# Demonstration of Two-Stage Temperature Control for Raytheon Hybrid Cryocoolers

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## ABSTRACT

A two stage temperature control algorithm has been demonstrated for the Raytheon Stirling/pulse tube hybrid (RSP2) cryocooler. This algorithm adjusts the input power and Stirling displacer phase command in order to independently control the temperatures of both cryocooler stages without the addition of any trim heat. The ability to independently control the temperatures of the two stages is a unique capability of Stirling/pulse tube hybrid cryocoolers to shift cooling capacity between the stages through the adjustment of the Stirling displacer phase. The Raytheon Low Temperature RSP2 (LT-RSP2) cryocooler was used to exercise the algorithm and demonstrate its performance in several scenarios, including during cool-down and under changing load conditions at constant $1^{st}$ and $2^{nd}$ stage temperatures.

## INTRODUCTION

A temperature control algorithm has been developed and demonstrated for the Raytheon Stirling/pulse tube hybrid (RSP2) two stage cryocooler. The algorithm is capable of independently controlling temperature at both stages and adjusting to changing loads over the capacity range of the RSP2 cryocoolers without the use of any trim heaters. This capability improves the overall efficiency of the cryocooler in an integrated configuration, as the use of trim heat for temperature control is directly translated to an increase in input power required. It also provides flexibility to both instrument designers and users and is unique to the RSP2 architecture. The benefits of efficiency and flexibility pay dividends in several different ways over the mission life cycle.

The typical design cycle for space-based instruments using active cryogenic cooling often requires cryocooler selection during the preliminary design phase, at which point the exact instrument load requirements are still being determined. For instruments utilizing a single stage cooler, this uncertainty is mitigated by requiring additional capacity margin from the cryocooler. When a two stage cryocooler is needed, e.g. to simultaneously cool both a detector and optical bench, this uncertainty becomes more significant. Requiring additional cooling capacity at both stages may cause the cryocooler to be oversized for the final application. Also, most two stage coolers have relatively constant ratios of first to second stage capacity as input power is varied; thus, any changes to the ratio of first and second stage load requirements will force the use of a heater on one of the stages if both temperatures must be controlled precisely. Stirling/pulse tube hybrid cryocoolers have a unique capability to shift load capacity between stages which, combined with the ability to perform independent two stage temperature control. This capability allows the RSP2 coolers to share margin between their two stages and efficiently adjust to the final load requirement ratio.

An additional consideration in the instrument design phase is that program cost and schedule constraints often preclude the design and qualification of a new cryocooler for each instrument. It then becomes desirable to re-use an existing cryocooler for temperatures and loads other than those that it was initially optimized for. For a single stage cooler, this may be done by simply modulating the input power, but for a two stage cryocooler this adaptation is generally more complex and may require hardware modifications or the use of trim heaters if both stage temperatures must be controlled precisely. The load shifting capability of the Stirling/pulse tube hybrid cooler significantly expands the operating range of temperatures and loads which can be achieved without making hardware changes. In combination with the ability to independently control each stage temperature, which eliminates the need for trim heat, this allows the RSP2 cryocoolers to operate more efficiently at off-nominal loads and temperatures.

During the integration and test phase of a mission, thermal model predictions of instrument load and temperature requirements are replaced with experimentally determined values. The actual cooling requirement which the cryocooler must meet often changes substantially at this point, particularly if changes in the operating temperatures are needed to improve the overall instrument performance. At this point, the combination of the load shifting and two stage independent temperature control capabilities of the RSP2 Stirling/pulse tube hybrid cryocoolers provides unique flexibility to optimize overall instrument performance while simultaneously minimizing the required cryocooler input power through the elimination of trim heat.

Finally, during operation on orbit the capabilities of load shifting and independently controlling stage temperatures deliver flexibility and convenience to the instrument operator. The RSP2 temperature control algorithm is capable of maintaining temperature set points at both stages without additional user input as heat rejection temperatures, parasitic loads, and instrument power dissipation vary. Also, as an instrument progresses towards its end of life it may experience performance degradation, increased parasitic loads, or a reduction in available power. In these situations the ability to shift load and independently control cryocooler stage temperatures may help to extend the mission lifetime by allowing flexibility in prioritizing available cooling capacity.

## BACKGROUND

Raytheon's Stirling / Pulse Tube Hybrid 2-Stage (RSP2) cryocoolers have been matured through an active development effort now spanning approximately 15 years [1,2]. They combine an actively driven Stirling first stage with a passive pulse tube second stage. The architecture of each RSP2 expander module is identical, the main differences being the size of the compressor module and the size of the Stirling piston and the pulse tube on the expander. In this way, the RSP2 architecture can be adapted to accommodate a wide variety of 1$^{st}$ and 2$^{nd}$ stage temperatures and load requirements. Nominal design temperatures (1$^{st}$ stage / 2$^{nd}$ stage) for the RSP2 coolers have included 55 K / 10 K for the LT-RSP2, 85 K / 35 K for the High Capacity (HC) RSP2, and 110 K / 58 K for the Mid-Capacity (MC) RSP2. Even with the compressor and expander sizes fixed, however, there remains a great deal of flexibility in operating temperature and load capacity for each of the RSP2 coolers; for example, the initial 60 K / 12 K testing at the beginning of the LT-RSP2 development effort was performed using the HC-RSP2, nominally designed for 85 K / 35 K operation [3].

For a given set of operating temperatures, the RSP2 cryocoolers are able to produce a range of cooling capacities at each stage. An example of this is shown in Figure 1, a load map for a production LT-RSP2 cryocooler operating at 55 K and 10 K for the first and second stage temperatures, respectively. In this figure it can be seen that for a given input power, the ratio of 55 K and 10 K capacities varies significantly with the Stirling phase angle. For example, at 350 W of input power the capacity can be varied from 4.4 W at 55 K and 0.2 W at 10 K to 2.2 W at 55 K and 0.36 W at 10 K by adjusting the Stirling phase angle from 85 degrees to 65 degrees. This was the tested range of Stirling phase angles for this cooler and these temperatures, however both higher and lower phases are possible and thus additional range in stage cooling capacities is possible as well. This

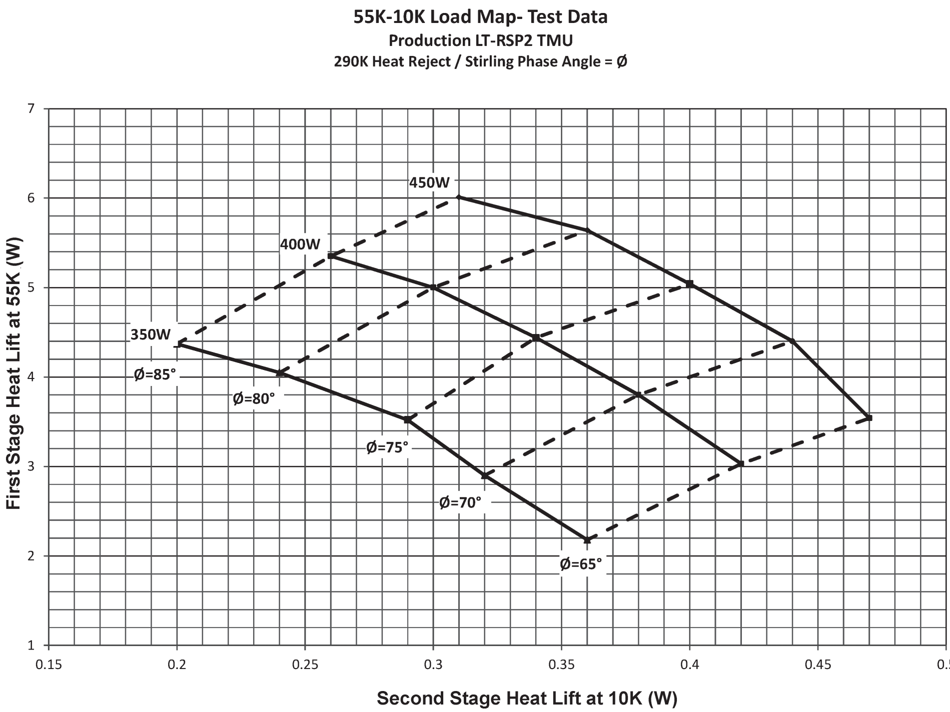


**Figure 1.** Load map showing LT-RSP2 cooling capacity at 55 K and 10 K as a function of Stirling phase.

unique capability of Stirling / pulse tube hybrid cryocoolers to trade capacity between their stages through variation of the Stirling phase angle is referred to as load shifting. For the RSP2 cryocoolers, it is implemented very easily through modulation of the displacer drive waveform produced by the cryocooler electronics. This load shifting capability also provides the basic mechanism for the independent two stage temperature control algorithm.

## TWO STAGE TEMPERATURE CONTROL

From Figure 1, it is apparent that each combination of first and second stage loads is met by a unique input power and Stirling phase angle. In its most basic form the two stage temperature control algorithm can be thought of as automatically seeking this combination of input power and phase, thereby finding the minimum input power which can hold the combination of loads. The actual implementation is a little more complex, as any combination of loads and stage temperatures within the cryocooler's capacity envelope can be commanded and a unique combination of input power and Stirling phase will be determined by the control algorithm. In a typical application the loads are not actually commanded; rather, they are the sum of the instrument parasitic and dissipative loads. The desired stage temperatures are simply commanded to the temperature control algorithm and the required input power and Stirling phase are determined.

Figure 2 shows a demonstration of the control algorithm's response to step changes in applied loads on each stage and the resulting cryocooler performance. The top chart in the figure shows a history of the first and second stage loads, which were varied during the test. The middle chart shows the Stirling phase and compressor input power adjustments made by the algorithm in response to the load changes.

At the bottom, the resulting first and second stage temperature histories are shown. The temperature set points were 55 K and 10 K for the first and second stages, respectively. During the test, a step change in the first stage applied load was made, followed by a step in the second stage

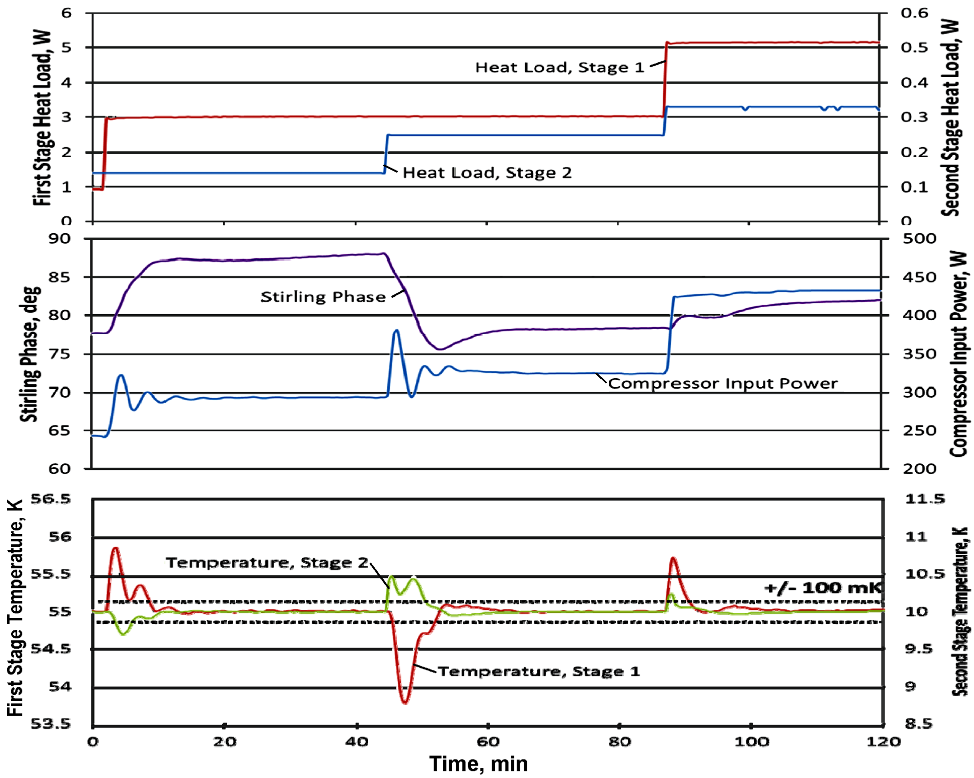


**Figure 2.** Demonstration of dual stage temperature control response to step functions in applied loads

load and finally a simultaneous step at both stages. The control algorithm responded to the first step by increasing both the input power and Stirling phase, consistent with the load map of Figure 1 which showed that an increase in phase results in an increase in first stage capacity and a decrease in second stage capacity. Likewise, in response to the second load step which was on the second stage, the control algorithm again increased the input power but decreased the phase angle. Finally, in response to the simultaneous load step the input power increased and a smaller adjustment was made to the Stirling phase angle. In each case the temperatures at both stages exhibited a brief transient response before converging again to the commanded temperatures of 55 K and 10 K. Temperature stability outside of the transient responses was well within the range of +/- 100 mK, a typical cryocooler temperature stability requirement. The transient responses are exaggerated in this test compared to what would be expected in an integrated configuration due to both a lack of thermal mass attached to either stage, which would greatly slow the temperature responses, and the generally unrealistic step changes in load.

A similar demonstration of controller performance in response to ramp changes in load is shown in Figure 3. First the first stage load is ramped from 1 W to 3 W over a 15 minute period, then the second stage load is ramped from 0.20 W to 0.42 W over a 10 minute interval. Again, temperature setpoints were 55 K and 10 K. As was the case for the step inputs, the controller increased the input power and Stirling phase in response to the increased first stage load, then increased the power and decreased the phase in response to the second stage load ramp. Temperature stability during controller adjustments was better for the load ramp inputs than it was for the step inputs, particularly for the first load increases on the first stage. Again, the temperature fluctuations seen in these controller demonstration tests are much larger than what would be expected for an integrated cryocooler and instrument due to the additional thermal mass of the instrument. The applied load changes are also greater in magnitude and occurring over a much shorter period of time than is typical for a cryocooler and instrument in an operational environment.

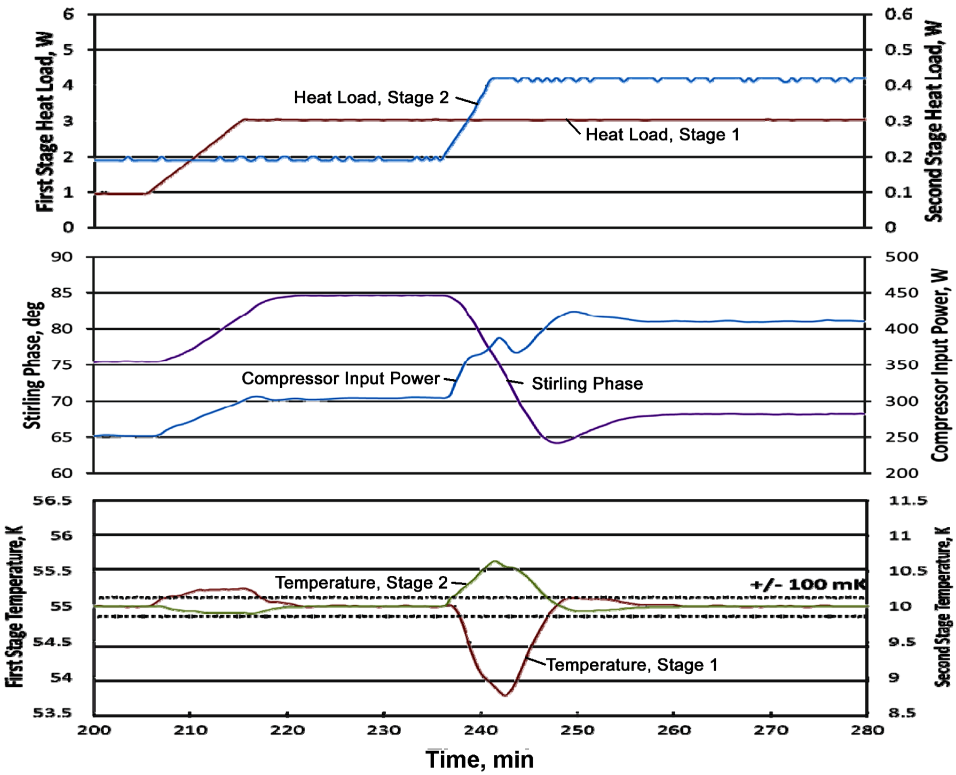


**Figure 3.** Demonstration of dual stage temperature control response to ramp functions in applied loads

The developed dual stage temperature control algorithm is capable of driving the RSP2 cryocoolers to a commanded set of first and second stage temperatures from any starting condition; the cryocooler does not need to be operating at or near the commanded temperatures before the controller can be utilized. A demonstration of this capability is given in Figure 4, which shows cooldown data for the LT-RSP2 cryocooler from an ambient (295 K) power off condition to 55 K and 8 K set points on the first and second stages. The controller begins by increasing the input power until it reaches its stroke limit while simultaneously shifting the Stirling phase from its starting point of 70 degrees to its nominal upper limit of 85 degrees.

The preference for higher phase angles and thus increased first stage cooling during cooldown stems from the larger thermal mass of the first stage, which typically drives the cooldown time of the RSP2 cryocoolers. From the figure, it can be seen that as the 1$^{st}$ and 2$^{nd}$ stage temperatures approach their set points, the input power is reduced along with the Stirling phase until the input power and phase required to maintain the desired stage temperatures are determined. No trim heat was added during this test and no user inputs were made except for the initial input of the desired temperature set points.

## CONCLUSIONS

A dual stage temperature control algorithm has been demonstrated for the Raytheon Stirling pulse tube hybrid two stage (RSP2) cryocoolers which is capable of independently controlling the temperature at each stage without the addition of any trim heat. The control algorithm utilizes the unique capability of Stirling / pulse tube cryocoolers to alter their ratio of first to second stage cooling capacities by variation of the Stirling phase angle. The controller seeks the unique combination of phase angle and input power which exactly holds the applied loads at a commanded set of temperatures; by doing so, it also minimizes the input power required to maintain the temperature

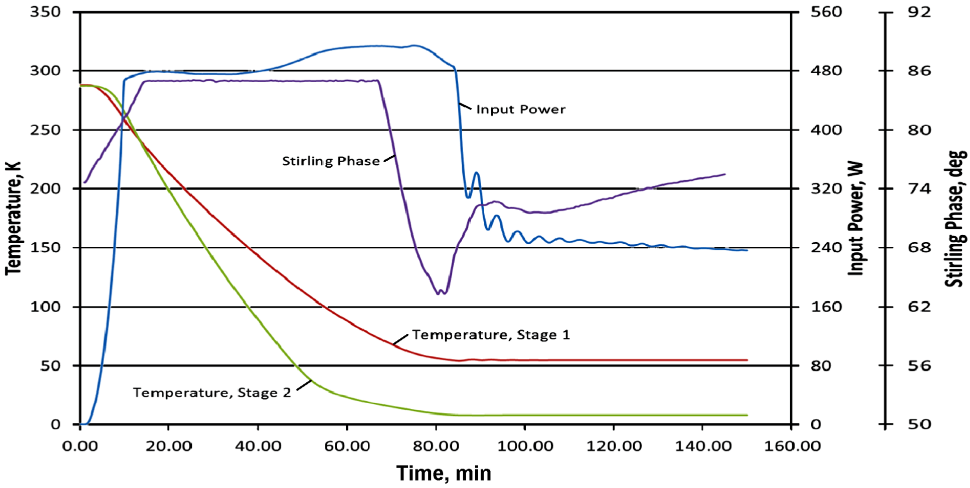


**Figure 4.** Demonstration of dual stage temperature control during cooldown from 295 K to 55 K / 8 K first/second stage temperatures.

setpoints. The capability to independently adjust the cooling capacity at both stages provided by the RSP2 cryocoolers and the dual stage temperature control algorithm provides valuable flexibility at every stage of a typical instrument design and mission cycle, from the preliminary design phase to end of life operation.

## ACKNOWLEDGEMENTS

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