

ON-ORBIT PERFORMANCE OF THE TES PULSE TUBE CRYOCOOLER SYSTEM AND THE INSTRUMENT - SIX YEARS IN SPACE

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ABSTRACT

The Tropospheric Emission Spectrometer (TES) instrument pulse tube cryocoolers began operation 36 days after launch of the NASA Earth Observing System (EOS) Aura spacecraft on July 15, 2004. TES is designed with four infrared Mercury Cadmium Telluride focal plane arrays in two separate housings cooled by a pair of Northrup Grumman Aerospace Systems (NGAS) single-stage pulse tube cryocoolers. The instrument also makes use of a two-stage passive cooler to cool the optical bench. The instrument is a high-resolution infrared imaging Fourier transform spectrometer with 3.3-15.4 micron spectral coverage. After four weeks of outgassing, the instrument optical bench and focal planes were cooled to their operating temperatures to begin science operations. During the early months of the mission, ice contamination of the cryogenic surfaces including the focal planes led to increased cryocooler loads and the need for periodic decontamination cycles. After a highly successful 5 years of continuous in-space operations, TES was granted a 2 year extension. This paper reports on the TES cryogenic system performance including the two-stage passive cooler. After a brief overview of the cryogenic design, the paper presents detailed data on the highly successful space operation of the pulse tube cryocoolers and instrument thermal design over the past six years since the original turn-on in 2004. The data shows the cryogenic contamination decreased substantially to where decontamination cycles are now performed every six months. The cooler stroke required for constant-temperature operation has not increased indicating near-constant cooler efficiency and the instrument's thermal design has also provided a nearly constant heat rejection sink. At this time TES continues to operate in space providing important Earth science data.

KEYWORDS: TES, EOS, Aura, cryocooler, pulse tube, passive cooler, remote sensing, cryocontamination, interferometer

INTRODUCTION

The TES instrument launched aboard the NASA Aura spacecraft is a high-resolution infrared imaging Fourier Transform Spectrometer (FTS) designed and built by the Jet Propulsion Laboratory for NASA. TES was designed specifically for determining the chemical state of the Earth's lower atmosphere (the *troposphere*). In particular, TES produces complete vertical profiles from the surface to 30⁺ km of important pollutant and greenhouse gases such as carbon monoxide, ozone, methane, and water vapor on a global scale every other day. A detailed description of the TES instrument, its science objectives, and measurement capabilities are found elsewhere [1-3].

Fundamental to meeting the science objectives, TES makes use of a pair of NGAS single-stage pulse tube cryocoolers to cool its four Mercury Cadmium Telluride (HgCdTe) focal planes to 65 K. A two-stage passive cooler provides cooling for the spectrometer at ~180 K. The cryocooler system design is tightly coupled with the overall thermal control design to maximize instrument performance.

The TES instrument is approximately 1 m cube size, weighs 385 kg and its average power use is ~230 watts. The instrument structure is built primarily from graphite composite materials and aluminum honeycomb radiators for thermal control of all the electronics including the cryocoolers. Loop heat pipes are used to transport the equipment waste heat to the nadir facing radiators. A detailed description of the instrument thermal control was published in 2000 [4]. The heart of the instrument is comprised of the interferometer running at ~180 K with its associated optics and two focal plane opto-mechanical assemblies (FPOMAs) which house the four cooled focal planes. The passive cooler first-stage runs at ~230 K and serves to intercept parasitic heat leaks from the near ~300 K surrounding environment.

The instrument contains four optically-conjugated 1x16 pixel HgCdTe detector arrays, housed in two separate FPOMAs separated by about 40 cm. The focal plane assemblies are cooled to 65 K by two separate identical long-life, low vibration, pulse tube coolers with the coldtip temperature controlled at 63.5 K. FIGURE 1 shows one of the NGAS pulse tube coolers and the aluminum flexible strap used to connect the coldtip to the focal plane mounts. The cryocooler beginning-of-life (BOL) heat load was ~650 mW at 65 K for both coolers. Historical accounts of the development efforts for the TES coolers are provided elsewhere [5-6].

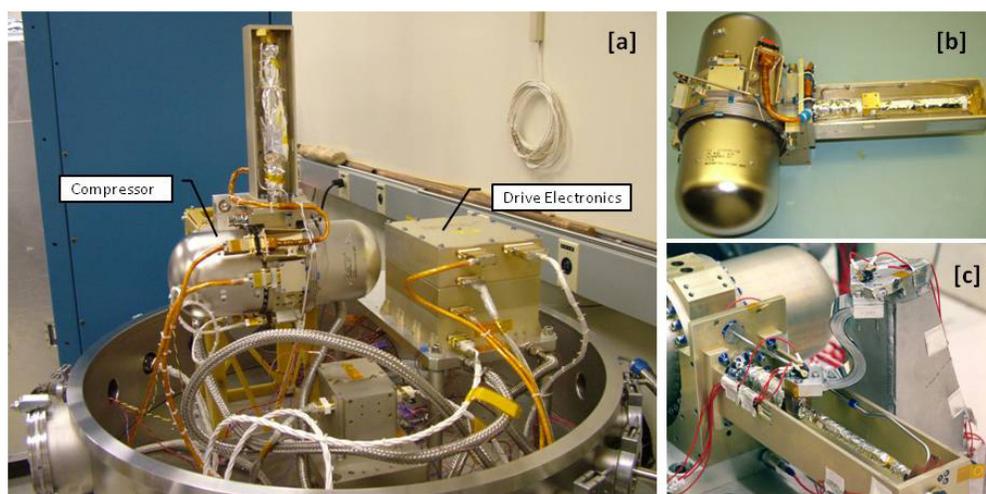


FIGURE 1. Flight NGAS pulse tube cryocooler: a) compressor with drive electronics, b) compressor, c) cooler coldtip with flexible aluminum strap.

CRYOGENIC SYSTEM FLIGHT PERFORMANCE

Initial In-Space Performance

The EOS Aura spacecraft carrying the TES instrument was successfully launched on July 15, 2004 aboard a Delta II launch vehicle from Vandenberg Air Force Base, California. Following launch, the instrument was subjected to a long outgassing and decontamination cycle prior to proceeding to normal science operations. A detailed description of the first three years of in-space operations is published elsewhere [7-8]. After a successful Earth shade deployment on day 26, the instrument was placed in decontamination mode for 10 days of additional outgassing with the optics bench at ~ 274 K and detectors at ~ 298 K. Both cryocoolers were powered on day 36 and the detectors achieved operational temperature ~ 12 hours later.

Although the instrument was subjected to a 36-day outgassing period to dissipate the residual moisture in the surrounding spacecraft structure and MLI from the as-launch condition, this was not sufficient because soon after, the cooler heat loads begin to increase due to contaminants adsorbing on the interferometer optics and the low emittance cryogenic surfaces. Only 12 days into science operations, the instrument was subjected to its first decontamination cycle driven by an optics infrared transmission loss greater than 60%. It was determined from science requirements that infrared transmission losses up to 60% could be tolerated and still be able to obtain adequate radiances. The first few decontamination cycles were allotted a total of 2 days with 1.5 days of outgassing and 12-hours for cooling the detectors to operational temperature. After this event, the ice buildup has been continuously monitored using the instrument itself to track the optical train infrared transmission loss within the broad absorption features of water at 4.2 and 10.4 μm . Although this was expected from test experience during thermal vacuum testing at JPL, the in-space conditions were different with the surrounding spacecraft and other instruments which made it difficult to predict the in-space behavior. Prior to launch, it was recognized that periodic decontamination cycles would be required and it was anticipated that decontamination cycles would be required at successively longer intervals.

Thin ice layers in the order of a few microns thick leads to increased surface effective emittance resulting in increased radiative parasitic heat loads [9]. The initial ice accumulation rates resulted in the cooler drive levels increasing at a rate of 0.467% per week prior to decontamination cycle #1 [7]. The cooler heat load increased for both coolers at a rate of 19 mW per week, which was not a problem because additional power was available for the coolers and the coolers could handle the increased heat loads. The cooler system input power increased demand was 0.58 W per week due to the increasing parasitic heat loads. At BOL, cooler A and B were operating at 42.7% and 50.5% drive level, respectively as shown in FIGURE 2.

The first four decontamination cycles were performed approximately every two weeks as shown in FIGURE 2. There is a significant change in the period between decontamination cycles in the subsequent five cycles as shown in the data. Over the first year, the general trend for all decontamination cycles is very similar with a noticeable difference in cooler drive slope decreasing as a function of time as expected. The requirement for a de-ice cycle is driven by detector loss of throughput signal and not due to increased cooler heat load.

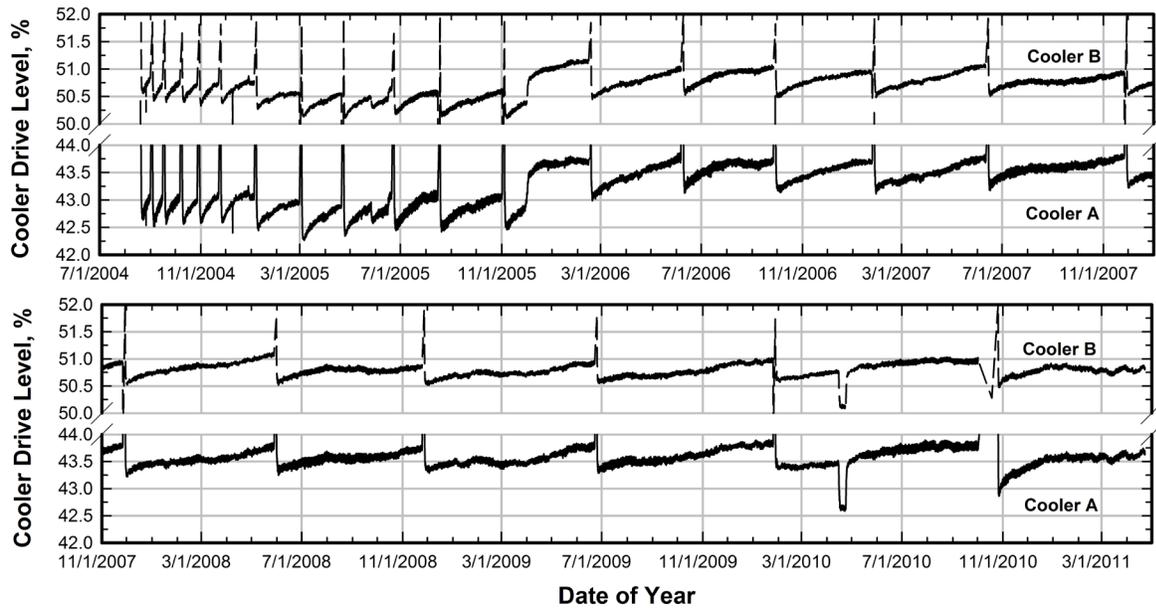


FIGURE 2. Cooler drive level on-orbit performance.

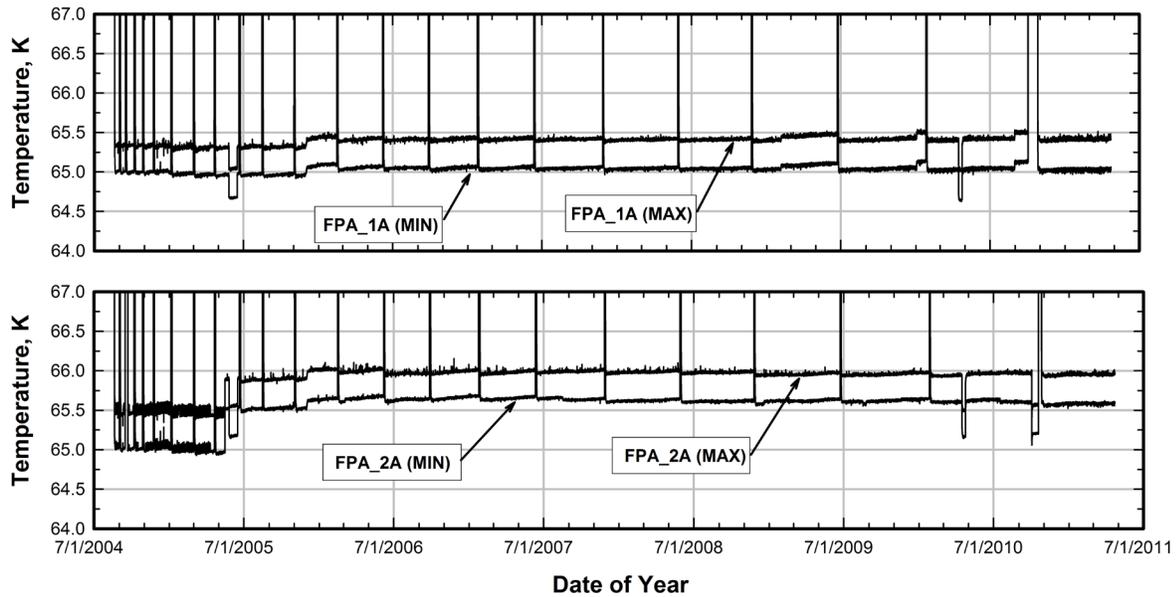


FIGURE 3. Focal plane temperature performance.

Long-Term Instrument De-Icing Performance

The cooler performance over the mission to date is shown in FIGURES 2-6. The cooler drive is shown in FIGURE 2 with the decontamination cycles shown as discontinuities in the data. In the first few months of science operations, decontamination cycles were performed every ~2 weeks, and now cycles are nominally done every ~6 months. It is noted that the level of icing has decreased over time. As shown in the data, the drive level also appears to level off in the first 3 to 4 weeks after each cooldown. The requirement for a de-ice cycle is driven by detector loss of throughput signal and not due to increased cooler heat load.

PERFORMANCE OVER THE MISSION DURATION

Cryocooler System

Over the past 6½ years since normal science operations began in mid August 2004, the TES instrument has performed exceptionally well producing world-class science with flawless cryocooler performance. The data shown in FIGURE 2 show the cooler drive level history to date. A likely independent indicator of the cooler's wearout health is the vibration output in the absence of increased heat loads. Both cooler's vibration history over the mission to date is shown in FIGURE 4 and shows no evidence of increased vibration. In fact, the data shows a slight decreasing trend. It should be noted that the cooler closed-loop vibration cancellation system have been turned off for the entire mission. The cooler heat rejection system (HRS) is of course a key driver for the performance and health of both coolers. The loop heat pipe-based HRS has performed exceptionally well maintaining the cooler heat sink temperature constant within 3 K. Both cryocoolers to date have gone through twenty-two start/stop cycles and have accumulated successfully in excess of 57,000 operating hours each. The drive levels and vibration signature for both coolers show no indication of performance degradation to date.

Cooler Heat Rejection System

The loop heat pipes for the cryocooler electronics and compressors have performed exceptionally well and have maintained the equipment at the expected nominal temperatures. The cryocooler drive electronics has been maintained at a temperature of 288 ± 1.5 K as shown in FIGURE 5. When the cryocooler compressors are operating, compressor A is maintained at a temperature of 270 ± 2.5 K and compressor B at 273 ± 2.5 K as shown in FIGURE 6. When the compressors are off, they are maintained at an average temperature of 269 K. The orbital temperature variation is less than 5 K p-p for both the compressors and cooler electronics.

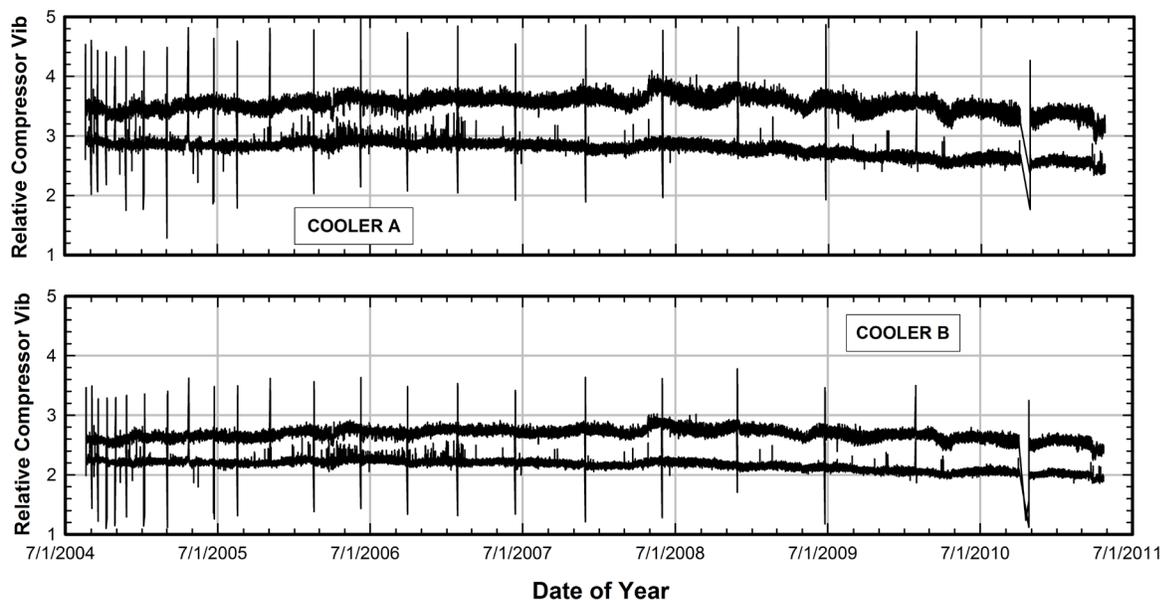


FIGURE 4. Vibration levels generated by the TES cryocoolers with their built-in vibration cancellation turned OFF over the entire mission to date.

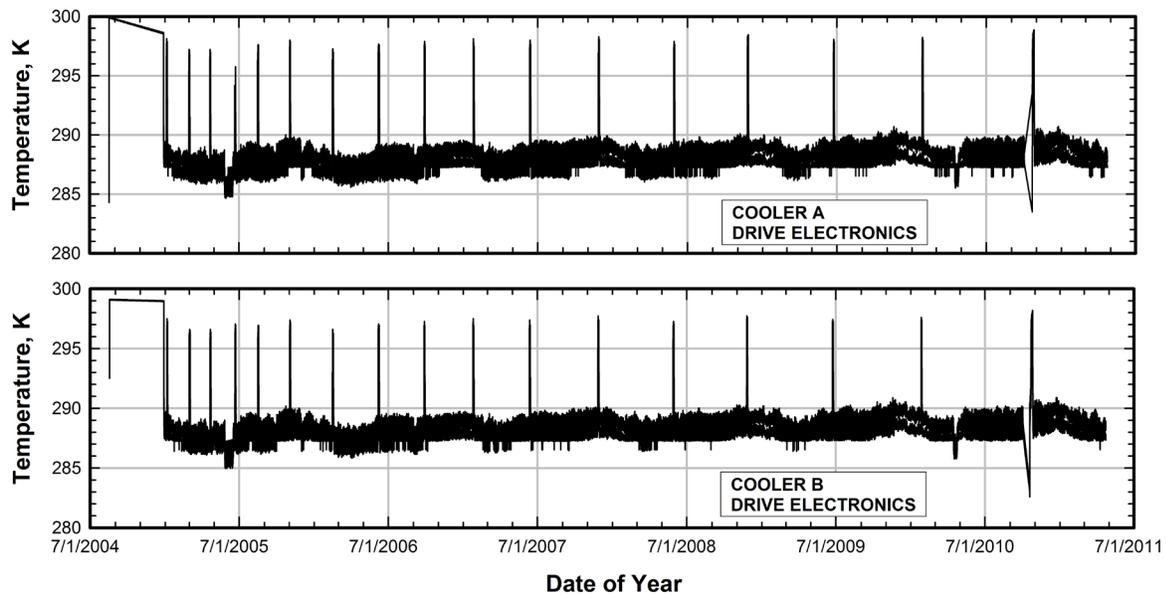


FIGURE 5. Cooler drive electronics temperature over the mission to date.

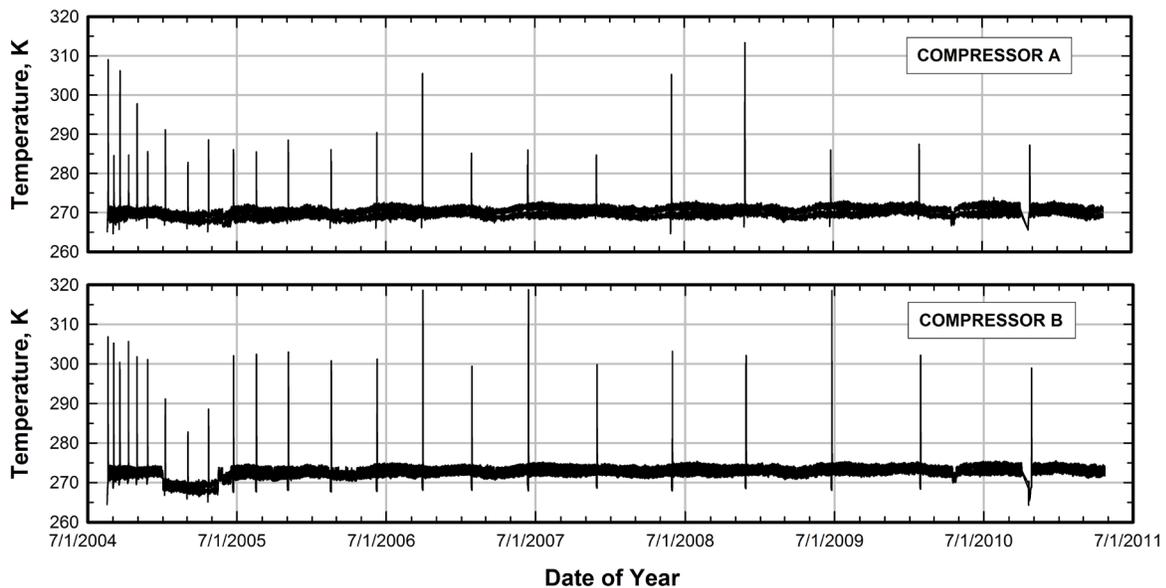


FIGURE 6. Cooler compressor temperature over the course of the mission to date.

Both coolers have been maintained at a fairly constant temperature within 3 K under operating and non-operating conditions for the life of the mission with the exception of the short 1-3 hour durations during cooler power on. The temperature spikes shown in FIGURES 5-6 are real and occur every time the coolers are power cycled. When the coolers are powered on, their temperature rises until the LHP starts, typically within 2 hours. These temperature excursions are due to the start-up behavior of the LHPs under low power conditions. On three occasions compressor B experienced a peak temperature of 45 C which is the absolute maximum expected from the LHPs. The HRS thermal design is open-loop and provides excellent heat transport to the radiator when the cooler is operating and decouples the cooler from the radiator when the cooler is OFF. Because the HRS thermal control is open-loop, the coolers see an orbital temperature variation of less than 3 K p-p.

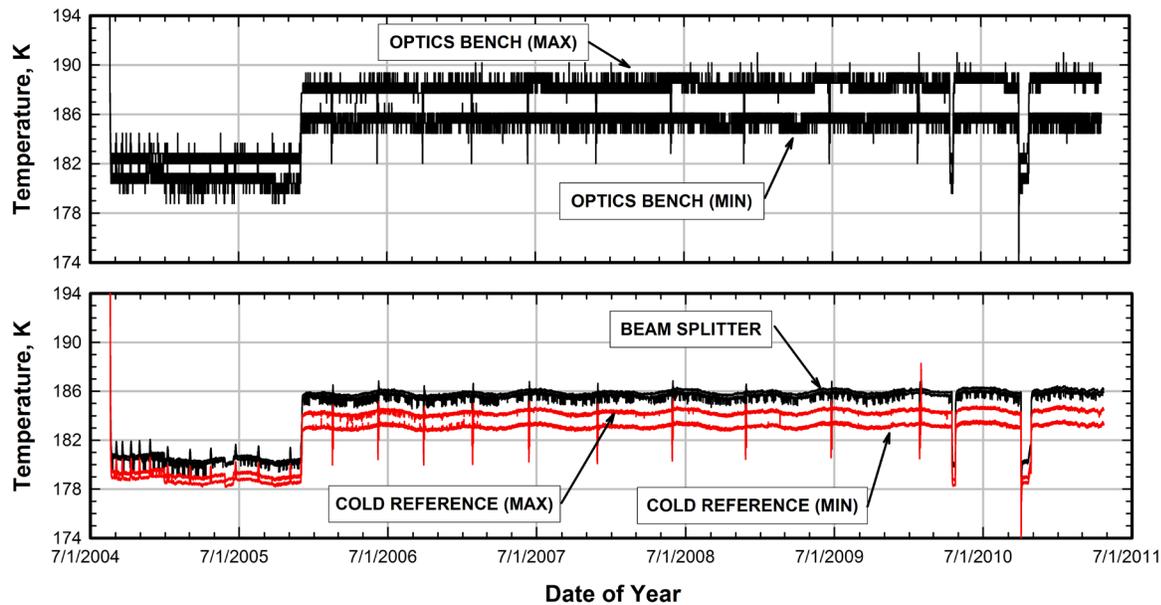


FIGURE 7. Optical bench, beam splitter and cold reference temperature over the mission to date.

Passive Cooler

The instrument's two-stage passive cooler provides the necessary cooling to maintain the interferometer and associated optics at ~ 180 K. The first-stage radiator at ~ 230 K serves to intercept radiative and conductive parasitic heat loads from the surroundings at 300 K. At 100% duty cycle, the 22 W optical bench operational heater maintains the optics at 182 K. It is desirable to operate the interferometer at a constant temperature for the life of the mission to obtain consistent high quality science data. The strategy was to run the operational heater at 100% duty cycle so that as material surfaces degrade and parasitic heat loads increase, the heater power required would decrease to maintain a constant interferometer temperature. This scheme was implemented from the start of the mission; however, six months after the start of science operations, the TES science team recommended that the optical bench temperature be increased to 187 K to improve the interferometer optical alignment and obtain higher quality science data. A plan was developed to use one of the decontamination heater circuits to provide the additional ~ 6 W or 28 W total needed to raise the temperature. The optical bench temperature was raised to 186.6 K on November 29, 2005 [7] as shown in FIGURE 7. The ON/OFF cycling of the decontamination heater results in a 0.5 K p-p optical bench variation. The science data quality has increased significantly since the optics bench temperature was increased. The passive cooler shows no evidence of performance degradation.

INTRUMENT SUBSYSTEMS FAULTS

Almost a year after launch, on May 26, 2005, the instrument detected an over current fault condition for the interferometer control subsystem (ICS) translator motor and the computer placed the instrument in safe mode. Table 1 shows the complete on-orbit time history of key events in space for the entire mission to date. While in safe mode, the instrument remains mostly powered on with only the signal chain electronics powered off including the detectors. The cryocoolers remain operating, and therefore, the detector

Table 1. TES on-orbit history of events for the entire mission to date.

Day of Day	Year	Date	Event
1	197	7/15/04	Launch, spacecraft (SC) powered up, survival heaters enabled at launch plus 165 minutes, SC placed in Survival mode.
2	199	7/17/04	SC transitioned to nadir pointing mode (Safe), Instrument powered "ON" at launch plus 52 hours.
6	202	7/20/04	Optical Bench Assembly (OBA) stabilized at ~266 K.
26	222	8/9/04	Earth shade deployed, decontamination heater powered "ON" ~1 hr after deployment, focal plane decontamination heaters ON to raise detectors to ~298 K; OBA decontamination heaters ON to raise OBA to ~274 K.
32	228	8/15/04	Focal plane decontamination heaters OFF; OBA decontamination heaters reduced to begin OBA cooldown to 180 K.
34	231	8/18/04	Both coolers electronics powered "ON".
36	233	8/20/04	Both cooler compressors powered "ON", Instrument in operational mode.
47	247	8/31/04	Decontamination cycle #1 started, detector decontamination heater turned "ON" after 12 days of operation, both compressors powered "OFF", detectors reach ~230 K.
49	249	9/2/04	Decontamination heater turned "OFF" after 2 days of decontamination, compressors powered "ON", both detectors at ~65 K approximately ~24 hours after powering "OFF" compressors.
165	362	12/27/04	Cooler electronics LHP suddenly turned on, cooler drive electronics temperature dropped from ~30.5 C to 6 C, optics bench dropped ~0.5 K.
315	146	5/26/05	Interferometer control subsystem (ICS) translator motor over current fault condition put instrument in Safe mode, detectors shut down.
335	166	6/15/05	TES returned to normal operations, science observations modified to mitigate the fault condition.
502	333	11/29/05	Optics bench setpoint changed from 181 K to 187 K, additional ~6 W heater power from decontamination circuit.
2100	105	4/15/10	Detection of pointing and control subsystem (PCS) track motor under temperature placed TES in Safe mode.
2107	112	4/22/10	Re-activated instrument and placed in Science mode, root cause of event was deterioration of motor flex cable.
2272	277	10/4/10	TES computer hard reset due to SEU event during SAA passage, after reset computer executed power on reset (POR), TES was placed in Safe mode, cooler A and drive electronics shut down and cooler B remained powered, AURA Command and Data Handling also experienced anomalies.
2295	300	10/27/10	TES returned to normal operations (Science), both coolers operating nominally.
2407	47	2/16/11	ICS translator motor velocity fault condition put instrument in Safe mode, detectors shut down. Returned to normal operations on 2/23/11.
2457	97	4/7/11	ICS translator motor over current fault condition put instrument in Safe mode, detectors shut down. Returned to normal operations on 4/11/11.
2465	105	4/15/11	Detection of PCS track motor under temperature placed TES in Safe mode. Returned to normal operations on 4/23/11.

temperature drops as shown in FIGURE 3. After extensive review of the fault condition, it was determined that it was safe to return to science operations. The science observations scenarios were modified to mitigate the translator motor over current fault.

Almost five years later, on April 15, 2010, the instrument fault protection detected a fault condition for the pointing control subsystem (PCS) and placed the instrument in safe mode. The PCS is a two-axis gimbal controlling the TES footprint locations, motion compensation and is also used to point to an internal blackbody calibration source. The safing of the instrument was triggered by an under temperature condition for the PCS. The temperature signal is carried on the same flex cable identified earlier to be the cause of the PCS motor track axis current spikes. These current spikes were first noticed on August 8,

2009. The root cause for both anomalies was determined to be the track motor flex cable deterioration. The instrument was safely returned to science operation within a week and a plan was implemented to limit the number of transitions to view the blackbody to extend the PCS useful life.

On October 4, 2010, the TES computer experienced a hard reset due to a single-event upset (SEU) while flying over the South Atlantic Anomaly (SAA). After the reset, the computer executed a power on reset (POR) and placed the instrument in safe mode. The AURA spacecraft command and data handling (C&DH) subsystem also experienced anomalies during the same SAA fly-through. As a result of the hard reset of the flight computer both cryocoolers were expected to shut down. However, only cooler A shut down and cooler B remained on due to the fact that the power relay that feeds cooler B failed to open. This anomaly was previously seen during observatory thermal vacuum testing in October 2003. The root cause of this anomaly from 2003 was never determined. This was mitigated by the fact that the power line feeding cooler B could be disabled by the spacecraft if needed. In addition, due to the computer hard reset, communication with cooler B was lost. The TES flight software requires a communication delay flag before allowing commanding to the cooler. This flag was disabled as a result of the hard reset and prevented communications with the cooler. The communication delay flag was sent and communications with cooler B were re-established. The cooler was commanded to shut down to proceed to a decontamination cycle since cooler A was already shut down. Both detectors were de-iced for the 22nd time, and subsequent to this, the compressors were powered on to proceed to nominal science operations. This event resulted in no change in performance for either cryocooler. Both TES coolers have operated flawlessly without incident since this event.

Recently, the ICS translator motor experienced two fault conditions which placed the instrument in safe mode on February 16 and April 7, 2011. The first was due to an excess ICS velocity fault whereas the second was caused by an over current condition. The direct cause of both of these faults is due to the degradation of the ICS encoder bearing which has a limited lifetime, and was anticipated prior to launch, to be the key life-limiting component of the entire instrument. As the bearing wears out the motor experiences irregular periods of increased motor current and velocity events which are becoming more frequent with time. Fault protection was modified to increase the number of consecutive velocity and over current events required to trigger a fault condition. In addition, an ICS maintenance macro was designed and implemented to enhance lubrication of the bearing which is executed on a regular basis.

The last fault event occurred on April 15, 2011 which placed the instrument in safe mode. The PCS generated the same fault condition previously experienced exactly a year before. The fault is a PCS track motor under temperature known to be caused by the deterioration of the motor flex cable.

SUMMARY

Over the past six years the TES instrument has produced exceptional science with flawless cryocooler performance since the start of the science mode operations 36 days after launch. Also, the cryocooler thermal control system provided by the loop heat pipe-based HRS has performed exceptionally well over the life mission to date. Ice contamination rates decreased significantly within the first year. Decontamination cycles are now performed approximately every ~6 months and take less than 2 days to complete. To date the instrument has undergone a total of 22 decontamination cycles raising the detector temperature from 65 K to ~230 K each time, with no evidence of detector damage

or performance degradation due to this thermal cycling. Although periodic decontamination cycles are effective means to boil-off contaminants, they are stressful and add risk for mechanical fatigue failure of cryogenic detectors and other components. The science need for a decontamination cycle is traded against the loss of science data for ~2 days and the added risk. In summary, the TES mechanisms are showing increasing signs of aging; however, the cryocooler system has performed beyond expectations and is expected to continue for the remainder of the extended 7 year mission.

ACKNOWLEDGEMENTS

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