Design and Testing of a Cryogenic Capillary Pumped Loop Flight Experiment

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Abstract. This paper details the flight configuration and pre-flight performance test results of the fifth generation cryogenic capillary pumped loop (CCPL-5). This device will fly on STS-95 in October 1998 as part of the CRYOTSU Flight Experiment. This flight represents the first in-space demonstration of a CCPL, a miniaturized two-phase fluid circulator for thermally linking cryogenic cooling sources to remote cryogenic components. CCPL-5 utilizes N_2 as the working fluid and has a practical operating range of 75-110 K. Test results indicate that CCPL-5, which weighs about 200 grams, can transport over 10 W of cooling a distance of 0.25 m (or more) with less than a 5 K temperature drop.

INTRODUCTION

For most ground and space-based cryogenic systems, the coupling of a cooling source to a cooled component is accomplished with a flexible conductive link (FCL) like a copper braid. In most cases, this approach works very well. However, as the transport length and heat loads are increased, the FCL becomes very heavy and inefficient. In these cases, the preferred thermal coupling device is the fluid circulator. Fluid circulators can be single or two-phase devices, with mechanical or capillary pumping mechanisms. Two-phase fluid circulators include the cryogenic capillary pumped loop (CCPL), the cryogenic loop heat pipe (CLHP), and cryogenic heat pipes. Single-phase fluid circulators include the cryogenic pumped gas loop (CPGL).

The use of single or two-phase fluid circulators as coupling devices in space cryogenic systems is not new. The DSP satellite uses a single-phase helium CPGL to thermally link a cold radiator to an IR focal plane (Bugby, 1996). Cryogenic heat pipes have flown on numerous flights including CRYOHP and CRYOFD (Beam, 1992 and Thienel, 1998). In addition, the NICMOS Cooling System (NCS) uses a single-phase neon CPGL to couple a reverse-Brayton cycle cryocooler to the HST NICMOS instrument (Nellis, 1998).

From an applications standpoint, SBIRS-Low may be the first system to utilize a CCPL. For this system, a CCPL is being designed to transport 10-15 W of cooling across a 2-axis gimbal. Figure 1 illustrates the concept. Before this system can be implemented, the CCPL-5 flight experiment must demonstrate the technology in a 0-g environment.

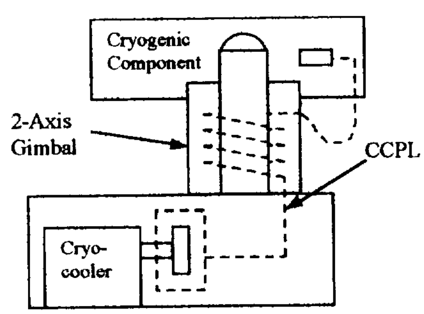

FIGURE 1. CCPL Concept for SBIRS-Low

The purpose of this paper is to describe the design and testing of the CCPL-5 flight experiment, which will fly on STS-95 as part of the CRYOTSU thermal management flight experiment. The paper is organized as follows. First, background on ambient and cryogenic CPL technology is provided. Next, the CCPL-5 laboratory test set-up and results are described and analyzed. Finally, the CCPL-5 flight configuration is described.

BACKGROUND

A cryogenic CPL can be used to thermally link a cryogenic cooling source to a remote cryogenic component. An ambient CPL can be used to transport heat from one or more power-dissipating components to a remote space-facing radiator. Despite these seemingly different heat transport functions, CCPLs and CPLs are quite similar. However, there are differences in their construction and operation, as described below.

Ambient CPL Technology

Based on heat pipe principles, CPLs are passive thermal control devices capable of transporting heat over large distances with minimal temperature drop. A CPL is comprised of an evaporator, condenser, reservoir, transport lines and working fluid. Figure 2 shows a CPL with a 3-port evaporator, an approach that is typically employed in single evaporator systems. In this system, the reservoir and liquid lines connect directly into the evaporator core.

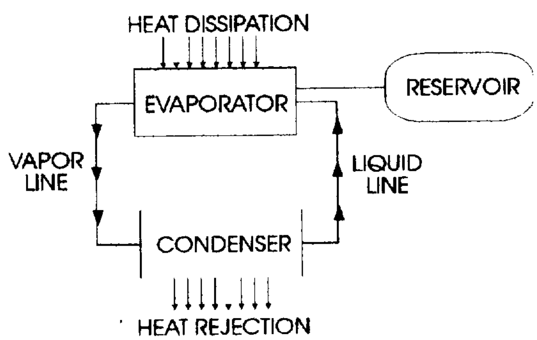

FIGURE 2. CPL With 3-Port Evaporator

Fluid circulation ensues when heat is applied to the evaporator, which contains a porous saturated wick. The liquid within the saturated wick evaporates, but it is immediately replenished via capillary action. Since only the liquid that evaporates is replenished, the system self-regulates. The vapor then flows to the condenser before returning to the evaporator as liquid. To prevent bubble formation and growth in the evaporator core (an occurrence that can de-prime the system), the condenser must provide several degrees of subcooling.

In all CPLs, there is a thermostatically controlled, cold-biased reservoir that controls the saturation temperature. Variations in load (i.e., evaporator power) and condenser environment are handled passively. The fluid level in the reservoir rises or falls as needed to balance the saturation pressure as the vapor front in the condenser moves in or out depending on how the power and/or condenser environment are changing.

Cryogenic CPL Technology

Although CCPLs and ambient CPLs are quite similar in design and operation, the supercritical environment surrounding a CCPL necessitates two unique design features. The first is a liquid-cooled shield (LCS). The second is a "hot reservoir". A CCPL also has a normal CPL reservoir, referred to as the "cold reservoir". Figure 3 illustrates a typical CCPL plumbing arrangement.

The LCS surrounds the liquid and cold reservoir lines of a CCPL to reduce parasitics and maintain subcooling. The source of LCS cooling is a section of condenser tubing that has been diverted from the condenser to the evaporator and back. The LCS is directly attached to this diverted section of tube.

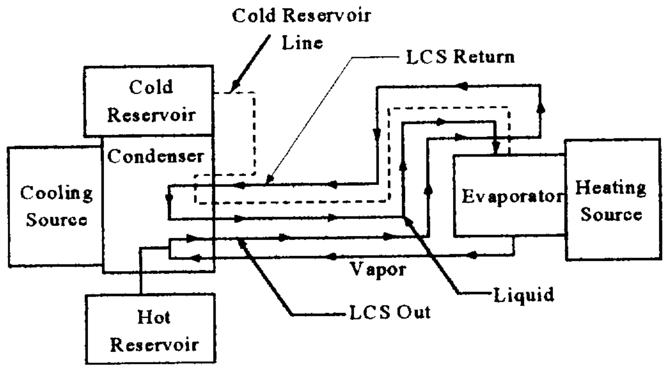

FIGURE 3. CCPL Flow Diagram

The hot reservoir serves two functions. The first is to lower the fill pressure of the system. A very high fill pressure would be required to provide the necessary mass of fluid for cryogenic temperature operation. The second is to aid in CCPL start-up. By appropriate plumbing and application of cold reservoir heater power, the working fluid can be shuttled between the reservoirs to cool the evaporator during start-up.

From a cryogenic integration standpoint, the CCPL provides two major advantages over the traditional FCL. The first advantage, by virtue of its small size and weight, is that it can be attached directly to the cryocooler and cooled component. This direct coupling can substantially reduce the system ΔT while minimizing cryocooler cooling power and input electrical power. The second advantage, an operational attribute of all fluid circulators, is diode action. To achieve diode action with an FCL-coupled system, a separate thermal switch is needed.

DESIGN AND TESTING

To demonstrate the cryogenic integration advantages of a CCPL, the condenser of the CCPL-5 flight unit was designed to bolt directly to the cold head of a Hughes 7044H tactical cryocooler. Within a very small flight envelope in the CRYOTSU Hitchhiker canister, a transport length of 0.25 m was effected by coiling the stainless steel, 1.27 mm inner diameter lines as shown in Figure 4. To ensure the system would perform properly, a laboratory test program was carried out. That laboratory performance test program and its results are described below.

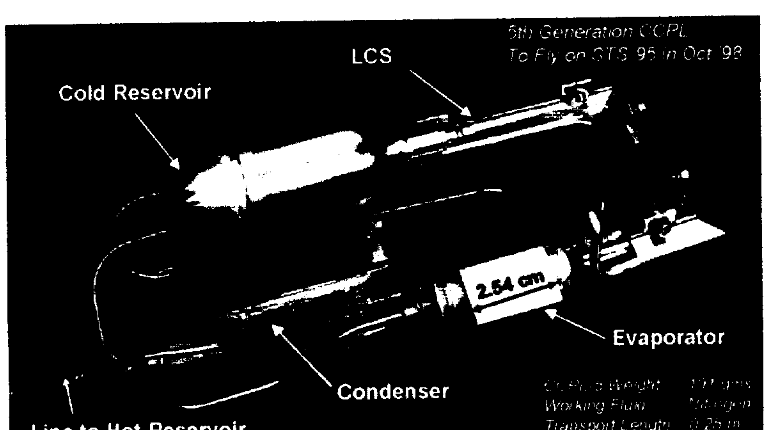

FIGURE 4. CCPL-5 Flight Unit

Test Objectives and Set-Up

The principal objectives of the performance test were as follows: (1) verify CCPL-5 functionality; (2) identify the optimum charge pressure for flight; and (3) evaluate the acceptability of the flight instrumentation.

The test set-up is illustrated in Figure 5. As indicated in the figure, the CCPL-5 condenser was bolted to an OFHC copper bracket that simulated the Hughes 7044H cryocooler mounting interface. This bracket was bolted to the 2nd stage cold head of a G-M cryocooler. Also attached to the 2nd stage cold head was an OFHC copper strap that was connected to an OFHC copper bar bolted to the G-M cooler 1st stage cold head. The strap and bar were used to augment the cooling power of the 2nd stage for shorter cooldowns and enhanced test capability (such as the maximum power tests described later). Lastly, as Figure 5 indicates, all the laboratory tests were conducted with the CCPL-5 flight unit in a vertical orientation. That is, the tests were conducted with the evaporator completely above the condenser (evaporator flow axis parallel to the gravity vector).

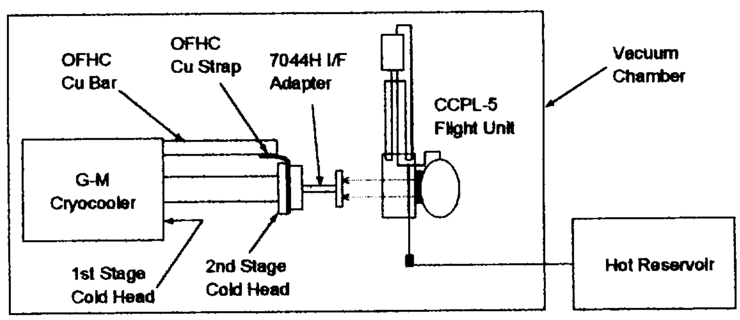

FIGURE 5. CCPL-5 Test Set-Up

Test Instrumentation

A total of 7 kapton heaters and 6 silicon diodes were used to instrument the system. Heaters were positioned on the cold head, condenser, cold reservoir, and evaporator. The condenser, cold reservoir, and evaporator had two heaters each for flight redundancy. Silicon diodes were mounted to the cold head, condenser, cold reservoir (exit), evaporator saddle, LCS mid-point, and the vapor line at the evaporator exit. A pressure transducer was positioned along the line between the hot reservoir and the vacuum chamber feed-through to measure system pressure during testing. The output of the pressure transducer was output digitally and recorded by hand. All silicon diode readings were recorded to a PC in one-minute intervals. Figure 6 illustrates the layout of the ground test instrumentation.

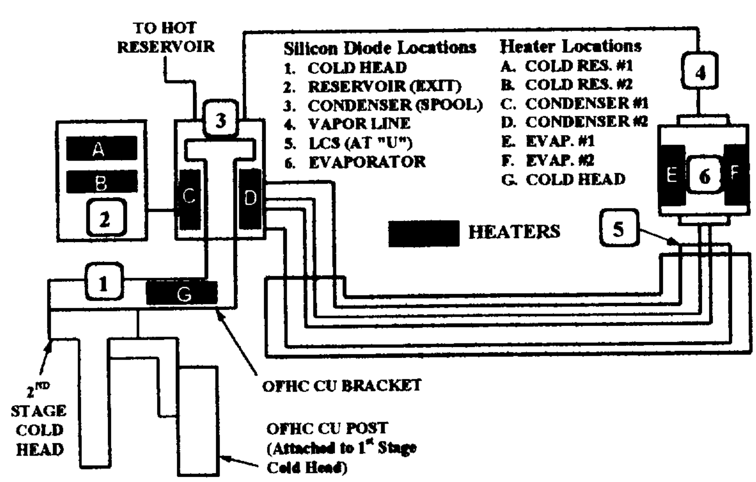

FIGURE 6. CCPL-5 Test Instrumentation

Pre-Test Calculations

Prior to the performance test, calculations were carried out to determine the charge pressure and the system pressure drop versus heat load (mass flow rate).

System Charge Pressure

As in any two-phase heat transport system, the amount of working fluid affects the operation of the system. Despite its apparent complexity, CCPL-5 can be thought of a having just two parts: a hot volume (V_{HOT}) and a cold volume (V_{CLD}). The hot volume includes the hot reservoir (1500 cc) and the transfer line (10 cc) giving a total hot volume of 1510 cc. The cold volume includes the cold reservoir (29.8 cc), 2.3 m of plumbing (2.9 cc) and the evaporator (1.5 cc) for a total cold volume of 34.2 cc.

At equilibrium, the pressure in the hot reservoir will equal the CCPL operating pressure. Assume the cold volume is filled with saturated liquid nitrogen at (T_S) and the hot volume is filled with ambient temperature (T_A) gaseous nitrogen at the corresponding saturation pressure (P_S). Equations (1) and (2) give the charge mass (m_{CH}) and the charge pressure (P_{CH}).

$$m_{CH} = V_{CLD}\, \rho_L\, (T_S) + V_{HOT}\, \rho_G\, (T_A, P_S) \tag{1}$$

$$P_{CH} = m_{CH}\, RT_A \,/\, [(V_{CLD} + V_{HOT})\, M] \tag{2}$$

Table 1 lists the charge mass and corresponding charge pressure for various values of T_S. In addition, since Equations (1) and (2) assume the cold part of the system is completely filled with liquid, the charge pressures indicated in Table 1 represent "fixed-conductance" charge levels. To achieve "variable-conductance" operation, the charge pressure must be less. Note that a charge pressure of 1.68 MPa (244 psi) corresponds to a saturation temperature of 80 K. Thus, the CCPL operating temperature at this level of charge should be close to 80 K.

TABLE 1. CCPL-5 Charge Mass and Pressure

T_A (K)	T_S (K)	P_S (MPa)	m_{CH} (kg)	P_{CH} (MPa)
294	65	0.0172	0.0298	1.69
294	70	0.0386	0.0294	1.66
294	75	0.0767	0.0294	1.66
294	80	0.137	0.0298	1.68
294	85	0.230	0.0306	1.73
294	90	0.360	0.0319	1.81
294	95	0.542	0.0342	1.93
294	100	0.780	0.0374	2.11
294	105	1.09	0.0417	2.36
294	110	1.47	0.0472	2.67

System Pressure Drop

The maximum heat load carrying capability of a CCPL is limited primarily by system pressure drop. The pressure drop cannot exceed the maximum capillary pumping capability of the evaporator. Thus, one way to estimate the maximum heat load carrying capability of a CCPL is to calculate the system pressure drop as a function of applied heat load and determine when that value exceeds the pumping capability of the evaporator.

The first step is to compute the mass flow rate and liquid and vapor velocities versus applied heat load. Using the heat of vaporization of nitrogen at 90 K ($\Delta H_{VAP} = 1.8 \times 10^5$ J/kg), Table 2 lists those quantities.

TABLE 2. CCPL-5 Flow Rates vs. Heat Load

Q (W)	mdot (kg/s)	v_L (m/s)	v_V (m/s)
1	5.56×10^{-6}	2.92×10^{-3}	0.29
2	1.11×10^{-5}	5.84×10^{-3}	0.58
4	2.22×10^{-5}	1.17×10^{-2}	1.15
6	3.33×10^{-5}	2.33×10^{-2}	1.73
8	4.44×10^{-5}	3.50×10^{-2}	2.31
10	5.56×10^{-5}	4.66×10^{-2}	2.89
12	6.66×10^{-5}	5.84×10^{-2}	3.46
14	7.77×10^{-5}	8.16×10^{-2}	4.04

The next step is to compute the Reynolds number ($Re = vD/\nu$) of the liquid and vapor, followed by the friction factor (f), and finally the pressure drop (ΔP). The relationship between the foregoing quantities is indicated in Equations (3) and (4) below. Table 3 lists Re and $\Delta P/L$ versus applied heat load. Due to the Re dependence in Equation (3), the results are most valid for the vapor at heat loads of 6 W and above.

$$f = 0.281\ Re^{-0.2375} \quad (5000 < Re < 200000) \tag{3}$$

$$\Delta P/L = (f / D)\ (1/2)\ \rho\ v^2 \tag{4}$$

TABLE 3. CCPL-5 Pressure Drop vs. Heat Load

Q (W)	Re_L (-)	Re_V (-)	$\Delta P_L/L$ (Pa/m)	$\Delta P_V/L$ (Pa/m)
1	51	864	12.7	36.9
2	101	1730	25.4	73.8
4	203	3450	51.0	529
6	304	5180	76.3	1012
8	405	6910	102	1525
10	506	8640	127	2022
12	608	10400	153	2643
14	709	12100	178	3365

Using the results in Table 3, the CCPL pressure drop for a "fully open" condenser (the worst-case) can be determined. When the condenser is fully open, the condenser, LCS, and vapor lines (1.62 m of total line length) will be filled with vapor. The surface tension of liquid nitrogen at 90 K is 6.18×10^{-3} N/m. The evaporator stainless steel wick has a 2 μm pore size (r_p). Thus, the maximum pumping head that can be generated (or pressure drop that can be overcome) is given by Equation (5).

$$\Delta P = 2\sigma / r_p \tag{5}$$

Substituting into Equation (5) yields a value for ΔP of 6180 Pa. If the entire pressure drop occurs in the length of line that is vapor (L = 1.62 m), the value of $\Delta P/L$ is 3815 Pa/m. Extrapolating the results in Table 3, the maximum heat load carrying capability of CCPL-5 is about 15 W. Other sources of pressure drop, such as the evaporator vapor space, will lower this value. Alternatively, if the condenser is not fully open at 15 W, then higher values are possible.

Test Procedure

The operational tests that were carried out with CCPL-5 consisted of the following: (a) start-up; (b) power cycling; and (c) high power. Each of these tests was carried out for a given system charge pressure. The charge pressures that were investigated were 1.86, 1.76, 1.65, 1.55, 1.45, and 1.34 MPa. The condenser set-point for all tests was 80 K.

Start-Up Test

The objective in this test was to start up the CCPL so that nitrogen was being continuously circulated in the system and the evaporator was absent of any vapor bubbles. The procedure was as follows: (a) cool condenser and cold reservoir to the desired condenser operating temperature; (b) apply cold reservoir heater power (5 W) to pressure-prime the evaporator; (c) apply 1 W to start-up the evaporator; and (d) reduce cold reservoir heater power to 0.5 W to maintain positive control. Depending on the thermal mass that needed to be cooled, step (b) could have been repeated several times. In the case of CCPL-5, the system started up with just one application of step (b).

Power Cycling Test

The objective in this test was to stress the CCPL-5 beyond what it might see in an actual application. After performing a successful start-up test, the procedure was to apply a sequence of heater powers to the evaporator. After each new power level, the system was allowed to reach a steady state (at least 1 hour). The heater power sequence used for this test was 2 W, 4 W, 6 W, 2 W, 6 W, and 8 W.

High Power Test

The objective in this test to determine the maximum power that CCPL-5 could transport without exceeding the evaporator pumping limit. The procedure was to increase the power in 1 W increments beginning with 8 W (the last power level in the Power Cycling Test). In each case, a steady-state was attained before increasing the power.

Test Results

The test results are shown in Tables 4-5. Listed are the steady-state temperatures of the evaporator (T_E), condenser (T_C), and cold reservoir (T_R) as well as the measured system pressure (P_{SYS}) and the saturation temperature (T_S) corresponding to P_{SYS}. A plot of the results for the 1.36 MPa charge is provided in Figure 7.

Overall, CCPL-5 performed very well, exhibiting stable behavior over a wide range of charge pressures and applied heater powers. The maximum power carrying capability of CCPL-5 ranged from 9-13 W.

Tables 4 and 5 indicate some rather large values for the system temperature difference ($\Delta T_{SYS} = T_E - T_C$). Since two-phase systems like CCPLs can operate with very small ΔT_{SYS} values, an explanation is warranted.

The quantity (ΔT_{SYS}) is the sum of two terms: ΔT_{SC} (equal to $T_S - T_C$) and ΔT_{ES} (equal to $T_E - T_S$). The first term (ΔT_{SC}) is a measure of subcooling. From a practical standpoint, 3-5 K of subcooling is needed to overcome parasitics and provide system robustness. One can limit ΔT_{SC} by setting P_{CH} such that T_S is the desired amount above T_C. If P_{CH} exceeds this ideal fill level, ΔT_{SC} will be higher than necessary. For CCPL-5, a charge in the range 1.34-1.45 MPa is close to the ideal match for a condenser set-point (T_C) of 80 K.

The second term (ΔT_{ES}) is a measure of evaporator effectiveness. It is a minimum when the applied load is small. Table 4 (Q_E = 1W) shows that ΔT_{ES} is only about 0.5 K for all charge pressures. At a load of 10 W, ΔT_{ES} is 10-11 K. In general, the magnitude of ΔT_{ES} is a function of evaporator design. An evaporator body made of Al or Cu, instead of stainless steel (the CCPL-5 construction material), could reduce ΔT_{ES}. If fact, it was analytically determined that the CCPL-5 evaporator has a shell-to-fluid conductance of 1 W/K, which accounts for the measured values of ΔT_{ES}. In sum, proper choice of P_{CH} and an improved evaporator can likely lower ΔT_{SYS} to less than 5 K at 10-15 W loads.

One final item to be addressed here relates to the 1.76 MPa results. For this case only, the cold reservoir heater power was set to 0 W for the power cycling and high power tests. Thus, for this case only, T_R was less than T_C. This result was unexpected since the condenser is between the cold reservoir and the cooling source. The explanation is that the silicon diodes on the condenser were located near the base of the spool, but not on the base of the spool. The cold reservoir, on the other hand, is thermally coupled to the base of the spool with a 0.15 W/K strap. When the cold reservoir heater was turned off, T_R dropped below T_C. Thus, the actual condenser sink temperature may be somewhat less than the reported value of T_C.

TABLE 4. CCPL-5 Results for Q_E = 1W, Q_R = 0.5 W

P_{CH} (MPa)	P_{SYS} (MPa)	T_E (K)	T_C (K)	T_R (K)	T_S (K)
1.86	0.56	95.9	80.7	86.2	95.4
1.76	0.43	92.6	80.5	83.1	92.2
1.65	0.36	90.6	77.8	86.7	90.1
1.55	0.29	88.0	81.2	86.4	87.6
1.45	0.21	84.4	80.0	83.1	84.0
1.34	0.20	84.1	80.0	82.7	83.7

TABLE 5. CCPL-5 Results for Q_E = 6 W, Q_R = 0.5 W

P_{CH} (MPa)	P_{SYS} (MPa)	T_E (K)	T_C (K)	T_R (K)	T_S (K)
1.86	0.57	101.0	80.5	86.7	95.6
1.76	0.39	96.3	78.3	77.8*	90.8
1.65	0.42	97.5	81.2	90.6	91.9
1.55	0.28	92.7	80.0	86.0	87.2
1.45	0.21	89.6	80.4	83.2	84.1
1.34	0.20	88.9	80.1	82.4	83.4

* Q_R = 0 W

TABLE 6. CCPL-5 Results for Q_E = 10 W, Q_R = 0.5 W

P_{CH} (MPa)	P_{SYS} (MPa)	T_E (K)	T_C (K)	T_R (K)	T_S (K)
1.86	0.57	105.7	80.1	86.1	95.6
1.76	0.40	101.4	79.0	77.6*	91.0
1.65	Maximum Power Limit Exceeded at 10 W				
1.55	0.28	97.9	80.1	86.0	87.2
1.45	0.21	95.1	80.6	83.1	84.1
1.34	0.19	94.5	80.3	82.2	83.3

* Q_R = 0 W

FLIGHT EXPERIMENT

CCPL-5 is slated to fly as part of the CRYOTSU Flight Experiment on STS-95 in October 1998. CRYOTSU is the fifth flight of the NASA/GSFC Cryogenic Test Bed, a Hitchhiker Get Away Special (GAS) Canister that provides a capability for conducting cryogenic experiments in space. The CTB provides five Hughes 7044H tactical cryocoolers and associated control electronics. Previous flights included CRYOHP, CRYOTP, and CRYOFD (2).

There are four separate CRYOTSU experiments, three cryogenic experiments and one ambient experiment. Included are CCPL-5, a 60 K Thermal Storage Unit (TSU) experiment, a cryogenic thermal switch experiment, and an ambient phase change experiment. A diagram is provided in Figure 8. A photograph is provided in Figure 9.

Flight Instrumentation and Charge

The flight instrumentation is somewhat different from that indicated in Figure 6. Instead of silicon diodes, the flight temperature sensors are platinum resistance thermometers (PRTs). The locations of the sensors are essentially identical to that indicated in the figure. Additionally, instead of user ("by hand") temperature control, the flight electronics are capable of controlling the temperature of the condenser and cold reservoir to within +/- 0.25 K. Lastly, instead of a G-M cryocooler, the flight experiment uses a Hughes 7044H tactical cryocooler as the cooling source, which only provides about 3.5 W of cooling at 80 K compared to over 15 W for the G-M cooler. Thus, during the flight experiment, the maximum evaporator heat load will be about 3 W. The charge pressure of nitrogen for the flight experiment was 1.41 MPa (205 psia).

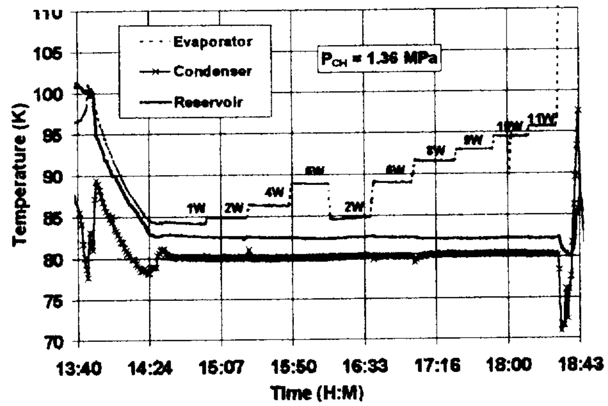

FIGURE 7. CCPL-5 Results for 1.36 MPa Charge

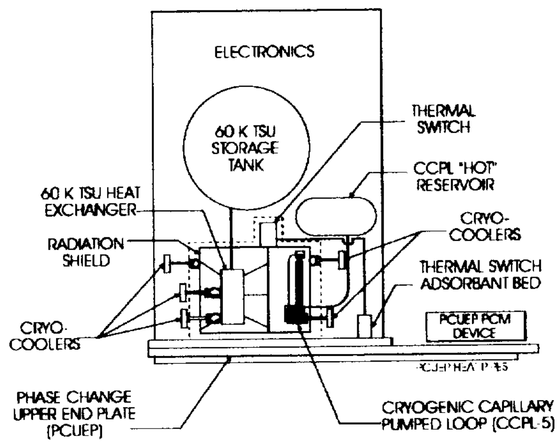

FIGURE 8. Diagram of CRYOTSU Flight Experiment

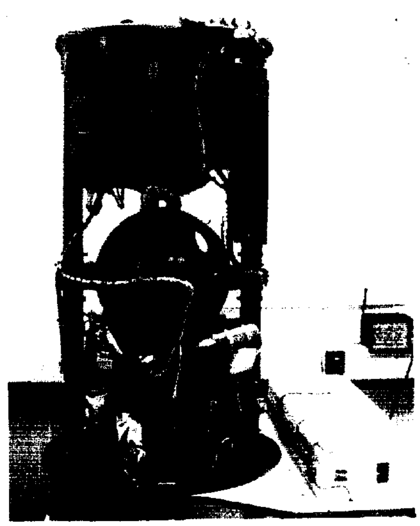

FIGURE 9. Photograph of CRYOTSU Flight Experiment

Hitchhiker Canister Ground Testing

At the time this paper was written, the CRYOTSU flight experiment was integrated into the Space Shuttle (STS-95) awaiting launch. Prior to integration, some limited testing was performed in the Hitchhiker canister to verify experiment functionality. CCPL-5 was started up several times and operated exactly as expected. The temperature control capability of the flight electronics functioned very well and eliminated one of the responsibilities of the experimenter compared to the laboratory testing described previously.

Objectives, Flight Plan and Future Work

The CCPL-5 flight experiment is intended to show that CCPLs are ready for use in advanced cryogenic space systems such as SBIRS-Low. Specifically, our goals are to demonstrate several start-ups from a supercritical state, to carry out extensive power-cycling tests, and to quantify the effects of zero-g on CCPL operation through comparison to ground test data. A future paper will describe whether any adverse or advantageous zero-g effects were observed during the mission. However, based on the good performance of ambient CPLs in space (such as CAPL-2 and others), the likelihood is quite high that CCPL-5 will perform as expected.

NOMENCLATURE

D	Diameter	<u>Subscripts</u>	
f	Friction Factor	C	Condenser
L	Length	CH	Charge
m	Mass	E	Evaporator
M	Molecular Weight	G	Gas
P	Pressure	L	Liquid
r	Radius	R	Reservoir
R	Gas Constant	S	Saturation
T	Temperature	<u>Greek</u>	
v	Velocity	ρ	Density
V	Volume	σ	Surface Tension

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