Raytheon Stirling/PulseTube Cryocooler Maturation Programs

C. S. Kirkconnell[1], R. C. Hon[1], and T. Roberts[2]

[1]Raytheon Space and Airborne Systems
El Segundo, CA, 90245, USA

[2]Air Force Research Laboratory/VSSS
Kirtland AFB, NM, 87117, USA

ABSTRACT

Raytheon has continued to advance the maturity of Stirling / pulse tube "hybrid" two-stage cryocooler technology. Two versions of this cryocooler are currently in test. The first one has been developed on an Air Force Research Laboratory (AFRL) program to cool large long wave infrared (LWIR) sensors. This cryocooler, called the High Capacity Raytheon Stirling / Pulse Tube Two-Stage (HC-RSP2) cooler, delivered 2.6 W at 35 K simultaneously with 16.2 W at 85 K for 513 W cryocooler input power during thermal vacuum testing. A second version, called the Medium Capacity (MC) RSP2 cryocooler, delivered 2.4 W at 58 K simultaneously with 6.1 W at 110 K for 166 W cryocooler input power during bench-top testing. These and additional test results are discussed. Lessons learned during the build and test of these two cryocoolers and their application to the continued evolution of the RSP2 cryocooler product line are presented.

INTRODUCTION

The Raytheon Stirling / pulse tube two-stage (RSP2) cryocooler has been discussed extensively in the past [1-6]. The RSP2 is a hybrid cryocooler with a Stirling upper stage and a pulse tube lower stage. There is a single working volume of gas. On the compression stroke, gas flows from the compressor through the first stage Stirling regenerator into the first stage expansion volume. Some of the gas then flows from the first stage into the second stage (pulse tube) regenerator into the second stage expansion volume, where it is further cooled. This particular thermodynamic system is mechanically simple to implement, and it has unique operational advantages over competing multistage linear cryocooler approaches, such as two-stage Stirlings or pulse tubes. These features and advantages are discussed extensively in the references provided.

Raytheon is developing the RSP2 in response to identified United States Government (USG) needs for two-stage cryocoolers, primarily to provide simultaneous optics and focal plane cooling for space-borne infrared sensors [7]. In recognition of the breadth of operational requirements, two differently-sized versions optimized for different temperatures are being developed. The "Medium Capacity" MC-RSP2 is presently optimized for 58 K / 110 K operation with measured capacity of 2.4 W / 6.1 W at those temperatures. The "High Capacity" HC-RSP2 is designed for 35 K / 85 K; measured capacity was 2.6 W and 16.2 W, respectively. Test details are provided herein.

Cryocoolers 15, edited by S.D. Miller and R.G. Ross, Jr.

Of important note is that these are both flight-design cryocoolers. All electrical feedthroughs are fully hermetic. The structural designs are robust and capable of surviving launch vibration. Safe, efficient operation has been demonstrated in representative thermal vacuum environments. While Raytheon continues to advance the state of the art and efficiency on this family of coolers, the two designs described herein are ready for immediate deployment on a space-borne payload.

HIGH CAPACITY RSP2 CRYOCOOLER

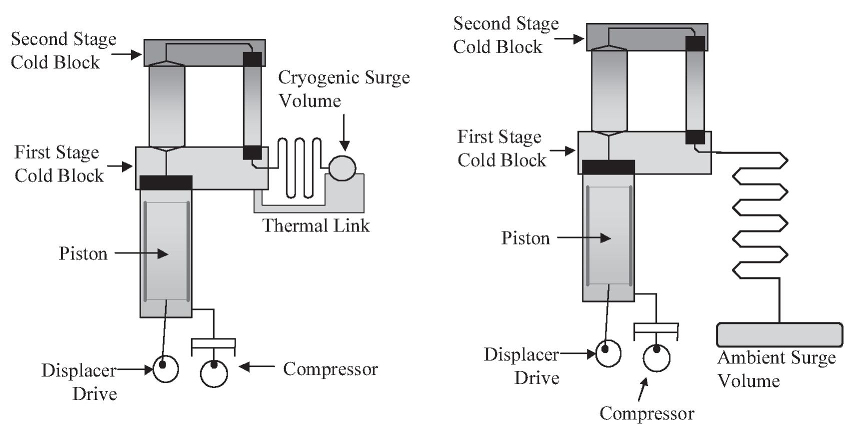
The HC-RSP2 program was first discussed at the Cryogenic Engineering Conference in 2007 [1]. Requirements and preliminary bench-top test results were presented. The required efficiency improvements to meet the performance objectives were quantified. Progress reported herein includes the accomplishment of the required efficiency upgrade, successful thermal vacuum testing, and successful radiated emissions testing.

Program Overview

The HC-RSP2 program is a Raytheon-primed, AFRL-managed development program with the objective being to develop a high capacity, two-stage cryocooler to meet the needs of future payloads requiring large capacity relative to existing space cryocoolers. The program is managed out of the AFRL Space Vehicles Directorate, Kirtland Air Force Base, New Mexico.

Upgrade to Flight Configuration

A Stirling / pulse tube hybrid cryocooler utilizes an inertance tube and surge volume to achieve the second stage phase shift, as is commonly done with many pulse tube expanders. The surge volume can be operated at ambient or the first stage (Stirling cold tip) temperature. Testing and analysis at Raytheon has shown that it is more thermodynamically efficient to locate the surge volume at the first stage temperature than at ambient. This is because the location of the surge volume at a warmer temperature than the first stage cold block introduces the opportunity for a thermal shuttle loss [1]. However, it is more convenient to use an ambient temperature surge volume for bench-top testing because the surge volume in that case does not have to reside within the test dewar. Figure 1 illustrates the point schematically.



(a) (b)

Figure 1. Surge volume options for RSP2 Cryocooler second stage phase shift. (a) Surge volume and inertance tube operate at nominally first stage cold block temperature. (b) Surge volume operates at nominally ambient temperature. Inertance tube temperature traverses from first stage temperature at one end to ambient at the other. Surge volume must by physically larger because the gas is less dense.

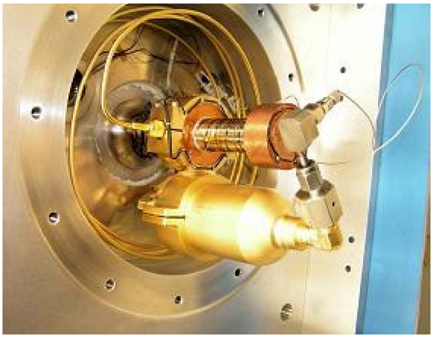


Figure 2. HC-RSP2 cold head as configured for thermal vacuum testing in accord with Figure 1a thermal layout. The pressure transducer shown was used to measure the pressure oscillation within the surge volume. This is a ground test feature only; flight version is capped and welded at the pressure tap location.

As described previously, the bench-top testing for the HC-RSP2 was done with an ambient temperature surge volume (as in Figure 1b). For the upgrade to a flight design in preparation for thermal vacuum testing, the ambient surge volume was replaced with a cryogenic surge volume and bracket to thermally link it to the first stage cold block. The inertance tube was reoptimized, a necessary step given the dramatically different pressure drop characteristics associated with isothermal operation at 85 K as compared to traversing from 85 K to 300 K. The HC-RSP2 cold head as configured for thermal vacuum testing is shown in Figure 2.

Thermal Vacuum Test Results

The HC-RSP2 as configured for thermal vacuum testing is shown in Figure 3. The thermal vacuum testing was primarily focused on establishing compliance with the thermodynamic perfor-

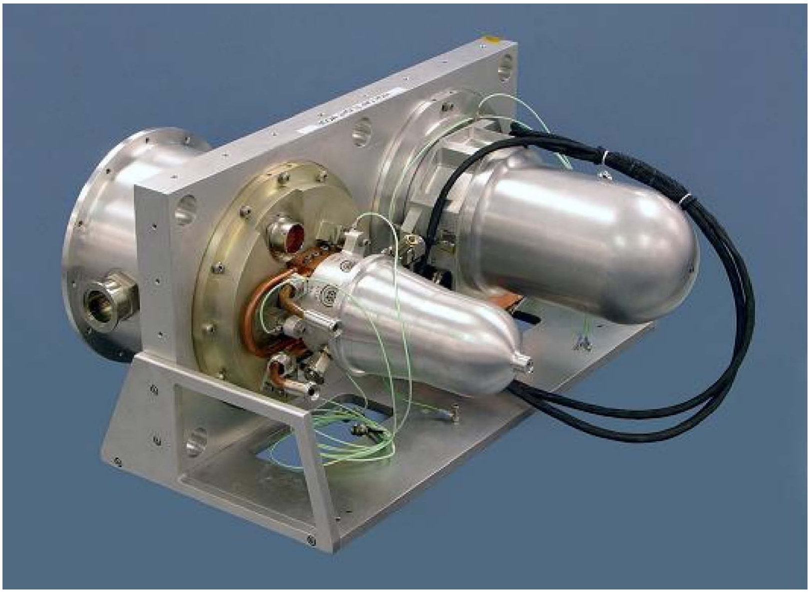


Figure 3. HC-RSP2 in test stand as tested in the thermal vacuum chamber. The primary purpose of the dewar shown is to also permit benchtop testing in the ambient environment, but since it is also used as the multilayer insulation (MLI) support structure, it remains with the cooler during thermal vacuum. The pump out port shown is simply left open to permit evacuation with the chamber's vacuum system.

mance objective of achieving refrigeration capacities of 2 W at 35 K + 18 W at 85 K for <500 W input power. To achieve this objective, significant improvement over the previous bench-top "risk reduction" (RR) test results had to be achieved through the implementation of a cryogenic surge volume and better optimized inertance tube. This is demonstrated by the data provided in Table 1. The "RR" column contains the data from the original bench-top test [1]. The "Objective" column is, as the name implies, the performance objective. "FD" is the Flight Design data taken during the thermal vacuum testing. The following definitions apply:

Q2 - Second stage net refrigeration capacity
Q1 - First stage net refrigeration capacity
P_IN - Total input power to the cryocooler
T2 - Second stage cold block temperature
T1 - First stage cold block temperature
Trej - Rejection temperature as measured on the expander warm flange
β_{C2} - Second stage Carnot efficiency
β_{C1} - First stage Carnot efficiency
Q2norm - Normalized expander capacity at second stage temperature
SPnorm - Normalized specific power

where

$$\beta_{C2} = \frac{T2}{Trej - T2}$$

$$\beta_{C1} = \frac{T1}{Trej - T1}$$

$$Q2norm = Q2 + Q1 * \frac{\beta_{C2}}{\beta_{C1}}$$

$$SPnorm = \frac{P\_IN}{Q2norm}$$

The appropriate units for the various variables are defined in Table 1.

As shown in Table 1, the capacity is slightly load-shifted towards the second stage as the system was configured and operated. Because the RSP2 has the ability to shift capacity between the stages by simply changing the mechanical phase angle of the driven expander piston, alternate load splits are achievable. For example, in preliminary bench-top testing of the FD configuration, 2.55 W at 35 K and 18.0 W at 95 K was measured for 509 W input power. The drive electronics are presently being reconfigured to provide simultaneous two-stage temperature control, which will make it much more efficient to vary loads, load splits, and temperatures. The plan is to resume testing and characterize the performance over a variety of loading conditions when these electronics come online.

Table 1. HC-RSP2 Test Results versus Performance Objectives

	RR	Objective	FD	Units
Q2	3.0	2.0	2.6	W
Q1	9.8	18.0	16.3	W
P_IN	497	500	513	W
T2	35	35	35	K
T1	85	85	85	K
Trej	300	300	300	K
β_{C2}	0.13	0.13	0.13	-
β_{C1}	0.40	0.40	0.40	-
Q2norm	6.22	8.01	8.05	W
SPnorm	79.90	62.40	63.76	W/W

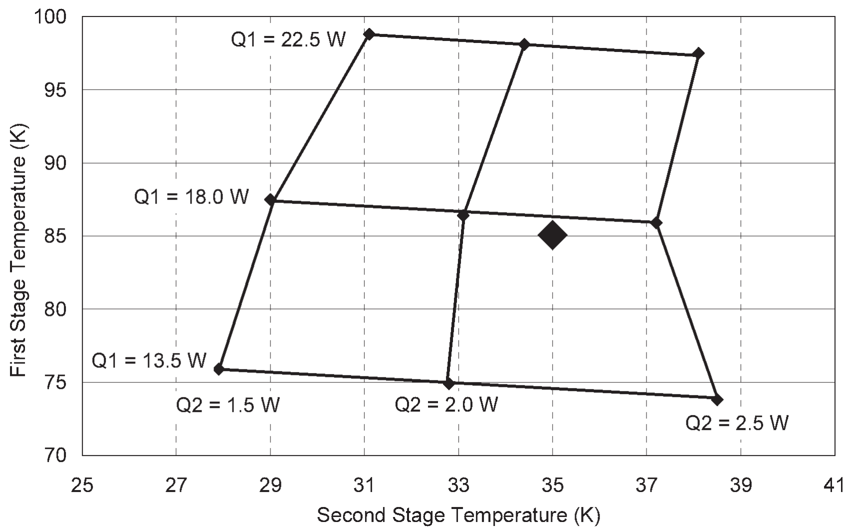


Figure 4. HC-RSP2 35 K / 85 K operation as measured in a thermal vacuum chamber at a rejection temperature of 300 K (diamond symbol). Data point transposed onto model-generated load map.

Several data points were captured at the design refrigeration temperatures for various rejections temperatures and before and after hot and cold excursions. The cryocooler was successfully operated at rejection temperatures from 280 K to 305 K. Survival (non-operational) was demonstrated at the temperature extremes of 225 K and 325 K. The cooler consistently returned to the same steady operating point, which is shown together with a model-generated load map in Figure 4. The correlation between the measured data and the model is excellent, although the capacity is somewhat shifted towards the second stage, as previously noted.

Radiated Electromagnetic Interference (EMI) Test Results

An EMI test was performed to characterize the magnetic field radiated emissions from the HC-RSP2 cryocooler. The test consisted of performing a MIL-STD-462 Test Method RE01 measurement, from 30 Hz to 100 kHz, with the antenna located 50 cm from the cryocooler. The measured data and the requirement are shown together in Figure 5, demonstrating compliance with the specification was achieved with considerable margin.

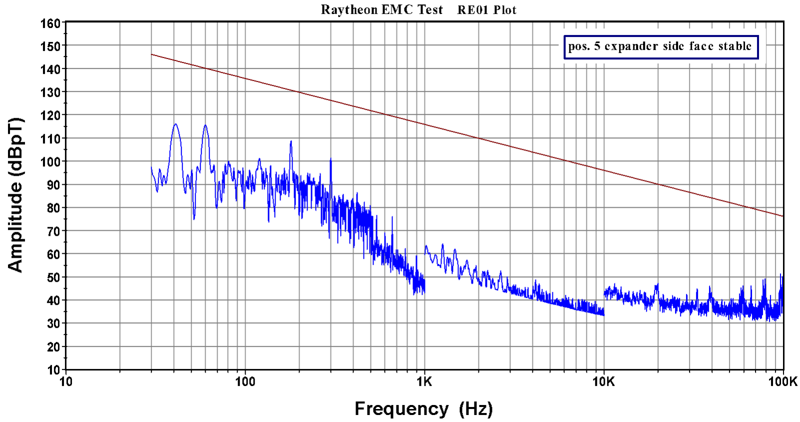


Figure 5. EMI test results for HC-RSP2. Several locations around the cooler at a distance of 50 cm were inspected. All data taken were compliant with considerable margin. Results shown are typical.

Table 2. MC-RSP2 Test Results.

Data Point	T1	T2	Q1	Q2	P_IN	SPnorm
	K	K	W	W	W	W/W
1	110	58	2.32	7.25	170	32.1
2	130	58	2.01	13.9	177	28.0
3	140	58	1.87	15.8	172	28.0

MID CAPACITY RSP2 (MC-RSP2) CRYOCOOLER

The MC-RSP2 cryocooler is a smaller, lower-capacity version of the HC-RSP2 cooler being developed on internal Raytheon funding. Its development is progressing in parallel with the HC-RSP2. As previously reported, the cold head design was finalized before the HC-RSP2 development successfully demonstrated the coaxial cold finger, so the unit features a “U-tube” second-stage design [1]. Future versions will be built with a coaxial second stage.

Initial benchtop testing of the MC-RSP2 has commenced. The test configuration is identical to that shown in Figure 2 with a cryogenic surge volume integrated inside the test dewar. For the initial testing, the second stage was held constant at 58 K while the first stage was varied from 110 K to 140 K; the rejection temperature was held between 292 and 294 K. The data are provided in Table 2. Although the design refrigeration temperatures are 58 K / 110 K, the cooler was shown to actually be more efficient at higher first stage temperatures. This may just be an artifact of the known characteristic of cryocoolers to trend to higher percentage of Carnot efficiency at higher refrigeration temperatures, or it may be because of the design and manufacturing details of the cooler itself. Additional testing is planned in the near future during which a broader range of operational temperatures will be fully explored.

The MC-RSP2 testing has been temporarily interrupted to support an internally-requested test of the MC-RSP2 configured as a single-stage Stirling cryocooler. Without the pulse tube second stage, the RSP2 is identically a single-stage Stirling. The purpose of the testing was thus to investigate the suitability of this design to meet a single-stage cooling need. However, with the originally-intended two-stage testing not yet completed, it was undesirable to permanently modify the cold head. (Such a modification requires machining off the pulse tube parts and capping the exposed flow port. This is straightforward and has been done successfully at Raytheon in the past, but is obviously a modification that is very difficult to reverse.) The selected approach was to instead cap the second stage at the inertance tube port with a VCR fitting as shown in Figure 6. This yields a highly-unoptimized Stirling design because of the entire pulse tube expander volume simply becomes a dead volume that

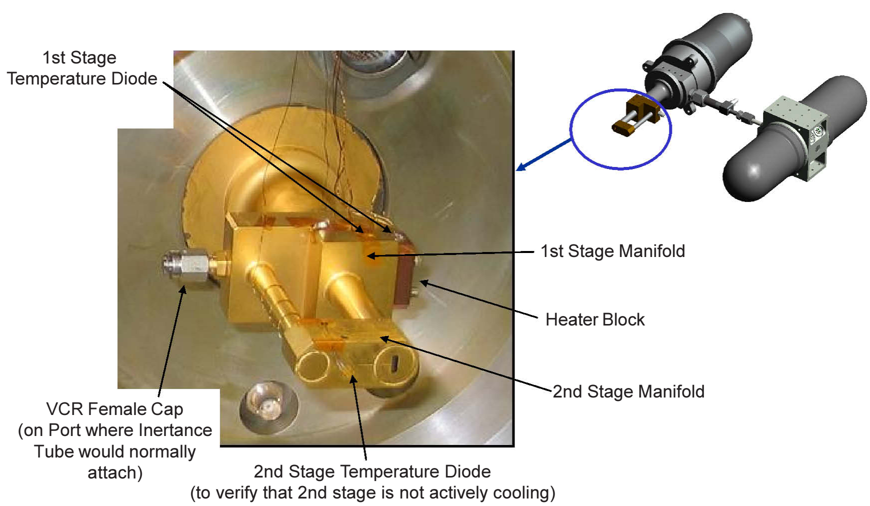


Figure 6. MC-RSP2 cold head temporarily configured as a single-stage Stirling.

isothermalizes at the refrigeration temperature produced by the Stirling stage. However, the configuration is amenable to mathematical simulation, so the projected performance can be modeled and compared to the experimental data. The results can then be used to effectively project the performance in a more prototypical Stirling configuration (without the pulse tube volumes present).

The performance of the cooler in this configuration was surprisingly respectable. The measured performance was 12.9 W at 110 K for 177 W of input power at a rejection temperature of 291 K. This was slightly lower than the 14.6 W predicted, but the specific power (13.6 W/W) was identical to the model. This most likely indicates some under accounting for the void volume effect arising from the large second-stage dead volume. Based upon these results, the predicted performance at this temperature should the second stage be completely removed is 18.1 W at 110 K for 237 W input power. Alternatively, the predicted performance at 95 K is 15.2 W capacity for 260 W input. For comparison, these input powers are 25% higher than would be expected for a single-stage Stirling of the same capacity designed originally as a single-stage cryocooler. The primary physical difference is that the single-stage Stirling by design would have a longer Stirling cold finger than the modified RSP2 cold head.

CONCLUSION

Two differently-sized but otherwise very similar RSP2 cryocoolers have been shown through a variety of testing to be ready for insertion into a flight program. The HC-RSP2 has been shown to be a high-efficiency, high-capacity cryocooler in thermal vacuum testing, rejecting over 500 W through its conductive interfaces without complication up to rejection temperatures of at least 305 K. The MC-RSP2 provides a lower-capacity alternative to the HC-RSP2. Testing and characterization of both of these cryocoolers is ongoing. In addition to the two-stage testing, a temporary modification to the MC-RSP2 was performed to facilitate the projected performance of that cooler as a single-stage Stirling.

ACKNOWLEDGMENTS

The authors would like to acknowledge the Missile Defense Agency for their financial support of these development efforts. We would also like to acknowledge Raytheon Cryocooler Team contributors Lowell Bellis and Thomas Pollack.

REFERENCES

1. Kirkconnell, C.S., Hon, R.C., Kesler, C.H., Roberts, T., “Raytheon Stirling / Pulse Tube Cryocooler Development,”*Adv. in Cryogenic Engineering*, Vol. 53, AIP, Melville, NY (2008), pp. 909-916.
2. Kirkconnell, C.S., Price, K.D., Ciccarelli, K.J., and Harvey, J.P., “Second Generation Raytheon Stirling/ Pulse Tube Hybrid Cold Head Design and Performance,” *Cryocoolers 12*, Springer Science, New York, NY (2005), pp. 127-131.
3. Kirkconnell, C. S., Price, K. D., Barr, M. C., and Russo, J. T, “A Novel Multi-Stage Expander Concept,” *Cryocoolers 11*, Kluwer Academic/Plenum Publishers, New York (2001), pp. 259-263.
4. Price, K. D. and Urbancek, V., “95 K High Efficiency Cryocooler Program,” *Cryocoolers 11*, Kluwer Academic/Plenum Publishers, New York (2001), pp. 183-188.
5. Price, K. D. and Kirkconnell, C. S., “Two Stage Hybrid Cryocooler Development,” *Cryocoolers 12*, Kluwer Academic/Plenum Publishers, New York (2003), pp. 233-239.
6. Finch, A.T., Price, K.D., and Kirkconnell, C.S., “Raytheon Stirling/Pulse Tube Two-Stage (RSP2) Cryocooler Advancements,” *Advances in Cryogenic Engineering* 49B, AIP, New York (2004), pp. 1285-1292.
7. Roberts, T. and Roush, F., “Cryogenic Refrigeration Systems as an Enabling Technology in Space Sensing Missions,” *Cryocoolers 14*, ICC Press, Boulder, CO (2007), pp. 595-604.
8. Kirkconnell, C. S. and Price, K. D., “Thermodynamic Optimization of Multi-Stage Cryocoolers,” *Cryocoolers 12*, Kluwer Academic/Plenum Publishers, New York (2003) pp. 69-78.
9. Kirkconnell, C.S., “Aerospace Cryocooler Selection for Optimum Payload Performance,” *Cryocoolers 14*, ICC Press, Boulder, CO (2007), pp. 605-614.