Conceptual Design and Development History of the MIRI Cryocooler System on JWST

R.G. Ross, Jr.

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91109

ABSTRACT

The Mid Infrared Instrument (MIRI) of the James Webb Space Telescope (JWST) is a demanding application for the use of space cryocoolers. Used to cool JWST's ~100 kg MIRI instrument down to 6 K, the MIRI Cryocooler is critical to enabling the mission's long-wave infrared science associated with studying the post-Big Bang early formation of the Universe.

The selection and design of MIRI and its cryocooler system started with the successes and limitations of JWST's precursor, the Hubble Space telescope. Planned as the follow-on to Hubble, JWST abandoned Hubble's astronaut-accessible low-Earth orbit for a colder and better-science environment a million miles from Earth. Targeting for this L2 location meant no servicing missions would be possible, and reliability and life would be critically important. JWST's increased size, with a 6.5 meter diameter mirror, meant significant deployments would be required post launch to allow the observatory to unfurl from its launch-vehicle shroud and separate the cold telescope from its hot and noisy spacecraft bus.

The MIRI cryocooler system met these mission constraints by positioning its dual compressors inside the spacecraft bus, while the MIRI instrument and the cryocooler's cold-end is positioned 10 meters away in the Science Instrument Module. Accommodating the 1.3-m deployment of the telescope away from the spacecraft and minimizing any vibration transmitted up the connecting refrigerant lines was a driving requirement on the cryocooler system. Providing MIRI's large refrigeration load at 6 K, while simultaneously cooling MIRI's 18 K radiation shield required an all-new hybrid Pulse Tube/Joule-Thomson cryocooler.

This paper provides an overview of the overall MIRI cryocooler system as it evolved to meet these demanding JWST requirements over its nearly 20-year development history. During this period it drew heavily upon ongoing Pulse Tube cooler developments as well as a history of earlier hybrid J–T cryocooler technologies.

INTRODUCTION

Chosen to replace the Hubble Space Telescope (HST), which was launched in 1990, the Next Generation Space Telescope, as it was initially called, focused on a new set of science objectives which demanded a dramatically colder and larger telescope and reduced radiation from a nearby Earth. An early objective was to position the telescope at the L2 Lagrange point, an Earth tracking

Cryocoolers 22, edited by R.G. Ross, Jr., J.R. Raab and S.D. Miller

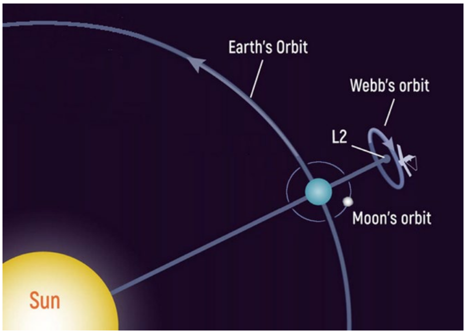

Figure 1. L2 Lagrange point orbit location

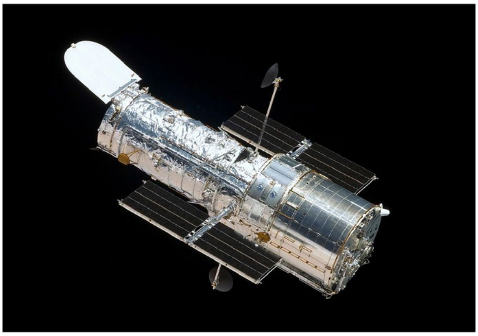

Figure 2. Hubble Space Telescope

orbit a million miles from Earth. At this unique point (Fig. 1), the combined gravity pull of Earth plus the sun, allows a spacecraft to stay a fixed distance away from Earth as the Earth circles the sun. This position has the advantages of a deep space thermal environment, yet good telemetry contact with Earth.

In contrast, the Hubble Space Telescope (HST), shown in Fig. 2, was designed as an astronaut-serviceable mission positioned in low Earth orbit with science objectives focused on measurements primarily in the ultraviolet and visible spectrums. These were met with a single 2.6 m solid glass mirror (Fig. 3) polished to a very high precision for use in the UV spectrum. To take advantage of astronaut servicing, HST was built like an equipment rack, with individual instruments having fixed geometries and mounting interfaces (Fig. 4) to allow instrument replacement and upgrades over time. A total of five servicing missions would be carried out over Hubble's lifetime.

A key early focus for a first replacement instrument for Hubble was a shortwave infrared instrument.[1] This led to a classic competition between a more "flight proven" cryostat (in this case the Near Infrared Camera and Multi-Object Spectrometer (NICMOS), cooled by an 80 K solid N2 dewar,[2] and the Hubble Imaging Michelson Spectrometer (HIMS) instrument,[3] cooled by an 80 K hydride sorption cryocooler.[4] In the end, the NICMOS instrument was selected and was installed in Hubble in 1997 on the second HST servicing mission. Unfortunately, the NICMOS dewar suffered a thermal short during launch that would prematurely end its in-space mission within 22 months.[5] Demonstrating the resilience of the Hubble design, a repair for the failed NICMOS dewar was designed and expeditiously fabricated—an 80 K turbo Brayton cryocooler designed and built by Creare.[6] It was successfully installed to cool down the NICMOS dewar on servicing mission 3B in 2002 and operated successfully for over 5 years.[7]

EARLY SPACE TELESCOPE AND INSTRUMENT DESIGN TRADES

Starting in the late 1990s, trade studies were actively underway for the Next Generation Space Telescope to replace Hubble. Four organizations, whose concepts are highlighted in Fig. 5, were developing competing designs. These four telescope designs were down-selected to two competing teams in 2002.

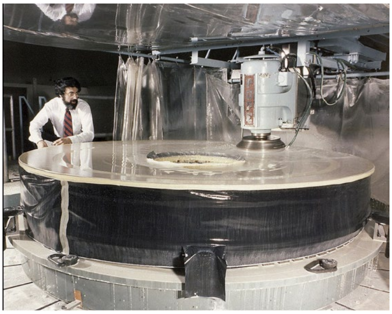

Figure 3. Polishing HST's 2.6 m primary mirror

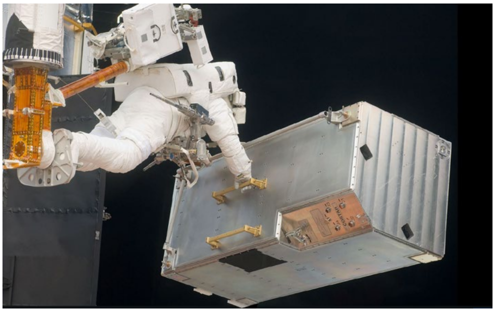

Figure 4. COSTAR instrument being removed from Hubble

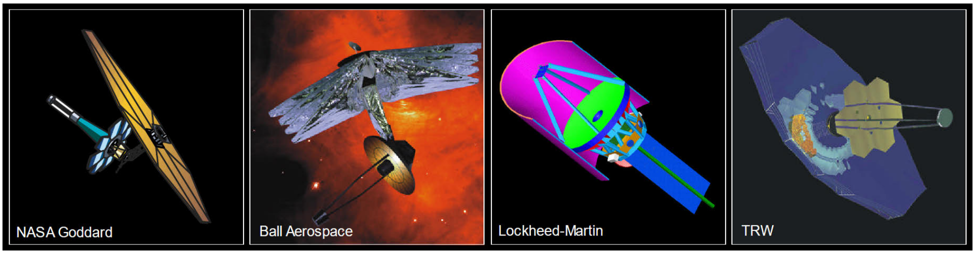

Figure 5. Early Next Generation Space Telescope (NGST) configurations.

At the same time, requests for instrument concepts were also under way, and a key interest was for a midwave infrared instrument with substantially longer wavelength capability than achieved with Hubble. This would be referred to as the Mid Infrared Instrument (MIRI). Viewing in this wavelength range would require Si:As detectors cooled to around 6 K, a difficult temperature to reach in space. One candidate cooling method would be a solid Hydrogen dewar, a second would be an all new 6 K cryocooler, as no 6 K cryocooler designs with space-level maturity existed at this time.

The ACTDP Cryocooler Development Project

To develop one or more candidate cryocooler technologies for the NGST, NASA initiated the Advanced Cryocooler Technology Development Program (ACTDP) in spring 2001 under the leadership of the Jet Propulsion Laboratory and in collaboration with the NASA Goddard Space Flight Center.[8] The ACTDP effort was structured in two phases: 1) an initial study phase followed by, 2) a hardware detailed design and test phase. A key early activity was generation of detailed requirements and specifications for a generic 6 K instrument on the NGST in summer 2001. This led to a community-wide request for 6 K/18 K cryocooler proposals in November 2001, and the award of four parallel Phase I contracts by April 2002. The four contractors included Ball Aerospace, Creare, Lockheed Martin, and TRW. As noted in Fig. 6, the Ball and TRW concepts were hybrid Joule-Thomson 6 K stages precooled by Stirling or Pulse Tube 18K upper stages, respectively. The Lockheed cooler was a 4-stage pulse tube with direct cooling to 18 K and 6 K, while the Creare was a turbo Brayton with 18 K and 6 K stages.[8]

Near the end of the ACTDP study phase in mid 2002, NASA selected the Next Generation Space Telescope concept proposed by TRW and Ball Aerospace (Fig. 7) and named the telescope after James Webb, the NASA director from 1961 to 1968. The selected JWST concept involved a large V-groove sunshade to cool a large 6.5-meter segmented mirror telescope and its adjacent instrument housing (ISIM) to on the order of 35 K. In contrast, large room-temperature electronics and high power dissipating components (like cryocooler compressors) would be housed in a spacecraft bus that separates 1.3-m (4 feet) away from the telescope following launch.

Commensurate with this maturing design for JWST, a first preliminary design of the MIRI instrument was also beginning to converge.[9] This allowed the JWST Project, over spring 2003, to

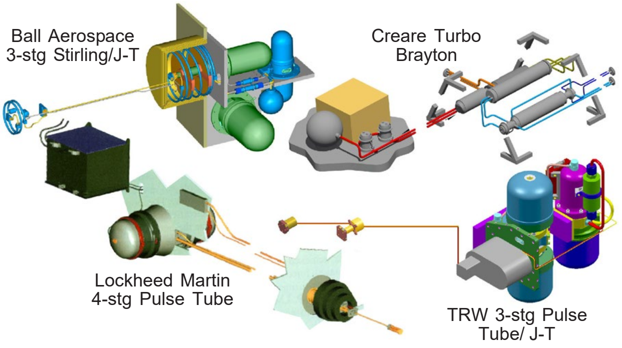

Figure 6. ACDTP study-phase 6 K cryoooler concepts.

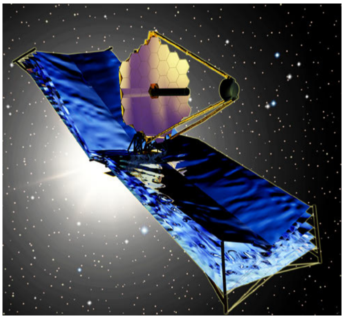

Figure 7. TRW JWST concept design.

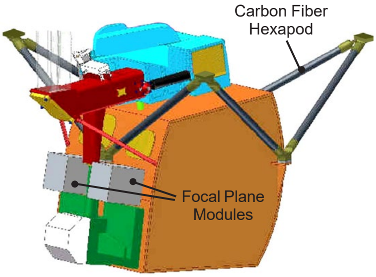

Figure 8. Original 2003 MIRI instrument concept.

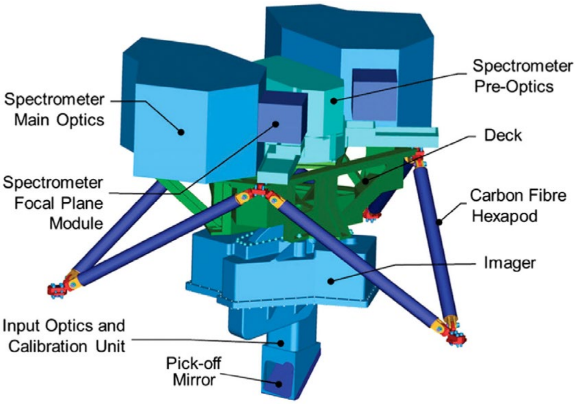

Figure 9. Final flight MIRI instrument concept.

initiate a detailed system design for a MIRI cryocooler with the ACTDP cryocooler development team actively participating with the TRW spacecraft, GSFC ISIM, and MIRI instrument teams.[10] The close interaction of these multi-discipline teams reflected the complexity of the cryocooler's multiple interfaces and would continue as a prominent feature of the MIRI cryocooler development over the coming years.

THE MIRI CRYOCOOLER DESIGN CONCEPT

The cryocooler design concept developed in 2003 for the MIRI application derived 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. For the most part, the 2003 MIRI cooler design is the same as is flying today in 2022.

MIRI Instrument Concept

Figure 8 illustrates the initial concept of the MIRI instrument at the time of the 2003 cooler integration study.[9] Except for obvious geometrical changes, its optical architecture and cryogenic design are pretty much unchanged in the final flight design shown in Fig. 9.[11] Structurally, the instrument is supported and thermally isolated from the Integrated Science Instrument Module (ISIM) via three pairs of T300 Carbon Fiber Reinforced Plastic (CFRP) struts. Cryogenically speaking, the instrument consists of three relatively low-power focal planes (~1 mW each) that require cooling to <6.8 K, plus a ~100 kg Optical Bench Assembly (OBA) that has to be cooled to below ~15 K. However, to minimize thermal gradients that could lead to optical distortions, the design preference was to have the entire instrument cooled to the same 6 K temperature.

In terms of refrigeration capacity, the primary cryogenic load presented by the instrument has three major components: 1) the radiation load from the ~35 K ISIM onto the 6 K instrument's outer surfaces, which will be covered with MLI, 2) the conductive load up the struts and cables from the ~35 K ISIM, and 3) the relatively modest 5 mW (inc. margin) electrical load for the three focal plane assemblies and periodic instrument mechanism actuations.

The radiation loading, in particular, was one of high uncertainty due to the poorly predictable emittance of MLI when exposed to radiation from surfaces with temperatures below 100 K.[12, 13, 14] In addition to the exaggerated inter-layer thermal conduction at low radiation levels, a key contributor to the loss of MLI effectiveness is the poor electrical conductivity (low RRR) of the thin vapor-deposited aluminum layers deposited on the MLI.[14] In the 2003 study, the application of an actively-cooled external radiation shield around MIRI was ruled out by the instrument team because of integration difficulties. This would later be changed.

A second key cryocooler capacity requirement was to cool the ~100 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.

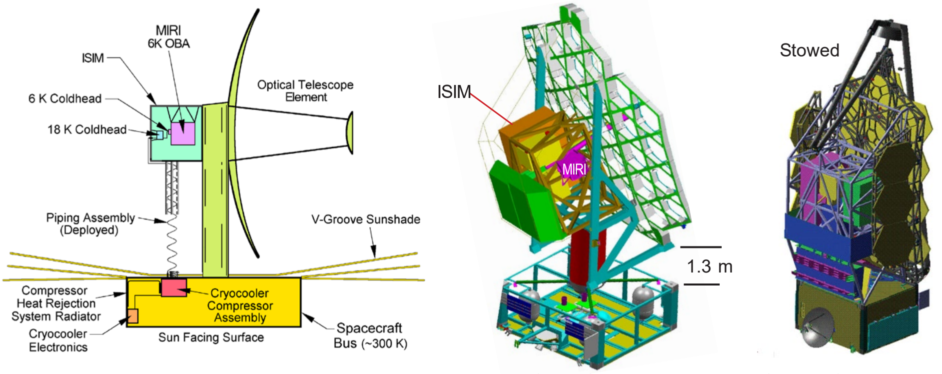

Figure 10. Overall James Webb Space Telescope configuration and cryocooler integration concept.

JWST Integration Concept

Figure 10 illustrates some of the configurational details of the JWST observatory at the time of the 2003 cooler integration study. In the JWST concept, the four 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's primary and secondary mirrors are in folded positions with the telescope tower hard-mounted to the top of the spacecraft bus. After launch, the telescope mirrors unfold after the entire tower and ISIM rise up approximately 1.3 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 ~1.3 meter deployment, must be highly flexible, and must not transmit vibration up the tower.

This overall JWST thermal compartmentalization places a constraint that any room-temperature cryocooler compressors be located in the spacecraft bus approximately 10 meters away from the cryogenic loads in the ISIM. Thus, the compressor-coldhead connection must also accommodate the 1.3 meter in-space deployment of the telescope away from the spacecraft following launch. One key advantage of this deployment is a somewhat relaxed requirement on cryocooler-generated vibration compared with, for example, HST. For JWST, it was assumed that the cryocoolers would be vibration-isolated from the spacecraft primary structure using some sort of conventional passive vibration isolation mounts. However, vibration transmission up the refrigerant lines was an unknown that would have to be addressed during the detailed development phase.

In terms of refrigeration capacity, the primary cryogenic load presented by the spacecraft has three major components: 1) the radiation load from the JWST tower onto the refrigerant lines connecting the compressors and the instrument, 2) the conductive load associated with supporting the lines off the tower and ISIM, and 3) the parasitic loads from the spacecraft onto the cryogenic refrigerator elements located within the spacecraft itself. These too had large uncertainties due to the complexity of these interfaces and predictions for the temperature of the tower and spacecraft surfaces.

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, would not be possible with JWST. Thus, reliability and long life would be particularly important for this mission. Although the complex nature of the compressor interfaces with the spacecraft and instrument made use of redundant cryocoolers problematic, use of redundant drive electronics was viewed as a desirable option.

Applicable ACTDP Cryocooler Concepts

In 2003, the goal of the ACTDP activity was 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.[8] However, reflecting the large uncertainty in these loads, the design approach taken was to substantially oversize the mechanical refrigeration capacity (stroke and power handling capacity)

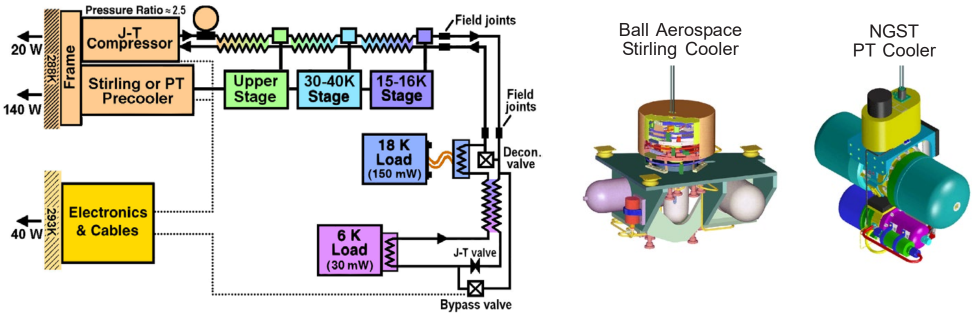

Figure 11. MIRI hybrid J-T cryocooler design showing both Northrup Grumman (NGST) and Ball Aerospace ACTDP cryocooler compressor suite options.

of compressors so that a 2x load growth would not require mechanical hardware redesign. Two of the ACTDP concepts, the Ball Aerospace and Northrop Grumman (formerly TRW) designs, were particularly well suited to the remote cooling requirements of the JWST application.[15,16]

These two concepts, illustrated in Fig. 11, 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. 10, 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.

Because these hybrid cryocoolers have an ~18 K stage as part of their design, this 18K stage can be used to intercept heat flowing down the MIRI structural bipods and electrical cabling, thus lowering the 6 K cooling load. In the eventual flight design, the 18K stage was used to cool a radiation shield to prevent radiation from the ~35 K ISIM from directly heating the MIRI instrument…but this wasn't incorporated until around 2009.

The Cryocooler Pinch Point

In terms of cooling performance, the hybrid 6 K coolers proposed for MIRI are similar to the 4 K cryocooler developments at RAL in the UK.[17] These 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 rapidly decreases to zero at the helium inversion temperature as shown in Fig. 12. To provide useful cooling capacity throughout the whole range of operating temperatures, the ACTDP cooler design includes a valve that bypasses the J-T working fluid around the J-T valve and the last recuperative heat-exchanger stage as shown in Fig. 11. Thus, at elevated temperatures, the J-T loop serves as a helium

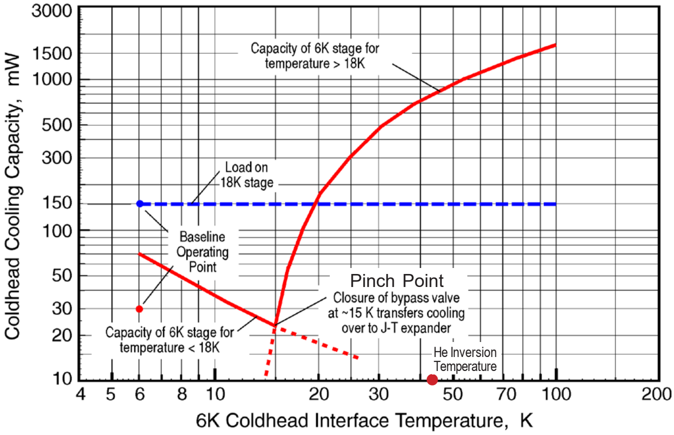

Figure 12. Cooling capacity versus temperature for hybrid MIRI cryocooler.

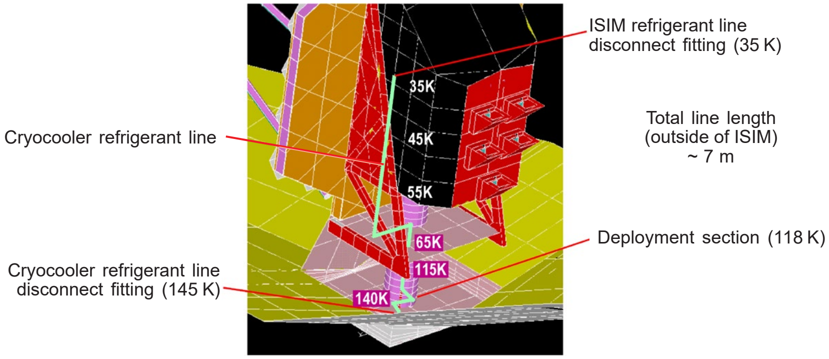

Figure 13. Radiation environment for the 18 K fluid lines that run between the spacecraft and the ISIM.

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 temperature is noted in Fig. 12. Also noted in Fig. 12 is the point of least cooling capacity, which occurs at temperatures just below the bypass valve closure temperature. This minimum cooling capacity located just below the bypass valve closure temperature presents an important pinch-point that must be carefully addressed to ensure that the cryogenic load—here the MIRI instrument—can be cooled down to its final 6 K operating temperature.

Estimating MIRI Cryocooler Cooling Loads

Given the conceptual cooler configuration discussed above and the projected physical attributes of the JWST spacecraft and MIRI instrument, considerable effort was made to accurately estimate the likely cooling loads and thus required cooling capacity of a JWST MIRI cryocooler. Generated estimates included both best estimate values based on the best estimate physical attributes of the hardware in 2003, as well as margined loads that included a 2x contingency factor to cover the uncertainties that always exist in the load estimates at this early stage in the design process. An additional end-of-life (EOL) estimate for each load element included contingencies for load growth over time due to things such as emittance increases of low-e surfaces due to gradual contamination of these surfaces.[18]

A particularly sensitive part of the cooler loads involved radiation onto the refrigerant lines that snake their way up the telescope tower between the spacecraft and the ISIM. Figure 13 illustrates the highly variable effective background radiation temperatures seen by the refrigerant lines as a function of position up the JWST observatory tower.[10] The resulting thermal radiation load is proportional to the fourth power of these background temperatures 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 were estimated based on scaling previously proven cryogenic support designs.[19]

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.[18, 20, 21] To address the likely radiation load growth on the refrigerant lines, the MIRI cryocooler incorporated a periodic defrost mode whereby warm, uncooled gas could be passed through the lines to raise their temperature sufficiently (>160 K) to evaporate condensed moisture when the maximum tolerable load level is reached. This defrost feature was incorporated via the 'decontamination valve,' shown in Fig. 11, that allows the refrigerant to bypass the 6 K load.

The largest loads on the MIRI cryocooler 6 K stage were seen to be the radiation loads from the ~35 K ISIM. These loads increase proportional to the 4th power of the ISIM temperature, so even a 5 K increase in the ISIM from 35 K to 40 K represents nearly a doubling of the 6 K load. In addition, the effective emittance of surfaces exposed to radiation from surfaces with temperatures below 100 K is subject to large uncertainties.[13, 14] Because the 40 K ISIM will effectively getter all water vapor to negligible levels, increased surface emittance of the MIRI instrument over time was expected to be very small.[22] The only contribution would be from gases such as nitrogen and oxygen

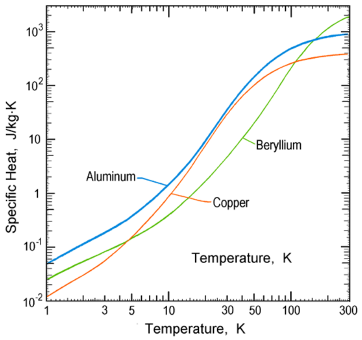

Figure 14. Specific heat vs. temperature.

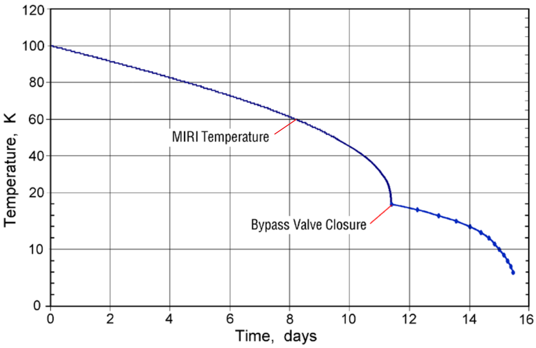

Figure 15. Predicted cooldown of the MIRI instrument vs time.

that are immobile at 6 K, but have vapor pressures above 10^{-4} torr at 35 K, and thus are not gettered by the ISIM surfaces.

Although the conductive loads up the MIRI struts and cabling are also sizeable loads, these had less uncertainty as they were well characterized in the MIRI instrument materials testing program.[23]

Cryocooler Sizing to Assure that MIRI Can Be Cooled Down

Because of the unique thermal performance of the hybrid MIRI cryocooler versus temperature, the cooldown performance of the overall MIRI cryogenic system must be carefully computed. As shown in Fig. 12, the most critical temperature range for this type of cooler is between the bypass valve turnoff temperature (the pinch point) and the ultimate 6 K load temperature. Above the pinch point, when the bypass valve in open, the precooler stage has substantial cooling capacity to cool the instrument.

Given the instrument's heat capacity, the predicted instrument loads, and the estimated cryocooler performance, one can estimate the predicted time for initial instrument cooldown. Figure 14 presents data on the specific heat of representative spacecraft materials as a function of temperature. For the 100-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 15 illustrates the predicted cooldown dynamics of the MIRI instrument from a starting temperature of 100 K.[10] In flight, the MIRI instrument would be allowed to cool passively through radiation and conduction to the ISIM until it had cooled to around 100 K. At this point the ISIM should have cooled sufficiently to have gettered any water vapor internal to the ISIM to negligible levels. As seen in Fig. 15, the predicted cooldown time after the cryocooler is energized is quite acceptable with this type of cooler, even with a very large (~100 kg) cold load, largely because the specific heat of materials drops so precipitously at these low temperatures.

After 6 K is reached, the refrigerator has substantial over capacity compared to the 6 K operational load. 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 through the pinch point. This unique thermal behavior of the hybrid MIRI cryocooler 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.

Predicting Instrument Warm-up and Re-cooldown Times

During the course of any space-science mission, there are events that may require instrument power to be turned off. These can be safety shutdowns or planned warm-ups for decontamination. With such an event, it is important that the instrument return to normal operation as soon as practical to maximize the science data collection. Prediction of the warm-up dynamics of the MIRI instrument in the event that the cryocooler is turned off were also made.[10] In this case the low heat capacity of the instrument at 6 K results in a relatively rapid warm-up, with the instrument exceeding 25 K within a day after it is turned off. From Fig. 15, it can be seen that the cooler can return the instrument from 40 to 6 K in just a few days, which is felt to be quite reasonable.

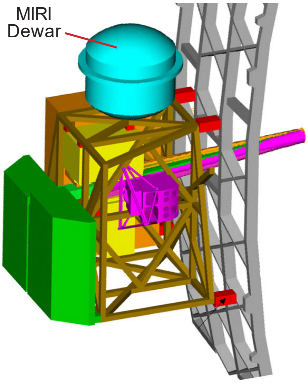

Figure 16. MIRI 6 K Dewar concept

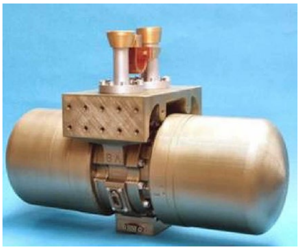

Figure 17. TRW 700 W high capacity HCC pulse tube cooler

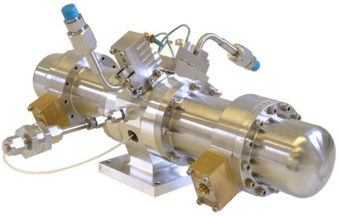

Figure 18. ACTDP development model J-T compressor

A BRIEF DETOUR TO A MIRI 6 K DEWAR

At the end of the 2003 MIRI cryocooler system integration study, the proposed cryocooler approach successfully met all of the MIRI/JWST design considerations and was shown to provide an attractive option for meeting the cooling needs of the MIRI instrument on JWST. However, during final deliberations at the JWST Project level, the decision was made to utilize a more mature 6 K solid hydrogen dewar technology to cool the MIRI instrument.[24] Thus, the ACTDP effort returned to its program of refining the design details of the candidate 6 K coolers and entering into a hardware fabrication and test phase to bring the key cooler components to a higher level of flight maturity.[25]

In summer 2004 Lockheed Martin Advanced Technology Center (ATC) was brought under contract to develop the MIRI 6 K solid hydrogen dewar subsystem. However, within a year the overall JWST spacecraft faced an increasing dilemma of unacceptable mass margins with respect to launch vehicle capability. A particularly troublesome issue was the large MIRI dewar mass located high on top of the ISIM (Fig. 16). One attractive means of solving JWST's mass issue was to revert to a cryocooler located low in the spacecraft bus to cool the MIRI instrument. Thus, another extensive cooler/dewar trade study was carried out in spring 2005. It led to the Lockheed MIRI 6K Dewar contract being abandoned, and a request for proposals (RFP) being drawn up to select one of the ACTDP cryocooler concepts for JWST.

In the MIRI cooler competition of late 2005, proposals were received covering all three ACTDP designs: the Ball Aerospace Stirling/J-T cooler,[15, 26] the Lockheed 4-stage pulse tube cooler,[27] and the Northrop Grumman pulse-tube/J-T cooler.[16,28,29] In spring 2006, the final MIRI cooler selection was awarded to the Northrop Grumman concept, and they were brought under contract to deliver a flight 6K/18K cryocooler for JWST under MIRI management at JPL.

DETAIL DESIGN AND DEVELOPMENT OF THE FLIGHT MIRI CRYOCOOLER

By the start of the MIRI flight-cooler contract, excellent progress had been made in bringing many of the critical elements of the Northrop Grumman ACTDP cryocooler to TRL6 level, and the efficiency and cooling capability of the critical elements had been confirmed in end-to-end system testing.[25,28,29] However, the transition to the MIRI flight build now required that the remaining elements of the cooler be addressed that had not been identified for development and TRL 6 demonstration during ACTDP.[30]

Elements that were in a relatively high state of inherited maturity included the pulse tube compressor (Fig. 17), which was a derivative of an existing 700 watt HCC compressor that was funded by the Air Force,[31] and the J-T compressor (Fig. 18), which was an existing HEC compressor modified with reed valves during ACTDP based on the methods used by RAL on their 4 K cooler.[17] Also, the cryocooler drive electronics had several versions in space, and was quite mature.[32]

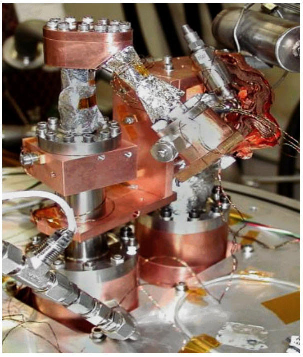

Figure 19. ACTDP Breadboard PT cooler

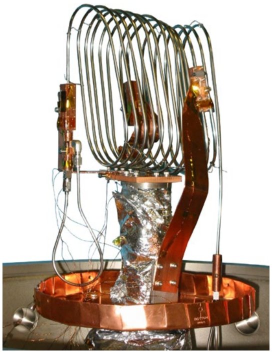

Figure 20. ACTDP breadboard recuperators

Also during ACTDP, several technologies achieved a TRL 4 level of maturity where breadboard testing and analyses validated the designs in all major functional areas, but the designs were not yet packaged to survive launch and integrate with flight interfaces. These included the development model 3-stage pulse tube with bolted joints (Fig. 19), which needed to be reduced to a flight-weight all-brazed design, and the key J-T flow system elements,[16, 25] such as the recuperators (Fig. 20) and J-T valve design.

Elements not addressed in ACTDP and with little flight maturity included the by-pass and decontamination valves, the refrigerant-line supports, the field joints that would be required to interconnect the system, and the refrigerant line deployment section (slinky).

One of the largest cooler development activities requiring substantial engineering effort during the flight build would be designing and managing the extensive mechanical and thermal interfaces between all of these hardware elements and their locations throughout the observatory. The organizational breath of these multiple interfaces required extensive team interactions across multiple organizations around the country including with the MIRI European Consortium. Managing the requirement specifications flowdown and performance verification of these multiple interfaces presented a formidable systems engineering challenge.[33]

3-Stage Pulse Tube Flight Design & Qualification

The MIRI 3-stage precooler had as its foundation, the high power (700 watt) two-stage HCC cryocooler shown earlier in Fig. 17. Subsequent work during the ACTDP time period added a low-temperature third stage pulse tube that provided the necessary 14-19 K precooling for MIRI. This was very similar to the Northrop Grumman 10 K pulse tube being developed for direct cooling of Si:As detectors for Air Force applications.[34, 35] While the necessary thermal performance of the MIRI 3rd stage was fully demonstrated on the ACTDP breadboard unit (Fig. 19), there remained the task of converting this demonstration unit into a flight qualified unit (Fig. 21) consistent with reliable flight manufacturing processes and with the necessary robustness to survive launch and provide long operational life. This was complicated by the unique design of the third stage pulse tube and by

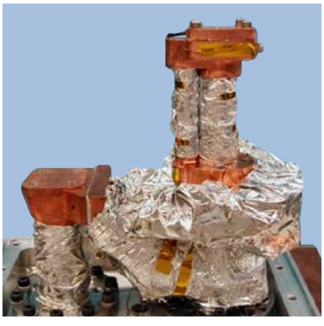

Figure 21. Flight-weight 3rd stage pulse tube.

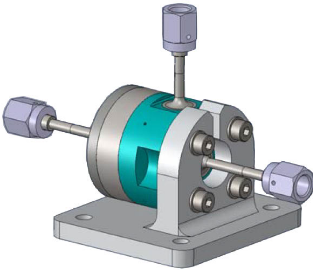

Figure 22. Rendering of JPL pressure-actuated piloted valve

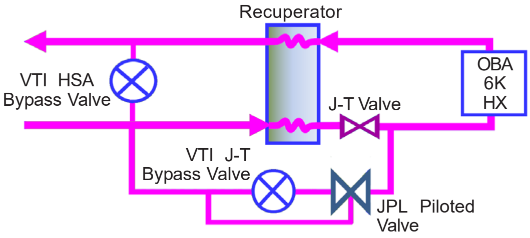

Figure 23. Schematic of MIRI HSA components including VTI bypass valves and the JPL piloted valve

compatibility issues between some of the breadboard pulse tube fabrication details and the relatively high braze temperatures required to assemble the flight units. During the multi-year flight pulse tube development effort, refined manufacturing techniques were successfully developed and qualified that preserved the excellent thermal performance previously demonstrated in the ACTDP breadboard unit.[36]

Bypass Valve Development

Another design element that required a particularly focused effort during the flight cooler build was the cryogenic bypass valve. With the original RAL 4K J-T cooler design concept for the bypass valve,[37, 38] the bypass valve was positioned where it remained at room temperature, thus avoiding the demands of a high-reliability cryogenic latching valve. For JWST, the RAL arrangement would require a large increase in complexity with a third refrigerant line in parallel with the two cryogenic lines running through the precooler recuperators and up the tower. However, achieving the necessary low leak rate at 18 K with a flight-quality latching valve positioned in the ISIM proved to be very demanding also. Several design iterations were pursued with valve designs from Valvetech, Inc., in Phelps, NY during the 2008 to 2014 time period. To bolster the reliability of the final MIRI bypass valve system, a JPL designed and fabricated pressure-actuated piloted valve (Fig. 22) was introduced in series with the flight VTI J-T bypass valve as shown in Fig. 23. Using the VTI valve as its pressure actuator, the JPL diaphragm-operated piloted valve achieves a very high sealing force that results in an exceptionally low leak rate.

To further increase system reliability, the flight VTI units contain micron-level particle filters and have redundant coils which are driven by either the primary or secondary PT electronics. In addition, the electronics software can vary the valve drive pulse width under user command to accommodate faults such as shorted coils.[39] The piloted valve also contains micron-level particle filters to protect its valve seats from contamination.

Flight Packaging of the 6K/18K J-T Assembly (HSA)

Packaging of the bypass valves, decontamination valve, 6 K recuperator, J-T valve and their associated elements of the 6K/18K J-T assembly (the HSA) also represented a significant development effort.[40] Mounted in the 35 to 40 K ISIM meant that the HSA needed to be both radiatively and conductively well isolated from its ISIM mounting environment adjacent to the MIRI instrument. Shown in Figs. 24 and 25 the flight HSA was housed in a gold-plated cylindrical enclosure, and supported from the ISIM structure using low conductivity struts designed and fabricated by JPL. The 6 K refrigerant lines run directly from the HSA to a custom 6 K heat exchanger mounted directly on the main structural deck of the MIRI instrument.

Refrigerant Line Structural Supports and Field Joints

Another aspect of the MIRI cooler that had to be addressed during the flight cooler development was the technology required to support the refrigerant lines with minimal heat conduction from the observatory tower and within the ISIM. Presented earlier, Figure 13 illustrated the complex range of temperatures along the refrigerant line route. Because the two parallel lines are at different temperatures (around 18 K and 22 K) they have to be isolated not only from the tower/ISIM structure, but also from one another. Two support concepts were developed: one by Northrop

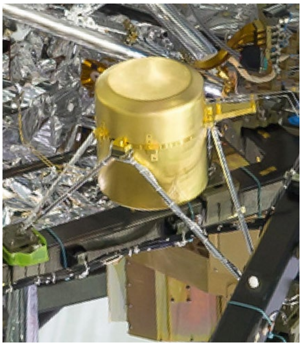

Figure 24. MIRI 18K J-T assembly (HSA) in ISIM.

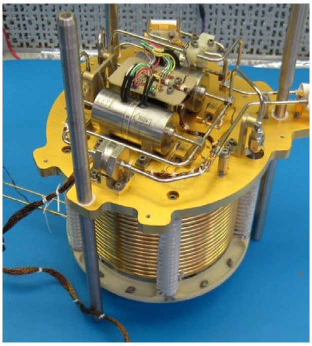

Figure 25. MIRI 18K J-T assembly (HSA) with cover off.

Figure 26. MIRI cooler refrigerant line support (GSFC model).

Grumman for use in the ISIM, and a second by NASA/GSFC to futher reduce the conductive parasitics in the tower line supports. Both are similar and employ a trapeze of springs (plus Kevlar strings for the GSFC design) to support the lines at periodic distances along the line's route from the Spacecraft to the MIRI cooler's 6K/18K J-T assembly (the HSA) within the ISIM. Figures 26 shows the GSFC design.

Because the refrigerant lines bridge across major structural elements of the observatory, they were also required to contain field joints to facilitate the interconnection of the various MIRI cooler assemblies multiple times during the spacecraft integration and testing campaign. To assure their reliability, an extensive field-joint qualification and mate-cycle-life program was conducted on aerospace-rated VCR fittings to ensure their ability to reliably meet MIRI's cycle-life and leak-rate requirements. An 1/8" fitting with 316L SS gaskets was selected for the flight design.

Added MIRI Instrument Radiation Shield

As the cooler was progressing through its detailed flight design phase, the MIRI instrument (shown in Fig. 9) was rapidly converging to its final design and held its Critical Design Review (CDR) in December 2006. One issue that was of concern was measurement of substantially higher emittance for the MIRI instrument external multi-layer-insulation (MLI) than expected…and thus higher 6 K loads on the cooler.[41, 42] This, together with ISIM temperatures that were creeping up, kept pushing up the required cryocooler load and increasing the required cooler electrical input power toward a new 475 watt flight allocation.[43]

Although the MIRI instrument lowered its MLI emittance some by using a thicker metallization layer on the MLI,[44, 41] by 2008 the increasing power issue demanded a solution to the shrinking power margins. The most attractive option appeared to be to add an intermediate-temperature radiation shield around the MIRI instrument to reduce its 6 K loads. The proposed shield (Figs. 27, 28, 29) would be designed and fabricated by NASA/GSFC for integration into the ISIM around the MIRI

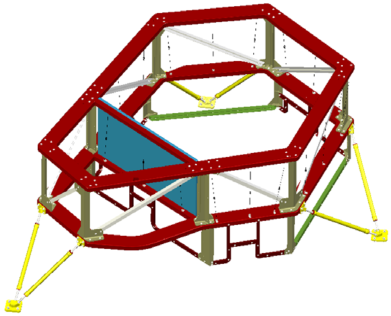

Figure 27. MIRI radiation shield frame and support structure design in 2010.

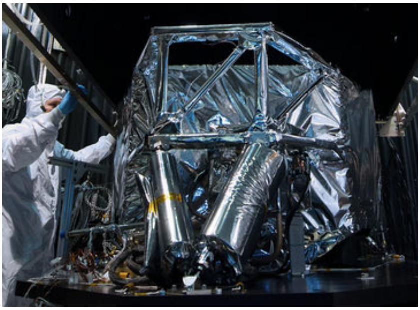

Figure 28. MIRI radiation shield with its MLI cover during thermal-vacuum testing

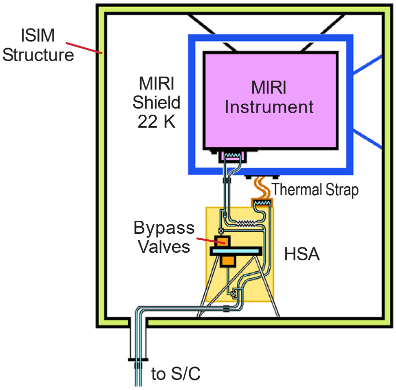

Figure 29. Schematic illustration of MIRI shield within the ISIM.

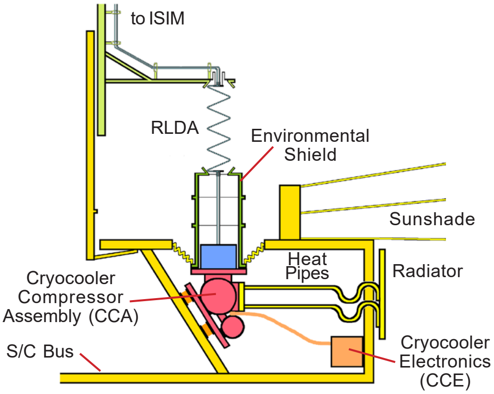

Figure 30. Schematic illustration of MIRI cryocooler compressor assembly mounting arrangement in S/C.

instrument, and would be actively cooled by the MIRI cryocooler's 18 K stage. This had a positive power benefit as the 18 K stage is substantially more thermodynamically efficient than the 6 K stage.[45] From the cooler's perspective, the required modifications were minimal, limited mostly to retrofitting an 18 K heat exchanger into the refrigerant lines for attachment to the new MIRI shield. However, fabricating and qualifying the shield was a major undertaking at NASA Goddard.

Environmental Shield and RLDA Development

One of the more extensive post-ACTDP cooler development efforts was engineering the spacecraft thermal and structural interface for the compressor assembly. During the early years of the observatory development, several major structural/thermal design iterations were pursued by the JWST spacecraft involving different structural and heat pipe/radiator configurations. The spacecraft design finally converged in late 2007 with the MIRI compressor assembly located fairly deep within the spacecraft to accommodate the final spacecraft heatpipe and structural support design.[29] Schematically illustrated in Fig. 30, this arrangement introduced a fairly challenging thermal environment for the PT compressor precooler stages and its recuperators (Fig. 31) that range in temperature down to 15 K. The adjacent region external to the spacecraft was also very challenging, as it is filled with sunshade elements and numerous cables and tower items connecting the spacecraft to the ISIM and telescope. Mechanical access and views to cold environments were severely restricted here.

To minimize the external parasitic loads on the precooler and its exiting 18 K refrigerant lines, a environmental shield was added to the system design as shown in Figs. 30 and 32.[29] An important function of the shield was to isolate the cryogenic components of the compressor assembly from water vapor and other contaminant gasses emanating from the room-temperature spacecraft. It's detailed design would take place over the coming years in conjunction with the detailed design of the spacecraft top deck, the flight cooler recuperator assembly, and the flight design of the Refrigerant

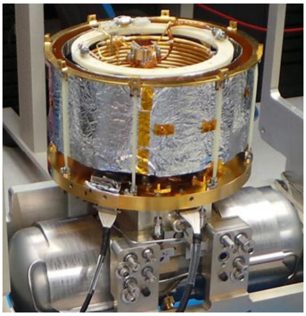

Figure 31. MIRI PT compressor with recuperators and inner shields[N16]

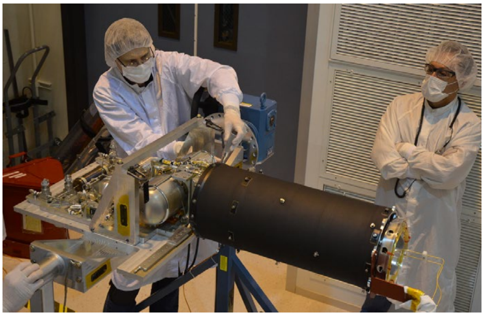

Figure 32. MIRI complete compressor assembly with mounted environmental shield (black)

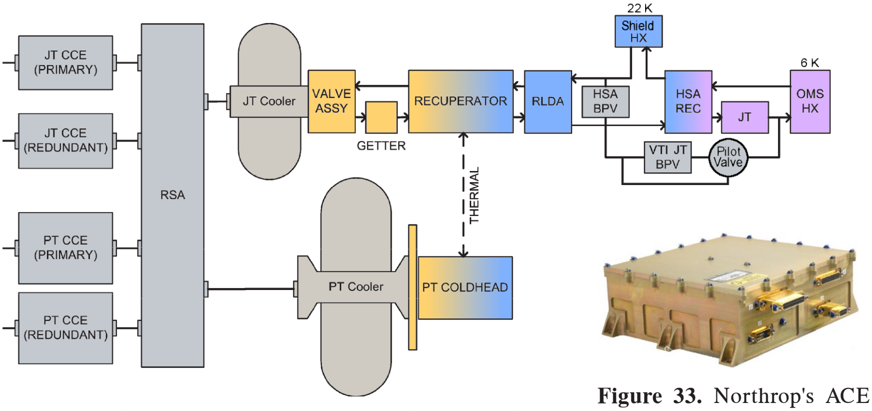

Figure 34. Block diagram of MIRI cryocooler and its electronics.

Figure 33. Northrop's ACE flight cryocooler electronics

Line Deployment Assembly (RLDA) or slinky. The lower half of the RLDA is structurally supported by the environmental shield, as are the cold refrigerant lines running within the shield. When the telescope is deployed following launch, the coiled refrigerant lines extend as the upper half of the RLDA, which is supported off the tower (Fig. 30), deploys away from the spacecraft.

Cooler Drive Electronics Development

The MIRI compressor drive electronics had as its foundation, the long history of TRW/Northrop Grumman cooler flight electronics starting back with the AIRS cryocooler electronics of 1998.[46] Northrop Grumman's most recent electronics for MIRI were their ACE (Advanced Cryocooler Electronics) design (Fig. 33) that power their flight HEC coolers at 180 watts.[32] Also existing was an engineering model of a larger version of the ACE electronics developed to power the larger 700 watt HCC cooler.[31] These ACE units are microprocessor controlled with all control functions in software. In addition to providing power to the compressors, they contain extensive data acquisition functionality, provide closed-loop vibration control based on accelerometers mounted on the compressors, have caging relays to snub piston motion during launch, and have active ripple suppression that reduces input current ripple on the S/C bus by 50 dB.[39]

For JWST, an early decision was to use redundant electronics for both the J-T compressor and the PT precooler with switching managed by a new Relay Switching Assembly (RSA) as illustrated in Fig. 34.[29] The electronics for the MIRI J-T compressor would use an upgraded version of the ACE electronics with added accommodation for 1553 command and telemetry and four-wire low-temperature Cernox temperature sensors for precision temperature control measurements. Also based on the ACE electronics, the MIRI PT precooler electronics would use a new flight packaging of two HEC-electronics power modules to achieve 360 watts of drive capability, together with the same drive and control boards as the J-T electronics. In addition, the MIRI PT electronics would contain a JPL-provided board to provide constant-current power for the latching bypass and decontamination valves, and 60-volt power for six heaters used in the various cooler temperature control functions.[39] The RSA switch assembly contains a set of redundant relays to switch the compressor power and sensor signals between the primary and redundant units.

Figure 35 provides a summary schematic of the overall MIRI instrument and its integration with the MIRI cryocooler.

FLIGHT COOLER INTEGRATION AND TEST

Prior to its use in the ISIM, telescope, and spacecraft I&T campaigns, the flight MIRI cooler was scheduled to be delivered to JPL in 2014 for extensive system-level testing with a surrogate MIRI instrument and observatory-system interfaces to confirm the total integrated cooler system-level performance. Completing the flight cooler in 2014 in preparation for delivery reached a feverish pitch and drew congressional-level attention as schedule reserves were rapidly consumed.[47, 48]

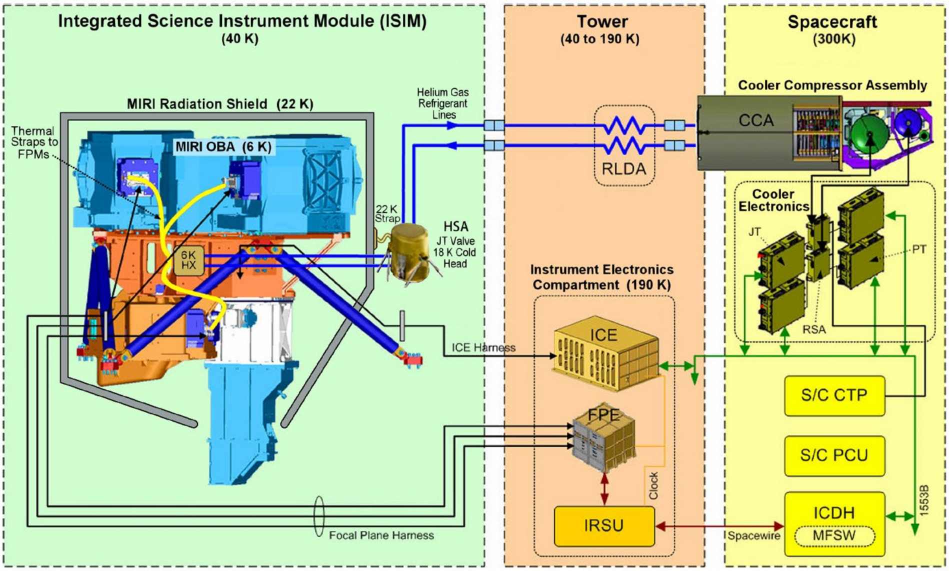

Figure 35. Schematic illustration of MIRI cryocooler instrument and cryocooler systems. Note that each of MIRI's three focal plane assemblies is conductively coupled to a point next to the 6 K heat exchanger with its own high-conductivity aluminum wire to minimize thermal gradients.[41]

After a herculean effort, the flight MIRI flight compressor assembly (Figure 36) successfully completed its component acceptance testing,[36] and in July 2015 was delivered to JPL for the start of assembly and system-level environmental and performance testing. At the same time, the cooler's flight J-T cold end components (the HSA and its ISIM refrigerant lines) were shipped to NASA/GSFC for integration with the MIRI instrument for the ISIM's cryo-vacuum testing campaign.

From this point on in the overall JWST integration and test campaign, the two halves of MIRI flight cryocooler would follow separate paths. After the year-long JPL tests, the flight compressor assembly and drive electronics were delivered to the spacecraft in July 2016 for use in the spacecraft buildup and system-level testing at Northrop Grumman in Redondo Beach, California. Meanwhile, the flight refrigerant lines and 18 K HSA would be used to provide the MIRI instrument's cooling during ISIM and OTIS (combined Optical Telescope plus ISIM) testing. A GSE compressor assembly would be used in place of the flight compressors for these ISIM and OTIS tests.

Well before testing began with the flight cooler hardware, a risk-reduction ISIM test (CV1-RR) was conducted at NASA Goddard in 2013 soon after the delivery of the MIRI flight instrument

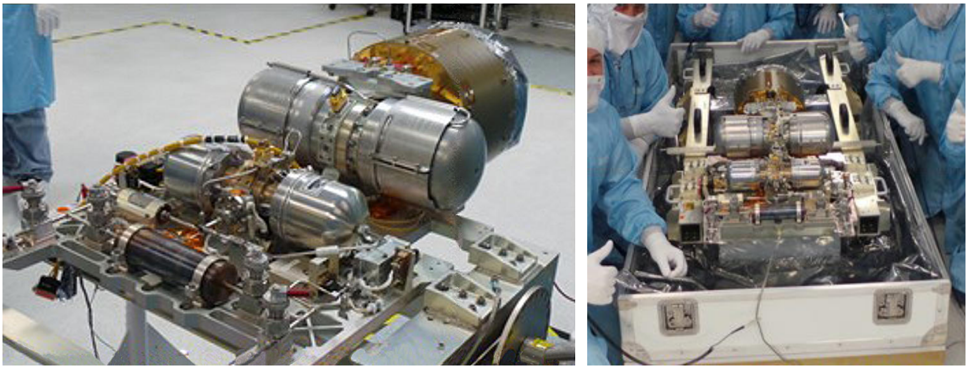

Figure 36. Completed MIRI flight compressor assembly ready to ship to JPL for system-level testing[16]

Figure 37. Integration of MIRI into ISIM in 2013.

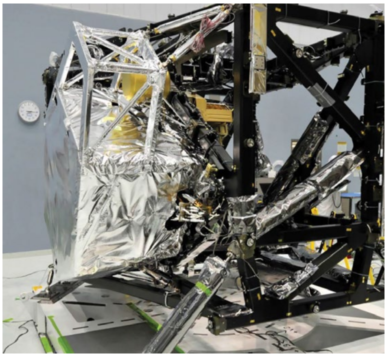

Figure 38. MIRI instrument in ISIM complete with GSFC-supplied radiation shield.

(Fig. 37). This testing of the MIRI instrument incorporated the GSFC-supplied radiation shield (Fig. 38) for the first time and used a GSE (ground support equipment) 18 K precooler together with a flightlike J-T HSA assembly for cooling the instrument.

Testing of the fully integrated ISIM began in summer 2014 and included all the ISIM flight instruments, plus the structure, harness radiator, and electronics. During this CV2 cryo-vacuum test, the ISIM and its instrument systems, including MIRI and its cooler, were put through a comprehensive sequence of thermal, optical, electrical, and operational tests that verified their complete end-to-end performance (Fig. 39). This would be followed by a suite of environmental tests including launch vibration and EMI, and then, in late 2015, culminated with a third 108-day-long cryo-vacuum test test (CV3) to confirm the post-environmental-test performance.[49]

From the Goddard cryo-vacuum tests, the ISIM and its instruments were next integrated in 2016 with the observatory's Optical Telescope Element (OTE) to allow testing of JWST's total end-to-end optical performance in a simulated space environment. This comprehensive OTIS (combined OTE+ISIM) test campaign was carried out in 2017 in NASA Johnson Space Center's the large T/V chamber (Chamber A) in Houston, Texas (Fig. 40).[50]

After the successful optical testing, the OTIS was shipped in February 2018 to Northrop Grumman in California for final integration with the JWST spacecraft (Fig. 41) and preparation for shipment to the launch site. In March 2020, during this spacecraft integration, the two MIRI cooler halves would finally be joined to become the MIRI flight cryocooler operating in space today.

SUMMARY

The Mid Infrared Instrument (MIRI) of the James Webb Space Telescope (JWST) and its associated cryocooler is one of the most demanding space cryogenic applications ever attempted. Planned as the follow-on to Hubble, JWST abandoned Hubble's astronaut-accessible low-Earth orbit for a colder and better-science environment 1.5 million km from Earth. Targeting for this L2 location meant no servicing missions would be possible, and significant deployments would be required post

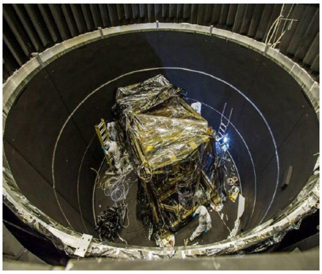

Figure 39. ISIM cryo-vacuum testing at GSFC.

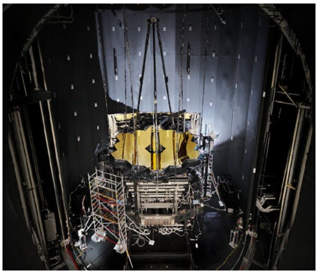

Figure 40. OTIS testing at Johnson Space Center

Figure 41. Observatory assembly and test at NGSS.

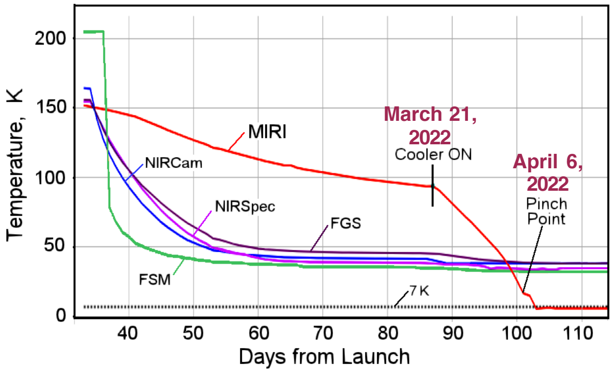

Figure 42. MIRI instrument successful cooldown to 6 K after reaching L2.

launch to allow the observatory to unfurl from its launch-vehicle shroud and separate the cold telescope and its instruments from its spacecraft bus.

The design of the MIRI cryocooler accommodated these mission constraints by positioning its hot and vibration-generating compressors inside the spacecraft bus, while the MIRI instrument and the cryocooler's cold-end were positioned 10 meters away in the Science Instrument Module on the back of the telescope's primary mirror. Providing MIRI's large refrigeration load at 6 K, while simultaneously integrating into every major part of the observatory led to one of the most technically complicated and management challenging space cryocoolers ever designed.

On December 25, 2021, JWST was successfully launched on its mission to L2 on top of an Ariane V launch vehicle from French Guiana. After successfully executing its extensive deployment campaign, the observatory reached L2 and began its initiation of science instrument and telescope operational verification and calibration. After MIRI self-cooled below 100 K, the MIRI cooler started cooldown on March 21, 2022, passed successfully through its 14 K pinchpoint on April 6, and reached the instrument's 5.9 K operational temperature two days later (Fig. 42).[51, 52]

With this essentially perfect first in-space cooldown, the MIRI cryocooler successfully completed this first critical phase of its 20-year development… an enormous accomplishment! However, the important operational phase comes next, with a goal of 5 to 10 years of science discoveries from what Stewart Wills of *Optics and Photonics News* calls the “Marvelous MIRI.”[53] As inspiring as the MIRI cryocooler engineering story is, the ultimate payoff is the science that the MIRI instrument will accomplish and the cryocooler will support over the next several years. Based on the excellent track record to date of Northrop Grumman cryocoolers, several with greater that 20-year lives in orbit,[54] we look forward to a long life for the MIRI cryocooler and instrument and await with anticipation the discovery of many fascinating new insights into our Universe's origins.

ACKNOWLEDGMENTS

The work described in this paper was carried out by an enormous team of folks, principally at Northrop Grumman in Redondo Beach, CA, at the Jet Propulsion Laboratory in Pasadena, CA, and at NASA/GSFC in Greenbelt, MD. The JWST spacecraft team at Northrop Grumman and the MIRI instrument team and its European Consortium played a critical roll in working with the cryocooler and ISIM teams to successfully integrate the cooler with the instrument and observatory.

Special recognition are due to Mike Petach and Jeff Raab of NGSS, Kim Banks of GSFC, and Konstantin Penanen of JPL who provided critical inputs to this manuscript and assumed key technical and management roles in the 20-year development of the MIRI cooler.

The research associated with this report was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (80NM0018D0004).

REFERENCES

1. E. J. Weiler, E.J., “Hubble Space Telescope Second Generation Instrument Selection,” Highlights of Astronomy, Vol. 8 (1989), D. McNally (ed.), pp. 441-442.
2. Miller, C.D., “Development of the Long-Lifetime Solid Nitrogen Dewar for NICMOS,” *Adv. in Cryogenic Engin.*, Vol. 43, Plenum Press, NY, 1998.
3. Vaughan, A.H., "Imaging Michelson Spectrometer For Hubble Space Telescope", *Proc. SPIE 1036, Precision Instrument Design* (1 May 1989).
4. Bard, S. and Jones, J.A., “Development and Testing of an 80 K Oxide Sorption Cryocooler,” *Cryocoolers 5* (1998), pp. 13-24.
5. Miller, C.D., “Pre- and Post-Launch Performance of the NICMOS Dewar,” *Adv. in Cryogenic Engin.*, Vol. 43, Plenum Press, NY, 1998.
6. Nellis, G.F., Dolan, F.X., McCormick, J.A., Swift, W.L., Sixsmith, H., “Reverse Brayton Cryocooler for NICMOS,” *Cryocoolers 10*, ed. R.G. Ross, Jr., New York: Kluwer Academic/Plenum Publishers, 1999, pp. 431- 438.
7. Swift, W.L., Dolan, F.X. and Zagorola, M.V., “The NICMOS Cooling SYSTEM-5 Years of Successful On-Orbit Operation,” *Advances in Cryogenic Engineering Transactions of the Cryogenic Engineering Conference* - CEC, Vol. 52. AIP Conference Proceedings, Volume 985 (2008), pp. 799-806.
8. Ross, R.G., Jr., Boyle, R.F., Key, R.W. and Coulter, D.R., “NASA Advanced Cryocooler Technology Development Program,” *Proceedings of the International Society of Optical Engineering (SPIE) Conference*, Waikoloa, Hawaii, August 22-28, 2002.
9. Wright, G.S., Bortoletto, F., Bruce, C.F., et al., “The NGST MIRI Instrument,” *Proc. SPIE 4850* (2003), pp. 493-503.
10. Ross, R.G., Jr. “A Study of the Use of 6K ACTDP Cryocoolers for the MIRI Instrument on JWST,” *Cryocoolers 13*, Springer Science & Business Media, New York, 2005, pp. 15-24.
11. Wright, G.S., Rieke, G., Barella, P., et al., “Design and Development of MIRI, the Mid-IR Instrument for JWST,” *Proc. SPIE 7010, Space Telescopes and Instrumentation* (2008).
12. Spradley, I.E., Nast, T.C., and Frank. D.J., “Experimental Studies of MLI Systems at Very Low Boundary Temperatures,” *Adv. in Cryogenic Engineering,* Vol. 35, 1990, pp. 477-486.
13. Ross, R.G., Jr., “Quantifying MLI Thermal Conduction in Cryogenic Applications from Experimental Data,” *Adv. in Cryogenic Engineering: Proceedings of the Cryogenic Engin. Conf. (CEC) 2015*, Vol. 101, IOP Publishing, Bristol, UK (2015), article 012017.
14. Ross, R.G., Jr., “Calculation of the Thermal Radiation Properties of Low-Emissivity Surfaces at Temperatures below 50 K,” JPL Internal MIRI Report, April 17, 2006.
15. Glaister, D. et al., “Ball Aerospace 4-10 K Space Cryocooler,” *Cryocoolers 13*, Kluwer Academic/ Plenum Publishers, New York (2005), pp. 1-8.
16. Raab, J. et al., “Advanced Cryocooler Technology Development Program (ACTDP) Cooler System,” *Cryocoolers 13*, Kluwer Academic/Plenum Publishers, New York (2005), pp. 9-14.
17. Orlowska, A., Bradshaw, T.W., and Hieatt, J., “Development Status of a 2.5 - 4K Closed Cycle Cooler Suitable for Space Use,” *Cryocoolers 8,* R.G. Ross Jr (*Ed*), Plenum, New York (1994), pp. 517-524.
18. Ross, R.G., Jr., “Cryocooler Load Increase due to External Contamination of Low-ϵ Cryogenic Surfaces,” *Cryocoolers 12*, Kluwer Academic/Plenum Publishers, New York (2003), pp. 727-736.
19. Ross, R.G., Jr., “Estimation of Thermal Conduction Loads for Structural Supports of Cryogenic Spacecraft Assemblies,” *Cryogenics*, Vol. 44, Issue: 6-8, June - August, 2004, pp. 421-424.
20. Ross, R.G., Jr., ”Estimation of In-Space Emittance (IR Absorptance) Increase of MIRI Refrigerant Lines over Time,” JPL MIRI internal Report, Jet Propulsion Laboratory, May 18, 2007.
21. Ferlet, M., JWST MIRI Preliminary External Contamination Impact Analysis, MIRI European Consortium document MIRI-TN-00029-RAL, December 11, 2003.
22. Heys, S., Swinyard, B., Ferlet, M., Eccleston, P., et al., “Thermal and Contamination Control of the Mid-Infrared Instrument for JWST,” *Proc. SPIE 5497* (2004), pp. 39-50.

23. Shaughnessy, B.M., Eccleston, P., Fereday, K.J., Canfer, S.J., Nørgaard-Nielsen, H.U., Jessen. N.C., "Thermal Conductivity Measurement below 40 K of the CFRP Tubes for the Mid-Infrared Instrument Mounting Struts," *Cryogenics* Vol. 47 (2007), pp. 348 - 352.

24. Wright, G.S. et al., "The JWST MIRI Instrument Concept," *Proc. SPIE 5487* (2004), pp. 653-663.

25. Ross, R.G., Jr., and Johnson, D.L., "NASA's Advanced Cryocooler Technology Development Program (ACTDP)," *Adv. in Cryogenic Engineering*, Vol. 51, Amer. Inst. of Physics, NY, 2006, pp. 607-614.

26. Glaister, D., Gully, W., Hendershott, P., Marquardt, E., Kotsubo, V., Ross, R.G., Jr., "Ball Aerospace 4-6 K Space Cryocooler," *Cryocoolers 14*, ICC Press, Boulder, CO (2007), pp. 41-48.

27. Nast, T., Olson, J., Roth, E., Evtimov, B., Frank, D., and Champagne, P., "Development of Remote Cooling Systems for Low-Temperature, Space-Borne Systems," *Cryocoolers 14*, ICC Press, Boulder, CO (2007), pp. 33-40.

28. Durand, D., Raab, J., Colbert, R., Michaelian, M., Nguyen, T., Petach, M., and Tward, E. "NGST Advanced Cryocooler Technology Development Program (ACTDP) Cooler System," *Advances in Cryogenic Engineering*, vol. 51, edited by J.G. Weisend II (2006), pp. 615-622.

29. Durand, D., Colbert, R., Jaco, C., Michaelian, M., Nguyen, T., Petach, P., and Tward, E., "NGST Advanced Cryocooler Technology Development Program (ACTDP) Cooler System," *Cryocoolers 14*, ICC Press, Boulder, Colorado (2007), pp. 21-26.

30. Durand, D., Colbert, R., Jaco, C., Michaelian, M., Nguyen, T., Petach, M., and Raab, J., "Mid InfraRed Instrument (MIRI) Cooler Subsystem Prototype Demonstration," *Advances in Cryogenic Engineering: Transactions of the Cryogenic Engineering Conference* – CEC, vol. 53, edited by J.G. Weisend II (2008), pp. 807-814.

31. Chan, C.K., Nguyen, T., Jaco, C., et al., "High Capacity Two-Stage Pulse Tube Cooler," *Cryocoolers 12*, Kluwer Academic/Plenum Publishers, New York (2003), pp. 219-224.

32. Harvey, D., Danial, A., et al., "Advanced Cryocooler Electronics for Space," Cryogenics, vol. 44, issue: 6-8, June-August 2004, pp. 589-593.

33. Banks, K., Larson, M., Aymergen, C., Zhang, B, "James Webb Space Telescope Mid-Infrared Instrument Cooler Systems Engineering," *Proc. SPIE 7017, Modeling, Systems Engineering, and Project Management for Astronomy III*, 70170A (2008).

34. T. Nguyen, R. Colbert, D. Durand, C. Jaco, M. Michaelian, and E. Tward, "10K Pulse Tube Cooler," *Cryocoolers 14*, ICC Press, Boulder, CO (2007), pp. 27-31.

35. Jaco, C., Nguyen, T., Raab, J., "10 K Pulse Tube Cooler Performance Data," *Cryocoolers 15*, ICC Press, Boulder, CO (2009), pp. 1-6.

36. Petach, M., Michaelian, M., Nguyen, T., Colbert, R., and Mullin, J., "Mid InfraRed Instrument (MIRI) Cooler Compressor Assembly Characterization," *Cryocoolers 19*, ICC Press, Boulder, CO (2016), pp. 1-8.

37. Bradshaw, T.W., Orlowska, A.H., and Jewell, C., "Life Test and Performance Testing of a 4K Cooler for Space Applications," *Cryocoolers 10,* R.G. Ross Jr (*Ed*), Plenum, New York (1999), pp. 521-528.

38. *Joule-Thomson By-pass for Cryogenic Cooler,* UK patent GB 2241565 27/5/94 and USA 5317878. July 1994.

39. Harvey, D., Flowers, T., Liu, N., et al., "James Webb Space Telescope Mid Infra-Red Instrument Cryocooler Electronics," *Cryocoolers 19*, ICC Press, Boulder, CO (2016), pp. 343-351.

40. Petach, M. and Michaelian, M., "Mid InfraRed Instrument (MIRI) Cooler Cold Head Assembly Acceptance Testing and Characterization," *Cryocoolers 18*, ICC Press, Boulder, CO (2014), pp. 11-18.

41. Wright, G.S., Wright, D., Goodson, G.B., Rieke, G.H., et al., "TheMid-Infrared Instrument for the James Webb Space Telescope, II: Design and Build," Publications of the Astronomical Society of the Pacific, 127:595–611, July 2015.

42. Shaughnessy, B.M. and Eccleston, P., "Thermal Design of the Mid-Infrared Instrument (MIRI) for the James Webb Space Telescope," *International Conference on Environmental Systems (ICES)*, 29 June to 2 July 2008, San Francisco, California, USA.

43. Durand, D., Adachi, D., Harvey, D., Jaco, C., Michaelian, M., Nguyen, T., Petach, M. and Raab, J., "Mid InfraRed Instrument (MIRI) Cooler Subsystem Design," *Cryocoolers 15*, ICC Press, Boulder, Colorado (2009), pp. 7-12.

44. Shaughnessy, B.M., “Thermal Design and Testing of the Mid-Infrared Instrument (MIRI) Optics Module,” 42nd International Conference on Environmental Systems, San Diego, California, AIAA, July 2012.

45. Petach, M., Durand, D., Michaelian, M., Raab, J. and Tward, E, “MIRI Cooler System Design Update,” *Cryocoolers 16*, ICC Press, Boulder, CO (2011), pp. 9-12.

46. Johnson, D.L., Collins, S.A., and Ross, R.G., Jr., “EMI Performance of the AIRS Cooler and Electronics,” *Cryocoolers 10*, Plenum Publishing Corp., New York (1999), pp. 771-780.

47. James Webb Space Telescope: Project Facing Increased Schedule Risk with Significant Work Remaining, *Report to Congressional Committees by United States Government Accountability Office,* December 2014.

48. Leone, D., “Manufacturing Issues Plague James Webb Space Telescope,” *SpaceNews*, November 14, 2014.

49. Kimble, R.A., Begoña Vilab, M., Van Campena, J.M., Birkmannc, S.M., et al.,“Cryo-Vacuum Testing of the JWST Integrated Science Instrument Module,” Space Telescopes and Instrumentation 2016: Optical, Infrared, and Millimeter Wave, Proc. of SPIE Vol. 9904, 990408 (2016).

50. Yang, K., Glazer, S.D., Thomson, S.R., Feinberg, L.D., et al., “Thermal Model Performance for the James Webb Space Telescope OTIS Cryo-Vacuum Test,” ICES-2018-35, 48th International Conference on Environmental Systems, 8-12 July 2018, Albuquerque, New Mexico.

51. Penanen, K., Breda, D., Moore, B., Naylor, B., et al., “Mid-Infrared Instrument Cryocooler on James Webb Space Telescope: Cooldown, Commissioning and Initial Performance,” *Cryocoolers 22,* ICC Press, Boulder, CO (2022), this proceedings.

52. Petach, M.B. and Moore, B., “Transient Thermal Model of the JWST MIRI Cryocooler,” *Cryocoolers 22*, ICC Press, Boulder, CO (2022), this proceedings.

53. Wills, S., “Marvelous MIRI,” *Optics and Photonics News*, April 2022.

54. Meyer, M. and Ross, R.G., Jr., “NASA Cryogenics Technical Discipline Team Updates Long-life Space Cryocooler Flight Operating Experience Survey,” *Cold Fact*s, v. 36, n.5, October 2020.