MECHANICALLY COOLED LARGE-VOLUME GERMANIUM DETECTOR SYSTEMS FOR NUCLEAR EXPLOSION MONITORING

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ABSTRACT

Compact maintenance free mechanical cooling systems are being developed to operate large volume (~570 cm^3, ~3 kg, 140% or larger) germanium detectors for field applications. We are using a new generation of Stirling-cycle mechanical coolers for operating the very largest volume germanium detectors with absolutely no maintenance or liquid nitrogen requirements. The user will be able to leave these systems unplugged on the shelf until needed. The flip of a switch will bring a system to life in ~1 hour for measurements. The maintenance-free operating lifetime of these detector systems will exceed five years. These features are necessary for remote long-duration liquid-nitrogen free deployment of large-volume germanium gamma-ray detector systems for Nuclear Explosion Monitoring (NEM). The Radionuclide Aerosol Sampler/Analyzer (RASA) will greatly benefit from the availability of such detectors by eliminating the need for liquid nitrogen at RASA sites while still allowing the very largest available germanium detectors to be utilized. These mechanically cooled germanium detector systems being developed here will provide the largest, most sensitive detectors possible for use with the RASA. To provide such systems, the appropriate technical fundamentals are being researched. Mechanical cooling of germanium detectors has historically been a difficult endeavor. The success or failure of mechanically cooled germanium detectors stems from three main technical issues: temperature, vacuum, and vibration. These factors affect one another. There is a particularly crucial relationship between vacuum and temperature. These factors will be experimentally studied both separately and together to insure a solid understanding of the physical limitations each factor places on a practical mechanically cooled germanium detector system for field use. Using this knowledge, a series of mechanically cooled germanium detector prototype systems are being designed and fabricated. Our collaborators at Pacific Northwest National Laboratory (PNNL) will evaluate these detector systems on the bench top and eventually in RASA systems to insure reliable and practical operation.

OBJECTIVES

Mechanical cooling systems will be developed to operate large volume (~570 cm^3, ~3 kg, ~140% or larger) germanium detectors for field use in rugged conditions. The hand-held "Detective" is an elegant example of a currently available mechanically cooled germanium detector system manufactured by Ortec (Keyser et al., 2003). This system uses a small Stirling-cycle cooler to cool a modest sized germanium detector to operating temperature overnight (~12 hours). Our project proposes to utilize a newer and larger generation of Stirling-cycle mechanical coolers to produce systems that will reliably cool the very largest germanium detectors while requiring no maintenance. The detectors will be cooled to a lower temperature, resulting in much more reliable detector operation. These new coolers have operating lifetimes in excess of five years. The coolers require no maintenance. We intend to develop germanium detector systems that can be left unattended, running or not, for several years with no maintenance. The flip of a switch brings the system to life. The relatively large heat lift of these coolers can cool a detector to operating temperature for gamma-ray measurements in ~1 hour. These features will make liquid-nitrogen free operation of the largest (~200%) germanium gamma-ray detectors viable and convenient for NEM. RASA is one system than will benefit from the availability of such detectors (Bowyer et al., 1997; Miley et al., 1998).

Mechanical cooling of germanium detectors has historically been a difficult endeavor. The success or failure of mechanically cooled germanium detectors stems from three main technical issues: temperature, vacuum, and vibration. These factors affect one another. There is a particularly crucial relationship between vacuum and temperature, as we shall explain. These three factors must be studied both separately and together to fully realize the most practical means of addressing their technical limitations.

Temperature is the most important fundamental parameter in the operation of any semiconductor detector. The temperature must be low enough to operate a large volume coaxial germanium detector with tolerable leakage current. Excessive leakage current, usually more than ~100 pA, causes noise in the spectroscopy of germanium detectors. Detector operating temperatures are usually below 100 K. Leakage current becomes more important for very large coaxial detectors. Large diameter germanium detectors have optimum energy resolution at relatively long shaping amplifier peaking times (6-12 μs). Leakage current affects the measured noise of germanium spectrometers more adversely at longer peaking times. These large p-type coaxial detectors should be operated as cold as possible to reduce the leakage current.

For the vast majority of germanium detector systems, a Dewar of liquid nitrogen provides a 77 K heat reservoir for cooling. The detector is usually coupled to the liquid nitrogen with a copper rod or braid. The detector temperature is always somewhat higher than 77 K, perhaps 82 K at the coldest and 100 K at the highest. The authors have personally built liquid-nitrogen cooled systems having a copper cooling path of approximately 0.8 W/K and a detector temperature of 82.5 K (Hull et al., 2002). That corresponds to about 4 W of cooling power (or heat lift) at 77 K. This is a reasonable (conservative) heat load for a recently pumped cryostat holding a large detector. The heat load stems from emissive (or infrared) load, conductive load from cryostat parts such as wires, and conductive gas load from the imperfect vacuum in the cryostat. However, the liquid nitrogen will always provide a 77 K heat sink and vacuum getter regardless of thermal load. The same is not true for a mechanically cooled detector system. In a mechanically cooled system the coldest temperature is created at the cold tip of the cooler as a result of the refrigeration cycle. The cold tip temperature is not a constant and is directly affected by the heat load placed on the cold tip. Fundamental thermodynamics dictate that all mechanical coolers remove less heat as the cold tip temperature decreases. This point can present difficulty in cooling a germanium detector. An increase in heat load will always increase the temperature of the cooler cold tip, the detector, and the cold vacuum getter surfaces. The heat-sink temperature does not remain constant as it does with liquid nitrogen. Over the long term, the imperfect vacuum in the cryostat can degrade causing an even larger conductive gas heat load on the cold tip. The cold tip warms up making it a poorer vacuum getter, hence, the detector temperature increases. If the temperature increases sufficiently, the detector leakage current increases; causing noise that degrades the spectroscopy.

Lower temperature operation decreases the detector leakage current providing a more reliable detector. In many cases, a few degrees can make the difference between acceptable and intolerable performance. We always make our detector systems as cold as possible. The leakage current of a rectifying semiconductor device (such as a germanium detector) arises from intrinsic-surface charge generation, rectifying-contact thermionic emission, and bulk generation (Sze, 1981; Malm, 1975; Grove, 1967; Hull and Pehl, 2005; and Pehl et al., 1973). All these current sources are proportional to *exp(-φ/kT)*. Here *φ* is some characteristic energy on the order of the germanium band gap ($\varphi \leq .7$ eV), *k* is the Boltzman constant, and *T* is the Kelvin temperature. This is an extremely strong function of temperature. More importantly, as a detector becomes larger, the larger area increases the emissive and gas conductive heat loads. In addition, all three sources of detector leakage current are proportional to either the volume or surface area of the detector. The leakage current will be higher for a larger detector than a smaller detector at any given temperature.

To operate a large mechanically cooled detector we must get the detector as cold as possible while under a heat load in the region of 3-5 W. Fortunately, we have identified a new generation of Stirling-cycle mechanical coolers having tremendous heat lift (cooling capacity), even at very low temperatures, approximately 6 W at 60 K. Produced for the telecommunications industry, these coolers claim operating lifetimes in excess of 5 years atop cell phone towers. A good deal of the inspiration for this project comes from the availability of this new generation of relatively inexpensive mechanical coolers. We are adapting these coolers for use with germanium detectors. Preliminary tests of one such cooler have been very encouraging. We purchased a Cryotel CT Stirling-cycle cooler from Sunpower. We never intended to use this cooler for large coaxial detectors but the following results were so impressive that we now have to consider such an application. Figure 1 shows a technical drawing of the cooler with the test cryostat we designed and built to evaluate the cooler. Figure 2 shows a photograph of the cooler and test cryostat.

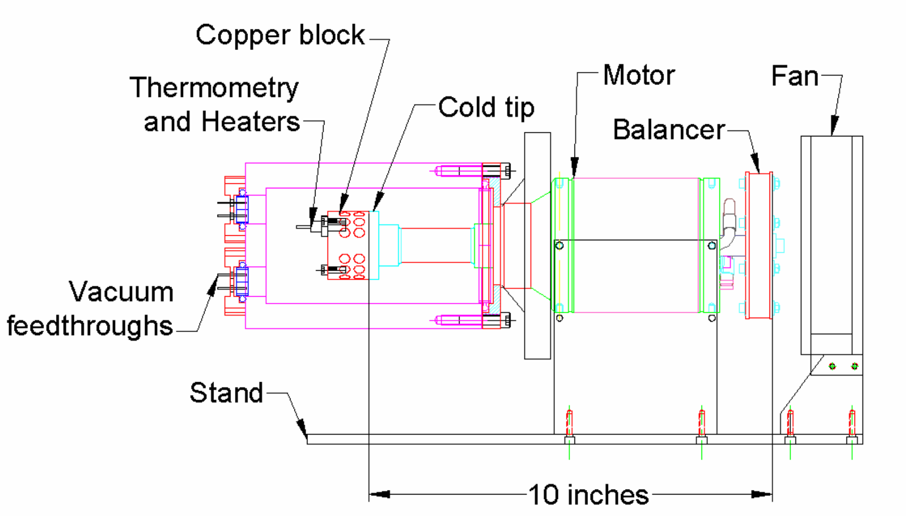

Figure 1. A technical drawing of the cooler and cryostat shows the basic test setup constructed for preliminary measurements. From left to right the diagram shows the cryostat body with vacuum feed throughs, the cold tip with copper block, the cooler motor, passive balancer, and finally the fan for air cooling. The entire structure has been mounted on an aluminum stand. The cooler is 10 inches long and 3 inches in diameter, far smaller than any useful liquid nitrogen Dewar.

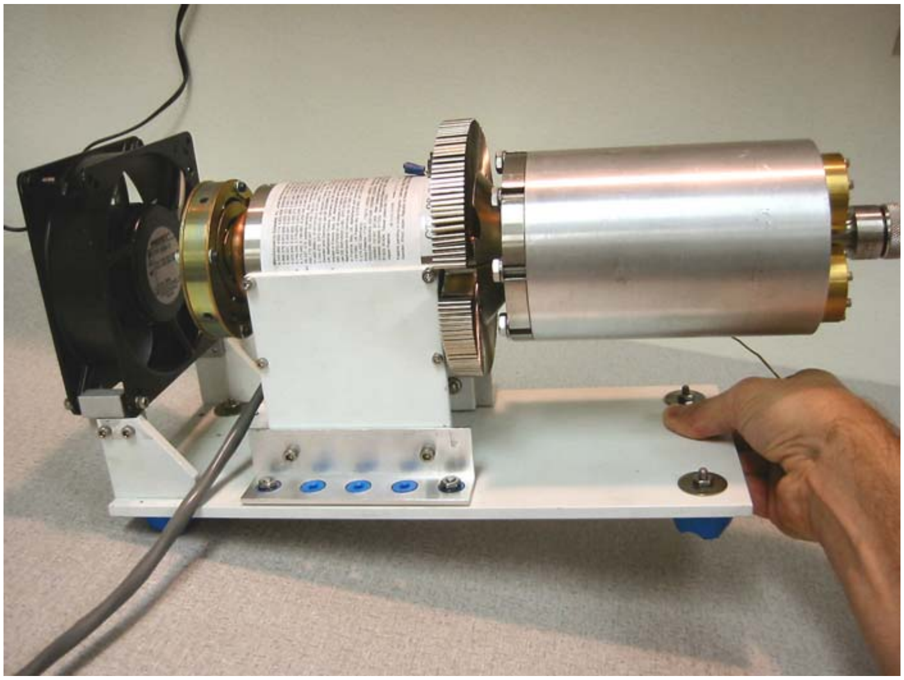

Figure 2. A photograph of the cooler and cryostat shows the basic test setup constructed for preliminary measurements. The cooler alone weighs only 3 kg. The only connection needed is power from the gray cable in the left foreground of the photo. The future germanium detector systems will be only a few inches longer than the cryostat pictured here.

A copper block was machined to fit on the cold tip of the cooler. The 500 g copper block has a cavity in the middle with many holes leading from the cavity to the outside of the block. The cavity was filled with molecular sieve held in with a fine-mesh stainless steel screen. The copper block was instrumented with silicon diodes calibrated for accurate (less than +/- .5 K) temperature monitoring. A power Zener diode on the copper block can apply power to simulate the heat load of a detector. The first time we cooled the system we were very pleased with the surprisingly short cool-down time. The copper block was cooled from room temperature to 77 K in 8 minutes and down to 40 K in 10 more minutes! With 4 W of heat load power applied to the copper block, it cooled from room temperature to 77 K in 20 min, and down to 54 K in an additional 15 minutes. This cooler has tremendous heat lift, even at very low temperatures. The cooler has cycled from room temperature down to under 40 K tens of times with perfect repeatability and no measurable degradation in performance. Figure 3 shows these cool-down curves. The cold tip cools a reasonable mass of copper (500 g) down to very low temperatures very quickly while fighting a realistic heat load. There is no infrared thermal shield in this test cryostat. Normally, a reflective infrared shield would be placed between the cold tip and the cryostat walls to diminish the infrared heat load on the system. With some cryostat engineering, these coolers are viable candidates for cooling large germanium detectors quickly and to very cold temperatures.

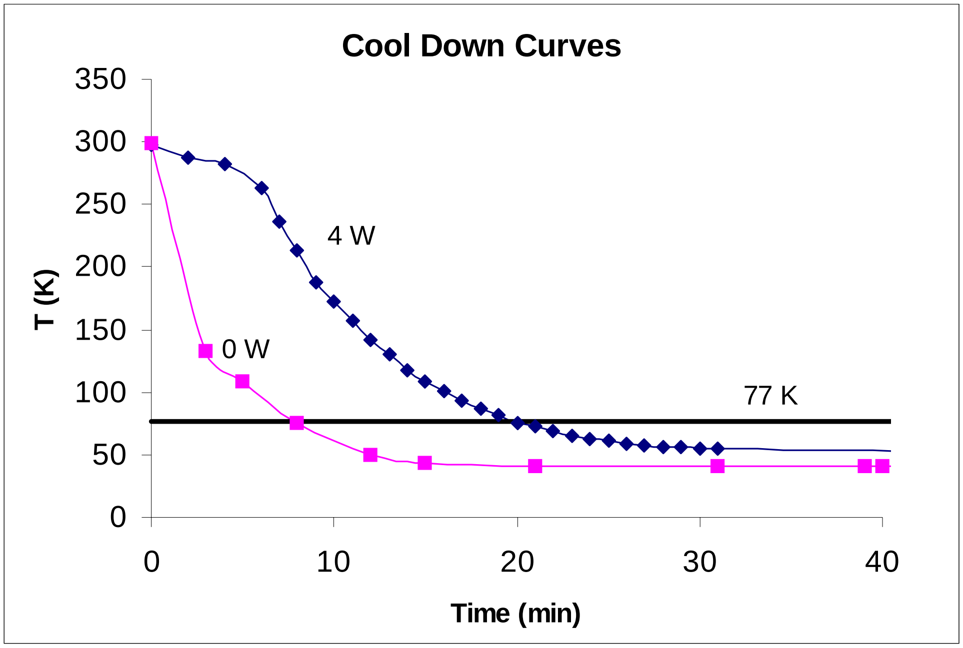

Figure 3. The lower cool-down curve represents the temperature of the copper block as a function of time after the cooler is turned on at room temperature with 0 W of applied heat load. The copper block reached 77 K in 8 minutes and the lowest temperature reached was ~40 K. The upper cool-down curve was measured with 4 W of power applied to the copper block. The copper block reached 77 K in 20 minutes.

The quality of the vacuum in the cryostat is extremely critical. Vacuum and temperature are inseparable factors in the operation of a mechanically cooled detector system. We have already found that the larger heat lift and colder temperature of the Sunpower cooler provides a good deal of passive vacuum pumping by cooling molecular sieve. However, there remain vacuum issues that are crucial for long duration operation. The cryostat vacuum must be of sufficient quality that no substantial thermally conductive gas heat load is placed on the cooler. This vacuum quality must remain for the intended lifetime of the instrument. This is more difficult and critical than apparent at first. Because the heat lift of a mechanical cooler decreases with lower temperature, it takes surprisingly little gas heat load to measurably increase the temperature of a mechanically cooled detector. With the temperature increase, more gases evolve from the cold surfaces further degrading the vacuum. This positive outgassing feedback can eventually degrade the vacuum until the detector temperature is too high for stable operation. The authors are aware of numerous detector systems that function for a period of many months before failing mysteriously. In most cases, the cause is almost certainly degradation of the vacuum in the cryostat.

In liquid-nitrogen cooled systems, the constant 77 K temperature of the walls of the cryostat and molecular sieve cover many vacuum sins that cannot be tolerated in a mechanically cooled system. Liquid nitrogen is always 77 K regardless of heat load. An increase in heat load only boils the liquid nitrogen faster but the temperature is always 77 K. The cold tip of a mechanical cooler can very quickly exceed 77 K with sufficient gas load. In this temperature range, condensed O_2, N_2, and Ar begin evolving from the cold surfaces and molecular sieve. Our preliminary tests have shown that vacuum remains an issue, even with the immense heat lift and low temperature of the Cryotel CT. The vacuum must be properly studied and handled in the context of a long-lived germanium detector system.

Any vacuum system is a dynamic situation. Atmospheric gases are constantly diffusing through vacuum seals. Internally, gases evolve from surfaces in the vacuum. These gas sources must be constantly pumped by something in the chamber or the vacuum degrades. Liquid-nitrogen cooled germanium detector systems use the 77 K walls of the cryostat combined with molecular sieve, activated charcoal, and other chemical gettering schemes to maintain the vacuum. Although elastomer o-rings make a vacuum seal that is considered to be “leak tight,” significant atmospheric gas can still diffuse through the o-rings. Metal seals reduce the diffusion by several orders of magnitude. However, standard metal seals generally require more sealing force and bolting infrastructure requiring a much bulkier cryostat. The question to be addressed here is: “What combination of vacuum seals, cryostat materials, design, and vacuum gettering is appropriate for a long-lived large volume mechanically cooled germanium detector?” This question must be addressed in the context of a viable detector system. For example, having a turbo molecular pumping station attached to the system at all times is not a viable option. The system must maintain its vacuum in a convenient and compact manner. The first step toward accomplishing this is better understanding of the constituents and sources of the gases spoiling the vacuum.

Figure 4 shows a plot reflecting the impact of vacuum degradation on our mechanically cooled test system. The plot shows the coldest obtainable temperature achieved with the cooler running at full power as a function of time after the system was last pumped with a high vacuum system. After the initial pump, the system is sealed off, cooled, tested, and allowed to sit in the air with no further external pumping. Every few days the system is cooled again to note any changes. The data curve shows the impact of allowing our system to sit in air for 3 weeks with Viton o-rings used for vacuum seals. The temperature increased from 38 K up to 56 K. The cooler is capable of lifting approximately 1 W at 38 K and 5 W at 56 K. Enough gas diffused into the system to cause a 4 W heat load in only three weeks. A brief pump with the high vacuum system eliminated the heat load and the cold tip cooled immediately back down to about 38 K, proving that the problem is a conductive gas heat load. The next questions are: Which gas species are present? and Where are these gasses coming from? The molecular sieve packed in the copper block should adsorb the common atmospheric gases quite well at these temperatures (Stern and DiPaolo, 1967).

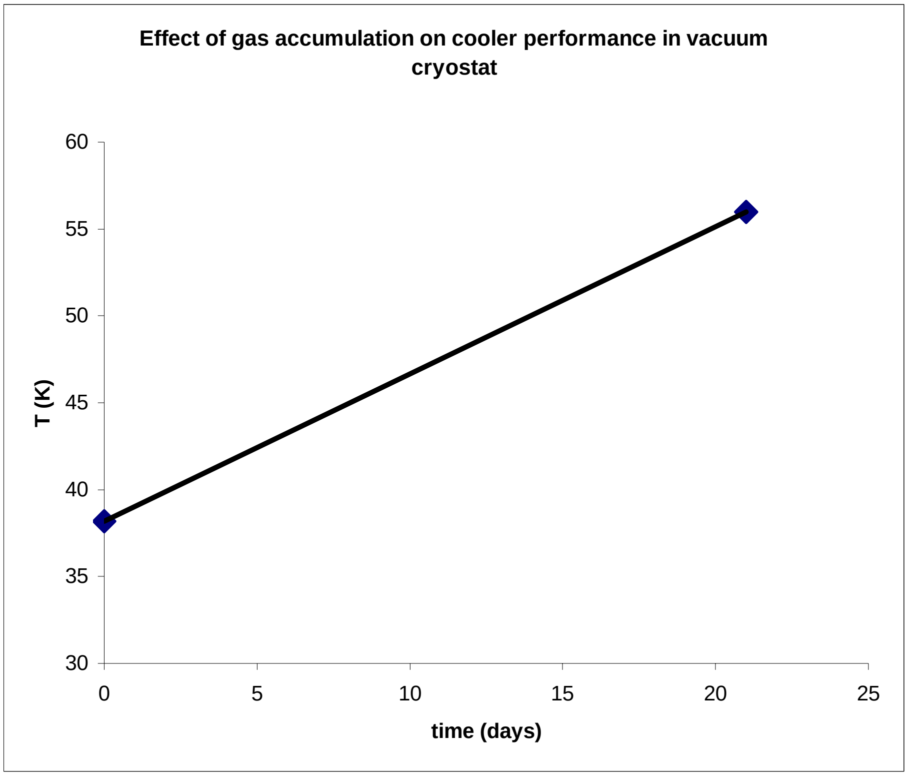

Figure 4. The temperature of the cooler increases as gases accumulate in the vacuum cryostat. The copper block (filled with molecular sieve) is at the temperatures shown. There is clearly some gas load accumulating that is not pumped by the cold molecular sieve. This degradation could eventually compromise the performance of a mechanically cooled germanium detector.

We have heard and discussed many different, semi-plausible arguments for these gas sources. Some of the explanations are very interesting and creative but none fully explain the data we have. An example of one explanation is: "The stainless steel in the chamber is reducing water vapor into H_2 and O_2, the H_2 is not gettered by your sieve even at 40 K so that is the source of this additional heat load." We have also been told the gas is oxygen from water vapor, although we would expect that oxygen and water vapor should be pumped very well by the cold molecular sieve. Some say it is H_2 coming from the aluminum cryostat walls. We ponder that it might even be helium diffusing through the braze joint in the mechanical cooler itself, although diffusion through metals is very small. These Stirling-cycle coolers have several atmospheres of helium inside as the working gas. There could also be helium diffusing into the vacuum from the atmosphere through the seals. Clearly some high quality quantitative measurements of the gas species present in such systems would be an excellent first step in properly addressing this issue. The very slight accumulation of gasses in a sealed vacuum chamber over long time periods must be studied quantitatively to understand this issue.

During this study we are assembling a vacuum pumping station with a Residual Gas Analyzer (RGA). The RGA will be used to monitor the quantity and species of these accumulating gases. We will monitor the gas quantity and species as a function of time and the temperature of the molecular sieve. We are making some simple vacuum boxes out of different common metals to see what gases accumulate as a function of the chamber wall materials. We have heard that H_2 comes out of some grades of aluminum and that Ar comes out of some stainless steel. There is surely some truth to many of these suggestions, particularly at ultra high vacuum levels ($< 10^{-9}$ Torr). However, we are seeing gas accumulations on the order of 10^{-4} Torr in a relatively short time. We need to know the dominant gas species so we can build our detector systems accordingly. This effort will result in good practical vacuum technology and better mechanically cooled germanium detectors.

The remaining issue to be addressed is the vibration of the mechanical cooler. Vibration of the mechanical cooler can cause microphonic noise adversely affecting the energy resolution of the detector. Microphonic noise can be devastating in some cases. In every other mechanically cooled detector we know of, the mechanical cooler contributes some measurable noise to the overall energy resolution of the system. Germanium detectors have such excellent energy resolution that their front-end electronics must necessarily be sensitive to small vibrations in the leads on either side of the detector. Since we want to mechanically cool the very largest diameter germanium detectors, microphonic considerations are very important. With larger diameter coaxial detectors come ballistic deficit concerns. Higher bias voltage must be used to operate the detector along with longer amplifier peaking times for optimum spectroscopic energy resolution. Longer peaking times are more susceptible to the generally low frequency microphonic noise caused by mechanical coolers. The cooler we have been testing does vibrate. We have been able to lessen the vibration somewhat with rubber isolation pads on the cooler stand. There are certainly other mechanical adjustments that can reduce the primary vibration source. In fact, the cooler vendor even sells an "active balancer" that can be tuned to dampen the vibrations characteristic of the particular cryostat. In addition, there are electronic tricks one can employ to lessen the effect on the final energy resolution of the system. If the frequency structure of the microphonic noise is known, it can be subtracted from the signal to lessen the impact on the system noise. Such additions will only be added if deemed necessary. We would like to keep the system as simple as possible. To evaluate the severity of the microphonics problem, we will fabricate and instrument a small guard-ring planar germanium detector in our test system. We make and use these small simple detectors to evaluate all kinds of detector, electronic, and cryostat issues. Using this detector we can evaluate the effect of the vibrating cooler on the spectroscopy of the system. This is a fast, inexpensive way to evaluate such things before loading a large expensive coaxial detector into the system.

We do not think microphonic noise will be an insurmountable problem for this system. In fact, we have made preliminary bench top measurements indicating the problem is not too significant. Five-inch long wires and various capacitors (to simulate the detector capacitance) were allowed to vibrate on the input junction gate field-effect transistor (JFET) of an operating preamplifier at room temperature. The box holding the preamplifier was clamped rigidly to the body of the mechanically cooled test cryostat. The output of the preamplifier was processed by a TC-244 spectroscopy amplifier and was calibrated with test capacitors and a pulser. The noise increased very slightly when the cooler was turned on. There is a brief burst of noise when the cooler starts. After that, the noise settles down. The cooler running at full power increased the root mean square (RMS) noise value only a few percent using a peaking time of 4-6 μs. Below 4 μs, the microphonic noise was not measurable. To be fair, we had no bias on the test capacitor. Detector bias voltage can greatly increase the measured microphonic noise. However, we have made side-by-side tests of small planar detectors (with bias voltage) in one of our liquid-nitrogen cooled test cryostats indicating further microphonic noise reduction when the JFET is cooled. These detectors use several hundred volts of bias for operation. In the same cryostat, we instrumented some detectors with cooled JFETs and some with room temperature JFETs. The detectors having cooled JFETs showed much less (~100x less) microphonic noise response when tapping on the side of the cryostat. The cooled JFET is much closer to the detector, providing a shorter sensitive gate lead between the detector and JFET. Since we will be cooling the JFET in our mechanically cooled detector system, we are optimistic about overcoming microphonic problems in a practical detector system.

For a mechanically cooled large volume coaxial detector to be viable, the temperature, vacuum, and noise caused by vibration must be under control for the lifetime of the detector system—several years. These factors are being studied in the laboratory at the most fundamental levels to insure a solid understanding. Based on these fundamental measurements, the best possible prototype detector-cooler systems will be fabricated for practical tests. Any changes in performance will be studied as a function of time. A prototype detector system will be field tested in RASA systems to insure reliable and practical operation. Our PHDs-PNNL team brings together vacuum, cryogenic, detector, electronic, and field-application expertise. With support for this project, the stage is set for the development of a new generation of mechanically cooled germanium detector systems. These systems promise fast reliable cooling and operation of the very largest germanium detectors. At the end of this project we will offer a new product line, the MCX mechanically cooled detector product line for use with RASA and similar detection systems.

RESEARCH ACCOMPLISHED

This project has just started. These are a few of the accomplishments to date.

A new mechanically cooled cryostat is being designed for this project. We call the cryostat MC0-a. This cryostat is slightly larger than our test cryostat described above. It will hold a brass detector dummy to simulate the heat capacity and area of a large coaxial germanium detector. Of course, a real germanium detector will eventually replace the brass dummy. The brass detector dummy will be 10-cm in diameter and 10-cm long. This is the size of the largest germanium detector conceivable at this time corresponding to a ~200% germanium coaxial detector. This cryostat will be used to determine the correct materials, seals, and design to be used for large mechanically cooled coaxial detectors.

At the same time, we have ordered the critical components of a vacuum pumping station suitable for quantitative analysis of the accumulating gas constituents in a sealed cryostat volume. We have ordered a Pfeiffer TSU 521 (6” nominal diameter) turbo-molecular pumping station and received an Ametek LC100M RGA with 100-amu range. We have ordered several vacuum valves and connection flanges. We will assemble these components to form a high-vacuum pumping station with the ability to quantify the species and pressure of numerous different gas species accumulating in our cryostats. A small-diameter bleeder valve will bypass the detector pumping port to further limit the conductance between the pump and the cryostat. The total pressure at the RGA head must be maintained below the high 10^{-5} Torr range to allow the RGA to operate properly. At the same time, we want to be able to measure the gases coming out of our test cryostat without them being pumped away immediately. The RGA needs time to sweep through the different atomic masses of the different possible accumulated gas species. Although common RGAs measure all gas species down to the 10^{-11} Torr level, dry gases (N_2, O_2, etc) are pumped off very quickly by a wide-open high vacuum pump. With the main vacuum valve open, the pumping station will also be used to pump the mechanically cooled cryostats before testing. We have decided to mount a series of different metal chambers on outer flanges of the vacuum pumping station. Each metal chamber will be a machined and cleaned right cylinder having an inside volume of 1 liter, comparable to the volume inside a germanium detector cryostat. We will fabricate three identical chambers, one each made of aluminum, brass, and stainless steel. Each of these three chambers will be pumped out over a several day period on the pumping station. The chambers will be individually sealed off (using a metal seal inside the vacuum chamber) from the rest of the vacuum system and allowed to sit for various amounts of time. Gasses evolving from the surfaces of these metals will accumulate in the chamber. With the RGA and pumping station based out in the 10^{-7} Torr range, the valves will be opened and the accumulated gas species will be released and measured. In this manner, any gasses coming from these common cryostat materials will be measurable. Once these gasses have been quantified, the lowest gas emitting metal cylinder will be removed and various materials, including high-purity germanium, will be placed in the cylinder and allowed to outgas for a period of time to determine any gasses coming from common materials (like Teflon) used in the cryostat.

Depending on the type and predominance of various gas species, we will react by modifying MC0-a to prevent these species from accumulating to as large a degree as possible. For example, if we see a predominance of hydrogen we will place palladium packets in the vacuum. Palladium is an excellent getter of hydrogen. There are also chemical getters for oxygen. If we see a predominance of other light gases like helium we may need to use a small (~1 cm^3) appendage ion pump on the system to remove this gas. It would be nice to avoid the additional complexity of such appendages if possible, unless they are deemed absolutely necessary by solid measurements. It is also possible that our molecular sieve is slowly outgassing small amounts of helium and neon. We will study this possibility by baking and pumping the entire system and the molecular sieve on the turbo pump for much longer periods of time (like weeks) before sealing and cooling the system. We will note any changes in the amount and type of gas accumulation.

The test cryostat, MC0-a, will be cooled down with the mechanical cooler to evaluate the impact of gasses on the temperature of the cold tip. First we will operate MC0-a with the copper block (with thermometry) only on the cooler cold tip while pumping on the cooler with the turbo pump. This will give us the baseline, lowest temperature to be expected. All gases accumulated after the seal-off valve is closed will add a heat load that is measurable by an increase in the coldest achievable temperature. The heat lift of the cooler is well known as a function of operating temperature. To a very good approximation, the power is: $P = (.224W/K)*(T-32K)$. Next we will seal off the test cryostat and operate the cooler. We will measure the temperature of the copper block as a function of time after the test cryostat has been allowed to sit in air. After a few weeks, we should measure a temperature increase with time similar to that discussed in our preliminary measurements. We will then open the cryostat to the RGA-turbo pump system to measure the accumulated gas species. This will be our first quantitative data on the important gas constituents affecting the vacuum and temperature of a large mechanically cooled germanium detector system.

CONCLUSION(S) AND RECOMMENDATIONS

This project has only just begun. As of yet, we have no sweeping conclusions or recommendations.

ACKNOWLEDGEMENTS

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