Small Space Cryocoolers

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Mechanical long life cryocoolers are an enabling technology used to cool a wide variety of detectors in space applications. These coolers provide cooling over a range of temperatures from 2K to 200K, cooling powers from tens of mW to tens of watts. Typical applications are missile warning, Earth and climate sciences, astronomy and cryogenic propellant management. Northrop Grumman Aerospace Systems (NGAS) has delivered most of the US flight cryocooler systems and has 16 long life pulse tube coolers on orbit with a cumulative 100 years of continuous orbital operation with no degradation. This paper will describe these cooler capabilities and the performance of the 800 gram microcooler.

I. Introduction

The first ever pulse tube cryocooler product was a long life space cooler, the mini space cooler[1] designed by Northrop Grumman Aerospace Systems (NGAS formerly TRW) in the early 1990's. This mini-pulse tube cooler was developed as a replacement for Stirling coolers because of producibility and reduced complexity. This followed 3 decades after the pulse tube cooling principle was first described[2] and one decade after the first long life space Stirling cooler was developed[3]. Since that time these non-wearing space cryocoolers have enabled a number of space infrared (ir) payloads for earth and atmospheric science, missile defense and long lived astronomical telescopes. As the specific mass has decreased, the low mass high performance pulse tube cryocoolers can enable a new generation of planetary payloads not only for ir imaging but also for particles and fields.

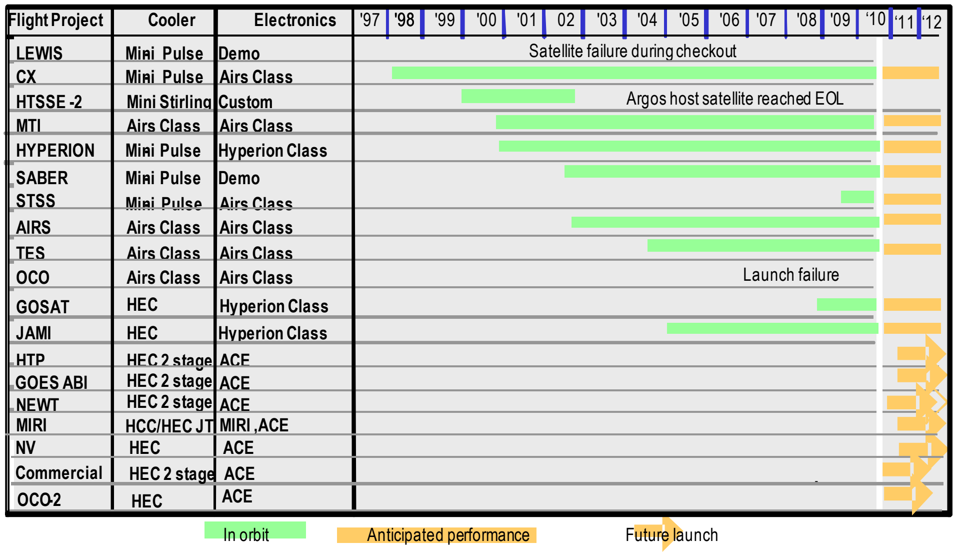

Figure 1. NGAS Cooler Flight History and Future

All the coolers made by NGAS are based on the principle of the Oxford Stirling flexure bearing technology[3] that results in zero wear because the flexures maintain a very stiff non-contacting gas bearing between a moving piston and cylinder. Following the launch of a single miniature Stirling cooler, all NGAS cryocoolers have been pulse tube coolers that use Oxford type flexure bearing moving coil compressors. They differ from the earlier Stirling technology in that the Stirling cooler cold head containing moving parts with small clearances across a large temperature gradient has been replaced by the completely passive no moving part pulse tube cold head.

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Figure 1 shows both the flight history and the planned future flights of NGAS coolers as of December 2010. 16 NGAS vibrationally balanced pulse tube coolers are currently in orbit and all are performing nominally without failure or changed performance. This represents 16 of the 19 long life United States space flexure bearing Stirling or pulse tube coolers in orbit and all the pulse tube coolers in orbit. Beginning in 1995, NGAS together with Oxford University developed a new, very low mass, high performance compressor whose mass per unit capacity is approximately ¼ that of the previous technology. This design has been scaled over an order of magnitude in capacity and size, including the compressor in the smallest 900 gm crycooler. Evolution of the cryocooler drive electronics with more than 28 flight electronics units delivered has paralleled that of the cryocoolers with current generation electronics in 3 power capacities and corresponding sizes and the fourth miniature size under development. The current generation of coolers and electronics and their capacities are illustrated in Figure 2 with the cooler capacities and the ultimate low temperature that can be reached determined by the compressor capacity and the number of cold head temperature stages. As an example, the high capacity cryocooler (HCC) labeled #1 in Figure 2 has been operated either as a one stage cooler with 10’s of watt cooling capacity, a 2 stage cooler for cooling large long wave ir focal planes and cold optics[4,5], a 3 stage 10K cooler for cooling Si:As long wave focal planes and cold optics[6] or for zero boiloff cooling of large space propellant tanks. This same 3 stage cooler will fly as the precooler for a 6K Joule Thomson cooler[7] for the James Webb Space Telescope (JWST) Mid Infra Red Instrument (MIRI). The 6K stage Joule Thomson (JT) driven by the TRL9 HEC compressor/circulator cools the instrument focal plane at a distance of 18 meters from the precooler. The input power is autonomously controlled by the cooler drive electronics[8] to maintain the commanded temperature while the low self-induced vibration of the vibrationally balanced compressor is further reduced autonomously with a feedback system.

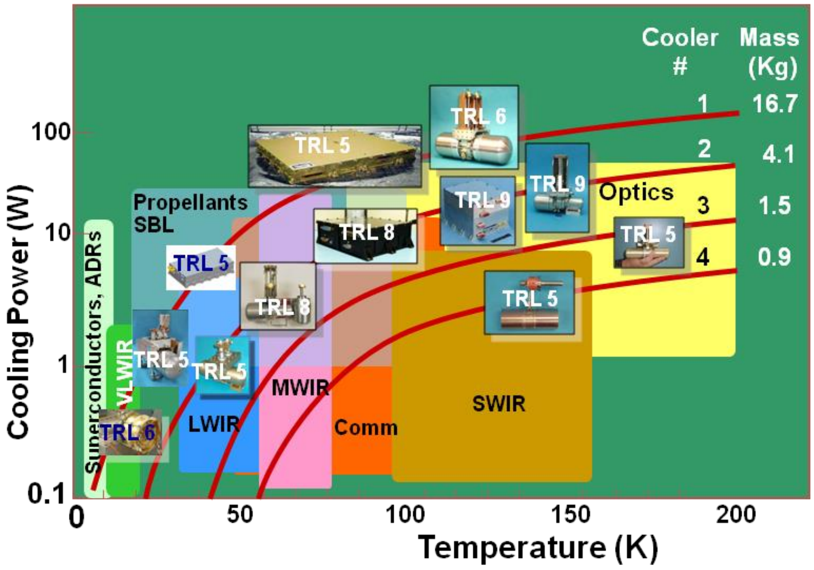


Figure 2. NGAS Cryocooler and Electronics Products

II. Pulse Tube Micro-cooler

The 900 gram pulse tube micro-cooler[9] shown in Figure 3 incorporates a vibrationally balanced compressor scaled from the TRL 9 HEC[10] compressor and a split configuration coaxial cold head. The space cooler was designed for dual space and tactical applications. Its split cold head is designed either to be bolted to a cold strap as is typically done for space coolers or to be integrated into a dewar in an integrated detector cooler assembly (IDCA) as is typically done in tactical instruments. Its 70 gram tactical electronics is also shown in Figure 3A. It can be operated in space with the space qualified 3.8 kg radiation hardened HEC electronics[8] that was designed for the larger (5x) capacity

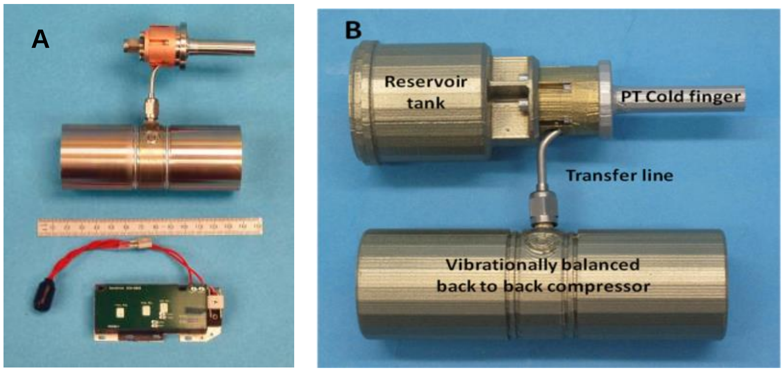


Figure 3. Micro-cooler A. *With tactical electronics* **B.** *Space configuration*

HEC cooler or with the smaller 250 gm space electronics now under development. The split mechanical cooler refrigerates via the cold block, rejecting heat at both the centerplate of the compressor and at the cold head mounting interface. Inside the compressor, flexure springs support the moving-coil linear motor that synchronously drives the opposed balanced pistons to minimize the vibration output. The flexure springs maintain alignment for the attached non-contacting pistons. The opposed pistons oscillate and produce a sinusoidal pressure wave and a phase shifted sinusoidal mass flow into the pulse tube cold head. The very small clearance between the cylinder and the piston that seals the compression space is maintained by the flexure springs so that the piston and cylinder never touch. The two vibrationally balanced opposed compressor halves operate at the resonant frequency in the 100Hz range. The pulse tube cold head is connected via a transfer line that can be customized for integration into a payload. The coaxial cold head components include the mounting flange, regenerator, cold block, pulse tube, and their tuning element of inertance and compliant reservoir tank. The internal wiring in the compressor is designed to have very low outgassing properties after the cooler is baked and hermetically sealed. All cooler drive power wiring exits the centerplate through a ceramic-insulated hermetic feedthrough connector designed to maintain the imtenal pressure for decades. Typically a platinum resistance thermometer (PRT) on the cold block measures the cooling temperature. If required, an accelerometer can be mounted on the compressor so that together with the signal conditioning electronics, the accelerometer provides a feedback signal to the vibration control algorithm in the drive electronics.

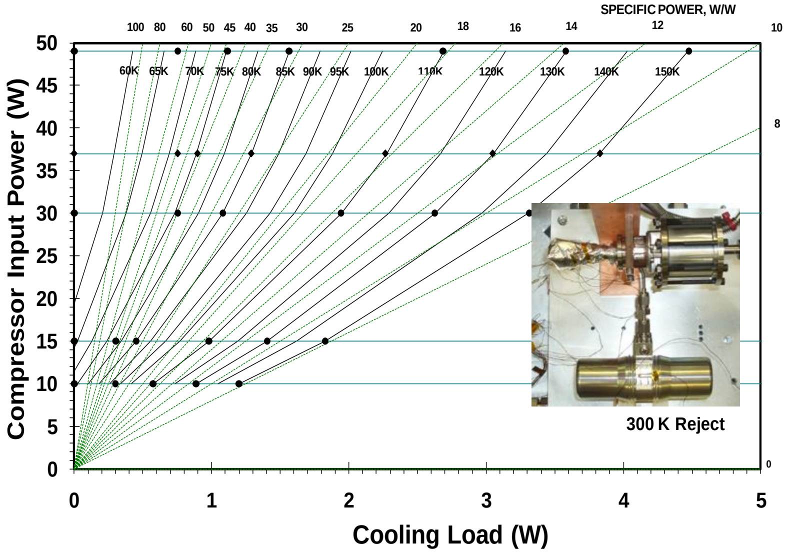


Figure 4. Micro-cooler performance

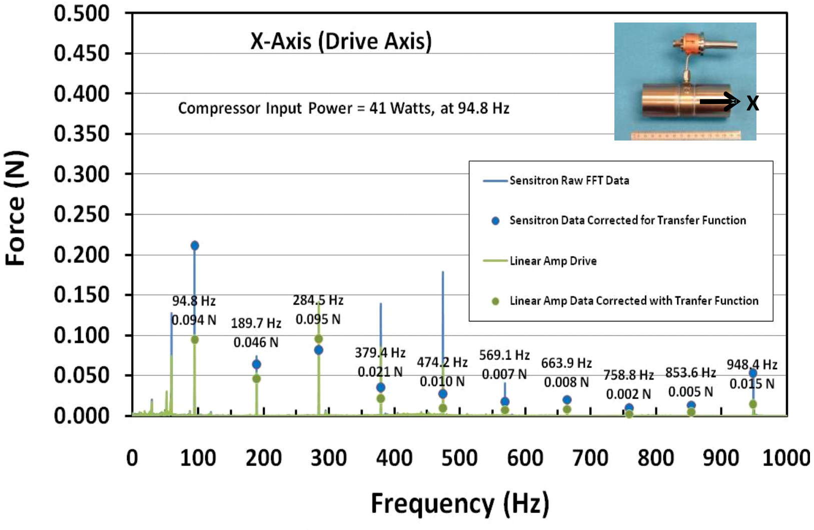


Figure 5. Micro-cooler self induced vibration along compressor drive axis

Current cooler performance for the space cooler version is shown in Figure 4. The as tested space cooler shown in Figure 4 is identical to the flight configuration shown in Figure 3B except that the reservoir tank end cap is sealed with a bolted flange rather than its welded flight configuration. The tests were conducted in a thermal vacuum chamber with varying input powers and reject temperatures. The measurements that were taken over a range of input powers shown by the data points of Figure 4 are presented with lines of constant input power measured between 10W and 49W and interpolated lines of constant cooling temperature overlaid over lines of constant specific power (input power/cooling power). The microcooler cooling capacity at 150K ranges from 1W to 4.5W as the compressor input power changes from 10W to 49W. Operating the cooler at lower reject temperature will result in more cooling for the same input power.

The exported vibration signature of the micro cooler without active vibration control has been characterized with the cooler being driven both with the tactical electronics and by laboratory electronics containing an output linear drive amplifier. Typical space flight electronics output without additional vibration control is similar to the linear electronics measurement. Figure 5 shows the typical output vibration along the axis of the moving pistons, the only moving parts, as measured with force transducers at the mounting surface of the cooler. Note that except for the facility background noise peaks at 60Hz and below, the vibration output occurs only at the fundamental drive frequency and its harmonics. The graph shows both the raw data and the actual output after it is corrected for the facility transfer function for both the tactical electronics and the linear electronics. Even without feedback and the use of vibration control algorithms in the drive electronics the vibration output is less than 100mN, i.e at levels that can't be detected by touch. As shown later for the larger HEC cooler, when feedback to the drive signal is used the vibration levels can be driven down to below 5mN. The exported vibration along the three axes for the first 5 harmonics of the 95Hz fundamental frequency out to 500Hz are shown in Figure 6 as a function of compressor input power for the linear drive amplifier case. Note that at all powers the exported vibration is <100mN for all harmonics in the compressor drive direction.

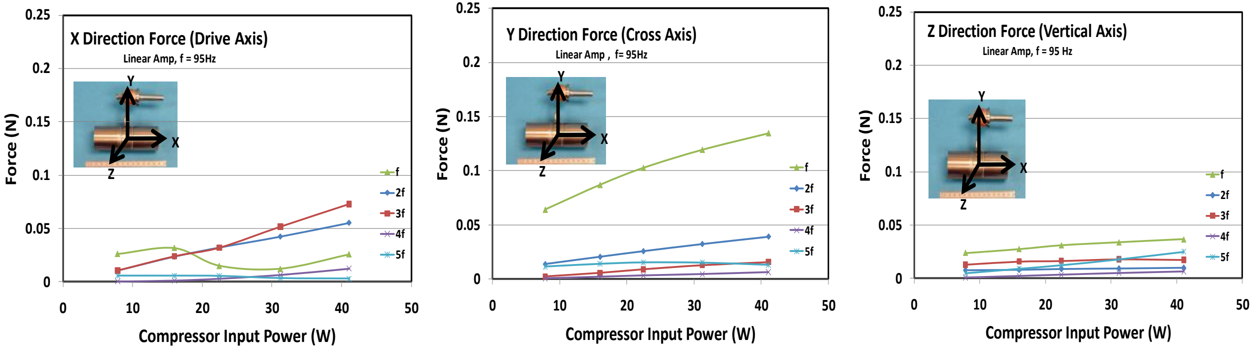


Figure 6. Micro-cooler self induced vibration as function of input power

III. High Efficiency Cooler (HEC): > 35K Single and 2 stage coolers

One and 2 stage versions of the TRL 9 HEC cooler family[10] are shown in multiple variants in Figure 7 together with the matched CCE[8]. They vary only in the customized cold heads that are optimized for the application. The compressor and flight electronics are common to all the coolers. They are the most mature of the current NGAS coolers and have been delivered for flight on 6 programs (Figure 1) and are currently being manufactured for 3 other programs. HEC coolers are operating in orbit on the Japanese Advanced Meteorological Imager (JAMI) (>5 years to date) and Greenhouse Gases Observing Satellite/Thermal and near IR sensor for carbon observation (GOSAT/TANSO) payloads and an additional 17 flight

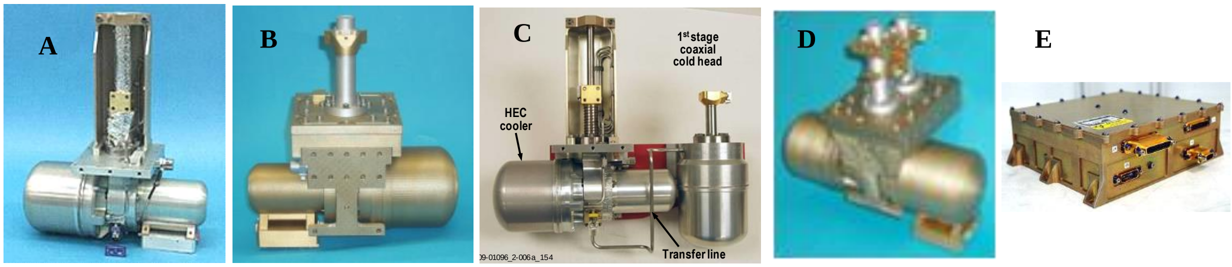


Figure 7. HEC Single and dual temperature coolers. A: *HEC single stage cooler with linear cold head.* **B:** *HEC single stage cooler with coaxial cold head.* **C:** *HEC 2 stage cooler (ABI cooler) with split coaxial cold head.* **D:** *HEC 2 stage cooler with integral coaxial cold heads.* **E:** *Cryocooler control electronics*

units (either one or 2 stage) have been delivered. The single stage integral HEC pulse tube cooler with linear cold head was originally designed to efficiently provide 10W of cooling at 95K as shown in the performance map (Figure 8A). The flight cooler has also been retuned and delivered to provide cooling at lower temperatures near 40K as shown in Figure 8B. Maximum input power to the HEC mechanical cooler is limited by the maximum 180 W output power of its TRL8 matching drive electronics. Adding a second coaxial cold head that is pneumatically connected to the HEC compressor through an approximately 0.5 meter transfer line has provided 2 temperature cooling for the Hybrid test Program (HTP) Advanced Baseline Imager (ABI) [Figure 7C] and Newt payloads as shown in Figure 9.

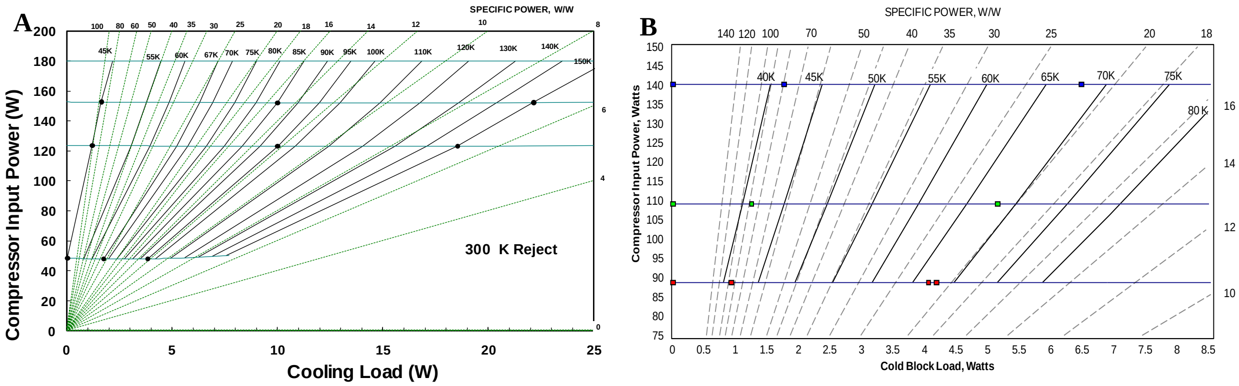


Figure 8. Performance Map for HEC linear cold head coolers. A: *Performance with cold head optimized for 95K.* **B:** *Performance with cold head optimized for temperatures below 60K*

This split configuration allowed the 1st stage cold head to be located near the device it was cooling. Although the basic components are the same, operating temperature and loads were accommodated by tuning the two cold heads with the passive inertance and transfer lines. The thermal performance of the two design variants are shown in Figures 9A and B.

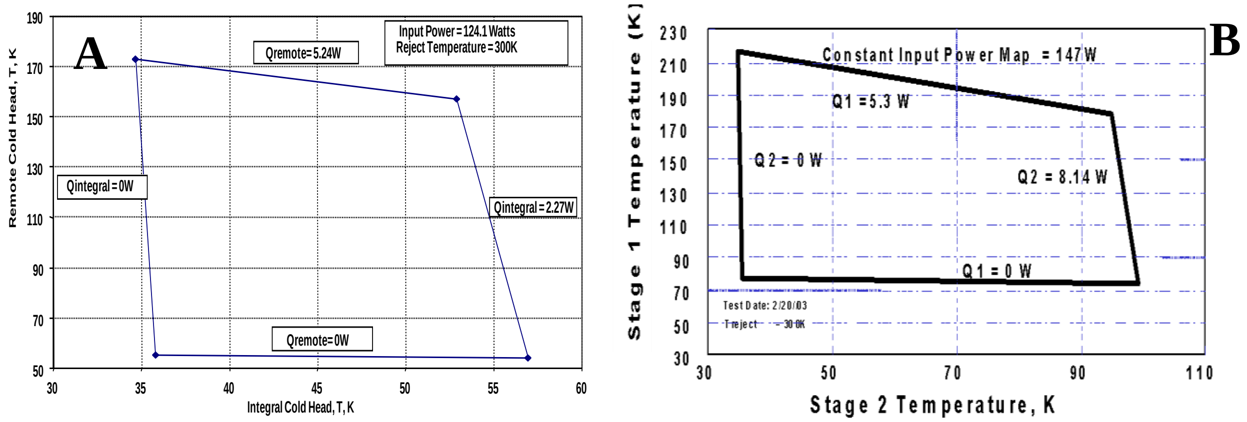


Figure 9. Performance Map of 2 stage coolers with 2nd stage remote coaxial cold head added to 1 stage HEC linear cold head cooler. *Cooler cold heads were tuned for program loads.* **A:** *ABI 2 Stage Cooler performance at Fixed 124.1W Input Power.* **B:** *HTP 2 Stage Cooler performance at fixed 147 W Input Power.*

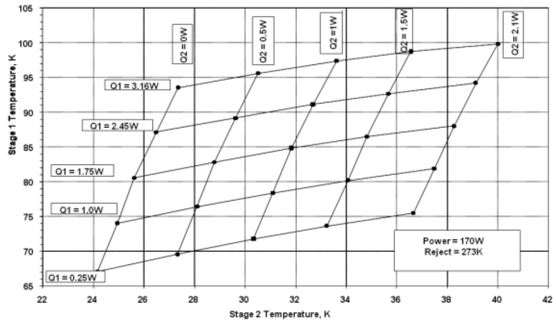
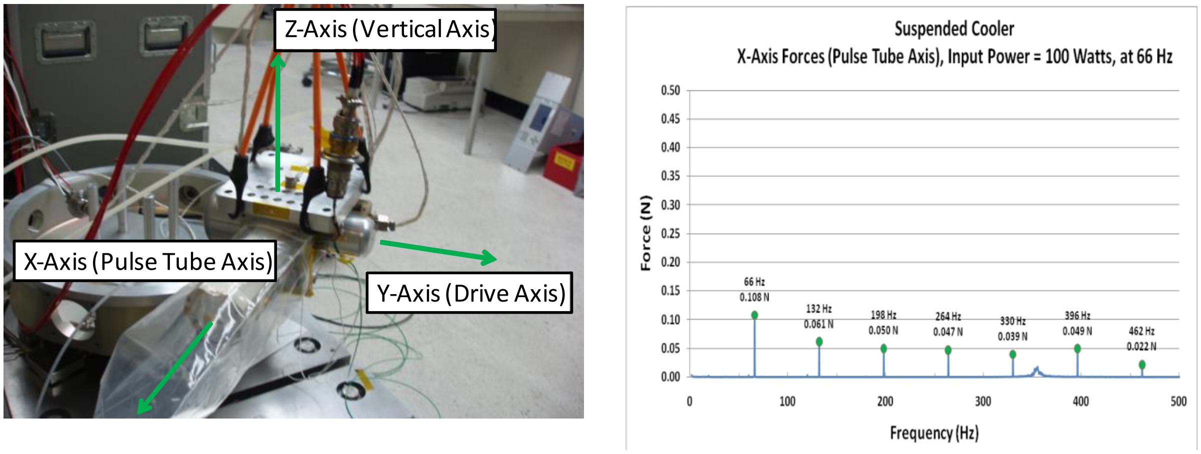


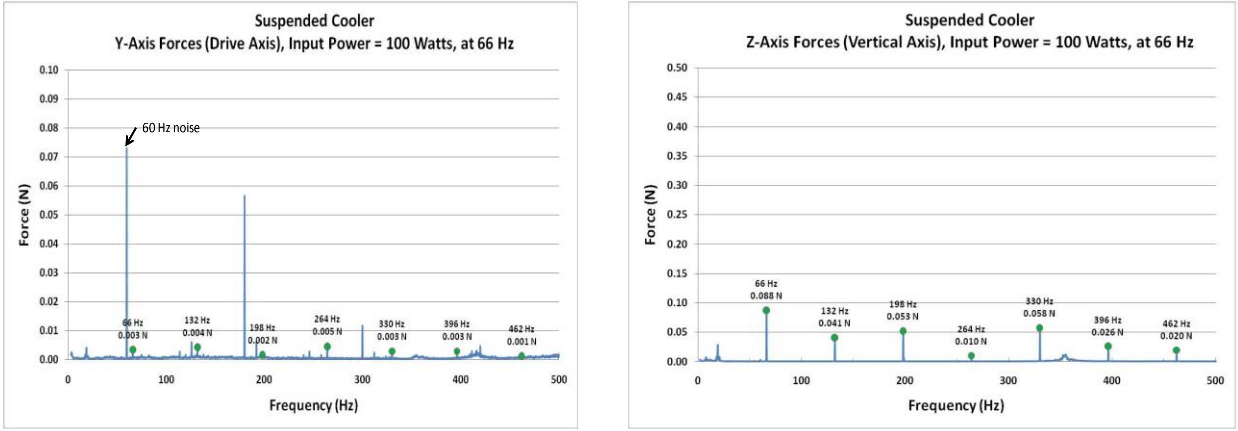
Figure 10. Performance Map for Integral Two-Stage Coaxial Pulse Tube Cooler

A 3rd variant of the 2 stage cooler replaces the 2 cold heads with a pair of integrally mounted coaxial cold heads in a parallel configuration as shown in Figure 7D. Figure 10 shows the thermal performance map at a fixed 170 W of input power for this integral two-stage co-axial pulse tube cooler base on the HEC compressor. This cooler provides usable cooling down to 35K in a light weight (<6 kg) and compact size with the flight heritage of the HEC cooler.

Since a real space payload system has a mount with some unknown compliance we measured the self induced vibration output at the 2 extreme boundary conditions of 1. the cooler suspended on bungee cords with the loop closed around the flight accelerometer and 2. when hard mounted to a 6 axis dynamometer similar to the measurements of Figures 5 and 6 . Figure 11A shows the suspended cooler and Figures 11B, 11C, and 11D show the measurements


A.

B. X-Axis Vibration Output (Pulse Tube Axis)


C. Y-axis Vibration Output (Drive Axis)

D. Z-axis Vibration Output

Figure 11. Cooler Vibration when HEC Cooler is Soft Mounted and loop is closed on flight accelerometer parallel to Y-Axis. *Soft Mounted Cooler is suspended from Bungee cords. It includes a rigid body water heat exchanger to remove heat while cooler is running.*

along the three axes when the cooler is hung by bungee cords. Note that the vibration output when controlled by feedback on the drive axis is below 10mN.

IV. High Cooling Power and Very Low Temperature Coolers

The high cooling power and very low temperature coolers are based on the use of the high capacity compressor shown as # 1 in Figure 2 and cover a wide range of cooling temperatures from 1.7K to room temperature and cooling power levels from milliwatts to >100 watts. The 2 stage High Capacity cooler (HCC) is shown in Figure 12A and its coaxial cold head variant is shown in Figure 12B. The coaxial cold head variant was used for the1st two stages of the 10K cooler shown in Figure 12C and the Mid Infra Red Instrument (MIRI) 6K cooler shown in Figure 12D. Figure 12E shows the large 720W capacity electronics. Not shown is the MIRI 360W capacity electronics. Typically cryocooler masses are <17kg. The HCC compressor can be driven at powers up to the 720 W capacity of its electronics if very large cooling powers are required. The HCC cooler of Figure 12A was originally designed to provide 2 stage cooling nominally at 35 and 85K as configured with its 2 parallel linear cold heads. The cooling performance at the two stages with input powers up to 600 W are shown in Figure 13A. This cooler is currently in life test at Air Force Research Laboratory (AFRL). The cooler can be readily retuned to shift load between stages, either in orbit or for larger range shifts by a minor cold head configuration change after manufacture. The performance of the coaxial cold head version of this cooler is shown in Figure 13B. Both versions are configured as

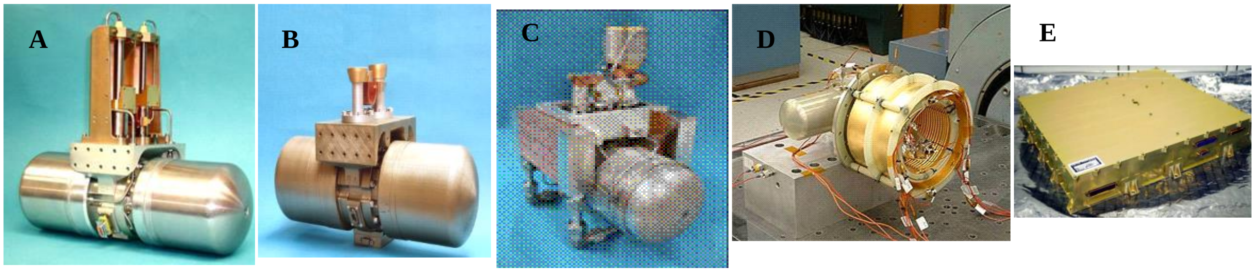


Figure 12. High capacity and low temperature coolers . A *HCC 2 stage cooler*. **B.** *HCC coaxial cold head cooler*. **C.** *3 stage 10K cooler* **D.** *MIRI 3 stage precooler with recuperators for lower temperature Joule Thomson 6K stage* **E.** *High capacity electronics*

integral coolers to ease payload integration with their single thermal and mechanical interfaces. The HCC cooler can be controlled and driven by the three variants of the cryocooler control electronics (CCE) that provide maximum output powers of 180, 360 and 720 W respectively. Choice of drive unit is made to minimize the electronics mass consistent with the maximum available input power to the electronics from the payload.

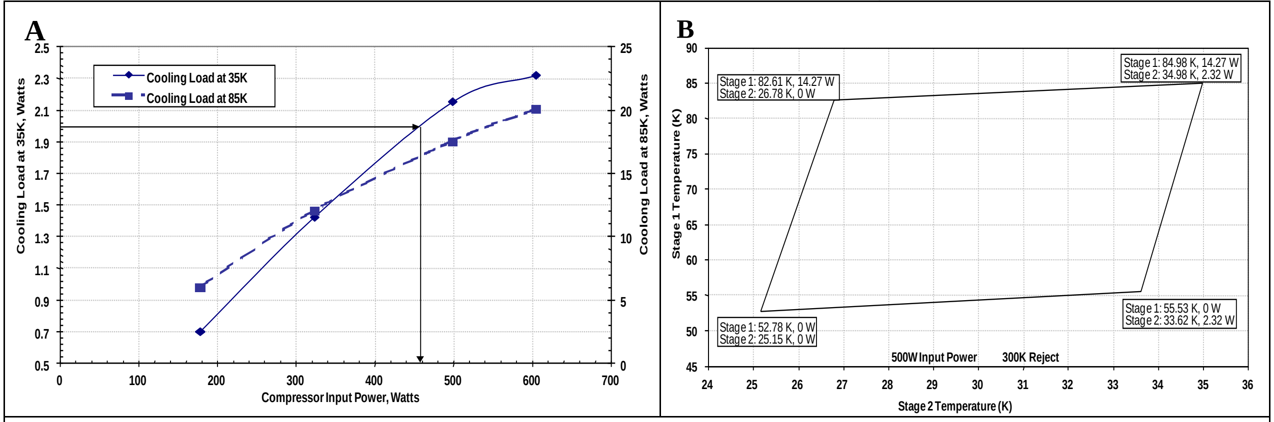


Figure 13. High Capacity 2 stage coolers. A. *Linear cold head cooler* **B.** *Coaxial cold head cooler*

The 3-stage 10K pulse tube cooler shown in Figure 12C mounted in a test fixture was designed to provide cooling at all three stages with the lowest stage operating at 10K. The first stage coaxial configuration cold head is also used to intercept heat in a parallel 2-stage serial configuration cold head. A performance map of this cooler with heat loads on the second and third stages is shown in Figure 14A with 300 W input power to the cooler. An engineering model (EM) version of this cooler was recently integrated into an Infra Red (IR) instrument and cooled its Si:As focal plane to 11K.

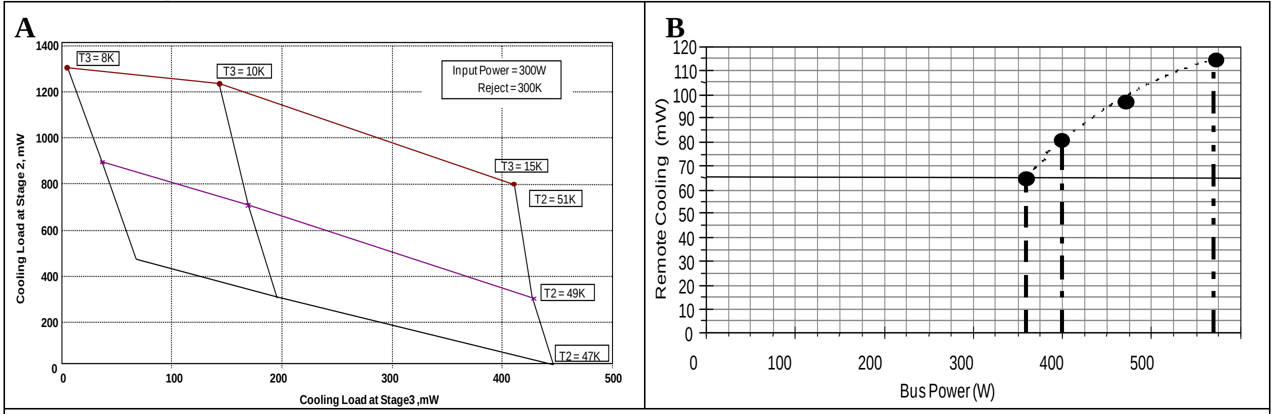


Figure 14. 3 stage Pulse tube cooler A. *10K Cooler Isotherms at 300K Reject and 300 W Input Power* **B.** *6K cooling of 4 stage hybrid pulse tube/JT cooler at a Distance of 10 meters from cooler*

The same 3 stage cooler design is used in the MIRI hybrid pulse tube/JT cooler Figure 12D as a precooler for the gas flowing in the recuperators of the fourth stage JT cooler. This approach allows the cooler to be on the spacecraft which is vibrationally isolated from the JWST telescope and instruments located many meters from the spacecraft. The 6.2K JT cooler stage is powered by a technical readiness level (TRL) 9 HEC single stage compressor and flight electronics. The measured performance of the MIRI demonstration cooler is shown in Figure 14B. The precooler also provides shield cooling at 17K at the MIRI instrument.

Conclusion

NGAS coolers cover a wide range of cooling temperatures from 1.7K to room temperature and cooling power levels from millewatts to 10's of watts. Widely varying needs are addressed with four basic compressor designs scaled from the TRL 9 HEC compressor and three cryocooler control electronic designs with power sections scaled from the TRL 8 180 W advanced cryocooler control electronics. By optimization of the pulse tube cold heads, adding cooler stages, customizing the mechanical configuration, and a very low temperature JT cooling stage with remote cooling has allowed this cooler family to address a wide range of requirements. NGAS flight coolers have demonstrated a total on orbit life of greater than 100 years with no failures or change of performance. Of these units 2 have been in continuous operation for 12 years to date.

References

1. E. Tward, CK Chan, J. Raab, R. Orsini, Miniature Long-Life Space-Qualified Pulse Tube and Stirling Cryocoolers, Cryocoolers 8: - Plenum Press, 1995
2. Gifford, W.E. and Longsworth, R.C. , Pulse Tube Refrigeration Progress, Advances in Cryogenic Engineering, Vol. 10, Plenum Press, New York, pp. 69-79
3. G. Davey, Review of the Oxford Cryocooler, Presented at the 1989 Cryogenic Engineering Conference, University of California Los Angeles, July 1989, Pages 1423-1430.
4. C. Jaco, T. Nguyen, R. Colbert, T. Pietrzak, C.K. Chan and E. Tward, High Capacity Staged Pulse Tube Cooler, Advances in Cryogenic Engineering (AIP Conference Proceedings), 49B, 1263 (2004).
5. Jaco C., Nguyen T, Tward E. "High Capacity Two-stage Coaxial Pulse Tube Cooler, Adv in Cryogenic Engineering, Vol. 53A, Amer. Institute of Physics, Melville, NY (2008), pp.530-537.
6. Nguyen, T., R. Colbert, D. Durand, C, Jaco, M. Michaelian, E. Tward , 10K Pulse Tube Cooler, Presented at the 14th International Cryocooler Conference, Annapolis, MD, June 2006, Pages 27-31.
7. D. Durand, D. Adachi, D. Harvey, C. Jaco, M. Michaelian, T. Nguyen, M. Petach, and J. Raab, "Mid InfraRed Instrument (MIRI) Cooler Subsystem Design," Cryocoolers 15, ICC Press, Boulder, CO (2009), pp 7 - 12.
8. D. Harvey, A. Danial, Thom Davis, J. Godden, M. Jackson, J. McCuskey, P. Valenzuela, Advanced Cryocooler Electronics for Space , Cryogenics , Volume 44, Issues 6-8 , June-August 2004, Pages 589-593.
9. M. Petach, M. Waterman, E. Tward and P. Bailey, Pulse Tube Microcooler for Space Applications, Presented at the 14th International Cryocooler Conference, Annapolis, MD, June 2006, Pages 89-93.
10. E. Tward, C. K. Chan, R. Colbert, C. Jaco, , T. Nguyen, R. Orsini, J. Raab , High Efficiency Cryocooler , Adv. In Cryogenic Engineering, Vol 47B, New York: Amer. Inst. of Physics, 2002, p. 1077.