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DEVELOPMENT OF THE CRYOGENIC CAPILLARY PUMPED LOOP

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ABSTRACT

A cryogenic capillary pumped loop (CPL) has been developed, designed, fabricated and successfully demonstrated by test. Using no moving parts, the novel device is able to start from a supercritical state and cool a remote dissipation source to 80-90K. Design studies were conducted for integration requirements and component design optimization and prototype units were designed, fabricated and successfully tested with excellent results. The development included the miniaturization of CPL technology to allow heat acquisition from sources with a small footprint and direct integration to a cryocooler cold finger.

Applications include the cooling of cryogenic electronics, sensors, and fuels. The technology possesses many advantages over cryogenic heat pipes including ground testability and mechanical isolation. Because of the CPLs ability to transport loads over a distance, cryocoolers can be located remotely from the detector (up to a meter away or across a gimbaled joint). In addition, it passively seeks the coldest rejection environment, allowing a single cryogenic CPL to enable switching between multiple passive cryogenic radiators.

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INTRODUCTION

CPLs are two-phase transport devices capable of transporting heat loads over long distances with minimal temperature drop across the system. The heat is acquired through the vaporization of the working fluid in an evaporator and rejected through condensation at a remote condenser. The system is passively pumped by means of surface tension forces developed in a porous wick structure located within the evaporator. For a further understanding of the room temperature CPL technology the reader is directed to Reference 1.

The development of the cryogenic CPL expanded off the extensive design, development, and test heritage of room temperature CPLs to create a loop which is capable of starting and sustaining operation at cryogenic temperatures. The extrapolation of CPL technology to cryogenic temperatures offers performance benefits which are not currently within the reach of traditional heat pipes. Specific advantages of CPL technology as it pertains to cryocooler integration include:

- Improved ground testability due to greater capillary pressures
- Improved mechanical isolation
- Faster diode shut down and lower reverse heat leaks
- Tighter control of detector temperature
- Ease of integration due to their flexibility

Perhaps the main reason designers should consider using cryogenic CPLs is that *they intrinsically seek the coldest rejection environment.* CPL technology has the ability to autonomously distribute heat to various sinks, switch between multiple sinks and provide diode action to prevent reverse heat transport from a hot sink.

Why CPL Versus LHP Technology

Traditional western CPL technology is much more pliant to cryogenic applications than loop heat pipe (LHP) technology. An LHP (Reference 2) is a type of CPL which is characterized by the presence of thermal and hydraulic connections between the reservoir (compensation chamber) and the evaporator. This connection is typically achieved though a secondary wick between the evaporator and compensation chamber. The fact that the CPL does *not* have a similar connection is what allows the reservoir to be co-located with the condenser at the cryocooler. By co-locating the CPL reservoir and cryocooler and the addition of a hot reservoir to the system, fluid shuttling can be used to bring the device from room temperature to cryogenic temperatures (one of the major technical challenges of this development effort).

The design attribute which provides "robustness" to room temperature LHPs, the connection between the compensation chamber and the evaporator, *becomes the impediment which prevents their use at cryogenic temperatures.* To drive an LHP below critical temperature, the compensation chamber would have to be co-located with the condenser at the cryocooler, thus requiring a capillary connection to the evaporator be carried across the transport section. This results in the same the orientation and flexibility constraints associated with cryogenic heat pipes due to the secondary wick in the compensation chamber. The second design limitation of LHPs, is the excessive design pressure a cryogenic LHP would experience at room temperatures. The presence of the hot reservoir in the cryogenic CPL minimizes this design pressure.

PROGAM OVERVIEW

During Phase I of this program (Reference 3), the feasibly of a cryogenic CPL was demonstrated. The design was developed through a series of thermal/fluid analyses which were performed to aid in the build of a breadboard unit and proof-of-concept testing. A closed-cycle prototype loop was fabricated and tested in 1993 using nitrogen as the working fluid. Nitrogen was selected over oxygen as a working fluid because of superior performance in start-up, reduced reservoir sizing, and tolerance of liquid line heat leaks. Low costs and reduced concerns over safety and material compatibility are also appealing. The unit was designed for a 1 meter transport length and used an evaporator with room temperature heritage UHMW polyethylene wick. Demonstrations included start-up from a supercritical state and steady operation under powers ranging up to 7W at 90K. With this task the viability of cryogenic CPL technology was successfully established.

The Phase II development (Reference 5) continued with the design and fabrication of third and fourth generation units. These designs focused on improved performance and component miniaturization for ease of integration. The Phase II development activities started with an industry search and survey to establish design criteria for the cryogenic CPL. This survey was following by a series of analytical studies which sought to optimize the design for performance, weight and mechanical envelope. Third and fourth generation units were designed and tested. The program successfully demonstrated system performance down to 1 watt at 90K with only 1.1K of subcooling required at the evaporator.

CANDIDATE APPLICATION SURVEY

An industry search and survey was conducted to optimize the development effort. The results of these surveys were rather surprising. In essence, it was found that existing cryocooler integration designs were limited by existing hardware options. In other words, since no prior hardware offered the functionality of CPLs, integration of CPLs into existing cryocooler systems was not as beneficial as a complete design overhaul. However, significant payoffs appeared to be possible if application engineers and CPL designers work together to develop new packaging configurations. The design goals selected resulted in technical challenges such as miniaturization and low heat loads. Extrapolation of the cryogenic CPL technology to applications with larger interfaces and larger heat loads is easily performed.

Selection of Candidate Application

A series of meetings was conducted with NASA/GSFC, JPL, AFRL in addition to conversations with various reviewers in industry. Based on the results, a plan was established to develop a light weight evaporator that can be used as a direct attachment for the focal plane array or at least be located inside the dewar. Ideally, the base plate on which the FPA is mounted, could be replaced by a dual CPL evaporator. The main design goals are summarized in Table1.

Table 1: Cryo CPL Phase II Design Goals

Attribute	Goal/Requirement
Nominal load	2 Watts
Transport distance	0.2 meter
Source temperature	80K
Total temperature drop	3 to 5K
Environment	10^{-5} Torr at 300K
Maximum survival temp.	350 K

System Integration

At the completion of the Phase I study, the most probable concept for integration of the CPL into cryocooler applications was a single CPL strapping multiple cryocoolers as shown in Figure 1. This concept required multiple parallel condensers in a single CPL. This concept had significant impacts on several components of the cryogenic CPL such as the hot and cold reservoir designs, the two pass condenser layout and more significantly, the evaporator.

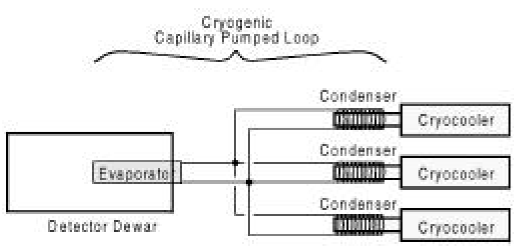

Figure 1: Integration of Redundant Cryocoolers

Even though the only known failure mechanism for cryogenic CPLs is loss of working fluid, the intolerance of the above depiction to this single fault drives the need for redundant CPLs, each with parallel condensers. Such a concept quickly becomes difficult to manage mechanically and thermally. Therefore parallel redundant CPL loops were pursued in which a dual stub-end evaporator would interface directly to the sensor or cold head and support heat acquisition for the two loops.

A more mature concept is presented in Figure 2. The expected high reliability of cryogenic CPLs is exploited to accept redundant strings of CPLs and cryocoolers. The evaporators will be built into the detector chip carrier, and the condensers will be integrally attached to the cryocooler cold fingers, thus eliminating thermal interfaces. This concept was defined as the baseline for the remainder of the development effort.

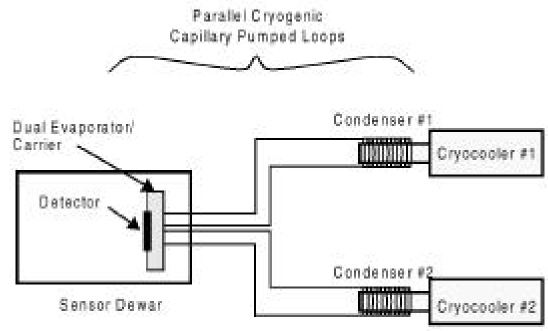

Figure 2: Current Concept; Parallel CPLs

DESIGN OVERVIEW

As stated prior, the cryogenic CPL is based on room temperature CPL technology. The third generation cryogenic CPL is shown in Figure 3. Modifications to the traditional loop design were required to extrapolate the technology to cryogenic temperatures.

The first issue was the required start-up from a supercritical state. A traditional CPL has a single reservoir plumbed on the liquid return side of the loop. The cryogenic CPL has two reservoirs as shown in Figure 4, a cold reservoir (similar to the room temperature technology) and a larger hot reservoir. The hot reservoir is key to supercritical start-up. The hot reservoir is used in conjunction with the cold reservoir to shuttle the fluid between the two. This shuttling has the effect of chilling the evaporator mass below critical. The hot reservoir is also key in reducing the maximum operating pressure at room temperature for the cryogenic CPL.

A second deviation from room temperature technology is the addition of a liquid cooled shield on the transport lines. This shield reduces the evironmental parasitics which can increase the loop temperature differential. For loops with a short transport section, the liquid cooled shield is not required.

The last deviation in the development of the cryogenic CPL was the utilization of a stainless steel wick in the evaporator (room temperature technology has historically used polyethylene).

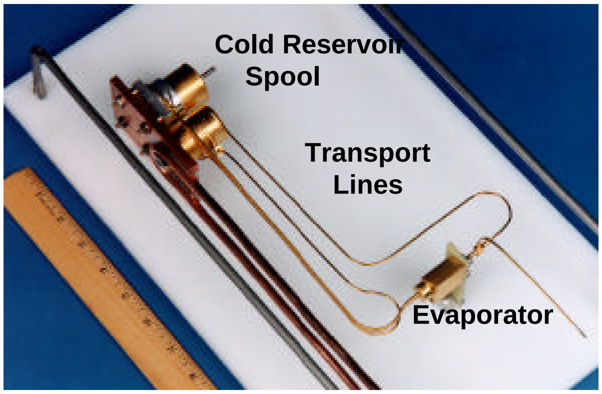

Figure 3: Photographs of the Cryogenic CPL

The condenser required a three pass design to optimize the integration of the hot reservoir and the liquid cooled shield. In this system, the hot reservoir line passes over the spool to chill the fluid which is displaced from the hot reservoir during the start-up cycling before it enters the loop. The hot reservoir line is then plumbed into the midpoint (roughly) of the condenser. After the hot reservoir tee, the condenser line leaves the spool and is used to chill the liquid cooled shield shown in Figure 9. The condenser line then makes a second pass over the spool before returning to the evaporator.

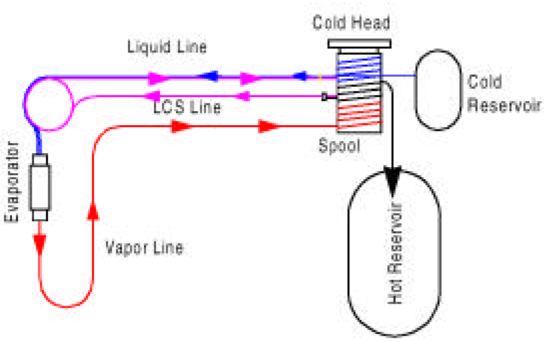

Figure 4: Cryogenic CPL Schematic

Overview of the Start-up Process

The start-up process for the cryogenic CPL is unique in that the system must be brought below critical before the loop can be started. This process requires fluid shuttling between the hot and cold reservoirs. The cold reservoir and condenser spool are both heat sunk to the cold head of a cryocooler. The cold reservoir also has a heater on it.

Initally as the cyrocooler cold head temperature drops, the cold reservoir and condenser are chilled. As the system pressure stabilizes and the cold reservoir reaches the desired operational temperature, the cold reservoir heater is enabled (referred to as a cold reservoir cycle). The heating of the cold reservoir expels cold fluid from the reservoir through the evaporator to the hot reservoir. This flow through the evaporator results in chilling of the evaporator and attached mass. The cold reservoir heater is then disabled after a few minutes. As the vapor in the cold reservoir recondenses, it pulls fluid from the hot reservoir through the evaporator and back into the cold reservoir.

These cycles are repeated (“fluid shuttling”) until the evaporator temperature drops to saturation. At this point, a load can be applied to the evaporator to start the loop.

Design Analyses

Several models were developed for the steady state and transient design sizing using SINDA/FLUINT, the NASA-standard heat transfer and fluid flow analyzer for thermal control. These included detailed models of the evaporator case, steady state sizing of the hot and cold reservoirs and transient filling of the hot reservoir, and line sizing along with many others.

The reservoir sizing analysis predicted the minimum cold and hot reservoir volumes required for the CPL based on system volumes and a sizing criteria. After calculating the minimum reservoir volumes required for a specific maximum design pressure, the analyses then predicted oversizing of both the cold and the hot reservoir for enhanced start-up. In the design of the fourth generation unit, the hot reservoir was over-sized to bring the maximum design pressure to 2 MPa. Based on a minimum cold reservoir, the hot reservoir sizing based on design pressure is summarized in Figure 5. Predictions for oversizing both reservoirs are summarized in Figure 6.

Transient Simulations

The start-up transient thermal hydraulic model developed during Phase I was correlated to third generation test data. This model simulates the cyclic two-phase quenching during the chill down and start-up of the cryogenic CPL. The Sinaps*Plus*® graphical depiction of the fluid network[1] is shown in Figure 7.

The model was developed to account for cryocooler efficiency, temperature varying conductivities and specific heats, full-range fluid descriptions built into

[1] Sinaps*Plus*®, developed by C&R Technologies, provides a complete graphical environment to SINDA/FLUINT for pre- and post-processing and interactive model debugging.

FLUINT, and tank compliances are specified for smoother hydraulic response during transient simulations.

The model also accounts for partial priming of the evaporator wick. This was achieved by using two parallel capillary pump devices in FLUINT, one representing the primed portion of the wick, the second representing the deprimed portion of the wick. This allows vapor to trickle back into the liquid core when partially primed. Additional logic was defined to evaluate the state of prime and then adjusts heat transfer coefficients within the evaporator and back conduction through the wick accordingly. A chill down transient from the correlated model is shown in Figure 8. This correlated data corresponds to the test data in Figure 10 herein.

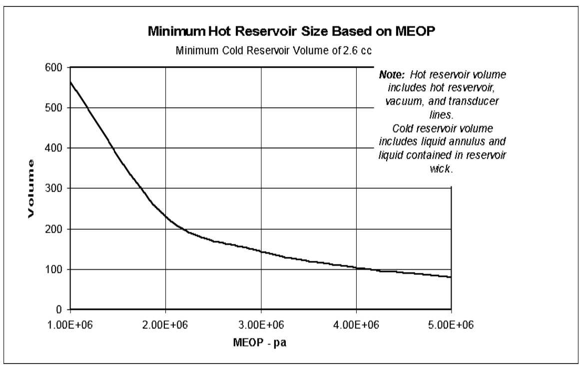

Figure 5: Minimum Hot Reservoir Volume

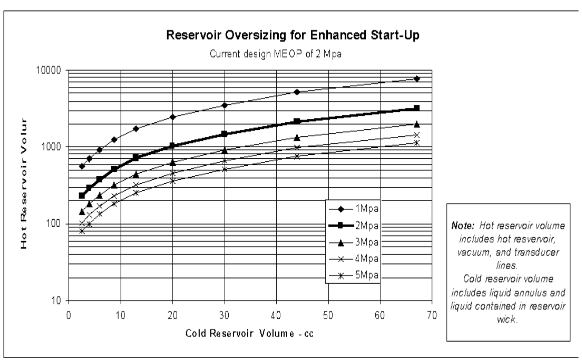

Figure 6: Reservoir Oversizing

DESIGN AND TEST

Third and fourth generation units were fabricated and tested. The evaporator for both of these units was 1.5 inches long and 0.5 inch diameter with an active length of one inch. The body was fabricated from 316 stainless steel with a 2.6 micron stainless steel wick. The liquid line was plumbed as a bayonet to enhance core flushing during start-up and to increase vapor bubble tolerance. The evaporator was attached to a copper saddle which provided the one inch square sensor mounting surface.

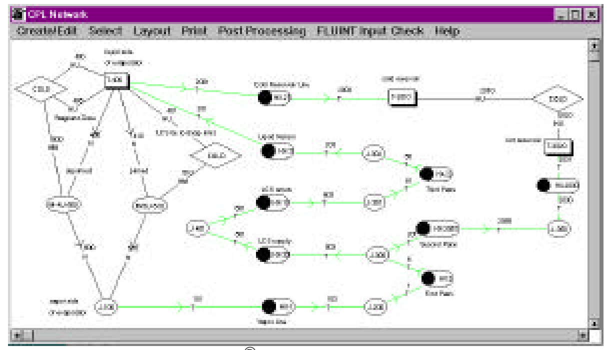

Figure 7: SinapsPlus® Depiction of Fluid Network

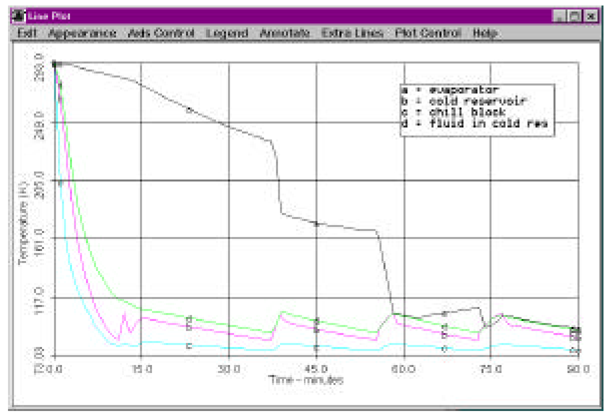

Figure8: Correlated Start-Up Prediction

The condenser was fabricated from 0.065 inch outer diameter stainless tubing coiled on a spool fabricated from 7074-141 copper. Grooves where machined on the outer surface of the spool to accommodate the condenser lines. The spool is designed to attach directly to a cold head.

The cold reservoir was fabricated from 316 stainless steel. The body is 1.62 inches long with an outer diameter of 1.185 inches and a wall thickness of 0.03 inch. The reservoir had an internal volume for expulsion of 16.26 cc and a total volume of 20.8 cc. The internal wick was machined from UHMW polyethylene. A reservoir heater was attached to the exterior of the body. The reservoir was thermally strapped to the cold head to provide the necessary cold bias required to enable positive heater control.

The unit was gold plated to minimize parasitic heating from the environment during cool down and operation. Figure 9 shows the unit[2] with the liquid cooled shield in place and the gold plating.

Figure 9: CPL With Liquid Cooled Shield

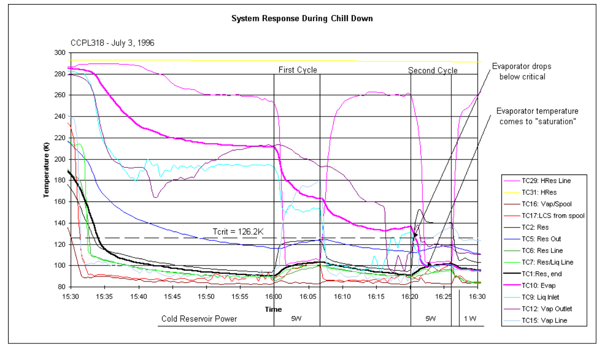

Figure 10: Chill Down Profile of CCPL

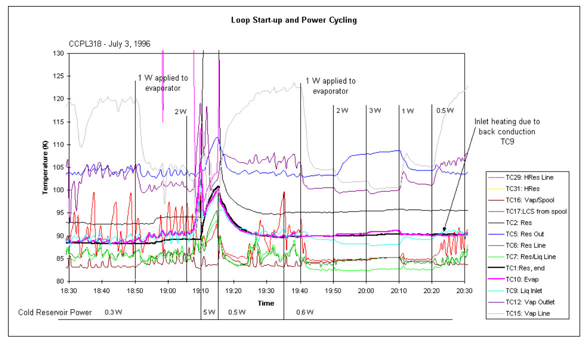

Figure 11: Low Power Start-Up of CCPL

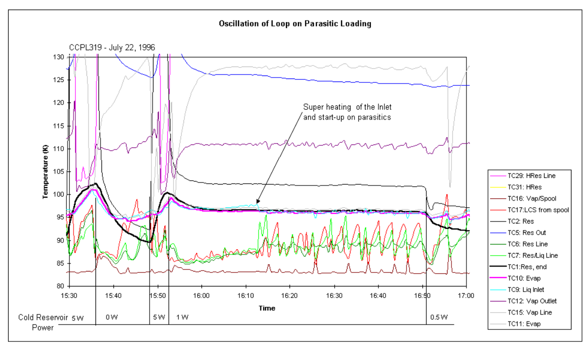

Figure 12: Operation on Parasitic Loading

Summary of Test Results

The results of the third generation test program were very positive. For this phase of testing, the unit was attached to an LN2 chilled plate in lieu of a cryocooler and placed in a ambient temperature vacuum chamber. The chamber was pumped down to $<10^{-3}$ torr. The hot reservoir was located outside of the chamber.

As shown in Figure 10, only two cold reservoir cycles were required to bring the evaporator and reservoir below 100K. *A successful start-up was demonstrated at 90K with a 1.0 watt heat load and 1.1K of subcooling at the evaporator* as shown at time=19:40 in Figure 11. The evaporator power was cycled up to 3 watts and back down to 0.5 watt.

Additional tests were performed to further assess low power start-up and the parasitic heating. Figure 12 depicts the temperature profile with only parasitic loading. Five reservoir cycles were performed. Three were required to bring the system below critical temperature and the evaporator to the saturation temperature. Two additional cycles were performed for assurance. After the fifth cycle, 1 watt was applied to the cold reservoir. At approximately 16:12, the evaporator was at saturation with slight super heating of the liquid inlet. The sudden drop in the inlet temperature indicates a start-up on parasitic loading. At this point oscillations commence. These occillations are an indication of pumping on parasitic loading with insufficient flowrate to clear the vapor line.

The ability of the system to self-start under parasitic loads was an unexpected bonus. The system was expected to reach a theoretical stall speed when the load dropped below the minimum required to sustain operation. Repeated reservoir cycling would have been necessary to bring the system below critical after a "stall". *With the ability to operate on parasitic loading, the system remains at temperature.* Only a single short reservoir cycle is required to clear the vapor in the evaporator core prior to application of the sensor load.

The final test assessed low power start-up and the ability to continue low power operation over an extended time period. The system was started with a 1 watt load to the evaporator. The system operated

[2] Unit shown is actually the flight unit for the CRYOTSU demonstration. It is shown in lieu of the fourth generation unit due to photo quality of the fourth generation unit.

very steadily while the power was incremented up to 3 watts and back down to 0.5 watt. At 0.5 watts oscillations commenced designating a low power threshold between 0.5 and 1 watt.

Chill Down from Supercritical

The fourth generation test program was performed in an ambient temperature vacuum chamber with the condenser spool attached to the 2nd stage of a 2-stage GM cryocooler. The testing was highlighted by the unexpected chill down of the unit with no fluid shuttling (cold reservoir cycling) as depicted in Figure 13. Further investigation and analysis of cooling capacities determined that the observed behavior was a result of a low rate of flow for fluid being pulled through the evaporator into the cold reservoir in response to the slow chill down rate of the cryocooler. In previous testing the chill down from ambient to 90K was achieved in 15 minutes versus the two hours required for the cryocooler used in this test. Due to the low flow rate, the evaporator mass chills more efficiently.

The unexpected chill down transient required the development of a new start-up procedure for the system. Between the third and fourth generation test programs, the start-up procedure has been bounded for a large span of chill down rates.

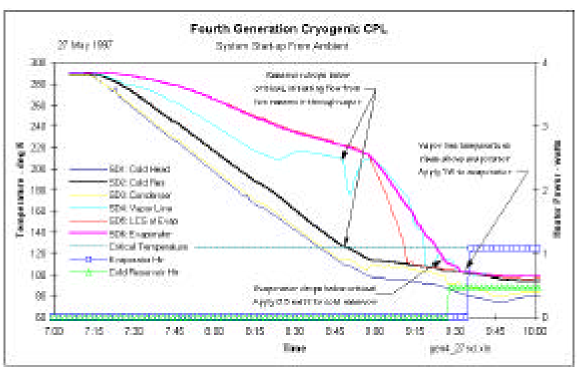

Figure 13: Start-up of the Fourth Generation Unit

Fixed Conductance Operation

The fourth generation unit was design for fixed conductance[3] operation. The unit was intentionally overcharged at the start of testing. After start-up, with the unit operational, charge was bled from the system until the desired temperature profiles where acquired.

At the conclusion of the bleed process the system was properly charged for fixed conductance operation at evaporator loads of 4 watts. In this scenario, *the system demonstrated the ability to transport 4.25 watts at 90K with a 3K differential between the evaporator and the condenser*. Typical response to power cycling is shown in Figure 14.

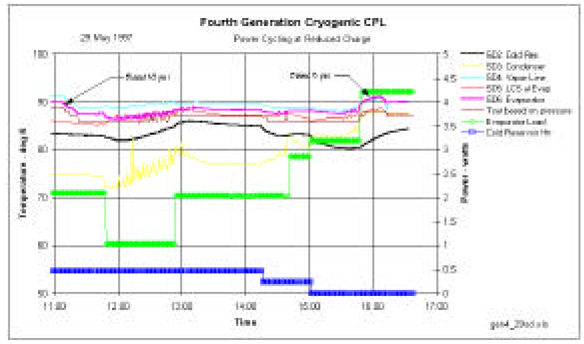

Figure 14: Fixed Conductance Power Cycling

In summary, the system responded better than expected for fixed conductance. It was previously believed, that a cryogenic CPL charged for fixed conductance operation would exhibit start-up difficulties due to fluid distribution in the loop during chill down. Surprisingly, the system exhibited no start-up difficulties and operated in a very robust manor throughout the power cycling.

Variable Conductance Operation

The system was restarted at the lower charge level to verify start-up. After start-up, the system was excersised in variable conductance mode as shown in Figure 15. At a 4 watt load, the system had an 6K temperature differential between the evaporator and the condenser. Stable operation of the CPL continued as the reservoir power was reduced to 0.1 watt at which point the loop differential had decreased to 3K. At 0.1 watt on the reservoir, the reservoir temperature dropped slightly below the saturation indicating a 0.25W minimum load is required to retain reservoir control during variable conductance mode. Subsequent power turn down on the evaporator resulted in a system deprime as expected. With a short reservoir cycle to reprime the system, the CPL was back in operation at a 1 watt evaporator load within 15 minutes.

CONCLUSIONS

In summary, cryogenic CPL technology has successfully been demonstrated to be capable of providing 1 to 7 watts of cooling capacity at 90K with minimal temperature differential across the loop. *This new technology offers cryogenic system designers an option to locate cryocoolers remotely in*

[3] Fixed conductance operation is characterized by the hard filling of the reservoir. During this mode, saturation temperature floats to balance energy . See reference 6.

addition to having unsurpassed off resistance and vibration isolation.

Continuing efforts at Swales Aerospace will provide the first flight experiment[4] of the cryogenic CPL in 1998 on the CRYOTSU gas canister through funding from Phillips Laboratory and NASA GSFC. This experiment will verify the 0-g operation of the cryogenic CPL. The unit to be flown, shown in Figure 9, is identical to the fourth genertion unit described herein with the execption of more complete gold plating.

This effort has demonstrated and matured cryogenic CPL technology thus opening a new, versatile and exciting integration option for the design of future cryogenic systems. Potential spin-offs from this development include the miniaturization of CPLs for room temperature applications in addition to the metal wick technology which can increase pumping capacity by an order of magnitude over existing polyethylene wicks for ammonia systems. A spin-off development funded by BMDO and Phillips Laboratory demonstrated the successful start-up from supercritical and subsequent operation of a neon unit for applications in the range of 30-40K (Reference 4).

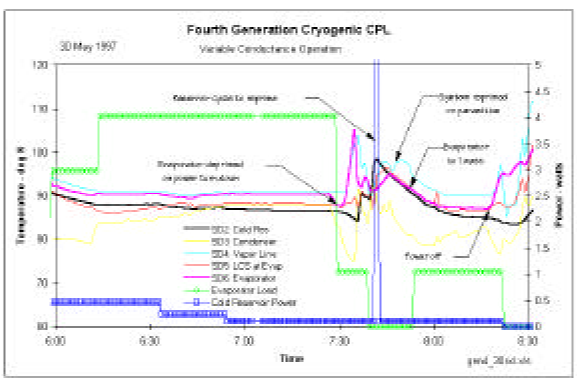

Figure 15: Variable Conductance Operation

REFERENCES

1) Ku, Jentung, *Overview of Capillary Pumped Loop Technology*, National Heat Transfer Conference, August 1993
2) Maidanik, Vershinin, Kholodov, Dolgirev, U.S. Patent Documents, *Heat Transfer Apparatus*, #4515209
3) Cullimore, B., *Cryogenic Capillary Pumped Loop Final Report for Phase I*, NASA/GSFC Contract NAS5-32415, June 1993
4) Bugby, D., Kroliczek, E., Cullimore, B., Baumann, J., *Experimental Investigation of a Neon Cryogenic Capillary Pumped Loop*, 32nd IECEC, No. 97272, 1997
5) Baumann, J., *Cryogenic Capillary Pumped Loop Final Report for Phase II*, NASA/GSFC Contract NAS5-32415, July 1997
6) Cullimore, B., *Constant Conductance Mode in Capillary Pumped Loops*, January 1996
7) Bugby, D., Nguyen T., Kroliczek, E., Ku, J., Swanson, T. , Cullimore, B., Baumann, J., *Development and Testing of a Cryogenic Capillary Pumped Loop Flight Experiment*, IECEC-98-I288, August 1998.

4 Reference 7 has a more complete discription of the flight experiment.