STEADY STATE ANALYSIS OF A CAPILLARY PUMPED LOOP

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DEDICATION

I would like to dedicate this work to my wife, Elizabeth, who has always supported me in everything that I do. I would also like to dedicate this to my mother and father for giving me the guidance to come this far.

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THESIS

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ABSTRACT

A steady state thermal and pressure drop model for a capillary pumped loop (CPL) was created in an effort to begin the characterization of the Capillary Pumped Loop Testbed at Phillips Laboratory. This model is an adaptation of an existing model for the loop heat pipe (LHP), and serves to calculate flow rates, temperatures, thermodynamic fluid conditions, and pressure drops throughout the system. The developed model can accommodate one or two evaporators and one condenser. Comparison to measured data from the testbed shows the model as a satisfactory prediction tool for temperature distribution, but fails to adequately predict the pressure drops encountered in the system. Recommendations are given to further analyze the heat transfer conductances in the evaporator and condenser using a more sophisticated calculation and model, and include a more sophisticated model of the pressure drop mechanisms. Also, further modeling of the influence and control of the reservoir is recommended.

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FIGURES

FIGURES, Cont.

Chapter 1

Introduction

This thesis is an effort to characterize the steady state operation of the capillary pumped loop (CPL) testbed at Phillips Laboratory, Kirtland Air Force Base, NM. The scope of the work here is to characterize two different configurations of the testbed to form a basis for developing a full characterization of the testbed in all possible steady state configurations. The model that is used is based on an existing model for a looped heat pipe (LHP), which is a thermodynamically similar device to the CPL.

The specific objectives of this work are reflected in each section. In Chapter 2 an overview of capillary pumped loop technology, as used in space applications, by generally describing the operation and uses of the technology. In Chapter 3, analytical equations are developed for the capillary loop thermodynamic operation, pressure drops, and heat transfer. This includes analysis in each particular section of the loop and generating equations for the CPL model. In Chapter 4, some examples of calculations are shown. In Chapter 5, the testing and the experimental testbed is discussed. The predicted data, based on the inputs to the experimental testbed, is then compared to experimental data gathered in the laboratory in Chapter 6. In Chapter 7, conclusions are drawn for improving the model.

Chapter 2

Capillary Pumped Loop Technology

The capillary pumped loop, or CPL, is used on spacecraft as a "thermal bus." A thermal bus is a closed system with the following elements: a heat acquisition device, a heat radiator or sink, a transport lines between the acquisition device and the radiator (sink), and an operation control devices (Faghri 1995). This bus is able to conductively acquire waste heat produced by the spacecraft and transport it to a location where the heat can be radiated to space. These thermal buses are required to transport up to 25kW of heat in certain applications. Favorable characteristics of a thermal bus are: high conductivity, flexibility, ease of integration, ground testability, low cost, low weight, and simplicity of design to name a few.

The capillary pumped loop (CPL) is very similar to its cousin technology, the heat pipe. Heat pipes are commonly used in current spacecraft designs for their excellent conductivity, but due to the design and operation of the heat pipe, there are difficulties in testing the device in a gravitational field and, due to its rigidity, the device presents limited configurations for integration into a spacecraft thermal bus.

The capillary pumped loop is a closed, two-phase device. Basically, the heat absorbed by the heat acquisition device, or evaporator, transfers heat to the working fluid through the latent heat of vaporization (Faghri 1995). The working vapor then carries the energy down the vapor transport lines to the radiator / sink, or condenser, and the energy

is transferred to the sink. The now condensed fluid is then transported to the evaporator by the capillary pumping of the evaporator wick. The working fluid in the loop remains close to the saturation temperature and pressure due to the control of a fluid reservoir. This temperature controlled reservoir of fluid and vapor is used to pressure prime and control the saturation temperature / pressure within the loop. A common configuration can be seen in Figure 2.1, below.

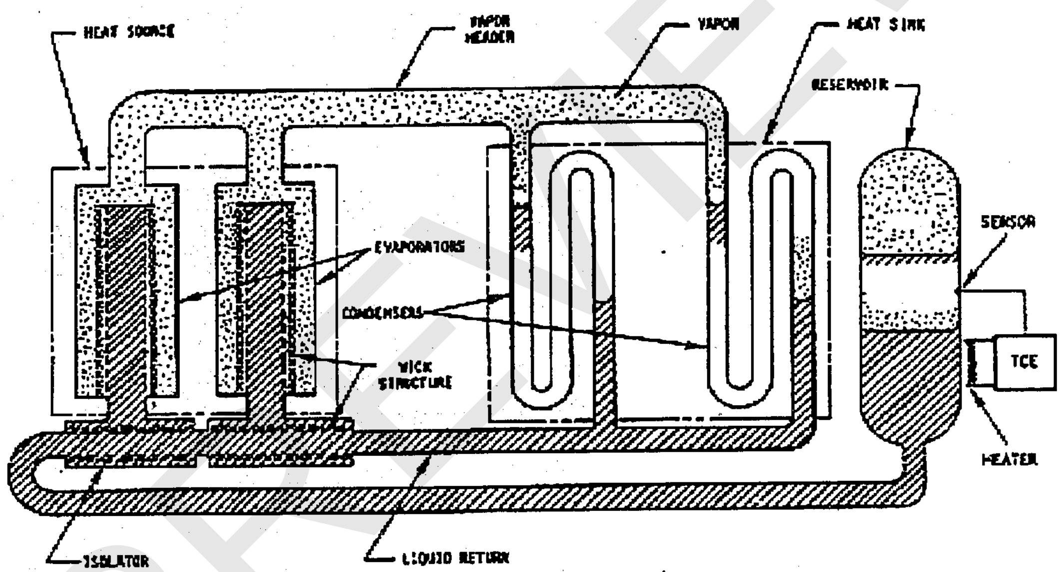

Figure 2.1 *CPL Configuration*

The CPL test bed within our laboratory also has a non-condensable gas trap, which is located in the liquid line after the condenser. Near the evaporator, in the liquid line, is an isolator that prevents vapor from back flowing from the evaporator into the liquid line.

The CPL evaporator transfers the heat to the working fluid and the liquid is vaporized with a very small temperature change (Faghri 1995). The minimum mass flow rate through the system is defined as:

$$\dot{m} = \frac{Q}{h_{fg}} \qquad [2.1]$$

This is the total heat flow through the system divided by the latent heat of vaporization. The capillary pumping pressure that a CPL wick can develop is expressed as (Buchlin and Tinari 1988):

$$\Delta P_{cap} = \frac{2\sigma \cos\theta_c}{r_c} \qquad [2.2]$$

This equation shows that the pumping pressure is dependent on the surface tension of the fluid, the effective pumping radius of the wick, and the liquid-solid contact angle (used if there is tilt from the horizontal in the evaporator).

The working fluid will only flow if the capillary pumping pressure developed by the passive surface tension in the evaporator wick exceeds the total pressure drops accumulated in the loop (Buchlin and Tinari 1988). This idea can be expressed as (Ku 1993):

$$\Delta P_{cap} \geq \Delta P_{evap} + \Delta P_{cond} + \Delta P_{vap} + \Delta P_{liq} + \Delta P_{g} \qquad [2.3]$$

The CPL has many useful characteristics that enhance its use as a thermal transport device. One of these advantages is having one directional flow, thus producing a diode

heat transfer effect (Faghri 1995). This is an extremely useful characteristic for a spacecraft thermal bus by ensuring the heat flow is away from the spacecraft payloads to the radiator. The CPL also exhibits variable conductance by utilizing the excess liquid storage in the reservoir. This is true because the reservoir exists is a state of pressure balance between the saturation pressure in the reservoir and the fluid pressure in the CPL (Faghri 1995). Any change in the operating conditions in the loop will cause a change in the saturation pressure in the reservoir and a resulting flow of fluid, into or out of the reservoir, to restore the pressure balance within the loop. The fluid flow into or out of the reservoir causes the condenser area exposed to the vapor to automatically adjust, therefore controlling the condensation heat transfer (Ku 1994). The reservoir is maintained at a specific temperature by electronic control of a heater which must be cycled on and off to maintain the set point (Ku 1994).

The CPL pressure - temperature diagram is depicted in Figure 2.2 (Ku 1994, fig. 5). Point 1 is located in the evaporator, where the fluid is vaporized at the saturation temperature, T(1), and at pressure P(1). The vapor flows through the vapor channels in the evaporator and drops to pressure P(2) near the end of the evaporator. When the vapor leaves the evaporator, it is superheated at T(2'). As the vapor travels down the vapor line, it will drop in temperature and pressure to T(3) and P(3), just before it enters the condenser. The vapor will cool inside of the condenser and drop slightly in pressure. When the fluid is cooled to the local saturation temperature and pressure it is now at

point 4, with T(4) and P(4). The vapor is condensed from point 4 to 5, where at point 5 it is completely liquid. Between points 4 and 5 is the two phase portion of the condenser, and is called the "subcooler" or the "inactive condenser." From point 5 to 6 to 7, the liquid is subcooled. Point 7 to 8 is the liquid transport section. Point 8' represents the local saturation state for point 8. The liquid is superheated inside of the wick until it reaches the meniscus, where it is vaporized. This is point 9, at temperature T(1) (Ku 1994).

Points 11 and 12 represent the entrance line to the reservoir and the reservoir itself, respectively. Point 12 represents the saturation state inside of the reservoir, which sets the condensation temperature at point 4. This is accomplished because the pressure difference between point 4 and 12 is only due to hydrostatic and flow losses. Thus setting the saturation state at point 12, the reservoir, one can control the vapor condensation temperature at point 4 (Ku 1994).

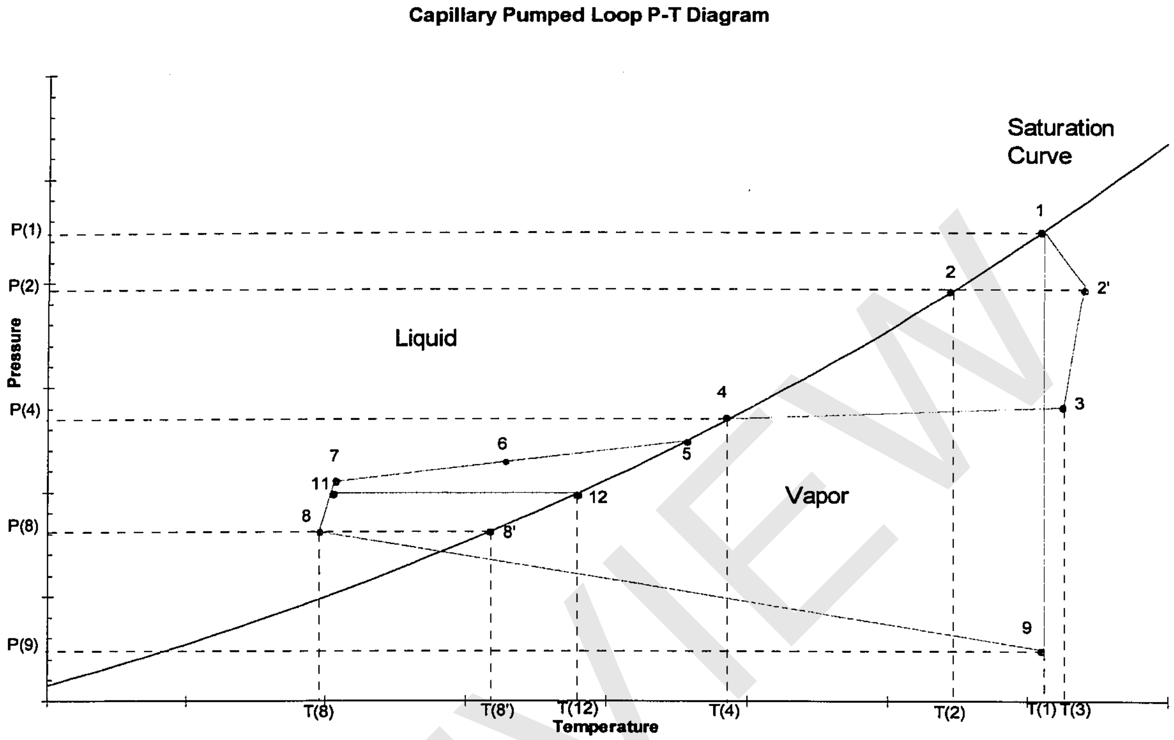

Figure 2.2 *CPL P-T Diagram*

The CPL temperature - entropy diagram is shown in Figure 2.3 (Ku 1994, fig. 3). The points shown on the TS diagram correspond to the points in the PT diagram. The reservoir is represented, once again, by point 12.

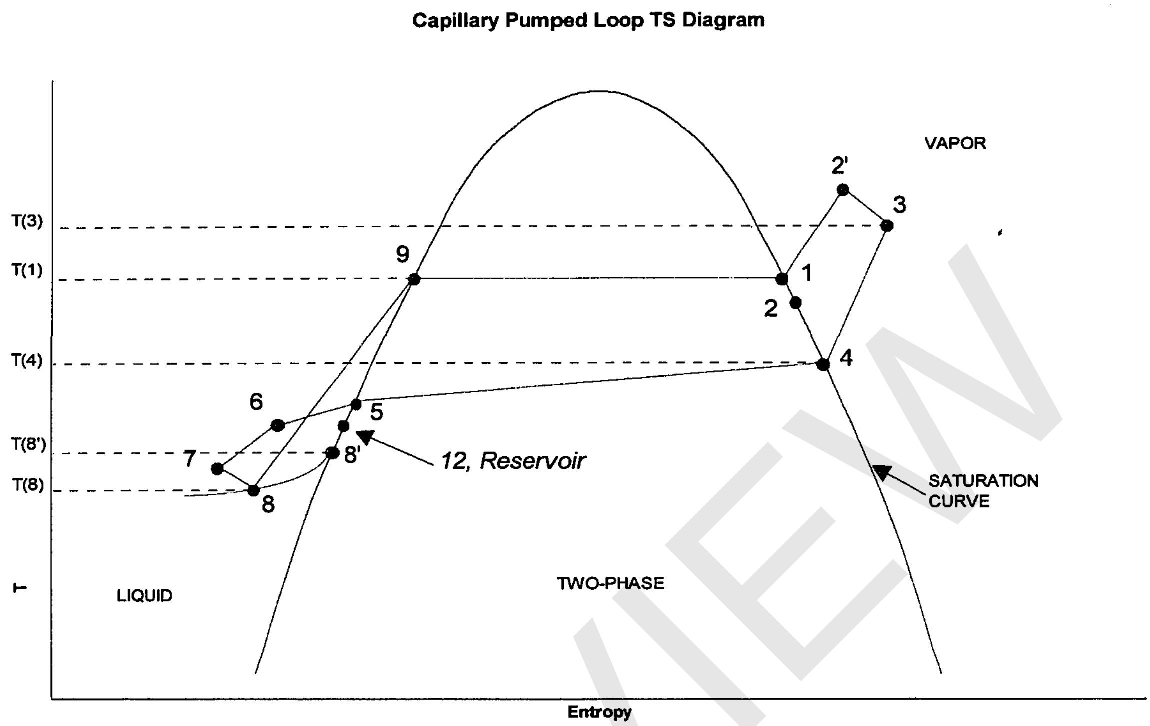

Figure 2.3 *CPL T-S Diagram*

Each section of the CPL has particular operating characteristics and contributions to the CPL. The CPL evaporator is the device in the loop which acquires the heat and provides the capillary pumping for the loop. The particular design of the evaporator used in the Phillips Laboratory testbed is an axially grooved 6063-T6 aluminum extrusion with a top and bottom plate. The wick is an ultrahigh molecular weight polyethylene fiber with 15 micron pores. The active length of the evaporator used is 0.381 meters (Gluck and Kaylor 1996). The working fluid enters the core of the wick and radiates outward to the vapor groove interface where it undergoes a phase change to vapor across the meniscus. This can be seen in Figure 2.4, section A. The axial groove fins are in

direct contact with the wick and the working fluid, and can be seen in the same figure, detail A.

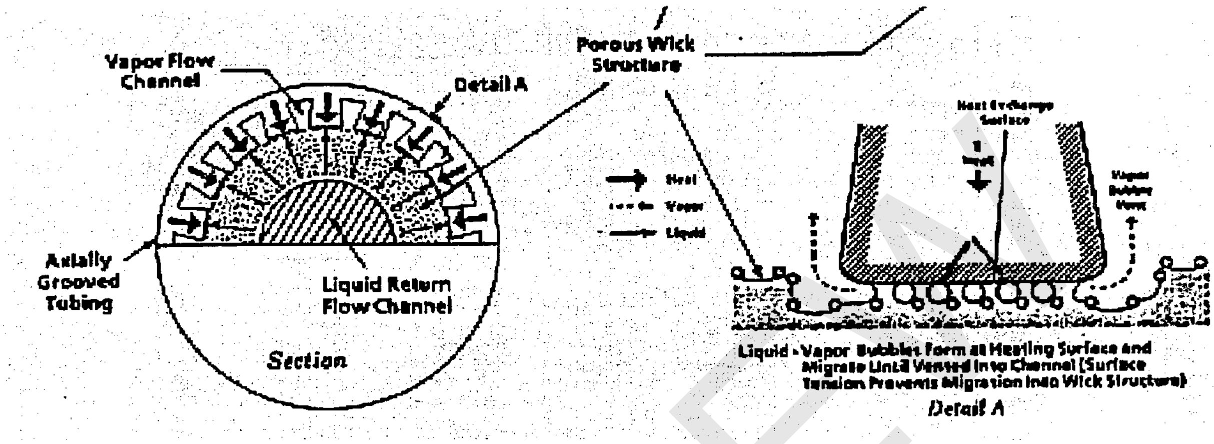

Figure 2.4 *CPL Evaporator Section*

A drawing of an evaporator similar to the one used in the CPL test bed can be seen in Figure 2.5.

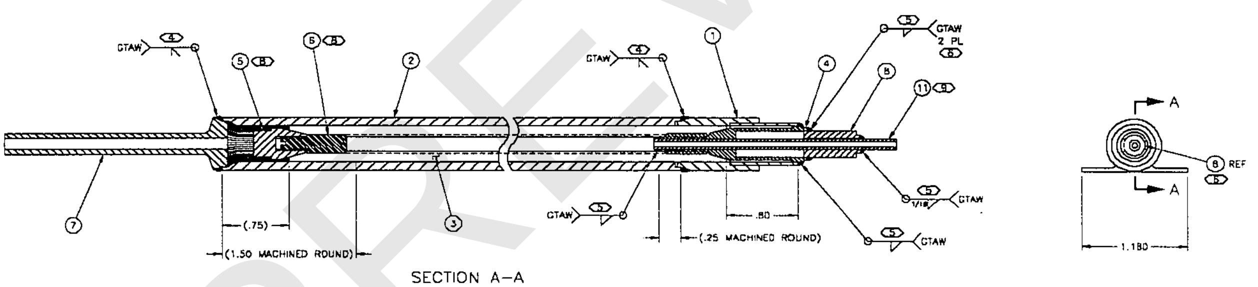

Figure 2.5 *CPL Evaporator Pump*

The term “dryout limit”, in CPL technology, refers to the maximum heat flux into the evaporator without forming vapor through the wick and into the liquid core of the evaporator and “drying out” the wick, thus de-priming the evaporator. An example of this can be seen in Figure 2.6.

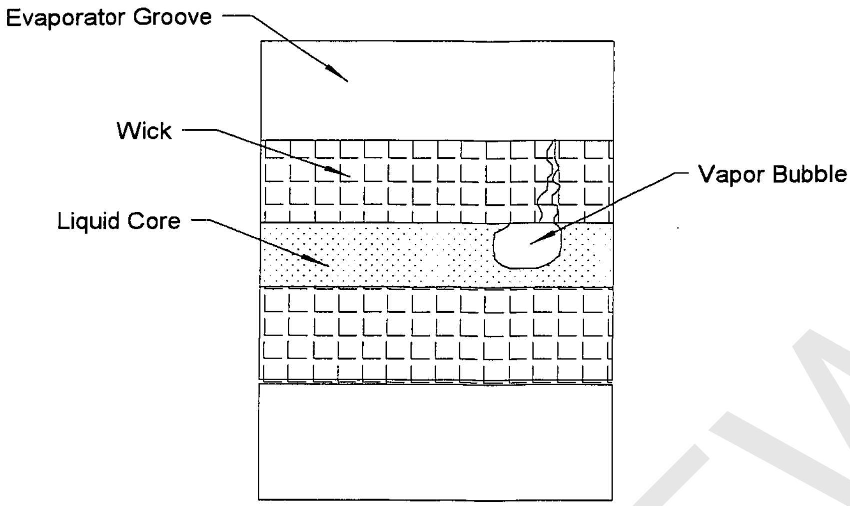

Figure 2.6 *Evaporator Cross Section Showing Wick Dryout*

The transport section used in the testbed is smooth walled stainless steel tubing, with an electropolish finish less than 0.6096 micrometer RMS to minimize the fluid flow pressure drop. The vapor line is 0.0127 m OD and 0.0102 m ID, the liquid line is 0.00635 m OD and 0.004572 m ID. The lines also have various valves and bends that contribute to the overall pressure drop (Gluck and Kaylor 1996).

The condenser used in the Phillips Laboratory testbed consists of two condensers, in parallel, on separate cold plates. Each condenser has a manifold header connecting eight flanged tubes, 0.003175 m ID, on either side. The condenser tubes are bonded and bolted to one side of the condenser plate. A similar set of tubes containing the FC-72 Fluorinert chilling loop is bonded to the opposite side of the plate (Gluck and Kaylor 1996).

The non-condensable gas trap (NCG) is located in the liquid line, just after the condenser. This device serves to prevent suspended vapor from working down the liquid line to the evaporators and causing a deprime. The NCG trap is essentially a wick structure similar to the evaporator and isolator. Figure 2.7 shows a cross section of a NCG similar to the one used in the CPL test bed.

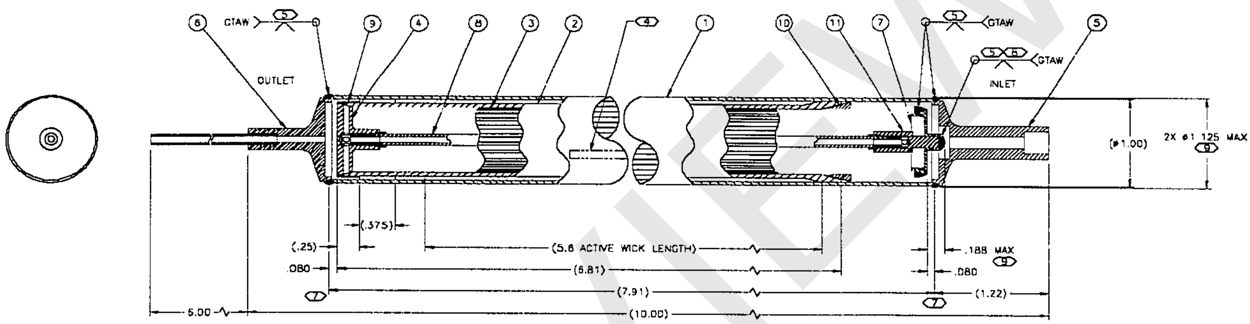

Figure 2.7 *CPL NCG Trap*

The reservoir's function is control the system operating temperature independent of the changes in heat load or sink temperature (Ku 1993). The reservoir maintains both liquid and vapor phases. The saturation temperature in the reservoir will control the system temperature and pressure. In order to do this, the condenser must also be partially full of liquid at all times (Ku 1993). The balancing liquid flow into and out of the reservoir corresponds to the movement of the liquid-vapor interface in the condenser. In the test bed, the reservoir maintains control by monitoring a reference pressure transducer. An electronic controller activates or de-activates a heater in the reservoir to maintain reference pressure at a particular set point. A picture of a reservoir and reservoir shroud similar to the one used in the testbed can be seen in Figure 2.8.

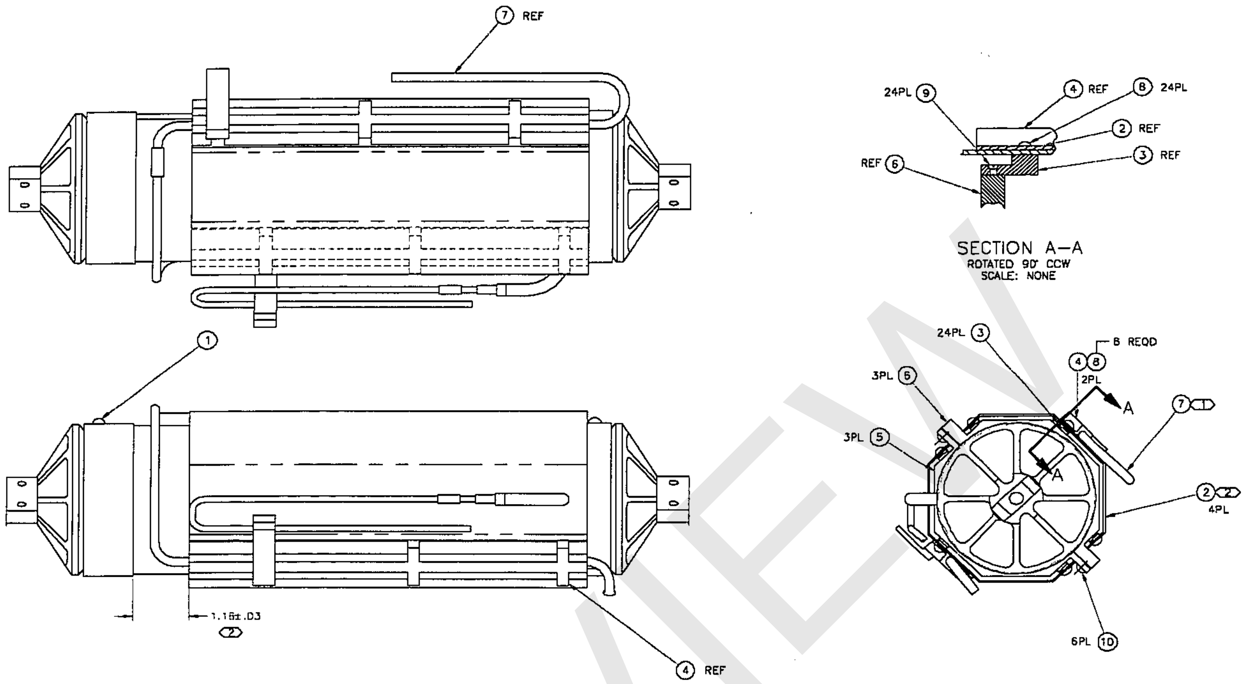

Figure 2.8 *CPL Reservoir*

Closer to the evaporators in the liquid line, the isolators serve to prevent the backflow of vapor from the evaporator into the liquid line. It is a wicked structure similar to the evaporator itself. This device is useful to prevent one evaporator deprime from depriming the other evaporators in the CPL. A picture of an isolator similar to the one used in the CPL testbed can be seen in Figure 2.9.

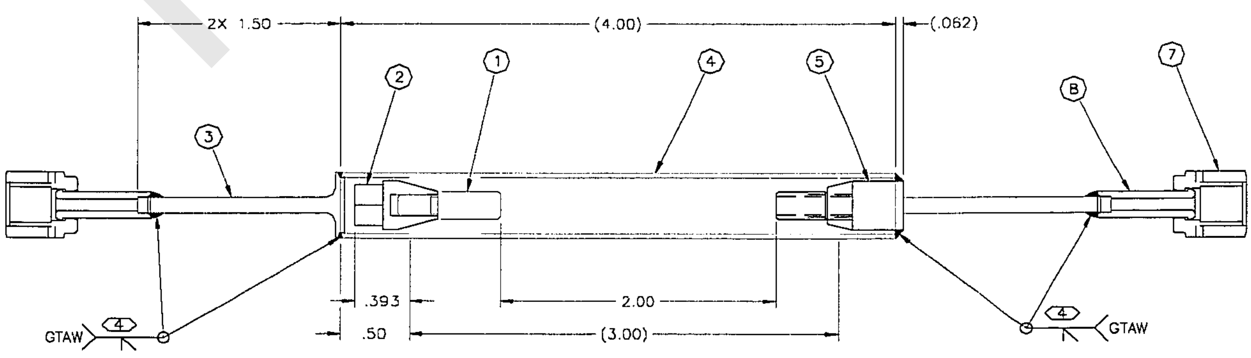

Figure 2.9 *CPL Isolator*

There are many aspects of the start up, or priming, transients that affect the CPL, but this work will only deal with the steady state aspects of CPL operation.

The capillary pumped loop is developing into the next generation of heat transport technology. The present and future needs of spacecraft designers for flexible, low cost, low maintenance thermal bus technology are pushing the refinement of capillary pumped loop technology for common use in spacecraft.