



GSFC· 2015

Introduction to Loop Heat Pipes

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Outline

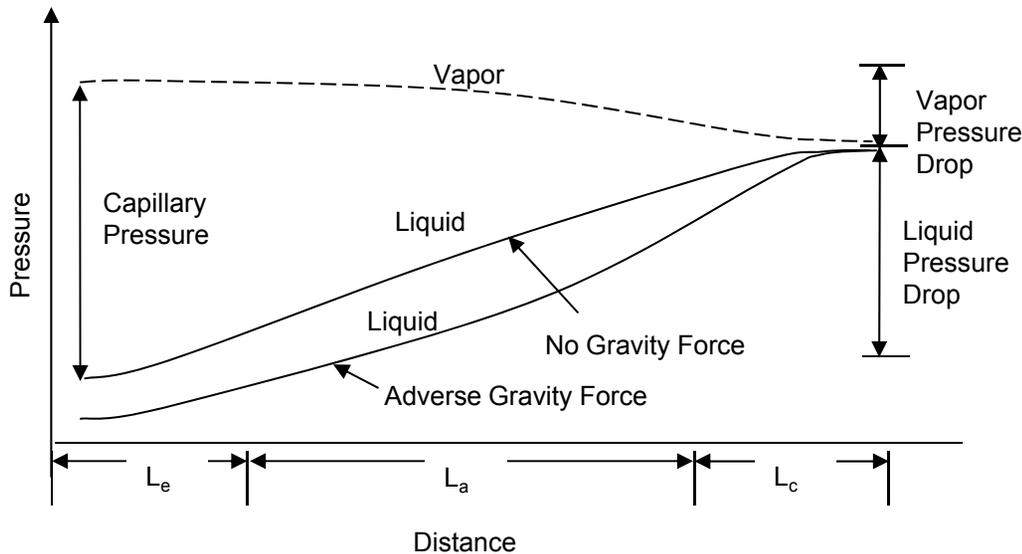
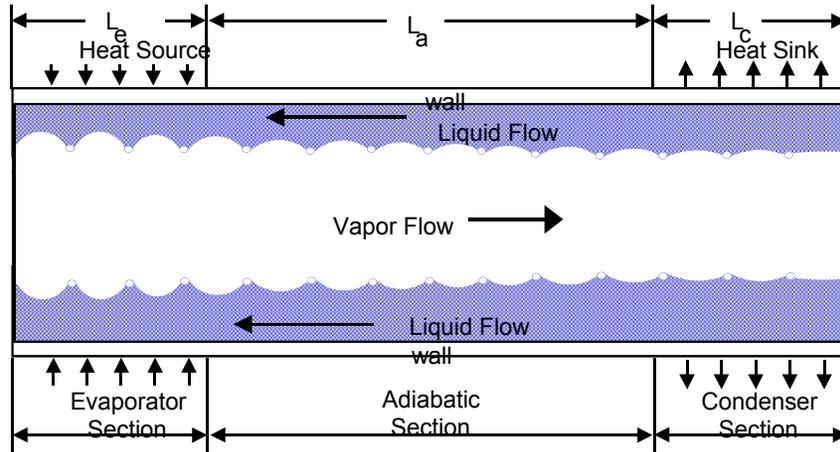
- **From Heat Pipe to Loop Heat Pipe (and Capillary Pumped Loop)**
- **LHP Operating Principles**
- **LHP Components Sizing and Fluid Inventory**
- **LHP Operating Temperature Control**
- **LHP Start-up**
- **LHP Shutdown**
- **LHP Analytical Modeling**
- **Recent LHP Technology Developments**



From Heat Pipe to Loop Heat Pipe and Capillary Pumped Loop



Heat Pipes - Heat Transport Limit



b) Vapor and liquid pressure distributions

- For proper heat pipe operation, the total pressure drop must not exceed its capillary pressure head .

$$\Delta P_{\text{tot}} \leq \Delta P_{\text{cap,max}}$$

$$\Delta P_{\text{tot}} = \Delta P_{\text{vap}} + \Delta P_{\text{liq}} + \Delta P_{\text{g}}$$

$$\Delta P_{\text{cap,max}} = \sigma \cos\theta / R_p$$

- Heat Transport Limit
 - $(QL)_{\text{max}} = Q_{\text{max}} L_{\text{eff}}$
 - $L_{\text{eff}} = 0.5 L_e + L_a + 0.5 L_c$
 - $(QL)_{\text{max}}$ measured in watt-inches or watt-meters

- Capillary pressure head:

$$\Delta P_{\text{cap}} \propto 1 / R_p$$

- Liquid pressure drop:

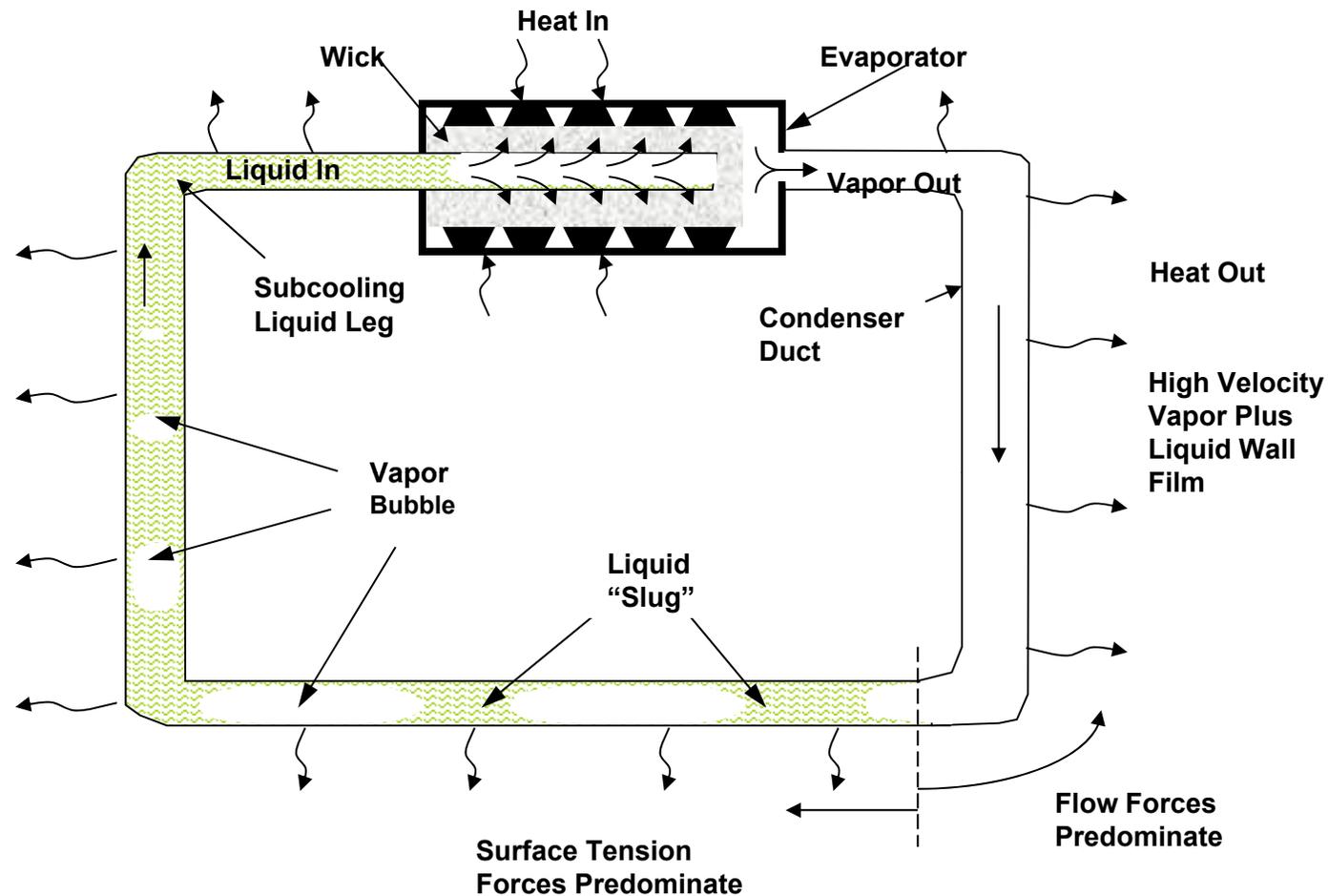
$$\Delta P_{\text{liq}} \propto 1 / R_p^2$$

- An optimal pore radius exists for maximum heat transport.

- Limited heat transport capability
- Limited pumping head against gravity



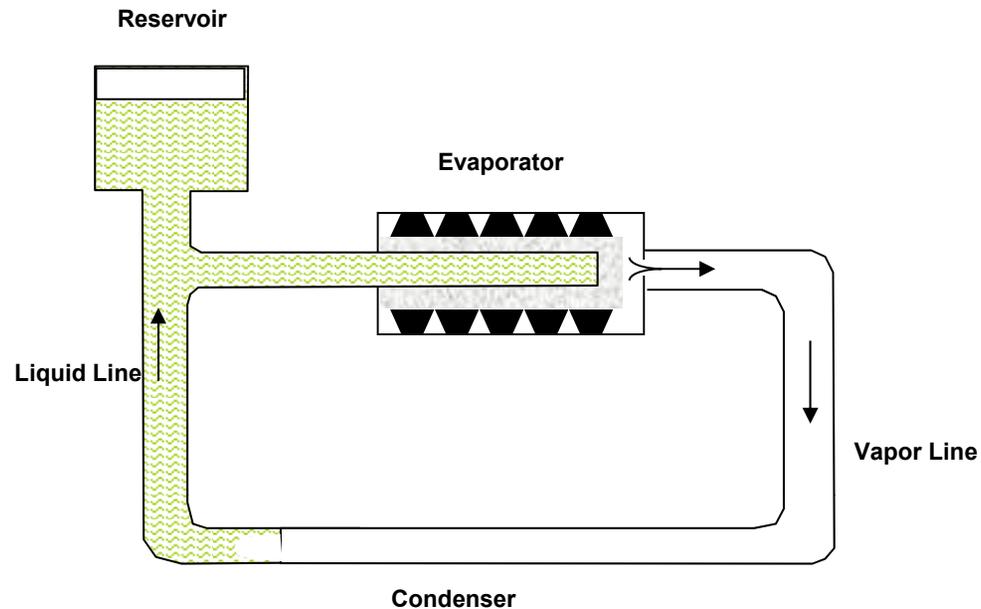
Constant Conductance Capillary Pumped Loop



- **Wicks are present only in the evaporator, and wick pores can be made small.**
- **Smooth tubes are used for rest of the loop, and can be separately sized to reduce pressure drops.**
- **Vapor and liquid flow in the same direction instead of countercurrent flows.**
- **Operating temperature varies with heat load and/or sink temperature.**



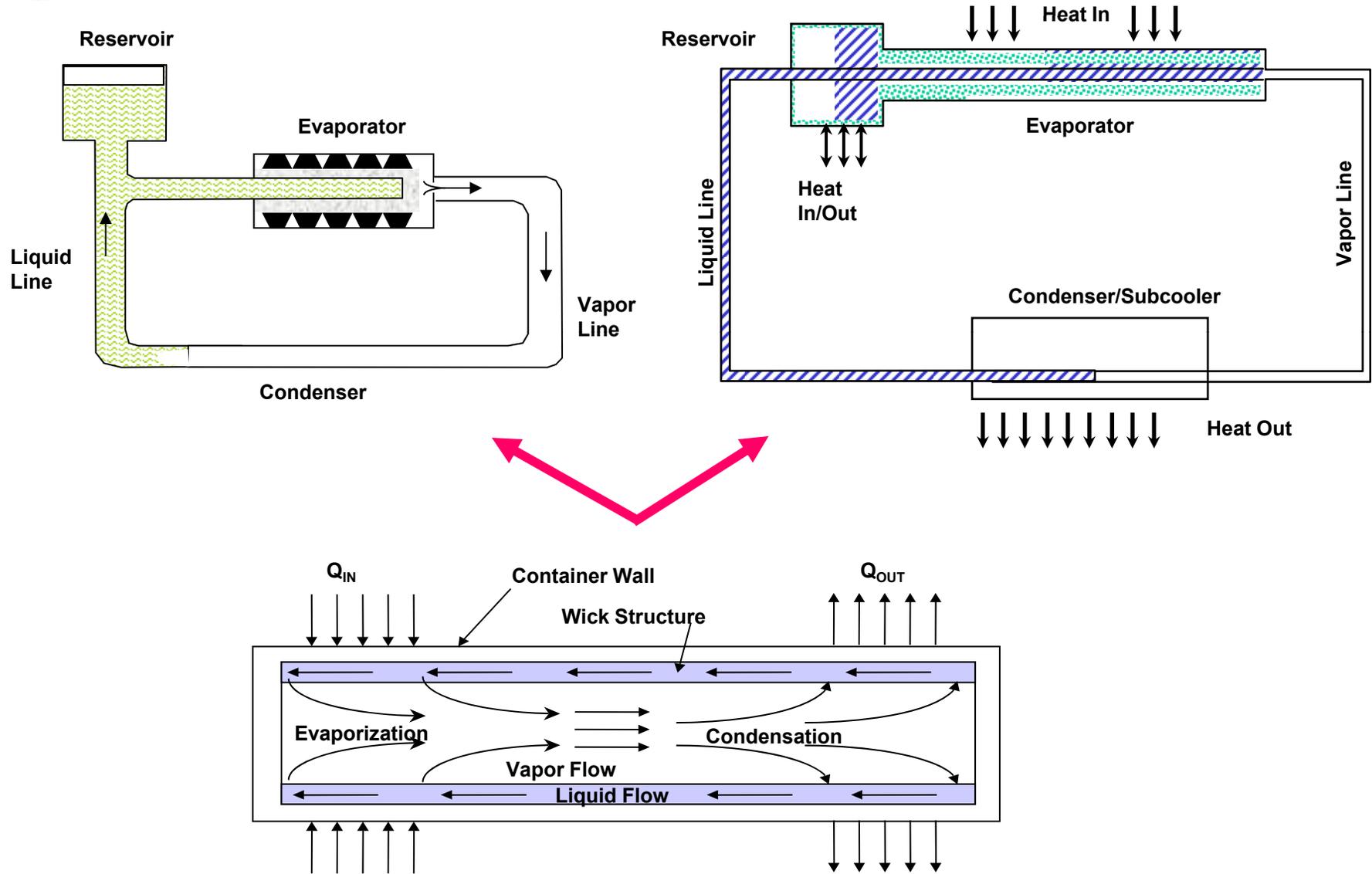
Variable Conductance Capillary Pumped Loop



- The reservoir stores excess liquid and controls the loop operating temperature.
- The operating temperature can be tightly controlled with small heater power.
- The loop can be easily modified or expanded with reservoir re-sizing.
- Pre-conditioning is required for start-up.
- Evaporator cannot tolerate vapor presence, may be prone to deprime during start-up.
- Polyethylene wick with pore sizes $\sim 20 \mu\text{m}$

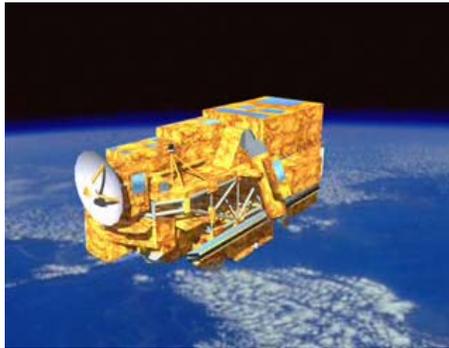


Capillary Two-Phase Thermal Devices





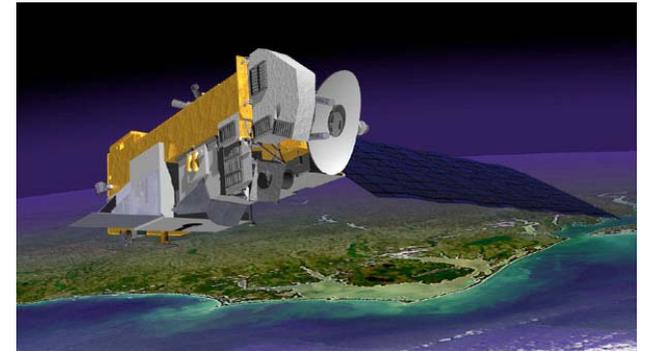
CPL and LHP Flight Applications – NASA Spacecraft



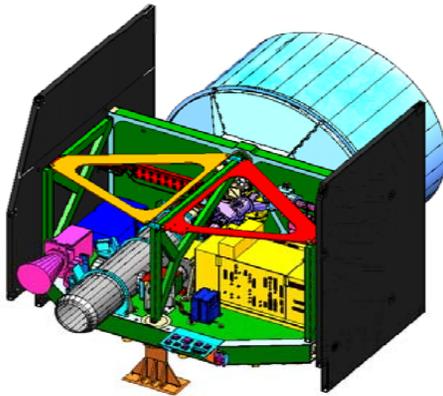
TERRA, 6 CPLs
Launched Dec
1999



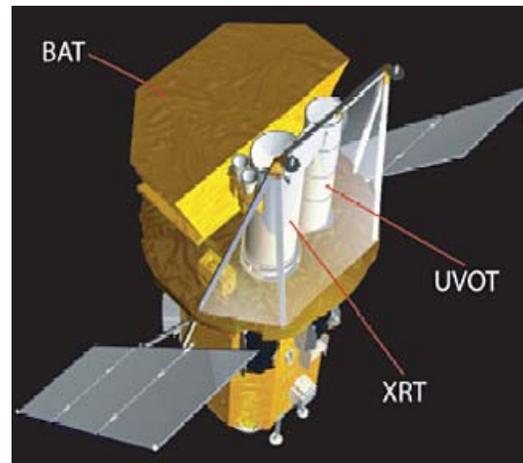
HST/SM - 3B; 1 CPL
Launched Feb 2002



AURA, 5 LHPs
Launched July 2004



ICESat, 2 LHPs
Launched Jan 2003



SWIFT, 2 LHPs
Launched Nov 2004



GOES N-Q, 5 LHPs each
Launched 2006



CPL and LHP Flight Applications – NASA Spacecraft



**GOES R-U, 4 LHPs each
To be launched**



**ICESat-2, 1 LHP
To be launched**



**SWOT, 4 LHPs
To be launched**

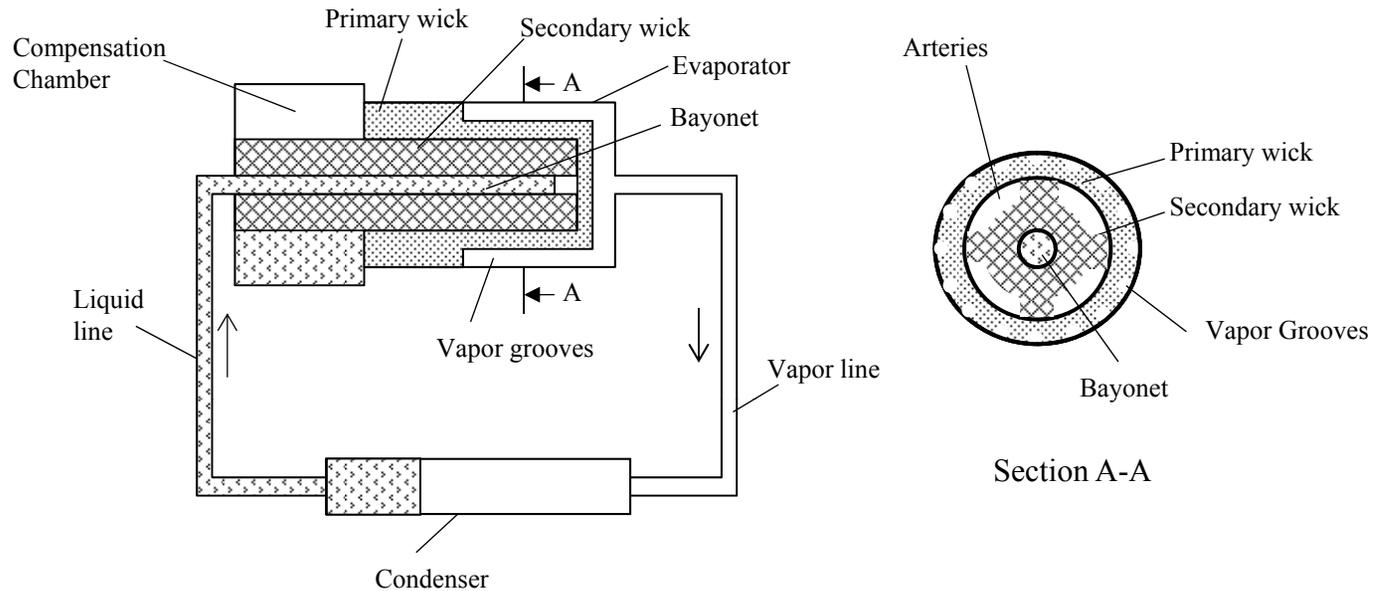
- **LHPs are also used on many DOD spacecraft and commercial satellites.**



Introduction to Loop Heat Pipes



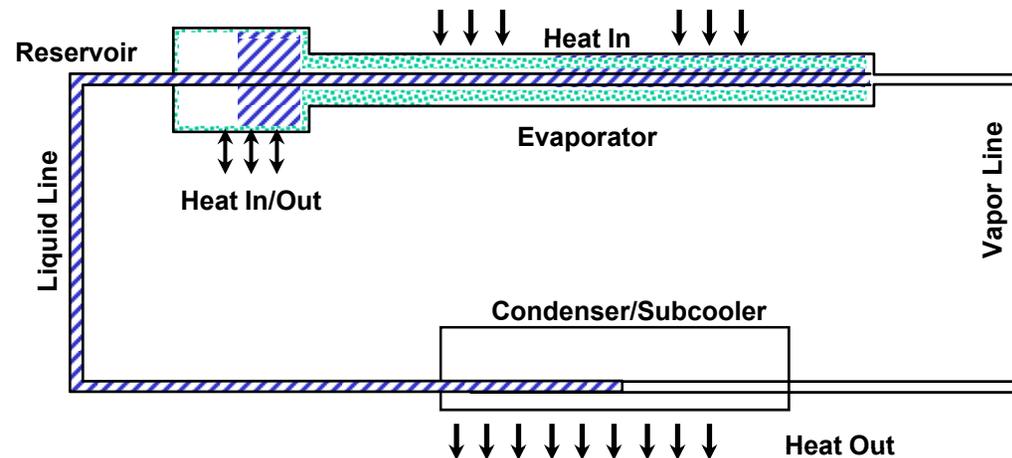
Schematic of an LHP



- **Main design features**
 - The reservoir (compensation chamber or CC) forms an integral part of the evaporator assembly.
 - A primary wick with fine pore sizes provides the pumping force.
 - A secondary wick connects the CC and evaporator, providing liquid supply.



Main Characteristics of LHP



- **High pumping capability**
 - Metal wicks with ~ 1 micron pores
 - 35 kPa pressure head with ammonia (~ 4 meters in one-G)
- **Robust operation**
 - Vapor tolerant: secondary wick provides liquid from CC to evaporator
- **Reservoir is plumbed in line with the flow circulation.**
 - Operating temperature depends on heat load, sink temperature, and surrounding temperature.
 - External power is required for temperature control.
 - Limited growth potential
 - Single evaporator most common



LHP Operating Principles – Pressure Balance

- The total pressure drop in the loop is the sum of viscous pressure drops in LHP components, plus any pressure drop due to body forces:

$$\Delta P_{\text{tot}} = \Delta P_{\text{groove}} + \Delta P_{\text{vap}} + \Delta P_{\text{cond}} + \Delta P_{\text{liq}} + \Delta P_{\text{wick}} + \Delta P_{\text{g}} \quad (1)$$

- The capillary pressure rise across the wick meniscus:

$$\Delta P_{\text{cap}} = 2\sigma \cos\theta / R \quad (2)$$

- The maximum capillary pressure rise that the wick can sustain:

$$\Delta P_{\text{cap, max}} = 2\sigma \cos\theta / r_p \quad (3)$$

r_p = radius of the largest pore in the wick

- The meniscus will adjust its radius of curvature so that the capillary pressure rise matches the total pressure drop which is a function of the operating condition:

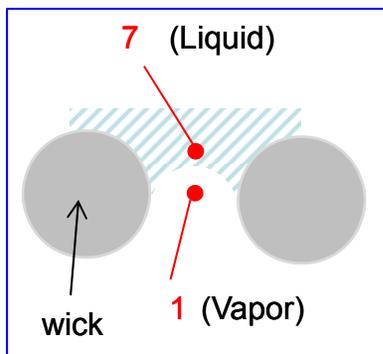
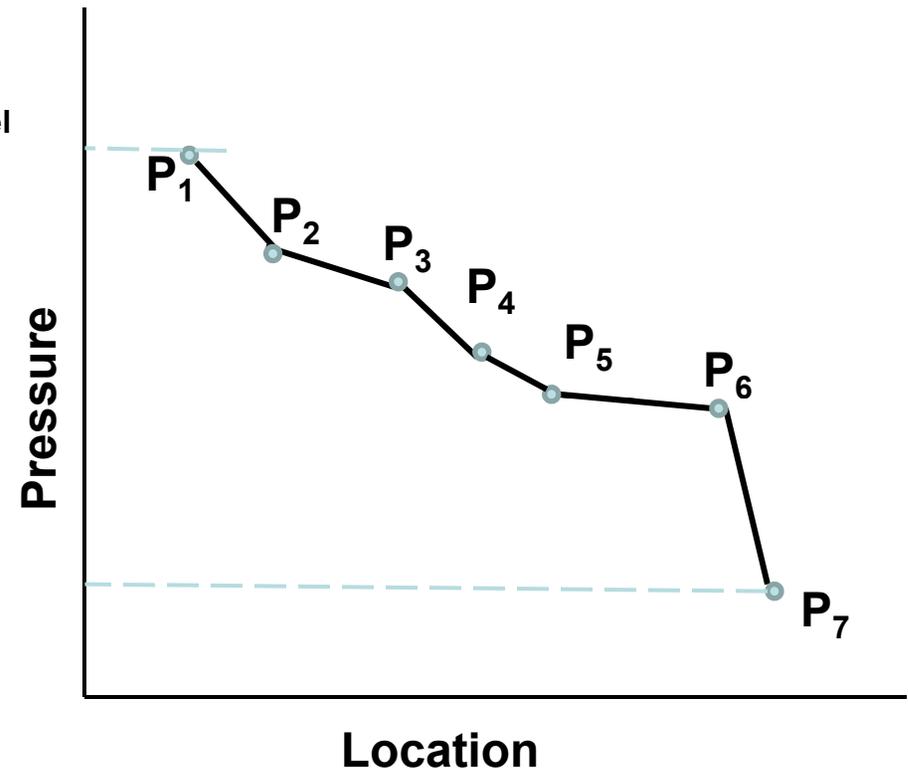
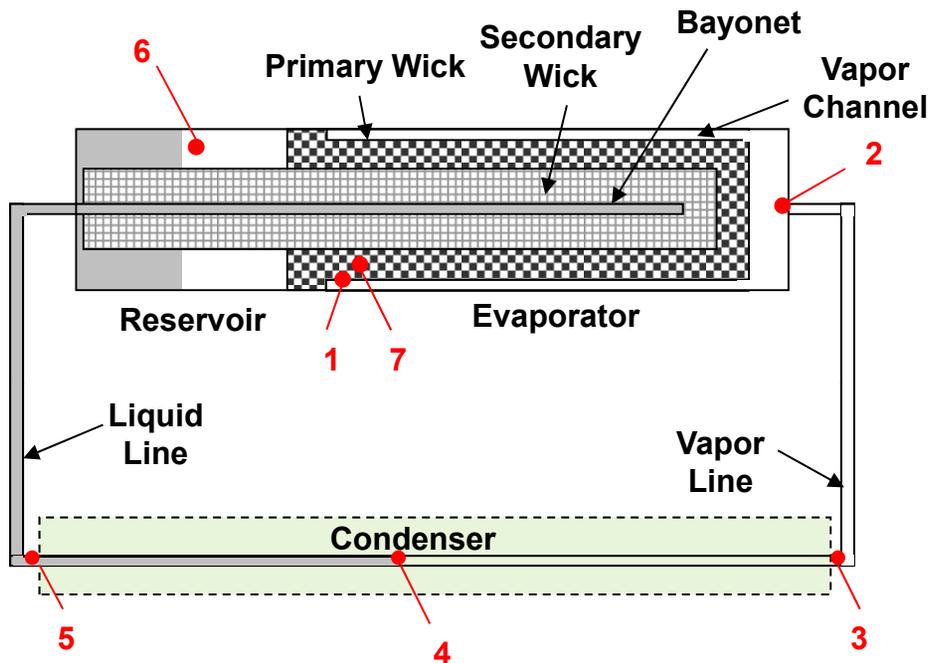
$$\Delta P_{\text{cap}} = \Delta P_{\text{tot}} \quad (4)$$

- The following relation must be satisfied at all times for proper LHP operation:

$$\Delta P_{\text{tot}} \leq \Delta P_{\text{cap, max}} \quad (5)$$



Pressure Profile in Gravity-Neutral LHP Operation Capillary Force Driven



- Evaporator core is considered part of reservoir.
- P_6 is the reservoir saturation pressure.
- All other pressures are governed by P_6
- All pressure drops are viscous pressure drops.



Thermodynamic Constraints in LHP Operation (1)

- For the working fluid in a saturation state, there is a one-to-one correspondence between the saturation temperature and the saturation pressure.
- There are three LHP elements where the working fluid exists in a two-phase state, i.e. evaporator, condenser and reservoir.
- There is a thermodynamic constraint between any two of the above-mentioned three elements, i.e. the pressure drop and the temperature drop between any two elements are thermodynamically linked. E.G.

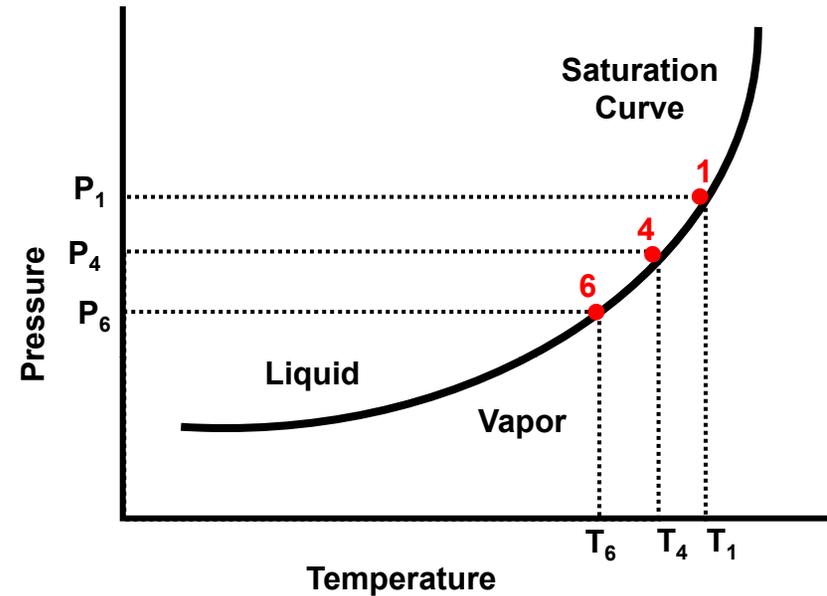
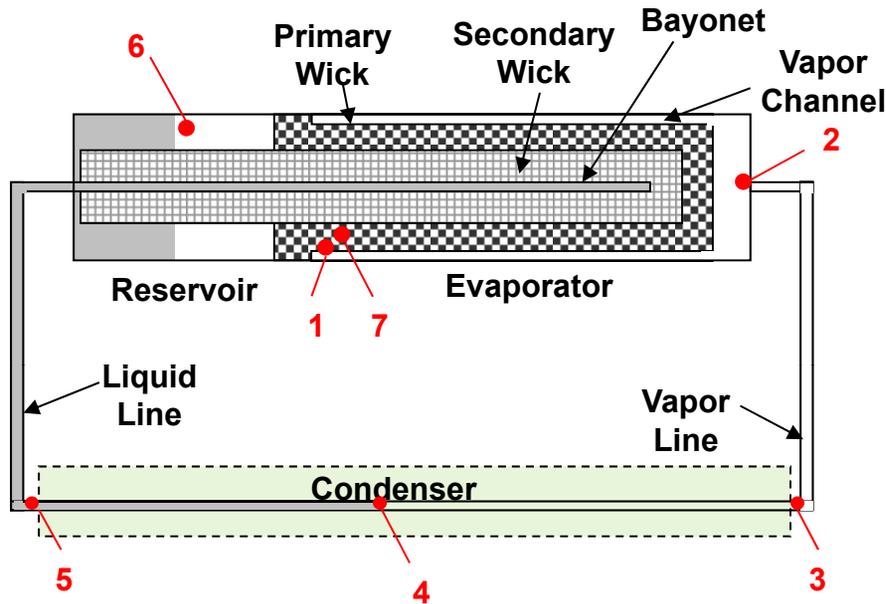
$$P_E - P_{cc} = (dP/dT) (T_E - T_{cc})$$

- The derivative dP/dT can be related to physical properties of the working fluid by the Clausius-Clapeyron equation:

$$dP/dT = \lambda / (T_{cc} \Delta v)$$



Thermodynamic Constraints in LHP Operation (2)



$$P_E - P_{\text{cond}} = (dP/dT) (T_E - T_{\text{cond}})$$

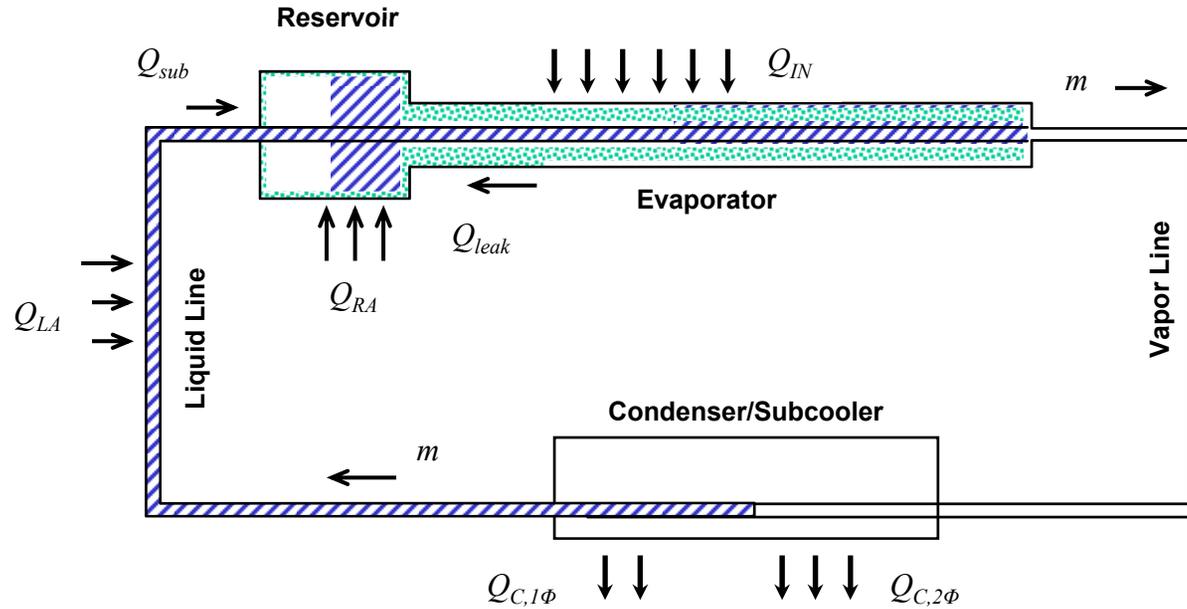
$$P_{\text{cond}} - P_{\text{cc}} = (dP/dT) (T_{\text{cond}} - T_{\text{cc}})$$

$$P_E - P_{\text{cc}} = (dP/dT) (T_E - T_{\text{cc}})$$

- Gravity affects the pressure drop, and hence the temperature difference.



LHP Operating Principles – Energy Balance



$$Q_{IN} = Q_E + Q_L$$

$$Q_L = G_{E,CC} (T_E - T_{CC})$$

$$Q_E = m \lambda$$

$$Q_{C,2\phi} = m \lambda = 2\pi D_c L_{c,2\phi} h_{c,2\phi} (T_{CC} - T_{c,wall})$$

$$T_{c,out} = f(m, L_{c,2\phi}, T_{c,wall})$$

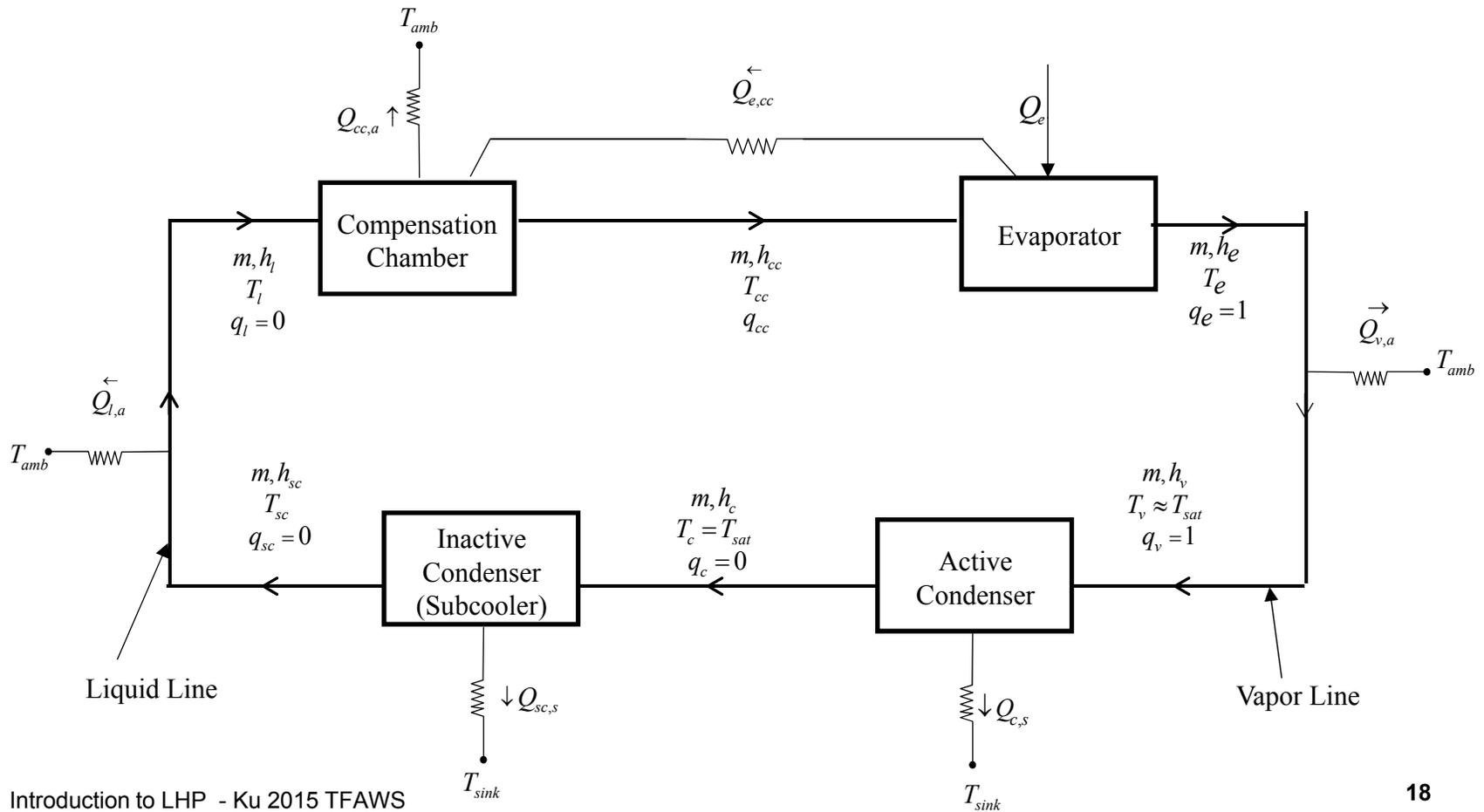
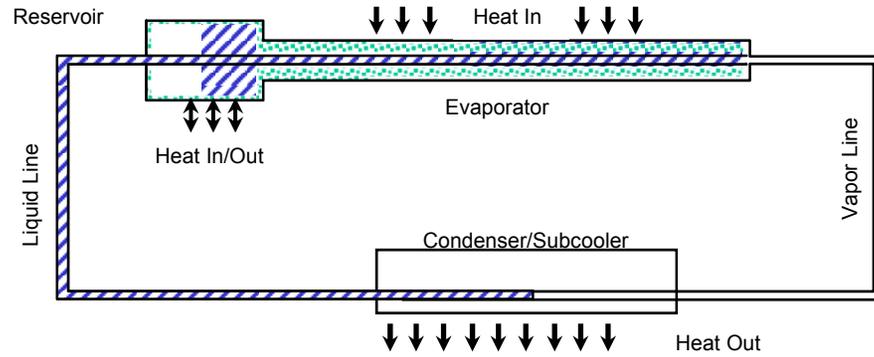
$$T_{IN} = f(T_{c,out}, m, L_{LL}, D_{LL}, T_{amb})$$

$$Q_{sub} = m C_P (T_{CC} - T_{IN})$$

$$Q_{leak} - Q_{sub} + Q_{RA} = 0$$



Simplified LHP Thermal Network





LHP Reservoir Sizing and Fluid Inventory

- The fluid inventory must satisfy the following relation under the cold start-up/operation ($\beta > 0$):

$$M = \rho_{l,c} (V_{loop} + \beta V_{cc}) + \rho_{v,c} (1 - \beta) V_{cc}$$

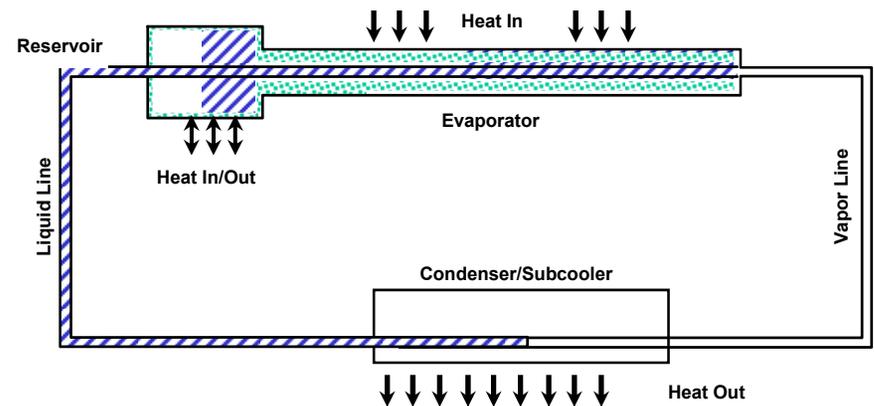
V_{loop} = Loop volume excluding CC

- The fluid inventory must also satisfy the following relation under the hot operating condition ($\alpha > 0$):

$$M = \rho_{l,h} [V_{liq} + V_{pw} + V_{sw} + (1 - \alpha) V_{cc}] + \rho_{v,h} (V_{gr} + V_{vap} + V_{con} + \alpha V_{cc})$$

- The values of α and β , selected at the designer's discretion, determine V_{cc} and M .
- The loop must contain all liquid volume at the maximum non-operating temperature:

$$M \leq \rho_{l, max} (V_{loop} + V_{cc})$$





ICESat-2 ATLAS LHP Charge Analysis

15% Fill in Cold Case

- Charge to maintain 15% CC fill fraction in the cold case startup conditions
- LHP requires 193.4 grams of ammonia

	Volume				Cold Start-up					Non-Operating Case					Operating Hot Case				
	in3	cc	in3	cc	liquid fraction	temp K	liquid dens gm/cc	vapor dens gm/cc	mass gms	liquid fraction	temp K	liquid dens gm/cc	vapor dens gm/cc	mass gms	liquid fraction	temp K	liquid dens gm/cc	vapor dens gm/cc	mass gms
Evaporator (vapor)	0.43	7.1	0.4	7.1	1.00	268	0.65	0.0029	4.6	1.00	333	0.54	0.0213	3.8	0.00	313	0.57	0.0126	0.1
Evaporator (liquid)	4.67	76.5	4.7	76.5	1.00	268	0.65	0.0029	49.5	1.00	333	0.54	0.0213	41.1	1.00	313	0.57	0.0126	43.6
Liquid Core	0.69	11.2	0.7	11.2	1.00	268	0.65	0.0029	7.3	1.00	333	0.54	0.0213	6.0	1.00	313	0.57	0.0126	6.4
Vapor transport line	1.28	21.0	1.3	21.0	1.00	233	0.69	0.0007	14.0	1.00	333	0.54	0.0213	11.3	0.00	313	0.57	0.0126	0.3
Condenser	4.92	80.6	4.9	80.6	1.00	233	0.69	0.0007	55.4	1.00	333	0.54	0.0213	43.3	0.12	313	0.57	0.0126	6.2
Liquid Transport Line	2.00	32.8	2.0	32.8	1.00	233	0.69	0.0007	21.9	1.00	333	0.54	0.0213	17.6	1.00	313	0.57	0.0126	18.7
Hydro-accumulator Wicks Liquid	0.24	3.9	0.2	3.9	1.00	268	0.65	0.0029	2.5	1.00	333	0.54	0.0213	2.1	1.00	313	0.57	0.0126	2.2
Hydro-accumulator Free Volume	23.50	385.1	23.5	385.1	0.15	268	0.65	0.0029	38.3	0.302	333	0.54	0.0213	68.2	0.518	313	0.57	0.0126	116.0
TOTAL	37.72	618.27	37.7	618.3					193.4					193.4					193.4

- 15% required reservoir liquid fraction at cold startup ($\beta = 0.15$)
- Design has 70% void volume in hot non-operational (processing) case at 60C
- 51.8% max fill at hot operating condition ($\alpha = 0.482$)

Typical values:

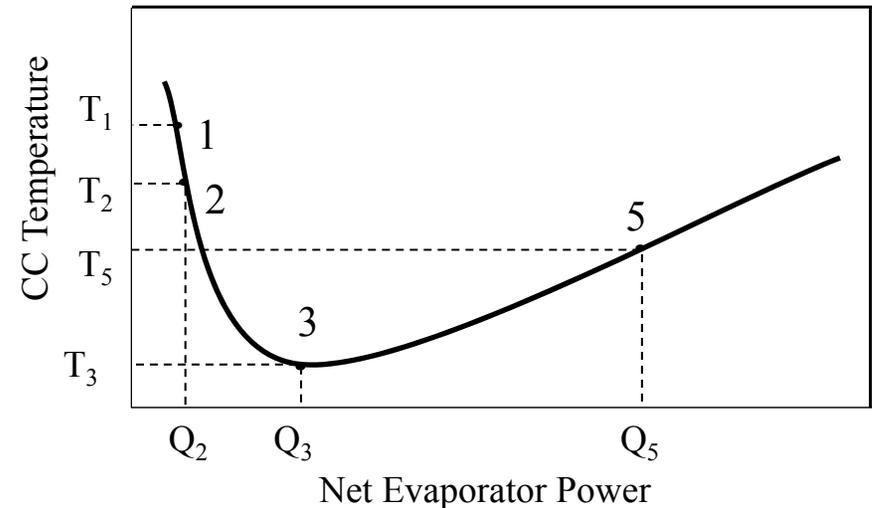
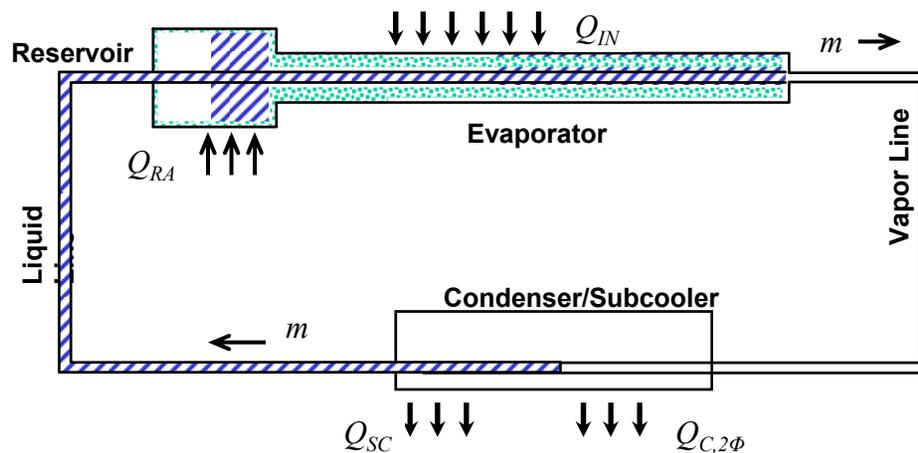
$\alpha \geq 0.15$ (≤ 0.85 liquid fraction)

$\beta \geq 0.15$ (0.15 liquid fraction)



LHP Operating Temperature

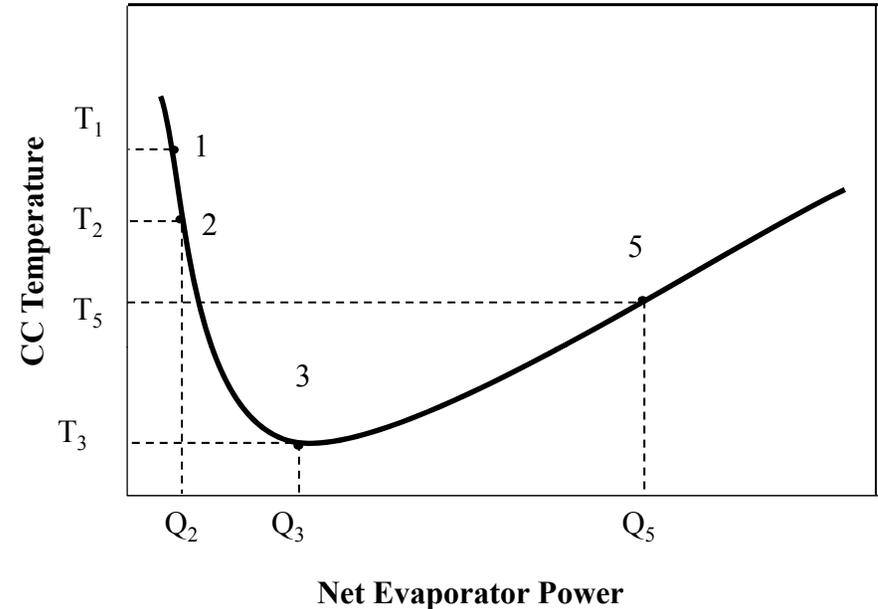
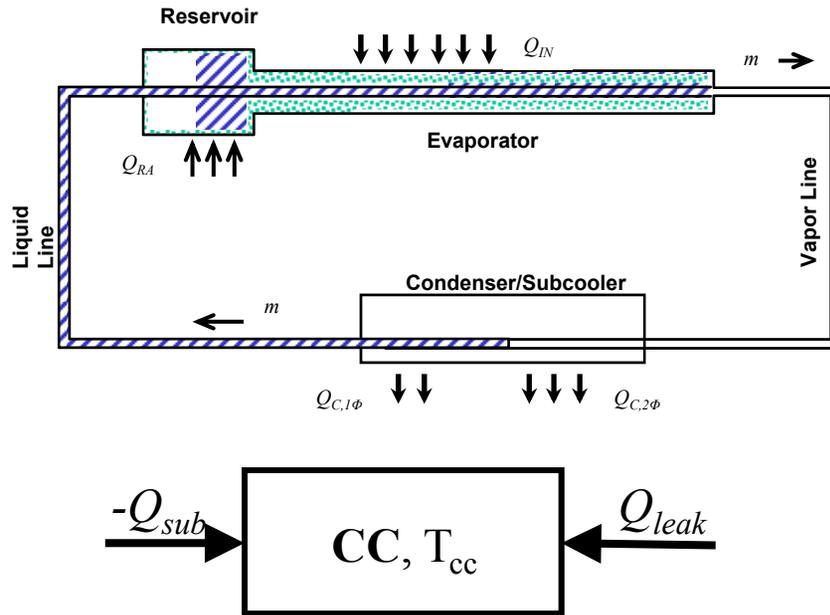
- The LHP operating temperature is governed by the CC saturation temperature.
- The CC temperature is a function of
 - Evaporator power
 - Condenser sink temperature
 - Ambient temperature
 - Evaporator/CC assembly design
- As the operating condition changes, the CC temperature will change during the transient, but eventually reaches a new steady temperature.





LHP Operating Temperature

No Active Control of CC Temperature



$$Q_{leak} - Q_{sub} = 0$$

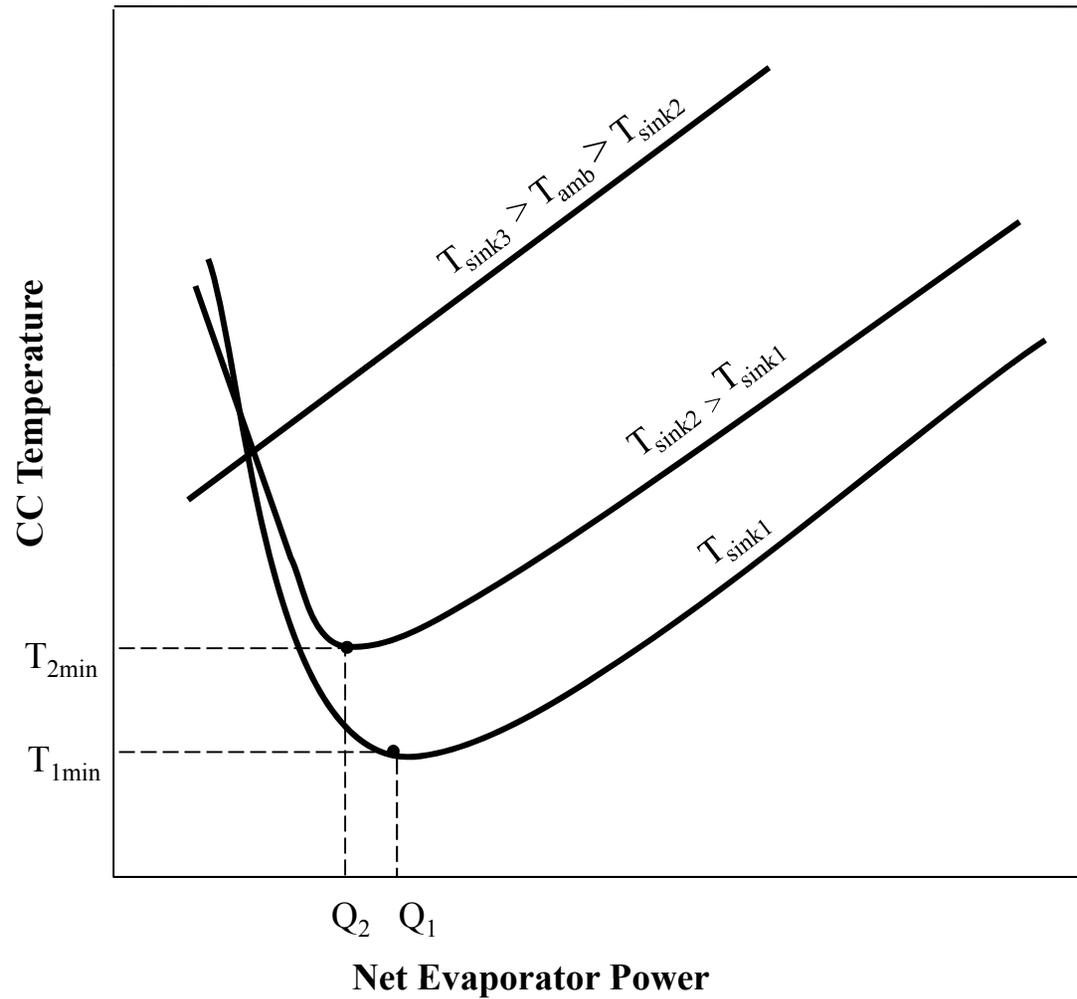
$$Q_{leak} = G_{E,cc}(T_E - T_{cc})$$

$$Q_{sub} = \dot{m}C_p(T_{cc} - T_{in})$$

- For a well insulated CC, T_{cc} is determined by energy balance between heat leak and liquid subcooling.
- T_{cc} changes with the evaporator power, condenser sink temperature, and ambient temperature.

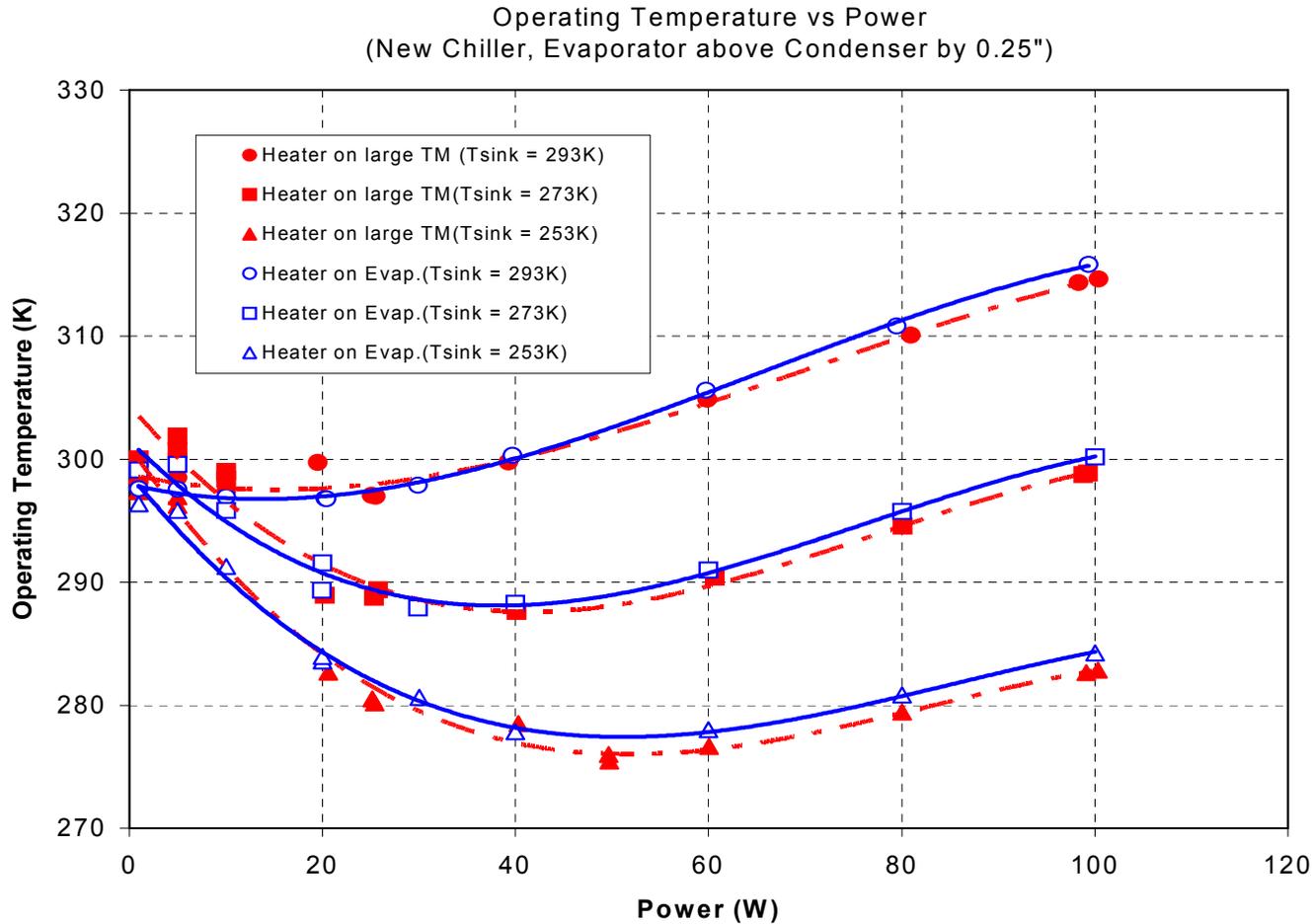


Effect of Sink Temperature on CC Temperature - Theory



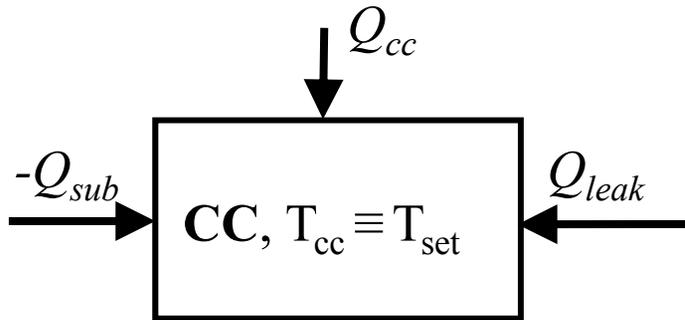


Ground Test Results of Thermacore miniLHP at Various Sink Temperatures



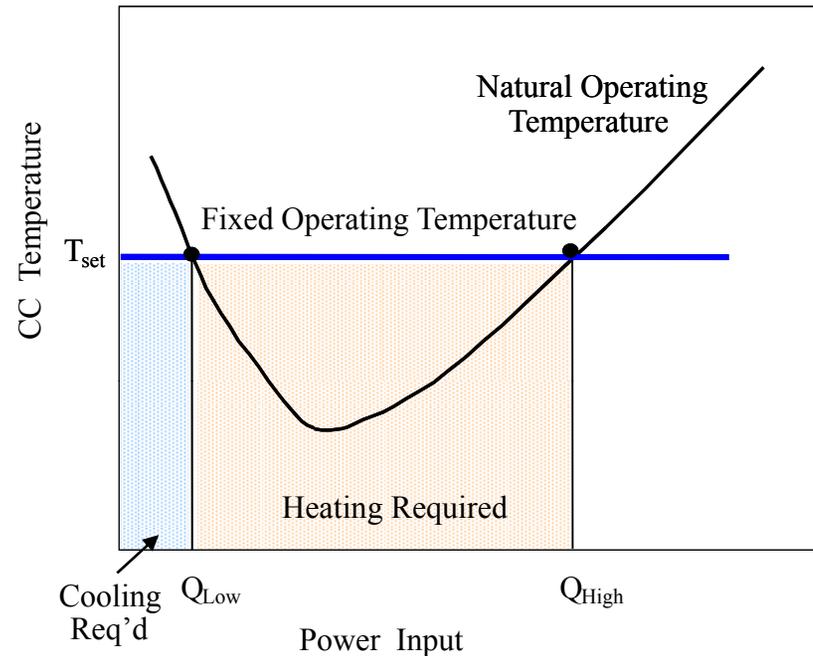


LHP Operating Temperature CC Temperature Controlled at T_{set}



$$Q_{leak} - Q_{sub} + Q_{cc} = 0$$

$$Q_{cc} = Q_{sub} - Q_{leak}$$



- **CC is cold biased, and electrical heaters are commonly used to maintain T_{cc} at T_{set} .**
- **Overall thermal conductance decreases.**
- **Q_{cc} varies with Q_{sc} , which in turns varies with evaporator power, condenser sink temperature, ambient temperature and number of coupling blocks.**
- **Q_{cc} can be large under certain operating conditions.**
- **Electrical heaters can only provide heating, not cooling, to CC.**

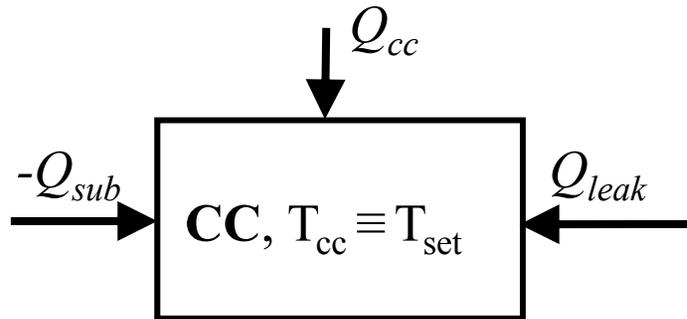


LHP Temperature Control Methods

- **All methods involve cold-biasing the CC and use external heat source to maintain CC temperature**
 - **Electric heater on CC only (Aura TES, GOES-R GLM)**
 - **Electric heater on CC and coupling blocks placed between vapor and liquid lines (ICESat GLAS)**
 - **Electric heater on CC and VCHP connecting the evaporator and liquid line (Swift BAT)**
 - **Pressure regulator on the vapor line with a bypass to liquid line (AMS)**
 - **TEC on CC with thermal strap connecting to the evaporator (heating and active cooling) – no electric heater (ST8)**
 - **Heat exchanger and separate subcooler (GOES-R ABI, ICESat-2 ATLAS)**

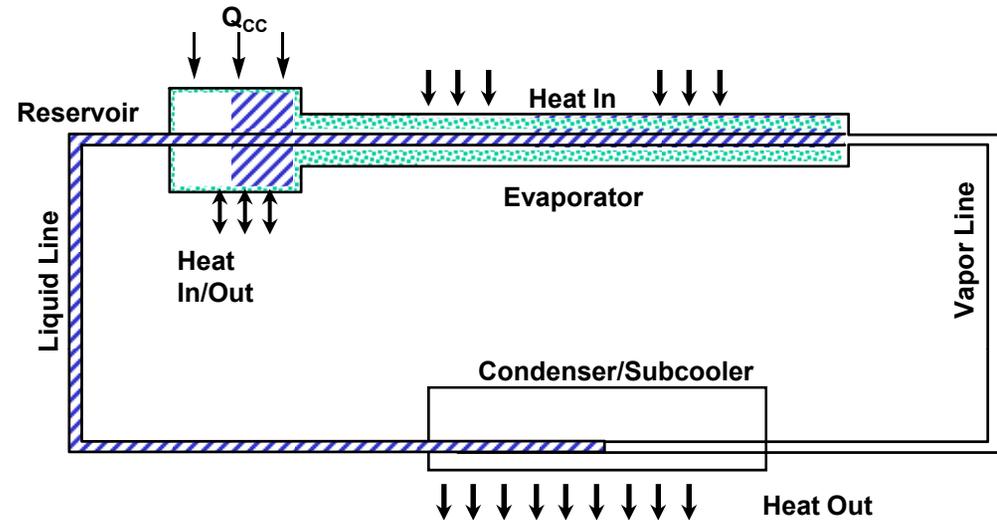


LHP Operating Temperature Control Electric Heater on CC



$$Q_{leak} - Q_{sub} + Q_{cc} = 0$$

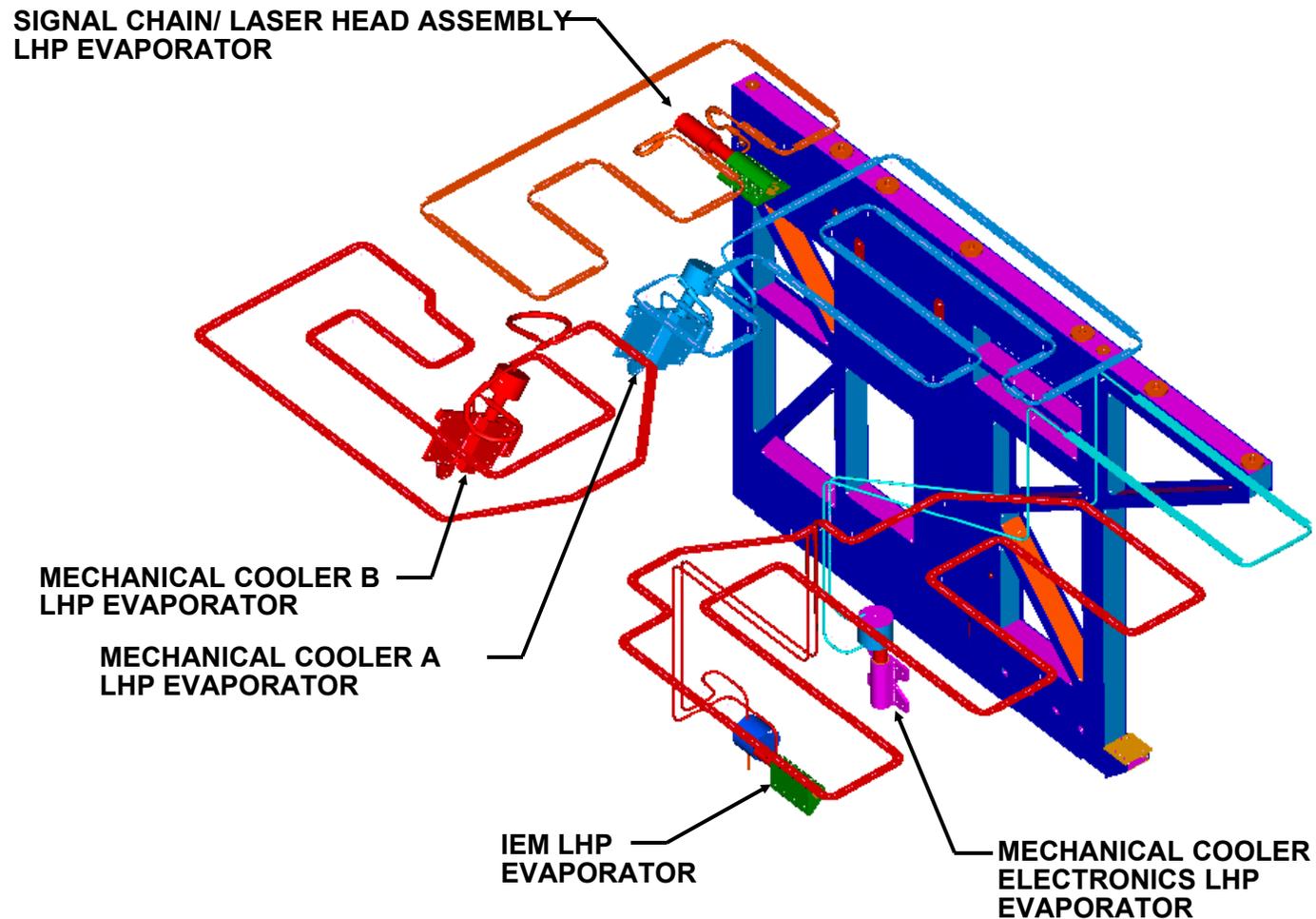
$$Q_{cc} = Q_{sub} - Q_{leak}$$



- **The electrical heater attached to the CC provides the necessary control heater power to the CC.**
- **Advantages: simplicity, direct heating**
- **Disadvantage: required control heater power could be large.**

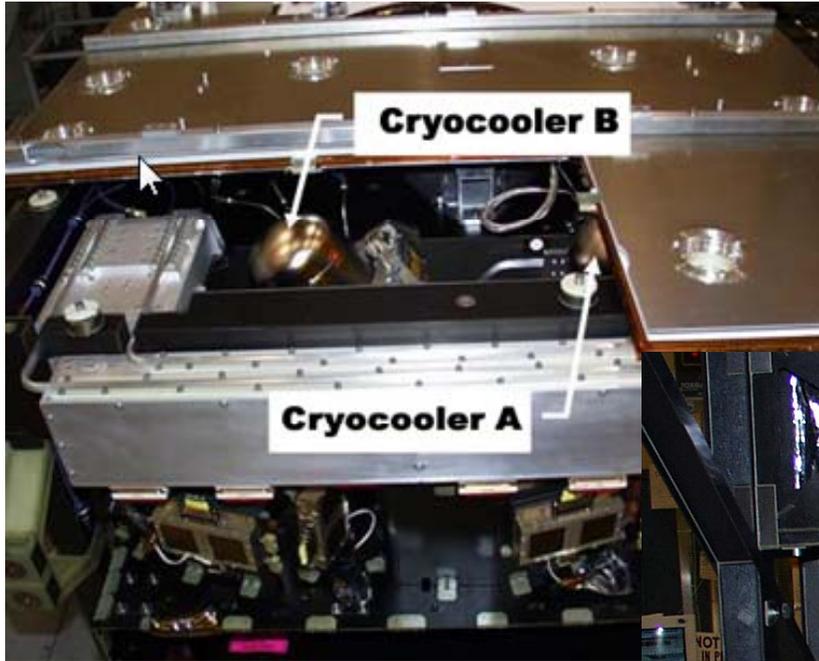


EOS-Aura Tropospheric Emission Spectrometer (TES) Instrument Loop Heat Pipe Layout

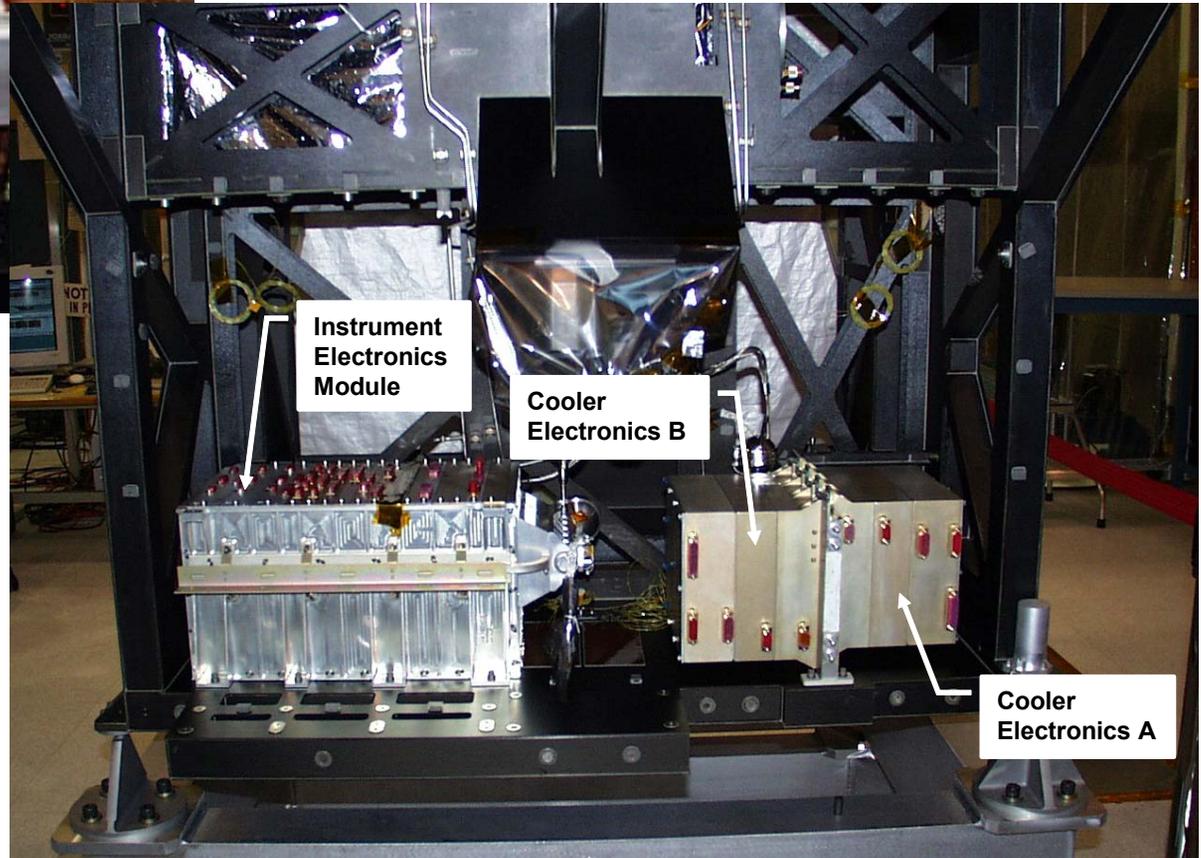




Tropospheric Emission Spectrometer (TES)

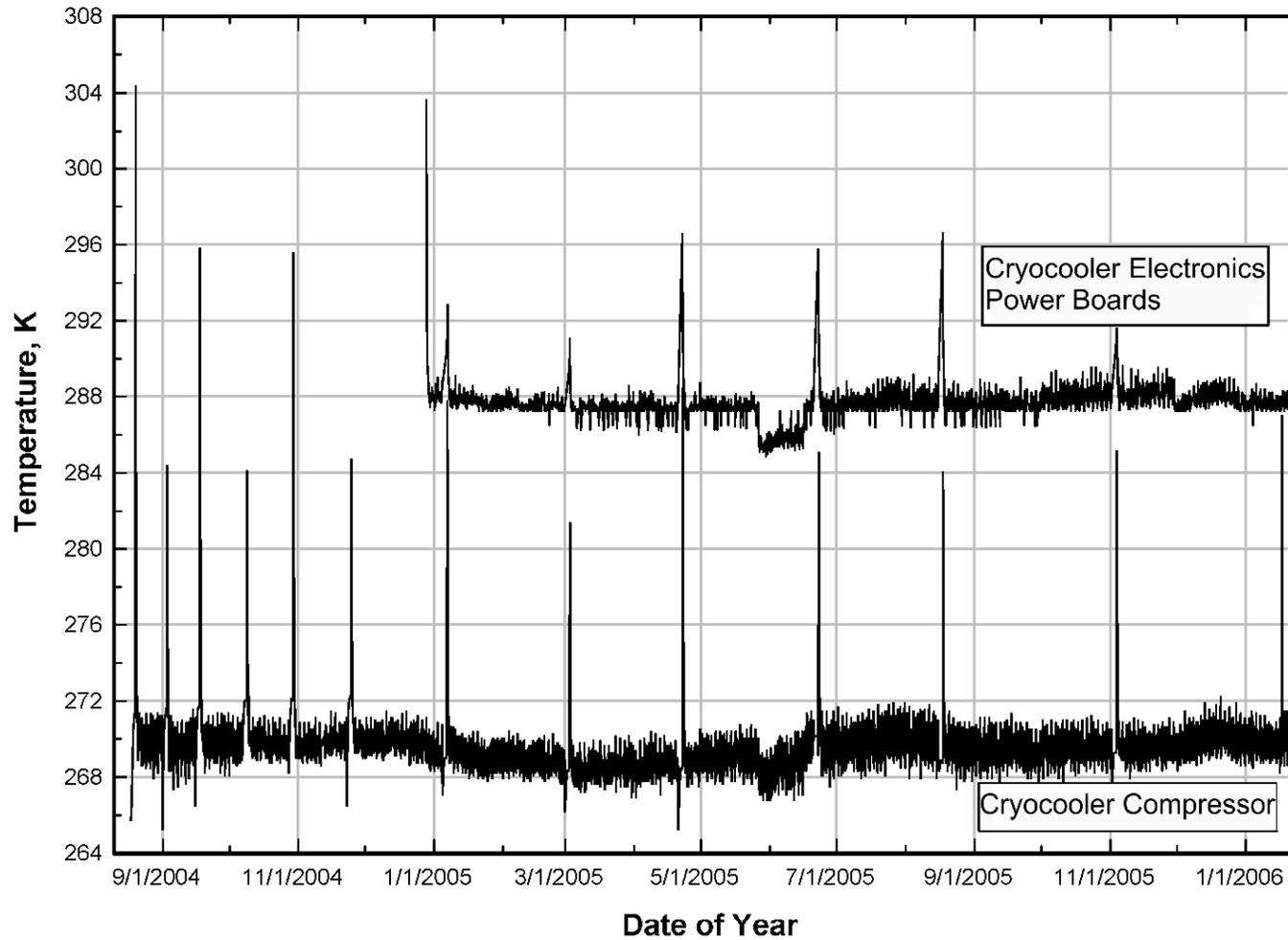


- CCHPs and LHPs manage equipment power dissipation from:
 - 2 Mechanical Cooler Compressors
 - Cooler electronics
 - Signal Chain and Laser Head electronics
 - Integrated Electronics Module (IEM)



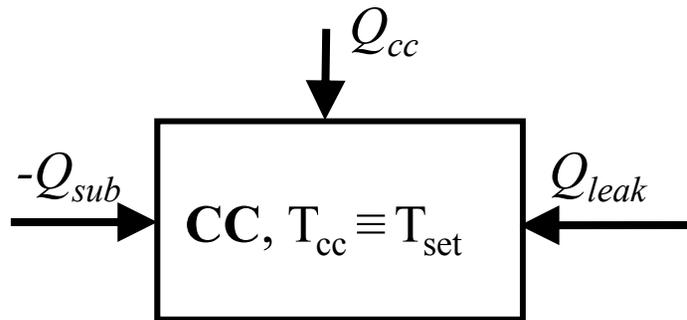


EOS-Aura TES Components Thermal Performance



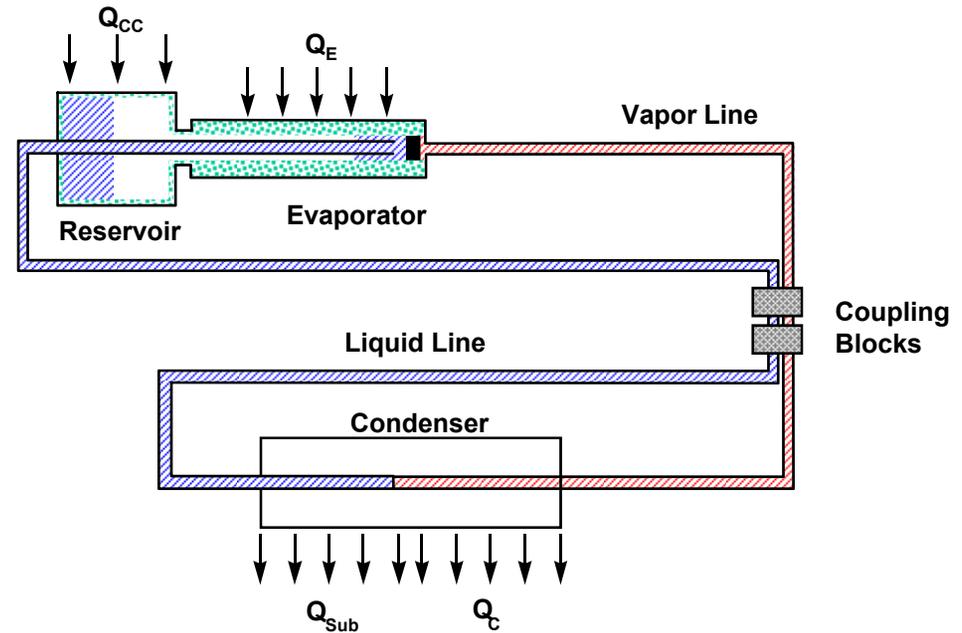


LHP Operating Temperature Control Use Coupling Blocks



$$Q_{leak} - Q_{sub} + Q_{cc} = 0$$

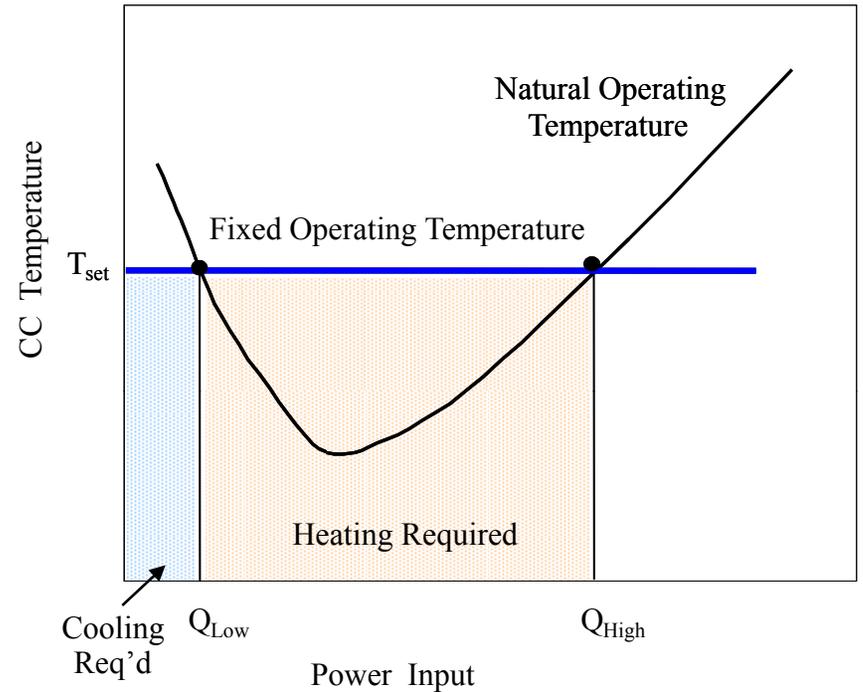
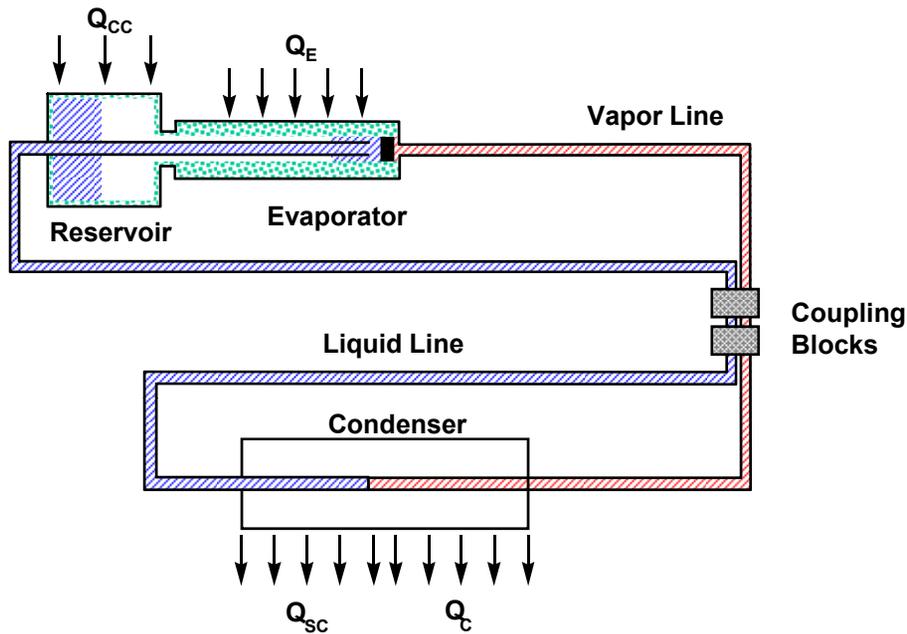
$$Q_{cc} = Q_{sub} - Q_{leak}$$



- The coupling blocks serve as a heat exchanger which transfers heat from the vapor line to the liquid line.
 - Re-distribution of LHP internal heat
- The reduction of liquid subcooling, Q_{sub} , leads to reduced Q_{cc} .
- The contact area of coupling blocks is determined by the LHP hot operational condition; the CC heater is then sized to accommodate the worst subcooling condition.



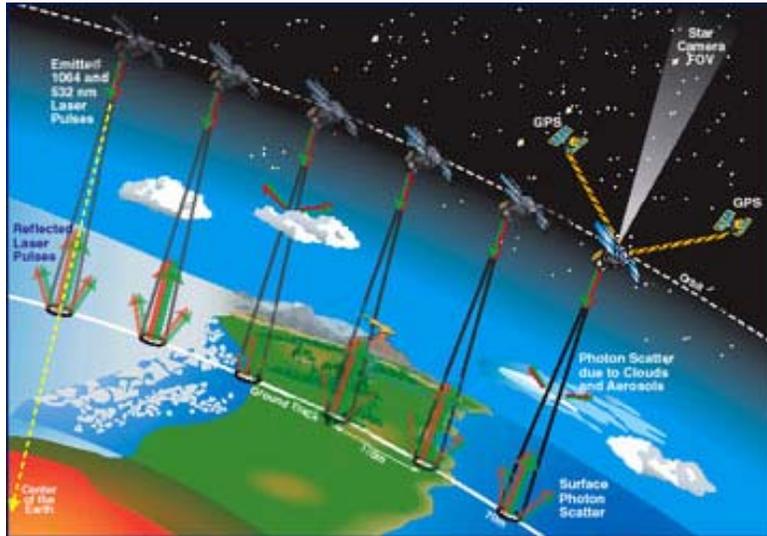
LHP Operating Temperature Control Use Coupling Blocks



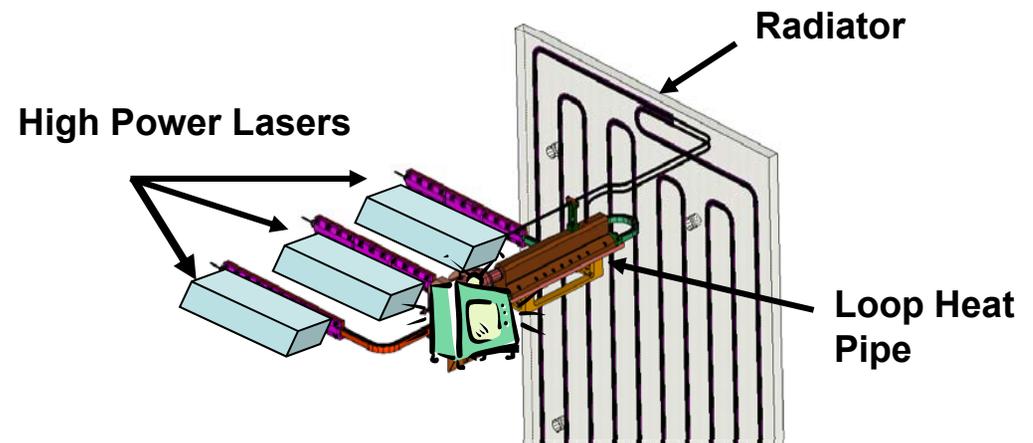
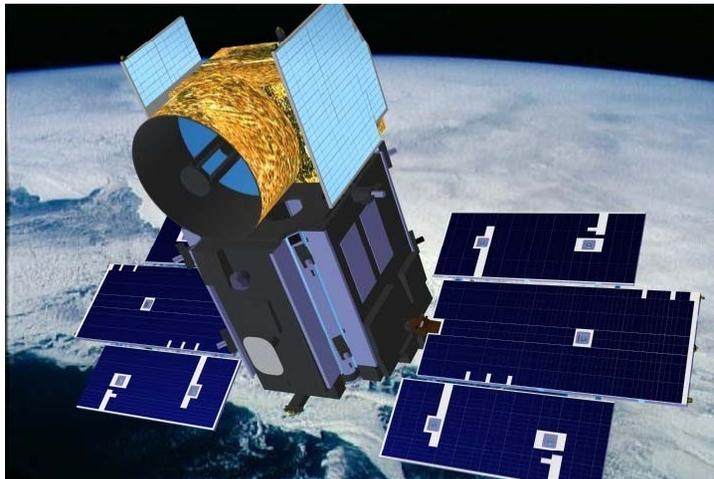
- **Advantages**
 - Easy to implement
 - Efficient in reducing CC control heater power
- **Disadvantages**
 - Increases the natural operating temperature at low and high powers
 - May add difficulty to low power start-up
 - May still require high CC control heater power under the cold condition.



LHPs on ICESat

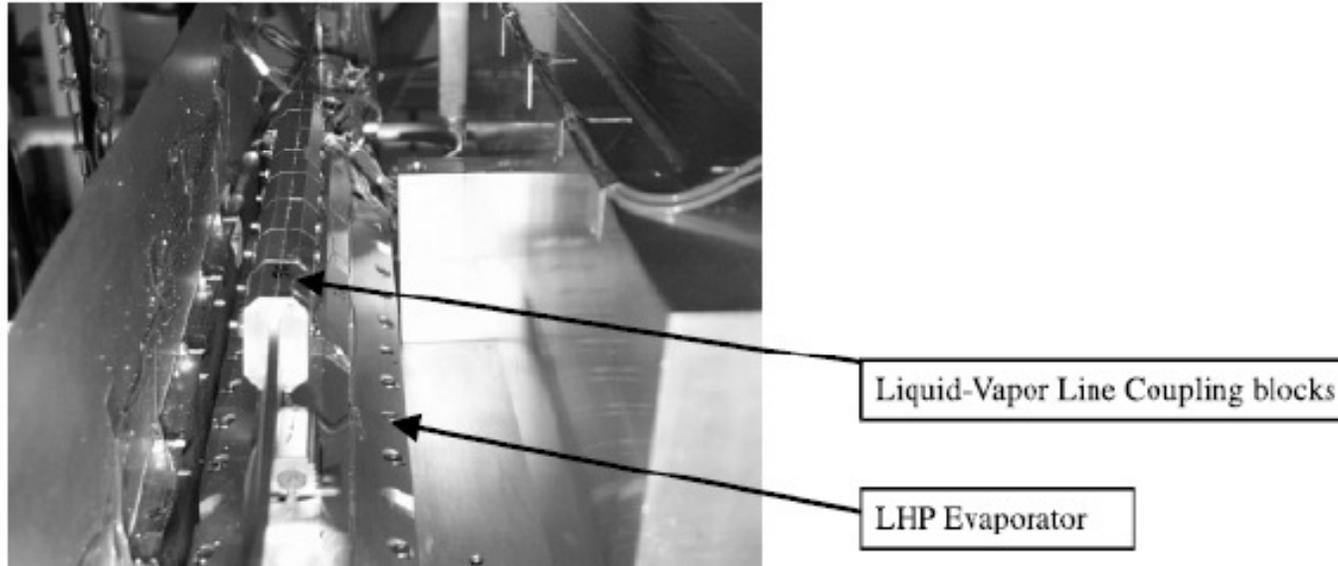


- GLAS has high powered lasers to measure polar ice thickness
- First known application of a two-phase loop to a laser
- 2 LHPs; Laser altimeter and power electronics
 - Propylene LHPs
- Launched January, 2003
- Both LHPs successfully turned on
- Very tight temperature control ~ 0.2 °C





Coupling Blocks on ICESat GLAS LHPs



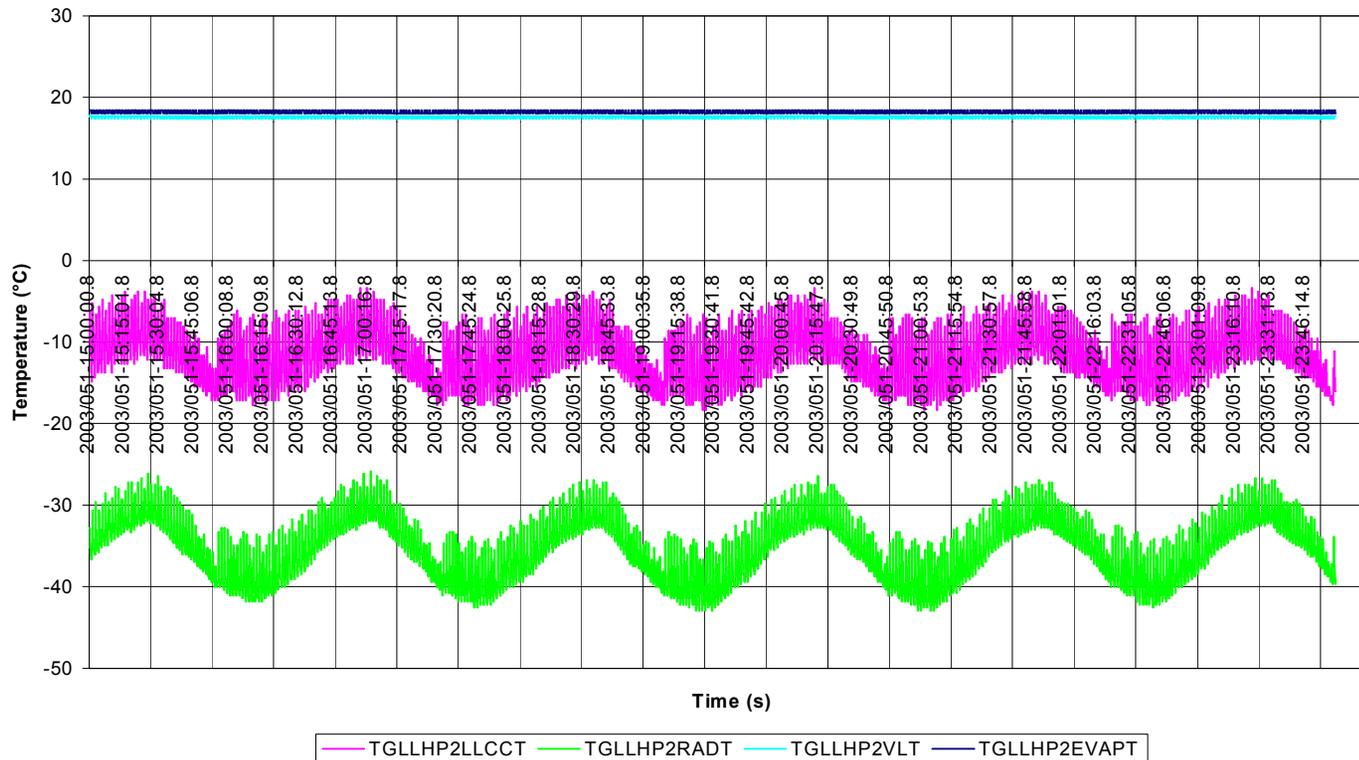
- **There are eight coupling blocks between the vapor and liquid lines for each LHP.**
 - Liquid subcooling is reduced by about one half.
- **The ICESat spacecraft was launched in January 2003.**
- **Both LHPs have been working very well.**



GLAS Laser Temperatures

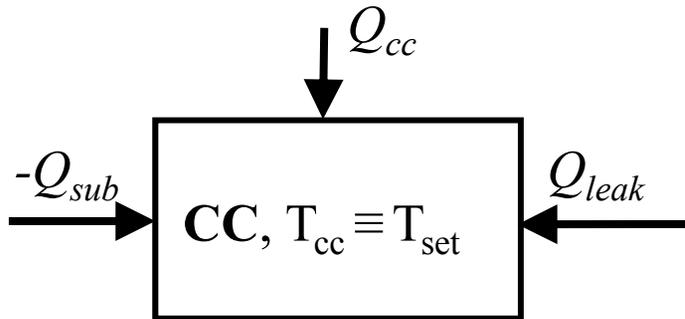
- LLHP active control is finer than can be measured in the laser telemetry when the LHP is at full 110 W of power

GLAS CLHP Transient Data 02/20/03 (Laser Turn-on, Turn off warmup heaters, all components powered)



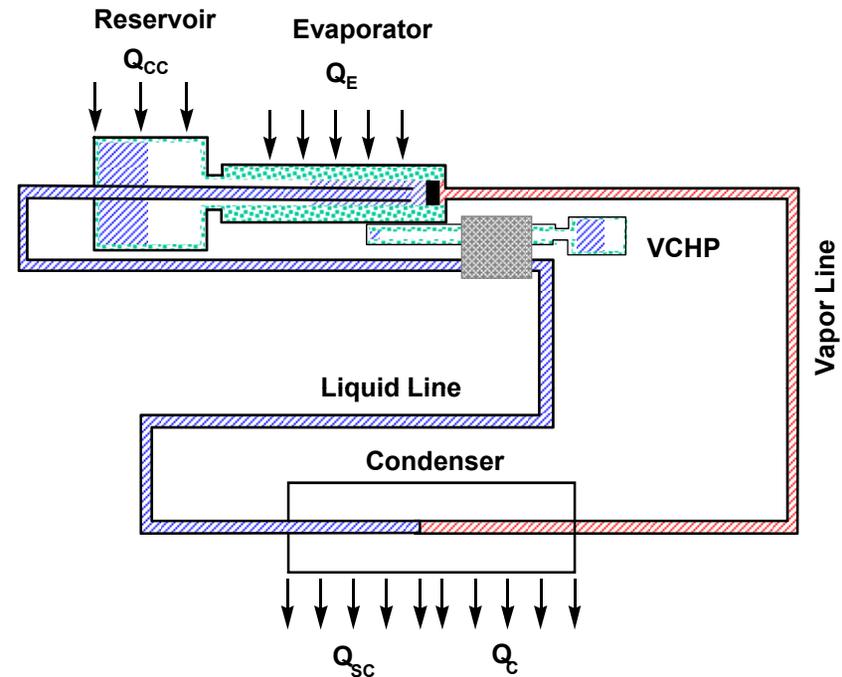


LHP Operating Temperature Control Use VCHP to Couple Evaporator and Liquid Line



$$Q_{leak} - Q_{sub} + Q_{cc} = 0$$

$$Q_{cc} = Q_{sub} - Q_{leak}$$

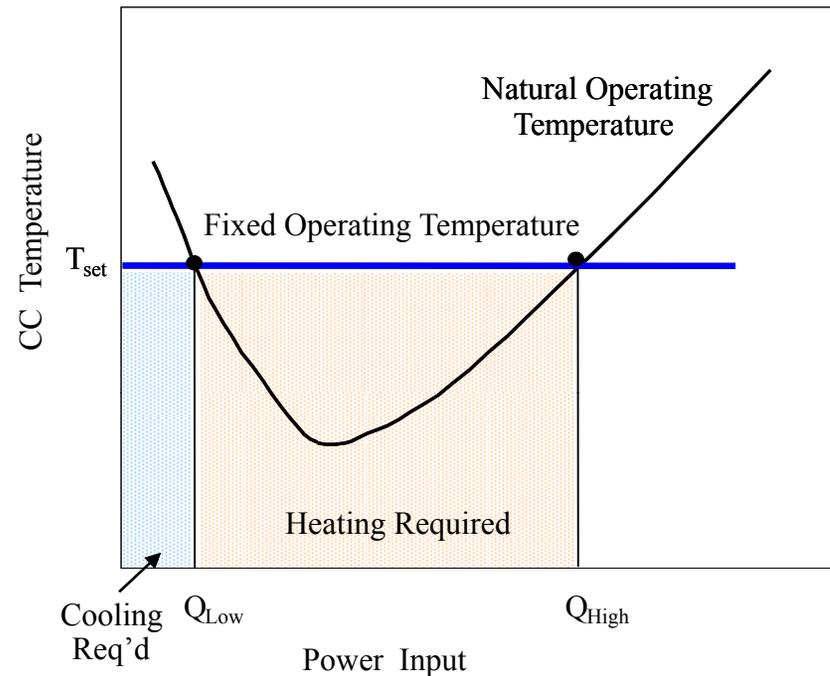
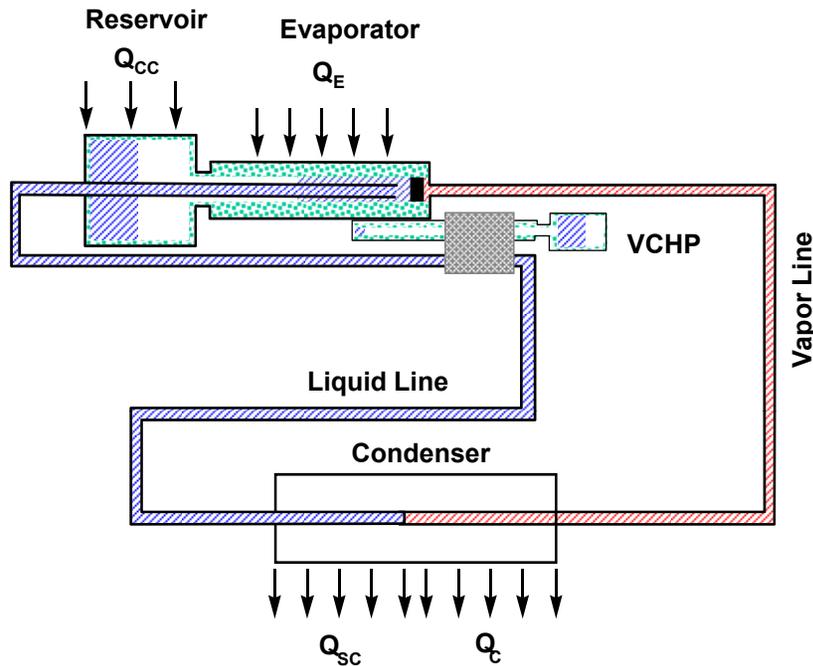


- The VCHP transmits heat from the evaporator to the liquid line when the return liquid is too cold, reducing the amount of liquid subcooling, Q_{sub} .
 - The required CC control heater power Q_{cc} is reduced.
- The VCHP is shut down when more subcooling is needed.



LHP Operating Temperature Control

Use VCHP to Couple Evaporator and Liquid Line

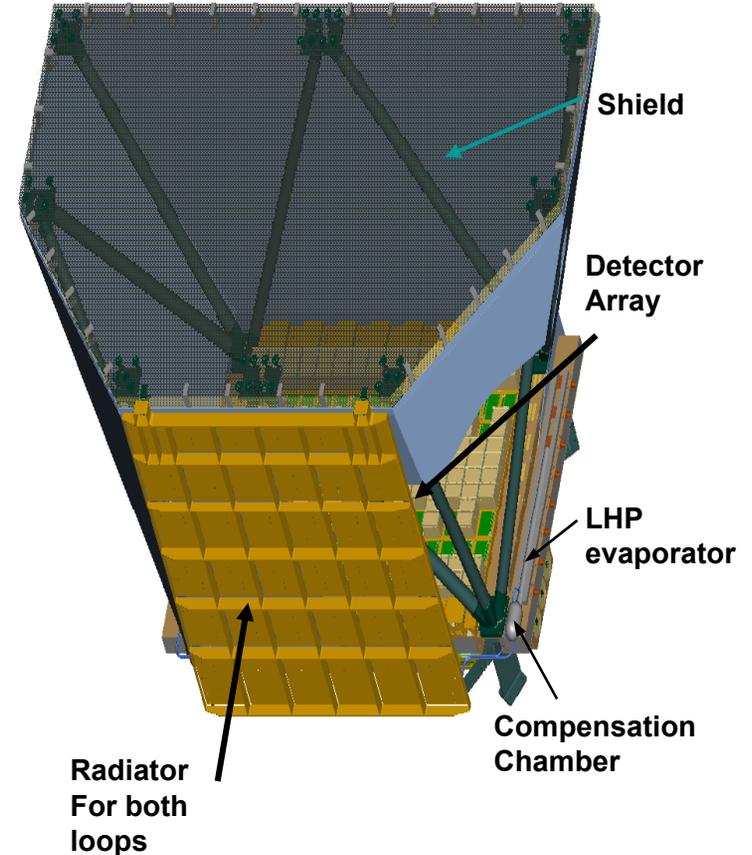
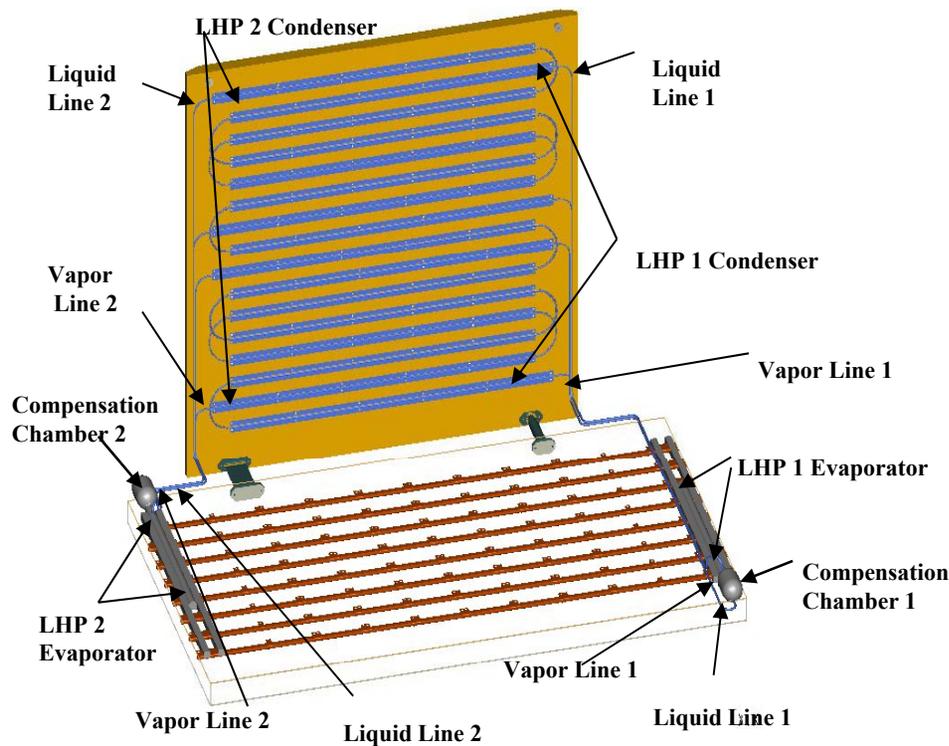


- **Advantage**
 - Active control of heating the liquid line versus passive heating when compared to the coupling blocks
- **Disadvantages**
 - Needs a VCHP, which may not be ground testable.
 - Needs an additional control device for the VCHP.
 - VCHP reservoir requires cold biasing.



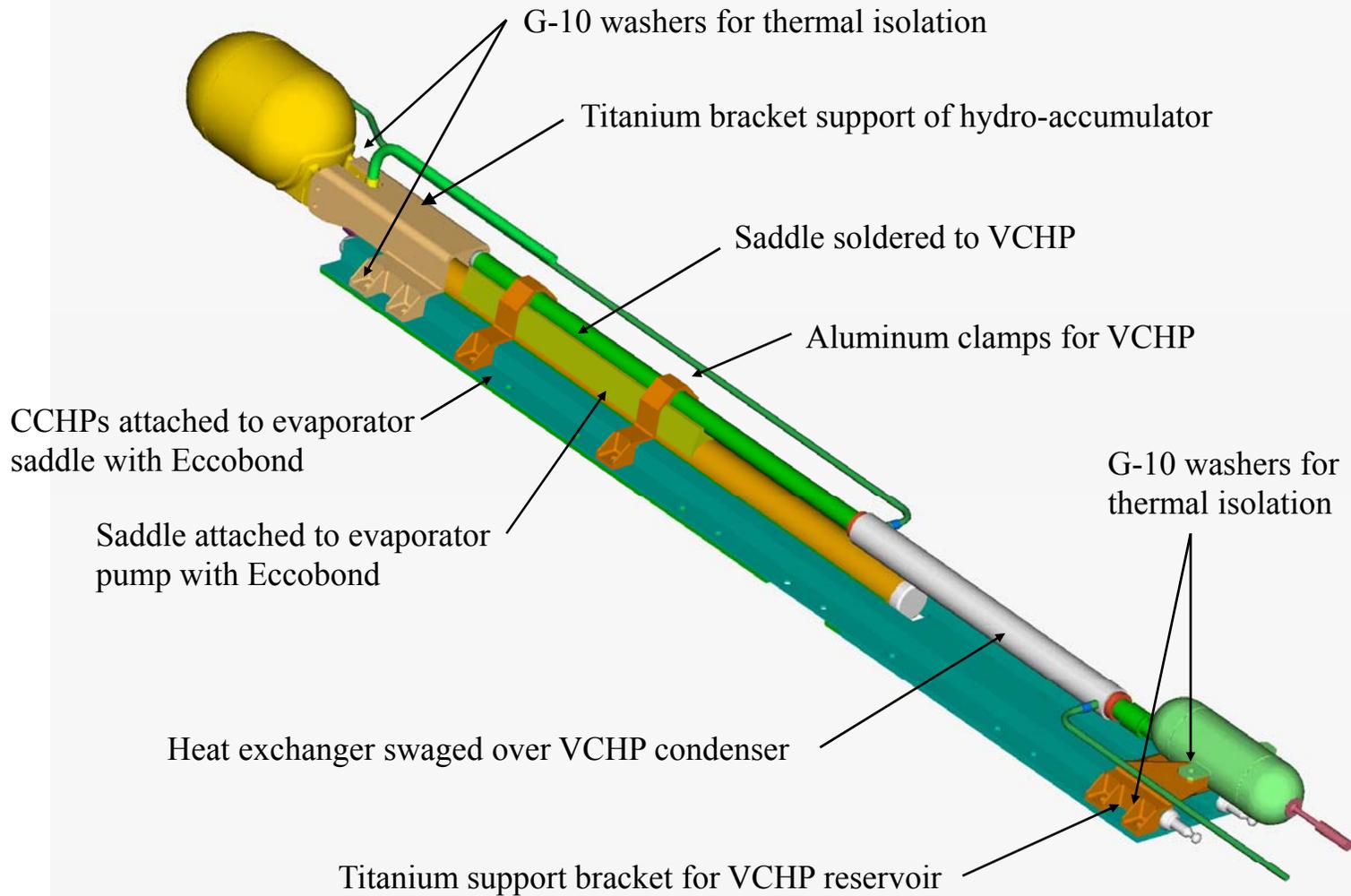
LHPs on SWIFT BAT

- **Burst Alert Telescope, a gamma ray detector array, is one of three instruments on Swift .**
- **Launched: November 20 , 2004**
- **Detector array has 8 CCHPs for isothermalization and transfer of 253 W to dual, redundant, LHPs located on each side.**



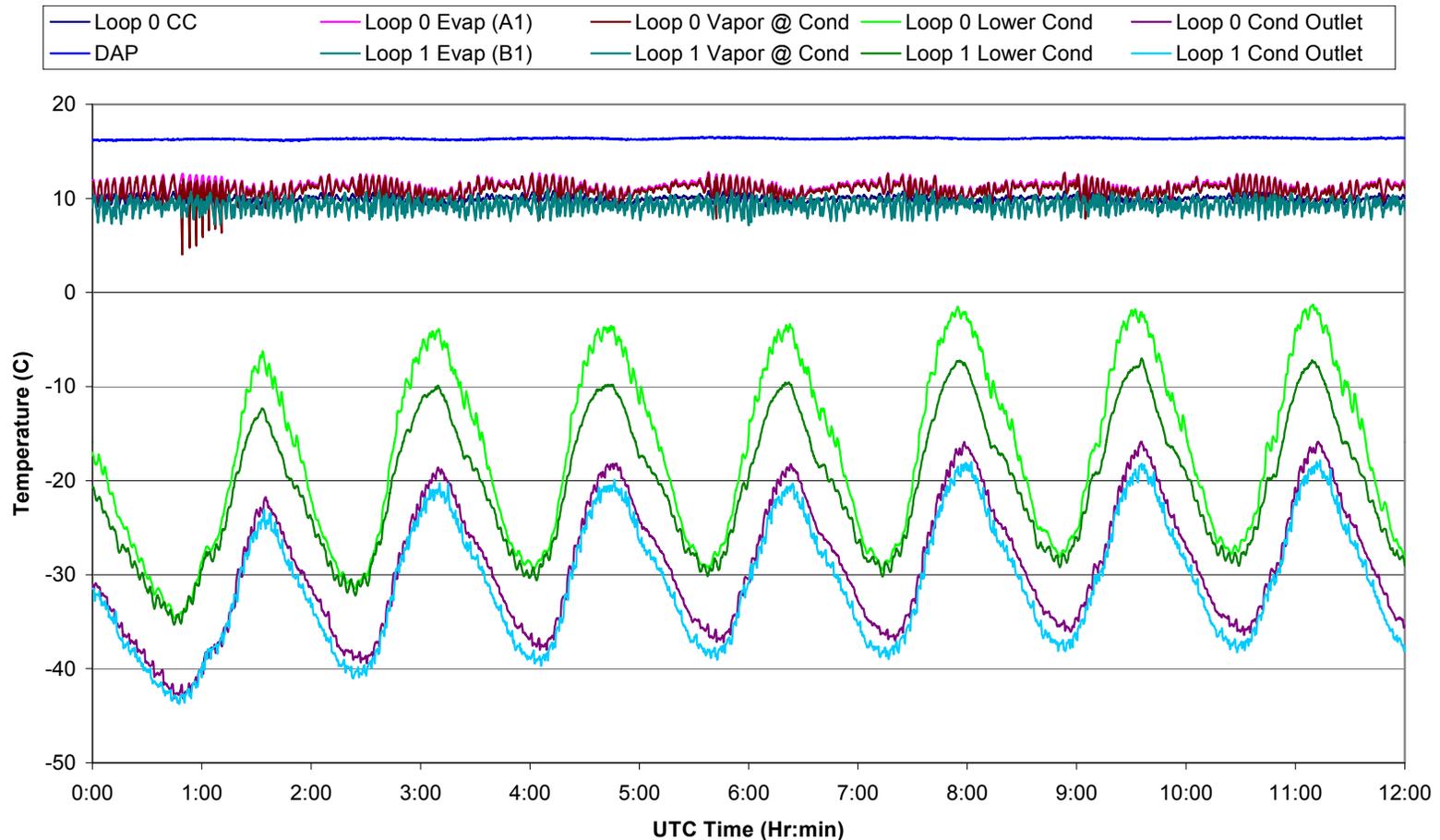


Swift BAT LHP Evaporator Assembly





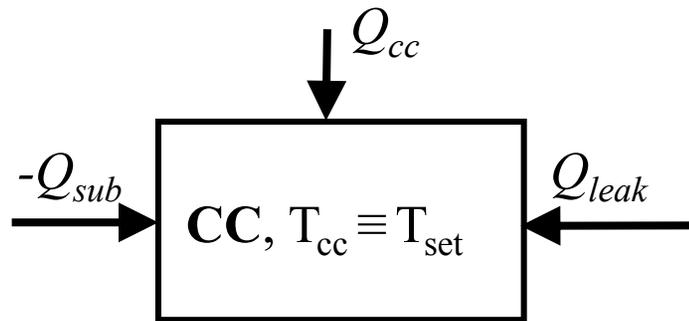
BAT Flight Data Both LHPs Day 013 (1/13/2005) Nominal Operation



- **Temperature fluctuations of detectors < 0.4 °C**
- **Frequent spacecraft slews have no noticeable effect on LHP operation.**
- **Flight results verify satisfactory operation of dual LHPs for tight temperature control.**

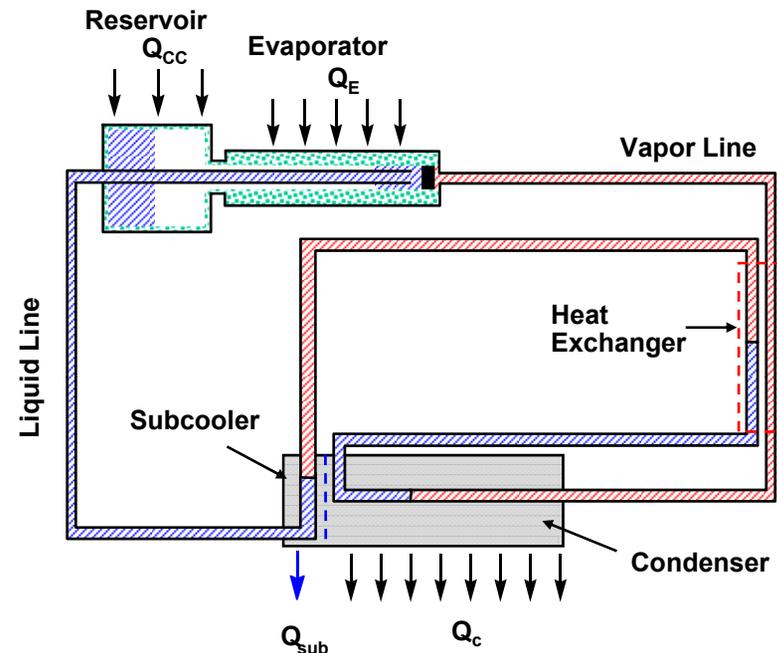


LHP Operating Temperature Control Use Heat Exchanger and Separate Subcooler



$$Q_{leak} - Q_{sub} + Q_{cc} = 0$$

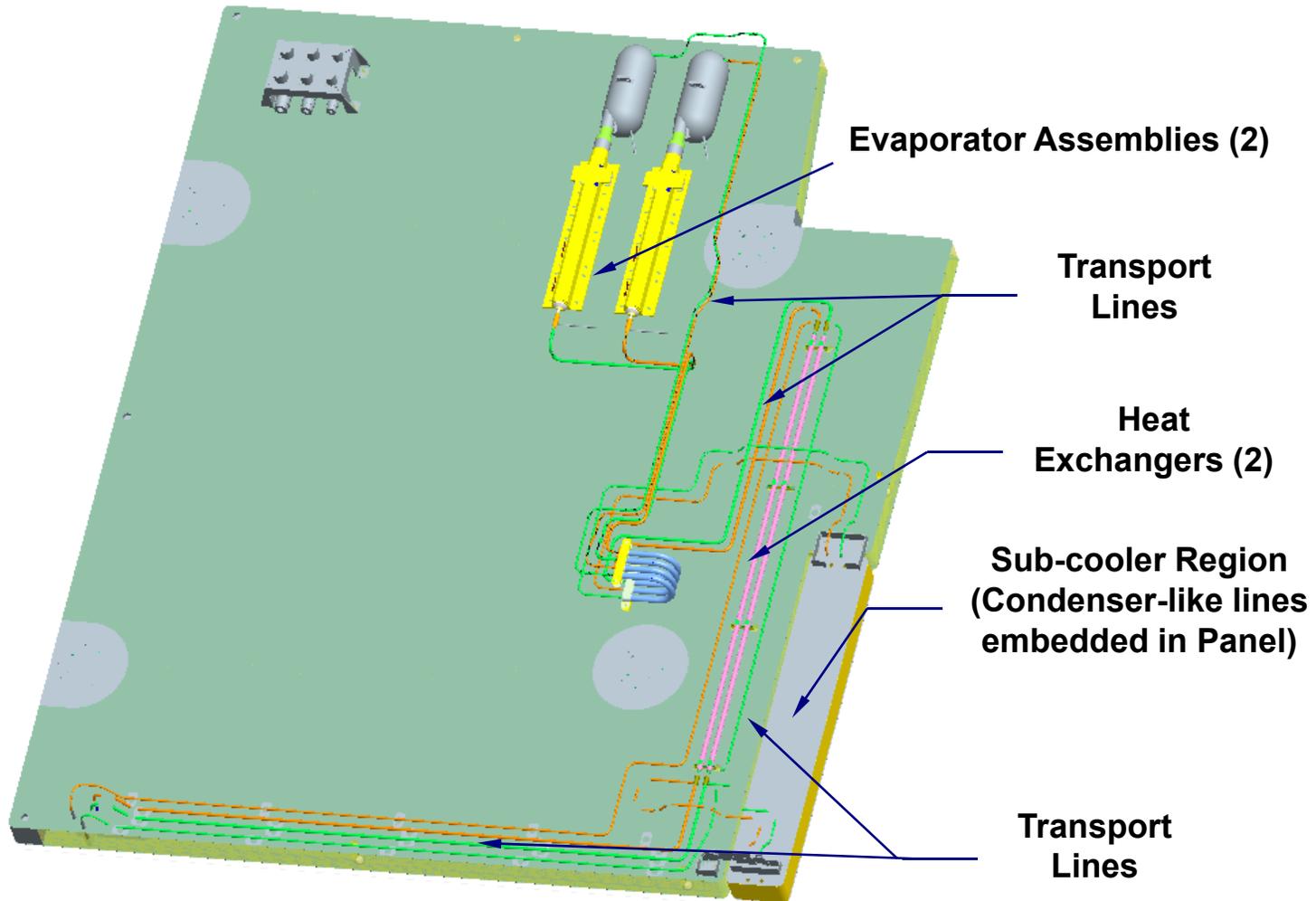
$$Q_{cc} = Q_{sub} - Q_{leak}$$



- The subcooler is separated from the condenser.
- The liquid line is coupled with the vapor line through a heat exchanger, where liquid is allowed to vaporize. The liquid line then enters the subcooler.
- With proper sizing, the heat exchanger will take away most of the subcooling, and the subcooler will provide slightly subcooled liquid to the CC.
- Results of TV testing of ABI LHPs indicate that the design meets the LHP temperature control and CC control heater power requirements.

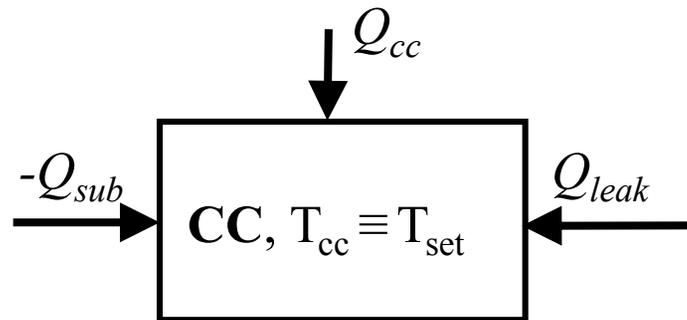


GOES-R ABI Radiator/LHP Assembly System Architecture



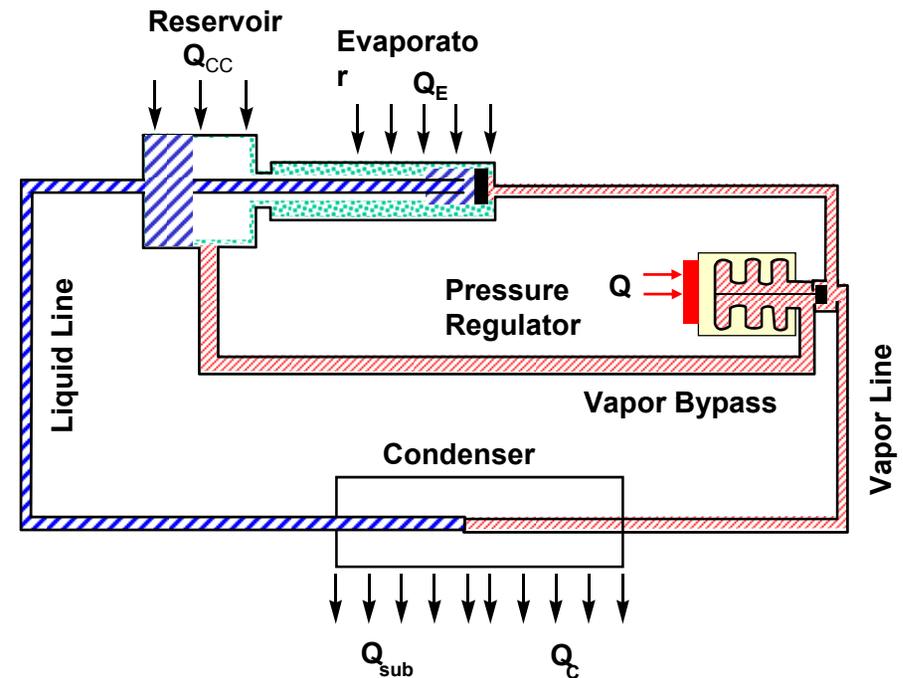


LHP Operating Temperature Control Use Pressure Regulator and Vapor Bypass



$$Q_{leak} - Q_{sub} + Q_{cc} = 0$$

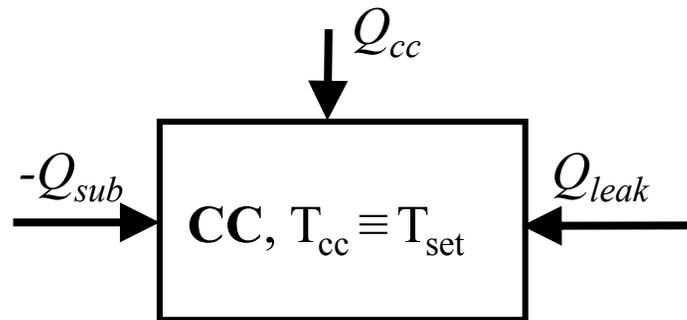
$$Q_{cc} = Q_{sub} - Q_{leak}$$



- The pressure regulator and vapor bypass valve allow some vapor to flow to the reservoir when needed.
 - Re-distribution of LHP internal heat
- The required reservoir control heater power Q_{cc} is reduced.
- Several variations of this approach.
 - Passive: no heater for bypass valve. A single set point temperature.
 - Active: bypass valve is controlled by an external heater.

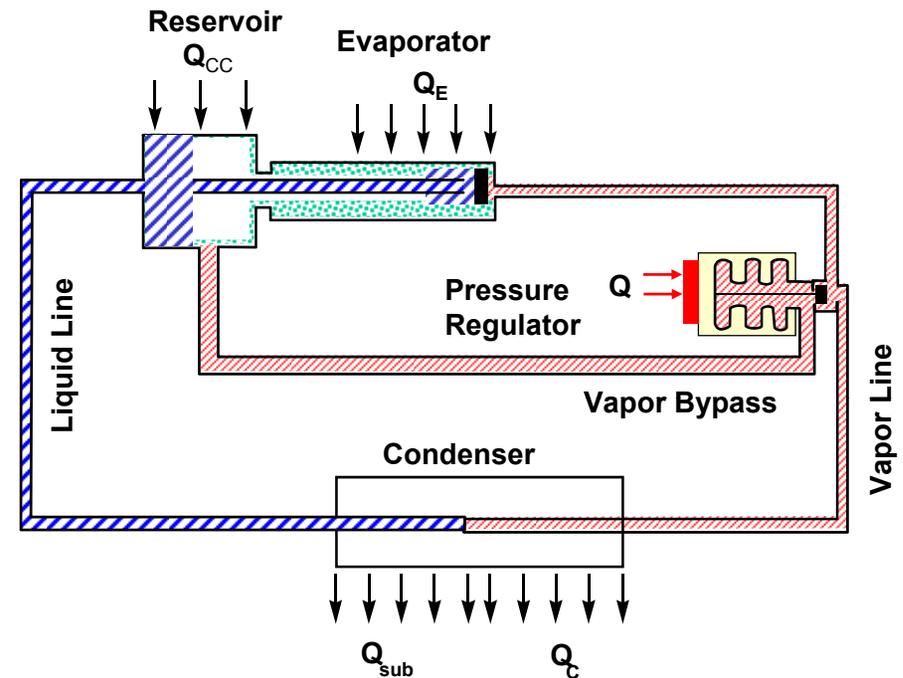


LHP Operating Temperature Control Use Pressure Regulator and Vapor Bypass



$$Q_{leak} - Q_{sub} + Q_{cc} = 0$$

$$Q_{cc} = Q_{sub} - Q_{leak}$$

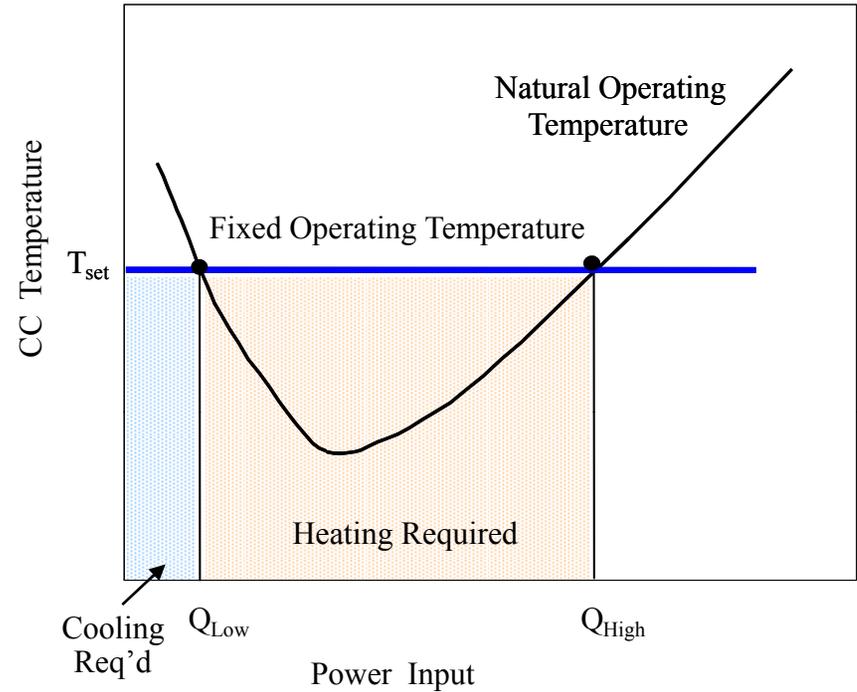
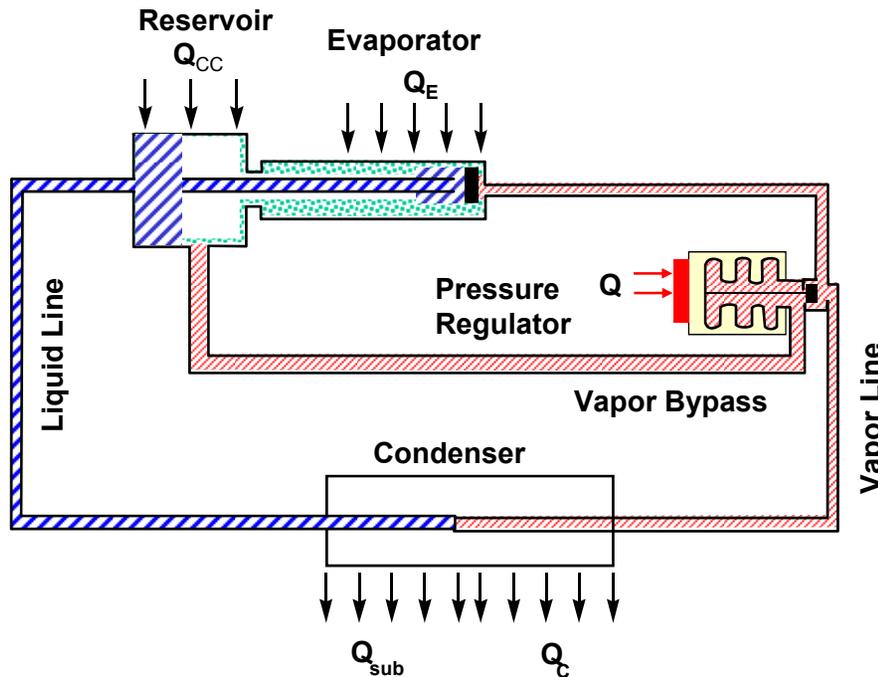


- The pressure regulator and vapor bypass valve allow some vapor to flow to the reservoir when needed.
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- The required reservoir control heater power Q_{cc} is reduced.
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 - Passive: no heater for bypass valve. A single set point temperature.
 - Active: bypass valve is controlled by an external heater.



LHP Operating Temperature

Use Pressure Regulator and Vapor Bypass



- **Advantages**
 - Requires very little CC control heater power.
- **Disadvantages**
 - More complex design.
 - Calculation of flow rate through bypass valve is complex.
 - Additional heater and controller for the pressure regulator

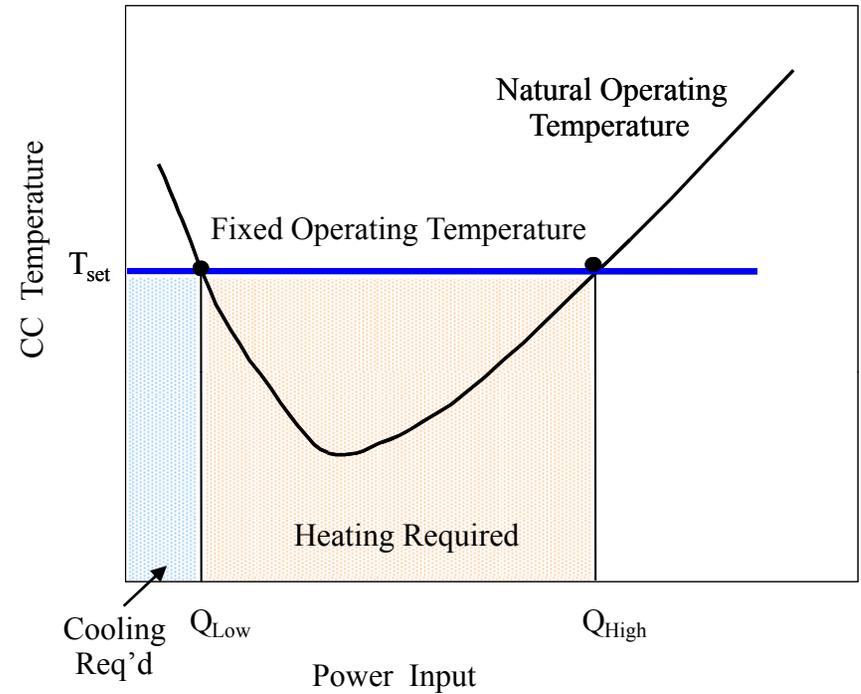
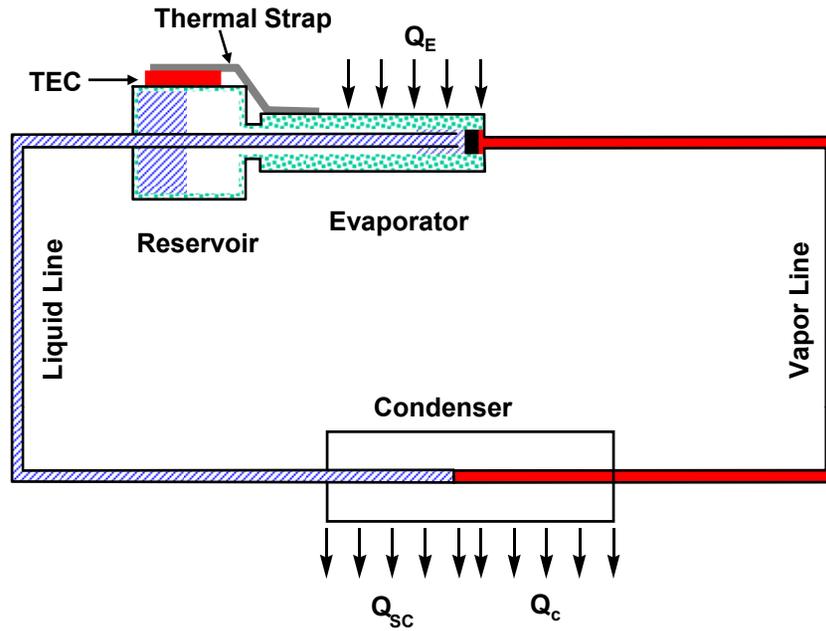


LHP Operating Temperature Control Use Pressure Regulator and Vapor Bypass

- **Passive bypass valve**
 - Yamal 2000 spacecraft, launched in 2003
 - Payload temperature was controlled within $\pm 2\text{K}$.
- **Active bypass valve**
 - TerraSAR satellite
 - Ground tests demonstrated temperature control within $\pm 0.5\text{K}$ for heat load of 5W to 15W and condenser sink temperature between 233K and 308K.
 - TerraSAR was launched in 2007. Thermal control system was functioning successfully.



LHP Operating Temperature Use TEC

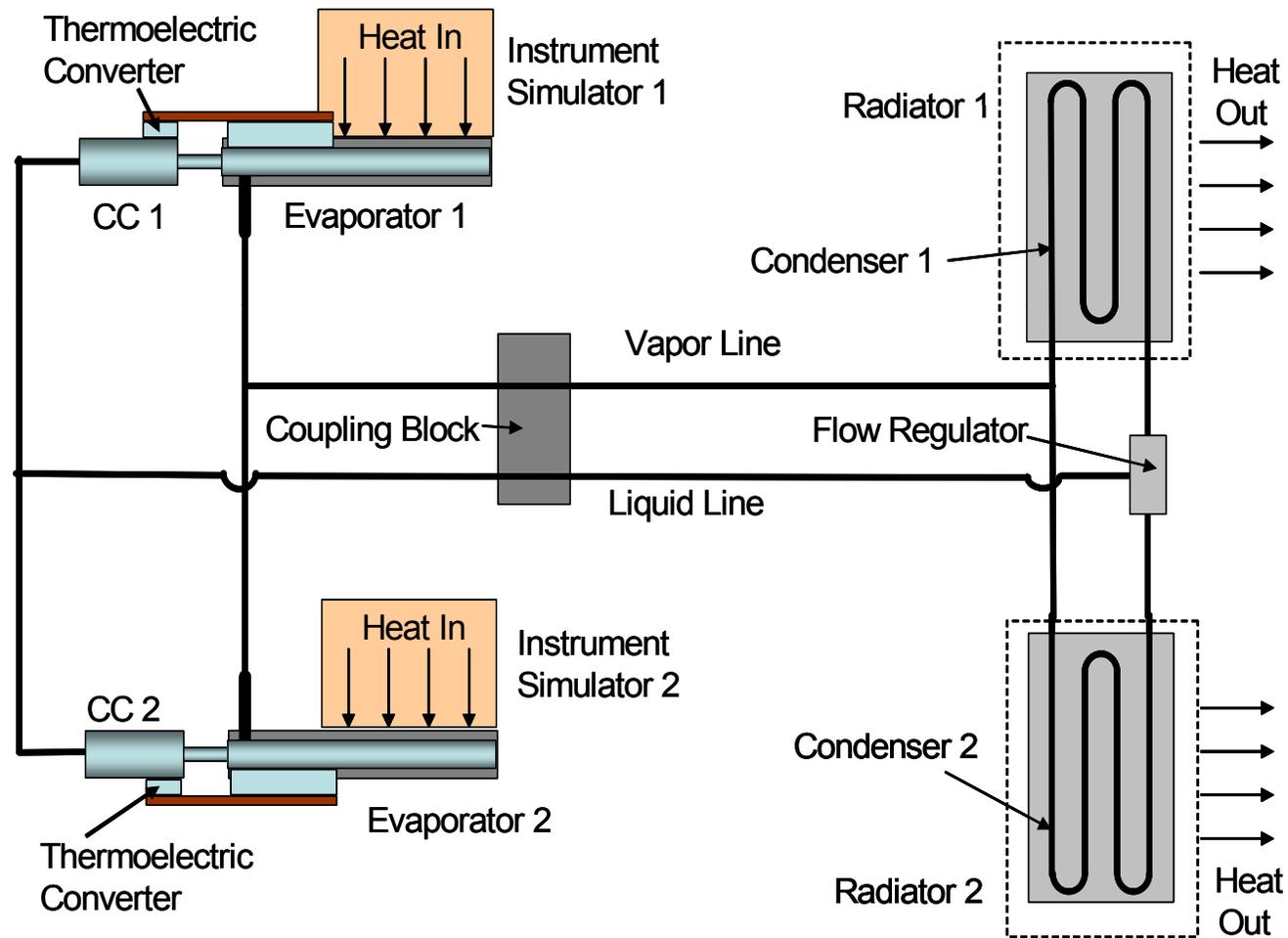


- **Advantages**
 - Can be used to heat or cool the CC
 - Changing the voltage polarity changes the mode of operation
 - Very efficient
- **Disadvantages**
 - More complex design
 - Additional mass



Schematic of ST 8 MLHP

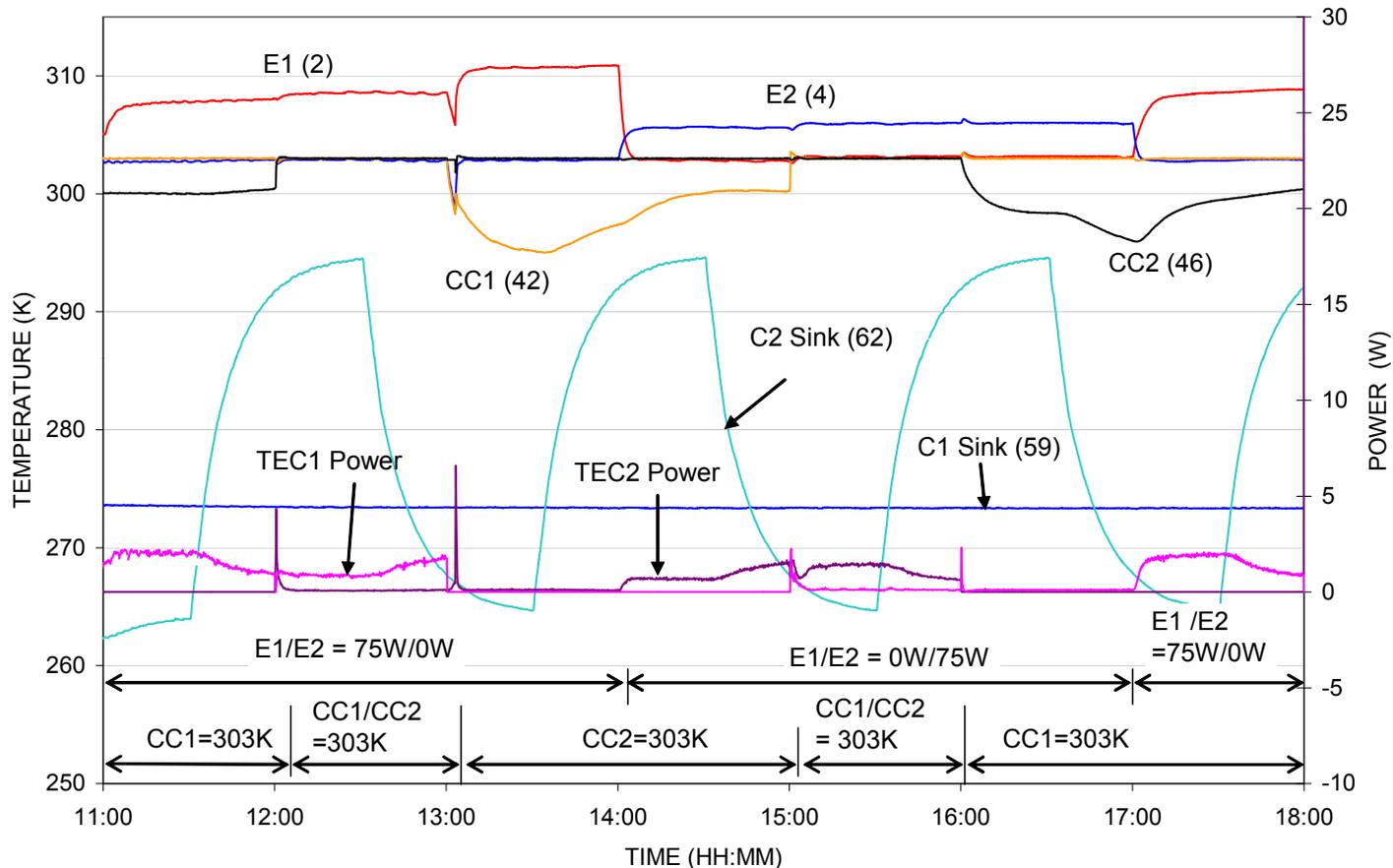
Use TECs and Coupling Blocks for CC Temperature Control





Loop Operating Temperature Control Using TECs Power and Sink Cycle Tests

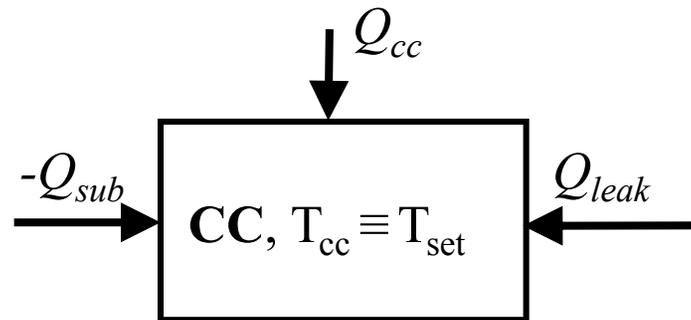
CETDP Temperature Control Test 5/25/2005



- The loop operating temperature was controlled within $\pm 0.5\text{K}$ by TECs regardless of changes in evaporator power and/or sink temperature, and regardless of which CC was being controlled.

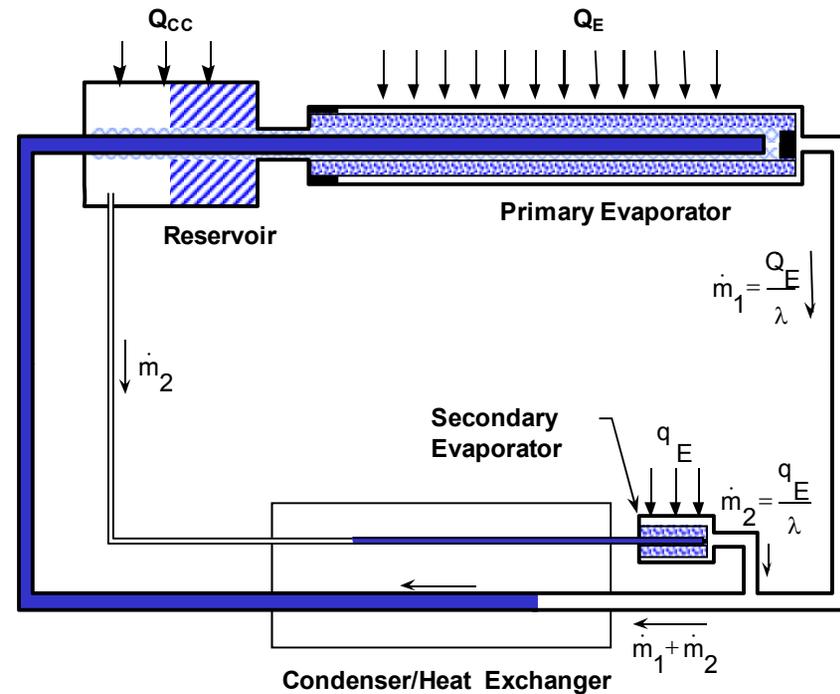


LHP Operating Temperature Control Use Secondary Evaporator



$$Q_{leak} - Q_{sub} + Q_{cc} = 0$$

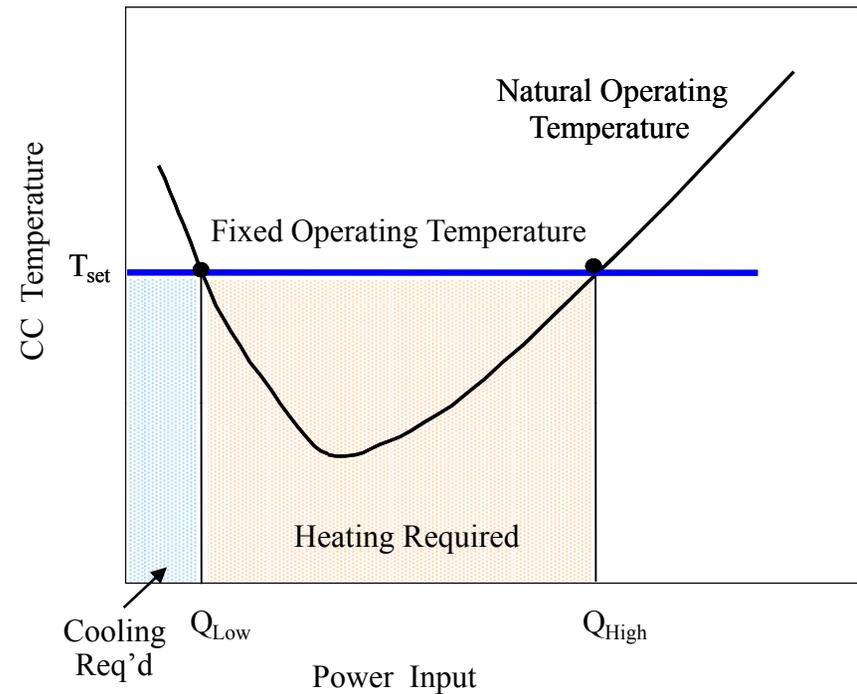
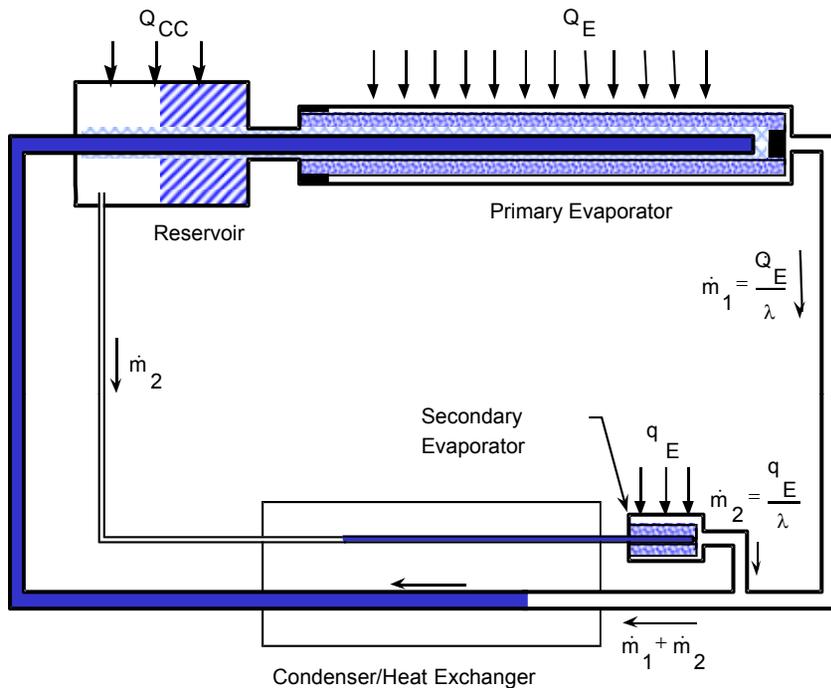
$$Q_{cc} = Q_{sub} - Q_{leak}$$



- The secondary evaporator forms an LHP within an LHP.
- The secondary loop cools the CC by drawing vapor out of the CC.
- Degenerates to the regular LHP when the secondary evaporator is not heated.



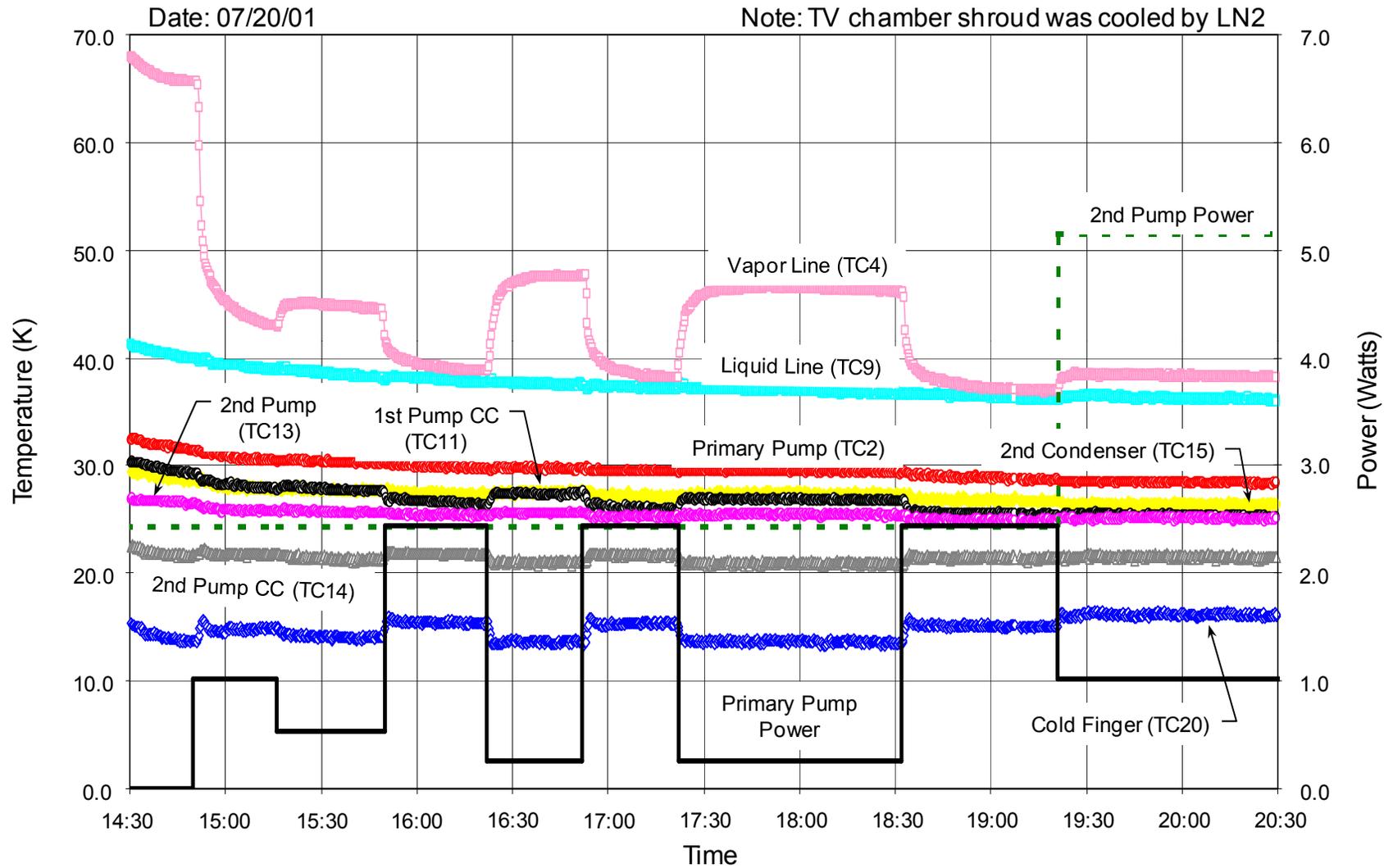
LHP Operating Temperature Control Use Secondary Evaporator



- **Advantages**
 - Active cooling of the CC – can quickly reprime the loop
 - Especially useful for cryogenic LHP for start-up and parasitic heat control
- **Disadvantages**
 - Needs an additional evaporator and transport lines
 - Still needs CC control heater



NASA H2-CLHP POWER CYCLING





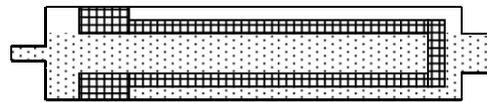
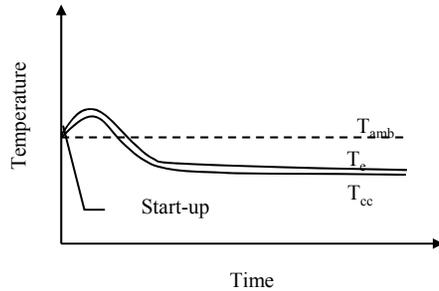
LHP Start-up

- **LHP Start-up is a complex phenomenon.**
- **The primary wick must be wetted prior to start-up.**
- **The loop start-up behavior depends on initial conditions inside the evaporator.**
 - **Vapor grooves on the outer surface of the primary wick**
 - **Liquid filled: superheat is required for nucleate boiling**
 - **Vapor presence: instant evaporation**
 - **Liquid core on the inner surface of the primary wick**
 - **Liquid filled: low heat leak**
 - **Vapor presence: high heat leak**
- **A minimum power is required for start-up under certain conditions.**

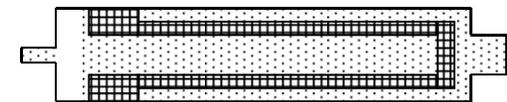
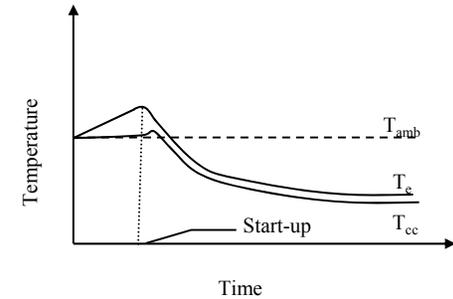


Four Start-up Scenarios for LHP

- **Vapor grooves**
 - **Liquid filled:** superheat is required for nucleate boiling
 - **Vapor presence:** instant evaporation

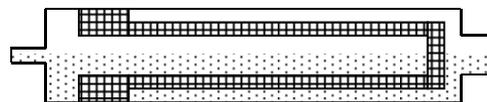
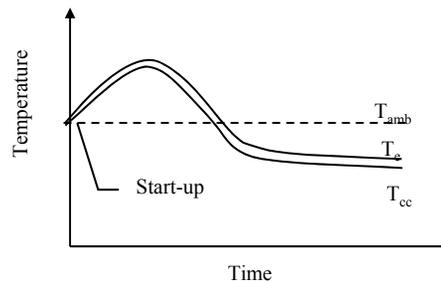


(a) Situation 1

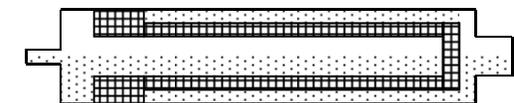
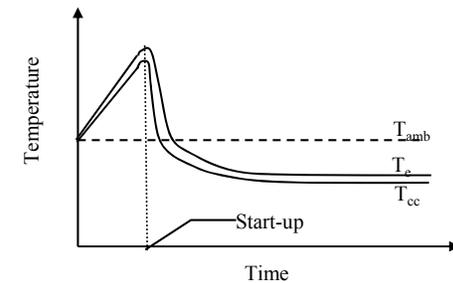


(c) Situation 3

- **Liquid core**
 - **Liquid filled:** low heat leak
 - **Vapor presence:** high heat leak



(b) Situation 2



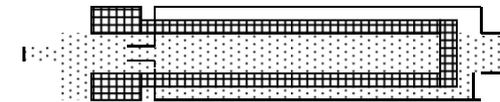
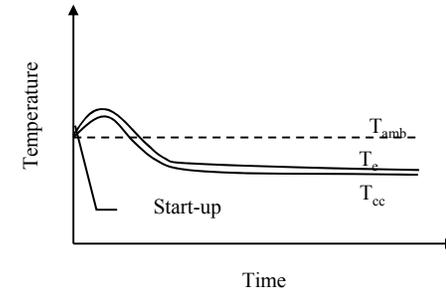
(d) Situation 4



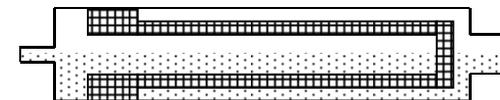
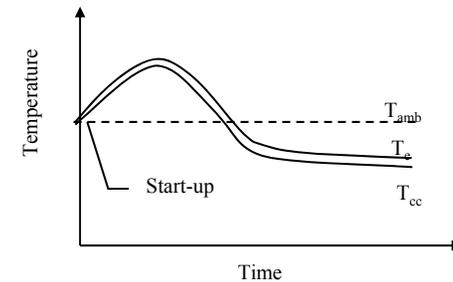
Vapor Presence in Vapor Grooves

- **Situation 1**
 - Vapor presence in vapor grooves
 - Core is liquid flooded; low heat leak
 - Instant liquid vaporization in grooves
 - Smooth start-up with no or small temperature overshoot during start-up transient

- **Situation 2**
 - Vapor presence in vapor grooves
 - Vapor presence in core; high heat leak
 - Instant liquid vaporization in grooves
 - Smooth start-up with possible large temperature overshoot during start-up transient



(a) Situation 1

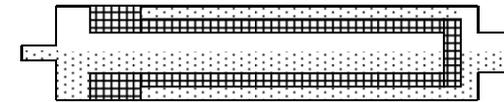
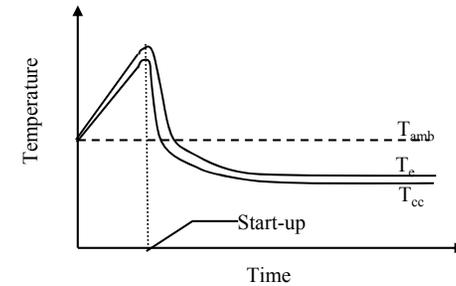


(b) Situation 2

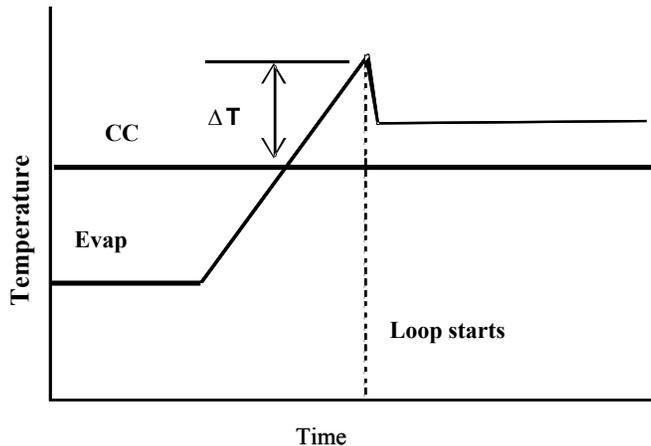


Worst Case Start-up – Situation 4

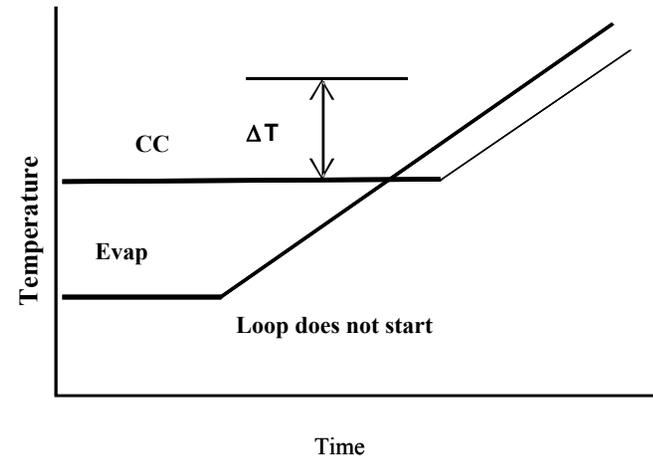
- **Situation 4**
 - Vapor grooves are flooded with liquid; superheat is required for nucleate boiling
 - Core contains vapor; high heat leak
 - The CC temperature rises along with the evaporator temperature
 - The required superheat may never be obtained before the maximum allowable temperature is reached.



(d) Situation 4



Desired

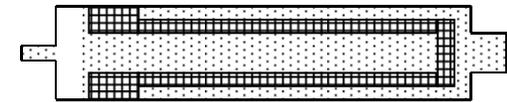
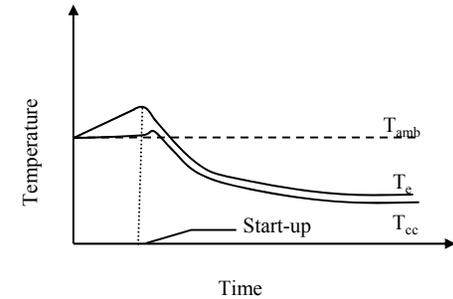


Actual

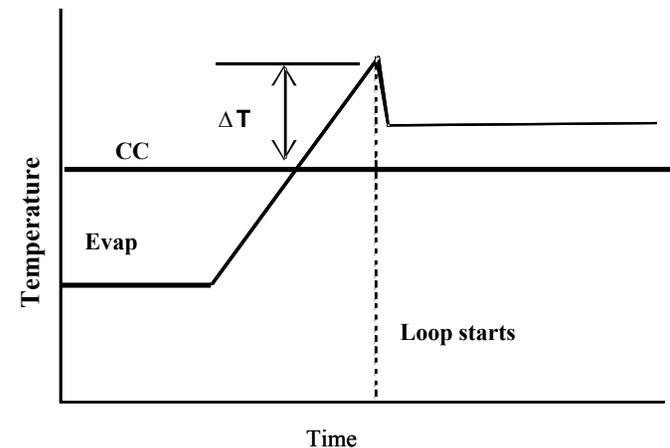


Situation 3 – Choosing Between Two Evils

- **Situation 3**
 - Vapor grooves are flooded with liquid; superheat is required for nucleate boiling
 - Core is flooded with liquid; low heat leak
 - The CC temperature remains constant or rises slowly while the evaporator temperature is rising
 - The required superheat will eventually be reached.
- The current practice for LHP start-up is to flood the entire loop prior to start-up to guarantee the wick is wetted, and sustain the burden of potentially high superheat for nucleate boiling at start-up – “the lesser of the two evils”.



(c) Situation 3



Desired and Actual



High and Low Power Start-up

- **With high power to the evaporator, liquid in the vapor grooves can be vaporized quickly regardless of the initial two-phase status in the grooves and the evaporator core.**
 - **The required superheat, if any, can be achieved in a short time.**
 - **Within the short time, the total heat leak is small.**
- **With low power to the evaporator, start-up could be problematic.**
 - **Under situation 4, the required superheat for nucleate boiling may never be achieved.**
 - **After the loop starts, a steady state may not be established within the allowable temperature limit at low powers due to a high heat leak from evaporator to CC if the core contains vapor.**



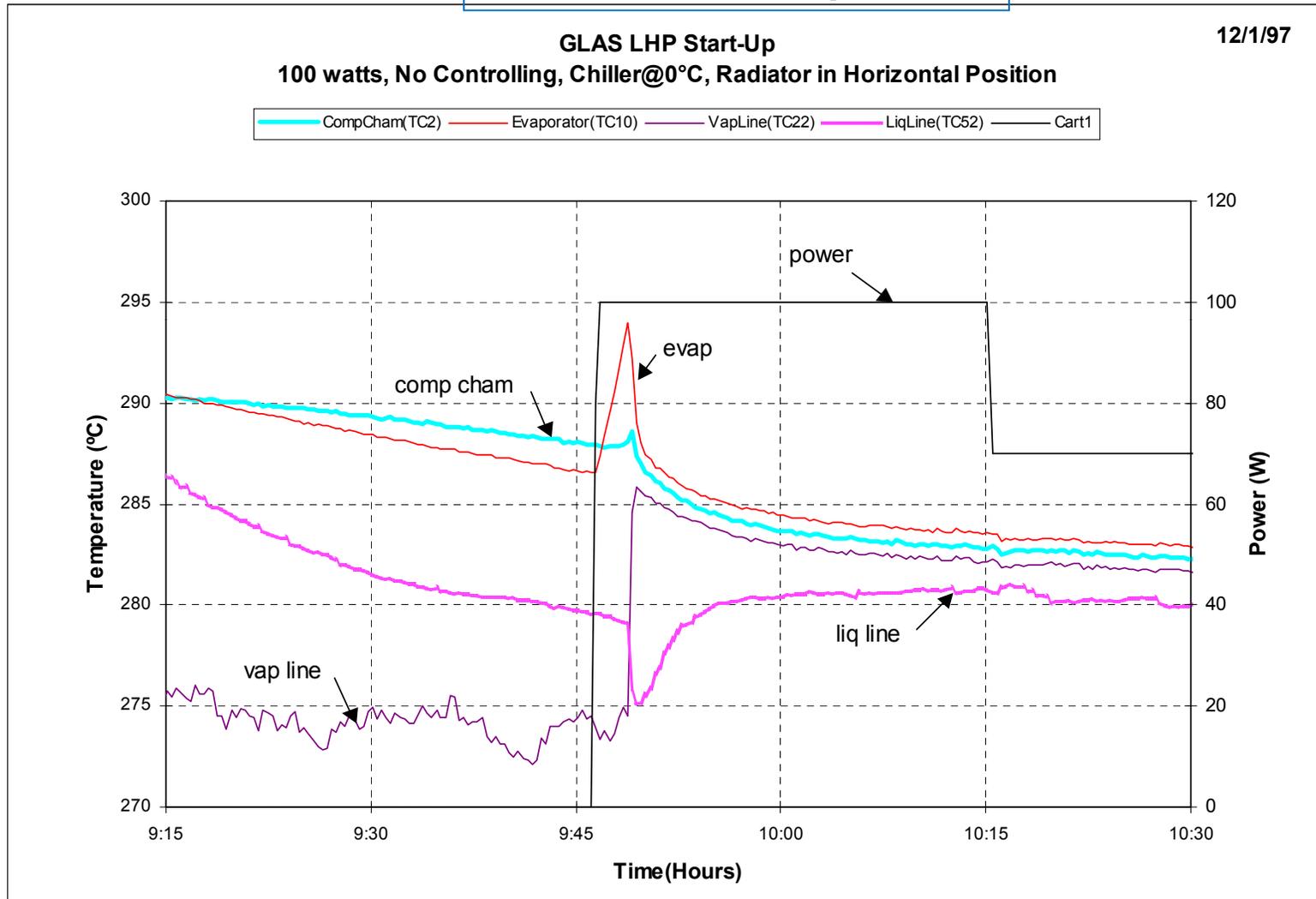
Some Examples of Start-up Tests

- **Indication of the inception of loop start-up:**
 - Sudden sharp increase of the vapor line temperature to the CC saturation temperature
 - Sudden sharp decrease of the liquid line temperature
- **Successful start-up**
 - The CC temperature approaches a SS
 - The vapor line temperature approaches a SS (same as or close to the CC temperature)
 - The evaporator temperature approaches a SS (slightly higher than the CC temperature)
- **Results of some start-up tests under various conditions follow.**



GLAS LHP Breadboard Start-up (Evaporator core is liquid-filled)

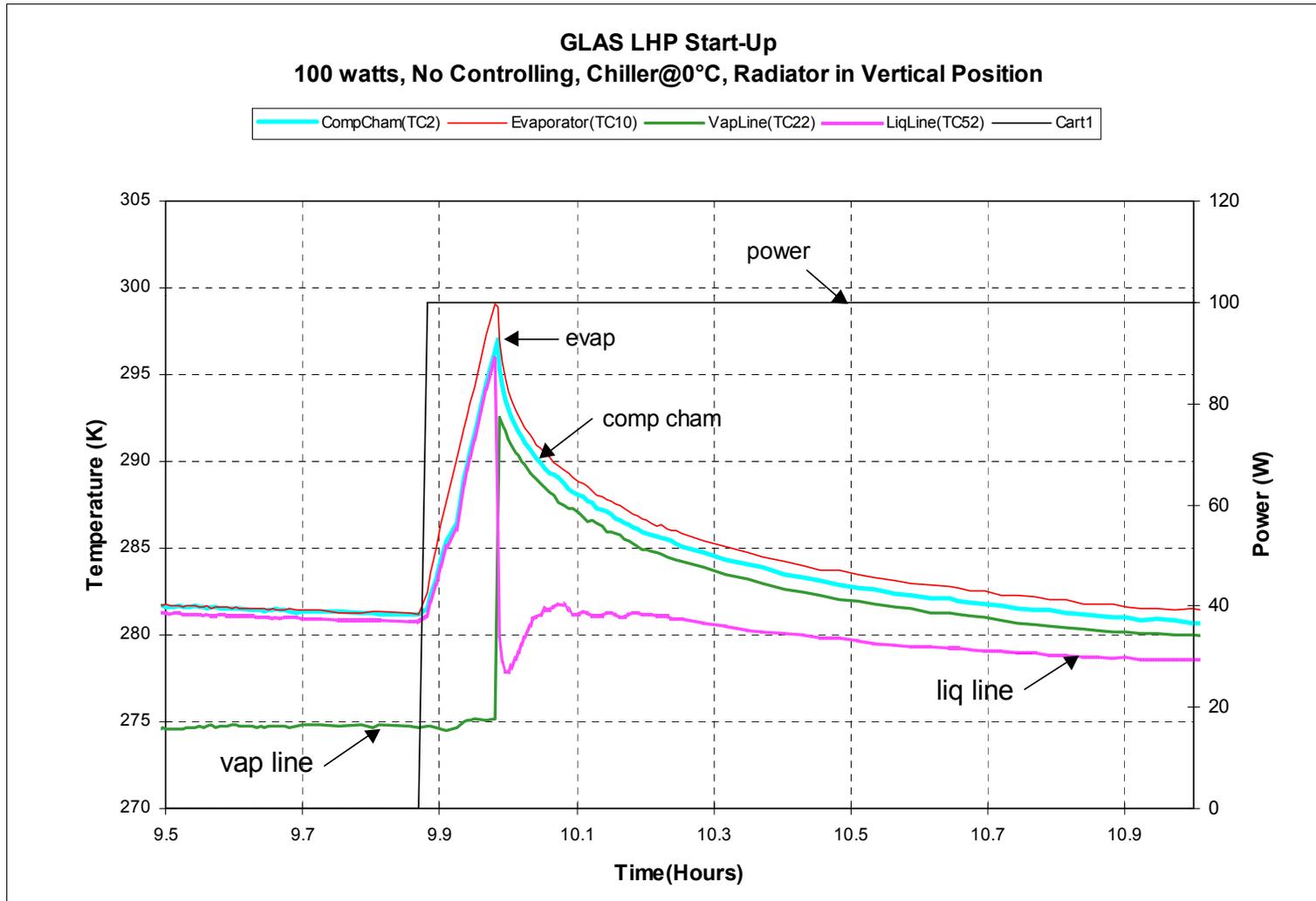
Situation 3 start-up





GLAS LHP Breadboard Start-up (Vapor present in evaporator core)

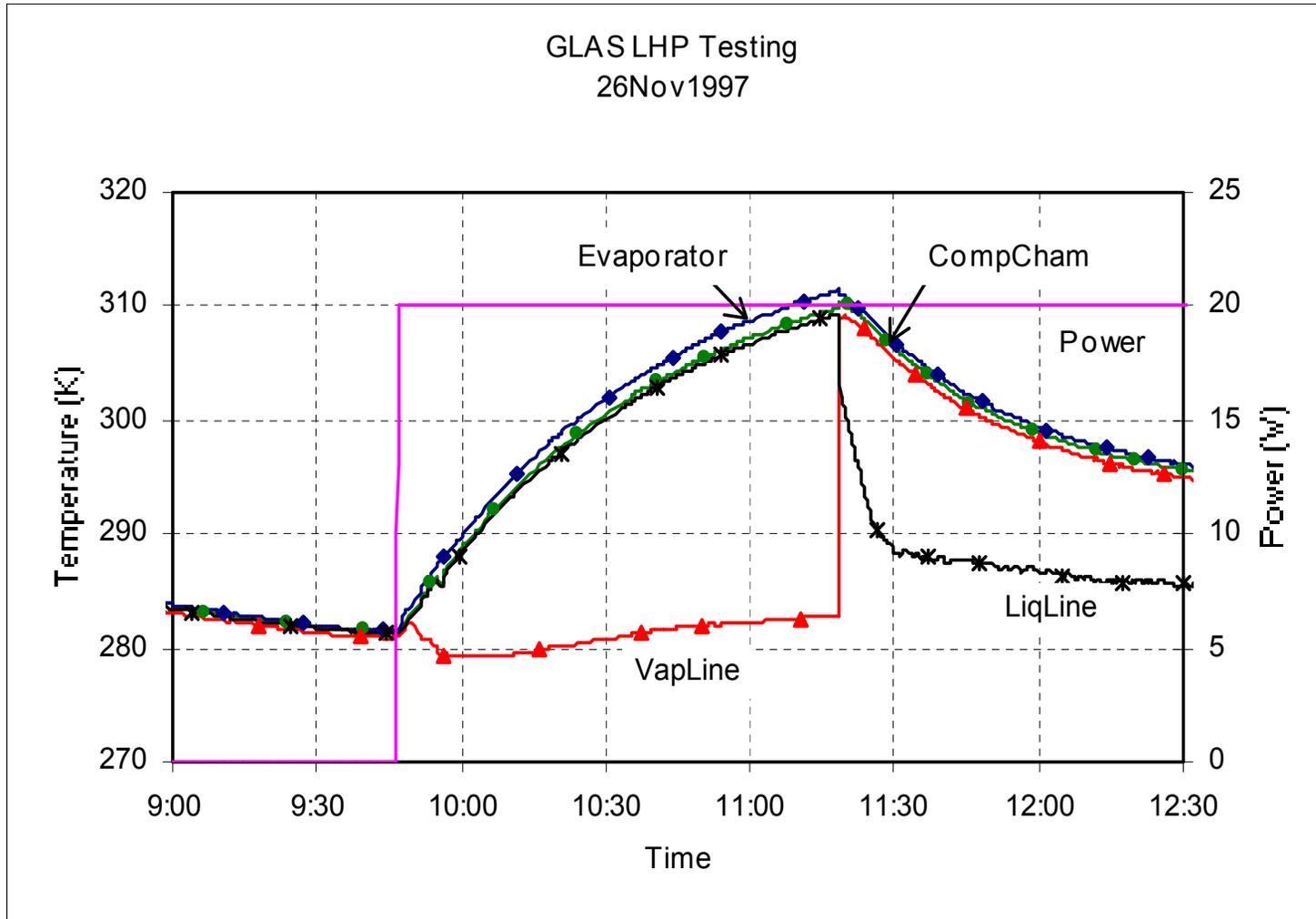
Situation 4 start-up: 100W





GLAS LHP Breadboard Start-up (Vapor present in evaporator core)

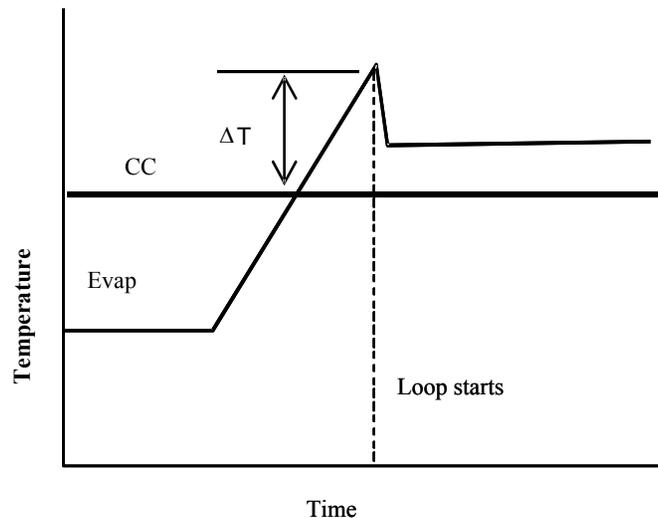
Situation 4 start-up: 20W



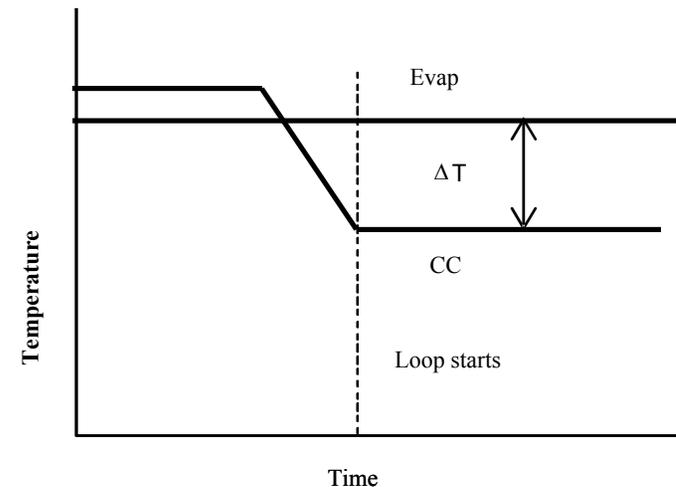


Enhancing the Start-up Success

- A small start-up heater is used to achieve the required superheat for nucleate boiling in a localized region to generate the first bubble in vapor grooves.
 - After vapor is present in grooves, liquid evaporation takes place instead of nucleate boiling, i.e. superheat is no longer required.
- Cool the CC using an active means (e.g. TEC).



Start-up heater raises the evaporator temperature quickly over a small area



TEC lowers the CC temperature



LHP Shutdown

- **Some instrument operation requires LHP to shutdown for a period of time.**
- **LHP can continue to pump fluid if the evaporator temperature is higher than the CC temperature.**
- **Requirements for LHP shutdown**
 - **No net heat load to evaporator**
 - **CC temperature is higher than evaporator temperature**
 - **Heating the CC is the only viable method**
- **When the CC temperature is higher than the evaporator temperature, fluid flow stops.**
 - **Loop will not restart as long as there is no net heat load to evaporator.**
 - **Loop may restart if the evaporator continues to receive net heat load and its temperature rises above the CC temperature.**
- **To guarantee that the payload stays above its minimum allowable temperature, the CC temperature control can be set slightly above that value during loop shutdown.**



Analytical Modeling of LHP

- **SINDA/Fluint can be used to model LHP operation.**
 - **CAPIL connector and CAPPMP macro to model wick**
 - **Phase suction option to model two-phase heat transfer**
 - **Tedious and time-consuming to build the detailed LHP model**
 - **Run time could be an issue**
- **Under NASA SBIR and the ST 8 Project, TTH Research Inc. has developed an LHP model specifically for the simulation LHP operation.**



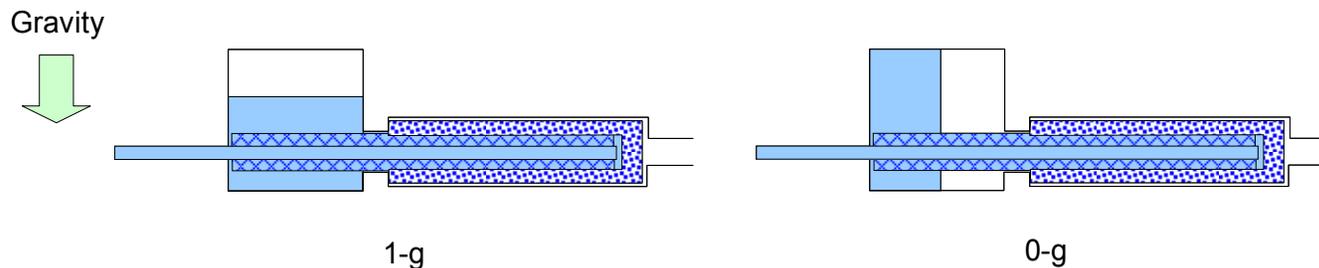
NASA LHP Analytical Model

- **Developed by TTH Research, Inc. under NASA SBIR Project in 2002.**
- **The objective was to develop an analytical model to simulate LHP steady state and transient behaviors**
 - **based upon *physical laws* and verified by test data**
 - **efficient and stable solutions**
 - **easy to use by thermal analysts (non-experts)**
 - **accurate and detailed predictions for LHP researchers (experts)**
 - **Can be used as a stand-alone model for LHP design, or a subroutine to general thermal analyzer (e.g. SINDA/Fluint)**
- **Additional funding for modeling the secondary wick was provided by DOD and the ST8 project in 2005.**



Modeling Approach

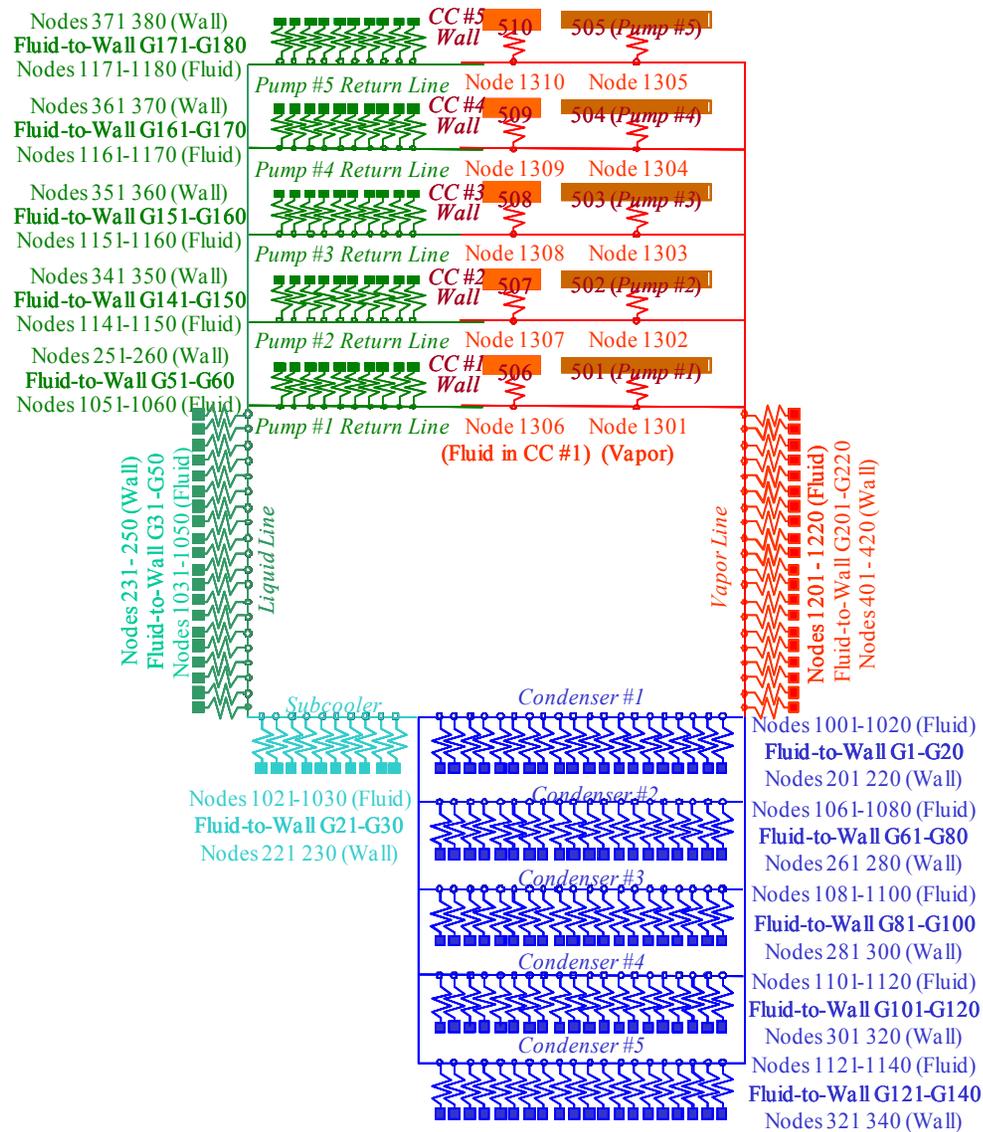
- Derive governing equations for each component and the overall loop based on mass, momentum and energy balance.
 - fluid movement based on pressure difference
 - improved heat leak model based on test data
 - two-phase correlations in condenser
 - database for fluid properties, wick performance characteristics
- Model Assumptions
 - One dimensional pipe flow
 - liquid and vapor at one temperature (saturation) inside the reservoir
 - track liquid level in CC at all times (including gravity effects)
 - Negligible amount of non-condensable gases
- Effects of gravity are included in the model.



Compensation Chamber Fluid Distribution as a function of Gravity



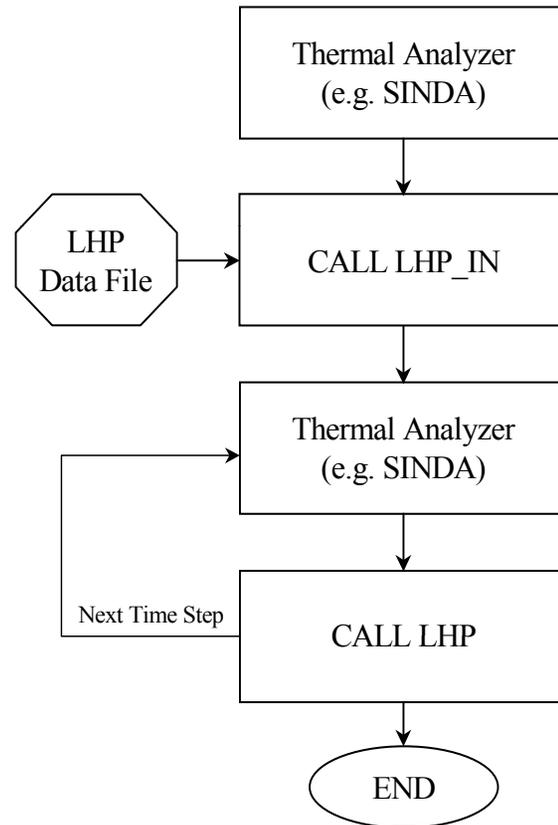
Nodal Map of LHP Analytical Model





LHP Analytical Model Solution Scheme

Two-Step Predictor-Corrector





LHP Analytical Model Input Data

- Vapor Line
 - O.D., wall thickness, length, material
- Liquid Line
 - O.D., wall thickness, length, material
- Condensers
 - No. of condensers
 - Condenser 1 O.D., wall thickness, length, material
 - Repeat for Condenser 2, Condenser 3, etc.
- Subcooler
 - O.D., wall thickness, length, material
- Evaporators
 - No. of evaporators
 - Evaporator 1
 - Vapor exit line: O.D., wall thickness, length, material
 - Liquid inlet line: O.D., wall thickness, length, material
 - Pump body O.D., length, material
 - Primary wick O.D., I.D., length, material, pore radius, permeability, porosity, thermal conductivity
 - Bayonet tube: O.D., I.D.
 - Vapor grooves: number of grooves, hydraulic diameter of each groove
 - Reservoir: O.D., I.D., length, material
 - Adverse elevation
 - Secondary wick: pore radius, permeability, cross sectional area, thermal conductivity, no. of vapor channels, hydraulic diameter of each vapor channel
 - Start-up initial condition (situation 1, 2, 3 or 4)
 - Superheat at start-up
 - Repeat for Evaporator 2, Evaporator 3, etc.
- Gravitational acceleration
- Working fluid



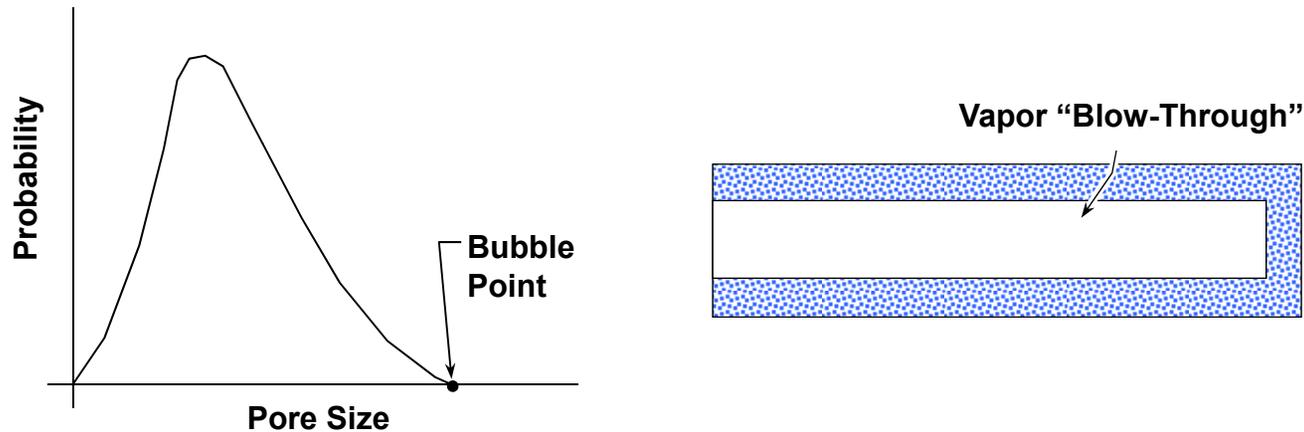
Model Capabilities

- **LHP with up to 5 evaporators and up to 5 condensers**
- **Simulation of steady state or transient behavior**
- **Database for more than 40 working fluids**
- **Database for wick properties based on empirical test data**
- **Default values for input data**
- **Gravity effects included**
- **A FORTRAN subroutine to be used with any thermal analyzer (e.g. SINDA, TMG)**



Model Limitations

- **The analytical model can predict when system pressure drop exceeds capillary limit of primary wick. The model cannot simulate loop behavior thereafter.**



- **Model does not take into account effects of insufficient liquid in reservoir (undercharged LHP in 1-g)**



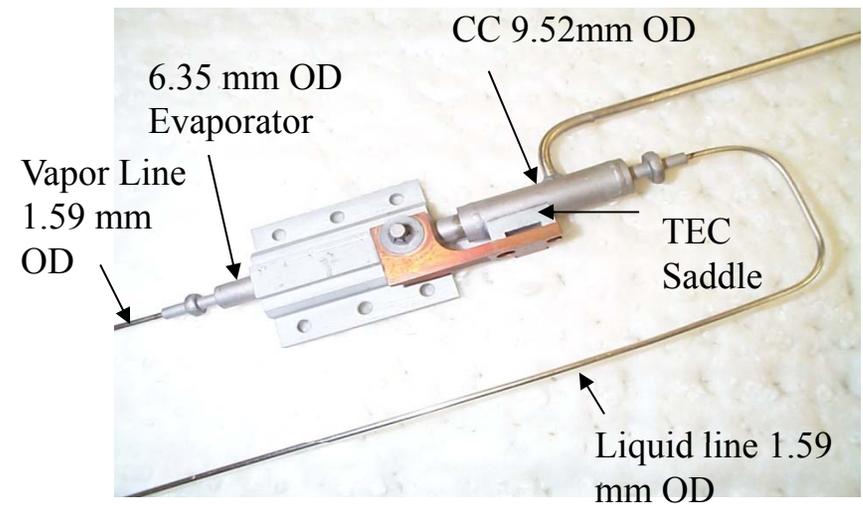
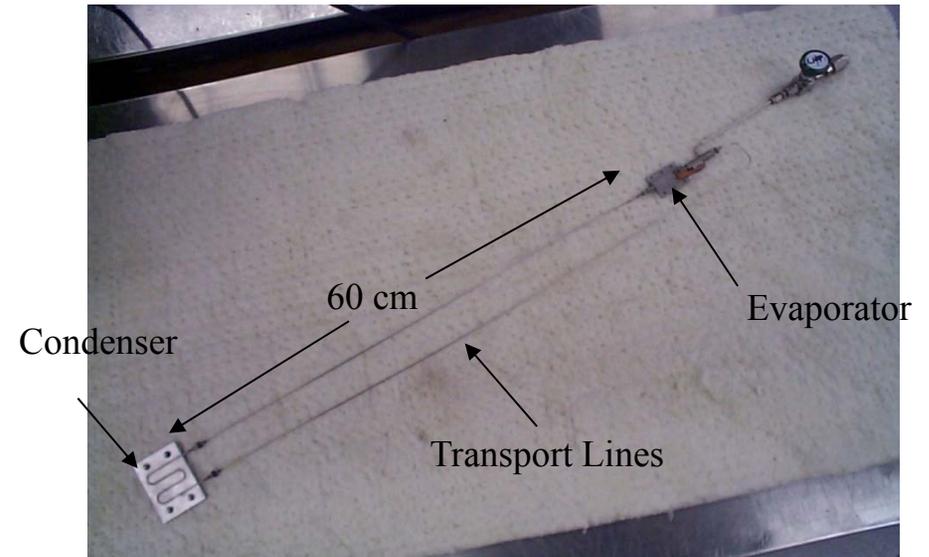
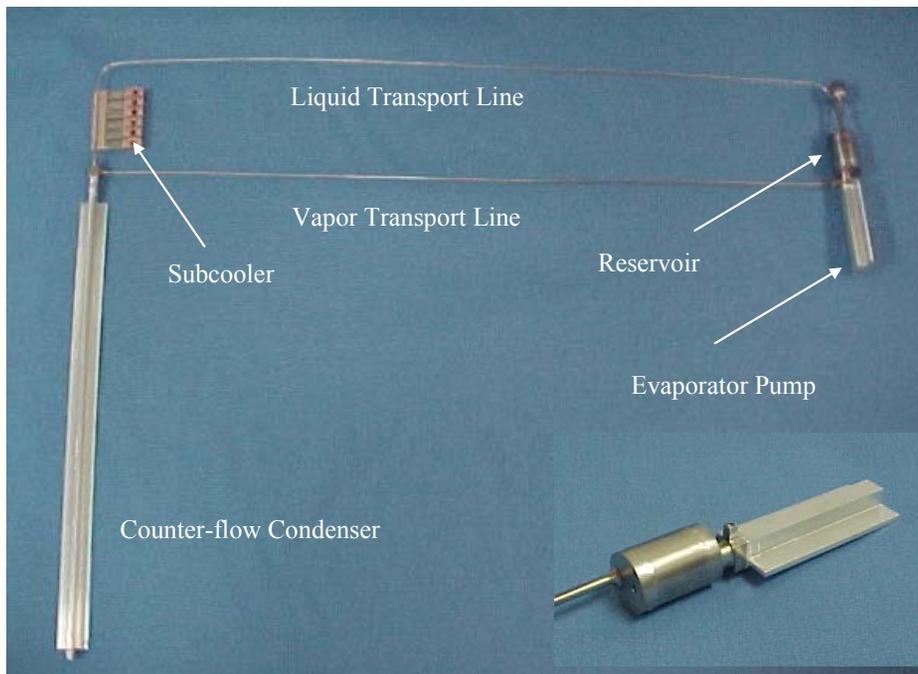
Recent LHP Technology Developments

- **Miniature LHP**
 - 6.35 mm diameter evaporator
- **A Single LHP with Multiple Evaporators and Multiple Condensers**
- **Hybrid CPL/LHP**
- **Cryogenic LHP**
 - Nitrogen LHP: ~75K-100K
 - Neon LHP: ~28K-44K
 - Hydrogen LHP: ~20K-30K
 - Helium LHP: ~2.7K-4.4K



CEDTP Miniature Loop Heat Pipes

- **Miniature LHPs under NASA CETDP program.**
 - **Breadboards built by Swales and Thermacore**

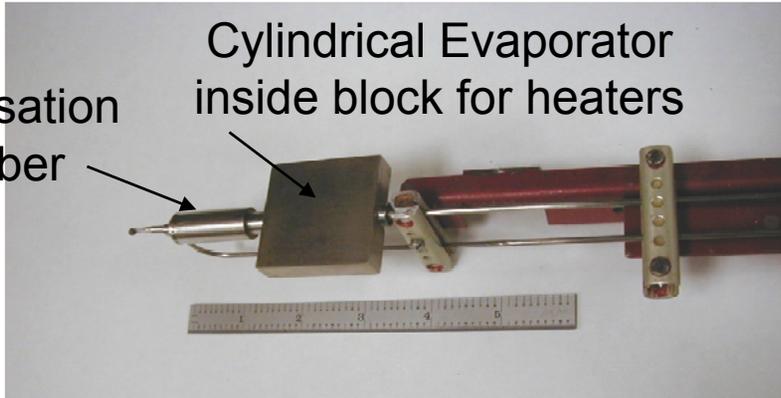




Mini LHP for CCQ Flight Experiment

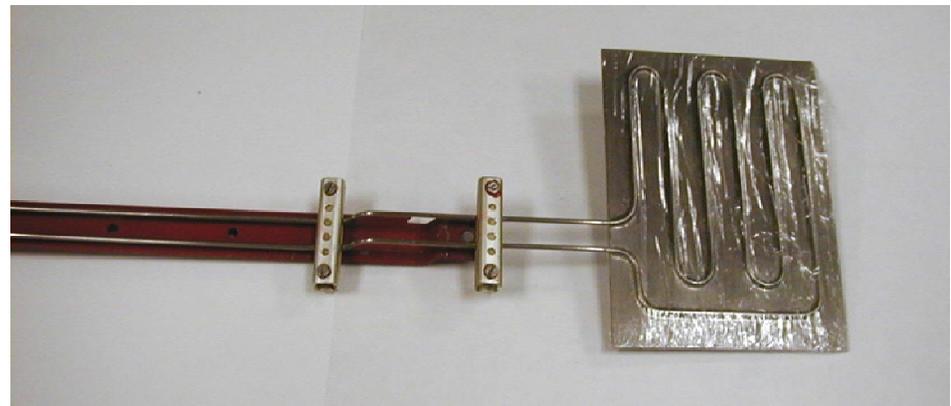
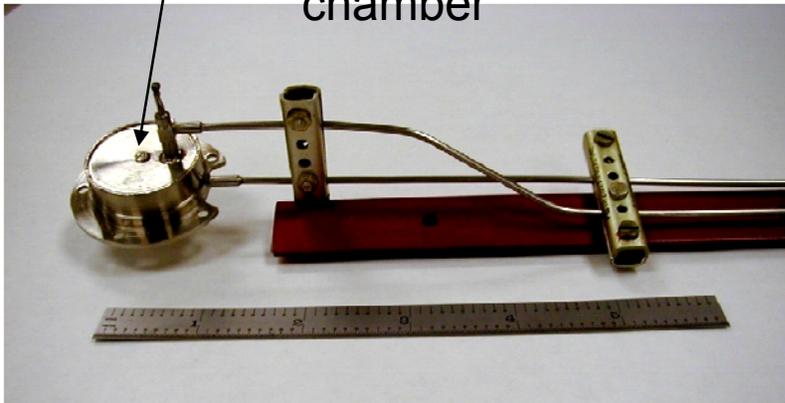
Compensation Chamber

Cylindrical Evaporator inside block for heaters



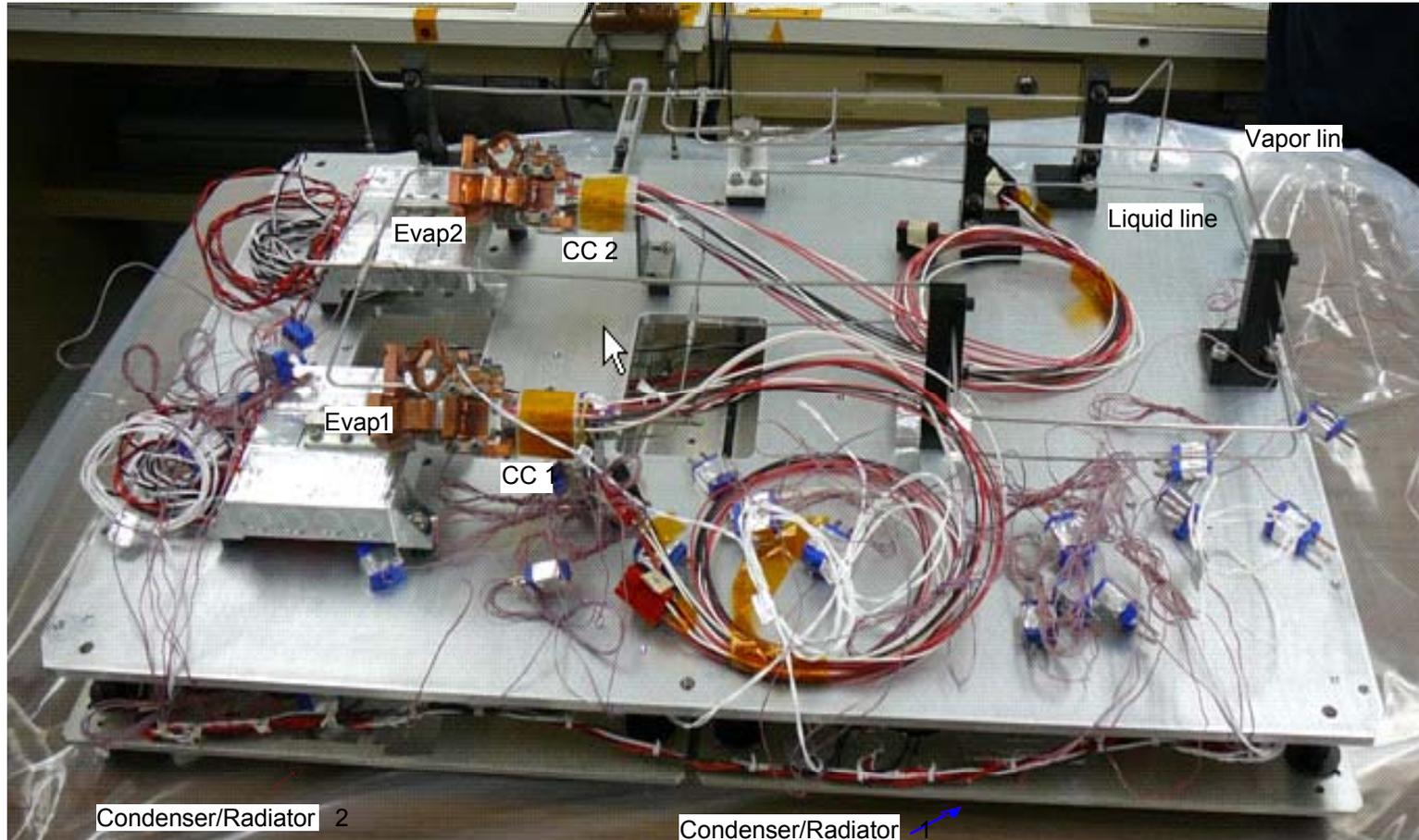
- **Made by Russians**
- **Flown for CCQ Flight Experiment (2012)**

Flat evaporator with integral compensation chamber





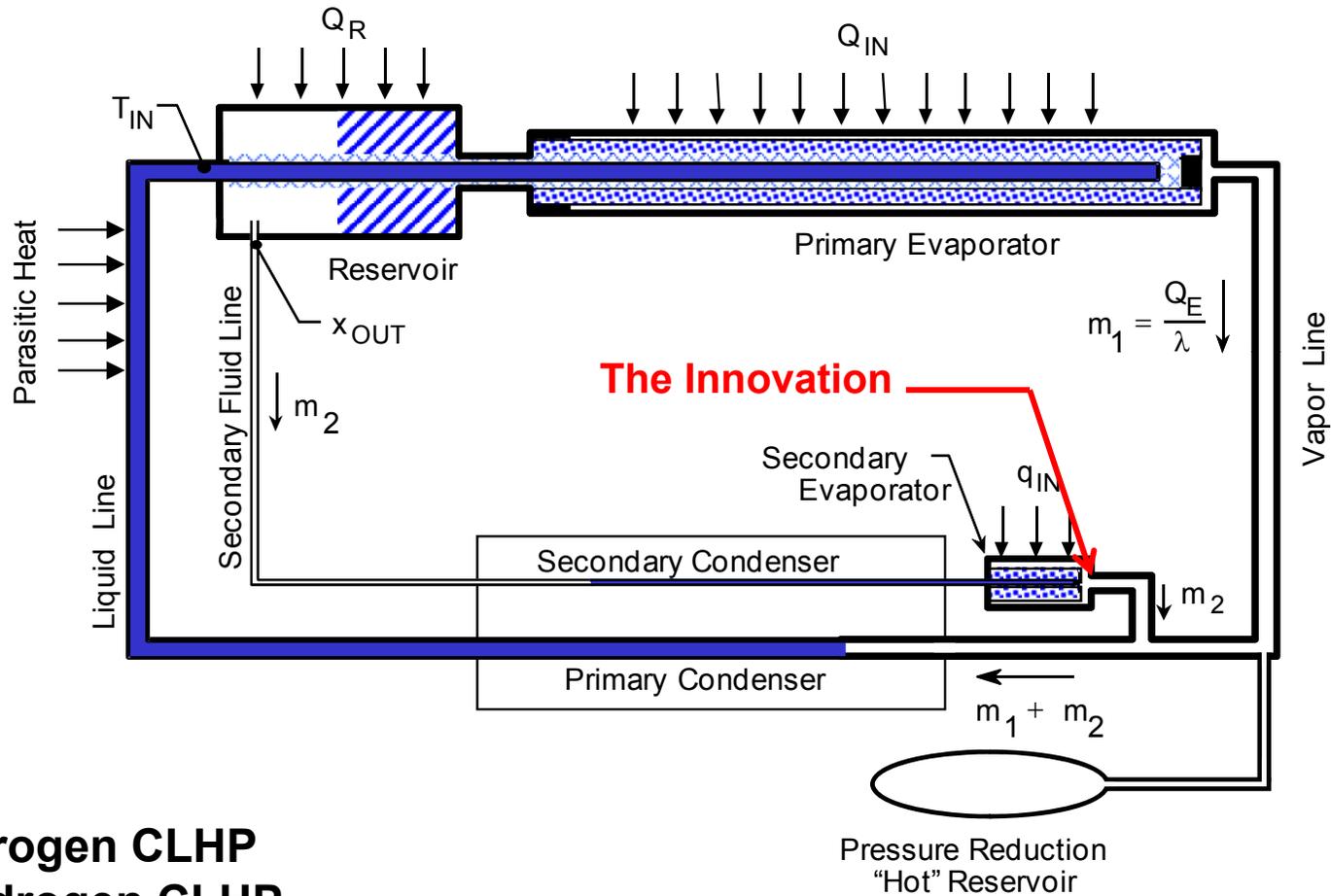
ST8 Thermal Loop - LHP Installed on Test Frame



- **A single LHP with two evaporators and two condensers**
- **Miniature LHP**
- **TECs for reservoir temperature control**



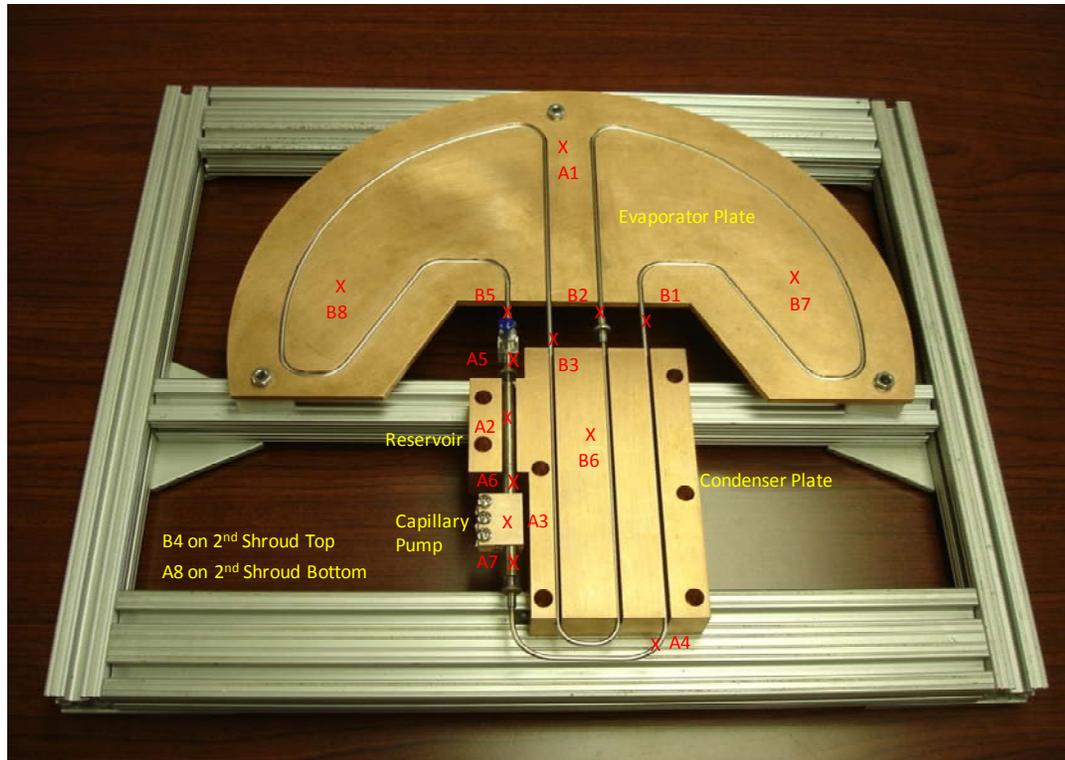
Cryogenic Loop Heat Pipe (CLHP)



- Nitrogen CLHP
- Hydrogen CLHP



CLHP for Large Area Cryocooling



- Delivered by TTH Research in 2007
- Manufactured by ThermoCore, Inc.

- **CLHP**
 - all stainless steel construction
 - capillary pump: 1/4"OD x 1.5"L
 - wick: 1.2 μ m x 45% porosity
 - reservoir: 1/4"OD x 2.5"L
 - transport line: 1/16"OD x 63"L
- **Evaporator Plate**
 - copper 10" ϕ 48 in²
- **Condenser Plate**
 - copper 3" x 5.5" x 1"
- **Hot reservoir**
 - 1000 ml (not shown)



Other Advanced Topics Not Covered in This Course

- **Temperature Oscillations in LHPs**
- **Temperature Hysteresis**
- **Effect of Secondary Wick on LHP Transient Operation**
- **Start-up and Re-start due to Reservoir Cold Shock**
- **Multiple LHPs Serving a Single Components (Swift ABT , GOES-R ABI, and GOES-R GLM)**
- **Gravity Effects**



LHP Summary (1 of 3)

- **Key to high heat transport of LHP**
 - Metal wicks with very fine porous wick
 - *High thermal conductivity affects operating temperature*
- **Key to robust LHP operation**
 - Integral evaporator and CC design
 - Secondary wick connecting CC to evaporator: vapor tolerant
- **Key to understanding LHP operation**
 - CC saturation temperature governs the loop operating temperature
 - CC is plumbed in line with flow circulation
 - CC temperature itself affected by operating conditions
 - Thermodynamic constraints: ΔP is linked to ΔT
 - CC volume and liquid inventory
- **Key to determining CC saturation temperature**
 - Net heat gain must be balanced by subcooling of returning liquid
 - Ambient temperature affects liquid subcooling



LHP Summary (2 of 3)

- **Heat leak from evaporator to CC affects**
 - Loop natural operating temperature
 - Overall system thermal conductance
 - Temperature hysteresis
- **Heat leak from evaporator to CC is affected by**
 - Wick thermal conductivity
 - Heat load to the evaporator
 - Two-phase status inside the evaporator core
- **Liquid subcooling is affected by**
 - Heat load to the evaporator
 - Temperature difference between sink and ambient
 - Parasitic heat gain/loss along the liquid line
- **CC sizing and liquid inventory**
 - Determined concurrently
 - Must satisfy cold start-up and hot operating conditions
 - Loop must not become liquid-filled at maximum non-operating temperature.



LHP Summary

3 of 3

- **The thermodynamic constraint (ΔP versus ΔT) affects**
 - Normal operation
 - Start-up
 - Operation with presence of body force and/or NCGs
 - Operation of an LHP with multiple evaporators
 - Operation of multiple LHPs
- **Operating temperature range**
 - **Never operate LHP near the freezing point except for rare extremely cold start-up transients**
 - **Never operate LHP near the critical point**



Questions?