4. Photomultiplier tubes

The primary design considerations for the PMT system are

- High photon detection efficiency.
- Minimal amount of radioactivities in all components, <120 ng/g U, < 90 ng/g Th, <0.2 mg/g K.
- Low failure rate for a 10 yr lifespan submerged in ultrapure water at a pressure of 200 kPa and for the seismic activity expected at the SNO site.
- Fast anode pulse rise time and fall time and low photoelectron transit time spread, for a single-photoelectron timing resolution standard deviation < 1.70 ns.
- Low dark current noise rate, < 8 kHz, at a charge gain of 10^7.
- Operating voltage less than 3000 V.
- Reasonable charge resolution, > 1.25 peak to valley.
- Low prepulse, late-pulse and after-pulse fractions, < 1.5%.
- Low sensitivity of PMT parameters to external magnetic field: at 100 mG, less than 10% gain reduction and less than 20% timing resolution degradation.

Raw materials from the manufacturers of the PMT components, bases, cables, and housings were assayed for radioactivity [33]. The leach rates of different types of glass and plastic were also measured.

The photomultiplier tubes (PMTs) are immersed in ultrapure water to a maximum depth of 22 m, corresponding to a maximum water pressure of 200 kPa above atmospheric pressure. The failure rate of the PMT components, which consist of the PMT, the resistor chain and the HV/signal cable, must be compatible with the expected approximate 10 yr detector lifetime. This puts severe constraints on the choice of glass for the PMT envelope, the shape of the envelope, the type of cable, and the design of the waterproof enclosure that protects the resistor chain. Raw materials from all manufacturers were assayed for radioactivity [33]. The dominant contributor to the contaminant content of the PMT is the glass which has a mass of 850 g and Th and U impurity levels of roughly 40 ppb. The leach rates of different types of glass and plastic were also measured.

Following detailed stress analysis of the proposed glass envelopes, a mushroom-shaped envelope was judged to be most suitable for this underwater application and least likely to deteriorate under long-term hydraulic pressure in UPW. Schott Glaswerke produced a new borosilicate glass (Schott 8246) for SNO. The Th and U impurities in this glass are less than 40 ppb. Its water resistance is rated as class 1 (same as Pyrex). In addition, this glass has outstanding optical transmission properties at short wavelengths, with a bulk light absorption coefficient of better than 0.5 cm^{-1} at 320 nm wavelength, and low He permeability. Schott refitted a furnace with a special low-radioactivity liner to produce 16,000 mouthblown bulbs for SNO and the LSND Project [34].

The most important PMT parameters are the noise rate, the efficiency, the transit-time spread and the amount of K, U and Th in each PMT. The energy resolution and the event vertex spatial resolution are largely determined by the first three parameters and the detector energy threshold is strongly affected by the radioactivities in the PMT components.

The Hamamatsu R1408 PMT was selected for use in SNO. A schematic drawing of the R1408 is shown in Fig. 6. From the measured U and Th concentrations in the internal parts and glass envelope, the total weight of Th and U in each PMT is estimated to be about 100 μg, about a factor of 14 below specifications. The 9438 inward facing PMTs collect the Cherenkov photons, providing a photocathode coverage at 31%. To improve the light collection efficiency, a 27 cm diameter light concentrator is mounted on each PMT, increasing the effective photocathode coverage to about 59%. The reflectivity of the concentrator reduces this figure to 54%. Of the inward facing tubes, 49 have a dynode tap and a second signal cable. These "low gain" channels extend the dynamic range of SNO at high light intensities by about a factor of 100. Another 91 PMTs without concentrators are mounted facing outward to detect light from muons and other sources in the region exterior to the PMT support structure.

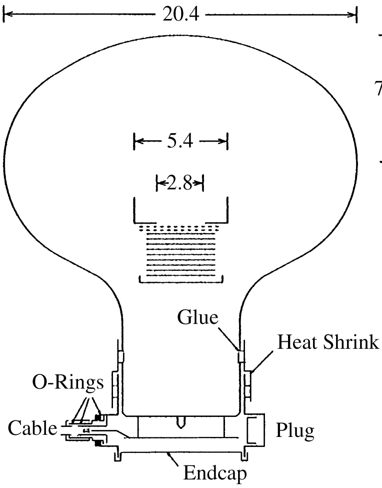

Fig. 6. A schematic of the Hamamatsu R1408 PMT and its waterproof enclosure. The nine dynodes are shown as solid horizontal lines. The focusing grid is shown as the dashed lines above the dynodes. The volume inside the enclosure is filled with soft silicone gel. The end cap is flexible to allow for thermal expansion. The plug is sealed with heat shrink and thermal adhesive. Dimensions are in cm.

The PMT anode is at positive high voltage, typically in the range 1700–2100 V, and the photocathode is at ground voltage. A single RG59/U type cable is used to carry the high-voltage and the fast anode pulse which is capacitively coupled to the front-end electronics. The primary concern in selecting materials for the resistor chain circuit board is radioactivity. Each two-layer kapton circuit board, with surface mounted components and a through-hole 0.0047-μF film capacitors for filtering and source termination, contains a total of about 2 μg of thorium and 0.6 μg of uranium, about a factor of five lower than the design goal.

The main function of the waterproof enclosure is to keep the PMT base dry when the PMT is deployed under water. There are two water barriers protecting the circuit board to ensure a low failure rate. The outer enclosure consists of a plastic housing, waterproof modified "TNC" connector and heat shrink tubing with thermal adhesive. (A connector was used to simplify construction and cabling.) The shrink tubing and adhesive are used to hold the plastic housing onto the PMT. The cavity inside the enclosure is filled with a silicone dielectric gel (GE RTV6196) which acts as the second water seal. The silicone gel contains less than 23 ng/g of Th and less than 12 ng/g of U. The polypropylene plastic housing contains less than 10 ppb of Th and less than 6 ppb of U. The heat shrink tubing is made of clear polyolefin which has low Th and U impurities. The TNC connector was provided by M/A-COM with modifications specified by SNO. These connectors exhibited breakdown at nominal high-voltage settings, a problem which was overcome by the addition of nitrogen gas to the water, as described in the previous section. Heat shrink and thermal adhesive seal the cable to the male connector.

The RG59/U type cable was designed by Belden, Inc. for SNO. It consists of a copper clad steel central conductor surrounded in succession by 1.85 mm thick solid polyethylene dielectric, 95% tinned copper braid, Duofoil bonded metallic shield and 1.3 mm thick high-density polyethylene outer jacket. The colouring compound mix in the outer jacket is reduced to 0.1% carbon black, the minimum amount needed to make the jacket opaque. Each PMT cable is 32 m long and contains between 10 and 17 μg of Th and a few μg of U. The attenuation at 400 MHz is 7.3 dB/30.5 m. The delay is 4.9 ns/m.

The Hamamatsu R1408 PMT has unusually stable gain characteristics with respect to the influence of weak magnetic fields [35]. In the SNO detector the earth's magnetic field is about 55 μT and points approximately 15° off the vertical axis. In such a field, the photon-detection efficiency average over all the PMTs would be about 82% of the detection efficiency at zero magnetic field. Because the PMT efficiency is reduced by less than 3% at magnetic field intensities of 20 μT, only the vertical component of the magnetic field in the SNO detector is cancelled with 14 horizontal field-compensation coils embedded in the cavity walls. With the proper currents, the maximum residual field in the PMT region is 19 μT, and the reduction in photodetection efficiency is about 2.5% from the zero-field value.

The single photoelectron test system and test results are described in detail in Refs. [36,37]. A total of 9829 PMTs passed the acceptance test. The average RMS timing resolution is found to be 1.7 ns, in line with the specification. The mean relative efficiency, defined in Ref. [36], is 10% better than specification. The mean noise rate is 2.3 kHz at 20°C. The cooler temperature in the detector (approximately 10°C) reduces the mean noise rate to approximately 500 Hz, including signals due to residual radioactivity in the detector. The mean operating voltage is 1875 V.

5. Photomultiplier tube support structure

The photomultiplier tubes, their light concentrators and associated hardware are collectively referred to as the PMT Support Structure or the PSUP. The geometry of this platform is fundamentally established by maximizing photon collection while minimizing background signals, fabrication costs, complexity, and transportation and installation intricacy. The D_2O target geometry, the PMT specifications, light concentrator performance, and cavity geometry all affect the final PSUP configuration.

The PSUP serves the additional function of providing a barrier between the core of the experiment (the D_2O target and light collection surfaces) and the outer regions of the experiment. This barrier shields the PMTs from light generated in the outer regions of the experiment. These regions include the cavity walls and the support piping and cabling for the experiment. Near the cavity walls the radioactivity in the surrounding rock creates a significant photon background. The complexity of the cabling and piping makes the outer region difficult to clean and keep clean during construction and the radioactive purity of the materials needed for some of these functions could not be reasonably controlled to the same levels as other detector components. The PSUP also functions as a highly impermeable barrier to waterborne contamination, ensuring that the highly purified water in the sensitive region between the PMTs and the AV is effectively isolated from the dirtier water in the outer regions.

The PSUP also supports the outward looking PMTs, LED calibration sources, and water-recirculation and monitoring piping.

The design criteria for the PSUP include:

- Maximizing the collection of optical signals from the D_2O target while minimizing a variety of background sources.
- Maintaining performance and integrity of the array, with no required maintenance, for at least a 10 yr span submerged in ultrapure water and for a variety of seismic conditions anticipated at the SNO site.
- Minimizing the mass of the components to reduce intrinsic backgrounds.
- Producing and fabricating the array from documented low radioactivity materials.
- Maintaining a high impermeability water barrier between the inner and outer light water regions.
- Maintaining an effective barrier to light generated in the outer regions.
- Minimizing the complications of transporting and installing the array at the underground site.
- Producing and fabricating the array from materials inimical to biological growth with low leaching characteristics, low magnetic susceptibility and low electrolytic characteristics.
- Utilizing materials and installation processes compatible with the underground (mining) environment.
- Installing the upper half of the geodesic sphere and supporting the loads of roughly half the detector array during which time the AV is constructed.

The PSUP is logically viewed as two systems – a geodesic sphere that functions as the main support system and the panel arrays that house the PMTs and concentrators. The geodesic sphere, an 889-cm radius three-frequency icosahedron, is shown in Fig. 2. Normally, this geodesic sphere would utilize 92 nodal connections between the 270 struts. This choice of geodesic structure uses three different strut lengths with similar linear dimensions. The topmost node is replaced with a hollow toroidal ring and the connecting struts shortened to accommodate the acrylic vessel chimney. Additional toroidal rings guide the acrylic vessel support ropes through the PSUP. Ninety-one outward viewing PMTs are supported on the PSUP struts. The design of the geodesic sphere and panel arrays is fully documented [38].