Raytheon Low Temperature RSP2 Cryocooler Performance

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ABSTRACT

The Raytheon Cryocooler Product Line has developed a Low Temperature Stirling / Pulse Tube Hybrid 2-Stage cryocooler (LT-RSP2) capable of providing heat lift at 55K and 10K simultaneously. The LT-RSP2 cryocooler is the latest step in the evolution of the RSP2 cryocooler product line with a compressor and expander architecture similar to the Raytheon Stirling one stage cryocooler (RS1), currently in operation on the Space Tracking and Surveillance System (STSS). The main difference between the RS1 and RSP2 cryocooler architectures is the addition of a coaxial pulse tube as the second stage. This paper reports on the performance characterization testing and planned activities.

INTRODUCTION

The development of practical low temperature (sub-12K) closed-cycle cryogenic coolers is being actively pursued by Raytheon Space and Airborne Systems due to the beneficial detector chemistries that are enabled by such a system. Si:As focal planes offer exceptional performance for LWIR astronomy and earth sensing applications, however cryogenic cooling to temperatures below 12K is required for operation. Existing, state of the art space and airborne cryocooler systems are generally incapable of providing cooling at cryogenic temperatures below ~12 Kelvin, and stored-cryogen systems have typically been employed instead. The amount of cryogen required is considerable, and can easily exceed the mass and volume of the instrument. Launch mass and volume limitations thus provide severe constraints on mission lifetime. Additionally, logistics of handling large amounts of cryogen add to costs during assembly, integration, test and deployment. A closed loop cryogenic solution would therefore offer not only smaller mass and volume, but longer mission lifetime and reduced logistics costs.

BACKGROUND

The kernel of the ongoing research is the Raytheon Stirling / pulse tube two-stage (RSP2) cryocooler architecture[1,2], which in the past has been primarily optimized for operation at higher temperatures such as 110K / 58K and 85K / 35K (note: xx K / yy K is shorthand for xx K Stirling first stage temperature and yy K pulse tube second stage temperature). Several RSP2 cryocoolers have been designed and extensively tested, most notably the Medium Capacity (MC-RSP2) and High Capacity (HC-RSP2) versions. Table 1 shows the capability of several RSP2 cryocoolers. The LT-RSP2 expander module shares many mechanical design features with the existing and well-

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Table 1. Performance specifications for several RSP2 cryocoolers

Parameter	High Capacity RSP2 Performance	Meduim Capacity RSP2 Performance Spec	Low Temperature RSP2 Performance Spec
Typical Operating Points	16.1 W @ 85 K 2.6 W @ 35 K	7.4W @ 110K 2.7W @ 58K	4.5W @ 55K 0.25W @ 10K
Power	530W	200W	440W
Mass	20Kg	11Kg	27Kg

understood RSP2 cryocoolers, however the cold head portion has been optimized to efficiently produce refrigeration at first and second stage temperatures of ~55 K and ~10 K, respectively.

The High Capacity Raytheon Stirling / Pulse Tube Hybrid 2-Stage cryocooler (HC-RSP2) was originally developed for AFRL to provide simultaneous cooling at temperatures of 85 K and 35 K. During testing performed in 2008 it was demonstrated that this stock-configuration cryocooler is capable of providing significant amounts of heat lift at 2nd stage temperatures as low as 12K, and modeling indicated that minor changes to the 2nd stage inertance tube / surge volume setup could yield improved performance. These changes were implemented and the cooler was successfully retested, producing >350 mW of heat lift at 12K. HC-RSP2 performance test results of both the stock and the low temperature optimized configuration are shown in Table 2. Figure 1 shows the surge volume and inertance tube modifications that were made prior to low temperature testing. Two noteworthy pieces of information were gained in the course of the modified HC-RSP2 testing. First, a significant amount of confidence was gained in the ability of the system thermodynamic model to accurately predict performance at temperatures below 15K. The second piece of information that was gained was the ability of a two-stage RSP2 type cold head to operate efficiently at low temperatures using existing regenerator technology.

Table 2. HC-RSP2 low temperature test data

Cooler Configuration:	Units	Stock HC-RSP2	HC-RSP2 with 12K-Optimized Surge Volume / Inertance Tube				
Test Data / Model:		Test	Model:	Test	Test	Test	Test
Expander Housing Temperature:	K	300	296	296	296	296	295
1st Stage Temperature:	K	65.5	65	65	65	65	65
1st Stage Heat Lift:	W	1.11	1.00	1.00	0.93	0.98	0.96
2nd Stage Temperature:	K	12.0	12.0	12.0	11.4	10.5	12.0
2nd Stage Heat Lift:	W	0.22	0.41	0.38	0.23	0.00	0.29
Compressor Input Power:	W	566	551	551	552	555	505

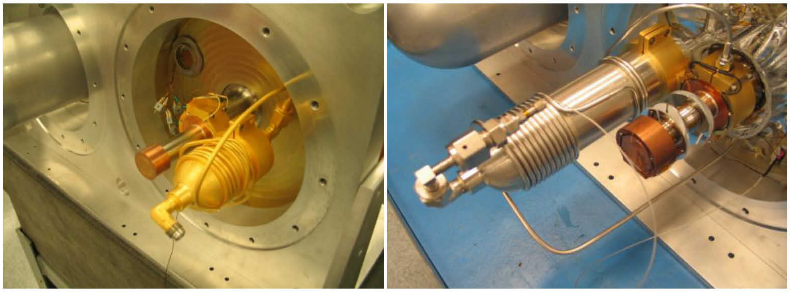

Figure 1. Stock HC-RSP2 cold head configuration (left) and the low temperature optimized version (right). The only change being the inertance tube length and surge volume size; same Stirling / pulse tube cold finger.

A comprehensive redesign of the system has been performed, the result of which is a robust 2-stage cryocooler system that is intended to efficiently produce relatively large amounts of cooling at 2nd stage temperatures <12 K. The Low Temperature RSP2 (LT-RSP2) has been assembled and characterized. Additionally, it has been successfully integrated and tested in a spectrometer.

LT-RSP2 DESIGN DETAILS

Following the encouraging results of HC-RSP2 low temperature testing in 2008, internal research and development funding was awarded in 2009 for the purpose of designing, fabricating and testing a fully-optimized Low Temperature RSP2 cryocooler (LT-RSP2). The LT-RSP2 architecture draws heavily from the HC-RSP2 cooler and several areas for optimization at lower temperature were identified and design improvements were implemented.

Figure 2 contains solid model images of the HC-RSP2 and LT-RSP2 compressor modules with the module masses indicated. The LT-RSP2 carries over several features from the legacy compressor design, including the effective heat rejection system and the inclusion of piston position sensors. As with the previous design, the new compressor includes secondary motor coils that allow for extremely high-fidelity vibration cancellation forces to be injected into the motor despite the high-power nature of the system. Typical of most long-life linear cryocoolers, the LT-RSP2 compressor contains dual-opposed, flexure-borne moving mechanisms in order to minimize vibration and ensure robustness. Though significant similarity exists between the two compressors, the LT-RSP2 version does incorporate an advanced internal architecture that reduces parts count and increases motor strength.

The LT-RSP2 expander module shown in Fig. 2 is essentially a heavily optimized version of the HC-RSP2 expander (also pictured). The warm-end internal mechanical and motor designs are largely unchanged, as no architectural changes were required in order to support the cold head. The heat rejection portions of the LT-RSP2 expander housing have been enlarged in order to accommodate significantly larger bolted interfaces to which heat pipes or thermal straps can be directly attached. The gas flow paths within the module's warm end have been redesigned in order to promote the effective transfer of heat from the working gas to the housing; these internal modifications are based on the results of computational fluid dynamics modeling efforts performed during the analysis of previous-generation machines.

Though the LT-RSP2 cold head geometries have been optimized in order to maximize efficiency at first and second stage temperatures of 50-60K and 10-15K, the cold end of the LT-RSP2

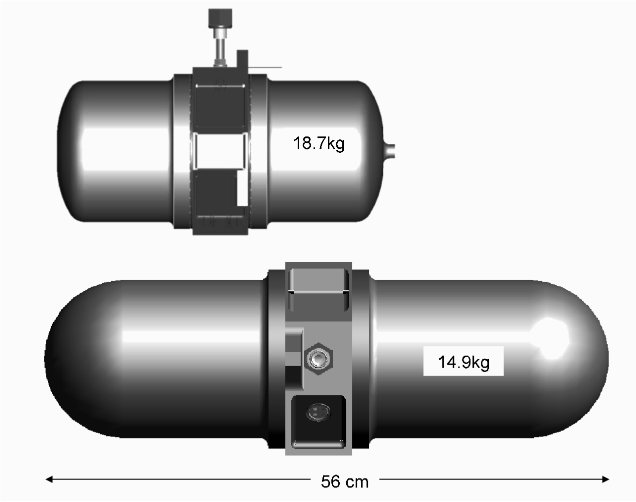

Figure 2. Comparison of HC-RSP2 (bottom) and LT-RSP2 (top) compressor modules. Scale same for both images.

expander is architecturally identical to that of the HC-RSP2 (see Fig. 3). The first stage is an actively-driven Stirling system while the second stage consists of a concentric pulse tube arrangement employing a cryogenic inertance tube / surge volume phase shifter. For reasons of risk reduction the regenerator types, materials and build processes have been left unchanged from those of the HC-RSP2. The material used to construct the pressure vessel thin-walled tubes has been changed to a lower thermal conductivity alloy in order to reduce the parasitic load of the second stage, and wall thicknesses have been appropriately modified to ensure a high first mode frequency (>300 Hz) and significant safety margin (1.25) with respect to proof-pressure testing. Figure 4 shows the assembled LT-RSP2 cryocooler ready for characterization testing.

LT-RSP2 CHARACTERIZATION TESTING

Initial characterization testing of the LT-RSP2 cryocooler began in January of 2011 using a test surge volume and inertance tube. A surge volume and inertance tube optimized for the LT-RSP2 machine and capable of being integrated into a space and airborne sensor was constructed in late 2011 and is shown integrated onto the 1st stage of the expander in Fig. 5.

During no load temperature testing it was observed that the minimum temperature achieved was 38.7K on the 1st stage and 5.9K on the 2nd stage for an input power of 600W as can be seen in Table 3.

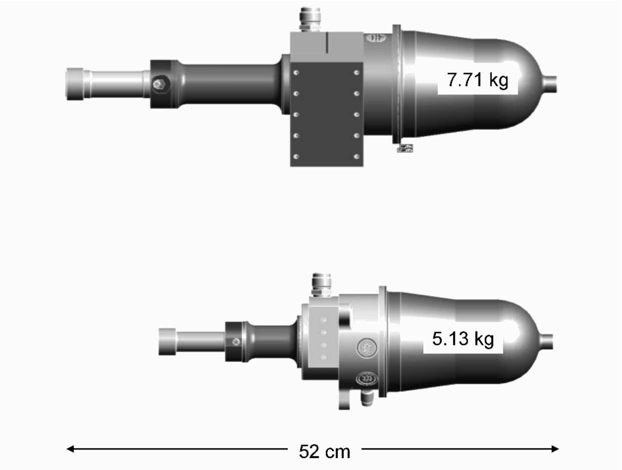

Figure 3. Comparison of HC-RSP2 (bottom) and LT-RSP2 (top) expander modules. Scale same for both images.

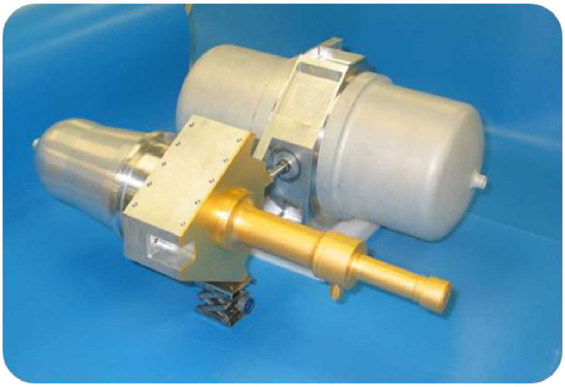

Figure 4. LT-RSP2 ready for initial characterization testing.

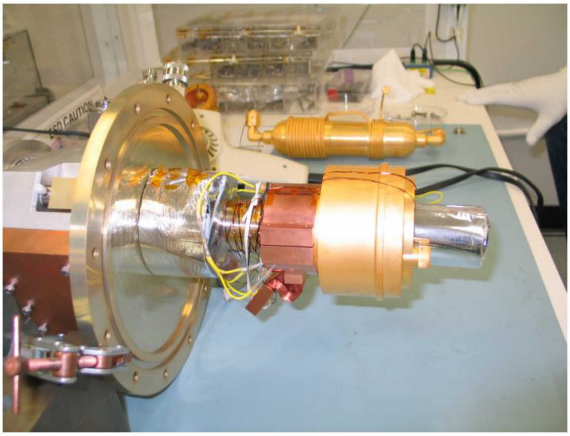

Figure 5. Flight surge volume and inertance tube integrated onto the LT-RSP2 expander. The test surge volume and inertance tube is shown in the background.

The LT-RSP2 has been designed for an instrument that requires a 1st stage temperature of 55K and a 2nd stage temperature of 10K at the cryocooler interface. Characterization testing has shown that at a nominal phase of 75 degrees the heat lift at 55K is 3.65W and at 10K it is 250mW for an input power of 435W. A power sweep at a nominal phase angle of 75 degrees is shown in Fig. 6.

As is the case with all RSP2 cryocoolers, the LT-RSP2 cryocooler has the ability to actively *load shift* from one stage to the other. This is a feature inherent to the RSP2 Stirling / pulse tube hybrid architecture and provides a means for temperature control without the need for trim heaters[1]. Load shifting allows for the ratio of refrigeration at the two stages to be altered via simple software commands, without a significant loss of overall efficiency. This capability is extremely valuable to systems utilizing two-stage cryocoolers in that it is unlikely that the refrigeration ratio of the two stages used to generate the thermodynamic design will be the actual ratio required of the cooler in operation. A two-stage cryocooler solution without the ability to load shift will be forced to operate in an off-nominal condition and may, as a result, suffer significantly in terms of efficiency and capability.

Figure 7 illustrates the ability to load shift from one stage to the other while keeping the input power and temperatures constant. For a constant input power of 450W and a phase angle (ø) of 85° the heat lift at 10K is 220mW and at 55K the heat lift is 5.4W. Similarly, at an input power of 450W and a phase angle (ø) of 65° the heat lift at 10K is 300mW and at 55K the heat lift is 1.4W. The input power and phase angle can be used to provide temperature control at the sensor level allowing the FPA and optical bench to be optimized while minimizing input power without the need for trim heaters. Table 4 shows a summary of the characterization test results and the calculated Carnot

Table 3. LT-RSP2 no load test data.

No Load LT-RSP2 Cryocooler Test Data		
1st Stage Temperature:	38.7	Kelvin
1st Stage Heat Lift:	0.0	Watts
2nd Stage Temperature:	5.9	Kelvin
2nd Stage Heat Lift:	0.000	Watts
Compressor Input Power:	600	Watts

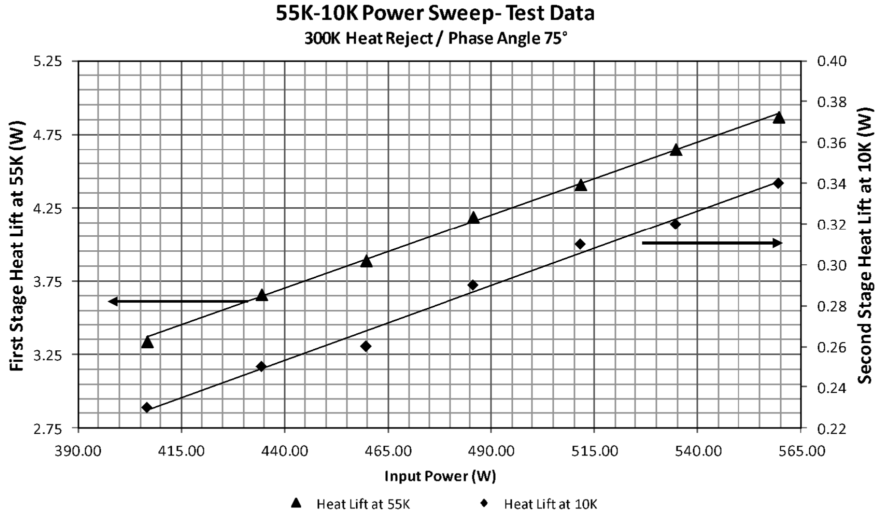

Figure 6. LT-RSP2 power sweep at a 1st stage temperature of 55K, a 2nd stage temperature of 10K, a constant phase angle of 75° and a heat reject temperature of 300K.

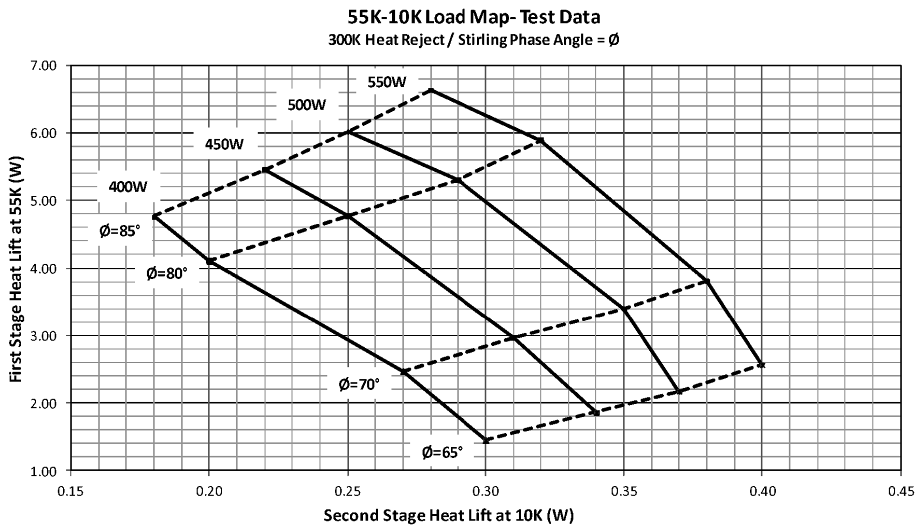

Figure 7. LT-RSP2 heat load capacity at 55K and 10K for input powers of 400W through 550W and phase angles varying from 65° thru 85°.

efficiency. An MLI shielding error was noted upon disassembly and when fixed an additional 90mW was gained on the 2nd stage. However time did not permit another round of characterization testing.

Upon successful integration into a sensor the compressor and expander were drawing a combined 370W of input power, the FPA was operating at its optimum temperature and the optical bench was at its set point. The initial integration into the sensor was a resounding success and a flight version of the compressor and expander are in fabrication.

Table 4. Characterization Test Results

Characterization Test Results																
Parameter	65 Degree Phase Angle				70 Degree Phase Angle				80 Degree Phase Angle				85 Degree Phase Angle			
1st Stage Temp (K)	55	55	55	55	55	55	55	55	55	55	55	55	55	55	55	55
2nd Stage Temp (K)	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
Reject Temp (K)	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300
1st Stage Heat Lift (W)	1.45	1.86	2.17	2.56	2.47	2.97	3.4	3.81	4.11	4.77	5.3	5.89	4.77	5.46	6.02	6.63
2nd Stage Heat Lift (W)	0.30	0.34	0.37	0.4	0.27	0.31	0.35	0.38	0.2	0.25	0.29	0.32	0.18	0.22	0.25	0.28
Input Power (W)	400.0	450	500	550	400	450	500	550	400	450	500	550	400	450	500	550
Carnot Efficiency	3.8%	4.0%	4.1%	4.2%	4.7%	4.9%	5.1%	5.1%	6.0%	6.3%	6.4%	6.5%	6.6%	6.8%	6.8%	6.8%

FUTURE DEVELOPMENTS

An advanced 1st stage regenerator will be tested in the IRAD machine in 2012, the main goal being a reduction in input power. A flight version of the LT-RSP2 is currently being fabricated and will undergo testing in late 2012. Additionally the LT-RSP2 machine forms the architecture for a 3-stage Stirling/pulse tube hybrid cooler called the RSP3 machine. The RSP3 machine has been shown in thermodynamic modeling to be capable of carrying significant load at 4K. A prototype machine is planned in the very near future.

CONCLUSION

Raytheon has demonstrated that a straightforward, two-stage, high frequency, linear cryocooler can be used for 10 K refrigeration. The LT-RSP2 provides an attractive option for space and airborne sensors in this temperature range because it avoids the complexity of an auxiliary J-T cryocooler while providing the operational controllability and flexibility inherently available in the RSP2 architecture. Focal plane and instrument cooling can be achieved using one machine optimized for packaging in a flight sensor.

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