Raytheon Low Temperature RSP2 Production Program

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ABSTRACT

Over the past 5 years, the Raytheon Cryocooler Product Line has been developing the Low Temperature Stirling / Pulse Tube Hybrid 2-Stage cryocooler (LT-RSP2) cryocooler. This paper reports on the design and 10 K performance testing of several cryocoolers as well as a comparison of two design iterations.

INTRODUCTION

The development of a 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 this system. Arsenic doped silicon (Si:As) focal planes offer exceptional performance for Long Wave Infrared (LWIR) astronomy and earth sensing applications; however, cryogenic cooling to temperatures below 12 K are required for their operation. Existing state of the art space and airborne closed cycle cryocooler systems are generally incapable of simultaneously holding the required loads below 12 K and 55 K, and stored-cryogen systems have typically been employed in their place. 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. A closed loop cryogenic solution would therefore offer not only a smaller mass and volume, but a longer mission lifetime and reduced logistics costs. To date, Raytheon has designed, built and tested 3 different Thermo-Mechanical Units (TMUs) that meet the Si:As systems requirements; the AFRL funded High Capacity-RSP2 (HC-RSP2), an IRAD funded LT-RSP2, and a production LT-RSP2 .

BACKGROUND

Over the years, several RSP2 cryocooler models have been matured and characterized. The Medium Capacity (MC-RSP2) and High Capacity (HC-RSP2) versions shown in Table 1 were the predecessors of the LT-RSP2 and helped guide the development. The architecture of each RSP2 expander module is identical, the main differences being the sizing of the compressor module and the size of the Stirling piston and the pulse tube on the expander.

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Table 1. Performance specifications for several RSP2 cryocoolers

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

* IRAD Unit Performance

HC-RSP2 LOW TEMPERATURE PERFORMANCE

The High Capacity Raytheon Stirling / Pulse Tube Hybrid 2-Stage cryocooler (HC-RSP2) was originally developed for the Air Force Research Lab (AFRL) to provide simultaneous cooling at temperatures of 85 K and 35 K [1]. During testing performed in 2008, it was demonstrated that the unit is capable of providing significant amounts of heat lift at 2nd stage temperatures as low as 12K. Thermodynamic modeling indicated that a minor change 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 12 K, as 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 during the course of the modified HC-RSP2 testing. First, a significant amount of confidence was gained by the ability of the system thermodynamic model to accurately predict performance at temperatures below 15 K. 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. Upon completion of the testing, internal investment was secured to develop a 10 K-55 K optimized design. The result is a robust 2-stage cryocooler system that is able of efficiently producing relatively large amounts of cooling at 2nd stage temperatures <10 K.

Table 2. HC-RSP2 low temperature test data configured with a "stock and low temperature surge volume and inertance tube.

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

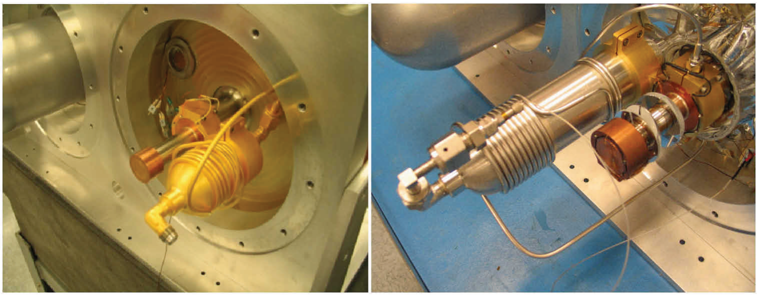


Figure 1. Stock HC-RSP2 cold head configuration (left) and the low temperature optimized version (right).

IRAD LT-RSP2 PERFORMANCE

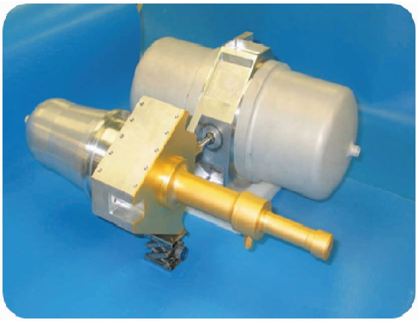
Following the encouraging results of HC-RSP2 low temperature testing in 2008, internal research and development funding was awarded in 2009 for the purpose of designing, fabricating and testing a fully-optimized LT-RSP2 cryocooler [2]. The LT-RSP2 architecture draws heavily from the HC-RSP2 cooler and several areas for optimization at lower temperature were identified and design improvements were implemented: the results of the optimization can be seen in Figure 2. Initial characterization testing of the IRAD LT-RSP2 cryocooler began in January of 2011 with no load temperature test showing 38.7 K on the 1st stage and 5.9 K on the 2nd stage for an input power of 600 W.

The LT-RSP2 has been designed for an instrument that requires a 1st stage temperature of 55 K and a 2nd stage temperature of 10 K at the cryocooler interface but can be utilized in an almost unlimited number of different temperature and load combinations due to the ability to load shift. 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 [2]. Load shifting allows for the ratio of refrigeration at the two stages to be altered via a simple software command of the phase angle (ø), 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. The load map shown in Figure 3 illustrates the ability to load shift from one stage to the other while keeping the input power and temperatures constant.

PRODUCTION LT-RSP2 PERFORMANCE

Once it was established that the IRAD LT-RSP2 was capable of handling the levied requirements (with margin), funding was secured to develop a production unit. Several areas were identified for optimization: the heat rejection flanges were increased in size, standard connectors were added for power and telemetry and the cryogenic surge volume was integrated onto the 1st stage. The production LT-RSP2 3D model is shown in Figure 4. Thermodynamic modeling indicated that if these changes were made the overall input power of the machine could be reduced.

Initial characterization testing of the production LT-RSP2 cryocooler began in July, 2013 with no load temperature test showing 35.5 K on the 1st stage and 5.46 K on the 2nd stage for an input power of 466 W, as shown in Figure 5. As expected, the no load temperatures were lower than seen on the IRAD cooler with 22% less power draw. After optimizing the fill pressure in the production cooler, a load map was created for and can be seen in Figure 6. Based upon the characterization and load map, the production LT-RSP2 is more than adequate for the intended application. Several more tests will be carried out over the coming months to qualify the system.



Parameter	Test Data
Heat Rejection Temperature	300 K
1st Stage Temperature	38.7 K
2nd Stage Temperature	5.9 K
1st Stage Heat Lift	0.0 W
2nd Stage Heat Lift	0.0 W
Input Power	600 W

Figure 2. IRAD LT-RSP2 configuration being prepared for initial testing (left) and no load test data (right).

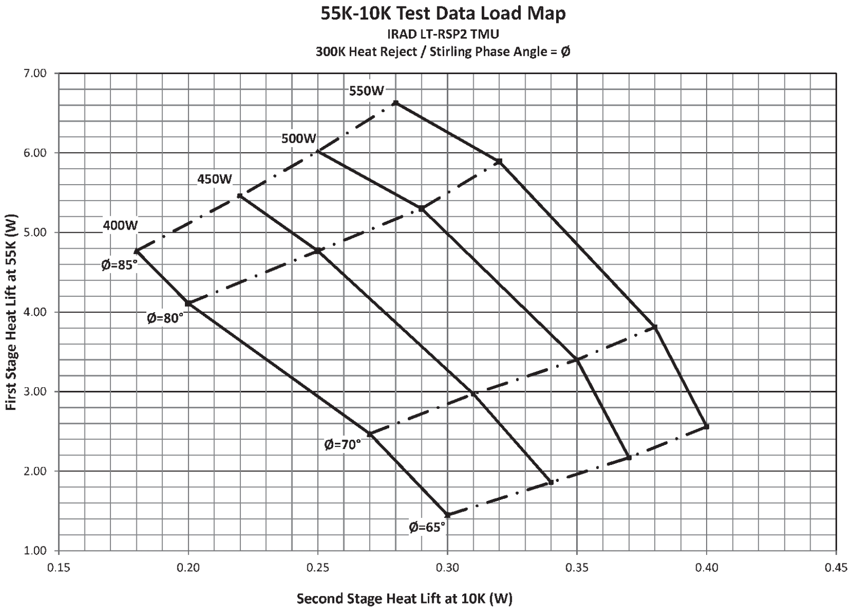


Figure 3. IRAD LT-RSP2 heat load capacity at 55 K and 10 K for input powers of 400 W thru 550 W and phase angles varying from 65° thru 85°.

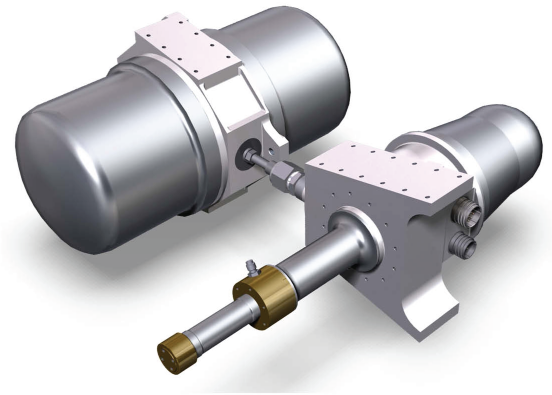
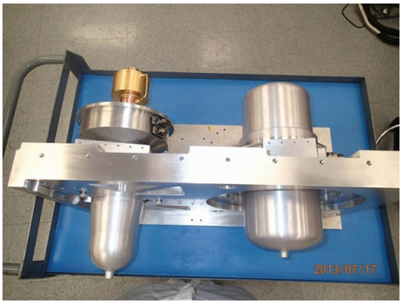


Figure 4. Production LT-RSP2 cryocooler model showing the increased heat rejection flanges and added connectors



Parameter	Test Data
Heat Rejection Temperature	300 K
1st Stage Temperature	35.5 K
2nd Stage Temperature	5.46 K
1st Stage Heat Lift	0.0 W
2nd Stage Heat Lift	0.0 W
Input Power	466 W

Figure 5. Production LT-RSP2 configuration being prepared for initial testing (left) and no load test data (right).

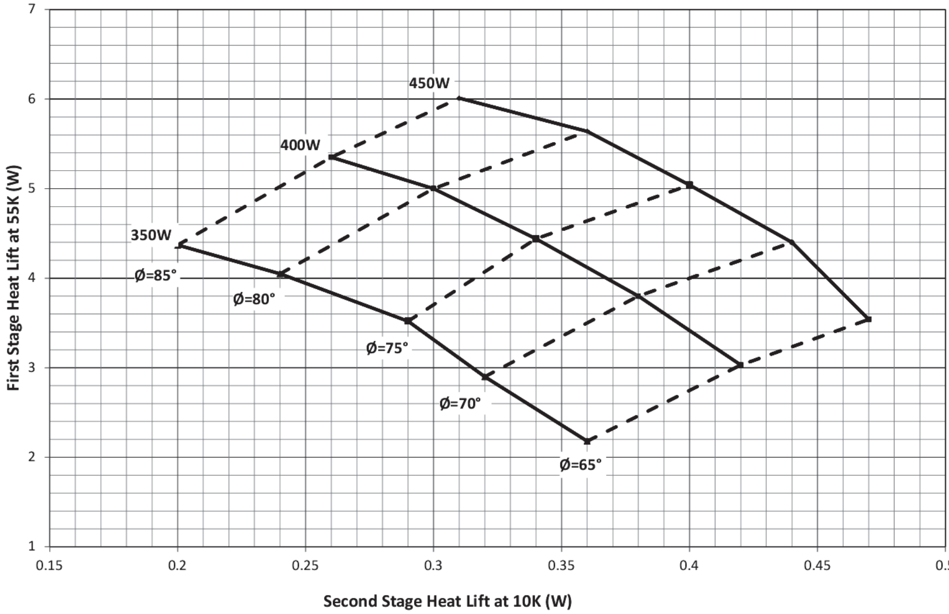


Figure 6. Production LT-RSP2 heat load capacity at 55 K and 10 K for input powers of 400 W thru 450 W and phase angles varying from 65° thru 85°.

Based upon the modifications made to the heat rejection surfaces, an increase in efficiency was expected and can be seen in the comparison between the two coolers in Figure 7. Depending on the phase angle, the production cooler was between 10% to 35% more efficiency than the IRAD cooler. This increase can be attributed to optimization of the heat rejection path from inside both the ex-

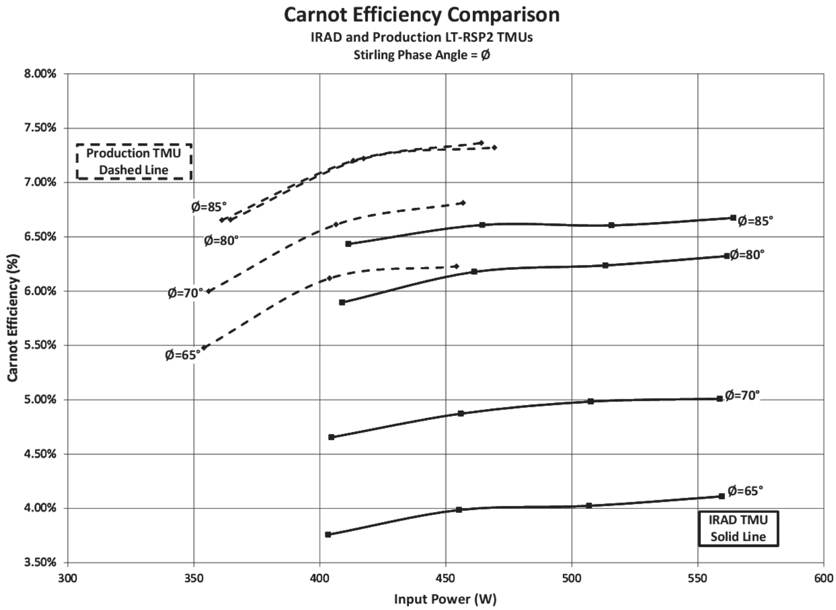


Figure 7. Carnot efficiency comparison at different phase angles and input power levels for both the production and IRAD LT-RSP2 cryocoolers.

pander and compressor to their respective heat rejection blocks. The thermal resistance inside the IRAD cooler was thoroughly analyzed and areas for improvement were identified and implemented when it came time to design and build the production cooler.

Exported disturbance is a significant concern for any cryocooler system and needs to be characterized. The production LT-RSP2 was placed on a characterized dynamometer to determine the exported disturbance level in the X, Y and Z axis. Figure 8 shows the exported disturbance levels with the Adaptive Feed Forward (AFF) algorithms implemented at a nominal input power of 400 W with the cooler carrying the required load. What is interesting is that these exported disturbance levels are in line with what was seen on a Raytheon single stage Stirling cryocooler at 115 W of input power. The results of the exported disturbance testing prove that Raytheon's patented AFF algorithms are capable of handling a wide variety of input power levels.

Planned testing in 2015 includes random vibration, thermo-vacuum and EMI/EMC. At the conclusion of the qualification testing a set of drive electronics will be mated to the production LT-RSP2 cryocooler and the system will be characterized for exported disturbance before being delivered to the next level for integration.

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 sensor.

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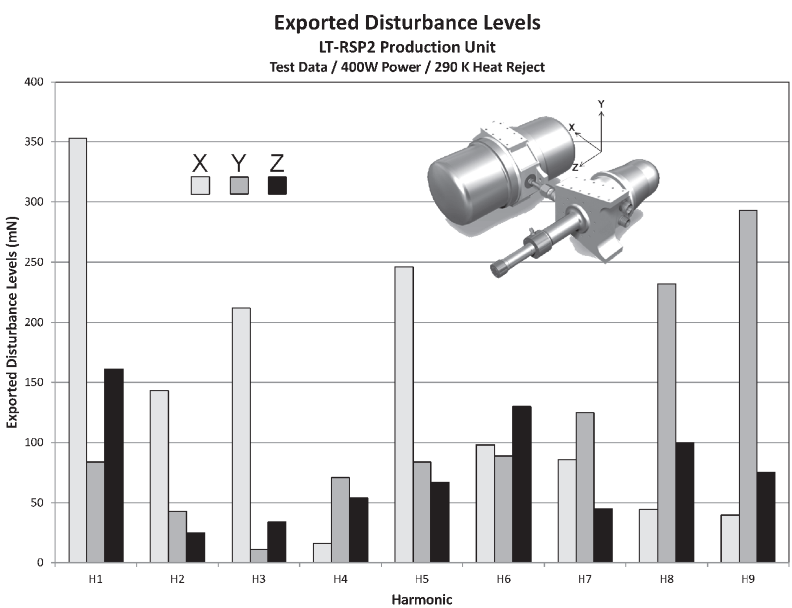

Figure 8. LT-RSP2 cryocooler production unit exported disturbance levels.

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2. Schaefer, B.R., Bellis, L., Ellis, M.J., and Conrad, T., “Raytheon Low Temperature RSP2 Cryocooler Performance,” *Cryocoolers 17*, ICC Press, Boulder, CO (2013), 2009, pp. 9-15.