AIRS Pulse Tube Cooler System-Level and In-Space Performance Comparison

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ABSTRACT

During this past year, JPL's Atmospheric Infrared Sounder (AIRS) instrument completed thermal vacuum testing at the spacecraft level, and was launched into Earth orbit on NASA's Earth Observing System Aqua platform on May 4, 2002. The instrument, which is designed to make precision measurements of atmospheric air temperature over the surface of the Earth, uses a redundant pair of TRW pulse tube cryocoolers operating at 55 K to cool its sensitive IR focal plane. This use of redundant coolers with no thermal switches creates certain challenges when it comes to performance measurement and verification at the systems level. In support of the mission, new test and analysis techniques have been developed to allow accurate intercomparison of cooler-level, instrument-level, spacecraft-level, and in-space performance of the coolers. The driver for the development of these techniques is the strong dependency of the performance of the cooler system on gravity. Specifically, the off-state conductance of the non-operating redundant cooler is highly dependent on convection, and thus gravity level and orientation. Because the instrument-level, spacecraft-level, and in-space environments have substantially different orientations and gravity levels, special test and analysis techniques had to be developed to allow accurate intercomparison of the results. This paper presents the derivation of the test and analysis techniques as well as the measured system-level performance of the flight AIRS coolers during instrument-level, spacecraft-level, and in-space operation.

INTRODUCTION

A critical aspect of the integration of a cryocooler into a high-value application, such as a multibillion dollar spacecraft, is monitoring and confirming the health of the cooler system after each important stage of integration and qualification testing: 1) after completion of the cooler itself and its qualification testing, 2) after integration of the cooler into its immediate application (instrument) and the instrument-level qualification testing, 3) after integration of the overall instrument onto the spacecraft and spacecraft-level qualification testing, and 4) after launch of the entire instrument/spacecraft system into space.

Initial testing of a development model cooler is generally relatively straightforward as such coolers may be fully instrumented with few constraints on access to measurement data such as true-rms input power to the compressor, or heat applied to the cold-load interface. In contrast, a flight model cooler often will come with space-quality drive electronics that provide little or no ability to accurately assess the internal distribution of power such as that going to the compressor. And once

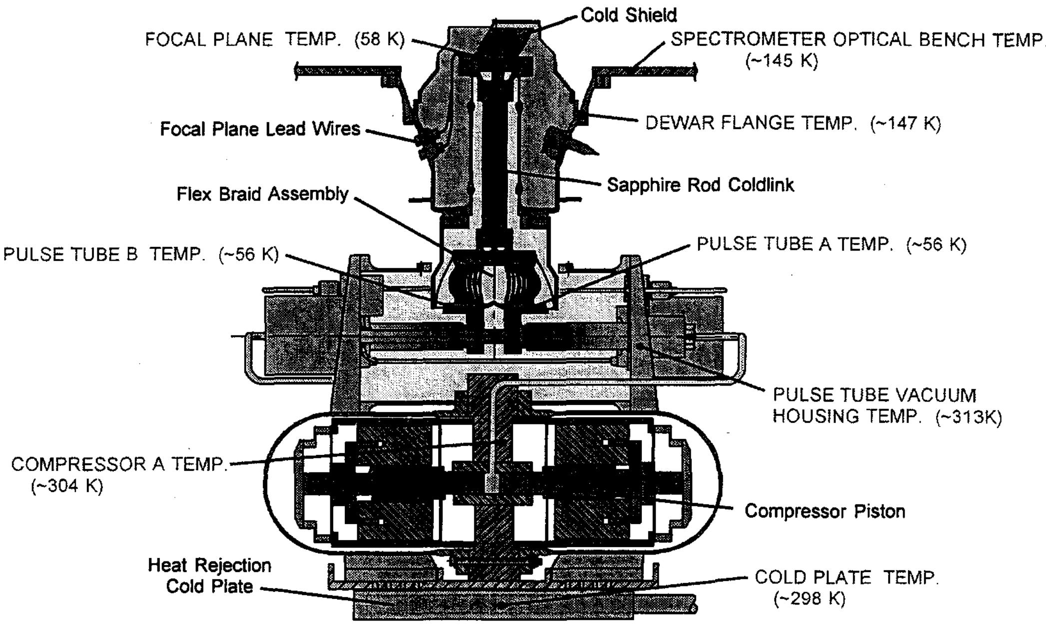

Figure 1. Schematic illustration of the cryogenic components of the AIRS instrument with the location of key temperature measurements.

the cooler is integrated into the instrument, generally the details of the cryogenic load become obscured by the dozens of unquantified load contributors and test environment variables such as MLI effectiveness, vacuum level, and background temperatures.

In addition to these typical performance verification issues, the AIRS instrument has a redundant pair of cryocoolers, and the thermal conduction loss to the off cooler, which equals ~40% of the total cryogenic load, is gravity and orientation dependent. This is because the conduction load of the off cooler is dominated by convection within its pulse tube, and the gaseous convection is highly sensitive to orientation with respect to gravity, and thus to the presence of gravity. The problem of cooler performance verification at the various stages of cooler, instrument, and spacecraft integration is further compounded by the inevitable fact that the cooler orientation is likely to be, and was for AIRS, different in each test, and was of course different again in space.

The focus of this paper is on how these issues of performance verification and tracking were successfully dealt with for the specific example of the AIRS instrument and its redundant pair of pulse tube cryocoolers.

AIRS INSTRUMENT CRYOGENIC AND CRYOCOOLER DESIGN

The technical foundation of the AIRS instrument is a cryogenically cooled infrared spectrometer that uses a pair of TRW 55 K pulse tube cryocoolers to cool the HgCdTe focal plane to 58 K.[1] The instrument also includes a 150 K-190 K two-stage cryogenic radiator to cool the optical bench assembly to around 150 K. Configurationally, the 58 K IR focal plane assembly is mounted integrally with the 150 K optical bench, which is in-turn shielded from the ambient portion of the instrument by the 190 K thermal radiation shield and MLI blankets. The ambient portion of the instrument contains the high power components including the instrument electronics and the cryocoolers and their electronics.

Figure 1 schematically illustrates the cryogenic elements of the AIRS instrument design. As noted, the system incorporates two independent 55 K pulse tube cryocoolers, a primary and a non-operating backup, each connected to the 58 K focal plane using a common high-conductance coldlink assembly. Ambient heat from the operating cooler is rejected to the coldplates located in the plane of the instrument/spacecraft interface. Table 1 provides a breakdown of the overall cryocooler beginning-of-life (BOL) refrigeration load measured on the AIRS Engineering Model (EM) instrument, and projections of representative end-of-life (EOL) properties. A key determiner of these BOL/EOL loads is the BOL/EOL temperature of the optical bench and pulse tube vacuum housing—assumed to be 145 K/160 K and 309 K/314 K, respectively.

Table 1. AIRS Baseline cryocooler heat loads for beginning-of-life (BOL)/end-of-life (EOL) optical bench (OB) and pulse tube vacuum housing temperatures of 145 K/160 K and 309 K/314 K, respectively.[1]

ITEM	Load (mW) BOL	Load (mW) EOL
FP and coldshield radiation load from OB	73	108
Focal plane electrical dissipation	193	193
Focal plane lead wire conduction	98	118
Focal plane structural support conduction	129	158
Radiation to coldlink from OB	17	24
Radiation to coldlink from vacuum housing	177	195
Off-state conduction of redundant cryocooler	486	496
Total cryocooler load	1173	1292

To provide an initial performance benchmark, extensive characterization of theAIRS cryocooler performance was carried out during the cooler development and qualification testing phases at TRW and JPL.[2] Of particular interest is the measurement of the cooler's off-state conduction as a function of orientation angle, shown in Fig. 2, and the cryocooler overall system-level refrigeration performance shown in Figs. 3a and 3b for a heatsink temperature of 25°C.

Because the AIRS coolers' pulse tubes face in opposite directions, the preferred orientation for testing is with the off cooler's pulse tube facing up as noted in the drawing in Fig. 2. This orientation inhibits convection and gives the ~0.5 watt conduction load expected in space as noted in Table 1. Note in Fig. 2 that when the off pulse tube is inverted or horizontal, the measured conduction load is double or triple the 0.5 watt value due to convection effects.

AIRS Cryocooler Instrument Level Testing

During instrument-level testing the cryocoolers' performance was repeatedly characterized to provide a prediction of the expected space performance, and to confirm that no degradation had occurred to either cooler due to imposed qualification test environments.[3] However, because of test geometry limitations, the pulse tube orientation was either fixed with the cooler A pulse tube vertically up, or with both pulse tubes horizontal. Thus, the data interpretation was immediately faced with the large and uncertain angle-dependent conduction load noted in Fig. 2. The means used to resolve the large gravity-dependent load increase was to run both coolers simultaneously, unlike their

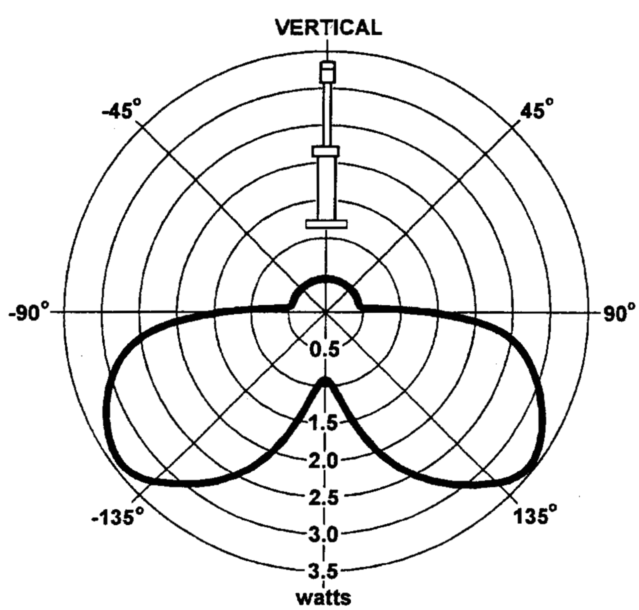

Figure 2. Measured off-state conduction of the AIRS cryocooler as a function of pulse tube orientation with respect to gravity.

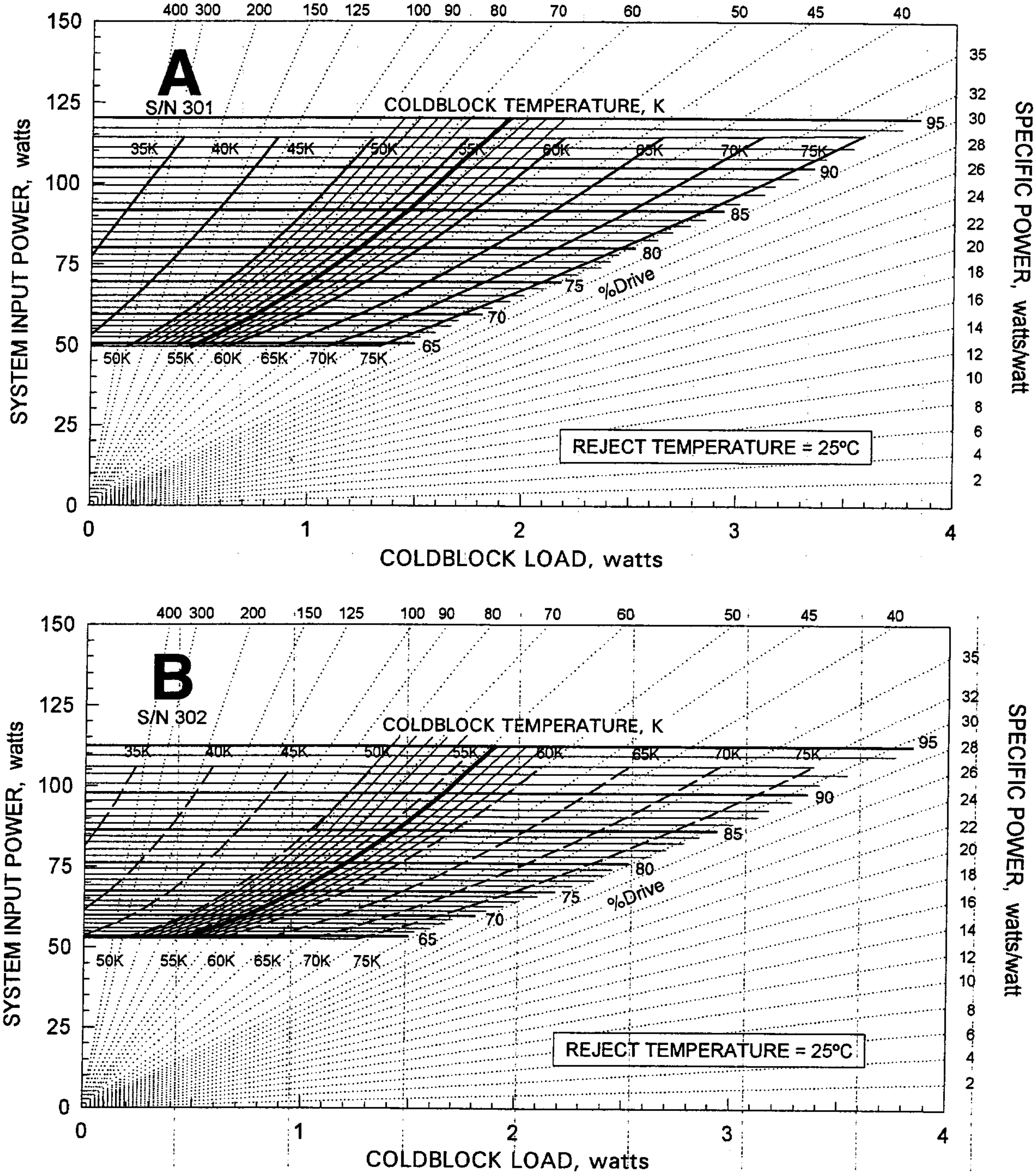

Figure 3. Measured cryocooler heat-load performance of AIRS coolers A (top) and AIRS cooler B (bottom) as a function of input power into the drive electronics and the %Drive compressor drive level.

operation in space. The challenge was thus to predict the coolers' eventual in-space performance and health from a test configuration that differed significantly from the space operating conditions.

TEST METHOD OVERVIEW

The test methodology developed for assessing cryocooler performance is fundamentally based on comparing the "measured cryogenic heat load" at any point in the integration and test flow against a "baseline predicted heat load" derived from analytical modeling calibrated using heritage measurements as presented in Ref. 2. The "baseline predicted heat load" is essentially that shown in Table 1, and involves contributions from the focal plane dewar assembly, from the cold rod and its flex braid

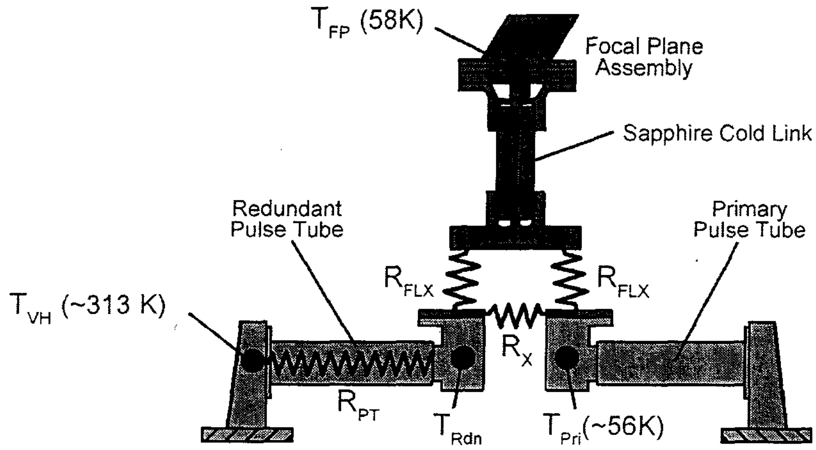

Figure 4. Electrical circuit analog for the interconnection of the coldend elements of the AIRS instrument.

assembly, and from the coldblock region of the pulse tubes themselves. As usual, the devil is in the details, and in this case the detail is how the heat load is "measured" when the second redundant pulse tube is presenting a large unknown heatload contribution.

The fundamentals behind the methodology are most easily seen by appealing to Fig. 4. This figure presents an electrical circuit analog for the interconnection of the two pulse tubes and the cold link assembly in the AIRS instrument. The resistor network flowing from the primary cooler through the redundant cooler represents the 'off cooler' thermal resistance to the ~313 K pulse tube heat rejection temperature. In particular the R_{PT} resistor represents the highly variable and thus unknown thermal resistance of the redundant pulse tube as noted in Fig. 2.

Appealing to Fig. 4, it is seen that the off-cooler heat load may also be defined in terms of the resistors R_X and R_{FLX} and the pulse tube coldblock temperatures T_{Pri} and T_{Rdn}, independent of the value of R_{PT}. The temperatures T_{Pri} and T_{Rdn} are indeed known, and are accurately measured in flight as part of the AIRS cooler closed-loop temperature control operation of the two coolers. Thus, we have a way of quantifying the load presented by the off cooler by monitoring the $\Delta T = (T_{Rdn} - T_{Pri})$ between the two pulse tube coldblocks. Because this $\Delta T = (T_{Rdn} - T_{Pri})$ is not always controllable, the performance assessment methodology uses ΔT as a characterization variable as shown in the detailed steps enumerated below.

Detailed Performance Measurement Steps

The rationale and details of each of the measurement steps are described below:

1) **Achieve Baseline Operating Conditions.** Adjust the cryocooler drive levels and heat rejection temperatures to achieve the baseline flight operating conditions as defined below:
   - Cryocooler cold plate temperature: 293 ±10K (preferably 293±1K)
   - Spectrometer Temperature: 155 ±10 K (preferably 154±1K)
   - Primary pulse tube temperature: 56 K±0.1K
   - Redundant pulse tube temperature to achieve $\Delta T = (T_{Rdn} - T_{Pri}) \approx 2$ K±1K
   - Focal plane temperature: 58K±2K

   Because this baseline set of operating conditions is not totally controllable, the critical parameters have been given a range and a preferred target value. The reference baseline load is then adjusted for the actual test conditions achieved, as described in step 3.

2) **Heat Load Determination.** No instrumentation is available to measure the total cryogenic heat load in the AIRS instrument. However, if the cooler performance has not degraded, the cooler input drive level, which is monitored in the flight system, can be used to estimate the cryogenic load. This requires the use of previously measured performance characteristics of the coolers as presented in Figs. 3a and 3b, with an appropriate correction applied if the heat rejection temperature is different from that used in the plots. Specifically, to determine the total cryocooler heat

load, a point is placed at the intersection of the cooler %Drive applied to the primary cooler and the effective coldblock temperature (T*) of the primary cooler. The effective coldblock temperature (T*) is the ~56 K coldblock test temperature adjusted to correct for compressor heat rejection temperatures that are different from the 298 K baseline for which Figs. 3a & 3b were generated. T* is defined in terms of the measured pulse tube coldblock temperature of the primary cooler (T_{Pri}) and the compressor cold plate temperature (T_{CP}) by the following equation:

$$T^* = T_{Pri} + (298\ K - T_{CP})/10 \qquad (1)$$

The total cryogenic heat load is then read from the plot abscissa directly below the plotted point. Equation (1) was derived using the measured relationship between heat rejection temperature and coldblock temperature shift as described in detail in Ref. 4

3) **Baseline Load Determination.** The AIRS cryocooler baseline heat load is the reference heat load used for comparison against the "measured" heat load in any give verification test. In particular, it is the data contained in Table 1 adjusted for the effects of the actual test temperature of the AIRS optical bench (dewar flange), and the actual test temperature of the AIRS cryocooler vacuum housing. Because the vacuum housing temperature is not measured directly, this temperature can written in terms of the cryocooler heat rejection temperature and the 15°C measured vacuum housing temperature rise above the reject temperature. In equation form, the baseline heat load is written as:

$$Q=(110\ \epsilon_{FP}+ 97\ \epsilon_{RD} + 11.3)(T_{DF}/100)^4 + (32.3\ \epsilon_{FLX}+ 30.6\ \epsilon_{PT})(T_{VH}/100)^4 + 2.58(T_{DF}-56) + 570 \qquad (2)$$

where: ϵ_F = Focal plane emittance (~0.04)
ϵ_{RD} = Sapphire rod emittance (~0.04)
ϵ_{FLX} = Flexlink MLI emittance (~0.06)
ϵ_{PT} = Pulse tube MLI emittance (~0.04)
T_{DF} = Dewar flange temperature (~155K)
T_{VH} = Pulse tube vacuum housing temperature (cold plate temperature + 15 K)

When the baseline parameter values shown above are used, Eq. 2 reproduces the baseline cryocooler load components presented in Table 1. The equation is also used to determine the baseline cryocooler load for other dewar flange and cooler cold plate temperatures.

4) **Heatload Variance.** Compute the variance (Δheatload) between the determined heat load and the baseline heat load for the test condition. This is just a subtraction of the results of step 2 from the results of step 3. The Δheatload is then plotted on a plot of Δheatload versus pulse tube temperature differential $\Delta T = T_{Rdn} - T_{Pri}$.
5) **Coldrod Heatload Assessment.** As an additional check on the system health, the temperature difference between the focal plane temperature and the average temperature of the two pulse tube cold blocks $T_{Ave} = (T_{Pri} + T_{Rdn})/2$ can be computed. Given the fixed thermal resistance of the coldrod assembly and flexbraid, this value provides an assessment of the dewar heatload conducted down the coldrod assembly that can be compared with heritage values.

AIRS COOLER DATA ANALYSIS

Using the above methodology, a number of AIRS cooler performance measurements have been analyzed using data acquired: 1) during AIRS instrument-level integration and test at Lockheed Martin (LMIRIS) in Lexington, MA in 1999, 2) during instrument checkout in the Aqua spacecraft thermal vacuum testing at TRW in Redondo Beach, CA during September 2001, and 3) after AIRS cooler turn-on in space in June 2002. During these tests the pulse tubes had a variety of orientations with respect to gravity, and in many cases both pulse tube coolers were run simultaneously to defeat the large convective heat load that would have occurred if the redundant cooler had been turned off.

Figure 5 provides an intercomparison of these three data sets made by plotting the difference between the measured cryocooler heat load and the baseline heat load against the pulse tube differen-

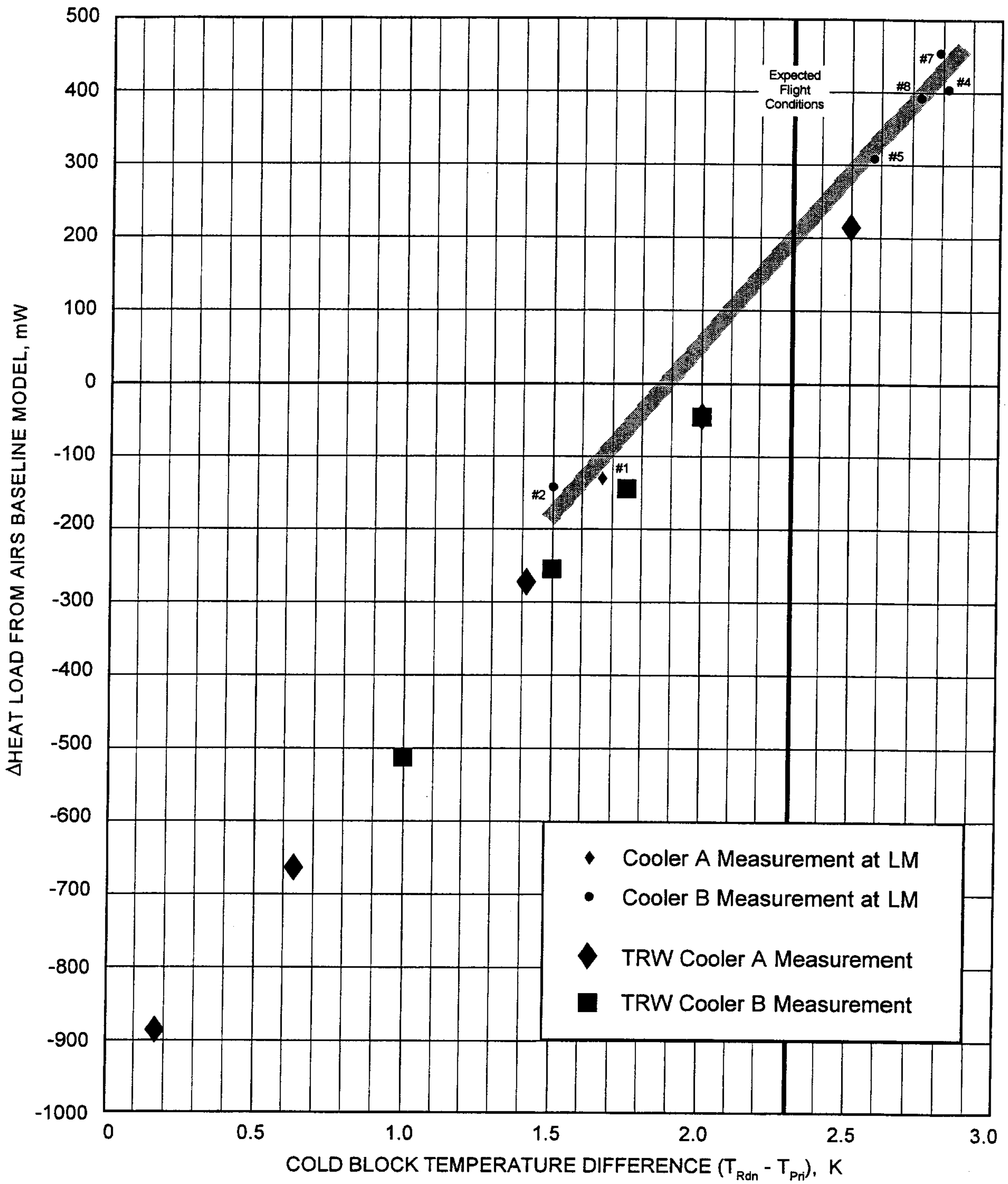

Figure 5. AIRS cryocooler Δheatload versus coldblock temperature difference; measurements made in TRW S/C T/V test and instrument-level measurements made at LMIRIS in Lexington, MA.

tial temperature ($\Delta T = T_{Rdn} - T_{Pri}$) as described earlier. Note the strong and uniform dependence of the measured performance on pulse tube temperature differential (ΔT) and the ability to easily interpret the relative performance of the various test cases. Understanding the performance of the primary operating cooler as a function of this temperature differential was an important accomplishment that enabled comparison of these diverse data sets.

Note that the measured data after spacecraft integration in 2001 are consistent with the cooler performance measured at the instrument level in 1999. If anything, the data suggest a ~80 mW improvement (lower load) and show no signs of any type of degradation. This improved performance may be partially due to the careful effort made to outgas the Aqua S/C and the AIRS instrument prior to cooling the spectrometer and coolers in the large spacecraft T/V chamber at TRW. Perhaps most important, these tests were conducted immediately after spectrometer cooldown, perhaps before any long-term contamination had a chance to build up on the low-emittance coldend surfaces.

SUMMARY

In summary, a test methodology has been developed that allows the thermal performance of a complex flight system to be monitored through changing environmental conditions using only the flight telemetry data. The needs and complexity of such performance monitoring are often overlooked during the initial instrument design phase, and may only surface late in the testing process. This was the case for AIRS, and it is hoped that the successful lessons learned presented here will be of value to future cryogenic applications. Most importantly, the acquired data confirmed that the AIRS coolers and dewar were performing to specification and ready to support the flight mission's science objectives.

ACKNOWLEDGMENT

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