an octagon plane are assembled, compressed and plug welded. After the scintillator modules are mounted on the steel plane, the strongback and detector plane assembly is raised into the vertical orientation by the 25-ton bridge crane and set on the detector support rails where it is supported by the steel plane "ears."

- **Compression rigs.** The compression rigs are used to apply 10-tons of compression to the octagonal steel plane assemblies while plug welds between the two layers of a plane are being made. Each rig consists of a rigid truss frame which mounts to the cavern wall and swings out over the assembly pedestal and strongback. Four compression jacks and a plug welder are mounted on the under side of each rig on a roller system.

- **Rolling gantry cranes.** Two 2-ton rail-mounted gantry cranes are used to transport steel plates and scintillator modules from storage racks to the two workstation assembly pedestals.

- **Steel plate storage carts.** These 45-ton capacity, 8-m long carts are used to store the steel plates delivered by the monorail, and to move them under the coverage of the workstation gantry cranes.

- **Scintillator carts.** These 2-ton capacity, 8.5-m long carts are used to move scintillator module crates from the shaft station to the Soudan 2 cavern testing and storage area, and from there to the MINOS assembly workstations.

- **Scintillator storage and test area.** A 150 m^2 elevated platform will be constructed in the Soudan 2 cavern for use as a scintillator storage and test area. This area is large enough to store 60 planes of scintillator modules, so that scintillator shipments can be suspended to avoid extreme weather conditions if necessary. The platform also provides space for testing scintillator modules as soon as they arrive underground.

Because each 11-ton detector plane is supported only by its two 1-inch thick ears, the hanging file support rails on which the ears rest are located as close as possible to the edges of the octagons. However, the ears have been lengthened to provide additional space between the sides of the steel planes and detector support structure columns. This allows the periphery of the detector planes to extend beyond the steel planes to accommodate the detector "hair" – the endpieces of the scintillator strip modules containing fiber optics and connectors, the WLS fiber light-injection hardware, and the radioactive source tube access points. The hair must not extend beyond the following maximum distances from the edges of the steel planes: 20 cm on the sides, 40 cm on the top, and 25 cm on the bottom. The bottom hair allowance corresponds to a distance from the bottom edge of the steel plane to the floor of 75 cm, which gives access for work on the bottom ends of detector elements. Any hair which is installed while the plane is horizontal (e.g., cable trays and clear-fiber-optics harnesses) must be protected from damage as the plane assembly is raised into the vertical orientation and rigged into place on the detector. For this purpose, an extra 10 cm of "keep clear" space has been provided on each side, between the vertical sides of the hair boundary and the vertical detector support columns.

In addition to these restrictions, the scintillator detector planes must be designed to fit under the steel plane ears and around the central magnet coil hole, both of which are rigidly connected from plane to plane, to set the spacing between the steel planes. The ends of the detector modules must also be tailored to fit under the axial bolts which connect each steel plane to its neighbors at the eight corners of the octagons.

7.3.3 Magnet coil

Each MINOS far detector supermodule is toroidally magnetized by a water-cooled copper-wire coil[9]. The coil for a supermodule is assembled and installed after all supermodule planes have been mounted. Each coil consists of a central section, in a water-cooled bore tube through the axial coil hole of a supermodule, and an air-cooled return section located in a floor trench directly beneath the central coil section. Each coil has 150 to 180 turns of 1.48 cm diameter insulated, stranded copper wire which is pulled through the bore tube along with additional cooling-water tubes. Each turn includes air-cooled vertical segments which connect the central and return sections. The turns are connected by crimping near the bottom end of one of the vertical segments. The 15,000 Amp-turn coil is designed to provide an average toroidal magnetic field of 1.5 T with minimum electrical power (and heat generation) and minimum temperature rise at the center of a supermodule (which could affect detector performance). Each coil dissipates 20 kW of electrical power and each coil power supply requires 29 kW of input power. The coil cooling-water transfers the heat generated by the coils to the cavern cooling system (described below in Section 7.4.1.6). The magnet steel and coils task (Chapter 4) provides the coil materials, assembly fixtures, power supplies, cooling system and field monitoring devices. The far detector installation task is responsible for installing and operating these systems. In particular, the coil cooling water system must be integrated into the MINOS cavern utilities infrastructure.

7.3.4 Scintillator planes

As described in Chapter 5, the MINOS active detector elements consist of 1-cm thick, 4.1-cm wide strips of plastic scintillator which are packaged into "modules" of 20 or 28 strips each. Each of the eight modules needed to construct a plane of MINOS scintillator detector is designed to fit around the steel plane support structures (ears, axial rods, and coil collars) while still allowing access to its fiber optics connectors. Scintillator modules are packaged at the fabrication facilities in special shipping crates which are designed to be easily rigged onto the Soudan hoist cage.

Storage space is provided in the Soudan 2 laboratory for up to five truckloads of modules (each truckload contains scintillator modules for about 12 detector planes), allowing shipments to be suspended during the coldest part of each winter if necessary. Empty shipping boxes are returned to the fabrication facility as soon as modules have been installed. Scintillator modules which fail performance tests will be returned to the fabrication facility for repair or rebuilding.

The far detector installation task also includes the installation of fiber optics connections between scintillator modules and multiplexing boxes, the multiplexing boxes themselves, the photodetectors and front end electronics. This is described in the following Section.

The scintillator modules and associated test equipment and protocols are supplied by the scintillator fabrication task (Chapter 5). This task also provides the barcode reader hardware and the database software system used to manage the inventories of scintillator, steel, electronics and other components at the Soudan site.

7.3.5 Electronics and data acquisition

Electronics and data acquisition hardware will be installed on each plane after it is mounted vertically on the completed detector. Front-end electronics will be located in crates at regular intervals along the four 45° faces of the octagon. Crates along the two upper faces will be supported on special cantilevered platforms attached to the side support structures, and can be accessed from the upper side walkways. Crates along the two lower faces will be located on similar platforms attached to the lower part of the detector support structure. These platforms will be built as part of the cavern construction and outfitting task. The arrangement is shown schematically in Figure 7.4. Each set of platforms is installed only after all nearby detector planes have been mounted in place. In addition, the installation task includes the complete installation, checkout and validation of all electronics components, including the photodetectors, multiplexing boxes, and fiber optics harnesses which connect them to the scintillator modules. All these components will be inspected and inventoried after arrival at Soudan, and a supply of spares will be maintained to replace faulty units.

As soon as a set of planes has been successfully read out through the electronics and data acquisition system, it becomes part of the operating detector, and will record calibration data from cosmic ray events while the remainder of the supermodule is being assembled. Operation of completed detector planes while others are being assembled and installed requires special precautions to suppress electrical noise generated by welders and other heavy equipment. Special quiet power circuits, with rf shielded transformers and a separate ground system, is provided for the electronics, and a low impedance ground grid is imbedded in the concrete floor to provide good grounding for welders and other construction equipment.

The electronics task supplies all electronics and data acquisition hardware, power supplies, crates, cables, test equipment and operating protocols. The installation task must provide the required platforms, access walkways, cable trays, electrical power and grounding systems.

7.4 Description of WBS elements

This Section describes the far detector installation activities included in each WBS-2.4 Level 3 task. The associated EDIA activities are included in the individual tasks at Level 4, and in the FY 1999 optimization and engineering program (Section 7.5). Most far detector EDIA work is performed under other tasks, e.g., magnet steel and coils, scintillator fabrication, and electronics. However, EDIA effort for engineering liaison to other tasks, and for installation oversight, is included under the far detector installation task.

7.4.1 Infrastructure (WBS 2.4.1)

This Section describes the far detector installation tasks associated with Items #1-6 of the technical requirements listed in Section 7.2. Nearly all experimental infrastructure will be

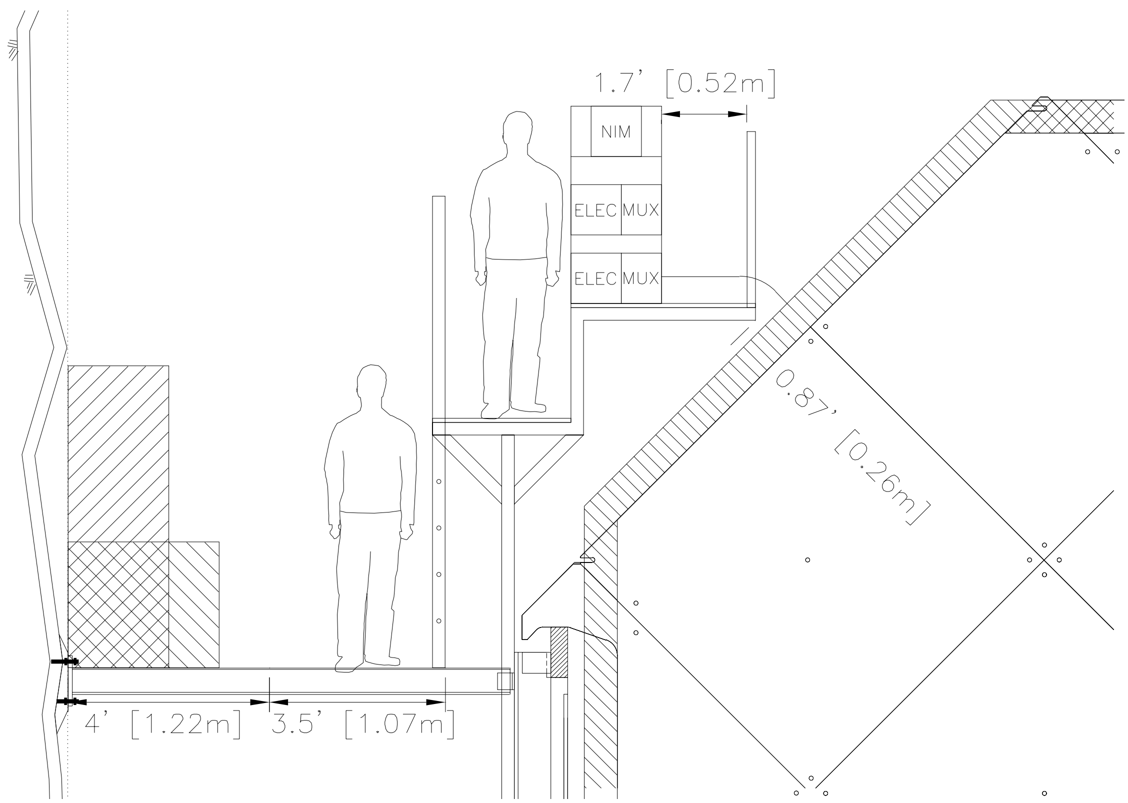

Figure 7.4: Sketch of one of the platforms used to support the multiplexing boxes and front-end electronics crates near one of the upper 45° faces of the MINOS detector. The walkway and personnel access platform is also shown. These platforms, and similar ones on the other three 45° faces, are installed only after all nearby detector planes have been mounted in place.

designed, fabricated and installed as part of the MINOS cavern construction and outfitting task. The surface building is being provided for MINOS use by the State of Minnesota. The far detector installation task includes performance tests of infrastructure equipment as well as its operation and maintenance.

7.4.1.1 Surface facilities

Receiving building. A 500 m^2 (15 m by 34 m) light industrial building will be constructed within one mile of the headframe for materials receiving and staging. The structure has a poured concrete floor, a 10-ton overhead crane and basic industrial building lighting and utilities. The structure has heat and air conditioning so that it can be used for storage of scintillator modules until they are moved underground. An additional 400 m^2 uncovered parking lot immediately adjacent to this building is used as a staging area.

During detector installation the receiving building facility is used for inspecting, sorting and packaging steel plates prior to loading onto the hoist cage. Each of the 486 8-m wide, 1-inch thick steel octagons of the MINOS far detector is assembled from eight 2-m wide, 0.5-inch thick plates which are up to 8-m long. These are delivered to Soudan from steel suppliers in large multi-truckload shipments. In the receiving building these shipments are unloaded, inspected and sorted into "bundles" each of which contains the four plates needed to construct one of the two layers of a steel octagon. These 5.5-ton bundles are loaded onto special "cage-loading" trucks designed to transport them to the headframe and transfer them to the MINOS shaft cage. The receiving building has enough space to store the steel plates and scintillator crates for one month's installation work (22 planes).

After the detector installation is complete, part of the surface receiving building will be converted for use as a computer center to support data acquisition activities. The remainder of the building will be used for office space and storage during the operation phase of MINOS.

Office space. The experiment will require some office space on the surface near the Soudan mine shaft headframe in order to coordinate detector installation activities. This is provided by a 100 m^2 enclosed area in the receiving building. The installation task provides office machines, telephone lines and necessary supplies for this facility.

7.4.1.2 Counting house and office areas

The existing Soudan 2 counting house facility will be converted for MINOS use as part of the cavern construction and outfitting task. This two-level facility contains areas for offices, computers, computer terminals and a lunchroom. The Soudan 2 lunchroom and sanitary facilities will be expanded to accommodate the large MINOS installation staff. Additional office space will be located on the Observation Deck (see Section 7.3.2). Some computer terminals will also be located along the East wall of the MINOS cavern, immediately adjacent to the detector supermodules and electronics, on the upper walkway. Detector electronics will be connected to computers in the counting house by a computer network fiber optics cable. The total area of underground office space will be about 40 m^2.

7.4.1.3 Mechanical work areas

The existing Soudan 2 staff shop, containing general purpose machine tools (lathe, milling machine, drill press, band saw), will be upgraded for MINOS installation work. The existing supplies of hand tools and mechanical parts will be maintained for MINOS use. New mechanical work areas will be set up at each of the two MINOS workstations, which will require supplies of general purpose hand tools and supplies in addition to the large steel plane assembly fixtures (plane assembly platforms, strongbacks, compression rigs) which are provided as part of the cavern outfitting task. Each workstation contains a work area of 120 m^2; other mechanical work areas will have a total area of about 140 m^2.

7.4.1.4 Electronics work areas

The existing Soudan 2 electronics work area, containing general purpose tools and instruments, will be upgraded for MINOS installation and repair work. Existing supplies of electronics components will also be maintained and expanded for MINOS use. New electronics work areas will be set up along the walkways adjacent to the supermodules for use during the cabling and checkout of newly installed detector planes. The total area of underground electronics work areas will be about 70 m^2.

7.4.1.5 Communications

The existing communications infrastructure which is already operating for the Soudan 2 experiment will be upgraded for MINOS. The current system relies on a number of twisted-pair telephone lines installed in the 713-m deep mine utilities shaft for telephone and computer network (Multinet-TCP/IP) connections to local telephone lines on the surface. These lines are also used to transmit data, including GPS clock data, from cosmic-ray surface detectors to the Soudan 2 underground data acquisition system. In addition, the underground experiment records the absolute time of every triggering event from an underground WWVB clock receiver which is connected to a surface antenna through a coaxial cable in the mine shaft.

For MINOS, a high-bandwidth fiber-optics communications line will be installed in the mine utilities shaft to supplement the existing surface-to-underground connections. This will support a high-capacity data link between the underground experiment and a local surface computer facility, and will also improve internet service. In addition, the WWVB clock system used for Soudan 2 will be upgraded to a GPS-based system, using a receiver on the surface to provide precise absolute time information to the underground data acquisition system over the fiber optics data link. The MINOS GPS timing system is an essential part of the communications link between the Fermilab Main Injector and the MINOS far detector, as described in Chapter 6. Installation of the improved communication lines in the Soudan mine utilities shaft is the responsibility of the far detector installation task. It will occur at the same time as the installation of the water-cooled chiller lines in the shaft, as described in the next Section.

7.4.1.6 Environmental control and monitoring

The basic infrastructure needed to maintain comfortable temperature and humidity levels in the MINOS laboratory is provided as part of the cavern construction and outfitting task. Operation and maintenance of these systems is transferred to the installation task at the time of beneficial occupancy of the MINOS cavern. During detector assembly it is also necessary to control the dust and dirt generated by construction activities, particularly welding. Electrical noise from welding and electrically powered machines is isolated from the detector electronics by using separate "quiet power" circuits and ground systems for the latter. A low impedance steel mesh built into the concrete of the cavern floor provides grounding for electrically noisy equipment. As data acquisition begins, environmental conditions are recorded from a number of sensors and transducers which are provided as part of the monitor and control system (supplied by the electronics task, described in Chapter 6).

As the installation process proceeds and the mass of operating detector grows, the electrical power consumption and heat generated in the cavern will gradually increase. Electrical heaters in the air ventilation system will be adjusted, and eventually turned off, to compensate for heat generated by detector systems. Eventually the air-cooling and magnet-coil cooling-water systems will be activated. Maximum power usage will occur when both detector supermodules and magnet coils are in full operation. This anticipated average power usage is summarized in Table 7.2. The heat generated by the magnet coils will be transferred directly to the cavern cooling system by an extension of the chilled water system.

Equipment	Average power
Soudan 2 Lab and detector	70 kW
CDMS experiment (Soudan 2 Lab)	50 kW
MINOS Lab lights and utilities	25 kW
MINOS electronics	25 kW
MINOS magnet coils	58 kW
MINOS cavern cooling	20 kW
Total Lab power	**248 kW**

Table 7.2: Time-averaged electrical power requirements of equipment in the MINOS and Soudan 2 laboratories during routine data acquisition operation. The total power load is the basis for the calculation of the 257 kW cavern cooling requirement, which includes an additional 9 kW for heat produced by personnel.

Most of the heat generated by the experiment will be removed from the underground laboratories by a heat exchange system which will transfer the heat to an air-cooled water chiller located on the surface. Piping will be installed in the mine utilities shaft between the MINOS cavern and the surface, and then extended horizontally to the chiller, which is located some distance from the shaft. Three intermediate heat exchangers with circulation pumps will be installed at intervals along the mine shaft to separate the system into pressure zones. A small fraction of the required cooling will be provided by the natural flow of cool air up the Soudan mine shaft. The cavern cooling system is described in detail in the Cavern

Construction and Outfitting Technical Design Report[1].

It is difficult to determine accurately the cooling capacity of the Soudan mine's natural air flow, which is currently adequate to cool the Soudan 2 laboratory. We expect that this natural air flow can supply substantial heat removal capacity, reducing the cost of the MINOS cavern cooling system described in the previous paragraph. We therefore plan to install the water-cooled heat-transfer system only after the MINOS cavern installation work is well under way and is generating sufficient heat for the cooling capacity of the natural air flow to be determined. The water-cooled system has been designed, and its cost estimated, under the assumption that it must remove all the heat produced by MINOS and CDMS (Table 7.2). The cavern cooling system has been designed to remove approximately twice the heat load which is currently anticipated.

The far detector installation task includes responsibility for maintaining and operating the cavern electrical utilities and the cooling and environmental control systems. Members of the far installation "startup" crew will work closely with the contractors during the cavern outfitting period to gain a working knowledge of all infrastructure systems and to ensure that they satisfy MINOS requirements.

7.4.1.7 Safety

Safety considerations have been included as integral design requirements for all far detector installation tasks. Issues which are specific to the Soudan underground environment, installation and operation are described in Reference [5]. Safety issues related to far detector systems are very similar to those for the near detector, which are discussed in the NuMI Project Preliminary Safety Assessment Document[6]. Safety protocols related to the underground environment are subject to review by the State Park DNR management, and are nearly the same as those which are currently in effect for the Soudan 2 experiment. Safety issues related to the rigging of massive detector components down the mine shaft and into the underground laboratories are discussed in the MINOS far detector cavern TDR[1] and in Reference [5]. Chapter 12 gives a summary of safety issues and responsibilities for the experiment.

7.4.2 Materials handling and testing (WBS 2.4.2)

This Section describes the far detector installation tasks associated with Item #7 of the technical requirements listed in Section 7.2. All major materials-handling equipment are designed, fabricated and installed as part of the cavern construction and outfitting task, as described in Section 7.3.2. The far detector installation task includes the assembly and performance testing of this equipment, as well as its operation and maintenance.

The present Section gives a detailed description of materials handling tasks during the installation period; the installation crew effort levels required to accomplish this work are summarized below in Section 7.4.3.

7.4.2.1 Moving components to workstations

The steel plane assembly process begins by moving the 8-m long steel plane sections and the crates of active detector modules underground using special fixtures and the west shaft cage. The procedure is optimized to maximize the number of cage loads which are moved per shift. The crew which moves materials underground is also responsible for keeping workstations supplied with all necessary components. Steel plane sections are delivered directly to the MINOS cavern by the monorail system, and the scintillator modules are tested in the Soudan 2 cavern before being delivered to workstations. Steel plane sections are stored in the plate storage carts in the workstation area, and moved onto the strongbacks by the 2-ton gantry cranes as needed to assemble the steel detector planes.

The following paragraphs describe the details of the steel handling procedures which have been used to estimate to cost of moving steel and scintillator detector components from the arriving delivery trucks to the underground workstations.

Surface day shift, 3 FTEs. When a shipment of steel plates arrives at Soudan, the delivery truck backs into the loading bay of the surface receiving building under the 10-ton overhead crane. The plates are unloaded using magnetic lifters and sorted into four piles: one pile for the two top-layer edge pieces, one pile for the top-layer middle pieces and the same for the bottom layer. Two work areas are provided for sorting the plates into "bundles" for shipping underground. The storage area has a capacity for 160 to 240 plates of steel (enough for 20 to 30 completed planes). As the steel is unloaded, each piece is inspected, weighed (using a built-in scale on the crane) and tagged with a barcode. These data are entered into a database to keep track of the location of specific plates after they are installed in the detector (e.g., for calculating the mass of each plane and for magnetic field modeling). The barcode reader and database system is the same one used for scintillator and electronics components.

Each bundle contains the four plates needed to construct one of the two layers of a single steel detector plane, arranged to minimize handling time underground. They are oriented so that their cambered edges match up, in order to reduce the widths of the gaps between plates in an assembled plane. Once the four plates are lined up, special bundle bolts with lifting hooks are inserted into the three central holes. For top-layer bundles, the lifting bolts use the plug-weld holes; the bottom-layer bundles have special lifting-bolt holes. All plate holes are provided by the steel fabricator.

After the steel plates are arranged in pre-sorted bundles for shipment underground, the bundles are placed on a special "cage-loading" truck which moves them to the mine shaft headframe. The truck is outfitted with special frames which guide the bundles as they are loaded into the shaft cage. Three plate bundles are loaded onto the truck, side by side with the plates oriented vertically and the long axis parallel to the truck bed, as shown in Figure 7.5. The truck is also equipped with an over-the-cab boom that holds the back end of each bundle as it is pulled into the cage.

Fourteen bundles of steel must be moved underground each week to keep up with the underground assembly schedule. At 50 minutes per cage load, only six bundles can be moved in one 8 hour shift (reconfiguring the cage takes a total of about 3 hours per shift). Thus two cage-loading trucks are provided so they can be loaded and ready at the beginning of the evening shift. The day-shift crew members also handle all other shipments arriving at Soudan, e.g., scintillator modules, electronics, office supplies.

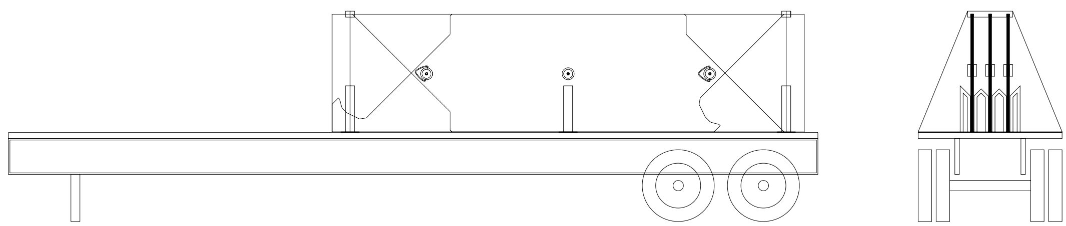

Figure 7.5: Sketch of one of the cage-loading trucks used to move bundles of steel plates from the receiving area to the mine shaft headframe. Each of the three bundles contains the four plates needed for one of the two layers of a steel detector plane.

Surface evening shift, 3 FTEs. Nearly all MINOS materials are moved underground during the evening shift (4 pm to midnight) in order to avoid interference with State Park and tourist activities. At the start of each evening shift the underground moving crew prepares the three-deck west shaft cage for MINOS use by removing the personnel decks and the front and back doors and panels of the cage (as described in the following Section). The cage-loading truck is backed up to the headframe so that the ends of the three steel bundles are close to the empty shell of the west shaft cage. The 7-ton hoist on the top of the cage is connected to electrical power. (A safety interlock ensures that the cage cannot move with the power cable plugged in.) The cage loading procedure, described in the next paragraph, is shown schematically in Figure 7.6.

The cage hoist attaches to the front lifting hook of a steel bundle and the cage-loading truck boom attaches to the back lifting point. The bundle is stabilized by the bundle frame on the truck as it is raised into the vertical orientation. As the cage hoist operator raises the bundle up into the cage, the truck boom operator slowly pays out cable, until the entire bundle is suspended in mid-air. The cage hoist continues to pull the bundle into the cage until it is suspended vertically, inside the cage, by the cage hoist. It is raised until the steel hooks mounted from the roof of the cage can be attached to the top lifting hook of the bundle. The load is now supported from this fixed point instead of from the two cables. Special clamps that can be quickly engaged are now used to secure the bottom of the plate. Once the load is secured, the truck moves out of the way and the power cord to the cage hoist is removed. The load is now ready to move underground. This loading procedure takes about 20 minutes. The cage now moves the steel bundle underground, where it is unloaded as described in the next Section. The surface crew prepares the next bundle for loading onto the cage while the underground crew unloads the previous bundle.

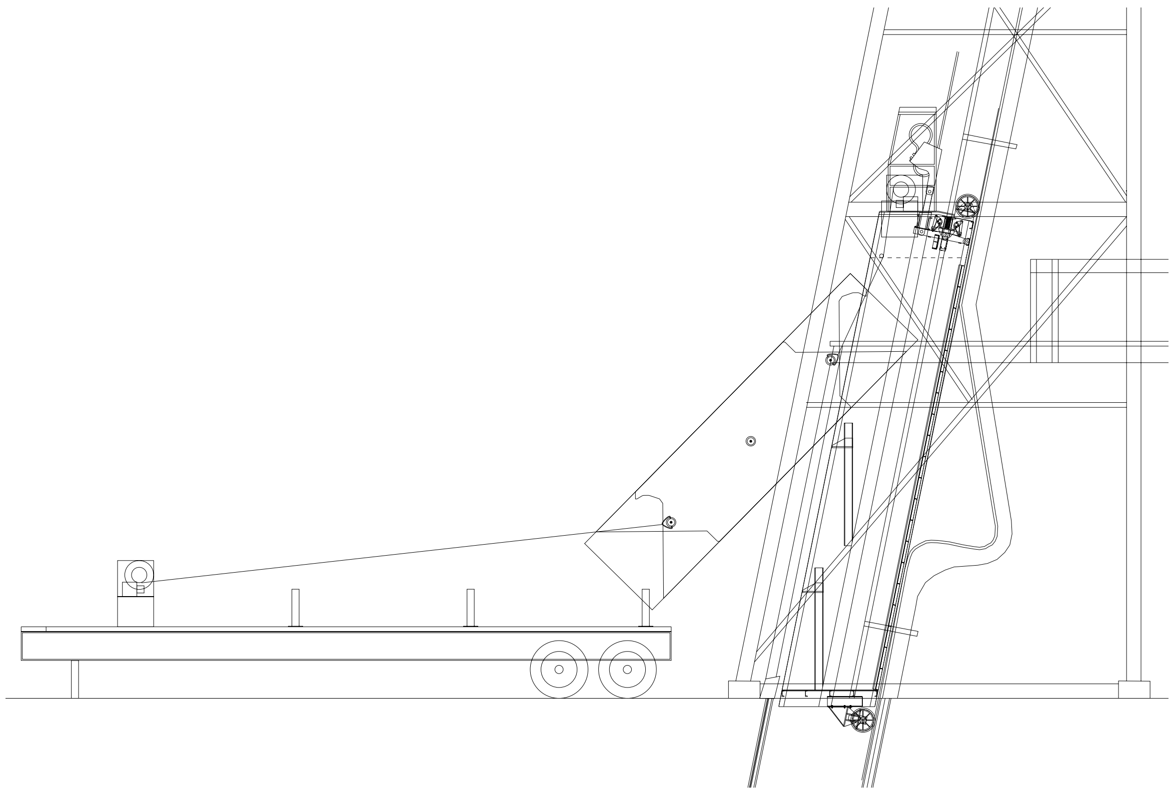

Figure 7.6: Sketch of the procedure used to load one of the presorted bundles of steel plates from the cage-loading truck (left) onto the Soudan mine shaft cage (right).

Underground evening shift, 3 FTEs. At the start of each evening shift (4 pm) the underground crew prepares the west-side shaft cage for moving steel plates (or scintillator module crates) underground. The procedure is similar to that used for the existing Soudan 2 cage. All the doors, internal floors and back panels are removed. The back panels and doors are light enough that they can be unbolted and removed by hand. The floor sections are removed as single pieces using a forklift. Depending on whether steel or scintillator is to be shipped that evening, the appropriate clamping fixtures (to hold the loads in place) are bolted in. Total time to take the cage apart is about 1.5 hours; the same time is required to clean and reassemble the cage at the end of each shift, if it is needed for tours the next morning. During the winter months the west cage can remain apart, saving 3 hours of work each evening shift.

The empty cage is sent to the surface where the surface crew loads the first steel bundle (or scintillator crate), as described in the previous Section. When the load arrives underground the cage is placed on the mine shaft "chairs" and the mine hoist cable is allowed to go slack. The chairs hold the cage in a stable position during the unloading process. The cage hoist is now powered up to assist with the unloading of the bundle. The cage hoist raises the bundle until it is free of the cage hooks. A cable is then used to attach the lower bundle hook to the "far" monorail hoist. The bundle is slowly pulled up until it is horizontal. Then the upper bundle hook is attached to the "near" monorail hoist. Once the monorail is supporting the load, the cage hoist is disconnected from electrical power and the empty cage is prepared to return to the surface. Figure 7.7 shows the unloading process schematically.

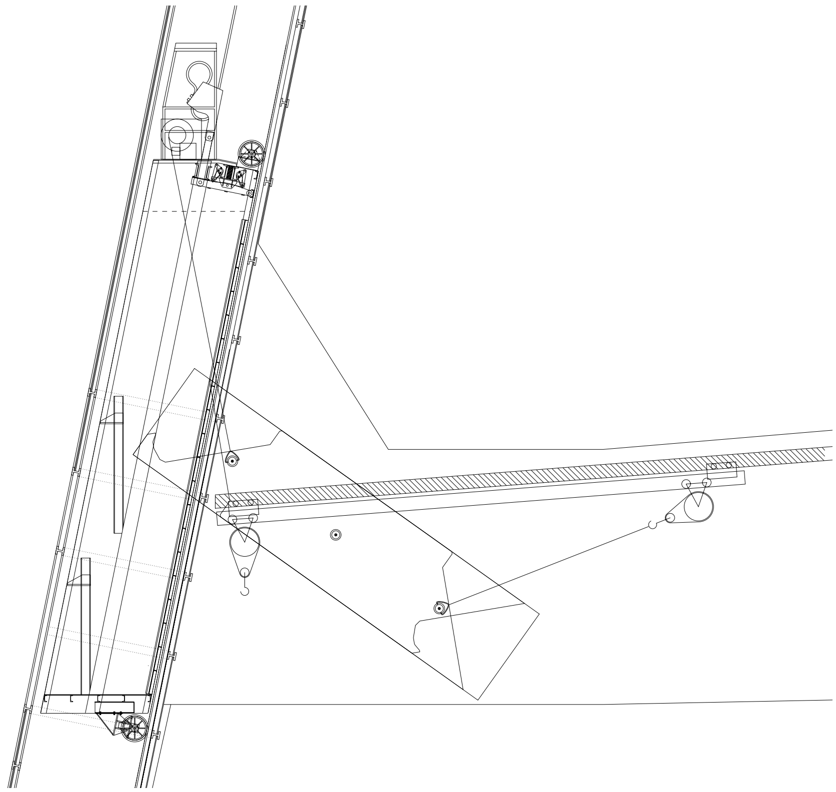

Figure 7.7: Sketch of the procedure used to unload one of the steel bundles at the Soudan mine underground shaft station. The shaft and cage are on the left and the entrance to the MINOS cavern is on the right. The monorail is the shaded bar along the entrance tunnel ceiling. The monorail's "near" hoist is on the left and the "far" hoist is on the right.

While the bundle is being moved into the MINOS cavern by the monorail, at a speed of 15 ft/min, the cage clamps and cage hoist power cable are stowed for the trip to the surface. Safety indicators in the engine house prevent the hoistman from moving the cage until the power cable is removed and all shaft doors are closed. When the steel bundle arrives in the MINOS hall it is placed in one of the two 45-ton plate storage carts. The bundle lifting bolts are removed and shipped to the surface for later use. The monorail trip and unloading procedure takes about 0.5 hour.

The total time to move one load underground is about 50 minutes, including the 5 minutes for the cage trip. Since there are effectively only 5 hours of hoist time per day, we can move only 6 bundles (or 3 planes) underground each evening. Thus, to keep the workstations stocked, steel is moved underground on three evenings/week or two evenings/week on alternate weeks.

Scintillator module handling. The handling procedure for scintillator shipping crates is very similar to that used for steel plate bundles. The same crew members who handle steel bundles also move the scintillator crates underground. During the winter months, if crates cannot be moved underground immediately after arrival at Soudan, they can be stored in a heated section of the surface receiving building to protect them from thermal stresses. The crates are not as heavy as the steel bundles but they are larger and more fragile. The same cage-loading truck is used for the steel plate bundles and the scintillator crates. The loading and unloading procedures are very similar to those described above for the steel bundles. When a scintillator crate arrives at the underground shaft station, it is lowered onto hand carts and rolled into the Soudan 2 cavern.

Once in the Soudan 2 cavern the scintillator crates are raised onto the elevated storage and testing area, shown in Figure 7.8. This platform is serviced by a local monorail trolley and hoist system, and is large enough to store 30 scintillator crates or about 60 planes of scintillator. This gives a three-month buffer so shipping from factories can be suspended during the coldest (and perhaps the warmest) months of the year.

Before the cage returns to the surface for the next scintillator crate, an empty scintillator crate is loaded into it for eventual return to the scintillator fabrication facility. The required storage area for 10 to 15 empty crates is provided in the surface receiving building.

The total loading time, including hauling the empty crate to the surface, is about 1.5 hours. This means that only three crates per evening can be moved underground, so it takes two evenings to move one delivery truckload of six scintillator crates underground. This provides enough scintillator modules for 12 detector planes, so scintillator crates need to be moved underground only every other week, on average, to keep up with the installation schedule.

Additional materials handling. During some evening shifts only pallet loads of miscellaneous materials and small equipment items are moved underground. For these shifts, only the cage doors and back panels need to be removed, and the smaller East cage can be used in addition to the 3-deck West cage. The use of both cages saves on expensive hoist trips because one cage automatically moves from the surface to the underground shaft station when the other moves in the opposite direction.

7.4.2.2 Storage requirements

Substantial storage space is required at Soudan for the largest detector components, the steel plates and the scintillator modules. As described in Section 7.4.1.1, steel plates are manufactured and delivered in large lots. The surface receiving building provides storage space for one month's supply of steel plates and the underground assembly workstation storage carts can hold a one week supply. These are inspected, packaged and stored until they are needed underground.

Scintillator modules are produced as needed by MINOS fabrication facilities, but are delivered in truckloads containing modules for approximately twelve detector planes. Since scintillator modules could be subjected to thermal gradient stresses (caused by differential contraction of components) during the extreme cold of midwinter in northern Minnesota, it may be desirable to avoid shipping during very cold weather. Module shipments are made in heated trucks and shipping crates are insulated. Shipments during the summer months utilize air-conditioned trucks, but could also be suspended if necessary during extreme temperature conditions. Nevertheless, underground storage is provided for up to five truckloads of scintillator modules (60 planes, or about two months supply). Large storage racks with

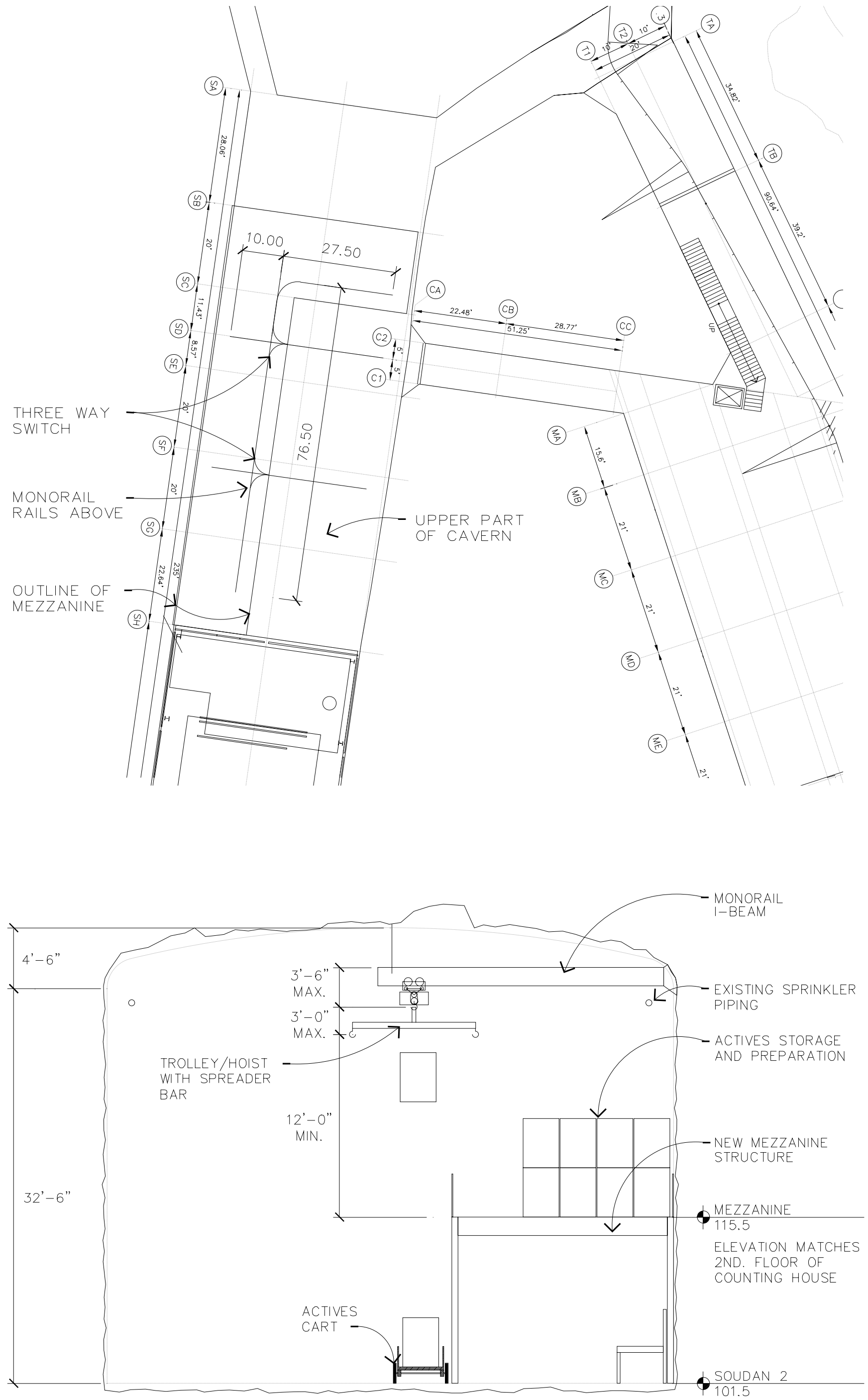

Figure 7.8: Sketches of the scintillator module storage and testing area in the Soudan 2 cavern. The top drawing is a plan view showing the outline of the new mezzanine platform and the track of the overhead monorail trolley/hoist system. The shaft station and entrance to the MINOS cavern are shown in the upper right corner. The bottom drawing is an elevation view of the mezzanine platform.

the required capacity are provided in the Soudan 2 cavern. Since it takes two evening shifts to move the scintillator crates from one truckload underground, heated and air conditioned storage space for scintillator shipping crates is provided in the surface receiving building.

Conflicts between use of the Soudan mine shaft cages by MINOS and for State Park tourists during the summer months require that all movement of MINOS equipment down the shaft occur during the evening (one shift per day) from mid-April through September. This imposes some scheduling constraints and requirements for short-term storage facilities. The Soudan 2 cavern is used for storage of smaller detector components such as photodetector and fiber optics assemblies, electronics modules and other supplies. A total storage area of 45 m^2 is provided for these materials.

7.4.2.3 Setup of installation fixtures

As described in Section 7.3.2, the detector plane installation fixtures are provided by the far detector cavern outfitting task[1]; conceptual designs for most of this equipment have been completed. The strongbacks, pedestals and compression rigs are assembled underground as part of the installation task. Other installation fixtures are assembled during the cavern outfitting period, before beneficial occupancy begins. Practical experience with prototypes of all of these assembly fixtures will be obtained as part of the steel plane prototype studies at Fermilab, as described in Sections 4.4.5 and 7.5.

7.4.2.4 Detector support structure

The support structure for the 5.4 kt MINOS far detector is provided by the far detector cavern outfitting task; it is described in Section 7.3.2 and in Reference [1]. Completed planes of steel and scintillator modules are mounted vertically on this structure using the 25-ton bridge crane. As shown in Figures 7.1 and 7.2, the detector support structure provides work space and access to the sides of the detector by steel-grillwork walkways which extend along its entire length. The structure also supports a set of special cross-bracing beams, called a "bookend," at the upstream end of each supermodule. A bookend acts like a permanent strongback, which rigidly constrains the first steel plane of each supermodule to be in a vertical plane, as described in Section 4.4.1.2. This first steel plane does not have a scintillator plane mounted on it. Each bookend structure also supports a crossover walkway which allows workers to cross between the elevated walkways on the two sides of the detector without returning to ground level. The bookend components are supplied by the magnet steel and coils task.

Special electronics platforms, which will be installed after detector planes are in place, allow photomultipliers, multiplexing boxes and front-end electronics crates to be arrayed along the centers of the four 45° faces of the octagonal detector. The electronics platforms are shown in Figure 7.4.

7.4.3 Detector assembly (WBS 2.4.3)

This Section describes the far detector installation tasks associated with Items #8 through 12 of the technical requirements listed in Section 7.2. Nearly all detector assembly equipment is designed and fabricated as part of the cavern outfitting, magnet steel and coils, and scintillator fabrication tasks. The far detector installation task includes the underground assembly and performance testing of some of this equipment, as well as its operation and maintenance.

The installation of the 486 planes of scintillator modules and steel, along with associated electronics, calibration and data acquisition equipment, is by far the largest part of the far detector installation task. Most of the cost of installation is for technical effort: 39 FTEs are be required during the peak installation period, as summarized in Table 7.3. This total includes the surface and underground moving crews described above in Section 7.4.2, but it does not include the "startup" crew described in Sections 7.1.2 and 7.1.3. The startup crew began its work in FY 1998, about three years before beneficial occupancy of the MINOS cavern; its strength increases from two to six people over the three year period. Startup crew members work closely with the architect engineering firm and with the cavern outfitting contractors. It also participates in the trial assembly of steel and detector planes at Fermilab to ensure that detector installation work gets off to a fast start as soon as beneficial occupancy of the Soudan cavern begins.

Worker/activity	Day shift	Eve. shift	Total FTEs
Supervisor	1	0	1
Coordinator	1	1	2
Crew boss	3	3	6
Welder	1	1	2
Steel/scint. assembler	6	6	12
Module tester & surveyor	2	1	3
Mat'l/supply mover	3	6	9
Plane installer	2	2	4
Total FTEs	**19**	**20**	**39**

Table 7.3: Summary of the technical effort required to install the MINOS far detector during the maximum installation-rate period. In addition to this effort, four physicists per shift are provided by the MINOS Collaboration to assist the technical staff. Effort units are FTEs (full time equivalents).

The three month period immediately following beneficial occupancy of the MINOS cavern is devoted to setup of installation fixtures and equipment. Installation of the first supermodule begins at the end of this time (when full beneficial occupancy occurs) with a technical effort level of 10 FTEs. This increases to the full 39 FTEs during the following three month startup period. Including this ramp-up process, the total technical effort needed for far detector installation is about 70 FTE-years over a 2 year period. In addition to this effort (shown in Table 7.3), the MINOS Collaboration will provide four physicists per shift (including postdocs and graduate students) to assist with the detector installation and performance testing.

The following schedule assumptions have been incorporated into a detailed installation model[4], which is used to determine the 2 year installation period for the 5.4 kt far detector:

- 250 day per year operation, two 8-hour shifts per day, 6.5 working hours per shift.
- Realistic allowances for vacations, holidays, illness and inefficiencies due to assembly flow and shift changes.
- Two workstations operate in parallel.
- Three month setup-commissioning period between beneficial occupancy of the MINOS cavern and the start of the plane installation start-up period.
- Three month start-up period for assembly crew training and manpower ramp-up.
- One week to install each magnet coil.
- Two detector planes completed and installed every 3.7 shifts after the start-up period, with two workstations.
- 12 months to complete the first supermodule (including startup).
- 10.5 months to complete the second supermodule.

The duties of the workers listed in Table 7.3 are described in detail in the far detector installation basis of estimate document[4]. These duties are summarized here:

- **Supervisor.** Perform high-level supervision of installation work and provide interfaces among installation workers, MINOS scientists and engineers, and the DNR.
- **Coordinator.** Provide the interface between installation workers and the University of Minnesota (assumed to be the employer of the installation workers). Order supplies, coordinate shipments of detector components, manage office machines and telephones.
- **Crew boss.** Manage daily activities of steel and scintillator installation workers and provide smooth transitions between shifts. One crew boss is assigned to each workstation and one to the materials moving crew. Provide the interface between the supervisor and the installation workers. Act as foreman and as a general replacement worker and troubleshooter.
- **Welder.** Certified welder: perform a small number of specialized welding operations, assist with routine welding and provide spot checks of routine operations.
- **Steel/scintillator assembler.** Assemble steel and scintillator components into detector planes at two workstations.
- **Module tester and surveyor.** Open scintillator module shipping crates in Soudan 2 cavern and perform radioactive-source and light-injection tests. Perform minor repairs. Place modules for each detector plane in a single crate to facilitate rapid mounting onto its steel plane, and move crates to workstations as needed. Operate detector plane survey cameras, survey detector plane locations. Assist with installation of detector planes as time permits.

- **Material/supply mover.** Surface crew: unload arriving trucks, inspect and repackage steel plates, load arriving materials onto shaft cages. Underground crew: perform cage configuration changes between personnel and material usage, unload material from cages and transport to MINOS and Soudan 2 cavern work areas using fork lifts, monorails and carts.
- **Plane installer.** Operate overhead bridge crane to move completed detector planes from workstations to the detector. Connect fiber optics harnesses and install photodetectors, multiplexing boxes, electronics crates and cabling. Assist physicists with detector plane turnon and calibration.

Table 7.4 gives a breakdown of the time allocated for the different steps of the plane assembly and mounting procedure. Each of the two workstations can assemble and mount a complete detector plane in three shifts. By coordinating their schedules, the two workstations together can install a plane every 1.85 shifts on average.

7.4.3.1 Steel plane assembly

The far detector installation tasks described in this Section are associated with Item #8 of the technical requirements listed in Section 7.2. Each 8-m wide, 1-inch thick steel detector plane is assembled from eight 2-m wide, 0.5-inch thick plates up to 8-m long. These are arranged in two overlapping horizontal layers with the plates in the top layer oriented perpendicular to the plates in the bottom layer. At each workstation the plates are stored in 45-ton carts, which are rolled out from under the overhead monorail using electric trolleys. The gantry crane is used to pick up each plate with plate clamps and place it in position on the strongback. The plates are then wedged together using hydraulic jacks mounted around the strongback. This minimizes the widths of the cracks between plates.

Plates in the top layer have 76 predrilled 1.0-inch diameter holes which are used to plug weld the two layers together under compression, as described in Section 4.4.2 and Section 7.3.2. Once all 8 plates are in place, the compression rig is positioned over a weld point. Typically four plug welds are made in one area. Four 5000-lb jacks compress the area around the welds before plug welding begins. The welding pattern starts in the middle and spirals to the outside of the plane. A total of 35 moves of the compression rig are needed to complete a plane. Each compression rig move, setup and set of plug welds (up to four welds per setup) takes 10 to 15 minutes. A total of 8 hours per plane is allotted for this welding procedure.

The plug welding makes use of a custom-built automated weld head incorporating an automatic wire feed, a submersed arc and a fume extraction system which eliminates nearly all air contamination. This device can be operated legally by the assembly technicians and does not require the services of the certified welder except to spot-check weld quality. The plug-weld areas are cleaned and painted while mounting fixtures for detector modules and fiber optics cables are being attached to the completed steel plane, as described in the next Section.

A magnetic flux integration coil[10] is installed on each plane just before the scintillator modules are mounted. This consists of a multi-turn pickup coil which passes through the central magnet coil hole at a single azimuth and terminates in a readout connector on the

Procedure	**Time**
Steel plane assembly (14 hours total)	
Align 4 bottom-layer plates	1.0 hour
Align 4 top-layer plates	1.0 hour
Move compression rig/welder into position	0.3 hour
Compress/weld at 35 locations, up to 4 welds each	8.0 hour
Remove compression rig/welder	0.2 hour
Tack weld switch plates on top steel face	1.5 hour
Install mounting tabs, bars, pickup coils	1.5 hour
Clean up surface for scintillator modules	0.5 hour
Scintillator plane assembly (6 hours total)	
Install 4 center modules	1.0 hour
Install remaining 4 modules	1.0 hour
Drill module mounting tabs, screw to modules	1.0 hour
Install fiber optics cables	1.0 hour
Performance tests and survey	2.0 hour
Detector plane mounting (4 hours total)	
Inspect plane, attach lifting fixture	0.5 hour
Raise plane to vertical orientation	0.5 hour
Move plane to working face of detector	0.5 hour
Position plane on detector face	0.5 hour
Connect axial rods, coil collars	1.5 hours
Return strongback to workstation	0.5 hours
Total assembly and mounting time	24 hours

Table 7.4: Breakdown of assembly and mounting times for one far detector steel-scintillator plane. Two workstations operate in parallel, so two planes can be mounted on the detector every 24 working hours, or two planes every 3.7 shifts at 6.5 working hours per shift.

edge of the steel plane. Sensitive current integration electronics is used to measure the change in flux through the pickup coil as the magnet coil is energized, and provides a measure of the effective magnetic permeability of each steel plane. These flux measurements are made on individual planes during the initial checkout of each supermodule's magnet; the pickup coils are not monitored during routine operation.

The steel plane assembly operation is performed on two planes in parallel at the two assembly workstations. Each assembly workstation operates independently, and has its own tools, fixtures, and 2-ton gantry crane. Each workstation is continuously staffed by three technicians; a single certified welder serves both workstations.

7.4.3.2 Detector plane assembly

The far detector installation tasks described in this Section are associated with Item #8 of the technical requirements listed in Section 7.2. Scintillator planes are assembled from eight scintillator modules, each one 82 cm or 115 cm wide, which are positioned on the steel plane to form an 8-m wide octagon. The detector plane assembly procedure involves the attachment of an array of scintillator modules to the face of a steel plane after the latter has been assembled, as described in the previous Section. Figure 7.9 is a flowchart of the detector plane assembly procedure. The mounting scheme secures the modules to the steel in a manner which is flexible enough to prevent damage from flexing of the steel plane as it is raised from the assembly pedestal and mounted on the detector. Any distortions of the 2.54-cm thick steel plane which stay within an idealized 4.04-cm thick planar volume will not damage the scintillator, as described in Section 4.2.2.

The scintillator modules, shown in Figure 5.11, are secured to the steel plane by three different mechanisms:

- **Switch plates.** The assembly technicians tack weld an array of switch plates to the plane's face, positioned at intervals of 2 m along the edges of the scintillator module locations. A special template is used to mark the locations of the switch plates before welding. Each switch plate assembly includes a steel packing strap which is pre-formed before installation to the shape required to hold a scintillator module in place. The switch plate design is shown schematically in Figure 7.10. The strap locations on adjacent modules are offset by 1 cm to minimize the gaps between modules.

- **Edge brackets and mounting bars.** Each of the eight scintillator modules has a module mounting bar built into each end, as described in Chapter 5. Self-tapping screws are used to attach the module mounting bars to mounting-tab edge brackets on the top face of the steel plane. These steel strips are tack welded around six sides of the plane by a certified welder. Figure 7.11 shows a sketch of how the mounting-tab edge brackets are used to attach a lower module mounting bar to its steel plane.

- **Shelf bars.** A steel shelf bar is mounted along one edge of each steel plane, under the long side of the scintillator module which will be on the bottom after the plane is mounted vertically on the detector. The shelf bar supports the weight of the scintillator plane and prevents the strips in the bottom module from being deformed by the weight of modules above it. The shelf bar is the structure along the bottom right-hand edge

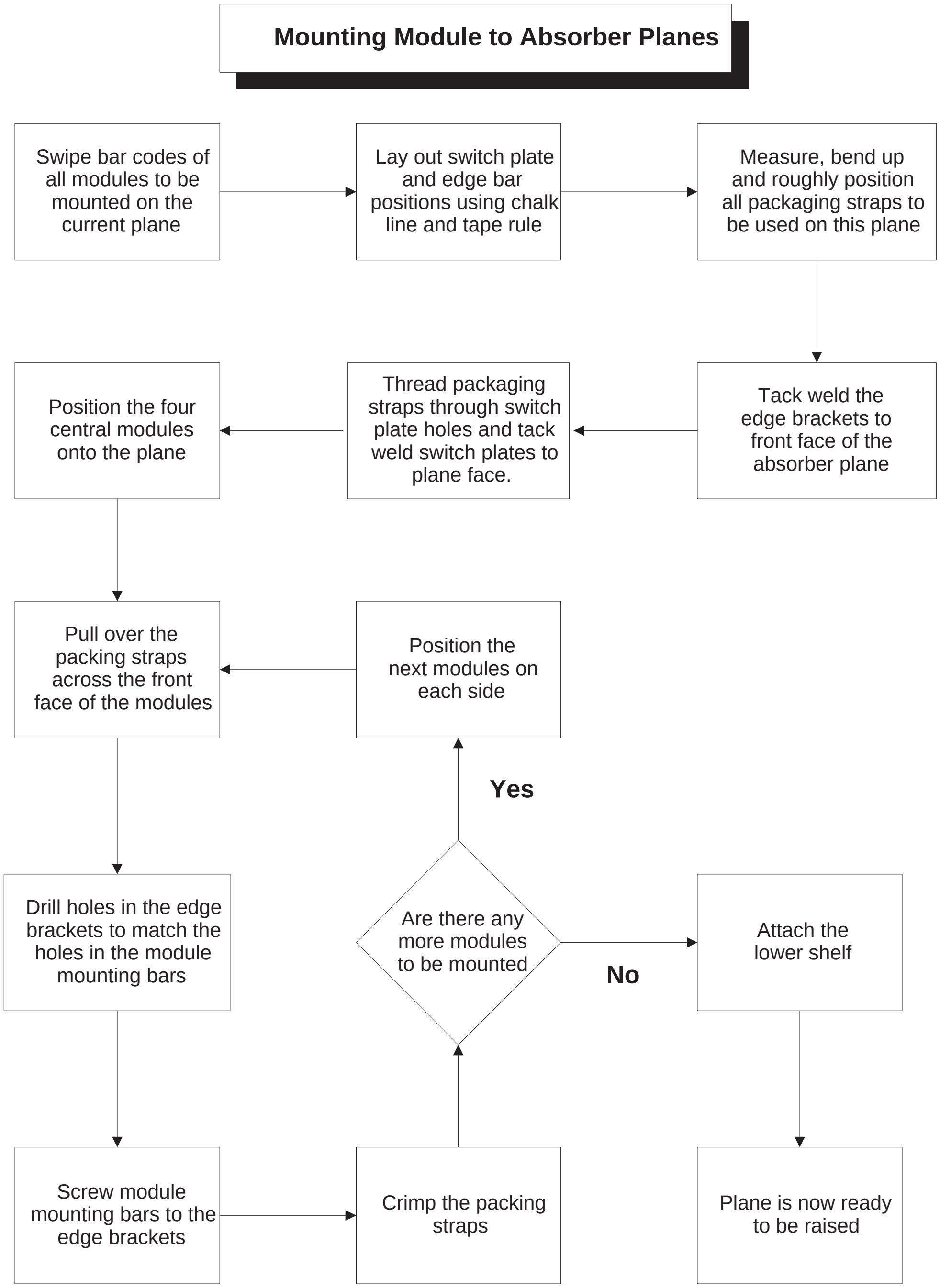

Figure 7.9: Flow chart showing the sequence of steps in the detector plane assembly process.

of the plane shown in Figure 5.11. Each shelf bar is attached to its plane by six adjustable brackets, which allow the bar to conform to module edge which it supports. The brackets are attached to the steel plane edge by short pieces of angle iron which are welded by the certified welder.

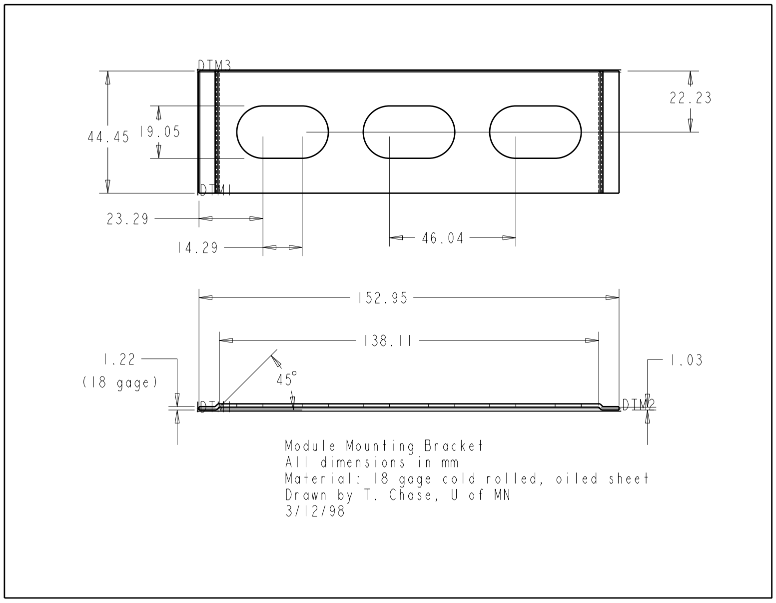

Figure 7.10: Sketch of the switch plate used to secure scintillator modules to steel detector planes with steel packing-straps.

After scintillator modules are mounted, they are given a final performance test using the WLS fiber light injection system and the portable photodetector system. Calibration tests and performance criteria are described in more detail in Chapter 5 and in Section 7.4.5 below.

Any detector modules which fail performance tests are replaced before the plane is mounted vertically on the detector. After a plane passes all tests, the clear fiber optics harnesses are installed in the cable tray around the periphery of the steel plane. The ends of these harnesses which will eventually plug into the multiplexing boxes are temporarily secured to the cable tray for protection during the plane mounting procedure. Finally, the locations of detector elements are recorded using a close-range photogrammetry camera system (see Section 7.4.4).

7.4.3.3 Detector plane mounting

This Section describes the far detector installation tasks associated with Item #9 of the technical requirements listed in Section 7.2. After the assembly and testing of each steel and scintillator detector plane is complete, the 25-ton overhead bridge crane raises the plane-strongback assembly into a vertical orientation and mounts it on the detector. While the plane is vertical, its weight is supported by the strongback support shelves along the bottom edge of the steel plane. The bottom layer of the steel plane rests on support shelves which

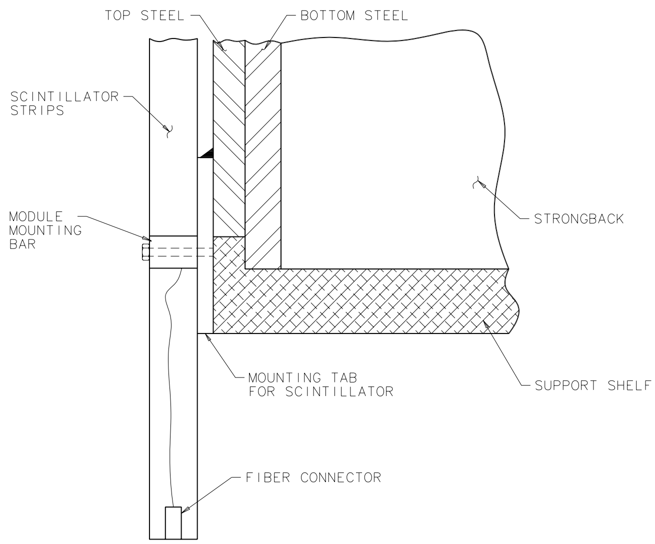

Figure 7.11: Sketch showing how the lower end of a scintillator module is attached to its steel plane using the module mounting bar and the mounting-tab edge bracket welded to the steel plane. The drawing also shows the strongback support shelf which supports the weight of the plane as it is raised into a vertical orientation prior to mounting. The other end of the scintillator module is attached in the same fashion, except that the strongback support shelf is replaced by a steel plane restraining clip on the upper end.

are configured to latch into the steel plane so that it cannot slip off the strongback during mounting. This is shown in Figure 7.11.

During the plane mounting procedure, the steel plane is prevented from tipping away from the strongback by special restraining clips which hold the top of the plane to the strongback. These top clips are released just before the plane "ears" are set on the rails, so that the strongback can be lowered away from the plane after the ears are resting on the support structure rails. In this way the weight of the strongback is never supported by the ears. Both the strongback support shelves and the restraining clips rely on having the width of the "top" steel octagon layer slightly smaller than the width of the "bottom" layer to allow them to grip the steel plane without touching the scintillator plane.

The crane uses a special lifting fixture connected to lifting points on the top end of the strongback. Clamps attached to the assembly pedestal hold the bottom end of the strongback in place while the top end is raised by the crane. A computerized crane control program controls the vertical and horizontal movement of the hook to simultaneously raise the plane-strongback assembly off the assembly pedestal. This program minimizes the force of the pedestal and safely raises the plane into the vertical orientation. The clamps on the pedestal automatically disengage when the plane is vertical, so that it can be moved down the length of the MINOS cavern to the detector planes which have been installed previously. During the lifting procedure all personnel at both workstations must stop work and move to safe locations for 10 to 15 minutes.

The clearance between the detector hair and detector support structure is only 10 cm. This tight tolerance will require the bridge to move rather slowly down the hall. Special protection "bumpers" prevent the plane from hitting the sides of the supports. After the plane is mounted on the detector, the spacing between planes is set to the standard 5.94-cm pitch by rigid fixed supports between the ears and around the coil holes of adjacent planes. This standard pitch allows 2.54 cm for the steel plane, 1.9 cm for the detector plane, and 1.5 cm for steel plane nonflatness. Additional stabilization of the detector planes, which must be kept vertical for structural integrity, is provided by eight axial bolts which attach each plane to its neighbors at the corners of the octagons.

Once the plane is in position, an operator in the special installation "cage" carried by the 2-ton bridge crane (see Section 7.3.2) installs the axial bolts and coil collar piece which hold the plane in place against the previously installed plane. After the plane is securely bolted into place, the steel flatness and position are measured using survey techniques described in Section 7.4.4.

7.4.3.4 Electronics installation

This Section describes the far detector installation tasks associated with Item #10 of the technical requirements listed in Section 7.2.

Figure 6.4 shows schematically the layout of electronics around the far detector. Cosmic ray events which occur in completed detector sections will be recorded by this system as soon as possible in order to validate the operation of the complete system of scintillator modules, electronics and data acquisition. This means that the elements which are common to all supermodules must be installed and brought into operation by the time the first few planes are installed on the first supermodule. These common elements include the hub interface crate and the central system, the trigger farm and the data acquisition system. The hub for the first section of the first supermodule must also be operational at this time. This early availability of the main elements of the electronics system will also provide an operational monitor system. Early experience with the operation of these systems in the far detector laboratory environment will be very valuable in identifying potential problems with electrical noise, the stability of detector systems, and possible operational interference from ongoing assembly work.

After all of the planes which are to be served by a single multiplexing box are in place, the electronics mounting platforms shown in Figure 7.4 are installed and the final fiber optics connections made between the planes and the multiplexing boxes. Installed detector planes and associated front end electronics are turned on and tested with calibration systems (light injection and radioactive source tubes) and cosmic rays at the earliest possible time. The installation and turnon of electronics system components will be performed by teams of installation technicians, physicists and electronics engineers.

7.4.3.5 Detector plane cabling and certification

This Section describes the far detector installation tasks associated with Item #11 of the technical requirements listed in Section 7.2. The final certification of detector plane operation is performed by MINOS Collaboration physicists assisted by installation technicians. After each plane has been mounted on the body of the detector, the clear fiber optics harnesses already installed on the plane are used to check for proper operation while it is still possible to remove the plane for repairs. A special portable multiplexing box, which can be temporarily attached to the fiber optics harnesses from the detector access walkways, is used for this purpose. The fiber optics harnesses are then connected to the permanent multiplexing boxes and read out through the experiment data acquisition system. Cosmic ray calibration data will be recorded continuously from all installed detector planes as soon as soon as they have passed all calibration performance tests.

7.4.3.6 Coil assembly, installation and certification

This Section describes the far detector installation tasks associated with Item #12 of the technical requirements listed in Section 7.2.

The design of the far detector magnet coils is described in Section 4.4.4. Each supermodule's 150- to 180-turn coil[9] consists of a water-cooled central section and an air-cooled current return section, as shown in Figure 7.12. As soon as the last plane of each supermodule is mounted, a one week coil installation period begins. First, the water-cooled bore tube is fabricated and inserted into the central coil hole of the supermodule. The bore tube is constructed from sections of 25 cm diameter, 3.2 mm thick rolled copper tube with eight longitudinal chilled water tubes (2-cm diameter copper refrigeration tubing) soldered to its inside surface. The bore tube is the same length as the supermodule, and provides chilled water cooling for the horizontal section of the central coil. It is fabricated in the area occupied by the plane assembly workstations.

After the bore tube is inserted into the supermodule coil hole, 150 to 180 flexible copper coil conductors and 7 additional copper cooling tubes are pulled through it. The conductors are commercial grade 1/0 stranded copper building wire (TGGT) with Teflon insulation, 1.48 cm in diameter. The coil conductors are pulled through the bore tube in small bundles, seven of which include 2-cm diameter copper cooling-water tubes. The procedure disperses the cooling tubes as uniformly as possible in order to maintain a homogenous temperature profile inside the coil. The bore tube is packed tightly to maintain good heat transfer between the conductor turns and the cooling tubes. After each coil turn has been installed in the bore tube, its remaining length is placed in fixtures provided for the horizontal and vertical return sections of the coil. The fixtures provide space between layers of the coil for air circulation. Coil installation requires 1.5-m long work spaces between supermodules.

Connections between the turns of the two coil sections and the power supply are made with a crimping tool and then insulated. The bore tube is designed to limit the temperature rise of the steel planes and scintillator near the coil hole to less than 2° C. The maximum operating temperature in all sections of the coil is expected to be less than 50° C, compared to the 200° C conductor temperature rating. The Teflon conductor insulation permits normal operation even if the return coil floor trench should be filled with water as the result of an accident. The 9° C chilled water for the cooling tubes removes heat from the central coil section directly to the cavern cooling system heat exchanger, as described in Section 7.4.1.6.

Magnet operation is monitored continuously by measuring the coil current. The relationship between the current and the toroidal magnetic field in each steel plane depends in a complicated way on the permeability of the steel and the geometry of the gaps between the plates which make up that plane. The average magnetic properties of each plane are measured using its flux integration coil soon after each supermodule's magnet coil is installed,

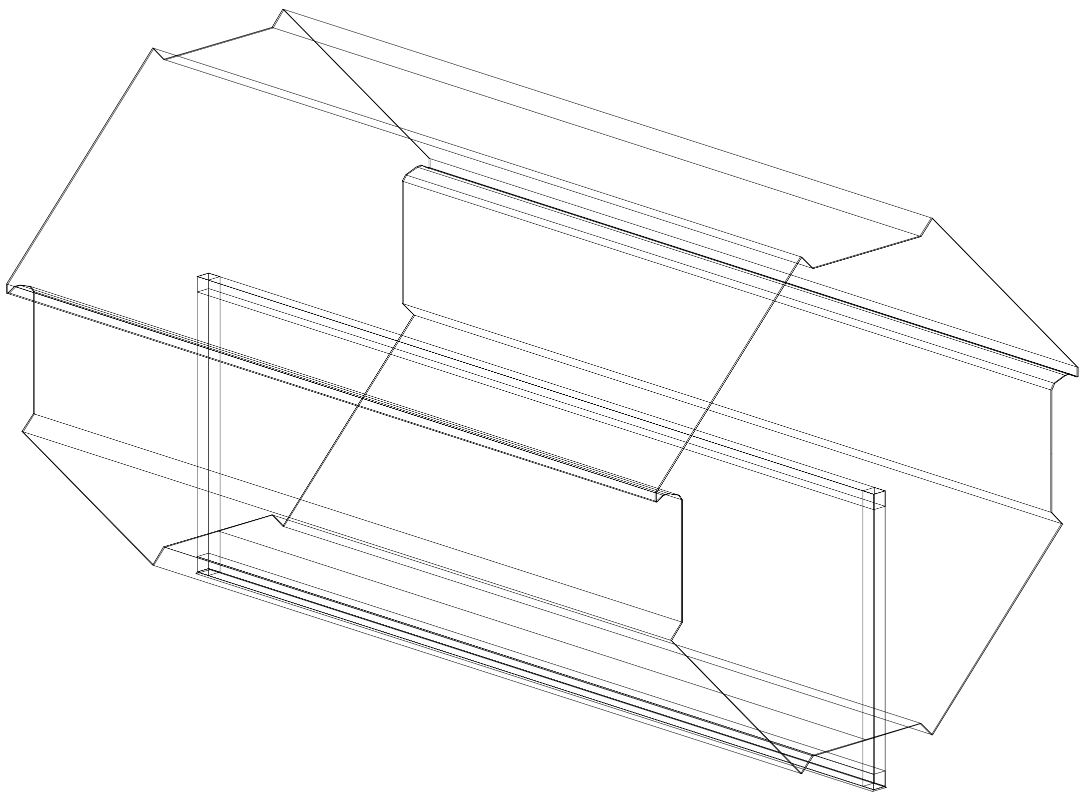

Figure 7.12: Sketch of the far detector coil geometry for one MINOS far detector supermodule. Each of the 150 to 180 turns of insulated copper wire is pulled through the water-cooled bore tube in the center of the detector. The return current section of each turn is supported by fixtures, which provide space for air circulation between layers of turns, along the vertical legs and in the horizontal floor trench. Splices between turns are made by crimping near one of the bottom corners of the coil.

as described in Section 7.4.3.1 above. Each plane is measured as part of the initial magnet certification procedure, but the pickup coils are not monitored during routine operation.

7.4.4 Alignment and survey (WBS 2.4.4)

This Section describes the far detector installation tasks associated with Item #13 of the technical requirements listed in Section 7.2.

The center of the several kilometer wide NuMI neutrino beam must be within about 75 m of the center of the MINOS far detector in order to be able to predict the energy spectrum in the far detector to 2%, or better than 1 GeV in each energy interval, based on the measured near detector spectrum. This is required for the CC-event-energy physics test, discussed in Section 3.7.1, which has the potential to measure neutrino oscillation parameters. Techniques for accomplishing this important survey task are described in the NuMI Facility Technical Design Report[11].

The orientation of the axis of the MINOS far detector relative to the axis of the NuMI neutrino beam will be determined by the accuracy of the underground survey measurements made during the MINOS cavern excavation at Soudan. The angle between the beam and detector axes is important only insofar as it affects the neutrino-event acceptance of the detector, primarily through the containment of muons. The MINOS detector magnet will focus most muons toward the detector axis, which removes most of the sensitivity to the angle between the beam and detector axes. This allows the far detector to be constructed on a flat, horizontal floor, and makes it insensitive to the 57 mr vertical pitch of the neutrino beam.

The absolute location and orientation of the MINOS cavern and detector support axis will be determined by standard underground survey techniques during the excavation phase of the experiment. Survey work will be performed under the joint supervision of CNA Consulting Engineers and the Fermilab Alignment Group. A final, precise survey of the detector orientation will be performed after the support structure is in place. Standard underground survey methods are expected to set the cavern axis orientation very accurately; for example, the Soudan 2 cavern axis was set parallel to the North-South direction to much better than 1° using these techniques.

The determination of the locations of all the scintillator strips in the MINOS far detector is the primary survey challenge for the far detector installation task. This information is needed for event reconstruction and as input to the detector-response Monte Carlo simulation program. This determination is expected to achieve an accuracy of ± 2 mm, and involves the following steps:

1. The location of scintillator strips within each scintillator module will be determined at the scintillator fabrication facilities and entered into the survey database.

2. The locations of individual scintillator modules will be measured by a close-range photogrammetry camera system which photographs each detector plane just before it is raised into position on the body of the detector. This is described in more detail below.

3. Offline analysis of these photographs will provide module locations relative to the individual steel plane coordinate systems for the survey database (see description below).

4. Survey targets on the edges and downstream face of each steel plane will be measured after installation to determine its location along the detector axis.

5. The flatness of each steel plane will be measured from its downstream surface after installation. This is to ensure that the plane is hanging stably and has not been deformed during mounting (see Section 4.4.1.3), and that it is flat enough to permit installation of the next plane.

6. The absolute location and orientation of each scintillator strip will be determined from the database information provided by the steps above.

7. These survey coordinates will be used to reconstruct the trajectories of cosmic-ray muons (mostly vertical) and muons from neutrino interactions (mostly horizontal). Fits to these trajectories will yield small corrections to the strip locations, and will also detect most types of errors in the survey database.

An example of a photographic survey system which might be used for MINOS is provided by Eos Systems[12], whose close-range photogrammetry software can achieve 1:8000 accuracy. The system requires:

- A medium format camera (2-inch $\times$ 2-inch format).
- A PhotoCD Pro scanner (larger than the standard retail 35 mm PhotoCD scanner).
- Clearly identifiable fiducial marks.
- About 6 photographs per plane.
- Eos Systems PhotoModeler software[12].

Relatively inexpensive medium-format cameras suitable for this use are available from several suppliers. Eos systems estimates that it would be a full time job for one person to take the photos and determine the coordinates of 100 points per plane at the MINOS plane installation rate. Most of this effort is for processing the photographs, and can be supplied by inexpensive student labor at collaboration universities.

Additional survey tasks include the determination of the locations for scintillator module mounting hardware, fiber optics cable brackets, and magnetic flux integration coils on the steel planes before scintillator modules are mounted. These are low precision applications which can be accomplished by the plane assembly crews through the use of templates, and will not require significant effort from the survey crew after the initial setup period.

7.4.5 Final checkout and validation

The performance tests described in this Section are used repeatedly throughout the assembly and installation process to ensure that all components are working properly before final installation. The tests are finally performed after each plane is installed on the detector and connected to its final photodetectors and electronics. Successful completion of this step constitutes the transition to routine operation and the completion of Item #14 of the technical requirements listed in Section 7.2.

The main goal of the performance validation task is to ensure that the response of scintillator modules meets design specifications. Changes in the response of MINOS scintillator, WLS fibers, photodetectors or electronics could be caused by changes in temperature, humidity, pressure and by environmental conditions experienced during shipping. Near and far detector response differences could result in differences in energy calibration, leading to reduced sensitivity to oscillations or even to spurious oscillation signals.

Calibration techniques and instrumentation are described in detail in Sections 5.4.6 and 6.4.1.2. These same techniques will be used at the fabrication facilities, at the near and far detectors and at the test beam calibration setup:

1. **Radioactive source tubes.** Each scintillator module has two built-in guide tubes, one at each end of the module, which cross the ends of all scintillator strips. Radioactive calibration sources can be moved inside the tubes to determine the light output at both ends of each strip. This technique measures the scintillator light output in addition to WLS fiber attenuation. Cross calibrated sources (which have been compared to the same reference source) will be used at the near and far detectors. The system can also be used to set photodetector gains when a detector plane is first turned on after installation.

2. **Module mapper.** The module mapper is an automated device which can scan the entire surface of a scintillator module with a rapidly moving ^{137}Cs source to detect variations in scintillator response. Module mappers are used at the module factories to certify the response uniformity of modules just before they are packaged for shipping. A mapper will be set up in the Soudan 2 cavern testing area to check the response of arriving modules as they are removed from shipping crates. It will be used to perform detailed response studies on every module in the first few shipments, and to spot check modules after routine installation has begun.

3. **Light injection at WLS fibers.** The bundles of WLS fibers at each end of a scintillator module pass through light-flasher injection blocks near the fiber optics connectors. The light flasher intensity can be varied to measure system response over its entire dynamic range. Light flasher intensity also is measured by a standard photodetector system to allow comparison of the responses of modules illuminated by different flashers and in different locations. All photodetector pixels can be illuminated and measured by this technique.

4. **Light injection at photodetectors.** A second light flasher system is used to illuminate photodetector pixels directly. This system will be used primarily for troubleshoot-

ing, and will not have the absolute calibration capability of the WLS fiber light flasher system.

5. **Charge injection at front-end electronics.** A special charge-injection circuit at the input to every preamplifier channel allows the response of photodetector electronics to be calibrated independently from that of the photodetector. This pulser-driven system can be used to check automatically the response of the complete electronics readout chain over its entire dynamic range.

6. **Cosmic-ray and neutrino-produced muons.** After detector planes have passed all validation checks and are in full operation, high energy muons from cosmic rays and neutrino interactions will provide the best measurement of the relative dE/dx response of the MINOS near and far detectors. This technique can only be used when enough scintillator planes have been installed to permit the selection of events with isolated single muon tracks. Although the energy spectrum of cosmic ray muons will be slightly different at the near and far detectors, and the spectrum of neutrino-induced muons could be different because of oscillations, the measurement of muon energy by curvature and range allows absolute calibrations of scintillator charge response to be made with muons of known energy. The main drawbacks of this technique are the low rate of muons at the far detector and the fact that scintillation light from single muons calibrates only a single point at the low end of the dynamic range of the system.

The radioactive-source and WLS fiber light-injection techniques will be used to confirm the proper response of scintillator module strips immediately after modules arrive in the underground laboratory. These methods will be used again to certify proper operation of strips just before each detector plane is installed in the main body of the detector. For both of these tests a portable photodetector array will be employed. After each plane is installed in the detector, it will be connected through its fiber optics harnesses to its final photodetector and electronics readout systems as soon as possible, i.e., after enough of its neighboring planes are installed so that the multiplexing box platforms can be put in place. The radioactive source and light injection calibrations will be repeated, and the accumulation of data from muons will be started. Radioactive source calibration will be performed occasionally on individual modules after installation. There will not be a permanently installed source driver system for automatic calibration of the whole far detector.

A second important validation task is to determine the magnetic field in each steel detector plane to obtain the relative calibration of muon energy measurements at the near and far detectors. A magnetic flux integration coil will be installed on each plane as described in Section 7.4.3.1, and the current in the magnet coil itself will be measured precisely. A magnetic field simulation model will provide a cross check on the direct magnetic measurements for a subset of the steel planes; the simulation will use maps of the gaps between the 2-m wide plates and measurements of the magnetic properties of the plates. The magnet power supply will be able to produce currents higher than those required for normal operation for short periods of time, allowing the magnet to be taken through a full hysteresis cycle to remove the effects of any residual fields. The magnetic field validation techniques will be fully tested with full size steel planes as part of the detector plane prototype program at Fermilab (see Section 4.4.5 and Section 7.5.1 below).

Other validation tests consist of simple checks to confirm that the parameters in the Monte Carlo simulation of the far detector are correct. The mass and thickness of the individual steel plates making up each detector plane will be measured on the surface, immediately after the plates arrive at Soudan. The survey database will provide an accurate geometrical model of the detector. Test beam measurements on a model of the MINOS calorimeter will be used to calibrate the Monte Carlo response parameters, and the relative dE/dx response of test-beam and far-detector modules will be determined from the radioactive source calibration technique.

7.5 Future optimization and engineering

Most of the activities described in this Section will occur during FY 1999. They are part of the engineering and design phases (included under EDIA costs) of the far detector installation tasks described in Section 7.4.

7.5.1 Trial assembly of prototype planes

The assembly of full size prototype planes of steel and scintillator is an important part of the engineering optimization process for the magnet steel and coils task and the scintillator fabrication task, as described in Chapters 4 and 5. This process has already started with the construction of the first (2-cm thick) steel plane prototype in the New Muon Lab at Fermilab. A series of increasingly more realistic steel and scintillator prototype planes will be built to optimize the installation and mounting procedures.

The prototype plane program requires the construction of a second hanging-file support structure so that planes can be removed from the main support structure and temporarily stored while other planes are returned to the assembly pedestal to try alternative scintillator module mounting techniques. The culmination of this process will be the assembly at Fermilab of two 4-plane structures (4 steel planes and 3 scintillator planes) with magnetized steel and operating scintillator modules. The first 4-plane prototype setup will be used to test and certify the designs of all installation fixtures, machines and assembly procedures.

The second 4-plane prototype will be used to train the far detector installation technical staff supervisors and crew bosses in the construction, calibration and operation techniques, beginning about a year before installation starts at Soudan. This process will involve the far-installation "startup" crew (see Section 7.4.3) and some of the assembly technicians. This will assure that the installation procedures are well understood by the time the outfitting of the MINOS far detector cavern begins. Assembly fixtures will be built for the two far detector workstations around this same time.

Of course the main focus of the first 4-plane prototype studies will be to test the procedures for assembling the steel detector planes, for mounting scintillator modules on steel planes, and for installing the planes of steel and scintillator on the support structure.

A second important goal of these studies will be to test the handling system for steel plates, scintillator crates and peripheral equipment which has been designed for use at Soudan. Most of the equipment, methods and constraints envisioned for this system are commonly used in similar applications, and do not require extensive prototype studies. In this category are both monorail systems, the gantry cranes, the bridge crane and the storage and transport carts. However, some of the equipment, methods and constraints have been designed specifically for MINOS, and do require prototype studies for engineering optimization. These procedures include the plate bundle sequence of surface unloading, hoisting underground, underground unloading, transfer by gantry crane from storage carts to the assembly pedestal, use of the compression rig, and plane-strongback pickup and transport. These installation issues will be evaluated during the initial 4-plane prototype tests. It is important to perform these tests before the new shaft cage is built because the mine shaft and headframe were designed for hoisting heavy loads from underground to the surface, but not for hoisting from the surface to underground. Neither may be significantly modified due to their historic nature.

The plan described below, using the plates acquired for the 4-plane prototype, would demonstrate that the currently proposed methods and equipment are suitable, provide time and motion information as a basis for better installation estimates, and provide a test bed for development of the bundling, strapping, packing and clamping hardware necessary. The entire plate bundling sequence will be simulated using the existing bridge cranes and related equipment present in the New Muon Lab at Fermilab, where the 4-plane prototype tests will be conducted. Specific stages are:

- Unload plates from a delivery truck, using a crane to simulate actual unloading procedures at Soudan.
- Rebundle the plates using the planned bundling holes, hardware and fixtures.
- Add banding and blocking to protect edges of plate bundles.
- Lift completed bundle on edge to test surface loading concept.
- Simulate loading in through the front of the cage, with the edge-stacked bundles lifted and rotated into position in a dimensionally-correct framework simulating the new cage. Accurately represent the load transfer from trailer to cage.
- Attach the plate bundle to the simulated cage, using bundling and clamping hardware.
- Detach the plate bundle from the simulated cage.
- Simulate unloading out through the back of the cage framework, with the bundle lowered and rotated into position for the monorail. Accurately represent the load transfer from cage to monorail.
- Place bundles in edge storage and unbundle.
- Simulate moving single plates from edge storage into place on the assembly pedestal.

7.5.2 Integration engineering

MINOS engineers have now completed detailed conceptual designs of all major detector systems in order to demonstrate technical feasibility and provide realistic bases for cost estimates and schedules. However, some of the interfaces between detector systems present engineering challenges which have only recently been addressed in detail, particularly for closely-related systems which have been designed by different groups. Further "integration" of MINOS detector systems will be the focus of much of the engineering optimization and prototype work during FY 1999. The final designs will be evaluated as part of the full-size detector plane prototype program at Fermilab. These studies will involve close collaboration among the installation, magnet steel and coils, scintillator fabrication and electronics tasks. Examples of integration areas include:

- Optimization of tradeoffs between labor-intensive procedures performed during scintillator fabrication and during installation. Installation tasks must often be performed serially because of limitations on space and manpower in the underground laboratory, so it is often efficient to expend extra effort for prefabrication at above-ground facilities in order to save time underground. Much engineering effort has already been devoted to optimization of such tasks, but more is needed.

- The mounting of detector modules on steel planes. Plans are now being made to test the designs for detector plane mounting described in this Report as part of the detector plane prototype program at Fermilab.

- The effect on scintillator modules of steel plane nonflatness, of steel plane deflections during installation and of stray magnetic fields.

- The mounting of photodetector and electronics hardware on the detector planes. Personnel access to this equipment, and the identification and replacement of faulty components, are issues of particular concern.

- The installation of the magnet coils in supermodules, the mechanical details of conductor splicing, and the installation and operation of the cooling system and power supply.

- Optimization of survey techniques and the required precision of survey measurements.

7.5.3 Electrical power and cooling issues

The engineering of the infrastructure systems needed for the MINOS underground laboratory at Soudan is already well advanced, as described in Section 7.4.1.6. The systems required are similar to those already in operation in the Soudan 2 laboratory, and will be built and installed as part of the MINOS cavern construction and outfitting task. Involvement of the installation "startup" crew (Sections 7.1.2 and 7.4.3) in the commissioning of the cavern infrastructure will ensure a smooth transition between the outfitting and far detector installation tasks. Two important differences between the MINOS and Soudan 2 infrastructure systems are the larger air cooling requirements of MINOS (260 kW *vs* 70 kW) and the larger population of workers required to install MINOS (39 FTEs in two shifts *vs* 6 FTEs in one shift).

The air cooling needs are of particular concern because the Soudan 2 laboratory appears to be close to saturating the natural cooling capacity of the Soudan mine shaft air flow. For this reason a water chiller system, with twice the cooling capacity needed for the anticipated 260 kW heat load, is being specified as part of the MINOS cavern outfitting bid package. However, a much less expensive air-cooled system is also being developed as an alternative to the conservative design used for the cost estimate. The alternative cavern cooling system would use large fans to transfer heat from a water-cooled chiller outside the MINOS cavern to the natural flow of cool air up the Soudan mine shaft. Initial calculations show that this would heat the mine-shaft air to a temperature in excess of 100° F. In order to predict the impact of this temperature rise on the Soudan mine shaft air flow (and also on wooden shaft timbers, bats and tourists), experimental measurements of the effect of large electric heaters have been made in the Soudan mine shaft during the past year.

Finally, the power needs of all MINOS and CDMS systems are being continuously reviewed to ensure that cooling costs are properly taken into account as the design of these experiments proceeds.

Chapter 7 References

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[7] The Fermilab NuMI Project Staff, "NuMI Project Cost and Schedule Plan," October 1998, Fermilab report NuMI-362.

[8] The University of Minnesota and the Minnesota Department of Natural Resources, "Environmental Assessment Worksheet for MINOS Excavation at Soudan," August 1997, Fermilab report NuMI-L-297.

[9] N. Bednar *et al.*, "Basis of Estimate for the MINOS Far Detector Magnet Coils," September 1998, Fermilab report NuMI-L-404.

[10] P. Schoessow *et al.*, "MINOS Toroid Magnetic Measurements," February 1998, Fermilab report NuMI-L-347.

[11] The Fermilab NuMI Group, "NuMI Facility Technical Design Report," October 1998, Fermilab report NuMI-346.

[12] Eos Systems in Vancouver, B.C., Canada provides PhotoModeler software which would be suitable for recording the locations of MINOS detector elements. The software uses scanned or digital photos to do close-range photogrammetry with ± 1 mm precision.