N93-13181

THE CAPILLARY PUMPED LOOP FLIGHT EXPERIMENT (CAPL) A PATHFINDER FOR EOS

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ABSTRACT

The CAPL shuttle flight experiment will provide micro-gravity verification of the prototype capillary pumped loop (CPL) thermal control system for EOS. The design of the experiment is discussed with particular emphasis on the new technology areas in ammonia two-phase reservoir design and heat pipe heat exchanger development. The thermal and hydrodynamic analysis techniques and results are also presented, including pressure losses, fluid flow, and on-orbit heat rejection capability. CAPL experiment results will be presented after the flight, presently planned for 1993.

INTRODUCTION

The enhanced Capillary Pumped Loop Flight Experiment (CAPL) is a follow-on to the initial Capillary Pumped Loop flight experiments described in [1]. The CAPL is a much larger experiment and is designed as a prototype of the Earth Observing System (EOS) instrument thermal control system which is based on capillary pumped two-phase technology. The Capillary Pumped Loop (CPL) utilizes the latent heat of vaporization in a closed thermal control system to transfer large amounts of heat over long distances. Two-phase systems offer significant weight and power savings compared to single phase systems currently in use. The CPL is a completely passive loop in that it has no mechanical moving parts that can wear out or introduce unwanted vibrations to the platform. However, the CPL does have limited pumping capability of approximately 3,450 N/m^2 (0.5 psi), so the system components must be designed for low pressure losses.

Verification of the CPL technology in micro-gravity is required prior to its implementation on the EOS platform. Gravitational effects on pressure losses, heat transfer coefficients, and fluid management must be evaluated and tested. The initial CPL experiment proved that the CPL technology can work in micro-gravity. However, this experiment was only a small scale demonstration of CPL technology and did not address a number of system characteristics inherent with larger systems required for EOS. The CAPL is a full size prototype with features such as long liquid transport lines and heat pipe heat exchangers that were not tested in the first experiment. The CAPL experiment is currently manifested for a shuttle flight in mid-1993. It is being developed by NASA Goddard Space Flight Center with NSI Technology Services Corporation as the prime contractor.

DESCRIPTION OF CAPL EXPERIMENT

A functional schematic for CAPL is illustrated in Figure 1. CAPL employs anhydrous ammonia as its working fluid. The main components of CAPL include two evaporator plates, a capillary starter pump, four heat pipe heat exchanger (HPHX) radiators, a subcooler, transport lines, and a two-phase reservoir. The CAPL components are packaged into the envelope shown in Figure 2. The experiment is mounted on top of a Get Away Special (GAS) bridge assembly through a Mission Peculiar Equipment (MPE) interface structure as depicted in Figure 3. The GAS bridge will be located near the rear bulkhead of the Space Shuttle.

Each of the two evaporator plates are made up by metallurgically bonding two capillary pumps to a rectangular aluminum block as shown in Figure 4. A capillary pump basically consists of an axially grooved aluminum extrusion and an annular porous wick insert [2]. In this controlled experiment, the heat source is simulated by heaters attached on the evaporator surface. Heat conducts into the capillary pumps where it vaporizes the liquid ammonia. The generated vapor travels along the vapor line to four heat exchangers where heat is removed to condense the vapor into saturated liquid. The removal of heat from each heat exchanger is carried out by radiating the heat to space via a heat pipe radiator as shown schematically in Figure 5. The saturated liquid ammonia must pass through a subcooler where heat is removed further to collapse any remaining vapor bubbles coming out of the heat exchangers in order to insure that no vapor could return to the capillary pumps to deprime (or dry out) the wicks inside them. The heat removal from the subcooler is provided by a radiator surface mounted to a portion of the liquid line. The 8 meter long vapor and liquid lines are intended to demonstrate the CPL pumping capability over long distances.

Another major component of CAPL is the two-phase reservoir. The reservoir serves as a storage for the liquid ammonia inside the loop. During the start-up process, heat is applied to the reservoir to vaporize a small amount of its liquid. The pressure building up inside the reservoir forces the remaining liquid out of the reservoir and into the loop. A porous wick structure is placed at the reservoir exit end to prevent vapor from coming out. Nevertheless the liquid coming out of the reservoir must pass through a subcooler, again to insure no vapor could reach the capillary pumps to deprime their wicks. The reservoir is also used to control the saturation temperature (set point) of the loop during operation by maintaining its temperature with heaters and a proportional power controller.

CAPL is currently designed to start-up with a fully flooded loop. That is, all components will be filled with liquid ammonia before the heaters on the evaporator plates can be turned on to commence the loop operation. This start-up method guarantees that the capillary pump wicks will always be primed when heat is applied to the evaporator plates. However, there is a serious problem associated with the fully flooded start-up when the capillary pumps are used to clear the vapor line of liquid ammonia. During the initial boiling of the ammonia inside the capillary pumps, the backflow of superheated liquid from the vapor side to the liquid side of the pumps creates a vapor blockage in the pump liquid inlet which consequently cuts off the liquid supply to the pump wicks and causes them to deprime. To alleviate this problem, a capillary starter pump and vapor line heaters are incorporated in the CAPL design. The capillary starter pump or the vapor line heaters will be used to generate the initial vapor space in the vapor line during the start-up process. Also, a mechanical pump package was added to the CAPL experiment as a backup for start-up operations. It is a small positive displacement, magnetically driven gear pump that is plumbed in parallel along the liquid line (see Figure 6). It is used to force liquid into the capillary pumps to prime the wicks even though there may be vapor bubbles in the liquid inlet of the capillary pumps.

The CAPL experiment employs a variety of instrumentation to evaluate its performance. These include 180 thermistors distributed throughout the experiment, an absolute pressure transducer, and two differential pressure transducers. The absolute pressure transducer measures system pressure in the reservoir while the differential pressure transducers measure pressure losses across the evaporator plates and the vapor line. The experiment also has a thermal flow meter to determine the ammonia mass flow rate.

The CAPL experiment has been designed to emulate the EOS platform thermal control system. Table 1 presents a comparison of the major characteristics of both CAPL and EOS thermal loop, showing the close correlation between the two systems.

Table 1. CAPL vs. EOS Major Characteristics

LATEST EOS	CAPL
30 to 600 Watts	50 to 1,200 Watts
3 to 8 Meter Transport Lines	8 Meter Transport Lines
Fully Flooded	Fully Flooded
1/4" OD Vapor Line	1/2" OD Vapor Line
1/8" OD Liquid Line	1/4" OD Liquid Line
2 Pound Ammonia Charge	4 Pound Ammonia Charge
1/2" OD Capillary Pumps	1/2" OD Capillary Pumps
HPHX Radiator	HPHX Radiator

Design of Two-Phase Reservoir and Heat Pipe/Heat Exchanger Radiators

Three prototypes of different reservoir designs were built and performance tested in a ground based test loop, with one design selected for the CAPL flight unit. The performance requirements for the reservoir include: (i) elimination of vapor expulsion under normal operations, (ii) minimization of exit port pressure drop, (iii) minimization of expulsion time, (iv) ability to control the CPL set point within ±0.5°C, and (v) ability to expel 2,800 cc of liquid ammonia to the loop. Dynatherm Corporation was chosen to build the CAPL flight reservoir based on their prototype design. The flight reservoir consists of a stainless steel cylindrical shell (approximately 8.9 cm in diameter and 66 cm long) and six porous polyethylene tubes which are positioned circumferentially around the reservoir inner surface. These polyethylene tubes extend over the length of the reservoir and are held in place by several layers of wire meshes, which are in turn spot welded to the reservoir inner wall (see Figure 7). The primary function of the tubes is to deliver liquid ammonia from anywhere inside the reservoir to the exit and to the heater zone with minimal flow resistance. Heaters are attached to the outer wall of the reservoir in the heater zone at the opposite end of the exit. Test results have been encouraging with liquid ammonia being pumped out at high adverse tilts. Further information on this reservoir can be found in Reference 7.

The heat pipe/heat exchanger (HPHX) radiator is utilized for CAPL heat rejection instead of a more efficient direct condensation radiator (DCR) due to EOS requirements. Over the multi-year life span of EOS, the probability of a meteoroid hit on a radiator is substantial. A hit on a DCR could result in loss of the entire ammonia charge of the loop and, therefore, loss of the loop operation. With a HPHX radiator, only the affected segment of the radiator is lost, but not the entire loop. Two prototypes of the HPHX designs were built and performance tested in a ground based test loop. The requirements imposed on the HPHX design are: (i) heat exchanger must accept a maximum heat load of 350W with less than 5°C temperature differential between the CPL and the header heat pipe, (ii) header heat pipe must have a minimum heat transport of 430 Watt-meters at 35°C with 0.25cm adverse tilt, (iii) spreader heat pipe must have a minimum heat transport of 180 Watt-meters at 35°C with 0.25cm adverse tilt, (iv) flow regulation must be provided when multiple units are tested in parallel, and (v) must have provisions for non-condensable gas (NCG) collection. OAO Corporation was selected to build the flight HPHX units for the CAPL experiment based on their prototype design. The OAO HPHX employs helical fin heat exchangers [3], 2.86cm OD header heat pipes, and 1.91cm OD spreader heat pipes. The header heat pipes are rated at 711 Watt-meters at 35°C with 0.25cm adverse tilt. The spreader heat pipes are rated at 432 Watt-meters under the same conditions. Heavy walled extrusions were utilized in manufacturing the header heat pipes so that the helical grooves could be cut into the outer surface of the heat pipes to form fluid flow passages for the heat exchangers, i.e. each header heat pipe becomes an integral part of a heat exchanger (see Figure 8). The helical grooves promote annular flow, and consequently the heat transfer coefficient of the heat exchangers will improve in both 1-g and 0-g environments. However, this design does not provide flow regulation when two or more heat exchangers are tested in parallel. To remedy this problem, a stand-alone flow regulator is included in each HPHX unit. The flow regulator is plumbed downstream of a heat exchanger. It is simply a porous polyethylene wick barrier used to prevent vapor from blowing through. It is also designed to collect non-condensible gases which are detrimental to proper operation of the loop. Further information on the HPHX can be found in Reference 8.

System Pressure Drop Analysis

The pumping capability of the CAPL capillary pumps can only extend to the capillary limit of the pump wicks. The maximum capillary limit of a porous medium is proportional to the working fluid surface tension and inversely proportional to the wick pore size. If the system pressure drop exceeds this limit under any operating condition, the wick will not be able to prevent vapor from penetrating into the wick structure to dry it out. The system pressure drop of CAPL during normal steady state operation includes the fictional pressure losses due to (1) vapor flow in the vapor line, (2) two-phase flow in the heat exchangers, (3) liquid flow in the sub-cooler and liquid line, and (4) both liquid and vapor flows in the capillary pumps.

Single-phase and two-phase pressure drop correlations for annular flow were used to compute the pressure losses [4]. The component pressure drops for CAPL operating at maximum power of 1,200W are summarized in Table 2. For a CPL system, the total system pressure drop increases with the amount of heat applied to the evaporator plates. Therefore there is a limit to the maximum power that can be applied to the CAPL evaporator plates, above which the system pressure drop exceeds the capillary limit. Table 2 shows that there is a very large margin in the CAPL pumping capability and the high transport limit for CAPL operation may not be reached in the flight tests.

Table 2. CAPL Pressure Drops

	Pressure Drop (Pa)		
CAPL Components	@10°C	@25°C	@35°C
Vapor Line (1/2" OD)	668	417	312
Liquid Line (1/4" OD)	362	319	294
Cold Plates	87	69	60
Liquid Isolators	183	160	146
HPHX	700	700	700
Thermal Flowmeter	276	276	276
Solenoid Valve	276	276	276
Total Pressure Drop			
- Normal Operation	2,552	2,217	2,064
- One Pump Fails	2,822	2,446	2,270
Capillary Limit	4,723	4,003	3,523
Margin			
- Normal Operation	1.85	1.80	1.70
- One Pump Fails	1.67	1.63	1.55

Fluid Flow and Thermal Analyses for CAPL in Orbit

The two-phase fluid flow in CAPL is, by itself, a complicated hydrodynamic problem. When coupled with another complex thermal system of the Space Shuttle environment via the capillary pumps, HPHX radiators, reservoir, and subcooler, it is almost impossible to simulate the experiment transient behaviors in orbit efficiently with any available analytical tool. The transient of the CAPL fluid flow is caused by two main forcing functions: (i) variation in power profile to the evaporator plates, and (ii) variation in ambient conditions which change constantly with the Space Shuttle position in orbit. Simplifications must be made with regard to the analytical model of CAPL if there is any hope to simulate the CAPL behavior within a reasonable amount of computing time. The transient hydrodynamics of a CPL system is very explosive and very important to a CPL designer during the "clearing of liquid in vapor line" event of the start-up process [5]. This event lasts less than 5 minutes for CAPL. Therefore, the Space Shuttle thermal environment is assumed to remain unchanged during this period. On the other hand, once the system gets started the hydrodynamic event responds almost instantaneously with the forcing functions, i.e. the time constant for the hydrodynamic system is much smaller than that of the thermal environment. The fluid flow is assumed to reach a quasi-steady state from one computational time step to the next. The fluid flow and thermal analyses of CAPL are provided by two computer models - a transient model for the start-up process and a quasi-steady state model for on-orbit operation.

Transient Fluid Flow Model

As mentioned before, the CAPL experiment is designed to start up with a fully flooded system. The vapor line is initially filled with liquid ammonia. The capillary starter pump will be used to clear liquid in the vapor line and return it to the reservoir. As heat is applied to the starter pump, the pump body begins to heat up but nothing happens until its temperature exceeds the loop saturation temperature, at which time vapor starts to be generated. Due to the large amount of liquid in the vapor line, the pressure in the starter pump outlet must increase high enough to displace a large liquid flow rate to the reservoir. The liquid flow rate to the reservoir is equal to the rate at which vapor is generated in the starter pump times the liquid to vapor density ratio. Therefore there is a limit to how much heat can be applied to the starter pump so that the pressure rise in the pump will not deprime its wick. A SINDA85/FLUINT model was used to study the hydrodynamic transients of the CAPL start-up with the capillary starter pump. The results in Figure 9 show the maximum allowable power level of 250W for the starter pump during the start-up process.

Quasi-Steady Fluid Flow / Transient Thermal Model

When the capillary starter pump completes the liquid purge in the vapor line, heaters on the evaporator plates will be turned on to commence the CPL operation. The liquid-vapor interface of the loop is confined in the heat exchangers. A change in power input to the evaporator plates and/or a variation in ambient conditions will cause the liquid-vapor interface to move forward or backward inside the heat exchangers. Due to large thermal masses of the evaporator plates and the HPHX radiators, sudden changes in power input or ambient condition will not cause an instantaneous increase or decrease in the mass flow rate in the loop. Hence the hydrodynamic transients become negligible in this case. Because the mass flow rate inside CAPL is very small and the rate of change of fluid mass flow rate is gradual, the fluid inertial effects were neglected. As a result, the fluid flow in the vapor phase can be assumed to be incompressible which leads to simplified energy and mass conservation equations.

A SINDA model was used to simulate the fluid flow in orbit. Correlations for two-phase flow pressure drop and heat transfer were utilized to determine the film coefficient between the fluid nodes and their thermal environment counterparts.

Heat Rejection Capability of CAPL Radiators / Radiator Model

There are wicks at both ends of the vapor line, capillary pump wicks at one end and flow regulator wicks at the other. Even though the high transport limit for CAPL may not be reached in flight tests at the maximum available power level, the capillary limit of the capillary pumps can still be exceeded if the heat exchangers cannot condense as much vapor as the pumps generate. The maximum heat rejection of the CAPL radiators depends on the Space Shuttle orientation, and the loop saturation temperature. The CAPL radiators consist of four 39cm x 254cm panels facing the same orientation in orbit. Each panel is used to remove heat from a heat exchanger.

A SINDA model was developed to study the performance of the CAPL radiator for different loop set points in various Shuttle orientations. The model was intended to determine the maximum power which CAPL can operate, either continuously or for some period of time in a particular orientation. The heat pipe conductances were provided by ground tests. The radiation couplings between the radiator panels and the environment nodes were computed by a TRASYS model [6]. Figure 10 shows the maximum heat rejection capability of the CAPL radiators when the experiment is in the bay-to-deep-space orientation.

CONCLUSION

Results have shown that CAPL can operate continuously at 1,200W in the bay-to-deep-space orientation and about 600W in the bay-to-earth orientation for at least 45 minutes. Sixteen 3 hour test cycles are requested for the CAPL flight experiment, four of which will be in the bay-to-deep-space orientation. Various power profiles and temperature set points will be tested. The CAPL experiment is currently manifested on STS-60 with a launch date of October 1993.

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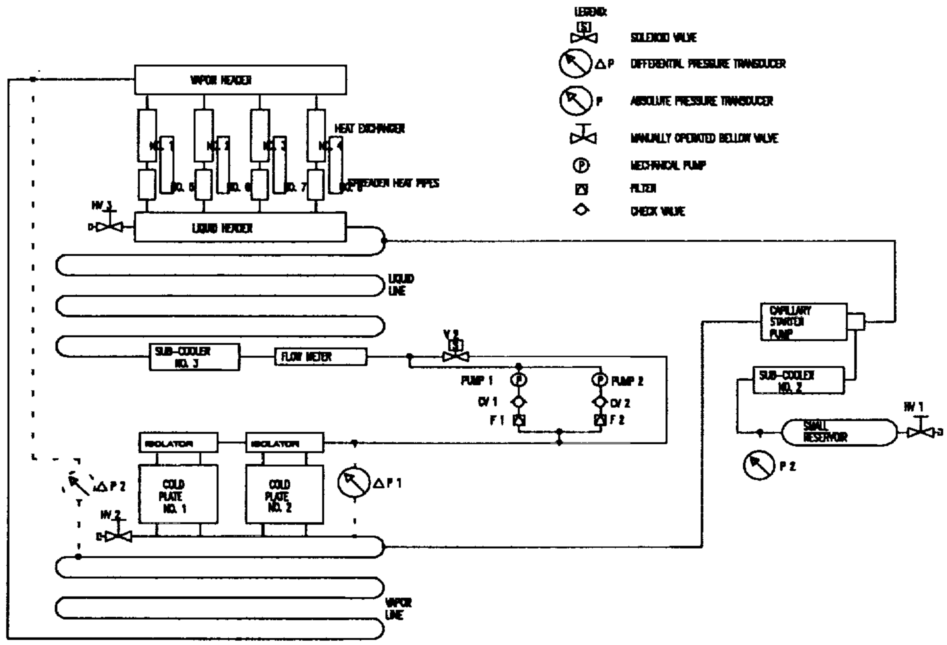


Figure 1. CAPL Functional Schematic

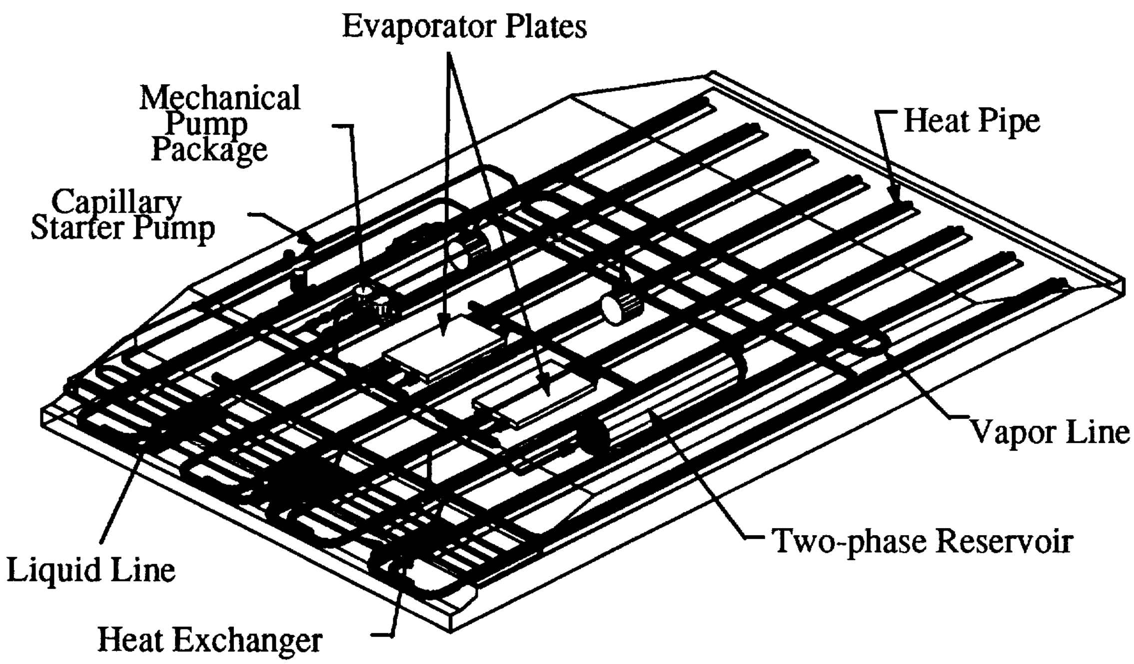


Figure 2. CAPL Flight Experiment

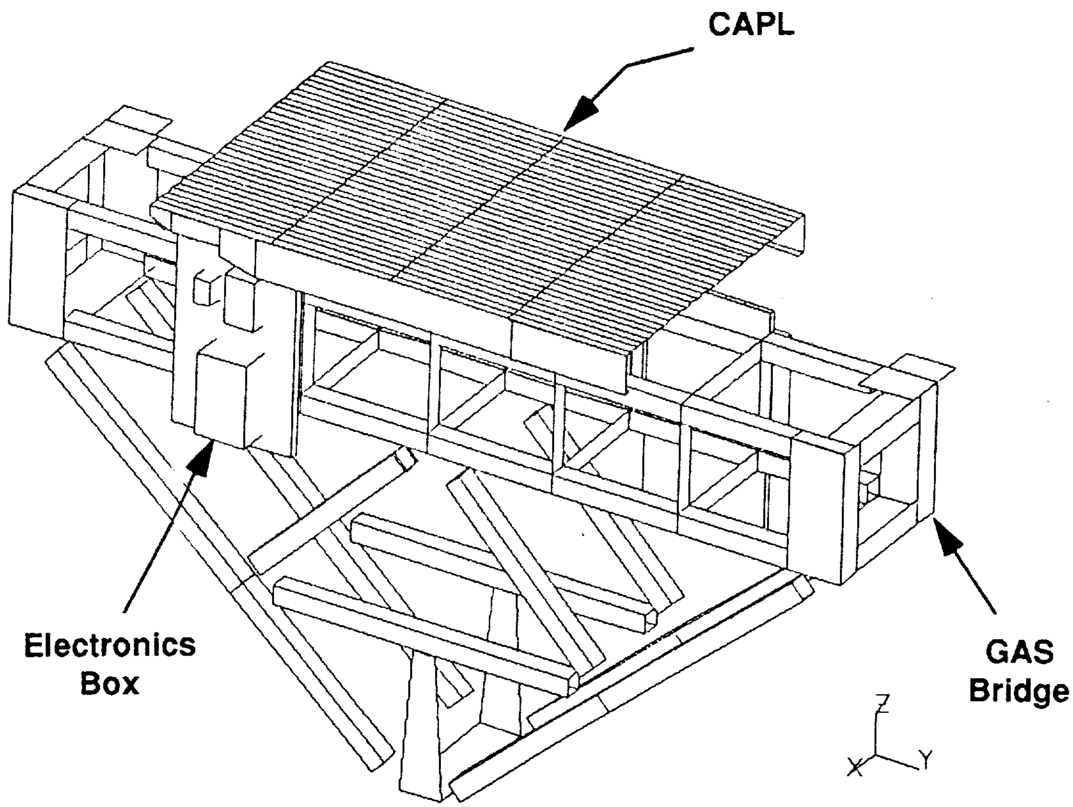


Figure 3

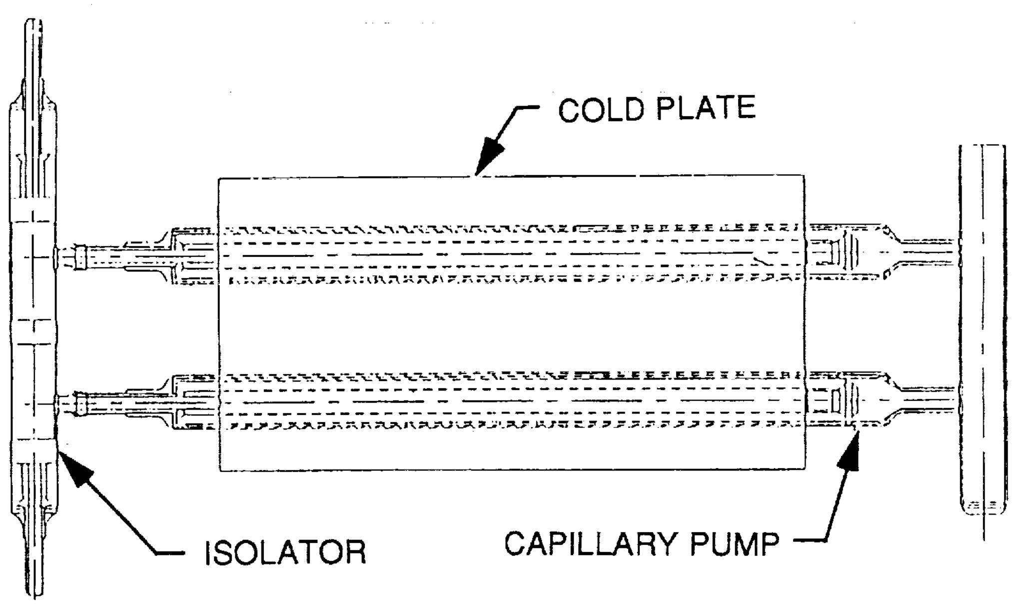


Figure 4

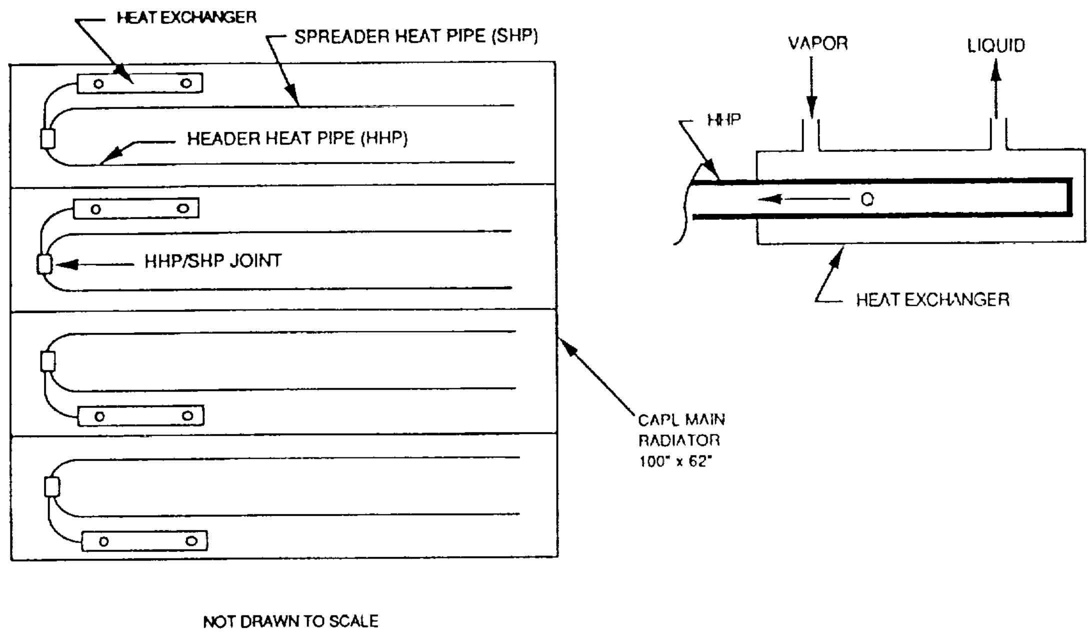


Figure 5

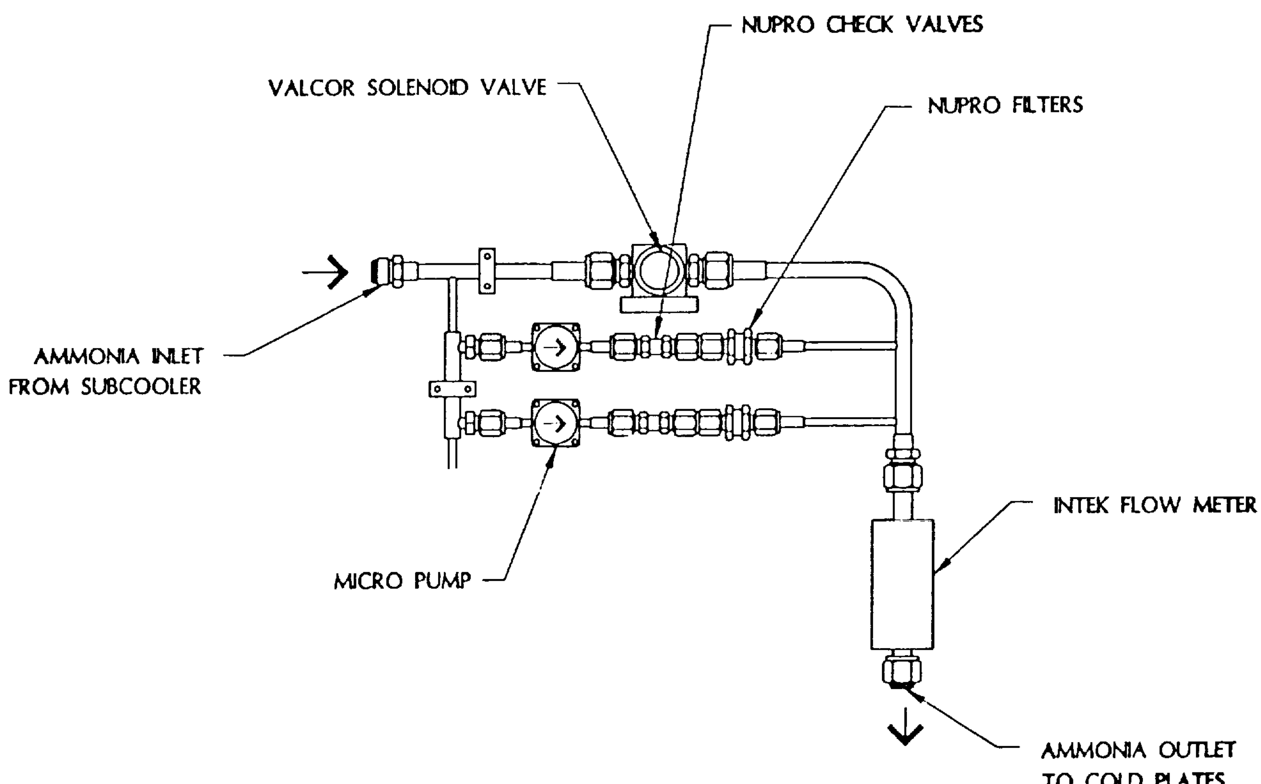


Figure 6

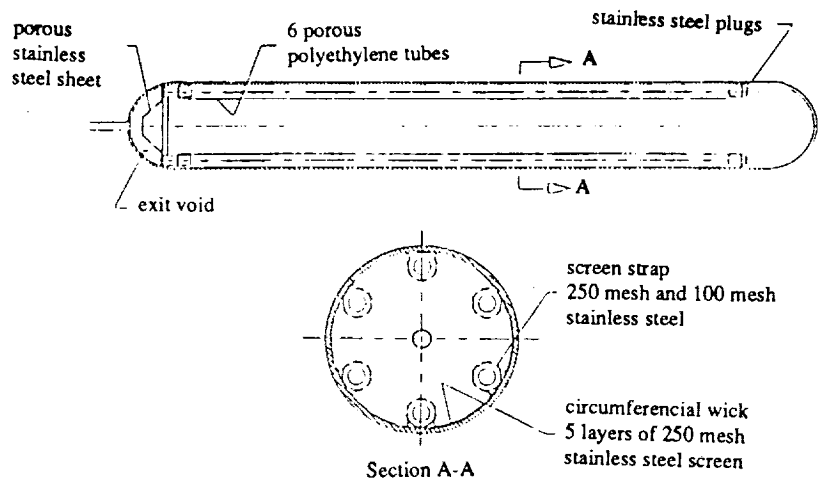
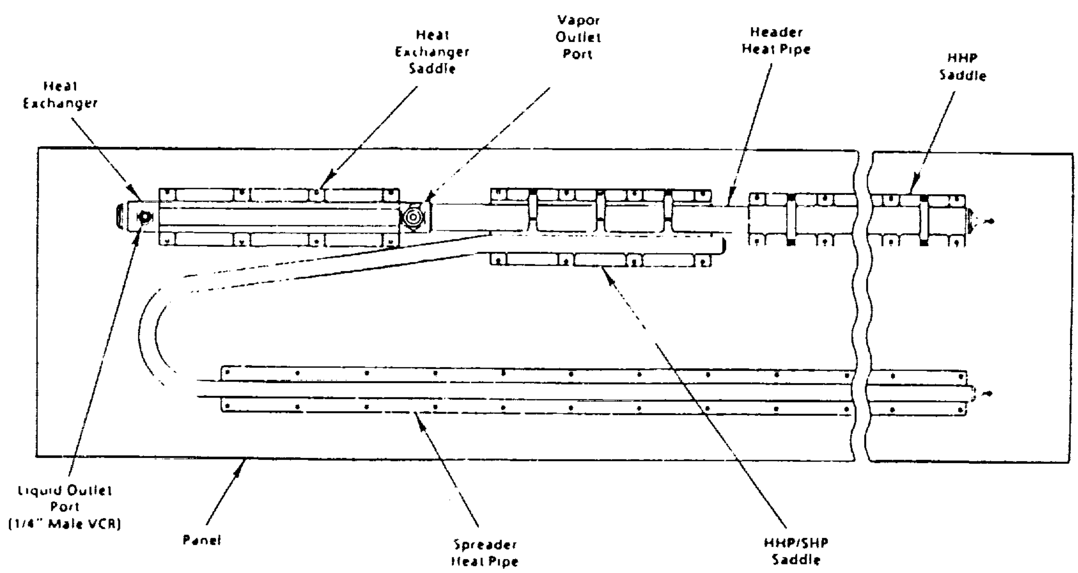
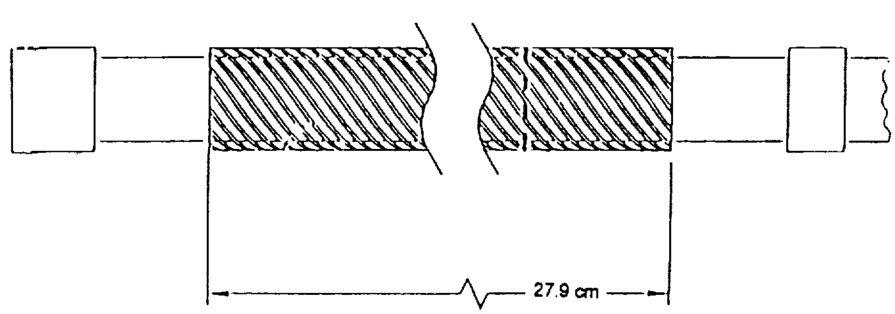


Figure 7



OAO HPHX Layout



OAO Heat Exchanger Design

Figure 8

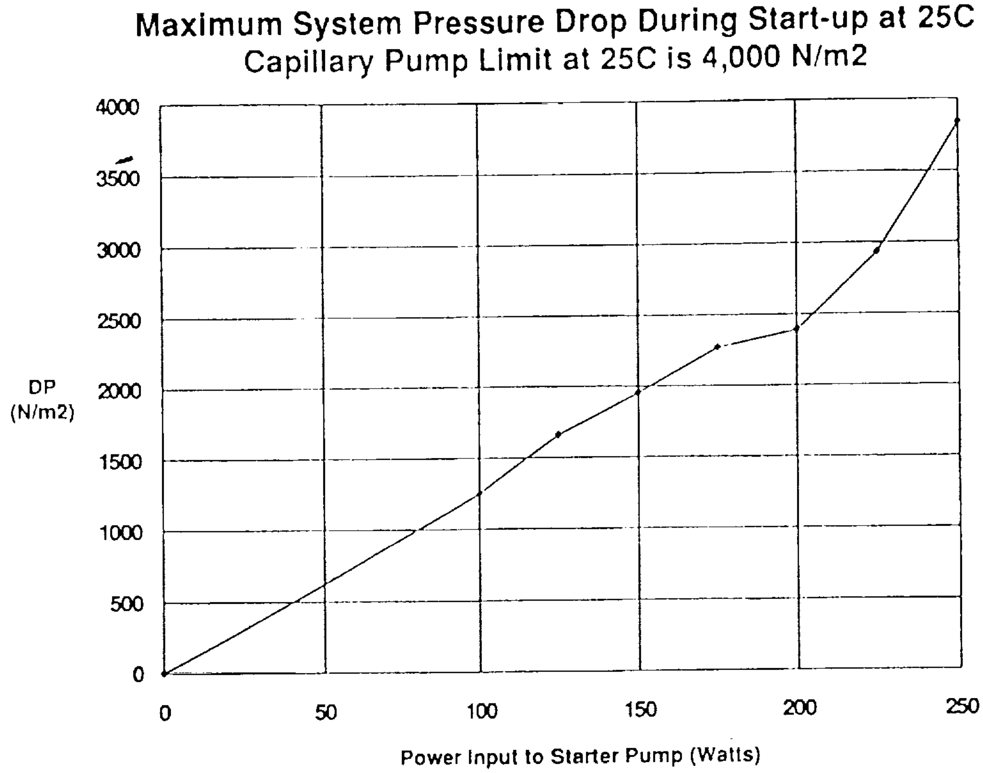


Figure 9

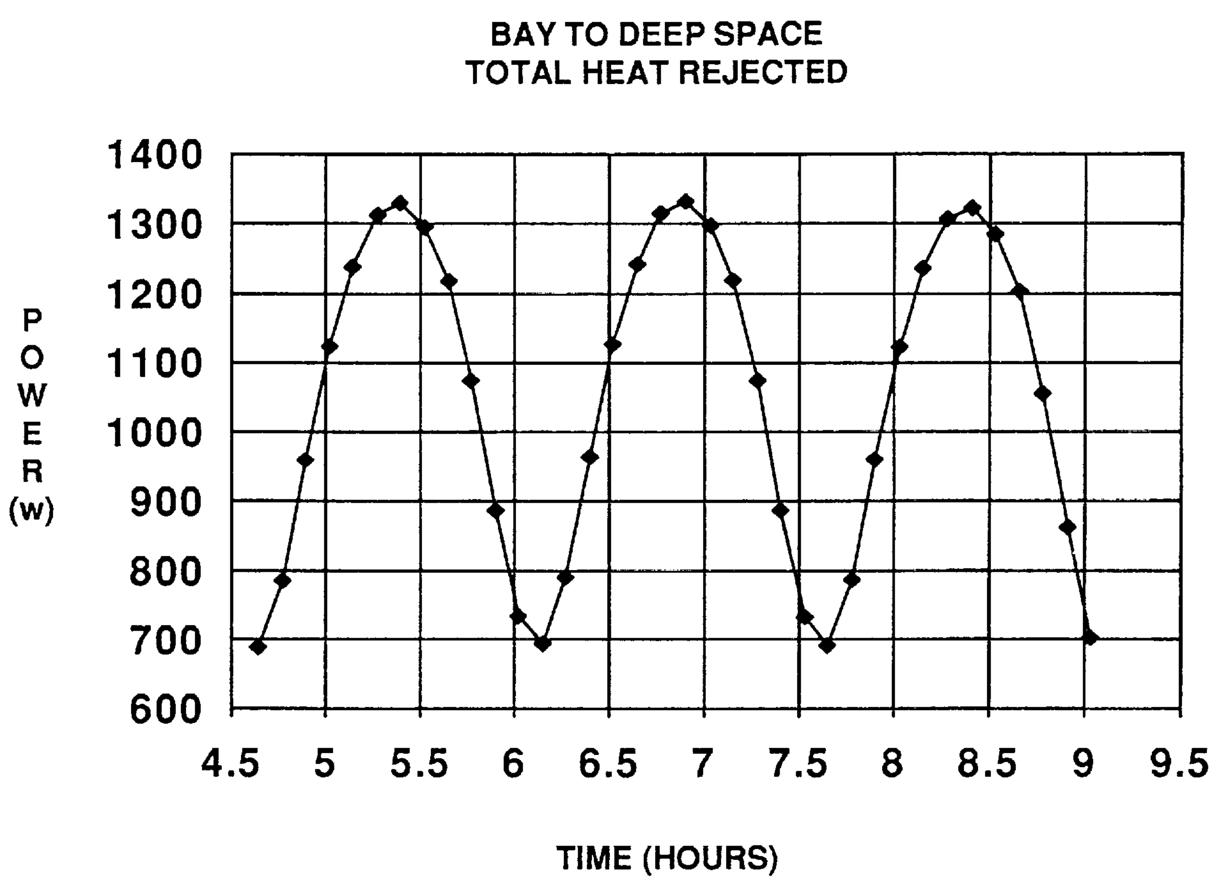


Figure 10