

Low Cost Split Stirling Cryogenic Cooler For Aerospace Applications

A Veprik¹, S Riabzev¹, C Kirkconnell², J Freeman²

¹RICOR, En Harod Ihud, 18960, Israel

²Iris Technology Corporation, 2811 McGaw Avenue, Irvine, CA 92614-5835 USA

ABSTRACT

Cryogenic coolers are usually conjugated with sensitive electronics and sensors of military, commercial or scientific space payloads. The general requirements are high reliability and power efficiency, low vibration export, ability to survive launch vibration extremes and long-term exposure to space radiation.

A long standing paradigm of using exclusively space heritage derivatives of legendary "Oxford" cryocoolers featuring linear actuators, flexural bearings, contactless seals and active vibration cancellation is so far the best known practice aiming at delivering high reliability components for the critical and usually expensive space missions.

The recent "responsive space" tendency calls for developing mini, micro and even nano-satellites being able of delivering high definition infrared vision capabilities and meeting the tight budget constraints.

This activity has spurred attempts of adapting leading-edge tactical cryogenic coolers to meet the above space requirements. The authors are disclosing theoretical and practical aspects of developing a space qualified cryogenic refrigerator based on the Ricor model K527 tactical cooler and Iris Technology radiation hardened, low cost cryocooler electronics.

The initially targeted applications are cost-sensitive flight experiments, but should the results show promise, some long-life "traditional" cryocooler missions may well be satisfied by this approach.

Keywords: responsive space, tactical split Stirling linear cooler, vibration, reliability.

INTRODUCTION

Development and deployment of the legendary "Oxford" split Stirling cryogenic cooler was a major breakthrough in space refrigeration. This success relied on pioneering the concepts of linear electro-dynamic actuation, flexural bearings, contactless clearance seals, motion sensors, independent active "magnitude-phase" motion control in both compressor and expander units along with active vibration cancellation. This compact and reliable cooler fast replaced then-traditional passive radiators, bulky liquid or solid cryogenes and eventually enabled a massive use of affordable mechanical cryogenic refrigeration in space [1-3].

Since then several generations of cryogenic coolers have been derived from the original "Oxford" legacy. This effort has produced highly reliable cryogenic coolers capable of delivering more than 10 years of continuous cryogenic refrigeration for a variety of critical space missions.

Cost saving has always been an objective, but it was always thought of as a secondary issue, provided the above objectives were met [2, 4, 7-9]. Because of the inherent design and manufacturing complexity, recurring costs were typically in the range of about \$2M per unit.

It also appeared that there is no way to prove the space cryocooler reliability using the ground Highly Accelerated Life and Stress Screen test techniques, normally relying on product exposure to a combination of harsh shock/vibration and temperature extremes. Since such conditions simply do not occur in space, it has therefore been widely accepted that such approaches are not capable of invoking typical failure mechanisms and are, therefore, not applicable to space cryogenic refrigerators [5, 6]. The result is that mission designers usually prefer using cryogenic coolers having already proven "space heritage," thus making it very difficult for alternative, probably more cost effective but less mature technologies a chance to be adopted for real space missions. Over time, this long-standing practice of only using equipment with proven "space heritage" has likely resulted in the use of outdated, oversized, overweight and overpriced cryogenic technologies.

The recent "responsive space" trend called for developing mini, micro and even nano-satellites for budget constrained missions and has prompted attempts to find a middle ground between the leading-edge tactical cryogenic coolers and traditional space coolers to optimally meet space requirements with a particular emphasis on low cost. These ideas were pioneered by Raytheon stepping forward with the concept of a compact, lightweight and cost saving space cryocooler. For the Raytheon approach described in [4,8], the "traditional" processor-intensive approach to the design of control/drive electronics has been abandoned in favor of radiation hardening of existing high reliability tactical electronics designs. This merging of space and tactical refrigeration technologies, heretofore seen as completely distinct, was novel. The above efforts resulted in a space cryocooler architecture that is projected to yield a 10-fold decrease in price for typical small lot builds (3 to 5 cryocooler systems).

In parallel with the Raytheon efforts, improvements have recently been made in split linear tactical cryogenic cooler technology. This has resulted in much improved reliability and raised significantly the level of confidence throughout the cryogenics community. Basically, those improvements involved the implementation of the above explained "contactless" design approach relying on compact flexural bearings. Further advances in the development of "moving magnet" linear actuators allowed for removing the driving coil from the compressor interior. This advancement eliminated failures originating from flying leads and gas leaks through electrical feedthroughs, along with contamination produced by wire varnish and soldering residuals. In an attempt to eliminate working agent leaks through the crushed metal seals, an all-welded approach was also adopted throughout the industry.

The above-mentioned trend toward developing mini and micro satellites opens up new business opportunities in the space cryocooler marketplace. Namely, order quantities are expected to be larger, required cold tip temperatures higher and needed heat lifts lower [10]. This is, therefore, a combination of temperature regimes and heat loads that has long been the province of tactical cryocoolers, making the adaptation of a tactical cryocooler to space applications, such as is proposed herein, an attractive pursuit.

The initially target is the "Operationally Responsive Space" programs, which may well be satisfied by this approach.

DESIGN PRINCIPLES OF RICOR K527 CRYOGENIC COOLER

Ricor recently reported on the successful development and fielding of the novel model K527 microminiature long-life split Stirling linear cryogenic cooler [14-18] for use in a wide range of portable hand held and gyrostabilized infrared imagers. Technical comparison [16] to coolers with the same cooling power at 80K@23°C indicates that this cooler is the smallest, lightest and most efficient model over the entire range.

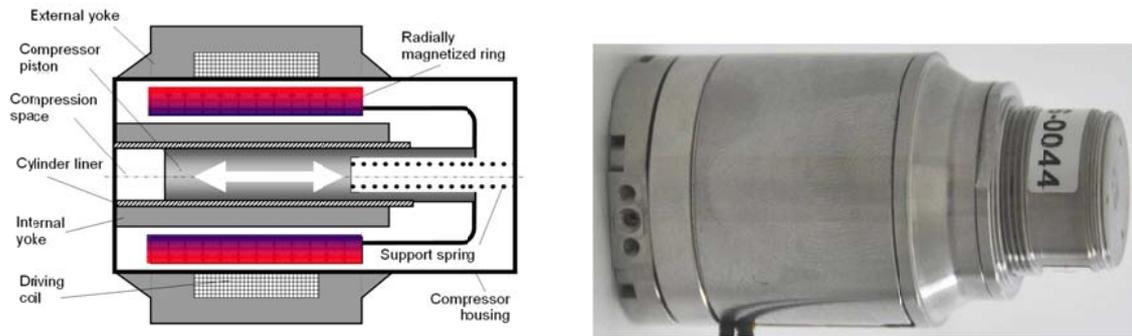


Figure 1. Schematics and external layout of a linear compressor

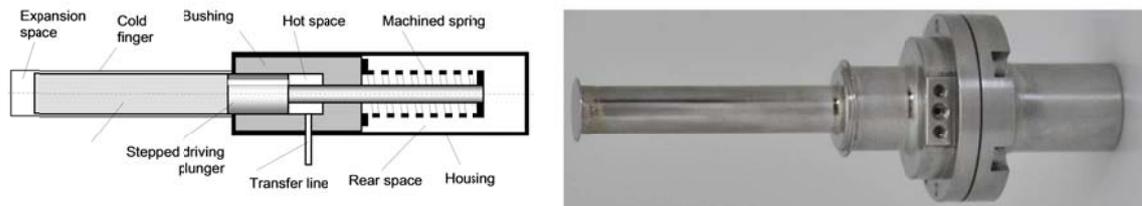


Figure 2. Schematic and external layout of a pneumatically driven expander

Because of the tight constraints imposed primarily on weight, price and cooling performance, the design of this cooler largely abandons the above described space-heritage features (flexural bearings, contactless clearance seals in dual-piston compressor, etc) in favor of mechanical simplicity.

Figure 1 shows the schematics and the external layout of the "moving magnet", resonant, single-piston compressor featuring a very light "magnet-piston" assembly guided by a contact seal made in the form of tightly matched piston-cylinder liners manufactured of tribological, wear resistant material.

Similar principles were applied to the design of a pneumatically actuated resonant "spring-mass" expander featuring contact clearance seals in the form of tightly matched bushing/plunger made of the above tribological, wear resistant material.

Figure 2 shows the external layout and the schematics of the pneumatically driven resonant spring-mass expander of the K527 cryogenic cooler [16].

The feasibility of this approach was proven recently in the course of an accelerated life test (including temperature extremes) [19] where a similar cooler lasted in excess of 45,000 hours. The post-test examination revealed that the geometry of the above mentioned critical components (i.e., clearance seals in compressor and expander) remained within manufacturing tolerances; no visible wear was observed.

As to the compressor induced wideband vibration export, reduction in the weight of the moving mass assembly was critical. Further, application of the combined principle of low frequency vibration mounting and tuned dynamic counterbalancing, as detailed in [15, 19] produced the effect of passive wideband vibration cancellation adequate for the most stringent space requirements.

THERMODYNAMIC DESIGN OF K527 CRYOGENIC COOLER

A computer modeling and optimization of geometric and functional parameters has been completed at the initial phase of the K527 Stirling cryocooler design. The baseline configuration was chosen with respect to the potential high efficiency, compactness, robustness and low cost. This cryogenic cooler was optimized to operate at conditions typical for the 95K hand-held IR imager, as explained in [16]. In order to perform optimally under typical space conditions, some

re-optimization might be needed. The major difference is that the typical reject temperature is essentially lower, say 0°C, and cold tip temperature might be lower, say 77K.

The working point for the cooler optimization was defined so as to produce total heat lift of 300mW@77K@0°C with a minimum power consumption. For the purpose of cooler redundancy and reasonably fast cool down times, the maximum available heat lift was specified to be at least 750mW@77K@0°C.

The K527 cryocooler modeling was performed in a SAGE™ [21] environment, relying on the above-defined specifications and baseline configuration. It was predicted, in particular, that at the above working point the power consumption would be 5.2W AC.

EXPERIMENTAL MAPPING

Cryocooler performance: theoretical prediction versus experiment

Detailed performance mapping of the K527 cryogenic cooler at different reject temperatures typical of aerospace applications, namely: -20°C, 0°C and +20°C, was performed in the temperature regulation mode (77K). The self-heatload typical for the used simulation Dewar is 130mW@77K@20°C. Figure 3 shows the experimentally obtained dependencies of the power consumption on the total heat load at different reject temperatures. The self-heatload typical for the simulation Dewar is 130mW@77K@20°C.

Figure 3 shows the experimentally obtained dependencies of the power consumption on the total heat load at different reject temperatures. Superimposed for reference are the outcomes of theoretical mapping obtained using SAGE software.

From Figure 3, the experimental and theoretical data are in fair agreement, especially at low heat loads (below 300mW). This satisfactory match indicates the suitability of the model to guide for further optimization of the cooler for different working conditions and for possible up-scaling of the K527 cryocooler for higher power applications.

The deviations observed at high powers may be explained by irreversible compression losses, insufficient heat rejection from the compression chamber, and oversaturation of the return iron. This is an area of ongoing investigation.

Figure 4 shows the dependencies of the power consumption (a), overall cryocooler COP (b) and compressor acoustic COP (c) on the heat lift at different reject temperatures. In particular, as seen in Figure 4.a, the cryocooler is capable of heat lifting of up to 1000mW@77K@20°C. The cooler COP reaches an impressive maximum of 5% at approximately 300mW of total heat lift, which is the representative working point, as seen in Figure 4.b. It is worth noting that such high value of the cooler COP (equivalent to 14% of Carnot efficiency) is typical of the best examples of rotary integral coolers.

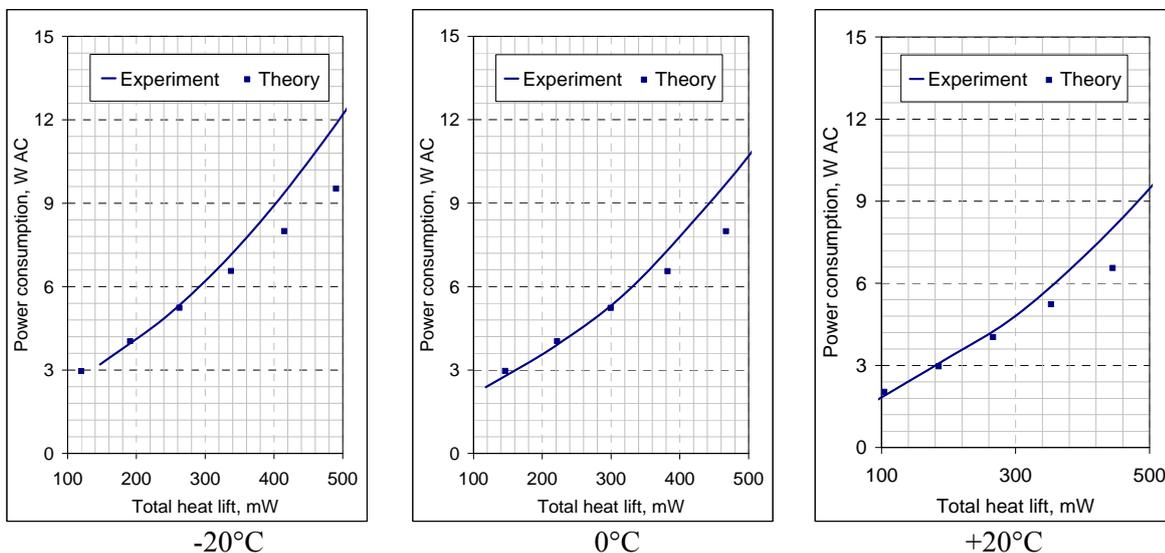


Figure 3. Power consumption as a function of total heat load at different reject temperatures.

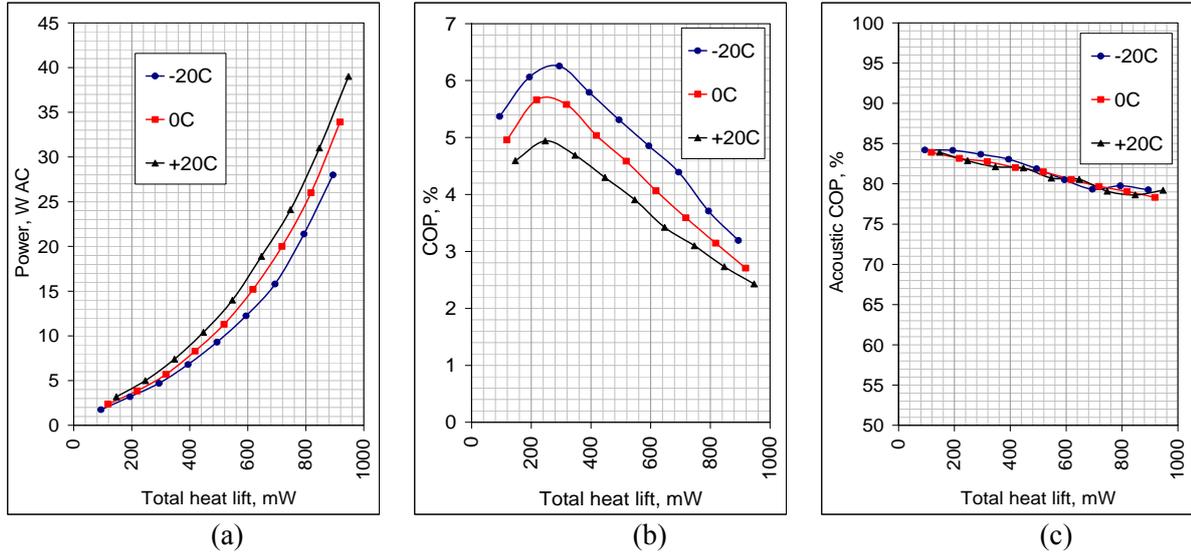


Figure 4. Cryocooler performance at different heat loads and reject temperatures.

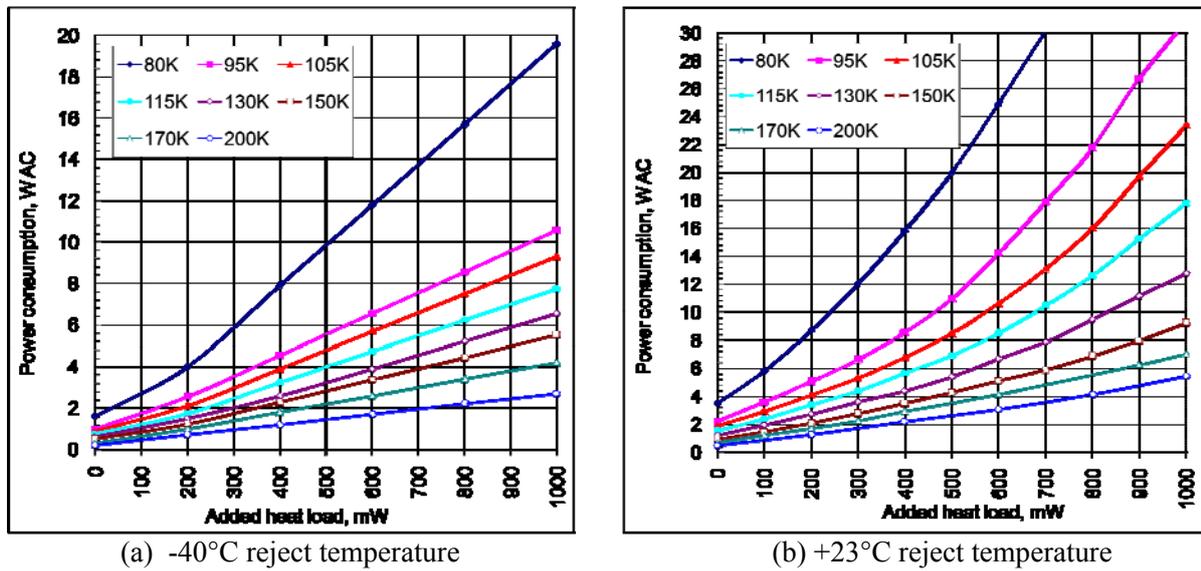


Figure 5. Cryocooler mapping at different temperatures, heatloads and reject temperatures

Further, the acoustic COP of compressor was calculated as a ratio of shaft and electrical powers. In Figure 4.c, the acoustic COP is well in excess of 80% over the entire range of working conditions, which can be considered as an excellent outcome, especially for such a miniature compressor. In [22], for example, the authors report on 92% COP observed in a much larger compressor working in the range 50-100W.

As it was mentioned above, the new generation of mini and micro satellites will use different detectors and electronics, most probably operating at higher temperatures and lower heat loads. The K527 cryogenic cooler offers a wide variety of options for such forthcoming applications.

Figure 5 shows the mapping of typical cooler performance at different cold tip temperatures ranging from 80K to 200K with added heat load ranging up to 1000mW at two reject temperatures: -40°C (a) and +23°C (b).

CONTROL/DRIVE ELECTRONICS

The Low Cost Cryocooler Electronics (LCCE), being developed by Iris Technology Corporation, is focused on providing space-qualified cryocooler electronics for cost-sensitive payloads and missions. A preliminary conceptual design for the LCCE is shown in Figure 6.

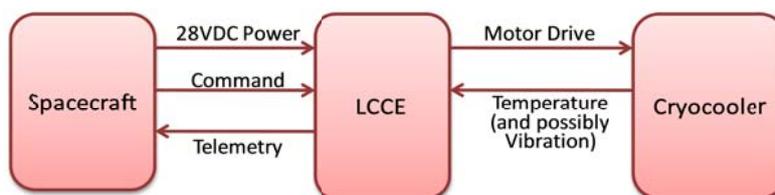
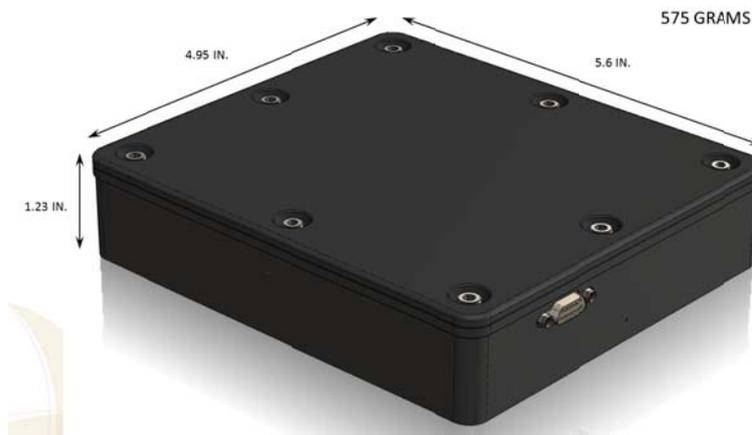


FIGURE 7. LCCE basic architecture.

LCCE is unique from any other cryocooler electronics available in that it will provide a fully space-qualified, radiation hard to more than 300 krad total ionizing dose solution at an affordable price. Since LCCE has been architected from the bottom up with the eventual recurring cost as a priority, the expected cost of the LCCE in small lot production is roughly 1/10th that of “traditional” space cryocooler electronics. This has been accomplished primarily through designing out complexity that is not required for many missions, and in so doing achieving tremendous reduction in radiation-hard parts cost and software. The LCCE, in short, provides tactical cooler electronics-like function in a space-qualified, radiation-hardened package.

The basic architecture for the LCCE is described in Figure 7. The spacecraft powers the LCCE directly off a 28 VDC bus; higher bus voltages are permissible with minor changes to the LCCE and/or the addition of a buck regulator. The LCCE accommodates a simple input command stream (on/off, temperature set point, operating frequency) and provides a comparably simple output telemetry stream (cold tip temperature, case temperature, motor voltage, etc.). The LCCE drives the cryocooler to the commanded set-point automatically, following software-programmable “soft start” power ramp, using the measured and indicated cold tip temperature to close the control loop. It is anticipated for some applications that additional capability in the cryocooler electronics may be desired, such as filtering of the low (drive) frequency current ripple, additional command and telemetry capability, additional commandable modes, etc. For these applications, an Advanced Module containing a programmable FPGA with a soft core processor may be added to the front end.

The LCCE circuits are packaged within a conduction-cooled, vacuum compatible housing.

During Phase I of a recently-completed United States Air Force Program, a brassboard LCCE circuit was designed and built using commercial off the shelf parts as an initial proof of concept and to serve as a test bed for the control code development.

Initial testing of the LCCE has been recently commenced. The first step was to assess the quality of sinusoidal drive signal, which was shown to be very clean with less than 0.03% total harmonic distortion. Amplitude control and sub-milliHz frequency resolution were successfully demonstrated.

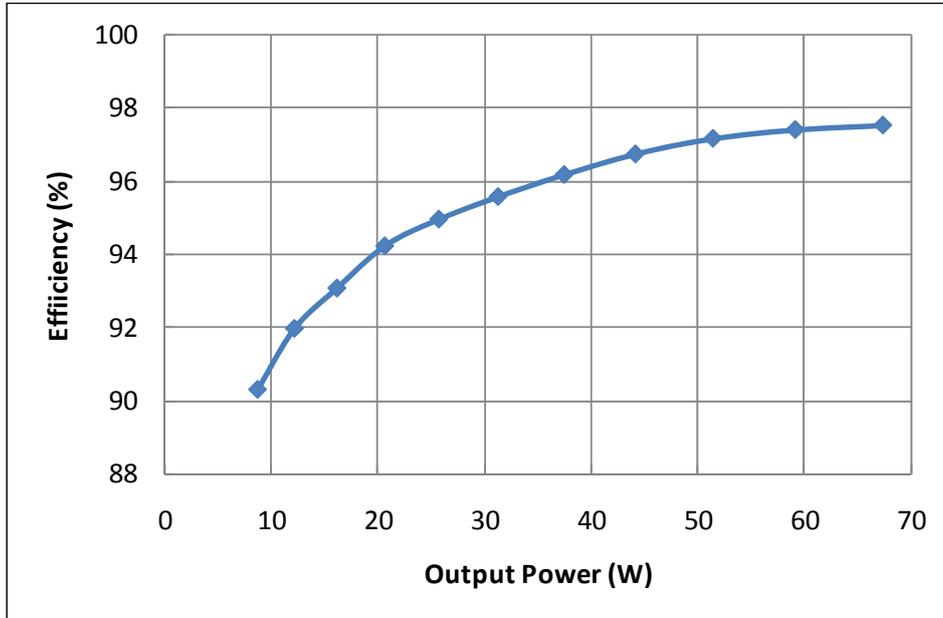


Figure 8. LCCE Motor drive efficiency

The LCCE is designed to provide in excess of 90% DC-to-AC conversion efficiency from 10 W to 100 W output power with less than 1W standby tare dissipation. The measured power conversion efficiency against a constant 10-ohm resistive load at 28 VDC input reveals that the LCCE works optimally at output powers above 50 W, see Figure 8. The LCCE as presently designed is evidently oversized for the K527. The authors expect to develop a slightly modified version optimized for lower power to meet a greater than 95% efficiency target over the expected K527 range of operation.

With basic operation demonstrated, the LCCE brassboard was integrated with the K527 cryocooler for a preliminary checkout, see Figure 9. During test, the LCCE unit was powered from an external DC power supply. Average input power varied from 25W max during cool down to 3W at the no-load control temperature of 92.2K, where the nominal temperature stability of approximately +/- 50 mK was achieved, as seen in Figure 10. Given that the LCCE as designed is nominally sized for a 100 W input power class cryocooler, the demonstrated control of the K527, achieved with no modification, is remarkable.

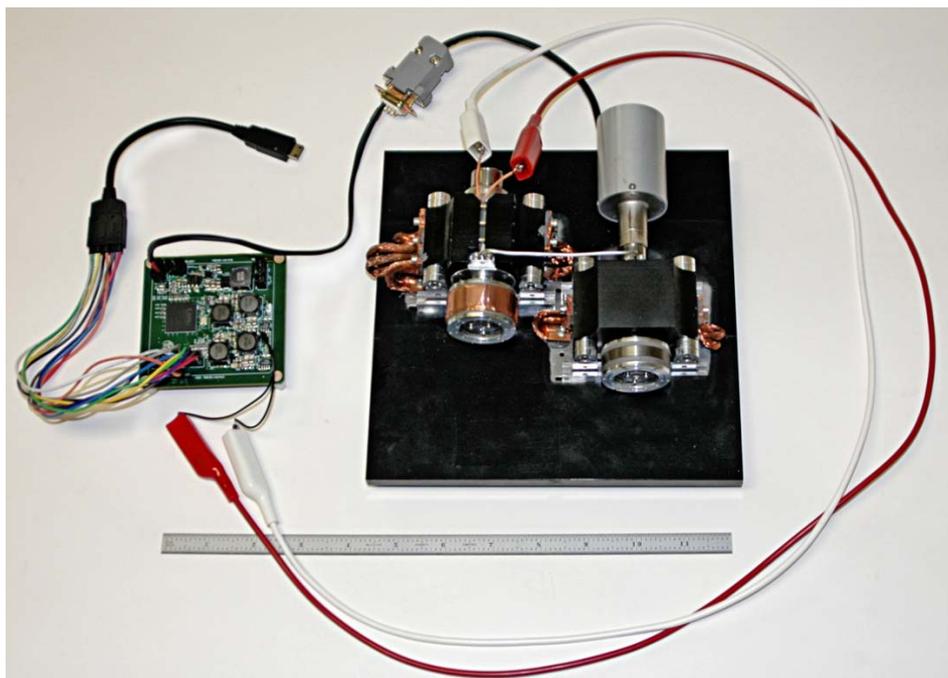


Figure 9. Iris LCCE brassboard integrated with the Ricor 527 technology demonstrator

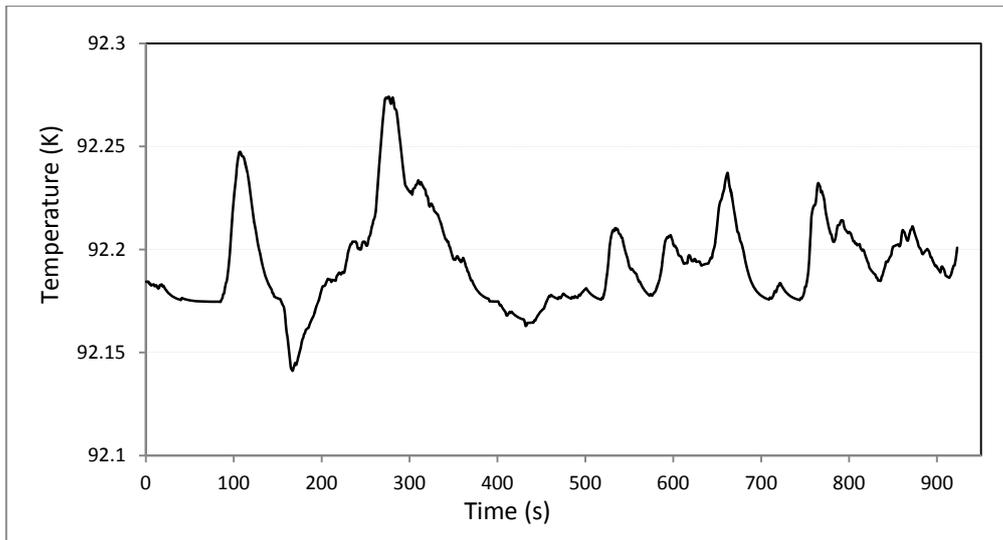


Figure 10. Typical temperature stability

The above describes the progress made during Phase I of the sponsoring USAF Program. Phase II was awarded in March 2011. During Phase II, a radiation hard version of the LCCE will be designed, fabricated, tested and qualified for spaceflight operations.

Recent progress has been reported in [23], where in a series of experiments a particular cryocooler control electronics was shown to successfully drive several very different types of cryocoolers and simulated cryocooler loads, including a space pulse tube cryocooler and long life tactical Stirling coolers.

REFERENCES

1. Bradshaw, T. W., Delderfield, J., Werrett, S. T. and Davey, G., "Performance of the Oxford miniature Stirling cycle refrigerator", *Advances in Cryogenic Engineering*, 31, (1985), pp. 801-809
2. Davey, G. and Orłowska, A. H., "Miniature Stirling cycle cooler", *Cryogenics* 27 (1987), pp. 148-151
3. Werret S. T., Peskett G. D., Davey G., Bradshaw T. W. and Delderfield J., "Development of a small Stirling cycle cooler for spaceflight applications", *Adv. Cryog. Eng.* 31, (1986), pp. 791-799
4. Kirkconnell, C., Pruitt, G., Price, K., Ross, B. and Derossett, W., "Low cost, lightweight space cryocoolers", *Cryocoolers* 12, (2003), pp. 183 - 190
5. Ross, R. G., "Cryocooler reliability and redundancy considerations for long-life space missions", *Cryocoolers* 11, (2000), pp. 637 - 648
6. Marquardt, E. D., "Cryocooler reliability issues for space applications", *Cryogenics*, 41, (2002), pp. 845-849
7. Hon, R., Kesler, C. and Sigurdson, D., "Integrated testing of a complete low cost space cryocooler system", *Cryocoolers* 15, (2009), pp. 125-132
8. Kirkconnell, C. S. and Ross, B. A., "Raytheon dual-use long life cryocooler", *Proc. of the SPIE*, 5783, (2005), pp. 169-177
9. Donabedian, M., *Spacecraft Thermal Control Handbook, Volume 2 - Cryogenics*, American Institute of Aeronautics and Astronautics/Aerospace Press, (2003), p. 641
10. Pettyjohn, E., "Compact cryocoolers for military microsatellite applications", *Cryocoolers* 16 (2011), pp. 709 - 713
11. Groep, W., Mullie, J., Willems, D., Wordragen, F. and Benchop, T., "The development of a new generation of miniature long life linear coolers", *Cryocoolers* 16, (2010), pp. 111-119
12. Rühlich, I., Wiedmann, T., Mai, M. and Rosenhagen C., "Flexure bearing compressor in the one-watt linear (OWL) envelope", (2007), *Proc. SPIE* 6542, 65422I
13. Meijers, M., Benschop, A. and Mullié, J., "High reliability coolers under development at Signaal-USFA", *Cryocoolers* 11, (2002), pp. 111-118.
14. Veprik, A., Vilenchik, H., Riabzev, S., and Pundak, N., "Microminiature linear split Stirling cryogenic cooler for portable infrared imagers", (2007), *Proc. SPIE* 6542, 65422F

15. Veprík, A., Zechtzer, S., Vilenchik, H., and Pundak, N., “Split Stirling linear cryogenic cooler for high-temperature infrared sensors”, *Proc. SPIE* (2009), 7298, 729816
16. Veprík, A., Zechtzer S. and Pundak N., “Split Stirling linear cryogenic cooler for a new generation of high temperature infrared imagers”, (2010), *Proc. SPIE* 7660, 76602K.
17. Veprík, A., Vilenchik, H., Riabzev, S., and Pundak, N., “Microminiature linear split stirling cryogenic cooler for portable infrared applications”, (2006), *Cryocoolers 14*, pp. 105-114
18. Veprík, A., Riabzev, S., Zechtzer S., and Pundak, N., “Compact linear split Stirling cryogenic cooler for high temperature infrared imagers”, *Cryocoolers 16*, (2010), pp. 121-132
19. Nachman, I., Veprík, A., and Pundak, N., “Life test result of Ricor K529N 1W linear cryocooler”, *Proc. SPIE* (2007), 6542, 65422G
20. Veprík, A., Babitsky, V., Pundak, N. and Riabzev, S., “Vibration control of linear split Stirling cryogenic cooler for airborne infrared application”, *Journal of Shock and Vibration* 7(6), (2000), pp. 363-379
21. Gedeon D., *Sage User’s Guide, Stirling, Pulse-Tube and Low-T Cooler Model Classes*, Athens, (2010), p.325
22. Redlich, R., Unger, R., and van der Walt, N., “Linear compressors: motor configuration, modulation and systems”, *International Compressor Engineering Conference*, (1996).
23. Freeman, J.J., Murphy, J.B. and Kirkconnell, C.S., “Experimental demonstration of cryocooler electronics with multiple mechanical cryocooler types”, *Proceedings of SPIE, Defense, Security and Sensing* (2012), in print.