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. A new generation of domestically produced Stirling-cycle mechanical coolers provide the basis for this evolution. When properly instrumented, these systems can cool the very largest volume germanium detectors with no maintenance or liquid nitrogen requirements. The user can leave these systems unplugged on the shelf until needed. The maintenance-free operating lifetime of these detector systems will exceed 5 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. The Radionuclide Aerosol Sampler/Analyzer (RASA) will greatly benefit from the availability of such detector systems by eliminating the need for liquid nitrogen at RASA sites while still allowing the very largest available germanium detectors to be utilized for the highest sensitivity measurements. To reliably provide such systems, the basic technical fundamentals are being investigated: temperature, vacuum, and vibration. A RASA cryostat and detector have been developed and fabricated. The cryostat has been tested and verified to cool a very large (as large as 10-cm long by 10-cm diameter) detector to temperatures as low as 50 K. The system is free of microphonic noise with the cooler operating at full power. The lower detector operating temperature, coupled with robust detector fabrication technology, provides a detector system that will operate reliably for a very long time (5+ years).

OBJECTIVES

PHDs Co. is developing mechanically cooled detector systems for large volume germanium detectors (~ 570 cm^3, ~ 3 kg, ~ 140 %, or larger) for field use in rugged conditions. A new generation of Stirling-cycle mechanical cooler is being used to reliably cool the very largest germanium detectors while requiring no maintenance. The detectors will be cooled to extremely low operating temperature, resulting in much more reliable detector operation. These new coolers have operating lifetimes that exceed five years. The coolers require no maintenance. Using these coolers, PHDs Co. is developing 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 a few hours. These features will make liquid-nitrogen free operation of the largest (~200%) germanium gamma-ray detectors viable and convenient for nuclear explosion monitoring. The RASA 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. A detailed analysis of these factors and their effects on detector performance was recorded last year (Hull et al., 2006). These factors are being studied in the laboratory at the most fundamental levels to insure a solid understanding. Based on this study, prototype detector-cooler systems are being designed and fabricated as prototypes for field tests.

RESEARCH ACCOMPLISHED

The first year of this project has seen several major accomplishments. A stable vacuum configuration has been realized for the RASA detector cryostat. A corresponding detector, cryostat, cooler system (called RASA1) has been designed, fabricated, and tested. After some fine tuning, the detector system shows no measurable microphonic noise with the cooler operating at full power. A detector operating temperature of 50 K was achieved with a cryostat capable of holding a 10-cm diameter x 10-cm long detector. A new preamplifier has been designed to accommodate the RASA1 detector. A system very similar to RASA1 was tested with a planar detector that shows excellent spectroscopy performance and a detector temperature of 45 K. A vacuum residual gas analyzer (RGA) system was placed in service to study vacuum accumulation of gases for the sake of making the most rugged, long lasting vacuum systems possible for RASA germanium detector systems.

The first prototype design for the RASA1 detector system is shown in Figure 1. RASA1 is specifically designed to fit into and operate with a RASA station in the field. The design provides centering of a coaxial germanium detector at the center point of the filter paper assembly in the RASA station. With a few simple internal part modifications, the design accommodates any detector size up to a diameter of 10 cm and a length of 10+ cm. As depicted in Figure 1, RASA1 is a relatively small overall assembly. The cooler, vacuum-cryostat body, and vacuum cap close together to accommodate all faculties essential to the operation of a germanium detector. A 7-cm diameter x 7-cm long coaxial germanium detector is being installed in the RASA1 as a demonstration of the system functionality. Emphasis was placed on the loading and holding the detector in a manner consistent with a rugged assembly. The detector is held in a specially designed capsule containing wave springs that can hold the detector with a force equivalent as high as 100 Gs if desired. Internal mechanical provisions shield the high voltage components from the signal gate lead to prevent microphonic noise. The design accommodates all metal vacuum seals to maintain the best possible vacuum for the longest possible duration. Emphasis was placed on cooling the detector to the very lowest temperature possible. The immediate design of such a RASA1 prototype system was a response to the urgent need for such a system as expressed to us by RASA users at Patrick Air Force base.

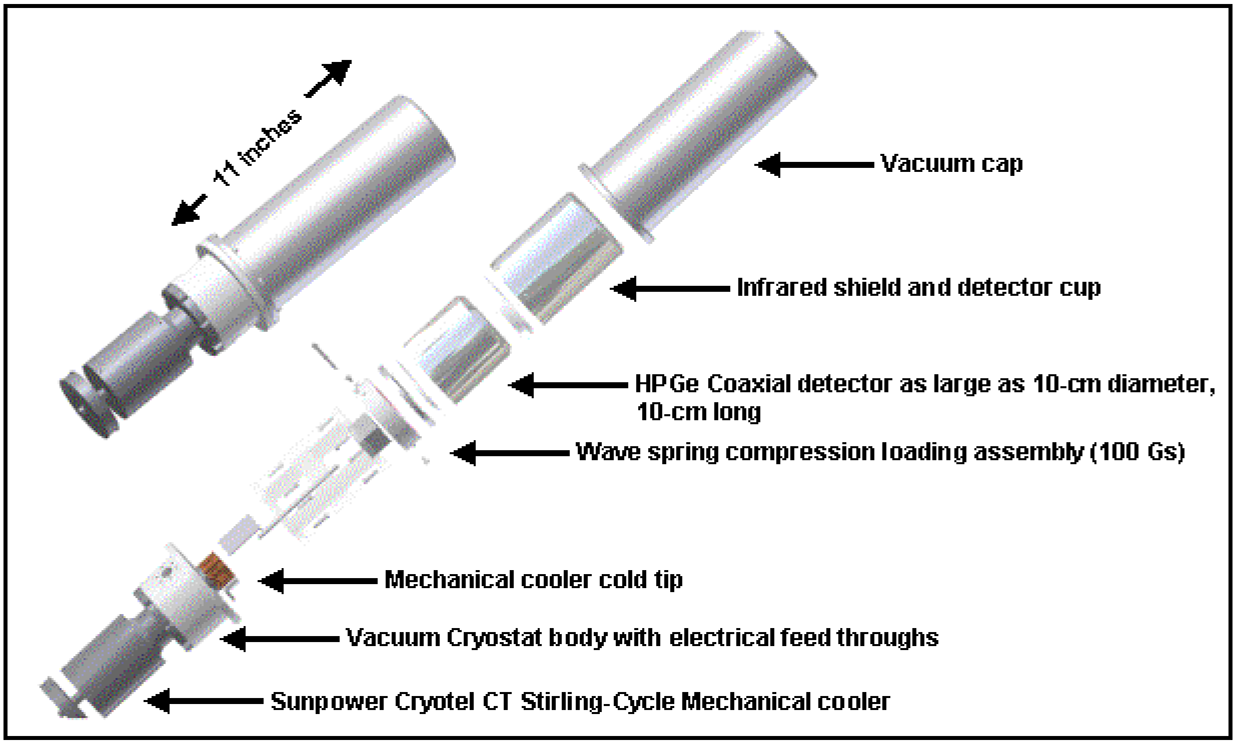

Figure 1. A drawing shows the assembled and unassembled RASA1 detector system design. The upper left view of the RASA1 shows that it is an integrated cooler-detector assembly.

Upon finishing the design, the mechanical parts for the RASA1 system were fabricated and assembled. The mechanical, electronic, and detector related parts were assembled and integrated with a Stirling-cycle mechanical cooler as shown in Figure 2. RASA1 was assembled with a brass dummy detector in place for thermal-vacuum-cryogenic testing. The vacuum integrity of the system was verified to be helium leak tight. The detector is extended a good distance away from the support structure. This assembly must be made in such a way to position the detector down the bore of the RASA system near the filter paper cylinder where the gamma rays are collected. Extending the detector outward in this manner was a challenging design requirement. Modifications were made to the detector support structure to insure solid holding of the detector during cooler operation. Although the detector cup is only 1.5 mm from the inside of the outer vacuum can, there appears to be no problem with the two surfaces contacting each other when the cooler is operated or when the system is shaken and moved in a normal manner. As described later, an early version of the detector support structure had the misfortune of resonating with a harmonic frequency of the vibrating mechanical cooler. This caused the end cap of the detector to literally “sing” with a very dramatic high-pitched tone. Replacing the support structure with a non-symmetric part eliminated the resonant vibration. In the present configuration shown in Figure 2, the system operates very quietly and has no measurable microphonic noise response in the detector spectroscopy channel at unipolar peaking times as long as $T_P = 8$ µs.

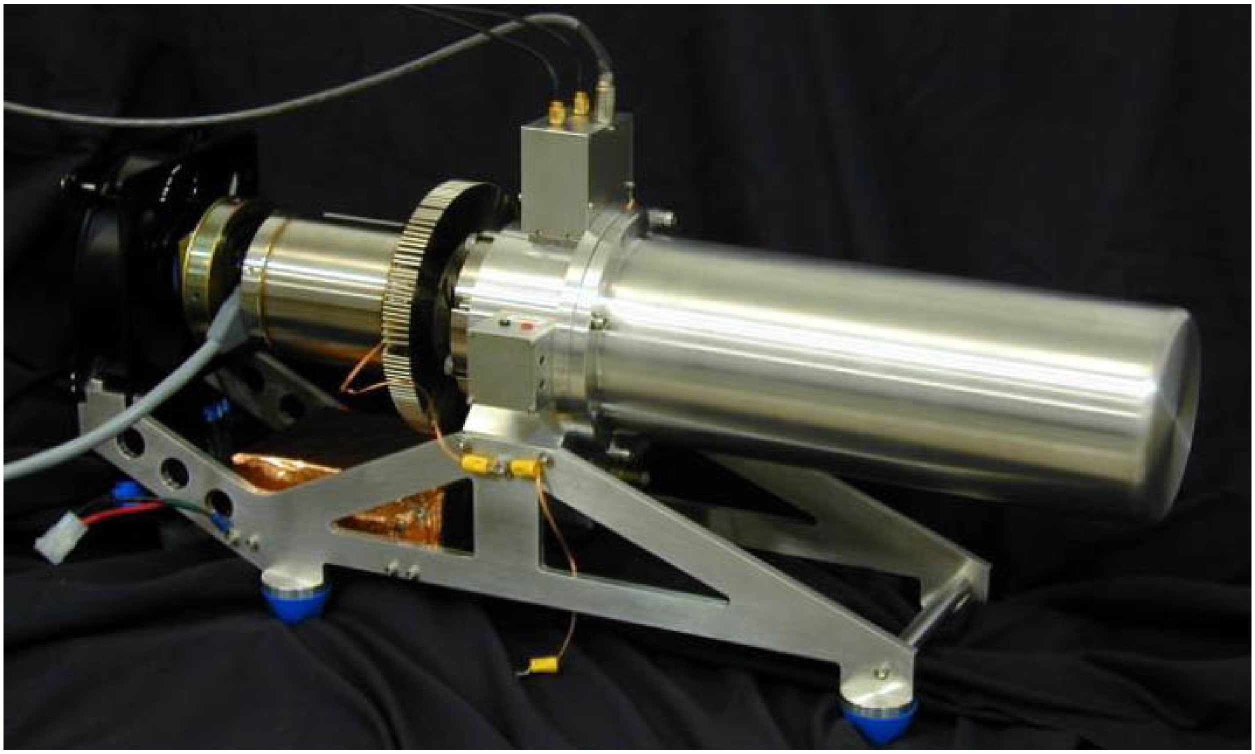

Figure 2 A photograph of the assembled RASA1 detector system.

After RASA1 was assembled as shown in Figure 2, several thermal vacuum cool-down tests were performed. Before each of these tests, the vacuum of the system was pumped to the $1x10^{-6}$ Torr level overnight and helium leak checked to insure vacuum integrity. For the first trial, the system was cooled with the cooler disconnected from the internal detector assembly to evaluate the cooler alone. As anticipated the cooler cold tip cooled to the lowest possible temperature (~ 35 K) in ~ 20 minutes. After the cooler performance was verified, the system was cooled with the internal detector assembly thermally connected to the cooler. The assembly held a 70 cm x 70 cm brass detector dummy. The cooler was switched on and the temperature of the detector assembly and the cooler cold tip were monitored as a function of time. The temperature of the detector and the cooler are shown in Figure 3 as a function of time. With the cooler operating at full (160 W) input power, the system reached equilibrium temperature of 43 K at the cold tip and 50 K at the detector. This is an excellent result. Maintaining the detector at an extremely low temperature, such as 50 K, will insure rugged and reliable detector operation. Nearly all of the problems with semiconductor detectors increase dramatically as a function of increasing temperature (Pehl et al., 1973). To show the operating temperature range of RASA1, the cooler was throttled back to the lowest input power setting (80 W). At this power setting, an equilibrium detector temperature of 73 K and cold tip temperature of 51 K were measured. Of course, higher detector temperatures can always be achieved by powering the Zener diode on the detector assembly. The Zener heater can place as much as 50 W of power on the detector assembly. This feature is useful to decrease the warm up time of the detector and for vacuum-baking the detector.

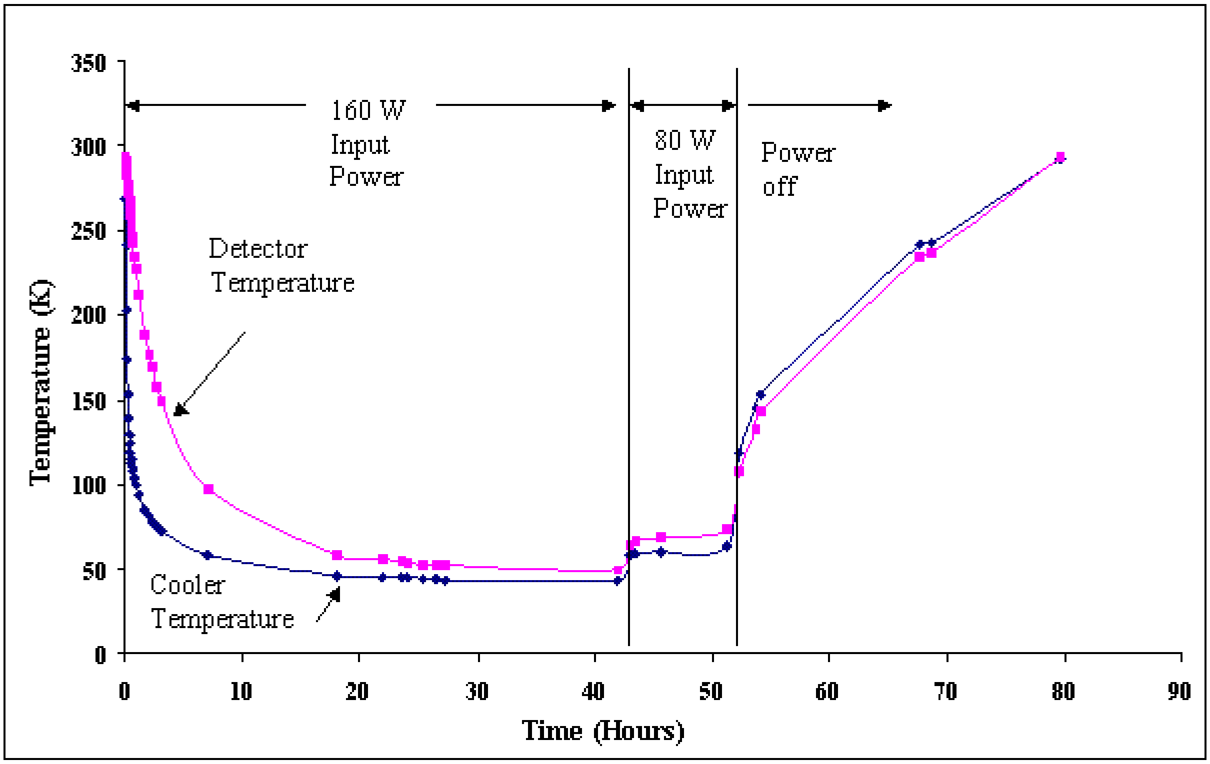

Figure 3 The cool-down curve for the RASA1 detector system with a thermal mass in place of the detector. The thermal mass has a heat capacity comparable to a 10-cm long, 10-cm diameter germanium detector.

Initially a problem was observed with the preamplifier used for RASA1. Standard PHDs Co. high bandwidth, low noise preamplifiers were initially used for RASA1. These preamplifiers were originally designed for gamma-ray imaging with germanium strip detectors. Consequently, the preamplifiers have relatively fast rise times to perform the high bandwidth measurements required for gamma-ray position location. The junction gate field effect transistor (JFET), feedback capacitor, and feedback resistors were removed from one of the preamplifiers and placed inside the cryostat on the detector assembly. The JFET was placed as close the detect detector signal contact as possible. The JFET is placed on a thermal standoff that allows the JFET to "self heat" to a temperature in the ~ 150 K region. This is done because JFETs have poor noise performance at or below liquid nitrogen temperature (77 K). The JFET, feedback capacitor, and feedback resistor installed inside the cryostat and while the rest of the preamplifier is outside the cryostat. Consequently, rather long (~ 9 inch) leads must connect the internal and external components. With these long leads in place, the preamplifier is unstable and oscillates uncontrollably with a 90-MHz sine wave from – 12 V to + 12 V. This situation is completely unacceptable for detector operation. Consequently, a new PHDs Co. preamplifier was designed that incorporates a stabilizing feature to eliminate the oscillation. The stability modification was required to successfully operate the back end of the preamplifier outside of the cryostat while operating the front end of the preamplifier inside the cryostat. The placement of three passive electronic components on the external preamplifier board provide more stable, lower bandwidth, low noise operation that is perfectly appropriate for RASA detector operation. On the other hand, if high bandwidth performance is desired for an imaging germanium strip detector, the components are not placed on the preamplifier board. A photograph shows the new preamplifier in Figure 4.

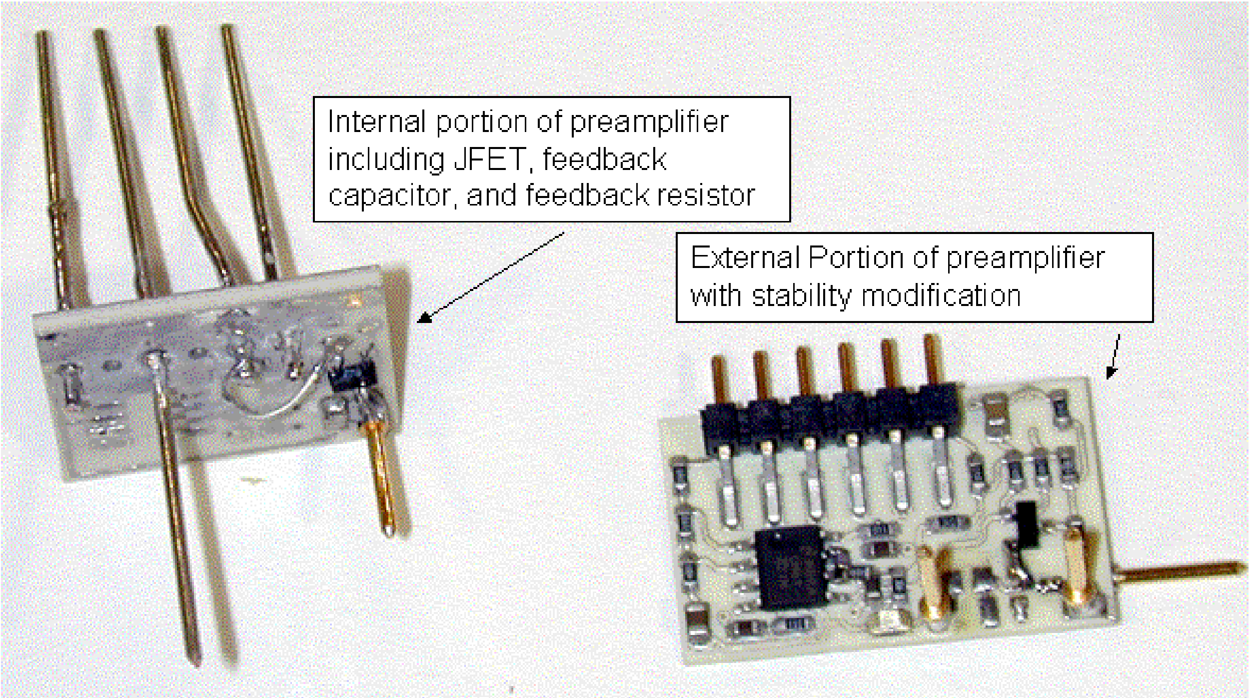

Figure 4 The RASA1 preamplifier accommodates low noise and the stability required for the RASA1 detector-cryostat geometry.

The most difficult part of the RASA1 system development was the battle against microphonic noise problems arising from the vibrating mechanical cooler. Microphonic noise from vibrating mechanical coolers has always been an Achilles heel for mechanically cooled germanium detector systems. We have developed a method for systematically testing the RASA1 cryostat with the preamplifier and cooler operating in the exact configuration of the final detector system. The cooler is operated and allowed to vibrate with the JFET gate lead connected to the beryllium-copper contact finger that makes connection to the inner bore of the detector in the final assembled prototype. We have found that this can be done at room temperature without pulling a vacuum on the cryostat. This enables us to move and feel vibrating parts inside and outside the cryostat while the cooler is operating to determine which components are causing problems. As described above, some of the originally designed mechanical vacuum parts in the cryostat have had to be discarded and replaced. Fortunately, after many trials and much machine work we have been able to completely eliminate any measurable microphonic noise at a unipolar peaking times as long as $T_P = 8$ µs. The thermal standoff that holds the detector assembly rigidly while allowing it to cool was found to be a problem. The part was made to be very sturdy and had a cylindrically symmetric design. Unfortunately, the part was found to resonate with the cooler frequency (60 Hz) or a harmonic thereof creating an audible ringing when the cooler was operating. By simply touching (and dampening) the vibrating part at almost any point on its surface, the ringing could be stopped. It seemed that breaking the symmetry of the part was enough to quell the vibration. We replaced the thermal standoff with a part purposely lacking cylindrical symmetry to eliminate this problem. In addition, the vacuum cap and infrared shield were both quite thin, only 0.030" thick. The ends of both thin parts also vibrated like drum heads in parallel to each other. These two parts were replaced with 0.060" thick parts to eliminate this problem. We also modified the fixture that holds the JFET, feedback capacitor, feedback resistor, and beryllium copper finger against the electrode(s) of the detector. The rigidity of this new internal assembly was required to eliminate the last measurable traces of microphonic noise. It is worth mentioning a note on the scale of the microphonic noise problem. The full width at half maximum (FWHM) of a 1332-keV gamma-ray peak from a good germanium detector should never exceed FWHM = 3 keV. At times during these battles against microphonic noise we measured a microphonic noise as high as FWHM = 15 keV. This would have been totally unacceptable for good detector performance. We reduced the microphonic noise to a level lower than the channel noise of the JFET with no capacitance on the gate, FWHM < 0.7 keV.

Using the same design prescriptions that will be used for RASA1, another detector system was fabricated for another of our projects. This system is called MG1. MG1 holds a planar germanium detector instrumented using the same configuration developed for RASA1. MG1 exhibits excellent noise performance using a unipolar peaking time of T_P = 6-8 µs. In Figure 5, the gamma-ray energy spectrum shown with MG1 demonstrates the viability of the technology. The RASA1 detector is being fabricated and integrated into RASA 1 using the same prescription and detector fabrication techniques used for the planar detector in MG1.

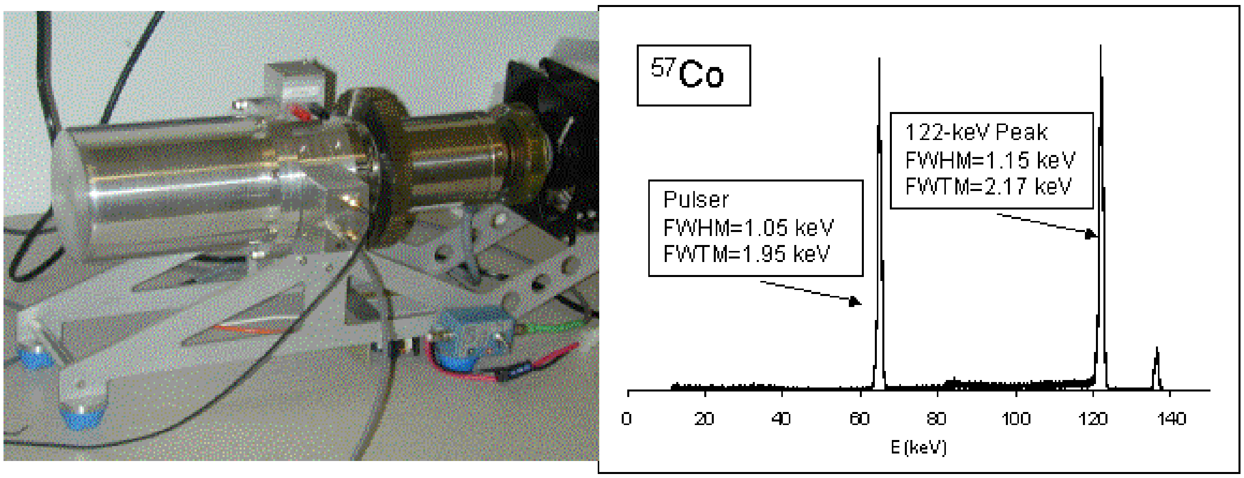

Figure 5 The leftmost view shows the planar detection system (MG1) mechanical cooled detector system. This system uses the same mechanical cooler and basic design to be used for RASA1. It has served as an excellent test bed for the electronic, cryostat, and detector combination to be used for RASA detectors. The energy spectrum on the right shows a noise FWHM = 1.05 keV with the cooler operating (and vibrating) at full power. A peaking time of T_P = 6 µs was used to make this measurement. The same energy resolution is measured with the cooler switched off. MG1 was built for radiation damage testing using a cryostat very similar to RASA1. The detector reaches a temperature of 45K.

In addition to all of the work specifically tied to the design and fabrication of the RASA1 prototype, a vacuum system has been placed in service for studying the accumulating gasses in vacuum. The foremost longevity problem for germanium detector systems is a gradual loss of vacuum integrity that occurs over year-long time periods. The system shown in Figure 6 has been assembled just to study the accumulation of gases in a metal cavity the size of a cryostat over long time periods. Metal-sealed cavities made of aluminum and stainless steel have been fabricated, pumped, and baked while on this vacuum system. The cavities are sealed off using an internal metal sealing valve. The cavities are allowed to evolve gasses over various time periods to study the accumulation over time. A residual gas analyzer shares the vacuum common to the cavities and the turbo molecular pump. The RGA determines the amount and species of gasses that accumulate in the metal cavities over time. This system has been brought up to operational status and demonstration measurements have been made that verify the intended operation of the system. Over the next year, long-term accumulation measurements will be made to determine the species and quantity of gases accumulating in germanium detector cryostats that cause the degradation of vacuum.

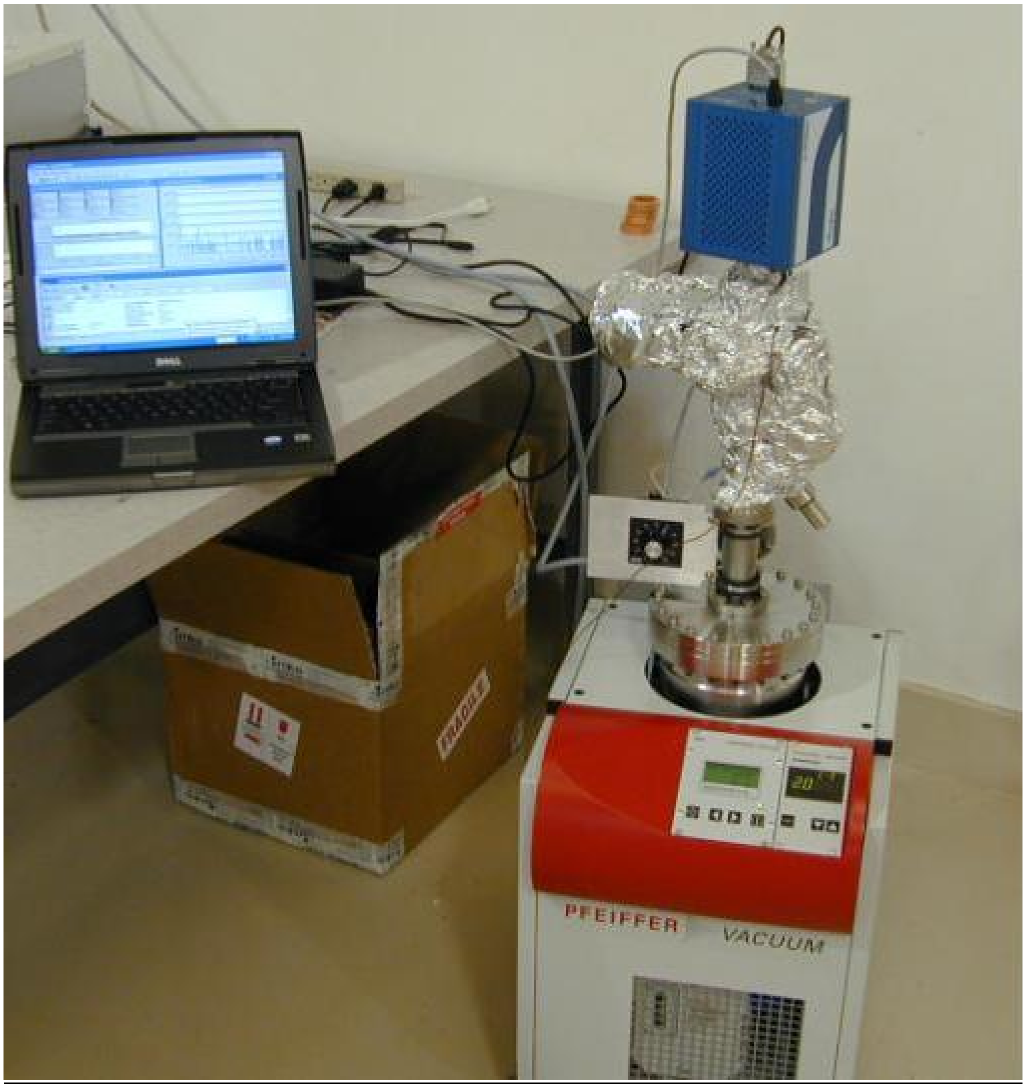

Figure 6 The turbo-molecular pumping station has a residual gas analyzer installed to perform gas accumulation studies pertinent to the fabrication of long-lasting cryogenic systems with excellent vacuum integrity.

CONCLUSIONS AND RECOMMENDATIONS

The RASA1 prototype has been designed and fabricated as a demonstration of a new integrated mechanical cooling system suitable for use with RASA stations. Good technical progress has been made to overcome the problems associated with a compact, mechanically cooled germanium detector system. These new systems will have extremely long operating lifetimes with no maintenance requirements. At the end of this project PHDs Co. will offer a new product line: the MCX mechanically cooled detector product line for use with RASA and similar remotely deployed detection systems.

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