Sunpower Cryotel™ Cryocoolers and Pulse Tube Cryocoolers

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Abstract. This paper focuses on the continuing expansion of Sunpower's CryoTel™ family of cryocoolers (currently the CryoTel™ CT, CryoTel™ MT, CryoTel™ LT, and CryoTel™ GT), and on Sunpower's various pulse tube development programs. The CryoTel™ coolers are commercially produced, linear, free-piston, integral Stirling cryocoolers designed for high efficiency and power density, low mass and long life. These crycoolers can be modulated and operate efficiently over a wide range of heat loads and ambient conditions. Sunpower has combined its commercially available linear compressor technology with Gedeon Associates' pulse tube expertise to develop single- and multi-stage pulse tube cryocoolers under two SBIR programs from NASA Goddard Space Flight Center (GSFC). Sunpower is also currently developing a single-stage pulse tube for a commercial customer. Within these various pulse tube programs, Sunpower has demonstrated inline, u-tube, and coaxial single-stage designs as well as two-stage and three-stage configurations. Test results for all of the CryoTel™ coolers and the coaxial pulse tube cooler are reported.

Keywords: Stirling, crycooler, CryoTel™, pulse tubes.
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INTRODUCTION

Sunpower is a research, development, and manufacturing company specializing in the development of free-piston linear machines including Stirling engines, Stirling coolers, pulse tube cryocoolers, and linear compressors. Sunpower also has small to medium volume manufacturing capabilities. This paper will focus on free-piston Stirling cryocoolers and pulse tube cryocoolers.

The CryoTel™ coolers are linear, free-piston, integral Stirling cryocoolers that make use of gas bearing technology for non-contact operation and a Digital Signal Processor (DSP) based controller for closed-loop temperature control. The CryoTel™ and controller can be configured to operate across a wide range of input voltages including 24Vdc to 240Vac. A summary of the features of Sunpower's CryoTel™ family of free-piston Stirling cryocoolers is shown in Table 1.

Sunpower has combined its commercially available linear compressor and cryocooler technology with Gedeon Associates' leadership in pulse tube design and analysis to develop single and multi-stage pulse tube cryocoolers under two SBIR programs from NASA Goddard Space Flight Center (GSFC). Sunpower is also currently developing a single-stage pulse tube for a commercial customer. Within these program parameters, Sunpower has demonstrated inline, u-tube, and coaxial single-stage designs as well as two-stage and three-stage configurations. These pulse tubes have been optimized for cold end temperatures ranging from 10K to 80K and operating frequencies from 30Hz to 70Hz.

STIRLING CRYOCOOLERS

Sunpower started the development of small scale Stirling coolers in the early 1990's with the introduction of the M223 and the M77 [1]. Following the success of these coolers in various applications for NASA and for residential refrigeration applications, Sunpower introduced a manufacturable version of a cryocooler known as the M87. The M87 was produced in limited quantities at Sunpower's on-site manufacturing facility to serve as the heart of an oxygen liquefaction device invented by In-X, a medical products company.

To fill a need in the industrial and telecommunication industry, Sunpower built on the new M87 design and cryocooler manufacturing capabilities, partnering with LG Electronics to introduce the CryoTel™ family of cryocoolers, which initially included the CT and the MT. The CT and MT

are now manufacturable designs which achieve similar size and input power[2].

TABLE 1. Summary of Features for the CryoTel™ CT, MT, Lt and GT.

	CT	MT	LT	GT
Mass	3.1 kg	2.0 kg	3.1 kg	3.1 kg
Lift	10.0 W at 77 K	5.0W at 77 K	1.5 W at 25.5 K	15.0 W at 77 K
Operating Temperature	35˚ C	35˚ C	32˚ C	35˚ C
Input Power	160 W	80 W	235 W	240 W

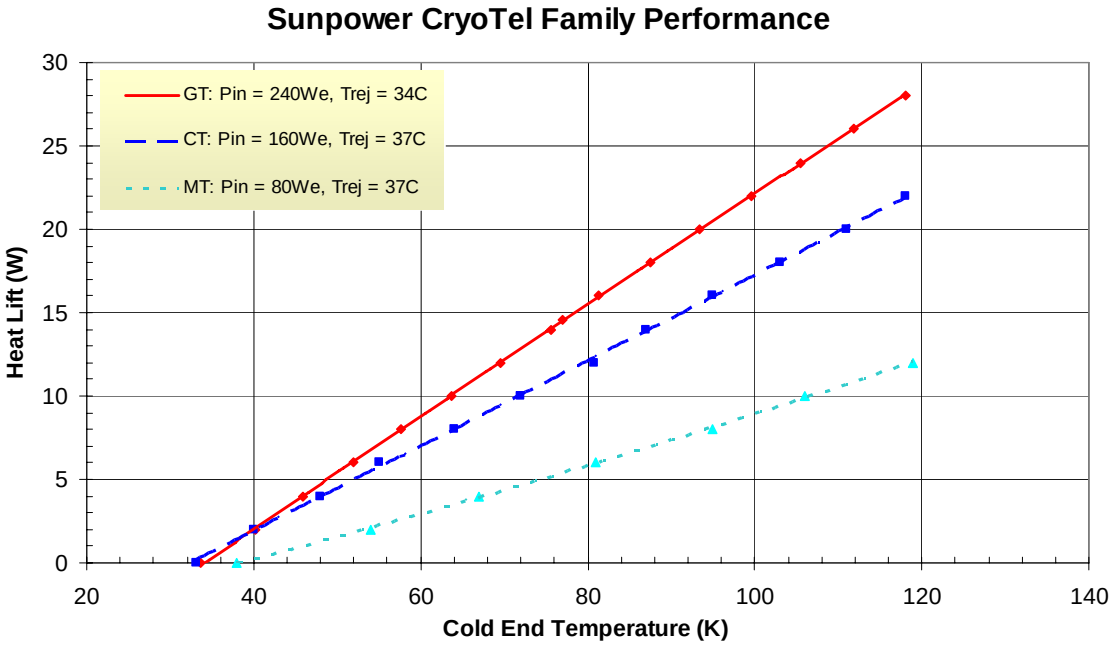

FIGURE 1. Performance Curves For CryoTel™ Gt, CT, and MT.

The CryoTel™ LT has a mass and footprint almost identical to the CT but is designed to reach a much lower no-load temperature with an increase in input power. In 2003, following the commercial success of the CryoTel™ CT as a high-performance, low cost cryocooler, Sunpower was awarded an SBIR contract to modify the CT to achieve a no load temperature of 20K with a single-stage Stirling cryocooler, based on a proven, commercially available design. The resulting cryocooler, designated the CryoTel™ LT, ultimately achieved a no load temperature of 21.7K and provided 1.5W of cooling at 25.5K with 235W of input power.

Development of the LT required CT design modifications including increasing the power capability of the motor and optimizing other components for performance in the 20K to 25K range. In addition to these low temperature design changes, Sunpower provided the LT with a new linear motor which fits into the CT package but can absorb much more input power. The linear motor modifications were the basis for the latest model: the CryoTel™ GT, which mimics the CT in appearance but can provide up to 50% more cooling power with a 50% increase in input power. The CryoTel™ GT is a higher power version of the CryoTel™ CT with identical mass and volume.

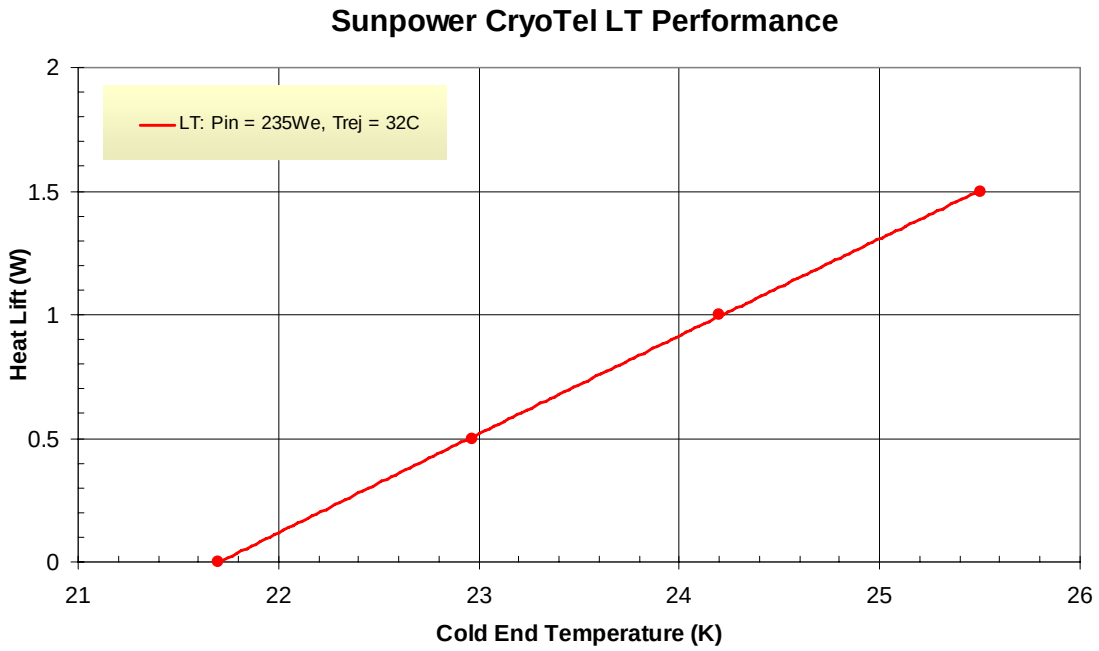

FIGURE 2. Performance Curve For Low Temperature CryoTel™ LT.

PULSE TUBE CRYOCOOLERS

Pulse tube cryocoolers (PTCs) are another solution to low temperature cooling. For some customers and some applications, the PTC has features that make it more desirable than a free-piston Stirling cryocooler.

In addition to the development of the LT and GT, Sunpower also teamed with Gedeon Associates to design and build single- and multi- stage pulse-tube cryocoolers. In January of 2004, Sunpower completed a NASA SBIR-funded development program to design, build, and test a three-stage PTC for cooling below 10K. Sunpower thus gained experience in building robust, low temperature regenerators and exposure to advanced joining and processing methods for multi-stage cold assemblies.

Sunpower is currently building prototypes of a newly designed, coaxial, single-stage PTC as part of a commercially funded development program. This new model of PTC introduces proprietary technology that eliminates the need for a buffer volume resulting in substantial savings in size and mass. The pressure wave generator for this PTC is a dual-opposed linear compressor built using components from Sunpower's commercially available CryoTel™ MT free-piston Stirling cryocooler. The dual-opposed configuration minimizes the overall vibration from the PTC. Basing the design on the CryoTel™ MT components allows access to mature, readily available parts, which shortens the design cycle and increases the confidence in performance and reliability. This configuration also reduces the orientation-dependent performance variations intrinsic to all PTC technology.

CONFIGURATION

Sunpower's Stirling coolers and engines are all beta, integral free-piston linear machines. The piston is oscillates about the center of a moving permanent magnet linear motor[3]. The CryoTel™ family of coolers are free-piston machines with no mechanical spring on the piston. Such a configuration simplifies the mechanical arrangement, allowing ease of assembly and reduction of potential side loads. When at rest, the piston can be located anywhere along its cylinder. The controller and the linear motor start-up sequence[4] move the piston to the vicinity of the pneumatic dynamic centering system.

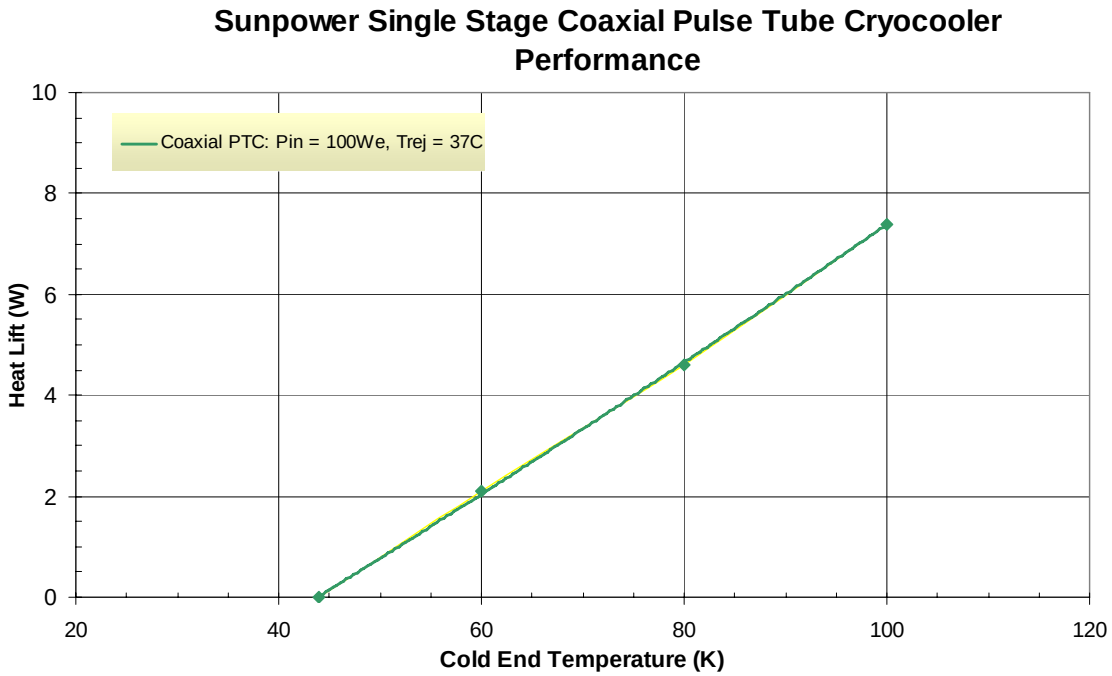

FIGURE 3. Performance Curve For Sunpower Single-Stage Coaxial PTC.

Sunpower's cryocoolers and PTCs use gas bearings to separate the moving parts and maintain non-contact operation. The gas bearings are activated within a few cycles of operation. The moving parts are coated with a dry bearing pair combination, with which we have extensive experience, to prevent friction related failures at startup.

The linear motors used in Sunpower's machines are Redlich-type moving magnet motors. The motor design is robust and well proven and is used in a number of commercial applications including cryocoolers. These motors are known for high efficiency and high power density due to various advantages:

- The motor winding has no end turns or dead turns. All of the copper used in the coil carries current that induces flux in the magnetic circuit, either reducing weight or increasing efficiency.
- The magnets never move beyond the pole faces, minimizing fringing effects and iron losses.
- There is zero mean lamination flux, which minimizes the amount of lamination material needed for a given motor design, reducing the overall weight of the motor.

One noteworthy difference between Sunpower's Stirling coolers and the PTC prototypes built and tested in our facility is that the PTCs do not have a displacer. The piston is the only moving part. Eliminating the displacer reduces the complexity of the piston and allows us to more readily use a mechanical spring in combination with a gas spring to resonate the piston. Using a mechanical spring has the advantage of establishing a known mean position for the piston when it is at rest.

The controllers for the CryoTel™ family of coolers and for the various PTCs are DSP-based and use reconstruction[5] to measure and control the piston amplitude. The Sunpower controllers provide closed loop temperature control with an accuracy of +/-0.1K. The controllers also have a serial communication port for monitoring and setting variables such as cold end temperature.

LIFE AND RELIABILITY

Many commercial applications for cryocoolers require a five year operating life. Due to the non-contact operation of Sunpower's cryocoolers, there are no friction-based failure modes. Each cooler typically has three planar springs and a check valve, each of which is designed for infinite life based on the fatigue properties of the respective materials. The measured rate of helium leaking through the pressure vessel of each cryocooler is low enough so that it will take approximately 100 years before the reduction of helium charge pressure will result in a measurable reduction in cooling performance. The result is that Sunpower's free-piston Stirling cryocoolers have the potential for extremely long mechanical operating life.

Evidence supports the long life potential of Sunpower's cryocoolers. An M223 high temperature Stirling cooler has been running at Sunpower continuously without maintenance since June of 1995, for a total of more than 84,000 hours. A Sunpower M77 cryocooler has been cooling the main sensor on the RHESSI solar flare satellite in space since February of 2002. That same M77 operated on the ground at NASA Goddard Space Flight Center for 14,000 hours prior to launch. One of Sunpower's cryocooler licensees has built and deployed between 3000 and 4000 machines, accumulating more than 55 million hours. This licensee advertises an MTBF of approximately 800,000 hours.

Since January of 2001, cryocoolers on test at Sunpower have accumulated more than 800,000 hours of operation. The most hours accumulated by a single cryocooler during this period is 34,000 hours. All cryocooler operating hours accumulated at Sunpower include the control electronics. These cryocoolers are periodically removed from the long term test rig so that the cooling capability of each machine can be individually measured on a calibrated performance test rig. A number of these tests have been done on CryoTel™ CTs during the past eighteen months. Figure 4 shows the average cooling power of all of the machines tested during each test interval, along with bars that represent the 95% confidence levels for all of the coolers tested. Using this statistical technique to show the performance drop-off versus time gives a worst case lift reduction of less than 0.5W (< 5%) for the eighteen month period.

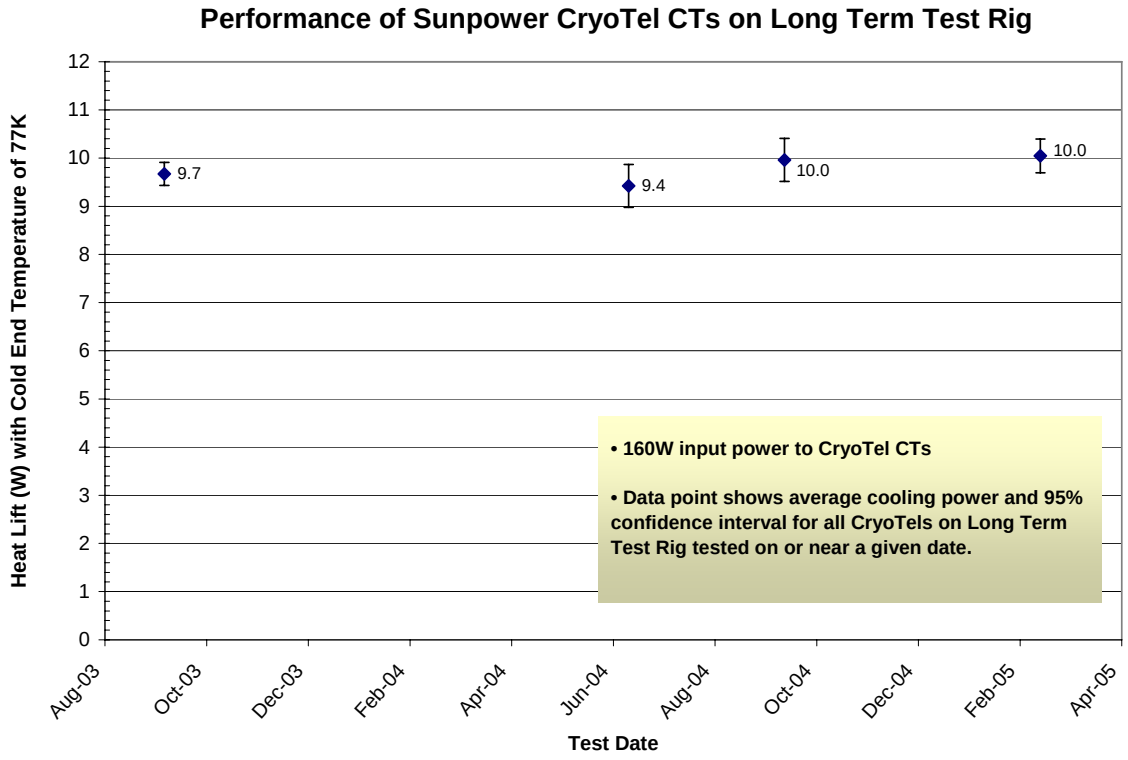

FIGURE 4. Long Term Performance Variation For CryoTel CTs.

A recognized possible long term failure mode of all types of cryocoolers is performance degradation due to outgassing of volatile materials from the internal components. The volatile materials tend to migrate to the cold end of the cryocooler and then condense and freeze, reducing the effectiveness of the internal acceptor heat exchanger and the regenerator. During Sunpower's 15 years of cryocooler development and manufacturing design, special attention was given to the selection of the materials for the main components. The use of plastic materials and polymers was minimized and scrutinized for low out-gassing rates. Sunpower follows a well established schedule for the vacuum bakeout of the cryocooler parts followed by final assembly and welding of the hermetic pressure vessel inside of a nitrogen filled glove box. The cryocoolers are then subjected to a number of cycles of deep vacuum and are then filled with helium. This

process is repeated to ensure that all volatiles, moisture and nitrogen are removed from the cryocooler prior to final charging and sealing of the pressure vessel.

MANUFACTURING CAPABILITIES

In Athens, Ohio, Sunpower supports one of the few factories in the world dedicated to the small volume commercial production of low cost, high performance free-piston Stirling cryocoolers. A medical product startup company came to Sunpower in 1998 looking for a cryocooler that could be used in an in-home oxygen liquefier to provide liquid oxygen for patients with various respiratory diseases. Starting with the hand-built, NASA-style M77 cryocooler, Sunpower initiated a design-for-manufacturing effort. Some features of the resulting cryocooler included:

- 50% reduction in part count
- 50% reduction in pressure vessel (braze/weld) joints
- Major subassemblies built as finished parts
- No additional machining during or after final assembly
- Automation of previously manual processes

Since 1998, over $10 million has been invested in Sunpower's cryocooler manufacturing facility. A number of design iterations were built and tested as part of the evolution towards the final version of the CryoTel™ CT. Since 2001, Sunpower has built more than 250 CTs. The ability to build and sell a commercial product at Sunpower adds a new dimension to Sunpower's existing intellectual property [6][7][8][9][10] and know-how.

All CryoTel™ CTs are now made in Sunpower's manufacturing facility from a full set of production drawings that are under Engineering Change Order (ECO) control. The CryoTel™ MT is at nearly the same status as the CT. As Sunpower builds more CTs and MTs, our understanding of product cost and lead time improves and we continue to develop multiple customers across a range of applications. The current production capacity at Sunpower is approximately 400 CryoTels™ per month.

Although the overall product development of Sunpower's pulse tube coolers has not advanced to the same level as the CryoTel™, the PTCs have many of the same or similar components and could also be produced at Sunpower's manufacturing facility.

CONCLUSION

Sunpower continues to expand its cryocooling options. The CryoTel™ LT and CryoTel™ GT have been added to the CryoTel™ family of coolers. The GT and MT are now production ready and continue to accumulate operating hours. Two new PTCs, a low temperature multi-stage version and a single-stage coaxial cooler, have been prototyped at Sunpower. The Sunpower cooler design uses state-of-the-art technology and know-how in combination with robust configurations. Sunpower coolers are of a compact size, high power density and high efficiency. Sunpower's DSP-based controller provides flexibility, adaptability and accuracy to all of the cryocooling options. Sunpower's volume manufacturing strategy includes a modern, in-house manufacturing facility at Sunpower in addition to potential off-shore manufacturing partners.

ACKNOWLEDGEMENTS

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