# MIRI Cooler System Design Update

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## ABSTRACT

The Mid InfraRed Instrument (MIRI) for the James Webb Space Telescope (JWST) requires cooling at 6 Kelvin for the SiAs focal planes, provided by the active cooler. The four stage cooler consists of: a three stage pulse tube pre-cooler, Joule Thompson (JT) circulator and upper stage recuperators, located on the JWST spacecraft bus, and the final stage recuperator and 6K JT expander, located at the remote instrument module with a 12 meter round trip line at 18-22K between the spacecraft and instrument. Since our last report on the cooler design, the JWST program has made design changes to the overall thermal design, including the addition by Goddard Space Flight Center (GSFC) of an actively cooled thermal shield surrounding the MIRI Optical Module to increase the overall thermal efficiency and thereby increase the margin between the cooler lift capability and the expected heat loads. This change shifts a portion of the thermal load from the 6K cooler stage to the 18-22K stage. Meeting the increased thermal load at 18-22K and realizing the benefit from the decreased load at 6K requires operating the cooler at a considerably different set of operating points. In this paper we report on the required changes to the cooler's operation and design, and demonstration that the basic design has the capacity to meet the new requirements.

## INTRODUCTION

The Mid InfraRed Instrument (MIRI) Cooler Subsystem cools the MIRI focal plane arrays to their operating temperature of 6.7 Kelvin using a closed cycle helium Joule-Thomson cooler pre-cooled by a three-stage pulse tube cryocooler. As described previously [1, 2, 3, and 4], the MIRI Cooler design provides a 6.2 Kelvin 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 Optical Module (OM). Figure 1 shows an updated functional block diagram of the MIRI Cooler. A heat exchanger has been added to the return path of the Joule-Thomson helium gas on the "18 Kelvin" side of the coldest recuperator to provide a thermal interface for the heat load from the actively cooled thermal shield surrounding the OM (see the dashed oval in Figure 1).

In terms of thermodynamic performance, thermal load applied to the shield heat exchanger (SH HX) and parasitic load on the refrigerant return line, including the Refrigerant Line Deployment Assembly (RLDA), are essentially equivalent and the driving requirement is

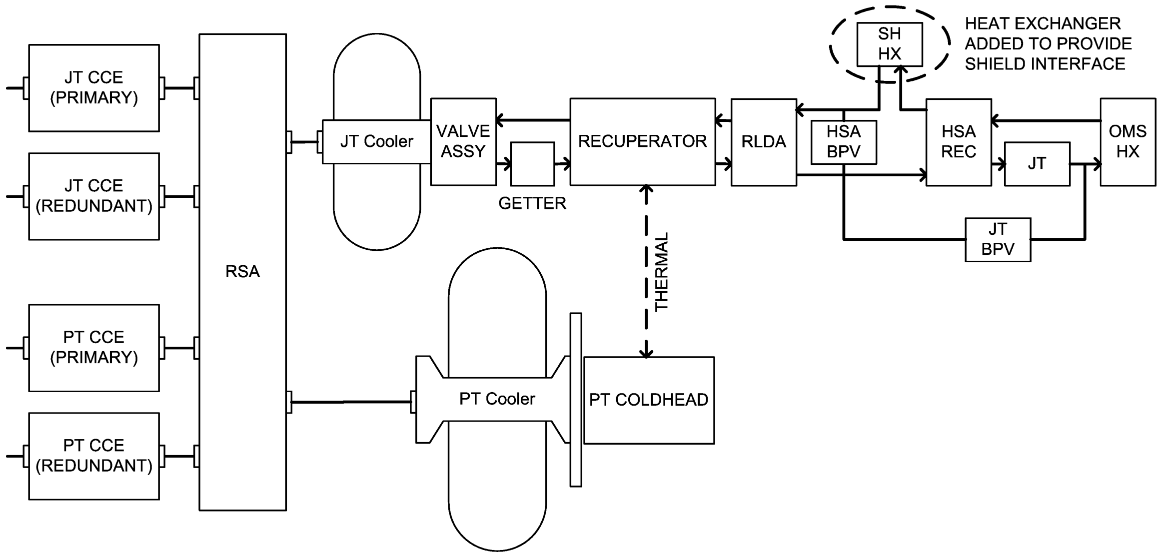


**Figure 1**. MIRI Cooler Subsystem Block Diagram as shown in Reference 4, except for the addition of the actively cooled shield heat exchanger "SH HX" shown in the dashed oval. "JT" stands for Joule-Thomson, "CCE" stands for Cryocooler Control Electronics, "RSA" stands for Relay Switch Assembly, "RLDA" 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.

the total heat load on the nominally 18 Kelvin stage of the cooler. The cooler had been designed and tested to heat loads in the steady state of 68 mW at 6.2 Kelvin with a simultaneous load of 79 mW divided equally between the refrigerant supply and return lines. Changes in the MIRI/JWST cryogenic system design led to the current cooler requirements of 55 mW at 6.2 Kelvin and 232 mW total load on the shield heat exchanger and on the refrigerant lines. The new requirements change the balance between the "18 Kelvin" and 6.2 Kelvin loads and represent an overall load increase. For small changes near the previous operating point, the relative effect on required input power of heat at 6.2 Kelvin is approximately six times that of the same amount of heat at 18 Kelvin (see Figure 5 of Reference 4, for example). With no other changes, the reduction of 13 mW at 6.2 Kelvin would be expected to enable an increase of roughly 78 mW at 18 Kelvin. The increase in 18 Kelvin load of 153 mW is nearly twice that.

The JT and PT compressors are each driven by a dedicated Cryocooler Control Electronics (CCE) unit. There are no changes to the design of either the JT-CCE or the PT-CCE required to adapt to the changed requirements. As has been the case, both CCEs are stand-by redundant, connected to their respective compressor through the Relay Switch Assembly (RSA).

## COOLER SUBSYSTEM PERFORMANCE TESTING

Functional performance testing of the Development Model (DM) Cooler was similar to that used to demonstrate Technology Readiness Level Six (TRL 6), as described in Reference 3. Key hardware changes from the previous testing include replacing the pulse tube pre-cooler with the one used to validate the reproducibility of the design (see Reference 4), replacing the laboratory version of the Joule-Thomson compressor with a higher fidelity, flight-like prototype, and changing the JT restriction to allow higher mass flow through the JT loop. The performance of the pulse tube pre-cooler is described in detail in Reference 4. In addition to design and construction consistent with flight hardware, the prototype Joule-Thomson compressor incorporates internal design changes leading to an increase in efficiency, at the compressor level, of approximately 25-30%. Figure 2 shows the prototype valved compressor. The JT restriction design remains unchanged, just the defining dimension was changed to allow the higher massflowrate. Other pieces of hardware from the TRL 6 testing series have been replaced with no intentional change in thermodynamic performance.

**Figure 2**. Flight-like prototype valved compressor used to circulate helium gas in the Joule-Thomson cooling loop.

Performance testing is conducted in a complete "end-to-end" test with the PT pre-cooler, pre-cooler recuperator, line representing the length of the RLDA, remote recuperator and all cold JT hardware in a 36 inch bell-jar vacuum chamber with cooled shields to provide the low background temperature for hardware to be located in the cold environment inside the Integrated Science Instrument Module (ISIM) in the application. Resistive heaters are used to apply explicit heat loads and simulate parasitic loads.

Figure 1 shows the highest performing approach to adding a thermal interface for the actively cooled shield, the addition of the shield heat exchanger. It is also possible to provide cooling to the shield by attaching it with a conductive strap to the structure of the HSA at a somewhat degraded performance. In the test, either configuration can be simulated by applying the heat to the appropriate heaters. For the heat exchanger design, all the shield heat is applied to the return refrigerant line. The design utilizing a conductive strap to the structure of the HSA was simulated by applying the specified shield heat load to the supply line. Both approaches were tested.

## RESULTS

Cooling lift at the OM heat exchanger was measured as a function of temperature, both in the initial cool-down, or "bypass" mode where the pre-cooled helium gas bypasses the Joule-Thomson restriction and passes directly through the OM heat exchanger, and in the Joule-Thomson mode. Heat is applied to the resistive heaters in close thermal contact with the refrigerant lines and the HSA structure during the test to represent the 18 Kelvin and line loads. The equivalent of 475 W of bus power is applied during the cool-down and data is taken near the steady state temperature with the equivalent of 400 W applied. From this data the maximum OM heat exchanger load at the pinch point and at steady state, corresponding to full bus power is measured. The thermal rejection temperature of the PT pre-cooler is controlled with an actively controlled liquid cooled heat exchanger.

Figure 3 shows the measured line load, equivalent to the sum of the load from the actively cooled shield and the parasitic load on the lines, and the cooler's lift at the OM heat exchanger for the pinch point and steady state for both design options for providing the shield interface, the thermal strap and the heat exchanger. In each case, two measurements are made, one with the applied line load below the required value and the other with the line load above the requirement, to enable accurate interpolation to the OM lift at the actual required line load value.

| Measured | | | | | | | Extrapolated to current requirements | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Mode | Line Load | OM Lift | OM Temp | HSA T | Bus Power | Trej | Local slope | Line Load | OM Lift | OM req |
| **Strap at Pinch Point** | | | | | | | **Strap at Pinch Point** | | | |
| Strap PP | 239mW | **52mW** | 19.9K | 20.0K | 476 W | 310K | -0.110mW/mW | 203.1mW | **56.1mW** | 56.4mW |
| Strap PP | 208mW | **56mW** | 19.0K | 19.2K | 471 W | 310K | | | | |
| No Load PP | 0mW | **97mW** | 15.2K | 13.9K | 470 W | 310K | | | | |
| **Strap at Steady State** | | | | | | | **Strap in Steady State** | | | |
| Strap SS | 239mW | **72mW** | 6.2K | 22.0K | 400 W | 306K | -0.164mW/mW | 232.3mW | **73.6mW** | 55.2mW |
| Strap SS | 208mW | **78mW** | 6.2K | 21.3K | 400 W | 306K | | | | |
| No Load SS | 0mW | **113mW** | 6.2K | 17.2K | 395 W | 307K | | | | |
| **HX at Pinch Point** | | | | | | | **HX at Pinch Point** | | | |
| HX PP | 241mW | **58mW** | 19.1K | 19.2K | 475 W | 310K | -0.160mW/mW | 203.1mW | **63.8mW** | 56.4mW |
| HX PP | 208mW | **63mW** | 18.3K | 18.4K | 476 W | 310K | | | | |
| No Load PP | 0mW | **97mW** | 15.2K | 13.9K | 470 W | 310K | | | | |
| **HX at Steady State** | | | | | | | **HX at Steady State** | | | |
| HX SS | 241mW | **75mW** | 6.2K | 21.7K | 400 W | 306K | -0.159mW/mW | 232.3mW | **76.2mW** | 55.2mW |
| HX SS | 208mW | **81mW** | 6.2K | 20.9K | 400 W | 306K | | | | |
| No Load SS | 0mW | **113mW** | 6.2K | 17.2K | 395 W | 307K | | | | |

**Figure 3**. Measured MIRI DM Cooler performance data points, left, consisting of two measurements near each required condition to characterize the local slope of OM heat lift as a function of line load and the extrapolated value at the required line load value, right. Measurements are made for each required condition, Pinch Point and Steady State for the heat exchanger approach, indicated by "HX," and for the passive thermal strap approach, indicated by "Strap." The limiting case where the line loads go to zero are also shown for reference. When the line loads are zero, there is no difference between the "Strap" and "HX" configuration, the data is simply repeated to provide a data set for each configuration.

These measured performance values meet the requirements for the MIRI Cooler application. Using a heat exchanger to provide the thermal interface to the actively cooled shield provides improved performance over the use of a thermal strap.

## CONCLUSION

The measurements reported here demonstrate the ability of the MIRI Cooler design to meet the modified cooling requirements, corresponding to changes in the overall MIRI and ISIM cryogenic design, including the addition of an actively cooled thermal intercept shield around the MIRI Optical Module. The net effect of the cryogenic system design changes and the newly demonstrated cooler capability is an increase in the overall margin of cooling capability over the expected thermal loads.

The thermodynamic model of the MIRI Cooler, anchored in measurements made during the demonstration of Technology Readiness Level Six (TRL 6), was used to predict cooler performance in the range of operating conditions beyond any the cooler had been characterized to previously. The model included the behavior of the thermal rejection system connected to the hot-side thermal interface of the pulse tube pre-cooler. A flight-like prototype Joule-Thomson compressor, replacing the laboratory version used in the TRL 6 testing performed previously, demonstrated increased thermodynamic efficiency. Adjusting the cooler design and operating conditions, using essentially unchanged components including the entire pulse tube pre-cooler, the Joule-Thomson compressor and recuperators, and the cryocooler control electronics driving the pulse tube pre-cooler and Joule-Thomson compressor, we were able to demonstrate in test the newly defined performance requirements. In addition to successfully adapting the design and operating parameters to meet the requirements for the MIRI/JWST mission, the design and modeling tools enable reliable performance predictions for other space-based astronomy applications.

## ACKNOWLEDGMENT

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