

OCO-2 Cryocooler Development, Integration, and Test

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ABSTRACT

The Orbiting Carbon Observatory (OCO-2) is currently in its final stages of assembly and checkout at this time in preparation for a July 2014 launch aboard a Delta II from Vandenberg Air Force Base in California. OCO-2 is designed to collect space-based global measurements of atmospheric carbon dioxide (CO₂) with the precision, resolution and coverage needed to characterize regional-scale sources and sinks of this important greenhouse gas. The observatory consists of a dedicated Orbital Sciences Corporation (OSC) LEOSTar-2 spacecraft bus that carries a single instrument. The instrument uses three HgCdTe focal plane arrays that are cooled by a Northrop Grumman Aerospace Systems (NGAS) High Efficiency Cryocooler (HEC) pulse tube cryocooler operating at 110 K. The cryocooler is powered and controlled by the NGAS Advanced Cryocooler Electronics (ACE).

The development of this cryocooler system was a collaborative effort that involved qualification and characterization testing at NGAS and JPL, instrument integration at JPL, and observatory integration at Orbital Sciences Corporation (OSC) in Gilbert, Arizona.

This paper presents the development, characterization, flight qualification and flight integration test results, including detailed thermal and temperature control performance within the flight instrument boundary conditions, for the OCO-2 cryocooler system.

NEED ATMOSPHERIC CO₂ MEASUREMENTS FROM SPACE – OCO REFLIGHT

In 2002, NASA selected the Orbiting Carbon Observatory mission (OCO) to return space-based measurements of atmospheric carbon dioxide (CO₂) with the sensitivity and spatial and temporal sampling required to quantify CO₂ sources and sinks. This was to be the most challenging atmospheric trace gas measurement ever attempted from space. While there have been advances in space-based CO₂ measurement capabilities since 2002, including JAXA IBUKI (GOSAT), no other existing or confirmed satellite sensor can provide the measurements needed to quantify both CO₂ sources and sinks. The unfortunate loss of OCO in early 2009 due to launch failure delayed delivery of this critical data. OCO measurements are widely viewed as essential to provide the scientific basis for developing greenhouse gas policies. Meeting the science and policy imperatives on the needed time scale could only be accomplished by launching an OCO rebuild on a fast-track schedule that capitalizes on the project's assets and innovations.

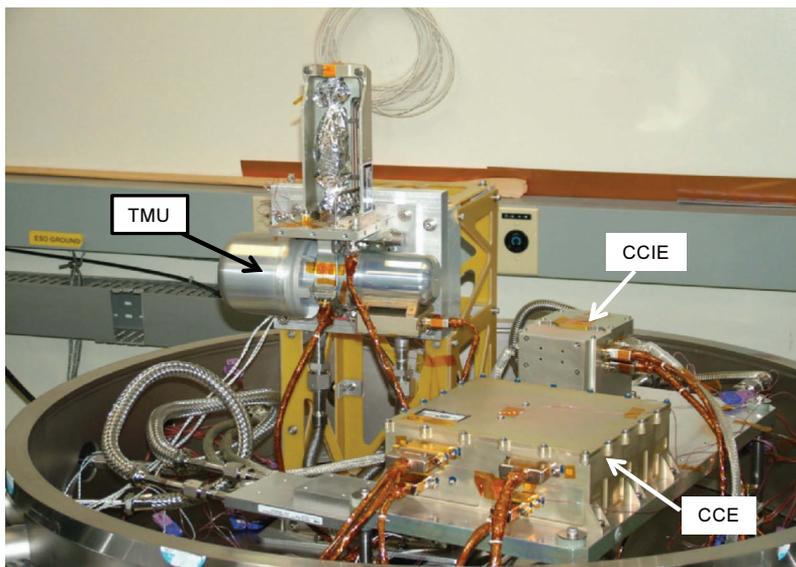


Figure 1. OCO-2 Cryocooler System Hardware Installed on Heat Exchangers in TVAC Chamber.

The OCO Project was granted funding to develop OCO-2 starting in June 2009, focused toward launch on a United Launch Alliance (ULA) Delta II 7320 launch vehicle in Summer 2014 and delivery of exploratory atmospheric CO₂ data products to the public as soon as early 2015.

FLIGHT COOLER SYSTEM

The OCO-2 cryocooler system consists of the elements shown in Fig. 1, including the Thermal Mechanical Unit (TMU), the Cryocooler Control Electronics (CCE) and flight cables for connecting the TMU and CCE. The CCE is supplied by NGAS, and is the next-generation Advanced Cryocooler Electronics (ACE) design after the AIRS/TES CCE. The TMU is the NGAS High Efficiency Cryocooler (HEC), which is a single stage linear pulse tube cooler designed to provide large refrigeration capabilities (15 W at 110 K) for users. The HEC was selected because it has similar design features to the original OCO cryocooler with respect to mechanical, thermal, software and electrical interfaces. This would help facilitate the integration of the TMU into the OCO-2 instrument.

An ancillary electronics unit, known as the Cryocooler Interface Electronics (CCIE), is the interface between the CCE and the instrument host electronics. The CCIE allowed the instrument host electronics and software design to remain unchanged from the original OCO. The spacecraft bus provides power to the CCIE, which in-turn passes the power through to the CCE after it performs EMI functions such as inrush current suppression. The CCIE also provides an FPGA that reformats command and telemetry data from the RS-422 interface of the host instrument to the LVDS interface of the cooler's ACE electronics.

Table 1 provides the mass of the system components; total weight is 9.5 kg.

Table 1. OCO-2 Cooler Hardware Weight Breakdown

	TMU	CCE	CCIE	Cables
Weight, kg	4.112	3.819	0.904	0.684

Table 2. Thermal Cycle Test Parameters

	Hot		Cold		Number of Cycles
	ON	OFF	ON	OFF	
TMU	323 K for 72 hrs	328 K for 12 hrs	258 K for 40 hrs	253 K for 12 hrs	3
CCE	323 K for 72 hrs	338 K for 8 hrs	253 K for 40 hrs	243 K for 6 hrs	3
CCIE	348 K for 72 hrs	348 K for 6 hrs	238 K for 24 hrs	238 K for 6 hrs	3

Table 3. Cooler Hardware Subjected Loads during Vibration Testing

	CCIE	CCE	TMU
Frequency (Hz)	Level	Level	Level
20	0.026 G ² /Hz	0.013 G ² /Hz	0.016 G ² /Hz
20 to 50	+6 dB/octave	+6 dB/octave	+6 dB/octave
50 to 300	0.16 G ² /Hz	0.08 G ² /Hz	0.10 G ² /Hz
300 to 2000	-6 dB/octave	-6 dB/octave	-6 dB/octave
2000	0.0037 G ² /Hz	0.0019 G ² /Hz	0.0023 G ² /Hz
Overall	9.1 G _{rms}	6.4 G _{rms}	7.2 G _{rms}

COOLER FLIGHT QUALIFICATION

Thermal and vibration qualification tests for the TMU and CCE were performed at NGAS, and thermal and vibration qualification of the CCIE were performed at JPL. The cryocooler system was thermally cycled to the levels shown in Table 2. Testing of the system before and after thermal cycling showed no degradation in performance. Random vibration testing was performed to the levels as shown in Table 3. The CCE was tested at flight acceptance (FA) level. The components passed vibration testing without difficulty.

EMC tests were performed to determine compliance with the specifications of MIL-STD-461 as tailored for OCO-2. The system passed CE01/03 conducted emissions tests and voltage/current ripple transients. The current ripple was measured to be less than 500 mA p-p (peak-to-peak) from 25 V to 35 V. The highest ripple captured was 215 mA p-p at 29.5 V. The system passed inrush current requirements. The maximum inrush was below 10 A and completed in a time duration less than 170 msec. The system passed conducted susceptibility tests CS01/02, CS06 and ± 3 V voltage transient tests. EMC measurements were generally made at the high end of input power to demonstrate the highest expected current ripple or emissions. The TMU was operated at a heat reject temperature of 298 K, and typically at 60-63 W of input power. No anomalies were noted during testing for all of these EMC tests.

CRYOGENIC SUBSYSTEM

The cryogenic subsystem (CSS), as shown in Fig. 2, provides the interface between the three mercury cadmium telluride (HgCdTe) focal plane arrays (FPA) and the TMU. The CSS was designed, manufactured and tested by Space Dynamics Laboratory (SDL). One FPA operates in the O₂ A-band at 0.76 μ m and the other two FPAs operate in the CO₂ bands at 1.6 μ m and 2.06 μ m. The CSS consists of three subassemblies, one for each FPA, and a flexible aluminum foil thermal link that connects each subassembly to the TMU. Each subassembly provides a mounting location for an FPA, while thermally isolating each FPA from the instrument optical bench and thermally coupling the FPAs to the TMU cold block. The FPA mounts consist of reentrant tri-fold G10 fiberglass/epoxy tube construction and MLI to minimize parasitic heat loads on the FPAs. With the TMU cold block controlled to 110 K, the CSS is designed to maintain the three FPAs at the desired temperature of 120 K.

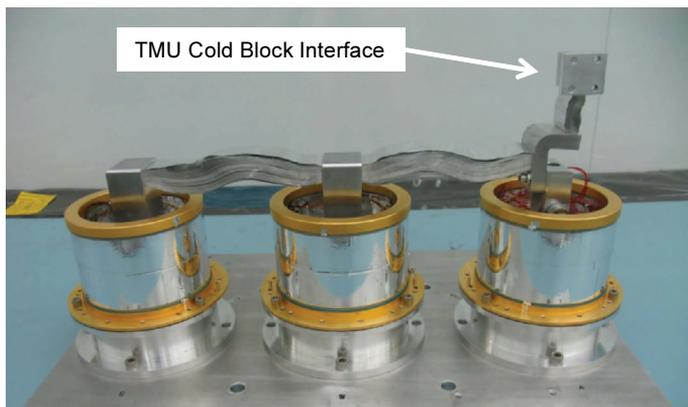


Figure 2. OCO-2 SDL Cryogenic Subsystem.

COOLER CHARACTERIZATION TESTING

Since the three FPAs are to operate at 120 K, the cooler system was characterized for 110 K isotherms in addition to load lines. The TMU was operated at a single drive frequency of 63 Hz, which is the optimal drive frequency recommended by NGAS for OCO's operating conditions. The data were plotted on multi-variable plots as shown in Figs. 3 and 4 to display the sensitivity of the cooler's thermal performance as a function of applied load to the cold block, cold block temperature, and heat rejection temperature.

Performance tests for the TMU were performed at a nominal reject temperature of 298 K, as well as at the OCO-2 allowable flight (AFT) limits of 303 K and 273 K. The measured performance of the TMU at 298 K reject temperature for varying drive levels is shown in Fig. 3. The performance data are shown in Fig. 4 for both hot and cold plateaus of 303 K and 273 K, respectively. These data show that for a 30 K change in heat reject temperature, there is a 350 mW change in refrigeration performance at 110 K.

With the heat load from the CSS to the TMU at the beginning of the mission expected to be 2.4 W at 110 K, the power at the input to the CCIE is about 45 W, thus meeting the key OCO-2 performance requirement, which requires that the TMU be able to provide cooling to 110 K with no more than 63 W of power at the input to the CCIE. As a note, the HEC is capable of delivering seven times this capacity at much higher input power. As a result, the TMU and CCE will not be operating at their highest possible efficiency at this low input power.

Cold block temperature stability measurements were made while varying input voltage and varying cryocooler and electronics reject temperatures. Although the CCE is capable of collecting data every two seconds, the cold block temperature stability measurements were typically taken at 15 second intervals. The OCO-2 instrument host electronics is limited to sampling CCE data at 80 second intervals.

Two sets of input voltage variations were performed; either 1) the input voltage was manually varied over a 4 V range as anticipated from the battery charging/discharging during a one orbit period, or 2) the input voltage was varied abruptly to 22V, 25V, 28V or 35V and then held stable for a period of one orbit at each of these voltages. Input voltage variations had no effect on the power to the TMU such that the compressor power stayed constant and the cold block stability remained at or less than 33 mK p-p over a 98 minute period (one orbit). During reject temperature ramp changes, the reject temperature was increased at a rate of 0.2 K/min from 273 K to 298 K. The increase in the reject temperature resulted in an increase in the motor power required by the compressor although the cold block temperature stability remained at or less than 60 mK p-p over a 98 minute period.

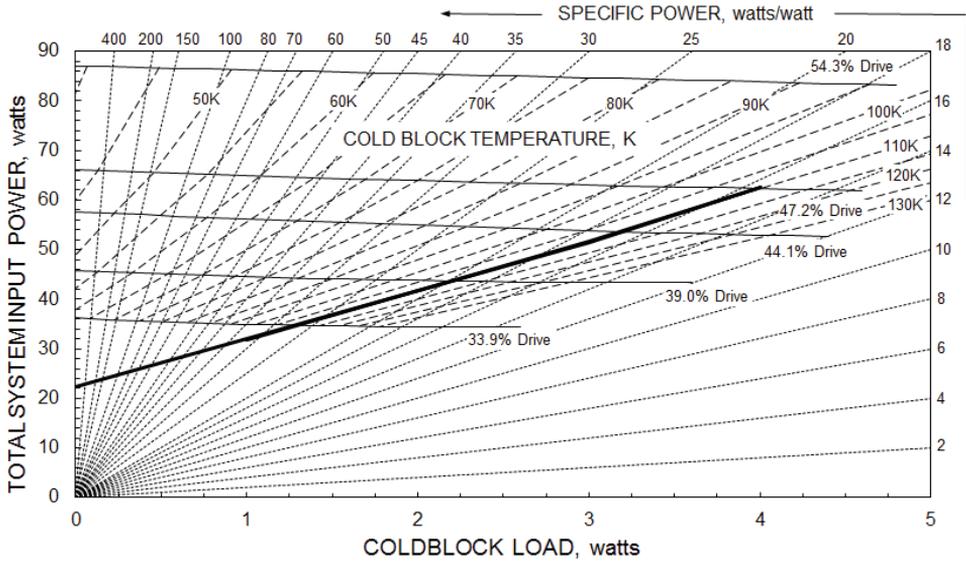


Figure 3. TMU Performance at 298 K Reject Temperature.

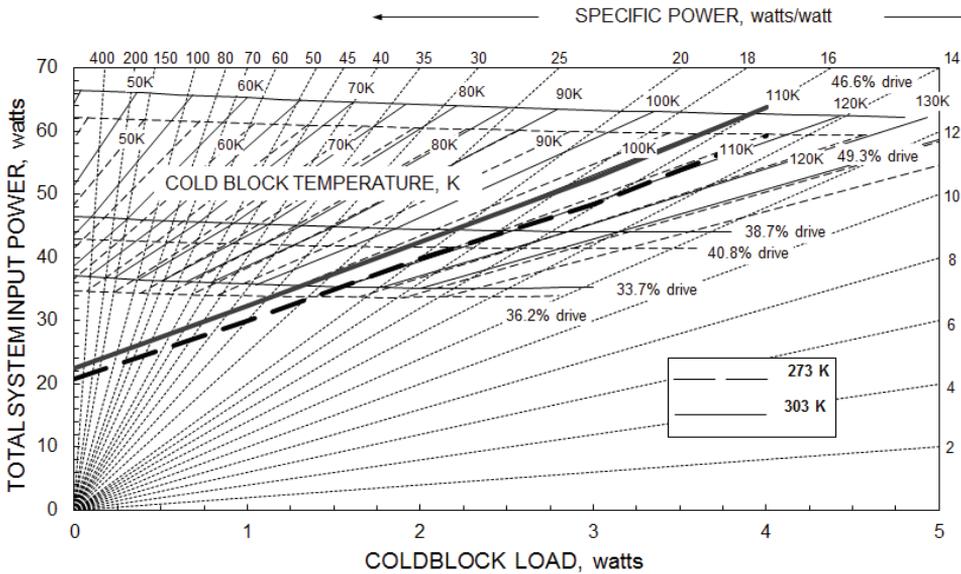


Figure 4. TMU Performance at 303 K (solid lines) and 273 K (dashed lines) Reject Temperature.

INSTRUMENT INTEGRATION

After successfully completing qualification and characterization testing, the cryocooler system was delivered to JPL for integration into the OCO-2 Instrument.

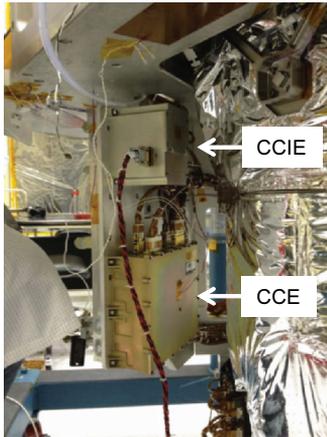


Figure 5. Bottom of OCO-2 Instrument (CCIE and CCE).

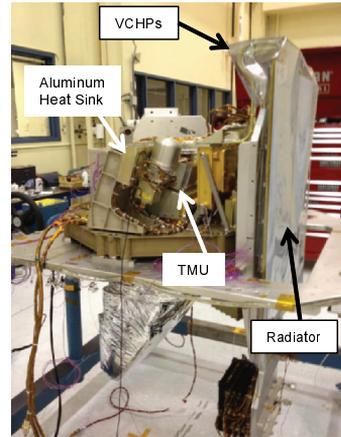


Figure 6. TMU Integrated onto OCO-2 Instrument.

The CCIE and CCE were later mounted at observatory-level to one of the six spacecraft panels on the Orbital Sciences Corporation (OSC) LEOStar-2 spacecraft bus. At instrument-level, the CCIE and CCE are mounted to a spacecraft simulator panel underneath the instrument as shown in Fig. 5.

As shown in Fig. 6, the TMU is mounted to a 6061-T6 aluminum heat sink, and variable conductance heat pipes (VCHP) transport the TMU waste heat to a radiator. The variable conductance heat pipes are standard aluminum axially extruded heat pipes with ammonia as the working fluid. The radiator is fabricated from standard aluminum honeycomb sandwich panels and is painted with common aerospace S13GLO white paint. This heat rejection system will be controlled in flight to provide a 288 K heat sink for the TMU that is stable to ± 5 K.

WATER OUTGASSING

During instrument integration, the TMU cold block is conductively coupled to the three FPAs via the SDL cryogenic subsystem (CSS). The cryogenic surfaces of the FPAs, the flexible thermal link and the TMU cold block are then wrapped with MLI. The innermost layer is a non-perforated sheet of aluminized mylar that effectively seals the cryogenic surfaces from the remaining MLI layers and the rest of the instrument shroud. To vent the volume surrounding the cryo-surface, three 0.25 inch diameter aluminized kapton vent tubes are arranged as shown in Fig. 7, such that one end is inserted into this volume (and directed to a surface of the flexible thermal link) and the other end is pointed out into the volume of the instrument shroud.

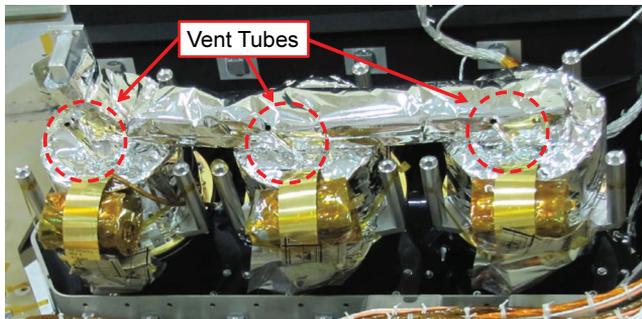


Figure 7. CSS Integration with MLI and Vent Tubes.

During launch, ascent and decontamination cycle, the CSS outgassing products migrate through the vent tubes and out into the instrument shroud volume due to the lower pressure in the instrument shroud volume ($\sim 10^{-7}$ torr). As shown in Fig. 8, a large aluminum vent pipe (2.5 inches in diameter, 30 inches in length) above the OCO-2 instrument provides a flow channel between the instrument shroud volume and the space vacuum outside the spacecraft. With the presumption that the space outside the anti-sun side of the spacecraft is of significantly lower pressure than that of the instrument shroud volume, the pressure differential between the two volumes will provide a driving force to cause the gas products to flow through the vent pipe to space. Thus, a pressure in the instrument shroud volume of $\sim 10^{-7}$ torr is hoped for.

After the decontamination period, the FPAs are cooled by the cryocooler. The cold (120 K) cold-link surfaces are designed to cryo-pump the residual contaminants, including some outgassing products from the shroud volume that will pass through the vent tubes. To keep the products from migrating to the FPAs, the products passing through the vent tubes from the shroud volume are designed to impinge on and stick to the cryo-surface of the cold thermal link assembly. The products will then remain stuck to the link's surfaces near the vent tube openings until the cryo-surfaces are warmed during a planned decontamination event. The desorbed products will then dislodge and travel back through the vent tubes into the instrument shroud volume and on into space via the shroud's 2.5 inch diameter vent pipe to space.

INSTRUMENT THERMAL VACUUM TEST RESULTS

The OCO-2 Instrument thermal vacuum test was successfully performed during April 1-27, 2012. During the test, the input bus voltage was maintained at 28 V, and the reject temperatures for the CCE and CCIE during optical functional testing were maintained between 297 and 300 K. As shown in Fig. 9, the test was performed with the instrument on its side to ensure that the VCHPs remain horizontal within $\pm 0.50^\circ$ to operate properly in a 1-G environment.

After chamber pump-down, the FPAs were warmed to the decontamination limit of 301 K for two days. The decontamination temperature was limited because the FPAs are required to not go above 303 K. The FPAs were then cooled to approximately 120 K as shown in Fig. 10 (day 096). The FPA cool-down duration to a stable operating temperature was approximately 36 hours, which easily meets the OCO-2 requirement that the three FPAs must be stable to within 0.5 K per 98 minute orbit within 72 hours after starting the transition out of decontamination.

Due to a short two-day decontamination period, the FPA temperature quickly increased at a rate of about $+0.14$ K/day during the first optical functional test — most likely due to water contamination within the CSS MLI and thermal link. This increase in temperature was expected and correlates with an increase in TMU motor drive level at a rate of $+0.2\%$ /day as shown in Fig. 10 (days 096-105). After launch, the instrument will enter a 30-40 day decontamination period before the TMU is turned on in order to allow time for water to exit the instrument.

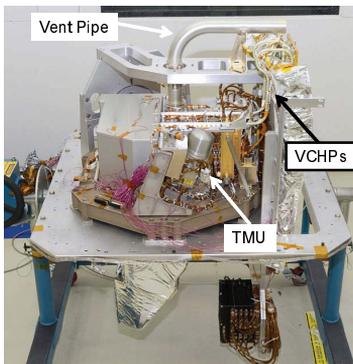


Figure 8. OCO-2 Instrument.

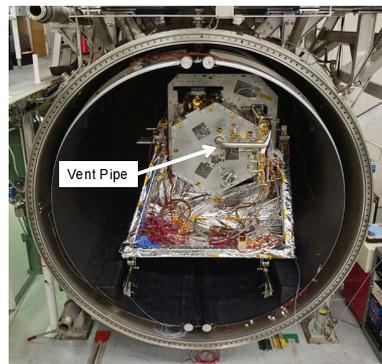


Figure 9. OCO-2 Instrument in TVAC Chamber.

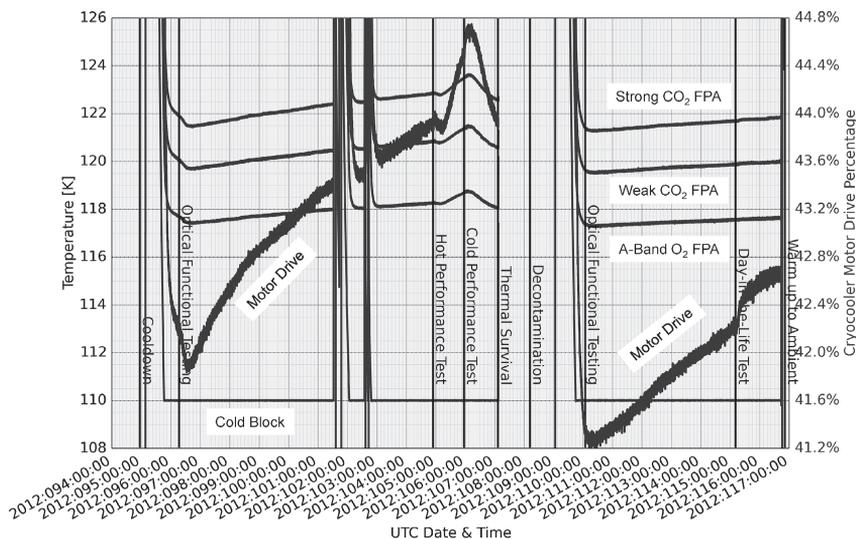


Figure 10. OCO-2 Instrument Thermal Vacuum Test with Cold Block at 110 K.

The CCE firmware monitors an accelerometer that turns off the TMU if acceleration over a certain threshold is detected. During the first optical functional test, movement of ground support equipment for optical alignment by personnel above the vacuum chamber produced a mechanical shock large enough to trip the accelerometer on four separate occasions (days 101-103). The TMU turned off, which resulted in a rise in FPA temperatures. At no time was the hardware in any danger, and no temperature violations occurred. The pre-programmed accelerometer trip level within the CCE was increased per NGAS direction, and the TMU operated uninterrupted for the rest of the instrument thermal vacuum test.

After testing the performance levels of the VCHPs at hot and cold instrument AFT limits and a subsequent survival test phase and second decontamination cycle (days 105-110), the FPA temperatures increased at a rate of about +0.07 K/day. The TMU motor drive level continued to increase at a rate of +0.2%/day during the second optical functional test (days 110-115). The decrease in FPA heating rate after the second cycle likely indicates that sufficient water had outgassed from the FPAs; however water continued to stick to the surface of the MLI and thermal link.

During the “Day-in-the-Life” test phase (days 115-117), the instrument was subjected to flight-like variations in boundary temperature. The boundary temperatures were adjusted by driving the GSE spacecraft simulated panels sinusoidally by ± 5 K and driving the VCHP radiator boundary GSE heat exchanger sinusoidally by ± 45 K. This resulted in the TMU reject temperature shifting by ± 1 K. The resulting temperature response of the FPAs easily met the OCO-2 requirement that the FPAs must be stable to within 0.5 K per 98 minute orbit.

Throughout the 27-day test, the operating system input power remained within the 63 W requirement and no increase in the TMU 47% drive limit was required to maintain 110 K.

OBSERVATORY THERMAL VACUUM TEST RESULTS

After successfully completing instrument-level testing, the Instrument was delivered to Orbital Sciences Corporation in Gilbert, Arizona for integration into the OCO-2 spacecraft. The CCIE and CCE were mounted to one of the six spacecraft panels on the OSC LEOSTar-2 spacecraft bus. The observatory is shown in Fig. 11. As shown in Fig. 12, the test was performed with the observatory on its side to ensure that the VCHPs remain horizontal within $\pm 0.50^\circ$ to operate properly in a 1-G environment.



Figure 11. OCO-2 Observatory.

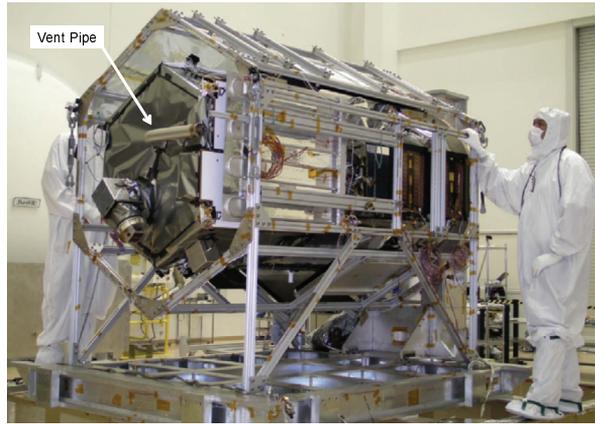


Figure 12. OCO-2 Observatory in TVAC Configuration.

The observatory thermal vacuum test was successfully performed during December 2-19, 2013. After a decontamination period of 60 hours, the FPAs were cooled from decontamination temperatures of approximately 301 K to 120 K in approximately 21 hours. This easily meets the OCO-2 requirement that the FPAs be stable to within 0.5 K per 98 minute orbit within 72 hours after starting the transition out of decontamination.

As shown in Fig. 13, the TMU motor drive level increased at a fast rate of +1.3%/day (again likely due to the short decontamination period and remaining water contamination within the CSS) during the spacecraft hot thermal balance test phase (341:14:00 – 342:09:00). With the TMU reject temperature and optical bench temperature remaining constant, the spacecraft transitioned to its cold thermal balance test phase (342:09:00 – 344:13:00), resulting in the TMU motor drive level dropping to a rate of +0.6%/day. After the cold thermal balance test phase was completed, the spacecraft transitioned into another hot test phase. During this test phase (344:18:00), the cold block temperature set point was lowered from 110 K to 107.5 K in order to bring the FPA temperatures closer to the 120 K range. The cold block setpoint change resulted in the TMU increasing its drive level by 0.8% in order to lower the cold block setpoint by 2.5 K. Also, the TMU motor drive level dropped its rate to +0.3%/day. As the spacecraft transitioned into another cold test phase (346:15:00), the TMU motor drive level remained stable momentarily then continued to rise at a rate of +0.3%/day.

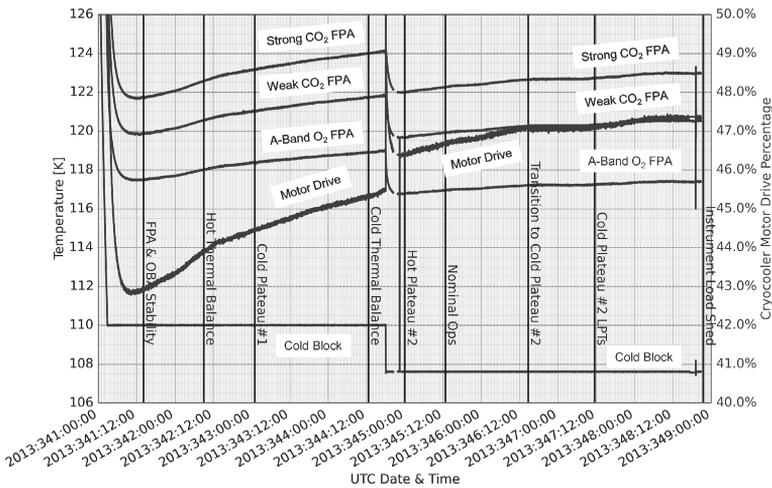


Figure 13. OCO-2 Observatory Thermal Vacuum Test with FPAs at Operating Temperature.

With improved conditions in space relative to water content, and a planned initial decontamination cycle of 30-40 days, water is expected to outgas from the FPAs, MLI and thermal link, exit the instrument shroud and vent pipe, and vent into space, never to return to the CSS. After the initial FPA on-orbit cooldown, it is predicted there will be a 0.1%/day increase in TMU drive level due to residual water on the MLI and thermal link during the initial phase of the mission. This rate will decrease to acceptable levels over time and after a FPA decontamination cycle, which will likely be necessary during the two-year mission.

After the completion of the observatory thermal vacuum test, the OCO-2 project allowed the TMU drive limit to be increased from 47% to 50% for the mission, in order to allow for a rapid on-orbit cooldown of the FPAs, and to reduce the possibility of decontamination periods in the mission in response to limitations in the spacecraft power budget.

After successfully completing observatory-level testing, the OCO-2 observatory was delivered to Vandenberg Air Force Base in California for integration onto a ULA Delta II launch vehicle, in preparation for a July 2014 launch.

SUMMARY

The OCO-2 observatory requires that its three focal plane arrays be cooled to 120 K for the duration of its two-year mission. The OCO-2 project selected the NGAS HEC pulse tube cryocooler to fulfill this requirement. Qualification and characterization of the cryocooler system was undertaken at NGAS and JPL. The resulting TMU and CCE can produce 2.4 W of cooling at 110 K with 45 W of power at the input to the CCIE, which meets the key OCO-2 cryocooler system requirement of cooling at the beginning of the mission to 110 K with no more than 63 W of power at the CCIE input.

Implementation of vent tubes connecting the cryogenic surfaces to the observatory exterior has been shown to effectively outgas water from within the instrument shroud during instrument and observatory thermal vacuum tests. With lessons learned from instrument and observatory thermal vacuum testing, improved conditions in space relative to water content, and given an extended decontamination cycle (30-40 days) immediately after achieving orbit, it is predicted that the TMU drive level will increase at a rate of 0.1%/day after the initial on-orbit cooldown of the FPAs. This rate will decrease to acceptable levels over time and after a FPA decontamination cycle, which will likely be necessary during the two-year mission.

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