Ball Klondike Cryocooler System Design, Development, Qualification and Performance

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ABSTRACT

Current and future cryogenic space payloads are pushing the limits of current space rated cryocooler systems. Industry expectations for future cryocooler systems include shorter lead time, >5x cost reduction, and higher efficiency/capacity. Ball has developed a productized, turn-key cryogenic cooling system called Klondike that meets and exceeds these expectations. The Ball Klondike Cryocooler System includes a TRL9 Low Exported Vibration Cryocooler Assembly (CCA) mated to a TRL8 Sunpower DS-30 cryocooler, TRL8 Iris Technology HP-LCCE2 Cryocooler Control Electronics (CCE), flight harnesses, cold-tip thermal strap, and standard heat rejection interface. The Klondike system successfully passed qualification and has been delivered to a government customer for a flight program of record. This paper discusses the design, development, qualification and thermodynamic and EFT (Exported Force and Torque) performance of the Klondike Cryocooler System.

INTRODUCTION

Historically aerospace cryocoolers have been designed for class A/B missions focused on high reliability (5-10 yr mission life) and high performance that has historically led to high cryocooler subsystem cost. In the past five years there has been industry emphasis on developing more cost-effective active cooling systems that push the state-of-the-art in Size, Weight and Power (SWAP) at a cost point significantly lower than heritage aerospace cryocooler systems. The driving force for lower cost active cooling systems is Proliferated LEO (PLEO) missions, smaller/compact payloads, and Class C missions with lifetimes of 1-3 years. To tackle this challenging problem, tactical cryocoolers are being adopted and qualified for space applications based on their attractive price point, small form factor and readily available industry base to supply in quantity [1, 2, 3]. Challenges with this approach include reducing the Cryocooler Control Electronics (CCE) cost by a similar amount and demonstrating a terrestrial cooler design can be successfully utilized in space applications.

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Iris HPLCCE2 Klondike CCA

Figure 1. Ball Klondike Cryocooler System that consists of Iris HPLCCE2 Cryocooler Control Electronics, High Performance CCA with Sunpower DS-30 TMU, S-link, and flight harnesses. Image blur is intentional to protect proprietary information..

For the past five years Ball has focused on developing low-cost, high capacity next generation active cooling solutions in collaboration with our partners at Sunpower Inc., CSA Moog, SDL and Iris Technology. The culmination of this development effort was completion of a government program that developed the Ball Klondike Cryocooler System – a productized, turn-key, low-cost, high performance cryogenic cooling system illustrated in Figure 1.

KLONDIKE CRYOCOOLER SYSTEM DESIGN AND DEVELOPMENT

The Ball Klondike Cryogenic System consists of the following integrated component technologies:

- Very high capacity, power and mass efficient Sunpower DS-30 cryocooler (TRL8) using a passive balancer for vibration cancelation of the displacer,
- Updated Ball Low Vibe CCA (Cryocooler Assembly) (TRL9)
- High conductance, low stiffness thermal strap from SDL/Ball (TRL8)
- Reduced form factor CCE (Cryocooler Control Electronics) from Iris Technology (TRL9)
- Complete set of flight harnesses (TRL8)

The remainder of this section discusses these various components in addition to the system level assembly.

Sunpower TMU

The Sunpower DS-30 TMU was selected based on very high thermodynamic performance, small volume, configurability with respect to performance and physical packaging, gravitational performance independence, and well-established space flight heritage of the fundamental cooler technology via the Sunpower MT/CT product lines. The DS-30 Stirling cryocooler directly leverages the Sunpower CT/GT/MT product lines but uses an opposed piston compressor in place of the heritage single piston compressor on the CT/GT/MT models. The DS-30 displacer is a free-piston Stirling design that uses a passive balancer to attenuate the displacer free-piston vibration during operation.

The Sunpower DS-30 TMU and thermodynamic performance at 77K is shown in Figure 2. Changes to the commercial design of the DS-30 for Klondike include a custom transfer line, custom conductive heat rejection interfaces developed in collaboration with Sunpower, and custom-tailored build processing for space flight in collaboration with Sunpower. In the Klondike System the DS-30 input power is limited to 240W based on the maximum output power of the Iris CCE discussed below.

Two high risk areas in adapting a tactical cryocooler, such as the DS-30, to space applications are: surviving launch/shock vibration environments and ensuring the Exported Force and Torque (EFT) is suitable or able to be attenuated to acceptable mission levels. To mitigate these risks, a loaner DS-30 TMU from Sunpower (non-flight configuration) was subjected to random vibration and EFT characterization.

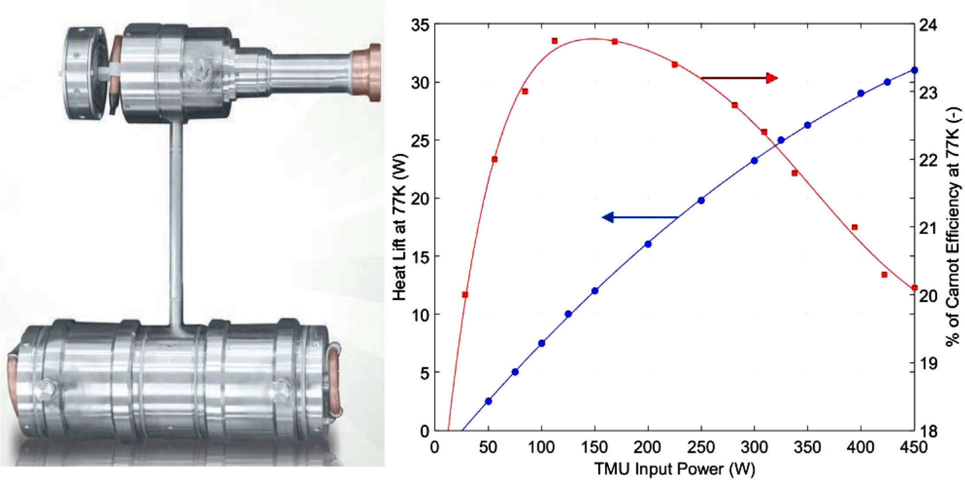
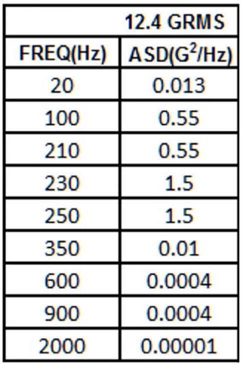


Figure 2. (Left) Sunpower DS-30 TMU and (Right) DS-30 Heat lift and Carnot efficiency as a function of input power.

The DS-30 TMU random vibration setup and PSD protoqual levels are shown in Figure 3. The PSD is a Ball derived environment from the response of the TMU interface when our launch lock base is shaken to historical PSD's for a wide range of Ball programs and is considered enveloping for future Klondike applications. During random vibe testing, response limiting was used at the cold tip due to greater excitation (higher Q) that we would realistically expect. This greater excitation was due to the cantilevered mounting arrangement of the displacer. Later testing on the CCA platform showed the gain was artificially high and that on our platform response limiting was not required. Testing was done with a heater block or S-link, both were response limited. Random vibration testing of the DS-30 was successful with no damage or performance degradation.

EFT performance of the DS-30 with the passive balancer was performed using a Ball in-house high-fidelity EFT test bed. The cooler was tested in a hard-mounted configuration using a Sunpower CCE with active cancelation for the compressor motors. The TMU was tested at multiple power levels and the EFT data presented is for a TMU input power of 250W, bounding for the Iris CCE output power limit. The frequency domain EFT results for all axes are shown in Figure 4. The magnitude of the forces and torques from the DS-30 were acceptable and compatible with our heritage CCA system.



	12.4 GRMS
FREQ(Hz)	ASD(G^2/Hz)
20	0.013
100	0.55
210	0.55
230	1.5
250	1.5
350	0.01
600	0.0004
900	0.0004
2000	0.00001

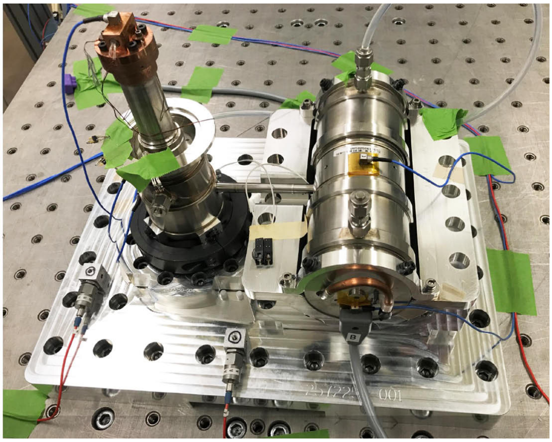


Figure 3. DS-30 random vibration (Left) PSD levels and, (Right) test setup. Note the configuration is not the flight configuration but provided a bounding case to assess performance through the CCA isolation assembly.

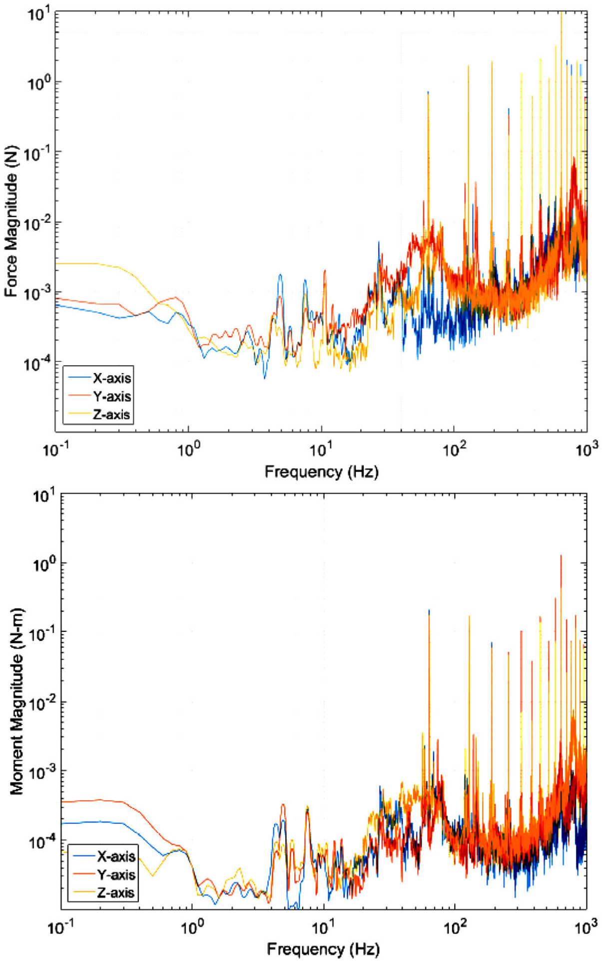


Figure 4. Hard mounted EFT performance for the DS-30 TMU. Note the configuration is not the flight configuration but provided a bounding case to assess performance through the CCA isolation assembly.

IRIS CCE

The CCE used to power the DS-30 TMU is the Iris Technology HPLCCE2 and is shown in Figure 5. The HPLCCE2 is TRL9 and capable of a maximum output power of 240W across two motor drives, active vibration cancellation for the first 5 harmonics, and possesses low mass with a small form factor. An additional key discriminator is the low entry point compared to heritage aerospace electronics and lead times are compatible with 18-24-month concept to launch missions.

Figure 5. IRIS HPLCCE2 low-cost cryocooler control electronics used in the Klondike Cryocooler System.

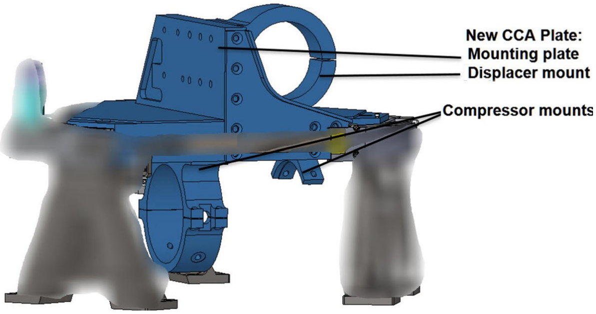


Figure 6. Ball heritage CCA updates required to mate to the DS-30 TMU. Image blur is intentional to protect proprietary information.

The Iris HPLCCE2 BOM was selectively updated for Klondike to meet or exceed NASA Mission Class C requirements. These BOM updates did not affect the form, fit or function of the CCE allowing heritage flight qualification to remain valid for Klondike.

Klondike Low Vibe Isolation Assembly

Ball Aerospace has had multiple jitter sensitive programs and applications that require very low levels of cryocooler generated EFT. In collaboration and partnership with Moog CSA (isolation component), NGAS, Ball, and Sunpower (cryocooler suppliers), and SDL (flexible link supplier), Ball has designed, built, and tested multiple Low Vibration CCAs for space and airborne applications. These CCAs significantly attenuate the already low EFT output from the TMUs approximately 50 times smaller than the original. More details of this Low Vibration CCA and its heritage performance can be found in Ref [4].

The Klondike system leverages 80% reuse of our heritage Low Vibration CCA with modifications to the center plate for interfacing to the DS-30 TMU. The CCA isolation plate retains all the heritage interfaces to the launch lock assembly and relocates the heritage standard Loop Heat Pipe (LHP) interface for thermal rejection from the TMU. The CCA plate redesign, shown in Figure 6, involved updating the CCA plate to support efficient conductive heat transport from the compressor and displacer to LHP interface and adding structural mounting features for the displacer and compressor to meet frequency requirements in the locked and unlocked states.

Klondike CCA

The Klondike CCA is the integration of the isolation assembly, DS-30 TMU, flight harnesses, and S-link. Not included is the LHP, but Ball can deliver an LHP if desired as part of the Klondike System. The delivered Klondike flight CCA is shown in Figure 7. Note that in Figure 7 the chiller

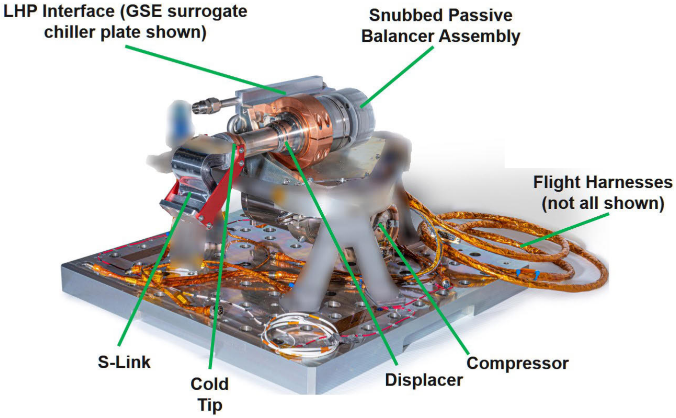
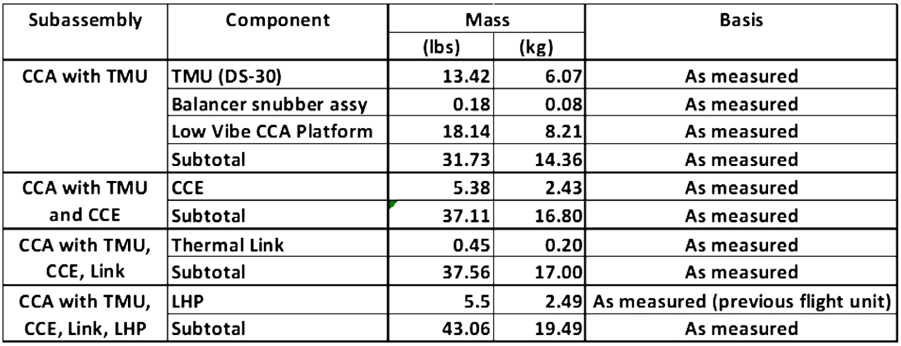


Figure 7. Ball Klondike CCA.

Table 1. Ball Klondike Cryocooler System mass allocations.



Subassembly	Component	Mass		Basis
		(lbs)	(kg)	
CCA with TMU	TMU (DS-30)	13.42	6.07	As measured
	Balancer snubber assy	0.18	0.08	As measured
	Low Vibe CCA Platform	18.14	8.21	As measured
	Subtotal	31.73	14.36	As measured
CCA with TMU and CCE	CCE	5.38	2.43	As measured
	Subtotal	37.11	16.80	As measured
CCA with TMU, CCE, Link	Thermal Link	0.45	0.20	As measured
	Subtotal	37.56	17.00	As measured
CCA with TMU, CCE, Link, LHP	LHP	5.5	2.49	As measured (previous flight unit)
	Subtotal	43.06	19.49	As measured

plate is a GSE surrogate for the LHP during testing, and the red-anodized brackets are GSE S-link supports prior to integration of the CCA with an instrument. The mass breakdown of the Klondike CCA, CCE and peripheral components is summarized in Table 1.

KLONDIKE FLIGHT QUALIFICATION

EMI/EMC Testing

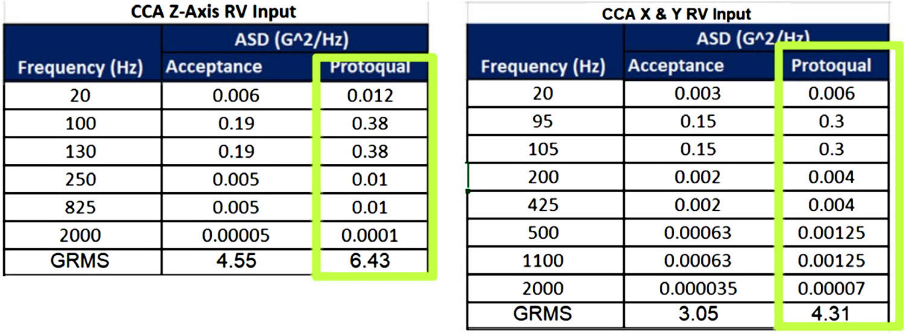
EMI/EMC performance data from a heritage flight program was used for qualification by similarity for the Iris CCE. Formal EMI/EMC testing of the CCA was not performed based on the unique EMI/EMC requirements of each program and lack of defined final cable construction, routing or lengths. Assessment of the standard EMI/EMC requirements for Klondike and compliance to these were deemed low risk by Ball and our customer. EMI/EMC testing is planned when a formal program requirement set is available.

Random Vibration Testing

Iris CCE random vibration testing was performed to acceptance levels based on heritage flight program PSD levels that were deemed bounding for present and future Klondike applications. Acceptance vibe levels were performed on the delivered flight unit as previous flight units were subjected to qualification level random vibration.

The DS-30 TMU PSD protoqual levels are shown in Table 2, while the random vibration test setup is shown in Figure 8. The PSD levels are a Ball derived environment from the response of the TMU interface when our launch lock base is shaken to historical PSD's for a wide range of Ball programs and is considered enveloping for future Klondike applications. During random vibe testing of the CCA, response limiting was not required in contrast to the previously discussed hard mount vibe test of the DS-30.

Table 2. Protoqual PSD levels used for random vibration testing.



CCA Z-Axis RV Input

Frequency (Hz)	ASD (G^2/Hz) Acceptance	Protoqual
20	0.006	0.012
100	0.19	0.38
130	0.19	0.38
250	0.005	0.01
825	0.005	0.01
2000	0.00005	0.0001
GRMS	4.55	6.43

CCA X & Y RV Input

Frequency (Hz)	ASD (G^2/Hz) Acceptance	Protoqual
20	0.003	0.006
95	0.15	0.3
105	0.15	0.3
200	0.002	0.004
425	0.002	0.004
500	0.00063	0.00125
1100	0.00063	0.00125
2000	0.000035	0.00007
GRMS	3.05	4.31

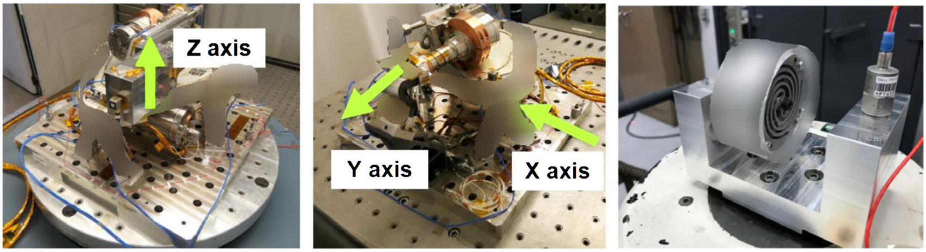


Figure 8. Klondike CCA random vibration test setup and loading axes; Right is Snubber and passive balancer assembly in random vibration testing.

During random vibration testing, the passive balancer attached to the displacer failed due to resonant excitation. The failed balancer was removed from the CCA and the qualification process was completed without further issues. Validation of this approach was performed through examination of the sine sweep with and without the passive balancer installed. This examination showed there was no response change of the overall CCA, and that was supported by the very small mass participation of the balancer relative to the overall CCA.

Investigation of the test video showed significant lateral and axial excitation of the passive balancer that led to failure of two spiral flexure arms in the passive balancer. To prevent future over-excitation and failure, a novel snubber design was rapidly developed and tested to verify performance. Testing the snubber and passive balancer assembly was performed separate from the Klondike CCA; see Figure 8. The PSD for the stand-alone vibration test of the passive balancer and snubber assembly were derived from a control accel located at this location on the CCA during initial CCA random vibration testing.

Subsequent testing of the passive balancer snubber assembly was performed without issues. The design of the snubber was validated and successfully limited the translational and rotational motion that led to failure of the initial passive balancer. Post-test inspection revealed light marks where the balancer contacted the snubber during random vibe but no particle generation was detected. Addition of the snubber also had no discernible impact on the EFT performance of the Klondike system.

TVAC Testing

CCE TVAC qualification was performed on heritage programs, and workmanship thermal cycling was performed at the box level for Klondike. The heritage launch lock components have been previously qualified and were not tested further. The updated CCA plate and TMU heat rejection I/F were thermal cycled to the TVAC profile shown in Figures 9 and 10. Post TVAC testing showed no performance degradation or issues with operation of the CCA or TMU.

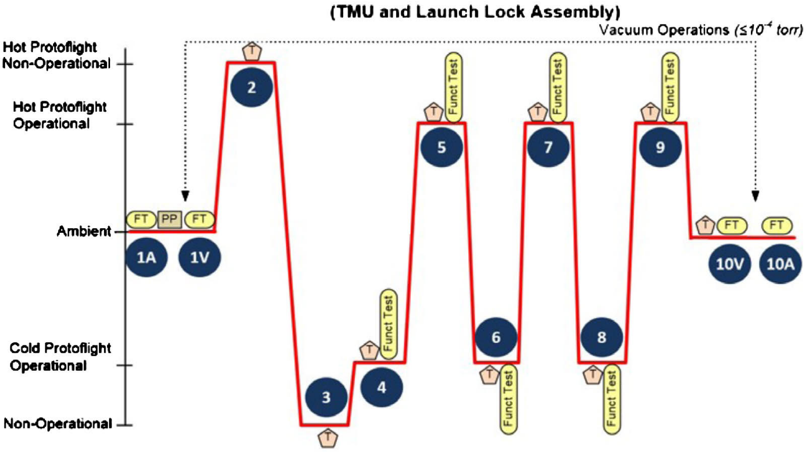


Figure 9. Klondike CCA Thermal cycle profile.

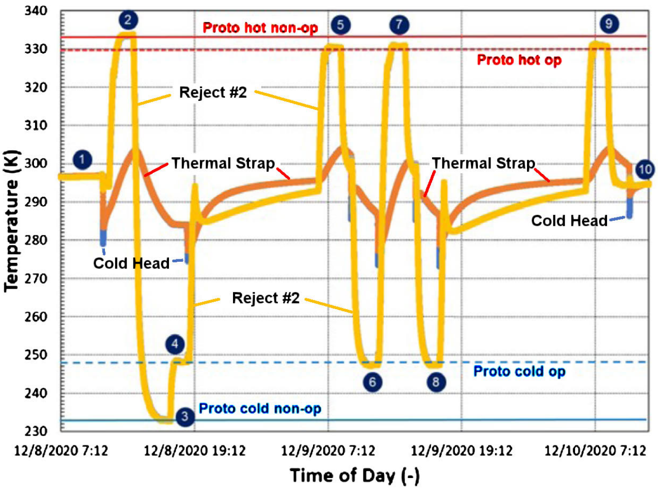


Figure 10. TVAC temperatures.

KLONDIKE SYSTEM LEVEL PERFORMANCE AND RELIABILITY

The Klondike Cryocooler system thermodynamic performance was characterized over a wide range of permutations to understand the performance envelope. Cooling performance, shown in Figure 11, was characterized as a function of rejection temperature, TMU input power, cold strap I/F temperature (hardware I/F), and cold tip temperature.

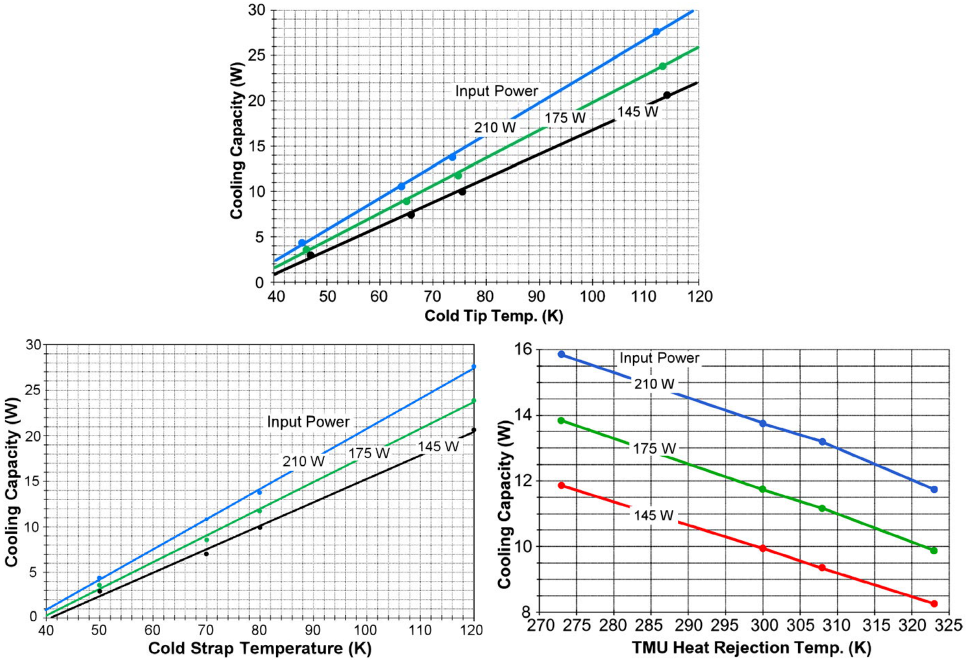


Figure 11. Klondike System performance: (Top & Left) Heat lift as a function of cold strap and cold tip temperature and TMU input power with 300 K heat rejection temperature; (Right) sensitivity of Heat lift at 80 K cold tip to heat rejection temperature as a function of TMU input power.

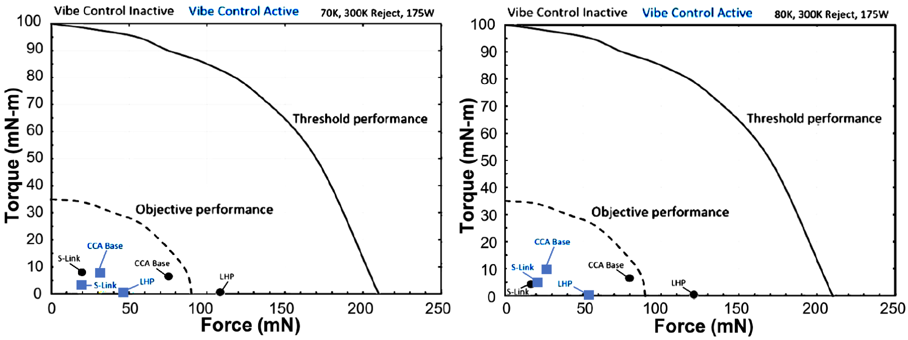


Figure 12. Klondike EFT performance at the mechanical interfaces to the system for 70K and 80K cold strap temperatures, 175W TMU input power, and with CCE vibration control Inactive (round black points) and Active (square blue points). These data represent the largest EFT values in any of the three axes across the first five harmonics of the drive frequency.

The only performance issue identified during the test was lower system level thermodynamic efficiency compared to our initial predictions. This manifested as a low CCE conversion efficiency attributed to poor impedance matching between the DS-30 TMU and the Iris CCE. Originally the Iris CCE was designed to work with a different tactical cryocooler that had an impedance that was 4x higher. Future Iris CCE's for Klondike will be impedance matched to the DS-30 dynamic motor impedance range resulting in increased thermodynamic efficiency for the Klondike Cryocooler System.

EFT testing of the Klondike system was performed at Ball using high-fidelity EFT test facilities. EFT data were extracted for the mechanical interfaces of the Klondike System: LHP interface, base interface, and S-link interface. Isolating these contributions included a combination of scaling heritage data for the LHP path and using different test setups for isolation of the S-link path. A subset of EFT results is shown in Figure 12**.** The data in Figure 12 represents the largest force or torque value for any axis across the first five harmonics for each noted mechanical interface.

Observation of the EFT data in Figure 12 shows excellent performance across the three mechanical interfaces of the Klondike CCA with CCE active cancellation inactive. As the LHP contribution is scaled based on heritage test data, we feel these EFT data are overly conservative and bound the EFT expected for a typical routing. The active cancellation algorithm in the Iris HPLCCE2 works very well and drove all interface maximum exported forces to <50mN and maximum exported torques to <10mN-m.

Reliability for the Klondike System was developed through Ball analysis of the Iris CCE proprietary reliability analysis, mechanical reliability calculations for the Low Vibe Isolation Assembly that have been delivered on heritage programs, and lifetest data for the Sunpower TMU. It should be noted that use of cooler life test data versus analytical predictions for the TMU provides a more valuable and realistic reliability calculation. The Klondike Cryocooler System reliability values are summarized in Table 3. Note the reliability number increases daily as more life test data

Table 3. Ball Klondike Cryocooler System reliability.

Component	Reliability		Falure rate (per Mhrs)	Basis
	Lifetime (years)			
	3	5		
Cooler TMU	0.9734	0.9561	1.0254	Life test hours
CCE	0.9868	0.9781	0.5047	MIL-HDBK-217F parts analysis
CCA	0.9976	0.9960	0.0908	MIL-HDBK-217F single string parts
			0.1910	MIL-HDBK-217F redund parts
Total	0.9583	0.9314	1.6219	Serial summation
Total 2:1 Redundancy	0.9991	0.9976		2:1 redundancy

are accumulated. The reliability data shown in Table 3 illustrate that the cumulative system-level reliability is compatible with all Class C missions and could be argued as being sufficient for Class B missions with a redundant approach.

CONCLUSIONS

The Ball Klondike product represents a leap forward in active cooling technology available to the space community. Klondike is geared toward and directly enables low-cost missions while preserving or exceeding the thermodynamic performance of larger and more costly heritage aerospace cooling systems. The Ball Klondike cryocooler system has successfully passed qualification and has been delivered to a government customer for a flight program of record.

Development work is underway on a second product line called Kodiak. Kodiak upgrades the Klondike system to support active cancelation of the compressor motors and the displacer, enables the full input power of the DS-30 (480W) and resulting heat lift, and optimizes performance for specific cooling ranges of interest.

ACKNOWLEDGMENT

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