Reliability for tactical cryocoolers

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ABSTRACT

For the past 18 years Carleton Life Support Systems has produced over 15,000 tactical cryogenic coolers that are primarily used in military infrared systems with excellent demonstrated reliability. As system reliability has improved, the cooler performance has emerged as a dominant component for reliability predictions. This has driven cooler reliability requirements to increase from a 1500-hour rotary cooler in chiefly ground applications to current requirements of 20,000 hours for linear coolers in advanced airborne applications. At the same time there is a push for improved cooldown time, lower power, lighter weight and smaller package.

This paper reviews our progress on extending cooler life. It reviews recent product returns and contends that the majority of issues are not primarily related to reliability. It also reviews how system performance specifications are restrictive to the cooler designer in achieving higher reliability in tactical coolers.

KEYWORDS: reliability, cryogenic, cryocooler

INTRODUCTION

Carleton Life Support Systems, previously known as Northrop Grumman Life Support, and Litton Life Support, builds cryocoolers that provide from 1/5 W to 1.5 Watts of nominal cooling at 77K (figure 1). Our coolers are fielded on military platforms as well as in commercial research laboratories that are located internationally. Although our name has evolved over the years, we maintained our dedicated staff at the same location.

Figure 1. Model 1051 (.6W), Model 1047 (1W), and Model 1040 (1/3W) Coolers

Cryocoolers are being utilized in a broad range of industrial and military applications that include communication, electro-optic IR sensing, and other sensor cooling. The environment and duty cycle for these applications impose different operational conditions on the cryocooler that impact the reliability of the unit. This paper focuses on the military tactical cryocooler that is used to cool infrared sensors. This application requires a rugged cooler that can withstand severe vibrational and shock loading as well as extreme thermal conditions. The operational characteristics require the cooler to be small and light weight, have a quick cooldown for mission readiness, and consume as little power as possible. These constraints drive the design to a cooler with limited design margin. It is this design margin that is matched with wear mechanisms to achieve the desired reliability lifetimes.

The first cryocoolers, circa 1960, were large systems with multiple porting and seats. In the 70's the 1-watt common module cooler became a workhorse for the military offering easily interchangeable components. Reliability for these units was 1500 hour MTBF largely driven by the seal wear and bearing components. These units were also prone to contamination. Clearance seals and linear drive coolers hit the scene in the 80's and provided a major improvement in reliability. An improvement from 1500 hours to >8000 hours has greatly enhanced system performance, however with improved system design and electronics, the system reliability is being dominated by the cryocooler. In spite of the improvements made in the last 20 years, cryocoolers continue to receive negative reliability reviews. Some of this is largely due to incidences of non-relevant failures that occur during the initial phases of a program. During this phase there are handling issues, integration issues, and unrecognized specification issues that result in the cooler being returned for repair. These failures inflate the perception that the cryocooler is not reliable, but are due to non-reliability issues. When the chargeable relevant failures are analyzed the results correlate to the demonstrated results.

METHODOLOGY

A key to the reliability process is obtaining failure rates on various components and summing them to arrive at an overall system reliability prediction. This prediction is used to determine life cycle costs, maintenance intervals, and determination of spares, just to name a few items. Therefore it is important that the reliability assumptions be well documented and communicated from the system level down to the cryocooler supplier to create a clear understanding of the meaning of the data. Providing cryocooler data that includes thermal and mechanical stressing would understate system performance and inflate life cycle costs, if the system analysis already includes de-rating factors for these stresses.

The basic reliability definitions have historically been driven by Military Standards. The basic definitions of reliability are Mean Time Between Failure (MTBF) and Mean Time To Failure (MTTF). In 1996 MIL-STD-781 was canceled eliminating a primary reference. The development of commercial software still uses reference to MIL-STD-781, but there is no active standard that defines terms. Initially with MIL-STD-781 B, only MTBF was used as a reliability factor. It was demonstrated through testing per plan IV-A, which meant testing without failure for MTBF*.89/N (N=number of units) hours. However, subsequent revisions have removed the test plans and added the term MTTF. MTBF is now the sum of test hours/N (N=number of failures). MTTF is defined as mean time until the first failure. The sum of test hours/ N (N = number of units) results in MTTF. This is similar to MTBF and is many times referred to as a factor for non-repairable items, while MTBF is for repairable items. Another development in defining reliability is to use confidence intervals to bound the lower MTTF. In this case the lower MTTF is determined by,

$$MTTF_{lower} = MTTF_{mean} - tstat * \frac{\sigma}{\sqrt{n}} \quad \text{(eqn. 1)}$$

tstat is the student-t probability associated with the confidence interval
σ is the standard deviation for the test
n is the number of units

Most recent specifications are requiring no maintenance, thus the use of MTTF is the appropriate statistic despite the repairability of cryocoolers.

Cryocoolers are principally a mechanical system. Tactical cryocoolers typically operate on the Stirling Cycle, which provides the optimum cooling power for weight and size. This system consists of a pump (reciprocating piston), a regenerator (reciprocating piston), and hermetic seals.

The piston seals, both compressor and regenerator, are clearance seals. However, in reality there are localized contact areas, which cause friction and produce wear. The wear is a function of temperature, operating frequency, and stroke length for a fixed material and surface conditions. The wear can manifest itself as a groove or uniform wear. Once wear begins the debris tends to migrate to the end of the piston and tends to induce localized wear. Utilizing weight loss analysis will not necessarily produce a failure rate criterion. Instead, blow-by flow rate and friction are the parameters that define seal performance. Carleton Life Support Systems uses this flow rate during manufacture to ensure proper sizing of pistons as well as a hot drop test to ensure low friction. Developing a flow rate degradation and friction test method would be desirable, however current measurement techniques require disassemble to collect the data. This disturbance of test corrupts the test conditions and precludes continuation of the test lifeline.

The environmental temperature generally reduces cooler performance as the temperature increases. In addition to the thermodynamic losses associated with heat rejection at higher temperatures, higher temperatures reduce the seal clearance resulting in increased friction and wear, while increased refrigeration demand associated with the dewar thermal transport requires a longer piston stroke. The increased stroke requires more input power to provide the refrigeration work. Therefore monitoring the input power is a good indicator of wear and life. Miskimins[1] and Kuo[2] have offered a work function analysis that relates cooler life to total work. This is useful in evaluating cooler life for different environmental situations. The analysis integrates the power consumption during a given reliability cycle to arrive at an end of life watt-hour factor. Knowing the power versus temperature relationship of the cooler, the power consumption can be applied to other scenarios.

Performance loss can also be caused by helium contamination. Gaseous species with condensation temperatures greater than 77K will condense in the regenerator. Contaminants can be introduced by using a bad gas source, unclean parts, outgassing of components, and gas trapped within the cooler. The gas source is usually not a concern as long as an ultra-pure grade of helium is used. Contamination issues have essentially been eliminated with cleaning and baking procedures for piece parts and using a purging process that alternately evacuates and charges the cooler with helium. This process greatly improves the transport of contaminates from the working volume, past the clearance seals, and out of the cooler.

The hermetic seals are static components but due to thermal expansion differences can potentially develop leaks with repeated thermal cycling. Cooler housings are welded closed, but the gas transfer line attachment to the cooler and to the Dewar uses two lead plated c-seal. The c-seal fails because the clamping force relaxes over time and does not adequately secure the c-seal. The clamping force on the seal is controlled via the screw torque. The resulting clamping force can vary depending on threads, lubrication, and hardware. Repeated thermal cycling has been shown to cause failure. Carleton Life Support Systems has tested an improved method for clamping to prevent relaxation.

Industry is considering pulse tubes for tactical cryocoolers primarily because they are expected to improve reliability. One of the prime failure elements is eliminated since the regenerator does not move in pulse tubes. The regenerator seal is more sensitive to dimensional variation than the compression piston, therefore the piston seal wear out mode is expected to be longer. There is a performance loss due to less efficient performance of pulse tubes, which will reduce seal life since more stroke will be needed to overcome the efficiency loss.

Drive electronics are designed into some cryocooler package. Thus they become a component in the failure rate summation. Electronic failure rates can often be found in handbooks, which facilitates predictions. These circuits typically contain components with failure rates several orders of magnitude less than the mechanical components. Thus the cryocooler reliability is dominated by the mechanical components.

The failure rate of mechanical systems is not contained in handbooks; therefore test data is needed to establish product reliability. Generating data on subcomponents is not practical in all cases since the wear rate is related to parameters associated with the assembly such as alignment, support, gas lubricity, physical size and operating speed. These parameters influence results of accelerated test methods in demonstrating Cryocooler reliability due to the dynamics of the assembly.

DATA

Reliability Demonstrations

Carleton Life Support Systems has performed reliability demonstrations in accordance with guidelines developed by the US Army, Night Vision Electronic Sensors Directorate(NVESD), Fort Belvoir, Virginia for the Standard Advanced Dewar Assembly I & II. This requires operating the cooler at –32ºC, 23ºC and 52ºC during the testing as shown in figure 2. Periodic performance tests are conducted to ensure compliance to specification requirements. A failure is defined as not meeting cooldown time, input power, or inability to maintain cooling at 77K with no relaxation of limits.

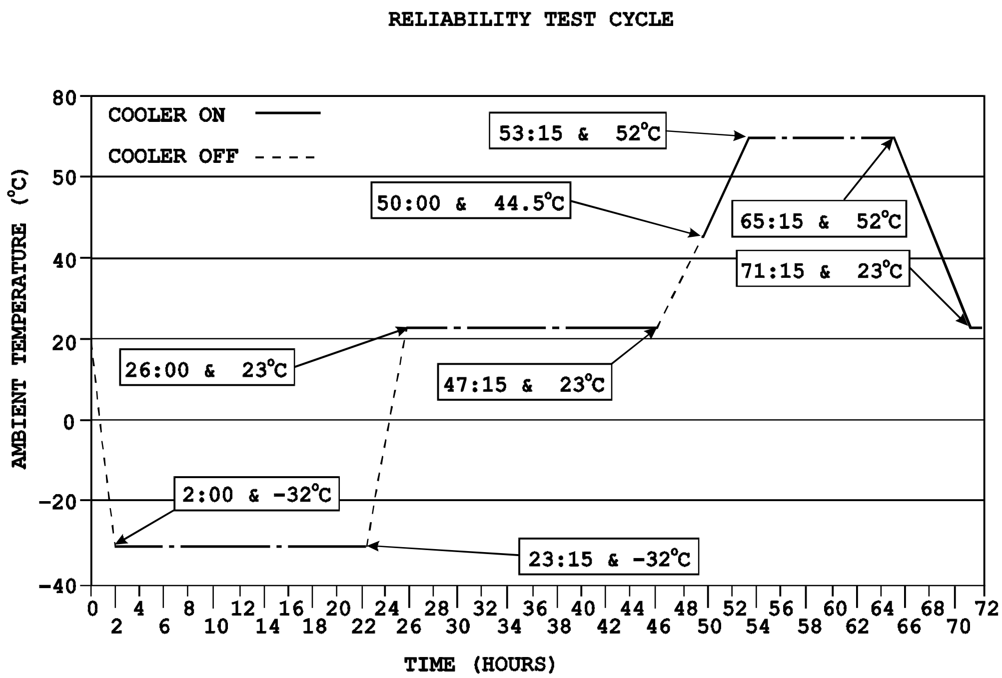

Figure 2. Reliability test profile

In 1998, a reliability demonstration was completed on four 1/3-Watt linear coolers using the NVESD profile. Table 1 shows the results of the testing that was terminated after 10,000 hours. The failed component was re-designed to correct the one failure mode. These results demonstrate in excess of 37,300 hour MTBF and a 9,375 hour MTTF.

Unit	Test Hours	Failure Mode
1	7,300	Feedthrough Header leak
2	10,000	None
3	10,000	None
4	10,000	None

Table 1. Summary of 1/3Watt testing (NVESD Profile)

In 2002, a reliability demonstration was completed on three 1-Watt linear coolers (SADA II) using the NVESD profile. Every 500 hours, the thermal cycling was interrupted to measure Output Vibration, cooler leak rate, and perform Acceptance Testing at –40ºC, 23ºC, and 60ºC. The units developed a leak (>1x10^{-7} scc/sec-He) at the expander-dewar interface with 6000, 6400, and 7400 hours. Examination of the seal and sealing surfaces did not reveal any anomaly that would account for leakage. The units were resealed and accumulated 8700 hours each. At this point all units easily passed Acceptance Testing and leak rate. One unit marginally failed output vibration level (.75 pounds force rms). Testing was discontinued. Officially these units demonstrated a lower life limit 6400 hours with 80% confidence based on the leakage failure. The compressor and regenerator demonstrated >8700 hours MTTF.

In September 2003, a reliability demonstration was begun on three 1.5-Watt linear coolers using the NVESD profile and has surpassed 2400 hours and is on-going. This test is expected to reach 6000 hours of testing by the end of 2004.

In 2004, a reliability demonstration will begin on a Lightweight 1-Watt Cooler. The test profile for this program will have a thermal cycle of 99% at 35ºC and 1% at 70ºC. Every 1000 hours, the units will receive 10 minutes of ESS vibration per axis, leak checking, and performance testing at –40C, 35C, and 63C. The goal of this test will be 20,000 hours MTTF and 45,000 hours MTBF. This test is expected to take 4 years to demonstrate the goals.

Field Returns

CLSS maintains a Service Group that is responsible for handling customer returns. This organization ensures that returns are received, processed, and returned in a timely manner. All returns are isolated to the failing component and the cause analyzed to determine if process or design changes are required. Failure Analysis Reports are provided when requested by the customer.

Many of the returns are classified as not chargeable against reliability. These include bent or damaged parts and problems that could not be verified (CNV). Damaged parts are the often the result of handling issues when installing the cooler into the system. The CNV issues occur in the early phases of a program, when integration issues surface. One such issue is the drive voltage during start-up. In this situation, the cooler is driven harder than it was designed and pistons hit stops causing a rapping noise. Either lowering the drive voltage or adjusting the cooler to operate with a higher voltage resolves the problem. The attention given these issues at program reviews often leads to a misconception of poor reliability, but these are non-chargeable to the reliability status of the cooler.

The relevant returns include gas leakage and seal wear as leading failure mechanisms. Gas leakage usually occurs at the expander/dewar interface. This seal is the largest seal and is more sensitive to thermal expansion mismatch issues. Another problem observed is that the hardware (flat washer and split washer) could be better optimized to reduce relaxation of clamping force. We have conducted a study that shows eliminating the split washer and using a hardened flat washer provides a more reliable seal than the prescribed hardware configuration. The seal wear is typically a result of improper sizing during the assembly process.

For our 1/3-Watt cooler, we have fielded 2400 units since 1999 for a total of 2,248,000 hours of field time. However, we do not know the real usage of the units. Our assumption is that these see an average 30% duty; therefore the fielded life is 674,400 hours. For this product line, we have had a total of 20 chargeable returns, giving this product a MTBF of returns 33,700 hours.

Data for other coolers has not been evaluated at this time.

In assessing cooler reliability, it would be very useful to know the real operating hours for the cooler when it is returned for repair. Only a few systems have incorporated elapse-timers. Our records indicate when a unit was shipped, but we can only guess at the real life of a unit.

CONCLUSIONS

Carleton Life Support Systems has continually made improvement in cryocooler manufacturing processes and designs. We utilize a gas purging cycle that effectively cleanses unwanted contaminates from the working volume. Our patented seal technology exhibits excellent wear characteristics and has demonstrated in excess of 10,000 hours of MTTF.

Carleton Life Support Systems cryocoolers are meeting the reliability requirements for major military programs. When reporting reliability, the test profile and failure criteria must be included for proper comparison. Alternate thermal profiles can be evaluated utilizing a power consumption model. Good communications is needed to ensure that component testing and reliability statistics properly reflect the intent and usage at the system/program level.

The long period of time required to demonstrate improved reliability is becoming a burden for several reasons: 1) products are required prior to completion of the demonstration, 2) product improvements cannot be quickly verified for reliability, 3) reliability of test equipment is often less than the product. The use of previous reliability data and design similarity must be used to obtain early confidence in product design. Product design margin is needed to ensure meeting reliability requirements. Consideration should be given to relaxation of requirements during a life test. Attempts to perform accelerated testing would require developing a correlation factor to normal performance levels. Accelerated testing can be used to identify failure modes, but not to quantify or demonstrate MTTF.

REFERENCES

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