

Thermal Performance of the Texas Instruments 1-W Linear Drive Cryocooler

D. L. Johnson

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California USA 91109

ABSTRACT

The thermal performance of the Texas Instruments (TI) 1-watt linear drive cryocooler was measured for coldtip temperatures varying from 23 K to 130 K over a range of heat reject temperatures (+50°C to -54°C), input voltage levels (7 Vrms to 10 Vrms), and operating frequencies (50 Hz to 65 Hz). The cooler was driven with a linear amplifier during performance testing to remove the effects of the cooler drive electronics to better understand cooler operation and thermal performance for a variety of environmental conditions that may be encompassed by different users. The wide heat sink temperature span provided a large variation in the refrigeration capacity of the cooler in terms of both the lowest attainable coldtip temperature and the refrigeration capacity at a given coldtip temperature. Over this large span of heat sink temperatures, the lowest achievable coldtip temperature varied from 45 K to 23 K, while the refrigeration capacity at a given temperature changed by as much as 650 mW. As one example, the refrigeration capacity at 77 K varied from 0.82 watts at +50°C to 1.45 watts at -54°C, with corresponding cooler input power levels of 31 watts and 27 watts, respectively.

Additional cooler tests were performed using the TI voltage-mode cooler drive electronics and DC-DC voltage converters to measure the electronics efficiencies in a simulated spacecraft operating mode. The cooler drive electronics was observed to operate with a nominal 70% efficiency, while this particular set of voltage converters operated with an nominal 83% efficiency. The efficiency of the electronics plays a large part in determining the overall spacecraft power requirements to operate the cooler as well as determining the thermal dissipation characteristics of the various electrical components. The results of all the performance measurements are presented in this paper.

INTRODUCTION

There is an increasing demand for low-cost cooling options for focal planes on short duration (1-2 year), low cost, space flight experiments, both on spacecraft that fly in a low earth orbit and on landers and rovers for planetary study. These applications place high demand on both the cooler operating conditions and on the thermal control of the cooler's environment because of the extreme temperature variations of the ambient environment and because of the limited available power.

With the emphasis on low cost, the success of recent flight experiments utilizing the Ricor 506B cryocooler¹ and the Texas Instruments (TI) 0.15 W cryocooler² have piqued the interest of the space science community in the use of these coolers. The Ricor cooler is representative of the rotary drive

cooler technology and the TI 0.15 W cooler is representative of the linear drive cooler technology. Coolers of both technology types were originally developed for military applications but are used extensively in commercial applications as well. As a second generation technology developed to overcome the limitations of the rotary cooler design, the linear drive cryocoolers provide all the necessary features for a short duration mission: low cost, low input power, low vibration, light weight, rugged, with a mean-time-to-failure (MTTF) between 3000 and 8000 hours, and are operable over a wide range of heat rejection temperatures (+71°C to -54°C). (These coolers are distinguishable from the linear drive, flexure-bearing Stirling and Pulse Tube cooler technology designed for multi-year life in space-borne applications.) These cryocoolers are ideal for applications where wide temperature extremes are encountered or where it is desirable to get the most performance out of a cooler by operating at low ambient temperatures. The linear drive cryocoolers are made by a host of manufacturers, but there is little in the way of a data base that describes in detail the performance of the cryocoolers over their entire operating space. The lack of performance data adds to the difficulty of the user community to select the cooler best suited for the prospective application.

The focus of this paper is to present the thermal performance capabilities of the TI 1-watt linear drive Stirling-cycle cryocooler over a wide ambient temperature range and cooler operating parameters to provide a large data base usable for a thermal designer. The performance measurements were made with the cooler driven with a low distortion linear amplifier to remove the effects of the cooler drive electronics. Significant levels of testing of the cooler were made to measure the performance over a wide range of cooler drive frequencies and input voltages, and with applied coldtip loads from 0 watts to 3 watts, covering coldtip temperatures from less than 30 K up to 130 K. Additional testing of the cooler was performed using the TI voltage-mode drive electronics and DC-DC voltage converters to measure the efficiency of the electronics in a simulated spacecraft electrical configuration. The results are reported in this paper.

COOLER DESCRIPTION

The Texas Instruments 1-watt linear drive split-Stirling cooler is sized to provide 1 watt of refrigeration at 77 K for a nominal input power into the cooler drive electronics of 32 watts³. The cryocooler and drive electronics can be operated in ambient temperatures ranging from +71°C to -54°C. The MTTF rating as specified by TI is for 4000 hours, but has been reported⁴ to be at least 5500 hours as an interim MTTF value collected during the course of ongoing endurance tests for coolers operating over a heat sink temperature range between +52°C and -32°C. The dual-opposed linear drive pistons provide minimal piston motion, and the balanced piston pair helps reduce cooler-generated vibration. The transfer line geometry for the cooler is determined by the user; the cooler used in these performance measurements had a transfer line 5 cm long, providing a compact cooler profile with minimal performance loss because of the short transfer line.

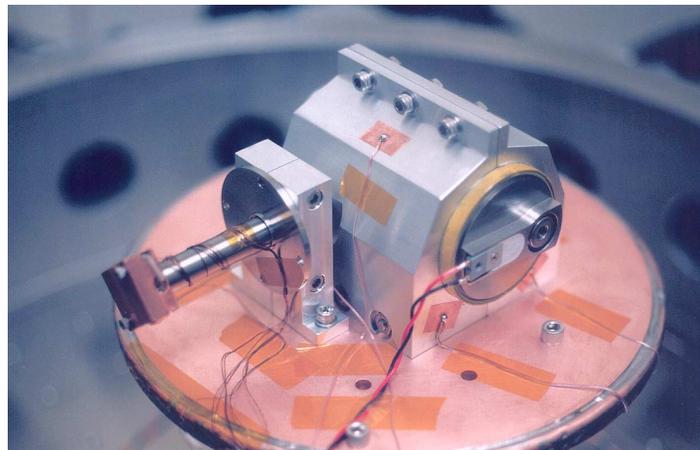


Figure 1. Test setup for thermal performance measurements of the cryocooler.

TEST APPARATUS AND TEST SETUP

The cooler was mounted on a copper heat sink plate supported on stainless steel thin-wall tube legs for thermal isolation from the vacuum chamber. The copper heat sink plate was cooled via a fluid loop connected to a recirculating chiller. The cooler body was supported with aluminum clam shells machined to the curvature of the compressor and expander bodies as shown in Fig. 1; these support clamps provide the heat transport mechanism to get the heat from the cooler to the heat sink plate. A thin sheet of indium was placed between the cooler and the clam shells to fill any voids. Thermocouples were placed on the compressor, the heat sink plate, and at the top and bottom of the clam shells to measure the temperature gradient in the clam shells. The entire cooler and heat sink plate were wrapped with MLI to minimize radiative losses between the cooler and the chamber wall.

The cooler was driven with a sinusoidal voltage waveform from a function generator amplified through a low distortion power amplifier. This permitted the drive frequency and compressor input voltage to be parametrically varied for performance mapping of the cooler. A true rms power meter was used to measure the voltage, current, and power into the compressor. A 20.8-gram heater block, outfitted with a resistive heater and two temperature sensing diodes, was attached to the coldtip. The coldfinger was completely wrapped with MLI to minimize radiation to the coldfinger.

THERMAL PERFORMANCE

The cooler was comprehensively tested over a broad range of heat sink temperatures from +50°C to -54°C and for coldtip temperatures ranging from the no-applied load temperature to 130 K, representing applied coldtip loads from 0 to 3 watts. At each heat sink temperature, the cooler was first operated at the nominal 55-Hz drive frequency with a 10-Vrms input level (roughly 85% of full drive voltage capability) to acquire a load line. Additional 10-Vrms load lines were then measured for other drive frequencies, varied in 5-Hz increments, to determine the optimal drive frequency. Load line performance data was recorded for the cooler operating at several different input voltage levels.

The thermal performance measurements are plotted on multi-variable plots to describe the cooler thermal performance dependence on the heat sink temperature, the cooler input voltage, coldtip load, and drive frequency. From these parameters, one can see the net effect on the overall cooler input power and attainable coldtip temperature, and on the cooler specific power (the cooler input power required to provide 1 W of refrigeration) under these operating conditions. The data are presented in the following figures.

Drive Voltage. Figures 2-7 show the performance of the cooler as a function of the input voltage for heat sink temperatures varying from +50°C to -54°C. The load line performance data were obtained by running the cooler at several constant input voltage levels, starting from a high of 10 Vrms. (The maximum input voltage to the compressor coils representing full stroke capability was approximately 11.6 Vrms as observed during initial cooldown of the cooler when operating with the cooler drive electronics.) Varying the input voltage between 10 Vrms and 9 Vrms results in an approximate 6 watt change in input power; this corresponds to a nominal change in refrigeration capacity of 150 mW at 50 K and 300 mW at 80 K.

Heat sink temperature. The heat sink temperature was varied over a very broad temperature range from +50°C to -54°C. The heat sink temperature was measured and maintained at the copper heat sink plate, with the cooler body temperature allowed to rise above the heat sink temperature. A temperature gradient of 5°C was measured between the heat sink plate and the end cap of the compressor body (next to the helium transfer line flange) when the cooler was operating with 35 watts of input power. The temperature at the expander helium transfer line inlet increased as much as 25°C above the heat sink plate temperature.

The cooler performance was found to be very sensitive to the heat sink temperature. The minimum coldtip temperature attainable for the 10 Vrms input load lines varied from 45 K with the +50°C heat sink, to 23 K with the -54°C heat sink. This corresponds to a change in an applied load

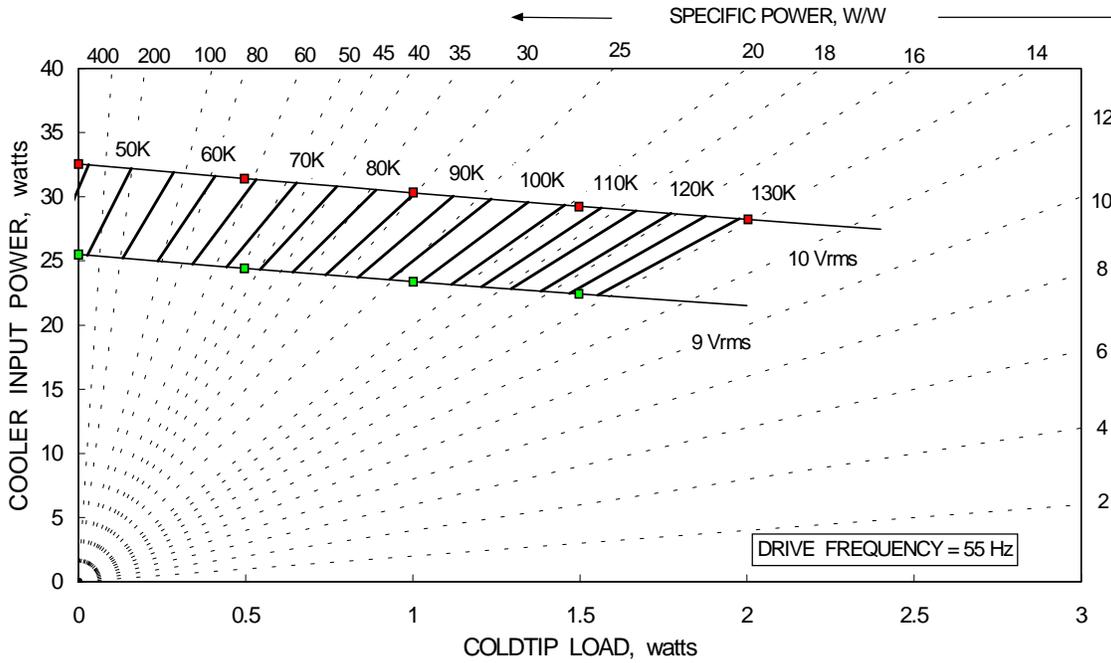


Figure 2. Thermal performance sensitivity to input voltage at +50-°C heat sink temperature.

of about 600 mW at 45 K. As another example, the cooling load at 77 K for the 10 Vrms input increased from 0.82 watts to 1.45 watts as the heat sink temperature was changed from its warmest to its coldest temperature. In terms of the specific power, this 77-K performance improved from 38 W/W at +50°C to 19 W/W at -54°C. In general it can be observed from the figures that a 20-°C temperature change in the heat sink resulted in an approximate 4-K change in coldtip temperature for temperatures below 60 K (or equivalently, to a 125-mW change in cooling capacity for a constant coldtip temperature). At temperatures above 100 K, there was as much as a 10-K change in coldtip temperature for a 20-°C heat sink temperature change (or similarly, this was equivalent to an approximate 125-mW change in cooling capacity at a given coldtip temperature).

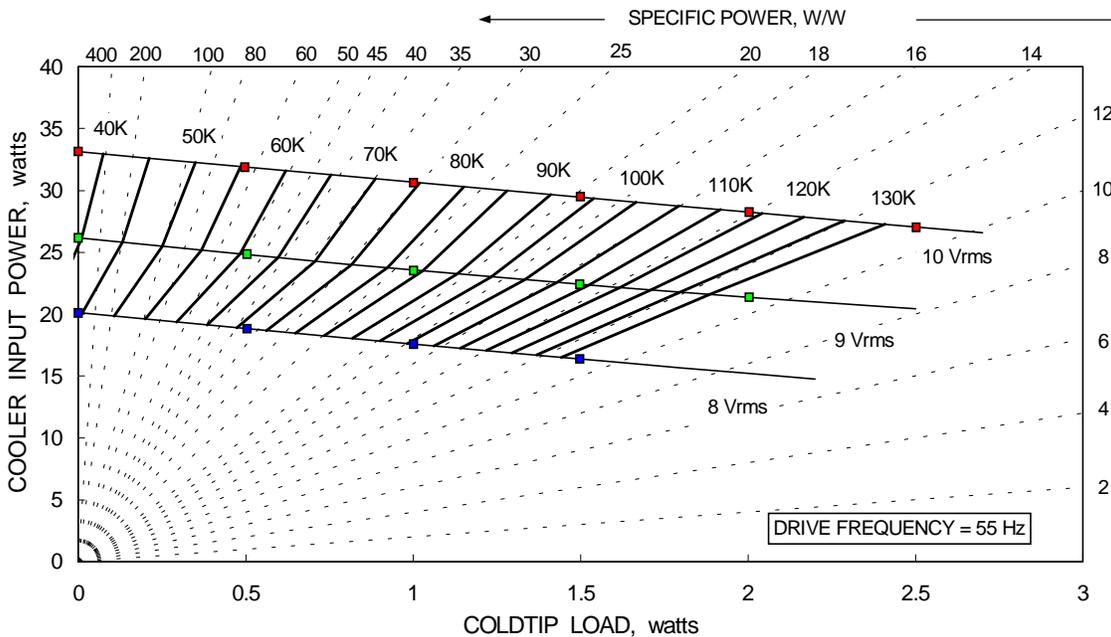


Figure 3. Thermal performance sensitivity to input voltage at +20-°C heat sink temperature.

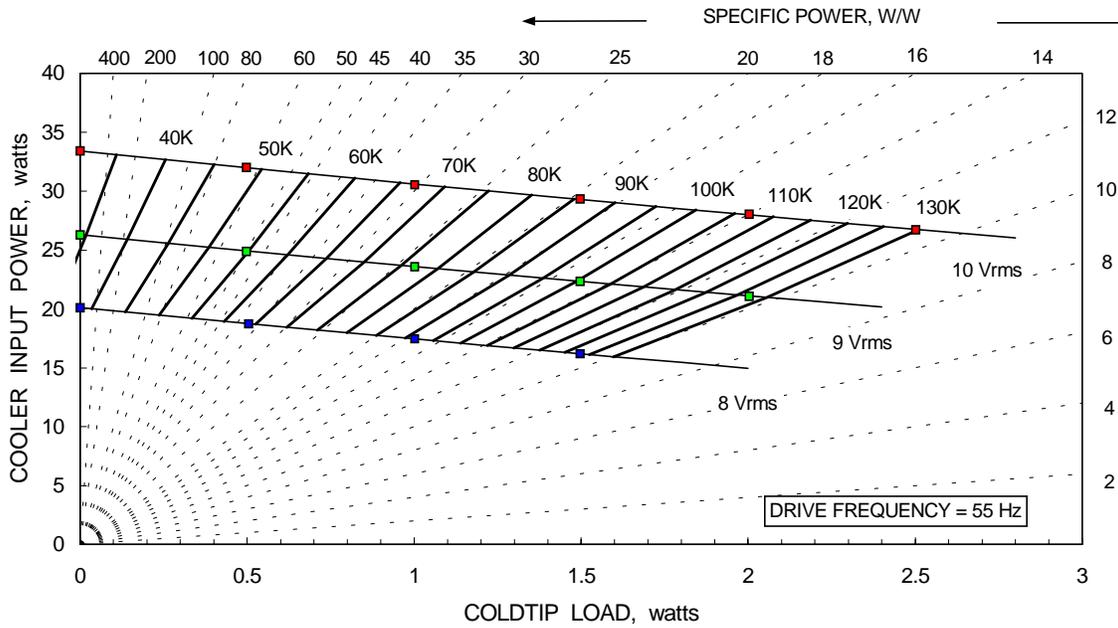


Figure 4. Thermal performance sensitivity to input voltage at 0°C heat sink temperature.

Drive frequency. The nominal drive frequency during these tests was 55 Hz. The frequency was varied in 5-Hz increments to compare the performance sensitivity at the different heat sink temperatures. Operating at or near the optimal drive frequency requires the least amount of cooler input power and also yielded the lowest specific power (watts of input power per watt of refrigeration). Over the range of heat sink temperatures the cooler was operated, the optimal drive frequency varied by more than 5 hertz. At the +50-°C heat sink temperature the cooler operated well at both 55 Hz and 60 Hz.(Fig. 8), with nearly identical specific powers at all but the warmest of coldtip temperatures. But the cooler required slightly less (2 watts) input power to operate at 55 Hz. At the -54-°C heat sink temperature, the cooler performed better with a 50-Hz drive frequency, requiring lower input power and operating with lower specific power over the entire range of coldtip temperatures observed. (Fig. 9).

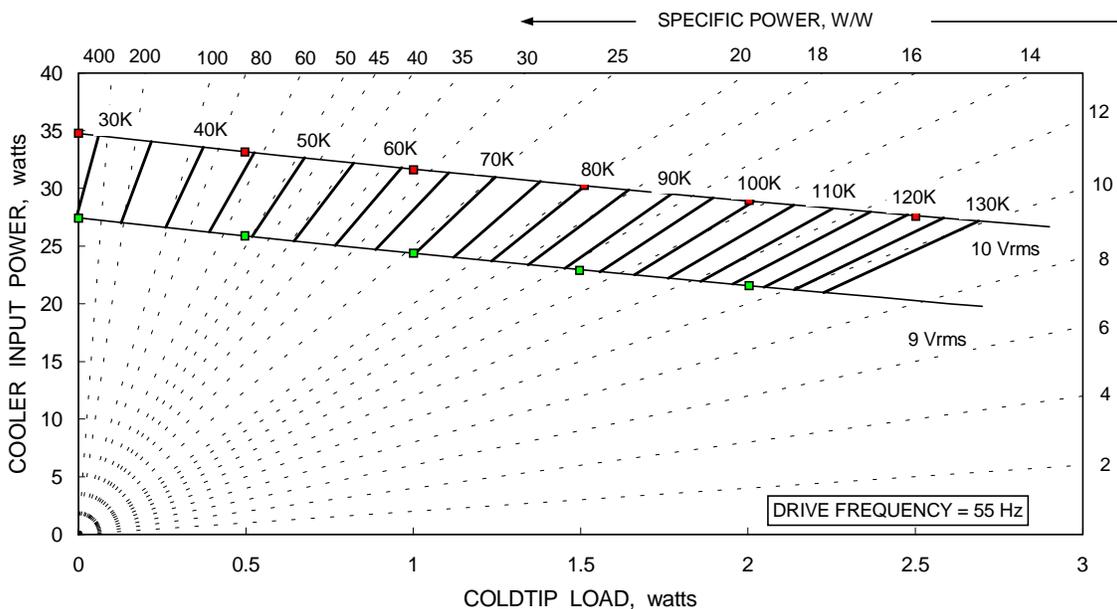


Figure 5. Thermal performance sensitivity to input voltage at -20°C heat sink temperature.

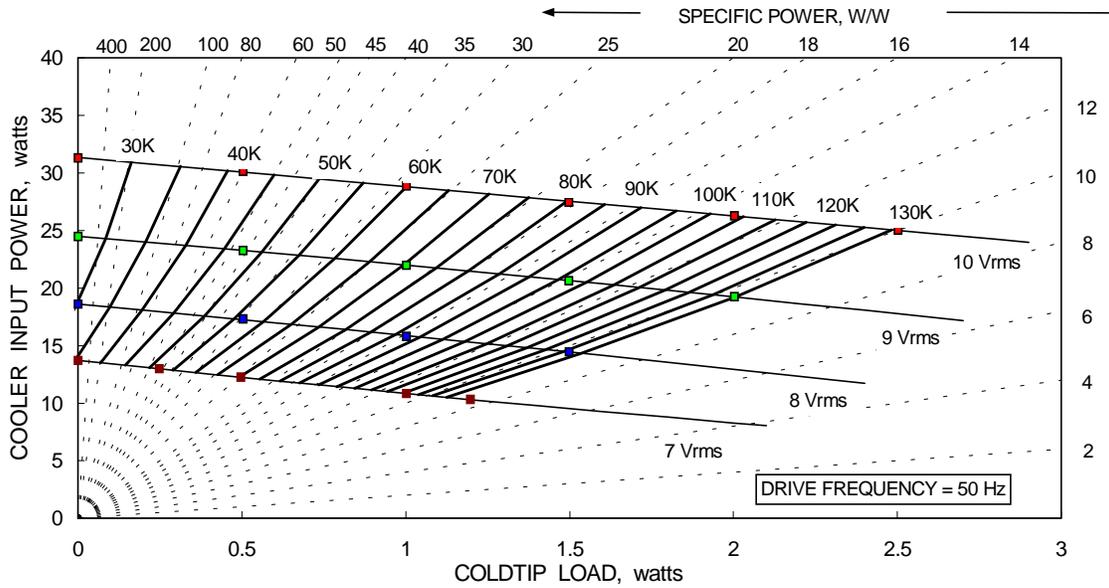


Figure 6. Thermal performance sensitivity to input voltage at -40°C heat sink temperature.

COOLER EFFICIENCY

Coefficient of Performance. Heat sink temperature is a very important external variable in cryocooler operation in that it directly enters into the Carnot efficiency of the cryocooler. The thermodynamic coefficient of performance (COP), the figure of merit for cryocoolers, is defined as the ratio of the net cooling power to the net applied input power (input electrical power - i^2R heating of the coil), and is expressed as a percentage of the ideal Carnot COP. Figure 10 shows the percent Carnot COP values for the 10-Vrms load line at each heat sink temperature.

Motor efficiency. The dominant losses in the motor design are due to the i^2R losses within the coil, which are a result of the coil resistance and the capacitive or inductive circulating currents (eddy currents). The motor efficiency can be defined as the ratio of the (input power - i^2R) to the input power. The motor efficiencies were found to be quite high also, ranging between 96–98% for the cooler for all heat sink tempera-

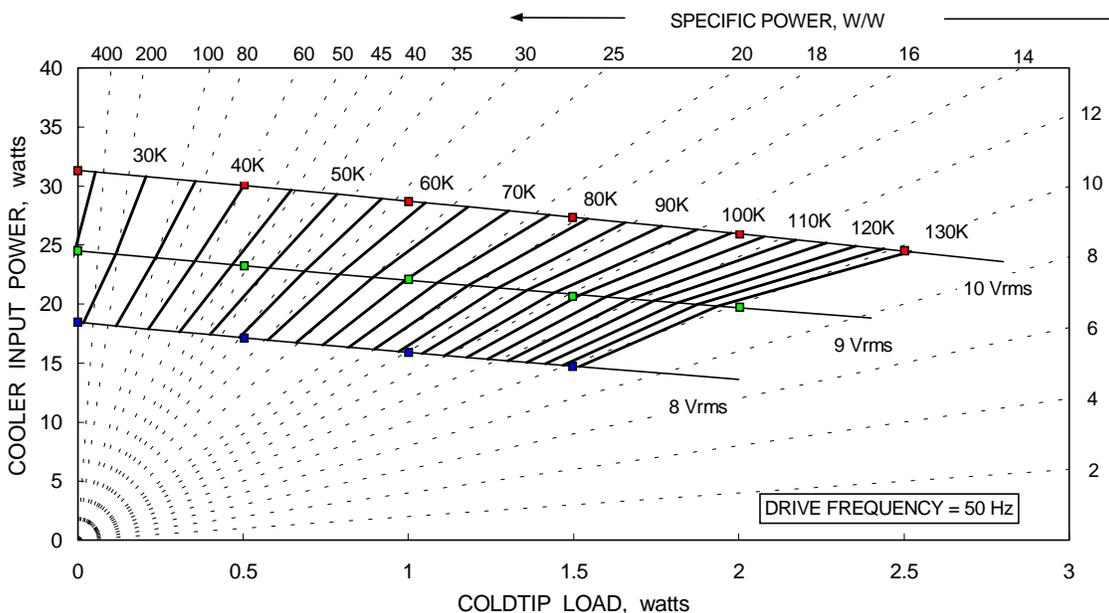


Figure 7. Thermal performance sensitivity to input voltage at -54°C heat sink temperature.

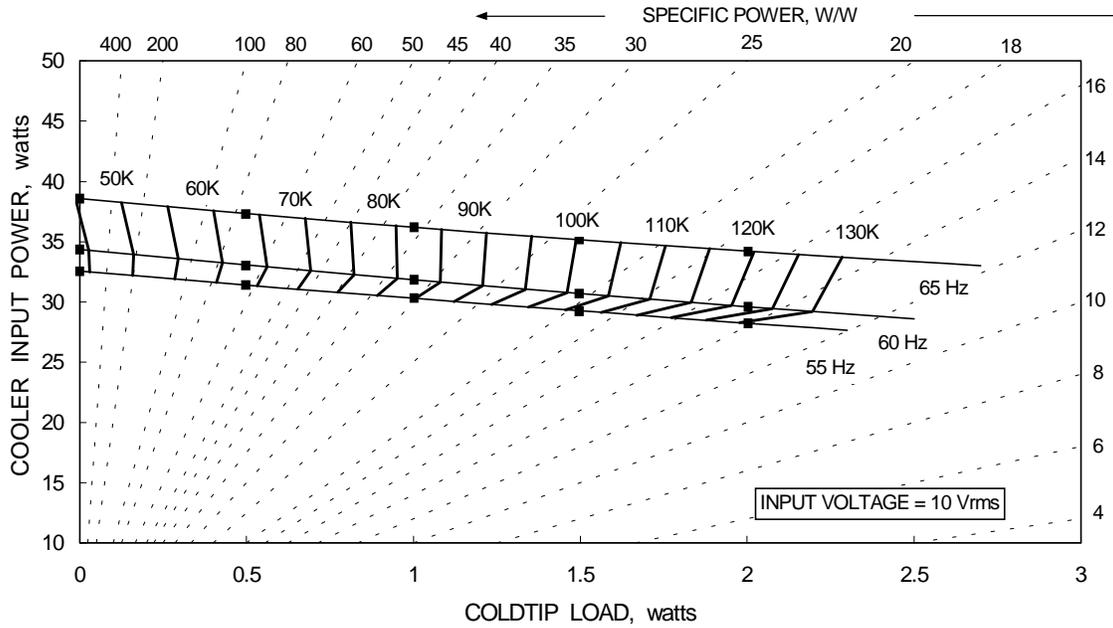


Figure 8. Thermal performance sensitivity to drive frequency at +50-°C heat sink temperature.

tures. The motor efficiency was found to be dependent on the drive frequency and the input voltage, increasing with increasing drive frequency and with increasing input voltage.

Power factors. The power factor is defined as the ratio of the input power to the product of the measured true rms voltage and true rms current. Non-unity power factors are caused by the presence of compressor drive forces, such as inertial forces and the mechanical-spring and gas-spring forces, that are not in phase with the compressor velocity. Thus minimizing these forces helps to achieve high power factor. The highest power factors recorded (.98-.99) were at the highest drive frequencies tested at the various heat sink temperatures and were independent of coldtip temperature. Operating the cooler at lower drive frequencies resulted in slightly lower power factors overall, and that were also found to vary from .96 for low coldtip temperatures to .82 at high coldtip temperatures. The high power factors indicate these motors are highly tuned and operating near the mechanical resonance.

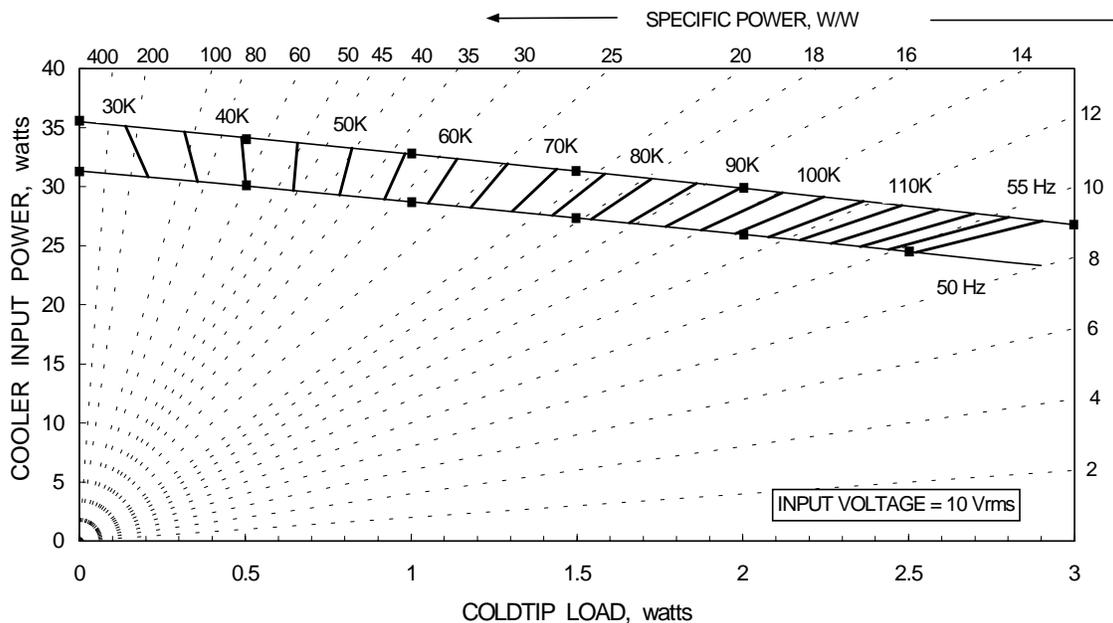


Figure 9. Thermal performance sensitivity to drive frequency at -54-°C heat sink temperature.

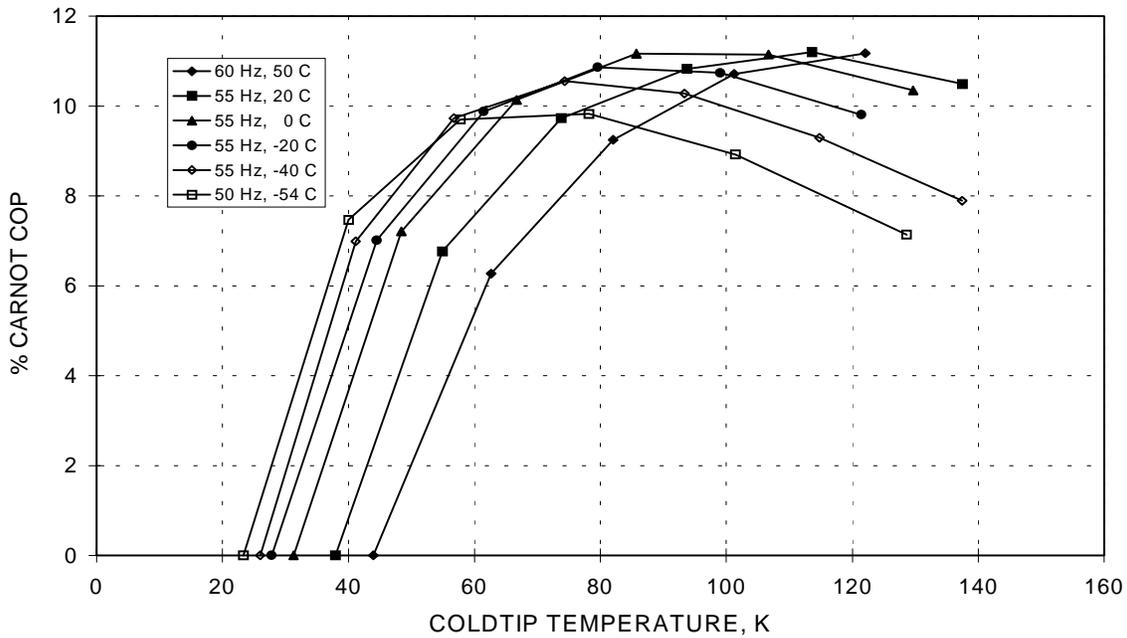


Figure 10. Sensitivity of the % Carnot COP to heat sink temperature for the 10-Vrms load lines.

COOLDOWN TIMES

Cooldown times were measured for various heat sink temperatures, input voltages, applied heat loads, and copper thermal masses. All parameters were held constant during the cool down period. Cooldown times were measured for thermal masses of 0 gm (bare coldtip), 20.8 gm, and 55.3 gm and give a first order linear dependence of the cooldown time versus thermal mass. Table 1 lists the cooldown times to reach 50 K under several operating conditions and cold tip thermal masses.

It should be noted that when operating the cooler with the cooler drive electronics, the cooler input voltage during cooldown is greater than 11 Vrms (see the next section). Operating with input voltages of less than 11 Vrms to the cooler during cooldowns would occur if the supply voltage to the cooler drive electronics were less than the minimum 17 VDC required by the electronics. In these instances the cooler drive electronics is effectively starving the cooler, preventing it from operating at full stroke.

Table 1. Cooldown time to reach 50 K.

Ambient Heat Sink (°C)	Input Voltage (Vrms)	Thermal Mass (gm)	Applied Load (mW)	Time to reach 50K (minutes)
+20	11.4*	20.8	0	15
+20	11.4*	20.8	200	16.5
0	11.4*	20.8	0	12.5
0	11.4*	20.8	200	14
+20	10	20.8	0	18
+20	9	20.8	0	23.5
0	10	20.8	0	15
-20	10	20.8	0	13.5
-40	10	20.8	0	12
+20	10	0	0	7.5
+20	10	55.3	0	33
-40	10	55.3	0	26

* Cooler drive electronics used in this instance.

As a final test to simulate the operation of the cooler on a spacecraft, the cooler was driven with the Texas Instrument's voltage-mode drive electronics card and DC–DC converters to measure the efficiency of the electronics under various operating conditions. A pair of Interpoint DC–DC converters (model MFLHP2812S) provide 24 VDC power to the cooler drive electronics, and were used in parallel to reduce the current load on the converters. The converters are used to provide isolation between the cooler and the spacecraft power bus, and are capable of providing the constant output voltage for DC input voltages ranging between 19 VDC and 40 VDC. The cooler drive electronics are operable with conditioned input voltages ranging from 17 VDC to 32 VDC.

Using the cooler drive electronics, the cooler operated at a drive frequency of 56 Hz. During cooldown, the cooler drive electronics drives the cooler at the maximum stroke by supplying full voltage to the cooler, starting with 11.6 Vrms at the start of the cooldown and decreasing to 11.2 Vrms as the cooler coldtip temperature drops to the 50-K range. The drive electronics continues to supply full voltage to the cooler until the coldtip temperature reaches the set point temperature, as monitored with a control diode. As this set point temperature is reached, the drive electronics reduces the input voltage (input power) to the cooler to a level where the cooler produces refrigeration equal to the thermal load on the coldfinger. If the thermal load on the coldfinger changes, the supplied input voltage to the cooler will likewise change to meet the new refrigeration requirements at the set point temperature.

During the test, the DC–DC converters were kept in ambient air and cooled with a fan. The cooler drive electronics card was wedge-locked into an aluminum card cage that fastened onto a cooling plate within the vacuum chamber, and was cooled to the same heat sink temperature as the cooler. The DC–DC converters and drive card efficiencies were measured using a three-channel true rms power meter inserted into the circuit at the input and output of the devices for simultaneous measurements. The measured efficiency of the converters varied between 81–84%, and the efficiency level was more dependent on the supply voltage than on the throughput to the cooler. The efficiency of the drive electronics ramped down from 75% at the start of the cooler cooldown to around 70% when the set point temperature was reached. The drive electronics efficiency remained around 70%, varying little as a function of either throughput power to the cooler or with changing heat sink temperature.

These measured efficiency numbers suggest that the overall efficiency of the electronics circuitry is on the order of 58%, that the DC power required to operate the cooler is 1.72 times larger than the power required by the cooler. Knowing these efficiency numbers also helps understand the heat dissipation characteristics of the cooler and cooler electronics.

SUMMARY

The Texas Instruments 1-watt cryocooler has been tested over a heat sink temperature range from +50°C to –54°C for a variety of input voltages and drive frequencies. The cooler was driven at several input voltages when driven with the external oscillator and amplifier; the highest input voltage was 10 Vrms, about 85% of maximum input voltage capability. The optimal drive frequency for the cooler performance depended on the heat sink temperature; a 55-Hz to 60-Hz drive frequency range was preferable at the warmest heat sink temperatures, and 45 Hz to 50 Hz was the preferred drive frequency range for the coldest heat sink temperatures. Under these conditions, the compressor input power (for the 10 Vrms input voltage) could be kept below 35 watts. Over the full heat sink temperature range the attainable no-load coldtip temperature varied from 45 K to under 24 K, corresponding to a 600-mW increase in refrigeration capacity at 45 K. At a 77-K coldtip temperature, a 630-mW change in refrigeration performance was measured over this range in heat sink temperatures.

During operation of the cooler with its drive electronics and simulated spacecraft circuit, the cooler drive frequency was 56 Hz and was driven with an input voltage of over 11 Vrms during the cooldown, and its set point operating temperature could be varied. The operating efficiency of the drive electronics was measured at a nominal 70% and the DC–DC converter efficiency was measured at a nominal 83%.

ACKNOWLEDGEMENTS

The work described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology. The work was sponsored by the Ballistic Missile Defense Organization under a contract with the National Aeronautics and Space Administration. Particular credit is due S. Leland for assembling the test setup and providing the Labview data acquisition program, and A. Lepe for the assistance in the data reduction and graphical presentations. The author wishes to thank Texas Instruments for the gracious loan of the cooler to perform these tests.

REFERENCES

1. Priest, R.E., *et al*, "Ricor K506B Cryocooler Performance during the Clementine Mission and Ground Testing: A Status Report", *Cryocoolers 8*, Plenum Press, New York,(1995), pp883-892.
2. Glaser, R., Ross, R.G., Jr., and Johnson, D.L., "STRV Cryocooler Tip Motion Suppression", *Cryocoolers 8*, Plenum Press, New York (1995), pp455-463.
3. Rawlings, R.M., Granger III, C.E., and Hindrichs, G.W., "Linear Drive Stirling Cryocooler: Qualification and Life Testing Results", *Cryocoolers 8*, Plenum Press, New York (1995), pp.121-127.
4. Dunmire, H, and Shaffer, J., "The DOD Family of Linear Drive Coolers for Weapon Systems", *Cryocoolers 9*, Plenum Press, New York (1997), pp.17-24.