State-of-the art cryocooler solutions for HPGe detectors

Cryo-Pulse 5 Plus: life time expectation and total cost of ownership

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Abstract

Despite the obvious advantages that electric coolers offer compared to liquid nitrogen (LN_2) to cool HPGe detectors, the limited cooler life time, higher initial investment and need for period maintenance have always been major drawbacks. This paper demonstrates that with the introduction of pulse tube coolers in CANBERRA's Cryo-Pulse 5 and Cryo-Pulse 5 Plus, these issues are no longer present.

In a first paragraph, the field data collected on Cryo-Pulse 5 (CP-5) and Cryo-Pulse 5 Plus (CP5-Plus) is combined with laboratory life time tests and theoretical models to calculate the expected life time of the cooler. In the second paragraph this expected life time is then used to calculate the return on investment (ROI) and total cost of ownership (TCO) of the CP5-Plus compared to LN_2-cooling.

Life time expectation of pulse tube coolers

Pulse tube coolers, such as the LPT9310 coaxial pulse-tube cooler, are recognized for their long expected lifetimes. There is theoretically no wear in the cooler, and the lifetime should thus be nearly infinite. The LPT9310 is used in the CP-5 from CANBERRA which was introduced late 2006 and its successor the CP5-Plus.

Over the past 9 years, some 1,100 CP5(-Plus)'s have been delivered. All these coolers together sum up a large amount of running hours. These accumulated hours are a good demonstration of the lifetime potential of this electrically refrigerated cryostat with LPT9310 pulse-tube cooler.

There are several approaches towards a statistical value for lifetime. The statistical term for lifetime is Mean Time To Failure (MTTF). More precisely, MTTF is the time after which 63.2% of all coolers will have failed.

The most basic method of determining MTTF is to look at the total amount of running hours, and divide that by the number of failures. For the installed base, this means:

> 1,100 coolers operating
> Steady delivery of coolers since November 2006
> Coolers are running an estimated 90% of the time
> In total 2 failures observed during that period. Running hours per failure are not known.

The total amount of running hours accumulates to approximately 32.8 million hours. In total, two cooler-related failures are known. One could very conservatively conclude that the average lifetime is 16.4 million hours.

However, this brute-force method does not take into account that the probability of failure could be dependent of time. For that, a more fundamental statistical approach is necessary. A method that is very commonly used for such a statistical approach is the so-called Weibull distribution. Weibull allows the estimation of not only the average lifetime of systems, but also, by means of a so-called shape factor, the type of failure mechanism. This shape factor could indicate for instance if the failure of a component is due to infant mortality, wear out, or random. In case wear-out is the mechanism, the chance of failure will increase over time. In case of infant mortality, the chance will decrease, and in case of random failure, the failure rate will be constant.

The Weibull distribution is based on the analysis of a population of coolers, and their failure as a function of time. Data fitting will then give the mean time to failure and the 'shape factor' indicating the failure mechanism. For the mathematical background of the Weibull distribution, we refer to e.g. [1]. Software is available to perform the analysis [2]. However, given the low number of failures, the Weibull distribution parameters cannot be estimated and thus used to estimate the MTTF of the coolers under study.

Another method for lifetime estimation is to look at individual failure mechanism. This method was presented by Ross [3] to determine the lifetime expectations of cryocoolers for space applications. The advantage of this method is that existing lifetime tests of other coolers can be used as well, as long as the individual failure modes are known. These failure modes, if they occur similarly, can then also be applied to other coolers. This method has already been presented by Thales in the past [4,5], and an update was presented in 2012 [6]. Failure modes and their probabilities can be determined from dedicated lifetime tests, or from installed base.

The lifetime estimation based on individual failure mode analysis uses the probability of each individual failure mode. Failure modes and their probability are determined by running lifetime tests (see e.g. [5]), complemented by data from the installed base. In this case, we know that the two failures from the field were caused by internal leaks in the pulse tube[1]. If we assume two failures of this internal leak in 32.8 million running hours, this means that the probability of this failure is $6.1 \cdot 10^{-8}$ hr^{-1}.

Other failure modes, present in the compressor, can be determined from two different sources:

- Lifetime test results from different coolers, all driven by flexure-bearing compressor;
- Installed base of coolers based on flexure-bearing compressors.

[1] The failure mechanism has been identified, and could be traced back to a leaking adhesive joint. Meanwhile, this adhesive joint has been redesigned to further reduce the risk of occurrence.

In the latter case, the entire installed base of flexure bearing compressors is used, not only the LPT9310 coolers. This further increases the amount of hours per failure.

	Lab lifetime date [cumulative compressor hours without failure]		Installed base fielded data	
FAILURE MECHANISM	*MTTF*	*1/MTTF*	*MTTF*	*1/MTTF*
Excessive Internal Cooler Contamination	723,573	1.4E-06	32,800,000	3.0E-8
Hermetic Seal or Feed through Leak	723,573	1.4E-06	32,800,000	3.0E-8
Comp. Flexure Breakage (fatigue)	723,573	1.4E-06	32,800,000	3.0E-8
Comp. Motor Wiring Isolation Breakdown	723,573	1.4E-06	32,800,000	3.0E-8
Comp. Piston Alignment Failure	723,573	1.4E-06	32,800,000	3.0E-8
Comp. Piston Blowby due to Seal Wear	723,573	1.4E-06	32,800,000	3.0E-8
Internal leak in cold head (based on field data only)	16,400,000	6.1E-08	16,400,000	6.1E-8
Total Failure probability	Sum (1/MTTF)	8.6E-06		2.4E-7
Expected MTTF		**119,000**		**4,150,000**

Table 1: Failure probability (1/MTTF) per failure mode, and their sum determining the expected MTTF for the entire cooler.

The expected MTTF based on the failure mode analysis is approximately 119,000 hours. MTTF estimation based on the installed base is over 4 million hours.

We can use this calculated MTTF to determine the amount of failures that should have been observed from the installed base. This is then a check to see if the quality of the estimation.

In order to do so, we also need the aging mechanism of these coolers. This is similar to the shape factor in the Weibull distribution. This factor determines how the failure rate evolves over time.

For pulse-tube coolers, it is expected that the failure rate is constant. There will be no increase in failure rate over time, as there are no wear mechanisms in the cooler. So any failures are completely random. In order to prove this estimation, we have analyzed two LPT9310 coolers from the installed base. These two coolers, with serial numbers 52 and 133, were returned to the factory and the performance was measured and compared to the original Acceptance Test measurements at the time they were built. The results are shown in table 2.

Cooler Serial No.	Operating hours	Qe at production	Qe after analysis
52	25581	4.7 W	4.7 W
133	18351	5.4 W	5.4 W

Table 2: Results of two analyzed coolers, their total amount of operating hours, and performance measurement at production and after analysis. Performance is measured at maximum input power and 80 K tip temperature.

The difference in performance measured at production and after analysis is much smaller than the measurement accuracy of 0.1 W. Therefore, it can be concluded that these two samples did not reduce performance over time.

A wear out mechanism is always associated with a reduction in performance. Wear-out could for instance lead to more friction, or to larger gaps in seals. Both these effects reduce the efficiency of the cooler. In table 2, one sees that there is no significant reduction in performance. Therefore, if there are wear mechanisms, they are not visible on the time scales corresponding to the lifetimes of these coolers. Therefore, we can assume that the failure mechanisms are completely random.

The survival probability and thus the reliability based on both estimations is shown in figure 1 below. The current situation, (1,100 coolers, 32.8 million running hours, so 29,800 average running hours per cooler) is indicated by the blue line. Reliabilities for both estimations are 78% and 99%. This means that out of 1,100 coolers, between 11 and 242 are expected to have failed. Considering that only 2 failures are known, it must be concluded that the MTTF indeed approaches very high numbers.

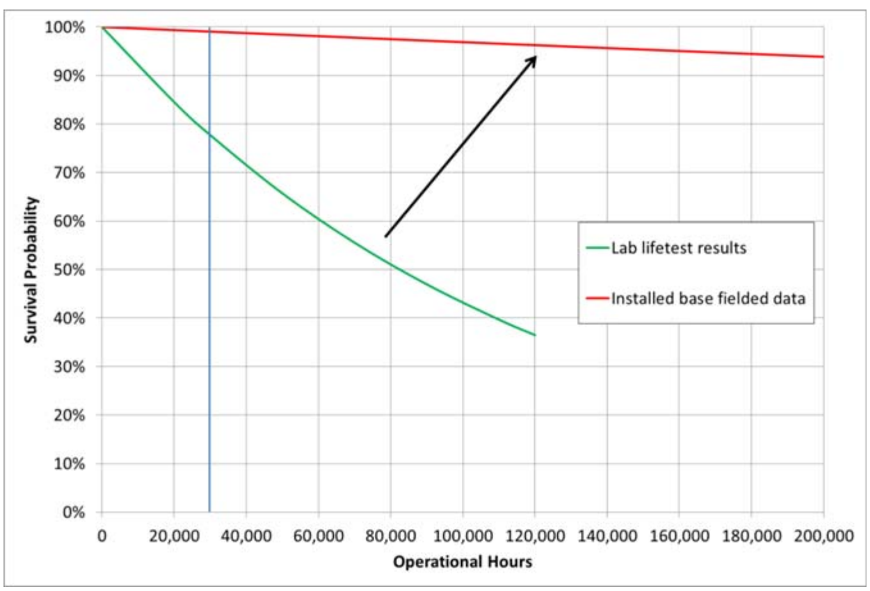

Figure 1: Survival probability for Pulse-Tube coolers based on liftetest and installed base determined MTTF, and a constant failure rate.

It can be seen in Figure 1 that the number of units running in life time testing limits the predicted MTTF; when a larger population is examined such as the population of fielded CP5(-Plus) units, a drastically higher reliability is demonstrated than when basing the analysis on life time testing alone.

It is furthermore worth noting that, based on 90% power ON time assumption, over 300 coolers have now exceeded 43800 running hours (5 years of continuous operation).

Cost comparison with LN_2-based system

The additional investment in an electrically cooled detector is about 26,000 USD higher than a comparable LN_2-cooled system. This higher initial cost should be valued against the lower yearly operating costs of the electric cooler.

The yearly cost to use liquid nitrogen (LN_2) to cooling HPGe detectors varies significantly from customer to customer, based their specific situation (proximity to LN_2-supplier, accessibility of detector system, number of detectors in operation,…). However, for the purpose of this analysis, a reasonable average of 6000 USD/year is taken based on the collected data. This average is valid for a single detector system and includes:

- LN2 consumption and rental costs
- Labor for preparations, filling and handling
- Loss of count time during refill

Following parameters were used for the ROI-analysis:

- Interest rate: 8%
- Inflation rate: 2%
- CP5-Plus life time: 11 years

The ROI-analysis gives following results (see figure 2):

- Payback period: 5 years
- N.P.V.: 22,600 USD

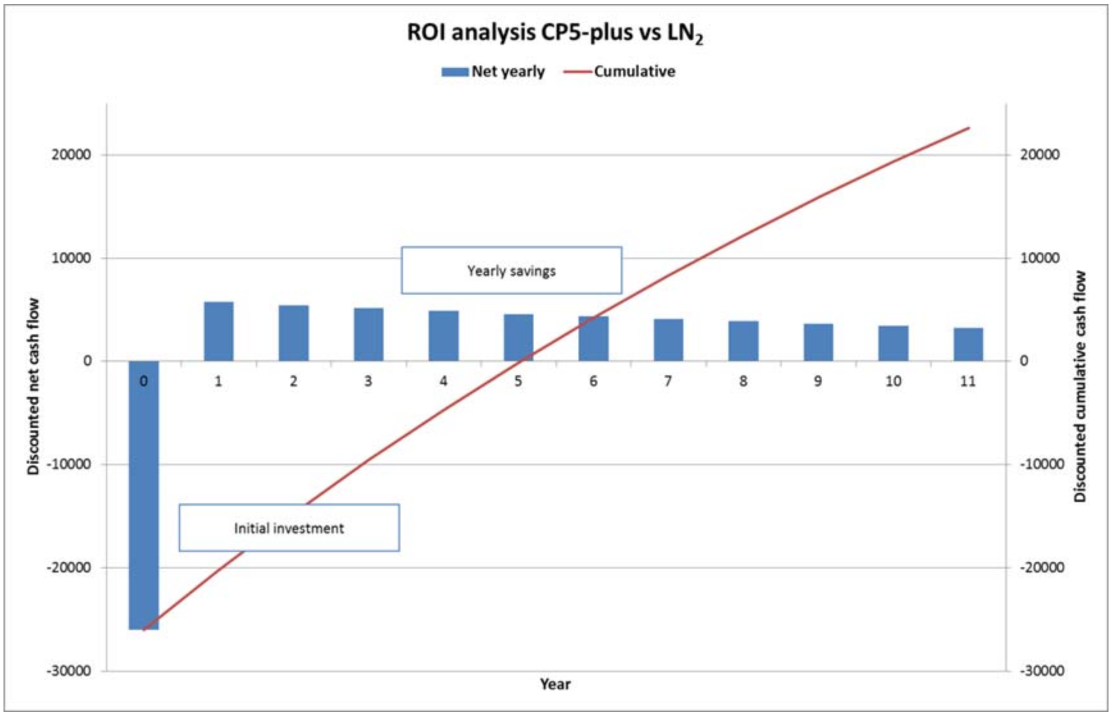

Figure 2: ROI analysis of CP5-Plus vs LN_2

The above analysis does not take into account any additional costs that are associated with operating a LN_2 installation, such as protective clothing and equipment for personnel and purchasing and maintaining an oxygen-level monitoring system.

On the other hand, the cooler in the CP5-Plus is completely maintenance free. The only required intervention will be the replacement of a cooling fan if it were to fail. The expected service life of such a fan is 5 years and it can be replaced by a service engineer during an on-site intervention. The cost of power consumption of the CP5-Plus is marginal. If the cooler is in operation 24/7, the annual power consumption will be about 875 kWh.

Cost of safety issues

In addition to the yearly cost savings related to the technical benefits of the CP5-Plus, this technology also significantly improves safety of operating and maintaining an HPGe detector system. There are serious risks related to the use of LN_2:

- > Injuries from handling bulky LN_2-containers,
- > Frostbite,
- > Asphyxiation due to oxygen depletion,
- > Increased radiation exposure on personnel during periodic filling.

Apart from the important social consideration related to these risks, there is also a potential cost factor. The average economic cost of a workplace injury in the US is estimated at 53,000 USD[2] and 59,000 EUR in the EU[3].

Conclusion

Experience with the installed base of pulse-tube coolers, continuously increasing lifetime numbers are observed. Earlier estimations, used at the time of introduction of the LPT9310, mentioned estimated MTTF of typically 20,000 hours. In the estimations mentioned above, it is indicated that actual MTTF of pulse tube coolers greatly exceeds these initial estimations. The best case MTTF of several millions of hours will not be realistic, as with operating life times exceeding 20 years, wear-like failure mechanisms are expected to influence reliability. However, these mechanisms have not yet become apparent in the analysis of fielded units or life time test data. Lifetimes of the coolers of more than 100,000 hours (12 years of operation) are clearly demonstrated (> 99% probability) with the present day installed base. This means that with the use of pulse-tube coolers on HPGe detectors, the cooler life time is now comparable to that of the detector part.

If these life time numbers are put into an ROI calculation, it can be demonstrated that the TCO of a Cryo-Pulse 5 Plus is often lower compared to an LN_2-cooled detector. Of course, this calculation largely depends on customer-specific parameters, as laboratory size and availability of LN_2.

Apart from economic factors, there are also important safety benefits associated with the use of LN_2-free detector systems.

References

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