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DESIGN AND TEST OF A COMPREHENSIVE FACILITY FOR LIFE-TESTING SPACE CRYOCOOLERS

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ABSTRACT

With the growing commitment of long-life Stirling cryocoolers to multi-year NASA and SDIO space applications, there is increasing need for quantitative data verifying the long-term performance of the coolers and identifying any possible time-dependent degradation or wear-out failures. To obtain such data, JPL has designed and fabricated comprehensive life-testing facilities for use by the Air Force Phillips Laboratory (AFPL) and the Jet Propulsion Laboratory (JPL). These life-test facilities are directed at acquiring quantitative cooler performance data in three areas: 1) refrigeration performance including thermal efficiency, long-term temperature stability and possible effects of contamination and wear, 2) level and stability of generated vibration including long-term performance of vibration cancellation technologies, and 3) illumination of any wear-out or random failure mechanisms that need to be corrected prior to flight hardware deliveries. To provide these functional capabilities, the developed life-test chambers incorporate a number of unique features including thermostatically controlled thermal-vacuum heatsink environments, continuous monitoring of cooler-generated vibration, and active fault detection.

INTRODUCTION

Worldwide cooler development programs involve the development of a number of long-life cryocoolers for future space applications. These coolers are intended to provide continuous cooling at cryogenic temperatures from below 10K to as high as 150K for periods of time up to 10 years; they utilize a variety of thermodynamic cycles such as Stirling, pulse tube, turbo-Brayton, and sorption. Although thermodynamic cooling performance is a necessary attribute, operational life and reliability is the critical parameter that separates these long-life space cryocoolers from the relatively short life (2000 to 5000 hour life) "tactical" coolers commonly used in ground and airborne applications.

There is an important need within the space-cooler community for thorough and accurate data on the reliability performance of these space cryocoolers to assist both systems developers in their design of cryogenic sensor systems, and cooler developers in their process of understanding design strengths and resolving identified limitations. Although early life-test data has become available for the first of the long-life space cryocoolers, the Oxford/BAe 80K cooler [1], no life tests have yet been initiated on the emerging second-generation coolers containing the advanced thermodynamic and vibration-suppression features required for the most recent space-instrument programs.

To meet the growing requirement for comprehensive life-test data on emerging space cryocoolers, JPL has developed specialized facilities specifically addressed to the unique demands of conducting life tests in simulated space environments and accurately measuring the broad array of critical performance parameters. The development effort reflects a combined program between the Air Force/Phillips Laboratory, Albuquerque, NM, and the Jet Propulsion Laboratory under a combination of SDIO and NASA funding. This paper first discusses the detailed test objective and approach addressed by the facility design, and then describes details of the thermal-vacuum test chambers and the performance measurement and data acquisition system.

LIFE TEST OBJECTIVES AND IMPLEMENTATION CONSIDERATIONS

There are at least three key objectives of life testing: one focused toward management-level needs, one focused toward the needs of the cooler development teams, and the third focused to the needs of the cooler users or application system designers.

1) The first objective is to demonstrate the ability of a test cryocooler to operate with good reliability over an extended period of time. This is the most general of the objectives and is focused toward providing confidence to high-level program management needing to judge the maturity of a particular cryocooler design and its general suitability to long-life space missions. Meeting this objective does not require that a cooler never fail; rather it requires that the number of failures and the type of failure mechanisms be consistent with reliably correcting any identified weaknesses within the budget and schedule constraints of the build cycle of a typical flight program.

2) The second objective is directed at the identification of failure modes and inadequate design features that need to be corrected. In particular, this objective is directed at detecting generic long-time-constant failure and degradation mechanisms that do not become visible until after an extended period of operation and aging. Examples include contamination due to extended outgassing of internal materials, long-term wear of contacting or rubbing parts, long-term thermal degradation of the physical properties of polymers (e.g. embrittlement, cracking, shrinkage), fatigue of cyclically loaded elements, long-term breakdown of electrical insulation materials, loss of dimensional stability of close tolerance parts, long-term creep of materials operating at high homologous temperatures (solders, polymers, gasket materials), and long-term drift of electronic component parameters. Although every attempt is made to adequately address long-time-constant mechanisms during the cryocooler design process, extended life data covering such mechanisms is often unavailable, and some critical issues are likely to escape early detection. Because such mechanisms are often common to every

cooler of the same design, even a single test cooler is often quite effective in identifying such mechanisms. On the other hand, long-time-constant mechanisms that stem from inadequate process control--such as cooler cleaning and outgassing, or part machining and assembly accuracy--generally require multiple test coolers to quantify the likely variability.

3) The third objective is to accurately quantify any long-term change in cryocooler performance that occurs over time. Although many long-time-constant mechanisms identified as part of the second objective cause catastrophic cooler failure and need to be corrected, others can lead to gradual erosion of performance, and be quite acceptable if properly taken into account during the application design process. This third objective is to accurately quantify the level and nature of any gradual change from initial beginning-of-life performance so that system designs using the cooler can introduce the necessary performance margin to account for the expected change.

To meet the above objectives, particularly the second and third, it is necessary to: 1) identify the cooler performance attributes of interest and how they can best be accurately monitored, and 2) identify the operating mode and environment that will best surface the critical long-term degradation and failure mechanisms without causing extraneous problems.

Key Performance Attributes

The primary cooler performance attribute of interest is cooler cold-end heat capacity and its stability for a given set of fixed input conditions such as piston stroke and input power; that is, constancy of refrigeration efficiency over many years. Stability of cold-end temperature over lesser periods of time is also important and relates to the ability to hold the cold end at a fixed temperature over time without excessive closed-loop temperature control.

In addition to cooler thermal performance, the ability of the cooler to maintain acceptably low levels of generated mechanical vibration over many years is also a critical issue for most precision space-instrument applications.

Test Environment Considerations

Because the degradation rate of most aging mechanisms is strongly dependent on ambient temperature, utilizing elevated temperatures to shorten the required test time is common in the field of life testing. Unfortunately, the presence of tight temperature-sensitive alignments and tolerances in most cryocoolers makes exposure to abnormal temperatures likely to cause rapid unrealistic failures that are not coupled to the real failure mechanisms of interest. This, combined with the fact that refrigeration efficiency is also highly sensitive to temperature, suggests that achieving realistic levels and tight control of operating temperature is key to being able to accurately measure long-term performance trends. This high sensitivity to temperature also argues for testing the cooler throughout its allowable flight heat-sink temperature [illegible]e, typically from 0 to 40°C for space cryocoolers, but not significantly beyond this range.

A second important life-test consideration is the issue of continuous operation versus start-stop cycles. The length of operating periods has been found to be critical to the gettering of both internal and external contaminants to the refrigerator cold-end. Long, multi-week continuous operating periods, typical of space-cooler applications, have been found to be more sensitive to contamination than short multi-hour periods typical of tactical applications. On the other hand, periodic turn-off cycles every few weeks, which are common in space flight, are also well known for initiating failures associated with differential-expansion and fatigue mechanisms. For example, Fig. 1 illustrates the power turn-off cycles required for the Oxford University ISAMS instrument to periodically decontaminate the cold-end components attached to the instrument's two Oxford 80K Stirling cryocoolers [2]. The fact that the rate of contamination in Fig. 1 decreases each cycle suggests that the contamination is external to the cryocooler; thus, the turn-off cycles provide valuable evidence about the nature and location of the contamination. Life-test data on tactical coolers also supports the importance of periodic turn-off periods involving warming to room temperature, and suggest that cycling can cause contaminants to redistribute in detrimental ways within the cold-end.

Life-test data gathered by the European Space Agency (ESA) on the Oxford University 80K cooler also shows that contamination mechanisms can be quite sensitive to the cooler cold-end temperature. In the ESA tests, the level of observed degradation was dramatically greater when the cooler was under load, than when the cooler was under no-load [1].

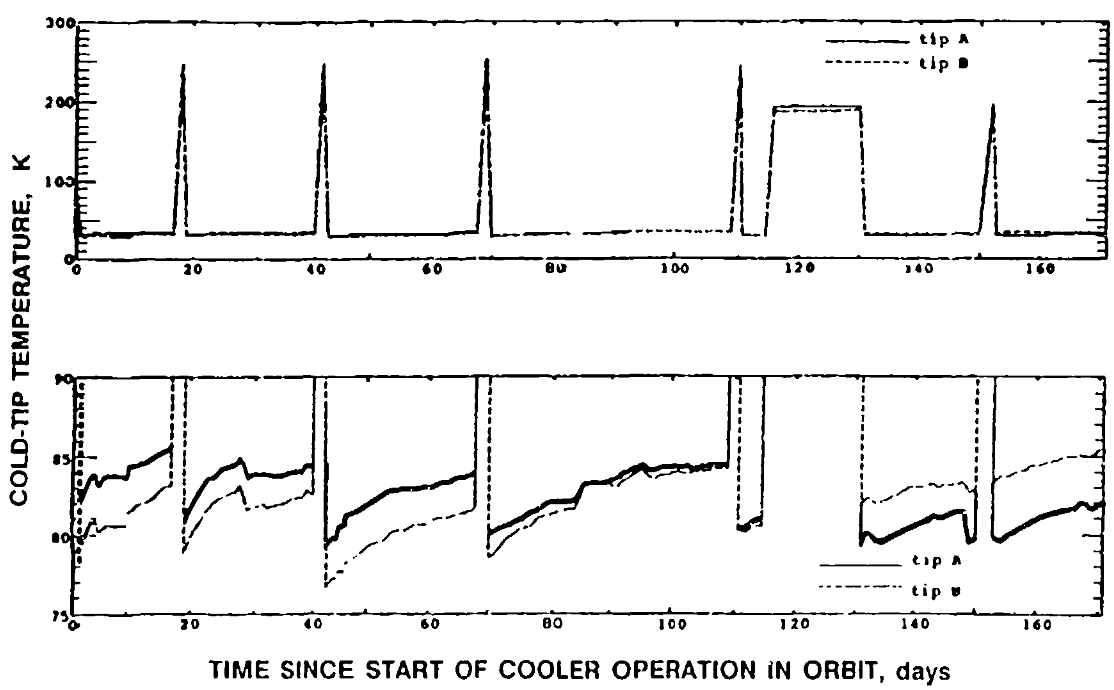

Fig. 1. ISAMS Oxford Stirling cooler performance in orbit aboard the NASA Upper Atmosphere Research Satellite (UARS).

We conclude from these data that a life-test cryocooler should be run at the expected application temperature (as opposed to under no-load conditions) and be periodically turned off and allowed to reach room-ambient temperature. Because buildup of contaminants has a relatively long time constant (many days), turn-off cycles should probably be conducted on the order of once per month for space cryocoolers, similar to the ISAMS flight history shown in Fig. 1.

As a last consideration, launch vibration can cause contact of otherwise non-contacting parts, thus leading to possible deterioration of critical alignments or generation of wear products. Since launch proceeds long-life operation in space, it is desirable to precondition the cooler prior to life testing by subjecting the cooler to flight-acceptance levels of launch vibration testing.

JPL LIFE-TEST IMPLEMENTATION APPROACH

In response to the above performance measurement needs and operating environmental sensitivities, the selected life-test implementation incorporates the following features:

1) The chosen fundamental measure of cooler performance is input power required to maintain the design cold-tip thermal load at the design cold-tip temperature (e.g. power required to maintain 2 watts at 65K). This power (or specific-power) performance can be most easily obtained by operating the cooler continuously at the desired fixed cold-tip temperature and cold-tip heat load. Unfortunately, many space coolers have only manual stroke control, and have no closed-loop means of temperature control. For manual-control coolers it is proposed to maintain operation near the desired load point (within 2°C) using periodic manual updating of the cooler stroke or applied heater load, and then to interpolate to the design-point specific power using the near-constant shape of the specific-power curve in the vicinity of the design point.

2) To provide the necessary stable environment to gather the power performance data, the life tests are conducted in a simulated space thermal-vacuum environment with carefully controlled heat-sink temperatures. This approach, which has been successfully demonstrated as part of JPL's extensive cooler characterization program [3,4], requires that the cryocooler reject its heat conductively--as in space; this results in realistic operating temperatures and thermal gradients within the cooler. Experience has shown that the heat sink temperature is accurately controllable and allows small deviations in cooler thermal performance to be monitored; the fluid-loop heat rejection system also allows the heat sink temperature to be easily varied throughout the flight temperature range (e.g. 0 to 40°C).

3) During life testing the cooler heatsink is slowly stepped throughout the flight temperature range; the cycle includes continuous cooler operation over sequential five-week periods; during each continuous-operation five-week period the heatsink temperature is varied weekly with sequential one-week operating periods at 20°, 0°, 20°,

40°, and 20°C, respectively. Each five-week sequence ends in a programmed cooler turn-off and warm-up to the 20°C heatsink temperature. The one-week duration at each heatsink temperature is chosen to allow adequate time for accurate temperature stability measurements to be made, and to allow repeat data to be acquired every two weeks at 20°C and every 5 weeks at the extreme (0°C and 40°C) temperatures. The turn-off excursion once every five weeks is bracketed by 20°C environments to allow accurate comparison of performance before and after the excursion.

4) In addition to the thermal performance, cooler generated vibration levels and spectrum are also measured over time; this is to assess changes in the vibration levels and spectrum caused by possible cooler degradation, or degradation of the vibration-suppression control electronics. The measurements are limited to qualitative measurements because precision multi-axis quantitative measurements would require a well-isolated, high-rigidity in situ vibration dynamometer for each cooler under test; this is considered beyond the scope of a life test. To achieve the high-quality qualitative measurements of vibration in the primary cooler axis requires that the thermal-vacuum test chambers be vibration-isolated from extraneous vibration sources such as vacuum pumps, chillers, and other coolers.

DETAILED TEST FACILITIES DESCRIPTION

Thermal Vacuum Test Chambers

The JPL developed thermal-vacuum test chambers, shown in Fig. 2, are custom-fabricated

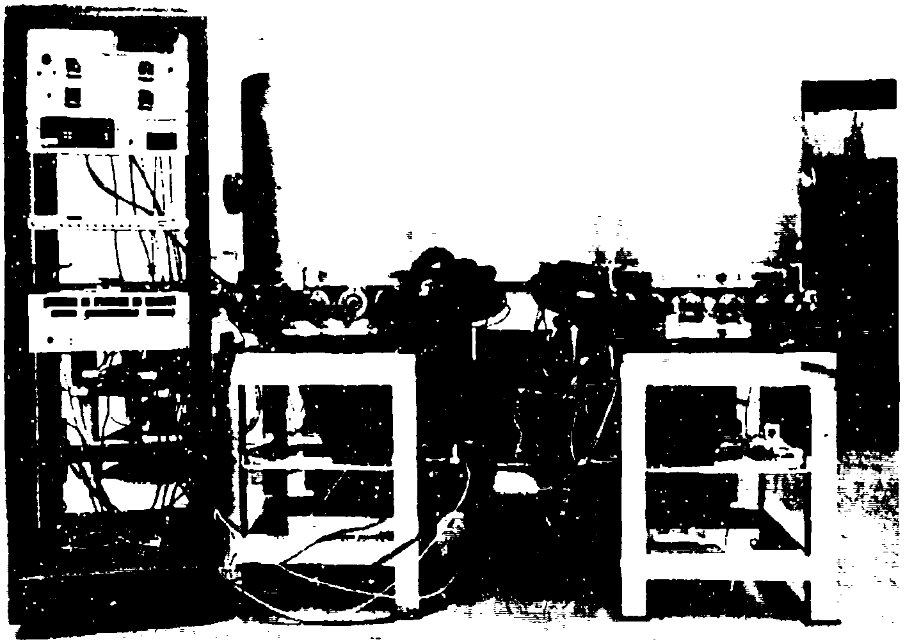

Fig. 2. JPL lifetest chamber installation overview.

24"-diameter bell jar assemblies connected to a central vacuum pumping system that uses a high-cleanliness turbo vacuum pump. Each chamber is equipped with an instrumentation collar to accommodate electrical and cooling-fluid feedthroughs, and a baseplate that is drilled with a pattern of tapped bolt holes to accommodate mounting of the test cooler within the chamber. An autoclosing gate valve is used to seal off each chamber from the central vacuum pumping system in the event of a pumping failure, and to allow a chamber to be opened while other chambers are under vacuum. Separation of the vacuum pumping system allows the pumps to be remote from the test chambers to minimize vibration, EMI and noise in the immediate vicinity of the cryocoolers under test. It also allows a single spare vacuum pump to back-up the total vacuum system in the event of a pump failure.

To allow cooler vibration measurements to be relatively free of background noise, each bell-jar assembly is vibration isolated from its structure using auto-leveling pneumatic air springs; this gives the bell-jar assembly a first natural frequency below 10 Hz, thus providing significant vibration isolation at the cooler drive frequency and harmonics.

Temperature control of each cooler is provided by a central fluid loop driven by a remotely located chiller system. The chiller system provides a flow of coolant at a temperature set approximately 10°C below the desired heatsink temperature for the cryocoolers. Like the central vacuum system, the remote location of the chiller and fluid pumping system minimizes vibration, EMI, noise and heat dissipation in the immediate vicinity of the cryocoolers under test.

To achieve accurate temperature control of each cooler heatsink (separate ones for each compressor and displacer) each bell-jar assembly is served by two fluid streams from the central chiller, and each stream is equipped with its own independent metering valve and temperature controller. Each fine-tuning controller actuates an inline immersion heater in its fluid stream to raise the individual heatsink assembly to the desired set-point value.

To provide for temperature control of each cooler element (e.g. compressor and displacer), a design-specific fluid-loop heat exchanger heatsink assembly is fabricated to interface to the cooler's heat rejection surfaces intended to be used in space. Each heatsink assembly also structurally supports the cooler element from the chamber base-plate via the vibration force transducers. Each cooler element is electrically connected to its manufacturer-supplied electronics via feed-throughs through the chamber collar. Fig. 3 shows the heatsink assemblies and structural supports for the British Aerospace (BAe) 80K cooler under life-test at JPL.

Following instrumentation of the cryocooler cold-tip with appropriate load heaters and cryodiodes, the cold finger is isolated from the chamber thermal radiation environment using a carefully manufactured canopy of multi-layer insulation (MLI).

<u>Instrumentation</u>

Life-test instrumentation includes all measurement transducers and their necessary conditioning electronics that interface to the data acquisition system. The total chamber

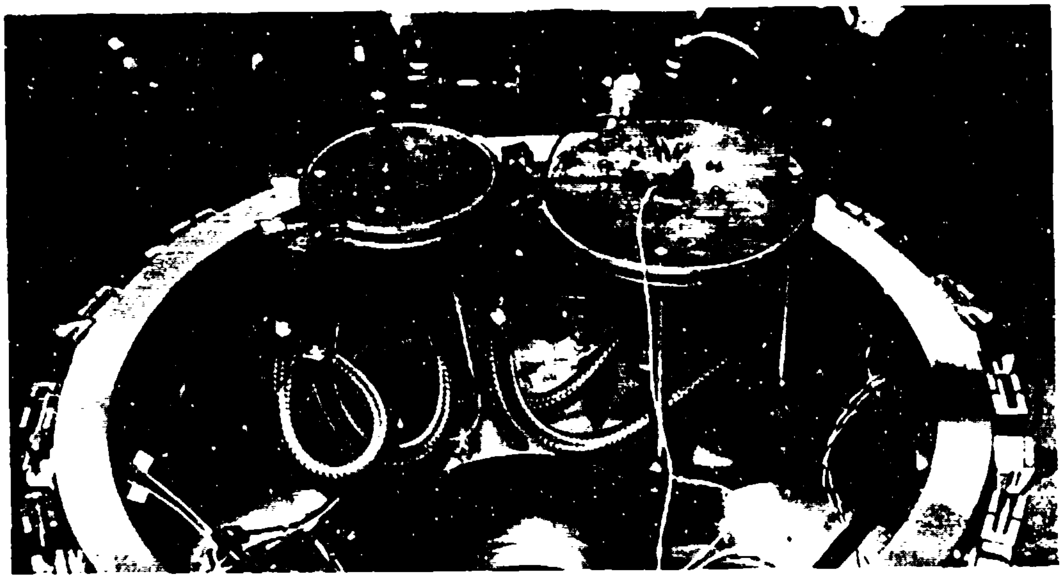

Fig. 3. Design-specific heatsink assemblies for JPL's BAe 80K cooler.

instrumentation falls into seven categories: 1) heatsink and cooler external case temperature transducers and conditioning electronics, 2) cold-tip cryodiode thermometry, 3) cold-tip heaters and power supplies, 4) cooler piston and displacer amplitudes, 5) compressor and displacer true-RMS power parameters, 6) vibration force transducers and conditioning electronics, and 7) chamber vacuum level instrumentation.

In the JPL-developed system, heatsink and cooler case temperatures are measured using thermocouples, as are ambient temperature and cooler drive electronics temperature. Cold-tip temperature is monitored via redundant Lakeshore Model 470 cryodiodes mounted to the cold tip. The level of vacuum in each bell-jar system is continually monitored using a cold cathode gage with integral alarm levels. The gage is used to shut the chamber gate valves in the event of loss of vacuum.

The cold-tip heater is either supplied by the cooler manufacturer, or is a (~500 ohm) precision thin-film resistor mounted in a custom fabricated mount for integration to the cooler coldfinger. It is important that the cold-tip heater only be actuated when the cooler cold-tip is cold and the cooler is operating; if the cooler is not running, application of cold-tip heater power can rapidly overheat and damage the cooler cold-tip. An important function of the data acquisition and control system is to protect against a misapplication of cold-tip heater power.

Conditioned analog signals (~1 volt per mm of stroke) representing the cooler piston and displacer amplitudes are monitored from the manufacturer-supplied cooler drive electronics. The input power to the cooler compressor and displacer are measured using a true-RMS digital power analyzer inserted into the cooler drive power cables. Correction to the power measurements must be made for I^2R power dissipation in the cooler leads

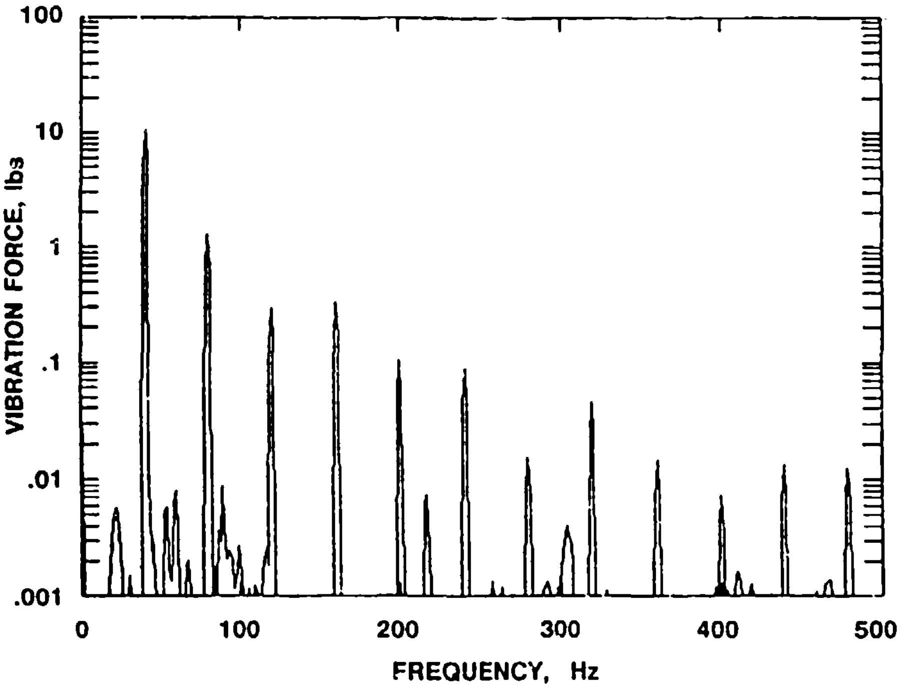

Fig. 4. Excellent low-noise vibration spectrum measurement of BAe 80K cooler in JPL lifetest chamber.

between the cooler and the power meter. This is done by subtracting the RMS current squared times the wire resistance from the power reading.

Cooler-generated vibration forces are measured using a piezoelectric force ring mounted between each cooler element (displacer and compressor) and the chamber base plate. These force transducers have a sensitivity range from 0.002 pounds to 100 pounds and are fed to the data acquisition system for spectrum analysis and A/D conversion. Figure 4 illustrates the excellent vibration spectrum achieved with JPL's BAe 80K cooler mounted in the life-test chamber. The low level of background noise achieved in the life-test facility compares favorably with the results achieved with JPL's 6 DOF force dynamometer with a 4000 pound seismic mass [5,6].

Data Acquisition and Control

The data acquisition and control system is responsible for sequencing the overall cooler test operations, logging the cooler performance and environment data in engineering units, archiving the measured data to mass storage (hard-disk, floppy, and back-up tape), providing realtime display of cooler performance parameters, and providing for cooler and system fault detection and safety shutdown. Final preparation of camera-ready plots of performance is done off-line, using the mass storage files, as part of the data reduction and documentation function.

The JPL data acquisition and control system is built around a 386 desk-top PC microcomputer that contains a GPIB board to interface to the IEEE 488 instruments, a relay board for controlling external on-off functions, and a fast A/D converter for acquiring vibration analog data; standard hard disks, floppies, and back-up tape transports are used for data archiving.

In addition to measuring and archiving the data, the life-test PC also tracks key performance parameters relative to preset bounds that indicate acceptable performance or dangerous out-of-bound operation. If the occurrence of an out-of-bound performance parameter is noted, the computer relay board is commanded to turn off the cooler and light a visual warning indicator. Key performance parameters to be monitored against fault levels include: compressor and displacer stroke, compressor and displacer power, cold-tip temperature, cold-tip heater power, and heatsink temperature. Separate control of the cold-tip heater is provided to enable the cold-tip heater to be actuated only when the cooler is turned on and running and the cold-tip has a temperature below 200 K.

SUMMARY

The recent development of a number of long-life miniature cryocoolers has led to an explosion of interest in multi-year-life space cryogenic instruments. To assist the space-instrument user community in understanding and applying these important new cryocoolers, the JPL has undertaken the development of specialized cryocooler life-testing facilities under the sponsorship of SDIO/AF Phillips Laboratory and the NASA Eos AIRS project. Over the coming months important space cryocoolers are scheduled to begin life testing in these facilities at JPL and at the AF Phillips Laboratory in Albuquerque, New Mexico. These tests are expected to provide extensive life-test thermal-performance and vibration data on key cryocoolers of interest to the space instrument community.

ACKNOWLEDGEMENT

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