Sunpower's CPT60 Pulse Tube Cryocooler

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ABSTRACT

Sunpower, Inc. in collaboration with Gedeon Associates has developed a new model of single stage, coaxial pulse tube cryocooler, the CPT60, through funding from Smach (SMArt teCHnologies) Co., Ltd. of Osaka, Japan. The CPT60 achieves 2 W of cooling power at 60 K with 100 W_e of input power and 37° C reject temperature (8.3% of Carnot) using forced air cooling with the cold head positioned cold-end-up. A dual-opposed piston configuration minimizes vibration and the coaxial cold head configuration results in a compact package and the appearance of a "Stirling-style" cold finger. The CPT60 makes use of Sunpower's half-wave inertance technology for acoustic tuning that eliminates the need for a buffer volume at the end of the inertance tube resulting in a smaller overall package. An overriding goal in the development program was to make use of Sunpower's successful Stirling cryocooler technology in two ways: 1) to use components directly available from the CryoTel Stirling cryocooler manufacturing line, and 2) to make customer interfaces and the overall cryocooler appearance as similar as possible to the CryoTel. After successfully testing a water-cooled prototype, the CPT60 was redesigned for hermetic sealing and air cooling. Three hermetic units were produced, tested and delivered to Smach.

REVIEW OF PULSE TUBE DEVELOPMENT AND SUNPOWER MANUFACTURING

Combining relevant experience in linear compressors and pulse tube modeling and design, Sunpower and Gedeon Associates have worked together for over six years developing high efficiency, linear compressor driven pulse tube cryocoolers. To date, NASA Goddard Space Flight Center in Greenbelt, MD has funded two collaborative Sunpower/Gedeon SBIR Phase II programs and one current SBIR Phase I program.

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The goal of the first SBIR Phase II effort was to demonstrate high efficiency in a single stage pulse tube cryocooler (PTC) driven by Sunpower's linear compressor technology.[1] An inline, u-tube and two stage PTC were each constructed incorporating inertance tubes functioning as acoustic tuning devices between the pulse tube and reservoir volume. The success of this program led to the commercially funded development program discussed here.

The second SBIR Phase II program focused on cooling at 6-10 K by developing a three stage PTC driven by a 30 Hz, 300 W_e dual-opposed linear compressor.[2] This provided valuable experience in multistage pulse tube cold head design, cryopackaging and low temperature regenerator design and fabrication. The current NASA SBIR Phase I program subject is an innovative approach to achieve cooling at 4.5 K using a multistage pulse tube cold head.

Sunpower's cryocooler manufacturing unit, which started operations in 1998, shares floor space and administrative staff with Sunpower's Research and Development arm. Sunpower Manufacturing produces the CryoTel line of Stirling cryocoolers including the CT, MT, and GT models.[3] Sunpower Manufacturing is currently capable of producing 100 units per month and could ramp up to 400 units per month within the existing facility. Not only does Sunpower Manufacturing offer the capability for volume production of cryocoolers at low cost, it also provides valuable product development resources to Sunpower that enable prototype designs with manufacturing as the realistic end goal. An established vendor base, process development experience, cleaning and assembly techniques, and quality assurance resources are all available as input early in the design of a new product. These resources would greatly benefit this development program.

DEVELOPMENT GOAL

Smach Co., Ltd. of Osaka, Japan is Sunpower's agent for sales of cryocoolers in Japan. A spin-off organization from a large electronics company, Smach also possesses expertise in the area of linear driver/control electronics directly applicable to pulse tube technology. Sunpower and Smach recognized the potential for a collaboration that would advance the state-of-the-art of Sunpower pulse tube technology, utilize Sunpower's manufacturing experience with Stirling cryocoolers, incorporate Smach's linear driver/control electronics, and capitalize on Smach's business and marketing contacts to promote the new pulse tube cryocooler system. This paper only discusses the development of the pulse tube cryocooler without covering the driver/controller electronics or current business activity.

Discussions began by assessing cryocoolers that were currently available to the Japanese market. Critical evaluation points included the existence of Sunpower Stirling cryocoolers, the state of PTC development at Sunpower, the desires of the Japanese market, and the relative merits of the two technologies to provide the best opportunity to serve the market. After careful consideration it was decided to develop a pulse tube cryocooler with the overriding goal of low cost and high performance and the following general attributes:

- Dual-opposed linear compressor for low vibration.
- Take advantage of the existing design and manufacturing benefits of the proven Sunpower CryoTel line of Stirling cryocoolers.
- Package envelope size similar to that of a CryoTel CT cryocooler.
- Make external interfaces similar to CryoTel cryocoolers.
- Thermal performance similar to the CryoTel CT and CryoTel MT cryocoolers (the MT and CT cryocoolers have different nominal operating input powers).

A coaxial cold head configuration, which resembles a Stirling-style cold head, was identified as the best option both to minimize the package envelope and to produce similar external interfaces as the CryoTel cryocoolers. Sunpower has previously constructed inline, u-tube, and multistage u-tube configurations, but the coaxial design presented a new opportunity for Sunpower. To achieve the goals of size, thermal performance, taking advantage of existing designs, and low vibration, the linear compressor was designed based on two opposed CryoTel

MT linear alternators. Sunpower's patent-pending half-wave inertance tube technology was used to eliminate the need for a buffer volume.

Since Sunpower had not yet produced a coaxial cold head or a hermetically sealed PTC, the program was laid out to first create a proof-of-concept laboratory prototype to demonstrate thermal performance. This unit was sealed with bolted flanges and o-rings that enabled the changing of a limited number of design features in the pursuit of the performance targets. Design features that were of particular concern were eddy flow losses in the pulse tube component resulting from the turning manifold, regenerator design and construction, free-convection losses within the pulse tube component due to cold-end-up orientation, flow distribution between the linear compressor and the annular regenerator, and the general design approach to facilitate processing and eventual hermetic sealing. After demonstrating the proof-of-concept prototype, Sunpower would deliver three hermetically sealed, air-cooled units. Table 1 summarizes some of the key goals of the hermetic units. The unit was named the CPT60 based on the Coaxial Pulse Tube configuration and the target temperature of 60 K.

MODELING AND DESIGN OPTIMIZATION

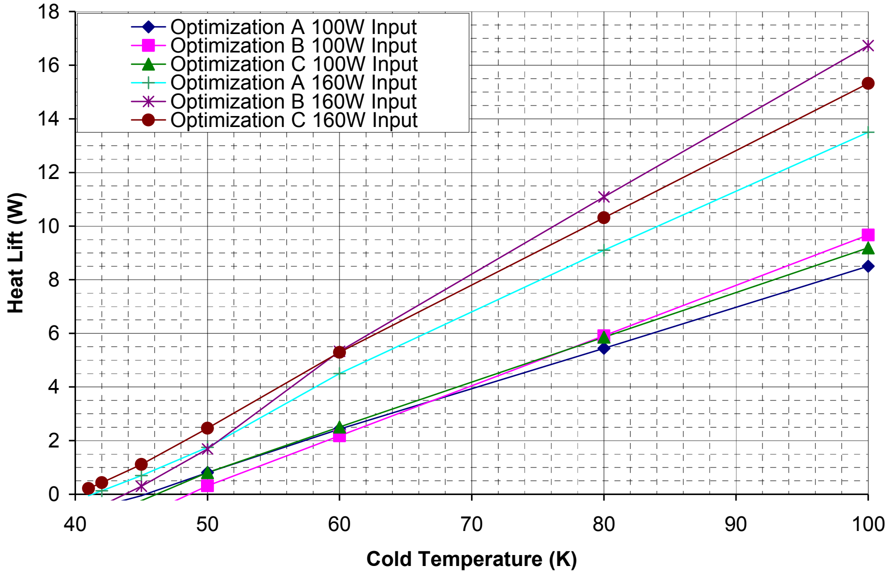
While Table 1 shows the primary design target of 2 W cooling power at 60 K and 100 W_e input, there was also an underlying secondary goal that the CPT60 should be capable of performing at the same nominal design point as the CryoTel CT. This target is 10 W of cooling power at 77 K with 160 W_e input. Input power and operating temperature are both critical parameters in the optimization of a pulse tube cryocooler. So the first task was to optimize the PTC using both primary design and off-design conditions.

Gedeon Associates performed a series of optimizations using the Sage simulation software based on various targets of input power and operating temperature. Figure 1 shows the simulated load curves of three different machines operating at both 100 W_e and 160 W_e, each optimized at different target temperatures. Optimization A has a target temperature of 60 K and nominal operating input power of 100 W_e. Optimization B is based on a target temperature of 77 K and nominal operating input power of 160 W_e. Optimization C has a target temperature of 60 K and nominal input power of 160 W_e. Table 2 summarizes the most important points of the curves in Figure 1. Note that each optimization did meet the nominal performance requirements. Due to its comfortable performance margin at 60 K and 100 W_e with 2.5 W of lift, moderate performance at 77 K and 160 W_e with 9.5 W of lift, and the lowest no-load temperature of 40.2 K at 160 W_e input, Sunpower selected Optimization C as the starting point for further design.

Another important design parameter in the optimization of the CPT60 was the requirement to meet performance with the cold head positioned cold-end-up. The cryocooler literature and previous experimental testing at Sunpower have shown the pulse tube cryocoolers are subject to free convection losses within the pulse tube's empty tube, and the cold-end-up orientation is not

Table 1. Summary of Key Development Goals of the CPT60 Pulse Tube Cryocooler.

	Development Goal
Cooling Capacity	2 W @ 60 K @ 37° C Reject (forced air)
Power Consumption	100 W_e
(% Carnot Performance)	*8.3%*
Power Supply Voltage	24 V_{DC}
Lowest Temperature	$\leq$ 40 K
Temperature Stability	+/- 0.1 K
Ambient Temperature	- 40° C to +60° C (survival only)
Mass	4.4 kg
Vibration	$\leq$ 10 µm, amplitude
Reliability (Lifetime)	$\geq$ 50,000 hrs



Size	180 x 200 x 120

Figure 1. Simulated load curves of three alternate optimizations each at 100 W_e and 160 W_e input.

Table 2. Summary of Important Points from Figure 1.

	Lift @ 60K, 100W_e	Lift @ 77K, 160W_e	No-load @ 160W_e
Optimization A	2.4W	8.3W	41.0K
Optimization B	2.2W	10.2W	43.7K
Optimization C	2.5W	9.5W	40.2K

the optimal orientation. Sunpower and Gedeon Associates addressed this issue by applying a combination of free convection principles, previous experimental evidence at Sunpower, and the Sage "Buoyant Stabilization" design factor to the design parameters of the pulse tube component. The goal was not only to achieve the target performance in the required orientation, but further to minimize changes in performance subject to all changes in orientation.

DESIGN, FABRICATION AND PROCESS DEVELOPMENT

From the beginning of the project the intended outcome was a hermetically sealed, manufactured pulse tube cryocooler that met the performance targets. Though the first part of the program focused on proving the performance of the proposed design in prototype form, we had to continually evaluate how we would achieve this design while eventually being required to hermetically seal the unit in a low cost manufacturing environment.

The first step was to make use of all available components, subassemblies, methods and processes already established in the Sunpower manufacturing facility. Specifically in terms of components this was most feasible to accomplish in the linear compressor. The linear alternator of the CryoTel MT cryocooler was chosen as the baseline on which to build the design of the dual-opposed linear compressor. The magnets, magnet can, inner and outer lamination components were procured directly from the manufacturing line. The alternator coil had to be re-designed for a different voltage than that of the MT. The piston-cylinder running pair was redesigned to account for the workspace dynamics and also to enable the integration of the gas bearing system on the stationary cylinder assembly rather than on the moving piston assembly as is done on the Stirling cryocoolers. The flex rod, a component that couples the piston to the piston spring and is a key to Sunpower's patented compliance technology, and the piston spring itself were also taken directly from manufacturing. The structural transition assembly was modified to accommodate the dual-opposed design. The welding techniques, other methods of joining, and the general assembly of the linear compressor, including the electrical feedthrough design and incorporation into the pressure vessel, were applied directly from Stirling manufacturing experience.

The cold head and inertance assemblies combined previous SBIR designs and newly developed Sunpower technology. Using IR&D funds, Sunpower and Gedeon Associates developed the half-wave inertance tube. This innovative approach eliminates the need for a buffer volume at the end of the inertance assembly by replacing the buffer volume with an extension of the inertance tube supporting a quarter-wavelength standing wave to produce the same acoustical boundary condition as the buffer volume. This design reduces the inertance assembly mass, size and manufacturing cost. To achieve the desired package envelope the inertance tube was designed to be wrapped around the linear compressor. Both the heat acceptor and heat rejector make use of copper screen heat exchangers diffusion bonded to copper housings. The annular configuration of the regenerator as well as the form of the individual stainless steel regenerator components were borrowed from recent Sunpower Stirling engine advances. Substantial effort was invested in the processing steps between diffusion bonding, brazing, and welding of components to sequentially build, test, and seal the cold head assembly. The diffusion bonding and brazing were outsourced to vendors while all welding was performed on-site using equipment from Sunpower Manufacturing. The linear compressor, cold head and inertance assemblies underwent vacuum bakeout at the component and subassembly level prior to joining.

The cooling fin assembly consisted of nickel plated copper fins that were soldered onto a copper ring. Once testing of the PTC with water cooling was completed, this cooling fin assembly was then placed on the main heat rejector through a shrink fit process to allow air cooling. This approach was again based on Sunpower's Stirling cryocooler fabrication method.

After the cooling fin assembly was installed the PTC was placed in a shroud/housing that contained the cooling fan and a Sunpower electronic driver/temperature controller. While the overall plan was for Smach to supply the driver/controller in the finished product, these production prototypes were supplied to Smach with modified Sunpower controllers.

Figure 2 shows the finished CPT60 assembly and Figure 3 shows the CPT60 air cooled package as delivered to Smach.

EXPERIMENTAL THERMAL PERFORMANCE

For all testing with the exception of the final pre-ship test, a variable frequency power supply was used to drive the PTC. This allowed us to sweep a small range of frequency to search for the best cooling performance around the nominal design frequency of 70 Hz. Prior to installation of cooling fins near the end of testing, a water jacket was used for heat rejection. Dynamic pressure transducers, FLDT's (Fast Linear Displacement Transducers) and phase meters were used for troubleshooting and guiding performance adjustments as permitted based on the stage of development of the assembly. Thermocouples measured all temperatures other than the cold temperature, which used a silicon diode. A resistive heating load was used to supply heat to the cold head, and power, voltage and current were measured for both the PTC input and heating load. A Data Acquisition System was used to monitor performance and also to capture test data.

The proof-of-concept prototype met the nominal target performance in its first iteration. The only shortcoming of the design was that the linear compressor would not operate up to 160 W_e input. Due to piston centering issues the piston would experience collisions around 155 W_e. Considering the success at the nominal operating point (100 W_e) and the delay in schedule that would result from addressing the situation it was decided to set 145 W_e as the upper operating limit to prevent collisions. The solution to this problem has been identified for future development.

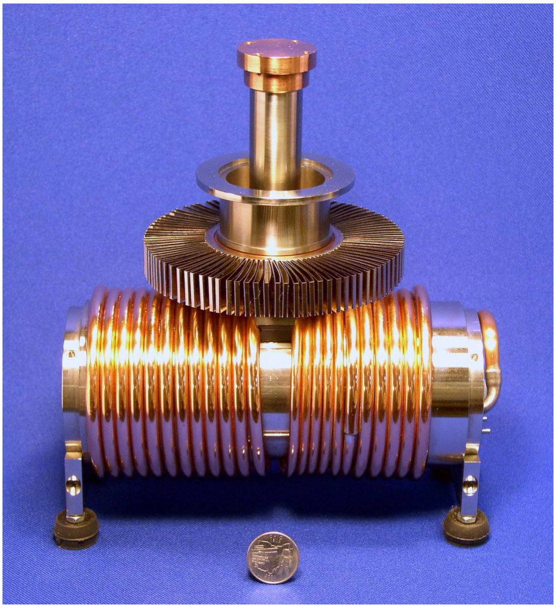


Figure 2. CPT60 production prototype hermetic assembly.

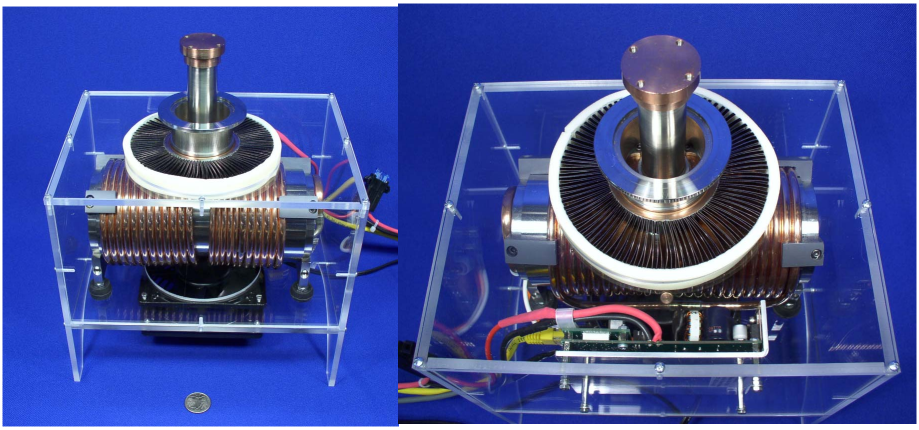


Figure 3. CPT60 package with forced air cooling and Sunpower driver/temperature controller.

The approach to testing for each unit was to produce a "pre-hermetic" linear compressor subassembly, cold head subassembly and inertance tube subassembly with only the interfaces between these entities remaining open. This allowed testing of these subassemblies with qualified laboratory subassemblies of the other entities to qualify the production subassemblies prior to hermetic joining. For example, a production cold head was tested with the laboratory prototype linear compressor and laboratory prototype inertance tube, both of which had their performance previously qualified with the laboratory prototype cold head. The production linear compressor was tested with the laboratory cold head and inertance tube, and so on. Additionally there was a qualification test for the stand-alone production linear compressor driving against an adiabatic volume of gas to check its performance. This allowed us to qualify a production linear compressor without the need for the rest of the cryocooler system.

Once the subassemblies were qualified they were joined to form the hermetic unit, with only the charge tube and one end of the inertance tube remaining open. Prior to final sealing a vacuum bakeout was performed on the entire assembly with the vacuum connected to the charge tube and the open end of the inertance tube. After completely hermetically sealing the PTC a performance test was conducted using water cooling. Then the cooling fin assembly was installed, and the PTC underwent a final qualification performance test. A DC fan was used for the cooling with the input voltage fixed, thus the reject temperature was able to vary based on ambient temperature and PTC input power.

The next few figures present various experimental data on the hermetic PTC units. Figure 4 shows a comparison of the thermal performance of the three units that were delivered. Important lessons were learned after CPT60-A1 and these lessons were applied to the next two units. The impact of these lessons is shown by the increase in performance compared to the first unit. Note for CPT60-A1 that the drop in performance between 60 K and 40 K is believed to be an error in the data, not real behavior. Figure 5 compares the thermal performance of CPT60-A2 with the laboratory prototype unit. This slight difference in performance from prototype to hermetic unit was consistent in each PTC delivered. Finally, Figure 6 shows thermal performance of the laboratory prototype at various orientations to test the sensitivity to gravity. The results show that indeed the performance is insensitive to orientation, as designed, with only a 10% difference in performance between cold-end-up and cold-end-down at the design point.

VIBRATION

The dual-opposed linear compressor configuration was chosen for its inherently low level of vibration. Throughout the construction of the linear compressor, the balancing of the two sides was checked frequently to minimize vibration by using an accelerometer. The effort was a challenge because of the low mass of the PTC and any difference in the mass of the two piston assemblies or change in stiffness of the structure, distortion from welding for example, had the potential to change the balancing of the system. The residual vibration of the hermetically sealed compressor in isolation was typically on the order of 2 microns amplitude at 100 W_e input.

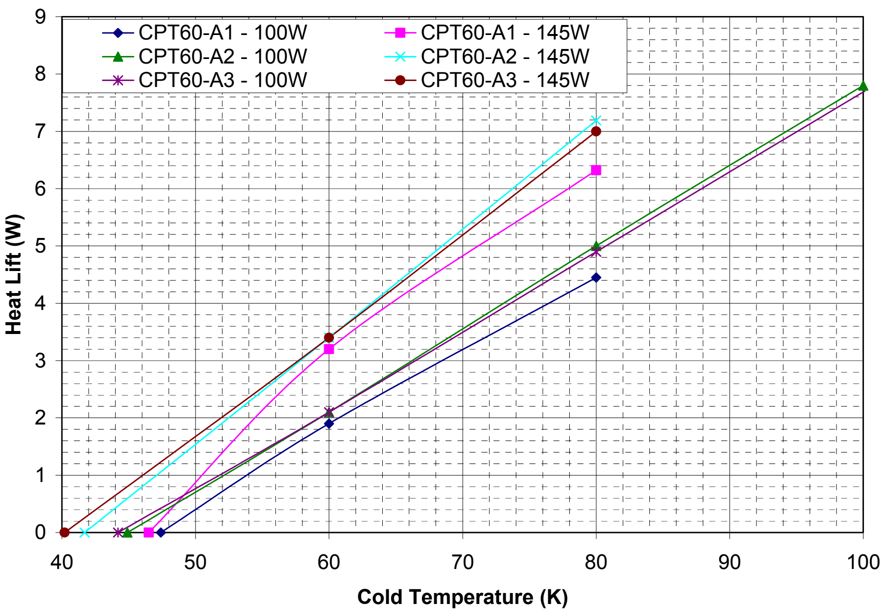


Figure 4. Comparison of the thermal performance of the three delivered hermetic PTC units.

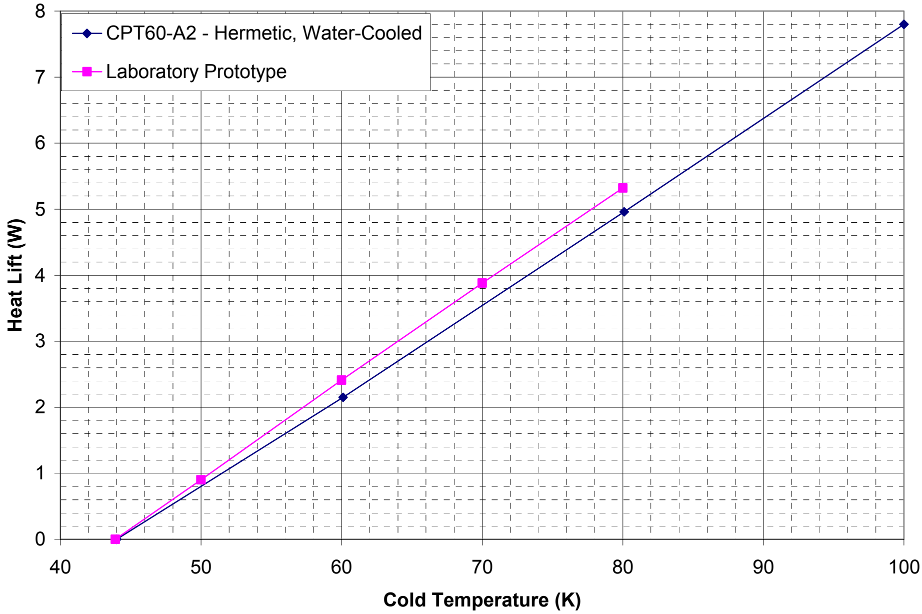


Figure 5. Comparison of the thermal performance of CPT60-A2 with the laboratory prototype unit.

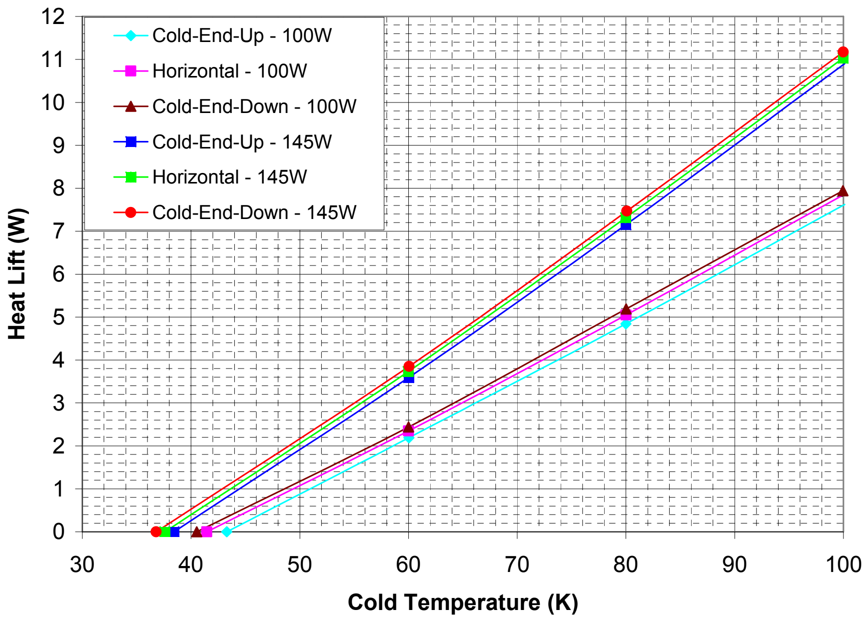


Figure 6. Thermal performance as a function of orientation for the laboratory prototype unit.

Unexpectedly, we found that a significant source of the vibration of the PTC assembly was due to the motion of the helium gas within the inertance tube. Our solution for this problem was to wind the inertance tube in an innovative fashion. By winding the inertance tube around one half of the compressor in one direction and then winding in the opposite direction around the other half, the forces from the oscillation of the gas in the inertance tube cancel each other, reducing vibration. Just as the forces of the moving components within the compressor cancel in an opposed configuration, this tube winding technique was intended to accomplish the same function.

To further reduce vibration the inertance tube coil was isolated from direct contact with the PTC structure by the use of a winding sleeve, or bobbin, placed upon soft foam rubber pads between the bobbin and the compressor pressure vessel wall. Additionally, the coil on each side of the compressor was clamped together to eliminate the axial spring motion of the wound coil. Finally, isolation pads were placed on the base of the PTC mounting plates. Many of these features can be seen in Figures 2 and 3.

This combined approach of tube winding and vibration isolation needed several iterations to achieve the vibration goal. Table 3 shows the results of vibration testing specifically for CPT60-A3, which met the development goal. CPT60-A2 had very similar vibration levels. CPT60-A1 had higher vibration levels and did not meet all the goals.

CONCLUSIONS

Sunpower, Inc. and Gedeon Associates have successfully completed the development of a coaxial pulse tube cryocooler under funding from Smach, Co., Ltd. The design incorporates a dual-opposed linear compressor, coaxial cold head configuration and proprietary half-wave inertance tube technology. Table 4 shows the accomplishments of the program versus the development goals. The data in Table 4 is from unit CPT60-A2 but is also representative of CPT60-A3. The first unit, CPT60-A1 did not quite meet the goals as well as these later units, but served as a valuable learning tool leading to the eventual success. We are very pleased with the results of this development program. Sunpower now has the first generation of hermetically sealed production pulse tube cryocoolers from which we can build and improve upon.

Table 3. Results of Vibration Testing for CPT60-A3.

Direction	**Axial** (along compressor)	**Vertical** (along cold head)	**Transverse**
On Compressor End	+/- 3.0 microns	+/- 3.4 microns	+/- 1.5 microns
On Cold Tip	+/- 6.5 microns	+/- 0.4 microns	+/- 4.4 microns
On Vacuum Flange	+/- 3.8 microns	+/- 0.8 microns	+/- 2.3 microns

Table 4. Comparison of Key Development Goals and Actual Results.

	Development Goal	**Actual Results (CPT60-A2)**
Cooling Capacity	2 W @ 60 K @ 37° C Reject (*forced air*)	2.1 W @ 60.0 K @ 33.7° C Reject (*forced air*)
Power Consumption	100 W_e	100.2 W_e
(% Carnot Performance)	8.3%	8.7%
Power Supply Voltage	24 V_{DC}	24 V_{DC}
Lowest Temperature	$\leq$ 40 K	41.7 K (*@ 145 W_e*)
Temperature Stability	+/- 0.1 K	Not required (*Smach provides*)
Ambient Temperature	- 40° C to +60° C (*survival only*)	Not tested
Mass	4.4 kg	4.6 kg (*PTC only*) 5.0 kg (*as shown in Figure 2*)
Vibration	$\leq$ 10 μm, amplitude	+/- 6.5 microns max (*axial*)
Reliability (Lifetime)	$\geq$ 50,000 hrs	Not proven
Size	180 x 200 x 120 mm	204 x 210 x 121 mm

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