Mid InfraRed Instrument (MIRI) Cooler Subsystem Design

D. Durand, D. Adachi, D. Harvey, C. Jaco, M. Michaelian, T. Nguyen, M. Petach, and J. Raab

Northrop Grumman Space Technology
Redondo Beach, California, 90278 USA

ABSTRACT

The Cooler Subsystem for the Mid InfraRed Instrument (MIRI) of the James Webb Space Telescope (JWST) features a 6.2 K Joule-Thomson (J-T) cooler precooled by a three-stage Pulse Tube (PT) cryocooler to provide 68 mW of cooling at the instrument's Optical Bench Assembly (OBA). Having demonstrated Technology Readiness Level 6 (TRL 6) in early 2007, the focus shifted to the flight cooler subsystem design. This paper includes additional characterization of the pulse tube pre-cooler, obtained since the last publication, and an update to the overall cooler subsystem performance estimate, anchored by the TRL 6 end-to-end performance tests. The performance model includes the efficiency of the Cryocooler Control Electronics (CCEs), as measured on previous flight and flight-like electronics units. The update to the total cooler system performance estimate also includes the effect of the thermal rejection system, used to conduct the heat dissipated at the compressor/pre-cooler assembly to the spacecraft radiators and the effectiveness of the radiators themselves.

INTRODUCTION

The Mid InfraRed Instrument (MIRI) Cooler Subsystem cools the MIRI focal plane arrays to the operating temperature of 6.7 K using a closed cycle helium Joule-Thomson cooler precooled by a three-stage pulse tube cryocooler. The MIRI Cooler design provides a 6.2 K remote cold head interface on the optical bench, near the focal plane modules. Much of the cooler hardware, including the Joule-Thomson compressor, the pulse tube pre-cooler, and cooler drive/control electronics is located in the spacecraft bus, several meters from the instrument's OBA, as has been shown previously.[1] Figure 1 shows a functional block diagram of the MIRI Cooler. The J-T and PT compressors are each driven by a dedicated Cryocooler Control Electronics (CCE) unit. The CCE driving the Joule-Thomson compressor (the J-T CCE) has a maximum drive power rating of 180 W, the same value as CCE designs on recent NGST flight programs based on High Efficiency Cryocooler (HEC) sized pulse tube cryocoolers. The CCE driving the Pulse Tube pre-cooler (the PT CCE) is twice as large, with a maximum drive power rating of 360 W. Both CCEs are standby redundant, connected to their respective compressor through the Relay Switch Assembly (RSA).

The MIRI Cooler must provide continuous cooling at the operating temperature of 6.2 K, the steady state mode, and cool the Optical Module Stage (OMS) down from 100 K to operating temperature. The first part of the cool-down is performed by circulating cold helium gas through the OMS

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

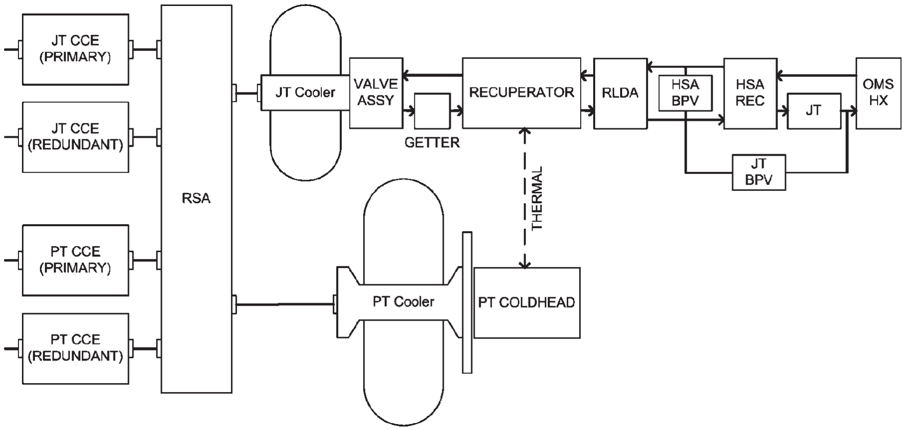

Figure 1. MIRI Cooler Subsystem Block Diagram. "J-T" stands for Joule-Thomson, "CCE" stands for Cryocooler Control Electronics, "RSA" stands for Relay Switch Assembly, "RLDA" stands for Refrigerant Line Deployment Assembly, and "BPV" stands for ByPass Valve. "HSA REC" is the lowest temperature recuperator, and "OMS HX" is the low temperature heat exchanger providing the interface to the load from the focal plane modules.

heat exchanger while bypassing the HSA recuperator and the Joule-Thomson (J-T) restriction. This "bypass mode" is used until the OMS is cooled to low enough temperature to transition into the J-T mode, in which the HSA recuperator and J-T restriction are used. The point of transition from the bypass mode into the J-T mode is the most stressing performance point, providing the least cooling power for the given bus power, and is known as the "pinch point." A key design driver is the need to meet both steady state and pinch point cooling loads with high efficiency.

PULSE TUBE PRECOOLER CHARACTERIZATION

The efficiency of the pulse tube pre-cooler is an important factor in the overall performance of the MIRI Cooler Subsystem. The pulse tube pre-cooler, working in conjunction with a multistage J-T recuperator, must cool the helium gas for the Joule-Thomson loop to a temperature of approximately 18 K for steady state operation and down to 14 K during cool-down. The PT pre-cooler requires more drive power during cool-down than at steady state. The spacecraft thermal rejection design is based on a fixed thermal conductance between the compressor assembly and the radiator, without active temperature control of the interface. This leads to a power dependence of the thermal rejection temperature at the pulse tube pre-cooler interface. The reject temperature will be higher during the cool-down, including the pinch point, than during steady state operation. Therefore, in order to complete the end-to-end performance model, the pulse tube pre-cooler performance is characterized as a stand-alone subassembly as a function of drive power, cold head temperature, and thermal reject temperature with simultaneous thermal loads on the second and third stages. The ranges of these operating conditions are chosen to envelope or match conditions expected during the different MIRI Cooler Subsystem modes of operation.

Figure 2 shows the pulse tube pre-cooler load line for higher power (300 W PV) and correspondingly higher applied load than are expected during operation, providing a performance measurement to anchor the model and demonstrating more than the required hardware capacity. The test was repeated after replacing the third stage of the pulse tube cold head with a second unit, demonstrating excellent unit to unit reproducibility of this key component.

Figure 3 the pinch point during cool-down. As with Figure 2, there are two load lines, one for the third stage pulse tube cold head Test Article 1 (TA1), and the other for Test Article 2 (TA2). Again, the data demonstrates excellent unit-to-unit consistency.

Figure 4 shows load lines for pulse tube cold head TA2 at two rejection temperatures. A laboratory fluid loop chiller is used to control the temperature at the thermal rejection interface.

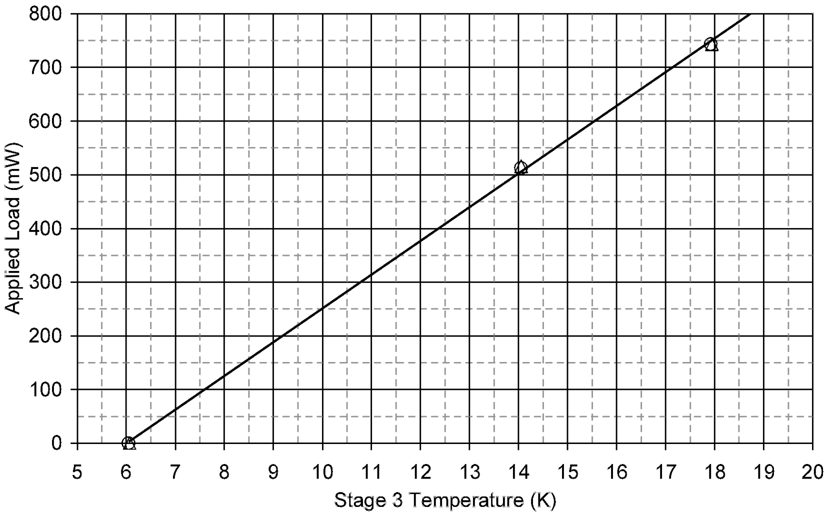

Figure 2. Pulse tube pre-cooler load line for 300 W PV drive power at 300 K reject temperature. The test was repeated for two test articles of the cold head third stage. The performance of Test Article 1 (open triangles) and Test Article 2 (open circles) are essentially identical. The sold line is a linear fit to the Test Article 1 data.

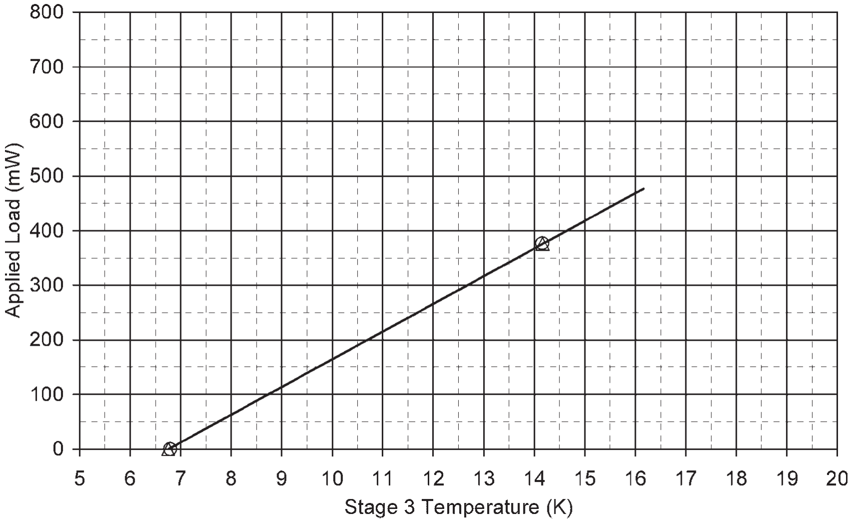

Figure 3. Pulse tube pre-cooler load line for 225 W PV drive power at 317 K rejection temperature with a constant 275 mW load applied to the second stage. The performance of Test Article 1 (open triangles) and Test Article 2 (open circles) are essentially identical. The sold line is a linear fit to the Test Article 1 data.

The rejection temperatures shown on Figure 4 are measured on the top of the center plate at the midpoint between the bases of the two pulse tube cold heads. They are approximately 5 K higher than the temperature at the head rejection interface. This data anchors the reject temperature dependence of the pulse tube pre-cooler performance over the range required to model the overall MIRI Cooler performance for both steady state and the pinch point

Figure 3 shows the load line with a constant 275 mW applied to the second stage of the pulse tube cold head and at drive power and rejection temperature close to the expected conditions for the pinch point. Figures 2 and 3 each contain data from two tests, one for the third stage pulse tube cold

Figure 4 shows load lines of the pulse tube pre-cooler for 133 W PV drive power at two rejection temperatures. A laboratory chiller is used to control the temperature at the PT cooler's thermal rejection interface during these tests. The rejection temperatures listed in the caption of Figure 4 are measured at a location on the cooler close to the base of the pulse tube cold head and some distance from the thermal rejection interface. As a result they are approximately 5 K higher than the temperature at the head rejection interface. This data anchors the reject temperature dependence of the pulse tube pre-cooler performance over the range required to model the overall MIRI Cooler performance for both steady state and the pinch point.

COOLER SUBSYSTEM PERFORMANCE ESTIMATES

The total cooler subsystem performance, expressed as the cooling lift provided at 6.2 K given the specified electric power drawn from the spacecraft bus, depends on several factors: the design and performance of the cooler Thermal-Mechanical Unit (TMU), the efficiency of the Cryocooler Control Electronics (CCE), the characteristics of the spacecraft thermal rejection system, and the external parasitic heat load on the exposed refrigerant lines and HSA. A thermodynamic performance model, anchored in component characterization tests and end-to-end test of the integrated thermal-mechanical unit, is used to calculate the expected cooler subsystem performance taking into account the modeled behavior of the spacecraft thermal rejection system.

Components of the J-T cooler, including the compressor, restriction, and recuperators, have been characterized in isolated tests and as part of end-to end tests. The pulse tube pre-cooler and J-T cooler compressors are each driven by an independent CCE unit. The CCE for the J-T compressor drive is closely based on our standard Advanced Cryocooler Electronics (ACE) design, rated up to 180 W of compressor drive. The CCE for pulse tube pre-cooler drive has twice the drive capability, 360 W compressor drive. The performance of the CCE units is characterized in terms of unit level efficiency over the range of drive levels. Cryocooler control electronics performance is based on the measured efficiency of previous flight or flight like units. The efficiency of the Pulse Tube

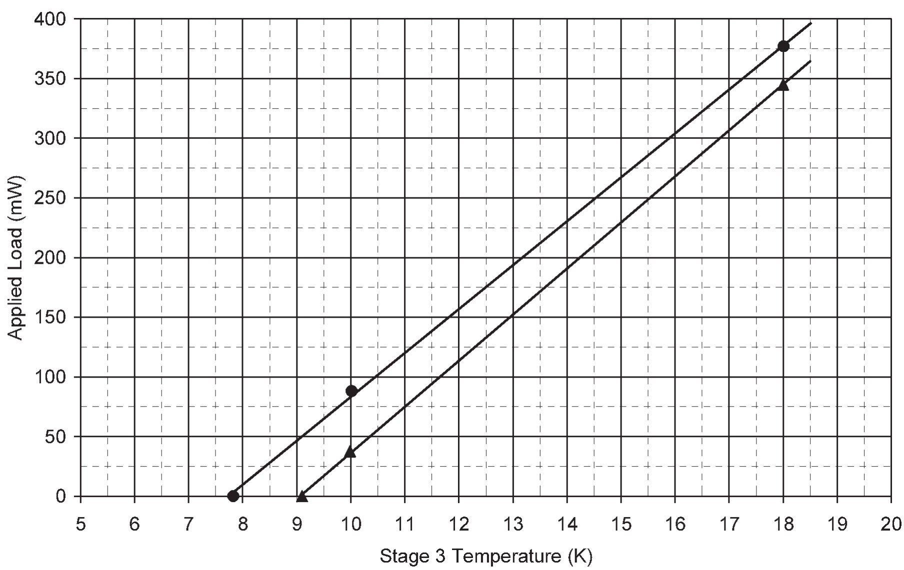

Figure 4. Pulse tube pre-cooler stage 3 load lines for two values of thermal rejection temperature for 133 W PV power. The solid circles (triangles) correspond to 300 K (317 K) reject temperature, as measured in the test. These temperatures are approximately 5 K higher than the thermal interface temperature in each case. Solid lines are linear fits to the data.

combines the characterized performance of the subassemblies to produce the total cooler integrated performance.

Table 1 shows the performance and some of the internal parameters for operation at steady state and at the pinch point. The thermal reject temperature is 298 K at steady state and 310 K at the pinch point.

Figure 5 shows the maximum lift available at the OMS heat exchanger as a function of the parasitic load on the refrigerant lines and HSA for both steady state and pinch point modes. Any pair of loads below the dashed line in Figure 5 can be accommodated by the cooler in steady state for less than 400 W and any pair of loads below the solid line in Figure 5 can be accommodated by the cooler at the pinch point for less than 475 W bus power.

Table 1 MIRI Cooler Performance at Steady State and at the Pinch Point.

	Steady State	Pinch Point
PT CCE Power Draw (W)	268	341
JT CCE Power Draw (W)	131	134
Total Power Draw (W)	**400**	**475**
PT Input Power (W)	208	269
JT Input Power (W)	101	103
Lift at lines and HSA (mW)	**77**	**77**
Lift at OMS (mW)	**90.2**	**75.3**

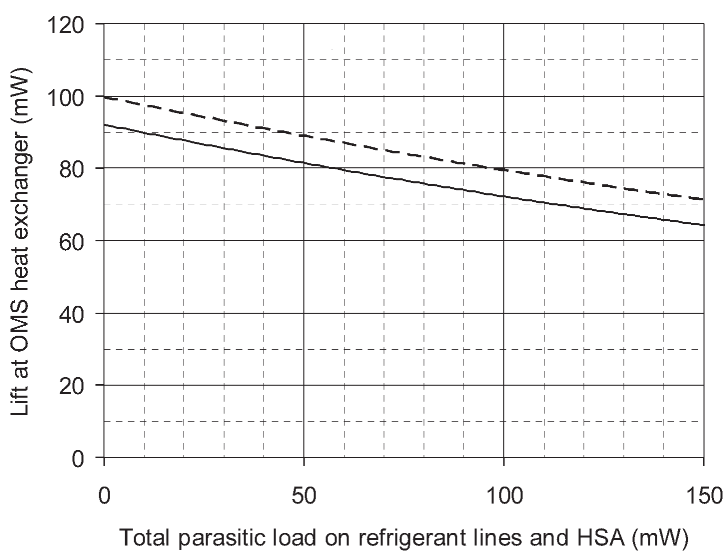

Figure 5. Lift available at the remote Optical Module Stage (OMS) heat exchanger as a function of the total external parasitic heat load on refrigerant lines and on the HSA, the assembly containing the cold J-T recuperator (the acronym "HSA" is left over from an earlier system design). The dashed line shows the OMS cooling at 6.2 K in the steady state with total bus power equal to 400 W. The solid line shows the OMS cooling at the pinch point with the total bus power equal to 475 W.

CONCLUSION

The MIRI Cooler Subsystem design provides sufficient cooling for both steady state operation and during cool-down taking into account the performance of the fixed conductance thermal rejection system of the host spacecraft. NGST's thermodynamic performance model of the MIRI Cooler Subsystem is anchored in extensive characterization tests of components and subassemblies as well as integrated end-to-end tests. The performance of the spacecraft thermal rejection system has been independently modeled and its effect has been incorporated in the overall performance model.

ACKNOWLEDGMENT

This work is funded by NASA and managed by the California Institute of Technology, Jet Propulsion Laboratory.

REFERENCES

1. Durand, D., Colbert, R., Jaco, C., Michaelian, M., Nguyen, T., Petach, M., and Tward, E.,"NGST Advanced Cryocooler Technology Development Program (ACTDP) Cooler System," *Cryocoolers 14*, ICC Press, Boulder, CO (2007), pp. 21 – 29.

2. Durand, D., Colbert, R., Jaco, C., Michaelian, M., Nguyen, T., Petach, M., and Raab, J., "Mid InfraRed Instrument (MIRI) Cooler Subsystem Prototype Demonstration," *Adv. in Cryogenic Engineering*, Vol. 53, Amer. Institute of Physics, Melville, NY (2008), pp. 807-814.