LPT9310 COTS Cooler for ECOSTRESS

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ABSTRACT

For the past several years, a significant effort has been performed at the Jet Propulsion Laboratory to characterize commercial-off-the-shelf (COTS) pulse tube cryocoolers for use in cost-effective spaceflight applications. This has resulted in the selection of the Thales LPT9310 cryocooler for the ECOSTRESS instrument that will fly on-board the Japanese Experiment Module – Exposed Facility (JEM-EF) of the International Space Station.

The Thales LPT9310 cryocooler nominally provides over 4 W of cooling capacity at 80 K, and has been produced in large quantities with a proven capability for multi-year continuous operation without an instance of cooler failure.

However, this capability has only been proven in terrestrial (commercial) applications. In order to provide sufficient justification for using an off-the-shelf cooler for a flight application, additional tests have been performed on the delivered flight coolers, to attain a sufficiently controlled level of quality while leveraging the heritage of the COTS cooler. The test program philosophy will be explained, and results will be discussed.

Restrictions in both the available electrical power and the heat exchanger fluid inlet temperature to the instruments onboard the JEM-EF eroded the performance margin maintained for the cryocoolers, prompting the need to find more efficient cryocoolers. Thales Cryogenics responded with an upgrade to the LPT9310, replacing the stainless steel pulse tube with titanium alloy, and a re-optimization of the regenerator matrix for 60K while leaving the baseline, qualified design parameters intact. The resulting performance enhancement from the additional cryocooler efficiency at lower temperatures will be presented.

INTRODUCTION

Figure 1 shows a Thales Cryogenics LPT9310 pulse-tube cooler. It is composed of a dual opposed-piston flexure-bearing moving magnet compressor coupled to a pulse-tube cold finger. The design of the cooler has strong ties to past and present space cryocoolers. The pulse-tube cold finger can be regarded as the commercial off-the-shelf sibling for the LPTC pulse tube, developed by CEA under ESA funding [1]. The 93xx compressor has served as the starting point for designed-for-space cooler developments, such as the LSF9330 flexure-bearing Stirling cooler [2] developed under ESA funding.

However, contrary to the LPTC and LSF9330 coolers, the LPT9310 was optimized for cost as well as minimum exported vibration and reliability, where some performance was sacrificed for a lower cost. This has resulted in a baseline LPT9310 design that is based on relatively inexpensive

Figure 1. LPT9310 cooler

parts and processes suitable for series production while incorporating all the design principles required for an extremely reliable cooler. As a result, it has been produced and deployed in large numbers for cooling Germanium detectors, an application where low vibrations and high reliability for 24/7 operation are required. It has accumulated a large amount of failure-free running hours [3].

PRIOR WORK: TESTING OF THE LPT9310 AT JPL

The LPT9310's proven reliability has resulted in interest from JPL in using this cooler for cost-sensitive space applications. Initial work performed by Paine [4] resulted in the successful use of this cooler in the PHyTIR technology demonstrator. Further work by Johnson et al., [5] was done to characterize the cooler and to perform preliminary robustness testing.

This prior work resulted in the LPT9310 being selected for the ECOSTRESS instrument.

ECOSTRESS INSTRUMENT DESIGN AND PROJECT

The ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) will measure the temperature of plants. This temperature data will be used to better understand how much water plants need and respond to heat stress. Figure 2 and Figure 3 show photographs of the instrument. ECOSTRESS will address three overarching science questions: 1) how is the terrestrial biosphere responds to changes in water availability? 2) how do changes in diurnal vegetation water stress impact the global carbon cycle? 3) can agricultural vulnerability be reduced through advanced monitoring of agricultural water consumptive use and improved drought estimation? The ECOSTRESS mission will answer these questions by accurately measuring the temperature of plants. Plants regulate their temperature by releasing water for evaporative cooling through tiny pores on their leaves. If they have sufficient water they can maintain their temperature but if there

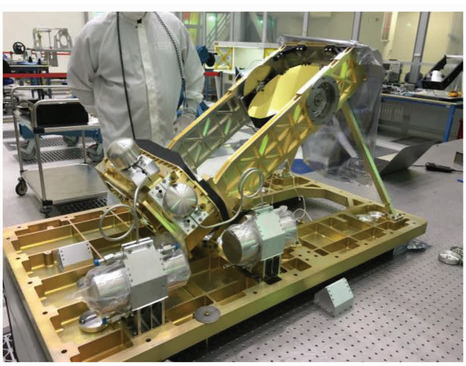

Figure 2. Radiometer buildup with two LPT9310 coolers shown.

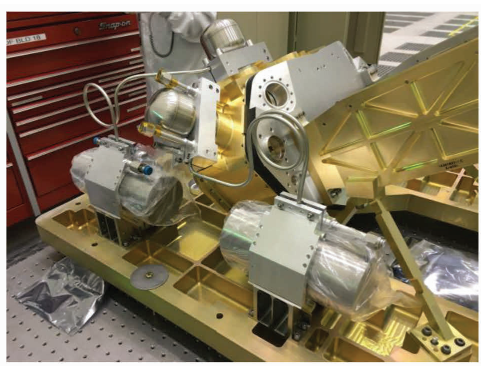

Figure 3. Close up of coolers with compressor and expander high performance heat exchangers.

is insufficient water, their temperatures rise and this temperature rise can be measured accurately with a space-based sensor. ECOSTRESS will use a multispectral thermal infrared radiometer to measure plant surface temperatures and will acquire the most detailed temperature images on the surface ever acquired from space. ECOSTRESS is manifested for launch in 2018 onboard the trunk of the SpaceX Dragon vehicle.

ECOSTRESS will be implemented by placing the existing Prototype HyspIRI Thermal Infrared Radiometer (PHyTIR) with design updates needed for flight qualification on the International Space Station (ISS) and using it to gather the measurements needed to address the science goals and objectives. PHyTIR was developed under the NASA Earth Science Technology Office (ESTO) Instrument Incubator Program (IIP). From the ISS, ECOSTRESS will provide data with 38-m in-track by 69-m cross-track spatial resolution and a predicted temperature sensitivity of ≤0.3 K. The ISS orbit allows excellent coverage of the selected targets including diurnal coverage. The existing hardware was developed to reduce the cost and risk for the thermal infrared radiometer on the future Hyperspectral Infrared Imager (HyspIRI) mission, A double-sided scan mirror, rotating at a constant 23.3 rpm, allows the telescope to view a 51°-wide nadir cross-track swath as well as two internal blackbody calibration targets every 1.29 seconds.

The optical signal is focused by a telescope onto a cryocooler cooled 65K focal plane containing a custom 13.2-μm-cutoff mercury-cadmium-telluride (MCT) infrared detector array. Spectral filters on the focal plane define 5 spectral bands in the 8-12.5 μm range and an additional band at 1.6 μm for geolocation and cloud detection (six bands total). The focal plane is cooled by two LPT9310 Thales cryocoolers while a third LPT9310 cools a cold shield to ~120K to reduce parasitic heat loads on the focal plane. The Thales COTS cooler drive electronics XPCDE4865 are used to power and control the coolers. An electronic switch with two XPCDE4865 units will drive each of the coolers independently providing sufficient redundancy for this class of mission. The LPT9310 cooler along with the XPCDE4865 were qualified to TRL 6 at JPL.

Heat rejection for the ECOSTRESS cryocoolers and electronics is provided by the cooling fluid loop on the ISS JEM-EF. The heat rejection system (HRS) was designed to remove ~950W of instrument power dissipation with 540W alone from the three cryocoolers. In October 2015 (near instrument PDR), JAXA along with the ISS recognized that the JEM-EF power and cooling resources were not sufficient to meet the new demands from current and future payloads. ECOSTRESS along with the other payloads in development were asked to reduced electrical power requirements and re-design their HRS with reduced coolant flow rates to a minimum of 155 kg/hr and maximum fluid inlet temperature of 24°C. The consequence of this was the erosion of all design margins for the cryogenic system and the estimated power saving was small with the 65K focal plane requirement. The focal plane performance was measured as a function of temperature and results indicated that 67K would yield adequate science but a lower temperature would be preferred. Further design trade-offs led to the final implementation of high performance fluid heat exchangers from MaxQ Technology (Tempe AZ, USA) for the cryocoolers to allow operation at lower skin temperatures and led to the choice for high efficiency cryocoolers. Thermal analysis of the re-designed LPT9310 cryocooler and the MaxQ heat rejection systems predicted sufficient cryogenic margin to proceed forward with a 25% reduction in cooler input power while maintaining the focal plane at 65K.

With uncertainty on the available instrument power and on the inlet temperature and flow rate of the heat transfer coolant that would be provided by JAXA, it was unclear if the three coolers; one cooler to cool the cold shield, and the two detector coolers could provide <65K cooling to the detectors. The limited input power to the instrument meant the coolers may have to be set no higher than 140 watts each. If the cooling fluid temperature (nominally set between 16℃ and 24 ℃) were to be delivered on the warm extreme, the coolers would operate with a skin temperature of about 40℃, which would also reduce the cooler refrigeration capacity. A third concern was that the mechanical layout of the coolers within the instrument placed the compressors on the instrument floor necessitating long transfer lines to reach their respective cooler cold heads. Cumulatively, these effects could result in insufficient cooling power from the coolers to maintain the detector less than 65K. As shown in Figure 4**,** thermal modeling suggested that the performance degradation due to the extended transfer line length (effects of flow losses and increased void volume) could reduce the

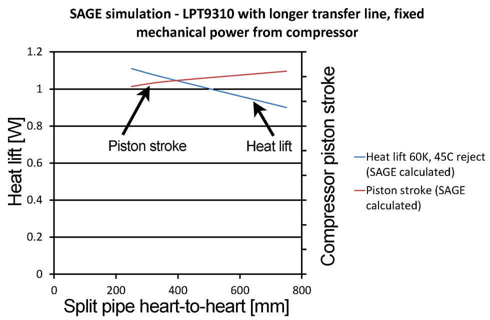

Figure 4. SAGE simulation of LPT9310 with longer transfer line.

refrigeration capacity of the coolers by an additional 200 mW. These performance limiting factors and the uncertainties convinced JPL that they needed Thales to implement a number of material upgrades to enhance LPT9310 cooler performances, as discussed in the following sections.

TRANSFER LINE PERFORMANCE

The requirements on the cooler for ECOSTRESS are a departure from what is typically required of the LPT9310. The required transfer line is significantly longer than the maximum specified value. Furthermore, the required cryogenic cold tip temperature of 60 K is lower than the operating point where the LPT9310 is typically used. (80 K). During initial discussions, the influence of the longer transfer line on cryogenic cold tip performance as well as the compressor stroke were modeled in the commercially-available SAGE® software. The result can be seen in Figure 4.

In order to verify that sufficient margin would be present with respect to compressor piston stroke, a test cooler was built with a long temporary transfer line. The standard LPT9310 specification limits the allowable center-to-center distance between the compressor and the pulse-tube to 500 mm, while distances exceeding 700 mm were expected. A test cooler was therefore built with a 750 mm center-to-center distance (straight transfer line). Sufficient margin for compressor piston stroke was found without the need for an increase in fill pressure.

ADDITIONAL SCREENING ON COMPRESSOR

The LPT9310 compressor can be expected to have an intrinsic high reliability, due to the flexure bearing and moving magnet design. A well-aligned flexure-bearing compressor can be expected to be near-free of wear, which eliminates compressor wear as a factor in cryocooler reliability. The standard parts inspection and manufacturing processes for such a compressor incorporate several steps to ensure that the desired wear-free piston motion is achieved. For the LPT9310 units delivered for ECOSTRESS, a number of additional tests were performed to verify this.

Two key ingredients are required for wear-free operation of a compressor. First, the flexure bearing needs to provide the as-designed high radial stiffness over its operating life. Second, the compressor piston needs to be aligned inside the cylinder such that the motion of the piston is in parallel to the cylinder, maintaining a constant radial gap over its entire stroke.

Even though the inspection criteria for flexure springs are well-understood and no faulty flexures have inadvertently passed the current Thales inspection criteria, flexures from the same production batch as those used in the compressors were subjected to 10^7 cycles of 110% of the physical stroke limit (end-stop stroke), or approximately 170% of the nominal steady-state stroke, as an additional test. This test is not normally performed for off-the-shelf coolers, but is routinely done for space compressors where additional screening is required, such as the Thales LPTC compressor. The flexure fatigue test cabinet can be seen in Figure 5.

In order to ensure that the alignment remained unchanged throughout testing, a ring-down test was performed after several steps in assembly and test. In this test, a DC current is briefly run through a motor coil in order to move a piston to the extreme position. The DC current is then removed and the motor back EMF is measured to monitor the damped oscillation of the piston. The ring-down test is used as a diagnostic test to monitor compressor performance after key steps in the cooler assembly and test sequence, such as:

- After additional run-in hours
- After proof pressure testing
- After acceptance-level random vibration testing

An example ring-down result plot can be seen in Figure 6.

ADDITIONAL COOLER-LEVEL TESTING

A number of additional assembly and test steps were performed on the coolers to ensure workmanship. An additional 168 hours of full-power operation were accumulated on each cooler. An additional bake-out at 100℃ was performed with the cooler internals vacuum pumped, to remove any residual contamination. The coolers were subjected to a proof pressure test to verify all welds and brazes. Finally, the EM coolers were subjected to acceptance-level random vibration, based on the "General Environmental Verification Standard (GEVS) For GSFC Flight Programs and Projects". The test configuration is seen in Figure 7. For the upgraded coolers described later, an updated spectrum was provided, representative of the expected launch loads on the cooler, as seen in Figure 8.

FURTHER ANALYSIS AND JUSTIFICATION

As has been pointed out before, the LPT9310 is a commercial product not developed to any applicable space standards. Analyzing the cooler with respect to specific standards will therefore result in a number of non-compliances. One specific area of attention is the properties of the LPT9310 as an item of pressurized hardware. As the cryocooler was not designed towards the proof pressure factor of safety typically required for flight (1.5X MEOP), a reduced pressure was used for proof testing. In order to provide evidence of the suitability of the cooler design, burst tests were performed on a separate pulse-tube as well as a compressor. Both compressor and pulse tube burst at the expected locations (see Figure 9) and met applicable burst pressure requirements, with burst pressures exceeding 100 bar in both cases, which provides a comfortable margin above the required burst pressure of 2X MEOP (Maximum Expected Operating Pressure) required.

EM TESTING OF STANDARD LPT9310 COOLERS

Upon delivery of the three ECOSTRESS EM coolers to JPL, cooler S/N 1280, with the longest transfer line (731 mm), was set up for thermal vacuum testing. Figure 10 shows the test setup used that was designed to simulate the operating conditions on the ISS. Prototype heat exchangers from MaxQ Technology, similar to the flight units, were bonded onto the compressor and expander with Nusil CV-2946 using 0.028 mm bond wire to guarantee the bond thickness. Braycote grease 601EF was lightly applied to the bonding surfaces prior to the Nusil in order to ensure that the bonds were not permanent.

The prototype heat exchangers were connected to a temperature and mass flow rate controlled fluid loop containing Fluorinert FC72 heat transfer fluid (the same as used on the ISS). The fluid

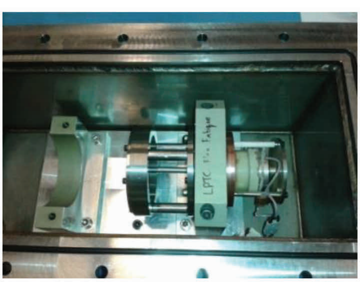

Figure 5. Flexure overstroke test.

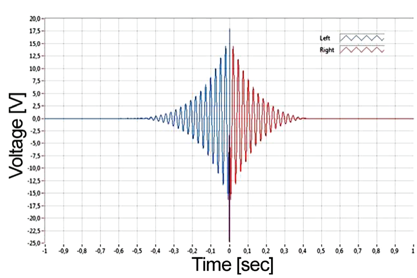

Figure 6. Ring-down test

Figure 7. Random vibration test.

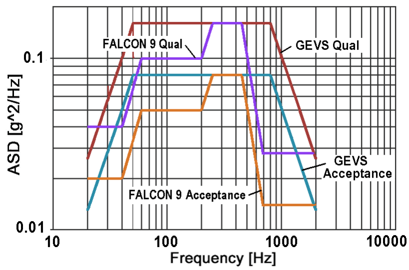

Figure 8. Random vibration spectra.

first passed through the expander heat exchangers and then the compressor heat exchangers. The fluid temperature was measured before the expander heat exchangers, between the expander and compressor, and after the compressor heat exchangers. The measurements were made by thermocouples fed directly into the fluid by means of T-connections. The fluid inlet temperature was defined as that measured before the expander heat exchangers.

The cryocooler was operated with Thales XPCDE 4865 drive electronics at 47 Hz. The input power to each compressor motor was measured using Yokogawa WT310 power meters. In addition, the heat rejection from the compressor and the expander was calculated from the product of the FC72 mass flow rate, the temperature dependent specific heat, and the temperature drop between the inlet and outlet of the heat exchangers. The sum of these gave an independent heat rejection measurement that closely agreed with the sum of the measured cooler input power and cold block heater power.

Cooler S/N 1280 was performance tested in thermal vacuum under worst case scenario ISS conditions, with the anticipated low FC72 fluid flow rate of 155 kg/hr, and at higher flow rate up to 182 kg/hr, and for several different possible FC72 fluid inlet temperature scenarios. Figure 11 shows the heat lift vs. the compressor input power for a fluid loop mass flow rate of 155 kg/hr, a 24°C fluid inlet temperature, and a 60 K cold tip. The heat lift increased nearly linearly with increasing compressor input power and reached a maximum of 1.68 W for 170 W of input power

Figure 12 shows the heat lift vs. cold tip temperature for two different compressor input powers with a 155 kg/hr fluid mass flow rate and a 24°C fluid inlet temperature. For a cold tip temperature of 60 K, the heat lift with 170 W of input power was nearly 0.4 W larger than with 140 W input power.

Figure 13 shows the sensitivity of the cooler heat lift as a function of the FC72 fluid inlet temperature for two different FC72 mass flow rates while the cooler operated with 140 W input power and with a 60 K cold tip temperature. For a given fluid inlet temperature, the heat lift at 182 kg/hr was slightly larger than at 155 kg/hr.

The long transfer line length (731 mm) of cooler S/N1280 had a much smaller effect on the performance than anticipated. The S/N 1280 was capable of 1.12 W of cooling at 60 K with a 40°C

Figure 9. Burst test, standard pulse tube.

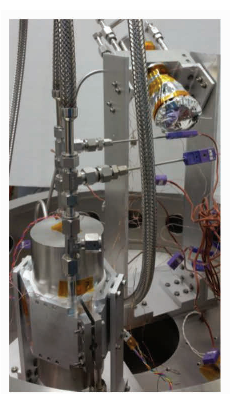

Figure 10. EM cooler TVAC test setup at JPL.

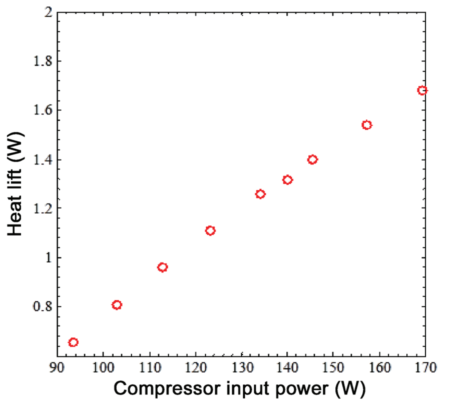

Figure 11. Heat lift vs. compressor input power for 155 kg/hr mass flow rate, 60 K cold tip, and 24°C fluid inlet temperature

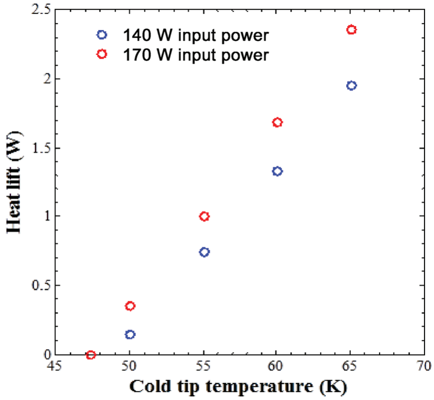

Figure 12. Heat lift vs. cold tip temperature for 155 kg/hr fluid flow rate and 24°C fluid inlet temperature at various compressor input powers.

compressor temperature measured on either side of the heat exchanger. In comparison, a standard LPT9310/17, with a transfer line length of 180 mm and operating under the same conditions, produced 1.19 W of cooling, suggesting that the S/N1280 cooler had only a performance reduction of 70 mW.

With the 140 watt input power limitation on the ECOSTRESS coolers the two coolers for the 60-K focal plane do provide sufficient cooling as designed, however there is an inadequate performance margin for the instrument. As such it was deemed imperative to find a performance enhancement design for ECOSTRESS.

LPT9310 HIGH PERFORMANCE

As the specified performance of the off-the-shelf LPT9310 shows insufficient margin versus the requirement, options were examined to build LPT9310 units with increased performance without invalidating the (off-the-shelf) heritage of the design. Two constraints were present:

- Schedule: only low-risk "first time right" changes, as the ECOSTRESS project schedule does not allow for an iterative design
- Interface: The upgraded cold heads needed to be usable as form-fit drop-in replacements for the existing "EM" coolers

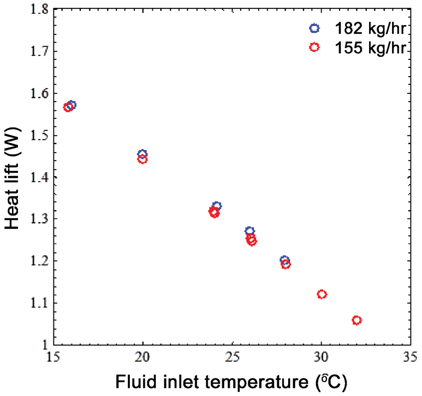

Figure 13. Heat lift vs. fluid inlet temperature for various mass flow rates with 140 W compressor input power and 60 K cold tip.

Table 1. Trade-off for improvement options.

Design option	Interface impact	Process and schedule risk	Selected
Optimized regenerator design	None	Low – Clear heritage present	Yes
Low conductance material between hot and cold	None	Medium – connection processes changed, but heritage present	Yes – outer tube (Titanium alloy)
High-conductance material on warm side	None / Low	High – significant impact on design, limited heritage, metal seals needed	No
Optimized cold heat exchanger	Medium	Medium – limited heritage, risk of design iteration	No
Optimized warm heat exchanger	Medium (potential)	High	No
Optimized inertance	High	High	No

Several material upgrades were tested in the past, but were discarded in the series-produced design because the cost increase outweighed the benefit for most (industrial, non-space) applications. However, because the ECOSTRESS focal plane array requires cooling at 60 K, a number of previously-discarded upgrade options were expected to provide a significant performance benefit. A trade-off was performed to select which upgrades to implement. Options for increasing the performances of a COTS pulse-tube cooler were described previously [6], these design options are repeated in Table 1 and the trade-off result is presented for each option.

It was decided to implement an optimized regenerator composition as well as a Titanium alloy outer tube. The former increases regenerator efficiency at 60 K, while the latter significantly reduces the parasitic loss.

The effect of performing these upgrades can be seen in a comparative measurement, Figure 14. Depending on the input power and reject temperature, the observed improvement was anywhere between 700 and 1000 mW at 60 K. Of this improvement, somewhere between 400 and 500 mW is explained by the reduced conduction loss through the outer tube (change to Titanium alloy), while the remainder is attributed to the increased regenerator efficiency.

A delta qualification program was performed on the LPT9310-HP. Apart from verifying the performance of the upgraded cold head, special attention was paid to all manufacturing (bonding) processes that were changed. Sample-level tests were performed, including tensile strength tests, and a pulse-tube was subjected to a fatigue cycle, including 8 proof pressure cycles, 50 pressure cycles to MEOP, and 80 cooldown-warmup cycles. The number of cycles was based on the fatigue cycle guidelines prescribed by ESA [7]. The pulse tube was subjected to qualification level random vibration testing (envelope spectrum encompassing the protoflight qualification levels for the Falcon 9) after which it was verified to be functional. Finally, a burst test was performed on the LPT9310 design, which resulted in a burst value of 140 bar.

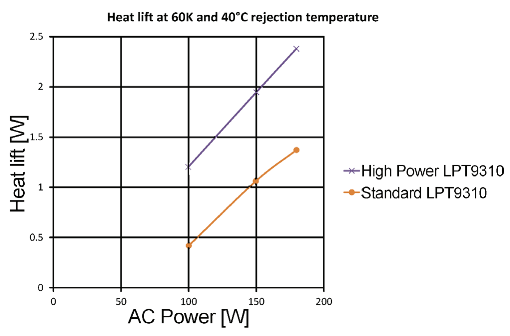

Figure 14. Performance LPT9310-HP vs standard.

CONCLUSION

Testing was performed on standard Thales LPT9310 coolers, which were delivered as engineering models to be used in JPL's ECOSTRESS instrument.

An upgraded high-performance version of the LPT9310 was subsequently built, with upgrades selected based on minimizing risk to schedule as well as avoiding changes to interface dimensions. A qualification test campaign was completed successfully, with the upgraded design meeting qualification-level robustness requirements after being subjected to fatigue cycling as well as providing the required efficiency increase.

Flight models are currently in production and will be delivered to JPL July 2016, with launch planned for 2018.

Future work is considered to investigate an upgraded LPT9310 with a true designed-for-space cryocooler compressor, such as the Thales LPTC compressor.

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