Raytheon Dual-Use Long Life Cryocooler Development

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ABSTRACT

Development of the Dual-Use Cryocooler (DUC) system has progressed substantially over the past two years, including the design, build and testing of a brassboard thermo-mechanical unit (TMU). Early design efforts were undertaken with simplicity as a goal, and as a result the brassboard TMU contained significantly less parts than typical space-level cryocoolers. Build time for the brassboard unit was extremely short, with the compressor being built in a matter of days as opposed to the more traditional timescale of weeks. The brassboard TMU was subjected to characterization testing in both horizontal and vertical orientations (to address sensitivity of the pulse-tube cold head to gravitational effects), and results from that set of tests have been correlated to the thermodynamic model. Several lessons were learned as the testing and correlation activities progressed, and improvements necessary to meet the intended performance objectives were identified for implementation in the deliverable system.

Significant progress was made in terms of electronics development as well. Existing tactical assets were heavily modified for use with the DUC, including the addition of separate drive circuits for each compressor motor. The operating software was modified to enable features not found in typical tactical systems such as first-order active vibration cancellation. Ultimately, the brassboard electronics were used to drive passive loads as well as an actual (representative) tactical Stirling cryocooler.

Keywords: cryocooler, pulse tube, Stirling, tactical, dual use, space

1. INTRODUCTION

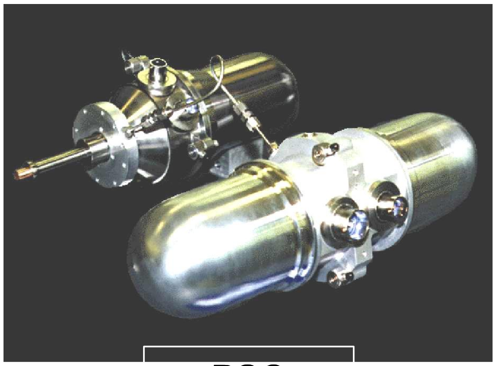
1.1 Dual-Use Cryocooler Background

The Raytheon Dual-Use Cryocooler (DUC) project had its inception a number of years ago, envisioned as a system capable of bridging the gap between the traditional space and tactical cryocooler domains [1,2]. Tactical cryocooler technology has been typified by single stage passive (pneumatic and resonant drive) Stirling machines, normally operating at temperature above 65K. These systems are driven by traditional motor drive amplifier circuits that are not enabled with active vibration control capability and are not radiation-hard. System operational lifetimes are usually in the 5000-10000 hours range. In the tactical cryocooler market, cost is as important a design driver as technical performance; these systems can be readily purchased for a price in the tens of thousands of dollars, and procurement lead time is typically a few months if not weeks.

The space cryocooler market is driven in the exact opposite way, as technical performance and reliability are essential in these applications. Space cryocooler systems are available in a number of thermodynamic configurations (Stirling, pulse-tube, reverse Brayton, single and multiple stage machines, etc.) and can operate at temperatures well below those attainable by tactical cryocoolers. Space cryocooler electronics are much more complex than their tactical counterparts, being high-reliability, radiation-hardened, and capable of active vibration cancellation as well as a host of other advanced functionalities. These types of systems typically have costs in the millions of dollars and require well over a year to procure.

Infrared Technology and Applications XXXIII, edited by Bjørn F. Andresen, Gabor F. Fulop, Paul R. Norton,
Proc. of SPIE Vol. 6542, 65422H, (2007) · 0277-786X/07/$18 · doi: 10.1117/12.719956

Space Cryocooler



PSC

Compressor ~ 16.5” x 4.9”D, 17.8 lbs

Tactical Cryocooler

Raytheon 7060-260S

Compressor ~ 4.5” x 1.58”D, 1.0 lbs

Fig. 1. Typical Raytheon-produced space (left) and tactical (right) cryocooler thermo-mechanical units. Note significant mass and package volume differences.

Raytheon has long-acknowledged that, for a growing number of applications, neither traditional space nor tactical cryocooler systems are optimal. Space systems are much too costly and long-lead for some applications, while tactical systems do not always possess the technical performance characteristics optimal, or perhaps even required, to fulfill mission objectives. Such applications include JSF, the DD(X) cruiser, the Low-Cost Kill Vehicle, and a variety of potential Responsive Space campaigns. All of these applications share the need for a reduced-cost (relative to space cryocoolers) cryocooler system that has an extremely long operational lifetime (relative to tactical cryocoolers). The prevailing approach across industry and government at present is to try to improve the performance of tactical designs to meet the more demanding emerging requirements. The Raytheon approach, described herein, is subtlety different in that the starting point for the mechanical cryocooler design finds its origins in traditional space cryocooler design practices.

1.2 Initial Design Trades

The initial design trades for the DUC system focused on identifying those characteristics of traditional tactical and space cryocooler systems that are most responsible for their incompatibility with the above-mentioned systems (price in the case of space systems and operational lifetime in the case of tactical systems). Many of these characteristics were suggested in a previous paper and discussed further here to put the present effort in context [3]. On the tactical side, issues of operational lifetime are mainly a result of rubbing seals (the degradation of which increases parasitic blow-by and generates significant gas contamination). Unacceptable levels of exported vibration are chiefly a result of using non-balanced compressor designs (rotary or single-piston linear) and / or passive-Stirling expander designs.

On the space side of the market, prohibitively high system costs and lead times were found, unsurprisingly, to be a result of high design complexity in both the TMU and the electronics. It was determined that electronics complexity is largely driven by the need for high-resolution active vibration cancellation. The amount of processing involved in implementing such a system places large demands on the electronics, necessitating an increased number of high-dollar parts and associated software. For space based imaging systems on stable platforms, the nominally 100 mN to 500 mN vibration levels exported from the cryocooler are typically significant to line of sight (LOS) error, which is obviously not the case for tactical imaging systems on much noisier fixed wing, rotary wing, missile, and mobile ground platforms. Thus this requirement is not expected to diminish as a trade driver for space-based applications. However, replacement of the current state of the art with a much simpler system can yield large amounts of savings in terms of electronics design complexity and production cost. Space cryocooler TMU designs exhibit a similar issue, in that design complexity drives up cost and lead times. This is especially true in multi-stage designs with very complex cold heads, and in Stirling machines in which a considerable amount of hardware is included inside of the TMU simply to cancel vibration induced by the Stirling displacer [4].

Having identified the important negative drivers in traditional space and tactical cryocooler systems, the DUC design process was undertaken. It was decided that the DUC system TMU would use a compressor that is largely based on traditional space-type designs, incorporating a dual-opposed motor design as well as flexure-borne moving elements and clearance-gap seals that completely eliminate the usual mechanisms of performance degradation and TMU failure. The TMU would, however, take design cues from tactical units in an effort to reduce parts count and internal complexity. A pulse-tube type expander was chosen for a variety of reasons, the most important of which is a complete lack of moving parts. This feature greatly reduces cost and assembly complexity, while also increasing reliability. Additionally, pulse-tube expander modules are inherently low in exported vibration and do not require dedicated drive electronics.

As the fundamental design features of the DUC TMU were settled, attention turned to the drive electronics. An examination of the relative strengths and weaknesses of space and tactical drive electronics underscored the fact that a great deal of complexity and cost are added to space drive electronics in order to gain a relatively small amount of performance in comparison to tactical units. Many sets of tactical cryocooler electronics contain a great deal of desired functionality including active temperature control, high-efficiency power drives, and necessary protection circuitry. Active vibration control is the main operational discriminator between tactical and space electronics, a feature that is of secondary importance for the DUC as the chosen TMU is inherently low in vibration (balanced compressor design and a pulse-tube type cold head). The decision was therefore made to upgrade a suitable set of tactical cryocooler electronics for the DUC system instead downgrading a set of space electronics.

2. DUAL USE CRYOCOOLER DESIGN AND BUILD PROCESS

2.1 DUC Thermo-Mechanical Unit (TMU)

As mentioned in above sections, the DUC TMU incorporates a dual-opposed, flexure-borne compressor module and a pulse-tube type expander module. The goal of the designs process was to produce a cryocooler TMU that is extremely long life while also being low in cost and short in build-time. The basic design rules were taken from legacy space cryocooler designs, though tactical cryocooler designs were studied for opportunities for parts-count reduction and design simplification. The compressor and expander modules were largely designed by a single, small team, ensuring that the two modules would function well as a single system while also encouraging the cross-use of lessons learned in the respective design tasks. As a brassboard unit, the first implementation of the DUC was to include several diagnostic features that would not be present in a production or flight system: LVDT position sensors (to be eliminated or replaced in a production system), pressure taps, and a laboratory-type inertance tube / surge volume setup.

The thermodynamic performance target for the DUC TMU was chosen to be 1.5W of heat lift at a cold-tip temperature of 67K for approximately 80W of input power, with the ability to effectively produce heat lift into the mid-50K range. A detailed thermodynamic / electrodynamic model was created in order to assess and optimize the design at a system level, while the motor topology was designed and optimized in a separate magnetics modeling suite. The compressor module was desired to be readily-reconfigurable (with very minor internal modification) such that it can be easily adapted to operate at higher or lower capacities while maintaining optimum efficiency. The expander module was to be a highly-scalable design, allowing the same basic mechanical design to be adapted to different operational conditions.

2.1.1 Expander Module

Having chosen a single-stage pulse tube design for the DUC expander module, additional design details were rapidly filled in. The choice was made to utilize a concentric pulse-tube design as opposed to the more traditional folded ("U-Tube") and unfolded designs. The concentric pulse-tube design leads to a smaller overall package, a more robust cold head, and a higher first-vibration mode. Additionally, the concentric design is conducive to simplified build techniques. Lastly, a novel regenerator design was identified and developed with the intention of vastly reducing the amount of time requires to integrate with the rest of the expander. In the event that the expander module is ill-suited to a particular application (heat lift and temperature requirements), the basic design can be readily reconfigured by swapping regenerator geometries, altering the inertance tube / surge volume configuration, and/or scaling the basic design.

Common, readily-available materials of construction (stainless steel and copper) were selected for low cost and manufacturability. The objective was to eliminate design features that have, in the past, complicated space cryocooler builds; inertial welds of dissimilar materials are a prime example of such design features that have complicated past space cryocooler builds. As a result, parts procurement for the expander module proceeded nominally with all parts arriving in-house in a timely manner. An assembly method was developed for the concentric portion of the system, including all necessary electron-beam weld and braze operations. This method was proven out through the production of a coupon which was subsequently taken through all pertinent operations (leak and proof pressure testing) and destructively inspected.

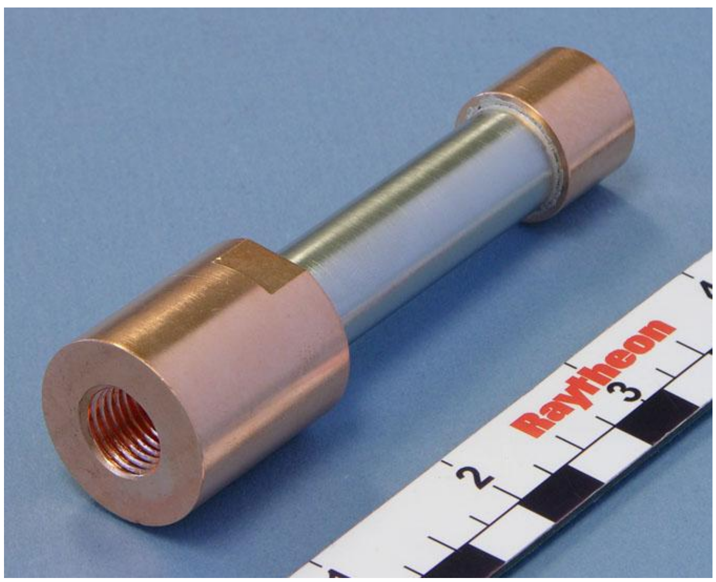


Fig. 2. Pulse-tube coupon after electron-beam weld and braze operations. Coupon was leak checked for hermeticity, proof pressure tested for structural integrity, and finally cross-sectioned and examined visually.

After destructive testing validated the assembly techniques, the brassboard expander module was constructed. Overall build time was significantly shorter than usual, chiefly a result of efficient design practices. The novel regenerator concept was proven at this level in that assembly of the regenerator into the expander module was a very short process with many fewer steps than usually required. The completed expander module was subjected to necessary checkout testing, involving proof-pressure testing (in order to assess weld/braze integrity) as well as flow testing (to ensure that no significant internal blockages were present). All module level integrity tests were successful.

2.1.2 Compressor Module

The central design goal of the DUC compressor was to maintain the long-life features of traditional space compressors while greatly reducing internal complexity and parts count. The inclusion of flexure-borne moving mechanisms and clearance-gap seals was necessitated by the extended lifetime requirement, however the rest of the compressor design was seen as a "clean-slate." Numerous space and tactical designs were studied for relative strengths and weaknesses, and a compressor design quickly converged that is reliable, mechanically simple, very low in parts count, and readily reconfigurable / scalable to different operating conditions and capacities.

The foundation of the DUC compressor module is a newly-designed integrated motor / cylinder structure that combines several pieces of the typical space cryocooler compressor into a single part. Extending this design methodology, various other pieces of the system were simplified or combined into single parts, the end result of which is a compressor module that contains less than half of the usual space compressor parts count while maintaining all of the necessary long-life, high-reliability features. The flexures used to suspend the various moving elements are a complete reuse of a previous design that has accumulated over 1 trillion full-stroke cycles without failure or degradation, and system clearance seals were designed to be temperature-insensitive such that the compressor can be safely run over a wide temperature range.

The success of the compressor design simplification effort was demonstrated during the assembly phase, in which the compressor module was built-up from piece-parts in a matter of days as opposed to the typical timeframe of four to six weeks. Alignment of the moving elements was performed successfully, and it has proven to be very stable and robust during initial testing. Proof-pressure and leak tests were performed without incident.

2.2 Low-Cost Space Cryocooler Electronics (LCSCE)

The design process for the LCSCE began by compiling a list of "essential" functionalities:

- Dual motor drive circuits
- Temperature control
- Cool down rate control
- Selectable operational frequency
- Short and Overload electronics protection
- User-settable output current limits
- Clear radiation-hardness upgrade path

The LCSCE, containing the above features, is well suited to a very wide variety of tactical and space missions requiring high reliability and low cost. Vibration control is the central missing element, though implementation of a full-featured vibration control system would necessitate a significant increase in complexity and cost. For most tactical applications and many low-cost space applications , this is a non-issue as vibration control is simply not required to meet overall system performance requirements; the DUC, having a balanced compressor and pulse-tube type expander, is inherently low in vibration output. Other, more vibration-sensitive applications may benefit greatly from a simple form of vibration control. For instance, a large percentage of total cryocooler vibration occurs in the compressor drive axis and at the fundamental operational frequency. Reduction of this vibration, essentially amounting to an electrical balance the compressor, is easily achievable and will pay large dividends at the system level. Software functionality to support this type of 1st order vibration control as well as other more complex versions was incorporated into the baseline LCSCE requirements. Ultimately, the LCSCE / DUC system will be able to support a very wide range of tactical and space missions with very little modification.

Comparing the above-mentioned desired functionalities to a variety of available tactical electronics platforms, it was found that a relatively small number of design modifications could be used to adapt a traditional tactical electronics set to meet the LCSCE requirements. The Raytheon Tactical Cryocooler product line produces such a set of tactical electronics, and a version was chosen that has excellent baseline performance and extensive legacy to past Raytheon cryocooler programs such as PAWS and ATFLIR. Necessary modifications were made to the basic platform, amounting to the addition of a second motor drive and a fleshing-out of the software such that each motor drive can be controlled independently of the other. The modified electronics were mounted into a test enclosure and basic checkout procedures with a tactical Stirling cryocooler were successfully performed.

Simultaneous with the modification and build of the LCSCE, the basic circuit designs and parts lists were reviewed in order to assess the path towards a radiation-hard design. A thorough assessment of the baseline design (performed by the Raytheon Space and Airborne Systems radiation group) revealed that simple component and packaging changes could be implemented, providing the LCSCE with 100krad TID radiation hardness, precluding the possibility of Single Event Latchup (SEL), and greatly reducing the probability of Single Event Upsets (SEU). Thus the LCSCE breadboard described herein provides a straightforward path towards a fully radiation hard set of space cryocooler electronics.

3. THERMODYNAMIC / ELECTRONIC TESTING

Initial build, integration and checkout operations were completed separately for both DUC TMU modules as well as the LCSC-E. Both the TMU and the LCSC-E were integrated with STE appropriate for benchtop testing, and initial characterization tests were performed. Figure 3 shows the DUC TMU in its test fixture with the test instrumentation electronics rack. A variety of interesting results were obtained for each part of the system, detailed below. (Integrated testing of the LCSCE and DUC TMU is planned for March 2007.)

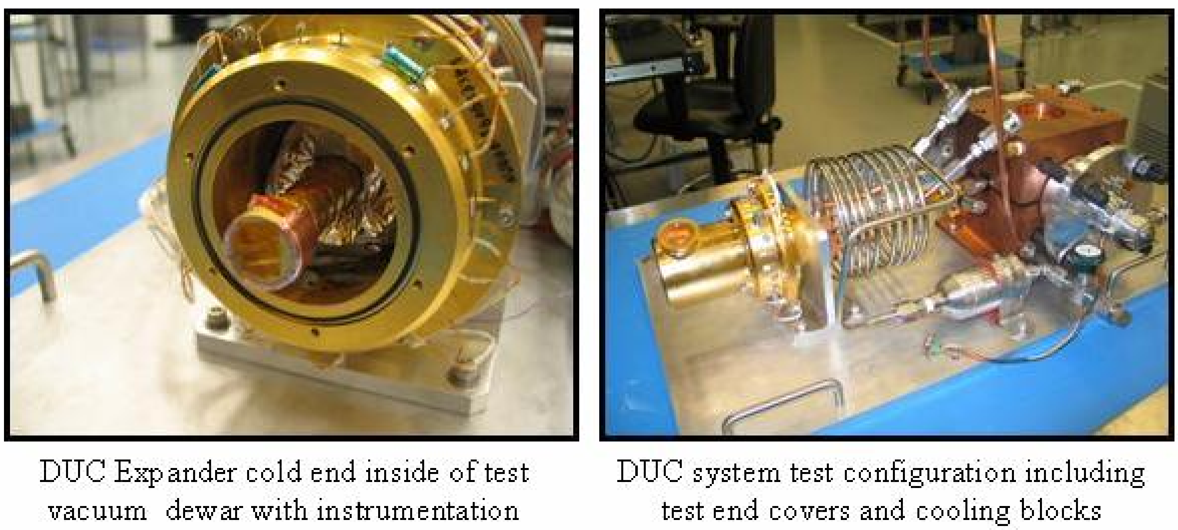


Fig. 3. Brassboard DUC TMU in test configuration. Note test endcover with LVDT in right figure.

3.1 Compressor Module Performance

Initial testing of the compressor was performed with test end caps that include linear variable differential transformers (LVDTs) to provide accurate piston position measurement to facilitate model correlation (reference Figure 3). After brassboard testing is complete, these end caps will be replaced with the flight-design end caps, which will be electron beam welded to the housing for long life hermeticity. The flight-design end caps do not feature piston position sensors.

As shown in Figure 3, above, initial compressor testing was done in an integrated state at the TMU level. Compressor performance was found to correlate extremely well with both the system and magnetics models. Efficiency (defined as the ratio of compressor PV power output divided by input electrical power) was within nominally five percent of the predicted values across a wide variety of operating conditions, and the compressor resonant frequency (59 Hz) was found to be extremely close to the predicted value (58 Hz). This is an indicator that the compressor pneumatic behavior, including clearance seal blow-by, is very close to the nominal design. In an electromagnetic sense, the compressor motor performance agrees extremely well with the models. Mechanically, the compressor module was found to be extremely stable, exhibiting a minimum of friction (as assessed by hysteresis testing, Figure 4).

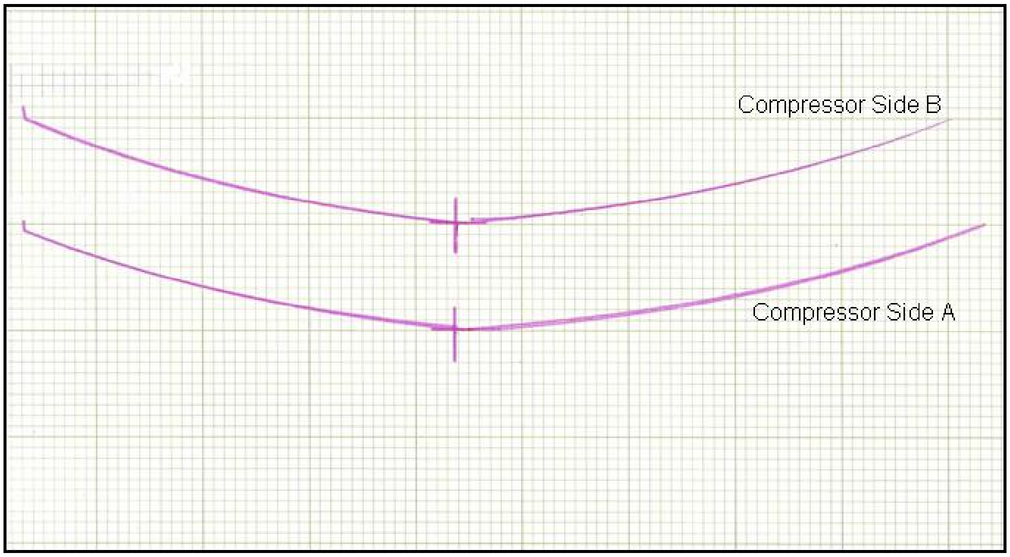


Fig. 4. Hysteresis test curves from DUC compressor module. Almost perfect retracing of lines indicates very little piston / cylinder friction.

An additional increment of funding was received in 2007 to improve the DUC brassboard TMU. As part of this effort, modifications to the compressor were made to increase the available piston stroke amplitude. As with the initial build, all alignment procedures were performed with ease and the completed module exhibited a minimum of friction between the moving and stationary parts. The machining operation accomplished the desired stroke increase, and the compressor module was able to be run at increased swept volume.

Compressor Reject Temperature (K):	Cold-Tip Temperature (K):	Frequency (Hz):	Compressor Stroke (% of Maximum):	Input Power (W):	Normalized Compressor Efficiency:
268	100	59	78	113.0	0.93
268	100	59	67	79.6	0.97
268	100	59	56	52.1	1.00
293	100	59	78	128.7	0.89
293	100	59	67	89.6	0.93
293	100	59	56	58.6	0.95
312	100	59	78	136.9	0.86
312	100	59	67	95.2	0.90
312	100	59	56	63.1	0.93
328	100	59	78	147.1	0.85
328	100	59	67	101.8	0.89
328	100	59	56	67.6	0.90

Fig. 5. Normalized compressor efficiency as a function of rejection temperature and stroke.

Additional testing was performed to assess the robustness of the compressor over a wide variety of rejection temperatures and operating powers. Though design methods are in place to desensitize the compressor performance to operational (rejection) temperature, it is nonetheless desirable to experimentally verify that the temperature insensitivity was indeed achieved. In terms of efficiency, this testing was intended to probe the effects of increased and decreased operating temperature on the compressor drive coils as well as the basic ability of the compressor to reject internally-generated heat. Towards these ends, the compressor was run at housing temperatures ranging from 268K through 328K, with input powers from 52W up to 147W. Figure 5 contains tabulated data from this set of tests, with stroke normalized with respect to the maximum possible stroke and efficiency normalized to the maximum efficiency recorded during this series of tests. At no temperature or power was the compressor found to exhibit reduced performance indicative of rubbing piston / cylinder seals, and compressor efficiency was found to vary by a maximum of 15% (relative to peak efficiency) over a 60K range of operating temperatures. This is a particularly interesting result because several of the operating points involved input powers approximately two times higher than the original design value of 75W. The DUC compressor has thus been shown to be very robust, with an internal thermal design capable of rejecting significantly more power than nominal at rejection temperatures as high as 328K. Testing at lower temperatures is planned in the very near future. Additionally, dynamometer tests are planned in order to assess the inherent vibration output of the compressor as well as the ability to reduce this vibration via the simple functionality built into the LCSC-E.

The brassboard DUC compressor module has been proven to be a high-performance, high-reliability, and very robust design that is also simple to build and inexpensive to procure. Though it presently exists in brassboard form, a production/flight packaging design (amounting to modified, reduce-size endcaps) exists and is ready to be implemented.

3.2 Expander Module Performance

Compressor rework issues overshadowed the expander module evaluation during initial testing phases, however a fairly thorough assessment was ultimately performed. The results of the assessment are mixed: thermodynamic performance was found to be lacking as compared to the model predictions, however the issues responsible for this discrepancy were able to be isolated and the rework plan is straightforward and already underway. By design, instrumentation such as transfer line and surge volume pressure taps, in combination with a very well-understood and predictable compressor module, allowed for the performance of the expander module to be assessed independently of the rest of the system. These diagnostic tools ultimately proved to be essential to the diagnosis of the expander module.

Initial testing involved no-load evaluation as well as the generation of load curves at temperatures well above no-load. The predicted no-load temperature of the DUC was expected to be approximately 48K, however the actual no-load was 18 K higher. The lack of performance was also present at temperatures above 100K, resulting in lower heat lift capacity and efficiency than predicted by the system models. The focus of testing thus shifted from TMU-level performance evaluation to compressor-level performance evaluation (see previous section) and diagnosis of the expander performance shortfall.

Gas contamination, exceedingly high parasitic axial conduction, and pressure-drop phenomena were initially considered as possibilities for explaining the expander performance shortfall. Gas contamination was ultimately ruled out for several reasons: the suspect behavior was present across several fill/purge operations, and Raytheon has in place very reliable fill / purge procedures that have been proven out in many past cryocooler builds. The issues of pressure-drop and axial conduction, however, could not be eliminated.

An examination of test telemetry revealed several noteworthy pieces of information. First, the pressure ratio at the transfer line was consistently high given the amount of compressor swept volume, indicating an excessive amount of flow-resistance in the system. Second, upon shutting down the cryocooler, the cold-tip temperature was found to rise at a higher-than-expected rate. In order to further investigate this effect, a series of warm-up curves were generated with varied amounts of heater power applied to the cold tip. Figure 6 contains the data taken from two such warm-up tests. The lower magenta curve represents the cold-tip temperature as a function of time with a known applied heat load. The middle blue curve represents the cold tip temperature as a function of time with no applied load. Analysis of the relative warm-up rates allows for the parasitic heat load to be evaluated as a function of temperature, and the results can be compared to model predictions; the DUC expander was found to exhibit parasitic heat loads significantly higher than would be expected based on the design. The calculated, normalized parasitic is represented by the upper yellow curve in Figure 6, with values on the secondary axis. As can be seen, test results indicate that the presently-configured DUC suffers from parasitic conduction 2-3 times normally expected values. This effect was seen across a variety of cold-tip orientations, indicating that it is an actual conduction issue as opposed to an effect caused by convection in the pulse-tube (which is of particular concern when the expander is oriented cold-end up, but not so much of a concern when it is oriented cold-end down).

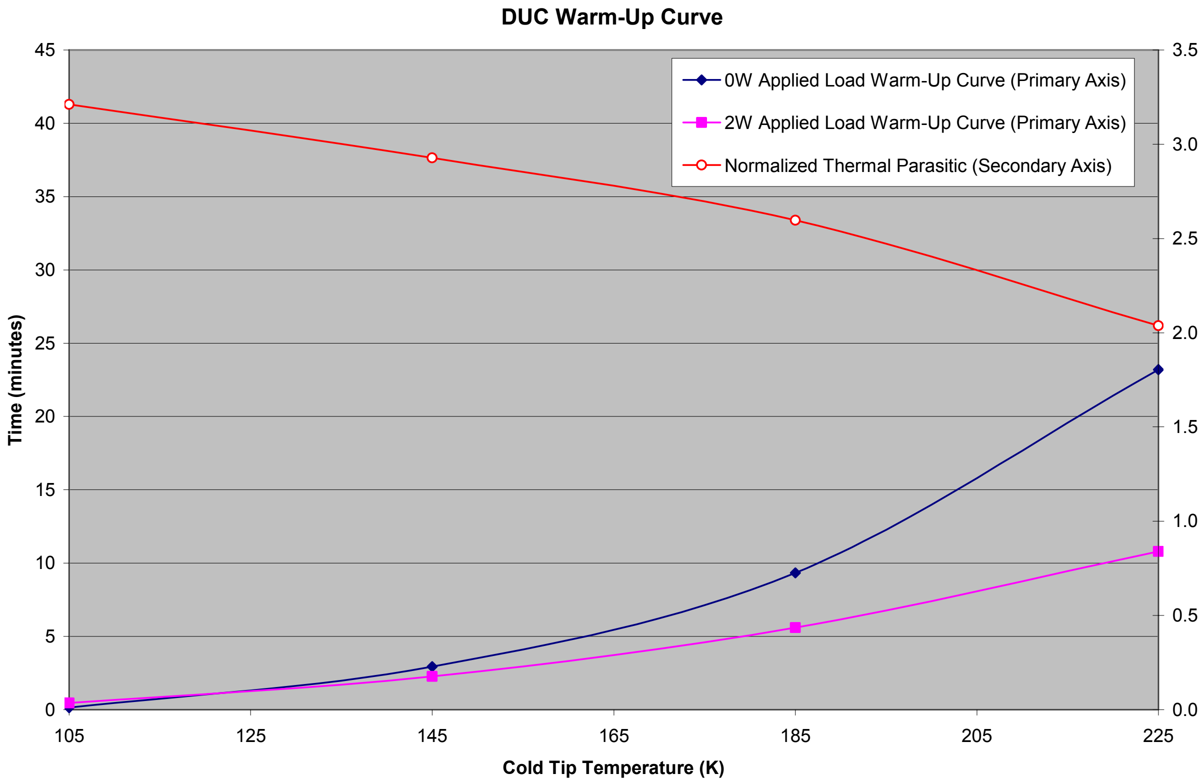


Fig. 6. DUC warm-up curves and calculate normalized parasitic. Warm-up curves on primary axis and normalized parasitic on secondary axis.

The two key pieces of information are therefore 1) increased flow resistance relative to model predictions and 2) higher than expected parasitic conduction. The thermodynamic models used by Raytheon have traditional been sufficiently accurate in the prediction of both of these quantities in similar pulse-tube systems, and so the search for resolution started at the main difference between this pulse-tube system and previous systems. Model accuracy can be affected by a variety of conditions such as unusual regenerator and pulse-tube aspect ratios, however this system was designed using proven practices in order to keep the model inside of its accurate range. No exotic or otherwise unusual materials were used in the design, and the inertance tube / surge volume system was of a typical design. One possibility therefore remained: the novel-construction regenerator. As mentioned in an above section, a new regenerator assembly technique was employed in an effort to greatly reduce the assembly time and variability associated with individually packing screens. Post-test analysis of similarly-constructed regenerators has shown that two effects associated with the construction technique are increased oscillating flow friction as well as increased conduction in the axial (warm-to-cold) direction. These are seemingly convenient results, in that they agree well with the performance characteristics that were observed.

The obvious path forward is to remove the novel regenerator and replace it with a traditional, well-understood packed-screen matrix. This work has already commenced, and a second expander module is being constructed specifically for the purpose. A final assessment of the DUC thermodynamic design will not be available until after the new expander is built and tested. The expectation is that the DUC will operate as predicted after rework.

3.3 LCSC-E Performance

After basic checkouts were performed, the brassboard LCSC-E was integrated into a suitable test setup and exercised in a series of tests of increasing complexity. A small amount of initial software debugging was required due to the changes involved in driving two independent motor drives, however the overall transition from constituent parts to usable brassboard hardware was straightforward. The first operational test of the hardware took place in Raytheon Tactical

Cryocooler laboratory facilities, and involved running the motor drives at moderately high-power into representative resistive loads (Linear cryocooler motors, in combination with typical cryocooler pneumatic systems, exhibit very resistive impedance). These tests were straightforward, and the LCSC-E motor drives performed at anticipated levels of efficiency (~85%) and drive resolution. Software performance was excellent, with all appropriate functionalities verified including those related to implementation of first order vibration cancellation.

A test was performed using a standard Raytheon tactical Stirling cryocooler of similar impedance to the DUC compressor, and the LCSC-E performed very well in all aspects; the drive circuitry was not affected by the reactive nature of the impedance during transients, and the temperature control loop performed well within the stated band of stability. The data gathered during this testing essentially completes the validation of the LCSC-E at the electronics module level.

The next step is to connect the LCSC-E to the actual DUC thermo-mechanical unit. This purpose of this test is threefold. First, verification is needed that the LCSC-E motor drive circuitry is compatible with the actual DUC motor impedance over a variety of operating conditions. The second objective of this test is to evaluate the performance of the LCSC-E temperature control loop during an actual cool down, a test that can obviously not be performed using resistive loads. The last aspect of the test is to evaluate the inherent and compensated vibration output of the DUC system; this test will take place on the cryocooler production laboratory dynamometer test station, allowing for direct measurement of 3-axis force and moment output. This testing is planned to commence in March 2007.

4. DUC PATH FORWARD

The majority of test activities described above were completed before the end of 2006. Initial results were generally very encouraging. The steps necessary to complete the flight-level development of the DUC system have been defined. These steps can be broken into two main groups: those required to complete brassboard development, and those that amount to design work to be performed after brassboard testing and before engineering model fabrication / build. The initial test results remain supportive of our performance projections as defined at the start of the development phase (Figure 7).

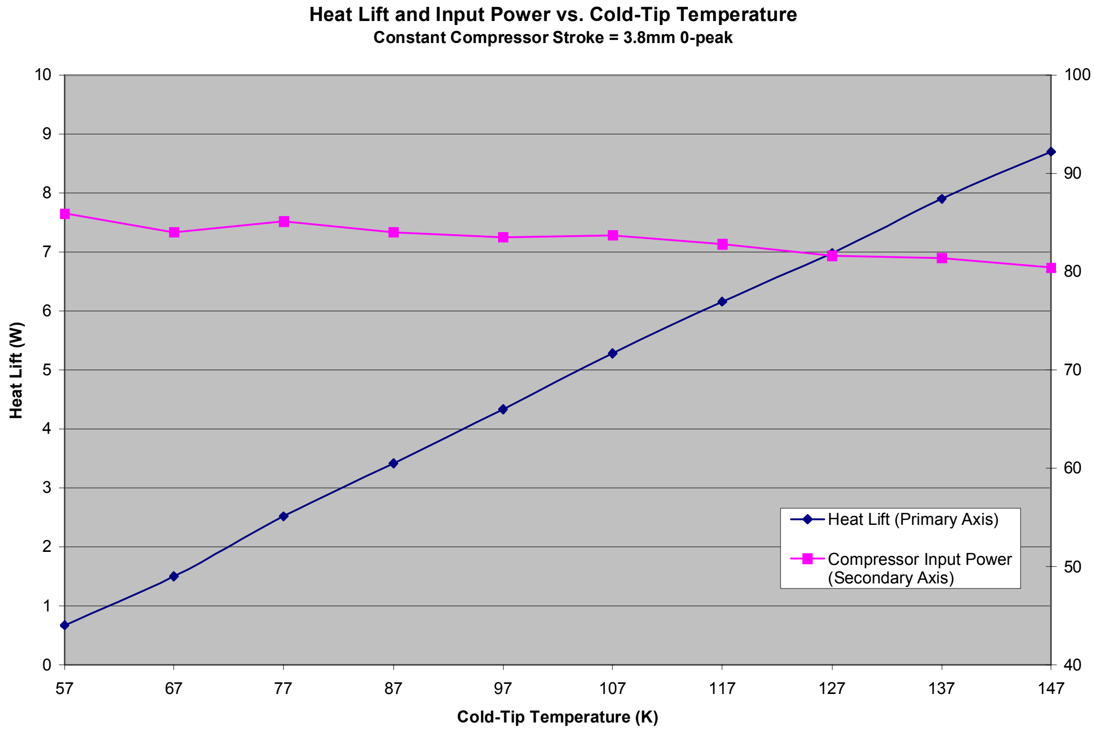


Fig. 7. Projected DUC heat lift and compressor input power as a function of cold-tip temperature.

4.1 Completion of Brassboard Phase

The first immediate issue to be addressed concerns the fabrication and build of a new expander module with an acceptable regenerator. To reduce risk and to definitively quantify the negative impact of the "defective" regenerator from the original build, the selected approach is to use a well-characterized packed-screen regenerator. This activity has already been funded, and purchase orders have been placed for the regenerator screens. With exception of these screens, all parts necessary to build a second expander module are in hand. Build of the expander is expected to proceed rapidly as many of the essential operations have already been completed, and it is hoped that performance of the unit can be verified by June 2007. An extensive set of thermodynamic and thermal tests are planned, including no-load temperature evaluation, load curve generation over a variety of operating ranges, and performance evaluation at a number of different heat-rejection temperatures. Testing will take place over several weeks time, after which a final evaluation can be performed and the expander design approved for maturation into a true flight design.

The second challenge to be addressed concerns characterizing the inherent and compensated exported vibration characteristics of the DUC. Vibration output has very little to do with thermodynamic performance, and so this test can be performed independently of the expander rebuild. All necessary hardware and test equipment is in hand, and the testing is presently scheduled for April 2007.

4.2 EM Design and Fabrication Issues

The remaining development steps for the flight-level DUC system are typical of the normal product evolution from brassboard to flight. The final design of a flight-packaged, radiation hard LCSCE is planned to commence late in 2007. The necessary circuit design and component selection work has already been performed, and a high-reliability but non radiation-hard version of the LCSC-E is presently being fabricated. This version of the LCSC-E, with minor amounts of chassis / packaging work, will likely be sufficient for a wide variety of terrestrial / tactical applications.

The only remaining TMU development task involves developing a volume and mass efficient packaging configuration for the inertance tube and surge volume. Several designs have been modeled and are being evaluated. The ideal design is one that can be adapted to work with any number of applications and platforms, and the choice of baseline configuration will likely depend heavily on the most prominent application being considered at the time of design finalization.

Having addressed the above issues, the DUC system will be a true flight-configured system that is ready to be taken through appropriate environmental testing. The sum of all required work can be performed in a relatively short amount of time, and it is Raytheon's hopes that this will occur before the end of 2007.

5. SUMMARY

Development of the DUC system began years ago with recognition that a considerable gap exists between the traditionally-space and traditionally-tactical markets. The DUC system was designed from the ground-up to fill this gap, and significant progress has been made. The remaining development and test activities are progressing rapidly. The DUC TMU is planned achieve TRL6 by the end of 2007 and the matching electronics by mid-2008.

ACKNOWLEDGMENTS

The TMU work described herein has been and is being supported by South Bay Science and Technology Corporation (SBSTC), with a significant amount of checkout and test work being completed by their test team. The cryocooler electronics work was in part funded by TechnoSoft, Inc., whose AML Product has been used by Raytheon for cryocooler design and analysis. Both the TMU and electronics efforts have been further supported with internal Raytheon product development funds.

The authors would like to express their sincere appreciation to Dr. Steven LeClair of MDA and Mr. Thomas Roberts of AFRL – Kirtland Air Force Base for their financial and programmatic support. We would like to extend our thanks to the members of the Raytheon Space Cryogenics Product Line and Jeff Cha of the Georgia Institute of Technology for his insight into various thermodynamic design issues.

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