Integrated Testing of a Complete Low Cost Space Cryocooler System

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ABSTRACT

Significant progress has been made on the Raytheon Low Cost Space Cryocooler (LCSC), also called the Dual Use Cryocooler (DUC) because of its applicability to space and terrestrial applications. Most notably, the DUC has been integrated and tested with a high reliability version of the Low Cost Space Cryocooler Electronics (LCSCE) module. Just as the DUC combines features from traditional tactical and space cryocoolers to achieve the required long-life operation at substantially lower cost than typical space cryocoolers, the LCSCE also embodies features from both the tactical and space cryocooler product lines. The LCSCE unit tested was fabricated from all military grade, high reliability components. Every component is either radiation hard to 100 krad total ionizing dose (TID) or replaceable in a straightforward way with a component that is. The LCSCE was shown to efficiently drive and control the DUC without issue. The integrated test results of the DUC with the LSCSE are presented.

INTRODUCTION

The use of cryogenic coolers, or cryocoolers, to support infrared sensing applications has driven the development of two distinct technology bases. On one hand there are cryocoolers designed to support space-based infrared sensing. These systems are required to have exceedingly long lifetimes (on the order of 10 years), high thermodynamic efficiency, extremely low exported vibration, low system mass, and must provide cooling at temperatures less than 50 K to enable MWIR to LWIR sensing. These stringent requirements drive more complicated cryocooler control electronics. The inherent complexity of both the thermal mechanical cryocooler and the accompanying control electronics for long-life space cryocooler systems results in a typical cryocooler system cost (cryocooler + control electronics) of several million dollars.

Space infrared sensing programs continue to drive the improvement of the current space cryocooler state of the art. These programs continually look for higher thermodynamic efficiency, lower exported vibration, lower mass and volume, simpler spacecraft integration, higher reliability and longer lifetime. Achieving lower cost has been an objective, but in the past it has been treated largely as a secondary objective relative to the aforementioned performance-based objectives.

On the other hand, tactical cryocooler systems are designed to minimize cost. These cryocooler systems are intended for terrestrial and/or serviceable systems, and are not traditionally required to

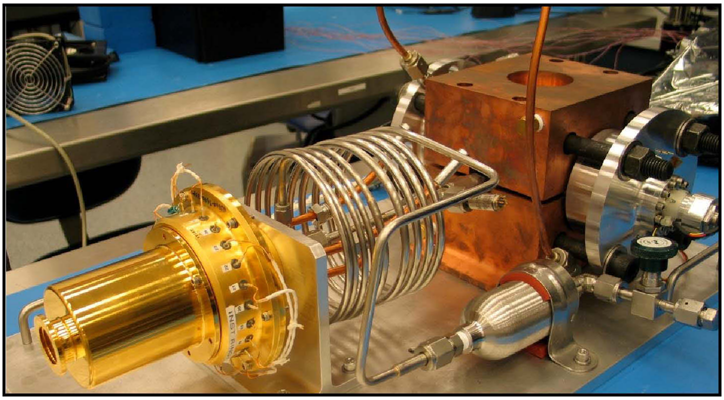

Figure 1. Raytheon Dual Use Cryocooler Thermo Mechanical Unit configured for bench top testing

have the extremely long lifetimes that the space cryocoolers have. Also, most tactical systems don't have the same low exported vibration and low temperature requirements as space cryocoolers. As such, the tactical thermo-mechanical cryocooler and its accompanying drive electronics are much simpler and less expensive than space cryocooler systems.

Recently, a different set of technology needs have been presented by new mission areas such as Operationally Responsive Space and long-life tactical applications such as the Joint Strike Fighter. These types of applications require cryocoolers with higher reliability and longer lifetimes than traditional tactical cryocoolers are able to provide, but cannot afford the high cost associated with the use of a high-reliability, long life space cryocooler. The Raytheon Low Cost Space Cryocooler, also known as the Dual Use Cryocooler (DUC), is designed to meet the unique needs of these types of programs.

SYSTEM DESCRIPTION

The Dual Use Cryocooler system is comprised of a thermo-mechanical unit (TMU) and control electronics unit. The TMU uses a coaxial pulse tube as the expansion mechanism and a dual opposed piston compressor to provide the thermodynamic power required to produce heat lift. The expander module contains no moving parts, allowing for very high reliability at a minimum of mechanical complexity. The compressor module makes use of clearance gap seals in order to provide long lifetime and high reliability, and has a total parts count approximately half that of typical Raytheon space cryocooler compressors. The brassboard DUC TMU, configured for bench top testing, is shown in Figure 1.

Two versions of the LCSCE exist: a simple brassboard and a more mature High Reliability version. The High Reliability Cryocooler Electronics (HRCE) design leverages features from several low cost tactical cryocooler electronics designs produced by Raytheon Vision Systems (RVS). The use of these tactical designs provided a well tested and feature rich base, in addition to intrinsically decreasing system complexity and cost while providing increased manufacturability (these legacy electronics have been successfully mass produced and operationally deployed). The PAWS-2 cooler electronics, one of the designs significantly leveraged for the HRCE, was flight qualified in the F-16, and has accumulated over 10,000 combat hours. The HRCE uses all military grade components and is shown in Figure 2.

DUC TMU DESIGN

The Dual Use Cryocooler (DUC) TMU is a long-life, low-cost cryocooling solution with applicability to both tactical and space systems operating at temperatures of 60 Kelvin and above. The unit was designed from the ground up, with the goal of providing the long life, high reliability

Figure 2. Raytheon High Reliability Cryocooler Electronics

qualities normally associated with space cryocoolers at a small fraction of the price. The DUC consists of two separate modules: a dual-opposed linear compressor and a single-stage concentric pulse tube expander cold head.

The DUC compressor module represents a mixing of elements from the tactical and space design methodologies. For instance, a flexure suspension system such as those found in most space cryocoolers was used in order to eliminate seal degradation and contamination generation. Simplified mechanical design methodologies from tactical compressors were used, allowing for a vast reduction in parts count relative to Raytheon's typical space compressor modules. This reduction of parts has the added effect of greatly reducing build time and increasing manufacturability. The DUC expander module is a single-stage, concentric pulse tube design that was designed to use a small number of piece parts and assembly operations, allowing for a high degree of manufacturability and a relatively low cost. The pulse-tube architecture, with no moving parts, provides very high reliability and low uncompensated exported disturbance levels relative to tactical Stirling expanders. Thermodynamically, the expander module is efficient at temperature above approximately 60 Kelvin, allowing for applicability to a wide variety of both space and tactical applications.

The thermodynamic design goal of the DUC is to provide 1.5 watts of heat lift capacity at a temperature of 67 Kelvin for approximately 84 watts of compressor input power. A production-configuration DUC is expected to have a mass of approximately 4.5 kg including an integral inertance tube and surge volume. The use of a two-module design allows for convenient mounting of the expander cold head separate from the compressor, which also allows for passive vibration isolation techniques to be employed when required. The production expander module will be approximately 6.5 inches in length and 3.4 inches in diameter, with a cold tip diameter of 0.9 inches. The compressor module measures less than 8.5 inches in length and 4 inches in diameter. The gas transfer line length can be varied from several inches to several feet depending on the system needs. The initial build of the DUC compressor module was completed within 5 days of receipt of the piece parts, including all alignment and checkout procedures. The compressor module has subsequently been operated over a wide variety of power levels and temperatures without failure.

Though the DUC is able to attain the original heat lift goal of 1.5 watts at 67 Kelvin, more input power is required than originally intended. Model correlation and analysis revealed that the input power delta is a result of an unanticipated flow restriction occurring at the inlet of the expander module. In response, Raytheon is performing a redesign of the expander module using internal funding. The warm-end flow passages designs and manufacturing techniques are being substantially modified in order to ensure a minimum of pressure drop. Further, the cold-end flow passages are being changed from the original DUC design to the design used by the RSP2 concentric pulse tube second stage; this design has demonstrated excellent performance and its inclusion in the DUC will serve to further reduce parasitic pressure drops. Fabrication, assembly and test of the third DUC expander module is presently funded and will be completed mid / late 2008.

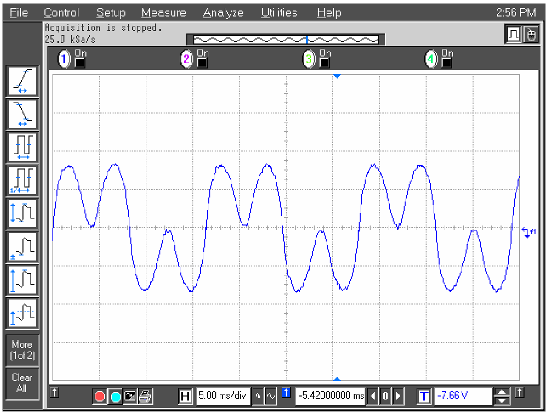

Figure 3. An oscilloscope capture illustrating arbitrary wave shaping capability

LOW COST SPACE CRYOCOOLER ELECTRONICS DESIGN

The fundamental design of the LCSCE was derived from a pre-existing set of simple cryocooler electronics, embodying many years of tactical cryocooler electronics experience. A variety of features were inherited from the legacy electronics including cold-tip temperature feedback and closed loop control, selectable operating frequency, output drive wave shaping, cool-down rate control, and over-current, thermal, and short-circuit protection. The board uses standard 28V DC input power and serial communication / control can be accomplished using USB or the more standard RS422/ 485. SpaceWire compatibility is a planned addition for the production system. A multiple-channel ADC is used to sense cold-tip temperature, board temperature, and bridge current, and spare ADC channels are reserved for the future addition of anti-knock or vibration control sensors.

The earliest phases of this effort were concerned with improving the digital architecture of the legacy electronics so as to increase resolution and flexibility. A second motor drive output circuit was also grafted into the legacy electronics using an additional PCB, and the closed-loop temperature control algorithm was modified slightly in order to increase both transient and steady-state performance. This work was performed in 2006 using a brassboard set of electronics. The ability to arbitrarily shape the output waveforms was also demonstrated at this time, as seen in Figure 3.

Work in 2007 began with the production of a new circuit card layout, allowing for integration of the two separate motor drive circuits and elimination of the second PCB. Two of these versions of the LCSCE were constructed using all military-grade components and a simple rectangular enclosure. These units, known as the “High Reliability Control Electronics (HRCE),” contain the features listed in Table 1.

Table 1. Present and planned future features of the LCSCE

Feature Description	Presently Implemented	Future Upgrade
Adjustable Frequency	X	
Adjustable Drive Voltage	X	
Programmable Soft start	X	
Short Circuit / Thermal Protection	X	
Independent Dual Output Capability	X	
Programmable Drive Waveform	X	
Compressor Power Estimate	X	
Closed-Loop Temperature Control	X	
Board Temperature Telemetry	X	
Piezoelectric Force Sensor Telemetry		X
Compressor Skin Temperature Telemetry		X

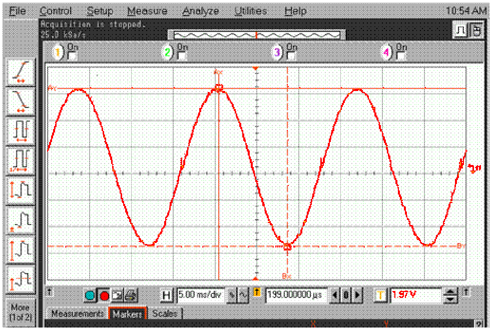

Figure 4. Cryo motor output drive at nearly full drive of 50 Wrms; F1 is 5V/div scale.

Initial checkout of the HRCE involved driving a tactical Stirling cryocooler. This thermo-mechanical unit, presently used in a variety of tactical programs, presents an electrical impedance that is similar in nature to that of the DUC TMU. During cooldown, compressor input powers of just over 40W were achieved at an end-to-end efficiency of slightly under 80%. Input power during steady-state temperature control was approximately 24 W, which the LCSCE was able to provide at an efficiency of 81.7%. Figure 4 shows the plant drive waveform. Testing and tuning of the LCSCE temperature control loop was also performed in this configuration.

INTEGRATED LCSCE / DUC TESTING

Following the optimization and testing of the LCSCE with the tactical Stirling cryocooler, the unit was transported to Raytheon Space and Airborne Systems in order to test with the DUC TMU. Both LCSCE output channels were utilized during this testing, which commenced in July of 2007. At the time of testing the temperature sensor at the cold tip of the DUC TMU was not functional, and closed-loop temperature control was therefore not demonstrated. Instead, a cryogenic temperature controller was used to apply a fixed heat load while the LCSCE was set to output approximately 100 W to the cryocooler. In the course to this testing the LCSCE / DUC TMU system was operated at high power for extended periods of time, during which no issues were encountered in either unit. Average LCSCE efficiency at this power level was approximately 83%. High-power cooldown curves, such as the one shown in Figure 5, were also generated.

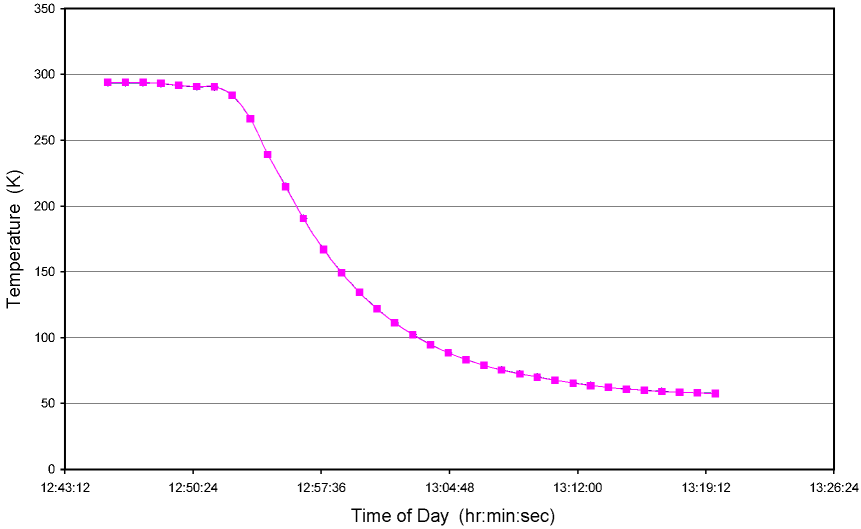

Figure 5. Cool-down curve for DUC driven by the LCSCE

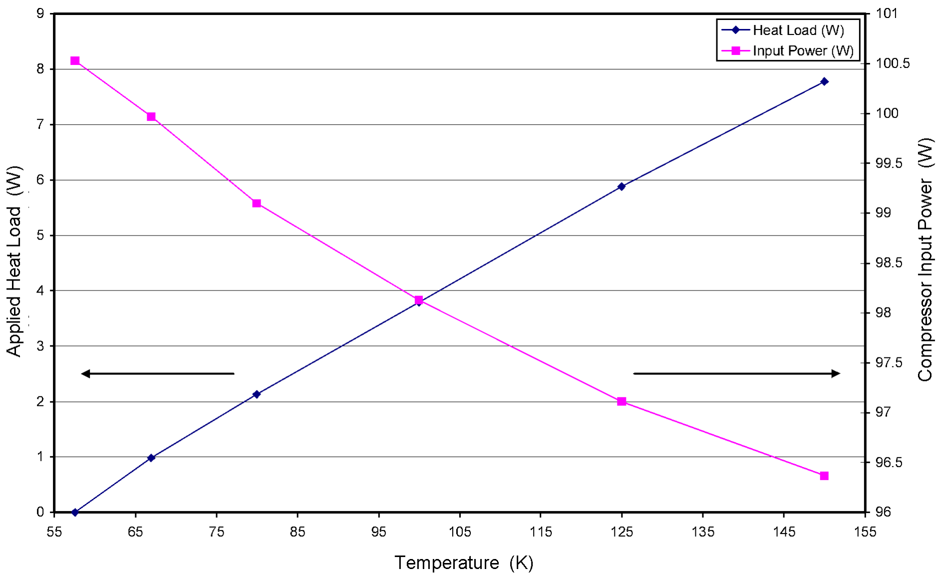

Figure 6. Load line for DUC driven by the LCSCE

A 100 watt load curve (Figure 6) was also generated in order to evaluate the performance of the DUC TMU relative to previous measurements made using an engineering rack. Performance had essentially remained the same, indicating that the DUC TMU has no preference for either the engineering test rack drive circuits or the LCSCE drive circuits. As previously mentioned, the efficiency and capacity of the DUC TMU is lower than predicted by the original thermodynamic model. Analysis of the previously-collected DUC TMU test data had shown that the input power as well as the transfer line pressure ratio are significantly higher than predicted by the thermodynamic model for any given stroke level, and attempts were made to characterize the issue. Ultimately, it was found that the addition of a flow restriction to the inlet of the expander module model is sufficient to bring the thermodynamic predictions into close agreement with test data. FEA modeling has been used in order to evaluate the exact location of the flow restriction and to appropriately revise the design. An updated expander module will be constructed and tested by mid / late 2008.

After completion of basic LCSCE + DUC TMU testing, the setup was partially disassembled in order to repair the cold tip temperature sensor. Completion of this work allowed for the LCSCE to drive the DUC TMU in closed-loop temperature control mode for the first time. Programmatic reasons prohibited extensive testing in this configuration, though several hours of operation were captured as illustrated in Figure 7. The test essentially consisted of operation at a 67 Kelvin setpoint with a slowly increasing cold tip heat load. As previously noted, the control loop coefficients of the LCSCE had been tuned using a tactical Stirling cryocooler that has significantly different operational qualities than the DUC. As a result, temperature stability during parts of the test was relatively poor, with the cold-tip temperature oscillating around the setpoint in a range of ~0.6 Kelvin peak to peak. This instability was especially prevalent with low applied heat loads, and stability was found to significantly improve as the cold tip heat load was increased. At high heat load levels, stability in the range of several tens of milliKelvin was able to be achieved. It is expected that overall temperature stability will be greatly improved given the opportunity to retune the control coefficients specifically for the DUC TMU.

FUTURE WORK

In terms of its ability to provide high reliability cryogenic cooling at relatively low cost, the Dual Use Cryocooler system effectively fills the gap between tactical and space cryocooler systems.

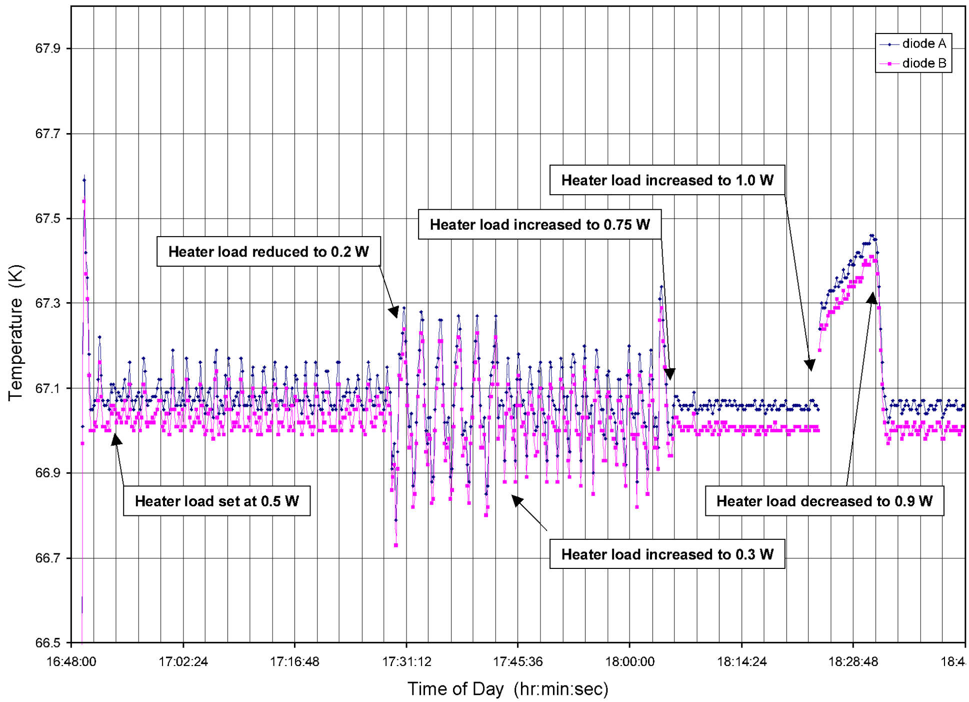

Figure 7. Data taken from closed-loop testing of the LCSCE and DUC.

A variety of present and future applications, including several operationally responsive space and long-life tactical applications, will directly benefit from the availability of a long life, radiation-hardened cryocooler system that can be purchased at a fraction of the cost of typical space cryocoolers. As a result, further investments into the development of the system are being made using both internal Raytheon and external contract funding.

The most immediate development activity being pursued concerns completion of the third DUC expander module. As mentioned previously, this expander module will have substantially lower pressure drop as compared to the present implementation, allowing for an increase in overall efficiency and capacity. Several changes to the external expander surfaces will also be implemented in order to better accommodate the thermal and structural interface needs of potential applications. The thermal interface flats on the warm end of the module will be redesigned in order to accommodate appropriately-sized heat pipes. The inertance tube and surge volume will also be combined into an integral unit that is much more compact than the laboratory units presently employed. This structure will have a variety of mounting options, including remote-mount, placement on the warm end of the expander module, or placement on the end of the compressor module.

A second group of modifications that are planned concern internal and external elements of the compressor module. Presently existing in brassboard form, the compressor makes use of a combined cylindrical thermal / structural interface. While this system is adequate for laboratory testing purposes, it could prove troublesome during integration with actual sensor systems. In response, the external surfaces will likely be redesigned with separate flat, bolted thermal and structural interfaces. Provisions for the use of piezoelectric force sensors will be included as well. Internally, several design modifications will be performed in order to lightweight the motor while improving efficiency and robustness.

As previously mentioned, the DUC control electronics presently exist in “High Reliability” form, with military-grade components and a simple rectangular enclosure. Design and production of a radiation-hardened, flight-packaged version is planned to begin mid-2008, with the production packaging being backward-compatible with the non radiation-hardened version of the electronics.

The final product of the work described above will be a complete flight-model DUC system, including both the TMU and the drive electronics. A series of tests is planned in order to verify the flight-readiness of the system through the usual environmental and qualification tests: engineering burn-in, thermal-vacuum, applied vibration, and life test. In addition, the DUC system will undergo exported-disturbance testing on a dynamometer test station. This test will provide extremely useful data relating to the intrinsic level of vibration forces produced by the cooler at various power levels, as well as the applicability of "set-and-forget" balancing using the dual motor control electronics' dual motor drives. Further, evaluation of several simplified active vibration reduction methods will be performed.

SUMMARY

The DUC has been integrated and tested with a High Reliability Low Cost Space Cryocooler Electronics module. During testing the electronics were shown to efficiently drive and control the DUC without issue, paving the way for the build and demonstration of a flight model Dual Use Cryocooler System.

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