IMPROVEMENT IN GE DETECTOR COOLING

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ABSTRACT

High Purity Germanium (HPGe) detectors used in International Monitoring System (IMS) radionuclide monitoring stations must operate unattended in remote locations for up to six months between maintenance intervals. Recent technology advances have resulted in availability of Stirling and pulse tube cryocoolers with lifetimes well in excess of 20,000 hours. The Cryo-Cycle™ and Cryo-Pulse® 5 are two such commercial products being modified and evaluated for application in IMS Radionuclide Aerosol Sampler/Analyzer (RASA) systems. The Cryo-Pulse® 5 makes use of pulse tube cryocooler technology for the direct cooling of germanium detectors. Improvements are being implemented by the addition of ultra-high vacuum detector chamber technology, inclusive of all metal vacuum seals, to increase reliability and decrease downtime following brief power outages. A remote detector chamber (RDC) is incorporated to reduce the streaming path and decrease interference due to background radiation. The detector chamber is sized to accept large detectors in excess of 100% relative efficiency at 1.33MeV. The Cryo-Cycle™ is a hybrid cryostat having a liquid nitrogen (LN) reservoir and self contained Stirling cryocooler that condenses boil-off gas to maintain the LN supply indefinitely and provide a seven day cooling buffer in the event of component or power failures. The Cryo-Cycle™ is being integrated with a nitrogen generator for initial remote filling and top-off of LN to improve remote use and long term reliability. Details on the progress of both efforts are presented.

OBJECTIVES

The RASA Mark 4 and implementation of the Cryo-Pulse® 5 and Cryo-Cycle™ have been described previously by Yocum et al., (2008, 2009). The RASA was developed at the Pacific Northwest National Laboratory (PNNL) in the 1990s to meet Comprehensive Nuclear-Test-Ban Treaty (CTBT) requirements for aerosol radionuclide measurements, as described by Bowyer et al. (1997) and Miley et al. (1998). The electromechanically cooled HPGe detectors incorporated into aerosol samplers currently operating in the field rely mainly on Joule-Thomson direct coolers. Performance of Joule-Thomson (J-T) coolers for this application has been problematic. The standard Cryo-Pulse® 5 has been under evaluation and operating successfully in a prototype RASA system for two years at Patrick AFB, Florida.

The goal of this project is to investigate improvements in HPGe detector cooling technology for use in the RASA Mark 4. Explorations in both direct pulse tube cooling and hybrid Stirling cooling are being conducted. CANBERRA Cryo-Pulse® 5 and the Cryo-Cycle™ standard products provide the starting point for this effort. UHV technology is being incorporated in the Cryo-Pulse® 5 to improve long-term vacuum integrity and to eliminate the possibility of partial thermal cycles. This includes the use of metal vacuum seals, onboard vacuum pumps such as non-evaporable getter (NEG) pumps and ion pumps, improvements in cryostat end cap sealing, and use of UHV compatible internal components. Vibration isolation and mitigation techniques are being investigated to further enhance overall performance.

A nitrogen (N_2) gas generator is being integrated with the Cryo-Cycle™ cooler to maintain a seven-day cooling buffer in the event of a power outage. An uninterruptible power supply (UPS) will be used with both direct and hybrid coolers to provide redundant protection against partial thermal cycles and to keep the Cryo-Pulse® 5 at operating temperature in the event of short power outages.

RESEARCH ACCOMPLISHED

The UHV Cryo-Pulse® 5 design described previously has been implemented and progress on the final assembly of the hardware is reported. The results of our tests on the Cryo-Cycle™ hybrid cryostat with an integral nitrogen gas generator are also detailed.

Direct Electric Cryo-cooling Improvements

For the RASA application a 4.0 inch diameter detector chamber was designed to fit inside the 4.3 inch diameter shield penetration of the RASA Mark 4. Figure 1 is an outline drawing showing the UHV Cryo-Pulse® 5 in relation to the RASA shield and filter paper. The RASA uses radiation shielding to reduce interference from background radiation and to increase sensitivity. To maximize the effectiveness of the shielding, a RDC is incorporated. The RDC allows the shield penetration to be effectively closed by insertion of lead back shielding directly behind the detector chamber after it is assembled into the shield (i.e. no-stream-path design). Back shielding in close proximity to the detector element further reduces the background and increases the sensitivity when compared to long end cap detector chambers. The benefit of the RDC and back shielding is clearly illustrated in Figure 1. The RDC is designed to accept germanium detector elements greater than 100% relative efficiency. All materials used within the vacuum envelope are UHV compatible for added vacuum reliability and to allow quick recovery from short power outages.

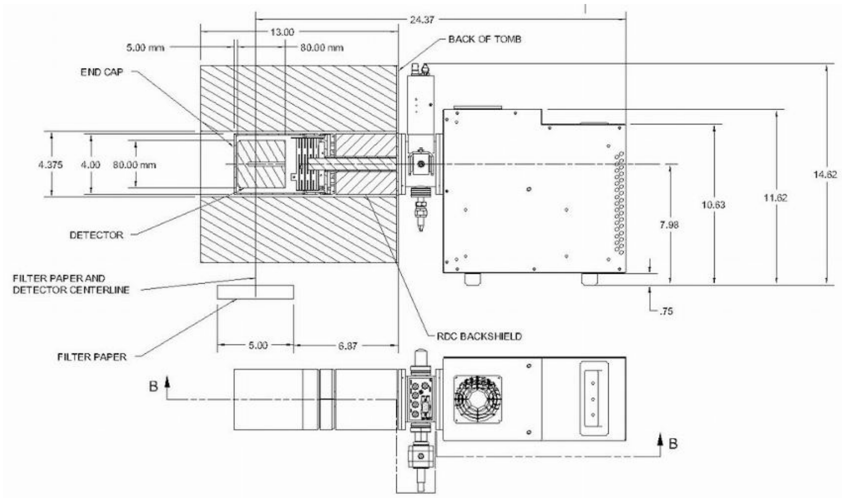

Figure 1. UHV Cryo-Pulse® 5 (Units are in inches unless otherwise indicated.)

Long term reliability of the UHV Cryo-Pulse® 5 is primarily dependant on the cooler reliability and the vacuum integrity. Historically these have been the two most common failure modes for RASA detectors. Pulse tube cooler reliability has reached the point that the lifetime is expected to exceed 50,000 hours, and a 5-year prorated warranty is offered as a standard feature. Vacuum integrity is improved by use of UHV materials and assembly techniques. The vacuum enclosure is made of stainless steel, aluminum, and copper with ceramic electrical feedthroughs. All fixed joints are welded or brazed with careful attention to weldment design to eliminate trapped gasses and virtual leaks. Demountable vacuum seals comprise metal knife edge seals (i.e., Conflat), indium compression seals, and swaged pinch seals. Internal hardware is made of copper, stainless steel, aluminum, and ceramic. The AC coupled FET assembly consists primarily of ceramic components assembled on a ceramic printed circuit board. Solder connections are made using 96% tin with 4% silver. The insulation for the high and low voltage wires inside the cryostat is one area of compromise; wires are insulated with polyimide resin. The UHV Cryo-Pulse® 5 assembly with and without the end cap in place is shown in Figure 2.

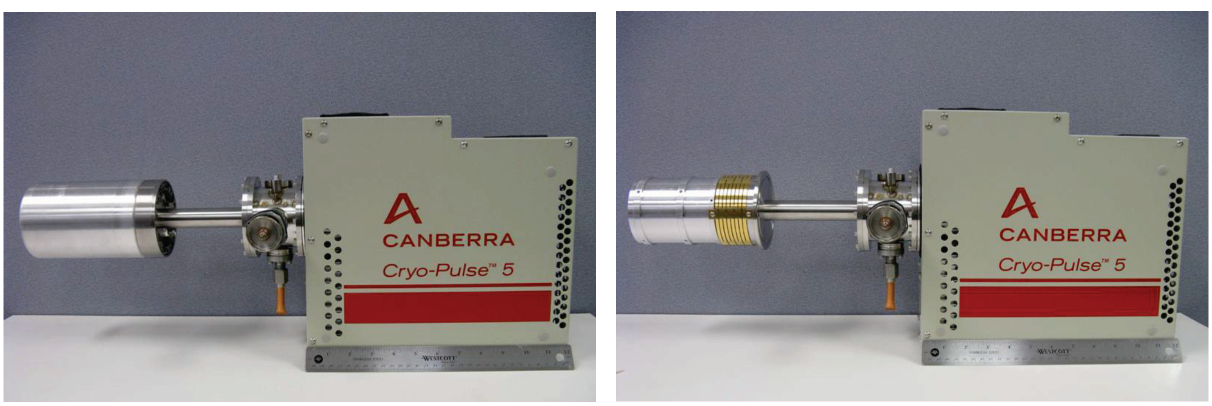

Figure 2. UHV Cryo-Pulse® 5 shown with and without end cap.

The vacuum integrity of the cryostat depends on proper use of materials and assembly techniques, as well as the method used to manage the residual gas evolution inside the cryostat. The UHV Cryo-Pulse® 5 incorporates a non-evaporable getter (NEG) pump and an ion pump. The NEG pump is effective at permanently removing chemically reactive gases such as carbon, oxygen, and nitrogen. Hydrogen is reversibly pumped by NEG pumps, but is only released in quantity by heating the getter to temperatures well in excess of 100 °C. NEG pumps may be regenerated by heating to approximately 200 °C at which point the hydrogen is released and must be pumped away. The adsorbed reactive gasses diffuse into the bulk of the getter leaving a clean reactive surface layer. Non-reactive gasses such as helium and other noble gasses are controlled by use of an ion pump. The ion pump ionizes residual gas atoms that are then accelerated by an intense electric field. The energetic ions impinge on metal electrode plates where they chemically react or become buried by sputtering of the electrodes. The ion pump on the Cryo-Pulse® 5 has a pumping speed of approximately 0.5 liters/second.

The cryostat components have been fabricated and tested and assembly is nearly complete. Residual gas analysis, vibration analysis, and thermal characterization of the system will be performed prior to mounting the detector element. Evaluation of detector performance will conclude the tests.

Circuitry to Mitigate Microphonics Response (MR)

Tests have been performed to determine that an AC coupled preamplifier is sufficiently low in noise and gives satisfactory MR performance for the RASA application. The final cooled FET assembly has been built and installed in the cryostat. Additional test were performed to demonstrate the benefit of increasing the second stage filter capacitance to reduce the effective MR caused by the relative motion of the high voltage components to ground surfaces inside the cryostat. In addition lead routing and electrical isolation of low and high impedance leads have also been designed to minimize MR.

Mechanical Vibration Isolation

Vibrations in the high voltage circuit and or high impedance portions of the low voltage signal circuit inside the cryostat cause MR induced noise in germanium (Ge) detector systems. Capacitive coupling between these circuits and nearby conductors at a different potential results in a modulation of charge in the signal circuit. This ΔQ is amplified along with the signal. The signal-to-noise ratio is degraded to a degree dependant upon the frequency, amplitude, and repeatability of the resultant perturbations. High frequency vibration in the range of 10's of kHz and higher can be effectively filtered by shaping amplifiers typically used in spectroscopy systems. Random frequencies in the audio range down to 10's of Hz are difficult to filter or suppress without degrading the signal.

The most common approach to mitigating MR originating inside the cryostat is to reduce the transfer of vibration to high voltage components, high impedance leads and components, and nearby ground planes. This can be accomplished externally by reducing the vibration from external sources such as fans or the pulse tube compressor. Coupling of external vibrations to the cryostat body can be reduced by inertial damping or mechanical isolation techniques such as the addition of mass or insertion of flexible couplings at strategic locations. Similarly vibrations that make their way to the external vacuum enclosure can be reduced or prevented from transferring through the mechanical connections to the high impedance detector circuit inside the cryostat by isolating, damping, or restraining circuit components. The mechanical flexures that support the internal components provide flexible vibration isolation and thermal isolation while providing mechanical support. All of these methods have been incorporated into our design to mitigate the effects of the compressor and pulse tube vibrations.

Cryo-Cycle™ Hybrid Cryostat Improvements

The Cryo-Cycle™ HPGe detector cooler is a closed-system N_2 re-liquefier incorporating a 15 Watt free-piston linear Stirling cooler manufactured by SunPower, Inc., Athens, Ohio. This hybrid system has the same footprint as a standard 30-liter LN_2 Dewar and receives dipstick HPGe detector cryostats like those commonly used in other LN_2-based systems. The Cryo-Cycle™ continually condenses the LN boil-off inside a closed Dewar to maintain a 22-liter reservoir of LN. Once charged, the system does not require additional N_2 except in the event of a long-duration power outage or to replace gas loss due to seal leakage. Make-up can be added by topping off with LN or by adding N_2 gas. A N_2 gas generator was integrated with the standard Cryo-Cycle™ to allow unattended operation in the RASA. In controlled environments such as the instrument bay inside RASA systems, the only maintenance required will be semi-annual filter cleaning for both the Cryo-Cycle™- and Cryo-Pulse® 5-based systems.

A Domnick Hunter Model G1, N_2 gas generator was procured for integration with the Cryo-Cycle™. The G1 generator is a self-contained unit that uses 115 V, 60 Hz power and produces 0.75 liters/min. of N_2 gas containing less than 10 ppm oxygen (O_2). Filter cleaning or changes are required on a semi-annual basis at a cost of about $100. The internal compressor requires replacement every 2-3 years at a cost of $600. The molecular sieve beds are expected to last 10 years. Cost of the unit is $7,500 and it comes with a 2-year manufacturer's warranty. The specifications for the Domnick Hunter G1 N_2 gas generator can be viewed at: www.domnickhunter.com/documents/products/174004740_01_EN.pdf.

The gas extractor is connected to the cryostat as shown schematically in Figure 3 and Figure 4. In the configuration shown the G1 gas generator operates continually to provide high purity N_2 gas to Cryo-Cycle™ through a gas solenoid valve. A time-delay-relay circuit must be added if the gas generator is to be operated intermittently because the G1 requires 6-12 hours to achieve acceptable purity of the N_2 gas after start-up. As tested here, a Canberra model 7186 liquid nitrogen level (LN) controller senses the level of the LN in the Cryo-Cycle™ Dewar and operates the solenoid valve that directs the gas flow to either the Dewar or a vent. A precision pressure regulator maintains the pressure of the gas feed to precisely 2.5 psig. This pressure forces the Cryo-Cycle™ cooler into high power cooling mode so the maximum 15 W cooling capacity of the Stirling cooler is made available to liquefy the N_2 gas. When the gas flow is diverted to the vent the Cryo-Cycle™ returns to its normal operating pressure of 1.5 psig and the Stirling cooler operates at a lower cooling power sufficient to condense the boil-off gas and maintain the LN level in the Dewar.

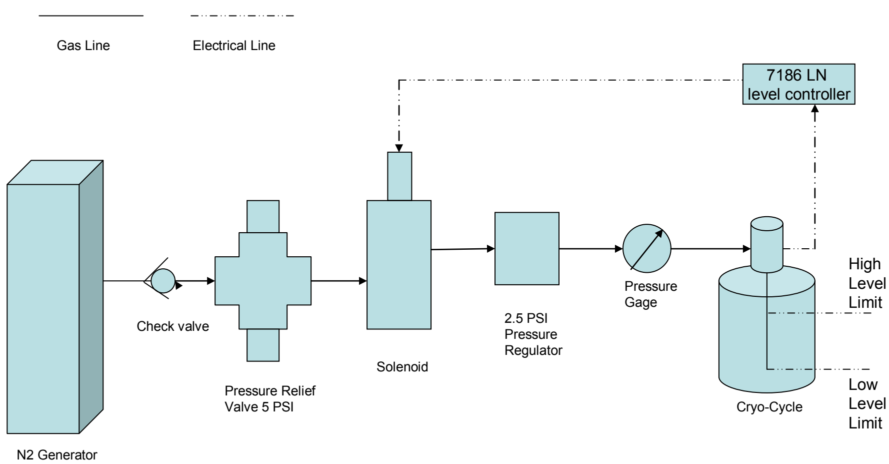

Figure 3. Block diagram of the nitrogen gas generator test assembly.

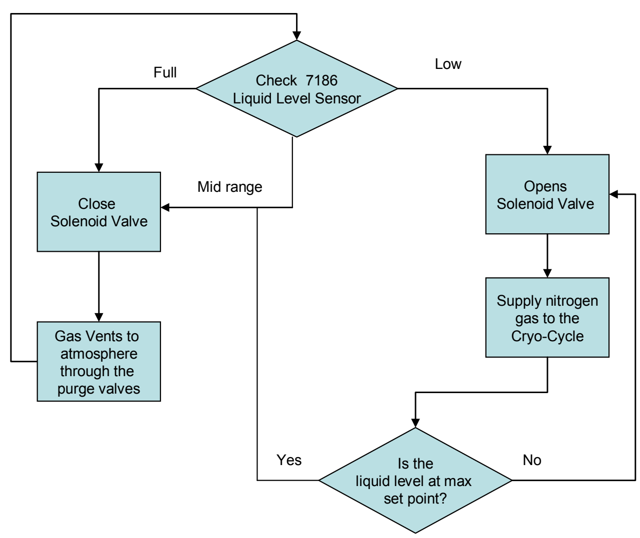

Figure 4. Flow chart showing the operation of the gas extractor with the Canberra 7186 LN level controller and hybrid cryostat.

Tests were performed to characterize the total heat load of the Cryo-Cycle™ and the operation of the system described above. The test setup is shown in Figure 5. The heat load was determined by measuring weight loss vs. time for the system with the Stirling cooler turned off. The results of this test are shown in Figure 6. A liter of LN weighs 1.78 lb so the loss rate from the graph is 2.2 liter/day. Since the heat of vaporization for LN is 199 J/g then 2.2 liter/day is equivalent to a heat load of 4.1 W. If the cooling power of the Stirling cooler is 15 W this implies that when the system is operating there should be excess cooling power of 10.1 W available for converting externally supplied N_2 gas to LN.

Figure 5. LN Level Controller, N_2 generator, and Cryo-Cycle™ test setup.

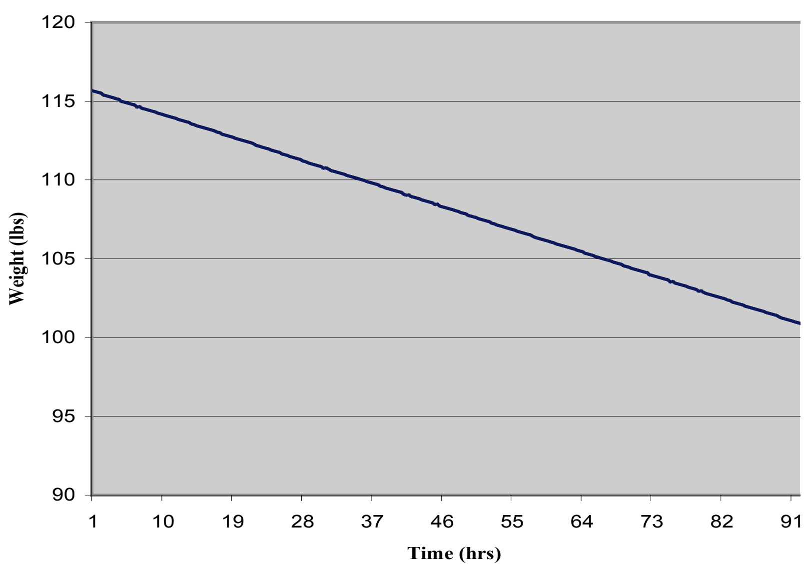

Figure 6. Cryo-Cycle™ weight vs. time with the Stirling cooler off.

The ability of the Cryo-Cycle™ to cool from room temperature with the G1 gas generator providing the N_2 gas was measured by monitoring the weight of the system with the Stirling cooler operating at full power. A 2 kg detector was mounted in the cryostat and the detector temperature was monitored during the cooldown. The results are shown in Figure 7. The data show that LN began accumulating in the Dewar approximately 24 h after the beginning of the cooldown. The slope appears to be linear after about 40 h. The temperature readings on the detector holder indicated that equilibrium temperature of 95 K was reached about 43 h after the beginning of cooldown. When the system reached equilibrium it was observed that the Stirling cooler was cycling on and off indicating that the supply of N_2 was insufficient to utilize all of the available cooling capacity. The cooldown curve from 55 h to 118 h indicates that LN was accumulating at a rate of about 2.4 lb/d. This means that N_2 was being supplied at a rate of 650 cm^3/min, which is well below the specified production rate of 750 cm^3/min for the G1 gas generator. Subsequent tests with a flow meter confirmed the N_2 production rate of 650 cm^3/min.

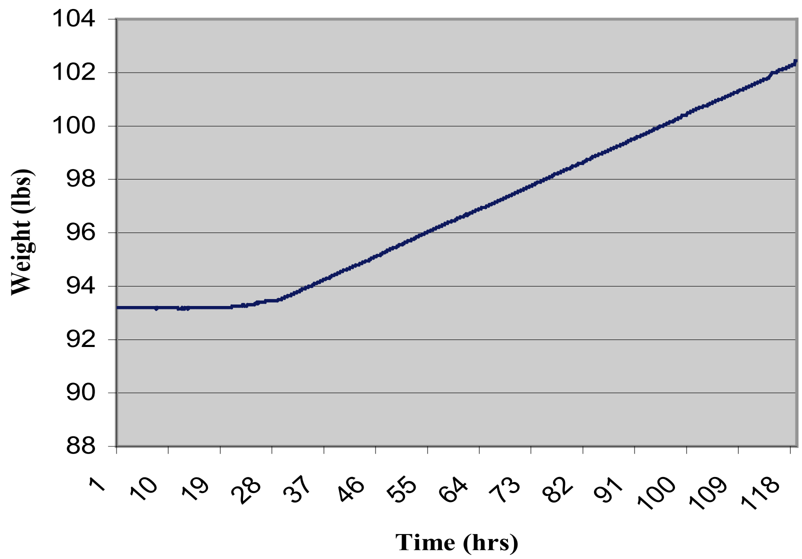

Figure 7. Cryo-Cycle™ cooldown from room temperature with nitrogen generator feed.

When gas is introduced into a cold, operating Cryo-Cycle™, it must first be cooled from room temperature to 77 K before it is condensed to liquid. The specific heat capacity of nitrogen gas at room temperature is 1.039 kJ/kg-K and varies only slightly down to 77 K. Therefore, cooling 808 g of gas over 24 h requires 2.16 W of cooling power. When gas is introduced into a cold, operating Cryo-Cycle™, the cooling power required to cool the gas and liquefy 1 l/day of LN is the combination of 2.16 W to cool the gas from room temperature to 77 K and 1.86 W to liquefy the gas, for a total of ~4 W. Given the excess cooling capacity that was calculated above the test unit should be able to make roughly 2.5 l/d of LN in addition to keeping the detector cold. The maximum that can be expected in this test setup is 1.34 l/d because of the limited 650 cm^3/min N_2 gas production rate of the nitrogen generator. The time required to cool the detector and fill the Dewar to its 22 liter capacity is roughly 18 days for this system. The detector is usable two days after cool down begins.

CONCLUSIONS AND RECOMMENDATIONS

Improvements to the Cryo-Pulse® 5 have been designed and fabricated. Testing and assembly of the mechanical and electrical components are complete with the exception of connecting the detector chamber and service body assembly to the cooler vacuum housing. Residual gas analysis, vibration analysis, thermal, and detector performance evaluation will be performed following completion of the assembly.

The Cryo-Cycle™ has been tested with a N_2 gas generator. Cool down from room temperature and maintenance of the LN level with the 1786 LN level controller has been demonstrated. Long term testing will continue. Operation with a UPS will be performed and susceptibility of the system to long and short term power outages will be investigated.

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