Waterproofed Photomultiplier Tube Assemblies for the Daya Bay Reactor Neutrino Experiment (Postprint)

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Abstract

In the Daya Bay Reactor Neutrino Experiment 960 20-cm-diameter waterproof photomultiplier tubes are used to instrument three water pools as Cherenkov detectors for detecting cosmic-ray muons. Of these 960 photomultiplier tubes, 341 are recycled from the MACRO experiment. A systematic program was undertaken to refurbish them as waterproof assemblies. In the context of passing the water leakage check, a success rate better than 97% was achieved. Details of the design, fabrication, testing, operation, and performance of these waterproofed photomultiplier-tube assemblies are presented.

Full Text

Preamble

Waterproofed Photomultiplier Tube Assemblies for the Daya Bay Reactor Neutrino Experiment

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Abstract

The Daya Bay Reactor Neutrino Experiment employs 960 20-cm-diameter waterproof photomultiplier tubes to instrument three water pools as Cherenkov detectors for cosmic-ray muon detection. Of these, 341 photomultiplier tubes were recycled from the MACRO experiment through a systematic refurbishment program to create waterproof assemblies. The process achieved a success rate exceeding 97% in passing water leakage checks. This paper presents detailed information on the design, fabrication, testing, operation, and performance of these waterproofed photomultiplier-tube assemblies.

Keywords: Daya Bay, reactor, anti-neutrino, waterproof, photomultiplier tube, MACRO
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1. Introduction

The Daya Bay Reactor Neutrino Experiment is designed to measure the neutrino-mixing angle 13 with high precision [1]. To achieve this goal, the experiment utilizes detectors located in one far and two near underground experimental sites at different distances from three pairs of reactors. At each site, multiple detectors filled with 0.1% Gd-loaded liquid scintillator detect electron anti-neutrinos from the reactors. Each site benefits from significant overburden to reduce the cosmic-ray muon flux, and each anti-neutrino detector (AD) is submerged in a water pool to suppress ambient gamma-ray and neutron backgrounds. Except at the top, each water pool is segmented into two optically isolated zones that are instrumented with 20-cm-diameter photomultiplier tubes (PMTs) as independent water Cherenkov detectors for muon detection [2].

In each of the two near sites (EH1 and EH2), the water pool measures approximately 16 m × 10 m × 10 m and is instrumented with 288 20-cm waterproof PMTs. In the far site (EH3), the water pool measures approximately 16 m × 16 m × 10 m and contains 384 20-cm PMTs. Of the 960 total PMTs, 619 are new Hamamatsu R5912 PMTs [3] custom-built as waterproof assemblies for

Daya Bay. Since the PMTs in the water pools serve only for muon tagging, we elected to recycle PMTs previously used in the MACRO (Monopole, Astrophysics and Cosmic Ray Observatory) experiment in Italy [4]. We successfully waterproofed approximately 400 MACRO PMTs that passed pressure testing in water, selecting 341 of them for instrumentation of the Daya Bay water pools.

Section 2 discusses the design of the waterproof PMT assemblies, including the MACRO PMT, voltage divider, potting shell, and studies of potting materials. Section 3 describes the potting procedure in detail, including the pressure test used to verify waterproofing. Based on initial pressure test results, we improved the fabrication procedure and successfully completed mass production of all ~400 waterproofed PMTs. Assemblies that passed both pressure testing and subsequent electrical testing were installed in the water pools, and their performance during data taking is presented here. Section 4 provides a summary.

2.1. MACRO PMT

The MACRO PMTs we used are EMI (now Electron Tubes) models 9350KA and D642KB [5]. These tubes feature a 20-cm-diameter hemispherical glass window with a blue-green sensitive bialkali photocathode, 11 high-gain SbCs dynodes, and 3 BeCu dynodes in a linear-focused design for good linearity and timing. Since their structure, geometry, and light detection characteristics are similar to those of the newly purchased Hamamatsu R5912, the 9350KA and D642KB represent viable candidates for instrumenting the Cherenkov detectors of the Daya Bay experiment. However, in the MACRO experiment these PMTs were immersed in mineral oil with unsealed bases, whereas at Daya Bay they are submerged in ultra-pure water and subjected to greater pressures. Therefore, we needed to encapsulate the electrical components in the bases with epoxy to make them waterproof and ensure they could withstand sufficient pressure before installation in the Daya Bay water pools.

2.2. Design of Voltage Divider

In the MACRO experiment, two cables operated each PMT: one carrying negative high-voltage (HV) and the other carrying the signal. In the Daya Bay experiment, however, a single cable carries both positive HV and signal from the base to a decoupler, which isolates the signals from the applied HV and directs them to the front-end electronics. Consequently, we designed and fabricated new bases for the MACRO PMTs. Several operational characteristics of the PMTs are sensitive to the base design, including the working HV at a particular gain, rise and fall times, linearity, and collection efficiency. Generally, the specifications of the MACRO PMTs are similar to those of the Hamamatsu R5912s; for example, a maximum gain of 3×10^{7} at a HV of less than 2 kV, and linearity better than $\pm5\%$ at 60 mA peak anode current.

Our circuit design, shown in Figure 1 [Figure 1: see original paper], uses resistor values following the manufacturer's recommendation for the EMI 9350KA.

In particular, the resistor between the photocathode and first dynode provides a potential difference of approximately 450 V at our nominal operating voltage. Our tests demonstrated that similar performance is achieved for the EMI D642KB PMTs with the same circuit design. Based on evaluation of several prototypes, we found that the combination of a 50-Ω terminating resistor (R30) and no damping resistor (R31) at the anode output provided an optimal waveform, minimizing both the recovery time after overshoot and the ratio of overshoot amplitude to signal amplitude. We carefully laid out the circuit to reduce potential electromagnetic interference between components.

2.3. Design of Potting Shell

To ensure reliable operation of the refurbished MACRO PMTs in water, their bases must be well sealed. The potting shell design must minimize contact between epoxy and water while satisfying the constraint that the potted tube geometry and PMT mounts remain compatible with those for the purchased Hamamatsu waterproof assemblies. To achieve this, we scanned and modeled the profiles of several MACRO PMTs using a coordinate measuring machine (CMM). We then measured the tube length, socket diameter, and dome diameter of all 400 MACRO PMTs, finding that parameter variations remained within tolerance for mounting the potted PMTs on support frames for installation.

The right drawing of Figure 2 [Figure 2: see original paper] shows a vertical cross-section of the two-piece potting shell. One piece is the acrylic base that sits on the cone-shaped glass envelope of the PMT and holds the plastic socket with connecting pins; the voltage-divider board plugs onto this socket. The other piece is the acrylic cap, which joins with the acrylic base. The top of the acrylic cap features a crossing rib design that strengthens the potting shell. The side wall of the acrylic cap has an opening that allows the coaxial cable to exit the base, while another opening in the top (labeled as ‘filling hole’ in Figure 2) permits pouring epoxy into the volume between the two acrylic pieces to seal the PMT base.

At the narrow end of the acrylic base, four layers of protection extend from inside to outside: epoxy, sealant, mastic tape, and sealant. At the acrylic cap, the coaxial cable also has four layers of protection: epoxy, sealing plug, sealing acrylic cap, and mastic tape. We sealed the acrylic base and acrylic cap together with acrylic cement. The filling hole in the top of the acrylic cap is closed by a smaller acrylic cap and sealed with the same acrylic cement. Thus, whichever side of the potting shell contacts water, multiple layers of protection prevent water from entering the potting shell and reaching the electrical connections.

2.4. Potting Materials

2.4.1. Epoxy

Epoxy is the most critical component of the potting materials, playing the key role in sealing quality. It must be compatible with the electrical circuitry of the base, the PMT glass, and the cable jacket. We considered the following criteria when selecting epoxy: (1) suitability for casting with low viscosity; (2) curing at room temperature or below; (3) good bonding with acrylic, polyethylene (PE), and glass; (4) exothermal temperature rise during curing not exceeding 105°C (PE limit); (5) suitability for protecting electronics against long-term submersion in ultra-pure water at 23°C; and (6) acceptable natural radioactivity levels.

Based on these criteria, we selected three candidates for testing: Master Bond EP42-2LV, Master Bond EP30M3LV, and 3M Scotch Cast SC2130. We chose 3M Scotch Cast SC2130 for its low viscosity, lower surface and center curing temperatures, slower hardening, softer 'feel' (indicating greater elasticity), and absence of temperature spikes in casting tests. The exothermal test procedure involved pouring epoxy into a mold and placing a temperature sensor just below the surface at the center (Figure 3 [Figure 3: see original paper]). The maximum temperature of 3M Scotch Cast SC2130 within 30 minutes was 61°C. We determined the natural radioactivity of 3M Scotch Cast SC2130 to be 38 ± 10 ppb from the ^{238}U series, 51 ± 15 ppb for the ^{232}Th sequence, and $(0.24 \pm 0.01)\%$ for natural potassium—sufficiently low that this radioactive background source does not impact the performance of the water Cherenkov detectors.

2.4.2. Mastic Tape

Mastic tape serves as another important sealing material, bonding the acrylic base to the cone-shaped portion of the PMT glass envelope and sealing the space between the coaxial cable and the opening of the acrylic cap. We selected 3M Scotch Seal 2229 for its merits: it seals effectively against dust, soil, and water. We determined the radioactivity of Scotch Seal 2229 mastic tape to be 1.78 ppm (^{238}U series), 4.5 ppm (^{232}Th sequence), and 0.142% (natural K). Since only a small amount of this tape is used in each assembly, the radioactive contaminants pose no concern.

2.4.3. Marine Sealant and Foam Donut

We employed additional sealing materials to mitigate leakage, including 3M Marine Adhesive Sealant Fast Cure 5200, normally used in marine underwater applications. We applied the marine sealant inside and outside the acrylic base around the mastic tape, as shown in the right drawing of Figure 2, where it is labeled as "RTV."

CMM scans of 14 MACRO PMTs revealed variation in the cylindricality of the blue socket from 100 µm to 280 µm. As shown in the left drawing of Figure

4 [Figure 4: see original paper], the distance between the centerlines of the socket and the cone-shaped bottom of the PMT varied with an average of 1.8 mm (maximum difference 3.4 mm), indicating a slight angle between the two centerlines. Accordingly, we first applied marine sealant to the socket connector. Because of this angle, we added a PE foam donut in the clearance between the acrylic base and socket (see the right image of Figure 4 [Figure 4: see original paper]) and sealed around the mastic tape inside the acrylic shell with marine sealant.

2.4.4. Cable Sealing

The cable carrying the signal and HV is a 52-m-long 50-Ω coaxial cable (model C07947E) manufactured by Judd Wire Inc., with a high-density polyethylene outer jacket [6]. As shown in Figure 2, an opening in the side wall of the acrylic cap allows the coaxial cable to penetrate. We selected a custom-made steel/plastic sealing plug from the University of Wisconsin-Madison Physical Sciences Lab (UW-PSL) to create the seal between the cable and the acrylic cap opening, as shown in Figure 5 [Figure 5: see original paper]. The sealing plug diameter matches the acrylic shell opening size, with two O-rings sealing the plug-cap interface and two smaller O-rings sealing the cable inside the sealing plug.

To provide additional protection against water entering along the coaxial cable, we etched the cable jacket to improve epoxy adhesion. We tested both chemical etching and plasma etching, with the latter yielding superior results. After etching approximately 20 cm of the jacket, we dipped the cable into Scotch Cast SC2130 potting compound and cured it overnight before trimming and soldering it onto the voltage-divider board. All components—including acrylic shells, epoxy, mastic tape, marine sealant, and cable sealing plug—are compatible with ultra-pure water.

3. Mass Production of Waterproof PMT Assemblies

To complete base sealing for approximately 400 PMTs, we established a potting laboratory for mass production, partitioned into specialized areas for cleaning, assembly, potting, and mechanical and electrical acceptance testing. The potting of all 400 PMTs required approximately six months, completing in March 2010.

3.1. Screening Test

Before cleaning, we tested each MACRO PMT with a removable base in a dark box, viewing its noise signals with an oscilloscope and requiring consistency with single photoelectron signals. We rejected PMTs that failed this check. Additionally, we verified the integrity of each coaxial cable.

3.2. Cleaning

We cleaned components passing visual inspection with detergent (Alconox) dissolved in 60°C water in an ultrasonic cleaner for 10 minutes. After thorough brushing and rinsing in ultra-pure water, we cleaned the components again with 60°C ultra-pure water in another ultrasonic cleaner for 10 minutes. We then baked all cleaned acrylic potting components at 60°C in an oven for approximately six hours, performing another visual inspection after baking before assembly onto cleaned PMTs. We cleaned voltage-divider boards with ethanol at 40°C in an ultrasonic cleaner for 3 minutes.

We also carefully cleaned the MACRO PMTs themselves, gently wiping the glass surface with fiberless cloths. The plastic sockets typically contained residual mineral oil from the MACRO experiment; to remove it, we submerged the socket in ethanol for 5 to 30 minutes depending on oil quantity.

3.3. Assembly

Prior to assembly, we annealed acrylic shells in an oven to release mechanical stress from the molding process. We performed assembly inside a laminar-flow fume hood to maintain cleanliness. The process consisted of several steps. First, we attached the acrylic base to the PMT. We then applied water-jet-cut mastic tape to the cone-shaped region of the glass envelope at the proper height, using a heat gun to soften the mastic tape beforehand to improve sealing quality. After applying the mastic tape, we pressed the acrylic base onto it so that the glass, mastic tape, and acrylic base adhered tightly together.

We then used marine sealant to fill the space between the acrylic base and PMT socket, also applying it around the outer perimeter between the acrylic base and PMT glass. The marine sealant required approximately 24 hours to cure. The left side of Figure 6 [Figure 6: see original paper] shows a MACRO PMT with the acrylic base assembled.

The next step involved assembling the PMT base with its HV cable and acrylic cap. We fed the HV cable into the acrylic cap through the side wall opening and soldered the etched end (without an SHV connector) onto the voltage-divider board. The right picture of Figure 6 [Figure 6: see original paper] shows this result. We then pushed the pre-assembled UW-PSL sealing plug on the cable into the side wall opening. After the marine sealant on the acrylic base cured and we placed the polyethylene donut, we plugged the voltage-divider board onto the PMT socket. We joined the acrylic base and acrylic cap with WeldOn-3 and WeldOn-16 acrylic cements, which cure in less than 30 minutes. Approximately one hour after applying the acrylic cements, we placed the PMT under a fume hood.

3.4. Potting

The final assembly step involved sealing the PMT base with epoxy. We thoroughly mixed the two components of 3M Scotch Cast SC2130 epoxy and removed air bubbles with a vacuum degassing chamber. We then poured the degassed epoxy into the acrylic shell through the top filling hole in the cap until the voltage-divider circuit board was fully immersed. The epoxy normally cured in 40 minutes. After four hours to overnight, we sealed the filling hole with a small acrylic cap and acrylic cement. We then sealed the opening containing the UW-PSL sealing plug with a flat acrylic cap that also served as cable strain relief. Once the acrylic cement cured, we applied mastic tape to the region where the cable exited the acrylic cap. Figure 7 [Figure 7: see original paper] shows the completely assembled PMT units.

3.5. Mechanical and Electrical Acceptance Tests

3.5.1. Pressure Test We subjected each potted PMT to a pressure test that mimicked working conditions in the Daya Bay water pools. The basic approach involved partially submerging each potted assembly in deionized (DI) water inside a 47.3-liter pressure tank (maximum gauge pressure: 5.52×10^5 Pa). We then pressurized the tank to a predetermined value for a specified period, after which we inspected the assembly for water leakage.

Prior to pressure testing, we visually inspected all seals of each potted PMT assembly to ensure the sealants were completely dry and free of defects such as small holes. To prevent fluid entry during pressure testing, we encapsulated the end of the coaxial cable with an SHV connector inside a custom-built cable end-sealing tube. Figure 8 [Figure 8: see original paper] shows the components of the sealing tube (left) and the assembled sealing tube with cable in place (right).

We then installed the potted PMT assembly in the partially filled pressure tank, submerging the potted portion in water while keeping the glass bulb in air. We placed the cable end-sealing tube on a plastic top with an indentation to prevent rolling. After sealing the tank, we applied pressure slowly and monitored it with a pressure gauge on the lid. Each assembly typically underwent pressure testing for 8 to 15 hours, with a subset tested for approximately 40 hours. After testing, we visually inspected the PMT assembly for leaks or damage.

During initial mass production, a small number of assemblies failed the pressure test. One failure mode involved water infiltration into the cable end-sealing tube due to damage in the fragile cable jacket. For these cases, we located the damaged region by immersing the cable in soda water and looking for an electrically conducting path between the cable ground braid and the water. After patching the damaged area with mastic tape and covering it with heat-shrink tubing and electrical tape, we repeated the pressure test to confirm successful repair. We also revised the screening test to include a cable integrity check before assembly.

Another failure mode involved fracturing of the glass envelope. Although the manufacturer specified a maximum allowable pressure of 101 kPa, a few PMTs imploded at 82.7 kPa during testing, while others experienced cracked glass domes. We measured the glass thickness in these cracked tubes, finding the top portion of the glass bulb reached 3 mm thickness, but at approximately halfway up the bottom hemisphere from the dynode structure, the thickness was about 1 mm or less. Consequently, cracking usually occurred in the bottom hemisphere below the equator. This observation motivated us to weigh bare PMTs before and after potting, revealing that imploded or cracked PMTs had a net weight of less than 540 g.

Since PMT assemblies would be installed at different depths in the water pools, we decided to apply lower pressure (P) for tubes with net mass (M) below 540 g: specifically, $P = 41.4$ kPa for $M < 540$ g, and $P = 82.7$ kPa for $M > 540$ g. We installed potted MACRO assemblies that passed testing at 41.4 kPa in the upper eighth of the water pools (static pressure ≤ 12 kPa), while those surviving 82.7 kPa were installed in the upper half of each pool (< 41 kPa). We populated the lower halves of the water pools exclusively with new Hamamatsu PMTs. We temporarily set aside potted but unweighed MACRO tubes. After potting all tubes, we identified the correlation between before- and after-potting masses (left plot of Figure 9 [Figure 9: see original paper]), which allowed us to estimate the net mass of tubes not weighed before potting and apply appropriate test pressure. The right plot of Figure 9 shows the distributions of before-potting net mass for passed and failed assemblies, demonstrating that tubes breaking during testing tend to have smaller mass.

During mass production, we potted eight tubes per day and performed pressure tests on two to three potted assemblies. By the end of March 2010, we had produced 386 waterproofed assemblies, with 52 assembled before revising potting and acceptance testing procedures. Of these early assemblies, 50 were tested and 36 passed, yielding a 72% success rate. The remaining 334 tubes were assembled after refining potting and pressure testing procedures; among them, 190 were tested with 176 passing, improving the success rate to approximately 93%. We sent six of these 176 waterproofed assemblies to Rensselaer Polytechnic Institute for long-term pressure testing. Ultimately, we had 352 waterproofed PMT assemblies available for use, including 146 that had not been pressure-tested. We later tested these in the Surface Assembly Building at Daya Bay from August through December 2010, achieving a success rate greater than 95%.

3.5.2. Electrical Test We established a testing facility at Dongguan University of Technology (DGUT), approximately two hours from Daya Bay, to test all PMT assemblies for the experiment. We sent the 352 waterproofed MACRO PMT assemblies to DGUT for electrical testing at the end of March. The test included measuring the single photoelectron spectrum and its peak-to-valley ratio (P/V), gain as a function of applied HV, dark rate, and after-pulsing ratio

(APR), where APR is defined as the probability of observing a pulse exceeding 0.25 photoelectron within approximately 20 µs after the main pulse. Figure 10 [Figure 10: see original paper] shows distributions of HV for operating PMTs at gains of 1$×10^{7}$ (black) and 2$×10^{7}$ (red), P/V at 1$×10^{7}$ gain, APR at 1$×10^{7}$ gain, and dark rates at gains of 1$×10^{7}$ (black) and 2$×10^{7}$ (red) for the 352 MACRO PMTs. Seventeen assemblies did not meet requirements: one showed no output, two had P/V less than two, four had APR larger than 10%, and ten had dark rates higher than 10 kHz at gains of [0.3–3]$×10^{7}$. We determined that six of the ten noisy PMTs with dark rates just above 10 kHz and two others with P/V slightly below two could still be used. In total, 343 waterproofed MACRO PMTs were available for the experiment.

3.6. Performance of Waterproofed PMT Assemblies at Daya Bay

By the end of 2011, we had installed and commissioned all waterproof PMT assemblies in the three experimental sites. Of these, 104 of the 288 PMTs in both EH1 and EH2, and 133 of the 384 PMTs in EH3 were waterproofed MACRO PMTs. Taking EH1 as an example, the singles rates of the PMTs were 2–8 kHz in the inner partition of the water pool and 10–16 kHz in the outer partition. We observed no noticeable difference in singles rates between the new Hamamatsu and refurbished MACRO waterproof PMTs [2].

Over nearly one year of data-taking, several waterproofed assemblies failed. The left plot of Figure 11 [Figure 11: see original paper] shows the cumulative number of failures over this time. The mass distribution of PMTs that failed in the water pools closely resembles that of PMTs that failed pressure testing during fabrication (shown in Figure 9). From late July through September 2012, we paused steady data-taking to perform special AD calibration measurements and install the last two ADs (one in EH2 and one in EH3). During this period, we investigated failed PMTs in the water pools, replacing all but one with spare Hamamatsu PMTs. We made 6, 5, and 2 replacements in EH1, EH2, and EH3 respectively. We tested failed PMTs for cable leaks using a custom-made cable/air pressurization tube, finding no cable leaks. All but two of the failed PMTs exhibited cracks in the glass extending from the dome equator near the support ring upward away from the base. One of the remaining two failed PMTs imploded after data-taking paused and we removed it from EH1, while we removed the other from EH2 due to a high dark rate potentially caused by base leakage.

Upon refilling the pools, 2 and 6 new failures occurred in EH2 and EH3 respectively. We hypothesize that pressure changes across the PMT glass during draining and filling triggered these failures. We decided not to drain the pools again to replace these new failures due to the risk of causing additional failures. After all, the very small number of such failures has minimal impact on water Cherenkov counter performance. During the subsequent two years of steady data-taking, 20 additional MACRO PMT assemblies failed in the three pools (see the right plot of Figure 11 [Figure 11: see original paper]). Since October 2012 (corresponding to 70 weeks in Figure 11), the failure rate appears to have stabilized to \$ \$0.5 PMT/month.

4. Summary

We successfully fabricated 386 waterproofed PMT assemblies by recycling MACRO PMTs. While this effort was motivated by avoiding the expense of purchasing new waterproof PMT assemblies, the complexity and cost ultimately proved higher than expected. We installed 341 of these waterproofed PMTs in the muon system of the Daya Bay experiment, representing slightly more than one third of all PMTs in the water pools. During the first twelve months of operation, 15 of these 341 PMTs malfunctioned in the water pools, but only one failure appears attributable to imperfect base sealing. The electrical performance of the waterproofed MACRO PMTs has been very similar to that of the new Hamamatsu waterproof R5912 PMTs.

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