Chapter 4

Phototube Support Structure

The photomultiplier tube support structure (PSS) includes the hardware for supporting the 1280 main and 240 veto photomultiplier tubes (PMT's), the optical barrier separating the main and veto oil volumes, the fixtures for support and strain-relief of the PMT cables, and support for the various in-tank calibration and monitoring systems. The dimensions of the sections of the PSS are chosen to uniformly distribute the main PMT's over the inner surface of the optical barrier and the veto PMT's over the tank wall.

4.1 Design constraints

The allocation of PMT's in the main tank and veto and the thickness of the veto region were determined by physics considerations and were arrived at using Monte Carlo simulation of signal and background events. The Monte Carlo studies used a full GEANT simulation, including tracking of individual Čerenkov and scintillation photons, with wavelength-dependent absorption, reflection, and detection efficiency. Analysis of events in the main tank indicated that at least 10% photocathode coverage (defined by treating the photocathodes as flat disks with diameter equal to the PMT diameter) was needed to provide the required particle identification quality. When tuned to the secondary requirement that veto and main channels not be mixed in the same electronics crate, a final number of 1280 main phototubes resulted.

The total number of PMT's available is limited by cost and the number of available electronics channels. This allows 240 veto PMT's, and the issue is whether the veto region then yields sufficient light to reject muons from cosmic rays and beam-neutrino interactions outside the tank with efficiency $> 99\%$, the design goal. Monte Carlo studies, including conservative estimates of the albedo of the painted surfaces in the veto (see Sec. 4.3), indicated that the light yield with a 35-cm veto thickness was high enough to allow reasonable thresholds in the face of noise and light leaked from the main tank. Separate calculations showed that shadowing of muon tracks by the struts and cables that will penetrate the veto region were negligible.

It is not possible to distribute the phototubes over the sphere with exact uniformity. For reasons of structure and ease of installation, the PMT's are deployed in evenly-spaced horizontal rows. The number of tubes in each row must be even and is chosen to maintain horizontal spacing that is as close to uniform and as close to the vertical spacing as possible. The final variable in the layout is the horizontal "clocking" of each row. Monte Carlo studies showed that this is not a serious issue. In any case, adjacent rows typically do not match in number of tubes, so any initial correlation is lost as the rows go around the tank. Near the equator, however, there are several rows that could line up. For this reason, even-numbered rows start with a tube at $\phi = 0$, and odd-numbered rows start with the first tube shifted by half the horizontal spacing of the tubes.

Most of the PMT's used in MiniBooNE are 8-inch Hamamatsu R1408's recycled from LSND. However, as discussed in Chapter 6, we have purchased 330 newer R5912 tubes (also 8-inch). As these new tubes have better time and charge resolution, all will be used in the main tank. They have been assigned random positions in the tank, with a distribution of new and old tubes shown in Fig. 4.1.

4.2 Structure

Besides the obvious requirement of adequate strength, the PSS must be straightforward to install and must be tolerant of deviations of the tank wall from a perfect sphere. (Industry standards limit such deviations to 1%, or about 5 inches.)

The basic design of the support structure is shown in Fig. 4.2. The optical barrier and inner PMT's are mounted on a set of latitudinal hoops or "lats," each made of sections of 2-inch diameter, $\frac{1}{8}$-inch-wall aluminum tubing. The sections are independently supported, but are connected by sleeves to aid alignment. Each hoop section is clamped to 1-inch-diameter steel struts (see Fig. 4.3), which are in turn bolted to bosses welded to the tank wall. The 1280 PMT's viewing the main oil volume are mounted on the panels of the optical barrier.

The PSS is designed to be tolerant of irregularities in the shape of the tank wall and in the position and orientation of the bosses welded to it. After the tank was complete and the bosses welded on, the Fermilab Alignment Group surveyed the boss locations. As shown in Fig. 4.4, the survey indicated radial excursions on the order of an inch in the tank wall. We fabricated the struts in $\frac{1}{4}$-inch increments in length, with each boss assigned a strut length based on the survey. The base of each strut is a disk with a recessed ball-bearing at

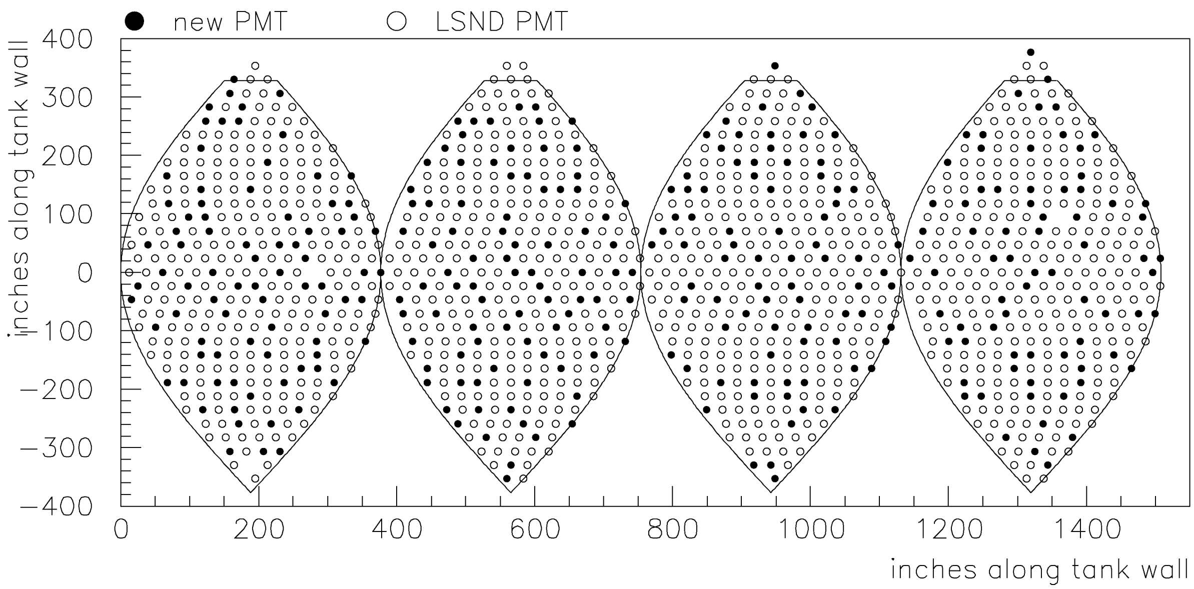

Figure 4.1: Main phototube layout. PMT's are not drawn to scale. There are a few gaps in this map where tubes had not yet been assigned.

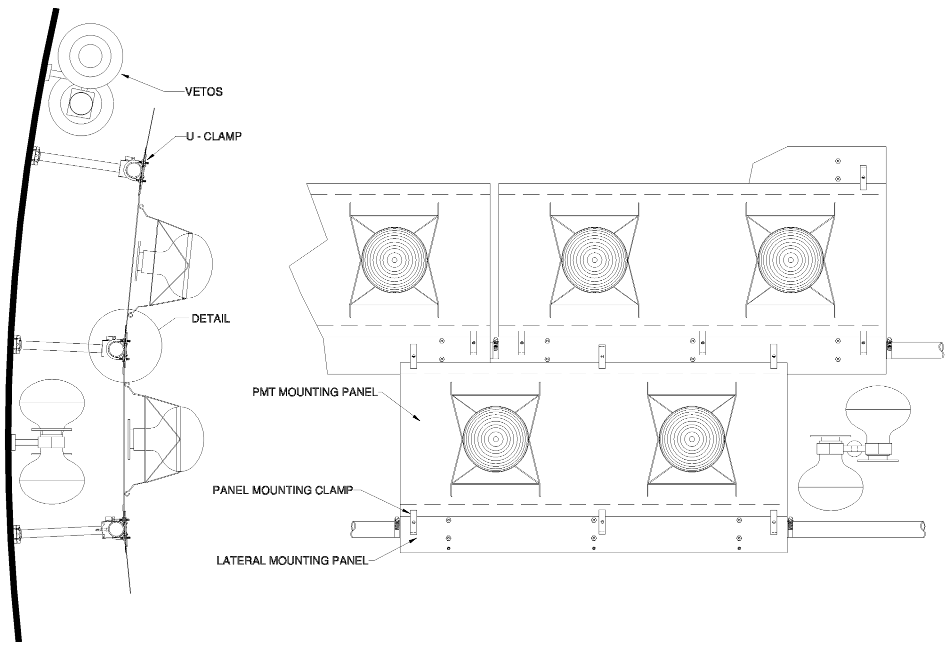

Figure 4.2: Overview of the Phototube Support System. Note: this figure shows an obsolete version of the veto cluster.

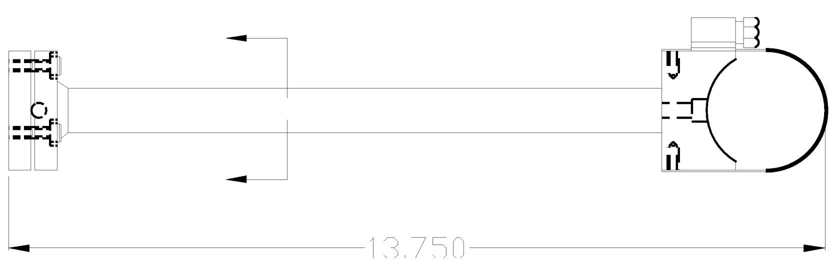

Figure 4.3: Struts with mounting hardware. The boss, welded to the tank wall, is on the left; the clamp for holding a lat section is on the right.

the center. This provides a pivot point, and the relative tightening of the three mounting bolts can move the other end of the strut by about an inch in any direction. This provides further compensation for irregularities in the tank wall and allowed generous tolerances in the placement of the bosses on the tank wall, minimizing the cost of their installation.

The panels of the optical barrier are made from $\frac{1}{16}$-inch aluminum sheet. Each panel is approximately 4 feet wide by 2 feet high and holds two PMT's. We had anticipated rolling the panels to the correct curvature. However, experience with a full-scale prototype of a section of the PSS indicated that flat panels easily conformed to the lats, resulting in substantial cost savings. When mounted, each row of panels forms a section of a cone, with the whole optical barrier approximating a sphere. Figure 4.5 shows a typical panel. The panels do not mount directly to the lats. Instead, the panels mount to 6-inch-wide strips which in turn mount to the lats using U-bolts. The panels are attached to the strips by clips. The lower clips clamp the panels to the strips, while the upper clips capture the panels without clamping them. Gaps of about $1''$ are left between adjacent strips and panels in the same rows. These gaps are blocked by thin aluminum strips, pop-riveted to the strip or panel on one side. This arrangement has a number of virtues:

- The overlap provides a robust optical barrier.
- Variable gaps between panels horizontally and vertically allow loose mechanical tolerances, easing installation.
- The use of the strips and clips decouples the horizontal positions of panels in adjacent rows. This and the gaps mean that installation variations do not accumulate as rows are added.
- The fact that the panels are clamped only along one edge (and, similarly, the inserts connecting the lat pipe sections are only fastened on one end) allows the structure to shift slightly after installation.

It is also worth noting that, with the exception of the polar caps, each piece of the PSS can be carried by one person.

The ability of the sections of the structure to slide a little may be important when the tank is filled with oil. A finite element analysis of the tank showed that, while the displacements of the tank wall were, as expected, very small, differential motion of nearby struts could magnify this effect. The largest relative displacements, about 3 mm, occurred between strut pairs that straddled the region where a tank leg joined the sphere. Because our ability to handle differential horizontal motion is more restricted, we modified the boss layout to have bosses centered horizontally on each leg (see Fig. 4.4), reducing the maximum relative horizontal displacement to less than 0.5 mm.

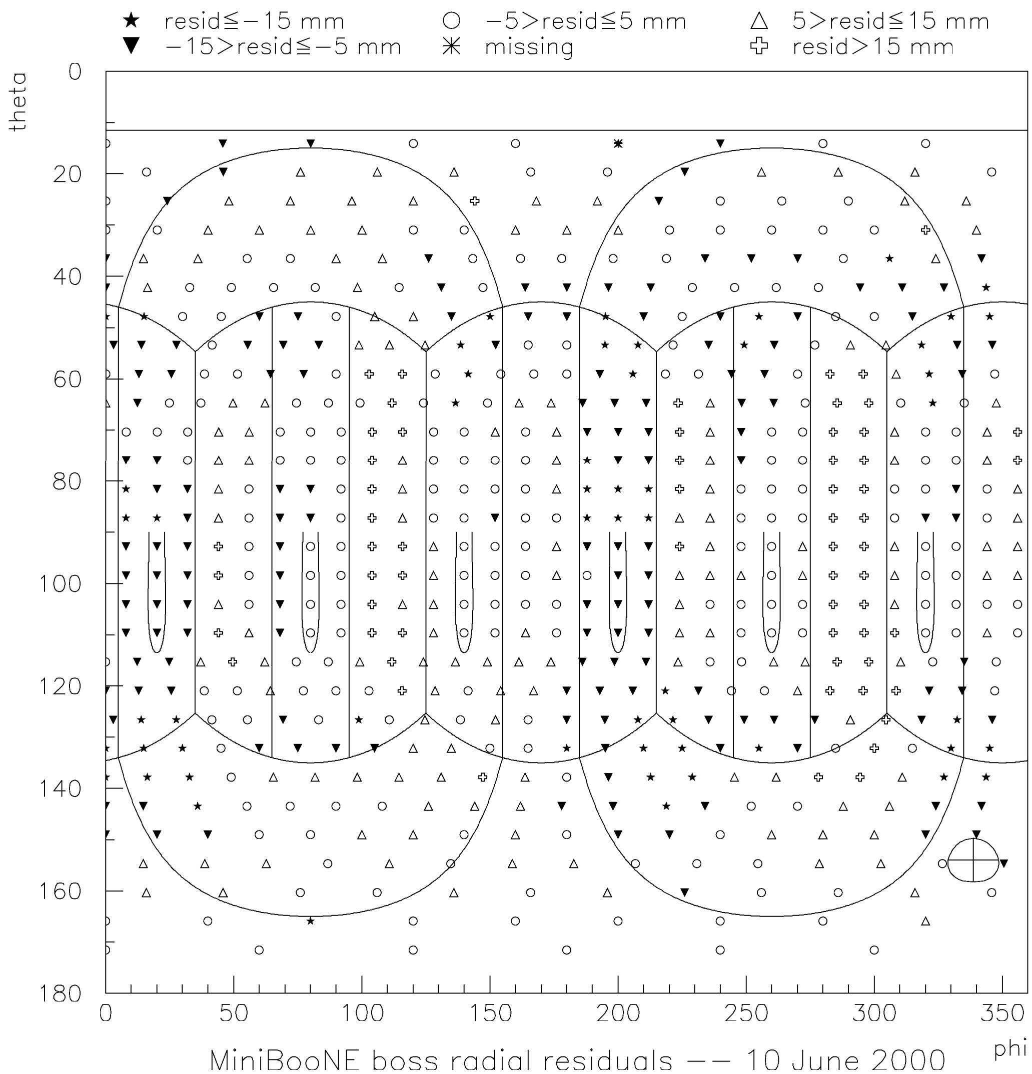

Figure 4.4: Survey of radial deviations of the tank from the best-fit sphere. Each main boss has been surveyed. In this cylindrical projection, the long lines are the edges of the panels forming the tank, the U-shaped lines are where the legs join the tank, and the squashed circle is the access port.

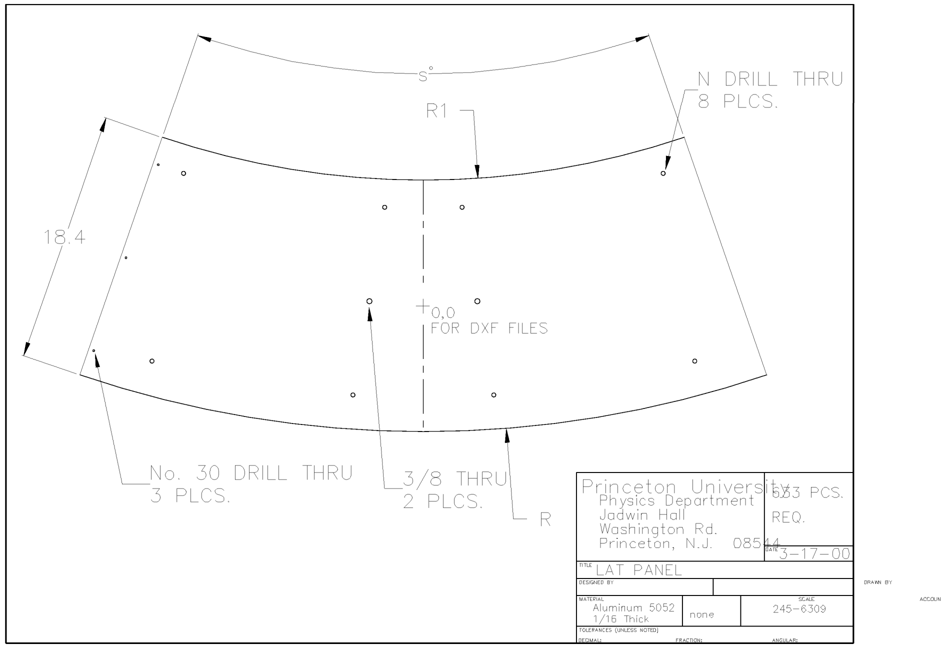

Figure 4.5: A typical panel of the optical barrier.

To ensure uniform distribution of the oil during filling and circulation, there are several ports through the optical barrier. These are equipped with baffles to prevent light from crossing the barrier.

Two PMT's are mounted to each panel using the existing PMT mounts from LSND (see Fig. 4.6). The majority of the LSND PMT's will be left in their mounts when they are removed from LSND. Some LSND tubes, to be used in the MiniBooNE veto, have to be removed from the stands. New tubes will be mounted in the stands thus freed up. The stands attach to blocks mounted on the panels. These blocks are designed to accomodate both existing sizes of LSND stand. When LSND was opened to harvest the phototubes, it was found that about 100 tubes had floated out of their stands. It was thus necessary to modify the support scheme. This is discussed in Sec. 4.6.

The veto PMT's are mounted in pairs on struts attached to bosses welded to the tank wall. Since the veto mounts were initially designed to use the same sticky foam tape that failed in the LSND mounts, a more secure scheme was

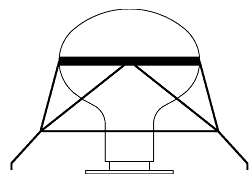

Figure 4.6: 8-inch photomultiplier in LSND stand.

developed. This scheme is shown in Fig. 4.7. Each phototube rests on a viton o-ring which in turn sits on a step in the end of an aluminum pipe. A cross of stainless steel wire captures the globe of the tube against the o-ring, while nylon screws center the neck of the tube in the pipe. The orientation of each cluster on its strut can be varied to avoid obstructions. Monte Carlo studies showed no differences in average light collection among various possible patterns in the orientation.

Tables 4.1 and 4.2 show the layout of main-tank and veto PMT's. The main PMT's are about 55 cm apart; the veto tubes are about 2 m apart. Table 4.3 gives the placement and dimensions of the latitudinal hoops. Table 4.4 shows the weight of various PSS components. These weights can be compared to the approximately 38 tons of the tank shell itself and the approximately 800 tons of oil.

To facilitate installation, the top and bottom "polar caps" will be treated specially. Each will hold the polar PMT, the next row of 6 PMT's, and, on the back, the polar veto cluster. The bottom cap will have to accomodate the coaxial fill pipe (see Sec. 3.5.3). The top cap will also hold the scintillator cubes of the calibration system (see Chapter 5). Each cap will be lowered into place as a unit, with the PMT's already mounted to it (see Sec. 4.7). Fig. 4.8 shows how the top polar cap is mounted. A white panel will be mounted just under the surface of the oil in the access portal to facilitate light collection in this region.

4.3 Surface finishes

Surfaces of the detector have been painted to provide high albedo in the veto volume and low albedo in the main volume. Reflection of light in the main volume of the detector can cause Čerenkov light to appear isotropic and delayed, degrading particle identification. We thus want surfaces in the main volume to be non-reflective. In the veto volume we simply want to maximize the total light collected by the sparse array of PMT's. Therefore surfaces in the veto volume are to be reflective. The inner surface of the tank wall, the bosses, the struts,

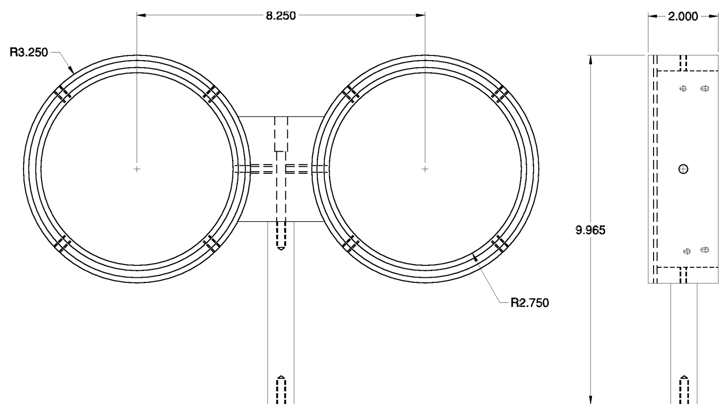

Figure 4.7: Veto PMT cluster. The strut mounts to a boss welded to the tank wall. The PMT's sit in the rings.

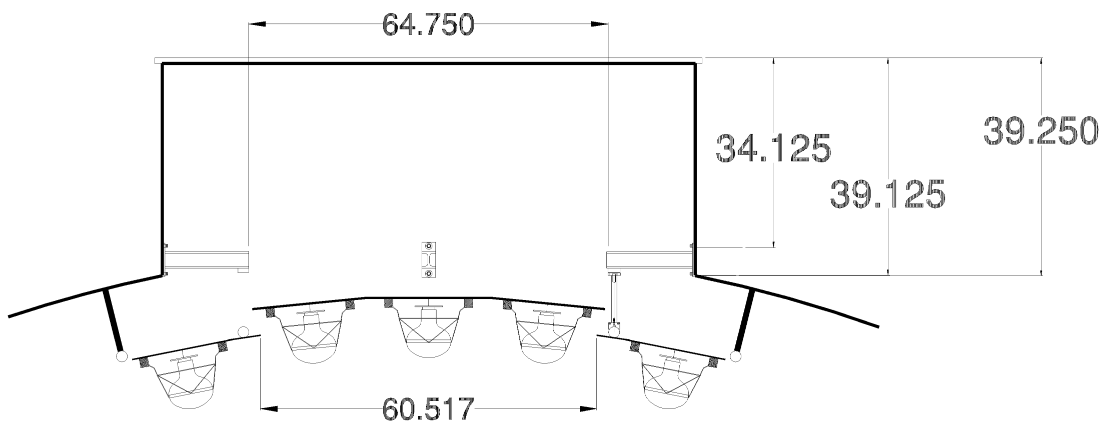

Figure 4.8: The top polar cap.

Row	θ (deg)	Number of PMT's	$\Delta\phi$ (deg)	Spacing (cm)
1	0.000	1		
2	5.625	6	60.00	57.14
3	11.250	12	30.00	56.87
4	16.875	18	20.00	56.41
5	22.500	24	15.00	55.77
6	28.125	30	12.00	54.96
7	33.750	36	10.00	53.98
8	39.375	40	9.00	55.48
9	45.000	44	8.18	56.21
10	50.625	48	7.50	56.33
11	56.250	52	6.92	55.93
12	61.875	56	6.43	55.09
13	67.500	58	6.21	55.72
14	73.125	60	6.00	55.79
15	78.750	62	5.81	55.33
16	84.375	62	5.81	56.15
17	90.000	62	5.81	56.42
18	95.625	62	5.81	56.15
19	101.250	62	5.81	55.33
20	106.875	60	6.00	55.79
21	112.500	58	6.21	55.72
22	118.125	56	6.43	55.09
23	123.750	52	6.92	55.93
24	129.375	48	7.50	56.33
25	135.000	44	8.18	56.21
26	140.625	40	9.00	55.48
27	146.250	36	10.00	53.98
28	151.875	30	12.00	54.96
29	157.500	24	15.00	55.77
30	163.125	18	20.00	56.41
31	168.750	12	30.00	56.87
32	174.375	6	60.00	57.14
33	180.000	1		

Table 4.1: Layout of PMT's in the main tank. "Spacing" is the horizontal separation of the PMT's (measured from the centers of the globes) and can be compared to the row separation of 54.7 cm.

Row	θ (deg)	Number of PMT's	$\Delta\phi$ (deg)	Spacing (cm)
1	0.0	2		
2	18.0	12	60.00	193.22
3	36.0	22	32.73	200.47
4	54.0	30	24.00	202.35
5	72.0	36	20.00	198.23
6	90.0	36	20.00	208.43
7	108.0	36	20.00	198.23
8	126.0	30	24.00	202.35
9	144.0	22	32.73	200.47
10	162.0	12	60.00	193.22
11	180.0	2		

Table 4.2: Layout of PMT's in the veto. The tubes are mounted in pairs. "Spacing" is the horizontal separation of the PMT's (measured from the centers of the clusters) and can be compared to the row separation of 187.6 cm.

Lat	θ (deg)	Diameter (ft)	Circumference (ft)
1*	2.812	1.86	5.84
2	8.438	5.56	17.46
3	14.063	9.20	28.91
4	19.688	12.76	40.08
5	25.312	16.19	50.87
6	30.937	19.47	61.16
7	36.563	22.56	70.87
8	42.188	25.43	79.90
9	47.813	28.06	88.15
10	53.438	30.42	95.56
11	59.063	32.48	102.05
12	64.688	34.23	107.55
13	70.313	35.66	112.02
14	75.938	36.74	115.41
15	81.562	37.46	117.68
16	87.188	37.82	118.83

Table 4.3: Location and dimensions of the latitudinal hoops. Only the top hemisphere is shown; the bottom is a mirror image of the top. * The top lat doesn't actually exist: it is subsumed into the polar cap.

Part	Total weight (tons)
panels/lat strips	2.1
lats	0.9
bosses/struts	1.0
hardware	0.05
PMTs/bases	1.5
LSND stands	0.3
cables (in tank)	0.7
Total	6.6

Table 4.4: Total weight, in tons, of various PSS components.

the latitudinal hoops, and the outer side of the panels, strips, and overlaps of the optical barrier are painted white. The inner side of the optical barrier is painted black. Small parts on the inner surface of the optical barrier, such as the clips and PMT mounting blocks, are black-anodized.

We have measured the albedo of various paints in air using a tungsten lamp and integrating sphere. Figure 4.9 presents these measurements for several candidate white coatings. All of the measured coatings provide better than 80% albedo at wavelengths above 425 nm. We use a conservative model of the measured albedo as a function of wavelength in our Monte Carlo simulations. The solid curve in Fig. 4.9 is the albedo published by Bicron for its paint. Of note is that our measurements at 436 and 545 nm confirm the published curve, but our measurement at 405 nm falls short. We have also measured albedos in oil by immersing a sample, a light source (an alpha emitter embedded in scintillator), and a detecting PMT. These in-oil measurements confirmed our rankings of candidate surface treatments.

The steel tank was painted after construction with Plasite 9060, a white epoxy coating. Plasite Protective Coatings (Green Bay, Wisconsin) markets this tank lining to the food and beverage industries, saying that it will not impart taste or odor, and that it meets FDA requirements for direct food contact. Our own tests indicated that it will not contaminate mineral oil (see below). The manufacturer's specifications for application of the coating included sandblasting the tank surface to "white metal," application of the coating to a dry film thickness of 12-14 mils in two coats, and elevated temperature curing.

The components of the phototube support structure were painted with coatings manufactured by Sherwin-Williams. We found that these coatings were non-contaminating. In albedo tests of samples gathered from various manufacturers, the S-W white offered the highest albedos, whereas the S-W black offered the lowest. The white is an aircraft paint (Jet Glo High Gloss) and the flat black is a military paint (camouflage chemical agent resistant coating). Application included a primer (the same primer for both aluminum and steel)

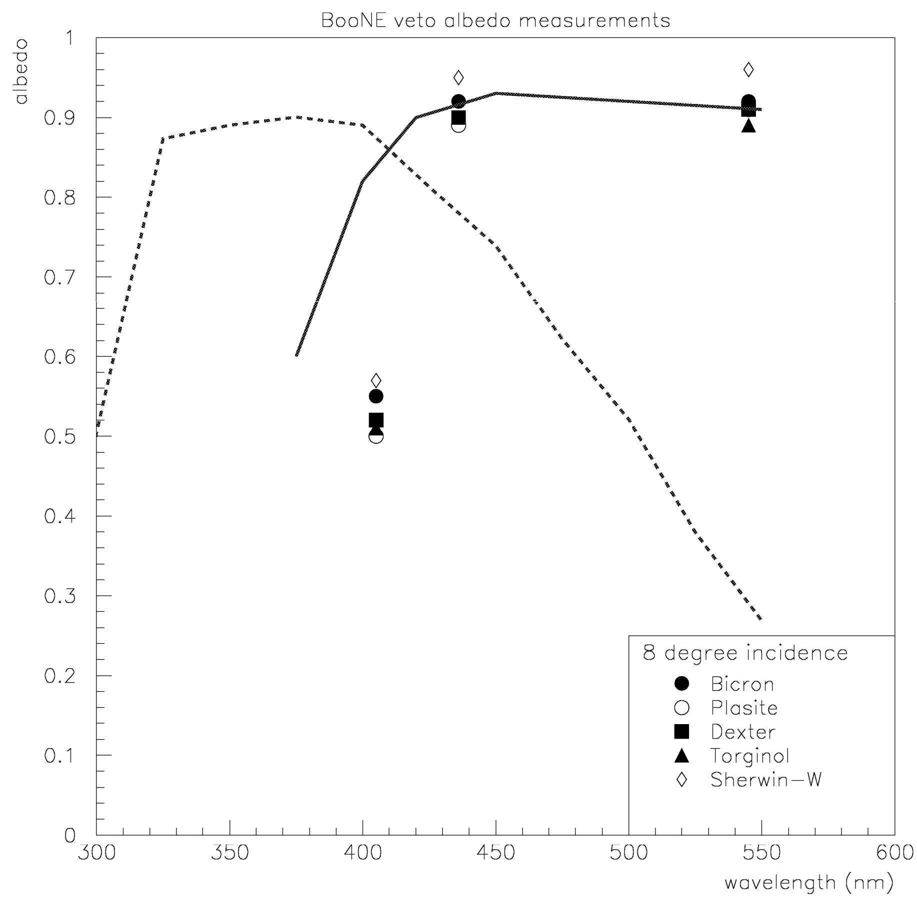

Figure 4.9: Albedo measurements for a variety of candidate white coatings. Also shown: the albedo curve published by Bicron for its paint (solid), and the phototube quantum efficiency in arbitrary units (dashed).

followed by a single pass of topcoat for a total dry film thickness of about 3 mils and elevated-temperature curing.

Some of the smaller pieces of the PSS — panel clips, the blocks to which the PMT stands attach, calibration cubes — were black anodized. This process was shown to be non-contaminating, and is a fast, cost-effective way to finish a large number of small pieces. However, a smooth black anodized aluminum surface offers fairly high albedo at large incidence angles; to achieve lower albedo the surface must be scuffed (e.g., sandblasted) prior to anodizing. Anodizing was considered for the panels and rejected because of the need for low albedo over the full range of incidence angles and the concern that sandblasting might curl the panels. The smaller pieces were deburred in a tumbler, which left them slightly scuffed, making them ideal candidates for anodizing.

4.4 Oil compatibility

All materials in the tank will be immersed in mineral oil. We must be confident that these materials will not contaminate the mineral oil over the duration of the experiment. The materials and their potential for contaminating the mineral oil are:

- Painted surfaces: Of particular concern is the leaching of residual solvent from incompletely cured paint. Solvents contribute additional scintillating components to the mineral oil.

- Plastics: Plastic components, such as cable jackets, contain plasticizers, which can be the cause of contamination. A plasticizer is a material, usually an organic compound, that gets added to a polymer in order to produce a flexible plastic. Plasticizers tend to be volatile to some degree; for example, the fogging of the interior of car windshields is due primarily to the release of plasticizers from dashboards.

- Metals: The carbon steel tank will be painted, as will the aluminum components of the phototube support structure. Nevertheless, some metal may be exposed to the oil, through pores and nicks in the paint, and because some "buried" surfaces, like the inside of the latitudinal hoop tubing, will be difficult to paint. It is believed that metals do not cause contamination of the mineral oil directly, but their presence acts as a catalyst for oxidation, particularly at temperatures above 140°F. Oxidation decreases the oil's attenuation length. Oxidation should not be a problem in MiniBooNE because the oil will be kept in a nitrogen environment at fairly low temperature, below 70°F.

The surface coatings — the white of the veto volume and the black of the main volume — present the largest surface area of material in the oil and therefore present the greatest threat of contamination. This, along with evidence that the black paint used in LSND caused some problems, made us choose coatings for MiniBooNE carefully. (LSND experienced a rising level of scintillation over the approximately six years of its operation). The same care and testing procedures were applied to all candidate materials to be put into the tank.

Any material proposed for use in the tank was soaked in oil, usually for at least a week and often longer, with a sample at room temperature and another at 150°F to speed the aging process. The optical properties of the oil were then measured. A spectrophotometer is used to look for changes in light absorption, and a flourimeter is used to look for changes in scintillation properties.

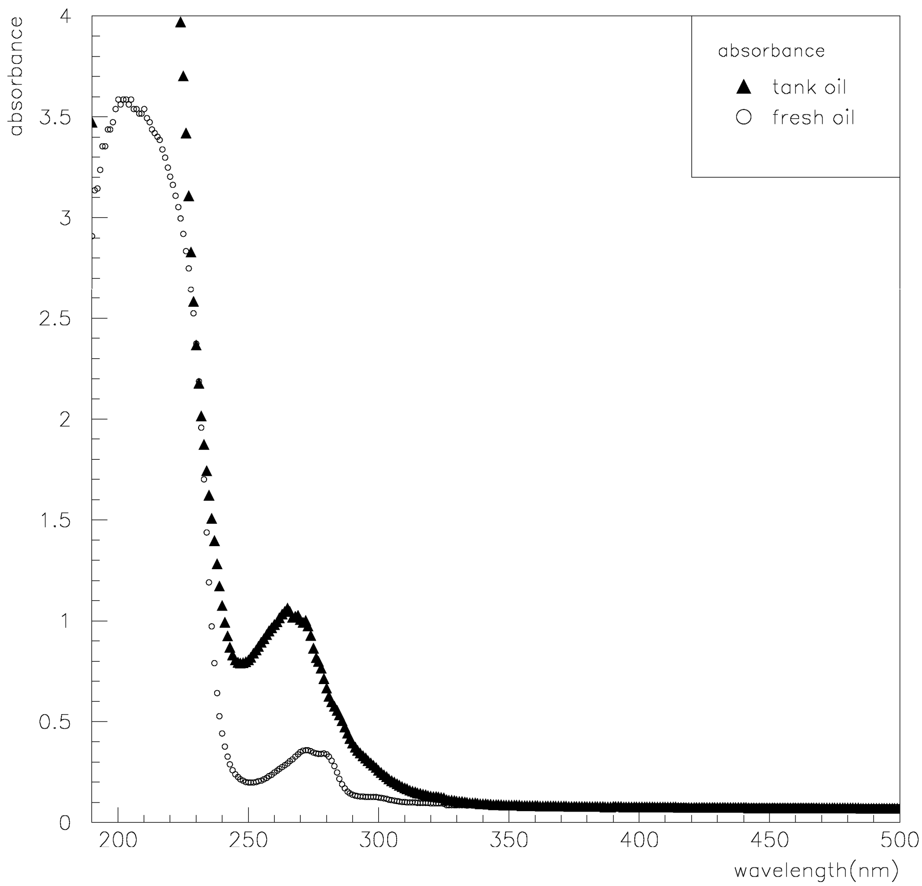

Figure 4.10: Absorbance spectra of fresh mineral oil from the Witco Corporation (circles) and oil from the LSND storage tank (triangles).

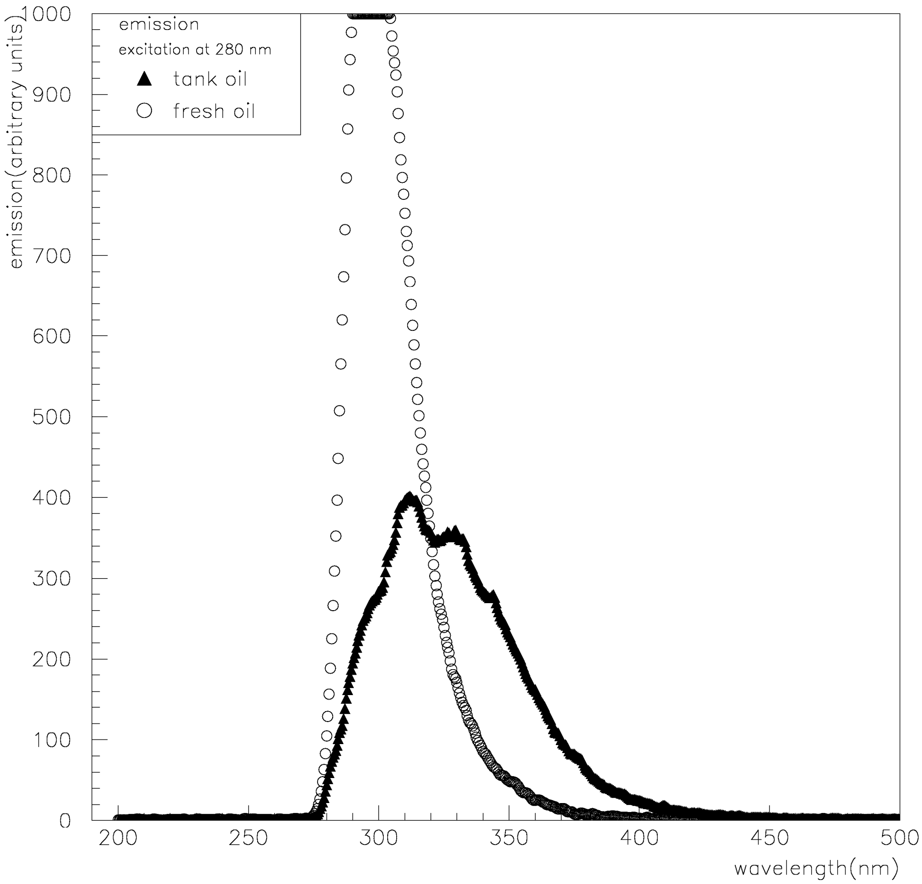

Figure 4.11: Emission spectra of fresh mineral oil from the Witco Corporation (circles) and oil from the LSND storage tank (triangles). The samples have been excited at 280 nm.

Examples of these measurements are shown in Figs. 4.10 and 4.11, which present the absorbance in 1 cm of oil (defined as $-\log_{10} T$, where T is the transmission) and emission spectra, respectively, for a sample of recently acquired "fresh" WITCO mineral oil and for oil drawn from the LSND storage tank in 1998.

LSND has a 52,000 gallon oil storage tank that was prepared internally in the same way its the detector tank. In December 1992, oil was delivered to the LSND storage tank. In April 1993 50,000 gallons were transferred to the LSND detector, and subsequently b-PBD scintillator was added to the detector oil.

Oil from the LSND storage tank therefore provides a sample of *pure* mineral oil from LSND. Whereas fresh mineral oil is odorless, the LSND storage tank oil has the smell of paint (which is also true for the oil from the LSND detector). Compared with the fresh oil, the storage tank oil absorbs significantly more light at 250 to 300 nm. The emission spectra of Fig. 4.11 were produced after excitation at 280 nm. The storage tank oil has a significantly broader excitation spectrum. Both of these measurements indicate the presence of contaminants in the storage tank oil.

The chosen tank and PSS coatings were found not to change the optical properties of the oil. In addition, we have confirmed that metals do not cause contamination of the oil at room temperature and that they seem to catalyze oxidation at higher temperature. Our tests with aluminum and copper in oil at 150°F indicate contamination (the copper is worse), and the contamination at 150°F is much smaller when the samples are kept in a nitrogen environment. Therefore unpainted metal is acceptable in MiniBooNE (we will have some unpainted aluminum, but no copper), because the oil will be cool and under nitrogen.

We found that PVC-jacketed cables, including the RG-58C/U with a "non-contaminating" jacket used in LSND, contaminate mineral oil. An example of these results is given in Fig. 4.12, which shows absorbance for oil in which new samples of PVC-jacketed RG58 were soaked for one week at room temperature. Further tests indicate that as the cable soaks its contamination rate decreases (the rate at which material leaches from the cable decreases). The bottom of Fig. 4.12 shows absorbance when the same cables are soaked again for one week in fresh oil. The top of Fig. 4.13 shows absorbance for oil in which a sample of cable from LSND (i.e., the cable was immersed in the LSND tank during the life of the LSND experiment) soaked for one week at room temperature.

Teflon-jacketed cables were found to be non-contaminating and were chosen as a feasible alternative to PVC. The bottom of Fig. 4.13 shows absorbance for oils in which teflon-jacketed cables soaked at 150°F. One of the samples shown was allowed to soak for over two months, with no contamination observed.

The bases and necks of the LSND phototubes were coated in Hysol potting compound. New Hysol samples and samples taken from an LSND phototube were found to contaminate oil. Therefore we chose a new encapsulant, epoxy EP21LV from Master Bond (Hackensack, New Jersey). This epoxy meets FDA requirements for food compatibility and was found to be non-contaminating in our tests. Both MiniBooNE's old and new phototubes will be potted in Master Bond epoxy — in the case of the old tubes, the Master Bond will go right over the Hysol.

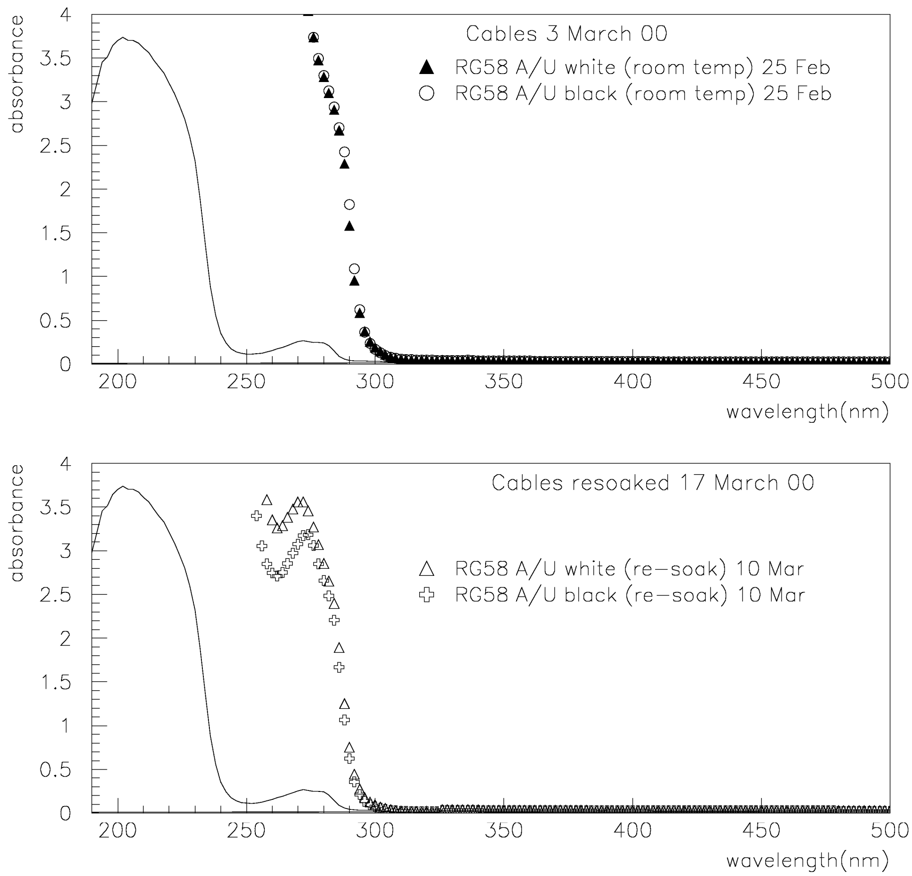

Figure 4.12: Absorbance spectra for oil in which new samples of PVC-jacketed cable soaked. Top, black and white RG58 began to soak at room temperature on 25 Feb 2000 and the oil absorbance was measured on 3 March. Bottom, the same cables were put into fresh oil on 10 March and the oil absorbance was measured on 17 March. The solid line is the control spectrum for oil in which nothing soaked.

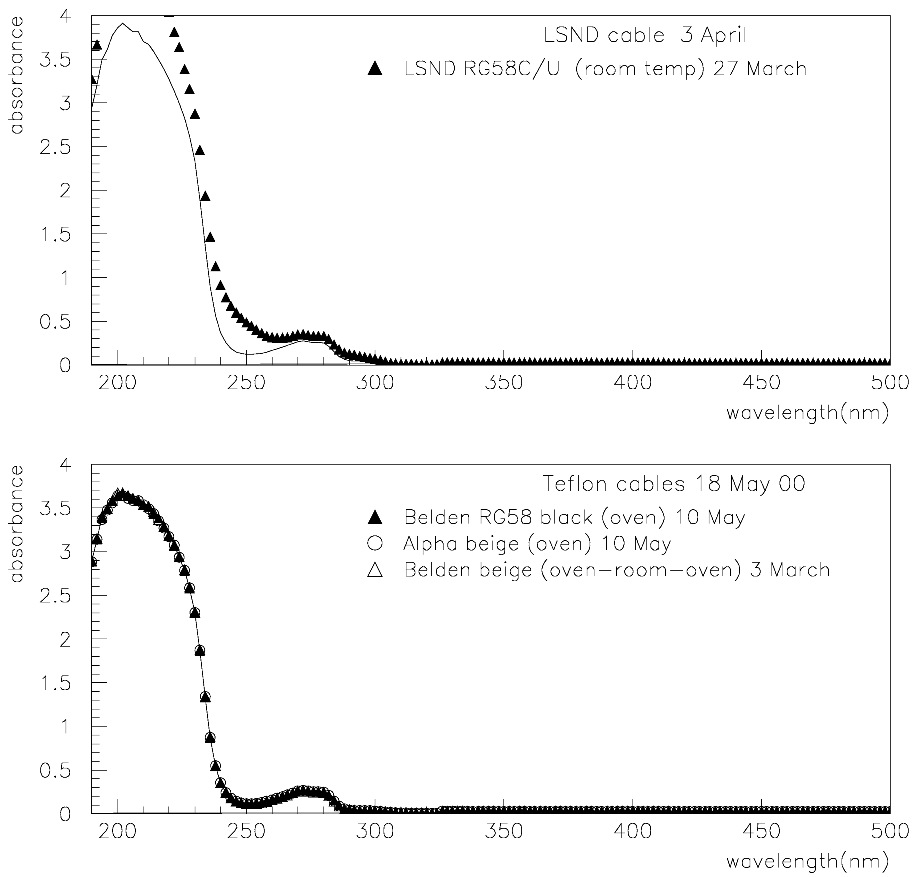

Figure 4.13: Absorbance spectra. Top, a sample of cable from LSND (i.e. a piece of cable that was immersed in the LSND tank during the duration of the LSND experiment) began to soak on 27 March 2000 and the oil absorbance was measured on 3 April. Bottom, oil absorbance measurements for oil samples exposed to teflon-jacketed cables at 150°F.

4.5 In-tank cable plant

We describe here the cable runs to and from the in-tank components, primarily from a mechanical point of view. The remaining cabling is described in Secs. 3.5.4 and 6.8; all electrical considerations are described in the electronics section, Chapter 6. We concentrate on the connections to the 8-inch photomultiplier tubes. Where they differ, connections to the various calibration elements are discussed with the calibration systems themselves.

The in-tank cable run links the photomultiplier tubes to the preamplifiers, located in crates in the tank access area next to the tank access port. A single RG-58 cable both supplies high voltage to a PMT and carries the signal from PMT to preamp. As described in the previous section, we use a teflon-jacketed cable, Belden 88240, for compatibility with the mineral oil. This cable has the further advantage of being plenum-rated. It is thus suited for the run under the computer floor to the preamps. As most of the run is in the veto section of the tank, we use cable with a white jacket. The cable terminates at the preamp end in a SHV jack which mounts into a multi-connector block. The run from this connector is down the preamp rack and under the floor of the tank access area to the access portal of the tank.

The penetration of the tank wall is through airtight feedthroughs bolted to the flange on the tank's access portal (Sec. 3.2.4). The oil level in the access portal remains below these flanges – the seal is to maintain the nitrogen atmosphere in the tank. Each flange accepts four bundles of 98 cables. For mechanical reasons, each bundle is divided into two 49-cable sub-bundles, each with its own feedthrough. A feedthrough and the panel on which it mounts to a tank flange are shown in Fig. 4.14. The feedthrough is made of two aluminum plates with holes for the 49 cables. Captured between the plates on each cable is an o-ring, making a gas-tight seal.

To maintain uniformity in pulse shape from tube to tube, cables of a fixed length, 100 feet, were used for almost all channels, despite the disparity in the length of the cable runs to the top and bottom of the tank. (As a hedge, a few of the cables with the longest runs were cut to 110 feet. The excess can be removed if 100 feet suffices.) Since there is a lot of excess cable, and we do not want excessive slack that will block light collection in the tank, the each cable is captured in the feedthrough with only the length necessary to reach the PMT (with extra slack for splicing and rounded up to the next 5-foot increment) extending from the inner side. The bulk of the slack is thus gathered under the computer floor in front of the preamp racks.

The bundles were all fabricated in advance: the cables were cut to length, threaded through the feedthrough, captured with the appropriate lengths on either side, and labelled, and the SHV connector mounted and tested. Each bundle was then passed through the port in the tank as a unit. Once through the port, each bundle was strain-relieved at the bottom of the access portal in a heavy bar mounted on studs welded to the tank. From this corner, the cable

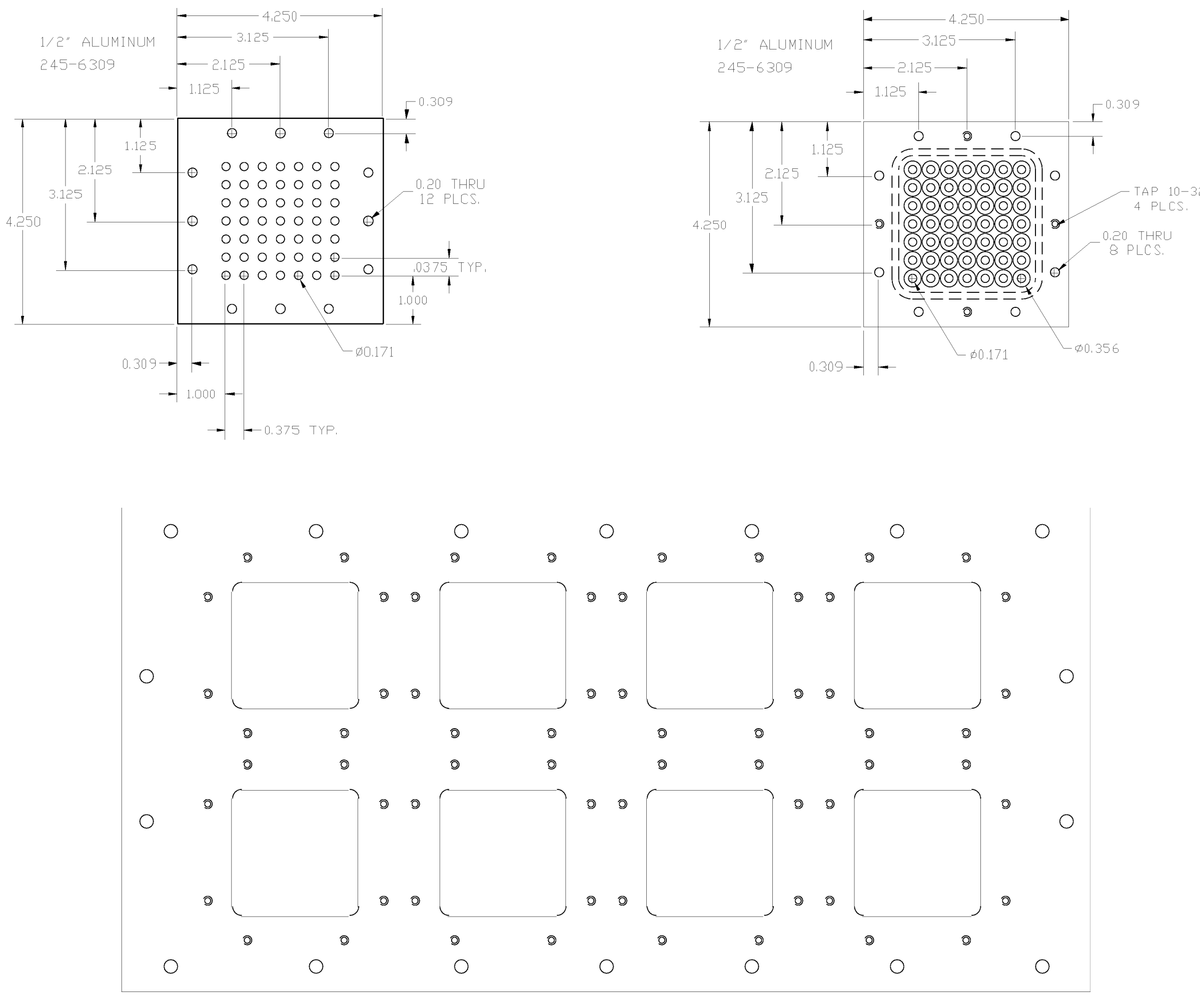

Figure 4.14: Cable feedthrough and mounting panel.

bundles run down the tank wall, held in place by steel straps spanning pairs of studs on the wall. Each cable bundle serves the main and veto PMT's in a vertical slice of the tank from top to bottom. At a horizontal row of main or veto PMT's, cables are peeled from the nearest bundle and routed to each PMT. Cables for the main PMT's cross the veto region and penetrate the optical barrier through pairs of holes near the center of each panel. We simply let each cable run from the tank wall directly to its hole in the optical barrier, except where this path would drape the cable directly in front of a veto PMT. After passing through the optical barrier, the cable is spliced to the 5-foot piece of cable that is permanently attached to the PMT base. The splice is made with a coaxial splice kit (Raychem B-202-81, formerly D-150-0071). This system was used in LSND and found to be very reliable. To seal out oil, the splice is covered with a length of $\frac{3}{8}''$ teflon shrinktube (SPC Technology SST-024), which shrinks onto o-rings on either side of the splice.

As each splice is made, it is tested. Prior to splicing, a pulser is connected to the cable at the preamp end and the reflection (at about 370 ns) is observed on the scope. Since the bases are back-terminated, the disappearance of the reflection indicates both that the splice is good and that the labels at the two ends of the cable match.

4.6 PMT preparation

After the PMT's have the bases attached, are tested, and are assigned to a location in the tank, they are prepared for installation. This process consists of these steps for each tube:

- It is washed in a mild solution of detergent and distilled water, then rinsed in clean distilled water, then allowed to dry for 24 hours. The main purpose is to remove the scintillator-doped oil residue from LSND.
- New tubes are mounted in stands. Old tubes destined for the main tank are re-mounted in stands. The centering clips that hold the neck of the tube are not installed until after dipping.
- It is dipped in black Master Bond EP21LV encapsulant from the base up to the bottom of the globe. This is to protect the oil from the components of the base and vice versa and may also serve to attenuate any light generated by breakdown in the dynode structure of the tube. Old tubes were already coated in black Hysol. This was found to contaminate mineral oil (Sec. 4.4), so the old tubes are also dipped in Master Bond.
- Veto tubes are removed from their stands and mounted in veto mounts.
- Main tubes have the centering clips attached around the tube neck. A stripe of Master Bond is run down the neck of the tube over the silicone rubber

cushion on each centering clip. This attachment serves as a mechanical backup in case the metal band and foam tape at the tube's equator slip, as they occasionally did in LSND.

This work is done in a cleanroom. It was found that maintaining low humidity was necessary for the proper curing of the Master Bond.

4.7 Installation

The installation of the PSS begins with the tank plant in this state:

— The tank is complete, the bosses and other mounting features are welded in place.

— The tank has been painted with the final veto-white paint and is free from debris and clean.

— The buildings enclosing the tank access are in place as are facilities to keep the tank and a modest-sized staging area in the enclosure clean.

— The hoist is installed in the tank access area.

An intricate scaffolding system is required for the installation of the apparatus in the tank. The system must allow access to virtually the entire inner surface of the tank to allow cabling, veto installation, and attachments to the preinstalled bosses. The scaffold must also have an area where work can be done up to approximately 30 inches from the tank wall for installation of lats, optical barrier panels, and PMT's.

The scaffolding was supplied and installed by Bartlett Services, Inc. It consists of six levels with an internal stairwell. The structure is supported by legs and diagonal braces that rest against the tank wall. The painted surface of the tank is protected by rubber pads. Work is done on the top level, which is then lowered or removed to allow access further down the tank wall. The working level extends horizontally to within a few inches of the tank wall, providing a safe, stable work space.

Personnel access to and from the tank is via the 36-inch access port ("manhole") near the bottom of the tank. Light tools and parts are also brought into and removed from the tank via this pathway, which consists of a spiral stairway down the side of the vault and a ladder through the manhole that gives access to the bottom level of the scaffolding. A small temporary clean room surrounds the access port. Heavier objects are lowered through the top access portal using the electric hoist. Ventilation is maintained by blowers delivering air through the manhole and withdrawing it from the top portal. The experience of tank construction companies shows this to be completely adequate.

With the scaffolding in the tank, the cable bundles were installed as described in Sec. 4.5. Installation of the PSS itself begins near the top, starting with the top lat. We work down from there, with each cycle of installation ending when the top remaining deck of the scaffolding is reached. The strategy is to install as much hardware as possible at each level before any PMT's are mounted.

The first steps at each level involve installing the lat pipes to the desired height using a rotating-laser level that traces a horizontal line around the tank. The height reference is a measuring tape hanging from the top access portal. It was calibrated by using the laser level to transfer the survey coordinates of many bosses to the tape and averaging.

One installation cycle proceeds in these steps:

- Peel out the cables needed from the bundles on the tank wall.
- Install latitudinal hoops as far down as the scaffolding allows.
  - Attach struts to bosses on tank wall. Each strut has an assigned length.
  - Set the rotating-laser optical level to the desired lat height.
  - Adjust strut base screws to pivot the clamp end of each strut to the laser. A fixture that attaches to the clamp end has a scribe mark where the center of the lat will be.
  - Install latitudinal hoop sections and their linking sleeves.
  - Measure several diameters of the hoop and compare the height to the previous lat with a measuring jig.

We then go back up to the top bare lat and work down again, installing the optical barrier and rows of main and veto PMT's. The order of these operations depends somewhat on convenience of reach.

- Mount lat strips on lats using U-bolts.
- Rivet overlap panels to strips.
- Bolt panel clips to rivet nuts on strips.
- Install a row of veto clusters if there will be one behind this row of panels.
  - Attach veto strut to boss.
  - Mount veto cluster on strut.
  - Orient the cluster on the strut to 1) give clearance from lat pipes, 2) keep photocathodes as far from steel struts as possible, and 3) minimize the hardware shadowing the tubes.
  - Splice cables.
  - Test splices (see Sec. 4.5).

- Mount a row of optical barrier panels.
  - Locate the first panel to provide the correct "clocking" of this row.
  - Attach panels to upper and lower lat strips using clips.
  - Adjust gaps between panels to give uniform PMT spacing.
  - Rivet overlap panels to main panels.
  - Run cables across veto and through holes in panel.
- Install a row of main PMT's, two per panel.
  - Bolt mounting blocks to rivet nuts in panels.
  - Attach stands holding PMT's to mounting blocks.
  - Splice cables.
  - Test splices (see Sec. 4.5).
  - Feed cable back through hole in panel till the splice rests against the panel. This leaves the white cable in the veto and the black cable, attached to the base, in the main tank.) Coil slack in black cable and tie to stand.
- Lower or remove the top deck of scaffolding.

In practice, each cycle allows the installation of 2-3 rows of main tubes and takes approximately two weeks. We estimate that the PMT's end up placed with respect to their nominal positions within $\frac{1}{2}''$ radially, $\frac{1}{2}''$ in height, and $\frac{1}{2}''$ horizontally within a row. The "clocking" precision of a whole row is approximately 1-2$''$.

At regular intervals, the tank ports are closed and the installed PMT's and cabling are tested at high voltage using a temporarily-installed flasher system.

After the installation reaches the manhole (offset approximately 8 feet horizontally from the bottom of the tank), the installation of several panels will be skipped to allow continued access. At this point, work on the top polar cap and the bottom of the tank will go in parallel to facilitate installation of the calibration equipment (see next chapter) that hangs in the tank. The PMT's at the bottom of the tank will be installed onto the bottom polar cap outside of the tank. This cap will be lowered into place as a unit and the coaxial fill pipe installed. The calibration flasks will be hung from their wires and their hanging wires fastened to the optical barrier at the bottom. When this step is complete, the top polar cap with its PMT's and calibration cubes will be lowered into place.

Finally, we will work toward the manhole, installing the skipped panels and PMT's. The top light reflector will be installed just below the nominal oil level, a white panel will be installed in the manhole trunk, and the access portal hatches will be sealed.