JPL Cryocooler Development and Test Program Overview

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ABSTRACT

Many near-term and future space-instrument programs within NASA and the Ballistic Missile Defense Organization (BMDO) depend on the successful development of long-life, low-vibration space cryocoolers. The most demanding near-term programs include a number of science instruments selected for NASA's Earth Observing System (Eos) program, and a number of space reconnaissance instruments associated with the BMDO's Brilliant Eyes program; both of these programs require delivery of similar types of flight coolers in the next few years.

To help ensure the success of these cooler commitments, the Jet Propulsion Laboratory (JPL) has implemented an extensive cryocooler program in support of the NASA/JPL AIRS project, the Air Force Phillips Laboratory (AFPL), and the Air Force Space and Missiles Systems Division (SMC). This program is directed at assisting industry in developing advanced cryocoolers that successfully address the broad array of complex performance requirements needed for NASA and BMDO long-life space instruments. The JPL cryocooler program includes extensive characterization of industry-developed cryocoolers, development and flight testing of advanced sorption cooler systems for detector cooling to 10 K, development of mechanical cryocooler enhancement technologies, and flight tests of advanced low-vibration Stirling-cooler systems.

INTRODUCTION

Many near-term and future space-instrument programs within NASA and BMDO depend on the successful development of long-life, low-vibration space cryocoolers. The high level of commonality that exists between the NASA and BMDO cooler requirements has fostered a highly collaborative, cooperative program involving both NASA and DoD laboratories supporting major contractual development efforts within the world-wide aerospace industry. JPL, under a combination of NASA and BMDO funding, is playing an extensive role in assisting industry in the development of advanced cryocoolers to meet both NASA's and BMDO's needs. The JPL cryocooler program is focused in four areas:

1) Active support is being provided to NASA/JPL and BMDO flight projects in the selection, application and/or acquisition of cryocoolers meeting their needs. This activity plays an important role in identifying the key performance and integration requirements that must be

addressed by the cryocoolers, and the key cryocooler integration issues that must be addressed by the interfacing science instruments. Several JPL flight instruments involving cryocoolers are currently being supported. The largest JPL/NASA activity is the Eos Atmospheric Infrared Sounder (AIRS) instrument, which has just awarded its flight procurement for long-life, low-vibration pulse tube cryocoolers providing 1.5 watts of cooling at 55 K. The key BMDO activity is support to the Brilliant Eyes program and its contractors in the development of 10-K sorption coolers, and the evaluation and selection of 60-K mechanical cryocoolers.

2) Extensive characterization testing of industry-developed cryocoolers is being conducted to provide a thorough performance database for use by instrument developers and the cryocooler development community. JPL initiated an extensive cryocooler characterization program in support of the Eos AIRS instrument in 1989, and greatly expanded the effort under AFPL/BMDO sponsorship in 1992. Over the past few years 9 different cryocooler models have been extensively characterized to provide a thorough cryocooler performance database for the BMDO/NASA-wide community.

3) Flight tests of important cryocooler developments are being conducted to provide reliable flight heritage data, and to insure thorough qualification status and compliance with launch vehicle safety and cryosystem integration constraints. JPL is managing three ongoing cryocooler flight experiments scheduled for launch in the 1994/1995 timeframe: the Brilliant Eyes Ten Kelvin Sorption Cryocooler Experiment (BETSCE), the NASA IN-STEP Hughes Cryo System Experiment (CSE), and the Space Technology Research Vehicle (STRV) Cryocooler Vibration Suppression Experiment.

4) Research is being conducted on cryocooler enhancement technologies needed to help the community meet identified short-falls in cryocooler performance. The principal focus of this activity is in the development of advanced vibration-free sorption refrigerators for operation in the range of 10 to 30 K, and on the development of advanced cryocooler vibration suppression systems and cold-end integration technologies for Stirling and pulse tube cryocoolers.

These JPL cryocooler programs are summarized below and described in detail in the cited references. For ease in presentation, the activities are grouped according to operating temperature, starting with 55- to 80-K mechanical cryocooler activities and ending with 10-K sorption cooler activities.

MECHANICAL CRYOCOOLER CHARACTERIZATION

AIRS Cryocooler Development and Characterization

In 1989 JPL initiated an extensive cryocooler characterization program in support of the JPL AIRS instrument, which is scheduled to fly on the NASA Eos PM platform in the 2000 timeframe; the JPL AIRS cryocooler program also supports other JPL and NASA instruments requiring advanced high-capacity (55 to 60 K) low-vibration coolers. To provide the foundation of cryocooler performance data needed for these programs, JPL established a state-of-the-art cryocooler test facility including many special-purpose test setups and data acquisition methods for measuring generated vibration, thermal performance, off-state conduction, EMI, and launch survivability. The first cooler extensively characterized at JPL was the British Aerospace (BAe) 80 K "Oxford" cooler that JPL purchased in 1990; this cooler has served as the pathfinder for the development of many of the test facilities and test methods used today, and a wealth of data has been generated on the robust performance of this cooler.[1-5]

Expanded Characterization Program for BMDO

With the recognized need within the space-cooler community for thorough and accurate data on the performance of emerging space cryocoolers, the JPL cryocooler characterization program was greatly expanded in 1992 under the sponsorship of the Ballistic Missile Defense Organization/Air Force Phillips Laboratory in collaboration with the AIRS project.[6] The objective of the expanded test program was to gather data covering all aspects of cooler performance affecting instrument compatibility including thermodynamic cooling capacity, cold finger off-state parasitics, location and amount of rejected heat, generated vibration, EMI, and launch survivability. Direct comparison of cooler characteristics was enabled through the use of a common set of instrumentation, test procedures, and test facilities. Standardized test-result formats and parameter ranges are used to aid comparison and interpretation of cryocooler performance.

Since the characterization of the BAe 80 K cooler, eight additional state-of-the-art cryocoolers, shown in Fig.1, have been extensively characterized under the joint BMDO/AIRS sponsorship. Four other coolers have been less extensively tested to provide data for particular applications; these partially-characterized coolers include the Lockheed-Lucas 1710C common-compression-space Stirling cooler, the TRW 35 K pulse tube cooler, the TRW 0.25-watt 65 K mini-Stirling cooler, and the Magavox MX7049 tactical Stirling cooler.

Comprehensive databases have been developed for the following coolers:

British Aerospace 80 K cooler[7]
British Aerospace 55 K cooler[8]
British Aerospace 50-80 K Cooler[9]
Hughes 65 K SSC cooler[10]
Lockheed SCRS cooler[11]
Stirling Technology Co. 80 K cooler[12]
Sunpower 140 K cooler[13,14]
TI 0.2-watt 80 K tactical cooler
Hughes 7044H tactical cooler

In addition to the individual cooler test reports, summary papers have been written describing generic performance trends of present-day space cryocoolers; these include thermal performance trends,[15] generated vibration trends,[16] resonance characteristics,[17] and EMI characteristics.[18] These overview papers are intended to provide the user community with generic design data suitable for preliminary design purposes, prior to the selection of a particular cooler.

Stirling Cooler Technology Enhancement

Because of the demanding requirements of the AIRS instrument, focused technology development efforts have been directed at key high-risk, high-payoff areas such as improved thermal efficiency and reduced vibration. Advanced single-axis narrow-band vibration control systems have been developed under contract with SatCon Technology Corporation,[19,20] and advanced 3-axis vibration suppression systems have been developed at JPL[21] and through a contract with the Massachusetts Institute of Technology.[22]

To greatly improve thermal efficiency, JPL has developed the concept of the heat interceptor, shown in Fig. 2. In this concept, a cryogenic radiator at 150 to 190 K is tied into the cold-finger of a Stirling or pulse tube cooler, and used to nearly double the cryocooler efficiency.[23]

AIRS Cooler Development under LIRIS Subcontracts

In order to expand the performance of the first generation BAe 80 K cooler to meet the AIRS requirements, JPL's AIRS instrument systems contractor, Loral Infrared & Imaging Systems, Inc. (LIRIS), has contracted with BAe and Lockheed-Lucas for the development-testing of advanced second-generation Stirling cryocoolers with the needed capacity, efficiency and low vibration. This contractual effort proved the feasibility of achieving the AIRS requirements, and fostered important design improvements associated with reduced off-state conduction down the cold finger, and high accuracy cold-tip temperature regulation via compressor piston stroke control.[24,25]

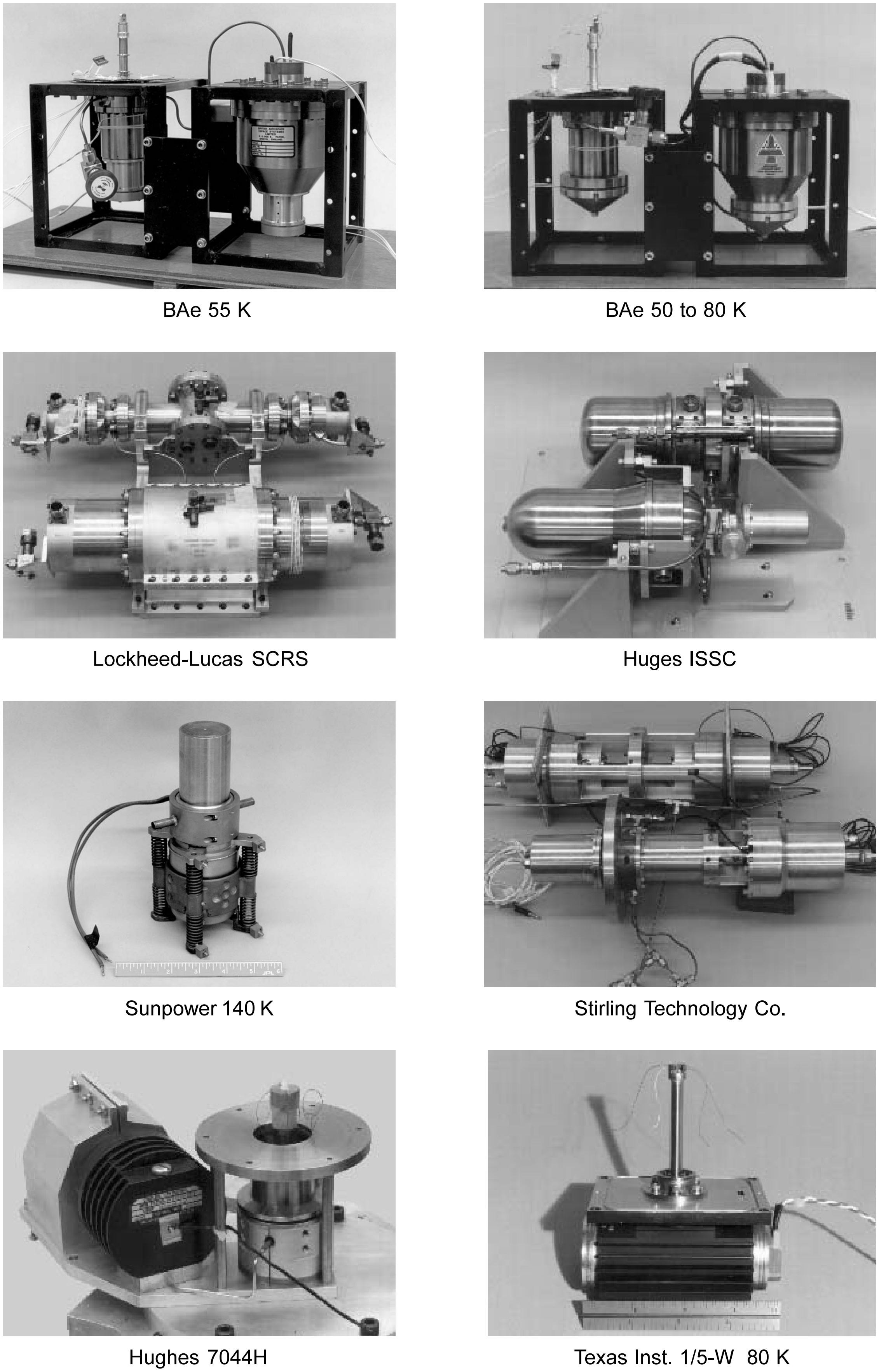

Figure 1. Recent cryocoolers characterized at JPL in support of BMDO and AIRS.

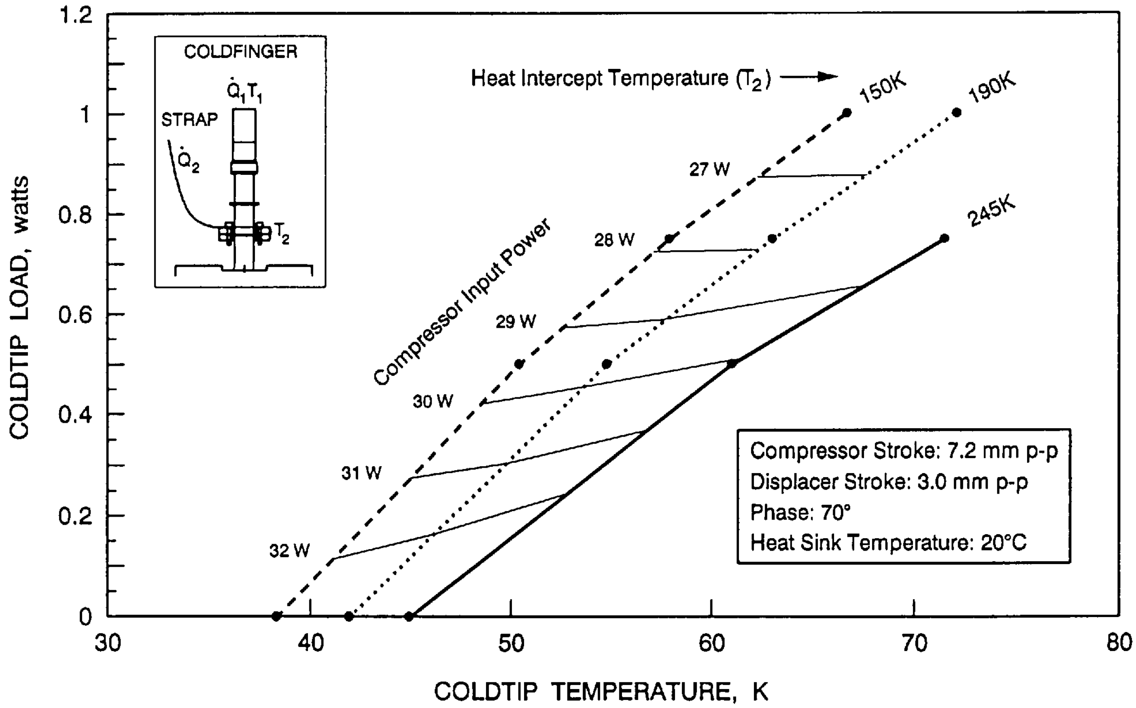

Figure 2. Thermal performance gain of the BAe 80 K cooler versus heat interceptor temperature.

In the spring of 1994, LIRIS awarded TRW the contract to develop and produce the flight coolers for the AIRS instrument. The selected state-of-the-art pulse tube cooler has excellent thermal performance, Fig. 3, comparable to the best Stirling coolers, and has a number of features that greatly improve instrument integration. These include reduced mass, size and complexity, increased stiffness, and reduced vibration at the cold head. Figure 4 graphically illustrates these important advantages of the TRW/AIRS pulse tube configuration.

Cryocooler Life-Test Facility Development

With the growing commitment of long-life Stirling cryocoolers to multi-year NASA and BMDO space applications, there is an important need for quantitative reliability data verifying the long-term performance of space cryocoolers 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 and the Jet Propulsion Lab.[26] To acquire the needed quantitative cooler performance data, 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.

JPL STIRLING COOLER FLIGHT EXPERIMENTS

To provide flight-heritage performance data, and to thoroughly demonstrate flight qualification status and compliance with launch vehicle safety and cryosystem integration constraints, JPL is managing two ongoing Stirling-cooler flight experiments scheduled for launch in the 1994/1995 timeframe: the NASA IN-STEP Cryo System Experiment, and the STRV Cryocooler Vibration Suppression Experiment.

NASA IN-STEP Cryo System Experiment

Under JPL management, the Hughes Aircraft Co. has developed a cryosystem flight experiment to validate and characterize the on-orbit performance of a hybrid cryogenic cooling system integrating three advanced technologies: a 2-watt 65 K low-vibration long-life Stirling cooler

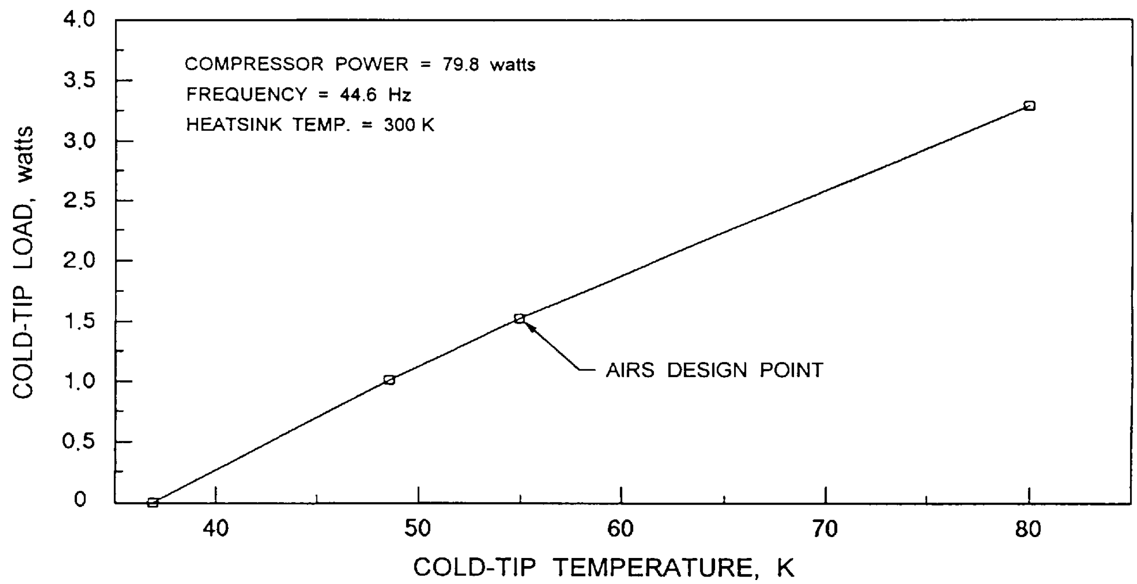

Figure 3. Thermal performance of the TRW pulse tube cryocooler at the AIRS design point.

developed by Hughes under AFPL/BMDO sponsorship, a diode oxygen heat pipe thermal switch that also enables physical separation between the cryocooler and the thermal load, and a thermal-energy storage device that provides a stable thermal sink at cryogenic temperatures. A key feature of the experiment is the on-orbit measurement of the vibration generated by the advanced, fully counterbalanced, second-generation Stirling cryocooler in contrast to typical short-life "tactical" coolers, which are also used in the experiment for thermal shield cooling.

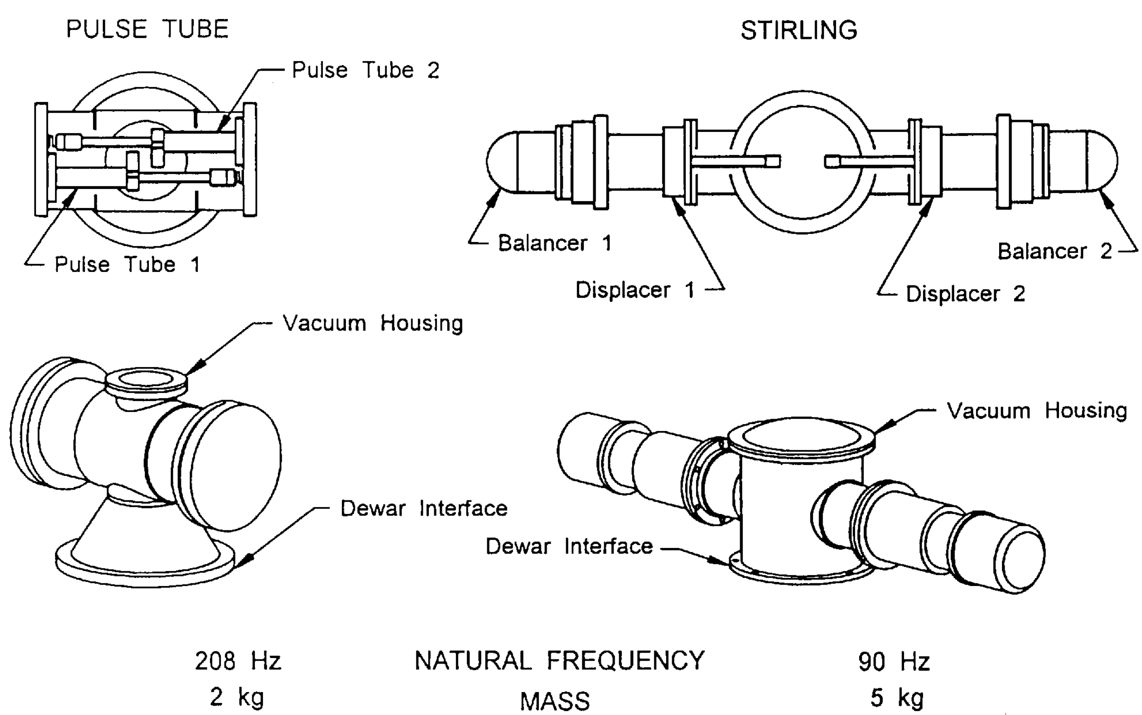

Figure 4. Comparison of the integration attributes of pulse tube and Stirling cryocoolers in the AIRS instrument setting

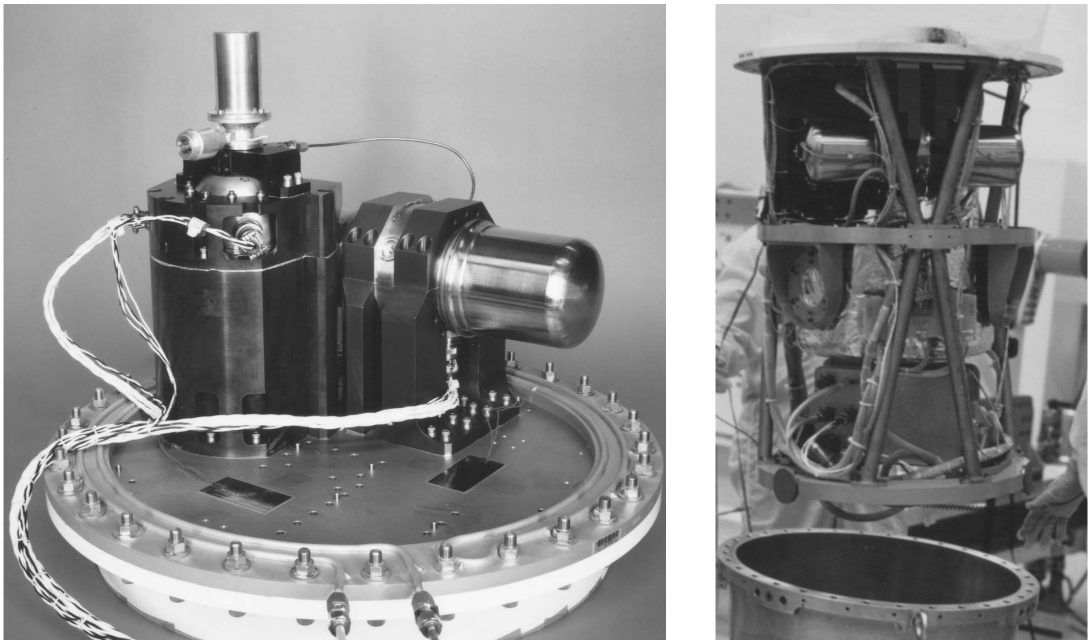

Figure 5. Hughes IN-STEP Cryo System Experiment (CSE) during system testing.

The NASA-sponsored experiment, shown in Fig. 5, completed system-level testing this spring and is presently undergoing launch vehicle integration. Launch aboard the Shuttle is scheduled for February 1995. A large number of valuable lessons on Stirling cooler system integration have been derived from this effort.[27]

STRV Cryocooler Vibration Suppression Experiment

Under BMDO sponsorship, JPL is also developing a flight experiment to demonstrate more advanced control technologies for quieting cryocooler tip vibration in three axes.[21,28] This experiment is a small 15-watt payload aboard the Space Technology Research Vehicle (STRV-1b), a small English satellite that was launched on an Ariane-4 on June 17, 1994. To meet stringent power, weight, and space constraints, the experiment makes use of the tiny 1/5-watt 80 K Texas Instruments tactical Stirling cooler. Two different vibration-cancellation actuator techniques are being demonstrated: 1) applique ceramic piezoelectric actuators that are bonded to the coldfinger and stretch the coldfinger to cancel tip motion, and 2) commercial low voltage piezoelectric translators that similarly cancel tip motion by moving the entire cryocooler in three axes. Motion of the coldfinger tip is measured in all three axes to 10 nanometer accuracy using eddy-current transducers. Two types of control systems are also being demonstrated: 1) an analog control system that uses a bandpass filter to track the drive signal and suppress it, and 2) a unique narrow-band adaptive feed-forward system that continually updates a steady-state command signal to each actuator to cancel the tip vibration. Either control system can be used with either actuator.

TEN KELVIN BRILLIANT-EYES SORPTION COOLER DEVELOPMENT

One of the concepts for the Brilliant Eyes (BE) surveillance satellite system involves a long-wavelength infrared detector focal plane that requires periodic operation near 10 K. To provide the necessary cryogenic cooling, a novel periodic 10-K sorption cooler concept was invented by Dr. Al Johnson of The Aerospace Corp. in collaboration with Mr. Jack Jones of JPL.[29,30] The basic feasibility of the unique 10-K hydrogen/hydride sorption cryocooler was demonstrated at

JPL in a series of proof-of-principle experiments in 1991.[31] Based on this successful demonstration, a comprehensive program was undertaken with industry to reduce the concept to a working prototype and to prove its viability in a space demonstration flight experiment. Additional elements of the program include component-level characterization and reliability physics investigations, and the design of an engineering model flight system more accurately scaled to the requirements and interfaces of the actual BE mission.

The Periodic Sorption Cryocooler Concept

The operation of the 10-K periodic sorption cryocooler system is based on alternately heating and cooling beds of metal hydride powders to circulate hydrogen in a closed cycle, and periodically cool the detector cold head assembly to 10 K on command.[29,30,31] Cooldown to 10 K occurs in two separate steps. First, a valve is opened to release high-pressure hydrogen at about 10 MPA (1500 psia) from the storage tank. The hydrogen gas is circulated past a 60-K upper stage -- cooled by second-generation Stirling or pulse tube coolers such as the BMDO PSC coolers or the AIRS coolers -- and then flows through a Joule-Thomson refrigeration loop where it is cooled and partially liquefied at 25 to 30 K. The liquid is collected in a wick contained in the cryogen reservoir, and all unliquefied hydrogen vapor is absorbed by a hydride sorbent bed. The second cooldown step begins after a sufficient quantity of liquid hydrogen is collected (about 0.5 to 2 g). At this point the J-T flow is stopped and solid H_2 at ~10 K is produced by vacuum pumping the cold head reservoir with a low-pressure sorbent bed. The process is sized to provide sufficient solid hydrogen to absorb the infrared sensor heat load over the required 10- to 30-minute operating period. Following the operational period, the cryocooler is recharged by heating the sorbent beds; this drives off the hydrogen and returns it to the storage tank.

BETSCE 10-K Sorption Flight Experiment

A critical part of the 10-K sorption cooler development effort is the Brilliant Eyes Ten-Kelvin Sorption Cryocooler Experiment (BETSCE).[32] This Shuttle side-wall-mounted flight experiment, shown during system-level testing in Fig. 6, is in the final stages of environmental testing at JPL and was originally scheduled for launch in 1995 aboard the BMDO Shuttle Pallet Satellite

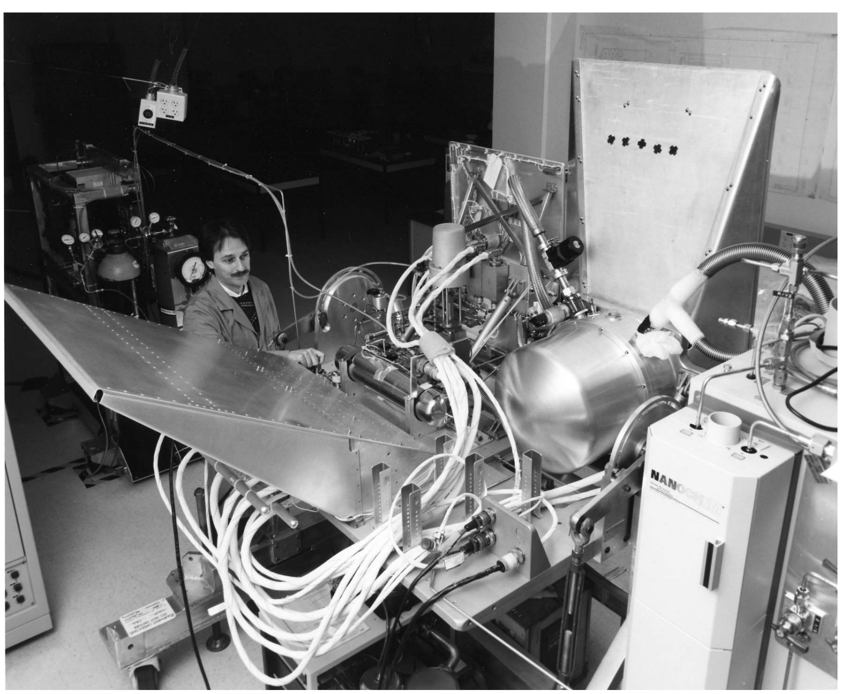

Figure 6. Brilliant Eyes Ten Kelvin Sorption Cooler Experiment (BETSCE) during system-level testing at JPL.

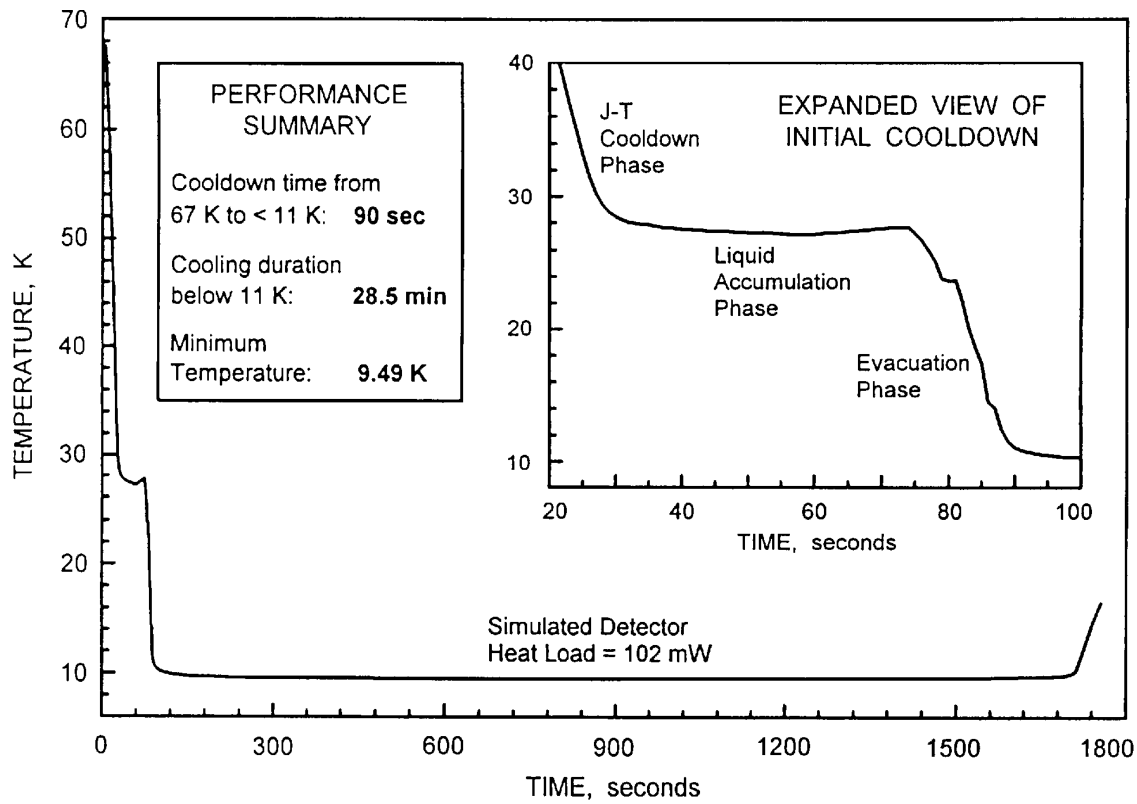

Figure 7. Successful ground-test demonstration of the 10-K cooling performance of the BETSCE cryocooler.

(SPAS III) mission. With the cancellation of the SPAS III mission, launch is currently in the process of being reprogrammed.

The BETSCE objectives are to: (1) demonstrate the 10-K sorption cooler technology in a microgravity space environment, (2) advance the enabling technologies and integration techniques by developing an automated, space flightworthy cryosystem, and (3) characterize spaceflight performance and develop the needed flight database to support the planned 10-K flight-cooler development efforts. Key technologies and elements to be characterized include hydride sorbent beds,[33] phase-change materials, heat sinks, heat exchangers and other refrigeration loop components, the cold-head assembly containing a wicked solid/liquid cryogen reservoir, cycle process controls, and cycle repeatability.

This all-new cryocooler system was designed and fabricated for the first time for this flight experiment, and has achieved its operational performance goals on-cost and on-schedule. Figure 7 shows the successful ground-test data that confirms the ability of the cooler to cool the focal plane to below 10 K in well under 2 minutes, and to maintain the temperature for over 20 minutes with a detector heat load of 100 mW.[34]

Component-Level Characterization and Reliability Physics Investigations

Supporting the BETSCE flight experiment, JPL has a 10-K basic technology development activity directed at providing the technology base required to design and manufacture high reliability 10-K hydride sorption cryocoolers.[16] The key focus of this activity is on developing the analytical modeling tools to allow the total thermodynamic system to be understood and optimized, and developing the reliability physics and design understanding of the key issues governing the lifetime and reliability of the system. Extensive analytical models have been developed and verified with the ground test data,[35] and several activities are currently underway to verify the long term reliability of the system.[36] These reliability physics activities include heater and container-material aging studies, studies to determine the effects of purity and manufacturing techniques on hydride isotherm properties, and studies to establish requirements for preventing migration and compaction of the hydride power.

During the design and qualification of BETSCE, extensive data has also been developed on the flightworthiness of all of the key elements of the system. Studies, for example, have characterized the kinetics and absorption capabilities of the fast absorption beds containing phase-change-material (PCM) heatsinks, extensively researched suitable valves and seat materials, and developed complete control algorithms for the operation of the refrigerator.

10-K Engineering Model Development

To provide the necessary transition between the shuttle based BETSCE flight experiment and an eventual flight BE cooler, a JPL contract to develop a flight-like engineering model 10-K cooler has been initiated with Allied Signal Aerospace. The engineering model design is directed at the cooling requirements, mission constraints, satellite designs and interfaces of the actual BE mission application. Close cooperation between the Allied Signal 10-K cooler development team, the BE system developers, and JPL is planned to maximize the technology handoff from BETSCE, and to insure meeting the requirements of the BE mission.

SUMMARY

The growing demand for long-wavelength infrared imaging instruments for space observational applications has led to a rapidly expanding near-term commitment to mechanical cryocoolers for long-life NASA and BMDO space missions. To help ensure the success of these cooler commitments, the Jet Propulsion Laboratory has implemented an extensive cryocooler program directed at assisting in the development of advanced cryocooler technologies that successfully address the broad array of complex performance requirements needed. The JPL cryocooler program is making good progress in the characterization of industry-developed Stirling and pulse tube coolers, the development and flight test of advanced sorption cooler systems for detector cooling to 10 K, and the development and flight test of advanced low-vibration Stirling-cooler systems.

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