Modifications to the MIRI cryocooler design to provide significant lift in the 2K to 4K range

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Abstract. A high Technology Readiness Level cryocooler with significant cooling in the 2K to 4K regime will enable a variety of missions ranging from large infrared space telescopes to superconducting and quantum applications. The cryocooler for the MIRI instrument on JWST was designed for operation at 6K, and with relatively minor changes this design can achieve significant lift in the 2K to 4K region. This paper provides curves of predicted lift vs. power for a variety of operating temperatures, based on the model anchored by tests of the MIRI cooler. The modifications are described, and their mass impacts are estimated. These mass and performance estimates enable payload and mission planners to explore new mission classes.

1. Introduction
This study was motivated by space astrophysics applications that require the precooling of very low temperature sensors to temperatures below 2K, and in some cases the cooling of telescope mirrors to temperatures as low as 4K [1]. Space sensors such as those on the Herschel and Astro-H missions require cooling to 50mK in order to achieve sensitivity at very long infrared and mm wavelengths. To date these sensors have been cooled with various low temperature cooling stages such as adiabatic demagnetization refrigerators (ADR) or closed cycle adsorption driven ⁴He evaporative coolers or dilution refrigerators. All of these devices reject their heat to a precooler operating in the 1.3K to 4.5K temperature range, depending on type and their design configurations. A second application to achieve background limited sensitivity out at these wavelengths requires cooling of telescope reflectors to the 4K temperature range [2,3]. To date this has been accomplished with stored cryogens on missions such as IRAS, COBE and Spitzer with the telescope design and mirror size limited by the lifetime of the cryogen. Next generation instruments with 4K reflectors in the 10 meter size range will require large capacity mechanical cryocoolers.

NGAS has developed and manufactured a large number of space flight cryocoolers covering the temperature range from 6K to 200K [4]. The cryocooler that we modeled in this study is based on modifications to the Mid Infrared Instrument (MIRI) flight cooler [5,6,7] manufactured by NGAS for NASA’s James Webb Space Telescope (JWST) shown in Figure 1. As a result the modeled cooler is a relatively mature Technology Readiness Level 6 (TRL 6) and includes major subsystems that are TRL 8. The MIRI cryocooler was designed to cool a sensor and its shields to 6K and 18K, respectively. We will show that with relatively minor modifications, this cooler could address the precooling needs of the very low temperature sensors and even the cooling of large reflectors to the 4K temperature range.
Figure 1. MIRI Cooler and some of its major subsystems.

Figure 2 shows a block diagram of the cooler. The cooler is a hybrid pulse tube/ Joule Thomson (JT) cooler. A three stage pulse tube cooler precools the circulating helium gas for the lowest temperature JT stage. The three stage pulse tube cooler [8] was originally designed as a 10K cooler that can also provide additional cooling at each of its three stages for other components including thermal shields. The pulse tube and JT coolers have independent working gases and independent gas volumes. For this study, no changes were made to the pulse tube precooler - all changes were to the JT cooler.

The existing MIRI Joule Thomson cooler uses the TRL 9 HEC compressor with the addition of rectifying reed valves to pressurize and circulate the 4He JT gas. It acts as a vibrationally balanced single compression stage compressor. The JT recuperators (R2, R3, R4) through which the JT stage’s pressurized helium flows are precooled at each of the three pulse tube stages. The precooled helium then passes through the JT recuperator (R1) and is further cooled to 6 K at the JT expander. The bypass valve can be used to precool a large heat capacity load, if necessary. The fact that the JT cooling stage can be located many meters from the basic cooler as it is on MIRI is especially relevant to the cooling of a large reflector.
The MIRI cooler can be modified to operate efficiently at lower temperatures, as previously described [9], by adding another JT compressor to act as an additional compression stage, increasing the recuperator tube size modestly, and optimizing the length of the JT restriction. These modifications are indicated in the red text in Figure 2. In the previous paper [9] a point design for a large cooler telescope cooled to 4.5K was presented. In this current study, we extend this modeling to provide predictions of the performance of the modified MIRI cooler over a broad range of conditions suitable for supporting a range of potential future missions.

For this modeling effort we changed the operating conditions and/or changed the working fluid. In addition we modeled changing the single stage JT compressor to a multistage higher pressure ratio JT compressor. In all cases we changed the operating conditions of the PT precooler in order to optimize precooling for the JT cooler but made no hardware changes to the PT precooler. For the JT cooler working fluid we modeled the use of $^4$He for temperatures above 4K and the use of $^3$He for temperatures below 4K where it becomes advantageous.

The model used in this study was previously used in the development of the MIRI cooler and has been compared against measurements from that cooler [6]. Both a detailed SAGE model, and a reduced model were developed and compared against the measured performance of the MIRI Cooler. For this work, the reduced model and NIST REFPROP 9 fluid properties were used.

2. Results
The current MIRI stage cooler was designed for cooling a primary load at 6K with an additional upper stage heat exchanger for remotely intercepting parasitic loads at 18K. Figure 3 shows the predicted cooling vs input power of this configuration with its single compression stage JT compressor (Figure 1) when $^4$He gas is used as the working gas for cooling at 6K and 18K. The model includes the power dissipation of the MIRI flight electronics, hence we report the power going into the cooler’s drive electronics, i.e. the spacecraft bus power. Based on the approximately 5% to 10% difference between the model and measurements over the range of measurements shown in figure 3, we expect that the modeling results for the proposed configurations have a similar approximately +/- 10% uncertainty band for the cases that use $^4$He, with higher uncertainty for the configurations that use $^3$He.
Next we show the predicted performance of the cooler when we use $^4$He and augment the existing single stage JT compressor with an additional compressor stage with larger swept volume. This allows achieving the same mass flowrates as the MIRI cooler but with lower input pressures and a larger compression ratio, thus allowing lower temperature operation. For this configuration, we can use a design variant of the MIRI compressor that has larger pistons. We have previously demonstrated cooling at 4.5K with the development model of the MIRI cooler, utilizing a laboratory compressor for the additional lower compression stage [10]. Subsequently, we have developed to Critical Design Review level a flight version of the compressor with pistons that are approximately twice the diameter of the MIRI JT compressor. This new design variant has been originally developed for use in a heat engine application [11], then prototyped and taken to released drawing status on subsequent NASA programs. Based on this thermoacoustic power convertor (TAPC) development heritage we call this the TAPC compressor. It uses the same motor and flexure design as the existing MIRI compressor, the only significant difference is the larger piston diameter. The TAPC compressor would need reed valves added to it to make it a JT compressor, similar to the prior addition of reed valves to the HEC pulse tube cryocooler compressor to make it a JT compressor. The MIRI reed valve design would be scaled to the larger area needed for the lower pressure operation. The use of this new design variant of the JT compressor for the additional lower stages is the basis for the model predictions that follow.

There are two configurations in which we can utilize the TAPC design as an additional compressor. The simplest of these is to add it as a lower stage in the usual back to back configuration, which then results in a two stage compression of the helium. Referring to Figure 2, the first stage of compression is from the TAPC compressor sides “C”& “D” and the second stage is from the MIRI compressor sides “A”&“B”. The predicted results for this configuration at 4.5K are shown in Figure 4. The predicted lift shown in Figure 4 is about 20% greater than the measurements and predictions in the prior demonstration [10], which is because the current predictions allow the use of a JT restriction length that is optimized to the design point, as opposed to previously having to use the JT restriction hardware that was optimized for 6.2K operation. With this configuration the cooler is predicted to lift 157 mW at 4.5K with no intercept load, or 97 mW lift at 4K with 250mW of load intercepted at approximately 15K.

| Number of Stages | Description       | T (K) | Compressor Staging | Pressure ratio | Inlet Pressure (Bar) | cm$^3$/stage Ideal volume ratios and bottlenecks |
|------------------|-------------------|-------|--------------------|----------------|----------------------|-----------------------------------------------|
| 1 stage          | MIRI              | 6.2K  | A&B                | 3:1            | 4.2                  | 6 6                                           |
| 2 stage          | TAPC+MIRI         | 4.5K  | D&C > A&B          | 9:1            | 0.9                  | 30>6 30 >10 (18>6)                             |
| 3 stage          | Split TAPC + MIRI | 4.5K  | D >C>A & B         | 27:1           | 0.9                  | 15>15>6 15>5,1.7                               |
| 4 stage          | Split TAPC + Split MIRI | 2.5K  | D > C > A & B > B  | 81:1           | 0.3                  | 15>15>3>3 15>5>1.7>0.6                       |

For additional lift at 4.5K we can make each half of the TAPC compressor act as an independent compression stage, similar to the configuration flown by ESA on the Planck mission [12,13]. Referring to Figure 2, the first stage of compression is then from the TAPC compressor sides “D”, the second stage of compression comes from the TAPC compressor side “C” and the third stage of compression is from the back-to-back MIRI JT compressor sides “A”&“B”. This provides three stages of compression, but reduces the swept volume of the lowest stage by a factor of two. Figure 5 shows that this is an acceptable trade that results in a significant increase in lift at all bus powers. With this configuration the cooler can lift 200 mW at 4.5K with no intercept load, or 140 mW lift at 4K with 250mW of load intercepted at approximately 18K.
Figure 4. Predicted heat lift at 4.5K using MIRI cooler with two stage compression implemented via back-to-back TAPC compressor with $^4$He.

Figure 5. Lift at 4.5K for the configuration in which the TAPC compressor is set up as two stages, and the MIRI compressor is used as the third stage, and the gas used is $^4$He.

Since the power split between the Pulse Tube precooler and the JT compressor can be varied by command, there are many possible combinations of intercept temperature, intercept load and lift at 4.5K. To illustrate a representative set of conditions, we have modeled the case in which the intercept load is always four times the load at 4.5K, both for the case of a constant 18 K intercept temperature, and for
the case where the intercept temperature is allowed to vary so as to minimize the total power needed. These predicted results are shown in Figure 6.

Figure 6. 4.5K lift with 3 stage compressor and ⁴He. Intercept load is 4X the 4.5 load. a) constant intercept temperature of 18K, b) intercept temperature varied to minimize the Bus Power.

This cooler configuration can be extended to lower temperature by switching to ³He, and reducing the operating pressure. Efficient operation at these low temperatures is achieved by splitting the two halves of the MIRI JT compressor into independent stages, which in conjunction with the split TAPC compressor provides 4 stage compression. Referring to Figure 2, the first stage of compression is from the TAPC compressor sides “D”, the second stage from the TAPC compressor side “C”, the third stage is from the MIRI compressor sides “B” and the fourth stage is the MIRI compressor sides “A”. This four stage compression not only accommodates the lower pressure, the resulting high compression ratios also mean that substantial cooling power is achieved at mass flowrates substantially lower than in the MIRI cooler application. This reduced mass flow rate allows recuperator lengths to be reduced by a factor of four, which helps to counteract the pressure drop in the recuperators that results from the lower gas density and lower operating pressures. To further accommodate the reduced pressure, the tubing diameter in the lower recuperator is increased by approximately two times relative to the MIRI cooler dimensions. The predicted lift in this configuration at 2.5K and 1.7K is shown in figure 7.

Figure 7. Lift at 2.5K and 1.7K with compressor configured for four compression stages, using ³He.
The model results discussed above are summarized in Table 2 as heat lift and bus power at the maximum cooler capability, both for the case with no intercept load and with 250 mW intercept load.

| Number of Stages | Description | T (K) | Gas  | Max Lift with no intercept | Max Lift with 250mW intercept | Bus Power |
|------------------|-------------|-------|------|----------------------------|-------------------------------|-----------|
| 1 stage          | MIRI        | 6.2K  | 4He  | 216mW @ 6.2K               | 154mW @ 6.2K                 | 510Wdc    |
|                  |             |       |      |                            | 250mW @ 15K                  |           |
| 2 stage          | TAPC+MIRI  | 4.5K  | 4He  | 157mW @ 4.5K               | 97mW @ 4.5K                  | 545Wdc    |
|                  |             |       |      |                            | 250mW @ 15K                  |           |
| 3 stage          | Split TAPC + MIRI | 4.5K  | 4He  | 200mW @ 4.5K               | 145mW @ 4.5K                 | 526Wdc    |
|                  |             |       |      |                            | 250mW @ 15K                  |           |
| 4 stage          | Split TAPC + Split MIRI | 2.5K  | 3He  | 54mW @ 2.5K                | 37mW @ 2.5K                  | 497Wdc    |
|                  |             |       |      |                            | 250mW @ 14K                  |           |
| 4 stage          | Split TAPC + Split MIRI | 1.7K  | 3He  | 10mW @ 1.7K                | 6mW @ 1.7K                   | 458Wdc    |
|                  |             |       |      |                            | 250mW @ 14K                  |           |

The addition of the second compressor and its electronics is estimated to increase the mass of the cooler by approximately 10 kg.

3. Conclusion
This modeling study shows that a hybrid pulse tube / Joule Thomson cryocooler based on the MIRI cooler can provide an effective solution for large cryogenic space missions that requires significant cooling in the 4K to 2K range. The modifications are confined to the addition of an existing design compressor with its drive electronics, and the resizing of the throttle, and, in the case of operation at 1.7K, resizing of the lower recuperator. This approach reduces the hardware development needed for achieving the lift requirements of next generation space telescopes, and can guide future demonstrations at correlated conditions in the lab.

4. References
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7
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