

Cryocooler selection considerations for outdoor Gamma ray sensor cooling

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ABSTRACT

Screening cargo to detect nuclear materials at ports, airports, train terminals and other critical installations is one of the major challenges facing the US Department of Homeland Security and similar organizations worldwide. An effective method of identifying hidden radioactive materials is the detection of Gamma rays transmitted through the cargo container. Accurate detection and identification can be only achieved using cryogenically- cooled High Purity Germanium (HPGe) detectors. A Portal detection system developed and manufactured by ORTEC Corporation contains several such cryogenically cooled sensors (see Fig 1).

This paper presents the main design considerations for selection of a cryo cooler for this application where long life, reliability, operation over extreme outdoor temperatures and with a low vibration signature are the main technical drivers. The paper further discusses the different cooling alternatives and the technical challenges of achieving a minimal foot print and interchangeability.

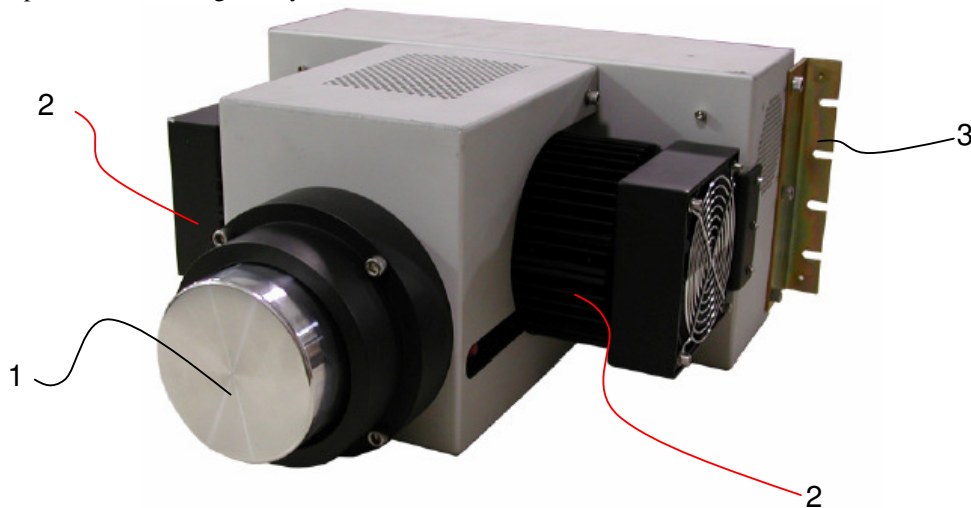


Fig 1-Ametek IDM

Fig 1 shows Ametek latest IDM design where the cryogenically cooled detector (1) faces the screened object and the Stirling compressors (2) are cooled by fins and thermally shorted to the bracket (3) in order to achieve ambient operation.

Keywords: Stirling cryo cooler, Germanium detectors, design considerations, cooling power, reliability, compactness, dirty bomb.

INTRODUCTION TO APPLICATION CHALLENGE

[1] Because of a small band gap (0.7 eV), room temperature operation of Ge detectors results in poor resolution. This can be overcome by cooling the detector to cryogenic temperatures to reduce the noise level due to leakage currents. To add complexity, in the past, some of the detectors (Ge)Li had to be kept continuously at cryogenic temperature to prevent catastrophic drift of the Lithium. This problem, however, has been resolved by the introduction of HPGe detectors.

Historically, in the absence of a reliable and inexpensive closed loop cooler, the cooling of the detector was achieved using a liquid Nitrogen (LN2) Dewar. As long as LN2 is present the detector will stay at a temperature close to 77K. Fig 2 describes such a Dewar and further provides with cross section to show the dewar/detector system parts. The advantage of such system is its very low level of vibrations (only the boil off of the LN2) and its low capital cost. The disadvantages however are significant. The Dewar orientation is restricted. Its operation/maintenance cost and complexity are fairly high - LN2 boil off and the requirement to regularly replenish. The weight of the Dewar, (that was originally designed to last for a week without adding LN2), is much greater than the weight of the detector which restricts portable use. For portal systems where a number of detectors are engaged, the use of a Dewar is close to impossible unless the system incorporates an LN2 auto refill mechanism that adds significant cost and complexity.

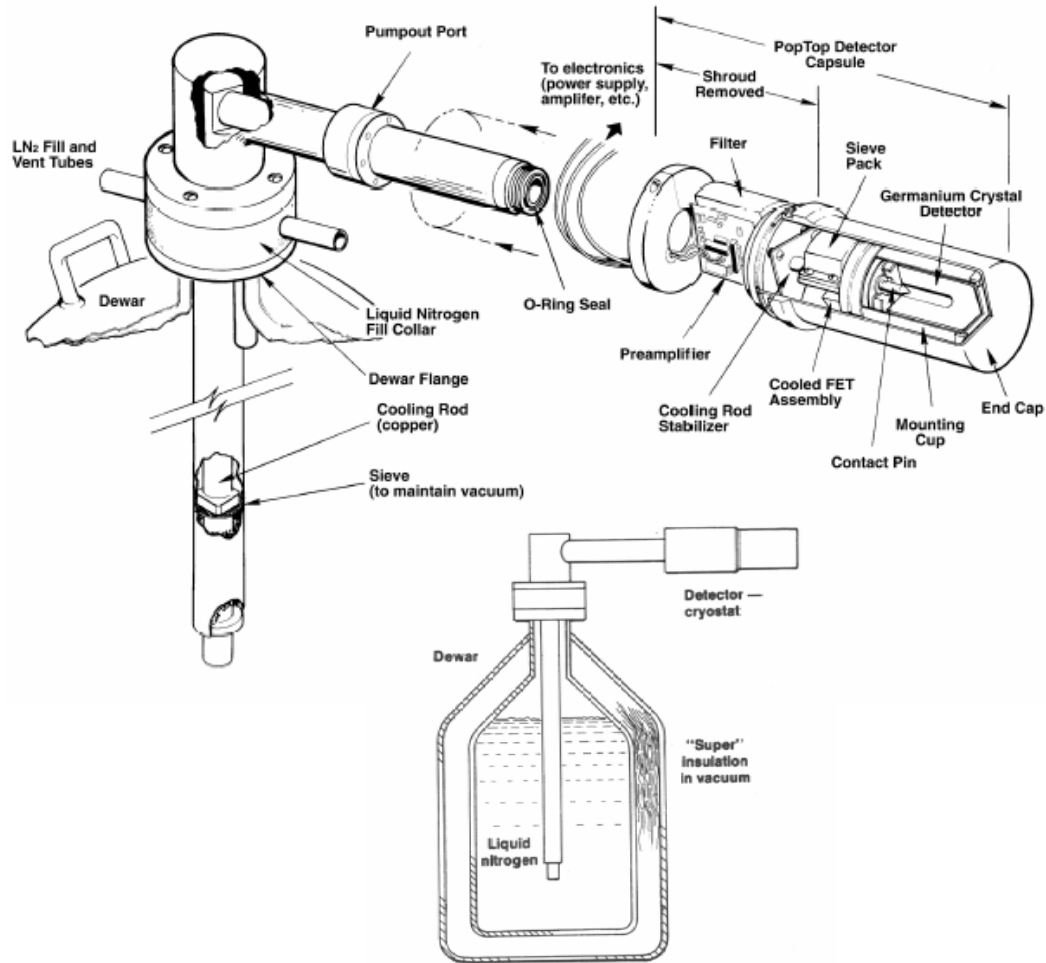


Fig 2-LN2 dewar and HPGe detector [1]

A further development of the above cooling method took place when several studies [1] showed that HPGe detectors could achieve good resolution at an elevated temperature of slightly below 130K. Mechanical closed cycle coolers based on the Joule Thompson and later Kleemenko cycle have been demonstrated. These coolers demonstrated good thermal performance but the vibration they introduced degraded the detection performance. This was later solved using mechanical and/or electrical filters.

The advantage of closed cycle coolers is simplicity of operation. The issues related to LN2 refill and orientation are eliminated but these coolers were still somewhat limited for portable application due to size weight and bulkiness. Each cooler requires a remote gas compressor connected via sealed compressed gas lines. These compressor assisted cooling units are still bulky and inconvenient to operate, especially in the case of portal applications. A portal rig of 4 detectors will need 4 compressors to be located remotely. The lost space and thermal inefficiency associated with this is significant.

The problems of weight, size and space have been solved by the introduction of Stirling based cryo coolers. These coolers are very efficient from the thermal stand point and so require less input power and are smaller and lighter than the compressor assisted coolers. They can also be integrated into a portable multi detector rig to reduce or even eliminate the need for peripheral components.

MAIN DESIGN CONSIDERATIONS TO BE COVERED

1. THERMAL PERFORMANCE AND RELIABILITY

1.1. The Challenges:

The thermal mass of the detector means that it may take a few hours to achieve the desired cryogenic temperatures. A typical requirement is 24/7 system availability over years, so careful attention must be given to cryostat design and serviceability/modularity of the system.

1.2. The solution:

1.2.1. Unit

ORTEC's Interchangeable Detector Module (IDM) is designed to achieve a long life by using an all metal seal cryostat which does not use the normal molecular sieve as a cryo-pump. The all-metal construction combined with the powerful cooler results in a robust long-life unit which can be temperature cycled, either completely or partially. The cooler can be turned off and back on at any time, greatly aiding service operations.

1.2.2. Cooler

(See Fig 3 and Fig 4)

Designed to work continuously for 3 years or more, the K-535 Mean Time Between Failure (MTBF) is well over 28,000 hours [2]. An ongoing accelerated life test (Fig 2) has produced an accumulated run time of 60,000 hrs taken from 3 units. An additional conservative acceleration factor of 2.5 increases this number to 150,000 hrs [3]. Thus ORTEC's design goals of > five year operation should be attained.

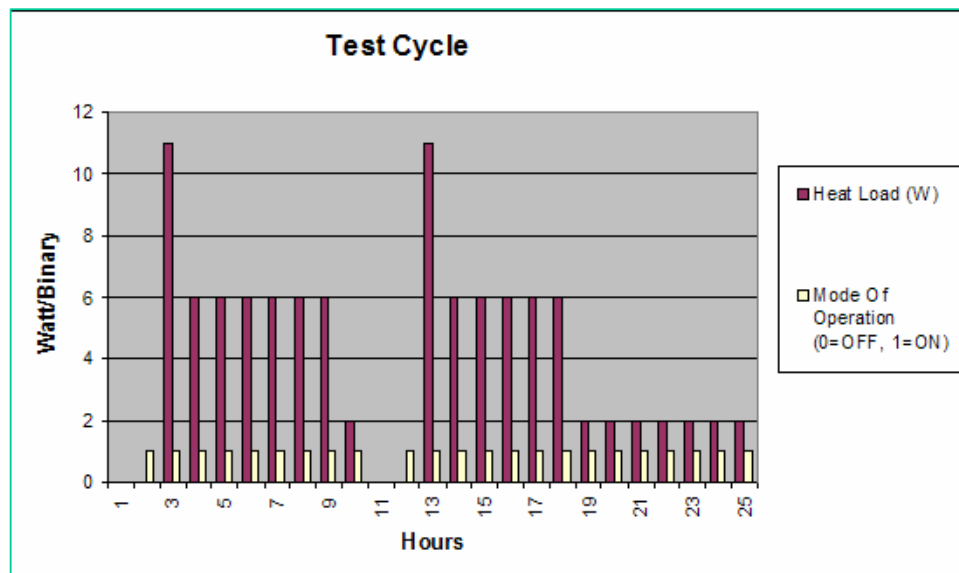


Fig 3-K535 Accelerated Life Test

The heat load cycles throughout the day (between 0W to 11W) and the coolers are turned On/Off twice a day. Both factors shorten the coolers life hence accelerating the test.

The cooler mechanism (See Fig 4) incorporates some unique components that contribute to its demonstrated long operating life:

Compressor pistons (Fig4 item 2):

Moving magnets-Coil (4) leads are not subject to yield.

Non contacting operation is achieved through tight clearances resulting in high efficiency and low wear.

Flexural bearings (3) minimize the radial displacement and achieve accurate linear motion.

Displacer (regenerator)

Flexural bearings (1) maintain the reciprocation of the linear displacer (5) and minimize radial displacement that could result in wear between the displacer and the cold head (6).

Other internal parts

Ultra clean assembly methods, the use of very low vapor pressure materials and metal crushed seals reduce / eliminate gas contamination.

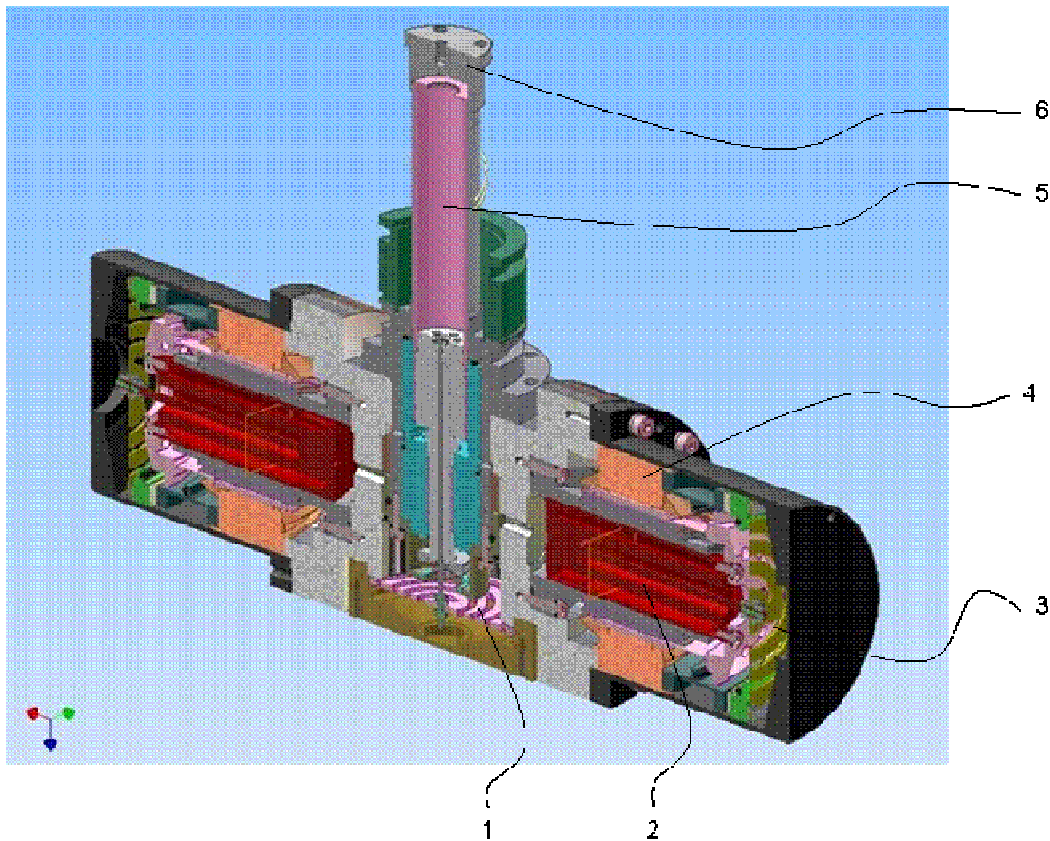


Fig 4-K535 Cross Section

Power redundancy (See Fig 5):

Ricor K-535 is specified to deliver 7W @ 70K @ 23°C body temperature.

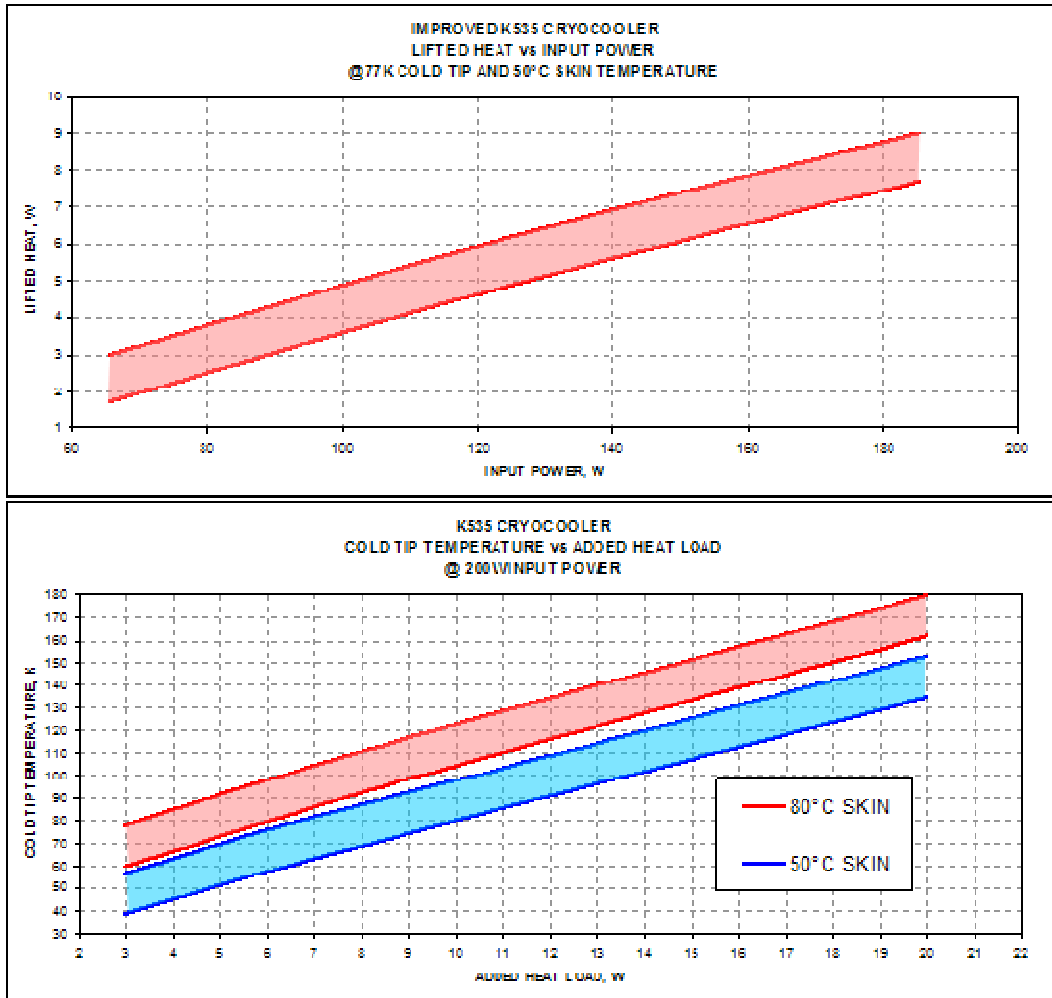


Fig 5-K535 Cooling Power Charts

The heat lift of the K535 model provides close to 50% power redundancy even when the requirement is to cool 2 detectors.

This redundancy prolongs the cooler life by decreasing a major stress factor which is the input current.

As the cooling power requirement goes up the cooler draws more current which in return shortens the life of electronic circuits hence may result with over all shorter cooler life span.

2. LOW LEVEL OF VIBRATION

2.1. The Challenge:

Mechanical vibration may negatively affect the input signal resulting in poor resolution and false detection.

2.2. The solution:

In order to improve detector sensitivity the Ricor K-535 uses a balanced twin piston design and an efficient thermal link which couples the detector to cooler. For especially sensitive applications it is possible to incorporate an additional dampening mechanism [4] which minimizes 1st harmonic forces and reduces the overall forces by x 80.

Fig-6 describes a cross section of the Ricor K-535 Low Vibration version. This cooler design is very similar to the regular cooler and shares the same parts (e.g. cold finger (1), displacer assembly (2) and compressor assembly (3)) but also incorporates a unique mechanism of mass and spring (4) which passively reduces the forces in the cold finger-displacer axis.

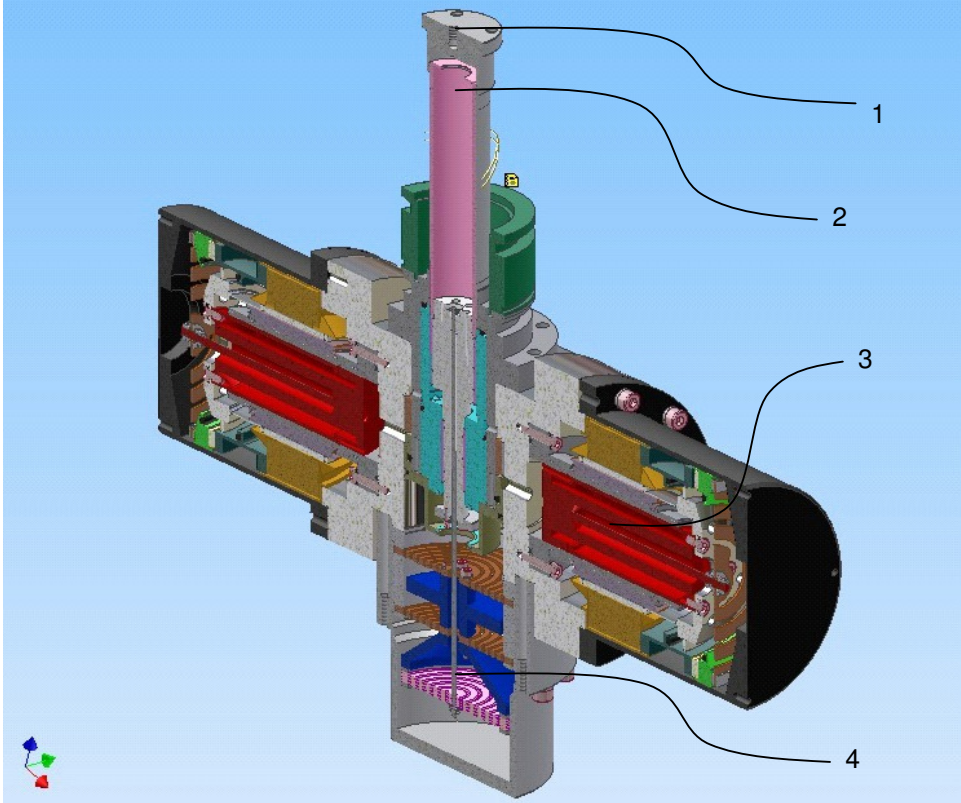


Fig 6-K535 LV-Cross Section

A comparison test of LV cooler vs. regular cooler is shown in Fig 7. The mechanical dampening system of the cooler is able to bring the level of vibrations at the operation frequency, down by almost 2 decades. An additional dampening using formed bellows [5] (Ultra Low Vibration-ULV see Fig. 8) attenuates the vibrations at higher frequencies.

Typical self-induced force along expander axis

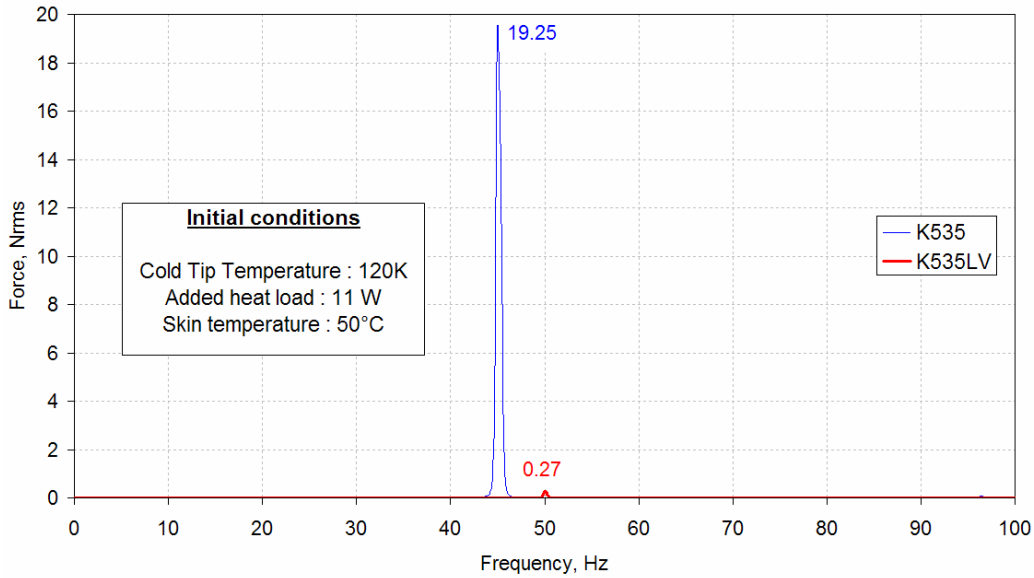


Fig 7-K535 LV vs. Regular Cooler

Force transfer along expander axis

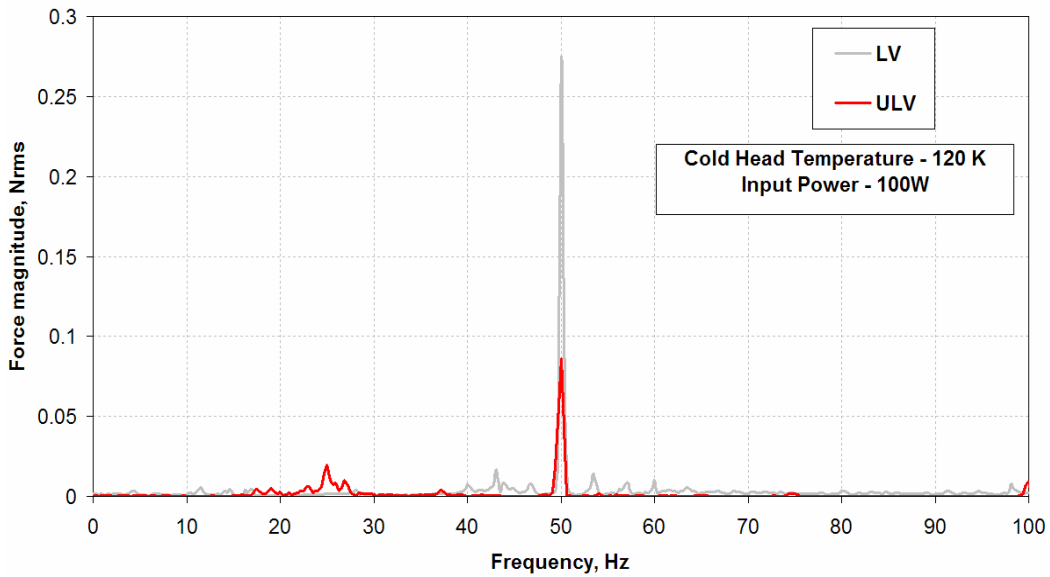


Fig 8-K535 LV vs. K535 ULV

3. OUTDOOR OPERATING CONDITIONS

3.1. The Challenge:

Outdoor conditions: The requirement is to withstand outdoor conditions and temp ranges from -40 C to 50+ C and humidity of 0 to 100. This is not practical at the extremes so enclosures must be employed for many applications. The

challenge is to provide a detector module including detector, cooler, and all supporting electronics in a compact, robust, energy efficient package.

3.2. The solution:

3.2.1. Unit

Ortec Interchangeable Detector Module (IDM) is designed to work under all environmental conditions when properly enclosed. Systems integrators will find the IDM can be easily integrated into scalable systems due to its robust cooling capacity and moderate power requirements.

3.2.2. Cooler

The Ricor K-535, originally designed to operate in outdoor conditions on cellular antennas is equipped to withstand harsh ambient by incorporating the following attributes:

All connections are weld sealed; all exterior parts are made either from SST304L or AL-7075 black Sulfuric acid anodized. To verify it's suitable for the task, before leaving the factory each cooler passes a stringent acceptance test procedure (ATP) which includes operation in ambient of +70°C -20°C in a climatic chamber.

4. COST CONSIDERATION

The portal monitoring system, single module incorporates multiple detectors. The number of detectors per system varies depending on the application and requirements. The application is sensitive to cost so an inexpensive cooler that can, if needed, cool up to 3 detectors has a significant advantage in terms of both cost and flexibility. The Ricor K-535 has the advantage of being able to cool multiple detectors to reduce cost of ownership. The supply lines have also been designed to support a swift ramp up to mass production with flexibility based on the Kan Ban concept, where the parts supply to the assembly line is carried out directly and visually controlled by the line team. By this approach the line is always ready to accept orders on short notice and save the space and cost of the traditional stockroom supply. This approach achieves good cost control during large scale deployments.

5. SIMPLICITY, COMPACTNESS

Unlike split coolers, an integral linear cooler such as the Ricor K-535 has the advantage of being a completely stand alone unit which doesn't required any external support or bracket. The design of Ametek's IDM capitalizes on this unique feature by minimizing the unit foot print. This combined with the ability to mount to a variety of racks/brackets means the combined IDM unit is practically a drop-in detector regardless of the portal rack system manufacturer.

CONCLUSION

The parameter	LN2	Joule-Thompson/Kleemenko[5]	Stirling
Cooling power	Unlimited-Depends on flow	10W @ 94K	13W @ 94K
Reliability (estimated MTBF)	N/A	50,000	>30,000
Compactness	Bulky, requires dewar and automated filling mechanism	Bulky-Requires compressor and gas lines	Compact-stand alone cooler
Typical facility requirements	Dewar and refill insulated lines	Electricity, cooling water, insulated lines (if compressor is located remotely).	Electricity
Capital cost	Low unless an automated filling is needed. If it is needed, the cost is high.	Medium	Medium
Operating cost	High. Refill of gas.	Low-Medium 0.5 kW power	Low- <50 W steady state power
Vibrations	Minimal	Low	Low

Ease of use	Low w/o auto refill.	High	High
Operation flexibility	None, base temp is predetermined by gas or mixture.	None, base temp is predetermined by gas or mixture.	High-temp can be altered “on the fly”

With the proliferation of nuclear material and technology across the world and the imminent threat of smuggling, nuclear material detection has become a major challenge for the free world. HPGe gamma detectors are the only technology that can precisely detect these materials. HPGe detectors need to be cooled to cryogenic temperature. As shown in the above table, Stirling technology coolers outperform all other options.

The Ricor K-535, is an integral Stirling based cooler that has been refined to provide optimal cryo cooling for portal nuclear material detectors.

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