CRYOGENIC TWO-PHASE FLIGHT EXPERIMENT; RESULTS OVERVIEW

T. Swanson and M. Buchko, NASA Goddard Space Flight Center
P. Brennan, OAO Corporation
M. Bello, The Aerospace Corporation
M. Stoyanof, Phillips Laboratory

Abstract

This paper focuses on the flight results of the Cryogenic Two-Phase Flight Experiment (CRYOTP), which was a Hitchhiker based experiment that flew on the space shuttle Columbia in March of 1994 (STS-62). CRYOTP tested two new technologies for advanced cryogenic thermal control; the Space Heat Pipe (SHP), which was a constant conductance cryogenic heat pipe, and the Brilliant Eyes Thermal Storage Unit (BETSU), which was a cryogenic phase-change thermal storage device. These two devices were tested independently during the mission. Analysis of the flight data indicated that the SHP was unable to start in either of two attempts, for reasons related to the fluid charge, parasitic heat leaks, and cryocooler capacity. The BETSU test article was successfully operated with more than 250 hours of on-orbit testing including several cooldown cycles and 56 freeze/thaw cycles. Some degradation was observed with the five tactical cryocoolers used as thermal sinks, and one of the cryocoolers failed completely after 331 hours of operation. Post-flight analysis indicated that this problem was most likely due to failure of an electrical controller internal to the unit.

Introduction

The Cryogenic Two-Phase Flight Experiment (CRYOTP) was designed to flight test two new, thermal control cryogenic test articles; the Space Heat Pipe (SHP) and the Brilliant Eyes Thermal Storage Unit (BETSU). CRYOTP was flown as a Hitchhiker-based experiment aboard the space shuttle Columbia on STS-62 in March of 1994 as part of the Office of Advanced Science and Technology (OAST-2) primary payload. The SHP was a constant conductance nitrogen cryogenic heat pipe designed to operate from approximately 80K to 110K. While oxygen heat pipes were successfully flown on the Cryogenic Heat Pipe Flight Experiment (CRYOHP) mission in December of 1992, the SHP marked the first flight test of a nitrogen heat pipe. Perceived advantages of the SHP included use of a non-flammable working fluid (nitrogen) and a high performance wick design. The SHP employed a titanium tube for pressure containment and five parallel fibrous copper wicks for axial fluid transport. Cryogenic working fluids like liquid nitrogen have relatively poor liquid transport factors and low static wicking heights. The fibrous wick employed in the SHP alleviated this problem by providing significantly better capillary pumping height (>25 mm) than the axially grooved CRYOHP heat pipes. The SHP was provided to the NASA Goddard Space Flight Center (GSFC) through a Small Business Innovative Research (SBIR) Phase II contract. Reference 1 describes this test article in detail.

The BETSU test article is a 2500 joule thermal storage device utilizing 2-methylpentane as a Phase Change Material (PCM). The PCM has a nominal liquid/solid phase change at 120 K. This type of device would be very useful for providing a totally quiescent, heat absorbing environment for a sensor, optics, or shroud. The BETSU was provided to the CRYOTP experiment by the US Air Force/Phillips Laboratory. Reference 2 describes the BETSU test article in detail.

In order to meet very stringent budget and schedule constraints, the cryogenic test bed from CRYOHP was reused. The two oxygen heat pipes tested in this experiment were removed and replaced with the SHP and BETSU test articles. GSFC was responsible for overall program management and integration of the CRYOTP experiment. This included refurbishment of the cryogenic test bed from the previous experiment, integration of the two test articles, systems verification, and delivery to the Hitchhiker (HH) carrier. GSFC also functioned as the Principal Investigator (PI) for SHP. Aerospace Corporation acted as PI for BETSU.

The CRYOTP experiment had a number of technical and programmatic objectives. These were as follows:

- Demonstrate startup of the SHP from a supercritical condition in microgravity.
- Determine the SHP's heat transport characteristics in microgravity.
- Employ SHP flight data to update and validate analytical predictions..
- Demonstrate the steady-state and transient performance of the BETSU test article in a microgravity environment.
- Validate the analytical predictions for BETSU.
- Determine the correlation between the ground and flight data for both test articles.
- Demonstrate the feasibility of reusing an existing test bed for minimal cost (10% of the original) and quick turnaround (1 year).

All of the above objectives were achieved except for the first two. The SHP failed to start during flight operations. Two cooldowns were attempted from an initial temperature of 270 - 300K. Failure to start can be attributed to the relationship between the length of the liquid slug at the condenser end, the parasitic heat leaks on the transport and evaporator sections, and the available cooling capacity. The BETSU testing was a complete success, and a total of about 250 hours of data was acquired over the 14 day mission. Flight data correlated very well with predictions, and the feasibility of the PCM concept was fully demonstrated. Some interesting science on subcooling effects was also observed.

The following sections provide a more complete description of the CRYOTP test bed and the SHP and BETSU test articles. Flight results are then summarized and compared with analytical predictions. The cryocooler failure is also briefly addressed.

Test Bed Description

The CRYOTP test bed (Figure 1) utilized much of the hardware used in the CRYOHP Flight Experiment flown in December of 1992 aboard STS-53. The CRYOHP experiment is described in detail in References 3 and 4. Each of the CRYOTP test articles was operated independently with its own set of cryogenic refrigerators as shown in Figure 2. The cryogenic refrigerators are tactical cryocoolers (Hughes Model No. 7044H) and were selected because they provide approximately 3.5 watts of cooling capacity at 80K with a power draw of approximately 100 watts. Vibration isolators consisting of multiple braided copper straps connected in parallel were used to interface each cryocooler to one of two aluminum thermal shunts. One thermal shunt was connected to an individual test article, as shown in Figure 2. The vibration isolators effectively dampened vibration transmission from the cold heads while providing a thermal conductance of approximately 2 W/°C. Tests conducted in the CRYOHP program showed that although there are acceleration levels of approximately 70 x 10^{-3} g's at the cryocooler cold heads, the vibration level at the heat pipe was less than 2 x 10^{-3} g.

Three cryocoolers were dedicated to the SHP to permit tests near the freezing point of nitrogen (63.1K) and to demonstrate up to 5 watts transport at 80K. The BETSU device was integrated with the two cryocoolers. Ground and flight operations consisted of operating only one test article at a time because of HH electrical power constraints and limited CRYOTP radiative heat dissipation.

SHP Description

The SHP is a "U" shaped titanium/aluminum alloy (Ti-6Al-4V, ELI) nitrogen heat pipe that used six parallel fibrous copper cables to form the capillary wick structure. The porous metal cables are held against the interior wall surface with a beryllium-copper spring. The individual cables run the length of the heat pipe and are equally spaced around the inner circumference. Titanium/aluminum end caps are electron beam welded to the evaporator and condenser ends, and a titanium (CP-2) fill tube is welded to the evaporator end cap. Titanium (CP-2) saddles were clamped to the evaporator and condenser ends to provide a flat mounting surface for the thermal shunt and electrical heaters. Graphite foil was used as a filler material to provide a thermally conductive interface between the saddles and the heat pipe. Primary and redundant

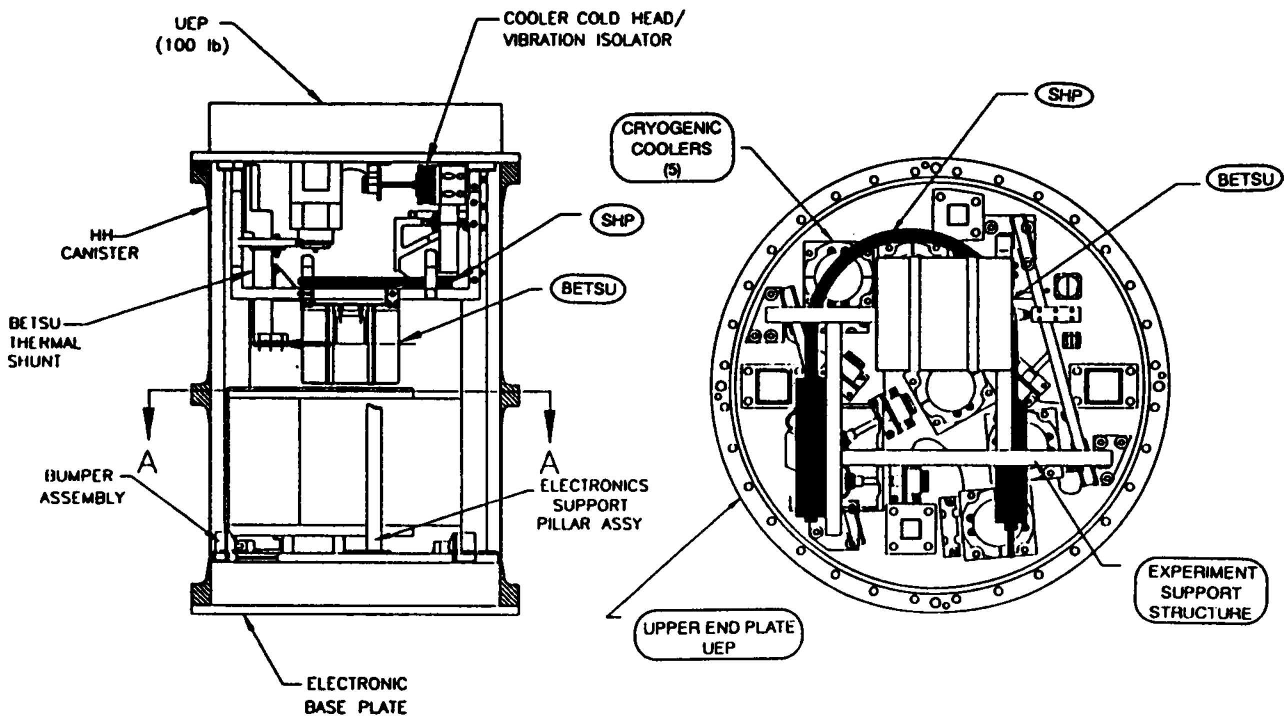

Figure 1. CRYOTP Flight Experiment

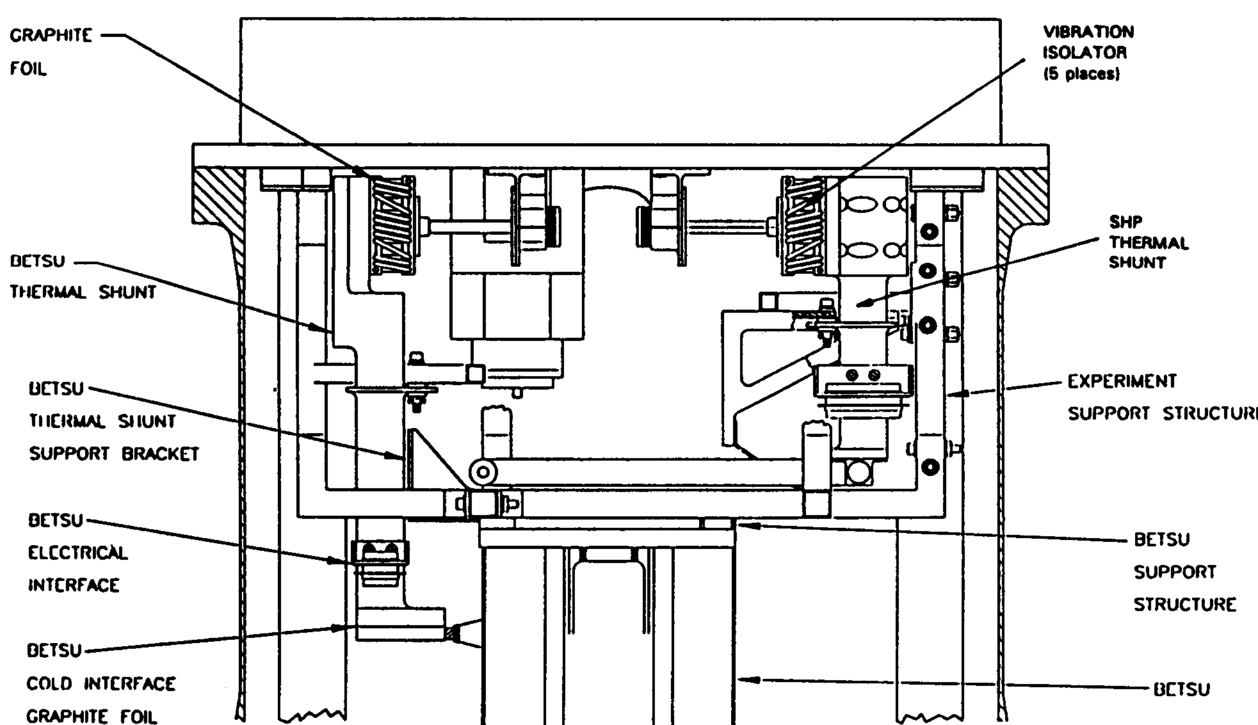

Figure 2. Test Article Integration

Kapton foil heaters and thermostats were epoxied to the both saddles. Eight (8) Platinum Resistance Thermometers (PRTs) were used to measure temperatures along the 91.8 cm long heat pipe at the locations shown in Figure 3. The design of the SHP is summarized in Table 1. Four additional PRTs were located on the SHP thermal shunt and cryocooler cold heads.

Thermal vacuum ground tests consisted of cooling the SHP down to and below the nitrogen critical point (126.2K) until the heat pipe was isothermalized. The SHP was typically cooled to 80K for conducting heat transport tests at various tilts. These tests consisted of applying heat to the evaporator section in 0.5 watt increments until evaporator dryout was indicated. The cooling capacity of the cryocoolers is a constant at a given temperature, so a trim heater on the condenser end of the SHP was used to balance the cooling load and maintain the desired operating temperature during the transport tests.

Table 1
Space Heat Pipe (SHP) Design

Dimensions/Specifications	
Heat Pipe Total Length	91.8 cm
Evaporator Length	12.7 cm
Condenser Length	17.8 cm
Wall Outer Diameter	1.5 cm
Wall Inner Diameter	1.026 cm
Geometry	U-Shaped
Total Mass	549 grams
Wick Material	6 fibrous copper cables 3.2 mm dia. held against the ID
Heat Pipe Tube Material	Ti-6Al-4V (ELI)
Working Fluid	24.1 grams pure nitrogen

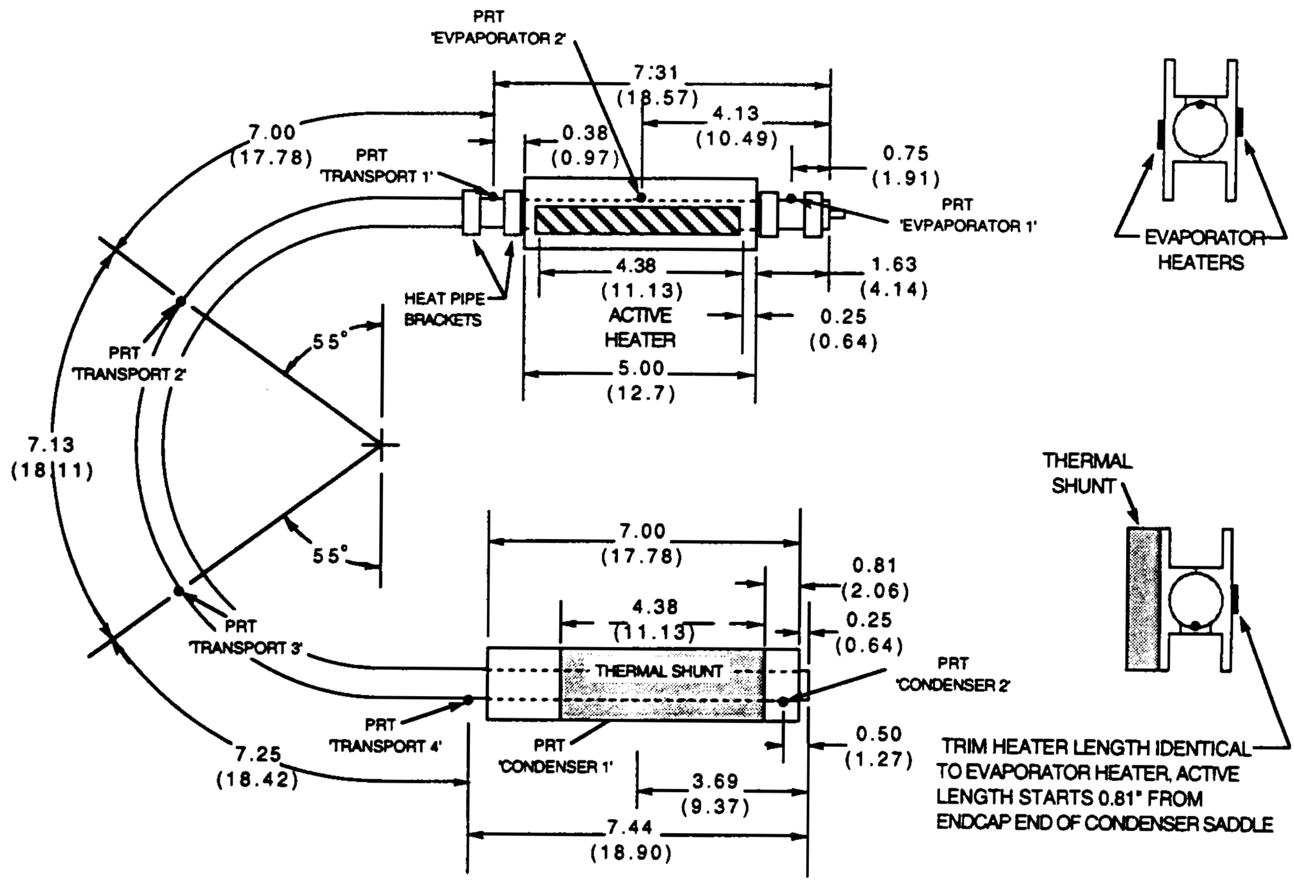

Figure 3. SHP Instrumentation Schematic

BETSU Description

The BETSU consisted of a PCM canister surrounded by gold-plated aluminum radiation shields and mounted inside an aluminum shell enclosure. Schematics of the BETSU are presented in Figures 4 and 5 and the PCM's canister design is summarized in Table 2. An aluminum plate with redundant Kapton foil heaters was attached to one face of the PCM canister using flexible copper straps. A large flexible copper strap was attached to the opposite face of the canister and extended beyond the enclosure to the aluminum thermal shunt to thermally couple the PCM to two cryocoolers. This strap, referred to as the Q-Meter, was used to determine the heat flow from the PCM based on the measured temperature drop across the strap. The Q-meter conductance was approximately 0.25 W/°C. The PCM canister weighed less than 0.34 Kg including instrumentation and the Q-Meter. Conductive heat leaks were minimized by suspending the PCM canister within the BETSU enclosure using six titanium wire tension straps (and six dacron braid straps as backup).

The PCM canister was a welded aluminum cylinder with aluminum fins vacuum-brazed to the two flat internal faces. The fins were in an 'accordion' configuration and were perforated to permit cross-flow of the melted PCM. Approximately 35 grams of 2-methylpentane with 3% acetone was used to provide approximately 2500 Joules of energy storage at a freeze/thaw temperature of 120K. The acetone was present to minimize sub-cooling effects that tend to extend the freezing temperature range, which results in less precise or potentially unacceptable temperature control. BETSU flight and thermal vacuum ground tests consisted of cooling down the PCM canister to 120K and then conducting multiple freeze/thaw cycles at different cooling and heating rates. Heat was applied to the PCM canister at discrete levels to vary the rate at which the PCM thawed, and to determine the total energy that was stored. A commandable trim heater and fixed 4 and 6 watt boost heaters are attached to the BETSU thermal shunt to provide precise control of the rate at which heat was removed from the PCM canister. A total of 14 PRTs were used to monitor the temperature across the BETSU and the cryocoolers. Calibration tests were conducted at approximately 135K and 110K to permit an accurate determination of parasitic heat inputs.

Table 2
Design Summary for BETSU PCM Canister

Phase Change Material	2-Methylpentane & 3% acetone
Theoretical Capacity Available	2,500 joules
Maximum Pressure at 80°C	3.81 Bars
Nominal Void Volume at 120K	33%
Maximum ΔT in PCM @ 1w	0.3 K
Volume Percent Metal Fin	24%
Inside Diameter, cm	6.1
Inside Length, cm	2.9
L/D	0.48
PCM Weight, grams	35.3
Canister Total Weight, grams	136
Canister Wall Thickness, mm	0.254
PCM to Wall Conductance Ratio	18
PCM to Fin Conductance Ratio	16
Fin Thickness, mm	0.2
Fin Density, fins per cm	11.9
Canister Material	6061-T6 Aluminum
Fin Material	3003-0 Aluminum

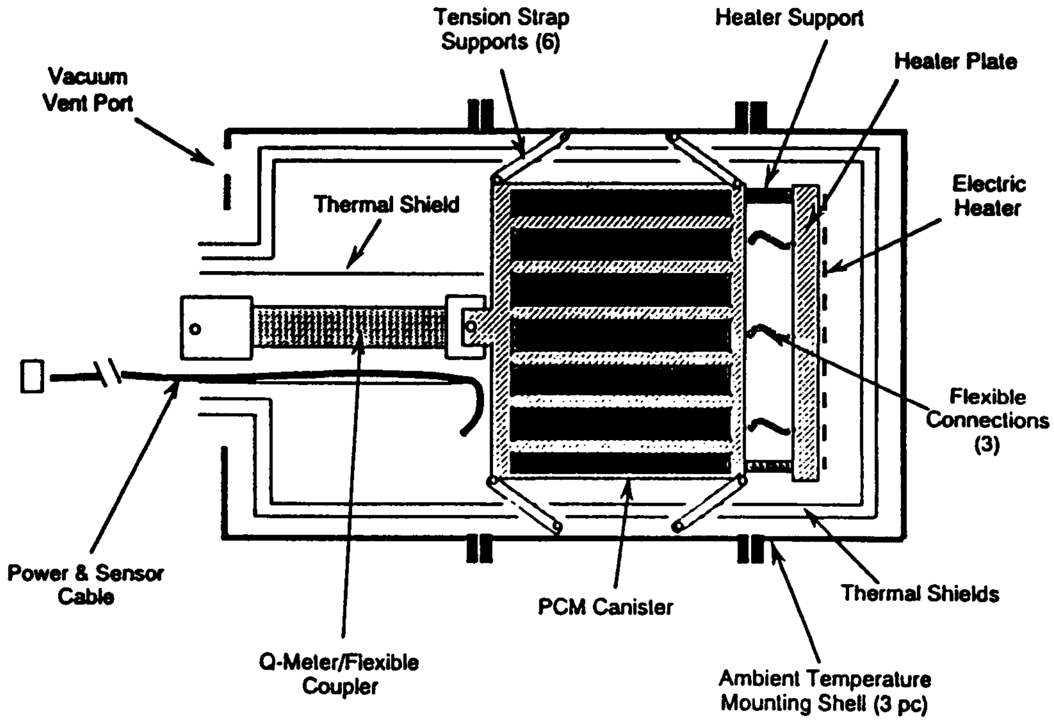

Figure 4. BETSU Thermal Structure

Approximate size: 6" Diameter by 10" Long (1.7 lbs)

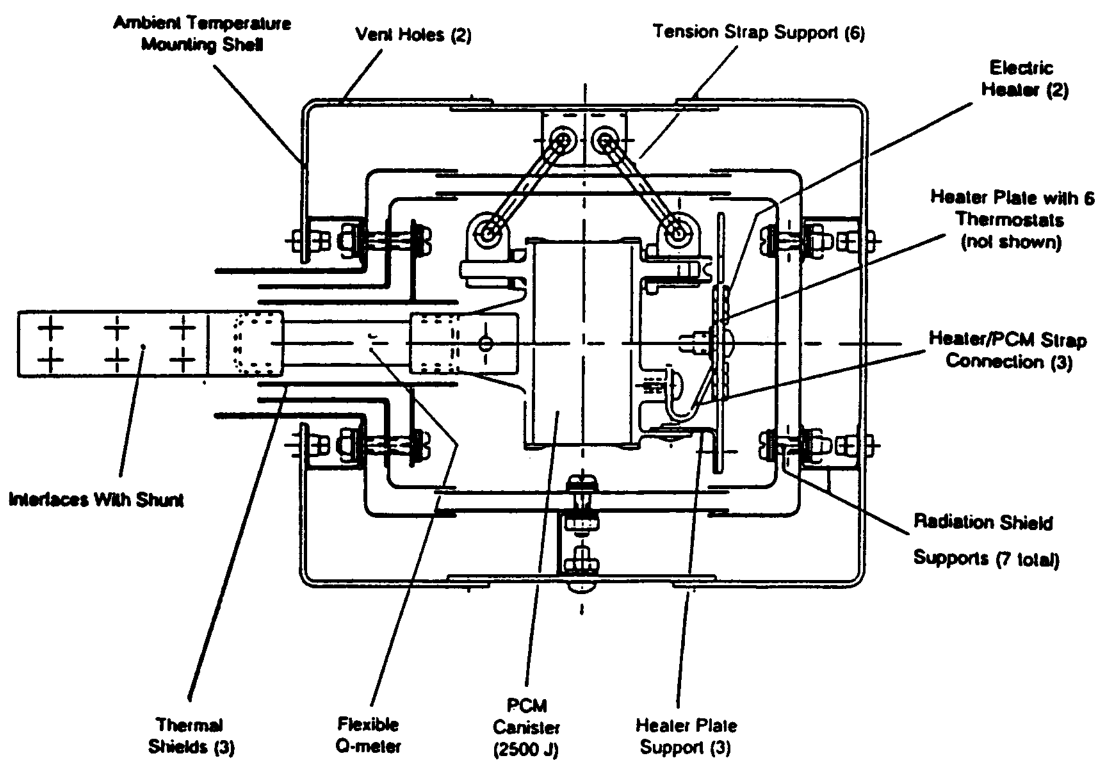

Figure 5. BETSU Mechanical Assembly

CRYOTP Integration

The CRYOTP experiment was installed within a HitchHiker-G canister for flight aboard the Space Shuttle. The SHP and BETSU test articles were mounted to a common stainless steel support structure and shared the same CRYOTP Electronics Control Module (CECM) and Power Distribution Box (PDB). The experiment structure and the coolers were mounted directly to the canister's Upper End Plate (UEP). The standard UEP was modified for the CRYOHP experiment to increase both its thermal mass (by approximately 40 kg) and its heat rejection area. The increased UEP heat capacity permitted continuous operation for 12 hours or more with cryocooler compressor body temperatures of less than 70°C. Up to 320 watts of heat could be dissipated while in an earth viewing or colder environment. The SHP was suspended from the stainless steel structure using three Kevlar wire/G-10 fiberglass sub-assembliesto minimize thermal conduction losses and induced vibration levels (shown in Figure 6). Graphite foil thermal interfaces and G-10 isolators were used throughout the experiment as necessary. The heat pipe, thermal shunts, and the cryocooler cold head vibration isolators were wrapped with Multi-Layer Insulation (MLI) blankets to minimize radiation heat leaks.

Thermistors were used throughout the experiment for housekeeping temperature measurements. Primary and redundant kapton foil heaters were used to provide heat input to each test article and to permit control at a specific operating temperature. Real-time series commands were used to apply incremental heater power to the test articles. The SHP's heaters could be incremented in 0.5 watt steps from 0 to 7.5 watts. The BETSU's input heater power could be varied in 0.25 watt increments between 0 and 4 watts. Three series thermostats were used with each heater to provide a two-fault tolerance against a runaway heater failure.

After the final ground testing of the BETSU and SHP were complete, the CRYOTP experiment was delivered to the Hitchhiker OAST-2 carrier for integration. Power, commands and telemetry for the experiment were provided by the Hitchhiker avionics mounted adjacent to CRYOTP on the OAST-2 bridge. Real-time telemetry was downloaded to the Payload Operations Control Center (POCC) at GSFC. Commands were forwarded from the POCC to permit real-time control of the experiment.

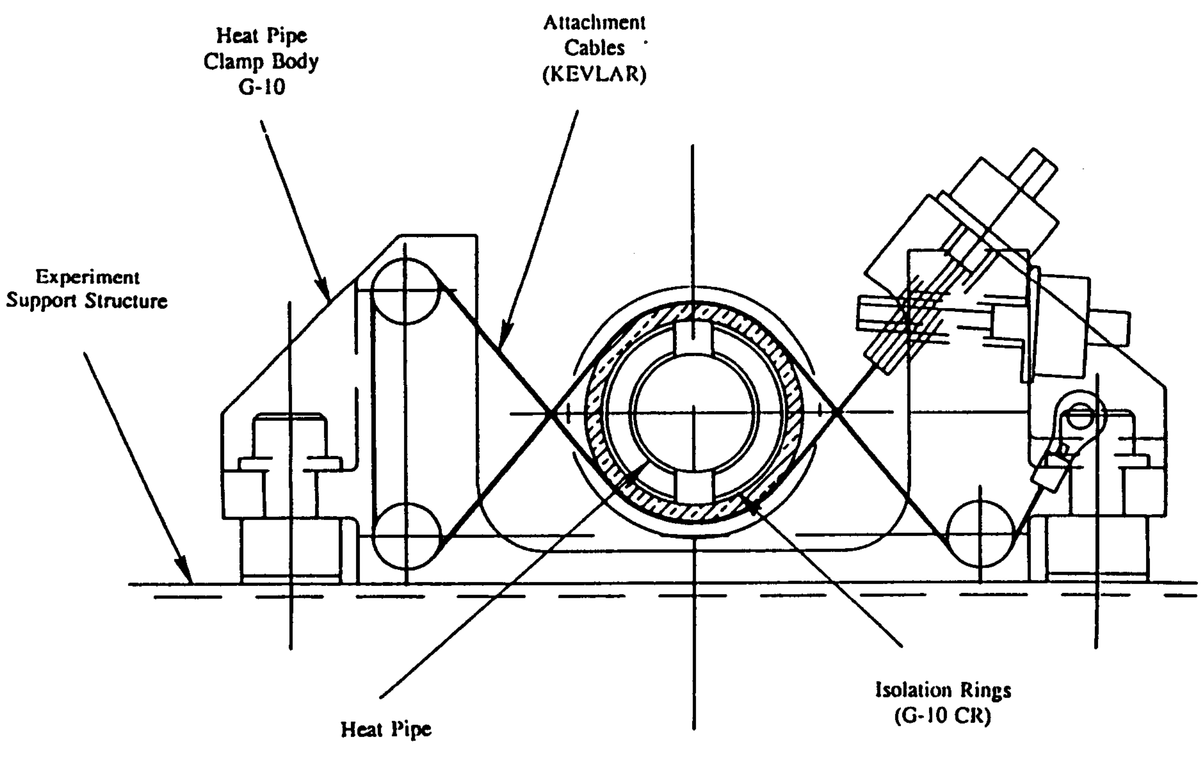

Figure 6. SHP Attachment and Isolation Supports (3 Places)

Flight Results

The CRYOTP experiment was activated approximately 9 hours after launch and tests were performed continuously over the following thirteen days. The experiment was deactivated on flight day fourteen just prior to shuttle deorbit.

SHP Test Results

The cooldown of the SHP was initiated within minutes of the CRYOTP activation. The transient cooldown temperatures of the heat pipe's condenser and evaporator sections are shown in Figure 7 along with cryocooler #2's cold head temperature for the two flight test cycles. The second cooldown cycle was conducted on flight day six of the mission. Heat pipe axial temperature profiles are shown for the first cooldown cycle in Figure 8; similar profiles were experienced in the second cycle. The SHP did not isothermalize in either cooldown cycle, but rather reached a non-operational near steady-state condition in which the evaporator temperature remained well above the critical point of nitrogen. The axial temperature profiles indicate that only the last 30 cm of the heat pipe cooled below the critical temperature, a result one would expect if the heat pipe had lost its fluid charge. However, when the SHP was de-integrated from the CRYOTP test bed post-flight the nitrogen was vented and measured to be design charge of 24.1 grams. In the liquid state this mass represents more than 40% of the internal volume of the heat pipe at 80K. The cooldown and startup of the SHP during CRYOTP thermal vacuum ground tests is compared to Flight Cycle #1 in Figure 9. Ground tests were conducted with the SHP at a slight adverse tilt (~ 1 mm). Startup and isothermalization were accomplished at about 85K within seven hours from the start of cooldown.

The failure of the SHP to startup and isothermalize in microgravity is attributed to supercritical startup limit not readily observable in ground tests. The SHP never cooled sufficiently to drop the internal pressure of the heat pipe below the critical pressure of nitrogen, and therefore the wick could not be primed. Since the condenser section was well below the critical temperature a large liquid slug was formed. This liquid slug extended into the transport section of the SHP and effectively blocked the condenser, separating the evaporator from the cooling source. At this point no convective heat transfer could take place within the heat pipe. The heat pipe essentially reached a steady-state condition in which the parasitic heat load along the pipe was equal to the cooling rate available by axial conduction through the heat pipe wall. This operating condition can only be reached in microgravity. During ground testing heat pipes are capillary-limited to small angles of adverse elevation, and the liquid slug forms a puddle along the bottom of the heat pipe. Startup is thus aided by gravity-assisted liquid return and natural convection, along with axial heat conduction.

In fairness it must be noted that the SHP might have eventually started if given enough time. The transport section was slowly cooling (although much slower than in ground tests) but both cooldown attempts had to be terminated due to operational contraints. The first attempt was terminated to allow BETSU testing to begin. The second cooldown cycle was ended when one of the cryocoolers (Hughes tactical cryogenic refrigerator, Model No. 7044H) used as a heat sink failed. At this point the parasitics through the failed cryocooler were large enough that further cooling of the pipe was impossible. Despite these problems, significant observations of cryogenic heat pipe behavior were gained from the SHP tests; the vapor-to-liquid volume ratio should be maximized, allowance must be made for the size of the liquid slug (a reservoir could provide this), a low thermal conductivity wall material such as titanium is a disadvantage for startup (although beneficial for diode action and pressure containment), and the relationship between cooling capacity and parasitics is especially important.

BETSU Test Results

The first BETSU cooldown cycle was initiated upon termination of the SHP's first test cycle, approximately 23 hours into the mission. Transient data for the heat input side of the PCM canister is presented in Figure 10 for both BETSU cooldowns. In each of these cycles supercooling occurred because the PCM was being cooled from a totally melted state. In the first cycle the PCM did not start to freeze until it reached a temperature about 112K, and was further supercooled to 105K. In following freeze/thaw cycles freezing occurred at about 117K. The plateau shown in the second cooldown cycle at 135K is due to the application of heater power during a calibration test. The PCM was supercooled to 105K in this case, and subsequent freezing occured around 120K. Figure 11 presents a comparison of flight cooldown cycle #1 with the thermal vacuum ground test data. The temperature profiles are nearly identical with supercooling and freezing occurring at the points for both the flight and ground tests.

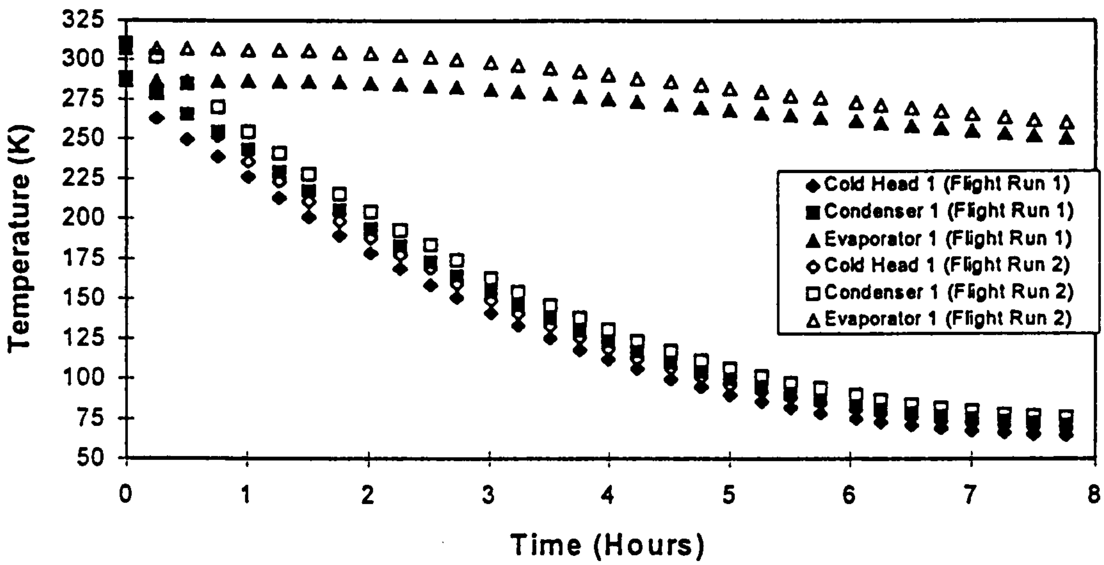

Figure 7. SHP Transient Cooldown Cycles 1 and 2

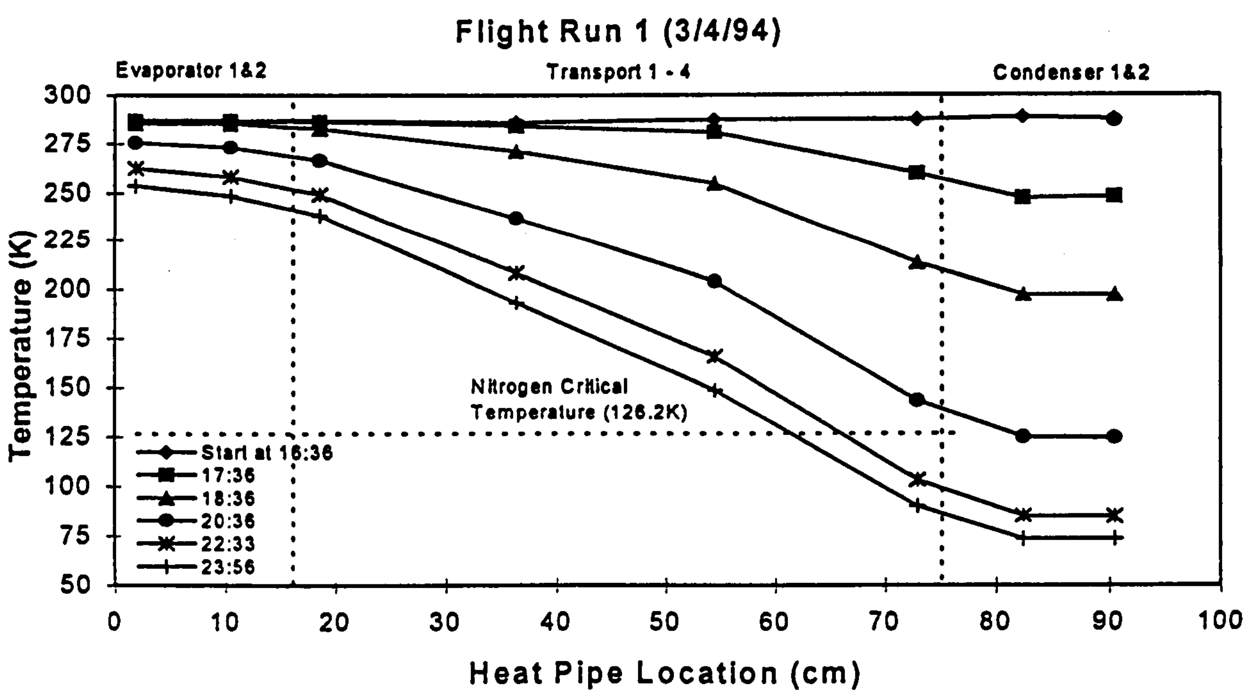

Figure 8. SHP Axial Temperature Profiles During Cooldown

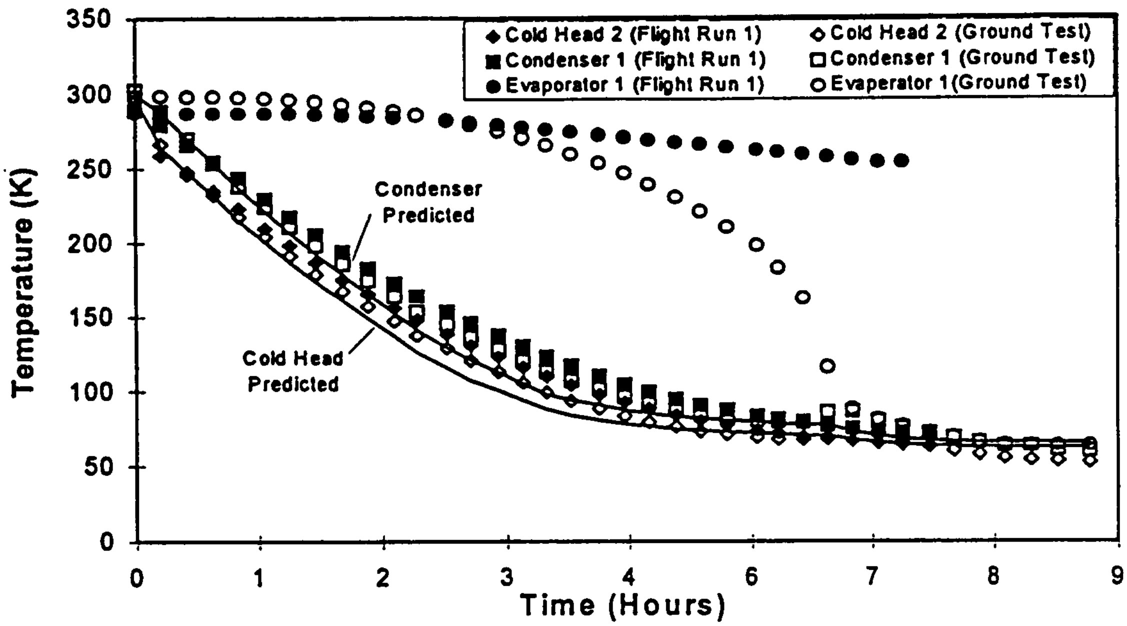

Figure 9. Comparison of SHP Ground and Flight Transient Cooldowns

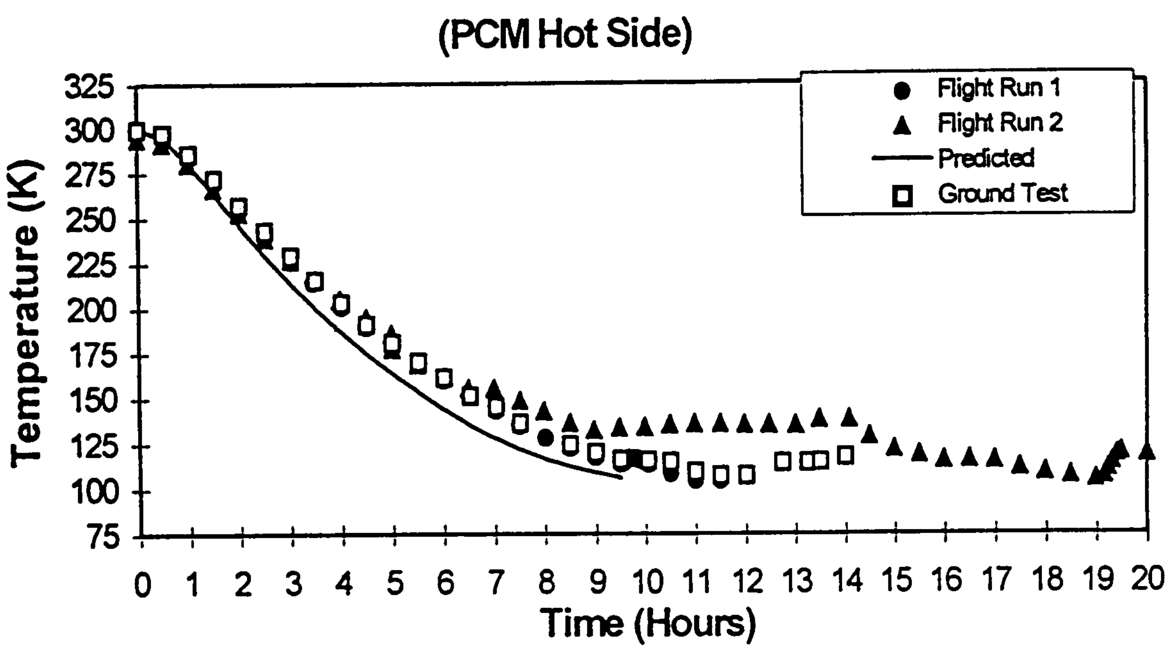

Figure 10. Comparison of BETSU Ground and Flight Transient Cooldowns

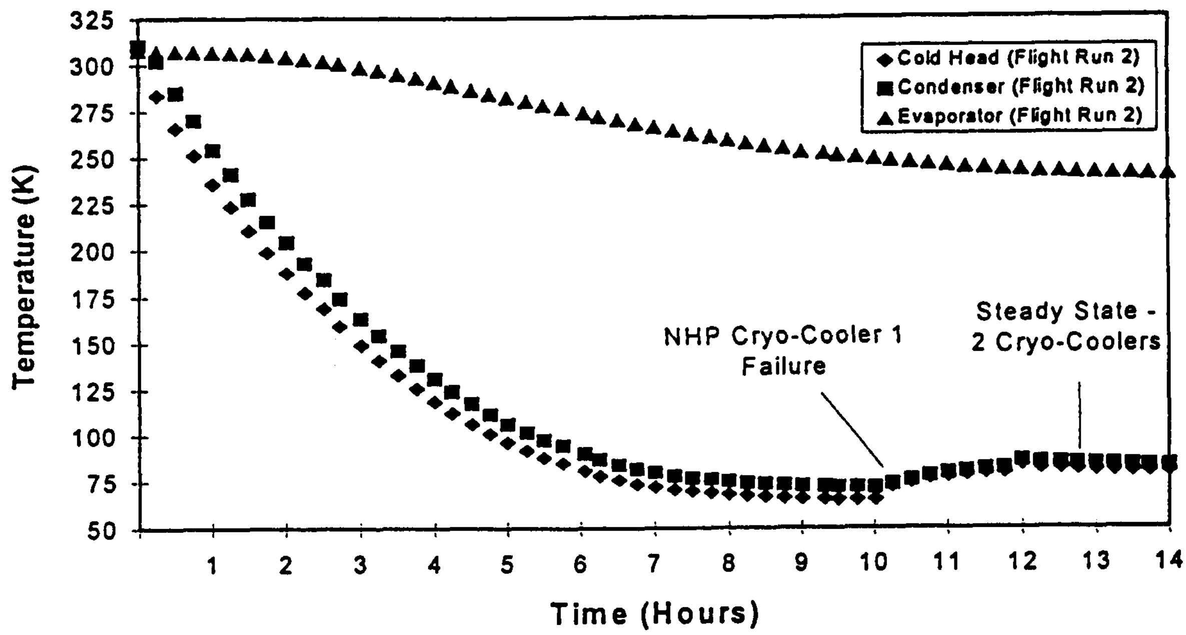

Figure 11. SHP Cryocooler Failure

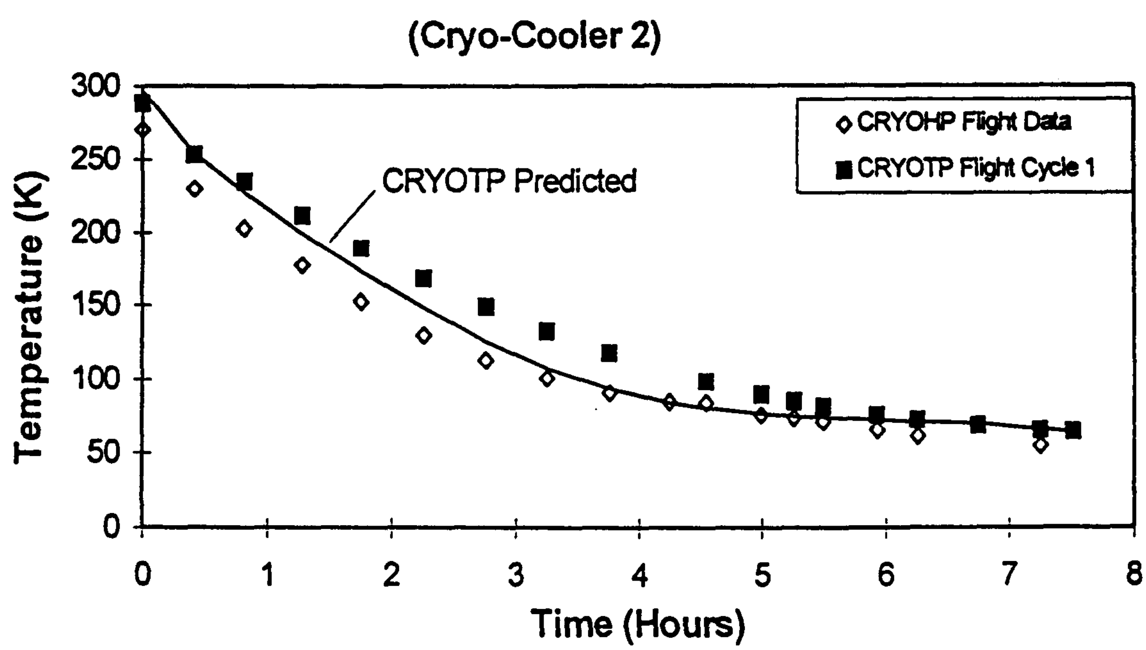

Figure 12. Comparison of Three-Cooler Cold Head Transient Cooldown
for CRYOHP and CRYOTP Missions

More than 250 hours of on-orbit test data consisting of 56 freeze/thaw cycles and 26 steady-state calibrations were completed. Supercooling was acceptable (<3°C at a 1 watt cooling rate) as long as the PCM was never completely melted. The solid particles in the liquid/solid mixture apparently provide nucleation sites for freezing that minimize the supercooling effect. Results of the ground and flight tests show that virtually all of the stored energy (2472 J) is released during two-phase cycling with temperature control at 119K ± 1.5K and with a 1 watt heating or cooling rate. The 3°C difference is primarily caused by two-phase subcooling that is difficult to totally eliminate. Test results show that the supercooling effect was more pronounced as the cooling rate was increased. This implies that increasing the PCM canister's internal thermal conductance and effective heat transfer surfaces (decreasing the cooling flux) is a potential method for providing tighter temperature control.

Cryocooler Performance

CRYOTP represented the second flight of the five tactical cryocoolers. These cryocoolers were all procured in the spring of 1992 for the CRYOHP flight. Total operational time for these cryocoolers is shown in Table 3. The manufacturer indicated that these cryocoolers should have a nominal time to failure of 2000 hours. However, as previously mentioned, the SHP cryocooler #1 failed after only 331 hours of operation. Interestingly, this was the cryocooler with the lowest total operational time. Failure was indicated by a sudden increase in cold head temperature and a reduction in the net cooling effect on the SHP test article. No warning of impending failure was evident. Several unsuccessful attempts were made to recover the the cryocooler by cycling the power on and off. With only two cryocoolers working the SHP condenser came to a steady-state temperature of about 81.5K. The resulting parasitic heat leak through the non-functional cryocooler was estimated to be about 1 W. Additional in-flight and post-flight testing indicated that this cryocooler could not recover its cooling capacity. The cryocooler appeared to draw the same amount of power post-failure, and there was no evidence for frictional heating at the cold head. Loss of the helium working fluid was suspected, but post-flight testing revealed that this was not the problem. Failure of an electrical controller internal to the unit is now the suspected culprit. Confirmation will require that the cooler be disassembled, which has not yet been performed due to funding constraints.

In addition, comparisons of the flight data from CRYOHP and CRYOTP appears to show that the three cryocoolers servicing the SHP side of the experiment may have experienced some minor degradation prior to the CRYOTP flight (Figure 12). Data from the BETSU testing also indicates that the net cooling capacity for the two cryocoolers on this side of the experiment degraded at about 1K per day during the CRYOTP flight. Post-flight testing suggested that this reduction was not due to a change in cryocooler capacity (unless performance was recovered over time). An increase in parasitics during flight may have been the cause of the appararent degradation in performance. At cryogenic temperatures the system is very sensitive to contaminants that would reduce the effectiveness of the multi-layer insulation.

	BETSU1	BETSU2	SHP1	SHP2	SHP3
Pre CRYOHP Flight	43	38	135	207	286
Post CRYOHP Flight	126	125	202	266	358
Pre CRYOTP Flight	296	254	311	378	469
Post CRYOTP Flight	559	518	331	421	512
Total Flight Time	346	351	87	101	115

Conclusions

The flight of the CRYOTP experiment in March of 1994 demonstrated the effectiveness of two new cryogenic test articles in a microgravity environment. The SHP test article was not able to start within the available time and operational constraints, but valuable lessons were learned from this experience. A new startup criteria regarding the relationship between fluid inventory and internal volume for cryogenic heat pipes was observed. Other valuable design criteria for cryogenic heat pipes were also obtained. The failure of the SHP to start, despite successful ground testing, once again demonstrated the need for flight testing of two-phase heat transfer systems, since ground testing can be misleading due to gravity effects. A proven transient startup model is also needed to reliably predict heat pipe performance in microgravity.

The BETSU testing was completely successful, with 56 freeze/thaw cycles at 120K accomplished. Precise temperature and thermal calibration data were also obtained. Supercooling and melt/freeze behavior was essentially the same as observed in ground testing, and the analytical model was verified to be accurate.

Failure of one of the five tactical cryocoolers, despite it being far short of its rated lifetime, and the back parasitics associated with this failure demonstrates the need to address cryocooler reliability.

Another major conclusion from the CRYOTP flight was the demonstrated ability to fly a new experiment at modest cost and with a very accelerated schedule. This was made possible through reuse of an existing test bed and a highly experienced team of people. None of the above observations could have been learned from ground testing alone, hence the value of the flight experiment.

Acknowledgements

The CRYOTP experiment was funded jointly by the U.S. Air Force through Phillips Laboratory and the Space Test Program (STP), and by NASA through the Goddard Space Flight Center.

References

1. Rosenfeld, J., and Keller, R., "Sintered Powder Artery-Free Cryogenic Heat Pipe", Final Report, Contract No. NAS5-30783, prepared by Thermacore, Inc. for NASA Goddard Space Flight Center, Greenbelt, MD, 1994.

2. Stoyanof, M., and Glaister, D., "Design and Performance of a Two-Phase Thermal Storage Unit at 120 Kelvin", SAE Technical Series Paper No. 94-1155, April, 1994.

3. Brennan, P., Stouffer, C., Thienel, L., Morgan, M., "Performance of the Cryogenic Heat Pipe Experiment (CRYOHP)", SAE Paper No. 92-1408, 22nd Int. Conf. on Environmental Systems, Seattle, WA, July 13-16, 1992.

4. Brennan, P., Thienel, L., Swanson, T., Morgan, M., "Flight Data for the Cryogenic Heat Pipe (CRYOHP) Experiment", AIAA Paper No. 93-2735, AIAA 28th Thermophysics Conf., Orlando, FL, July 6-9, 1993.