FLIGHT TESTING OF
THE CAPILLARY PUMPED LOOP FLIGHT EXPERIMENT

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ABSTRACT

The Capillary Pumped Loop Flight Experiment (CAPL) employs a passive two-phase thermal control system that uses the latent heat of vaporization of ammonia to transfer heat over long distances. CAPL was designed as a prototype of the Earth Observing System (EOS) instrument thermal control systems. The purpose of the mission was to provide validation of the system performance in micro-gravity, prior to implementation on EOS. CAPL was flown on STS-60 in February, 1994, with some unexpected results related to gravitational effects on two-phase systems. Flight test results and post flight investigations will be addressed, along with a brief description of the experiment design.

INTRODUCTION - EXPERIMENT DESCRIPTION

CAPL was developed as a follow-on to the initial Capillary Pumped Loop (CPL) Get Away Special (GAS) and Hitchhiker flight experiments that were flown in 1985 and 1986 [1]. These small-scale experiments were highly successful and demonstrated the feasibility of using capillary pumped loop (CPL) technology in micro-gravity. CAPL was a much larger experiment and was a prototype of the EOS-AM instrument thermal control systems. EOS has six separate CPL's to provide redundant thermal control of three of its instruments [2]. The original CAPL experiment is now designated as "CAPL 1" to differentiate it from the redesigned "CAPL 2", planned for flight in July 1995. Additional detailed descriptions of the original CAPL experiment are given in references 3 and 4.

<u>Experiment Structure</u> - The CAPL experiment measures 1.57 m by 2.54 m by 0.36 m deep (62" by 100" by 14") and weighs approximately 181 kg (400 pounds). The experiment components were sandwiched between the CAPL radiator and a Hitchhiker mounting plate that was used to mount CAPL to the GAS bridge aboard the Space Shuttle (see Figures 1 and 2)

<u>Capillary Evaporators</u> - CAPL 1 had two capillary evaporator plates (cold plates) that were an approximate simulation of the cold plates that will be used on the EOS-AM spacecraft. Each plate contained two small diameter (1.38 cm outer diameter, 0.545 in.) capillary evaporators (see Figure 3). Instrument power dissipation was simulated with heaters located on top of the plates, with up to 600 Watts of heater power on each plate.

<u>Heat Pipe Heat Exchangers (HPHX's)</u> - The vapor traveled through an eight-meter long, 1.27 cm (1/2 in) O.D. vapor line to four heat pipe heat exchangers which condensed the ammonia vapor and

transferred the heat to the radiator via eight heat pipes. This method of heat rejection has been selected for EOS (and CAPL) instead of a direct condensation radiator because it greatly reduces the vulnerability to meteoroids since the cold plate fluid loop is separated from the radiator fluid loop. The HPHX utilized spiral grooved channels machined into a heavy wall heat pipe to accomplish vapor condensation and heat transport to the radiator [9]. An external flow regulator provided flow balancing between parallel HPHXs and trapped non-condensible gases in the flow.

<u>Subcooler</u> - The ammonia liquid returned to the cold plates via an eight-meter long 0.64 cm (1/4 in) O.D. liquid line which was attached to a separate radiator to insure that the liquid was subcooled below its saturation temperature prior to entering the capillary pumps.

<u>Reservoir</u> - A two-phase temperature controlled reservoir was used to establish the loop operating or saturation temperature and to automatically maintain the proper liquid inventory in the loop. A new reservoir design was employed for the CAPL experiment. It utilized a combination of wall screens, porous polyethylene flow tubes, and a sintered stainless steel vapor barrier for fluid management and temperature control [10].

<u>Starter pump</u> - A capillary starter pump, vapor line heaters, and cold plate vapor header heaters were used to prime the cold plates and ready the system for start-up. The capillary starter pump is similar in design to the evaporator pumps, however, its liquid core is plumbed in series to the reservoir to insure that it stays primed during the start-up process.

<u>Mechanical Pumps</u> - The experiment also included a pair of mechanical pumps and associated valving. The mechanical pumps were included as a back-up for start-up and repriming operations, and were also used to test hybrid (mechanical pump assisted) loop operation.

<u>Instrumentation</u> - CAPL was instrumented with a variety of sensors, including 180 thermistors which were used to measure temperatures throughout the experiment. In addition, there was a differential pressure transducer to measure the pressure rise in the cold plates, and another to measure the pressure drop along the vapor line. An absolute pressure transducer measured the saturation pressure at the reservoir. There was also a thermal flowmeter in the liquid transport line to measure ammonia flow rates.

<u>Electronics</u> - CAPL utilized the Temperature Control System (TCS) electronics, in conjunction with the Hitchhiker avionics and standard Shuttle services for power, data, and command of the experiment. Real time data monitoring and control of CAPL was accomplished from the Hitchhiker control center at NASA Goddard via commercial 486PC computers with specialized software. This capability allowed for modifications to the power profiles and startup techniques during the mission.

PREFLIGHT TESTING

The CAPL experiment underwent an extensive functional test program before flight which included prototype development and testing, flight component testing, system level ambient functional testing, and thermal vacuum testing. This testing has been documented in numerous reports and papers, with the Thermal Vacuum test results and the Flight Component Test Results given in References 4 and 5 respectively.

The ground test program showed that the HPHXs and reservoir exceeded their design requirements. However, the cold plates were found to be more temperamental than many capillary pumps that have been tested to date. Pump deprimes occurred during power reduction from high power levels or when the power level was low enough to allow liquid condensation in the vapor lines. Also, start-ups were initially very difficult and usually ended with pump deprimes until start-up procedures were developed that cleared the vapor lines and pump vapor grooves of liquid prior to start-up. The start-ups were then very reliable - IN ONE G. Once the pumps were started, they generally performed well and exceeded the EOS requirements for power levels and temperature stability.

<u>START-UP PROCESS</u> - (Refer to CAPL flow schematic, figure 4). The first step in starting the loop is to apply power to the reservoir to establish the loop saturation temperature and to insure that the capillary pumps have liquid for priming. For a fully flooded or "stressful" start-up, the entire loop is filled with liquid when heat is applied to the capillary pumps. Nucleate boiling then occurs in the capillary pump vapor grooves after the saturation temperature is exceeded. The liquid must "superheat" before boiling is initiated as defined by the Clausius-Clapeyron equation (see Figure 5, excerpted from reference 6). The onset of boiling is a highly dynamic transient event that results in a pressure spike and the rapid formation of vapor (figure 6). Vapor can be forced through the pump wick and into the core of the pump, and a deprime can occur if the vapor bubble is large enough to block the flow of liquid to the wick.

<u>Pump Diameter</u> - One of the reasons for the start-up difficulty with the CAPL 1 pumps has been traced to the pump diameter. Due to EOS weight considerations, the pumps used on CAPL 1 were 1.27 cm (1/2 in) in diameter versus 2.54 cm (1 in) for those used on the first CPL ground test loops and flight experiments (see Figure 7). The smaller diameter pump has a much thinner wick and smaller inner core, making these pumps much more susceptible to vapor penetration and blockage of the core. The larger diameter pumps start more readily than the smaller pumps from a fully flooded condition, although there has been some evidence of vapor penetration of the core of the larger diameter pumps as well.

<u>Vapor Line Heaters</u> - A solution to the start-up problem was developed that relies on clearing the grooves and vapor lines of liquid prior to pump start-up. This resulted in essentially zero superheat since a vapor space was created that eliminated nucleate boiling during pump start-up (see Figure 8). One way of achieving the clearing process involved the use of heaters on the vapor line and a heater on the vapor header of the cold plates. When these heaters were powered, they would vaporize the liquid in the vapor lines and vapor would be forced into the pump grooves. At this point, power was applied to the cold plates and a "non-stressful" start-up of the system was accomplished - IN ONE G. Once the loop

was started, it then operated normally for a variety of power levels, saturation temperatures, and sink conditions.

Starter Pump - Another method of clearing the liquid from the vapor lines and pump grooves was also employed on CAPL. This involved the use of a capillary starter pump (see Figure 9). The starter pump is a standard large diameter capillary pump with a bayonet tube inserted into the core, which is then plumbed in a series connection to the reservoir (refer to Figure 4). For start-up, power is applied directly to the starter pump with the loop in a fully flooded condition. As the starter pump generates vapor, liquid displaced from the vapor line must pass through the pump core before it enters the reservoir. This clears vapor bubbles that may have penetrated the wick and provides a repriming action that results in a highly reliable start-up process for the starter pump. Once the starter pump is running, the vapor it creates clears the liquid from the vapor lines and pump vapor grooves and leads to a "non-stressful" startup for the cold plates - IN ONE G. The starter pump, in combination with the vapor header heater, led to highly reliable start-ups and ground testing showed that CAPL met all of the EOS transport requirements. Further details on capillary pumped loop start-up issues can be found in reference 7.

Thermal Vacuum Tests - A mission operations plan was developed pre-flight to run a number of tests, with up to 145 hours of on orbit operations planned. The majority of the tests were initially conducted in a thermal vacuum chamber to provide a one-g data base for comparison to the flight data. The primary tests were the EOS power profiles that simulated EOS instrument power dissipations, with power levels ranging from 100 to 200 watts per cold plate. Other tests included high and low power, asymmetric loading, subcooling limit, saturation temperature transitions, mechanical pump assist, and induced deprime/reprime. Further details of these tests can be found in reference 4. Again, the start-up procedures entailed the use of the vapor line and vapor header heaters or the use of the starter pump with the vapor header heaters to clear the grooves of the evaporator pumps prior to cold plate activation.

Ground Start-up - The groove clearing process was easily verified by monitoring the thermistor data during the tests. A typical ground start-up for evaporator pump #4 is shown in figure 10 from the thermal vacuum testing. The saturation temperature was first set by energizing the reservoir heaters at hour 19.1. The cold plate heaters were also used briefly to pre-heat the plate (hour 19.5), but its temperature was not allowed to reach the saturation temperature. The vapor line heaters were then used to clear the vapor lines of liquid, followed by the vapor header heater which was used to clear the pump grooves. This was evidenced by the pump body temperature (E4 PB3), which reached the saturation temperature shortly after the vapor header heater was activated (hour 20.25), thus indicating the presence of vapor in the pump grooves. Fifty watts of power was then applied to the plate (hour 20.3) and its temperature remained near the saturation temperature with little or no superheat, thus demonstrating normal priming and temperature control.

FLIGHT RESULTS

Flight - The CAPL experiment was flown on the Space Shuttle Discovery in February 1994 (STS-60). The first startup attempt was not successful, although conflicts with other experiments for commanding capability interfered with timely heater activations. However, subsequent attempts were only partially successful, and there was no start-up in which all four evaporator pumps started simultaneously. Table 1 summarizes the various start-up attempts and shows which pumps started, if any. NONE of the start-ups were successful in clearing the pump grooves, even though this had been done routinely on the ground. Various startup methods were attempted, although it was obvious after the first few attempts that clearing the grooves would not be possible on-orbit with the CAPL 1 design.

Flight Start-up - Figure 11 shows a typical failed start-up from the flight. In this case the pump outlet (E4 Outlet) was cleared of liquid with the vapor header heater as evidenced by a temperature higher than the reservoir temperature (hour 8.75). However, the pump body (E4 PB3) temperature remained below saturation thus showing that the grooves were filled with liquid, even though the vapor header heater and the starter pump had been activated and left on for some time. Nonetheless, a startup was attempted at hour 9 with the application of 36 watts to the cold plate. The pump then experienced approximately 1.5 degrees of superheat as seen by E4 PB3 temperature at hour 9.1. When boiling started, the pump temperature dropped to saturation for a few minutes indicating possible priming and inspiring false hope to the test conductor. However, once the liquid in the pump was vaporized, the pump temperature rose quickly since there was no pumping action to provide additional liquid, thus showing a pump deprime.

FLIGHT OPERATION - As seen in Table 1, many start-ups were partially successful with two or three of the four pumps primed. In all of these cases, the pumps experienced some superheat, but started nonetheless. For these cases, either no vapor was forced into the core at the onset of nucleate boiling, or the amount of vapor in the core was not severe enough to cause a deprime. A successful start-up of pump #1 is shown in Figure 12, which is the same system startup shown in Figure 11 where pump #4 deprimed. Shortly after 36 W was applied to the plate at hour 9, the pump body temperature (E1 PB3) increased and exhibited approximately 1 degree C of superheat before boiling was initiated. At this point, the pump temperature dropped quickly to the saturation temperature and remained there, indicating a primed pump. At hour 9.5, power was increased to 125 watts, yet the pump temperature stayed near saturation, indicating a good prime. The pump continued to operate normally for the remainder of the test.

Four of the startups resulted in 2 primed pumps on one of the cold plates. This allowed the planned flight testing to continue and a number of tests were performed that demonstrated the proper operation of the loop in microgravity. In one case, after two pumps were primed, a reservoir pressure prime was successful in bringing all four pumps on-line for approximately 9 hours until the loop had to be shut down for other shuttle experiments. In all cases, the loop performed well and exceeded the EOS requirements for heat transport and temperature control, with no unexpected pump deprimes once the loop was started. Figure 13 shows the results for a typical EOS instrument power profile. The pump temperature stayed near the saturation temperature even though the power was varied from 125 watts to 250 watts and back to 125 watts, thus demonstrating proper thermal control and loop operation.

Component Testing - Flight testing confirmed the proper operation of the reservoir, heat pipe heat exchangers, and starter pump in microgravity. In addition, the loop electronics and instrumentation performed well, and hybrid operation with the mechanical pumps was accomplished. The performance of all of these components exceeded their design requirements. Additional details of the CAPL 1 flight will be available when the flight report is published.

Starter Pump - The starter pump performance was particularly encouraging in that it started on every attempt (25 times), even under adverse conditions. A typical starter pump activation is shown in Figure 14. The pump temperature increased rapidly after power was applied just prior to hour 19.6, and actually exceeded the reservoir temperature by several degrees, indicating a highly stressful start-up. This continued while liquid was being purged from the vapor line and forced into the reservoir. Once this process was complete near hour 19.7, the starter pump temperature dropped to the saturation temperature and the pump operated normally. The starter pump never deprimed because it was plumbed directly to the reservoir feed line. As the vapor line was cleared, the liquid displaced from it had to pass through the core of the starter pump before entering the reservoir. This kept the pump primed and eliminated any adverse effects caused by vapor bubbles that may have penetrated the wick. The starter pump always started successfully, even at a -8 degree C saturation temperature, which is more stressful than warmer levels due to the change in the thermodynamic properties of ammonia with temperature.

POST FLIGHT INVESTIGATIONS

Post flight testing of CAPL showed that its behavior on the ground was the same after the mission as it was before flight, thus eliminating the possibility of a severe anomaly such as a large loss of ammonia or a transport line blockage. This confirmed that the start-up difficulties were due to gravitational effects. Figure 15 is a diagram based on temperature data, comparing the approximate location of the liquid/vapor interface in the pump for microgravity and one-g. In one-g, gravity pulled the liquid from the top grooves of the pump as a vapor space was created by the vapor header heater. This provided the needed clearing of the grooves for a successful pump start-up. In microgravity, there was vertical stratification of the liquid/vapor interface and the grooves remained flooded, even when the vapor header heater was allowed to run to its thermostat limit of 50 degrees C. The best on-orbit conditions were obtained when the starter pump was used in conjunction with the vapor header heater to develop a pressure head on the vapor side of the loop. While this did succeed in pushing the liquid/vapor interface into the pump outlet, the pump grooves remained flooded and "non-stressful " start-ups were not possible.

<u>"Heat Pipe Effect"</u> - The evaporator pumps are constructed by inserting a wick into a heat pipe extrusion, with the grooves acting as vapor channels and the wick acting as the pump. However, the grooves themselves have a pumping capability based on the equation:

$$P = 2 \quad /R$$

where P is the pumping pressure, is the surface tension of the ammonia, and R is the pumping radius based on the groove geometry. Calculations for CAPL yield a groove pumping capability of approximately 98 Pascal at 25 C, which is sufficient to keep the grooves flooded in microgravity, even with the vapor lines clear. This pumping effect was easily overcome on the ground by gravitational forces. The HPHX's were located 8.9 cm (3.5 in) lower than the evaporator cold plates, representing a 520 Pascal gravitational pressure rise (pumping head) in ground tests. Thus, the vapor generated by the starter pump preferentially cleared the vapor grooves in the cold plate evaporators before flowing to the HPHX's, resulting in a "non-stressful" start-up. In microgravity, there was no gravitational pressure head to overcome, and therefore the vapor flowed to the condenser rather than clearing the pump grooves. This kept the grooves flooded and led to "stressful" start-ups that often led to pump deprimes. Analysis comparing the one-g and microgravity cases is shown in Figure 16. Unfortunately, the effects of this phenomena were not realized before the mission, and the difficulties experienced in microgravity were totally unexpected.

CAPL 2 FLIGHT VERIFICATION

Discussion of a CAPL reflight was started even before the CAPL 1 flight was completed. Initial redesign efforts focused on revised vapor outlet heater locations, increased starter pump power, and higher vapor line pressure drop to clear the pump grooves in microgravity. This effort was continued through a Reflight Design Review, which was held in June, 1994. One of the recommendations at the review (made by Mr. Brent Cullimore) was to replace the traditional CPL with a loop that utilizes only a single starter pump [8]. A heat pipe imbedded in the cold plate would be used to provide the required isothermalization of the plate and carry heat to the starter pump. This intriguing suggestion led to the construction of a prototype Starter Pump Cold Plate (SCP). Testing of this design was very encouraging and the Starter Pump System is now baselined for EOS and CAPL-2 (see Figure 17). This system is very robust, always starts from a fully flooded condition without groove clearing, and can withstand conditions that would deprime a traditional CPL. The success of the starter pump on CAPL 1 also lends credence to this design.

CAPL 2 has been designed to more accurately reflect the EOS design and to serve as a microgravity verification of the EOS CPL loops. The starter pump cold plate is the same size as the EOS plate and the liquid and vapor line lengths and diameters have been changed to more accurately reflect the current EOS design. CAPL 2 is scheduled for a flight in July 1995 on the Space Shuttle Endeavor. Results of that mission will be published as they become available.

CONCLUSION

The CAPL 1 flight reinforces the need for microgravity flight verification of gravitationally sensitive systems prior to their implementation on spacecraft. Even though the performance of CAPL 1 could have been anticipated and corrected before the mission, it is very difficult to anticipate the effects of microgravity from a one-g environment. A successful flight of CAPL 2 will demonstrate the operation of the starter pump system in microgravity and will lead to its use on EOS and other space based systems.

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2. EOS-AM Critical Design Review, Thermal Subsystems Technical Audit, Martin Marietta Corporation, Princeton NJ, January 1995.

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9. Ku, J., Yun, S., "A Prototype Heat Pipe Heat Exchanger for the Capillary Pumped Loop Flight Experiment," AIAA Paper 92-2910, AIAA 27th Thermophysics Conference, Nashville, TN, July 1992.

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Table 1: CAPL Flight Start-Up Conditions

Start-up #	Starter Pump Power (W)	Vapor Header Power (W)	Vapor Line Power (W)	Cold Plate Power Plate 1 (W)	Cold Plate Power Plate 2 (W)	Capillary pumps started E1	E2	E3	E4	Saturation Temperature (C)	average Radiator Temperature (C)	REPRIME METHOD (before start) pressure prime	mech pump	COMMENTS
1		33-off	54-off	126	124			?		25	-7	N/A	N/A	
2	145	33-off		126	124					28	3	X		
3	145			64	63		?			25	-19		X	
4	145	33-off		126	124		X	X	X	14	0	X	X	
5		33-off	56-off	127	124	X		X		16.9	2	X	X	
6	145	33		35	36	X	X			19	5	X	X	
7		33-off	104-off	35	36	X			X	21	1	X	X	cold plate power cycled
8	145	33-off		35	36		X			20	1	X	X	cold plate power cycled
9	145	33-off?		35	36	X		X		-10.1	-40	X	X	
10	145	33		34	35	X		X	X	-2	-36	X	X	
11		33	54-off	35	35	X				7.9	-13	X	X	
12	145	33		35	36	X				11	-8	X	X	
13	145	33		35	36		X		X	10	-2	?	X	
14	145	33-off		126	126	?				18	-2	X	X	sacrificial plate 2
15	145			125	36/96				?	18	-4	X	X	sacrificial plate 1
16	145	33		35	36		X		X	14	-1	X	X	
17	145			122	123					16.9	1	X	X	MMA Procedure
18	145	33-off		32	32					22	1	X	X	PRCS firings
19	145	33		32	32		X	X		5	-5		X	
20	145			32	32	X				10	-7	X	X	
21				125	125	X	X		X	25	0		X	hybrid assist start-up

X indicates that the pump operated successfully

- off indicates that the heater was used, but that it was off when cold plate power was applied

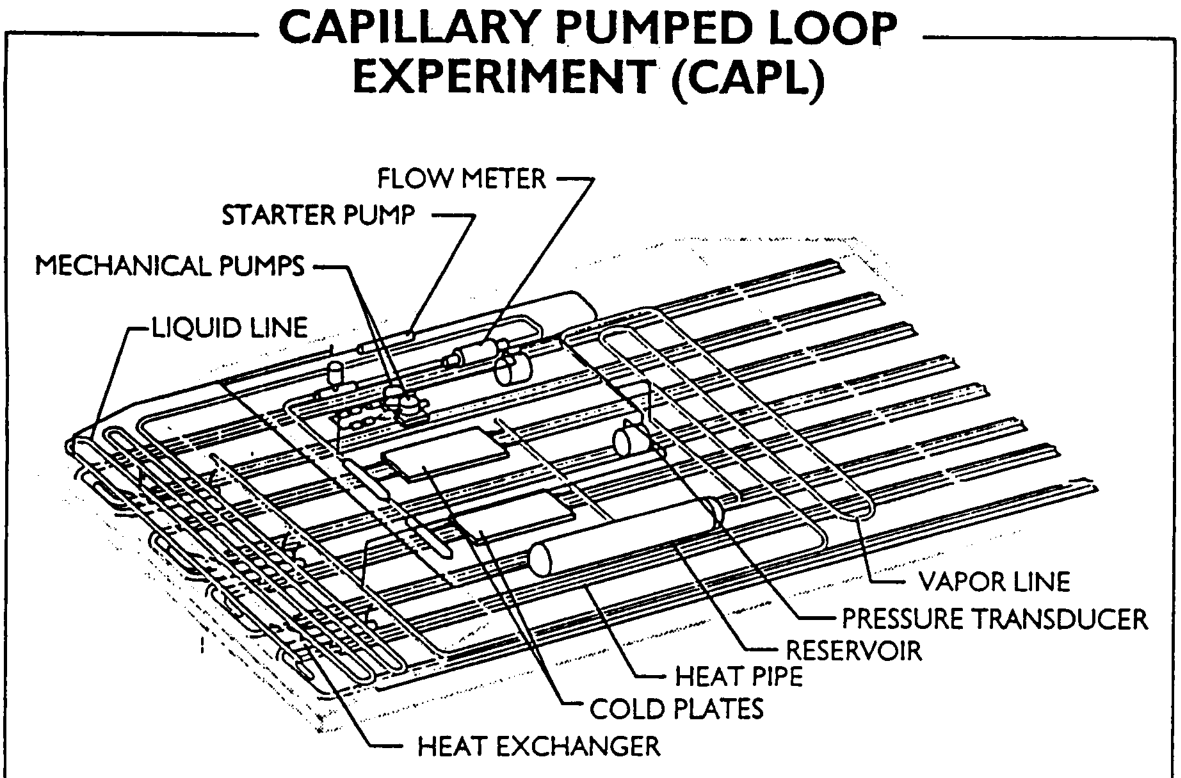


Figure 1

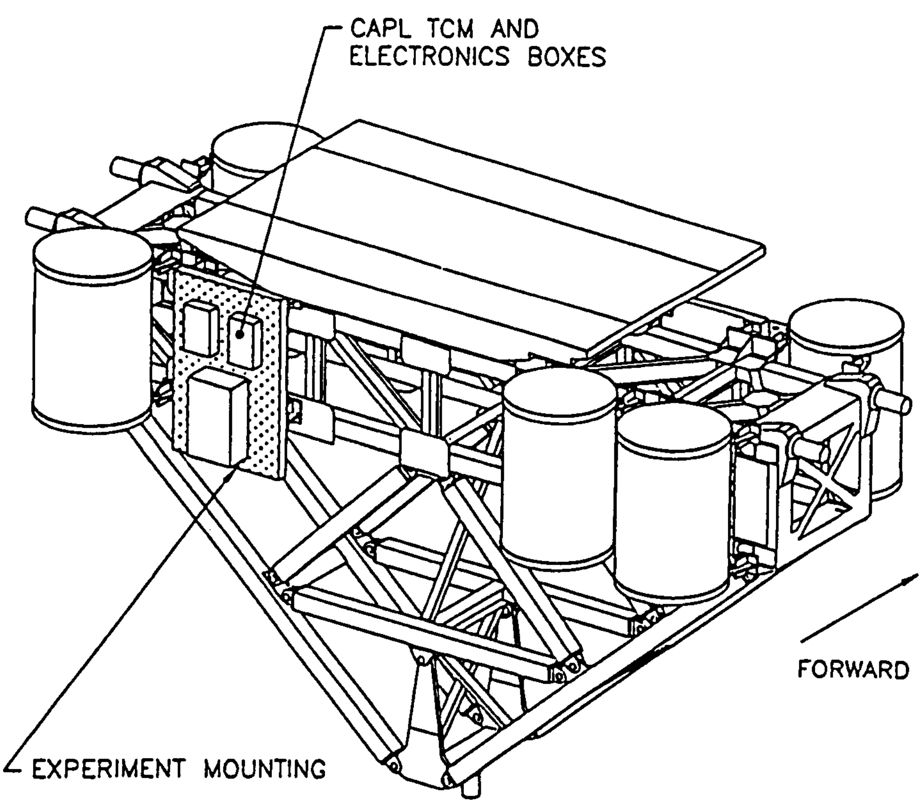


Figure 2 CAPL on the GAS Bridge

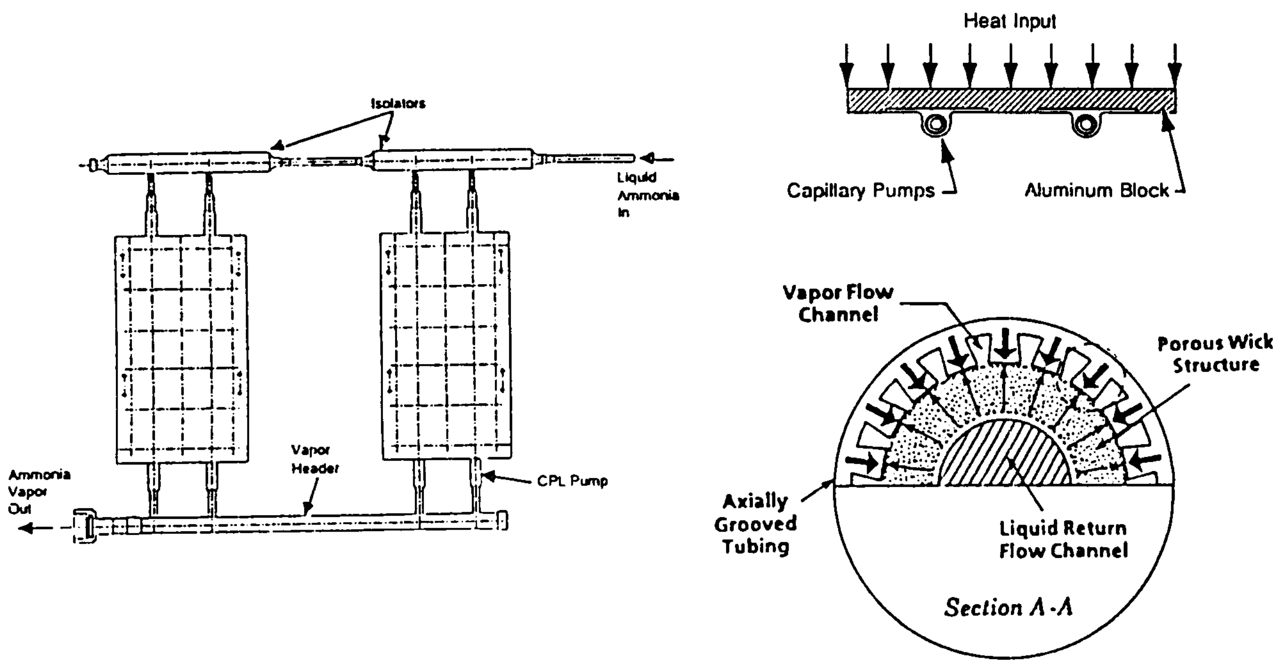


Figure 3 Capillary Evaporator Plates

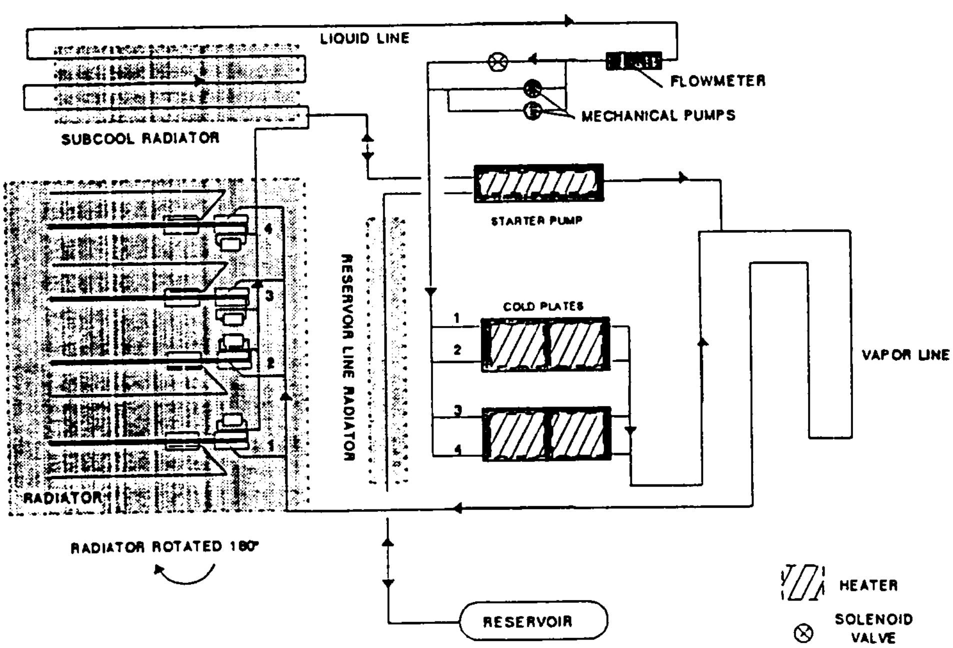


Figure 4 CAPL Flow Schematic

NUCLEATE BOILING THEORY

- **CLAUSIUS-CLAPEYRON EQUATION**

$$T_L - T_{RES.} \cong \frac{RT^2_{RES.}}{\lambda P_{RES.}}\left(\frac{2\sigma}{r}\right) \quad \text{where } T_L = T_V \text{ and } P_L = P_{RES.}$$

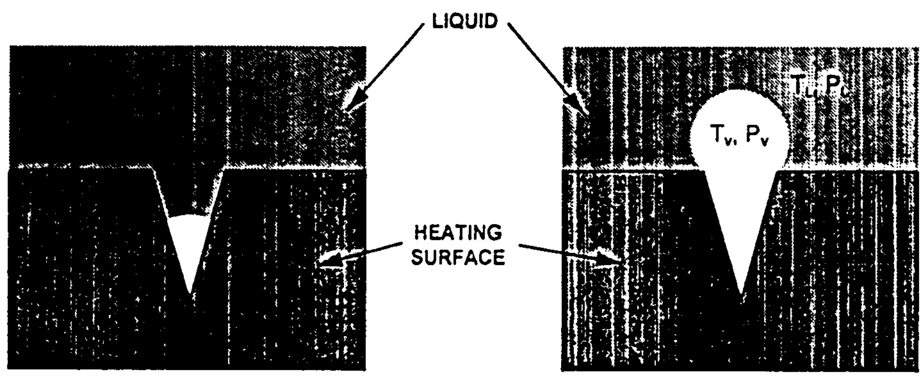


Figure 5

PRESSURE DROP AND TEMPERATURES DURING START-UP WITH HIGH SUPERHEAT

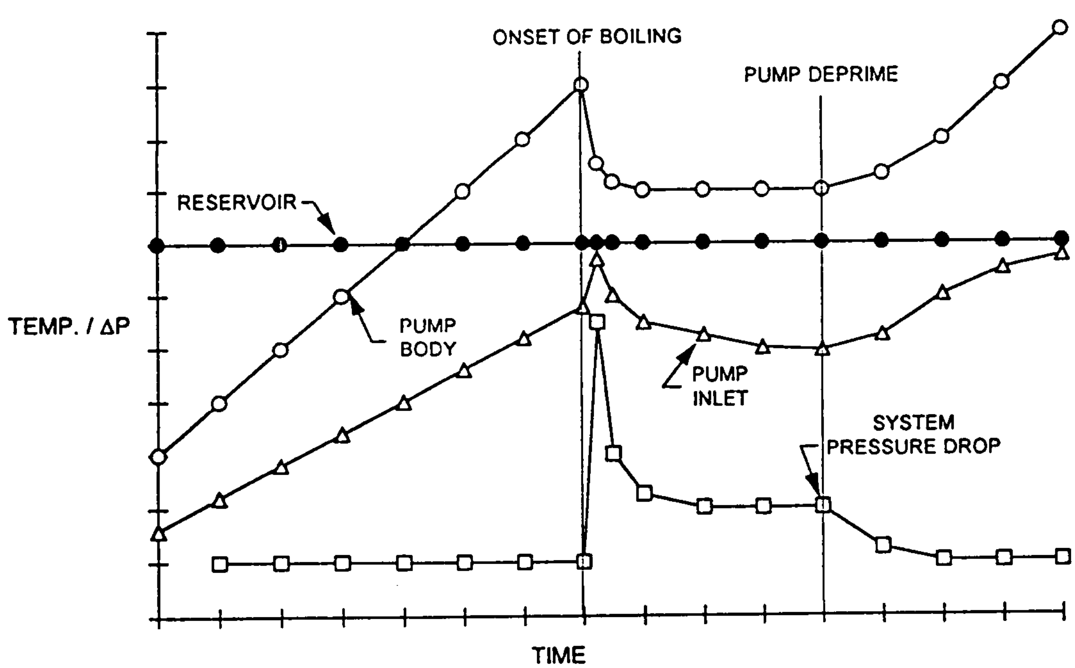


Figure 6

THREE EVAPORATOR PUMP DESIGNS

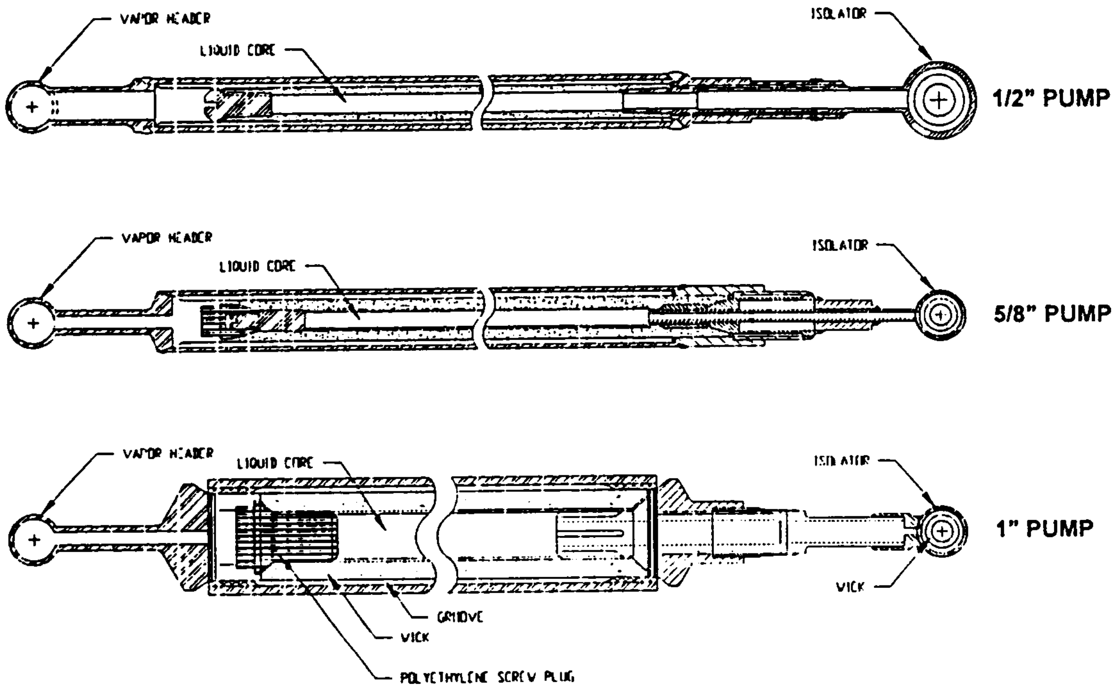


Figure 7

PRESSURE DROP AND TEMPERATURES DURING START-UP WITHOUT SUPERHEAT

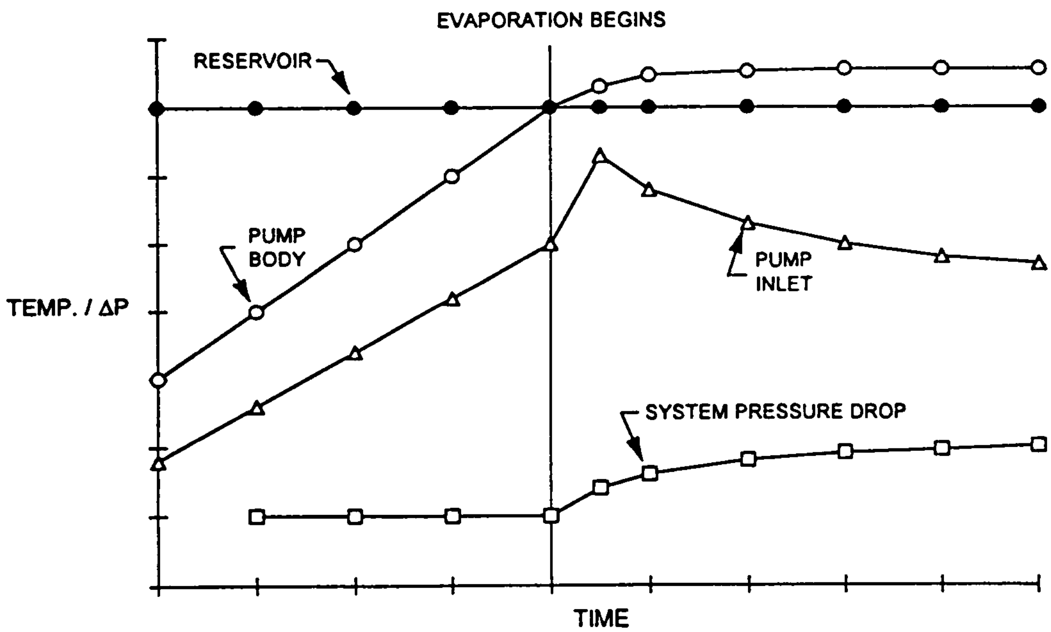


Figure 8

SCHEMATIC OF A CAPILLARY STARTER PUMP

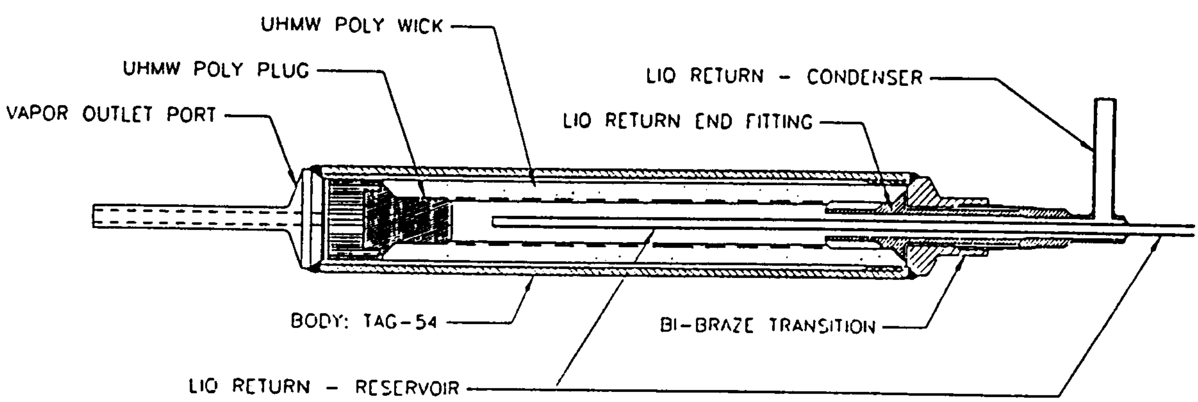


Figure 9

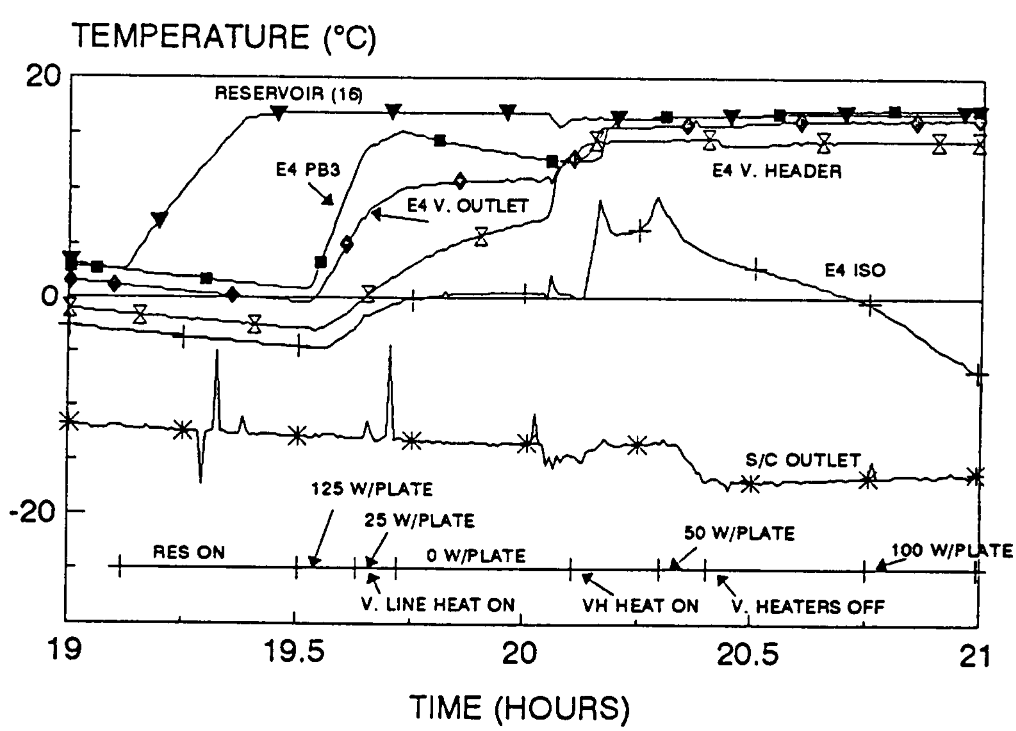


Fig 10: Start-Up #4, Thermal Vacuum

(5/15/93; filter = 5)

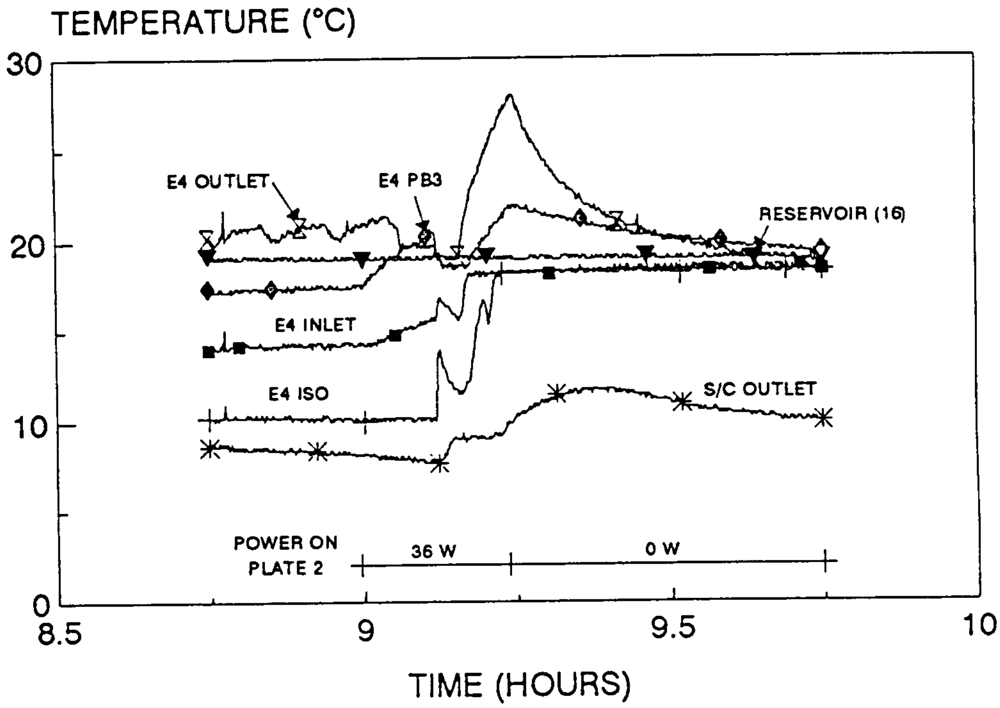


Figure 11: CAPL start-up # 6, FLIGHT
Evaporator #4, failure
(2/4/94, no filter)

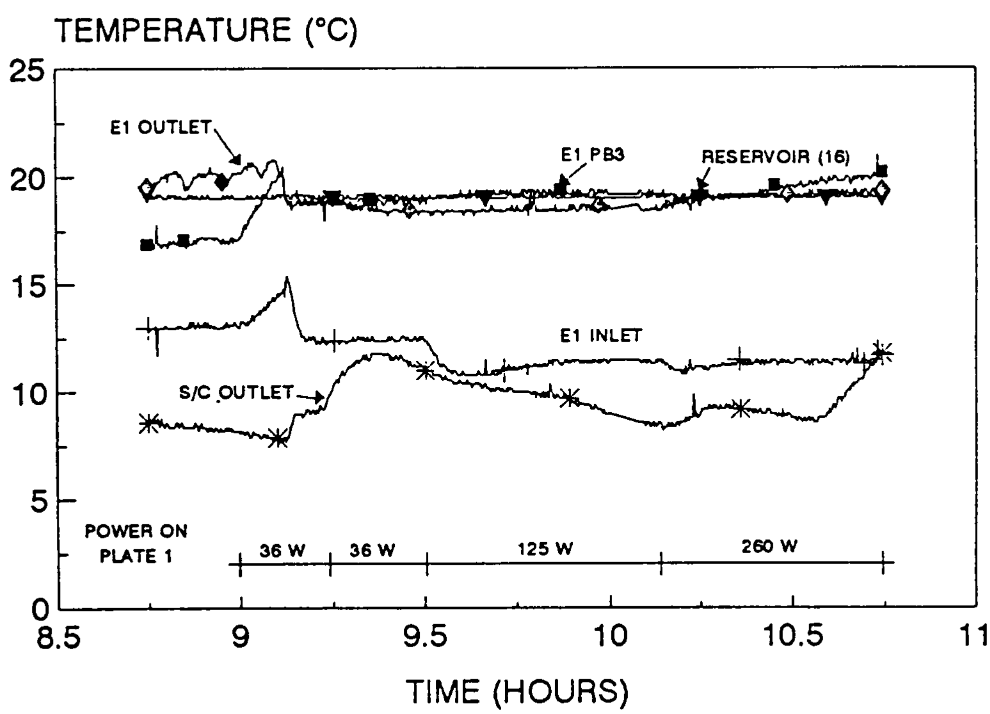


Figure 12: EOS start-up # 6, FLIGHT
Evaporator #1, successful
(2/4/94, filter = 2)

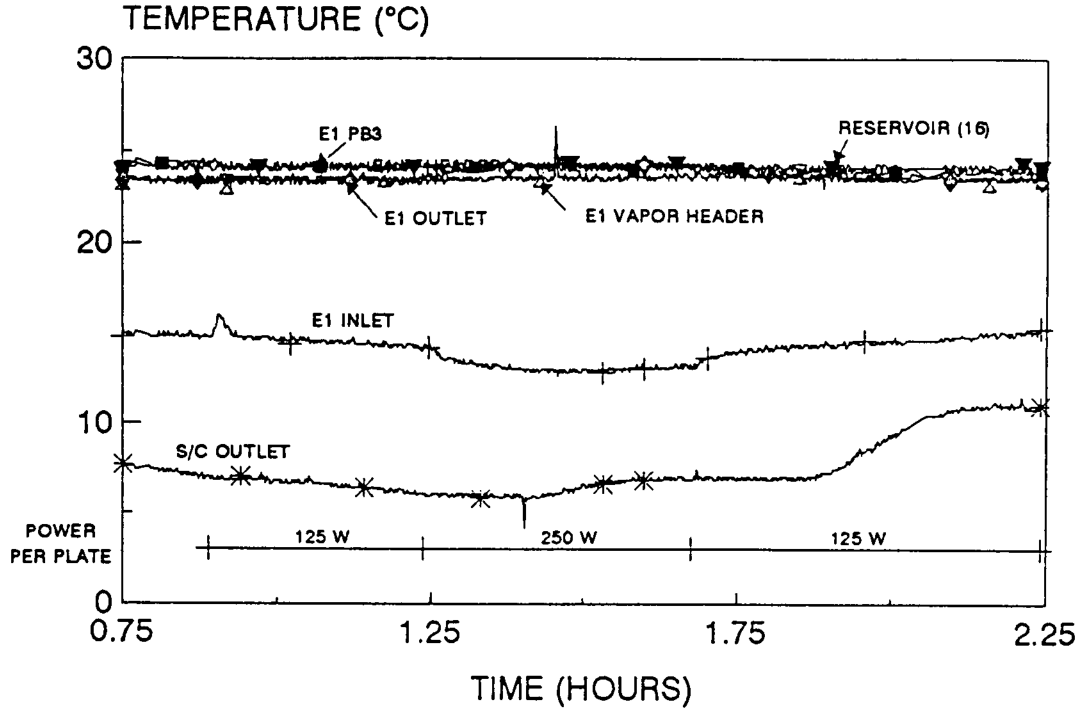


Figure 13: EOS Profile B1 - flight
Evaporator 1, Successful
(2/5/94, no filter)

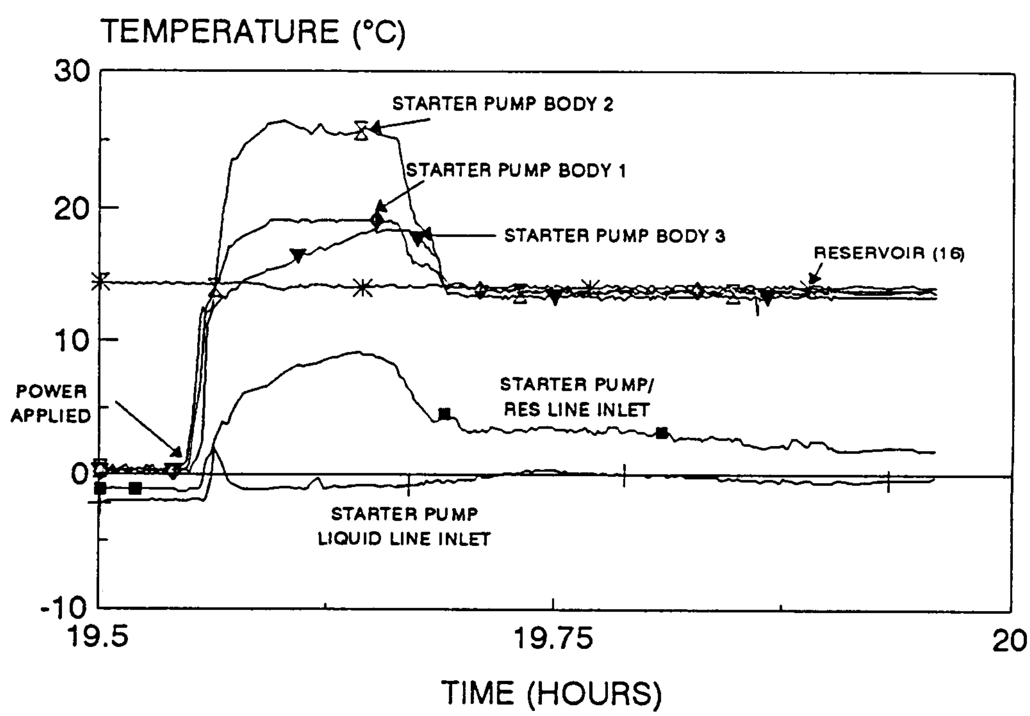
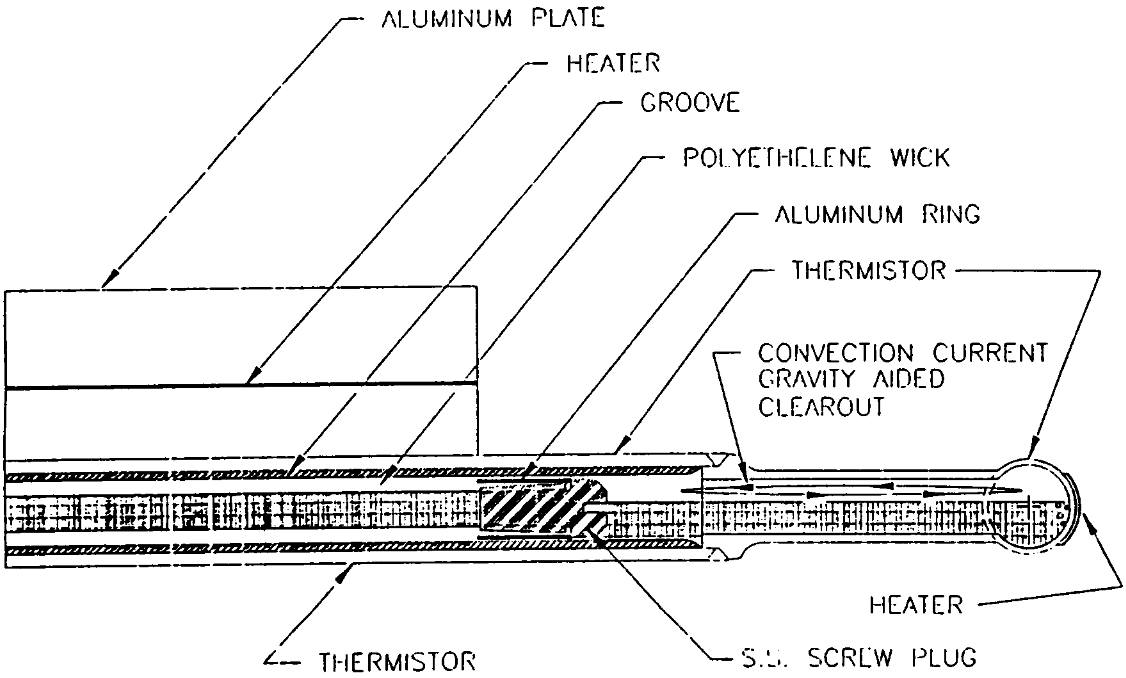


Figure 14: Starter Pump Start-Up - flight
150 W on starter pump
(2/3/94)

GRAVITY INFLUENCED START-UP



START-UP IN MICRO-GRAVITY

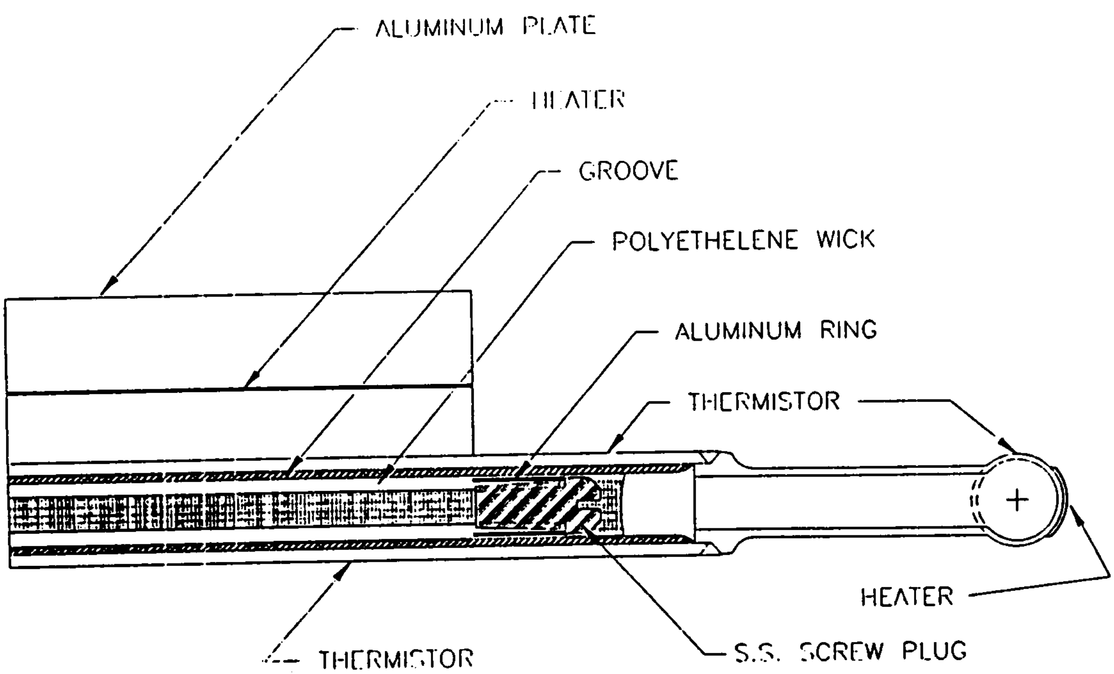
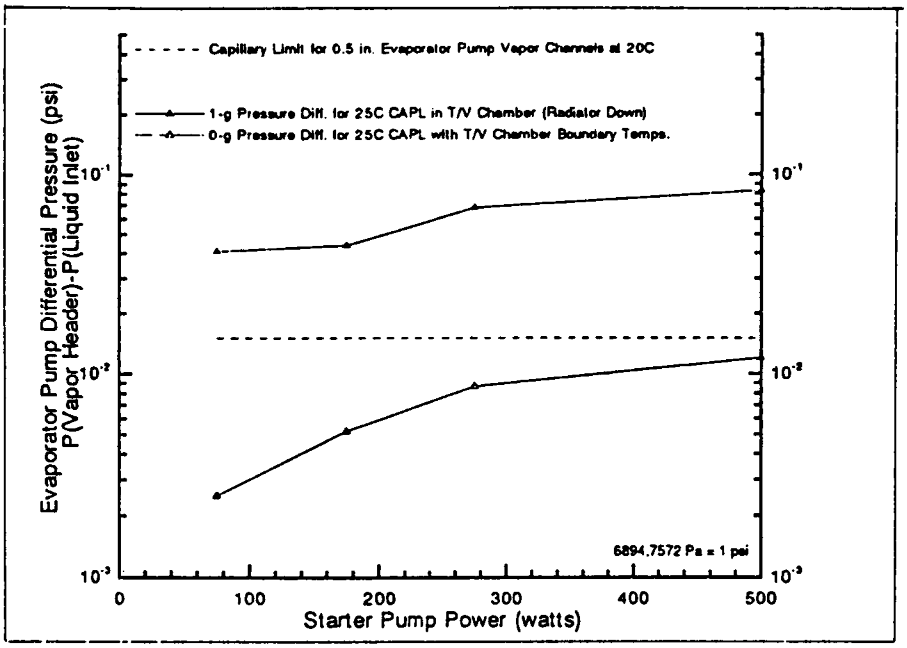


Figure 15



Available CAPL-1 starter pump heater power of ~150 watts is insufficient to clear the evaporator pump vapor channels in 0-g, but is adequate in 1-g.

Figure 16

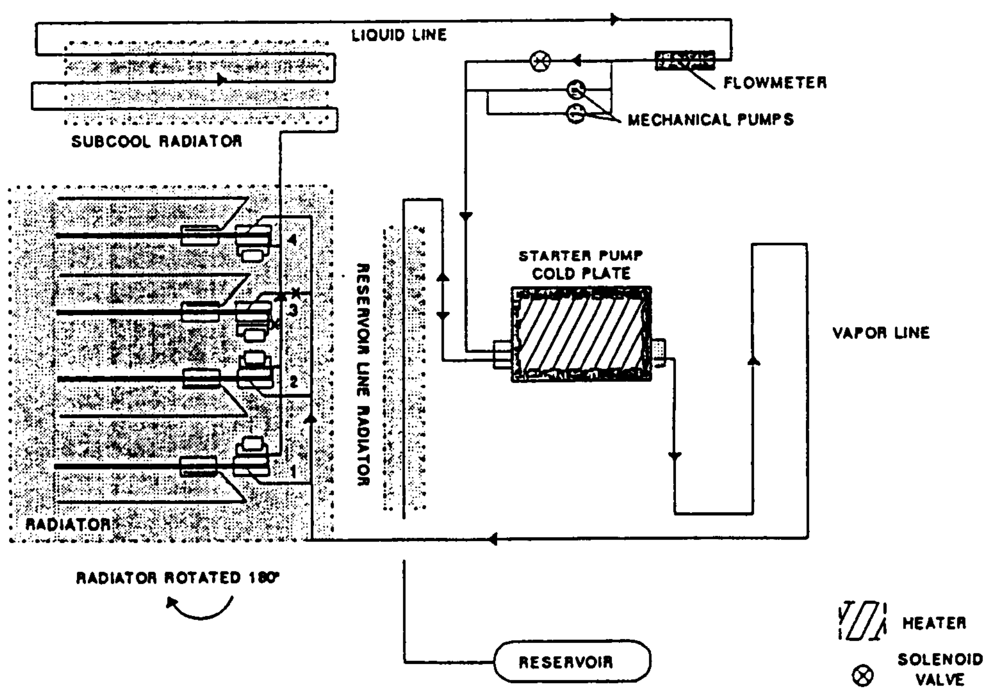


Figure 17

CAPL 2 FLOW SCHEMATIC
STARTER PUMP COLD PLATE