Ground Testing of a 10 K Sorption Cryocooler Flight Experiment (BETSCE)

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ABSTRACT

The Brilliant Eyes Ten-Kelvin Sorption Cryocooler Experiment (BETSCE) is a Space Shuttle side-wall-mounted flight experiment designed to demonstrate 10 K sorption cryocooler technology in a space environment. The BETSCE objectives are to: (1) provide a thorough end-to-end characterization and space performance validation of a complete, multistage, automated, closed-cycle hydride sorption cryocooler in the 10 to 30 K temperature range, (2) acquire the quantitative microgravity database required to provide confident engineering design, scaling and optimization, (3) advance the enabling technologies and resolve integration issues, and (4) provide hardware qualification and safety verification heritage.

BETSCE ground tests were the first-ever demonstration of a complete closed-cycle 10 K sorption cryocooler. Test results exceeded functional requirements, as the BETSCE cooler was able to cooldown from 70 K to < 11 K in 95 seconds, sustain a simulated detector heat load of 100 mW for > 20 minutes, achieve a minimum temperature of 9.5 K with load, and demonstrate excellent repeatability with continued cycling. The sorbent beds achieved a compression ratio of 8.3 x 105, and were able to recycle the system in under 5.5 hours. This paper summarizes functional and environmental ground test results, planned characterization tests, important development challenges that were overcome, and valuable lessons-learned. The planned spaceflight experiment will enable early insertion of sorption cryocooler technology into future long-life, low-vibration, spacecraft sensor cooling applications in the 10 to 30 K temperature range.

INTRODUCTION

A growing number of space remote sensing instruments use long wavelength IR and submillimeter imaging detectors that require operating temperatures in the 10 to 30 K temperature range. Examples include astrophysics space telescopes, earth and planetary atmospheric, geologic and resource mapping satellites, space superconducting electronics, and military surveillance satellites. The demanding cooling requirements of these applications, including minimal allowable generated vibration and electromagnetic fields, and lifetimes of 5 to 10 years, can be provided by hydride sorption cryocooler technology.

The concept for a continuous 10 K sorption cryocooler was originally developed by Jones in 1984.1 In 1991, Johnson and Jones recognized that a periodic 10 K sorption cryocooler offers repeated quick cooldowns and low average power consumption for applications where intermittent operation is sufficient.[2] The proof-of-principle of a periodic 10 K sorption cooler stage was experimentally demonstrated and analytical concept design studies were conducted in 1992,3 The Brilliant Eyes Ten-Kelvin Sorption Cryocooler Experiment (BETSCE) described here provides the space performance validation that will enable the early insertion of this new technology into future space missions, and establish the microgravity database required for development and production of periodic and continuous 10 to 30 K sorption cryocooler systems.

The 10 K periodic sorption cryocooler concept has been described in detail elsewhere.[4] The concept is based on sequentially heating beds containing metal hydride powders to circulate hydrogen as the refrigerant fluid in a closed cycle Joule-Thomson (J-T) refrigeration system. On command, it periodically cools the hydrogen to 10 K from an upper stage temperature of ≥ 60 K that can be provided by one of the emerging long-life mechanical cooler systems,

Object ive

The BETSCE objectives are to: (1) provide a thorough end-to-end characterization and space performance validation of a complete, multistage, automated, closed-cycle hydride sorption cryocooler in the 10 to 30 K temperature range, (2) acquire the quantitative microgravity database required to provide confident engineering design, scaling and optimization, (3) advance the enabling technologies and resolve integration issues, and (4) provide hardware qualification and safety verification heritage.

Requirements

The basic functional requirements selected for the BETSCE instrument are representative of the periodic cooling goals of the Brilliant Eyes (BE) infrared sensor system:[5] (1) to demonstrate cooldown from 60 K to ≤ 11K within 2 minutes, (2) sustain an I*R simulated detector heat load of ≥ 100 mW at ≤ 11 K for ≥ 10 minutes, (3) completely recycle the system so that it can be operated at least once each day, (4) demonstrate repeatability of cyclic operation by completing at least 3 full cycles, and (5) record the data required to characterize the spaceflight performance. Although targeted to BE, meeting these requirements completely validates the 10 K sorption cryocooler process in space.

Key operating parameters will be varied to fully exercise and characterize the system. Sufficient in-flight operating experience and data will be obtained to effectively evaluate and understand microgravity performance. Thermal processes, energy management, liquid and solid cryogen management, and process controls will be demonstrated.

Microgravity Issues

There are several important design areas where characterization and validation in the microgravity space environment is required to provide confident scaling and optimization for future flight applications. BETSCE is designed to acquire needed microgravity data in each of these key areas: (1) phase separation and capture of liquid hydrogen during the formation of two-phase gaseous and liquid hydrogen at 25-30 K, (2) phase separation and capture of solid hydrogen during the formation of three-phase gaseous, liquid and solid hydrogen at 13.8-9.5 K, (3) liquid and solid hydrogen retention in the wicked cold head reservoir assembly when subjected to zero-gravity effects (e.g. Marangoni surface tension variations with temperature), (4) heat and mass transfer mechanics within the hydride powder beds and phase change materials in the absence of gravity-dependent natural convection and one-g contact forces, (5) supercooling of the phase change materials in microgravity, and (6) Joule-Thomson (J-T) efficiency and heat exchanger effect iveness in the absence of gravit y-dependent mixed natural and forced convection.

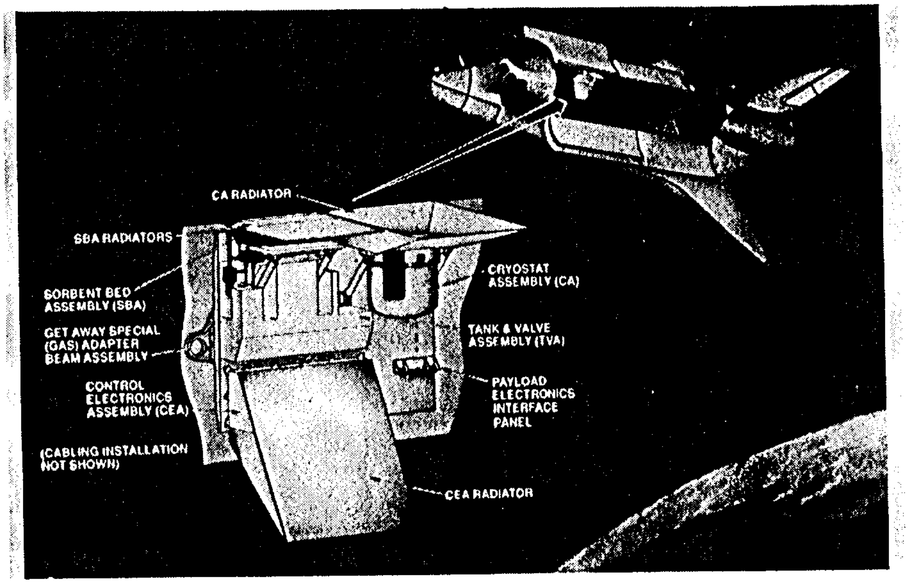


Figure 1. BETSCE mounted on a Get-Away Special adapter **beam.**

A detailed understanding of these microgravity issues will enable elimination of excessive design margins, which is expected to result in significant weight savings for future 10 K cooler systems.

EXPERIMENT DESIGN

Ovm-view

The BETSCE instrument mounts on the Shuttle orbiter payload bay side-wall to a Small Payload Accommodation (SPA) Get Away Special (GAS) adapter beam carrier, as shown in Figure 1. Power from the Shuttle 28 VDC power bus and crew inputs from the Standard Switch Panel (SSP) reach BETSCE via Shuttle cabling, BETSCE data/ commands are downlinked/ uplinked via standard Shuttle Payload Data Interleave (PDI)/ Payload Signal Processor (PSP) interfaces. Waste heat from BETSCE is radiated to space by flat plate passive radiators oriented out (+Z) of the Shuttle bay. No Shuttle safety-critical services are required.

The BETSCE instrument contains four integrated subsystems: Sorbent Bed Assembly, Cryostat Assembly, Tank and Valve Assembly, and Control Electronics Assembly. BETSCE was developed as a collaborative team effort between industry, university and government. The Sorbent Bed Assembly was developed by Aerojet Electronic Systems Division (AESD), the Cryostat Assembly was developed by APD Cryogenics, Inc., the upper stage Stirling coolers for the Cryostat Assembly were provided by Hughes Aircraft Corp., the n-hexadecane phase change material was furnished by ESLI, Inc., and the sorbent materials were characterized by the University of Vermont. JPL is responsible for overall project management, principle investigator team, system design, design and fabrication of the Control Electronics Assembly, Tank and Valve Assembly, Structure and Cabling subsystems, structural and thermal systems analyses, system integration and test, Shuttle integration support, mission operations, and postflight data analysis.

Experiment Operation

Startup Conditioning Sequences. The BETSCE cycle operation can be visualized with the aid of the fluid schematic shown in Fig. 2. At launch, more than 93°/0 of the -33 g total fill of hydrogen in the BETSCE system is in hydride form, When the experiment is powered up, the hydrogen must be released from the hydride beds. First, the High Pressure Sorbent Bed is heated to transfer its hydrogen to the 4 liter storage tank, and then allowed to cool down. Next, the Low Pressure and Fast Absorber Sorbent Beds are heated in turn to transfer their hydrogen to the High Pressure bed, and then allowed to cool down. Finally, the High Pressure Sorbent Bed is heated again to bring the H_2 storage tank to operating pressure (< 10.3 MPa at 300 K), and again

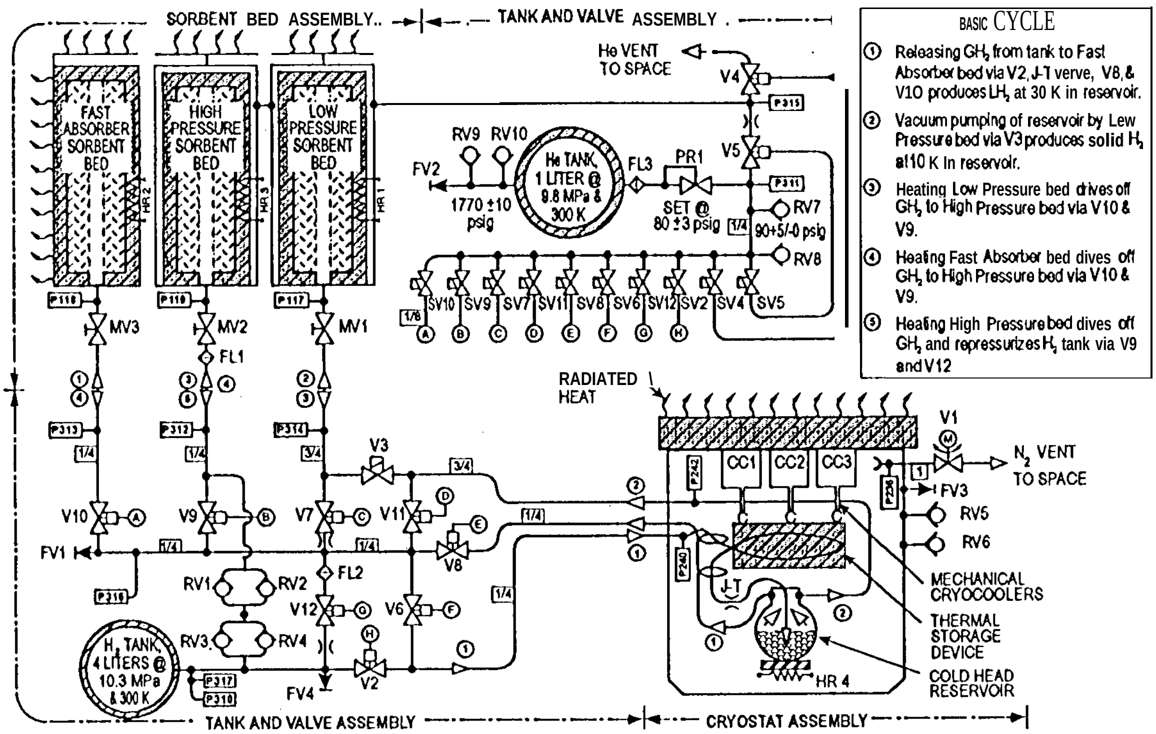


Figure 2. BETSCE fluid schematic.

coolers pre-chill the cryostat thermal storage device and cold head to 60-70 K. With startup conditioning sequences completed, BETSCE is ready to enter its operating cycle.

Operating Cycle. Cooldown is initiated by releasing pressurized H_2 gas from the storage tank to the Fast Absorber Sorbent Bed by way of the cryostat, whose pre-chilled heat sink, heat exchangers, and J-T valve produce liquid H_2 at 26-28 K in the cold head reservoir. Next, solid H_2 at ≤ 11 K is produced by vacuum pumping the cold head reservoir with the low pressure sorbent bed. Under simulated sensor heat load provided by an electrical resistance heater, and continued vacuum pumping, the solid H_2 sublimates and is absorbed by the low pressure sorbent bed until it is consumed. Next, hydrogen is returned to the tank and pressurized by sequentially heating the sorbent beds as before, to complete the cycle. The total cycle time is between 8 and 15 hours, depending on the Shuttle attitude and thermal environment.. Results of detailed BETSCE orbital thermal analysis-based predictions of cycle times as a function of Shuttle attitudes are summarized in Ref. 6.

The nominal seven day mission allows for the completion of 8 cycles. In each cycle, preplanned variations of event timing or parameters are introduced to fully map operating characteristics and microgravit y effects, Following the final sorption cycle, the mechanical coolers are shut down and the warmup of the thermal storage device and cold head is observed. While warmup is proceeding, hydrogen is returned to the sorbent beds until they are fully hydrided. Then BETSCE is configured for landing and powered off,

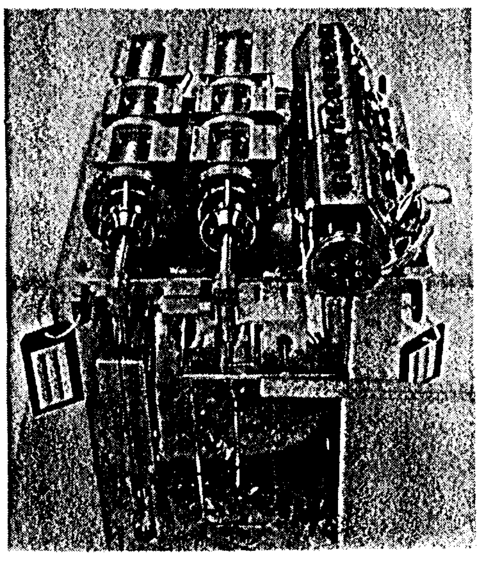
Hardware Design

Sorbent Bed Assembly. The BETSCE Sorbent 13ed Assembly contains three separate sorbent beds, each tailored to meet specific performance needs. The Fast Absorber Sorbent Bed can rapidly absorb a large quantity of hydrogen, > 8 g in < 70 seconds, to enable the production of liquid hydrogen in the cryostat. The Low Pressure Sorbent Bed is capable of rapidly absorbing> 0,7 g hydrogen in < 20 seconds at "low pressure, < 1.3 x 10-s MPa (O. 1 torr), to enable the production of solid hydrogen at < 11 K. Then it can continue to absorb > 0.82 g of sublimating pressure (> 10.8 MPa) when heated to about 275°C. The overall compression ratio is an impressive 8.3 x 10^5, which is achieved thermally instead of mechanically, The Low Pressure Sorbent Bed sorbent material is zirconium-nickel (ZrNi) hydride. The Fast Absorber and High Pressure Sorbent Beds contain lanthanum-nickel-tin ($LaNi_{4.8}Sn_{0.2}$) hydride.

Besides hydride, each sorbent bed contains cartridge-type heater elements, a heat sink/ radiator, and either a gas gap heat switch or phase change material thermal capacitor. All pressure-containment elements are 3 16L corrosion resistant stainless steel (CRES), a material highly resistant to hydrogen embrittlement. All joints are fusion welded. Multiple heaters are brazed to the outside of the pressure containers. Surrounding the high and low pressure beds' hydride containers are 3.8 mm (O. 150-inch) wide vacuum spaces that function as gas gap heat switches. These gaps are either filled with helium to provide conductive paths between the hydrides and heat sinks/ radiators, or evacuated to the vacuum of space to provide thermal isolation. Hydride in the Fast Absorber Sorbent Bed is enclosed in seven finned pressure containers, located in seven sealed cylindrical chambers filled with n-hexadecane, a paraffin phase change material (PCM) that serves as a thermal capacitor, Heat generated by the hydride during hydrogen absorption melts the phase change material to minimize hydride temperature rise, and thus maintain a suitable hydrogen liquefaction pressure and temperature in the cryostat. Manual valves MV1 -3 in Fig. 2 are used only to prevent contamination of the sorbent materials prior to system integration. They are lockwired in the open position for flight. Figure 3 shows the complete Sorbent Bed Assembly, with thermal radiators removed, prior to system integration. Further Sorbent Bed Assembly design details are presented in Refs. 5 and 7.

Cryostat Assembly. The BETSCE Cryostat Assembly comprises the thermal storage device (TSD), mechanical cryocoolers, reservoir, heat exchangers and J-T valve, associated tubing, outer shell, vacuum vent motor-driven valve VI, and radiator panel. The cryostat outer shell is vented to space vacuum by V1 when BETSCE is operating. The TSD is a 2.2 kg solid aluminum cold sink supported from the cryostat outer shell by a low-thermal-conductance G-1 O fiberglass cylinder. The TSD also serves as a radiation shield that surrounds the cold head to minimize parasitic heat leaks. During the initial hours of BETSCE operation, the TSD is chilled to 60-70 K. In each subsequent cooldown cycle, hydrogen gas circulating through the warm counterflow heat exchanger and then TSD heat exchanger tubing is cooled before finally entering the cold J-T loop counter-flow heat exchanger. Heat surrendered by the hydrogen, as well as the parasitic conduction and radiative heat leaks from the cryostat outer shell, is removed from the TSD by an assembly of three mechanical cryocoolers.

BETSCE contains three Hughes Model 7044H split-Stirling rotary drive advanced tactical coolers. Two coolers are operated simultaneously, and the third is a flight spare. The Cryostat



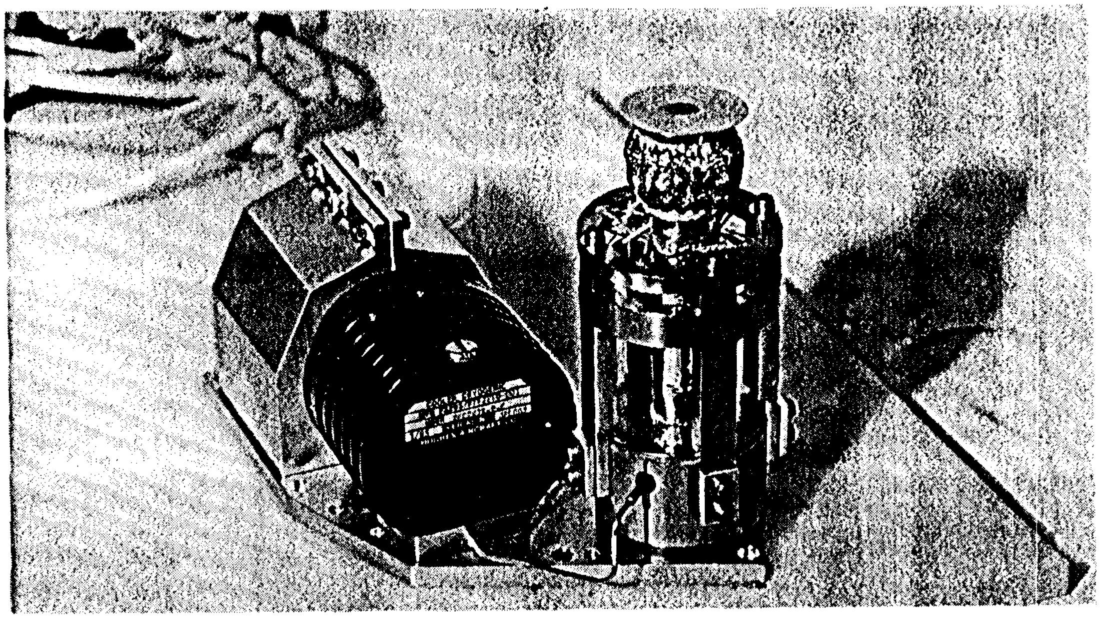


Figure 4. 60 K Stirling cooler with high conductance copper strap interface to TSD.

Assembly radiator is capable of rejecting the -200 mW dissipated by two coolers operating at maximum capacity. It is important to minimize the cooler power dissipation because cooler lifetime degrades as the compressor case temperature rises. To minimize cooler power dissipation, electronic control circuits packaged in the cooler motor housing enable feedback temperature control that throttles input power when the setpoint temperature of 65 K is approached. To minimize operating hours accrued by the mechanical coolers during ground testing, a liquid nitrogen cooling 'loop was attached to the TSD. Exhausting the nitrogen to a vacuum pump enables ground test TSD operation at -70 K.

Specialized brackets containing low thermal conductance Kevlar support cables were developed to support the Stirling cooler cold tips during launch. High thermal conductance copper straps, with three-axes of movement, and with a measured thermal conductance of 0.65 W/K, connect the Stirling cooler cold tips to the TSD, as shown in Fig. 4.

Figure 5 shows the Cryostat Assembly with the outer shell and the radiation shield removed. The spherical cold head contains a rolled copper screen/ fiber-paper wick designed to retain liquid hydrogen in microgravity, as illustrated in Fig, 6. The Joule-Thomson expansion valve is a 0.178 mm (0.007 inch) I. D., 40.6 cm (16 inch) long capillary tube. Liquid hydrogen produced by the expansion in the capillary tube is collected in the wick, while the vapor returns through the counterflow heat exchangers.

Prior to delivery to JPL for system integration, APD performed 47 open-cycle tests to characterize cryostat performance, achieving 10 K by using a vacuum pump to simulate the Low Pressure Sorbent Bed.

Tank and Valve Assembly. The BETSCE Tank and Valve Assembly contains a 4-liter hydrogen tank, a 1-liter helium tank, helium pressure regulator, helium relief valves, solenoid-operated valves, pneumatically actuated hydrogen control valves, pressure and temperature transducers, and associated pressurized tubing and components, as shown in Fig. 2. V3 is a normally-closed 1.91 cm (%-inch) solenoid-operated valve that isolates the Low Pressure Sorbent Bed, and is capable of passing the required H_2 flow rate at low pressure with minimal pressure drop. V2 and V4-V1 2 are pneumatically-actuated hydrogen control valves. The helium actuation gas is controlled by solenoid valves SV2, and SV4-SV12. The gas gap heat switches are filled with helium by actuating SV5 (and thus V5) and evacuated to space by actuating SV4 (and thus V4).

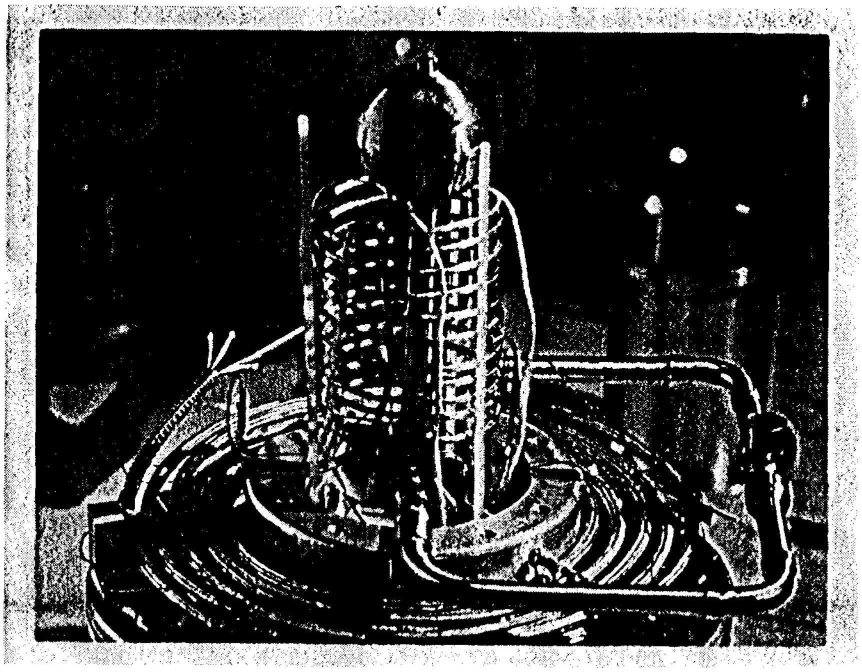
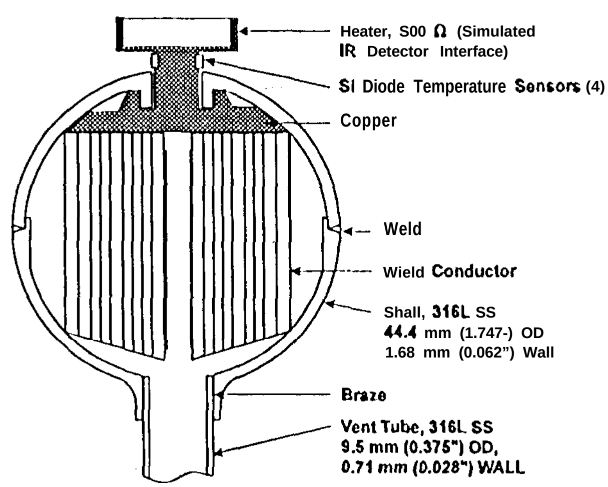


Figure 5. Cryostat cold head assembly,

Control Electronics Assembly and Instrumentation. The BETSCE Control Electronics Assembly directs the instrument through a series of pre-programmed sequences. Data on the status and performance of the instrument is acquired and stored in nonvolatile memory for postflight retrieval and analysis. Performance data is also downlinked to ground personnel so that experiment progress can be assessed. Commands can be uplinked to modify sequence timing or parameters based on observed performance.

The Control Electronics contains two Remote Sensor Cutoff Assemblies; essentially electrically-operated thermostatic switches controlled by temperature sensor/ feedback loops. These assemblies provide two-fault tolerant protection against runaway heaters in the Sorbent Bed Assembly. In addition, temperature control heater circuits in the various BETSCE assemblies are used to prevent electrical components from getting too cold (< - 10°C). Each heater circuit contains three Elmwood thermostats in series to protect against a runaway heater condition, These thermostats provide control independent from the Control Electronics Assembly processor.

BETSCE contains an array of 96 temperature, pressure, voltage and current sensors strategically located throughout the instrument that are monitored by the Control Electronics Assembly.



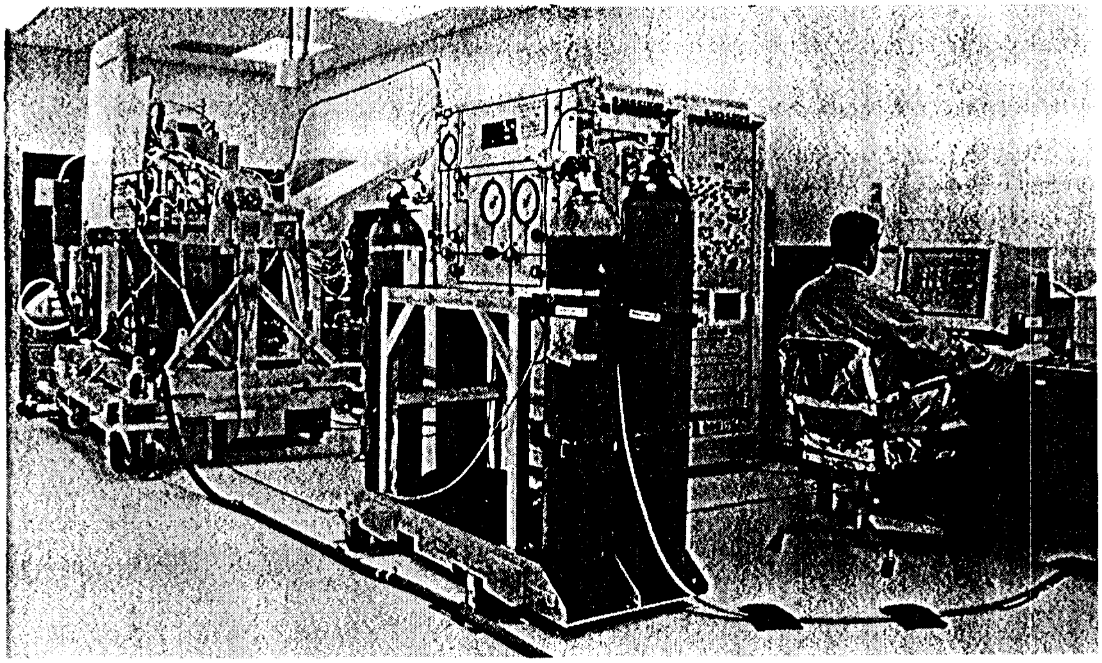


Figure 7. BETSCE instrument with ground support equipment.

Macintosh-based LabVIEW visual programming language is used to provide a highly interactive operator interface that permits continuous monitoring, backup data storage, and command capability. The monitoring and command capability provided by this system is used both for ground testing as well as for the Payload Operations Control Center (POCC). Figure 7 shows the integrated BETSCE instrument with its ground support equipment and operator interface,

VERIFICATION TEST RESULTS

The BETSCE verification test program consists of three major elements: (1) basic functional testing to validate that BETSCE meets performance requirements, (2) environmental testing to verify that BETSCE meets all Shuttle interface and safety requirements, and (3) additional characterization testing to extensively map the cooler performance and gain a detailed understanding of important performance sensitivities. This paper focuses on the results of the basic functional testing. Environmental testing is nearly completed, and the additional characterization testing is planned for the future.

Functional Test Results

Figure 8 shows the integrated BETSCE instrument in test in a horizontal configuration, Figure 9 shows coldhead cooldown data for a typical test run. The sorbent bed recharge cycle is shown in Fig, 10. The basic performance requirements have been clearly exceeded, as summarized in Table 1. A total of twenty-five cycles were completed as of April 1994.

Clogging of the J-T loop due to freeze-out of gaseous contaminants was observed for a number of cycles. After running a series of diagnostic tests, including several open-cycle runs, the source of the problem was isolated to the sorbent beds. By collecting desorbed gas from the Fast Absorber Sorbent Bed in a liquid nitrogen-cooled Saran carbon-filled cold trap, it was determined that the sorbent beds were producing large quantities of water and nitrogen. The problem is being addressed in two ways: making the system tolerant to these contaminants, and eliminating the contaminant source,

To make the system tolerant to contaminants, an activated resin-filled "Nanochem" filter that chemically absorbs water oxygen, carbon dioxide and complex hydrocarb[illegible] and is capable of

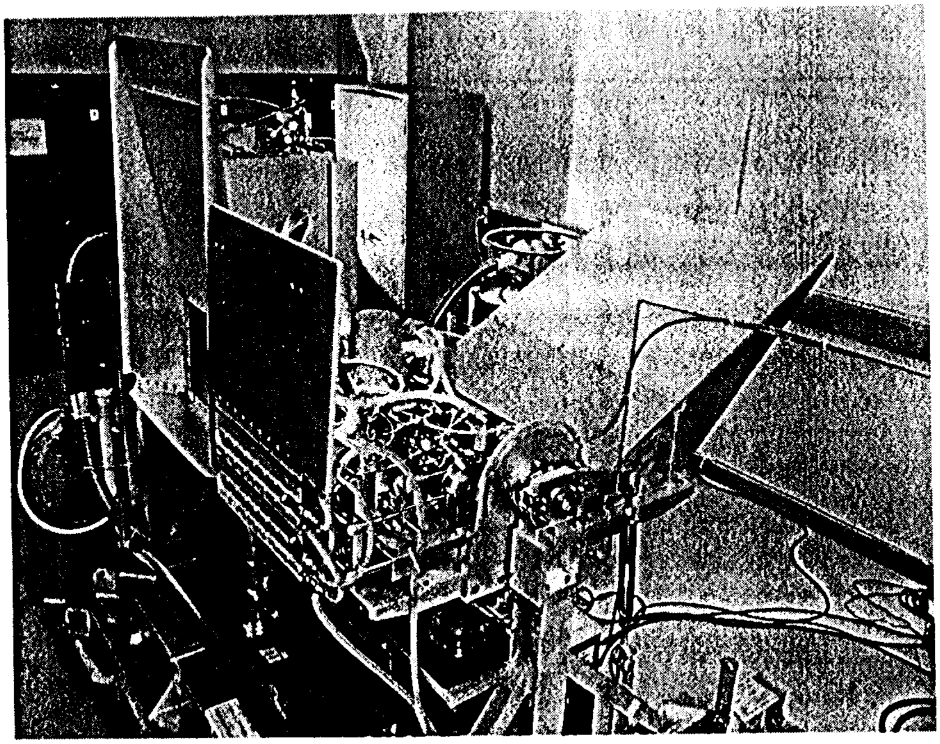
Table 1. BETSCE functional test summary.

BETSCE PERFORMANCE PARAMETER	REQUIREMENT	DEMONSTRATED IN GROUND TEST
Quick cooldown from 60 K to <11 K:	<120 seconds	<95 seconds (from 70 K)
Duration at< 11 K with 100 mW load:	10 minutes	>20 minutes
Minimum temperature (with 100 mW load):	< 11 K	9.49 K
Recycle time:	< 24 hours	5.5 hours

purifying hydrogen to the part-per-billion level, was added to the BETSCE flight system (FL2 in Fig. 2). Because this filter is not an effective getter for nitrogen, a Saran carbon filled cold trap was also added to the ground test system. If necessary, the flight system can be later modified to incorporate a flight version of this cold trap.

The attempt to eliminate contaminants at the source focused on vacuum bakeout of the sorbent beds to significantly higher temperatures and longer duration than performed previously. The nominal maximum cycle temperature of the High, Low, and Fast Absorber Sorbent Beds are 276°C, 282°C, and 87°C, respectively. In the recent vacuum-bakeout cleaning process, the High, Low, and Fast Absorber Sorbent Beds were heated to 295°C (+19°C), 3 13°C (+31°C), and 108°C (+21°C), respectively. The Fast Absorber Sorbent Bed bakeout temperature was limited to 108°C to prevent problems caused by expansion of the n-hexadecane PCM. If the recent 68 hour 108”C bakeout proves to be insufficient, then a later attempt may be made to bake the bed to above 200”C by temporarily removing the n-hexadecane. This higher fidelity cleanup will be delayed until after completion of environmental testing.

Test results for the first seven cycles after this latest sorbent bed bake-out process, and incorporation of the cold trap, indicated none of the flow rate or cooldown irregularities noted in the earlier clogged runs, Furthermore, the repeatability in temperature, pressure, and flow rate profiles has been excellent, as shown for the five cycles in Fig, 9. Future tests will be conducted with the cold trap removed.



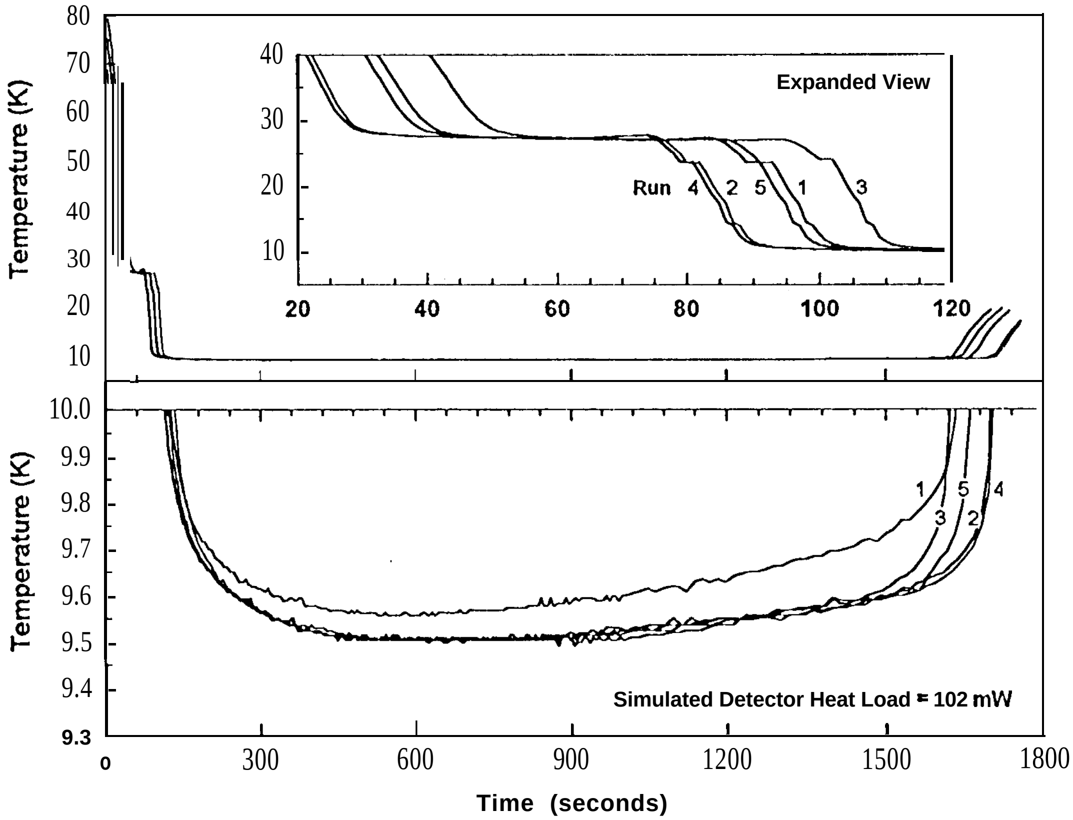


Figure 9. BETSCE cooldown test data, and repeatability.

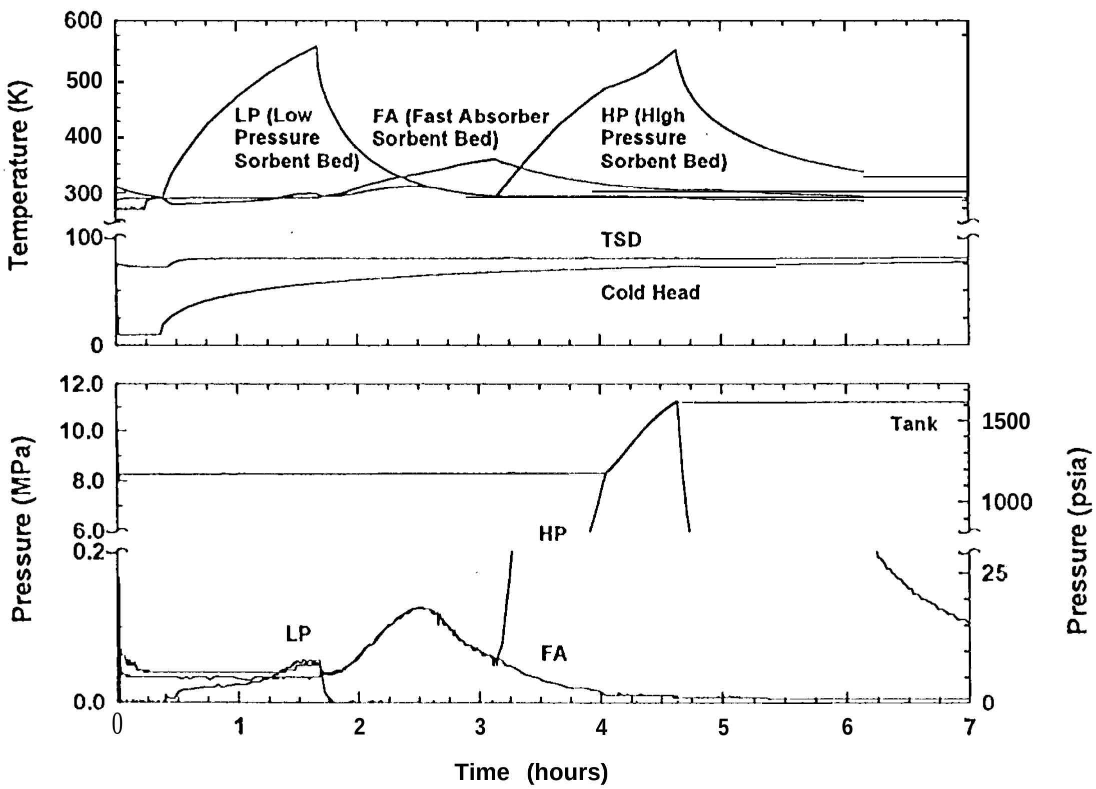


Figure 10. BETSCE cycle test data.

Performance Characterization/ Sensitivity Testing

BETSCE provides a useful test bed for gaining a detailed understanding of the performance sensitivity to a number of important design and operational parameters. The knowledge obtained from systematic characterization testing is expected to lead to important design improvements for future systems. Planned tests include varying the following parameters: cold head orientation (to determine sensitivity to adverse-gravity forces), cold head heat load, liquid accumulation time, sorbent bed heat sink temperature, sorbent bed heater power, and gas-gap fill pressure.

Some preliminary characterization tests have been performed, including a series of separate tests conducted with the Fast Absorber Sorbent Bed isolated from the system. With the High Pressure Sorbent Bed case temperature set to an initial temperature of 275 K, the bed was successfully able to absorb the burst of hydrogen released during the quick-cooldown phase. The significance of this result is that it clearly indicates that only 2 beds are needed for an operational flight 10 K sorption cooler, resulting in a lighter and simpler system, For most free-flyer spacecraft applications, a radiator operating temperature of <275 K is not too difficult to achieve. The BETSCE Fast Absorber Sorbent Bed, optimized for quick absorption with minimal temperature and pressure rise, is only needed if the thermal "environment temperature is above about 280-290 K, which is possible for some Shuttle attitudes. Additional tests are planned to determine the precise maximum High Pressure Sorbent Bed radiator temperature that permits successful operation without the need for a third, fast absorbing, sorbent bed.

The initial functional tests were conducted without an orifice at the inlet to the Low Pressure Sorbent Bed (below V7 in Fig. 2). The maximum cooling duration at <11 K was 20 minutes, regardless of liquid accumulation time. When the orifice was added, the cooling duration increased to 26 minutes, It is possible that when V7 is suddenly opened, some liquid hydrogen collected in the cold head is inadvertently withdrawn when it is exposed to the vacuum in the Low Pressure Sorbent Bed. The addition of an orifice may prevent, or reduce, this liquid hydrogen loss. Additional tests will be conducted with the cold head upside-down, both using V7 (and its orifice) and bypassing V7 by opening V3 directly. These tests should confirm whether cold head liquid retention efficiency is affected by sudden pressure reduction,

Environmental Testing

The environmental test phase includes all required testing to qualify BETSCE for flight on the Shuttle. The 3-axis flight vibration tests, and acoustic tests were successfully completed in June 1994. Conducted and radiated electromagnetic emissions measurements, and final interface and safety verification measurements are planned for completion by the end of June 1994. Additional testing to increase confidence in the flight hardware, including thermal-vacuum test will be conducted at a later date if additional funding becomes available.

FUTURE FLIGHT COOLER DESIGN IMPROVEMENTS

Based on the BETSCE hardware development experience and analysis of the BETSCE test results to date, a number of valuable lessons-learned can be applied to improve the design of future operational 10 K sorption cryocooler systems. First, it is important to recognize that the size and weight of a 10 K cryocooler can be greatly reduced from that of BETSCE. The BETSCE instrument is essentially an adaptable test bed that allows extensive characterization testing of an experimental 10 K sorption cryocooler system, within the highly constrained Shuttle safety and interface requirements. Little effort was made to minimize the size, weight, or power requirement, as the BETSCE resources were focused on developing the important new technology elements of the system, particularly those that need to be validated in microgravity. Because BETSCE was the first-ever demonstration of a complete closed-cycle 10 K sorption cooler, many key components in the Sorbent Bed and Cryostat assemblies needed significant development effort. Technologies for compact and lightweight structure, electronics, pressure vessels, radiators, and integrated valve and tubing manifolds are available, but the expense and schedule risk of incorporating them into BETSCE were unwarranted. Another important weight driver for BETSCE was the warm thermal environment that resulted from being mounted inside the Shuttle payload bay. This led to the need for large and heavy thermal radiators, which make BETSCE adaptable to almost any Shuttle flight. Possibly the most important BETSCE weight driver was safety. No hydrogen payload has ever flown before on the Shuttle. To minimize the substantial risk of late design changes imposed by NASA safety review committees, BETSCE was designed to be as rugged as possible, with a significant associated weight penalty.

The total weight of the BETSCE instrument is 324 kg. However, only about 80 kg is allocated to the actual 10 K cryocooler. The remainder includes unique support structure to mount BETSCE to the Shuttle GAS adapter beam on the payload bay side wall, thermal control in the Shuttle environment (including large thermal radiators), high-capacity data acquisition and control system, and unique BETSCE assembly and integration aids (e.g. sorbent bed isolation valves and support brackets) that could be eliminated for an operational 10 K cryocooler system.

With careful attention to efficient cooler design and spacecraft/ instrument/ cooler integration, the weight of an operational 10 K sorption cryocooler can be further reduced from BETSCE's 80 kg to 25-30 kg. For example, the storage tank weights can be reduced by about 12 kg by use of existing lightweight composite tanks instead of the thick-walled stainless steel BETSCE pressure vessels. Complete elimination of the Fast Absorber Sorbent Bed will save -11 kg. The hydrogen loop components, including the coldhead, can be designed with thinner wall components than used on BETSCE, thus resulting in lower gas consumption, and thus lighter sorbent beds, saving -10 kg. Replacing the three tactical coolers used by BETSCE with lightweight long-life Stirling or pulse-tube coolers for the upper stage will save another few kg, Use of a single-stream regenerative TSD instead of the nearly isothermal BETSCE TSD will save several additional kg. In addition to reducing the size and mass of the TSD, this design also reduces the heat load that needs to be removed by the upper stage mechanical cooler. Use of a compact valve and tubing manifold, and the elimination of many of BETSCE's valves is expected to save -10 kg. Note that most of the BETSCE valves are not needed for an operational flight cooler,[2,4] and have only been included to enable separate characterization experiments using isolated sections of the BETSCE test bed system. In addition, the heavy BETSCE pneumatic valve system can be completely replaced by solenoid-operated valves.

For a long-life flight cooler it is necessary to completely eliminate the contamination problems encountered by BETSCE. It is crucial that the system be designed to minimize real and virtual leaks. Electropolished tubing and fitting should be used wherever possible, and use of organic materials (e.g. in valve seats) should be minimized, All joints should be welded or brazed, and butt-welds should be used instead of socket welds to minimize virtual leak sources. Welds are preferred to braze joints to minimize flux contaminants and trapped volumes. It is important to pay special attention to filter manufacturing processes and cleaning procedures, especially for the filters contained within sorbent beds, These filters have very large surface areas that can trap adsorbed contaminants, and should be subjected to numerous fill/ flush and vacuum bake-outs prior to loading of sorbent material. Prolonged bake-outs in a hydrogen environment followed by vacuum should be conducted to chemically reduce oxide coatings, After filling with hydride, the sealed sorbent beds should undergo additional prolonged hot fill/ flushes and vacuum-bake-outs at temperatures well-above the normal cycling temperatures. After integration, the entire system must be meticulously cleaned prior to hydrogen fill, including numerous hot gas fill/ flush procedures, and prolonged vacuum bake-outs. The system should be filled with purified research grade hydrogen, In-line filters should be included to protect valves and the J-T refrigeration loop from solid particulates. To further reduce the risk of clogging, an in-line cold trap getter should be installed to continually remove gas phase contaminants that may be generated in the closed-cycle cooler, It is also recommended that the getter be periodically heated and allowed to vent accumulated contaminants to space. Any lost gas can be accommodated by including extra make-up gas in the hydrogen supply tank, Proper attention to cleanliness is tedious and time [illegible] effort up front is likely to save time later.

SUMMARY AND CONCLUSIONS

Successful ground testing of BETSCE has been the first-ever demonstration of a complete closed-cycle 10 K sorption cryocooler. Test data demonstrated that BETSCE exceeds its functional requirements, including cooling down to <11 K in under 95 seconds, sustaining a simulated I^2R detector heat load of 100 mW for over 20 minutes, achieving a minimum temperature of 9.5 K (with 100 mW heat load), and excellent cycle repeatability. The sorbent beds achieved a compression ratio of 8.3×10^5, and were able to recycle the system in under 5.5 hours. Environmental tests are nearly completed, and will fully qualify BETSCE for flight on the Shuttle. Initial characterization tests have demonstrated that a separate Fast Absorber Sorbent Bed is not necessary, and thus a 2-sorbent bed design is sufficient for applications where radiators can achieve temperatures below 275 K. Future ground characterization testing will enable thorough performance mapping, and identification of important performance sensitivities to varying operational and environmental conditions. Finally, flight testing of BETSCE is expected to provide the end-to-end characterization and validation, and the quantitative microgravity database that will enable early insertion of 10-30 K sorption cryocooler technology into future long-life, low-vibration, space remote sensing missions.

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