Abstract. The Air Force Research Laboratory (AFRL) spacecraft component thermal research group has been devoted to evaluating lifetime performance of space cryocooler technology for over twenty years. Long-life data is essential for confirming design lifetimes for space cryocoolers. Continuous operation in a simulated space environment is the only accepted method to test for degradation. AFRL has provided raw data and detailed evaluations to cryocooler developers for advancing the technology, correcting discovered deficiencies, and improving cryocooler designs. At AFRL, units of varying design and refrigeration cycles were instrumented in state-of-the-art experiment stands to provide space-like conditions and were equipped with software data acquisition to track critical cryocooler operating parameters. This data allowed an assessment of the technology’s ability to meet the desired lifetime and documented any long-term changes in performance. This paper will outline a final report of the various flight cryocoolers tested in our laboratory. The data summarized includes the seven cryocoolers tested during 2014-2015. These seven coolers have a combined total of 433,326 hours (49.5 years) of operation.

1. Introduction
Endurance tests conducted by the Air Force Research Laboratory (AFRL) were focused on verification of cryocooler reliability and lifetime. The AFRL spacecraft component thermal research (SCTR) facility provided procedures, equipment and instrumentation to enable long-duration endurance evaluation in environmental conditions simulating actual space use. Data was obtained throughout cooler design life-time or until cooler failure. Recorded data was used to identify cooler instabilities, as well as possible failure modes and performance degradation. Identified cooler design flaws were then reported so that future coolers could be designed to fix fatal flaws. The objective of the endurance evaluation was 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, was tested. The main goal was to identify life-limiting factors that could be corrected in the follow-on iteration designs.

2. Profiles
The life test data for cryocoolers at the spacecraft component thermal research (SCTR) facility prior to 2014 has been reported earlier along with initial characterizations [1-5]. This paper focuses on the
Table 1. Nominal operating conditions for the seven coolers tested at the SCTRG facility over the past year.

| Cooler  | Cold end Temp. K | Heat Load W | Rejection Temp. K | Lifetime Hours (3/12/15) |
|---------|------------------|-------------|-------------------|--------------------------|
| NGAS HEC | 95               | 10          | 300               | 80,128                   |
| NGAS MPT | 150              | 1.0         | 300               | 82,858                   |
| NGAS HCC | 35/85            | 2.0/17.0    | 300               | 34,120                   |
| NGAS 6020 | 60               | 2.0         | 300               | 103,421                  |
| Ball 35/60 | 35/60           | 0.4/0.6     | 300               | 87,216                   |
| Sunpower CT | 77              | 4           | 300               | 6,603                    |
| L3       | 110              | 2           | 300               | 38,980                   |

life-data since 2014. During the past year, seven cryocoolers were under life tests, four from TRW/NGAS, one from Ball, one from Sunpower, and one from L3. Table 1 lists these coolers and their nominal operating range.

The SCTR group fit each cooler with silicon diodes for reading stage temperatures as well as thermocouples to accurately measure the temperature profile of the entire cooler. The cooler load was provided by a resistive heater and each cooler was connected to a chiller to maintain desired rejection temperature. Every cooler was also placed under vacuum to maintain space-like operating conditions. Each cooler that was integrated with flight electronics had its own set of internal temperature sensors. The SCTR group has seen variations in the external and internal temperature readings. Most often each cooler was set so that its own internal temperature readings are at design point.

![TRW 6020 Pulse Tube Cryocooler Composite Load/Input Power Plots](image)

Figure 1. NGAS 6020 original load lines compared with characterization performed in January 2015. Cooler performance would drift over time; this test was done after the cooler performance had settled.
2.1 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. In November of 2014 the heat exchanger plates (cold plates), used to regulate T reject, began to leak the heat rejection fluid that is cycled by the chiller. The vacuum was compromised and the cooler was turned off until the cold plates could be repaired. The cold plates were repaired, the MLI was replaced on the cold tip, and endurance testing resumed in December of 2014.

**Endurance Evaluation:** The SCTRG observed up to a 10 % increase in input power for 6020 to reach its design point of lifting 2 W at 60 K. When the cooler is initially turned on its input power necessary to lift 2 W at 60 K stabilizes at powers as low as only 5 % greater than it did originally, but after the cooler has run for a couple of days the input power required to keep the load at 60 K steadily increases. SCTR was attempting to better understand the reason for cooler performance changes. The cooler has currently logged over 103,000 hours. Figure 1 shows the final load lines for this cooler compared with the original performance tests.

2.2 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 was operated by flight electronics under vacuum. The cooler had begun to be difficult to restart, with initialization sometimes requiring more than 10 attempts, although no difficulties were experienced in 2014/2015 [1,2].

![Ball Aerospace 35/60K Cooler Dual Load 80% Stroke Loadline, 300 K T reject](image)

**Figure 2.** Ball 35/60 endurance evaluation. Original input power, mid and cold-tip temperatures compared with the final 2015 characterization.
Endurance Evaluation: Originally, 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, the cooler cold tip load was reduced to 0.3 W and compressor was maintained at 91% stroke, while endurance tests continued. In December 2013 the Ball cooler was subjected to another load test. The cooler 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. In July of 2014 the load test was performed again. With a 0.3W load applied to both the middle stage and cold tip, the cold tip measured 45.6 K and the mid stage 56.8K. It does not appear that any further changes in performance occurred in the past year. Ball was in endurance testing for over 87,000 hours. Figure 2 details the load tests performed.

2.3 Sunpower CT
The SCTRG acquired the Sunpower CT, GT, MT and L3 cryocoolers in 2008 to evaluate in support of high temperature applications for the CHIRP program. In application CT cooled the optics and L3 cooled the focal plane array. The Sunpower Cryotel CT cryocooler is a Stirling terrestrial cooler developed in the early 2000’s for commercial applications in the telecommunications industry. It is designed as a 10W 77K cooler and advertised as having a mean time to failure of over 200,000 hours. The SCTR lab began testing the CT cooler in October of 2008 and characterized it through late 2009. The CT cooler was restarted in April of 2014 to resume endurance testing due to the long life advertised.

Endurance Evaluation: The CT cooler accumulated over 6600 hours of operating time with no change in performance see figures 3 and 4.

Figure 3. Cold tip temperature, and reject temperature for the Sunpower CT cooler since May 2014.
2.4 Northrop Grumman Aerospace (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. In December of 2014 HCC was turned off due to a fluid leak in the heat rejection lines. This leak was repaired in January of 2015. New MLI was installed in February of 2015 and a load test was performed, shown in figure 5 [1,2,4].

Endurance Evaluation: HCC accumulated over 34,000 hours since integration in 2006. Over its lifetime HCC deviated very little from design point when operated at nominal conditions. Outside of nominal operating conditions HCC has been seen to vary slightly from the original load test.

2.5 Northrop Grumman Aerospace (NGAS) High Efficiency Cooler (HEC)

The NGAS, formally TRW, HEC cooler was built using Oxford type compressors 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).

There have been several changes to the operating conditions of HEC since its original characterization and load line test in May of 2002. In June of 2002 the SCTR lab observed an anomaly in which noise in the current sense circuit caused an over current trip condition. TRW instructed the SCTR lab to increase the bus voltage from 54V to 59V to correct this anomaly. Increasing the bus voltage caused the percent drive to be shifted up by ~8% (90% of the original 54V bus voltage was 48.6V while 48.6V is 82.4% of the new 59V bus voltage).
Due to these changes in test operation the drive levels in the last years of testing were approximately 10% higher than the initial drive level in 2002. Therefore an 80% drive today is the approximate equivalent of a 90% drive level in 2002. This drive level results in an input power of ~ 150 W to hold a rejection temperature of 300K with a 10W heat load.

Since integration in 2002 HEC was operated in continuous life-test, only shut-down during routine maintenance and laboratory upgrades (in 2008) and to repair a cooling system leak and reapply MLI in 2015. HEC accumulated over 80,000 hours of lifetime operation \[1,2,3\].

**Endurance evaluation:** The NGAS HEC cooler displayed relatively little change in performance over the years. In 2015 HEC was re-characterized shown in figure 6 utilizing the same operating conditions and test set-up as the original characterization. At 80% drive signal (~equal to 90% original drive signal) and a 10 watt heat lift the temperature stabilized less than 1 K cooler and input power required to reach stabilization of temperature increased by 1%.

### 2.6 L3 B1500

The L3 B1500 is a split Stirling cryocooler. The SCTRG acquired the Sunpower CT, GT, MT and L3 cryocoolers in 2008 to test in support of high temperature applications for the CHIRP program. In application CT cooled the optics and L3 cooled the focal plane array. From 2009-2012 the L3 cooler was power cycled as part of its endurance testing. From 2012-2013 L3 was run at a constant cold end temperature with no load. In 2014 a 4W load was applied and L3 was set to temperature control mode at 110K.

**Endurance Evaluation:** The L3 B1500 accumulated over 38,900 hours of operating time since 2009, and has seen little deviation from initial performance.
2.7 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. MPT was not operated with flight electronics at the SCTR lab; rather MPT used rack electronics. This drive signal was adjusted periodically to maintain temperature. The cooler was set to cool 1 W at 150 K and operated in endurance mode [1,2,5].

Endurance Evaluation: Since initial characterization was reported in 2004 MPT accumulated over 87,000 hours in endurance mode saw little drift in performance. Over its life-test the required power to maintain 1 W at 150 K, design point for MPT, increased from 11.3 W to 11.95 W, an increase of 5.5 % of original input power requirements. figure 7 shows the change in performance of the NGAS MPT cooler.

3. Conclusions and Acknowledgement

The endurance testing of seven coolers over the past year is reported. Of the seven coolers four were from TRW/NGAS, one from Ball, one from Sunpower, and one from L3.

2015 marks the end of cryocooler characterization at AFRL. SCTR would like to thank AFRL for funding the endurance work started under Missile Defense Agency (MDA) over the years. We would
Figure 7. NGAS MPT original load test compared to the final load test performed in 2015. Small variations in performance are notable at lower temperatures.

also like to thank Ball Aerospace, Northrup Grumman and Raytheon for their many conversations and help with the coolers described here.

References

[1] Martin KW and Fraser T (2014) Air Force Research Laboratory Spacecraft Cryocooler Endurance Evaluation Update ICC 18 pp 609-616
[2] Oliver E, Yarbough SA, Abhyankar NS, and Tomlinson BJ (2004) Air Force Research Laboratory Spacecraft Cryocooler Endurance Evaluation Update: 2000-2002 Advances in Cryogenic Engineering vol 49 B pp 1221-1228
[3] Yarbough SA, Abhyankar NS, Tomlinson BJ, and Davis TM (2004) Performance Characterization of the TRW 95 K High Efficiency Cryocooler Advances in Cryogenic Engineering vol 49 B pp 1277-1284
[4] Sutliff J, and Roberts T (2007) Multistage Pulse Tube Refrigeration Characterization of the Northrup Grumman High Capacity Cooler – An Update Advances in Cryogenic Engineering vol 53 B pp 917-923
[5] Abhyankar NS, Davis T M, and Curran DGT (2004) Characterization of the NGST 150 K Mini Pulse Tube Cryocooler Cryocoolers 13 pp 85-92