Build a Cooled PMT Probe Enclosure – Results, Lessons Learned, and Recommendations for Future Development

S.E. NickolsTechnical Note , March 2022

Abstract

Cooled photomultiplier tubes (PMTs) offer lower dark currents and stabilized responsivity compared to room-temperature PMTs. In the dark and at room temperature, the dominant mode of photocathode emission is thermionic, so cooling down the photocathode to around -25^{o}C drastically reduces the noise and dark counts from a PMT. We constructed a thermoelectrically-cooled housing to experiment with cooling a standard 2” face-on PMT. Although appropriate PMT noise reduction was achieved (one order of magnitude), the thermal efficiency of our do-it-yourself housing design was low, so lessons learned from this build will be used in the development of an improved second-generation cooled housing.

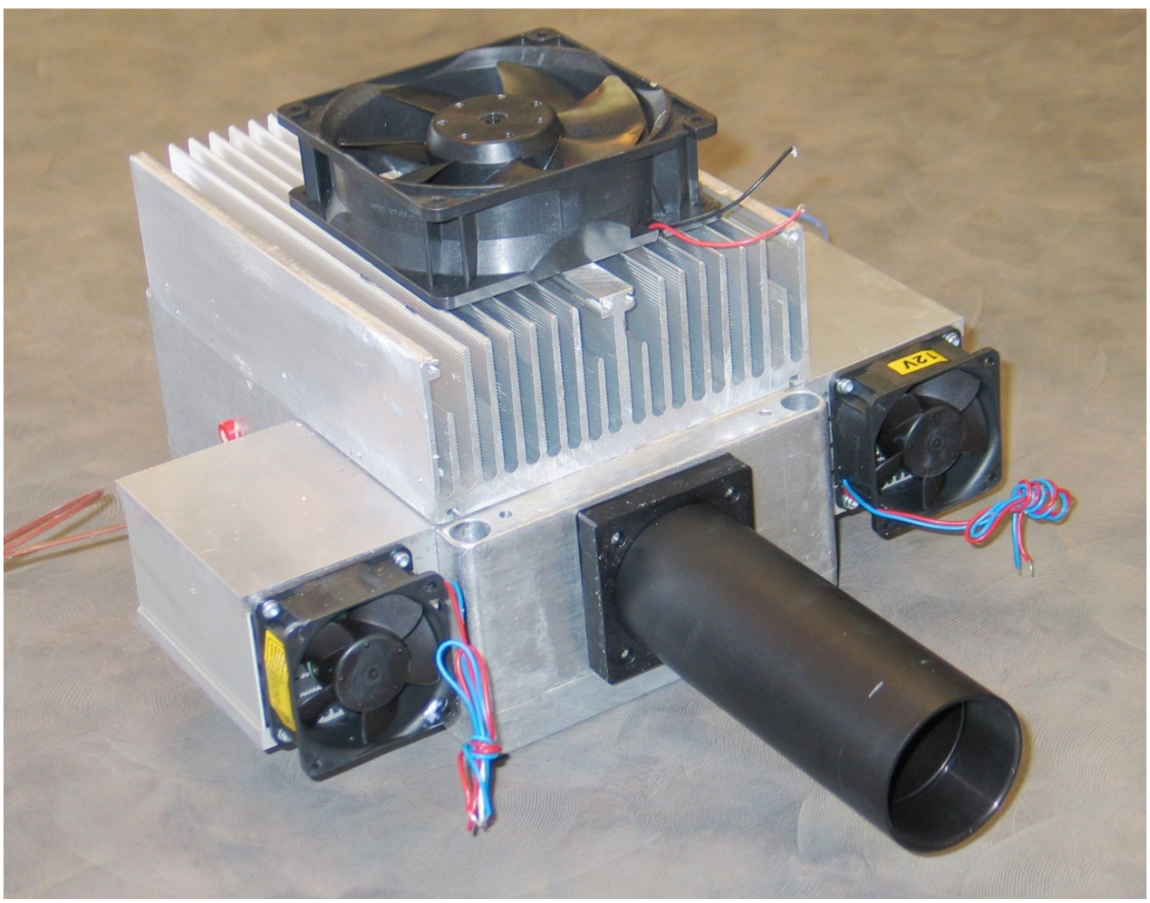

Figure 1 – A cooled PMT enclosure. The unit cools a 2” PMT to -20^{o}C using four thermoelectric cooler modules and three fans.

Introduction

In the dark and at room temperature, the dominant mode of photocathode emission is thermionic. Figure 2 and Table 1 show the effect of temperature on dark counts for typical photocathode types, demonstrating that PMT photocathode cooling is highly advantageous in low level detection. This figure also shows that for standard photocathode materials there is little advantage in cooling below -25 °C.

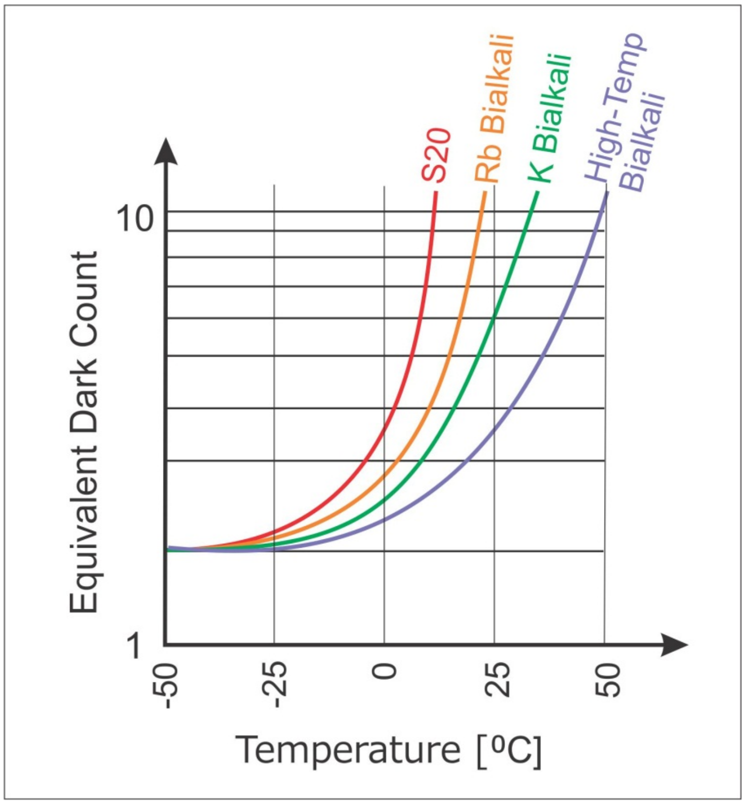

Figure 2 – Effect of photocathode temperature on PMT dark counts

Cathode Dark Current (A/cm^{-2})									
Type	50 °C	20 °C	10 °C	0 °C	−10 °C	−20 °C	−30 °C	−40 °C	−180 °C
S I	—	10^{-11}	$8x10^{-13}$	10^{-13}	10^{-14}	$2x10^{-15}$	10^{-15}	$6x10^{-16}$	$6x10^{-19}$
S I I	$5x10^{-16}$	10^{-17}	$3x10^{-18}$	10^{-18}	$4x10^{-19}$	$3x10^{-19}$	$2x10^{-19}$	$1.5x10^{-19}$	—
S20	10^{-14}	10^{-16}	$2x10^{-17}$	$7x10^{-18}$	10^{-18}	$5x10^{-19}$	$3x10^{-19}$	$2.5x10^{-19}$	—
Bialkali	$3x10^{-17}$	10^{-18}	$5x10^{-19}$	$3x10^{-19}$	$2x10^{-19}$	$1.5x10^{-19}$	$1.5x10^{-19}$	$1.2x10^{-19}$	—

Table 1 – Typical dark current reduction at various temperatures for different photocathodes (from the 1984 Thorn EMI catalog of photomultiplier accessories and systems [3]).

Reducing dark counts is important in photon-counting applications, especially when attempting to detect photons in the near-infrared. For example, the dark count of OBB's 309 PMT, which has a wavelength range from 400 to 1200 nm, is 270,000 when not cooled—making it virtually useless for detecting almost anything but the strongest signal. However, when cooled to -20 °C, the dark count is reduced to just 40 counts. In general, the use of PMTs that detect above 600 nm almost mandates a cooled housing [1].

Commercial PMT cooling housings have been available for many years. Initially cooling was done by placing the PMT inside an insulated enclosure containing dry ice or liquid nitrogen. The PMT was allowed to be cooled by the vapors of the cryogenic "fuel." This technique is still used to chill PMTs where freedom from coolant lines is desirable. The photograph of Figure 3 shows one such commercial PMT enclosure that uses high density crushed dry ice to achieve a photocathode temperature of -75°C. A 3 lb charge of crushed ice lasts for 15 hours and takes approximately 1 hour to reach a stable photocathode temperature [2].

Figure 3 – Dry ice-cooled PMT housing model TE-241 manufactured by Products for Research. The dry ice chamber is shown open. This housing accommodates standard 53.4 mm diameter end-on PMTs.

Today, most PMT cooling housings use thermoelectric cooling (TEC) modules based on the Peltier effect to reduce the tube's temperature. These devices are electrically-powered solid-state active heat pumps which transfer heat from one side of the device to the other. As shown in Figure 4, a thermoelectric module consists of an array of p- and n-type semiconductor elements. The elements are arranged into an array that is electrically connected in series but thermally connected in parallel. This array is then affixed to two ceramic substrates, one on each side of the elements. Heat transfer occurs as electrons flow through the pairs of p- and n-type elements within the thermoelectric module.

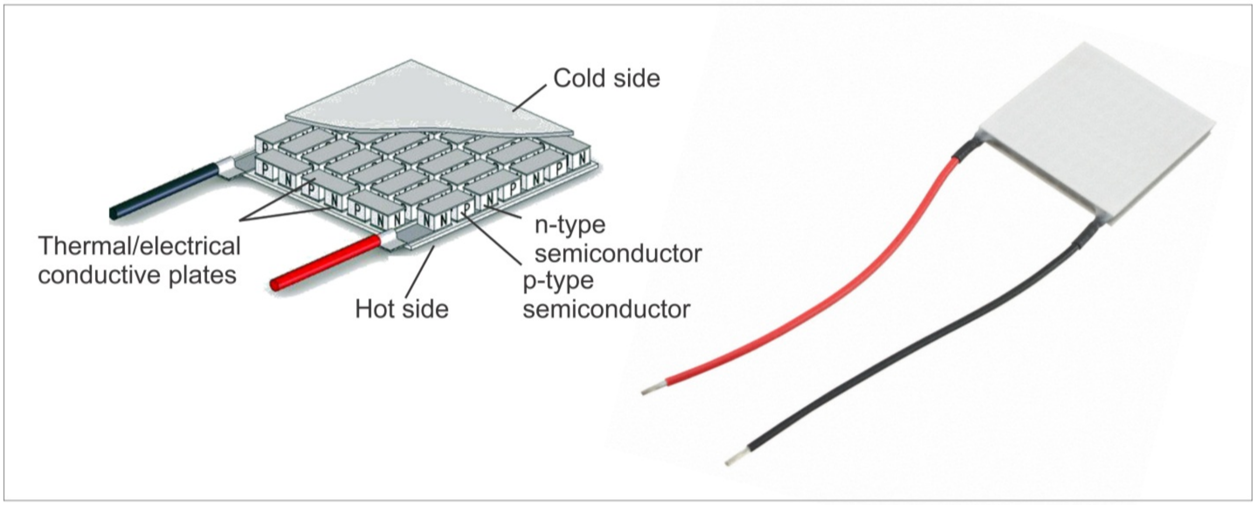

Figure 4 – A thermoelectric (TEC) module consists of an array of p- and n-type semiconductor elements. The elements are arranged into an array that is electrically connected in series but thermally connected in parallel. This array is then affixed to two ceramic substrates, one on each side of the elements. Heat transfer occurs as electrons flow through the pairs of p- and n-type elements within the thermoelectric module.

When powered by a DC current, the TEC module pumps heat from its cold face to the hot face. Since the process is not 100% efficient, the TEC produces heat as it performs work to pump heat (in the form of I^2R losses). The heat that accumulates on the hot face must thus be dissipated to facilitate the transfer of heat from the hot side of the module to the ambient. The most common heat sink is an aluminum plate that has fins attached to it. A fan is used to move ambient air through the heat sink to pick up heat from the module. Another style uses a plate with tubing embedded in it. A liquid is sent through the tubing to pick up heat from the module.

TEC modules are typically able to achieve temperature differences of around 60 °C across the TE module. Considering the inefficiencies involved in heat transfer, an appropriately used TEC module can typically cool an object by up to 45°C with respect to ambient temperature. Larger temperature differences can be achieved by stacking modules one on top of another, so that each module, or stage, acts like an electronic heat sink for the module above it. As the number of stages increases, the achievable temperature difference also increases. Unfortunately, the heat pumping capacity decreases as the number of stages increases.

For these reasons, passive or forced-air cooling is not usually as efficient as cooling the hot side with flowing cold water. However, the use of cooling lines is not always desirable, so commercial PMT housings are offered with both forced-air and flowing-water cooling options.

For the housing that we developed (Figure 1), we chose to use four 2-stage TEC modules, each with the following specifications:

Q_{max} =30.0 Watts

I_{max} =7.2 Amps @ 12 VDC

ΔT_{max}= 83°C

Dimensions: 40 mm × 40 mm × 6.9 mm

We chose to avoid the use of liquid cooling because we did not want to be limited to operating the device only where a source of cold tap water may be available. In addition, because of the danger that it carries, we wanted to avoid the presence of water in close proximity to our high voltage electronics. As such, we chose to use forced air cooling to dissipate the heat pumped by the TEC modules.

Design of the Cooled PMT Housing

For this project we retrofitted the PMT probe.We started the conversion by tightly wrapping the PMT with CONETIC magnetic shielding sheet. As shown in Figure 5, the shield was held together with aluminum adhesive tape. The outer diameter of the shield was made to fit snuggly inside a Thorlabs XT66-100 66 mm 10cm-long construction rail.

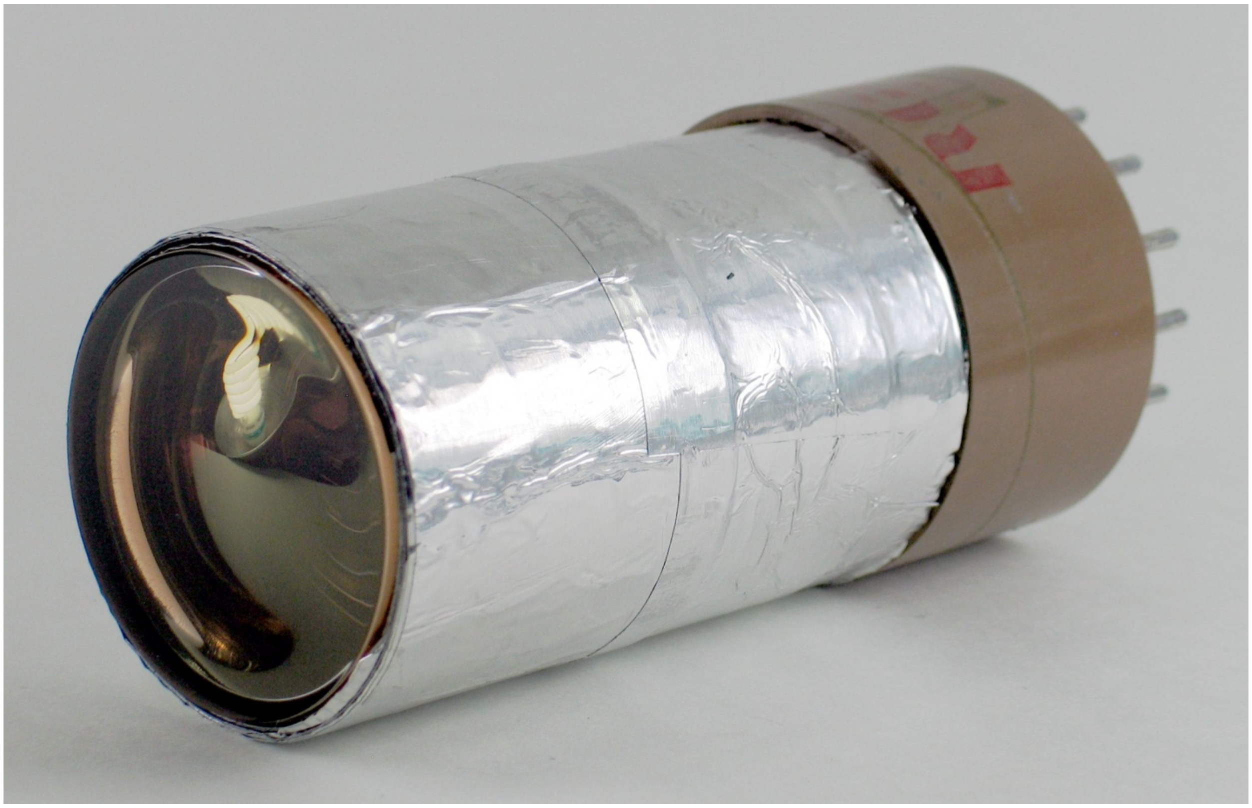

Figure 5 – The 2" RCA PMT was wrapped very tightly with CONETIC magnetic shielding sheet. The shield was held together with aluminum adhesive tape. The outer diameter of the shield was made to fit snuggly inside a Thorlabs XT66-100 66 mm 10cm-long construction rail.

Then, as shown in Figure 6, the four 2-stage thermoelectric cooling modules were glued with Artic Silver epoxy adhesive to the Thorlabs XT66-100 66 mm 10cm-long construction rail enclosing the PMT. The hot sides of the TEC modules were glued with the same adhesive to two machined aluminum blocks that serve as thermal interfaces to the die-cast enclosure. As shown in Figure 7, the PMT/thermoelectric cooling module assembly fits tightly inside the die-cast aluminum enclosure. Silver-loaded heat-conductive paste is used to ensure appropriate heat transfer between the aluminum blocks and the enclosure. The blocks are held tightly against the enclosure with four stainless-steel #8-32 × ½" screws.

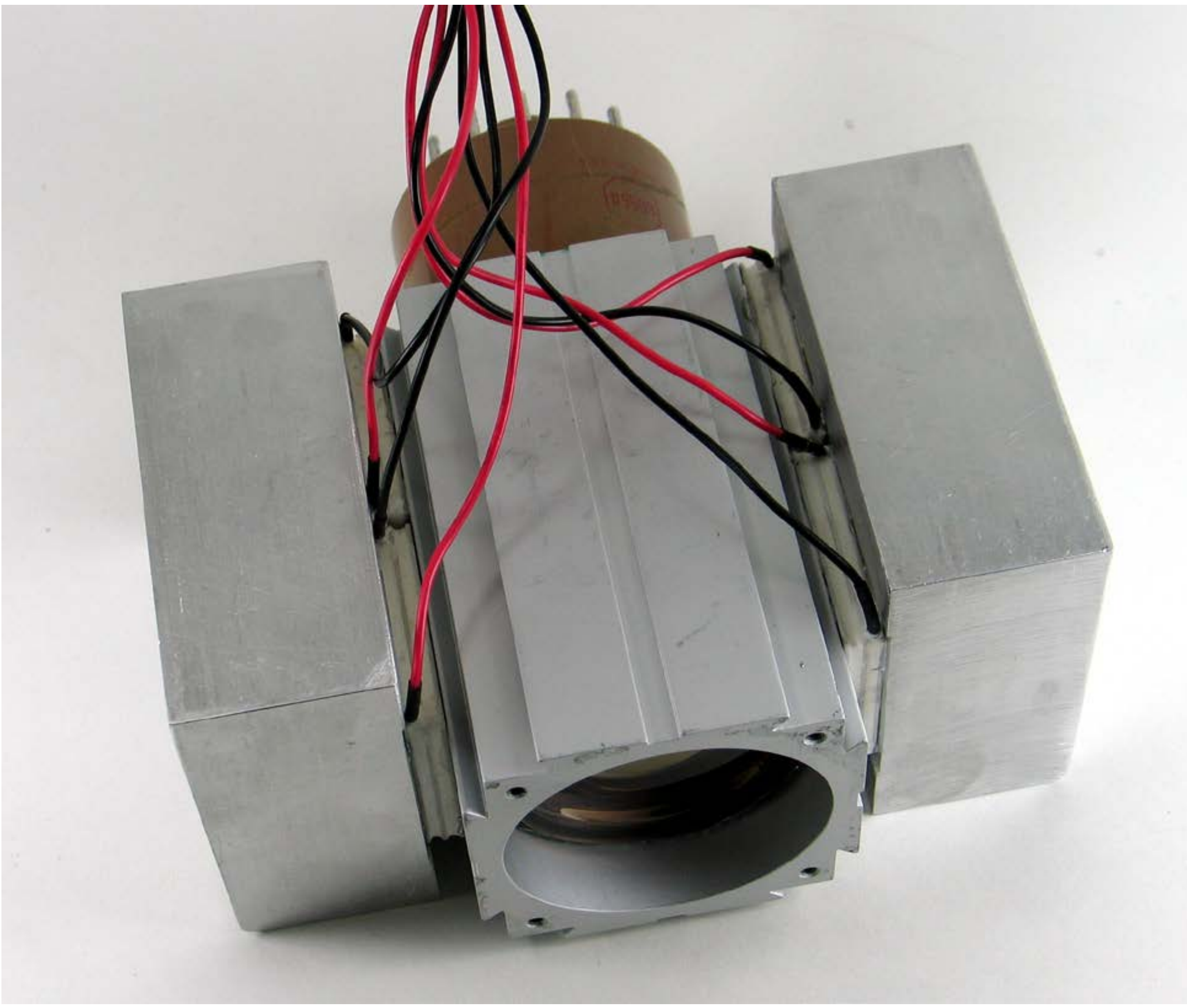

Figure 6 – Four 2-stage thermoelectric cooling modules are glued with Artic Silver epoxy adhesive to the Thorlabs XT66-100 66 mm 10cm-long construction rail enclosing the PMT and to two machined aluminum blocks that serve as thermal interfaces to the die-cast enclosure.

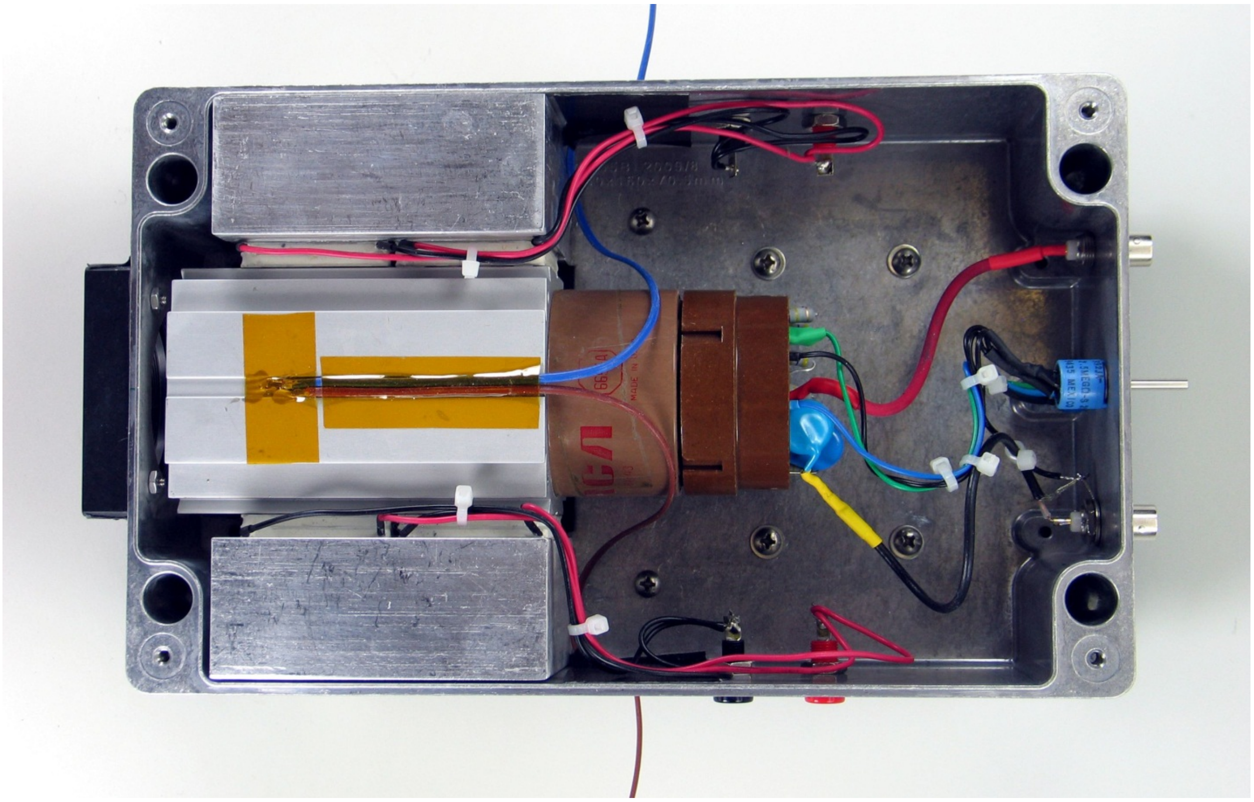

Figure 7 – The PMT/thermoelectric cooling module assembly fits tightly inside the die-cast aluminum enclosure. Silver-loaded heat-conductive paste is used to ensure appropriate heat transfer between the aluminum blocks and the enclosure. The blocks are held tightly against the enclosure with four stainless-steel #8-32 × ½" screws. A sheet of 0.079"-thick aerogel is placed between the bottom of the construction rail and the enclosure to provide thermal insulation.

As shown in Figure 8, we placed one K-type and one T-Type thermocouple in good thermal contact with the construction rail at the location of the PMT's cathode. The thermocouples were held in contact with the rail using Kapton tape, and a dab of Artic Silver epoxy was used to ensure proper thermal contact.

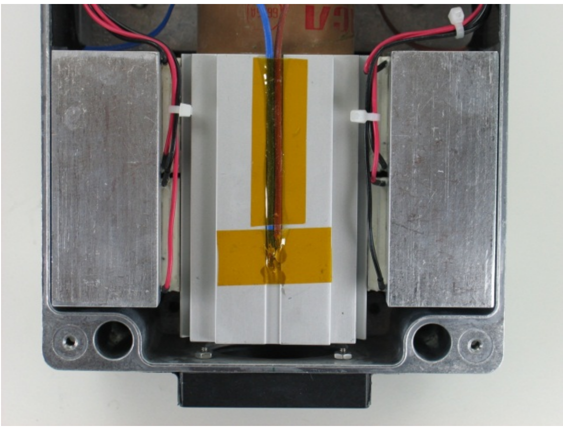

Figure 8 – One K-type and one T-Type thermocouples are placed in good thermal contact with the construction rail at the location of the PMT's cathode. The thermocouples are held in contact with the rail using Kapton tape, and a dab of Artic Silver epoxy is used to ensure proper thermal contact.

We used sheets of 0.079"-thick aerogel thermally insulate the PMT assembly from the aluminum blocks and die-cast enclosure. Lastly, we sprayed expanding foam insulation into all cavities prior to closing the enclosure.

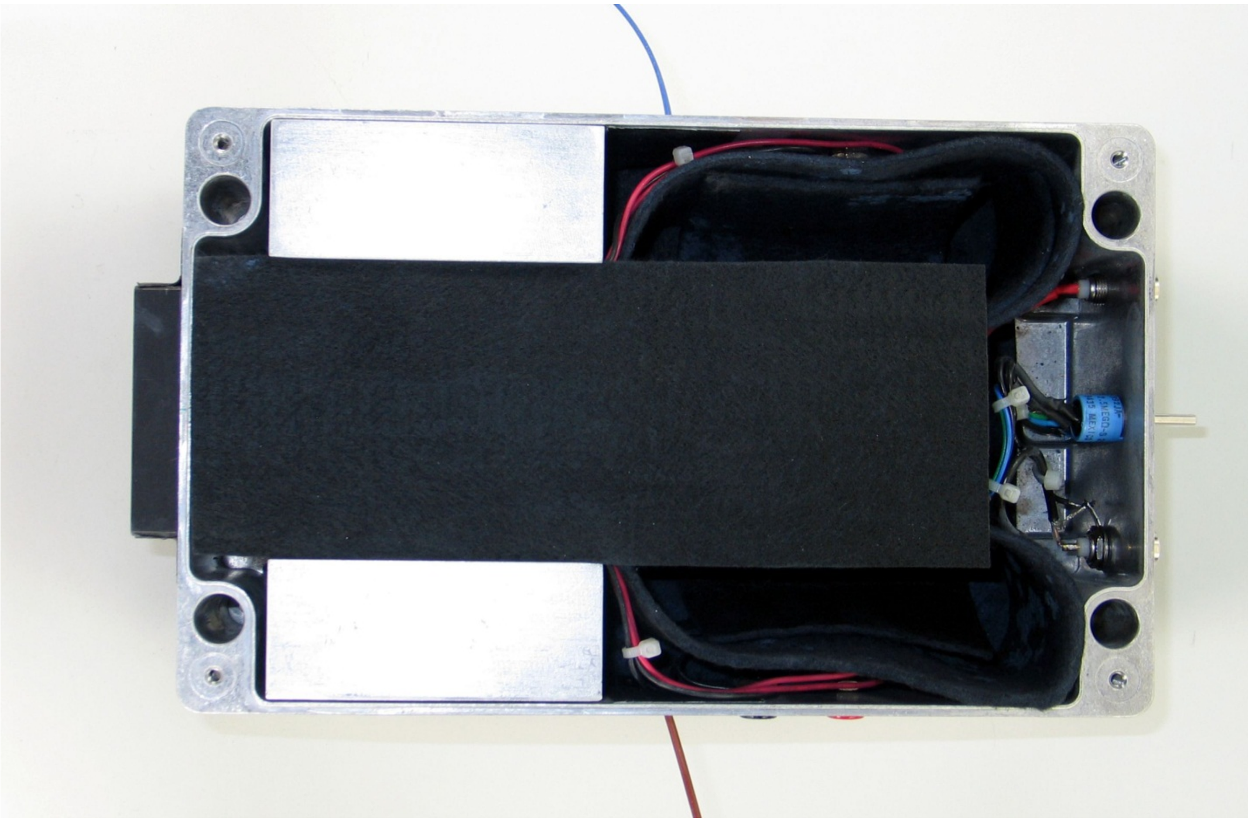

Figure 9 - 0.079"-thick aerogel is used to thermally insulate the PMT assembly. Expanding foam insulation was used prior to closing the enclosure.

Results

For our experiments, we used a RCA 6655A PMT, which has ten dynodes. The dynode voltage divider and anode pickup are shown in the schematic diagram of Figure 10. The PMT was powered at +1,250V from a PMT power supply .

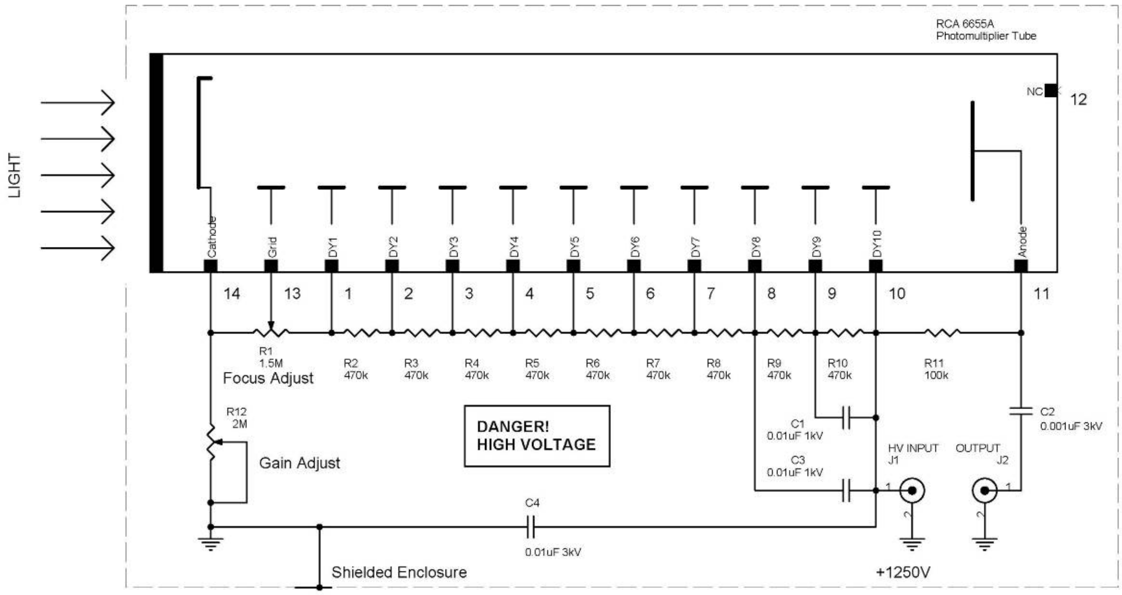

Figure 10 – Schematic diagram of the connections to the RCA 6655A PMT

The PMT's output was processed by a home-made scintillation processor. Spectra were obtained with an Ortec Maestro-32 MCA emulator card. The card's low-level discriminator was set to eliminate noise from the scintillation processor. Figure 11 shows the effect of cooling on the 6655A PMT. The dark counts due to thermoelectrons were reduced by an order of magnitude (a factor of 11.95 to be exact for the MCA's bin #10) when temperature was reduced from ambient (20^{o}C) to -23.5^{o}C. It must be noted that it took approximately 6 hours for the photocathode to reach thermal equilibrium in our setup.

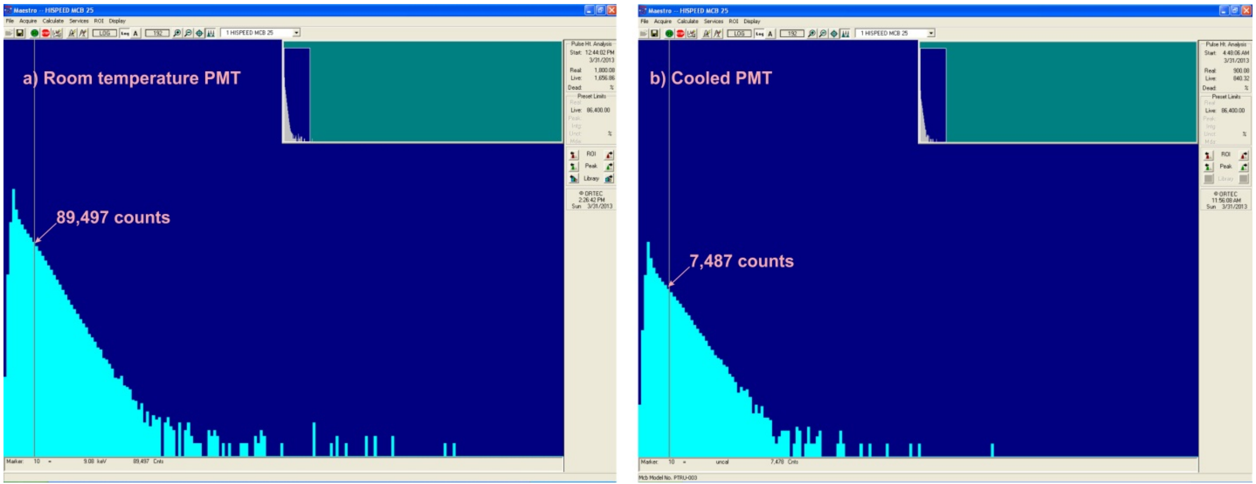

Figure 11 – Effect of cooling on dark counts in RCA 6655A PMT. Counting time 30 minutes: a) Room temperature (23^{o}C), b) PMT cooled to -13.5^{o}C.

Discussion, Conclusions, and Recommendations for Future Work

The author believed that the design would provide effective cooling of the PMT, and was originally hoping that the large top heat sink and fan plus only two of the four TEC modules would be needed to cool the PMT to the target -20°C. That was obviously not the case, requiring the use of all four TEC modules, and the addition of two forced-air tunnel heat sinks to the sides of the enclosure to reach -23°C at a 20°C room temperature.

Under ideal conditions with no heat load and in vacuum, the 2-stage TEC modules that we chose are capable of producing temperature differentials as great as ΔT_{max}= 83°C. The enclosure we built however is far from ideal, reaching a $\Delta T_{max} \approx$ 40°C. The difference between the ideal and actual performance is mostly the result of gradients that exist at the various interfaces between the photomultiplier and the heat exchange medium. In addition, there is also a heat load from dynode chain dissipation and an important amount of heat transferred from the housing case through the insulation.

In a future design, the following will be considered to improve the cooling efficiency of the housing:

1. Tighter coupling between the TEC's hot side and the heat sink. In the present design, transporting heat from the hot side of the TECs all the way to the heat sinks involves a tortuous path through relatively poor thermal conductors (aluminum blocks and die-cast enclosure) and various interfaces (heat-conductive adhesive). It is suggested that a future design will reduce the thermal distance between the TEC modules and the heat sink, and if needed, use highly-conductive materials (e.g. copper) for the interface components instead of aluminum.
2. Water-cooled heat-sink. In the present design, the PMT temperature is ultimately limited by the ambient temperature. For a future design, tap water cooling is suggested to provide a more effective means to dissipate heat into a medium that is commonly at much lower temperature (by around 10^{o}C) than typical room temperature.

Furthermore, it is obvious that cooling the whole PMT in order to cool the photocathode through the very loose thermal coupling within the tube is very inefficient. For this reason, PMT manufacturers have developed specialized metal-jacketed PMTs that place the photocathode in direct thermal contact with the jacket. For these PMTs, cooling efficiency is far superior to the old way, since appropriate cooling and thermal stabilization of the photocathode can be achieved within minutes.

Another possibility is to use one of the new subminiature PMTs. For example, the R7400U-series PMTs by Hamamatsu incorporate an 8-stage electron multiplier constructed with stacked thin electrodes (metal channel dynodes) into a TO-8 type metal can package 15mm in diameter and 10mm in height. The metal package is in direct contact with the photocathode, and because of the compact size of these PMTs, it is very easy to quickly chill the complete tube with a small TEC module.

References

1. Optical Building Blocks Corporation, "Dual Stage Thermo-Electrically Cooled PMT Housing", http://www.obbcorp.com/optical-components/light-detectors/cooled-PMT-detectors/Cooled-PMT-Housing.html.
2. Photocool, Products for Research, Inc., "Cooled PMT Housing Archive", http://www.photocool.com/crossref.htm.
3. Thorn EMI, Photomultiplier Accessories and Systems, PAS/1A/84, 1984.