JPL CRYOCOOLER DEVELOPMENT AND TEST PROGRAM OVERVIEW

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ABSTRACT

The growing demand for long-wavelength infrared imaging instruments for space observational applications, together with the emergence of the multi-year-life Oxford University 80 K Stirling-cycle cooler, has led to a rapidly expanding near-term commitment to mechanical cryocoolers for long-life NASA and SDIO space missions. To help ensure the success of these cooler commitments, the Jet Propulsion Laboratory (JPL) has implemented an extensive cryocooler program in cooperation with the Air Force Phillips Laboratory (AFPL), the Air Force Space Division, the Aerospace Corp., and NASA Goddard Space Flight Center. 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 SDIO long-life space instruments. The JPL cryocooler program includes extensive characterization and life testing of industry-developed Stirling coolers, development and test of advanced vibration-suppression systems for mechanical cryocoolers, flight tests of advanced low-vibration Stirling-cooler systems, and development and flight testing of advanced sorption cooler systems for detector cooling to 10 K.

INTRODUCTION

Extensive near-term and future space-instrument programs within NASA and the Strategic Defense Initiative Organization (SDIO) 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 SDIO's Brilliant Eyes and Brilliant Pebbles programs; all of these programs require delivery of similar types of flight coolers in the next few years.

The high level of commonality that exists between the NASA and SDIO 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 SDIO funding, is playing an

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extensive role in assisting industry in the development of advanced cryocoolers to meet both NASA's and SDIO's needs. The JPL cryocooler program is focused in four areas:

1) Active support of flight projects in the selection, application and 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. The major JPL activities in this area are support of the JPL/NASA Eos Atmospheric Infrared Sounder (AIRS) instrument in the acquisition of long-life, low-vibration 1.5-watt 55K Stirling coolers for cooling of longwave infrared focal planes to 60 K, and support to the SDIO Brilliant Eyes program in the development of an advanced cryocooler for periodic cooling to 10 K.

2) Extensive characterization testing of industry-developed cryocoolers to provide a consistent database of performance data 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 has expanded the effort under AFPL/SDIO sponsorship to provide a thorough cryocooler performance database for the SDIO/NASA-wide community.

3) Flight test of important cryocooler developments 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 timeframe: the NASA In-step Hughes Cryosystem Flight Experiment, the Space Technology Research Vehicle (STRV) Cryocooler Vibration Suppression Experiment, and the Brilliant Eyes Ten Kelvin Sorption Cryocooler Experiment (BETSCE).

4) Research of advanced cryocooler technologies needed to help the community meet identified short-falls in cryocooler performance. The principal focus of these activities is in the areas of cryocooler vibration suppression and development of advanced vibration-free sorption refrigerators, and the conduct of reliability physics investigations to establish the technology base for achieving and verifying multi-year cryocooler life.

These JPL cryocooler programs are summarized below and described in detail in the cited references. For ease in presentation, the activities are organized programmatically, starting with 55- to 80-K Stirling-cooler activities and ending with 10-K sorption-cooler activities.

STIRLING CRYOCOOLER CHARACTERIZATION

AIRS Cryocooler Development and Characterization

In 1989 JPL initiated an extensive Stirling cryocooler characterization program in support of the JPL Atmospheric Infrared Sounder (AIRS) instrument, which is scheduled to fly on

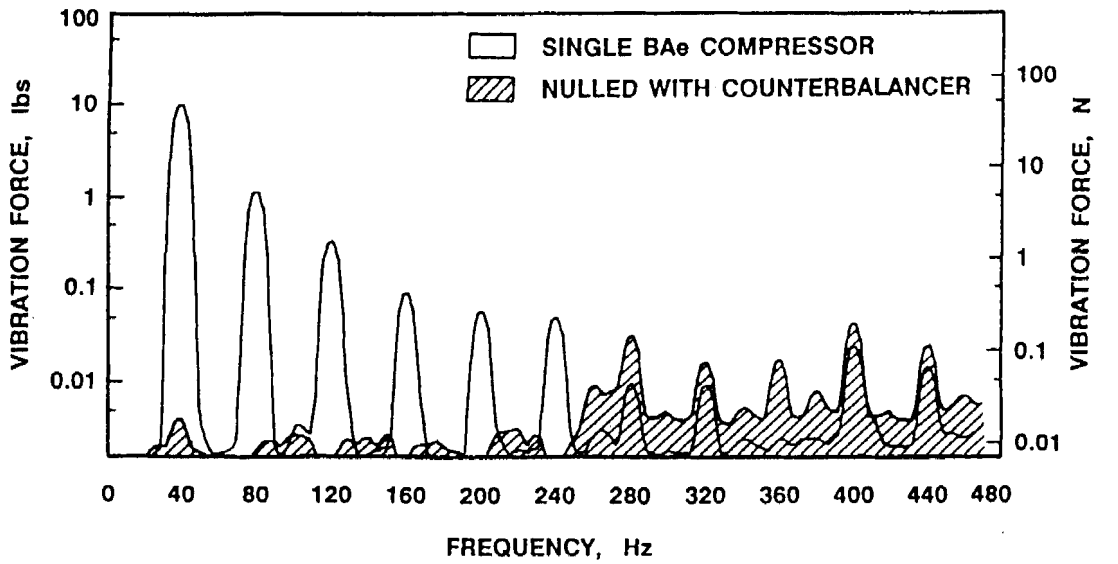


Fig. 1. Reduction of vibration harmonics of BAe 80K cooler coupled with active counterbalancer and SatCon narrowband controller [8,9].

the NASA Eos PM platform in the 1999 timeframe; the AIRS cooler program also supports other JPL and NASA instruments requiring advanced high-capacity (1.5-watt 55K) low-vibration Stirling coolers. To provide the foundation of Stirling-cooler data needed for this program, one of the first British Aerospace (BAe) 80 K "Oxford" coolers was purchased in 1990 and has been extensively characterized [1-5]. Over the past two years the characterization program also led to the design and development of unique and sophisticated cryocooler test facilities. Because the AIRS instrument is particularly sensitive to vibration during operation, an area of special emphasis has been applying advanced vibration control techniques to achieving high levels of vibration suppression. Figure 1 illustrates the 70 dB of vibration suppression achieved using an advanced single-axis narrow-band vibration control system developed under contract with SatCon Technology Corporation [8,9]. Advanced 3-axis vibration suppression systems are also currently under development at JPL and through a contract with the Massachusetts Institute of Technology.

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 coolers with the needed capacity, efficiency and low vibration. This contractual effort has proved the feasibility of achieving the AIRS requirements through the development and test of coolers referred to as AIRS 55K coolers [6,7]. Example performance curves for these coolers are presented in Fig. 2.

SDIO/AFPL Cryocooler Characterization Program

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

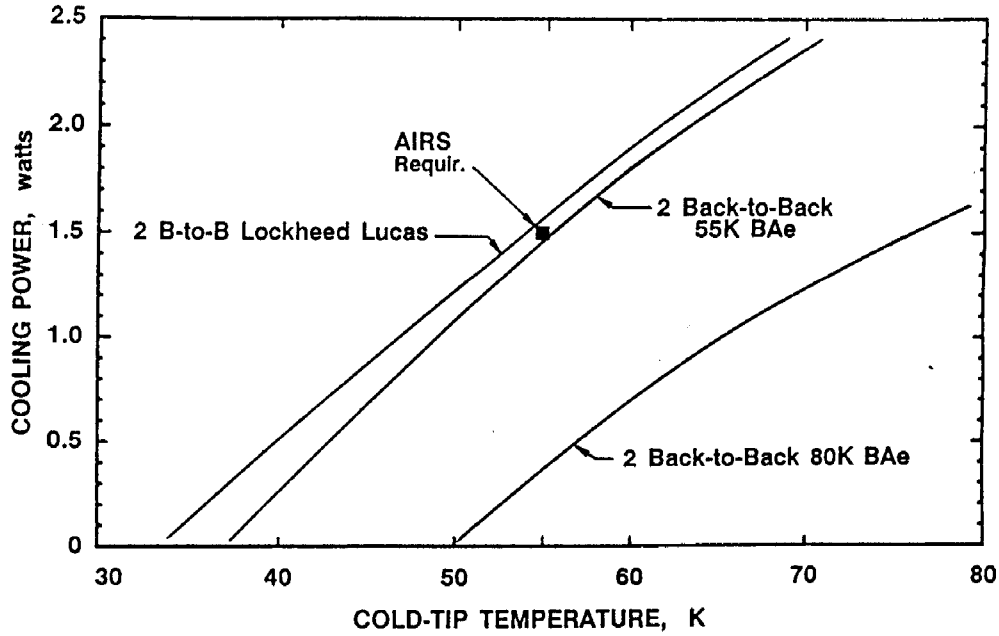


Fig. 2. Thermal performance of prototype AIRS 55K Stirling coolers compared to that of the original BAe 80K cooler.

program was expanded in 1992 under the sponsorship of the Strategic Defense Initiative Organization/Air Force Phillips Laboratory. The objective of the expanded test program is to gather thorough thermal, vibration, electromagnetic interference (EMI) and reliability performance data on space cryocoolers under development by, or of interest to the SDIO Community [10]. Current coolers under test, or about to be tested, include the Hughes and Creare 65 K SSC Stirling coolers -- both under development through AFPL/SDIO funding -- and coolers from BAe, Lockheed-Lucas, Stirling Technology Company, TRW, and Sunpower Corporation; in addition, several other manufacturers are in active discussions relative to testing of their coolers. The test program covers 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, and EMI. The JPL characterization program is designed to provide a comprehensive database obtained using a common set of instrumentation, test procedures, and test facilities. This helps provide standardization of test-result formats and parameter ranges to aid in comparing and interpreting cryocooler performance.

Cryocooler Life-Test Facility Development

With the growing commitment of long-life Stirling cryocoolers to multi-year NASA and SDIO space applications, there is also increasing need for quantitative reliability 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 is designing and fabricating comprehensive life-testing facilities for use by the Air Force Phillips Laboratory (AFPL) and the Jet Propulsion Lab [11]. These life-test facilities are directed at acquiring

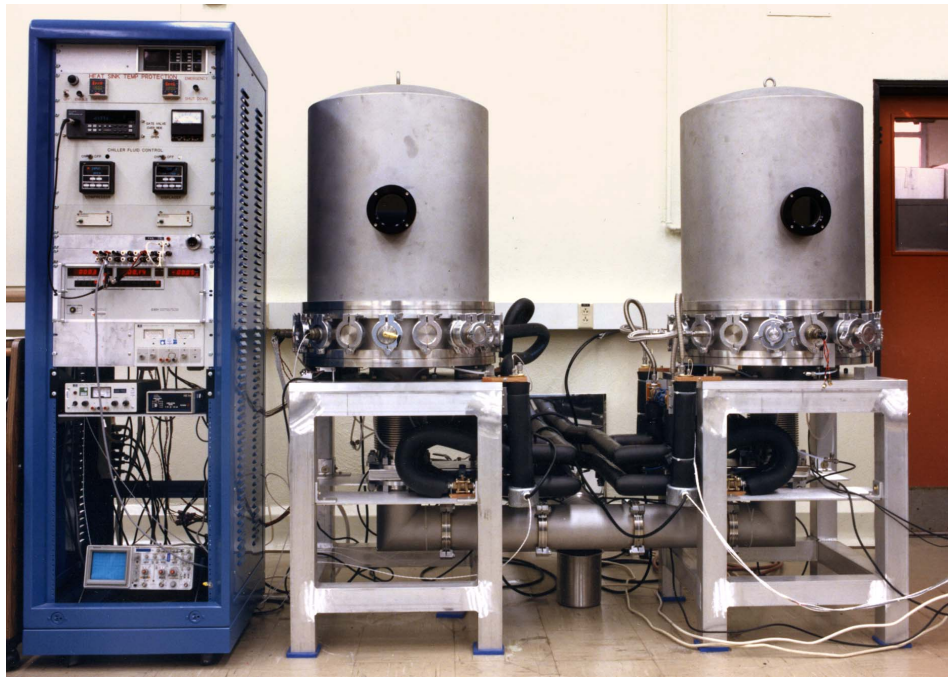


Fig. 3. JPL cryocooler lifetest chamber installation overview.

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, shown in Fig. 3, 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 timeframe: the NASA In-STEP Cryosystem Flight Experiment, and the STRV Cryocooler Vibration Suppression Experiment.

NASA In-STEP Cryosystem Flight Experiment

Under JPL management, the Hughes Aircraft Co. is developing a cryosystem flight experiment [12] to validate and characterize the on-orbit performance of a hybrid cryogenic cooling system integrating three advanced technologies: a 2-watt 65K low-vibration long-life

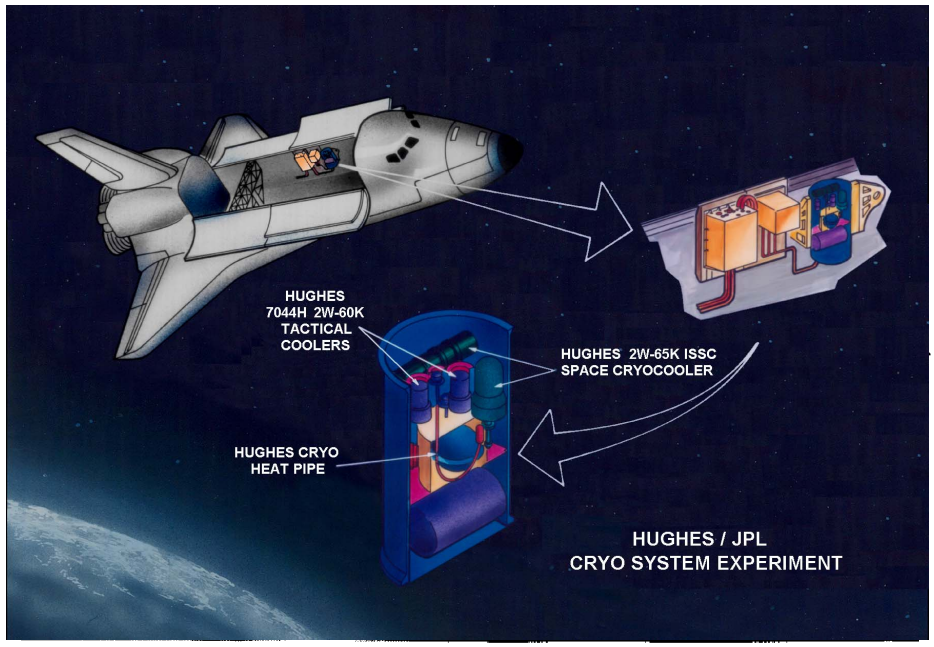


Fig. 4. Hughes In-step Cryo System Experiment (CSE) mounted in Shuttle bay.

Stirling cooler developed by Hughes under AFPL/SDIO 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 shield cooling. The NASA-sponsored experiment, illustrated in Fig. 4, is in the final stages of construction and is scheduled for launch aboard the Shuttle in mid-1994.

STRV Cryocooler Vibration Suppression Experiment

Under SDIO sponsorship, JPL is also developing a flight experiment to demonstrate more advanced control technologies for quieting cryocooler tip vibration in three axes [13]. This experiment is scheduled to fly as a small 15-watt payload on the Space Technology Research Vehicle (STRV-1b), a small English satellite scheduled for launch on the Ariane-4 in early 1994. To meet stringent power, weight, and space constraints, the experiment makes use of the tiny 1/5-watt Texas Instruments tactical Stirling cooler, shown in Fig. 5. 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

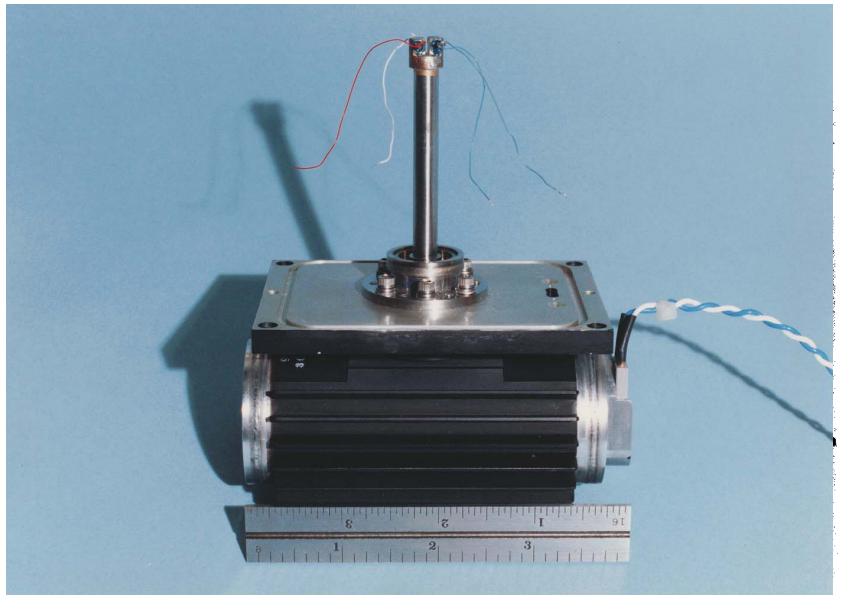


Fig. 5. Texas Instruments 1/5-watt 80K cooler to be flown in JPL STRV cryocooler vibration-suppression flight experiment.

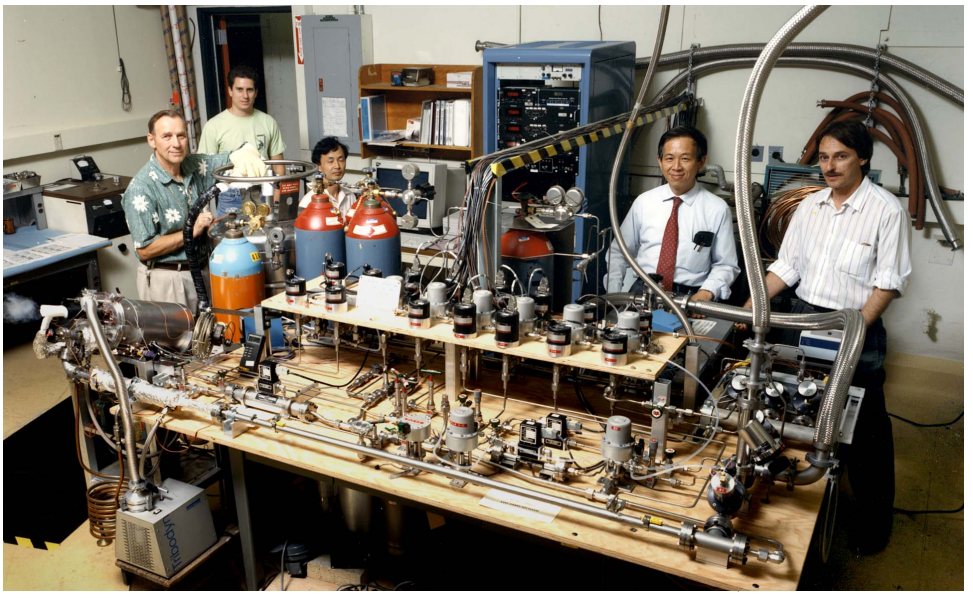
adaptive feed-forward system that continually updates a steady-state command signal to each actuator to cancel the tip vibration. Either control system can be used with either actuator.

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 at near 10 K. To provide the necessary cryogenic cooling, a novel periodic 10-K sorption cooler concept was invented by Dr. Al Johnson of Aerospace, Inc. in collaboration with Mr. Jack Jones of JPL [14,15]. The basic feasibility of the unique 10-K hydrogen/hydride sorption cryocooler was demonstrated at JPL in a series of proof-of-principal experiments in 1991 [16]. Figure 6 shows the breadboard cooler and the successful demonstration of the ability of the cooler to cooldown to below 10 K in under 2 minutes and maintain a detector heat load of 150 mW for over 30 minutes. Based on this successful demonstration, a comprehensive technology development program is now underway to advance the maturity level and mitigate the risks of utilizing this novel technology for spaceflight systems such as BE. The various elements of the development program include component-level characterization and reliability physics investigations, engineering model and protoflight development by industry, and a JPL BETSCE spaceflight technology demonstration experiment scheduled for launch in 1994.

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,



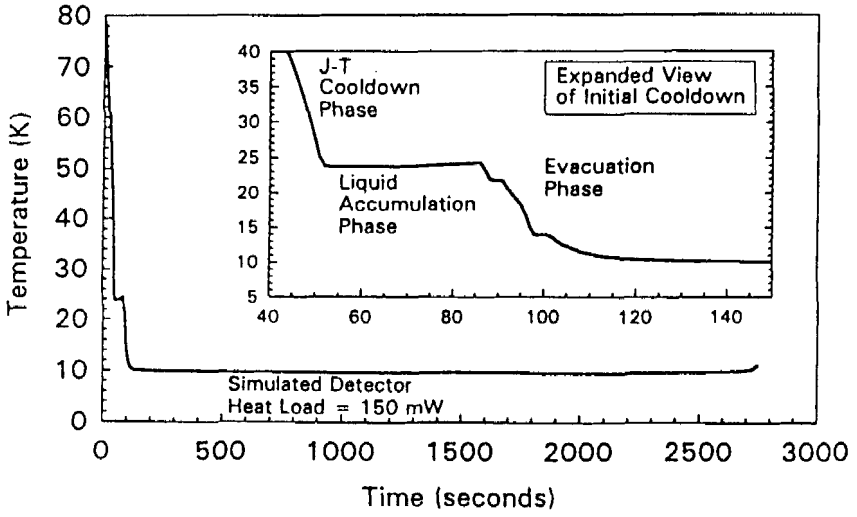


Fig. 6. JPL 10 K sorption proof-of-principle breadboard cooler and test results.

and periodically cool the detector cold head assembly to 10 K on command [14,15,16]. 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 coolers such as the SDIO SSC coolers or the AIRS coolers -- and then flows through a Joule-Thomson refrigeration loop where it is cooled and partially liquified at 25 to 30 K. The liquid is collected in a wick contained in the cryogen reservoir, and all unliquified 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 $\leq$ 11 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.

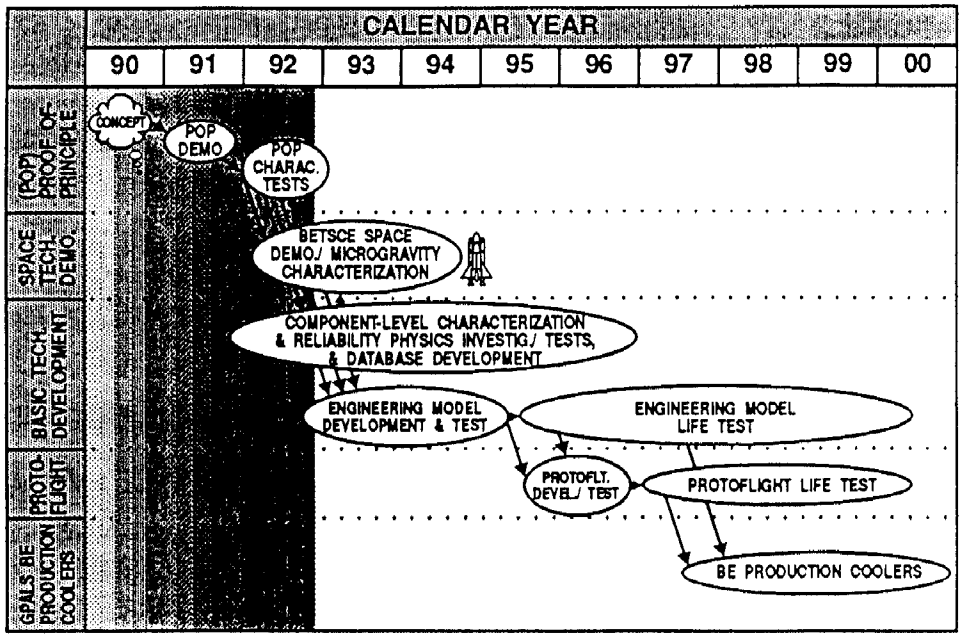


Fig. 7. JPL 10 K sorption cooler development roadmap.

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.

JPL 10-K Basic Technology Development Activity

Figure 7 presents a technology development roadmap that shows the evolution from the original periodic 10-K sorption cooler concept, through to BE cooler utilization [16]. The key activities ongoing in 1993 are the Basic Technology Development Activity and the BETSCE Flight Experiment.

Component-Level Characterization and Reliability Physics Investigations. This aspect of the 10-K basic technology development activity is directed at providing the basic technology base required to design and manufacture high reliability 10-K hydride sorption cryocooler stages [16]. A key initial focus is on issues associated with the candidate hydride materials including lanthanum-nickel-tin hydride ($LaNi_{4.8}Sn_{0.2}H_x$) for the upper sorption stage and zirconium-nickel ($ZrNiH_x$) hydride for the low-pressure sorption stage. Vanadium hydride (VH_x) is also planned to be studied for the upper sorption stage. Specific studies are currently underway to determine the effects of purity and manufacturing techniques on hydride isotherm properties, and to establish requirements for preventing migration and compaction of the hydride power. Other studies are making good progress in characterizing the kinetics and absorption capabilities of fast absorption beds containing phase-change-material (PCM) heatsinks. In addition to the tests associated with the hydride materials, other issues under investigation include the reliability physics of high-strength pressure-vessel container materials, electrical heaters, valves, phase change materials, and candidate cryostat thermal storage materials.

10-K Engineering Model Development. To provide the necessary precursor to eventual flight BE coolers, a flight-like engineering model is scheduled to be contracted to industry in early 1993. The engineering model will be targeted directly to the BE cooling requirements, mission constraints, satellite designs and interfaces. The engineering model effort will include parametric design trade-off studies directed to the performance range needed by system developers. As a result, close cooperation between the BE system developers and the 10-K cooler development team is planned to insure that the engineering model design is faithful to BE needs. Following comprehensive performance characterization testing, the engineering model will be subjected to life testing.

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) [17]. This Shuttle side-wall-mounted flight experiment, illustrated in Fig. 8, is scheduled for launch in 1994 in conjunction with the Shuttle Pallet Satellite (SPAS III) mission. 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, phase-change materials, heat sinks, heat exchangers and other refrigeration loop components, the cold-

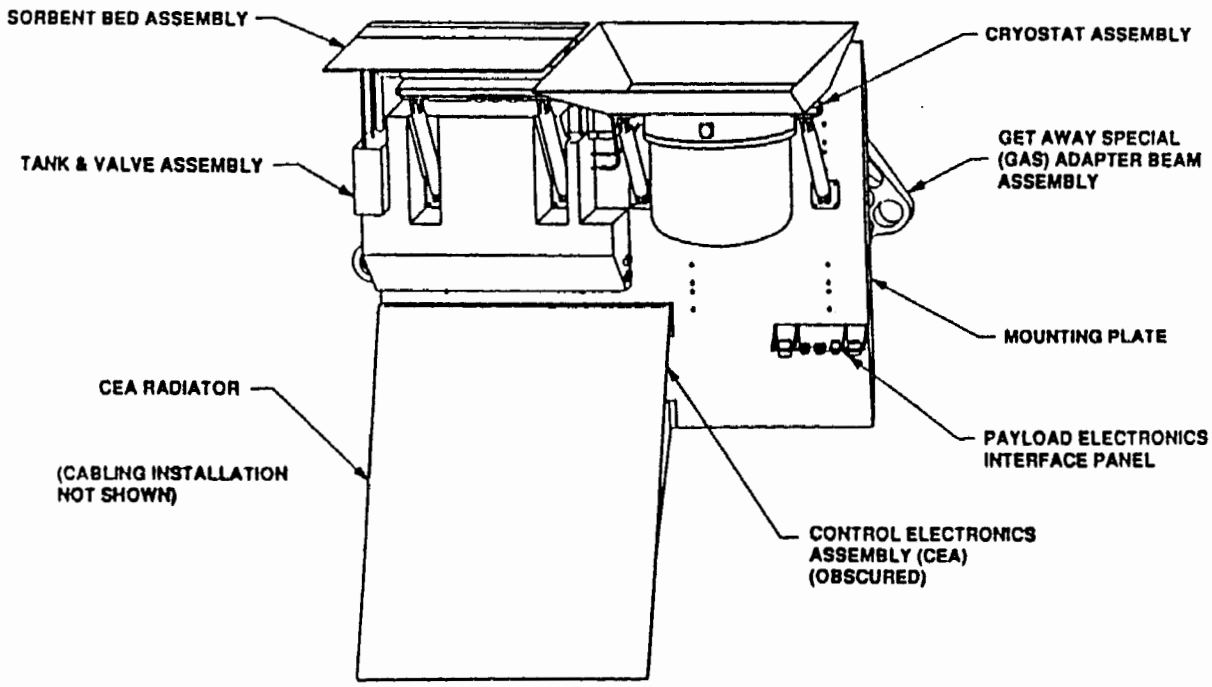


Fig. 8. Brilliant Eyes Ten Kelvin Sorption Cooler Experiment (BETSCE) side-wall mounted in Shuttle bay.

head assembly containing a wicked solid/liquid cryogen reservoir, cycle process controls, and cycle repeatability.

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 SDIO space missions. To help ensure the success of these cooler commitments, the Jet Propulsion Laboratory (JPL) 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 and life testing of industry-developed Stirling coolers, the development and test of advanced vibration-suppression systems, the flight test of advanced low-vibration Stirling-cooler systems, and the development and flight test of advanced sorption cooler systems for detector cooling to 10 K.

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REFERENCES

1. Ross, R.G., Jr., Johnson, D.L. and Sugimura, R.S., "Characterization of Miniature Stirling-cycle Cryocoolers for Space Application," Proceedings of the 6th International Cryocooler Conference, Plymouth, MA, DTRC-91/002, David Taylor Research Center (1991), p. 27-38.

2. Kotsubo, V., Johnson, D.L. and Ross, R.G., Jr., "Cold-tip Off-state Conduction Loss of Miniature Stirling Cycle Cryocoolers," Adv. Cryo. Engin., Vol. 37B (1991), p. 1037-1043.

3. Ross, R.G., Jr., Johnson, D.L. and Kotsubo, V., "Vibration Characterization and Control of Miniature Stirling-cycle Cryocoolers for Space Application," Adv. Cryo. Engin.," Vol. 37B (1991), p. 1019-1027.

4. Johnson, D.L. and Ross, R.G., Jr., "Electromagnetic Compatibility Characterization of a BAe Stirling-cycle Cryocooler for Space Applications," Adv. Cryo. Engin.," Vol. 37B (1991), p. 1045-1053.

5. Kotsubo, V.Y., Johnson, D.L., and Ross, R.G., Jr., "Calorimetric Thermal-Vacuum Performance Characterization of the BAe 80 K Space Cryocooler", SAE Paper No. 929037, Proceedings of the 27th Intersociety Energy Conversion Engineering Conference, San Diego, California, August 3-7, 1992, P-259, Vol. 5, pp. 5.101-5.107.

6. Jones, B., "Long Life Stirling Cycle Cooler Developments for the Space Application Range of 20K to 80K", 7th International Cryocooler Conference, Santa Fe, NM, November 17-19, 1992.

7. Hocking, B. and Weir, C., "Development and Space Qualification Testing a Range of Mechanical Cryocoolers", 7th International Cryocooler Conference, Santa Fe, NM, November 17-19, 1992.

8. Johnson, B.G., et al., "Demonstration of Active Vibration Control on a Stirling-cycle Cryocooler Testbed", Proceedings of the American Control Conference, Chicago IL, June 24-26, 1992.

9. Johnson, B.G., et al., "Demonstration of Active Vibration Reduction on a Stirling-cycle Cryocooler Testbed", 7th International Cryocooler Conference, Santa Fe, NM, November 17-19, 1992.

10. Johnson, D.L., Mon, G.R. and Ross, R.G., Jr., "Spacecraft Cooler Characterization", 7th International Cryocooler Conference, Santa Fe, NM, November 17-19, 1992.

11. Ross, R.G., Jr. and Johnson, D.L., "Design and Test of a Comprehensive Facility for Life Testing Space Cryocoolers", 7th International Cryocooler Conference, Santa Fe, NM, November 17-19, 1992.

12. Russo, S. and Sugimura, R., "NASA Cryo System Flight Experiment (CSE)",7th International Cryocooler Conference, Santa Fe, NM, November 17-19, 1992.

13. Glaser, R., Ross, R.G., Jr. and Johnson, D.L., "Cryocooler Tip Motion Suppression Using Active Control of Piezoelectric Actuators", 7th International Cryocooler Conference, Santa Fe, NM, November 17-19, 1992.

14. Johnson, A.L. and Jones, J.A., "Periodic 10 K Sorption Cooling," USA Patent Pending, 1992.

15. Johnson, A.L. and Jones, J.A., "Evolution of Periodic 10 K Sorption Cooling," 7th International Cryocooler Conference, Santa Fe, NM, November 17-19, 1992.

16. Bard, S., et al., "Development of a Periodic 10 K Sorption Cryocooler", 7th International Cryocooler Conference, Santa Fe, NM, November 17-19, 1992.

17. Bard, S., et al., "10 K Sorption Cryocooler Flight Experiment (BETSCE)," 7th International Cryocoolers Conference, Santa Fe, NM, November 17-19, 1992.