Thermal design and on-orbit performance of the ECOSTRESS instrument

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Abstract. The ECOSystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) instrument, designed and built for National Aeronautics and Space Administration (NASA) by Jet Propulsion Laboratory, launched on June 29, 2018 at 09:42:42 UTC aboard the SpaceX Falcon 9 rocket (Figure 1b) from Cape Canaveral Air Force Station Space Launch Complex 40 (SLC-40) on the CRS-15 mission to the International Space Station (ISS). On July 2, 2018, the Dragon spacecraft successfully rendezvous with ISS and docked at Node 2 (Figure 2a). Three days later, ECOSTRESS was extracted from the Dragon trunk and installed on the Japanese Experiment Module-External Facility (JEM-EF, also known as KIBO-EF) at EFU 10. The image of ECOSTRESS taken moments before JEM-EF installation is shown in Figure 2b. The instrument was powered on day 7 and successfully completed initialization and on-orbit checkout (IOC). Ensuing IOC instrument began its 12 month science mission.

The ECOSTRESS will scan the Earth with 38-meter in-track by 69-meter cross-track spatial resolution with a double-sided scan mirror, rotating at 25.4 revolution per minute along with a 65K focal plane with a mercury-cadmium-telluride (MCT) infrared detector array [1]. The science objective of the ECOSTRESS mission is to produce a drought indicator product called Evaporative Stress Index (ESI). ESI will indicate whether plants are stressed and that drought is likely to occur in that region.

To date, thermal control subsystem (TCS) has operated nominally and met all of its requirements. This paper provides a general overview of the thermal and cryogenic system design, thermal analysis results and reviews the on-orbit thermal performance.

1. Introduction
The Ecosytem Space-borne Thermal Radiometer on Space Station (ECOSTRESS) instrument (Figure 1a), designed and built for National Aeronautics and Space Administration (NASA) by Jet Propulsion Laboratory, launched on June 29, 2018 at 09:42:42 UTC aboard the SpaceX Falcon 9 rocket (Figure 1b) from Cape Canaveral Air Force Station Space Launch Complex 40 (SLC-40) on the CRS-15 mission to the International Space Station (ISS). On July 2, 2018, the Dragon spacecraft successfully rendezvous with ISS and docked at Node 2 (Figure 2a). Three days later, ECOSTRESS was extracted from the Dragon trunk and installed on the Japanese Experiment Module-External Facility (JEM-EF, also known as KIBO-EF) at EFU 10. The image of ECOSTRESS taken moments before JEM-EF installation is shown in Figure 2b. The instrument was powered on day 7 and successfully completed initialization and on-orbit checkout (IOC). Ensuing IOC instrument began its 12 month science mission.

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To date, thermal control subsystem (TCS) has operated nominally and met all of its requirements. This paper provides a general overview of the thermal and cryogenic system design and reviews the on-orbit thermal performance.

2. Instrument description
ECOSTRESS instrument is divided into three main parts: 1) enclosure structure, 2) radiometer assembly, and 3) support hardware. The enclosure structure is a six-sided box that provides mounting locations for radiometer assembly and support hardware. It is comprised of Cold panel (-Y), Zenith panel (-Z), PIU panel (-X), End panel
Figure 1. (a) ECOSTRESS installed in the unpressurized cargo of SpaceX Dragon spacecraft. (b) Launch of SpaceX Falcon 9 Rocket carrying ECOSTRESS on a CRS-15 Mission to ISS.

Figure 2. (a): International Space Station, Node 2 and KIBO (JEM-EF) Exposed Facility [2]. (b): Image of ECOSTRESS taken by ISS moments before JEM-EF installation [3].

(+X), Closeout panel (+Y), and NADIR panel (+Z). The enclosure structure and location of each panels are shown in Figure 3.

The radiometer assembly, shown in Figure 4, consists of Mercury Cadmium Telluride (MCT) infrared detector array, buffer board, optical elements, yoke assembly, single layer insulation, cold shield, flexible thermal link, blackbody calibration targets, mechanical cryocoolers, NADIR baffle, cold plates, and associated heat rejection system (HRS). The optical elements, primary (M1), secondary (M2), and tertiary (M3) mirrors are mounted on the bulkhead and three bipods provide thermal isolation and structural support for the radiometer. The onboard blackbody calibration targets are mounted on the Zenith panel.

The support hardware include Focal Plane Interface Electronics (FPIE), Cryocooler Control Multiplexer (CCM), Cryocooler Control Electronics (CCE), Power Conditioning Electronics (PCE), Mass Storage Unit (MSU), Wi-Fi Electronics Box Assembly (WEBA), Central Electronics Unit (CEU), thermal fluid system tube assembly, and Government Furnished Equipment (GFE). The HRS tube assembly, high power electronics boxes, and accumulator assembly are mounted on the –Y cold panel (tube-on plate heat exchanger) shown in Figure 5. The payload interface unit (PIU) is a Government Furnished Equipment (GFE) and it provides thermal, mechanical and electrical interface with JEM-EF. All GFE hardware (PIU, FRGF and H-fixture) and Wi-Fi antennae are externally mounted on the enclosure structures.
3. Thermal environments

The ISS is maintained in a nearly circular orbit with an average altitude of 400 km at an inclination of 51.6° to Earth’s equator with an orbit period of ~90 minutes and maximum eclipse of 36 minutes. The instruments on ISS are exposed to extreme hot and cold conditions, solar cycle and solar events, atomic energy, and high energy radiation [4]. The beta angle varies from -75° to +75° and maximum eclipse duration occurs at beta 0. The Torque Equilibrium Attitude (TEA) also varies throughout the mission and thermal design must account for these variations.

During launch, rendezvous and berth to ISS, and Dragon to JEM-EF transfer, ECOSTRESS is subject to extreme thermal conditions. Depending on launch vehicle’s flight trajectory and its orientation the Sun angle (the angle between direction normal to the Zenith plane and Sun vector) can fluctuate from -90° to +90°. In addition, ECOSTRESS is required to survive 7 hours unpowered during robotic arm transfer from Dragon trunk to JEM-EF. The environmental parameters assumed in the TCS design and analysis are shown in Table 1.

4. Requirements and design drivers

The thermal design is driven by four main requirements: (1) FPA must be cooled to 65K and maintain thermal stability of <100 mK over 2.4 sec, (2) all subsystem components must be maintained within specified operating and non-operating temperature limits shown in Table 2, (3) thermal fluid system must comply to the JEM-EF ATCS usage requirements specified in the JEM Payload Accommodation Handbook [5], and (4) design must be robust to changes in TCS power allocation. A summary of ECOSTRESS thermal requirements is listed in Table 3.

5. Thermal architecture

ECOSTRESS thermal architecture is shown in Figure 6. Thermal Control System (TCS) consists of a combination of active and passive components. The active components include mechanical cryocoolers and a pumped fluid loop with circulation provided by the JEM-EF ATCS. The FPA detector is cooled to 65K by a pair of mechanical cryocoolers, and an additional mechanical cryocooler cools an intermediate stage (cold shield) to 130K. The intermediate stage cooling reduces radiative and conductive parasitic loads into the FPA subsystem.
The passive components include MLI, heaters, low emissivity single layer insulation, flexible aluminum thermal links, and surface coatings. Flexible thermal links provide thermal connection between cryocooler cold-tip and FPA detector. The enclosure structure is covered in MLI. The warm blackbody target is controlled to 46°C with less than 1°C spatial gradient with flight software and heaters. Survival heaters maintain the support hardware within non-op AFT limits. Heaters on the cold shield and FPA subassembly are used for decontamination.

6. Heat rejection system (HRS)

The ECOSTRESS HRS is a single-phase liquid pumped fluid loop that was designed to collect all 800 W of payload dissipation and environmental heating. It is the thermal control system backbone and interfaces with all dissipating components. The working fluid is FC-72, a perfluorocarbon dielectric liquid manufactured by 3M. Fluid circulation is provided by the JEM-EF Active Thermal Control System (ATCS) and inlet temperature and pressure are controlled by the JEM-EF Fluid Coolant loop and Fluid Pressure control system. The exchange of heat with the environment is accomplished through the HRS Coolant loop. The ECOSTRESS HRS interface is designed to have five (5) independent flow loops to ensure system redundancy and allow for proper flow distribution. Each of the five flow loops consists of the Fluid Coolant Loop, Cryocooler Heat Rejection Skin, Blackbody Target Temperature and Spatial Gradient, Failure Tolerance, Mass Flow rate, Cryocooler power allocation, Survival Power, and Return Fluid Temperature.

The passive components include MLI, heaters, low emissivity single layer insulation, flexible aluminum thermal links, and surface coatings. Flexible thermal links provide thermal connection between cryocooler cold-tip and FPA detector. The enclosure structure is covered in MLI. The warm blackbody target is controlled to 46°C with less than 1°C spatial gradient with flight software and heaters. Survival heaters maintain the support hardware within non-op AFT limits. Heaters on the cold shield and FPA subassembly are used for decontamination.

Table 2. Allowable Flight Temperature Limits.

| ECOSTRESS | Allowable Flight Temperature |
|-----------|-------------------------------|
| Radiometer | Operating | Non-Operating |
| FPA | -208°C (65K) | -218°C (55K) to 35°C (308K) |
| Telescope (M1, M2, M3, Scan Mirror) | 10°C to 50°C | -15°C to 50°C |
| Cold Target Blackbody | 16°C to 24°C | -15°C to 50°C |
| Warm Target Blackbody | 10°C to 50°C | -15°C to 50°C |
| Support Hardware | |
| CCM | 10°C to 50°C | -15°C to 50°C |
| CCE | 10°C to 50°C | -15°C to 50°C |
| FPICE | 10°C to 50°C | -15°C to 50°C |
| PCE | 10°C to 50°C | -15°C to 50°C |
| CEU | 10°C to 50°C | -15°C to 50°C |
| WEB | 10°C to 50°C | -15°C to 50°C |
| MUS | 10°C to 50°C | -15°C to 50°C |
| WIFI Antenna | -20°C to 55°C | -20°C to 55°C |

Table 3. Thermal Requirements.

| Description | Requirements |
|-------------|--------------|
| FPA Operating Temp and Temporal Stability | < 65K, +/- 100 mK over 2.4 sec |
| Heat Rejection Method | JEM-EF ATCS (fluid loop) |
| Cryocooler Heat Rejection skin temperature | < 40°C |
| Instrument Cooldown Time | < 24 hrs |
| Fluid Pressure Drop | 52.4 kPa < DP < 57.9 kPa |
| MLI | Beta Cloth, e<sub>s</sub> < 0.04 |
| Blackbody Target Temperature and Spatial Gradient | 16°C to 24°C (cold)/40°C (warm), <1°C gradient over entire surface |
| Failure Tolerance | Two fault tolerant |
| Mass Flow rate | 155 kg/hr |
| Cryocooler power allocation | 432W |
| Survival Power | <120W |
| Return Fluid Temperature | < 50°C |

Figure 6. ECOSTRESS Thermal Architecture [6].
pressure is controlled to 20 +/- 4°C and 780 kPa or less, respectively. The mass flow rate delivery by JEM-EF is determined by the maximum payload dissipation and is regulated using a delta pressure control technique. This sets both a maximum and minimum system pressure drop. The mass flow rate and pressure drop range used for the ECOSTRESS Payload was 155 kg/hr and between 52.4 kPa and 57.9 kPa, respectively.

The final design of the HRS utilized discrete, friction-welded, compact heat exchangers for removing cryocooler compressor and expander thermal dissipation. Similar heat exchangers were also used for the Instrument’s cold black body calibration target where the JEM-EF supply fluid temperature provided the temperature calibration for the radiometer. Instrument and Payload engineering support equipment was thermally controlled using a structural thermal panel. Stainless steel tubing was bonded into a semi-circular groove on the panel exterior using a thermal epoxy. Dissipating support hardware was bolted to the panel interior and heat was conducted through the panel thickness and into the working fluid flowing through the tubing. The exterior of the structural thermal panel is shown in Figure 7. The use of discrete heat exchangers and tube-on-panel design of the ECOSTRESS HRS created a robust and more reconfigurable design compared to more traditional passive thermal control architectures.

6.1 HRS heat exchanger fitting selection and implementation

In order to facilitate payload integration activities, each HRS subassembly was installed using mechanical fittings. This allows for a plug-and-play assembly process and eliminates the need to do any welding on the Payload. Stainless steel interconnecting tube assemblies with orbital welded end fittings are used to connect each HRS subassembly into a complete serial loop.

Three types of mechanical fittings were used on the ECOSTRESS HRS heat exchangers: VCR/SAE and AN/SAE threaded fittings with Viton O-ring seals. Each fitting type required modification to meet Project requirements and Instrument layout geometric constraints. First, safety wire holes were added to the nut body in order to provide a locking feature in addition to installation preload. The internal diameter through the fitting was also increased to reduce the fitting pressure drop. These were used on the blackbody heat exchanger. The cryocooler compressor and expander heat exchangers did not have enough material on the inlet and outlet ports to accommodate a 9/16” internal thread. This required reducing the external thread size 7/16”-20. Another custom
fitting was fabricated by welding a SAE threaded Swagelok tube fitting to a VCR gland with a male nut. Lastly, an AN swivel-type elbow was used on portions of the expander heat exchanger. This fitting has a jam nut that can secure the elbow direction within a 360 degree rotation and compress the sealing O-ring when tightened. The only modification required to these off-the-shelf fittings manufactured by SSP was the addition of safety wire holes on the jam nut. Each of these fitting types are shown in Figure 8, Figure 9, and Figure 10. Figure 11 shows the fittings assembled on the expander heat exchanger tooling fixture. Figure 12 shows each of the three heat exchanger types along with the interconnecting tube assemblies as part of the fully integrated Payload HRS.

6.2 HRS verification
Prior to delivery of each HRS subassembly to system-level integration, several steps were taken to verify the integrity of the delivered hardware. The Fracture Critical classification of the HRS required that each weld and assembly workmanship was scrutinized. This included proof pressure tests to 1.5xMDP, burst demonstration to greater than 2.0xMDP for the heat exchangers and 4.0xMDP for other pressurized assemblies, and radiography and dye penetrant inspection of all welds post proof test. JEM-EF host accommodations require helium leak rate measurements of all welds and fittings, measurement of system level pressure drop, measurement of total HRS fluid volume, fluid system cleanliness verification for particle size distribution and non-volatile residue.

7. Non-planar cold plate
The liquid cooled cold plates used in ECOSTRESS TCS were provided by MaxQ Technology. The cold plates are comprised of optimally designed aluminium components that are joined using the Friction Stir Welding (FSW) method. As depicted in Figure 13. FSW is a joining process by which friction heat and a special tool are used to plasticize adjacent components, allowing mixing of the interface and subsequent material recombination as the tool progresses along the seam line. Since no other materials are introduced during the joining process, the result is a truly monolithic structure with welded properties very close to the parent material, in this case standard aluminium 6061-T6. Using this joining approach along with innovative design geometry and an advanced machining process, non-planar structures with high internal fin density were created to interface with the coolers.

The curved surface nature and particular geometry of the ECOSTRESS cold plates, shown in Figure 14, did present challenges in meeting the final dimensional requirements. Some material distortion took place during the localized heating from the FSW process. This required special tooling fixture, optimization of machining parameters and complex tool paths. The cold plate design details, model development, measured performance data, and HRS interface design approach can be found in [7].

To ensure acceptable reliability of all three designs, the products were subjected to non-destructive evaluation (NDE) of all welded joints. Dye penetrant test was in accordance with AMS 2644 Type 1, Method D, Level 4, Form A, using penetrant NASA STD 5009, Rev 04-07-2008. Radiography was in accordance with NASA STD 5009 Rev 04-07-2008. Flight unit acceptance was in accordance with AWS D17.3 Rev 10, Class A for penetrant and “No visible Lack of Fusion” criteria for radiography. Additionally, one unit of each design was subjected to a high pressure burst test of >2xMDP to ensure adequate safety margin.

8. Thermal model and flight temperature prediction
The ECOSTRESS thermal models (Detailed and Reduced) were built in Thermal Desktop (TD) 5.7 (Figure 15). The cryocooler cold tips were modelled as boundary nodes. The lift required to maintain each cold tip temperature was extracted from the model and the appropriate design margin was applied to the load to determine the cryocooler performance relative to the available cooling. Heat dissipated at the cryocoolers was assumed to be constant and was not considered to be a function of cooler lift. The detailed thermal model interfaced with the reduced International Space Station TD model and simulated the inlet fluid temperature and flow rate from the JAXA module through the use of a boundary node. For these analyses, the fluid inlet temperature and flow rate
were fixed at the extremes of the allowable range – cold temperature and fast flow rate for cold cases, hot temperature and slow flow rate for hot cases.

A reduced thermal model was also developed to support the JAXA interface. In order to accurately predict fluid inlet temperatures, the fluid loop needed to connect with the existing JAXA detailed JEM-EF module. This module was developed in TRASYS, and could not directly interface with ECOSTRESS’s TD fluid loop. Therefore, the fluid loop was simplified to a series of one-way conductors for the reduced thermal model. The RTM was also used to determine instrument temperatures during the SpaceX Dragon flight and transfer to the ISS.

All ECOSTRESS environments were thermally analysed, from launch to berthing at the ISS to robotic arm transfer to operation on the JEM-EF at EFU 10. The expected on-orbit temperatures for operation are summarized in Table 4. In addition to the standard hot and cold operational conditions, the ECOSTRESS instrument was analysed for pitch-yaw-roll (PYR) of the ISS for anticipated TEA variation. Certain attitudes of the ISS resulted in direct solar loading on the ECOSTRESS instrument, while others maintained ECOSTRESS in the shade. However, the highest analysed temperatures for ECOSTRESS were not found during any operational cases. The worst cases were found during the Dragon solo flight.

Since all analysis work for ECOSTRESS was completed prior to the selection of a definitive launch date, all possible orientations of the Dragon were required. When Dragon is launched and has a sun angle of 0°, ECOSTRESS would be exposed to direct solar loading for half of the orbit.

9. On-orbit performance

After a successful launch and on-orbit checkout, all three coolers were powered on July 8, 2018 for first cooldown. The FPA detector achieved operational temperature of 65K in approximately 4 hours. The data shown in Figure 17 shows the cooler cold tip, HRS fluid inlet and electronics temperatures from on-orbit power on to date. The on-orbit performance has been in family with ground test data and all three coolers and six CDE XPCDE4865 electronics have operated nominally and maintained the FPA at the operating temperature. Total power consumed by three coolers was approximately 165W to 240W including cooldown phase. The cooler HRS is a key driver for the performance and health of all three coolers. The HRS has performed nominally maintaining the cooler skin temperature well below 40°C. To date, all three coolers have accumulated in excess of 7,250 operating hours each. On day 210 after power on, ECOSTRESS detected a fault condition and put itself in standby mode with coolers off. On day 258, the instrument was powered cycled intentionally in preparation for uploading firmware updates. With the instrument in standby mode, the coolers remained off for a period of about 45 days until the instrument

![Figure 15. ECOSTRESS Detailed Thermal Model (One Panel Removed)](image1)

![Figure 16. Sample of ECOSTRESS Thermal Contour](image2)

![Figure 17. Cooler Coldtip, HRS Fluid Inlet and Electronics UMS Temperatures from Power On to date](image3)
was powered on again. The tube-on plate heat exchanger, non-planar cold plates, and entire HRS have performed exceptionally well and have maintained the equipment at the anticipated nominal temperatures. The on-orbit steady state temperature data (collected on 7/12/2018), flight temperature predictions, and associated AFT range are shown in Table 4. The agreement between flight data and model predictions was excellent. All system and component temperatures are within the expected AFT range and TCS has met all mission thermal performance requirements.

10. Conclusion
The ECOSTRESS instrument successfully launched on June 29, 2018 and has completed 9 months of operation in space. Instrument successfully completed initialization and on-orbit checkout and is currently gathering important Earth science data. The instrument thermal control subsystem has performed exceptionally well over the life mission to date. The TCS is maintaining equipment at the nominal temperatures and has met all thermal performance requirements. The cryocoolers, cooler electronics, cold plates, and HRS have performed beyond expectations and are expected to continue for the remainder of the instrument mission.

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