Cryocooler Load Increase due to External Contamination of Low-ϵ Cryogenic Surfaces

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INTRODUCTION

Cryocooler loads can be roughly divided into three types: 1) Electrical power dissipation such as from a motor or focal plane, 2) conductive parasitics down supports and electrical cables, and 3) radiation loads dependent on surface emittances and view factors of hot objects that surround the cryogenic surfaces. In general, the electrical and conductive loads are relatively stable and predictable over the mission. However, the radiation loads are strongly dependent on surface temperatures and emittances that can change over time in less predictable ways.

Key drivers for radiation loads are:

- The effective emissivity of the cryogenic surface area. Because the load is directly proportional to the emittance, very low emissivity levels ($\epsilon < 0.05$) can result in smaller loads. However, very small changes in the emittance ($\Delta\epsilon \approx 0.05$) will have a very large effect.
- The temperature of the hot background that is radiating to the low-emissivity surface. Often the hot background is large in surface area relative to the cryogenic surface; this makes it have an effective emittance near unity and makes the system insensitive to changes in its emittance. However, the temperature of the hot background is a dominating parameter because the radiation load varies as the fourth power of its absolute temperature.
- The total cryogenic surface area subject to radiation; the load is directly proportional to the total cryogenic surface area.

Given the above, the most sensitive parts of a cryogenic system will be high-surface-area parts at cryogenic temperatures that view high temperature surrounds, and utilize very low emittances to reduce the load.

One of the most difficult challenges faced by the cryogenic system designer is trying to predict the long-term emittance of low-emittance surfaces as they are affected by contamination by condensed water films and outgassing products over the life of a mission. A key unknown is the actual effective vacuum level achieved in space in the interior of a typical science instrument.

This paper attempts to compile available flight data on contamination effects experienced during multi-year space missions and ground tests to date as a help to those designing and conducting future long-life missions with cryocoolers.

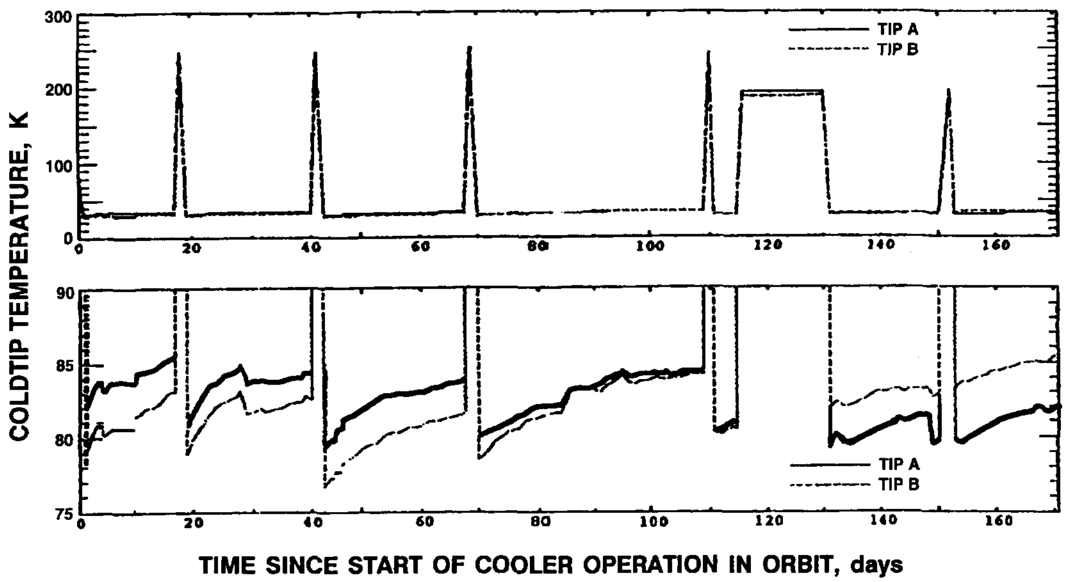

Figure 1. Coldtip temperature history for the ISAMS instrument aboard the UARS spacecraft.[1] Vertical excursions are decontamination cycles where the instrument was heated to near room temperature to outgas the contaminants that were gettered to the instrument's cold surfaces.

APPROACH TO ESTIMATING CONTAMINATION SENSITIVITY

Quantifying the rate of contamination and its effect on the cryogenic radiative load of a cryosystem is difficult at best, with little quantitative data or methodology in the literature. However, experience with cryogenic load increases during cryocooler flight missions and life testing provides quantitative insight into this important issue.

ISAMS Flight Experience

Figure 1 highlights the cryogenic temperature increase[1] experienced by the ISAMS instrument after it was launched aboard the UARS platform in September 1991. This application utilized two Oxford 80 K cryocoolers running at ~83% stroke to hold a number of cryogenic detectors near 80 K. Immediately after turn-on in orbit, it can be seen that the temperature of the detectors increased by around 5 K (from 80 to 85 K) over a three-week period. This temperature increase, which is considered to be the result of contamination gettered onto the cold plumbing's low-emittance surfaces, necessitated conducting a number of high-temperature decontamination cycles. Over time, the level of contamination slowly subsided, and after a year in orbit, the time required to reach a five-degree ΔT gradually increased to 2-3 months.

To estimate the level of load increase associated with the 5 K ΔT one can appeal to the performance curves[2] for the 80 K BAe cooler shown in Fig. 2. From these curves it is seen that a temperature change from 80 to 85 K at a constant piston stroke (83% of 8 mm = 6.64 mm) equates to a load increase of around 100 mW per cooler, or a 12% increase in the total cryogenic load. Understanding the actual level of emittance increase would require knowledge of the total cryogenic surface area involved.

MOPITT Flight Experience

As a second example, the MOPITT instrument initiated operation in March 2000 aboard the NASA EOS Terra spacecraft.[3] The instrument uses two back-to-back BAe 50-80K coolers to cool two detectors: #1 at around 92K, and #2 at around 85K. The instrument uses closed-loop control of the cooler stroke to maintain the #1 coldtip at a constant 78 K to control the #1 detector temperature, while the second cooler is forced to match the stroke of the first to maintain vibration control; the second cooler's cold-tip temperature thus varies somewhat.

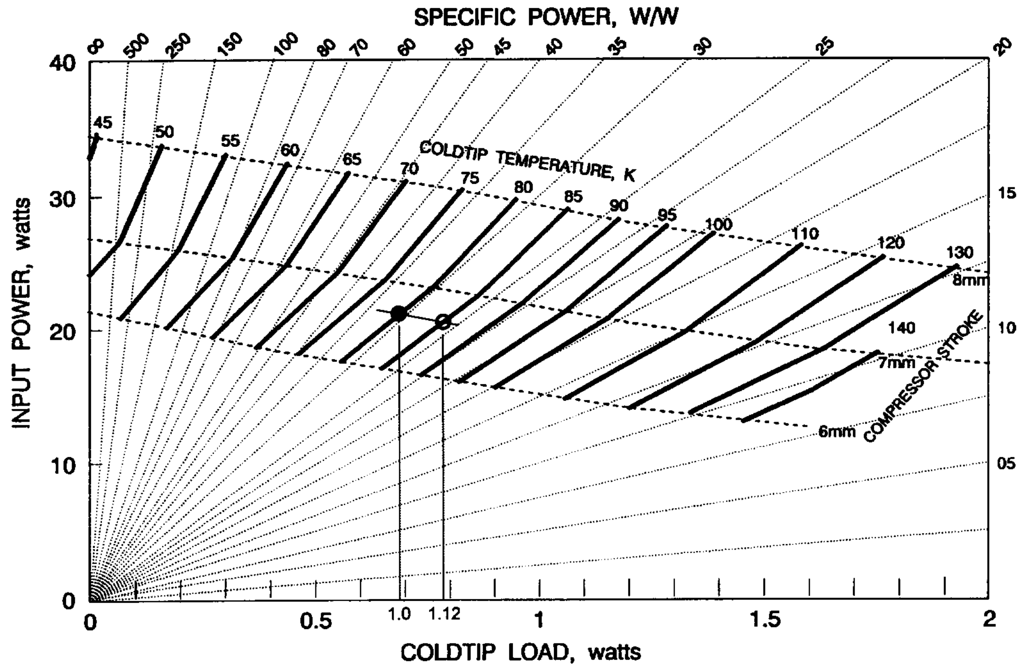

Figure 2. ISAMS warm-up data[1] superimposed on representative performance[2] of a BAe 80 K cryocooler plotted versus coldtip temperature, stroke, and input power for a 300 K heatsink temperature.

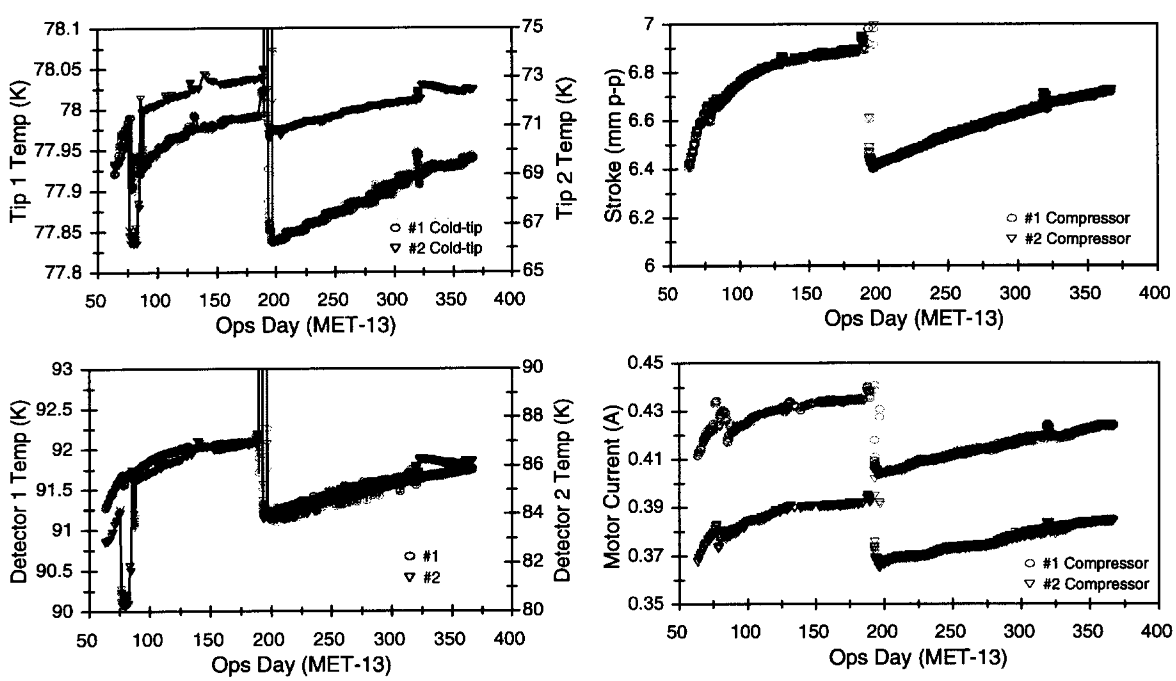

Figure 3. Cryocooler-coldtip and detector temperature and compressor stroke and current history for MOPITT instrument from beginning of mission to Ops day 370.

Figure 3 describes the stroke and temperature history of the MOPITT coolers during the first year of mission operation. Note the decontamination warm-up cycle that was carried out around day 190 to recover gradual deterioration of the instrument's science quality. During the first part of the mission it can be seen that the cooler stroke increased from 6.4 to 6.9 mm p-p to carry the gradually increasing cryogenic load. After the decontamination cycle, the load fully recovered to its original value and the cooler stroke returned to 6.4 mm. Note also that contamination after the warm-up cycle reoccurred at a much slower rate than the original contamination.

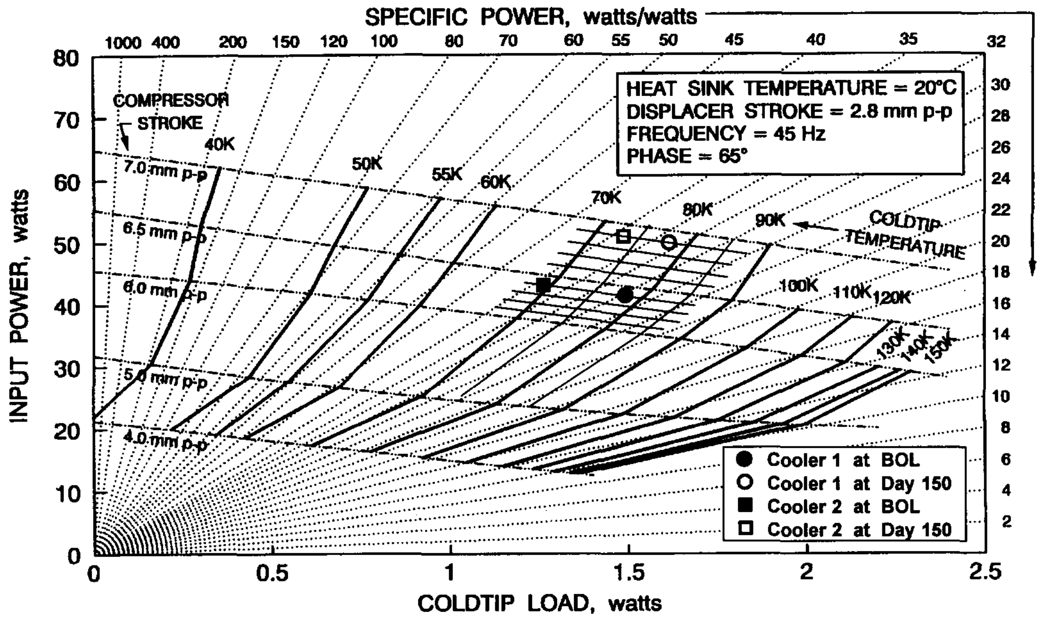

Figure 4. MOPITT cryocooler operating points superimposed on the performance[5] of a typical BAe 50-80K cryocooler plotted versus stroke, input power, coldtip load, and coldtip temperature.

To estimate the level of load increase that occurred one can examine representative curves[5] for the performance of the BAe 50-80K cooler as shown in Fig. 4. By plotting the MOPITT operating points on these curves it is seen that a stroke increase from 6.4 mm to 6.9 mm at the observed coldtip temperatures corresponds to a load increase of about 130 mW (8%) for cooler #1 and 230 mW (15%) for cooler #2. This is not too different from the ISAMS experience, although ISAMS conducted its decontamination cycles at more frequent intervals.

BAe 80 K Cooler Life Test Experience

As a third example, a BAe 80 K cooler was life-tested in a vacuum bell jar at TRW in 1992 for around 170 days.[6] During this lifetest the chamber was maintained with a vacuum around 10^{-5} torr, and the cryocooler coldfinger was wrapped with multilayer insulation (MLI). As shown in Fig. 5, the coldtip experienced a continuous temperature increase over the lifetest period at a near-

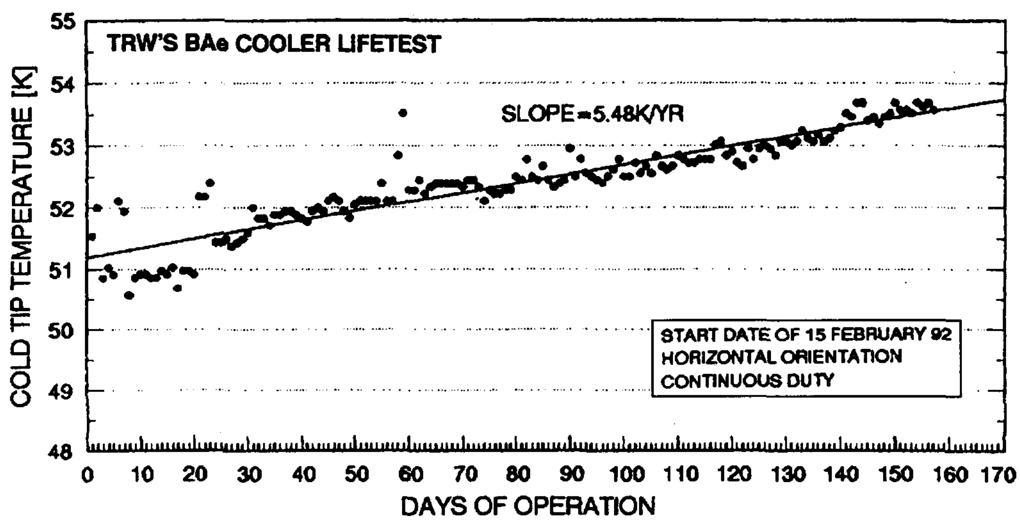

Figure 5. Performance degradation observed in lifetesting a BAe 80K cryocooler; performance degradation was determined to be increased radiation parasitics due to degradation of the coldfinger MLI properties due to gettered contaminants; performance returned to normal after a room-temperature decontamination cycle.

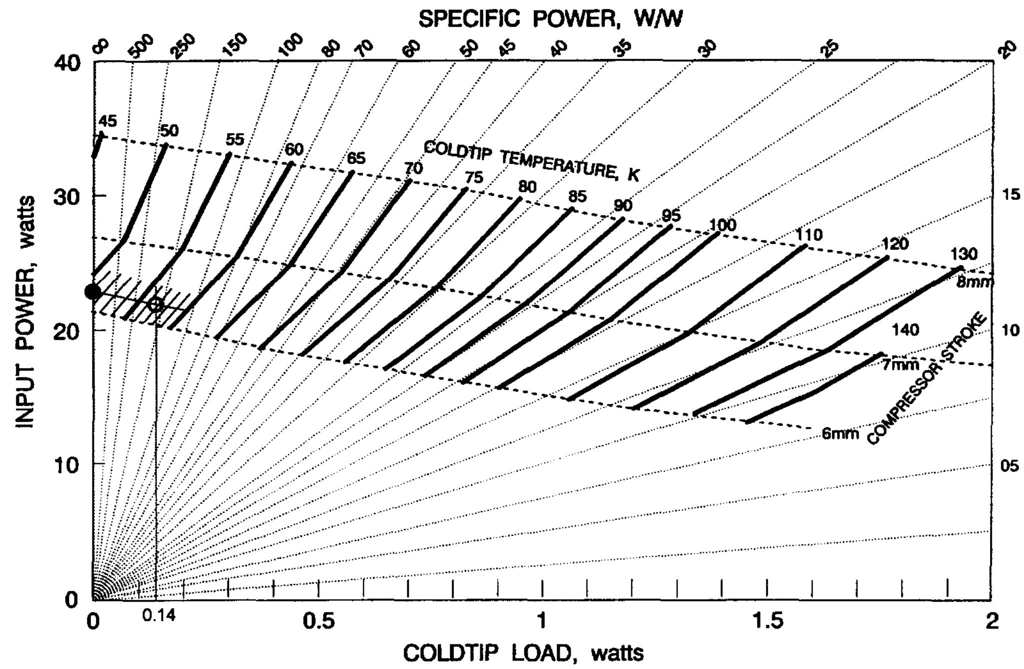

Figure 6. TRW lifetest data[6] superimposed on representative performance[2] of a BAe 80 K cryocooler plotted versus coldtip temperature, stroke, and input power for a 300 K heatsink temperature.

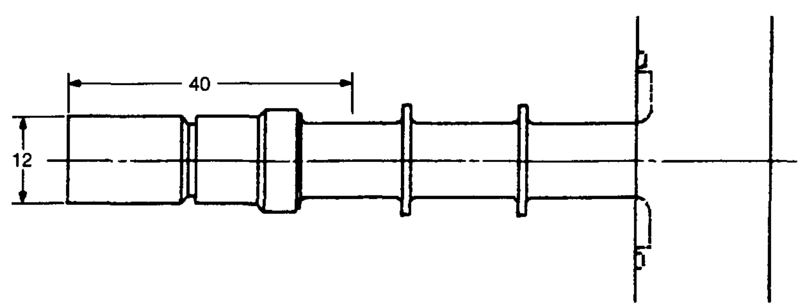

Figure 7. Scale drawing of the BAe 80K cryocooler coldfinger (dimensions are in mm); the estimated cryogenic surface area is approximately 25 cm^2.

constant rate of 5.48 K/year. Similar to the ISAMS and MOPITT performance, the performance degradation was traced to contamination of the low-emittance thermal surfaces. From Fig. 6 it can be seen that 5.48 K/year at around 52 K equates to a radiation load increase of around 140 mW/year, again similar to the ISAMS and MOPITT experience.

To evaluate the load increase in terms of emittance increase requires the surface area of the cold surfaces and the temperature of the hot surrounds. Figure 7 is a scale drawing of the BAe 80K coldfinger from which the MLI area has been estimated to be around 25 cm^2. The bell jar was at room ambient (296 K). Solving for the increased emittance gives:

$$\begin{aligned} \Delta\epsilon &= \Delta Q \,/\, [5.67 \times \text{area} \times (T_H/1000)^4] \\ &= 0.14\,\text{W} \,/\, [5.67 \times 25\,\text{cm}^2 \times (296/1000)^4] \\ &= 0.13/\text{year} \end{aligned}$$

CONCLUSIONS

Although the data set is small, experience indicates that around a 10-20% load increase may be expected on-orbit due to contamination of low-ϵ surfaces. This is for a typical cryogenic space instrument with a total cryogenic load on the order of one watt. Although a well established way to deal with the load increase and potential science degradation is to periodically boil off the contaminants by heating the cryogenic surfaces to near room temperature, this deep thermal cycling is very stressful in that it can lead to mechanical fatigue failure of detectors and other cycled components. To keep the decontamination cycling to an acceptable level, it appears that cryocoolers need to be able to accommodate a cryogenic load increase of 10-20% due to cryogenic surface contamination. Additional cooling capacity margin needs to be employed to provide for increases in radiation sink temperature and any gradual loss of the cooling capacity of the cryocooler itself.

ACKNOWLEDGMENT

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