A Study of the Use of 6K ACTDP Cryocoolers for the MIRI Instrument on JWST

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ABSTRACT

The Mid Infrared Instrument (MIRI) of the James Webb Space Telescope (JWST) is a demanding application for the use of space cryocoolers. During calendar year 2003 an extensive study was carried out examining the application to this mission of hybrid 6K/18K J-T cryocoolers developed by NASA as part of their Advanced Cryocooler Technology Development Program (ACTDP). Among the most challenging requirements of the MIRI application were the requirements to cool down the ~90 kg 6 K cooling load in less than 30 days and to restrict the location of the compressors with their heat dissipation and vibration generation to a remote spacecraft position some 12 meters away from the cryogenic load. Because the hybrid 6K/18K J-T cryocoolers have unique load-carrying capability as a function of temperature, the cooldown requirement was the primary consideration in cooler sizing. This paper presents the lessons learned and performance achieved in the MIRI cryocooler application. In the final proposed configuration, all of the MIRI/JWST design considerations were successfully met. Although the cryocooler option was eventually deselected in favor of a solid-hydrogen stored cryogen system, the cryocooler study offered an important opportunity for understanding and refining the performance and integration capabilities of this important new class of low-temperature space cryocoolers.

INTRODUCTION

Chosen to replace the Hubble Space Telescope (HST), which was first launched in 1990, the James Webb Space Telescope (JWST) is designed to examine the Universe in wavelengths between 0.6 and 28 microns during a mission lasting up to ten years. Unlike HST, which is in a Shuttle-accessible low-Earth orbit, JWST is designed to be located in deep space in an Earth-tracking L2 orbit. This location, a fixed 1.5 million km from Earth, will allow JWST's large ~6-meter telescope (illustrated in Fig. 1) to be passively cooled to ~35 K to enable unique new science.

The JWST instrument responsible for imaging the longest wavelengths is referred to as the Mid Infrared Instrument (MIRI). This instrument is being jointly developed by the European Space Agency (ESA) and NASA, with the Jet Propulsion Laboratory as manager. The MIRI instrument focal plane arrays require cooling to below 6.8 K, and its optics to below 15 K to suppress background noise levels to acceptable levels. Thus, unlike the other JWST instruments, MIRI requires supplemental active cooling to achieve temperatures on the order of 6 K.

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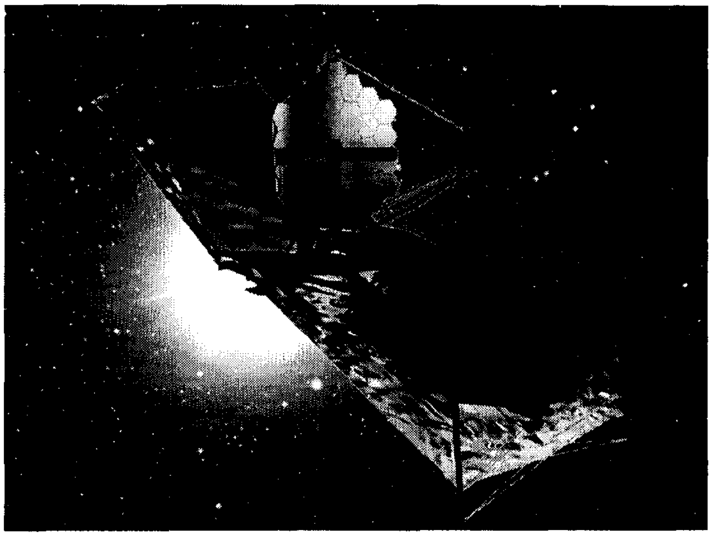

Figure 1. Overall James Webb Space Telescope configuration.

During their cryocooler/dewar trade study, two alternative approaches were examined by the MIRI team to provide the needed cooling: 1) a solid hydrogen cryostat, and 2) a 6 K/18 K mechanical cryocooler, the latter based on the cooler concepts being developed as part of NASA's Advanced Cryocooler Technology Development Program (ACTDP). Although the solid hydrogen stored cryogen system option was eventually selected in favor of a cryocooler, the cryocooler study offered an extremely valuable opportunity for understanding and refining the performance and integration capabilities of the ACTDP cryocooler concepts in an actual flight application.

THE MIRI CRYOCOOLER DESIGN CONCEPT

The cryocooler design concept for the MIRI application derives from three distinct areas: 1) the MIRI instrument itself, which represents the cooling load, 2) the overall JWST observatory, which provides most of the structural, thermal, electrical, and configurational interfaces, and 3) the ACTDP cryocoolers, which provide their own individual performance constraints. During the course of the cryocooler study the JWST observatory, and the MIRI instrument in particular, underwent modest configurational iterations typical of this stage in any project's development. Thus, the details presented here reflect the state of development in the spring of 2003, and are likely to be somewhat different from the design that exists at this time—a year later—or will exist in the future.

JWST Integration Concept

Figure 2 illustrates some of the configurational details of the JWST observatory at the time of this cooler integration study. In the JWST concept, the science instruments, including MIRI, are housed in the large ~35 K Integrated Science Instrument Module (ISIM) enclosure on the back of the ~35 K telescope. During launch, the telescope reflector is in a folded position with the telescope tower hard-mounted to the top of the spacecraft bus. After launch, the telescope reflector unfolds, and the entire tower and ISIM rise up approximately 1.5 m from the spacecraft bus to provide thermal and vibration isolation between the two. Thus, all cabling or plumbing connecting the ISIM instruments to the spacecraft must undergo this ~1.5 meter deployment, must be highly flexible, and must have minimal thermal conductance.

The overall JWST thermal compartmentalization places a constraint that any room-temperature cryocooler compressors be located in the spacecraft bus approximately 12 meters away from the cryogenic loads in the ISIM. Thus, the compressor-coldend connection must also accommodate the 1.5 meter in-space deployment of the telescope away from the spacecraft following launch. One key advantage of this deployment is a much relaxed requirement on cryocooler-generated vibration compared with, for example, HST. For JWST, the cryocoolers are assumed to be vibration-isolated from the spacecraft structure using standard vibration isolation mounts with perhaps a 15 Hz mounting frequency.

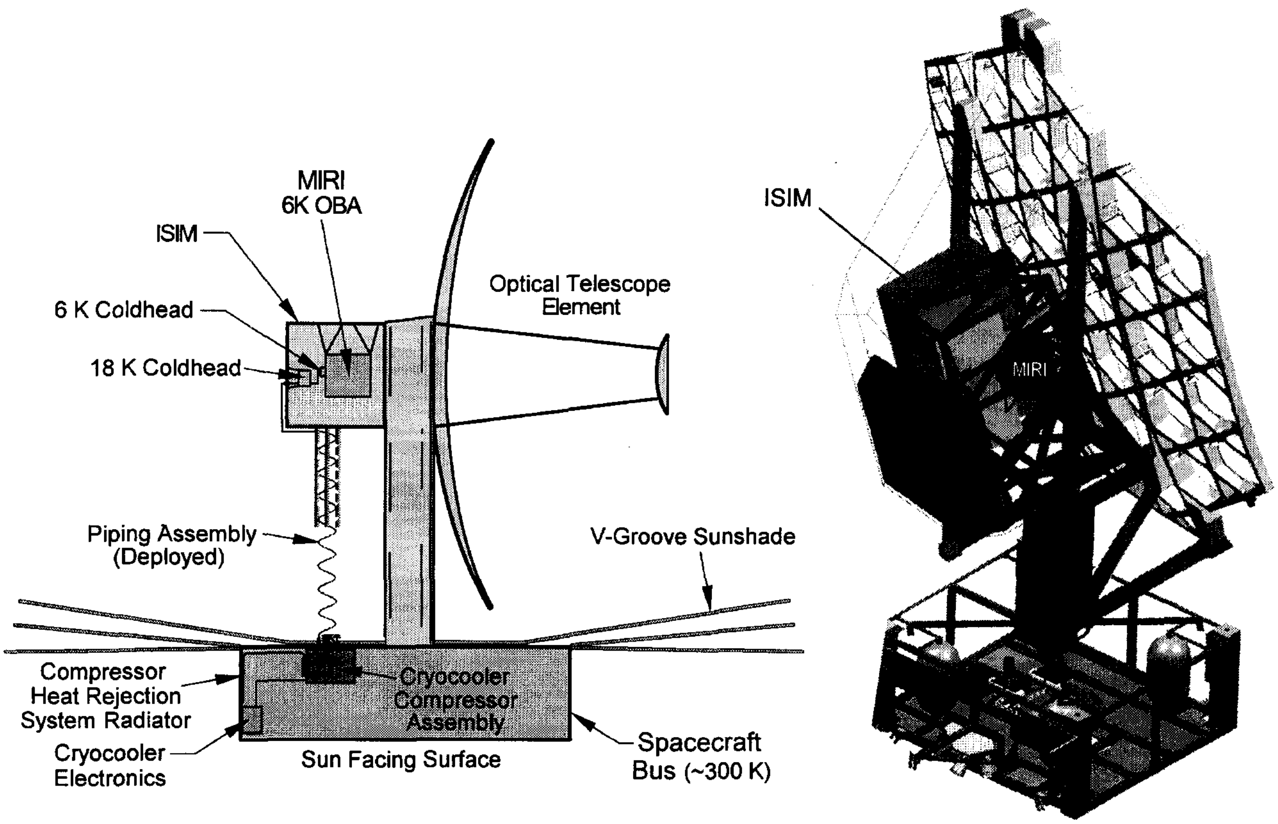

Figure 2. Overall James Webb Space Telescope configuration and cryocooler integration concept.

In terms of reliability and redundancy, an important implication of JWST's orbital location is that periodic repair and refurbishment, like was successfully used many times on HST, will not be possible with JWST. Thus, reliability and long life will be particularly important for this mission.

MIRI Instrument Concept

Figure 3 illustrates the generic concept of the MIRI instrument at the time of this cooler integration study. Structurally, the instrument is supported from the Integrated Science Instrument Module (ISIM) on the back of the JWST telescope via three pairs of low-conductivity struts. Strictly speaking, the instrument consists of three relatively low-power focal planes (~1 mW each) that require cooling to <6.8 K, plus a ~90 kg Optical Bench Assembly (OBA) that has to be cooled to below ~15 K. However, to avoid requiring two cooling temperatures, the instrument design in 2003 had the entire instrument integrated at roughly the same 6 K temperature.

In terms of refrigeration capacity, the primary cryogenic load presented to the cooler is approximately 10 mW, associated with conduction down the struts from the ~35 K ISIM structural interface, plus approximately 12mW of radiation load to MIRI from the ~40 K ISIM enclosure, plus 5 mW (inc. margin) for the focal planes. The radiation loading assumes the presence of MLI

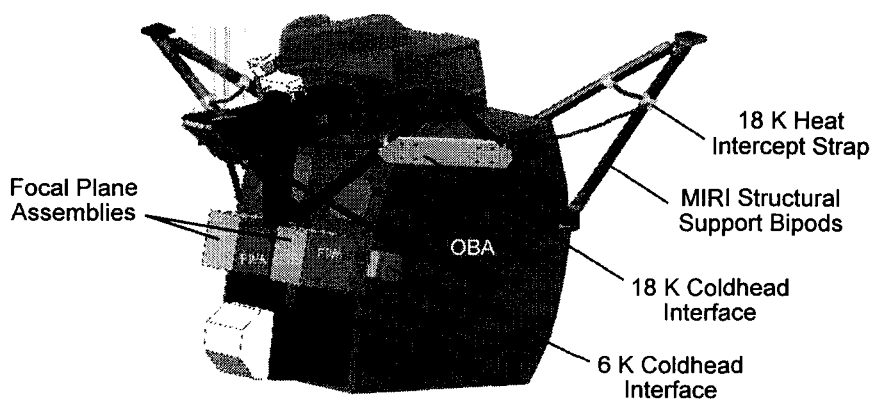

Figure 3. MIRI instrument conceptual design.

blankets on most of the instruments surfaces, but does not include the application of an external radiation shield, which was ruled out by the instrument provider because of integration difficulties.

A second key cryocooler capacity requirement was to cool the ~90 kg mass of the instrument from ~100 K to 6 K in less than 30 days in space, and quicker, if possible, during ground testing.

ACTDP Cryocooler Concept

In 2002, NASA initiated the Advanced Cryocooler Technology Development Program (ACTDP) as part of JPL's Terrestrial Planet Finder (TPF) project to develop the needed cryocooler technology for this class of space applications. The goal of the ACTDP activity is to build and test working models of up to three candidate cryocooler designs capable of providing 30 mW of cooling at 6 K together with 150 mW of cooling at 18 K.[1,2] Two of the ACTDP concepts, the Ball Aerospace and Northrup Grumman (formerly TRW) designs, are particularly well suited to the remote cooling requirements of the JWST application.[3,4] These two concepts, illustrated in Figs. 4 and 5, combine Stirling or pulse tube precoolers with a separate Joule-Thomson (J-T) stage that can provide simultaneous 6 K and 18 K cooling to a remote load many meters away from the compressor suite. For the MIRI application, as noted in Fig. 2, the compressor suite would be located in the JWST spacecraft bus, while the J-T coldhead would be mounted within the 35 K ISIM, adjacent to the MIRI instrument (see Figs. 2 and 4). This very clean mechanical interface allows the coolers and instrument to follow there own separate development and test paths and to be easily integrated together late in the ISIM integration and test phase.

Because the ACTDP cryocoolers have an ~18 K stage with greater than 150 mW of capacity as part of their design, this 18K stage was used to intercept heat flowing down the MIRI structural bipods and electrical cabling, thus lowering the 6 K cooling load by over 35%. These 18 K heat interceptors are schematically noted in Figs. 3 and 4.

In terms of cooling performance, the ACTDP hybrid coolers have a unique cooling trend versus temperature, quite different from pure regenerative coolers such as pulse tube and Stirling coolers. This is caused by the very different cooling behavior of the helium J-T system, which decreases

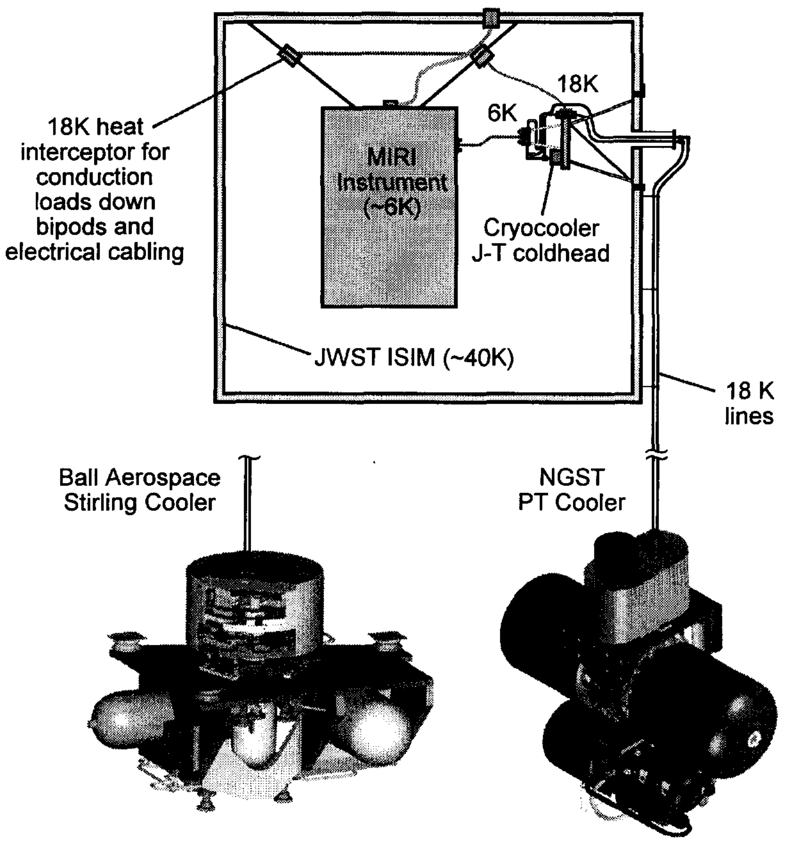

Figure 4. MIRI cryocooler conceptual design showing both Northrup Grumman (NGST) and Ball Aerospace ACTDP cryocooler compressor suite concepts.

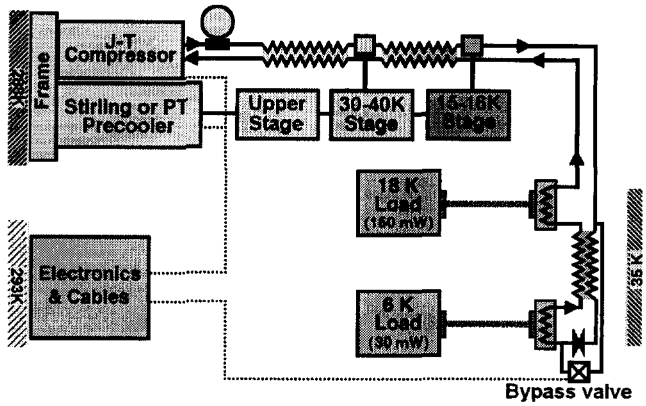

Figure 5. ACTDP hybrid J-T cryocooler flow diagram.

dramatically in cooling capacity with increasing precooling temperature as shown in Fig. 6. To provide augmented cooling capacity at elevated temperatures, the ACTDP coolers are fitted with valves that bypass the J-T working fluid around the J-T valve and the last recuperative heat-exchanger stage as shown in Fig. 5. Thus, at elevated temperatures, the J-T loop serves as a helium gas heat transfer loop to transfer the cooling capacity of the Stirling or pulse tube precooler directly to the 6 K and 18 K loads. This vastly increased cooling capacity above the bypass-valve closure temperatures is noted in Fig. 6. Also visible in Fig. 6 is the point of least cooling capacity, which occurs at temperatures just below the bypass valve closure temperature. This dip in cooling capacity below the bypass valve closure temperature presents an important pinch-point that must be carefully addressed to insure that the cryogenic load—here the MIRI instrument—can be cooled down to its final 6 K operating temperature.

MIRI CRYOCOOLER COOLING LOADS

Given the conceptual cooler configuration discussed above, Table 1 tabulates rough estimates of the expected cooling load contributions in the final 6 K equilibrium operating state of the MIRI instrument. It also includes a column of margined loads that include a 2x contingency factor to cover the uncertainties that exist in the load estimates this early in the design process. The largest loads on the 18 K stage are seen to be the heat interceptor loads from the MIRI graphite reinforced plastic (GRFP) struts, and the parasitic loads on the 18 K refrigerant lines, shown in Fig. 7, that run between the JWST spacecraft and the ISIM.

The far right column of Table 1 includes any end-of-life (EOL) load additions expected from load elements that can be expected to increase over the course of the JWST mission. These EOL

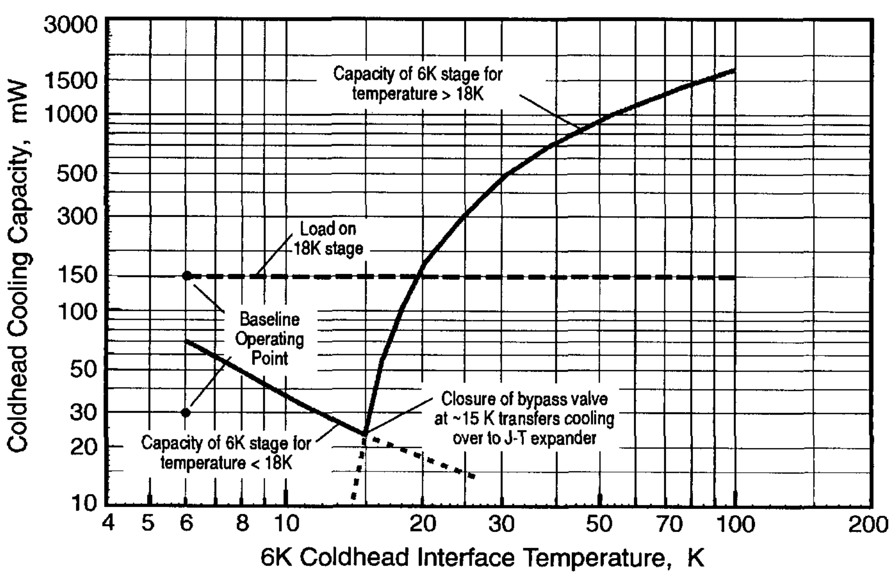

Figure 6. ACTDP cooling capacity versus temperature of the 6 K load.

Table 1. MIRI Cooler Baseline Loads with 18 K Heat Interceptor.

ITEM 6K Stage Loads	Cryocooler Load (mW) BOL Best Estimate	 BOL w/ Margin	 EOL w/Margin
MIRI radiation load from ISIM (40K)	7.2	11.8	12
MIRI Focal plane electrical dissipation	3.0	4.9	4.9
MIRI Electrical Harness conduction from 18 K intercept	* ~~8.3~~ 3.5	~~13.8~~ 5.8	5.8
MIRI Structural support conduction from 18K intercept	~~5.3~~ 2.0	~~11.5~~ 4.3	4.3
Radiation load on flexbraid connecting 6K stage to MIRI OBA	0.05	0.1	0.1
Radiation load on 6K stage from 18K stage (1500 cm²)	0.1	0.2	0.2
Support conduction from 18 K stage to 6K stage (0.5 kg)	1.15	2.3	2.3
Redundant cooler J-T & bypass valve lines from 18 K stage (3)	0.1	0.2	0.2
Conduction from redundant cooler J-T heater and temp sensor leads	0.05	0.1	0.1
Total 6 K cryocooler load	17.15	29.7	~30.0
18K Stage Loads			
MIRI structural conduction Intercept Load	10.0	20.0	20.0
MIRI harness conduction Intercept Load	15.0	30.0	30.0
Radiation load on 18K flexbraid to MIRI structure intercept	0.05	0.1	0.1
18K coldstage support conduction from 35K ISIM	2.2	4.4	4.4
Redundant cooler J-T lines from 35 K ISIM (2 lines, each 50 cm)	0.1	0.2	0.2
Harness conduction for J-T heater and temp sensors	0.04	0.1	0.1
Quick-cooldown & defrost-mode bypass valve harness conduction	0.1	0.1	0.1
Radiation load on 18K stage from 40K ISIM (1200 cm²)	1.0	2.0	2.0
18K line conduction from 35K ISIM feedthrough	1.0	2.0	2.0
Heat conducted down to 6K stage from 18K stage	-0.35	-0.7	-0.7
18K line support conduction external to ISIM (10 m)	10.0	20.0	20.0
Radiation load on 18K lines external to ISIM (10 m)	18.1	36.2	72.0
Total 18K cryocooler load	57.2	114.4	~150

*Crossed out numbers are original loads prior to inclusion of 18K heat interceptor

increases are dominated by increased radiation loading on the ~18 K refrigerant lines. Figure 7 describes the effective background radiation temperature seen by the refrigerant lines as a function of position up the JWST observatory tower. The resulting thermal radiation load is proportional to the fourth power of this background temperature and linearly proportional to the surface emittance of the lines and their external surface area. Also important, is the conductance of the standoffs required to support the refrigerant lines from the tower structure. These and other conductance loads in Table 1 were estimated based on scaling previously proven cryogenic support designs.[5] Although, the conductance is not subject to increase over time, the surface emittance of the lines can be expected to increase due to gettering of water vapor on the external surface of the 18 K lines over the course of the mission.[6]

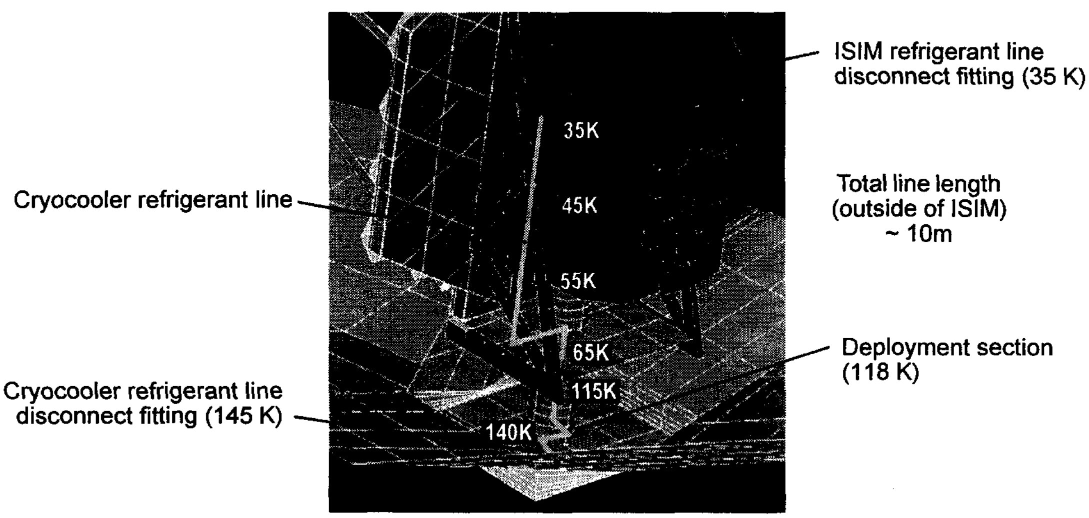

Figure 7. Radiation environment for the 18 K fluid lines that run between the spacecraft and the ISIM.

Two approaches to dealing with the radiation load increase have been considered: 1) wrapping the refrigerant lines with adequate multilayer insulation (MLI) to limit load growth over the JWST mission to the design level, or 2) incorporating a periodic defrost mode whereby warm, uncooled gas is passed through the lines to raise their temperature sufficiently (> 160 K) to evaporate condensed moisture when the design load level is reached. The 72mW line radiation load at EOL in Table 1 is felt to be an achievable goal for this EOL radiation design load for the refrigerant lines.

In reviewing the 6 K loads, it is seen that they are dominated nearly equally by the MIRI instrument radiation loads from the ~40K ISIM, and by the MIRI conduction loads down the GFRP bipods from the 18 K heat-interceptor temperature. Because the 40 K ISIM will effectively getter all water vapor to negligible levels, increased surface emittance of the MIRI instrument should be very small. The only contribution would be from condensed gases such as nitrogen and oxygen that are solid at 6 K, but still gases at 35 K, and thus not gettered by the ISIM surfaces.

CRYOCOOLER SIZING TO ASSURE THAT MIRI CAN BE COOLED DOWN

Because of the unique thermal performance of the hybrid ACTDP cryocoolers versus temperature, the cooldown performance of the overall MIRI cryogenic system must be carefully engineered. As shown in Fig. 5, the most critical temperature range for this type of cooler is between the bypass valve turnoff temperature and the ultimate 6 K load temperature. Figure 8 details the estimated MIRI loads and the ACTDP refrigerator performance over this temperature range. Also shown is a conceptual estimate of the input power required and how it might be throttled back as the final 6K operating point is achieved. Better power data must await breadboard testing of the ACTDP coolers.

In Fig. 8, the refrigerator is sized to provide approximately 50% more capacity than the sum of the total 6K loads in Table 1 in the critical 12 to 18 K temperature range. Note that when this is done, the refrigerator has substantial over capacity at 6K (> 70 mW) compared to the 6K operational load of 30 mW. Thus, for this type of application, the 6 K operational load is not the sizing condition; the critical sizing condition is the ability to cool down from 18 K to 12 K.

Note also that the lack of an 18 K radiation shield around the MIRI instrument exacerbates the cooldown issue by allowing a near-constant radiation load to exist in this critical 18 to 12 K temperature range. In contrast, the presence of the 18 K heat interceptor on the support structure causes the structural conduction loads to be zero at 18 K, and to climb relatively linearly between 18 and 6 K. Thus, the radiation loads on the MIRI instrument dominate the sizing of the cryocooler's 6K stage.

This unique thermal behavior of the hybrid ACTDP-type cryocoolers requires that the thermal load be managed more thoughtfully than with a conventional regenerative cryocooler, where the sizing condition is invariably at just the lowest operating temperature.

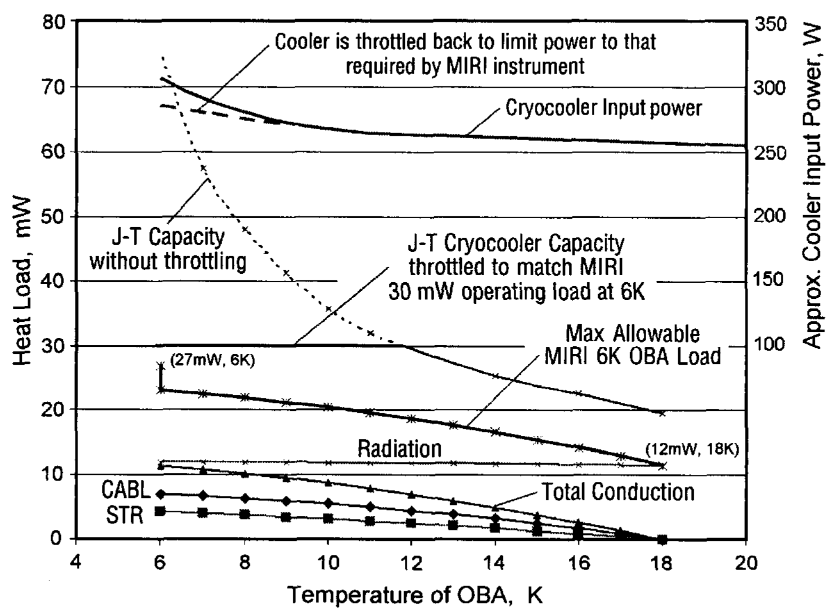

Figure 8. ACTDP cooling performance compared to the MIRI cooling loads.

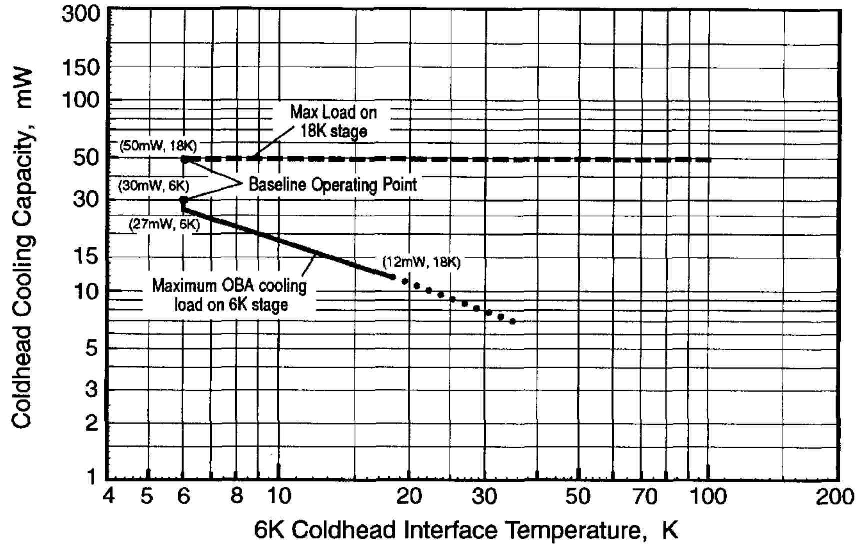

Figure 9. Example maximum allowable load requirement for ACTDP-type hybrid cryocooler.

Figure 9 displays an example design requirement for the maximum MIRI instrument load to be presented to the cryocooler. This plot presents the requirement as a 'not to be exceeded' load envelope as a function of temperature below 18 K, together with a simultaneous not-to-be-exceeded allocation for cooling from the cryocooler's 18 K stage. The numbers in this requirement are consistent with the margined MIRI loads presented in Table 1.

As a complement to the maximum-load requirement given in Fig. 9, the minimum allowable cryocooler performance must also be specified over the entire temperature range to insure that a positive margin exists between the cryogenic load and the cooler performance at all temperatures. An example of such a 'minimum allowable' cryocooler cooling performance for the MIRI application is shown in Fig. 10.

Predicting Instrument Cool-Down Time

Given the instrument's heat capacity, the instrument loads as detailed in Fig. 8, and the estimated cryocooler performance as shown in Fig. 6, one can estimate the predicted time for initial instrument cooldown. Figure 11 presents data on the specific heat of representative spacecraft materials as a function of temperature. For the 90-kg MIRI instrument the cooldown estimates can be based on the properties of aluminum, which is the dominant material in its design. Note that the specific heat of aluminum drops by a factor of 1000 between room temperature and 6 K.

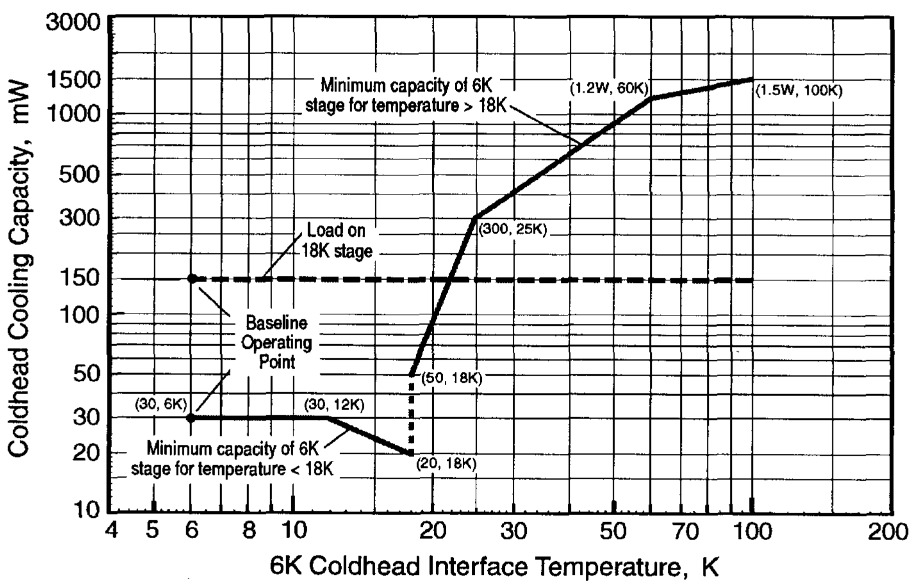

Figure 10. Example cooling performance requirement for ACTDP-type hybrid cryocooler.

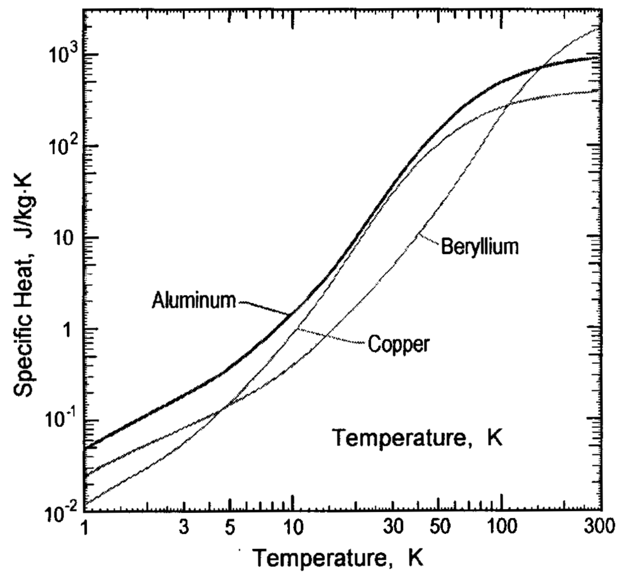

Figure 11. Specific heat versus temperature for representative spacecraft metals.

Figure 12 illustrates the predicted cooldown dynamics of the MIRI instrument from a starting temperature of 100 K. In flight, the MIRI instrument would be allowed to cool passively through radiation and conduction to the ISIM until the ISIM approaches its equilibrium temperature of around 40 K. At this point it is estimated that the MIRI instrument would have cooled to around 60 K. Thus, the predicted cooldown time after the cryocooler is energized would be approximately 7 days, with roughly equal time spent before and after the bypass valve is closed.

This calculation illustrates that, even with a very large (~90 kg) cold load, the cooldown time is quite acceptable with this type of cooler, largely because the specific heat of materials drops so precipitously at these low temperatures.

Predicting Instrument Warm-up and Re-cooldown Times

During the course of any space-science mission, there are events that may require power to the instruments to be turned off. These can be safety shutdowns or planned warm-ups for decontamination. With such an event, it is important that the instruments return to normal operation as soon as practical to maximize the science data collection. Figure 13 predicts the warm-up dynamics of the MIRI instrument in the event that the ACTDP cryocooler is turned off. Note that the low heat capacity of the instrument at 6 K results in a relatively rapid warm-up, with the instrument approaching the ISIM background temperature in a day or two after it is turned off. From Fig. 12, it can be seen that the cooler can return the instrument to operating temperature in about four days, which is felt to be quite reasonable.

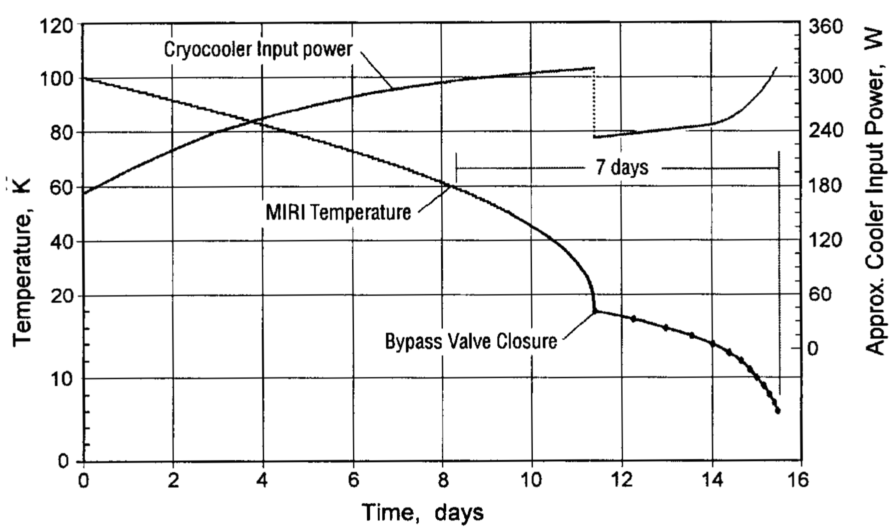

Figure 12. Predicted cooldown of the MIRI instrument versus time using an ACTDP cryocooler.

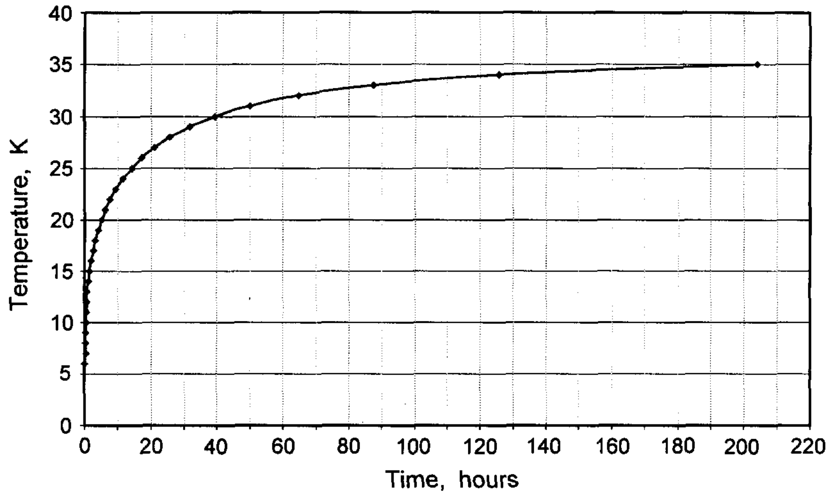

Figure 13. Predicted warm-up of the MIRI instrument versus time when the cryocooler is turned off.

SUMMARY

Because the MIRI Instrument on JWST is a demanding, yet representative application for the future use of space cryocoolers, it offered an important opportunity for understanding and refining the performance and integration capabilities of the hybrid J-T 6K/18K coolers being developed by NASA as part of their Advanced Cryocooler Technology Development Program (ACTDP). Among the most challenging requirements were the requirement to cool down the ~90 kg instrument in well less than 30 days and to restrict the location of the compressors to a remote spacecraft position some 12 meters from the cryogenic load. In the final analysis, the ACTDP cryocoolers successfully met all of the MIRI/JWST design considerations and were shown to provide an attractive option for meeting the cooling needs of future NASA missions.

ACKNOWLEDGMENT

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