Thermal Performance of Capillary Pumped Loops Onboard Terra Spacecraft

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Abstract

The Terra spacecraft is the flagship of NASA's Earth Science Enterprise. It provides global data on the state of atmosphere, land and oceans, as well as their interactions with solar radiation and one another. Three Terra instruments utilize Capillary Pumped Heat Transport System (CPHTS) for temperature control: Each CPHTS, consisting of two capillary pumped loops (CPLs) and several heat pipes and electrical heaters, is designed for instrument heat loads ranging from 25W to 264W. The working fluid is ammonia. Since the launch of the Terra spacecraft, each CPHTS has been providing a stable interface temperature specified by the instrument under all modes of spacecraft and instrument operations. The ability to change the CPHTS operating temperature upon demand while in service has also extended the useful life of one instrument. This paper describes the design and on-orbit performance of the CPHTS thermal systems.

1.0 Introduction

Capillary Pumped Loops (CPLs) are versatile two-phase heat transfer devices which can transport large heat loads over long distances with small temperature differences [1]. A CPL utilizes evaporation and condensation of the working fluid to transfer heat, and the surface tension developed at the vapor/liquid interface across the menisci on the porous wick to circulate the fluid. The loop can provide the instrument with a stable and constant interface temperature regardless of changes in the heat load and/or radiator sink condition. It works passively and requires no flow control devices or external pumping power. Because there are no moving parts, the loop is free from vibrations. After extensive ground tests and flight experiments, CPLs have reached technology readiness for space applications [2-3]. They found their first opportunity to service the orbiting satellite onboard the Terra spacecraft, NASA's first Earth Observing System (EOS) platform.

The Terra spacecraft, shown in Figure 1, is the flagship of NASA's Earth Science Enterprise. It provides global data on the state of atmosphere, land and oceans, as well as their interactions with solar radiation and one another. Early in the Terra development, three sensors were identified as requiring CPLs for thermal control [4-7], and these were Thermal Infrared Radiometer (TIR), Short-wave Infrared Radiometer (SWIR), and Measurements of Pollution in the Troposphere (MOPITT). The baseline design for Terra CPLs were evolved based on several ground tests and two Space Shuttle flight experiments that provide verification of its microgravity performance [2, 8]. The thermal control system for each of these sensors is called Capillary Pumped Heat Transport System (CPHTS). Each CPHTS consists of two independent CPLs and the associated heat pipes and heaters used in the evaporator and the condenser sections. Two CPLs are employed in each CPHTS because of the redundancy requirement although only one CPL is operational at any give time.

Following the successful launch of the Terra spacecraft on December 18, 1999, all three CPLs were successfully started, and since start-up, have provided an extremely stable thermal interface over the range of the instrument loads and external environments. Details of the Terra spacecraft and the CPHTS design can be found in the literature [9]. This paper will focus on the on-orbit performance of the CPLs, especially the start-up transients and the versatility of these loops in adapting to new operating conditions as the environments change.

2.0 Terra CPHTS

Figure 2 depicts a typical layout of the CPHTS for Terra. The CPHTS performs the function of heat acquisition, transport and rejection during mission operation. Each CPHTS consists of two independent CPLs, one primary and the other backup, to provide the heat transport path from the instrument to the dedicated radiator assembly. This allows the positioning of the instrument on the nadir deck offering unrestricted optimal earth viewing. All CPLs and heat pipes use anhydrous ammonia as the working fluid. The CPHTS was designed for instrument heat loads ranging from 25W to 264W, with corresponding heat fluxes of 0.016 to 0.16 W/cm^2.

The two evaporators, one from each CPL, are embedded in an isogrid aluminum cold plate (shown in Figure 3) which provides an interface with the sensor. Two U-shaped constant conductance heat pipes connect the two evaporators to improve heat distribution and limit the maximum temperature gradient on the cold plate to 5 ^{o}C. The evaporator is a three-port capillary starter pump (CSP) where the inlet side is connected to both the reservoir line and the liquid transport line. As shown in Figure 4, a bayonet tube is inserted in the center core of the CSP to provide flow and communication with the reservoir through the reservoir line. This design forces the liquid to flow from the condenser to the CSP center core before it reaches the reservoir, thus ensuring wetting of the evaporator wick. Such a three-port design greatly enhances the success of loop start-up and the robustness of loop operation. Each wick is made of polyethylene with a maximum pore radius of about 15 μm and a permeability of about 2×10^{-13} m^2. The wick provides a capillary pumping pressure of about 2600 Pa.

The condenser is made of an aluminum heat pipe heat exchanger (HPHX), which has a condensing exchanger with flow channels turning a helix around a heat pipe as shown in

Figure 5. The helical fins enhance thermal performance by providing a centrifugal force on the fluid which improves fluid mixing and increases the condensation heat transfer coefficient. It also provides a better simulation of the microgravity performance of the HPHX in ground tests. The HPHX is mounted internally in a honeycomb radiator panel and is connected to a heat pipe spreader network, which transfers heat over the radiator area. There are two HPHXs embedded in each CPHTS radiator, one from each of the two CPLs. The temperature difference between the ammonia vapor at the inlet and the ammonia liquid at the exit of the HPHX is designed to be at least 7 °C. Each CPHTS radiator assembly also includes a subcooled section which further cools the condensed liquid to be sufficiently colder than the loop saturation temperature. This temperature difference ensures that the liquid will not vaporize before returning to the CSP and that only liquid enters or exits the reservoir. Both the liquid and reservoir lines from both CPLs pass through the subcooled section which is mounted directly on the interior of the radiator's space-facing facesheet. A non-condensable gas (NCG) trap is located downstream of the subcooled section to remove any undissolved gases that may adversely affect CPL operation. The NCG trap on each CPL provides a 40 cubic centimeter storage volume capable of storing 100% margin based on predicted gas generation rate over a 7.5-year life.

Both the vapor line and liquid line are made of smooth stainless steel tubing and a flexible metal line. The flexible lines were needed in ground tests in order to place the radiator and the evaporator cold plate in the same horizontal position.

The reservoir which provides working fluid management and CPL temperature control is mounted on the back of the radiator panel and is connected to the CSP with tubing and a flexible line. The reservoir contains a wick structure which ensures only liquid will exit. Each reservoir has externally mounted heaters that are controlled by heater control electronics which maintain the reservoir at any of the 16 commandable set point temperatures ranging from 9 °C to 35 °C for normal operation and -23 °C for survival mode. A schematic of the reservoir is depicted in Figure 6.

Control of the CPHTS is achieved by the use of heaters which are regulated by either heater controller or thermostats. These heaters include CSP body heaters, pump exit heaters, vapor outlet heaters, vapor line heaters, pump inlet shutdown heaters, reservoir control heaters, and radiator survival heaters. The entire heater layout is shown in Figure 7.

3.0 On-Orbit Performance of CPHTS

3.1 CPHTS Operating Modes

There are three operating modes for each CPHTS: Normal Operation, Safe Hold, and Survival modes. Basic loop operation consists of setting the reservoir saturation temperature, and the enabling and disabling selected heaters to put the CPHTS into one of the three operating modes. Because the CPHTS contains no moving parts, control of the CPHTS is achieved by the use of heaters regulated by either heater controllers or thermostats.

Normal Operation: This is the normal operating mode with the loop active. The instrument provides heat to the CPHTS evaporator cold plate. As the instrument heat output changes, a pump body heater may be kept on if additional heat is needed to support the loop operation.

Safe Hold Mode: In this mode, the instrument is turned off. The primary loop of the CPHTS is operational with the pump body heaters providing the heat source to the evaporator cold plate. The CPHTS is ready for instrument turn-on.

Survival Mode: In this mode, the CPHTS loops are not running and they are not receiving heat from the instruments. However, the reservoir heaters, radiator survival heaters and other survival heaters are enabled at all times.

There are six operational procedures for changing the CPHTS operating modes: Set Reservoir, Standard Start-up, Contingency Start-up, Ready to Operational, Operational to Ready, and Shutdown procedures. The Set Reservoir procedure is for flooding a loop in preparation for start-up and for changing the loop operating temperature after it is already operational. The Standard Start-up procedure is used to initiate the heat transfer from the cold plate to the radiator using both pump body heaters. The Contingency Start-up procedure is used only if the Standard Start-up procedure did not result in a successful start-up, and requires the use of vapor line heaters, vapor outlet heater, and button heater prior to using the pump body heaters. The Ready to Operational procedure is used to transition the loop from using the pump body heaters to the instrument as the heat source. The Operational to Ready procedure is used to maintain heat flow when the instrument is not providing enough heat to maintain stable loop operation. This procedure is designed to keep the loop running by using the pump body heaters in the event that the instrument has to be turned off temporarily due to instrument anomaly. The Shutdown procedure is used to transition the loop from any mode to the Survival mode. The instrument is turned off, the pump body heaters are disabled, and heat is applied to the loop shutdown heater at the liquid inlet line to ensure that the evaporator pumped is vapor locked and the CPL is shut down.

The Shutdown procedure has not been used in Terra. The Set Reservoir, Ready to Operational and Operational to Ready procedures have been relatively simple and straightforward. However, start-up of the CPL has been an issue turned out to be problematic for the TIR CPHTS. The next section will address the CPL start-up issues and discuss two methods to start the loop.

3.2 CPL Start-up Issues

Before each CPHTS can begin to service the instrument, the designated operational CPL must start successfully. Unfortunately, start-up usually imposes the most severe condition on the CPL evaporator. There are two start-up procedures for Terra CPHTS: Standard Start-up and Contingency Start-up procedures.

Standard Start-up: In the standard start-up procedure, the reservoir is heated to the desired set point temperature that is higher than the rest of the loop. The entire loop is therefore flooded with liquid and the evaporator wick is completely wetted. Then both pump body heaters are enabled to initiate boiling in the evaporator and the subsequent flow circulation in the loop. As the flow circulation starts, vapor will flow in the vapor line and the vapor line temperature will rise to the reservoir saturation temperature. Meanwhile, the liquid line temperature will drop due to the flow of cold liquid from the condenser. Start-up is complete when the reservoir, pump body and vapor line temperatures have converged and stabilized to within 2 °C and he liquid line pump inlet temperature is at least 5 °C colder than the reservoir temperature.

There are two major issues with the standard start-up procedure [10]. First, a liquid superheat is required in order to initiate nucleate boiling in a fully flooded loop. When boiling does occur, the generation of vapor bubbles can lead to a explosion and the resulting pressure differential across the evaporator pump can be higher than the wick can sustain. Vapor will therefore penetrate through the wick. Second, as the vapor flowing along the vapor line clearing the liquid, there is very little condensation because the vapor line is insulated. Thus, the liquid in the vapor line and liquid line is flowing at the same volumetric rate as the vapor is being generated in the evaporator. Depending on the liquid to vapor density ratio, the mass flow rate can be an order of magnitude higher than that during steady operation. This also imposes a large pressure differential across the wick and may result in vapor penetration. The pressure differential will decrease substantially as the vapor reaches the condenser. Typical temperature and pressure profiles during start-up transient are shown in Figure 8. The three-port CSP is designed in such a way that the vapor bubbles can be removed by a sweeping action and/or by condensation through subcooled liquid flowing through the pump liquid core.

Another potential problem during the CPL start-up is the reservoir cold shock, that is, a sudden drop of the reservoir saturation temperature due to a rapid injection of cold liquid from the condenser as the vapor line is clearing liquid. The presence and the severity of the reservoir cold shock depends upon how much liquid is left in the reservoir prior to start-up and how much and how fast cold liquid is being injected into the reservoir after the loop starts. A severe reservoir cold shock can occur when the loop is significantly undercharged. If the reservoir saturation temperature drops below the temperature at the evaporator inlet, the CPL may deprime due to liquid flashing.

Contingency Start-up: In this start-up procedure the vapor line is clear of liquid, prior to applying heat to the evaporator, by turning on the vapor line heater and the evaporator outlet heater. This will reduce the pressure drop imposed upon the evaporator wick during start-up transient. The button heater at the outlet of the evaporator will also be turned on so that the superheat can be reduced or eliminated entirely. Using this procedure, the reservoir cold shock can also be reduced or eliminated because much less cold liquid is being injected into the reservoir and at a much slower rate. The cold liquid will have been heated to the reservoir set point temperature prior to start-up. Both body heaters are then enabled. After the loop starts successfully, the vapor line heater and the button heater aredisabled.

3.3 Overview of Terra CPHTS Performance

The CPHTS is required to provide a constant interface temperature (within +/- 0.5 °C) for the instrument under all operating modes. The heat load to the evaporator will vary as the instrument changes its mode of operation. The radiator sink temperature will also change continually as the spacecraft orbits the Earth. In addition, the CPHTS will be subjected to accelerations during spacecraft orbit burns. Because only one CPL in each CPHTS is operational at any given time, the other CPL is made inactive by raising its reservoir set point temperature 10 °C higher than that of the operational loop.

On December 19, 999, one day after Terra was launched, the MOPITT CHPTS Loop 1 started successfully using the Standard Start-up procedure with the two body pump heaters providing a total of 150W. The MOPITT Focal Plane cooled immediately when the cooler was turned on March 2, 2000. Both pump body heaters were then disabled. On March 17, 2000, the Loop 1 reservoir set point was lowered from 18.5 °C to 17 °C, and Loop 1 adapted to this change smoothly. It was decided at that time to enable one of the pump body heaters in order to ensure a stable loop operation.

The SWIR CPHTS Loop 1 started successfully on January 5, 2000 using the Standard Start-up procedure. One of the pump body heaters was left on after the instrument turn-on. Because its cooler performance has degraded over time and was running at a temperature higher than anticipated, Loop 1 reservoir set point temperature was lowered from 20 °C to 15.5 °C with 1.5 °C increments over a three-day period in July 2001. Then in January 2003, Loop 1 reservoir set point was again lowered from 15.5 °C to 12.5 °C in two steps. The change of operating temperature upon command while in service is one of the major advantages of CPLs. For MOPITT, it has resulted in optimal instrument performance, and has extended the useful life of the instrument. After the reservoir temperature was lowered to 12.5 °C, the pump body heaters were disabled; otherwise the radiator would not be able to dissipate the total heat.

Start-up of the TIR CPHTS Loop 1 was performed on January 7, 2000 using the Standard Start-up procedure. The loop deprimed 62 hours after the flow circulation was initiated. Start-up of Loop 2 was conducted on January 13, 2000 using the Standard Start-up procedure. Unfortunately, Loop 2 also deprimed 48 hours after the flow circulation began. The Contingency Start-up procedure was used to start Loop 2 on January 19, 2000 and the loop started successfully. Loop 2 deprimed on February 20, 2000 after four successive 300-second orbit inclination burns over a one-week period. Loop 2 started successfully again on February 24, 2000 using the Contingency Start-up procedure. At least one of the pump body heaters has been enabled for all modes of TIR CPHTS operation and the loop has been operational since then.

For over four years since the Terra spacecraft launch, the CPHTS thermal systems have been performing extraordinarily well in servicing the three instruments. The reservoir set point temperature can be controlled within +/- 0.1 °C, and all instruments have been maintained within their specified temperature ranges under all operating modes. A typical CPHTS performance is shown in Figure 9, where the MOPITT CPHTS Loop1 temperatures are illustrated during a reservoir set point change and later during the enabling of one pump body heater. The transition during the reservoir set point was very smooth. The evaporator provides a stable thermal interface for the instrument before, during, and after the transitions although other parts of the CPHTS underwent temperature changes in order to satisfy the energy balance.

The following section will describe some transient operations of the CPHTS thermal systems, including start-up, reservoir set point change, orbit burns and Safe Hold mode.

3.4 CPHTS Start-ups

Both MOPITT CPHTS Loop 1 and SWIR CPHTS Loop 1 started successfully on the first attempt using the Standard Start-up procedure. Figure 10 show the loop temperatures during SWIR Loop 1 start-up. With both pump body heaters enabled (150W total power), boiling of liquid occurred when the superheat reached 2 °C. The reservoir temperature dropped by 2 C ° right after the boiling incipience, and was raised to the set point of 20 °C by the control heaters. The loop start-up was evidenced by the rise of the vapor line temperature to the reservoir set point and the decrease of the liquid line temperature. The MOPITT Loop 1 displayed similar temperature profiles during start-up with a 7 °C superheat and a 2 °C reservoir cold shock.

Figure 11 shows the temperatures of TIR CPHTS Loop1 start-up using the Standard Start-up procedure. The superheat at the onset of nucleate boiling was 7 °C and the reservoir had a 7 °C cold shock. The loop deprimed after operating for 62 hours. Loop 2 was then started using the Standard Start-up procedure. The temperatures during start-up were almost the same as those shown in Figure 11. The loop operated for 48 hours before it deprimed. Note that after a 7 °C cold shock, the reservoir temperature was lower than the liquid inlet temperature of the evaporator. This could have resulted in the flashing of liquid. One possible reason for such a large cold shock is that both loops may not have sufficient fluid inventory.

The TIR CPHTS Loop 2 successfully started using the Contingency Start-up procedure. Figure 12 depicts the loop temperatures during start-up. The vapor line heaters were controlled by thermostats which caused the vapor line temperatures to fluctuate prior to start-up. After the vapor line was clear of liquid, both pump body heaters were enabled and the loop started without noticeable superheat or reservoir cold shock. The loop operated steadily for a month, and then deprimed after four successive 300-second orbit burns. Loop 2 started successfully again on February 24, 2000 and has been operational since. As will be described later, a corrective measure has been employed to prevent loop deprime during orbit burns.

3.5 Reservoir Set Point Change

One of the advantages of the CPLs is that the operating temperature can be changed while the loop is in service by simply sending commands to the reservoir control heaters. The operating temperature may need to be change for optimal instrument performance as was done by MOPITT shortly after the instrument turn-on (see Figure 10). Over the past four years, performance of the cooler for SWIR has gradually deteriorated, resulting in a much less efficient operation and higher component temperatures. The CPHTS reservoir temperature has been lowered form in July 2001, and again to 12 C° in January 2003. Figure 13 shows the set point temperature changes from 20 °C to 15.5 °C with increments of 1.5 °C over three days. The evaporator temperature followed the reservoir temperature at all times and provided a new interface temperature for the instrument after each set point change.

3.6 Operating Temperature Control

The reservoir set point temperature controls the CPL operating temperature. Figures 10 to 13 illustrate that the evaporator temperature follow the reservoir temperature and provide a very steady interface temperature for each instrument. The reservoir set point temperatures for the CPHTS systems have been controlled within +/- 0.1 °C for all operational CPLs. However, in the very early operation of the TIR CPHTS, the reservoir experienced some temperature control problems. The operating temperature was higher than desired and was fluctuating with an amplitude of 2 °C, as shown in Figure 14. Further investigations revealed that the reservoir control heater position in TIR was different from that of MOPITT and SWIR(by design for accommodation of ground testing). The cause of "erratic" loop temperatures results from the primary (A) control thermistor being located over a vapor/liquid transition area in the reservoir. Backup (B) control thermistor is located nearer the heater, and thus has a higher probability of being located over a vapor space. On January 24, 2000 control was switched from A side to B side. Immediately, loop temperatures dropped and stabilized at the expected temperature level. Loop temperatures have remained steady since then, as shown in Figure 15.

3.7 Spacecraft Orbit Burns

Since launch, the Terra spacecraft has made several drag make-up burns (about 30 seconds each) that maintain the correct attitude for the spacecraft, and more than 15 inclination burns (about 300 seconds each) that maintain the correct inclination for the orbital plane. Although the thruster firing only produces about 0.01G of acceleration, a prolonged orbit burn may have an adverse effect on the CPL operation. While the MOPITT CPHTS and the SWIR CPHTS were unaffected by a series of consecutive inclination burns as shown in Figure 16, the TIR CPHTS is more susceptible to orbit burns because the thrust vector is parallel to the axial direction of its reservoir. The acceleration can cause sloshing of fluid inside the reservoir and, when combining with the on and off cycle of the control heater, can produce a suction action on the evaporator liquid core, leading to bubble formation and an eventual deprime. This is the most likely cause of the third deprime of the TIR CPHTS. Precautions have been made since then to minimize the effect of thruster firing by enabling both pump body heaters and switching the reservoir heater control from B side to A Side for any inclination or drag make-up burns that were longer than 60 seconds. After the orbit burn, one pump body heater was disabled and the reservoir heater control was switched from Side A back to B Side. No CPHTS deprime has occurred since.

3.8 Safe Hold Mode

During the safe Hold Mode, the instrument is turned off, and the pump body heaters are enabled to provide the heat source for the CPHTS. For MOPITT CPHTS and TIR CPHTS, one of the pump body heaters is always enabled at all times. Thus, transitions between the Operational and Safe Hold modes are straightforward. For MOPITT CPHTS, both pump body heaters have been disabled since its reservoir set point was lowered to 12.5 °C. The transition from the Operational mode to Safe Hold mode requires enabling both pump body heaters *after* the instrument has been turned off, and disabling both pump body heaters *before* the instrument is turned on during the transition from the Safe Hold mode to Operational mode. Figures 17 and 18 show that the SWIR CPHTS provided stable interface temperature for the instrument before, during and after both transitions.

4.0 Conclusions

For more than four years, the CPHTS thermal control systems have been providing excellent services to the MOPITT, SWIR, and TIR instruments onboard the Terra spacecraft. Each CPHTS has met all technical requirements and is able to maintain a constant interface temperature for its instrument regardless of changes in the instrument operating mode, sink temperature, and spacecraft orbit burns. The ability to change the operating temperature upon command during service has afforded the instruments with optimal performance and has extended the useful life of the SWIR instrument. The success of the CPHTS has made a new era in spacecraft instrument and sensor thermal management.

The decision to integrate the CPL technology into the design and development of the Terra spacecraft in the early phase of the mission has contributed to the success of this program. Although the TIR CPHTS experienced some initial start-up difficulties, the alternative start-up method has produced successful results. The decision to install sufficient number of temperature sensors on the CPHTS also helped the diagnosis of any anomalies and the implementation of the corrective measures.

The position of the temperature control sensor on the reservoir has proven important in providing a steady set point temperature. Future missions using the CPL technology should pay special attention to this subject.

Each CPL in the CPHTS can transport more than 1000W of heat load. Each of the three instruments only dissipates less than 200W of waste heat. The CPL is more susceptible to deprime when operating in the low end of its capillary pumping capability. The pump

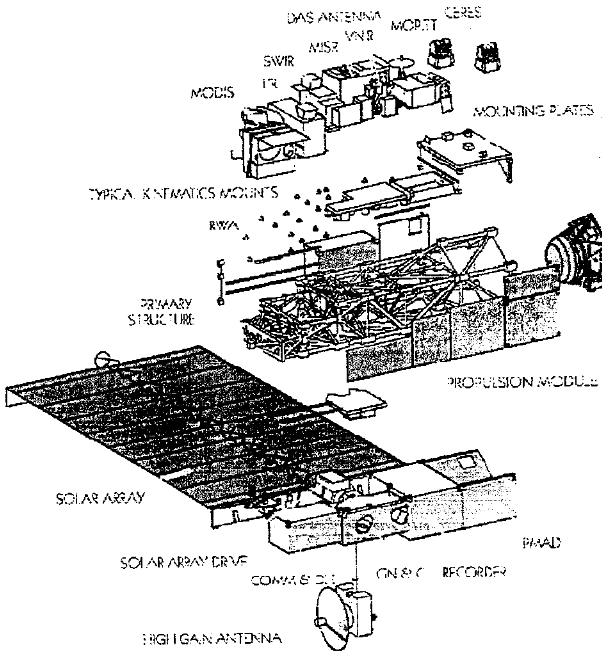


Figure 1

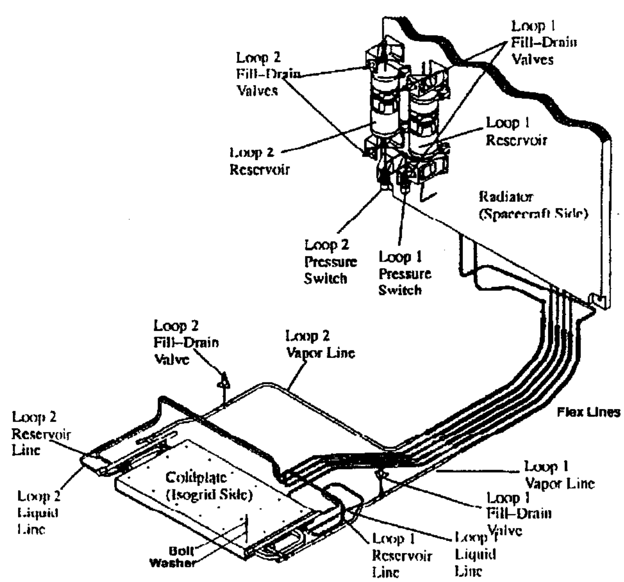


Figure 2

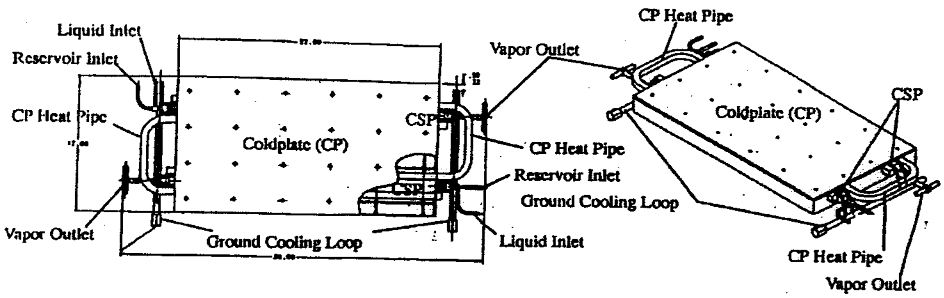
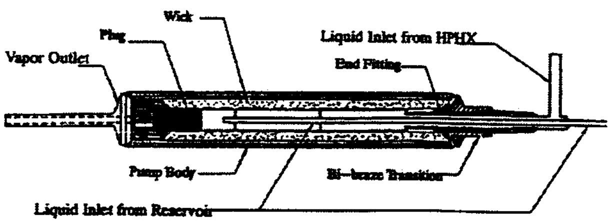


Figure 3



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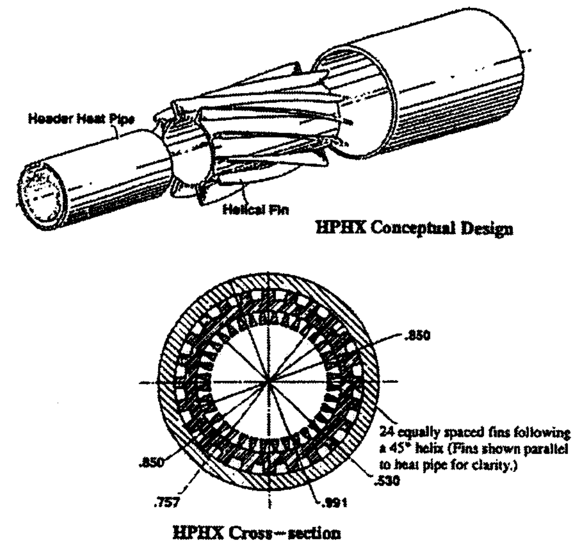

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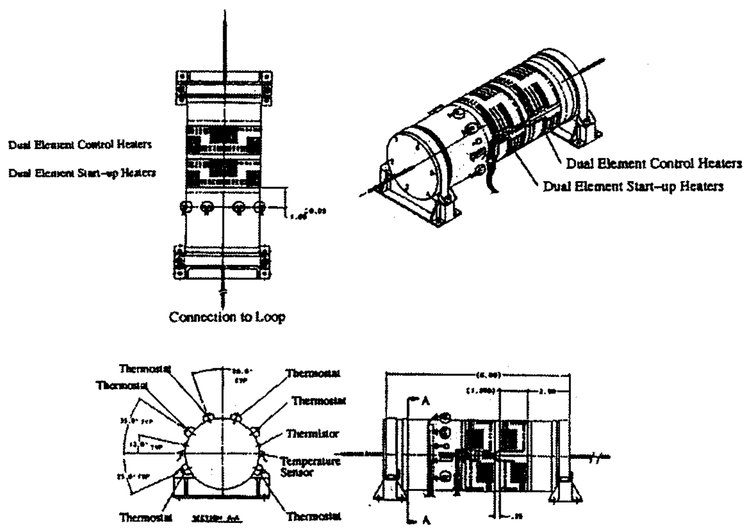


Figure 6

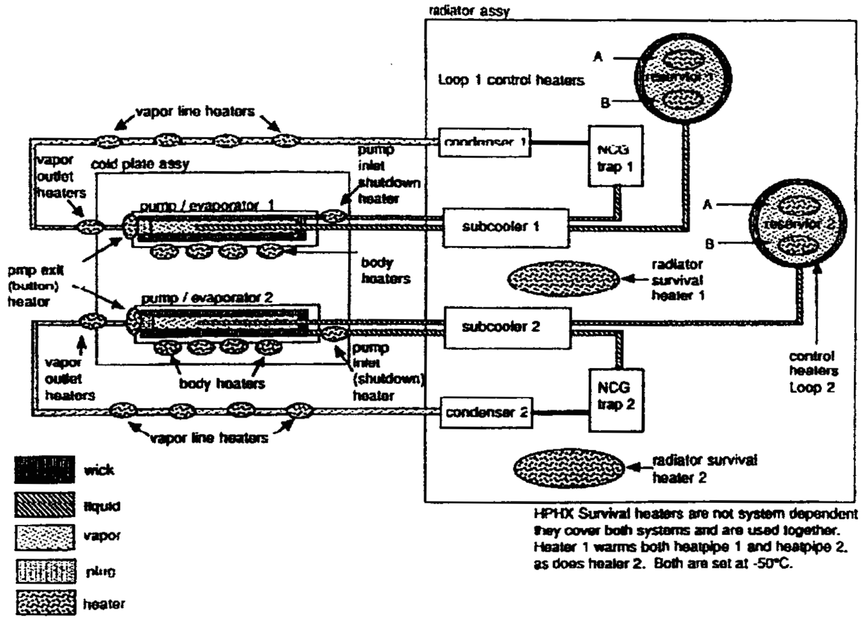


Figure 7

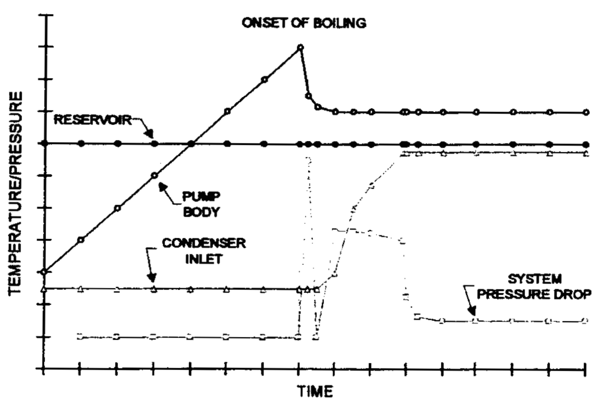


Figure 8

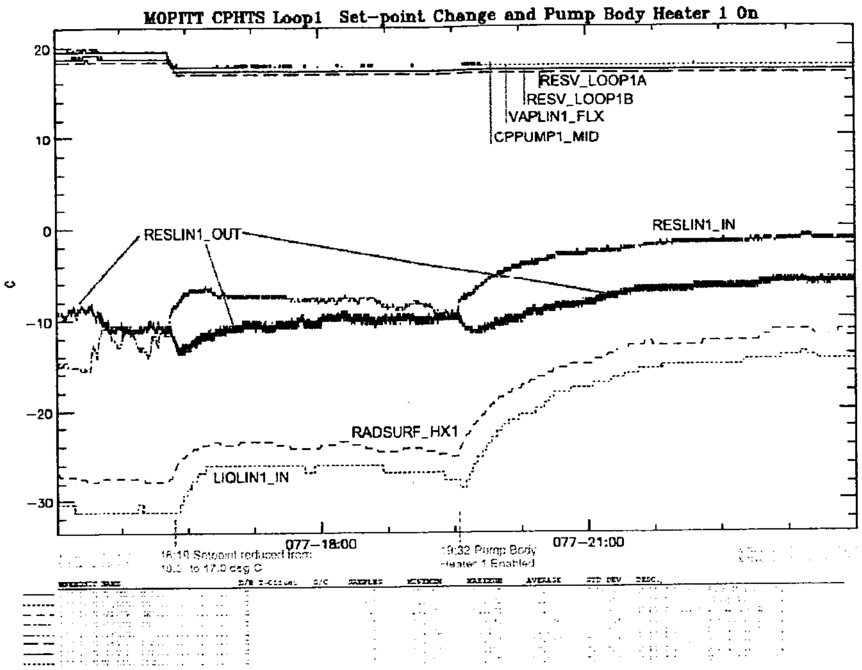


Figure 9

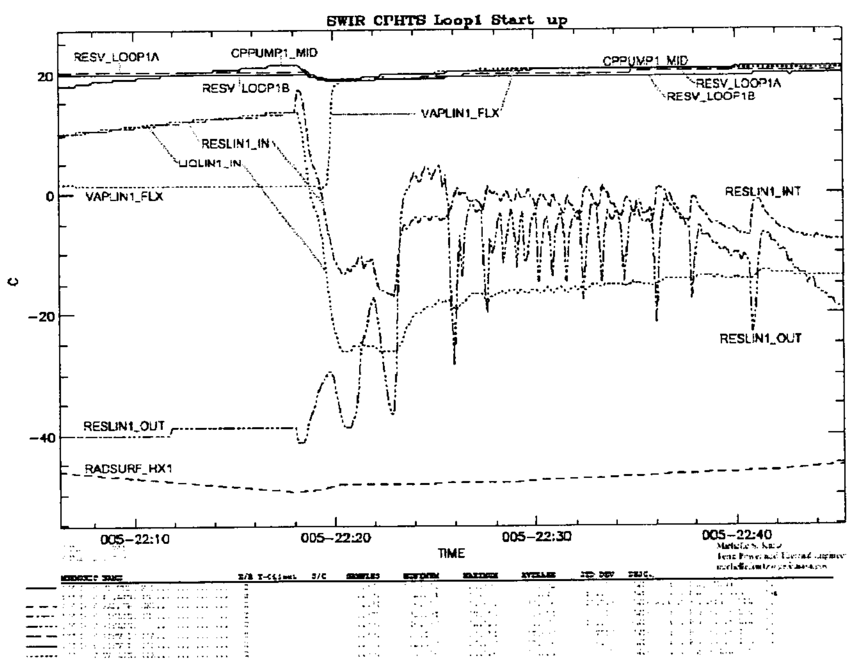


Figure 10

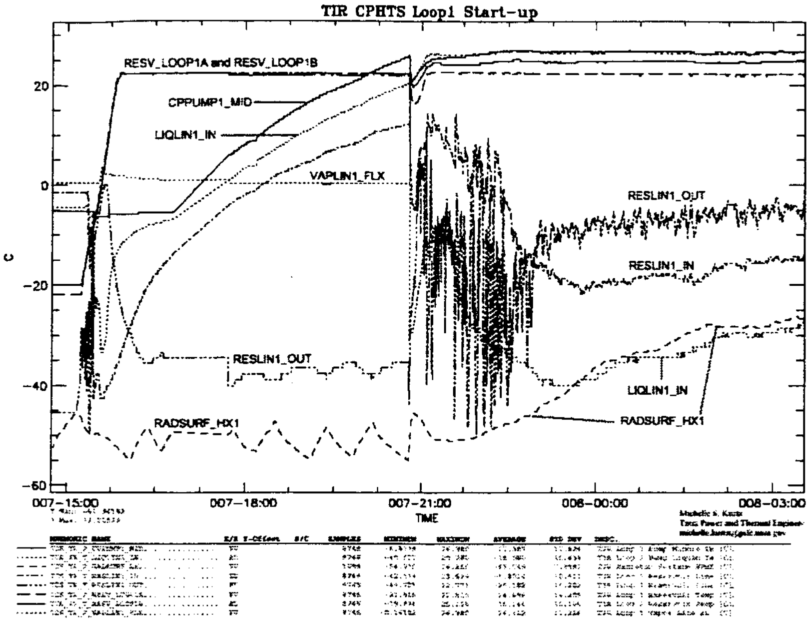


Figure 11

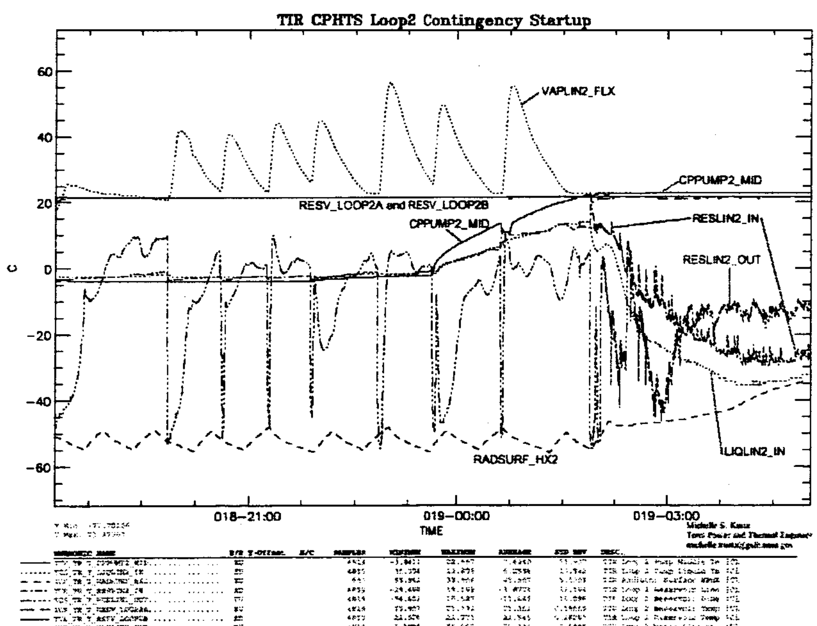
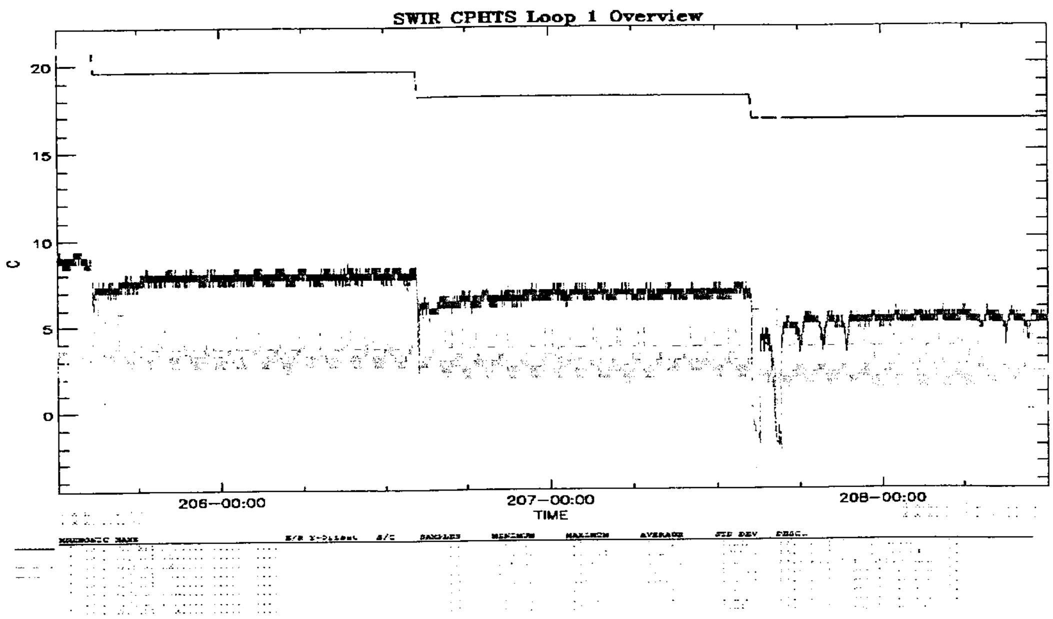


Figure 12



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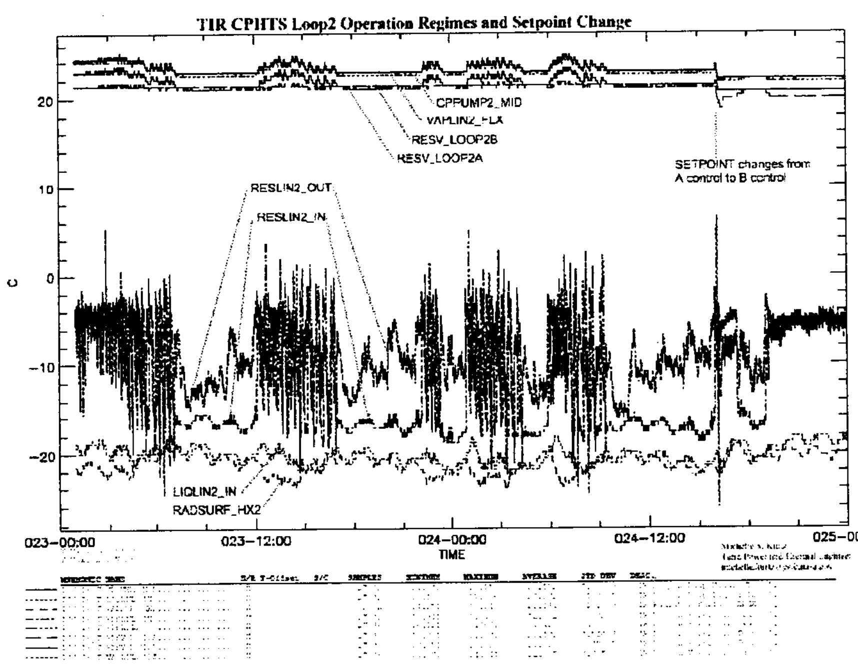

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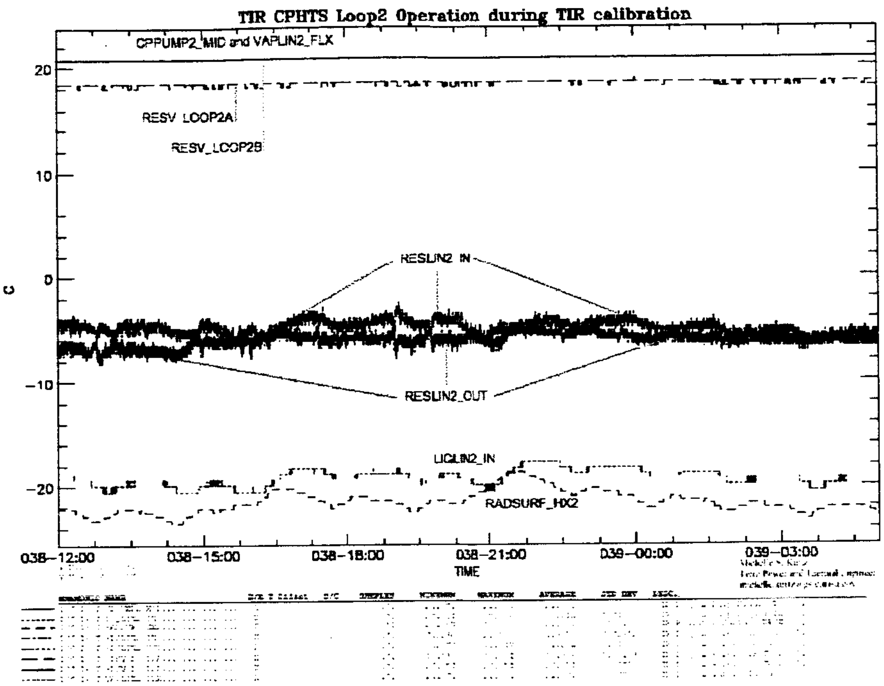
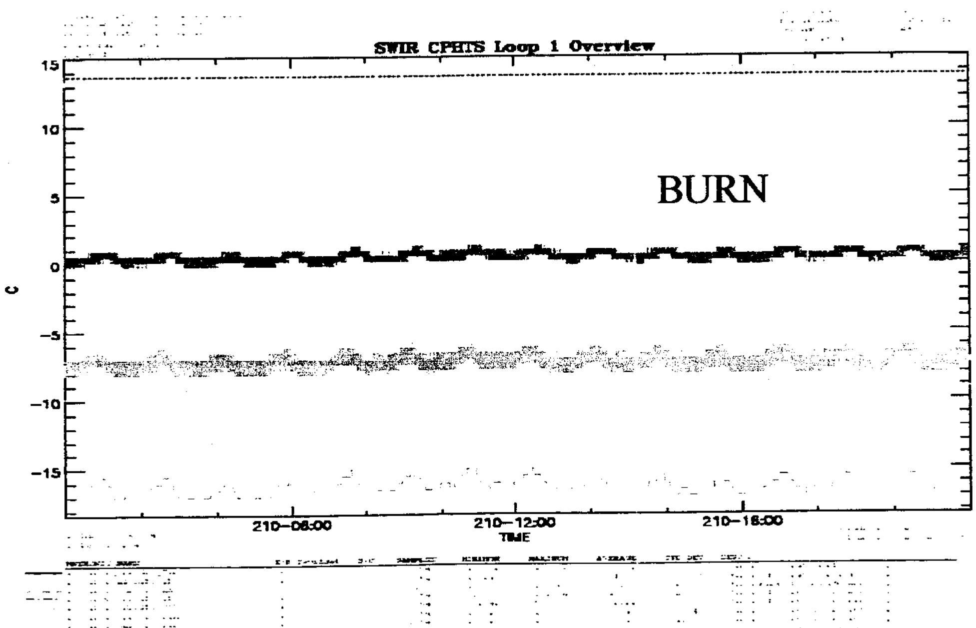


Figure 15



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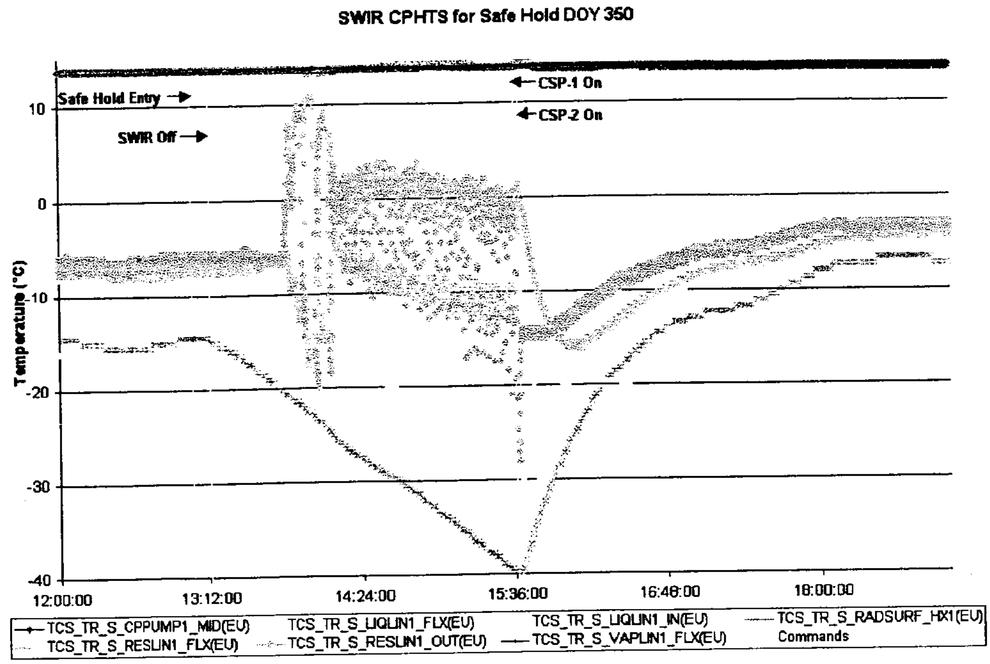

Figure 17

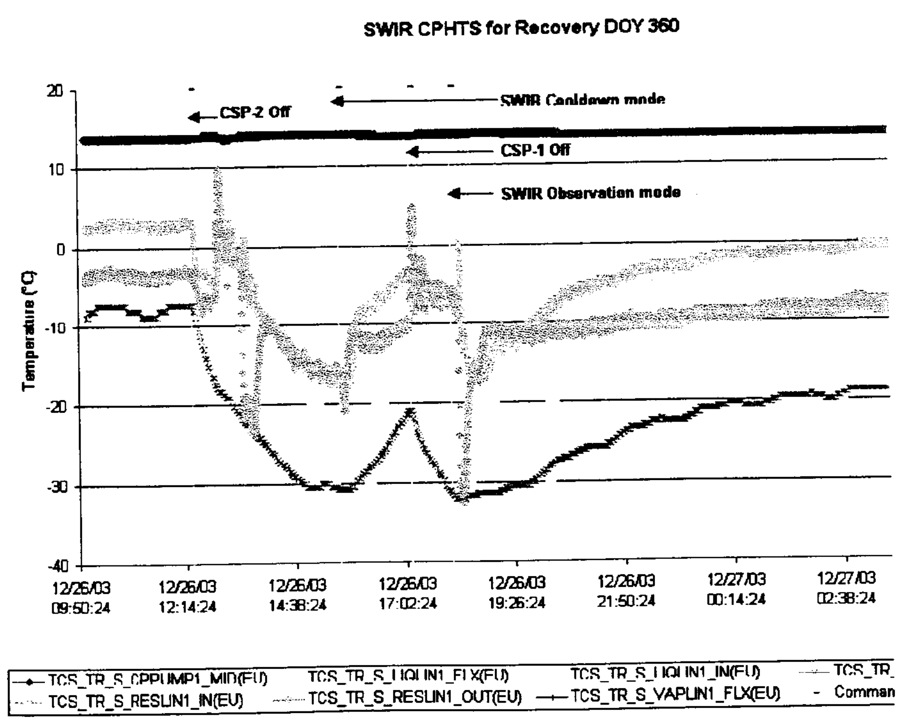

Figure 18