# Effect of gravity orientation on the thermal performance of Stirling-type pulse tube cryocoolers

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**Abstract**

The effect of angular orientation on the off-state conduction of pulse tube cryocoolers has been previously explored, as has the effect of orientation on the thermal performance of low-frequency (~2 Hz) GM-style pulse tube refrigerators. The significant effects that have been found are well explained by the presence of free convection that builds up in the hollow pulse tube when the hot end of the pulse tube is not higher than the cold end. This paper extends the investigation of angular orientation effects to the refrigeration performance of high frequency (~40 Hz) Stirling-type pulse tube cryocoolers typical of those used in long-life space applications. Strong orientation effects on the performance of such cryocoolers have recently been observed during system-level testing of both linear and U-tube type pulse tubes. To quantify the angular dependency effects, data have been gathered on both U-tube and linear type pulse tubes of two different manufacturers as a function of orientation angle, coldtip temperature, and compressor stroke.

*Keywords:* Pulse tube; Orientation dependence; Convection; Angular dependency

## Introduction

During the past year, several instances of fairly strong gravity-orientation dependent performance have been noted during ground testing of high-frequency Stirling-type pulse tube cryocoolers. In two cases the level of effect was large enough to prevent meeting system operational requirements during ground testing when the hot end of the pulse tube was not in an upward orientation. The effect was noted in tests involving both U-tube and linear pulse tube configurations built by two different manufacturers. All of the applications involved the use of classic Oxford-type linear compressors with drive frequencies in the 30 to 60 Hz range. Previously, gravity orientation dependence has been reported for pulse tubes driven at low frequency (2-10 Hz) using Gifford-McMahon compressors.[1,2] However, high frequency pulse tubes have often been thought of as free of any strong gravity orientation dependence.

Figure 1 schematically illustrates the two common pulse tube configurations: the linear and U-tube. Each traditionally involves a screen-filled regenerator mated to an adjoining open pulse tube. With the linear configuration, the regenerator and open pulse tube are arranged end-to-end on a common axis; with the U-tube, the open pulse tube is folded back parallel to the regenerator. In addition to the obvious difference in physical layout, one practical consideration is that the pulse tube and regenerator are often made the same length in the U-tube design, whereas the linear con-

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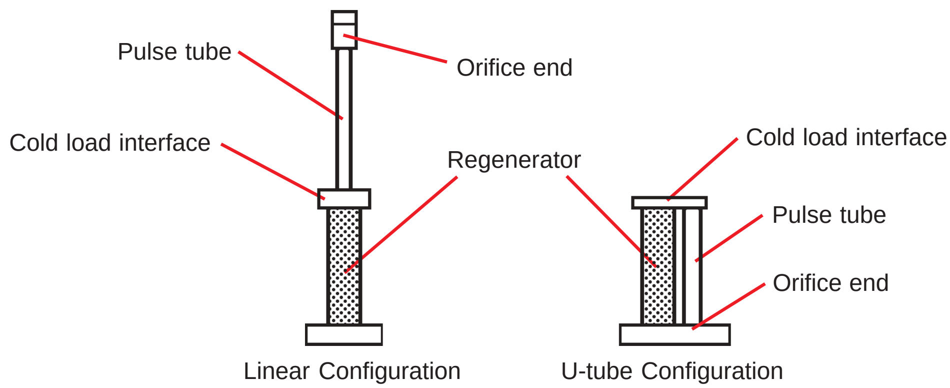


**Figure 1.** Leading pulse tube construction configurations.

figuration is not constrained by this consideration. As a result, the open pulse tube of a U-tube design often has a lower length/diameter ratio than that of a linear design.

The basic physics behind the gravity dependence is understood as free convection within the open pulse tube.[3] This convection is driven by the strong end-to-end temperature gradient within the open tube that varies from near room temperature at the orifice end, to the cooler's cryogenic operating temperature at the regenerator end. The regenerator itself has been found to be relatively immune to convection effects because of its dense filling with screens and particles.

The thermal loads associated with free convection within a non-operating cooler have also been well characterized in previous studies.[4] Off-state conduction enhanced by convection is particularly important when a primary cooler is operated in parallel with a non-operating backup cooler. In this case, the convective load in the 'off cooler' is a significant load on the operating cooler. Figure 2 presents representative data for the angular dependency found for this 'off-state' convective load.[4]

To quantify the recently observed orientation effects with high-frequency Stirling-type pulse tube cryocoolers, a series of detailed tests have been conducted to generate performance data on both U-tube and linear type pulse tubes of two different manufacturers as a function of orientation angle and compressor drive level (stroke).

The following sections discuss both the orientation effects observed during cryogenic system-level testing and the detailed results of these parametric pulse tube measurements.

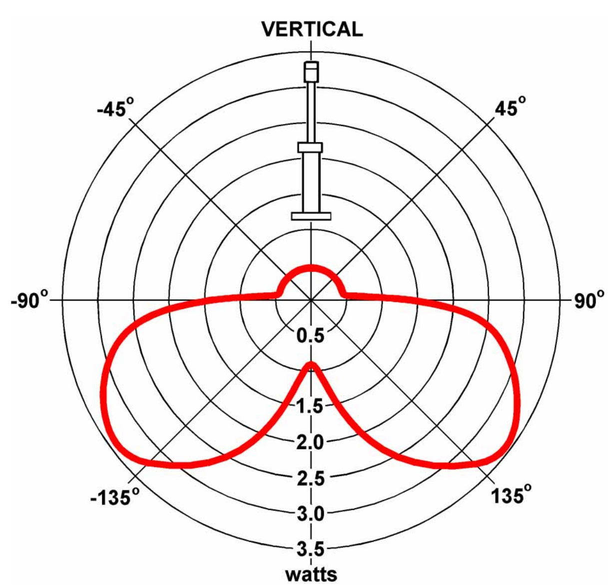


**Figure 2.** Conduction load of a non-operating linear pulse tube as a function of orientation angle with respect to gravity.

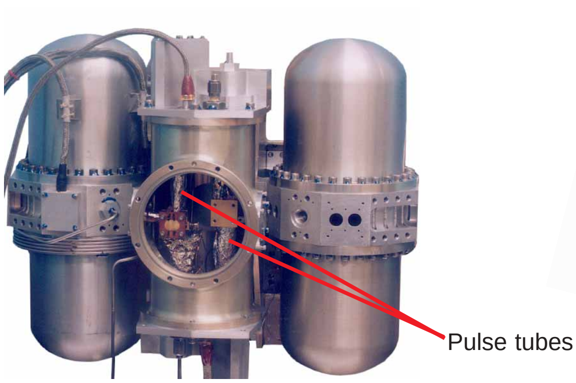


**Figure 3.** AIRS EM cooler system.

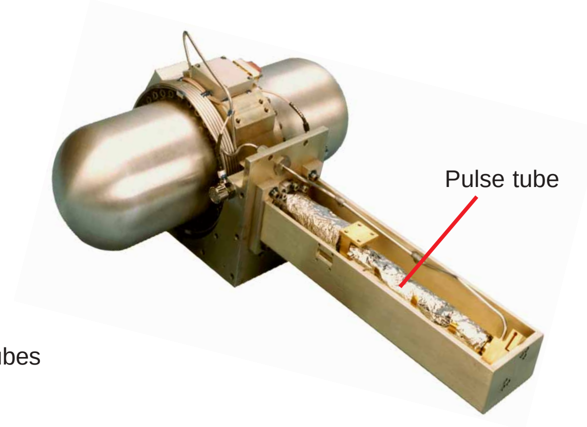


**Figure 4.** TES cooler system.

## Cooler System Test Observations

In spacecraft and instrument system-level testing, often the cryocooler gravity orientation is constrained by the requirements of the overall test setup and the test facility. In addition, the orientation will often be different in tests conducted at the instrument level as opposed to at the spacecraft level. If a cryocooler has a gravity orientation dependence, it often shows up when attempting to correlate cooler performance data taken at the cooler level, instrument level, and spacecraft level.

Experience with pulse tube cryocoolers in various system test sequences is described below. These examples provide a summary of the types of issues raised in testing.

### *Atmospheric Infrared Sounder (AIRS) instrument*

JPL's Atmospheric Infrared Sounder (AIRS) instrument was launched in May 2002 on NASA's Earth Observing System Aqua platform. Its mission is to measure the atmospheric air temperature using a HgCdTe focal plane cooled to 58 K by a redundant pair of 55 K TRW pulse tube coolers.[5,6] Shown in Fig. 3, the AIRS flight pulse tube coolers are of the linear type, with the pulse tubes of the primary and redundant cooler mounted side-by-side, but facing in opposite directions. Thus, gravity has two possible effects: 1) on the operating cooler, and 2) on the off-state conduction of the non-operating, standby cooler. If possible, during cooler testing the 'off-cooler' pulse tube was positioned vertically upward as defined in Fig. 2 to minimize convection enhanced off-state conduction. This led to the operating pulse tube positioned in the inverse (hot end down) 180° orientation. In addition, during instrument-level and spacecraft-level testing, both pulse tubes were often operated in a horizontal orientation, where convection effects can also be quite strong. The variable load caused by the various orientations of the off cooler were successfully managed through the application of special test and data reduction techniques.[7] However, during the multi-year test sequence involving operation at 0°, 90° and 180°, no noticable gravity orientation dependence was observed in the operating cooler.

### *TES Cooler Development*

The EOS Tropospheric Emission Spectrometer (TES) instrument is an infrared instrument designed to measure the state of the Earth's troposphere. TES uses two 57 K TRW (now NGST) pulse tube coolers to cool two separate focal planes to 62 K. As shown in Fig. 4, the two coolers are a variant of the TRW AIRS pulse tube cooler, but with the linear-style pulse tube hard mounted to the compressor.[8,9] The TES instrument completed instrument level testing in spring 2003, and will

**Figure 5.** Gamma-ray cooler system with U-tube type pulse tube.

complete spacecraft-level testing in the fall of 2003; it is scheduled for launch aboard NASA's Aura spacecraft in early 2004.

Within TES, the coolers are positioned at a downward angle from the instrument's nadir-pointing radiator. During all ground testing, this resulted in the pulse tubes pointing down at a 125° angle from vertical, as shown in Fig. 4; this is a worst-case orientation angle for convection effects.

In the first ground testing of the instrument's cryogenic assemblies by themselves, no gravity attitude effects were observed.[9] However, during instrument-level testing—which used the same pulse tube orientation—significant attitude orientation effects were discovered. The noted effect was that the instrument cryogenic load appeared higher than expected by about ~110 mW on Cooler A and ~310 mW on Cooler B. In addition, Cooler B exhibited a chaotic load behavior well explained by a buoyancy flow phenomena.

When gravity orientation was suspected as a possible cause, a test was run whereby the cooler cryogenic loads were increased by nearly 100% using the built-in focal-plane decontamination heaters. The idea behind this was to force the coolers to work harder in order to break up any free convection cells within the pulse tube. The data clearly showed that the buoyancy induced flow phenomena disappeared at the higher stroke level. In addition, the expected coldblock temperature control response returned, and the instrument load on the two coolers matched predictions within 30 mW.

*Gamma-ray cooler testing*

In the 2000 timeframe, JPL contracted with Lockheed Martin ATC to build a low cost pulse tube of the U-tube configuration to be driven by a tactical Stirling cooler compressor.[10] The successful new cooler achieved over 1.6 watts of cooling at 80 K at 23 W/W, and had the advantage of greatly reduced vibration at the coldtip and no life-limiting moving cold elements. However, the cooler also displayed a strong gravity orientation dependence. During recent system-level testing of the cooler with a gamma-ray detector, this orientation sensitivity required that the entire test facility be operated upside down. With the cooler cold tip vertically upward, which places the hot end of the pulse tube at the bottom, the cooler was unable to reach a no-load temperature below 80 K. In contrast, with the coldtip facing down, the cooler achieved a no-load temperature of 43 K, with plenty of capacity at 80 K to cool the gamma-ray detector.

**Figure 6.** IMAS Engineering model cooler No. 101.

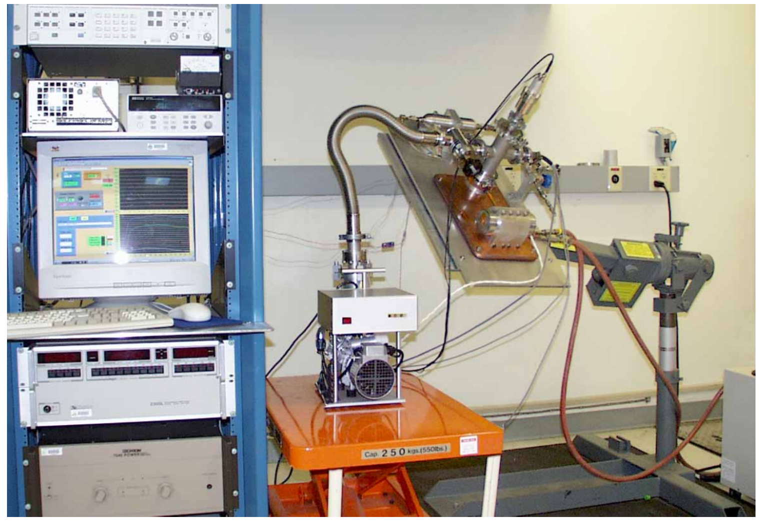

**Figure 7.** Cooler test facility allows operation at various angles with respect to gravity.

## Characterization of pulse tube orientation dependence

To understand and quantify the pulse tube orientation dependence noted in the above system-level tests, a special test program was undertaken at JPL using both the gamma-ray U-tube pulse tube cooler shown in Fig. 5, and the IMAS linear pulse tube cooler shown in Fig. 6. The IMAS cooler[11,12] was build by TRW (now NGST) for JPL in 1998 and uses a linear pulse tube very similar to the one used on AIRS and TES. A key observation was that the length-to-diameter ratio of the IMAS pulse tube is nearly double that of the gamma-ray pulse tube.

To capture the orientation-dependence data, a special rotating test facility, shown in Fig. 7, was used. It allowed the pulse tube cooler to be adjusted to any angle with respect to gravity, and provided precise control of the cryocooler heatsink temperature via a temperature-controlled fluid loop. As a first step in the investigation the performance of each cooler was characterized over a broad range or input powers and coldtip temperatures while in the preferred (convection free) orientation. These data are presented in Figs. 8 and 9, respectively.

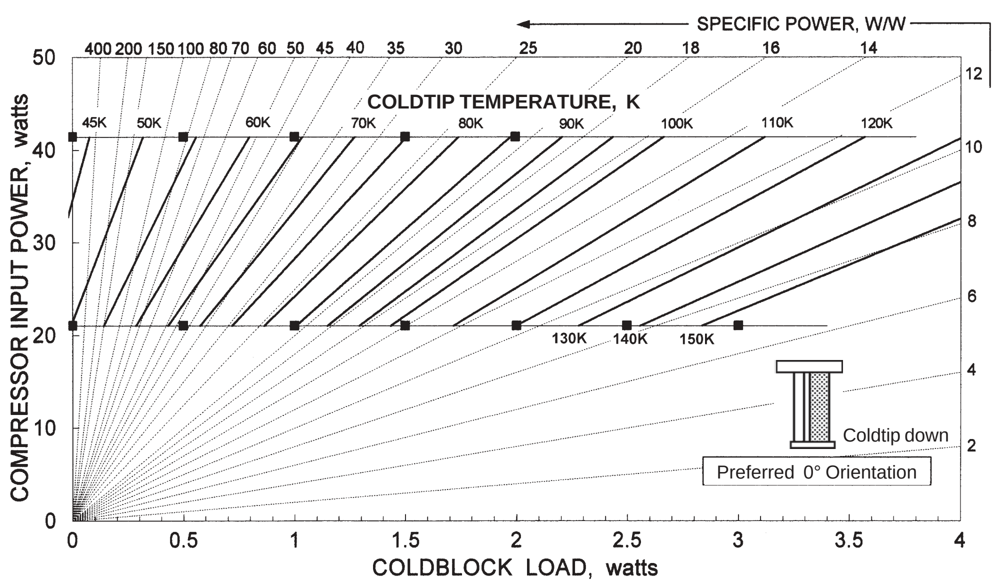


**Figure 8.** Measured performance of the gamma-ray pulse tube cooler at preferred (0°) orientation.

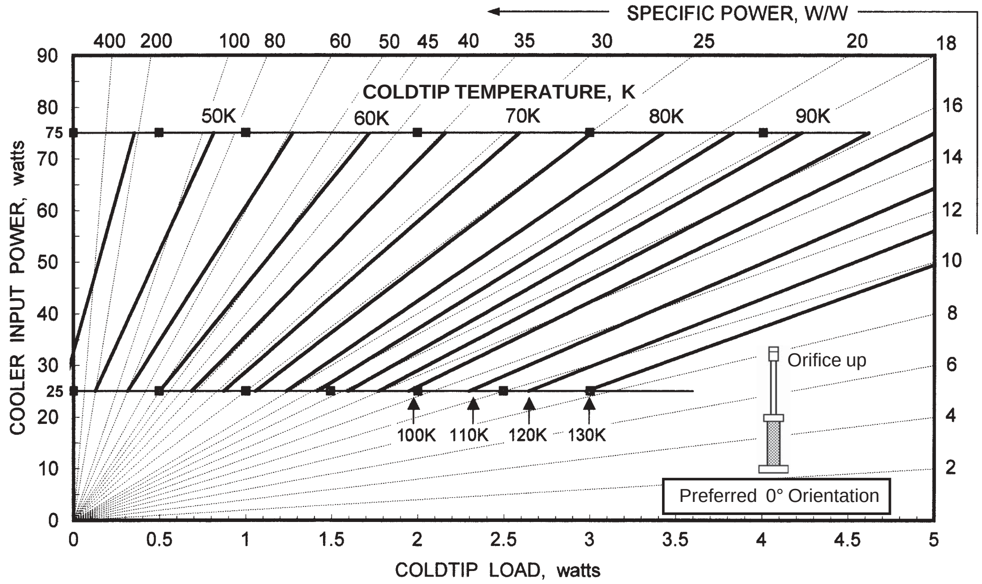


**Figure 9.** Measured performance of the IMAS pulse tube cooler at the preferred (0°) orientation.

*U-tube cooler orientation dependence*

Figure 10 shows the measured dependence of the gamma-ray cooler coldtip temperature on inclination angle with respect to gravity. These data were taken with a constant compressor input power of 40 watts—which is near the cooler's maximum stroke—and for various coldtip heater loads as shown; the drive frequency was 42 Hz, the coolers nominal value. Note that there is a significant increase in the coldtip temperature at angles beyond 80°, and that the angular dependence is similar to that of the increased off-state conduction shown earlier in Fig. 2. Note also that the data are very repeatable and well behaved, and that increased coldtip heater power, which varies the cooler no-load temperature, has no dramatic effect on the convection behavior.

To explore the expected dependency on pressure wave amplitude within the pulse tube, data were also acquired with the cooler operating at three input power levels: 20 watts, 30 watts, and

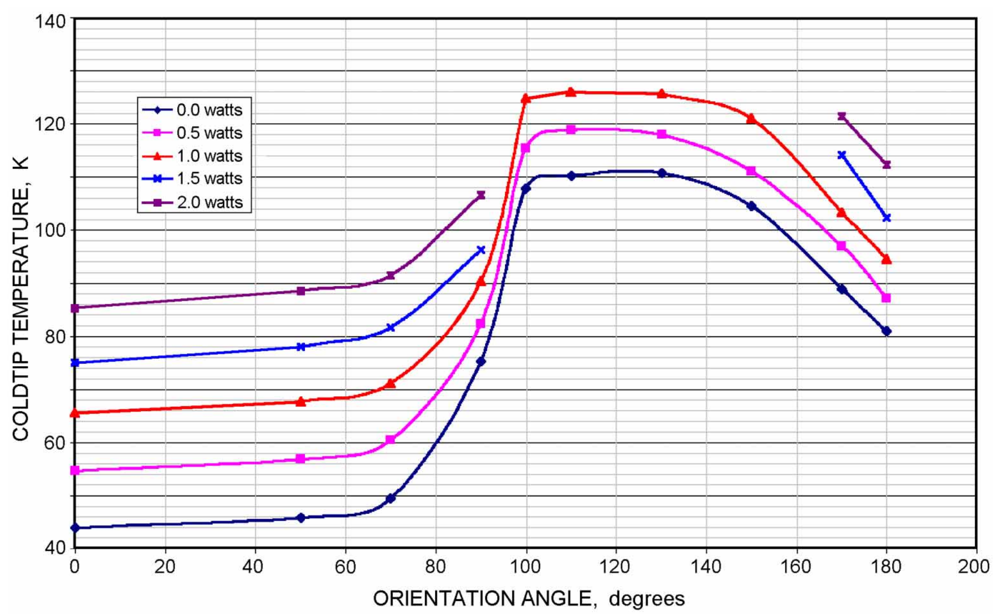


**Figure 10.** Dependence of coldtip temperature on inclination angle for gamma-ray U-tube pulse tube cooler as a function of coldtip heater power level.

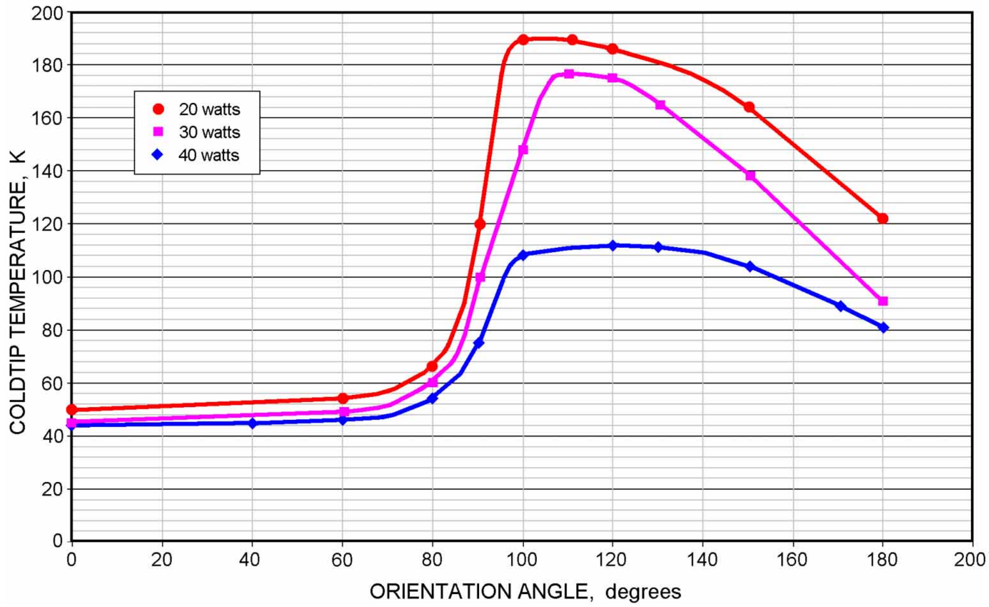


**Figure 11.** Dependence of no-load temperature on inclination angle for gamma-ray U-tube type pulse tube cooler as a function of compressor input power level.

40 watts. As shown in Fig. 11, the no-load temperature increase is found to be considerably larger for lower input power (stroke) levels. This is consistent with a higher amplitude pressure wave being able to break up the convection cell to some extent.

As a next step, the performance data in Fig. 8 were used to estimate the size of the parasitic load needed to increase the no-load temperature to the levels noted in Fig. 11. Figure 12 presents these calculated parasitic conduction loads as a function of angle using a polar-plot format. Note that the computed loads are quite large (>3 watts), and are very similar to the off-state conduction levels shown in Fig. 2.

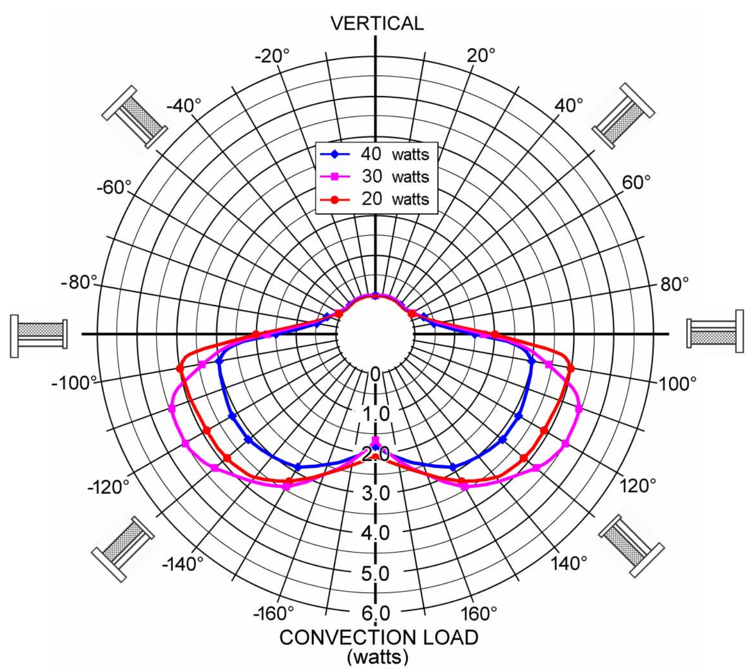


**Figure 12.** Computed parasitic convection load for gamma-ray U-tube type pulse tube cooler as a function of inclination angle.

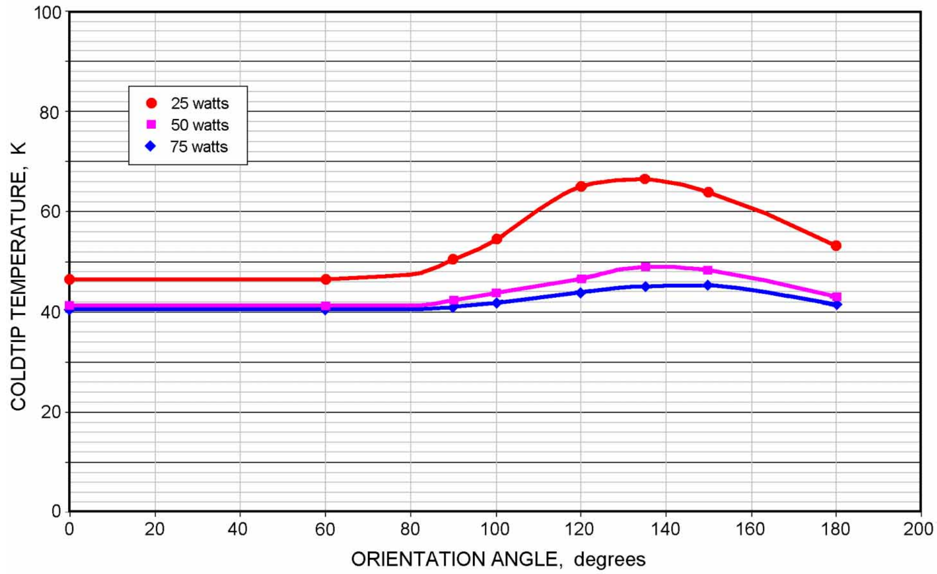


**Figure 13.** Dependence of no-load temperature on inclination angle for IMAS linear-type pulse tube cooler as a function of compressor input power level.

*Linear pulse tube cooler orientation dependence*

Figure 13 shows the less strong dependence of the IMAS cooler no-load temperature on inclination angle with respect to gravity. As with the gamma-ray cooler, these data were acquired with the cooler operating at three power levels; in this case: 25 watts, 50 watts and 75 watts, with the cooler's nominal drive frequency of 54 Hz. Note that the angular dependence is similar to the previous data, and that the no-load temperature increase is again larger for the lower input power (stroke) levels.

Figure 14, which makes use of the IMAS cooler performance data in Fig. 9, presents the estimated convection loads as a function of orientation angle. Although the load levels are much smaller than with the gamma-ray cooler, they are still appreciable (> 0.5 watt) for the worst case

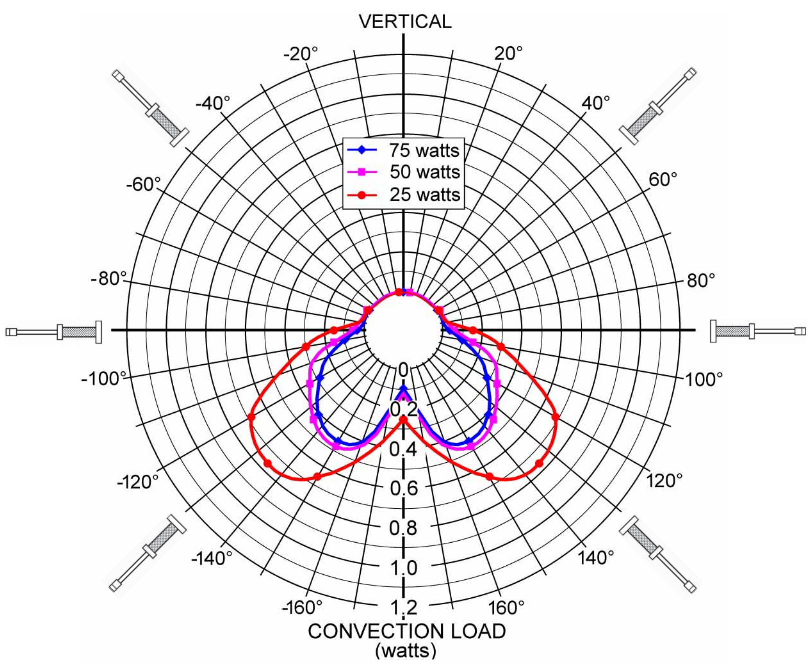


**Figure 14.** Computed parasitic convection load for IMAS linear-type pulse tube cooler as a function of inclination angle.

attitude, and are quite consistent with the ~300 mW parasitic loads observed during the TES instrument tests described earlier. It is speculated that the longer aspect ratio of the IMAS pulse tube is the reason for its convection parasitics being so much lower than those of the gamma-ray cooler.

## Summary

Gravity orientation has been found to have a modest effect on the performance of high frequency (30-60 Hz) Stirling-type pulse tube cryocoolers typical of those used in long-life space missions. The effects are very similar to those found previously in studies of the off-state conduction of pulse tube cryocoolers and in tests of the orientation sensitivity of low-frequency (~2 Hz) GM-style pulse tube cryocoolers.

To help quantify the angular dependency phenomena, this study has acquired data on both U-tube and linear-type pulse tubes. The data agree well with the orientation dependence observed at the system-level and the general angular dependence expected for convection processes. However, the significant difference observed between different pulse tube constructions suggests that there are important variables that need to be further understood and quantified. A key conclusion is that additional research is needed to identify the critical design drivers and to develop pulse tube designs that minimize convective effects in future space coolers.

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