Air Force Research Laboratory Spacecraft Cryocooler Endurance Evaluation Update

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ABSTRACT

Long-life test data is essential for confirming design lifetimes (sometimes 10 years or more) for space cryocoolers. Continuous operation in a simulated environment is the only accepted method to test for the degradation failure mechanisms. The Air Force Research Laboratory (AFRL) has been evaluating life test performance of space cryocooler technology for many years providing raw data and detailed evaluations to space designers and cryocooler developers for advancing the technology, correcting the discovered deficiencies, and improving cryocooler designs. At AFRL, units of varying design and refrigeration cycles are instrumented in state-of-the-art experiment stands that provide simulated space-like conditions and are equipped with software data acquisition to track critical cryocooler operating parameters. The collected data provides an assessment of the technology's ability to meet the desired lifetime and documents any long-term changes in performance. This paper documents the performance of AFRL tested cryocoolers over the past decade.

INTRODUCTION

Endurance tests conducted by the Air Force Research Laboratory (AFRL) are focused on the verification of cryocooler reliability and lifetime. The AFRL Spacecraft Component Thermal Research (SCTR) facility provides procedures, equipment and instrumentation to enable long-duration endurance evaluation with environmental conditions that simulate space use. Data is obtained throughout a cooler's design life-time or until the cooler fails. Recorded data is used to identify cooler instabilities, as well as possible failure modes and performance degradation. Identified cooler design flaws are then reported so that future coolers can be designed to fix fatal flaws. The objective of the endurance evaluation is to accumulate operating hours relative to the technology that was used to develop the cooler. A particular cooler's ability to maintain thermodynamic performance, as well as achieve long operational lifetimes, will be tested. The main goal is to identify life-limiting factors that can be corrected in the follow-on designs.

PROFILES

The life test data for cryocoolers at the AFRL SCTR facility prior to the year 2002 has been reported earlier along with initial characterizations. This paper focuses on the life-data collected

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since 2002 or since the initial characterization. During the past decade, six cryocooler underwent life tests, four from TRW/NGAS, one from Ball, and one from Raytheon. Table 1 lists these coolers and their nominal operating range.

The SCTR group fits each cooler with silicon diodes to read stage temperatures as well as a plethora of thermocouples to accurately measure the temperature profile of the entire cooler. The cooler load is provided with a resistive heater and each cooler is connected to a chiller to maintain a proper rejection temperature. Every cooler is also placed under vacuum to maintain space-like operating conditions. Each cooler that is integrated with flight electronics has its own set of internal temperature sensors. The SCTR group has seen variations in the external and internal temperature readings. Most times each cooler is set so that its own internal temperature readings are at design point. In 2008 the SCTR Facility was upgraded. Each cooler was put onto its own separate chiller, was put in its own separate vacuum system, and the control software was upgraded. All of the endurance tests were paused at the time of the upgrades.

Northop Grumman Aerospace (NGAS) High Efficiency Cooler (HEC)

The NGAS, formally TRW, HEC cooler was built using an Oxford type compressor and an optimized cold head. The cooler was built to lift 10 W at 95 K and to operate on orbit for 10 years with 95 percent reliability. This cooler design is currently used on JAMI (2004-Present) and GOSAT (2008-Present). HEC is tested using flight electronics that is under vacuum. HEC has internal temperature monitors at the cold tip and reject temperature plate. SCTR attached separate temperature sensors to record both the cold tip and reject temperatures. HEC is regulated to a 95 K cold tip reading on its internal temperature sensor, with a reject temperature of 300 K, on its internal sensor. The SCTR cold tip sensor is ~3.5 K warmer

Table 1. Nominal operating conditions for the six coolers tested at the SCTRG facility over the past decade.

Cooler	Cold end Temp. K	Heat Load W	Rejection Temp. K
NGAS HEC	95	10	300
NGAS MPT	150	1.0	300
NGAS HCC	35/85	2.0/17.0	300
NGAS 6020	60	2.0	300
Ball 35/60	35/60	0.4/0.6	300
Raytheon PSC	60	2.0	300

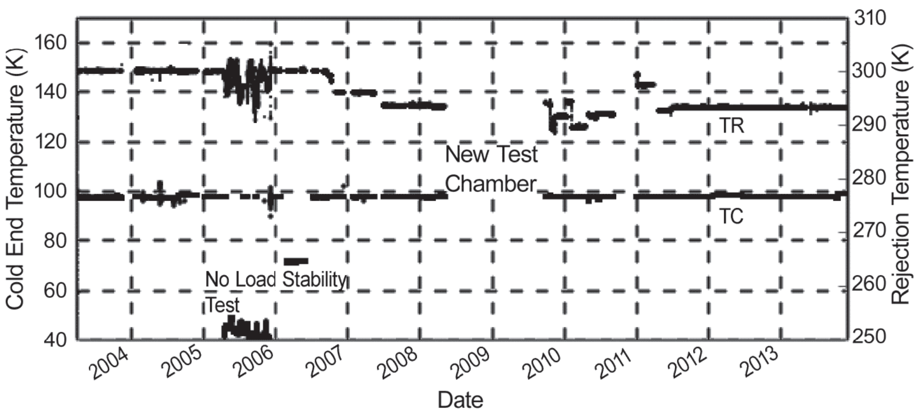

Figure 1. NGAS HEC endurance evaluation. Reject (TR) and cold end temperature (TC).

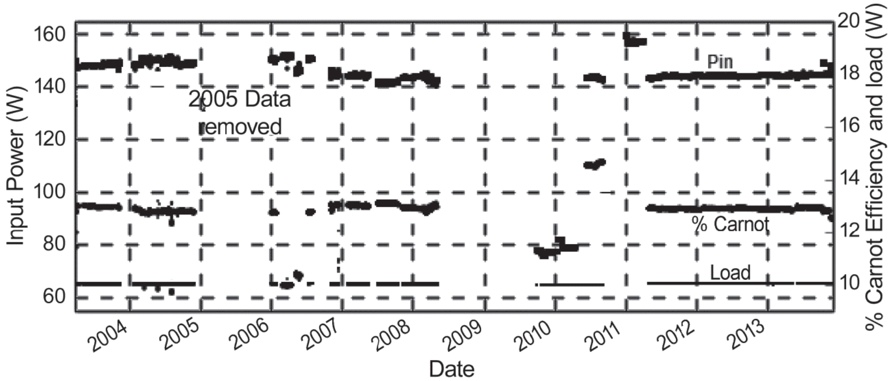

Figure 2. NGAS HEC endurance evaluation. Input power (Pin), % Carnot and load.

because of its location, while the reject temperature sensor is approximately 7 K colder because of its proximity to the recirculating chiller; Figure 1 shows these sensor readings over the past decade. Prior to 2007, SCTR had regulated the rejection temperature based on the external thermometer readings for characterization data collection. In 2007, the reject temperature was regulated so that HEC internal T Reject reading was 300 K. Since integration in 2002, HEC has been running in continuous life-test, and only shut-down occurred during routine maintenance and laboratory upgrades (in 2008). HEC has accumulated over 70,000 hours (8 years) of lifetime operation.

Endurance evaluation: The NGAS HEC cooler has shown relatively little change in performance over the years, as shown in Figure 2. In 2005 the SCTR examined behavior of the HEC under no load conditions and the data was noisy and the cold tip temperature was unstable. For clarity, this data was removed from Figure 2. In 2013 HEC, was re-characterized as shown in Figure 3 and Figure 4, utilizing the same operating conditions and test set-up as the original characterization. At 80% drive signal and a 10 watt heat lift the temperature stabilized 3 K warmer and input power required to reach stabilization of temperature increased by 2%.

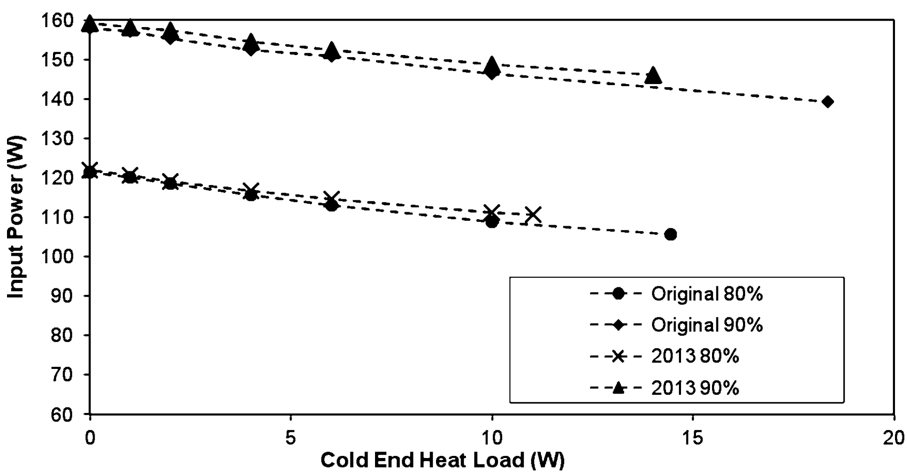

Figure 3. Input power required to reach temperature stabilization for a given load. Comparison of original performance versus 2013.

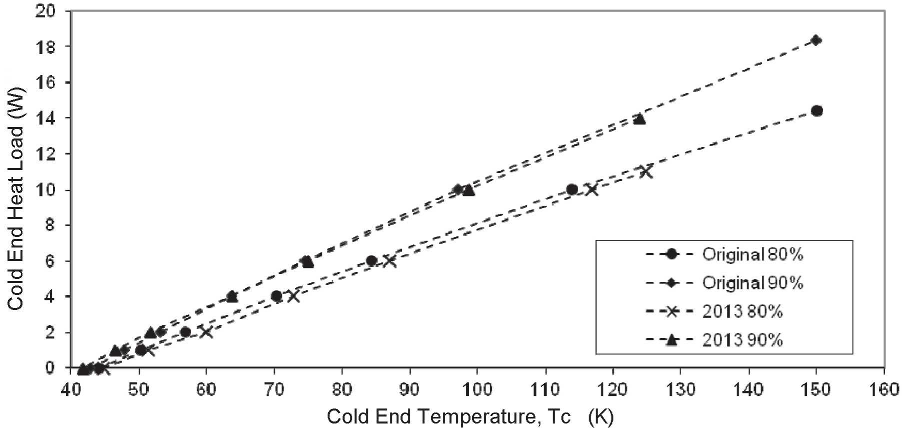

Figure 4. Original load line curves at constant drive signal compared with current performance.

NGAS Mini-Pulse Tube (MPT)

The NGAS Mini-Pulse Tube (MPT) cryocooler is an integral type orifice pulse tube cooler with an in-line compressor and balancer capable of minimizing vibration induced by the compressor piston. The MPT cooler has had a successful history as it has flown on a few different missions: SABER, CX sensors, Hyperion and STSS. The MPT was not operated with flight electronics; rather MPT uses rack electronics. The drive signal is adjusted periodically to maintain temperature. The cooler is set to cool 1 W at 150 K and is currently in endurance mode.

Endurance Evaluation: Since initial characterization was reported in 2004, MPT has accumulated over 72,000 hours in endurance mode and has seen a little drift in performance. Over its life-test, the required power to maintain 1 W at 150 K, a design point for the MPT, has increased from 11.3 W to 11.95 W, an increase of 5.5 % from the original input power requirements. Figure 5 shows the temperature history of the MPT since 2004 while Figure 6 shows the apparent changes in percent Carnot efficiency and changes in input power that merit further investigation.

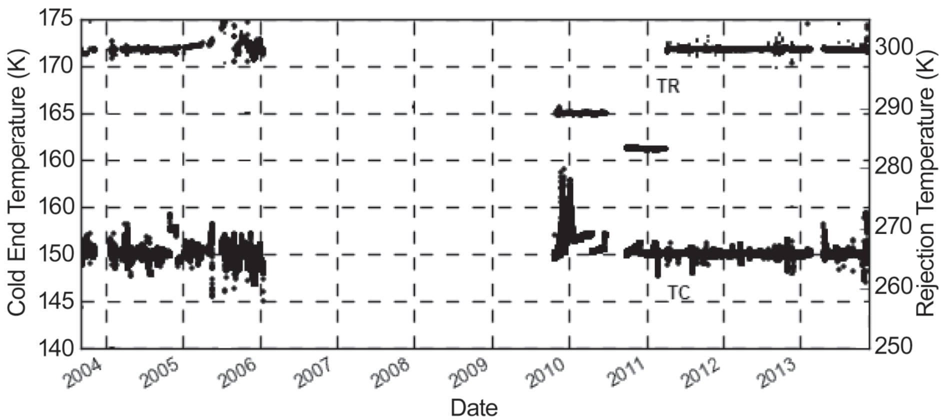

Figure 5. NGAS MPT endurance evaluation. Reject (TR) and cold tip (TC) temperatures.

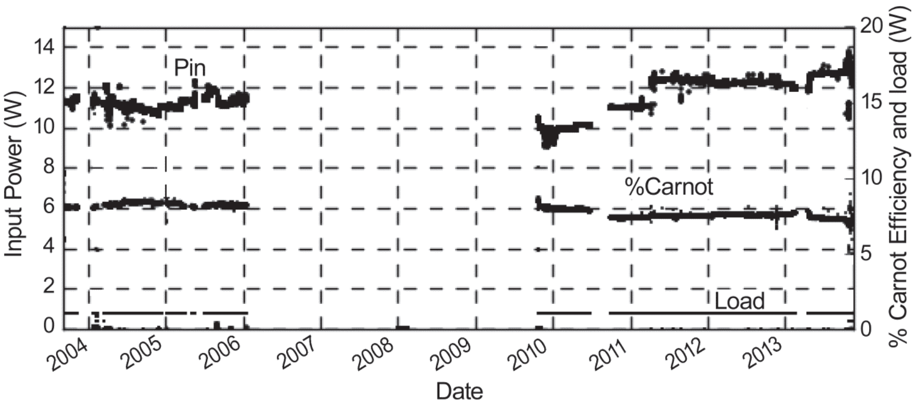

Figure 6. NGAS MPT endurance evaluation. Input power (Pin), % Carnot and load.

NGAS High Capacity Cooler (HCC)

The NGAS High Capacity Cooler (HCC) is a dual pulse tube cryocooler offering multiple cooling stages. NGAS HCC is operated by flight electronics that are maintained outside of the test environment. HCC is driven at 80 % drive signal, with 2 W and 16.5 W loads applied to the cold tip and mid stages, respectively. The cooler was initially tested at 95% drive and later was returned to 80% drive and has remained there for the duration of the life test.

Endurance Evaluation: HCC has accumulated over 26,000 hours since integration in 2006. Over its lifetime HCC has deviated very little from the design point when operated at nominal conditions. Outside of the nominal operating conditions, HCC has been seen to vary slightly from the original load test. Figure 7 shows the life test measurements recorded from HCC.

NGAS 6020

The NGAS 6020 is a pulse tube design which incorporates Oxford-style spiral flexure bearings in the compressor. This design has been in orbit operating on the MTI payload since 2000. The 10 cc compressor is balanced with back to back piston design eliminating the need for a balancer. Just before the end of 2011, the heat exchanger plates (cold plates), used to regulate the reject temperature, began to leak the thermal fluid cycled with the chiller. The vacuum was compromised

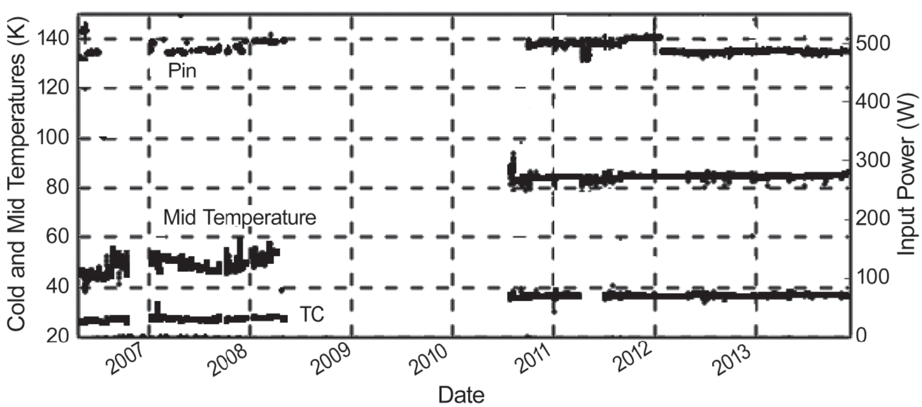

Figure 7. NGAS HCC endurance evaluation. Input power (Pin), mid and cold-tip (TC) temperatures.

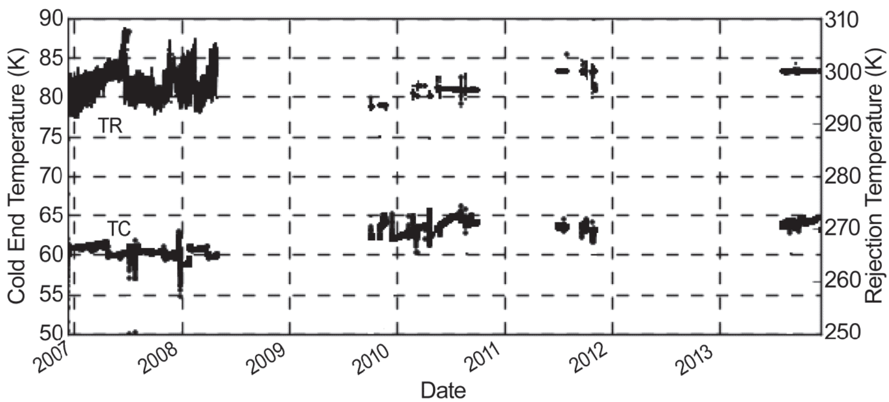

Figure 8. NGAS 6020 endurance evaluation. Reject (TR) and cold-tip (TC) temperatures.

and the cooler was turned off until the cold plates could be repaired. The cold plates were finally repaired in 2013 and the cooler was returned to endurance mode.

Endurance Evaluation: The SCTR has seen as large as a 10% increase in input power for the 6020 to reach its design point of lifting 2 W at 60 K. When the cooler is initially turned on, the input power necessary to lift 2 W at 60 K stabilizes at powers as low as only 5% larger then original. After the cooler has run for a couple of days, the input power required to keep the load at 60 K increases steadily. SCTR is currently trying to better understand the reason for the cooler performance changes. The cooler has currently logged over 96,000 hours, and will continue running until a complete cooler failure. Figure 9 shows the temperature history for the NGAS 6020, the cold tip temperature begins to drift upwards in 2010. Figure 10 details how the Carnot efficiency has decreased while the input power required to maintain 2 W at 60 K has increased. Figure 8 shows the temperature history while Figure 9 shows the input power and efficiency history of the 6020 cooler.

Ball Aerospace & Technologies Corporation 35/60 K PSC (Ball 35/60)

The Ball Aerospace 35/60 K cryocooler is a three stage, long life "Oxford" flexure spring, Stirling cycle device that was principally developed for dual load, dual temperature cooling at 35 K and 60 K. The cooler is operated by flight electronics which are under vacuum. The cooler has begun to be difficult to restart, with initialization sometimes requiring more than 10 attempts.

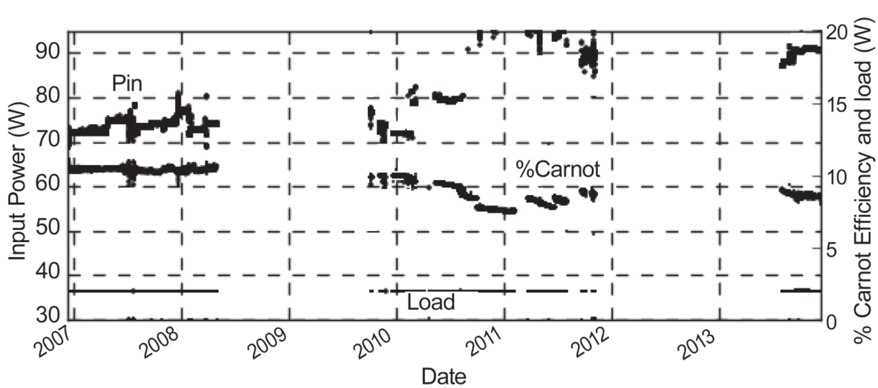

Figure 9. NGAS 6020 endurance evaluation. Input power (Pin), % Carnot and load.

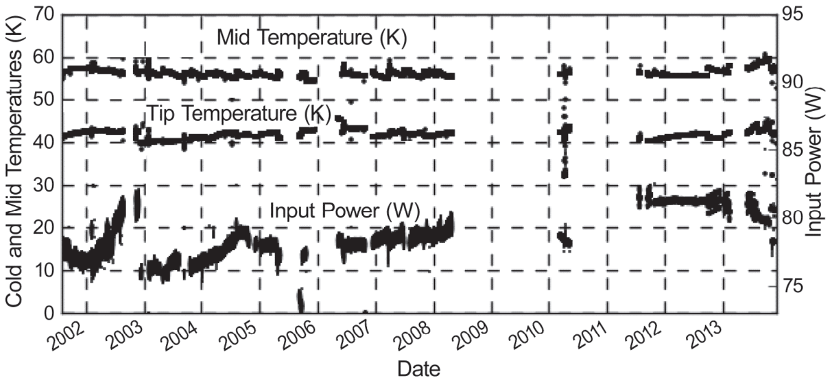

Figure 10. Ball 35/60 endurance evaluation. Input power, mid and cold-tip temperatures.

Endurance Evaluation: Since last reported in 2002, the Ball 35/60 has experienced some further degradation. Originally, the cooler input power was adjusted to maintain the cold tip temperature at 35 K with a 0.4 W and 0.6 W load at the cold tip and mid stage temperatures, respectively. In 2003, after over 19,000 hours of operation time, the cooler had degraded so much that maintaining the cold tip temperatures at 35 K became difficult. The cooler cold tip load was reduced to 0.3 W and compressor was maintained at a 91% stroke, while the endurance test continued. In December 2013, the Ball cryocooler was subjected to another load test. The cryocooler was set to 80 percent stroke with a 300 K reject temperature, and various loads were applied at the cold tip and mid stages. With a 0.3 W load applied to both the middle stage and cold tip, the cooler experienced a 27.25% increase in cold tip temperature (rising from 36.2 K to 46.07 K) and a 5% increase in mid stage temperature (rising from 55.3 K to 58.03 K) when compared to the original load line. Ball has been in endurance testing for over 80,000 hours (over 9 years). Figure 10 details the input power and stage temperatures since 2002.

Raytheon 2 W/60 K Protoflight Spacecraft Cryocooler (Raytheon PSC)

The Raytheon Protoflight Spacecraft Cryocooler (PSC) is a split-Stirling cryocooler running at 2.0 W/60 K. The Raytheon PSC was turned off and removed from chamber in 2007 after accumulating 52,000 hours (almost 6 years) in endurance mode. The cooler electronics had to be provided with an increasing amount of current to maintain operating conditions. The electronics began to draw more current than could be supplied. The Raytheon PSC cooler was outdated and this test was terminated.

CONCLUSIONS AND FUTURE WORK

The endurance testing of six coolers since 2002 is reported. Four coolers were manufactured by NGAS, one by Ball and one by Raytheon. The Raytheon endurance testing has been terminated but endurance tested continues for the remaining five coolers and will continue to failure. SCTRG has seen some cooler performance anomalies and will continue to monitor and attempt to diagnosis performance changes.

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REFERENCES

1. Oliver, E., Yarbough, S. A., Abhyankar, N. S., and Tomlinson ,B. J., “Air Force Research Laboratory Spacecraft Cryocooler Endurance Evaluation Update: 2000-2002,” *Adv. in Cryogenic Engineering*, Vol. 49B, Amer. Institute of Physics, Melville, NY (2004), pp. 1221-1228.

2. Yarbough, S. A., Abhyankar, N. S., Tomlinson, B. J., and Davis, T. M., “Performance Characterization of the TRW 95 K High Efficiency Cryocooler,” *Adv. in Cryogenic Engineering*, Vol. 49B, Amer. Institute of Physics, Melville, NY (2004), pp. 1277-1284.

3. Sutliff, J., and Roberts, T., “Multistage Pulse Tube Refrigeration Characterization of the Northrup Grumman High Capacity Cooler – An Update,” *Adv. in Cryogenic Engineering*, Vol. 53, Amer. Institute of Physics, Melville, NY (2008), pp. 917-923.

4. Abhyankar, N. S., Davis, T. M., and Curran, D. G. T., “Characterization of the NGST 150 K Mini Pulse Tube Cryocooler,” *Cryocoolers 13*, Kluwer Academic/Plenum Publishers, New York (2005), pp. 85-92