Chapter III B. Detector Design and Construction

The experiment will utilize techniques that have been developed for deep underground water Cherenkov detectors during the past decade. There will be four large water tanks located on independent sites ranging from 1 to 68 km from the neutrino source. Each tank will be equipped with a large array of photomultiplier tubes (PMTs) to detect the Cherenkov radiation produced by relativistic particles traversing the water. At each site the signals from the PMTs will be collected, analyzed and time marked for synchronization with the beam and the other detectors. In the first two subsections below the physical layout and installation procedures for the PMTs are described. An outline of the tank construction is given in the next subsection, the water purification system follows, and finally the physical plant at each site is discussed.

PMT Array

The PMT array must be able to locate the trajectory of single particles accurately in time and space and to identify each particle as a muon, electron or pizero, or to label an event as being due to a multiparticle interaction, and to measure particle momentum. A decade of experience with similar detectors has shown that a dense, regular array of PMTs covering the inner surface of a volume inside the tank can accomplish this purpose [1, 2]. The other critical function is to identify tracks entering or leaving the inner volume, including tracks from the large flux of cosmic rays impinging on the detector. This function is accomplished by a secondary array of PMTs which view an annular volume surrounding the inner volume. Each tank is therefore divided into an inner and outer (veto) volume, with approximately 90% of the PMTs looking inward, and the remainder looking outward, see Fig. 1. The inner volume is 15m in diameter and 15m high. The simulation of the detector response to various neutrino interactions and the reconstruction resolutions are discussed in Chapters IV and V.

To make the coverage as dense as possible in the most cost effective way, it has been decided to use 20cm diameter tubes mounted on a 70cm $\times$ 70cm grid looking inwards, and on an approximately 3m $\times$ 3m grid looking out, see Fig. 2. The effective collection area of each tube is augmented by a hybrid Winston cone mounted on the photocathode. With 2200 tubes facing the inner detector, this combination will provide about 6.5% area coverage from the photocathodes alone, enhanced to 10.4% by the Winston cones.

A number of tubes meet the requirements for the experiment; of particular interest are the R4558 and the R5912, manufactured by Hamamatsu. Both have 20cm diameter hemispherical photocathodes. The R4558 is identical to the tube used in the SNO detector, except that it is not constructed of low radioactivity glass. A sketch with its dimensions is shown in Fig. 3; the dimensions of the R5912 are similar. The Winston cones will be essentially identical to those used in SNO. A sketch with the cone dimensions is shown in Fig. 4.

The physical layout of the tube bases will also be a copy of the SNO design. However, there will be much larger light levels in the Brookhaven experiment, and timing information is more important than in SNO. Therefore the dynode voltage distribution will be configured in such a way as to provide the best possible timing information. This could help improve track vertex reconstruction for which the accuracy is determined by the spacing of the tubes on the grid and by the timing precision of each tube.

In this regard, the 10 stage box and line dynode structure of the R5912 provides better timing information than the 9 stage venetian blind chain of the R4558. The anode pulse rise time for the R5912 is 3ns and the transit time spread is 2.5ns, compared with 5ns and 3.5ns, respectively, for the R4558. Simulations studies are in progress to answer the question of how critical this timing is. A disadvantage of the R5912 is that its timing and energy response are sensitive to magnetic fields to a large enough extent that it would be necessary to shield these tubes against the earth's magnetic field. The R4558 also shows some sensitivity to magnetic fields, but it is not clear whether shielding would be necessary. A final decision on the choice of tube will be made after further simulation studies, and after a variety of test measurements have been made on each type.

The cable used to transmit the signal, as well as supply the PMT high voltage, is a modified version of 75 ohm RG59 developed for a similar use in the SNO detector. It is a special waterproof variant, designed for long term immersion in water. It has a high density polyethylene outer jacket, and a tinned copper braided shield that is flooded with a polyethylene wax to prevent water wicking along the braid. The braid is wrapped with an aluminum/polypropylene/aluminum laminate which acts as a vapor barrier to withstand long term immersion. The cable is shown in Fig. 5. To facilitate timing of the PMT signals, all cables will be the same length, approximately 60m. In order to bring the cables out of the tank, a feedthrough, complete with O-rings and other fixtures, will be epoxy bonded to each cable as shown in Fig. 6. The cables will be soldered directly, without connectors, to the PMT bases.

Because the tubes will be installed in water at depths up to 18m, it will be necessary to ensure tight waterproofing around the attachment points of the base and cable. This problem has been solved by both SuperKamiokande and SNO. A polyethylene frame is fitted snugly over the end of the glass bulb of the photomultiplier tube, and a second polyethylene frame then fits snugly over the first, and the combination completely contains the phototube base. The cable is brought out through a port on the second frame. The volume inside the frames is then filled with a suitable insulating epoxy (such as Sanyu Resin SZ-722) to prevent any water from leaking in. The entire assembly is also wrapped with heat shrink polyethylene tubing, mainly for aesthetic purposes. A view of the Kamiokande waterproofing structure, taken from [3], is shown in Fig. 7. E889 will use the SNO variant, which is quite similar.

After the tubes are installed in the tanks, there may be very long periods during which it will be impossible to access them for servicing. Therefore it will be necessary to test each tube for waterproofing, consistency of signal and absence of light leaks, before installation. An automated testing procedure has been developed by SNO, and the cost estimates for E889 include duplicating this system.

PMT installation

Each phototube will be fitted with a support cradle, shown in Fig. 8, which allows the PMT to be handled, supported and restrained. When the 0.7kg PMT is submerged there is a buoyant force of approximately 3kg that must be counteracted. The basic assembly element is shown in Fig. 9. The PMT and cradle are attached to a square, semirigid sheet of plastic 70cm on a side and 5mm thick. The side facing inwards is absorptive black, and that facing outwards is reflective. One eighth of these units have two PMTs mounted on them, one facing in and the other out. Note that the full unit consists of PMT, plastic sheet, and 60m of cable; the latter is strain relieved directly on the sheet.

Several schemes for installing the array of PMTs have been investigated. Since this is an above ground installation, we are convinced that the appropriate time to do the installation is before the tank is filled with water. This procedure will require access to the bottom of the tank, and limited access inside the tank above the level of the full array (16.5m above the bottom). To accomplish the latter we have provided for a cat walk above this level, accessible from outside the tank.

There are still two distinct support structures which can accomplish our needs. These are a rigid structure supported from the bottom and stabilized from the sides of the tank, or a flexible cable array hung from the tank roof or catwalk. Each of these schemes offers advantages and disadvantages, and the final decision will require both prototyping and careful value engineering to evaluate cost and schedule issues. In either case the top and bottom arrays are the same. A light framework, suspended from above, allows the PMT/sheet/cable units to be attached working from the floor of the tank. When the top array is complete, it is raised and suspended well above its final position, allowing work on the side arrays to proceed. When the sides are finished, the top array is moved into its final position and secured. At this time the bottom array is mounted on a similar framework already positioned in its final location, just 1.5m from the tank floor.

The side arrays are mounted either to a rigid, but lightweight, stainless steel framework, or to an array of stainless steel cables suspended from the tank roof or catwalk. A mobile boom is used to attach the PMT units to the structure. This unit has a cradle which can support two people. PMT units are independently delivered to the boom to obviate the need for large motions. They are attached starting at the top of the array and working downwards, to avoid working above (and possibly damaging) installed units, as shown in Fig. 10. The tanks are in fact large enough to permit two booms to work in parallel. An attractive variant of the cable support scheme would allow the PMT units to be attached to a pair of cables at ground level. The cables would then be raised either from hoists located on the catwalk, or from ground level hoists working through pulleys on the catwalk, as shown in Fig. 11. While this scheme has many attractive features, it does require more work at the catwalk level to secure completed PMT rows, and to position the hoist system.

As the PMT units are installed, the cables are immediately routed and secured. The cables are brought to an area at the bottom of the tank close to the electronics location outside the tanks, and the feedthroughs already on the cable are passed through special panels, the cables are secured for strain relief, and the feedthrough assembly is completed and leak checked.

When the sides and bottom array are complete, the installation equipment can be removed. At this point the installation process is complete and the tank can be cleaned, secured and filled.

Detector Sites and Construction

The site preparation and detector construction is similar at all sites. Minor differences are typically associated with the availability of existing utilities and roads. A brief description of the site preparation, tank construction, and support buildings will be given below ignoring the minor differences. An artists conception of a detector site is shown in Fig. 12.

Land improvements are necessary before the contractor can begin the water tank construction. Engineering tests on the soil will be conducted to determine its load bearing capability, needed for final engineering of the tank ring wall. Approximately an acre of land will be cleared around each tank location to provide a substantial area for construction. The entire area will be cleared of trees, grubbed, and graded. An access road will be built to allow all weather access to the detector site by car. These improvements are expected to be completed during the six months required for the tank contractor to obtain the steel.

An elevation view of a detector tank is shown in Fig. 13. The tank will be of conventional construction consisting of welded steel plates. It has been designed to allow for access and PMT installation at both the top and bottom of the tank; when the installation scheme is finalized any unnecessary options will be eliminated to reduce costs. Each tank will be 18m in diameter and 18m high with a domed steel roof and cat walk at the top. Two bolted doors are located at the bottom of the tank. A 6ft $\times$ 8ft door is provided for equipment access. The opening size has been matched to the requirement of using a telescoping boom inside the tank for PMT installation. A 3ft $\times$ 3ft port has been added for additional personnel access/egress. Above the water level of 18m is a large access door with a platform. This door will be accessible from the utility tower, discussed later. The door provides access to the interior, 1.5m wide, catwalk. The tank structure is designed to support a load of 15 tons evenly distributed on the inner edge of the catwalk. A ventilation and lighting system are provided for access into the top of the tank. A second smaller port with a caged staircase is provided as an alternate means of emergency egress from the catwalk. The interior surface of the tank will have a durable epoxy coating suitable for potable water systems. The roof and walls of the tanks will be insulated to a R-10 value to reduce heat transfer from the water to the air. It is expected that the contractor will need approximately three months at a detector location to complete the water tank.

The utility tower and support building will be built after the water tank is complete. A plan view of the water tank, utility tower, and support building is shown in Fig. 14. The utility tower is the central portion of the building structure and is more evident in the elevation view shown in Fig. 15. It provides access to the interior tank catwalk by a set of platform stairs. An option for a small elevator is included but will be eliminated if all tubes are installed from the bottom of the tank. A utility area will house water pipes and control cables which are routed from the mechanical equipment room to the top of the tank. In addition, this area can be used to route signal cables from the PMTs at the top surface of the detector to the electronics room. All cables from the PMTs to the electronics are the same length but follow routes of different length. The excess cable will be stored in cable trays within the tower. The functions of the utility tower can be achieved with other designs, and is unnecessary if the installation scheme does not require access to the top of the tank. The utility tower was conceived as a convenient centralized solution to tank access, cable routing, and plumbing needs.

The electronics room and office space are on the right hand side of the tower as depicted in Fig. 14. Once the experiment is operational, it is expected that preliminary data analysis and monitoring will occur primarily from the Brookhaven Physics Department. Therefore, only a modest office area for terminals or work stations is provided at the detector site. The electronics area has been sized to accommodate the expected electronics layout with some allowance for expansion. The electronics room and office area will have climate controls. The electronics will be protected from cooling failures with a temperature activated power shutoff. Appropriate alarms for smoke, fire and burglary are included in the building design. In addition, the electronics room will have a fire suppression system.

Water Filtration

Each tank will be filled with approximately 5 kilotons of water, which must be pure to achieve a long mean free path for Cherenkov light. Contaminants such as ions, organics and bacteria must be excluded as much as possible, and this purity must be maintained on a continuous basis. A filtration system has been designed to meet these criteria. It will be located in the mechanical equipment room on the left hand side of the utility tower.

The filtration system has fast and slow circulation components. A simplified schematic of the system is shown in Fig. 16. The fast circulation system will operate at 83 GPM, requiring 10 days to filter the volume. This system will use an ultraviolet lamp to kill bacteria and a final filter stage of 0.2 microns to remove bacterial fragments. The slow circulation system will have a flow capacity of 33 GPM. A prefilter stage will consist of activated carbon and mixed resin beds for deionization. This is followed by 5 micron and 1 micron filters. The water is further purified by filters with an absolute pore size of 0.5 microns. These absolute rated filters are guaranteed to remove bacteria and therefore an UV system is not employed in this part of the system. A final filter stage containing 0.2 micron filters will remove any potential debris generated by the previous stage and also provide redundancy. Monitors and controls are included in the system.

A reverse osmosis system was considered but rejected due to the large waste water stream generated (10%).

A heat exchanger, chiller, and oil fired heater have been added to the basic filtration system to maintain the water temperature at 10°C with a 5°C tolerance. This temperature was chosen to suppress bacterial growth in the water and decrease phototube noise. The capacity of the system has been matched to the R-10 insulation of the water tank and the expected weather extremes. Area heaters are placed about the equipment room to protect the plumbing from freezing. An emergency generator will supply sufficient power to maintain water circulation, and to run the oil burner and other critical systems, in the event of a power failure.

Tank Construction Schedule

The installation of utilities at the detector site will be closely coordinated with the site construction. The water supply system will be sufficiently complete so as to provide a source of water for testing the tank for leaks. The flow capacity is sufficient to fill the tank in a reasonable time period, although the initial filling using purified water will require at least one month since the slow circulation system will be used. Completion of the water supply system will be coordinated with the support building construction. AC line power is not required for tank construction, but is needed at the site immediately before construction of the support building. An isolation transformer will provide "clean" power for the experiment's electronics and computers preventing unwanted noise from the mechanical equipment.

The experiment will be given a phased beneficial occupancy of the detector site. Upon completion of the water tank, the experiment will have access to the interior to begin installation of the PMT supporting structure. The utility tower and support building will require approximately six months to complete. However, the utility tower and cable trays will be readied at the earliest possible date to allow the experiment to begin installation of the PMTs onto the support structure, including routing cables into the utility tower. This phased occupancy will be carefully coordinated with the contractor enabling the experiment to begin installation without interfering with a timely completion of site construction.

References

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[2] R. Becker-Szendy et al., Phys. Rev. Lett. **69** (1992) 1010.

[3] A. Suzuki et al., Nucl. Inst. Meth. **A329** (1993) 299.

Figure captions

Fig. 1. Detector station cross section.

Fig. 2. Arrangement of photomultiplier tubes within the tank.

Fig. 3. Physical dimensions of Hamamatsu R4558 PMT.

Fig. 4. Physical dimensions of the Winston cones.

Fig. 5. Cross section of Belden YR29304 cable.

Fig. 6. Cable feedthrough details.

Fig. 7. Details of the Super-Kamiokande PMT housing assembly (from [3]).

Fig. 8. Support structure for PMT and cable.

Fig. 9. Basic unit for PMT mounting.

Fig. 10. View of the installation procedure, including the mobile crane.

Fig. 11. Two methods for lifting the PMTs into position.

Fig. 12. Conceptual view of a detector site.

Fig. 13. Elevation view of a detector tank, including some details.

Fig. 14. Ground floor plan view of a detector site.

Fig. 15. Cross sectional view of a detector station, including the utility tower.

Fig. 16. The water purification system.