Introduction to Loop Heat Pipes

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THERMAL & FLUIDS ANALYSIS WORKSHOP

TFAWS

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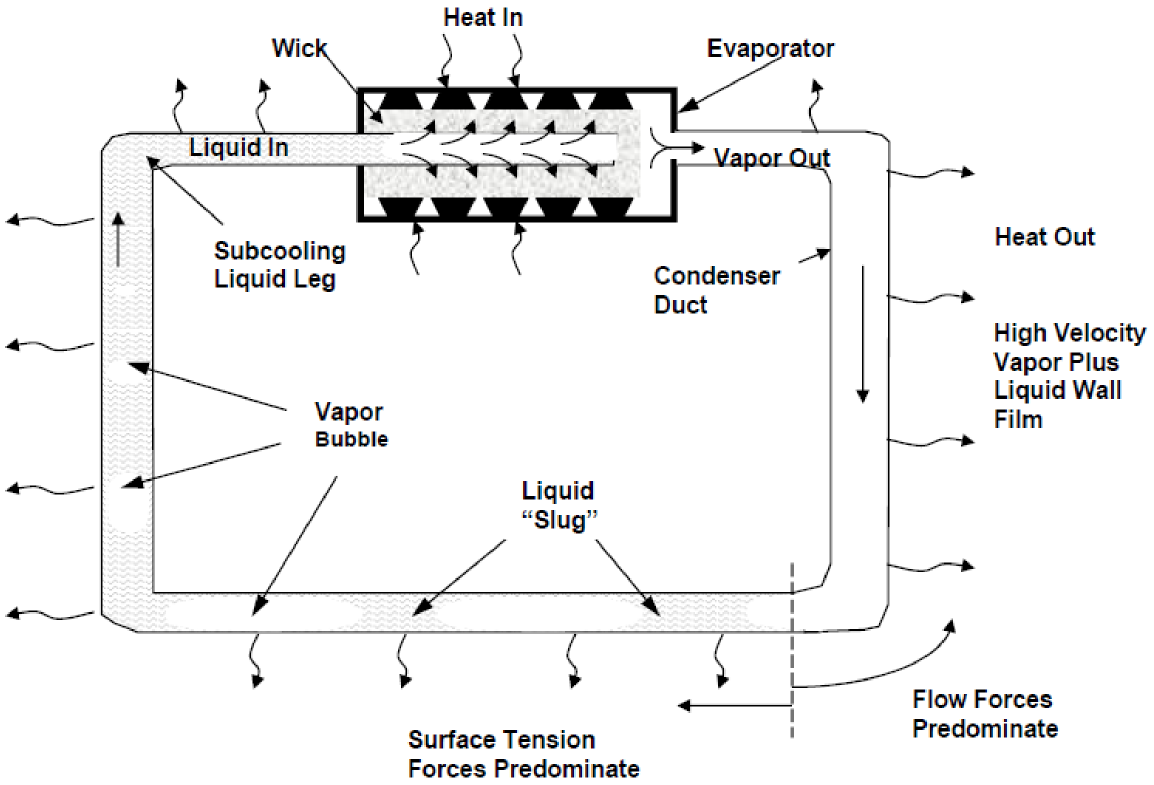
Outline

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

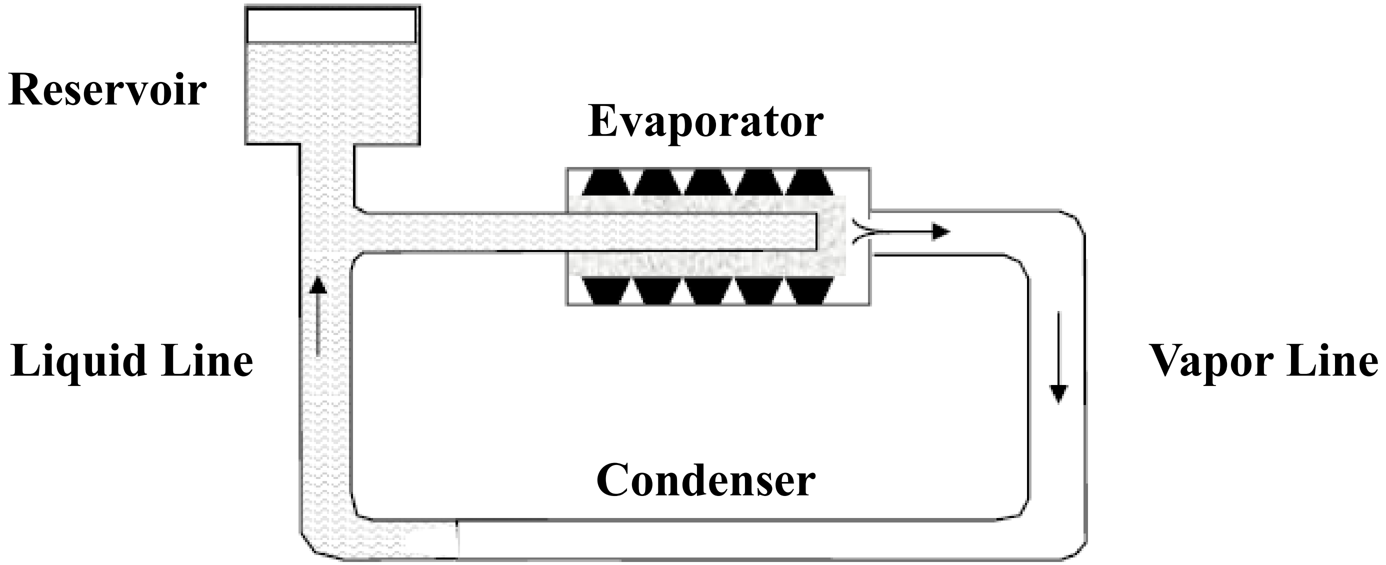
CAPILLARY PUMPED LOOPS

Constant Conductance Capillary Pumped Loop



- Wicks are present only in the evaporator, and wick pores can be made small.
- Smooth tubes can be sized independently 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.

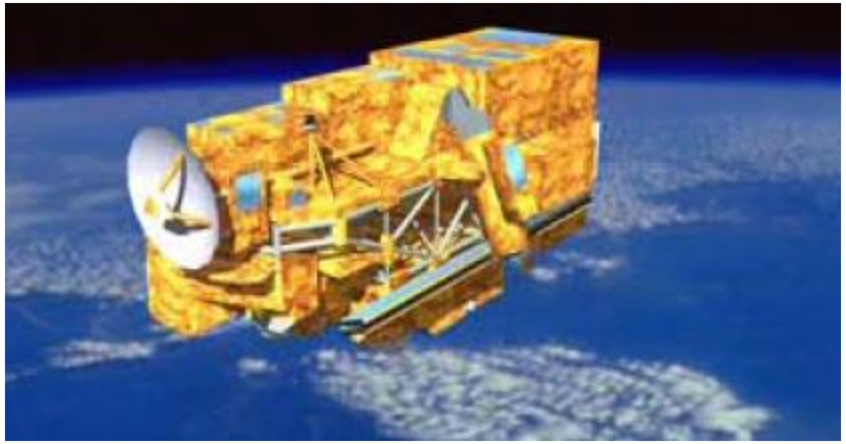
Variable Conductance Capillary Pumped Loop



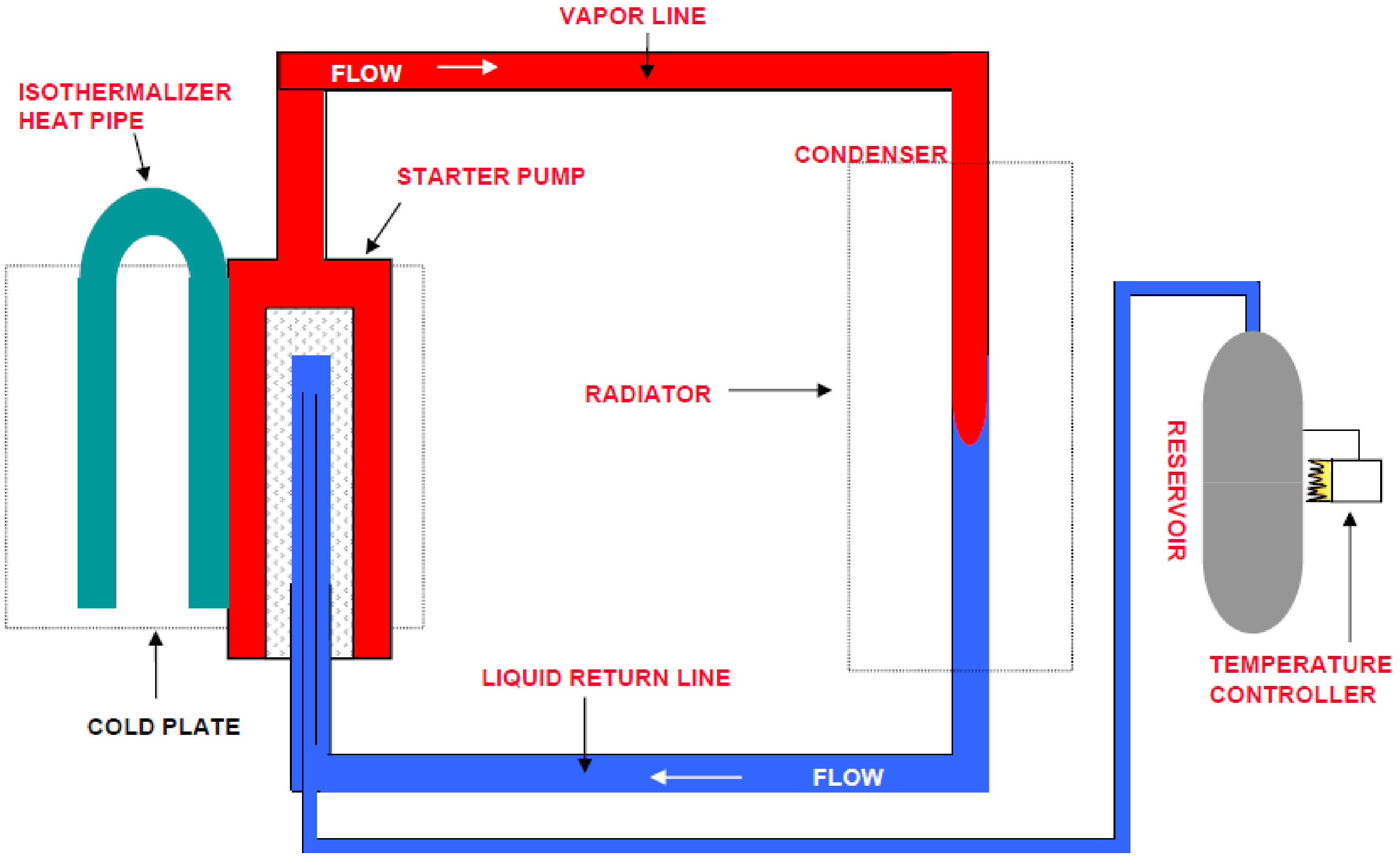
- The reservoir stores excess liquid and controls the loop temperature.
- The operating temperature can be tightly controlled with small heater power.
- The loop can be easily modified or expanded with reservoir re-sizing.
- Pre-conditioning is required for start-up.
- Evaporator cannot tolerate vapor presence, may be prone to dry out during start-up.
- Polyethylene wick with pore sizes ~ 20 µm
- Can accommodate multiple evaporators and condensers in a single loop.

Terra CPLs

- Two-phase loops (CPLs) are on SWIR, TIR and MOPPIT instruments
- On the second day after launch the first CPL system in a flight mission was started successfully.
- All 3 CPLs continue to demonstrate reliable, stable thermal control for their instruments
- SWIR set temperature reset three times

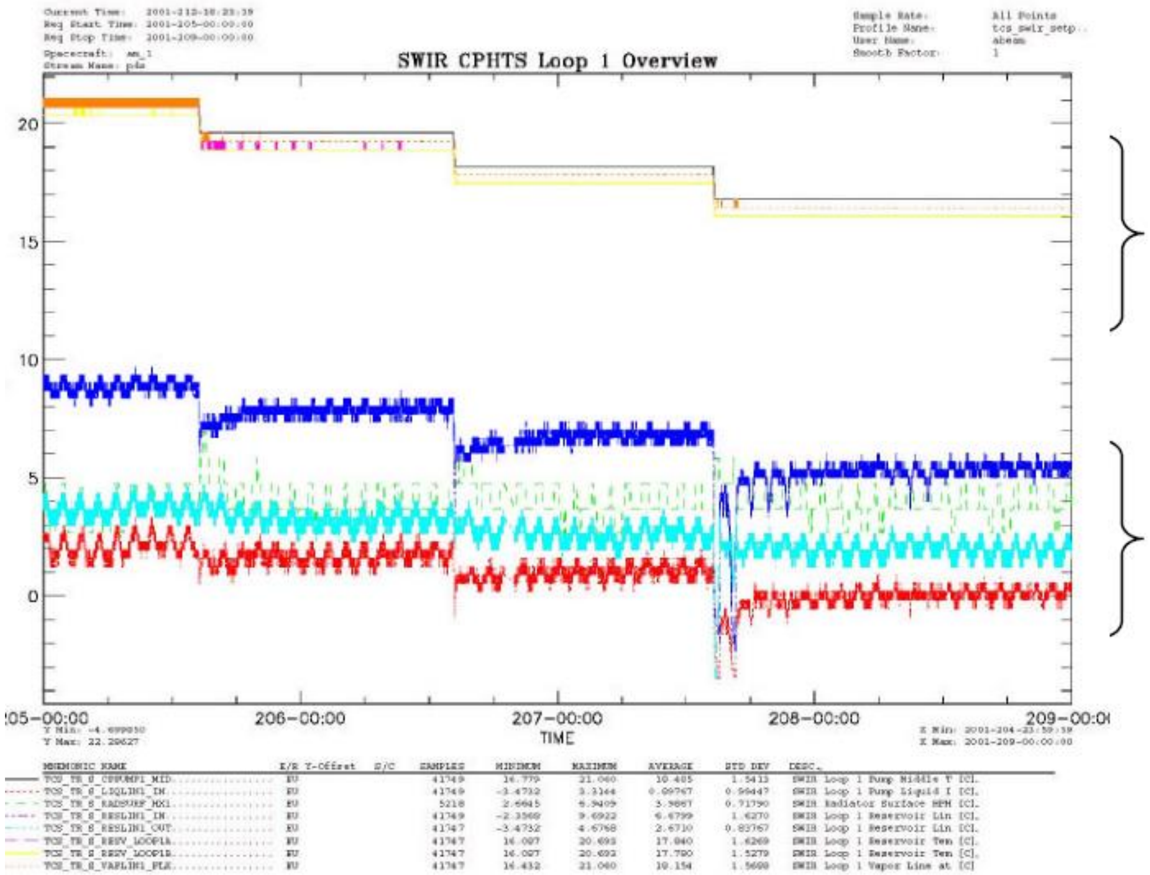


Terra CPL Flow Schematic



Terra - Temperature Reset with Stable Control for the ASTER-SWIR Instrument

- July of 2001 ASTER-SWIR cryo-coolers getting too hot.
- CPL loop temperature was reduced by 4.5 0C in 3 steps



Current Time: 2001-212-18:23:39
Req Start Time: 2001-205-00:00:00
Req Stop Time: 2001-209-00:00:00
Spacecraft: am_1
Stream Name: pds

Sample Rate: All Points
Profile Name: tcs_swir_setp..
User Name: abeam
Smooth Factor: 1

Y Min: -4.699850
Y Max: 22.29627

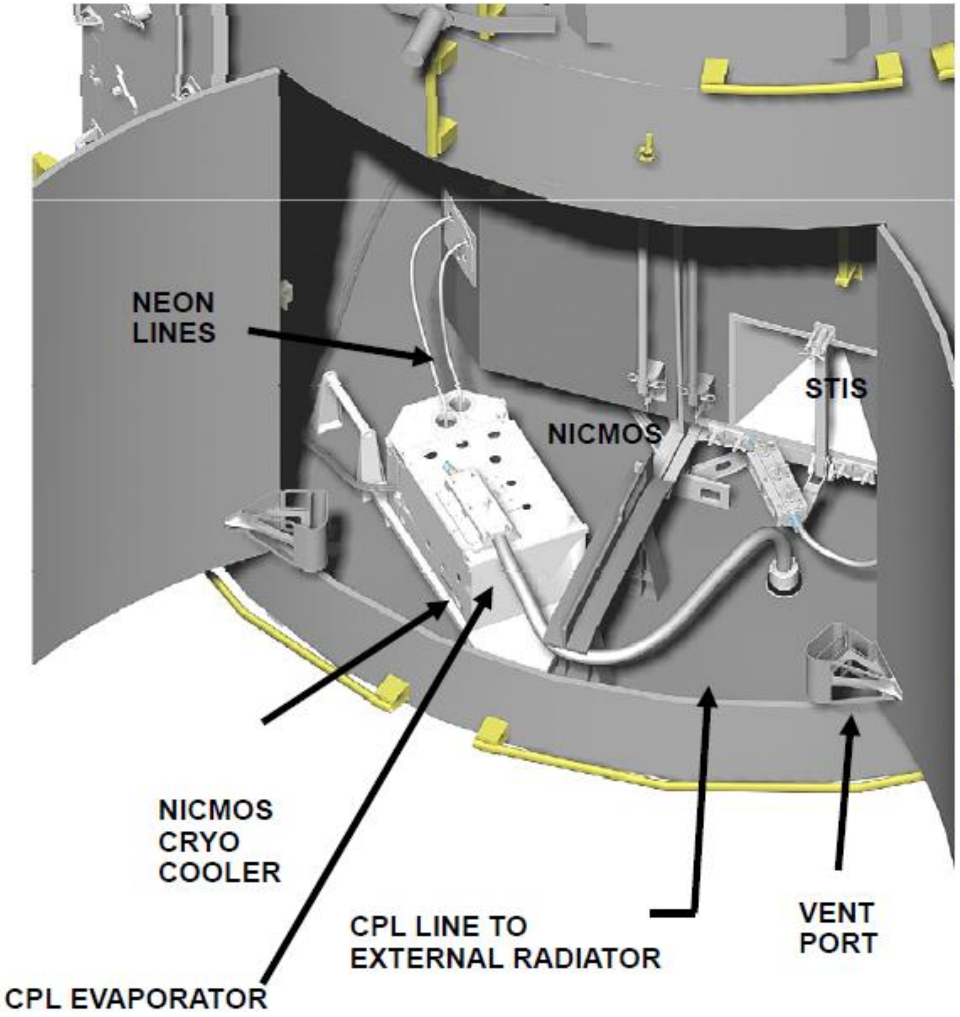
X Min: 2001-204-23:59:59
X Max: 2001-209-00:00:00

MNEMONIC NAME	E/R	Y-Offset	S/C	SAMPLES	MINIMUM	MAXIMUM	AVERAGE	STD DEV	DESC.
TCS_TR_S_CPPUMP1_MID.................	EU			41749	16.779	21.060	10.485	1.5413	SWIR Loop 1 Pump Middle T [C].
TCS_TR_S_LIQLIN1_IN..................	EU			41749	-3.4732	3.3144	0.09767	0.96447	SWIR Loop 1 Pump Liquid I [C].
TCS_TR_S_RADSURF_MX1.................	EU			5218	2.6645	6.9409	3.9867	0.71790	SWIR Radiator Surface MPM [C].
TCS_TR_S_RESLIN1_IN..................	EU			41749	-2.3569	9.6922	6.6799	1.6270	SWIR Loop 1 Reservoir Lin [C].
TCS_TR_S_RESLIN1_OUT.................	EU			41747	-3.4732	4.6768	2.6710	0.83767	SWIR Loop 1 Reservoir Lin [C].
TCS_TR_S_RESV_LOOP1A.................	EU			41747	16.097	20.693	17.840	1.6269	SWIR Loop 1 Reservoir Tem [C].
TCS_TR_S_RESV_LOOP1B.................	EU			41747	16.097	20.693	17.790	1.5279	SWIR Loop 1 Reservoir Tem [C].
TCS_TR_S_VAPLIN1_PLE.................	EU			41747	16.432	21.060	18.154	1.5688	SWIR Loop 1 Vapor Line at [C]

Reservoir and Instrument Interface temperatures change as commanded and then remain constant

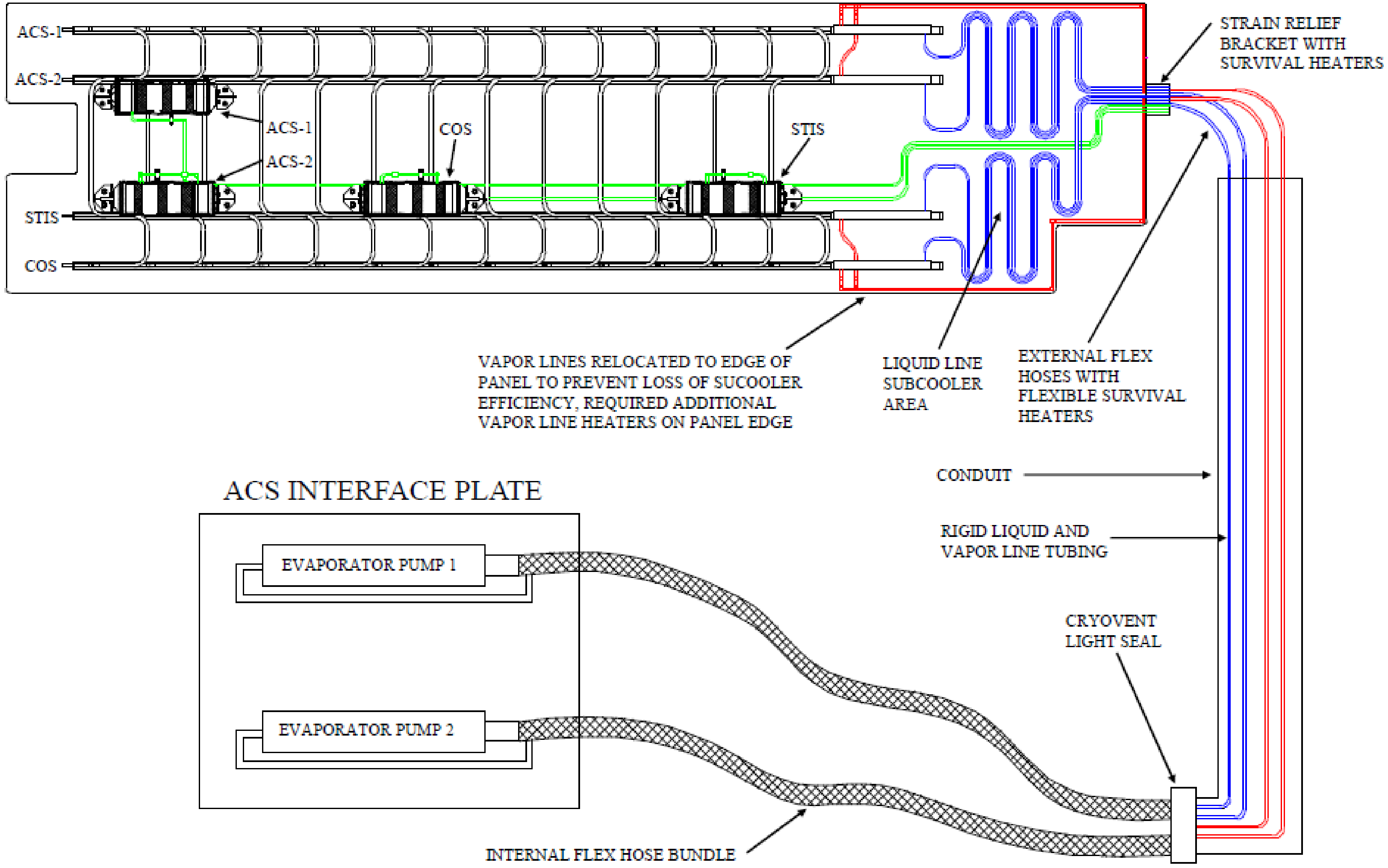
Radiator and various line temperatures adjust according to new set points

CPL on HST/SM-3B (STS-108, Feb/2002)

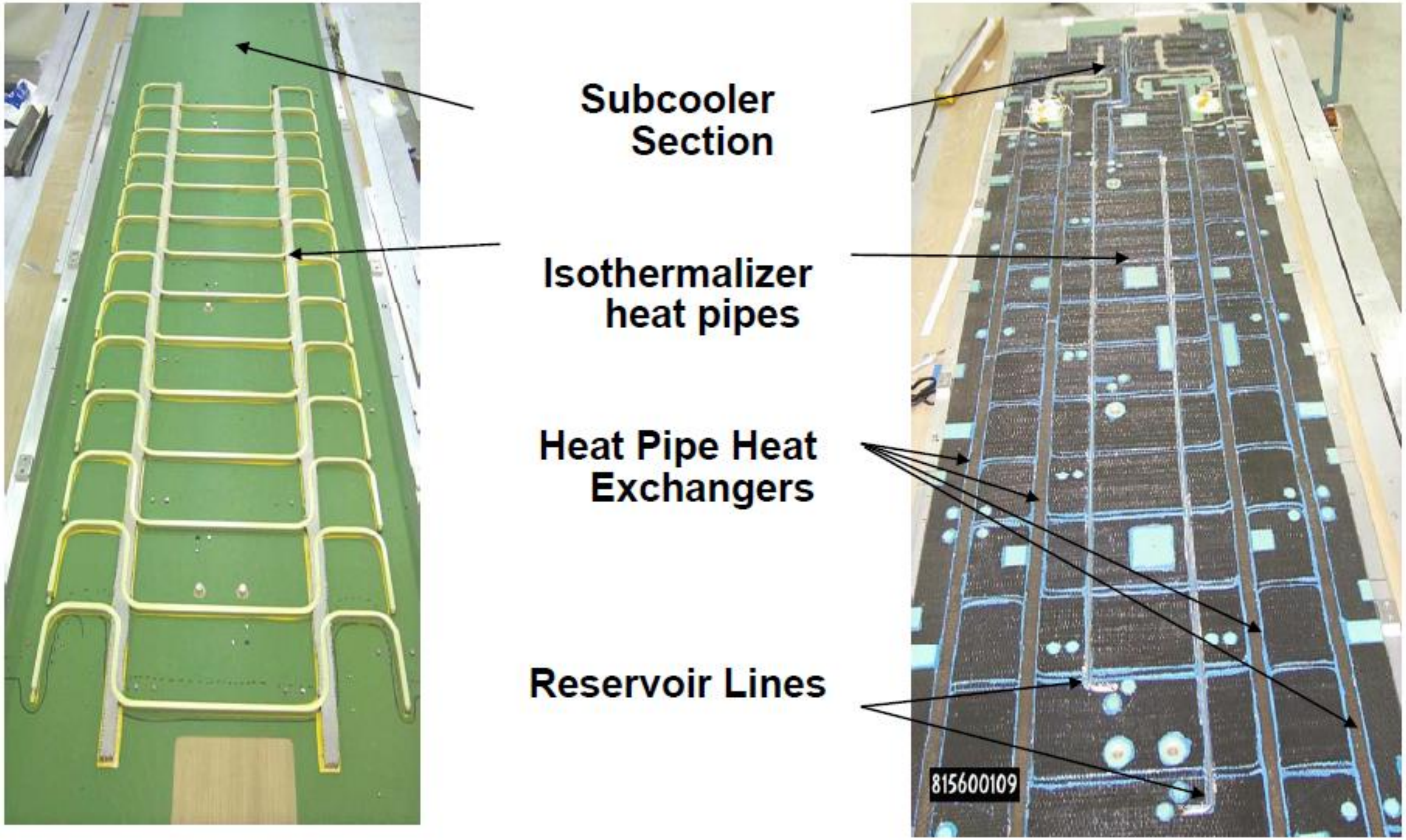


- CPL was added to HST Aft Shroud on SM-3B
- Astronauts fed CPL evaporator through bottom of shroud, attached it to cryo-cooler, and attached new radiator to handrails.
- CPL removes ~ 400 W heat from NICMOS cryocooler which allows the NICMOS sensor to be reactivated.
- Tight temperature control

HST ACS CPLs and ASCS Radiator Design



HST CPL/HP Radiator Assembly



Subcooler Section

Isothermalizer heat pipes

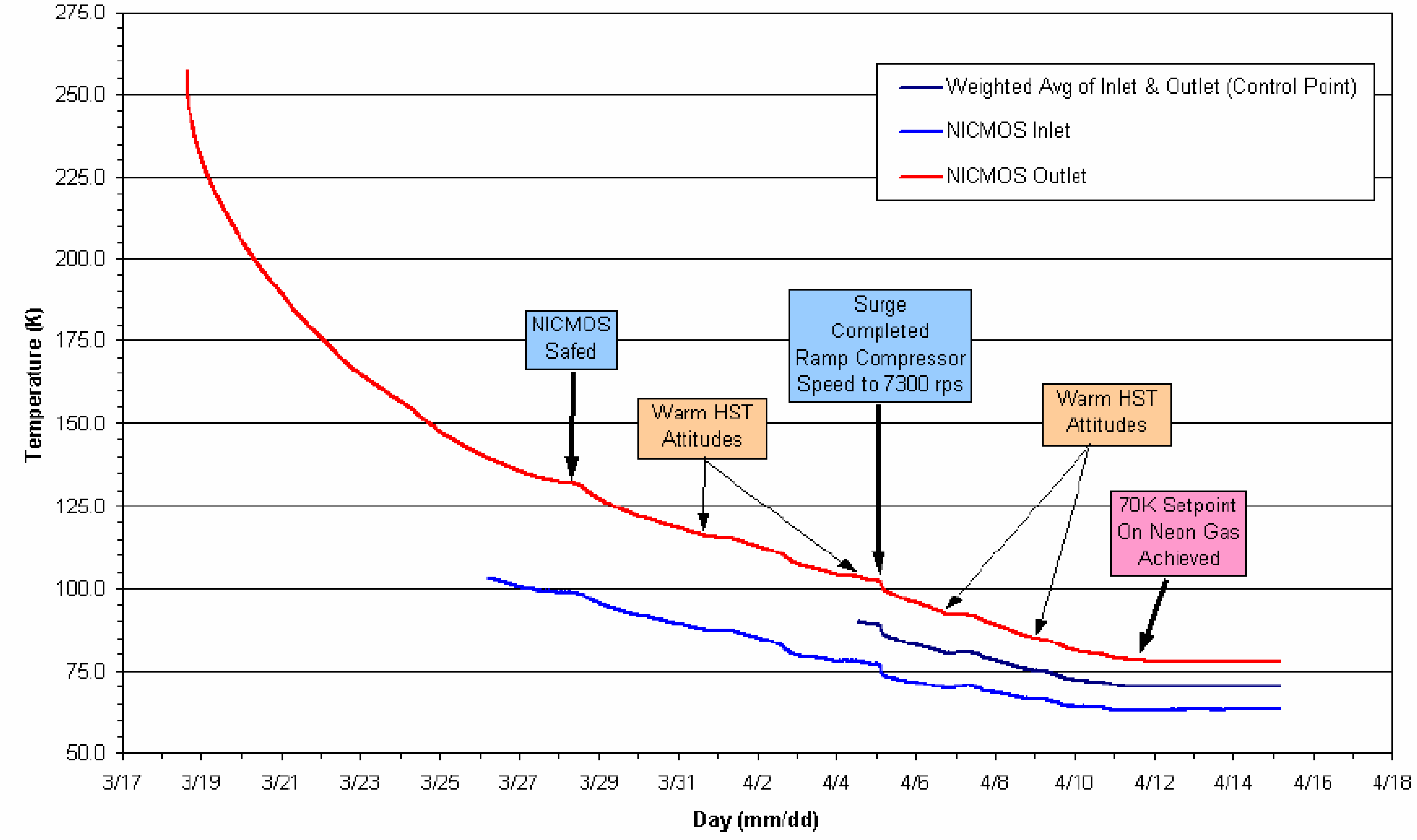
Heat Pipe Heat Exchangers

Reservoir Lines

CPL on HST

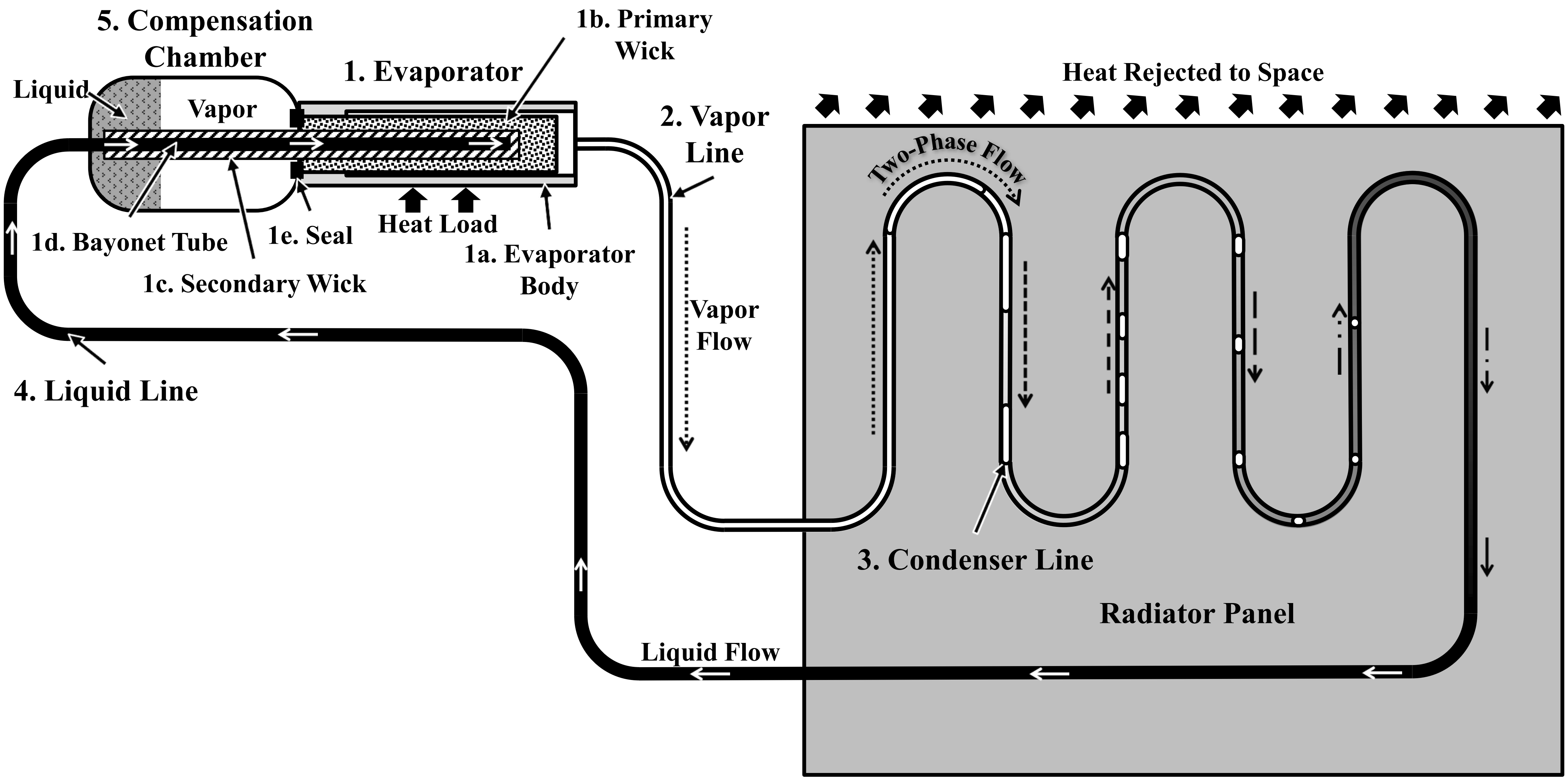
- The loop was fully charged and integrated with the radiator on the ground, and was installed to the HST by the astronaut.

HST NICMOS Temperatures (Neon)

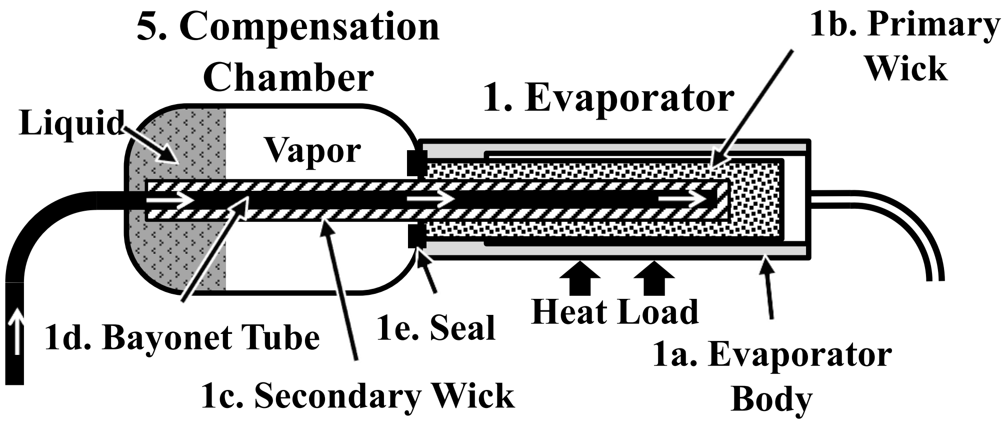


LOOP HEAT PIPES

Major Loop Heat Pipe Components



LHP Evaporator



- Evaporator elements:
  a) Evaporator body, a.k.a. “evaporator case,” a.k.a. “evaporator envelope”
  b) Primary wick
  c) Secondary wick
  d) Bayonet tube
  e) Seal

Typical Characteristics of LHP Primary Wicks

Material	Effective Pore Radius, μm	Permeability, $\times 10^{13}$, m^2	Porosity, %	Thermal Conductivity, W/(m K)
Stainless Steel	0.8 – 5	0.1 – 20	40 – 50	0.8 – 1.6
Titanium	1 – 10	2 – 20	55 – 70	0.6 – 1.5
Nickel	0.7 – 10	0.1 – 20	60 – 75	5 – 10
Polyethylene	10 – 20	>10	< 40	< 0.3
Copper	3 – 20	>100	55 – 75	30 – 50

Main Characteristics of LHP

- LHP differs from CPL in regards:
  - The reservoir forms an integral part of the evaporator assembly.
  - A secondary wick connects the reservoir and evaporator (primary wick).
- 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 design is the most common

LHP 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:

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

- The capillary pressure rise across the wick meniscus:

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

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

$$\Delta P_{cap,\ max} = 2\ \sigma \cos\theta\ / r_{p} \qquad (3)$$

where r_p – radius of the “largest pore” in the wick

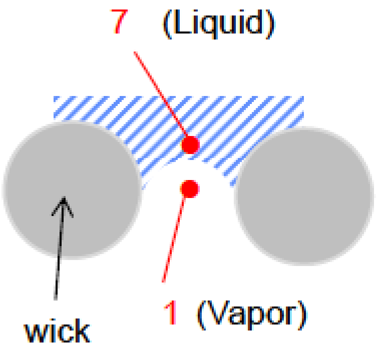
- The meniscus will adjust it radius of curvature so that the capillary pressure rise matches the total pressure drop which is a function of the operating condition:

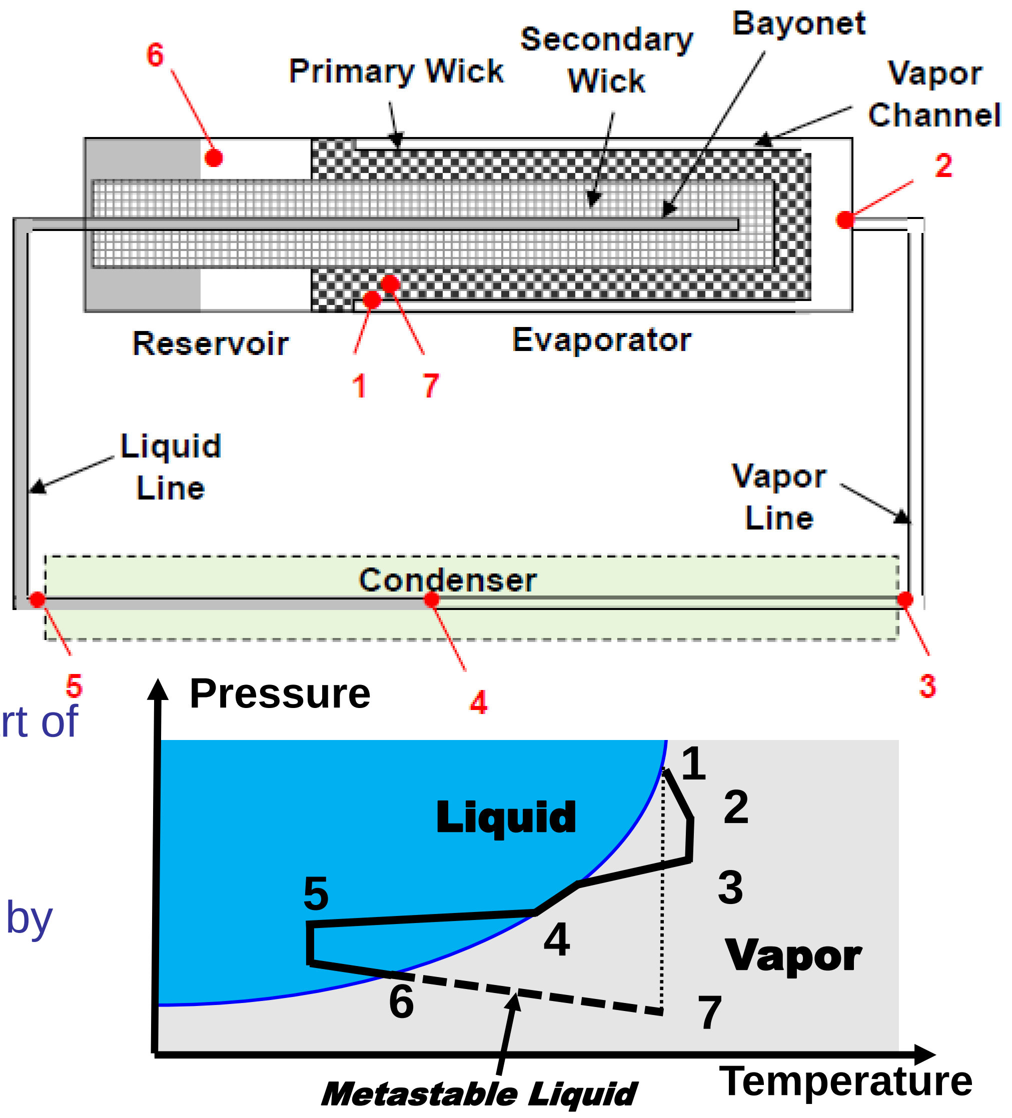
$$\Delta P_{cap} = \Delta P_{tot} \qquad (4)$$

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

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

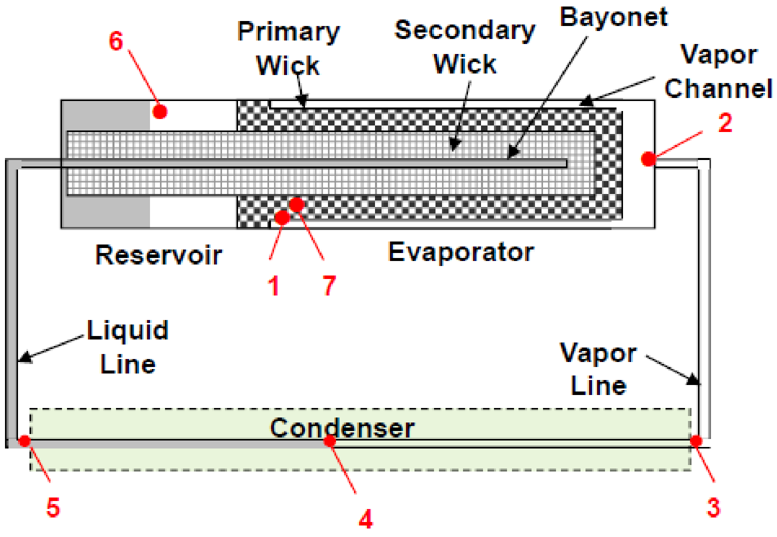
Pressure Profile in Gravity Neutral LHP Operation

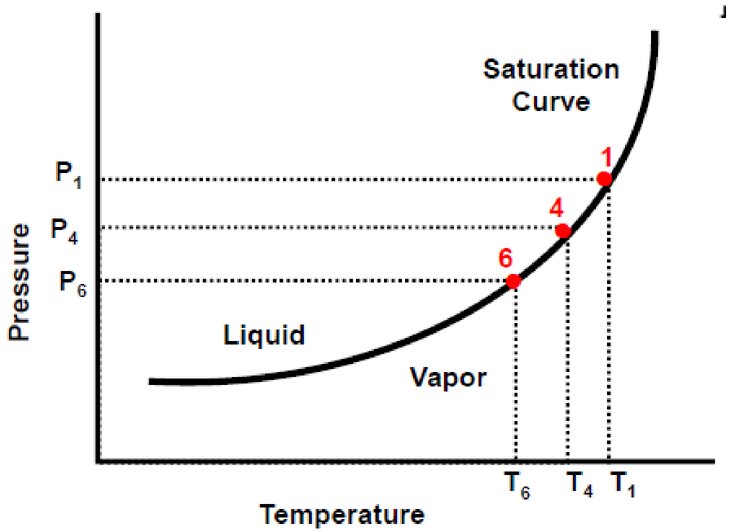




- Evaporator core is considered part of reservoir.
- P6 is the reservoir saturation pressure.
- All other pressures are governed by P6
- All pressure drops are viscous pressure drops.

Thermodynamic Constraints in LHP Operation



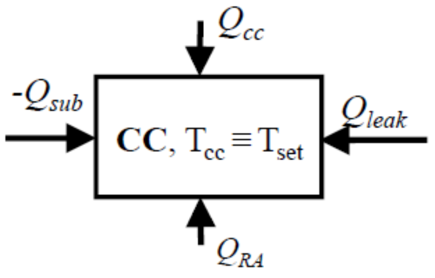


$$P_e - P_{cond} = (dP/dT)\,(T_e - T_{cond})$$
$$P_{cond} - P_{cc} = (dP/dT)\,(T_{cond} - T_{cc})$$
$$P_e - P_{cc} = (dP/dT)\,(T_e - T_{cc})$$

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

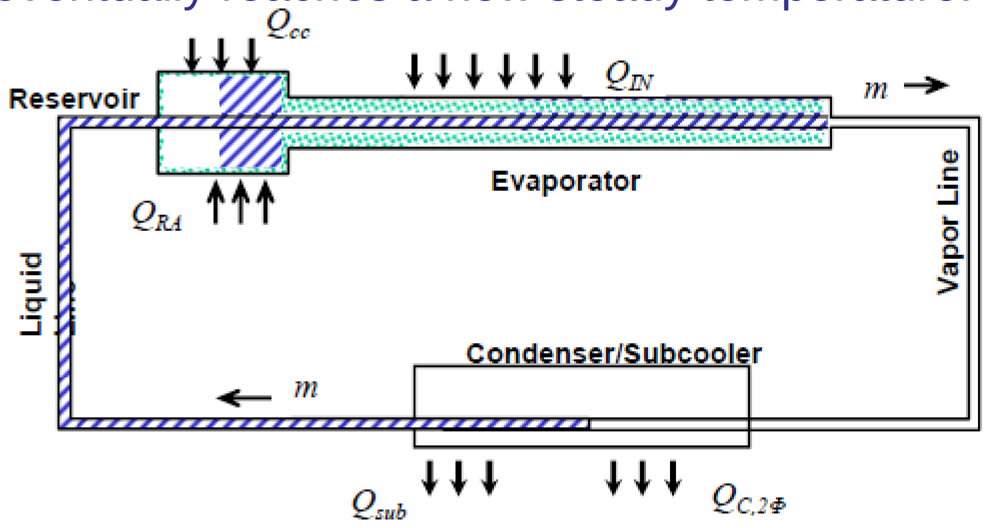
LHP Operating Temperature

- 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
  - Heat exchange between CC and ambient



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

- As the operating condition changes, the CC temperature will change during the transient, but eventually reaches a new steady temperature.



LHP Natural Operating Temperature

No Active Control of CC Temperature ($Q_{cc} = 0$)

- For a well insulated CC, T_{cc} is determined by energy balance between heat leak and liquid subcooling:

$$Q_{sub} = Q_{leak}$$

$$Q_{sub} = \dot{m}\big(h_v(T_{cc}) - h_l(T_l)\big)$$

$\dot{m}$ $-$ *mass flow rate*

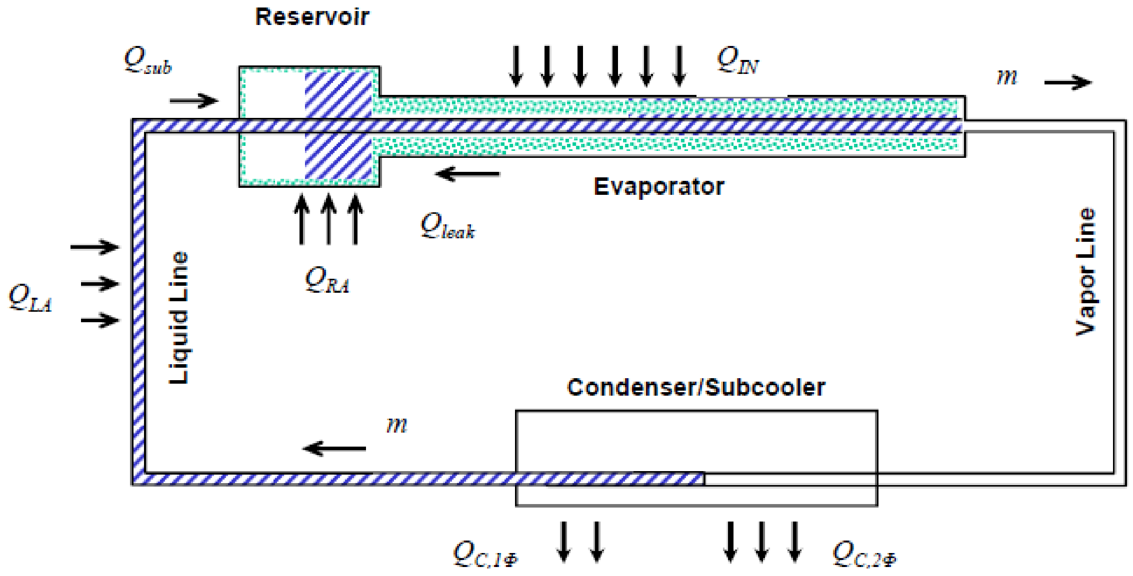
$h_v(T_{cc})$ $-$ enthalpy of vapor at CC temperautre

$h_l(T_l)$ $-$ enthalpy of liquid at liquid line temperautre

$$Q_{leak} = G_{e-cc}(T_e - T_{cc})$$

G_{e-cc} $-$ *conductance between evaporator and cc*

LHP Energy Balance



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

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

$$Q_E = m\ \lambda$$

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

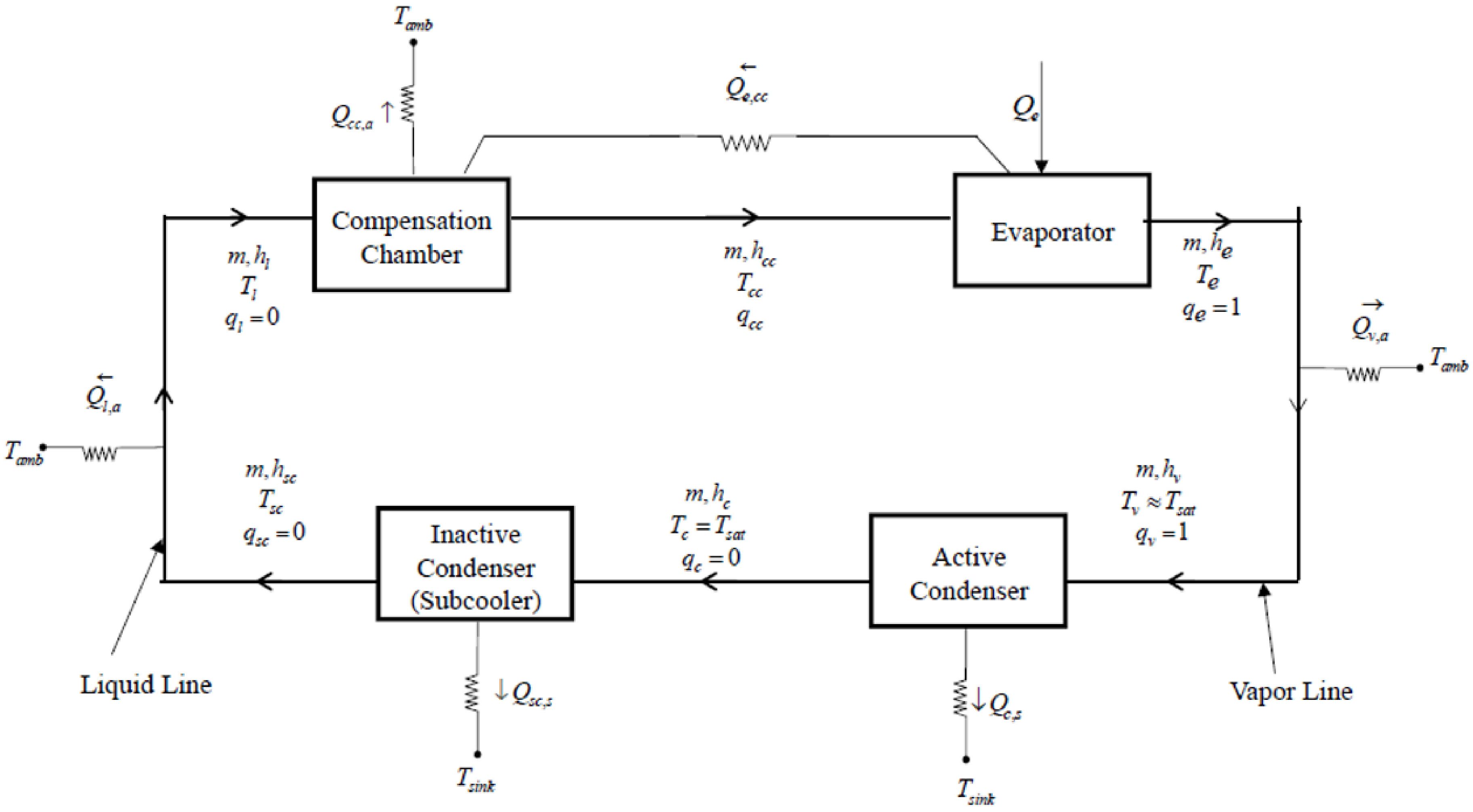
$$T_{c,out} = f(m\ , L_{c,2\phi}, T_{c,wall})$$

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

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

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

Simplified LHP Thermal Network

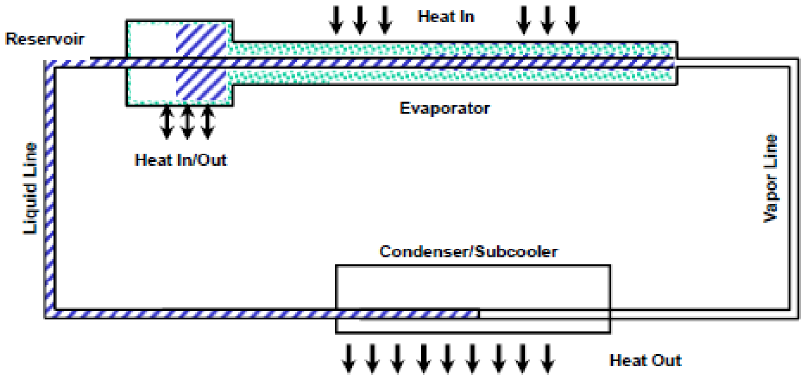


LHP Reservoir Sizing and Fluid Inventory

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:

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

LHP Modeling

- 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.

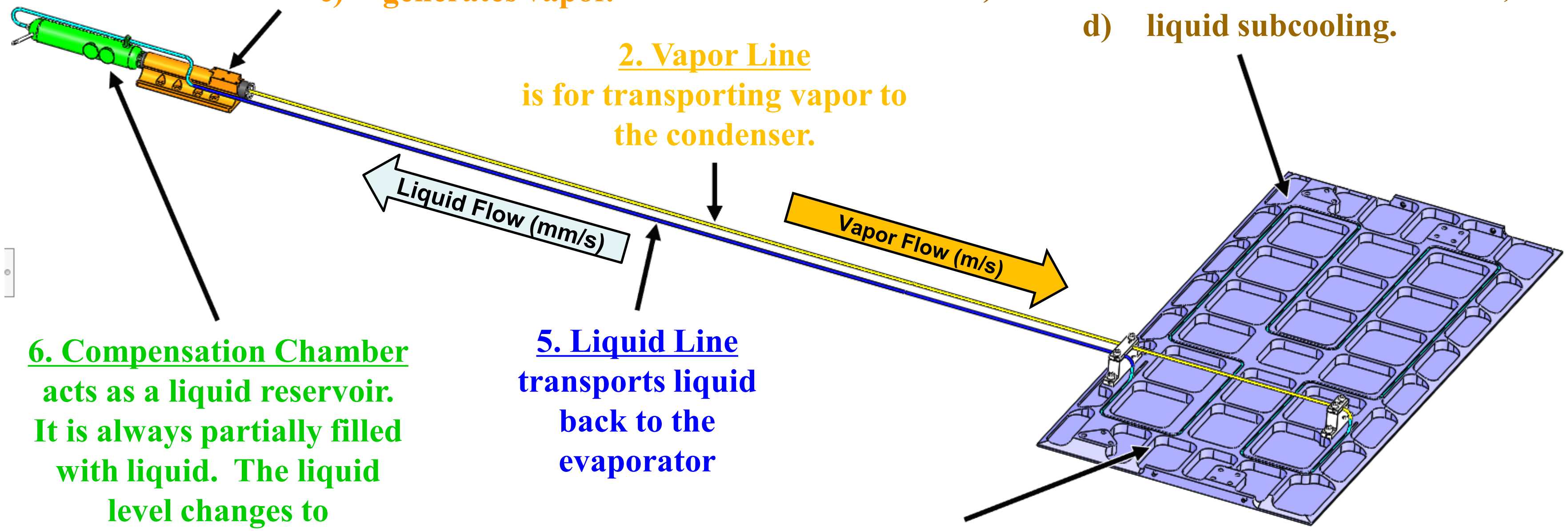
- LHP manufacturers develop their own models.
  - Design optimization
  - Performance prediction

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)

PACE OCI LHPs



1. **Evaporator**
   - a) thermally coupled to the heat source (FPA),
   - b) acquires heat (via conduction),
   - c) generates vapor.

2. Vapor Line
is for transporting vapor to the condenser.

3. Condenser Line
- a) is attached to the radiator panel,
- b) This is where vapor converts back into liquid,
- c) The heat conducts to the radiator,
- d) liquid subcooling.

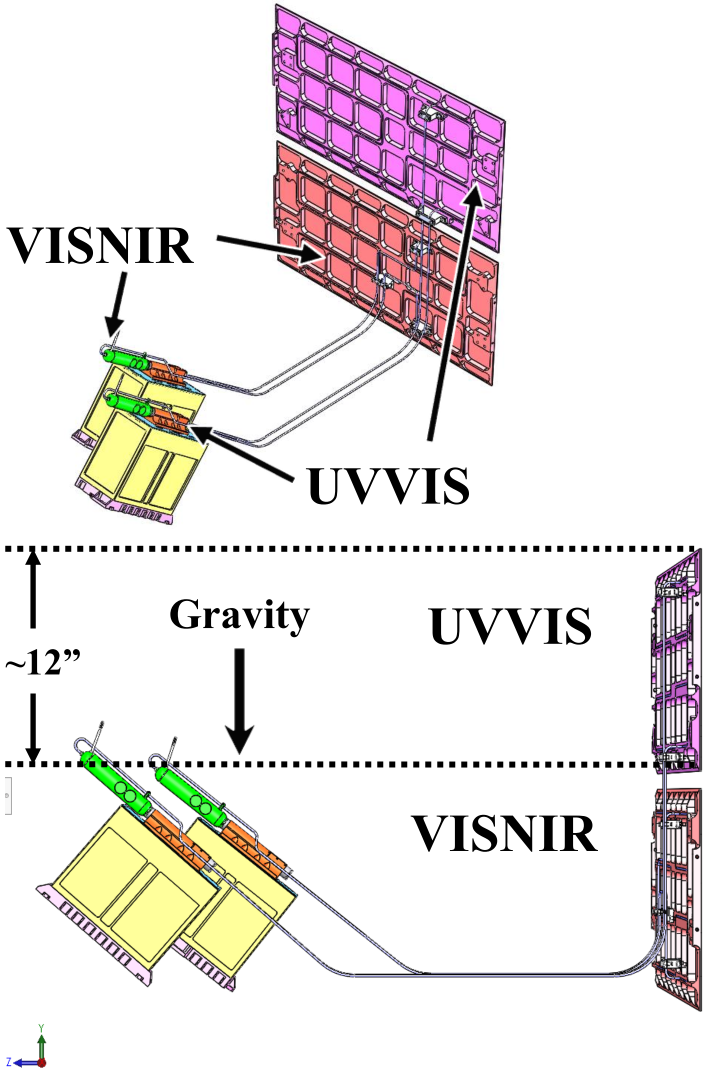
4. Radiator Panel
is attached to the condenser line. It radiates heat to a heat sink (space or cold plate/shroud).

5. Liquid Line
transports liquid back to the evaporator

6. Compensation Chamber
acts as a liquid reservoir. It is always partially filled with liquid. The liquid level changes to compensate for variation of liquid fraction in the condenser.

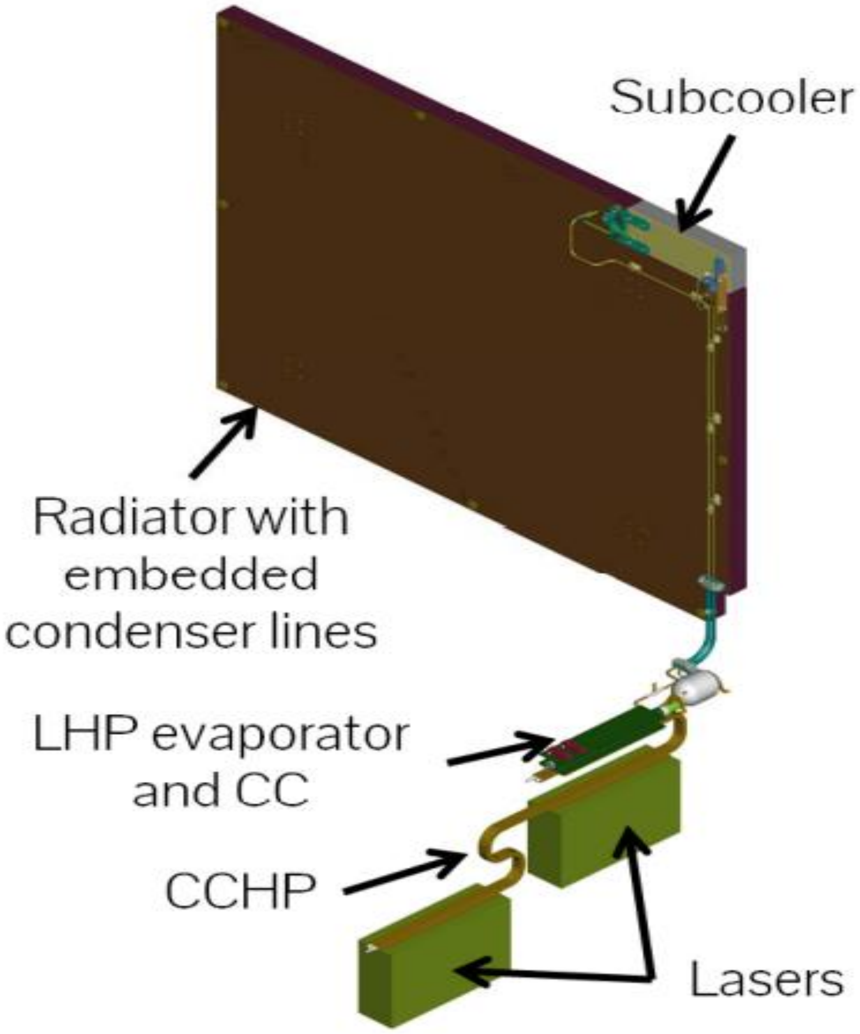
A liquid subcooling is produced naturally to compensate for the heat leaks and the control heater power.

PACE OCI LHPs (FLIGHT Configuration)

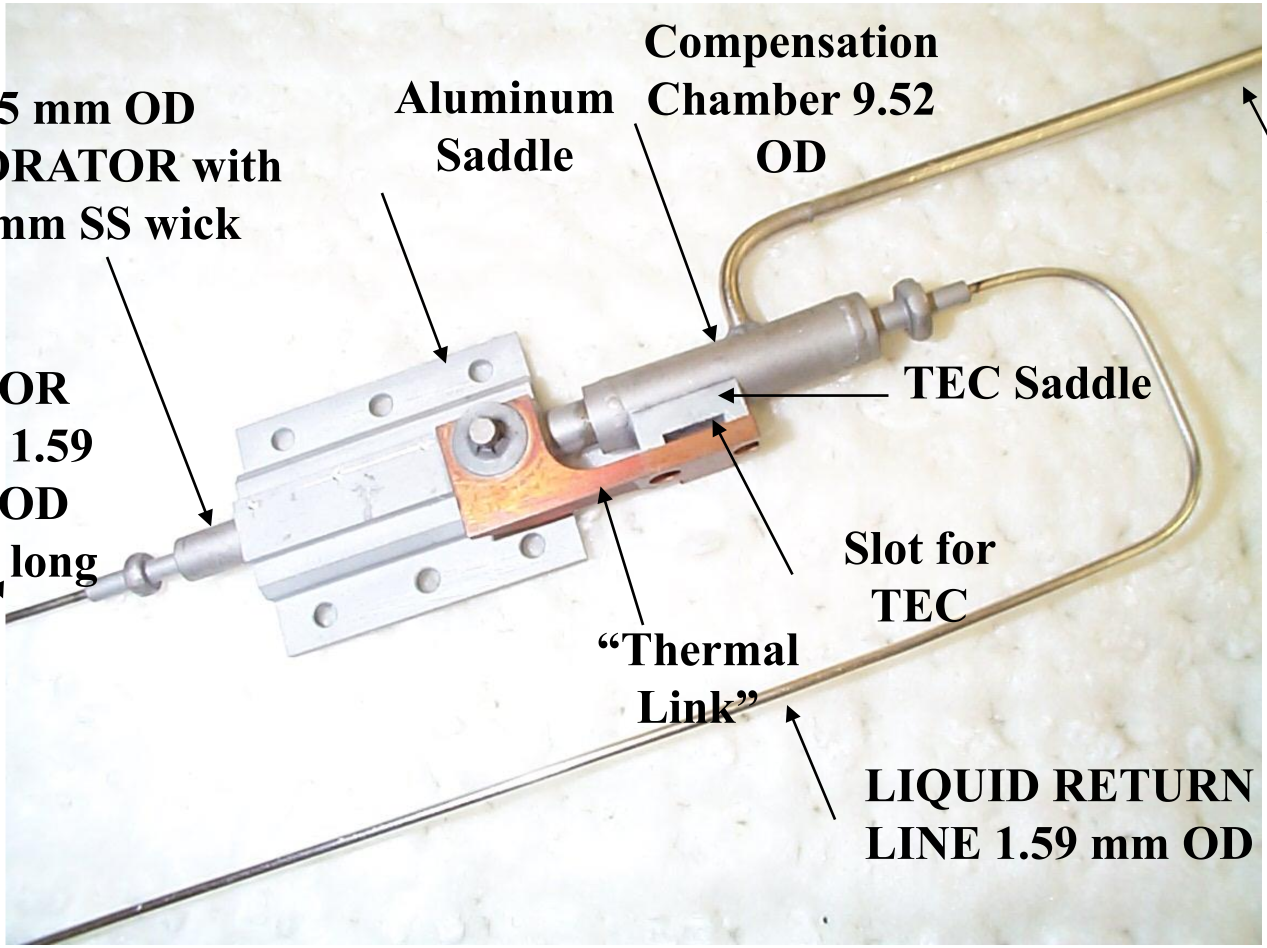


ICESAT-2 / ATLAS

- Redundant lasers are cooled via a single Laser Thermal Control System (LTCS) consisting of a constant conductance heat pipe (CCHP), a loop heat pipe (LHP), and a radiator.



Mini-LHP Evaporator



6.35 mm OD EVAPORATOR with 5.63 mm SS wick

Aluminum Saddle

Compensation Chamber 9.52 OD

FILL TUBE

VAPOR LINE 1.59 mm OD 60 cm long

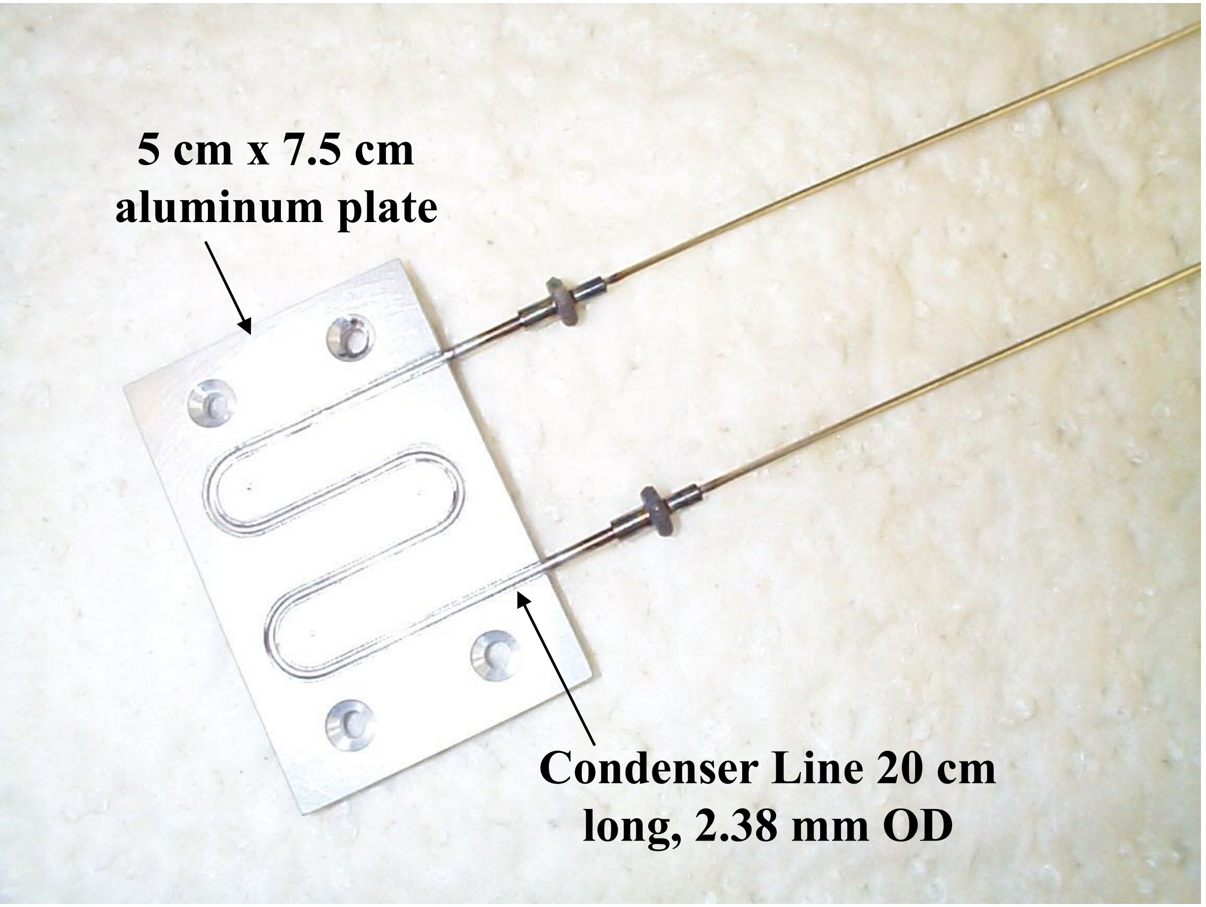
TEC Saddle

Slot for TEC

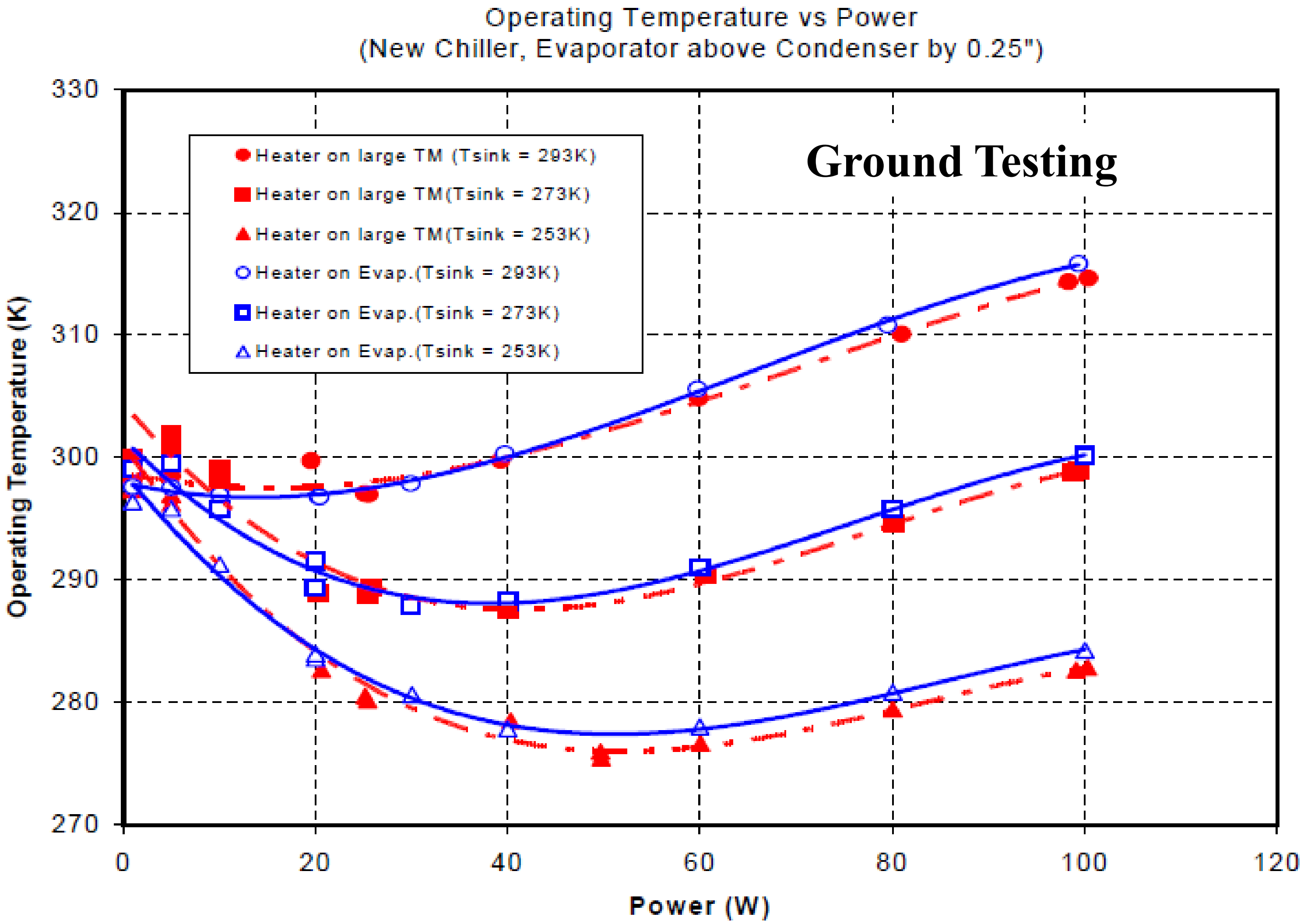
“Thermal Link”

LIQUID RETURN LINE 1.59 mm OD

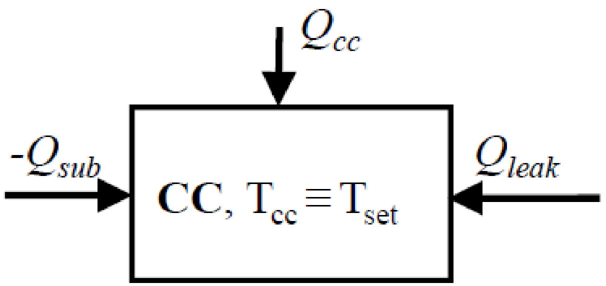
Mini-LHP Condenser



Mini-LHP at Various Sink Temperatures

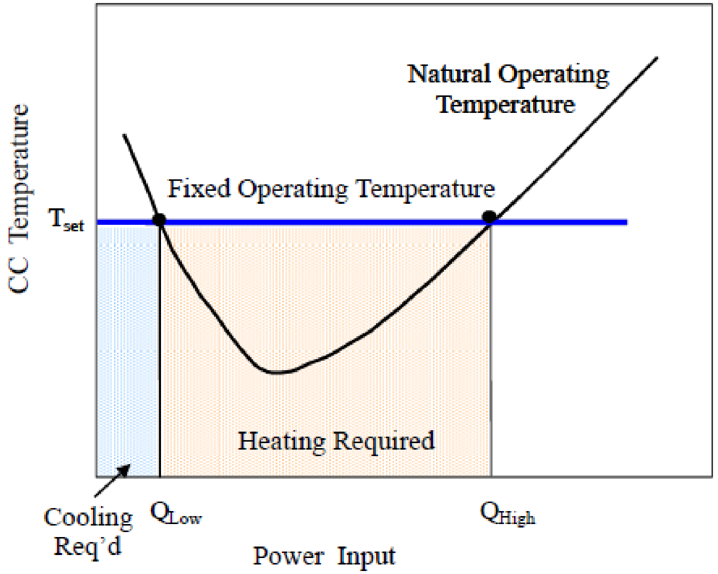


LHP Operation: CC Temperature Controlled at T_{set}



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

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

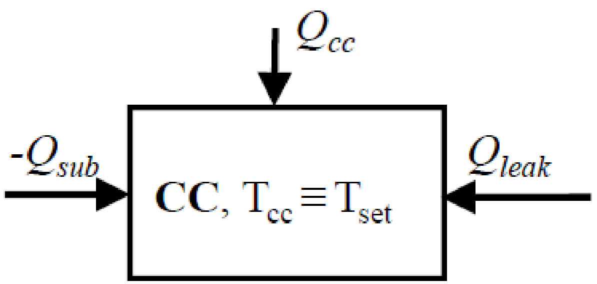


- CC is cold biased, and electrical heaters are commonly used to maintain T_{cc} at T_{set}.
- Overall thermal conductance decreases.
- Q_{cc} varies with Q_{sc}, which in turn varies with evaporator power, condenser sink temperature, ambient temperature and number of coupling blocks.
- Q_{cc} can be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

LHP Temperature Control Methods

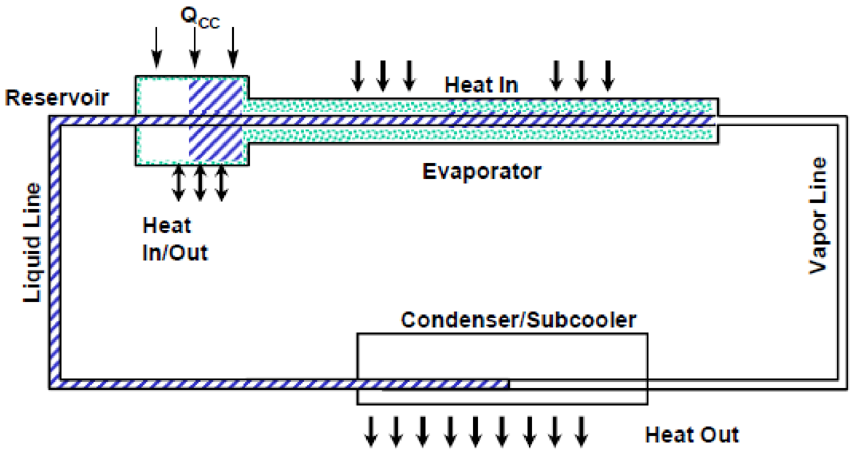
- All methods involve cold-biasing the CC and use external heat source to maintain CC temperature:
  1) Electric heater on CC only (Aura TES, GOES-R GLM, PACE OCI)
  2) Electric heater on CC and coupling blocks placed between vapor and liquid lines (ICESat GLAS)
  3) Electric heater on CC and VCHP connecting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

LHP Temp. Control with Electric Heater on CC



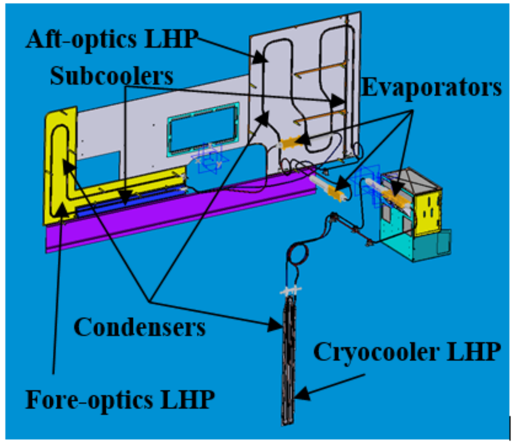
$$Q_{leak} - Q_{sub} + Q_{cc} = 0$$

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

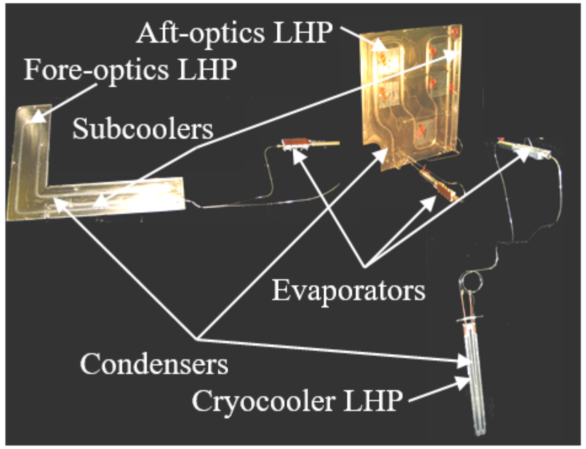


- The electrical heater attached to the CC provides the necessary Q_{cc} control heater power.
- Advantages: simplicity, direct heating
- Disadvantage: required control heater power could be large.

GIFTS LHPs

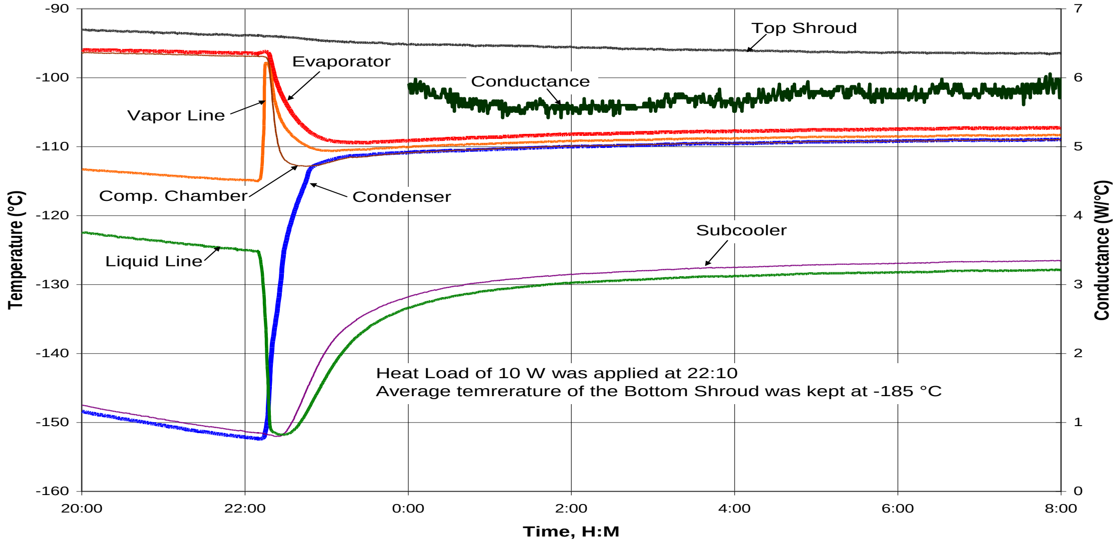


(a) Designed LHP Models



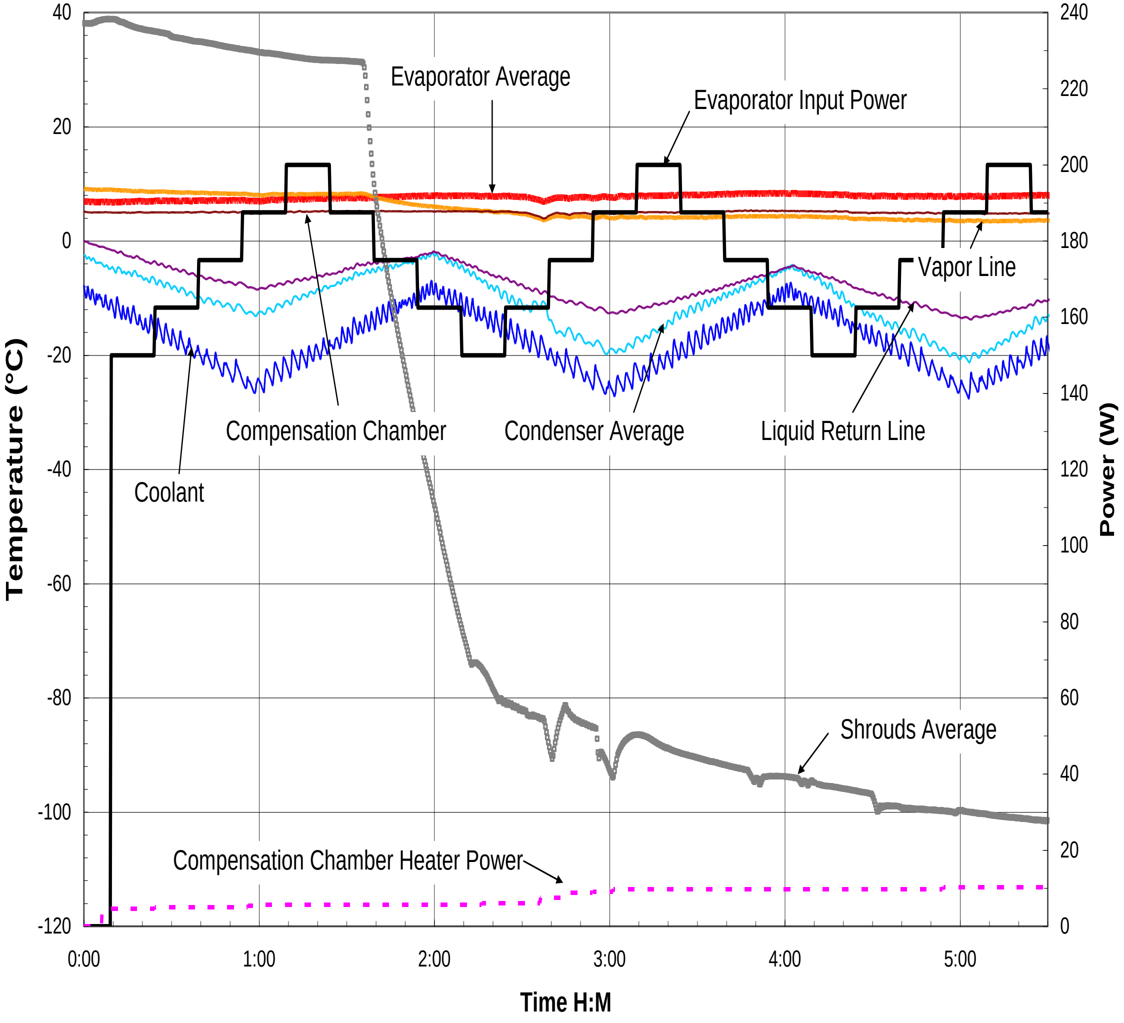
(b) Actual Hardware

Aft-Optics LHP (Ethane)

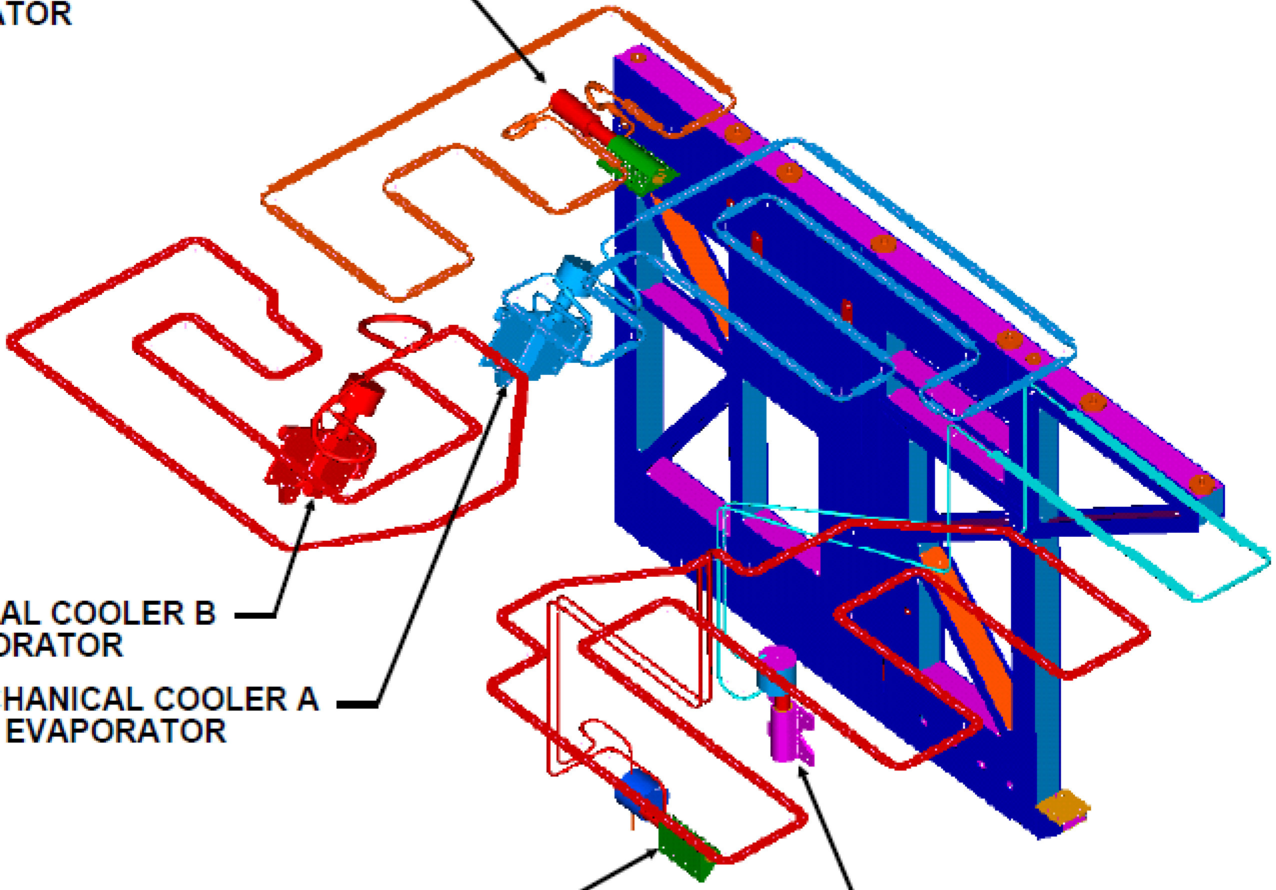


Heat Load of 10 W was applied at 22:10
Average temrerature of the Bottom Shroud was kept at -185 °C

Cryocooler LHP (Ammonia)



EOS-Aura TES Instrument LHP Layout



SIGNAL CHAIN/ LASER HEAD ASSEMBLY
LHP EVAPORATOR

MECHANICAL COOLER B
LHP EVAPORATOR

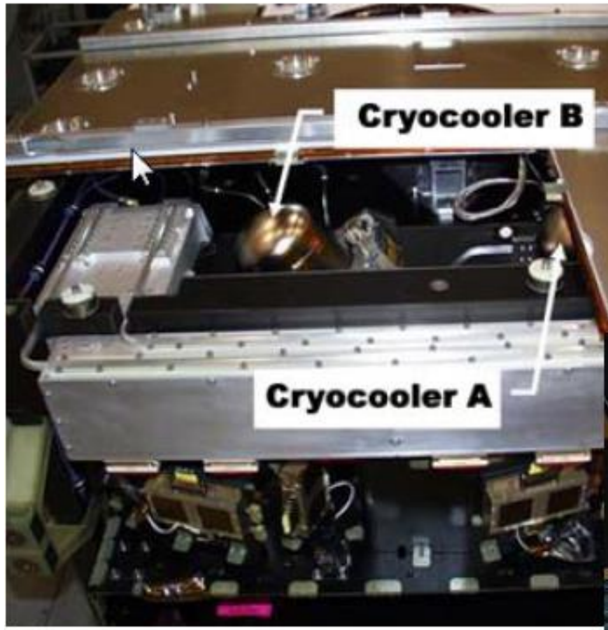
MECHANICAL COOLER A
LHP EVAPORATOR

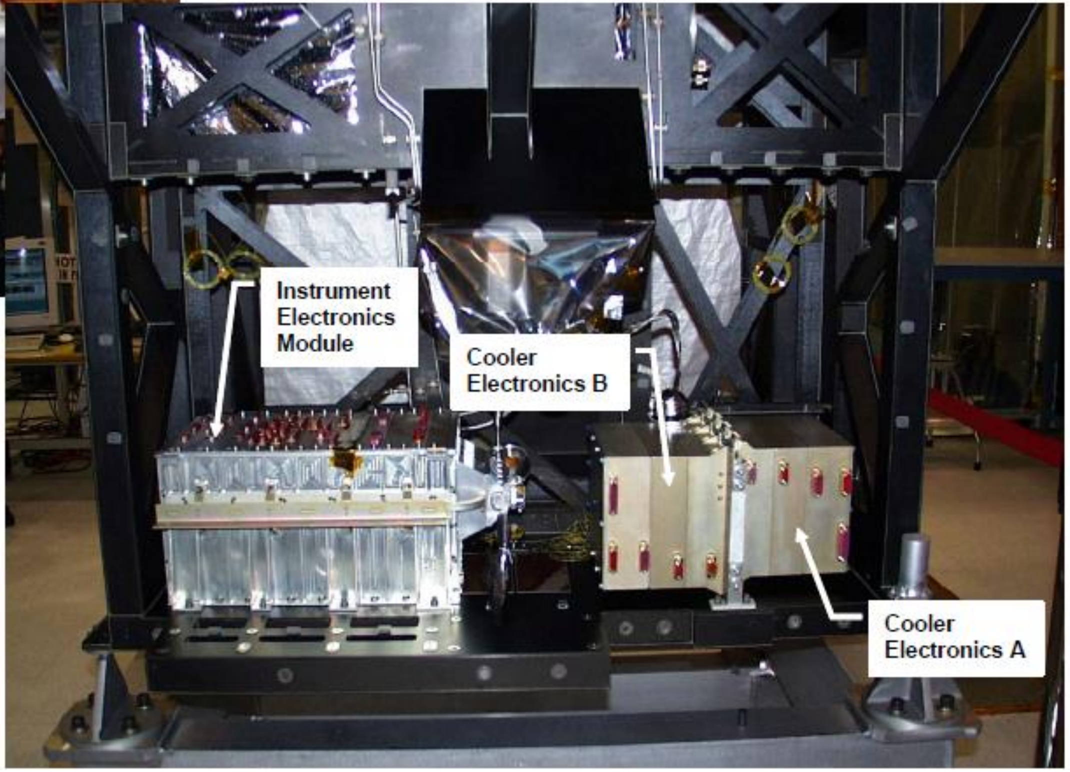
IEM LHP
EVAPORATOR

MECHANICAL COOLER
ELECTRONICS LHP
EVAPORATOR

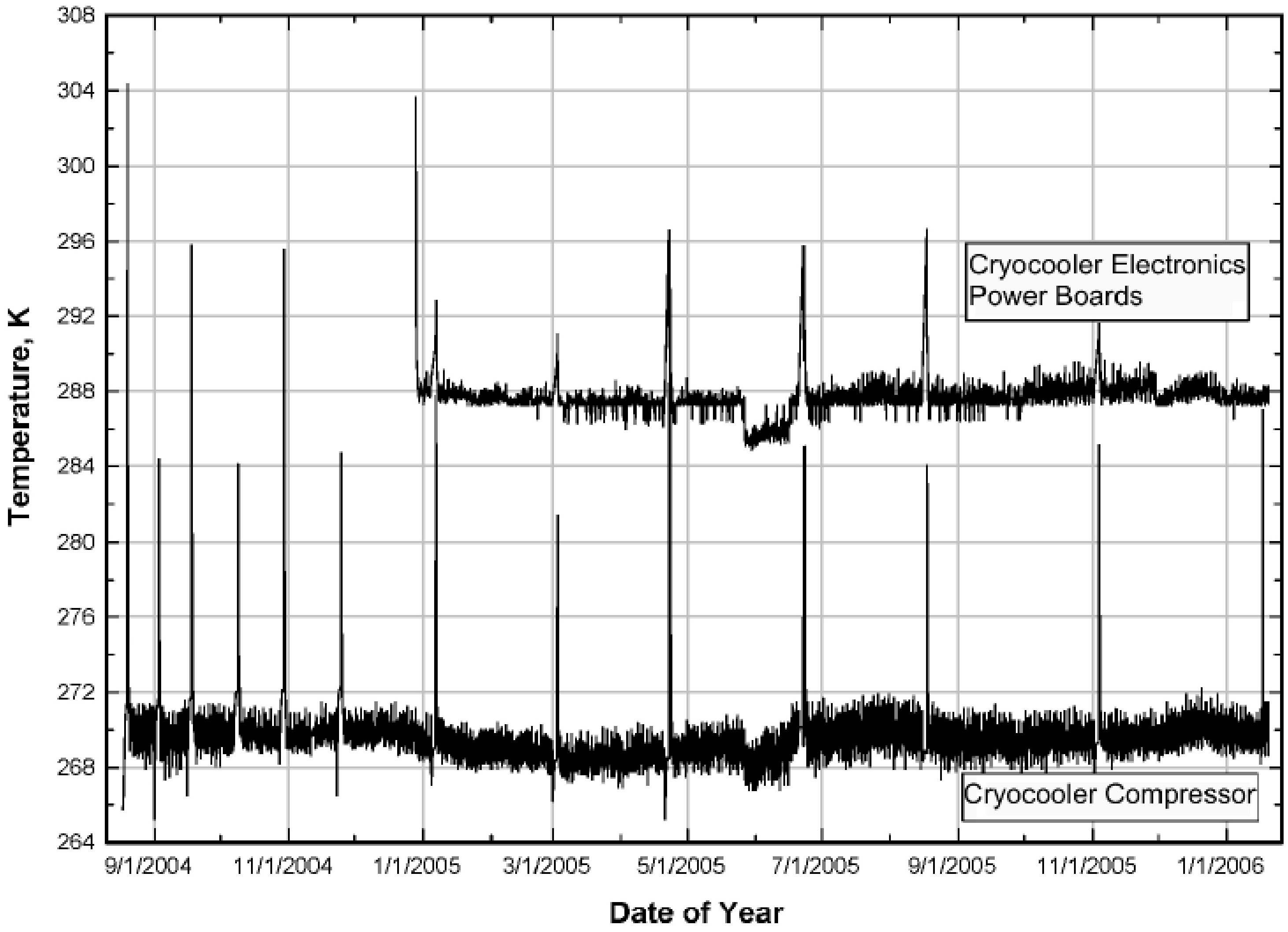
Tropospheric Emission Spectrometer (TES)

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

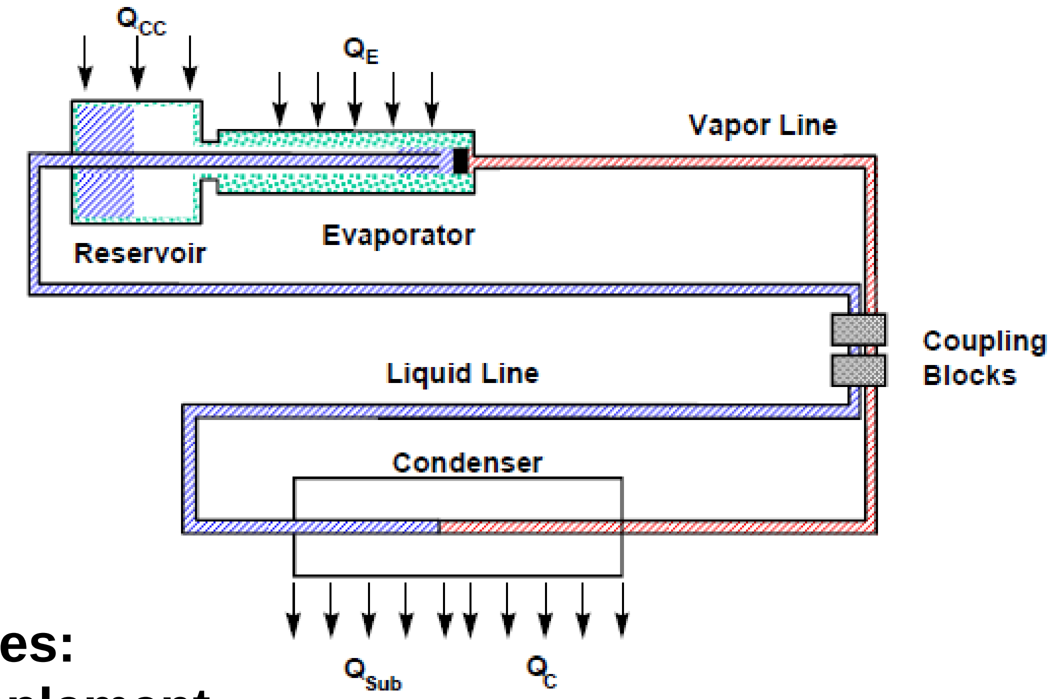




EOS-Aura TES Components Thermal Performance



LHP Temp. Control with Coupling Blocks



- The coupling blocks serve as a heat exchanger which transfers heat from the vapor line to the liquid line.
- 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.

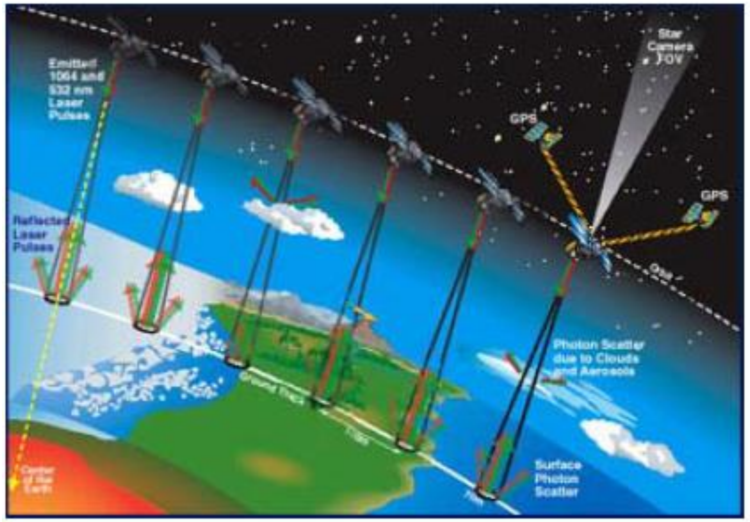
➢ Advantages:

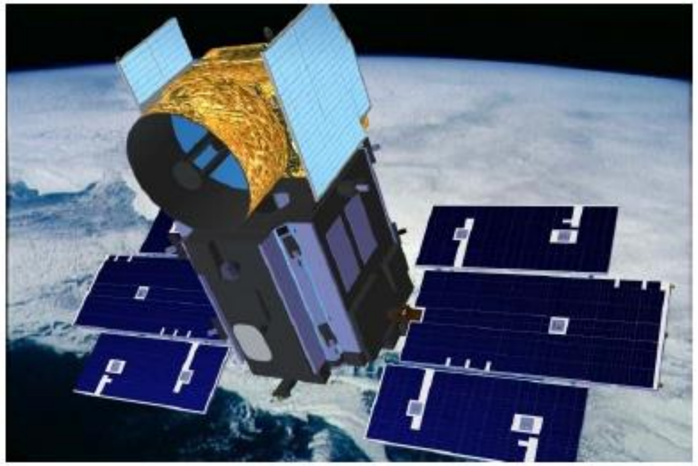
– Easy to implement
– Efficient in reducing CC control heater power

➢ Disadvantages:

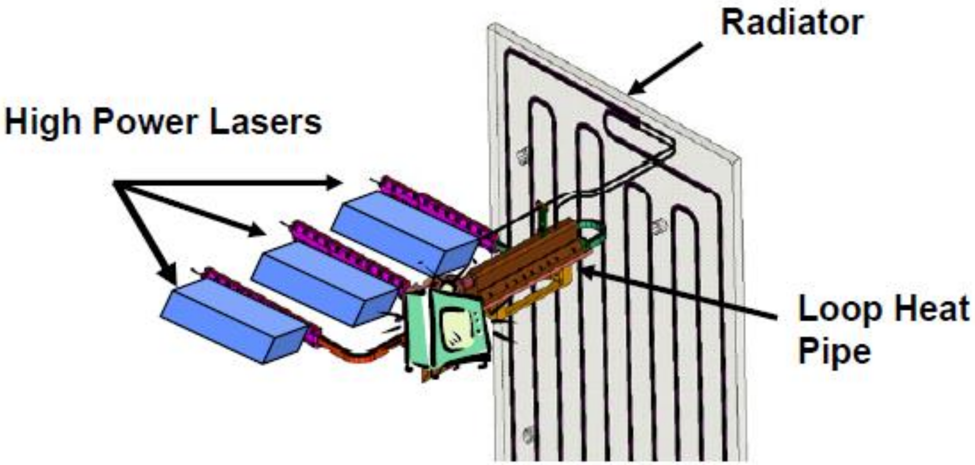
– Increases the natural operating temperature at low and high powers
– May add difficulty to low power start-up
– May still require high CC control heater power under the cold condition.

LHPs on ICESat

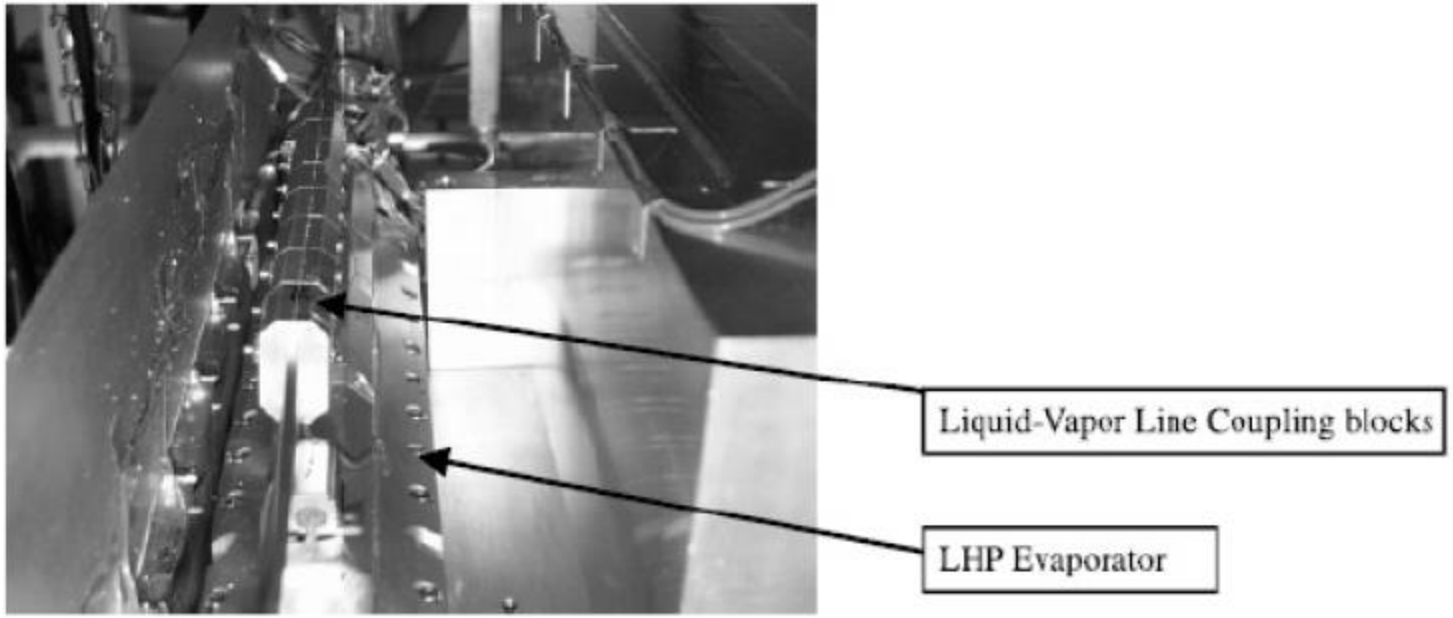




- GLAS has high powered lasers to measure polar ice thickness
- First known application of a two-phase loop to a laser
- 2 LHPs; Laser altimeter and power electronics
  - Propylene LHPs
- Launched January, 2003
- Both LHPs successfully turned on
- Very tight temperature control ~ 0.2 °C



Coupling Blocks on ICESat GLAS LHPs

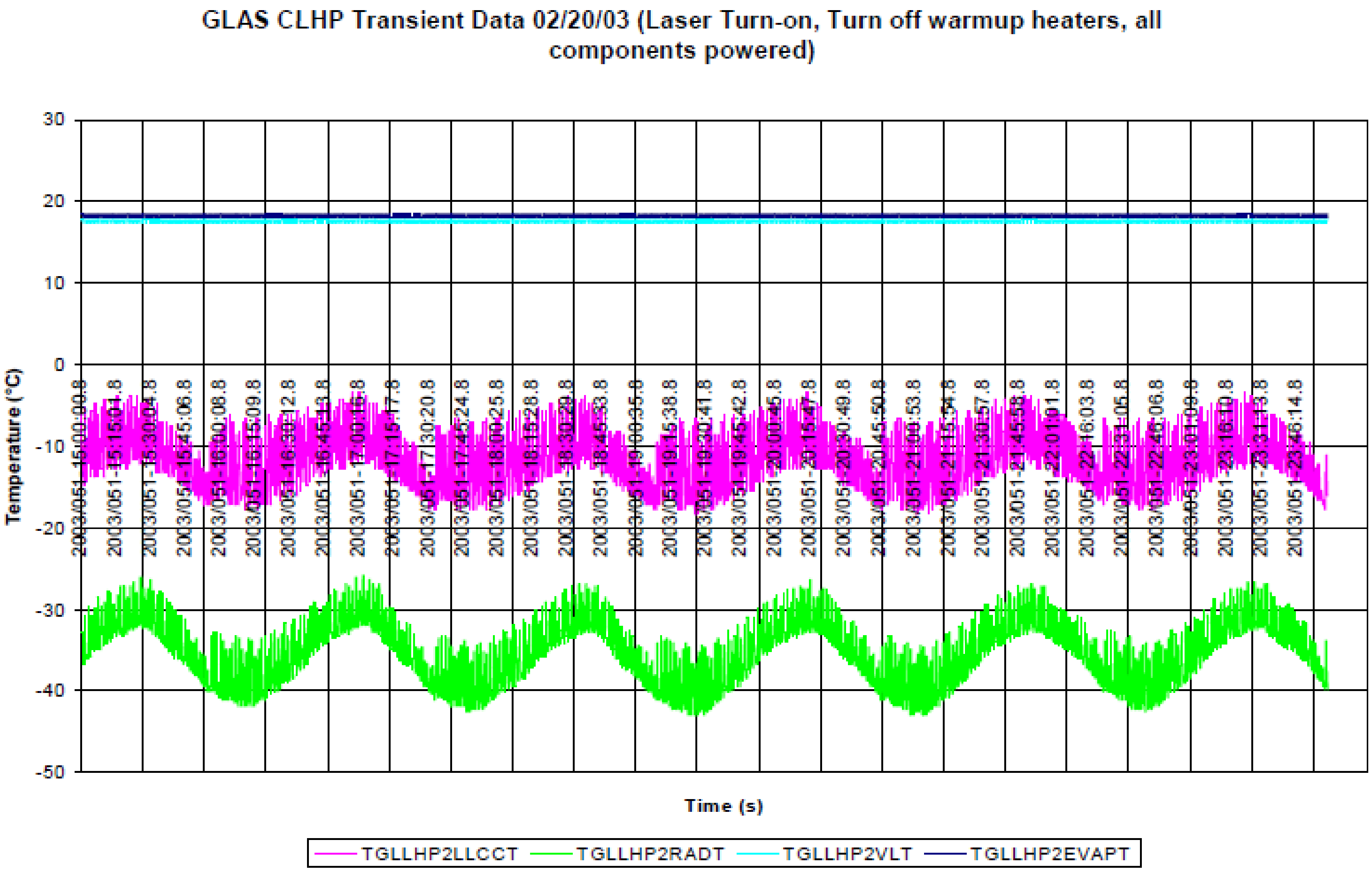


- There are eight coupling blocks between the vapor and liquid lines for each LHP.
  - Liquid subcooling is reduced by about one half.

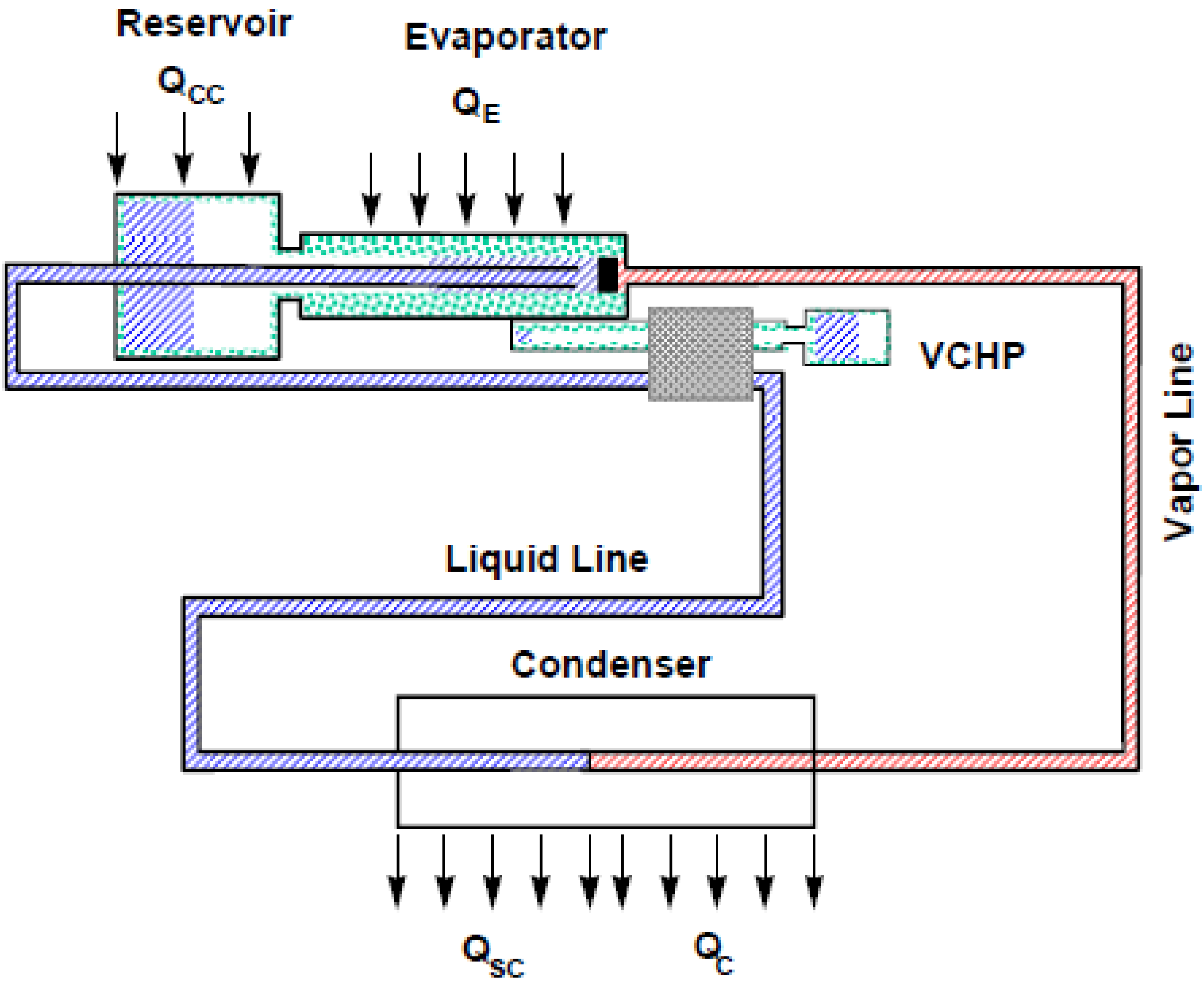
- The ICESat spacecraft was launched in January 2003.

- Both LHPs have been working very well.

GLAS Laser Temperatures



LHP Temp. Control with VCHP



- The VCHP transmits heat from the evaporator to the liquid line when the return liquid is too cold, reducing the amount of liquid subcooling entering compentation chamber. The required CC control heater power Qcc is reduced.
- The VCHP is shut down when more subcooling is needed.

➢ Advantage:

– Active control of heating the liquid line versus passive heating when compared to the coupling blocks

➢ Disadvantages:

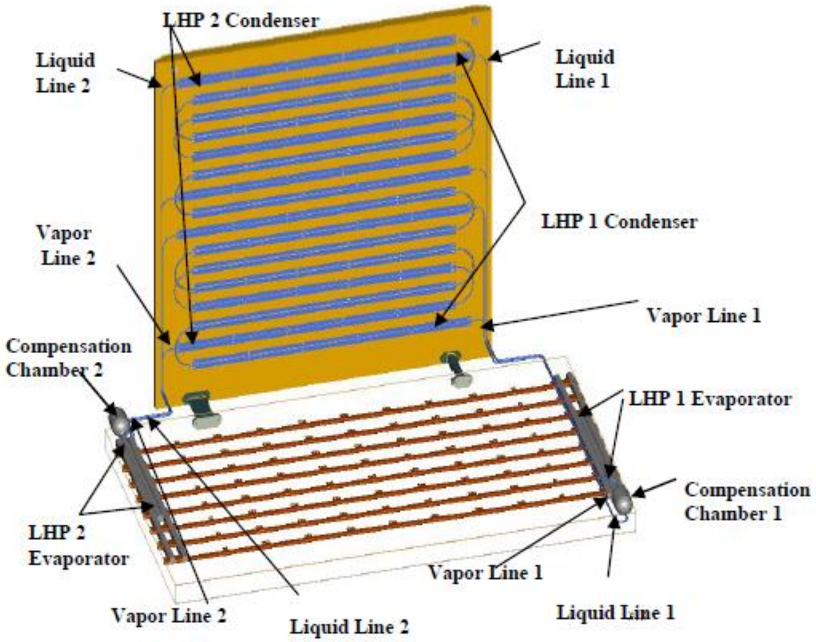
– Needs a VCHP, which may not be ground testable.

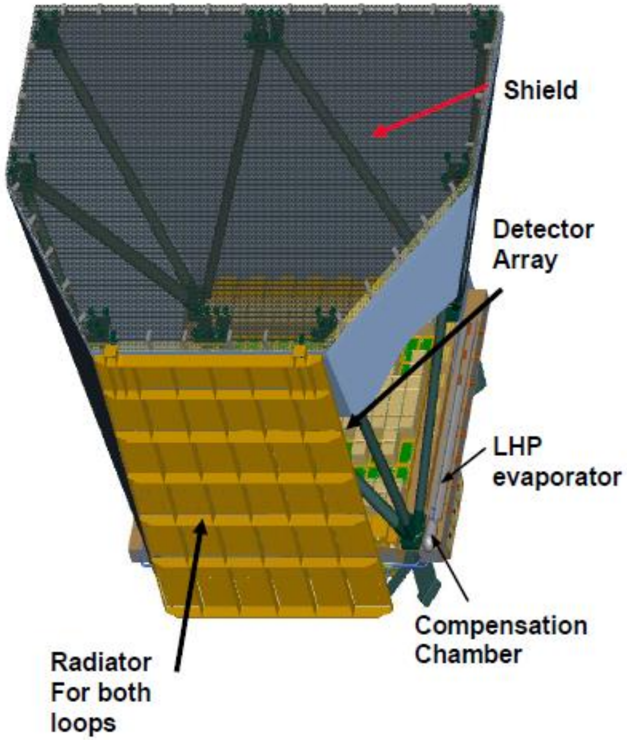
– Needs an additional control device for the VCHP.

– VCHP reservoir requires cold biasing.

CCHPs/VCHPs/LHPs on SWIFT ABT

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

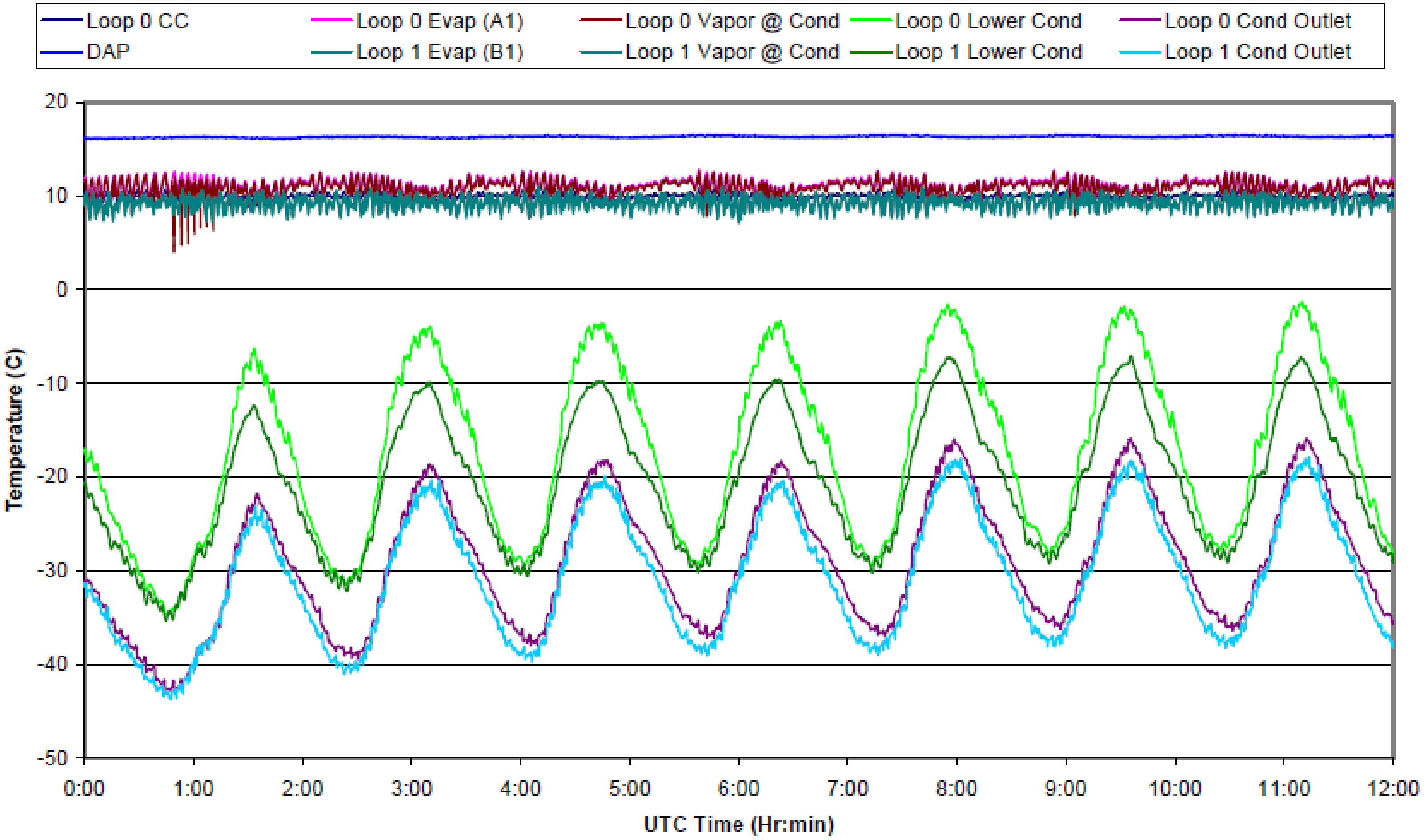




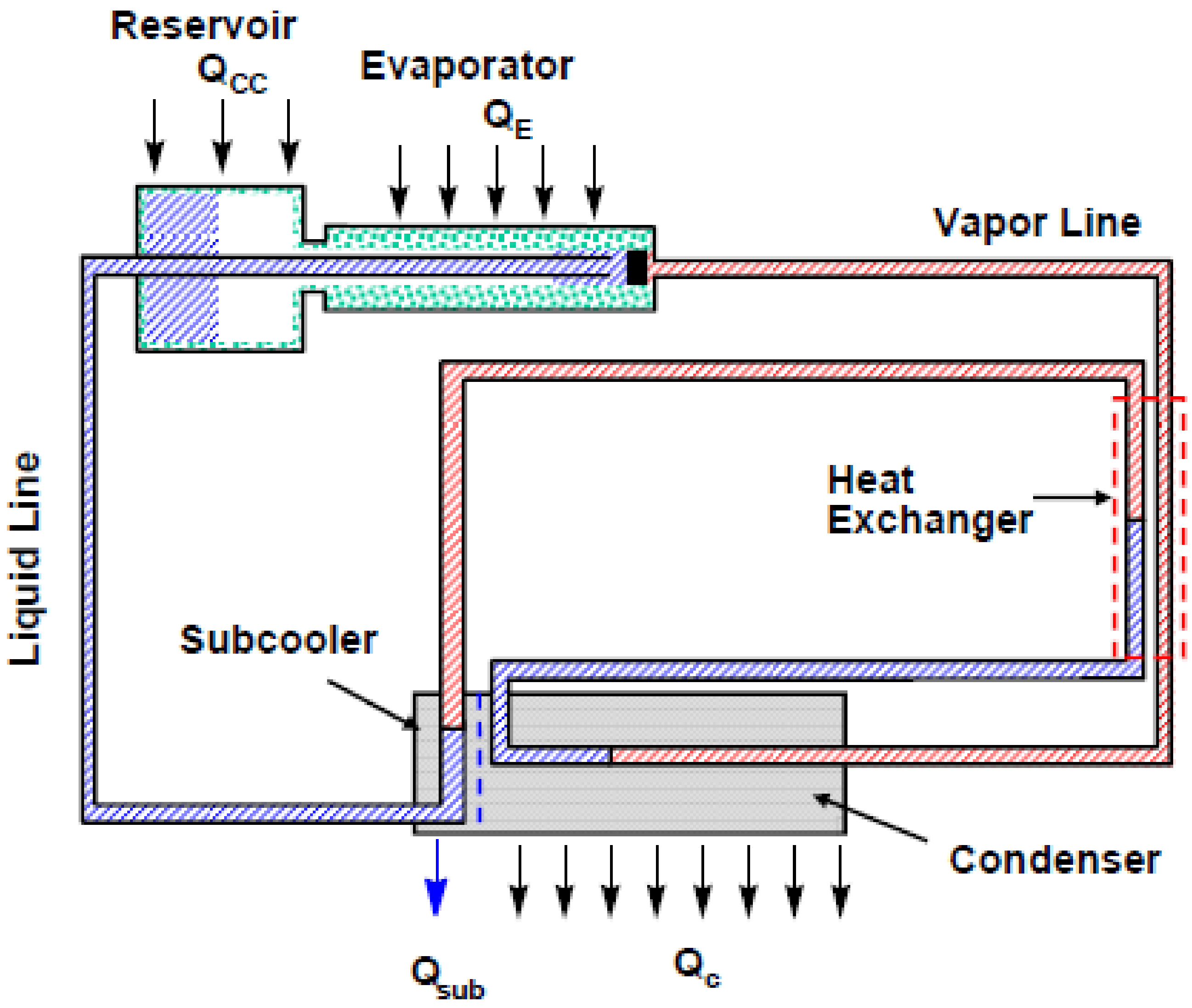
Swift BAT VCHPs and LHPs

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

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



LHP Temp. Control with HEX and Subcooler



- 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 (HEX) will take away most of the subcooling, and the subcooler provide slightly subcooled liquid to the CC

➢ **Advantages:**

– The natural operating temperature will be closer to T_{set} for heat loads between Q_{Low} and Q_{High}.

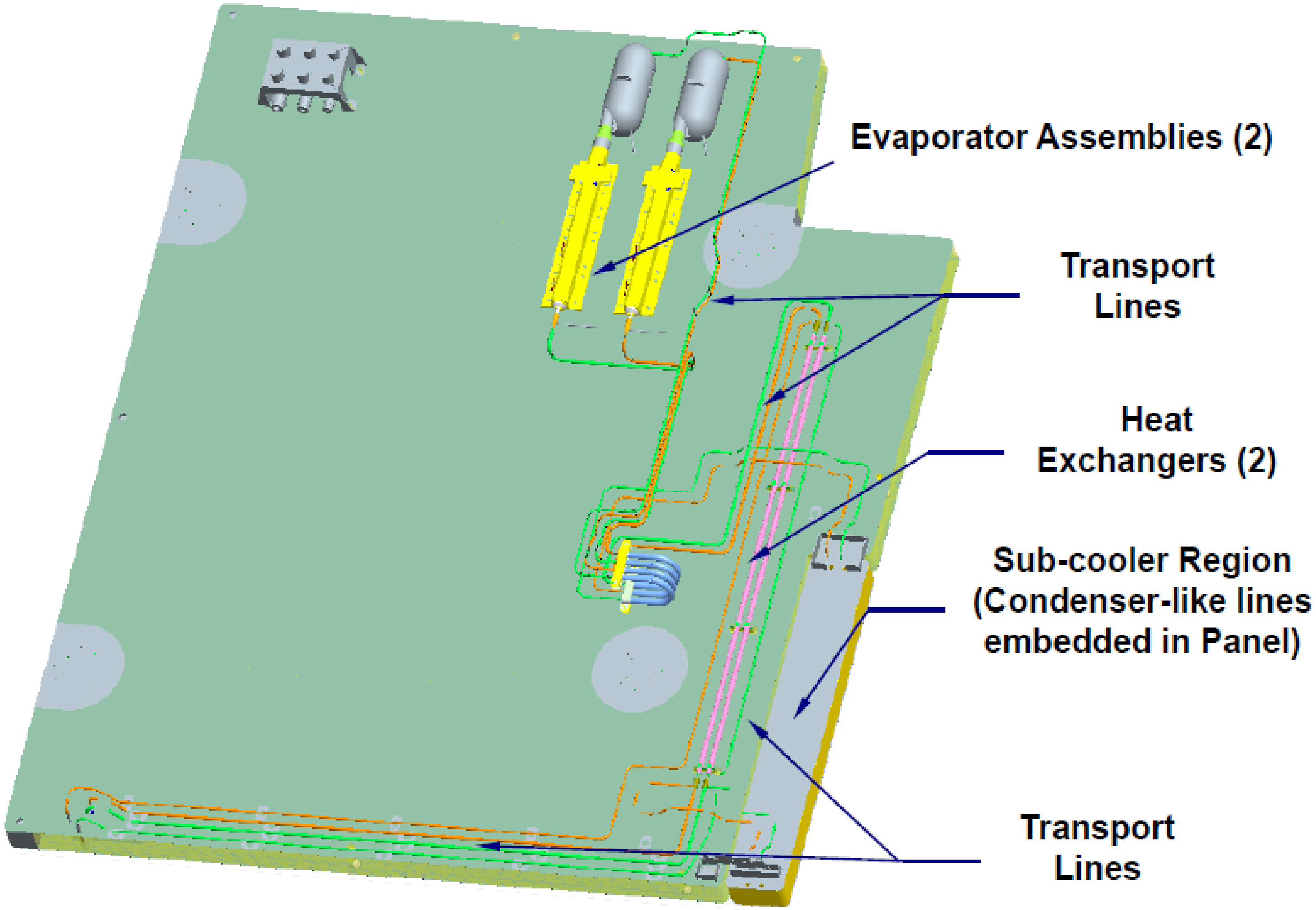
– The CC control heat power is reduced significantly.

➢ **Disadvantages:**

–Needs a separate subcooler.

– Needs a longer liquid line, which imposes a higher frictional pressure drop.

GOES-R ABI Radiator/LHP Assembly System



Evaporator Assemblies (2)

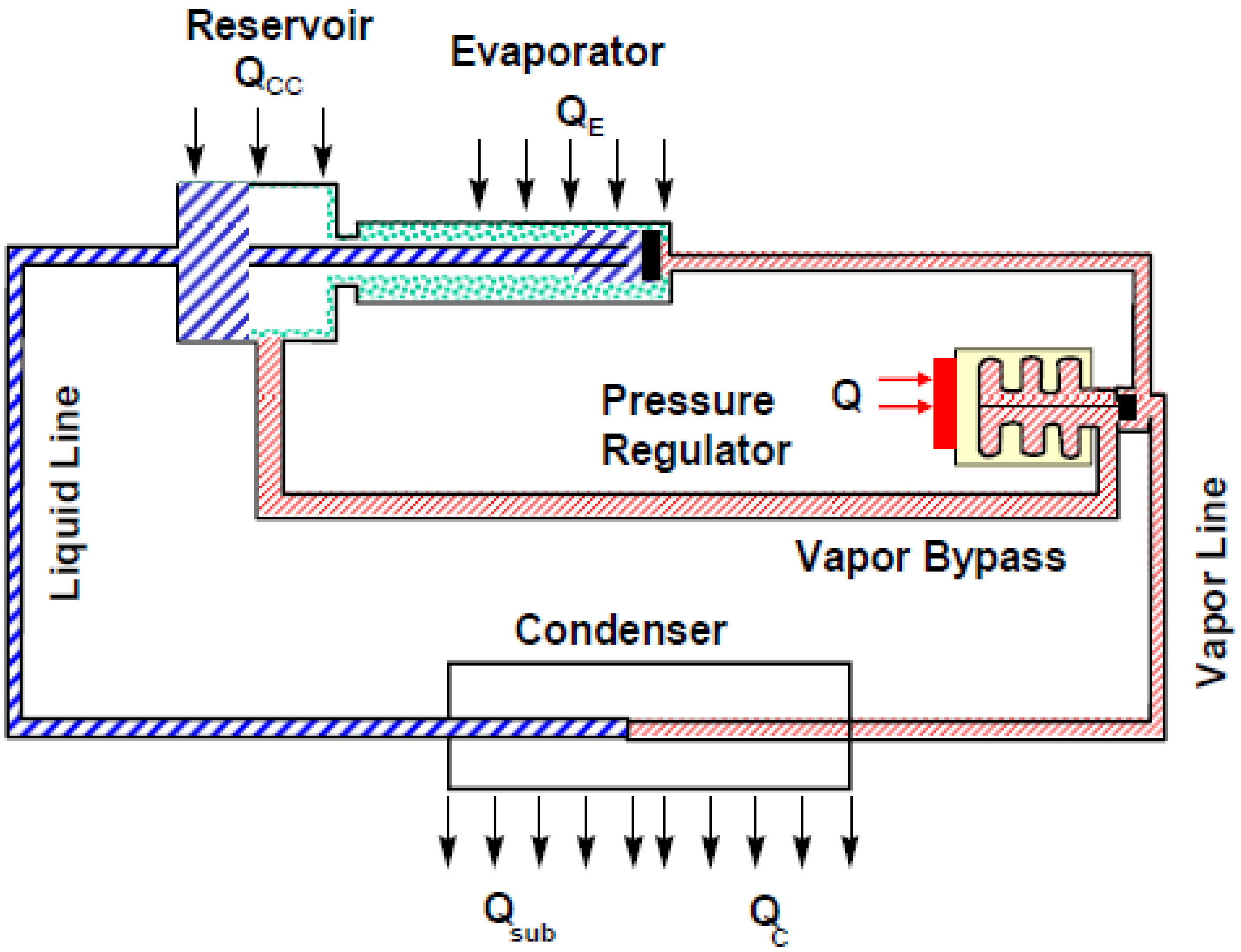
Transport Lines

Heat Exchangers (2)

Sub-cooler Region (Condenser-like lines embedded in Panel)

Transport Lines

LHP Temperature Control with 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

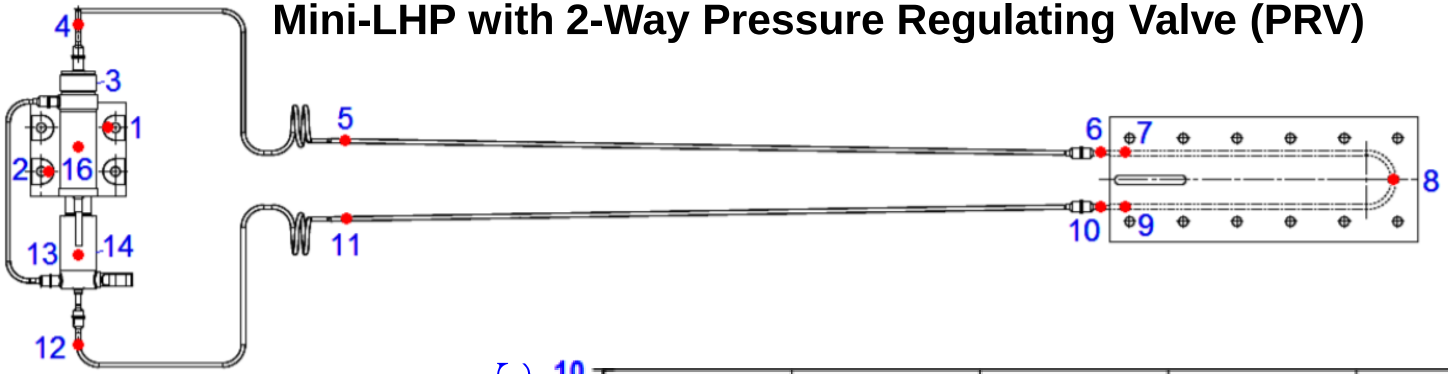
Space Applications of the LHP with Pressure Regulator and Vapor Bypass

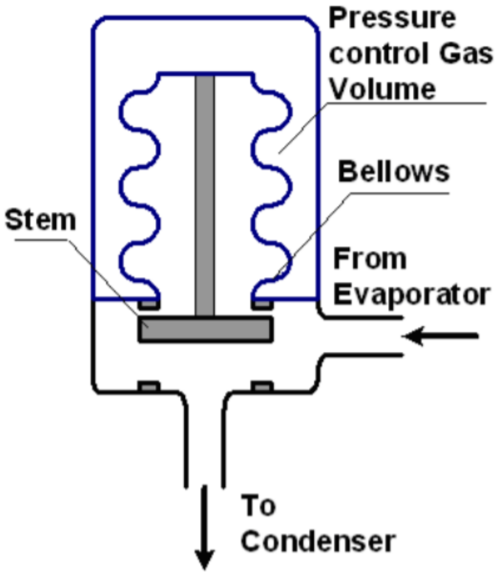
- Passive bypass valve
  - Yamal 2000 spacecraft, launched in 2003
  - Payload temperature was controlled within ± 2K.

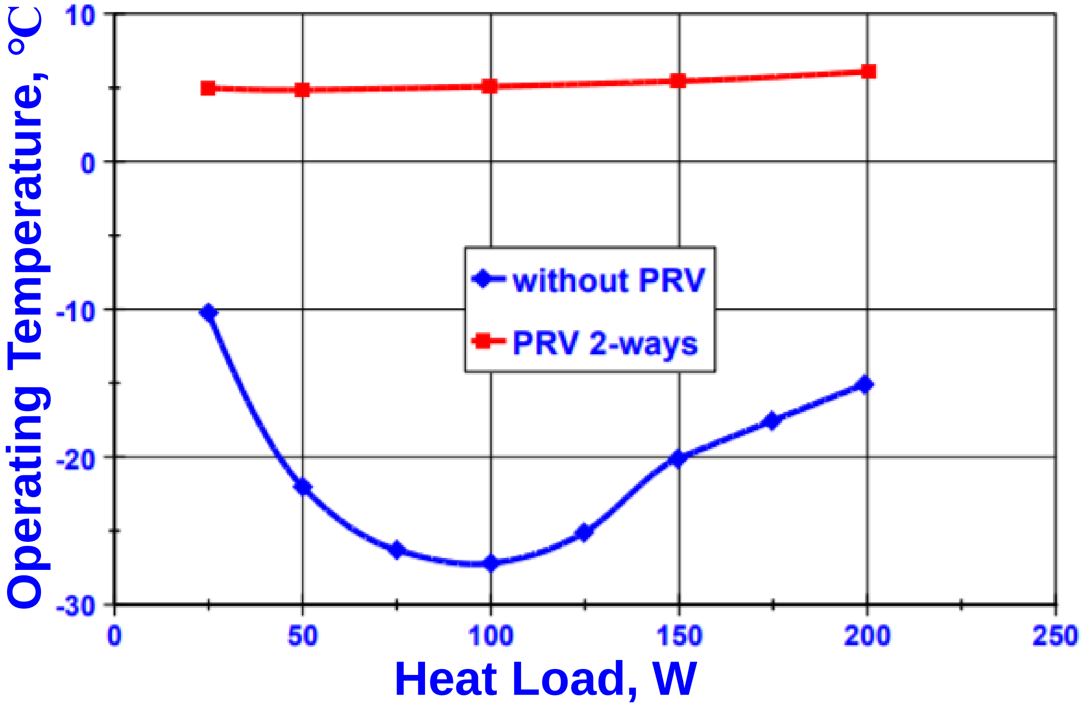
- Active bypass valve
  - TerraSAR satellite
  - Ground tests demonstrated temperature control within ±0.5K for heat load of 5W to 15W and condenser sink temperature between 233K and 308K.
  - TerraSAR was launched in 2007. Thermal control system was functioning successfully.

LHP Temp. Control with 2-Way PRV (Ref. 18)

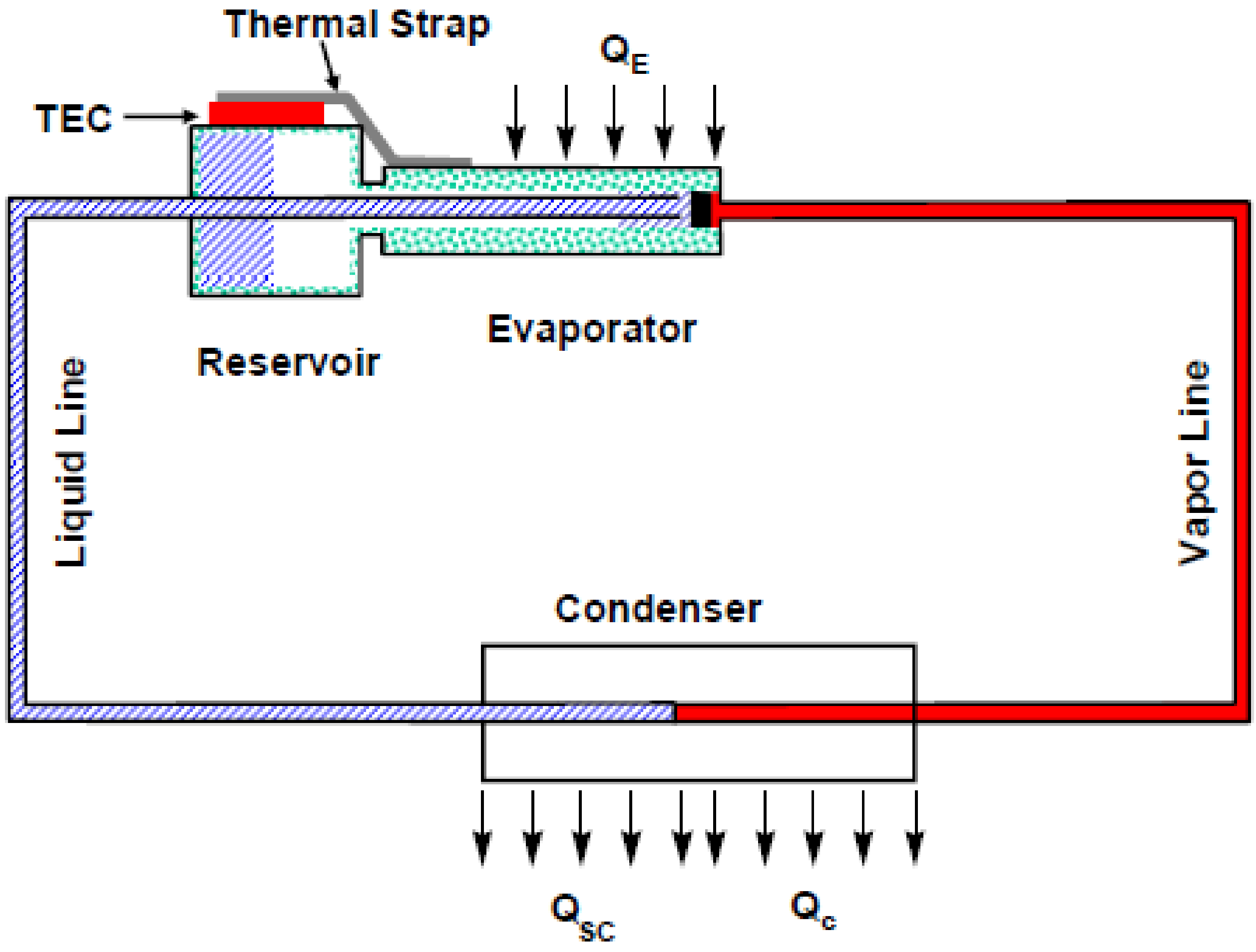
Mini-LHP with 2-Way Pressure Regulating Valve (PRV)



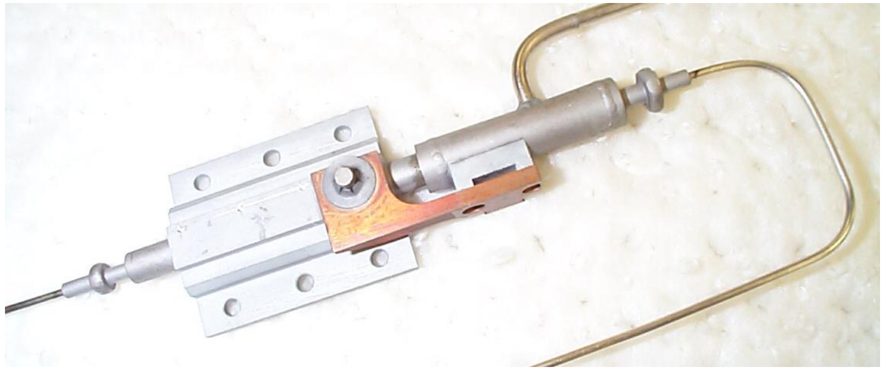




TEC for LHP Temperature Control

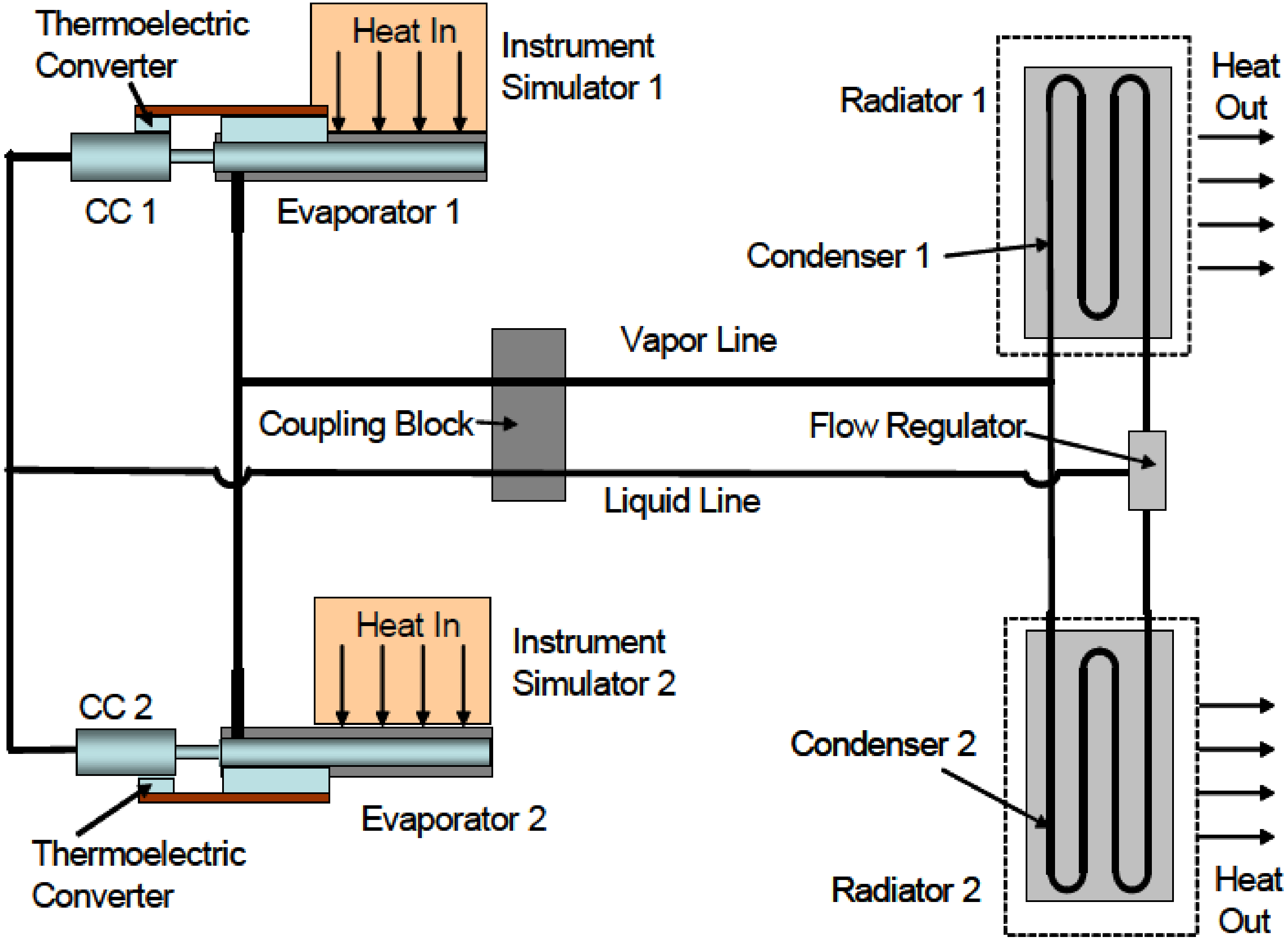


Miniature LHP Pump

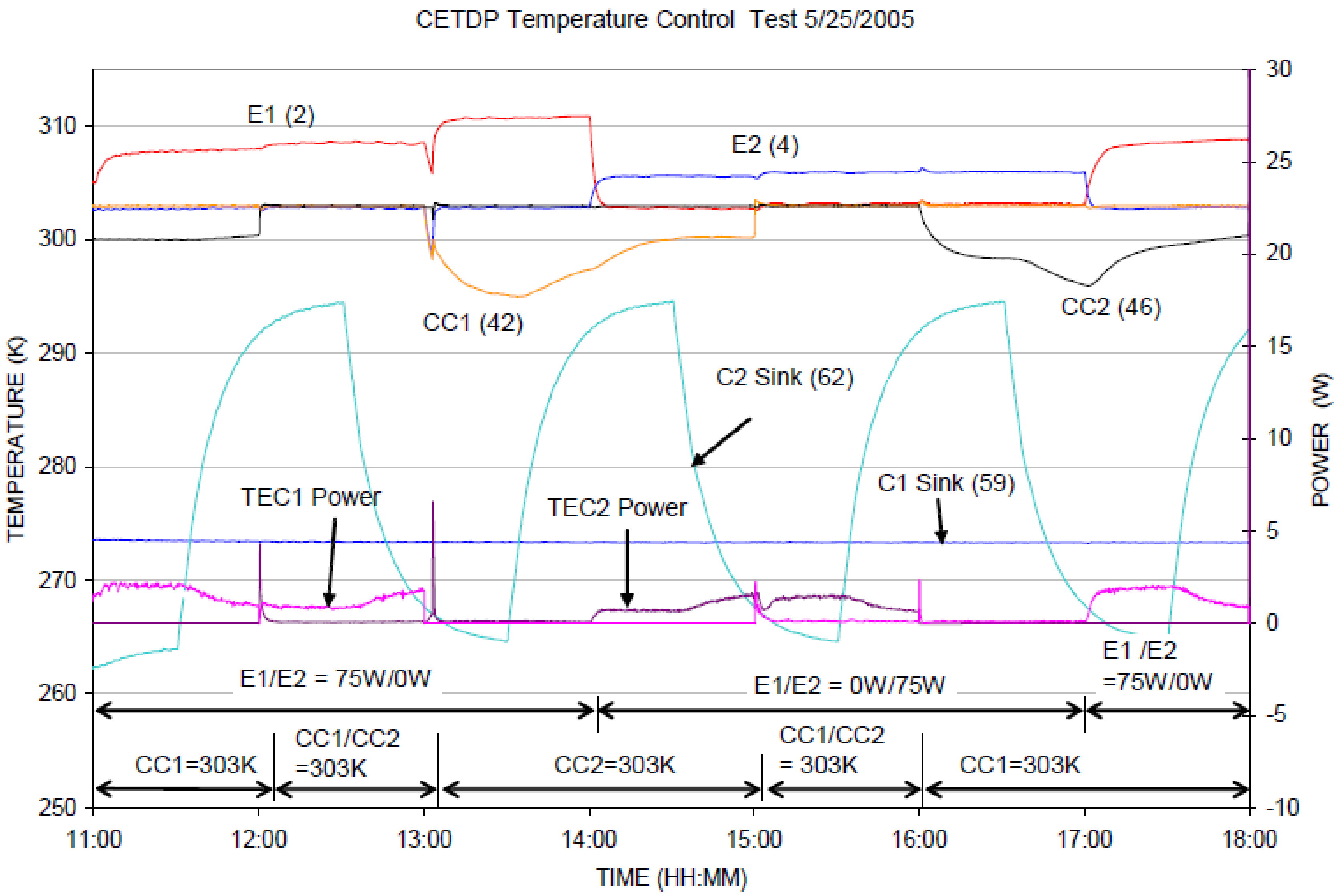


- **Advantages:**
  - Can be used to heat or cool the CC
  - Changing the voltage polarity changes the mode of operation
  - Very efficient
- **Disadvantages:**
  - More complex design
  - Additional mass

ST 8 MLHP with TEC and Coupling Blocks

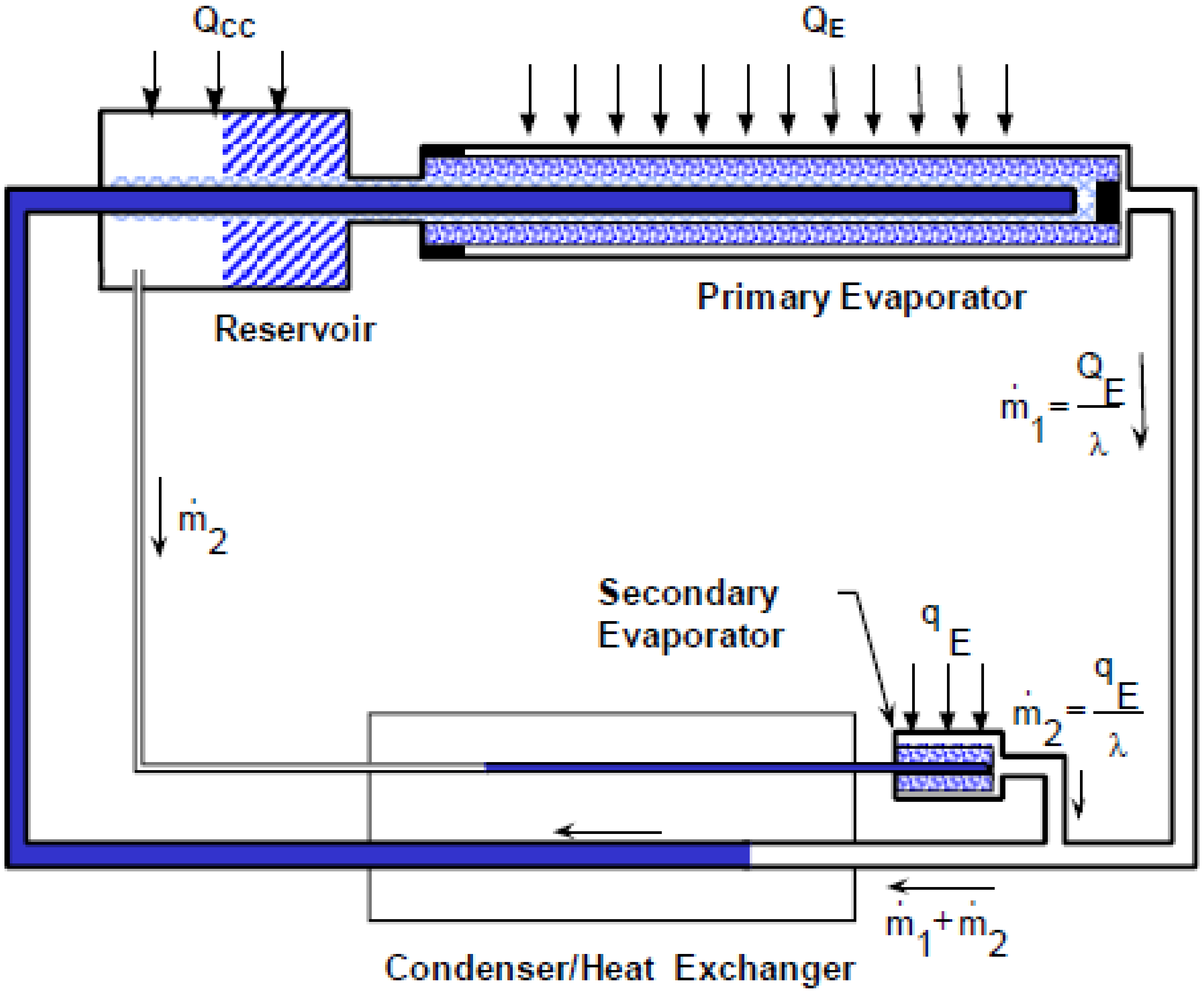


TECs Power and Sink Cycle Tests (ST 8 MLHP)



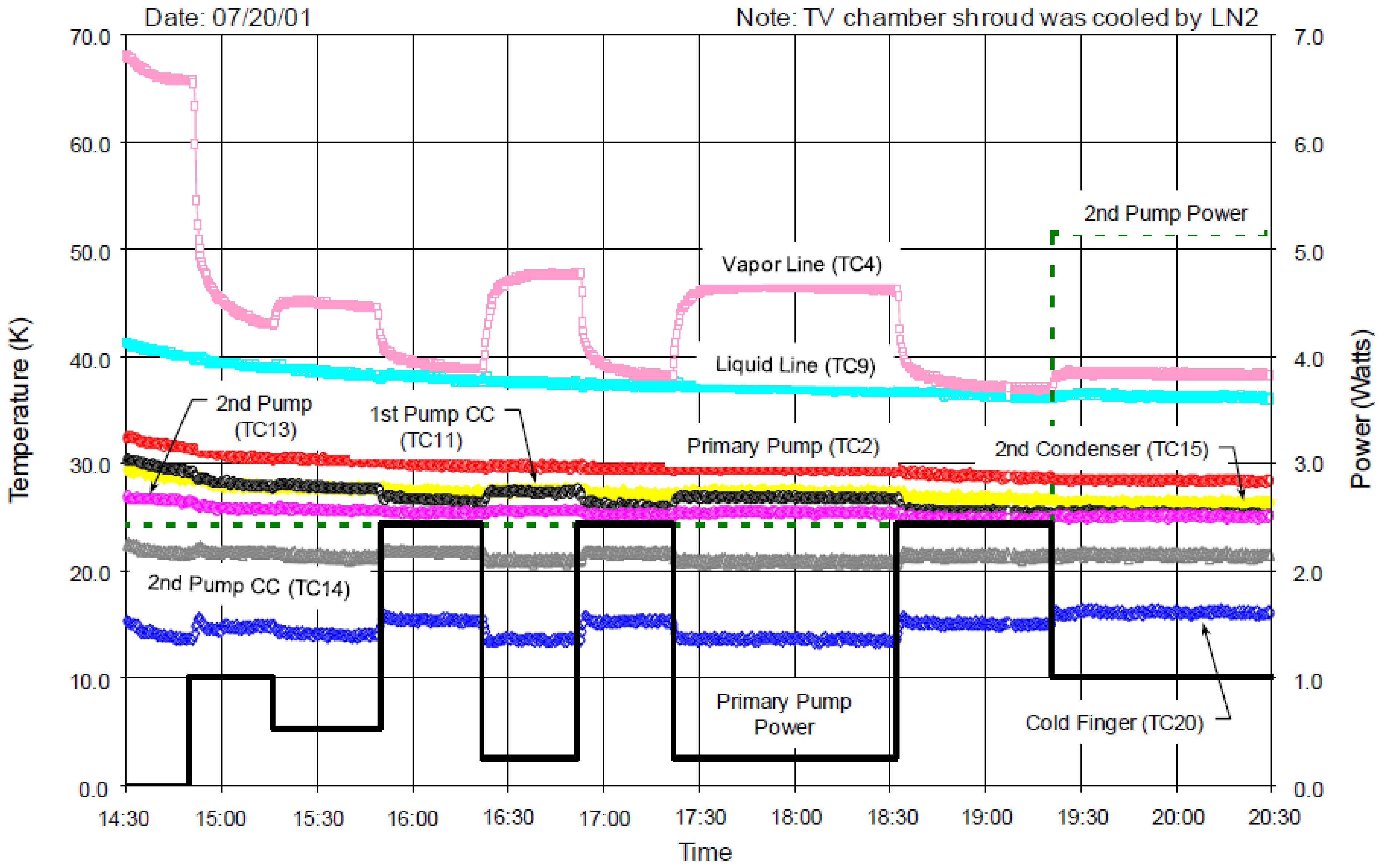
- The LHP operating temperature was controlled within ±0.5K by TECs regardless of changes in evaporator power and/or sink temperature, and regardless of which CC was controlled.

LHP with Secondary Evaporator



- The secondary loop cools the CC by drawing vapor out of the CC.
- Becomes a regular LHP when the secondary evaporator is not heated

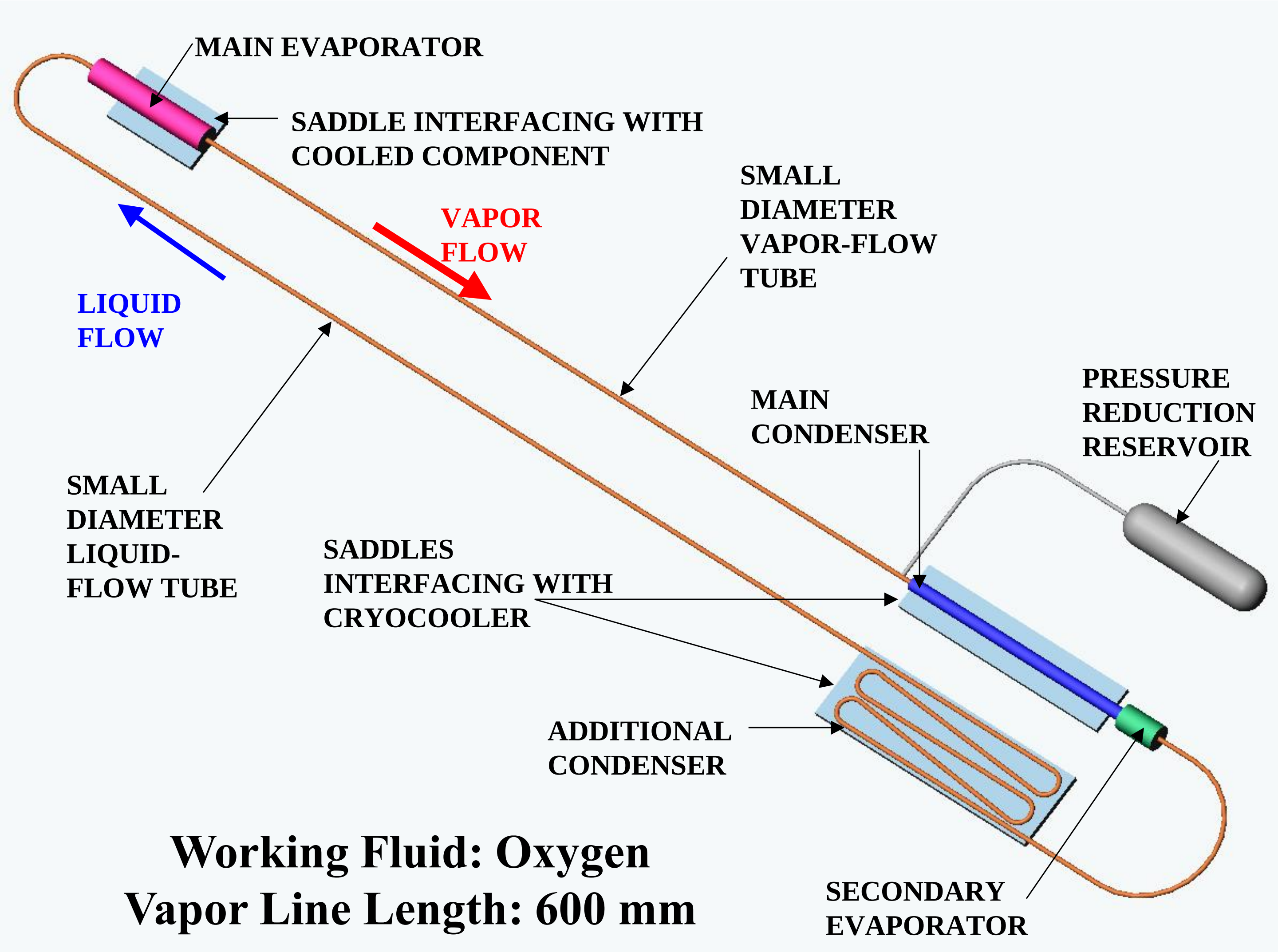
NASA Hydrogen LHP Power Cycling



Cryogenic LHPs

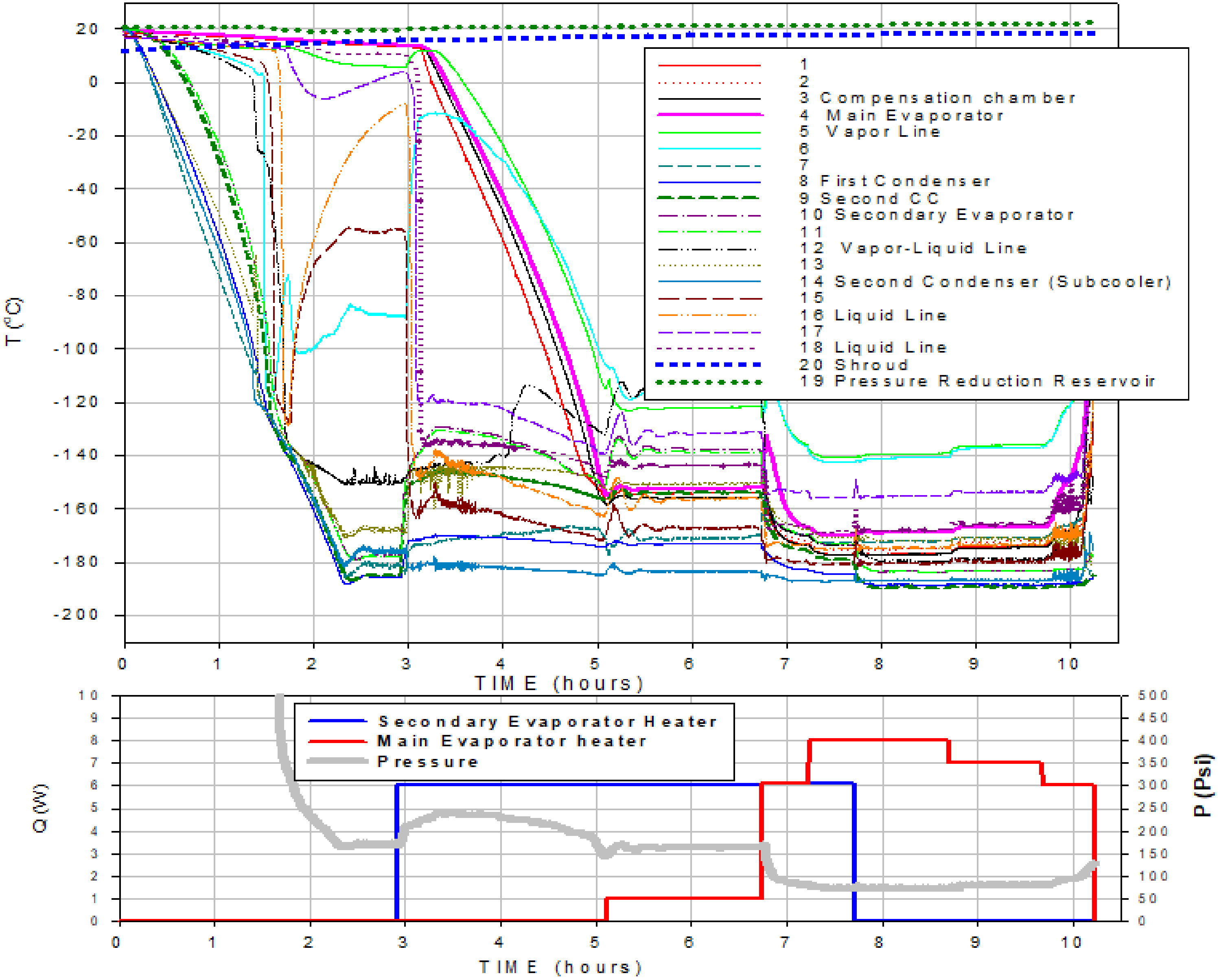
- Cryogenic LHPs with the following working fluids were produced and TVAC tested:
  - Nitrogen LHP: ~75K - 100K
  - Oxygen LHP: ~70K - 120K
  - Neon LHP: ~28K - 44K
  - Hydrogen LHP: ~20K - 30K
  - Helium LHP: ~2.7K - 4.4K

Cryo-LHP with Two Evaporators in Series



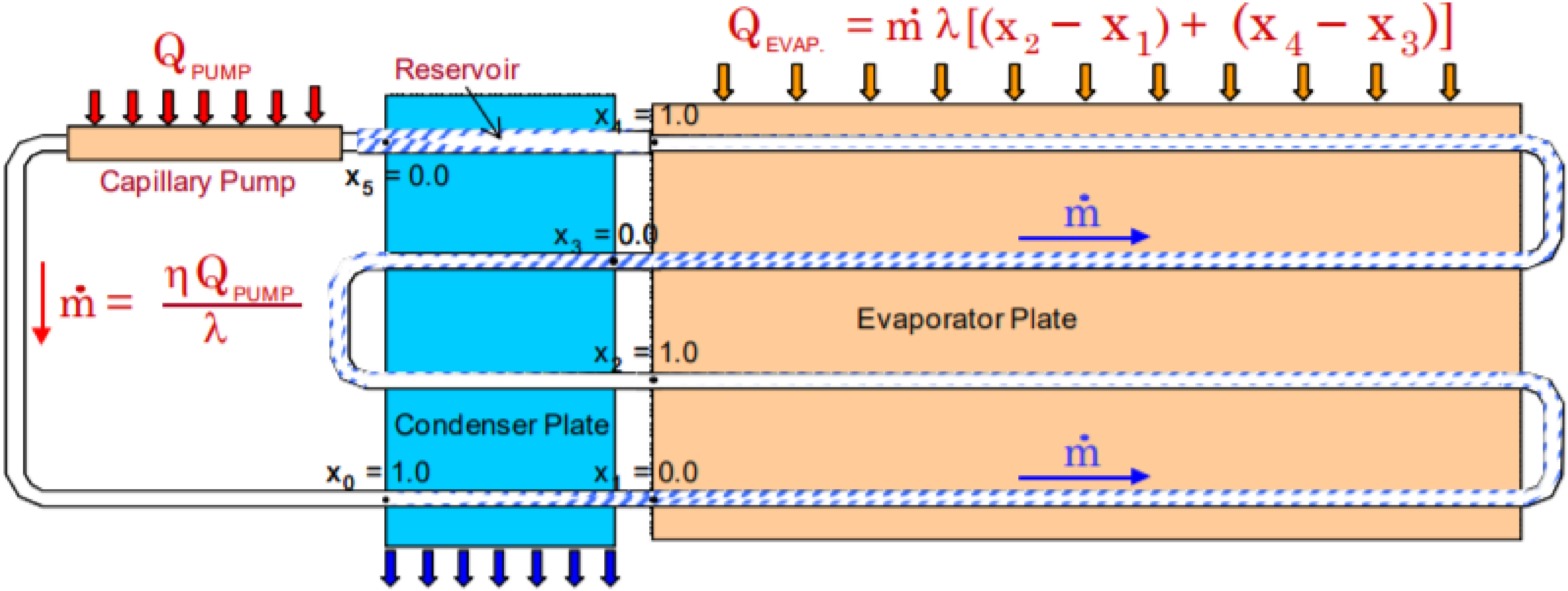
Working Fluid: Oxygen
Vapor Line Length: 600 mm

Startup and Operation of the Cryo-LHP with the Shrouds at Room Temperature



Working Fluid: Oxygen

LHP for Large Area Cooling



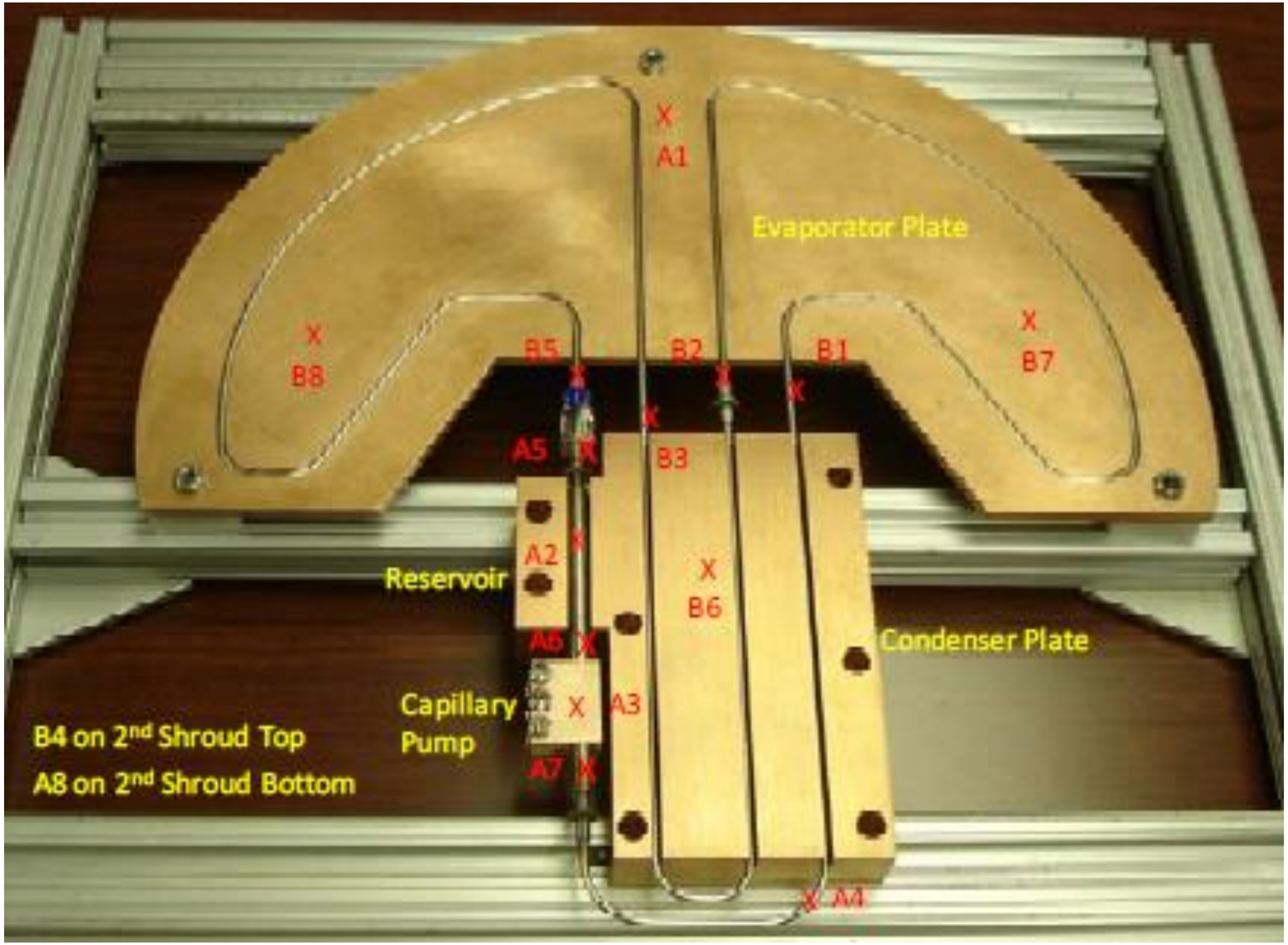
$$Q_{EVAP.} = \dot{m}\,\lambda\,[(x_2 - x_1) + (x_4 - x_3)]$$

$$\dot{m} = \frac{\eta Q_{PUMP}}{\lambda}$$

$$Q_{COND.} = Q_{EVAP} + Q_{PUMP}$$

$$Q_{cond} = \dot{m}\lambda\,[(x_0 - x_1) + (x_2 - x_3) + (x_4 - x_5)]$$

Helium LHP for Large Area Cooling



LHP Startup

- LHP Start-up is a complex phenomenon.
  - The primary wick must be wetted prior to start-up.

- The loop start-up behavior depends on the 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

- See Ref. 14 for startup scenarios

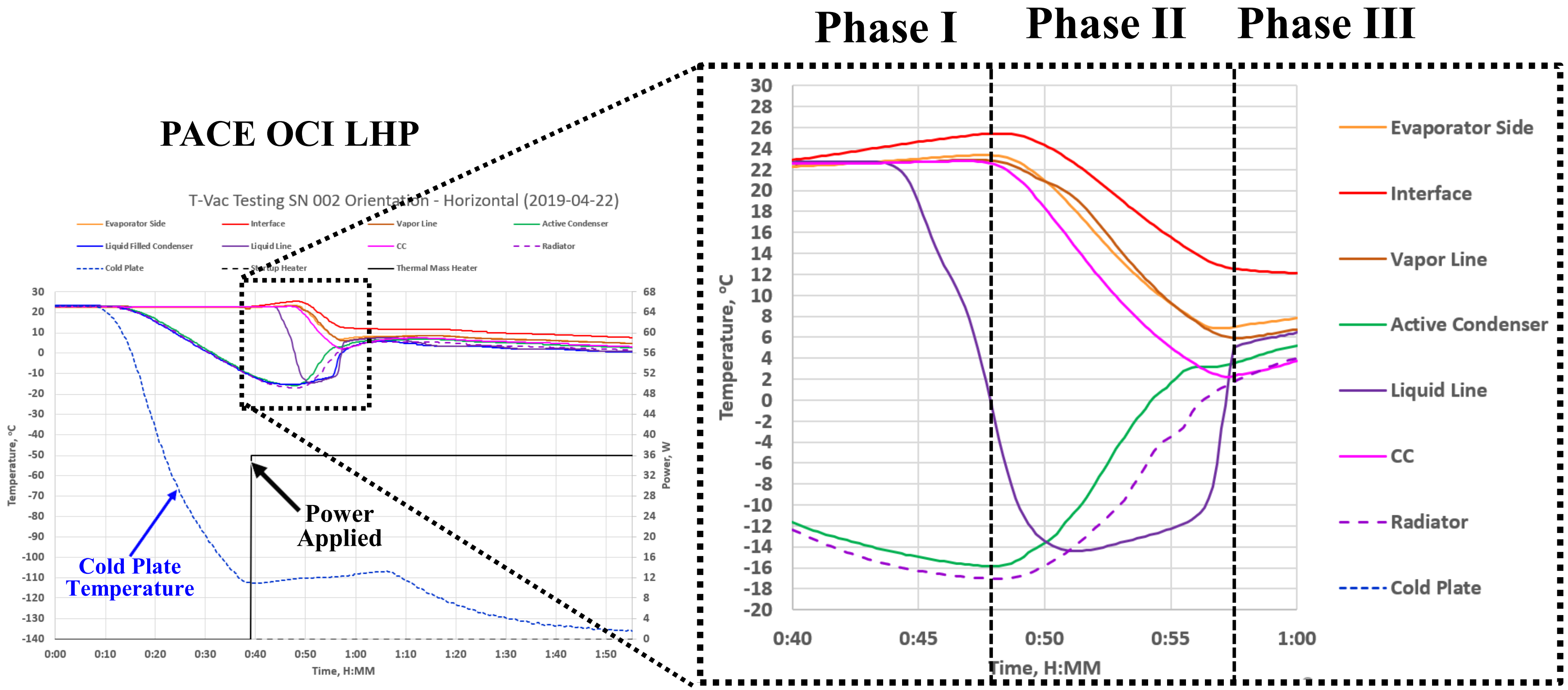
LHP Startup Phases

LHP startup can be divided into three phases:

Phase I. Superheat development.

Phase II. Boiling in the wick and beginning of flow.

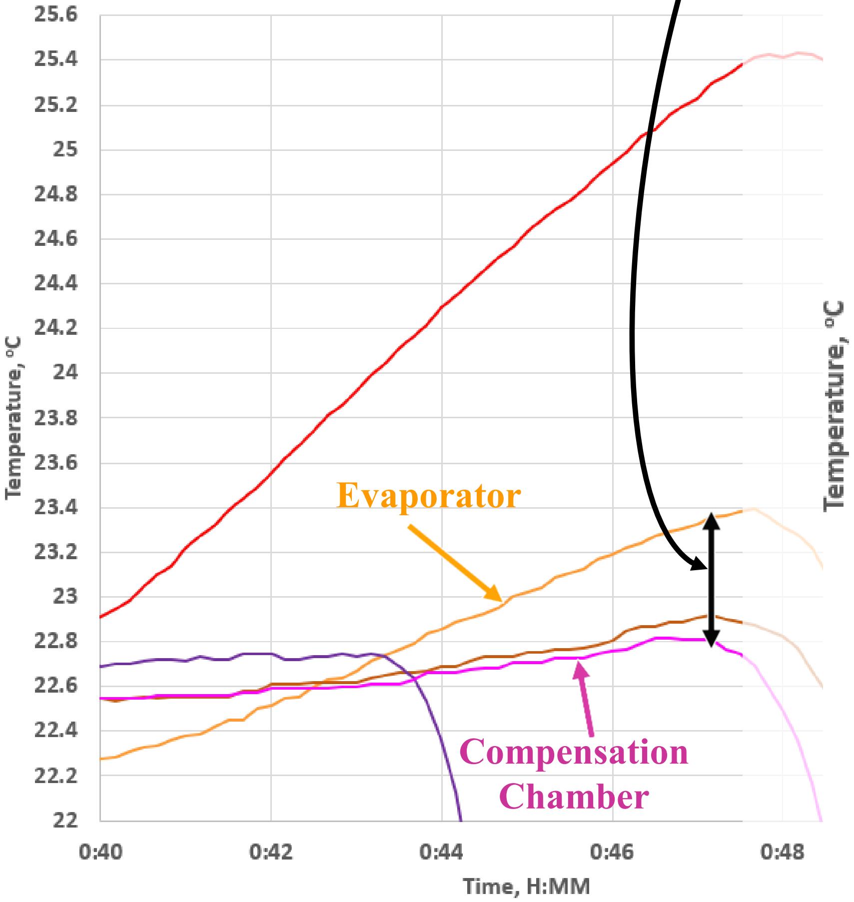
Phase III. Approaching a steady-state or an oscillatory behavior.



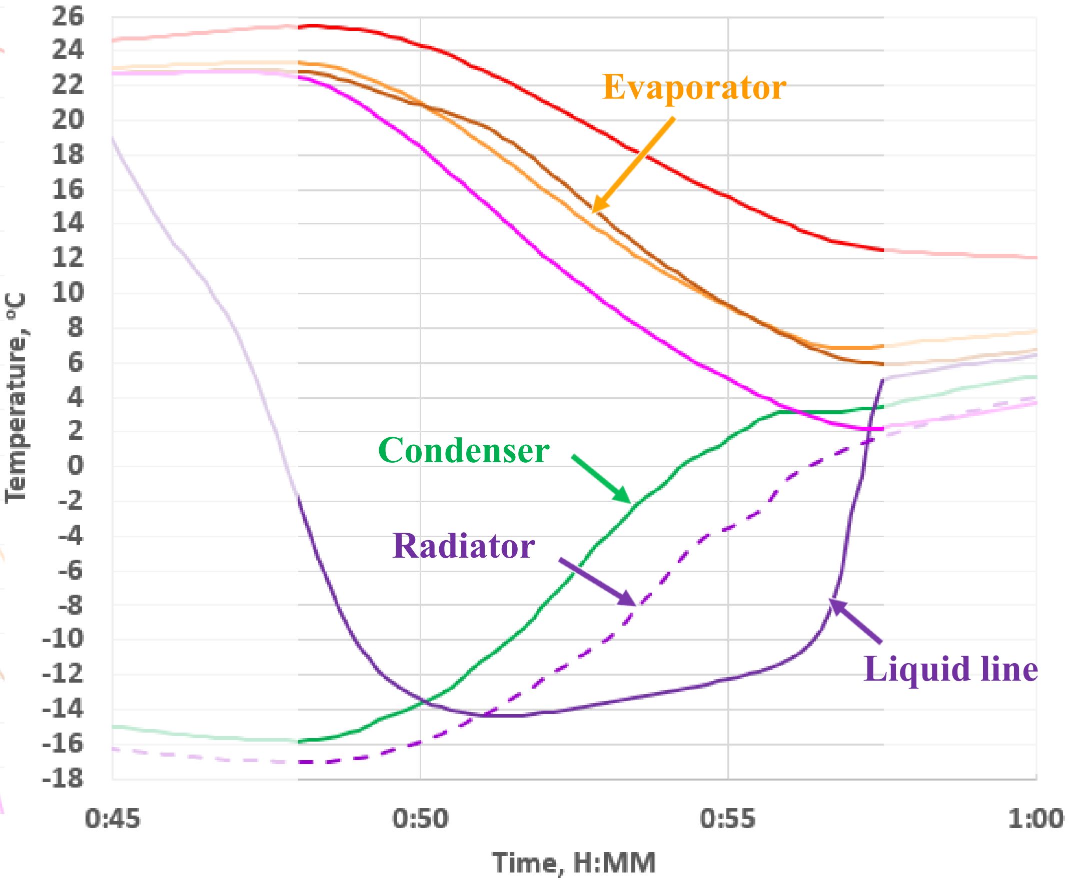
PACE OCI LHP

LHP Startup (Phases I and II)

Phase I. Superheat development
Evaporator temperature shall be increasing faster than the compensation chamber temperature. The temperature difference will reach about 1ºC.

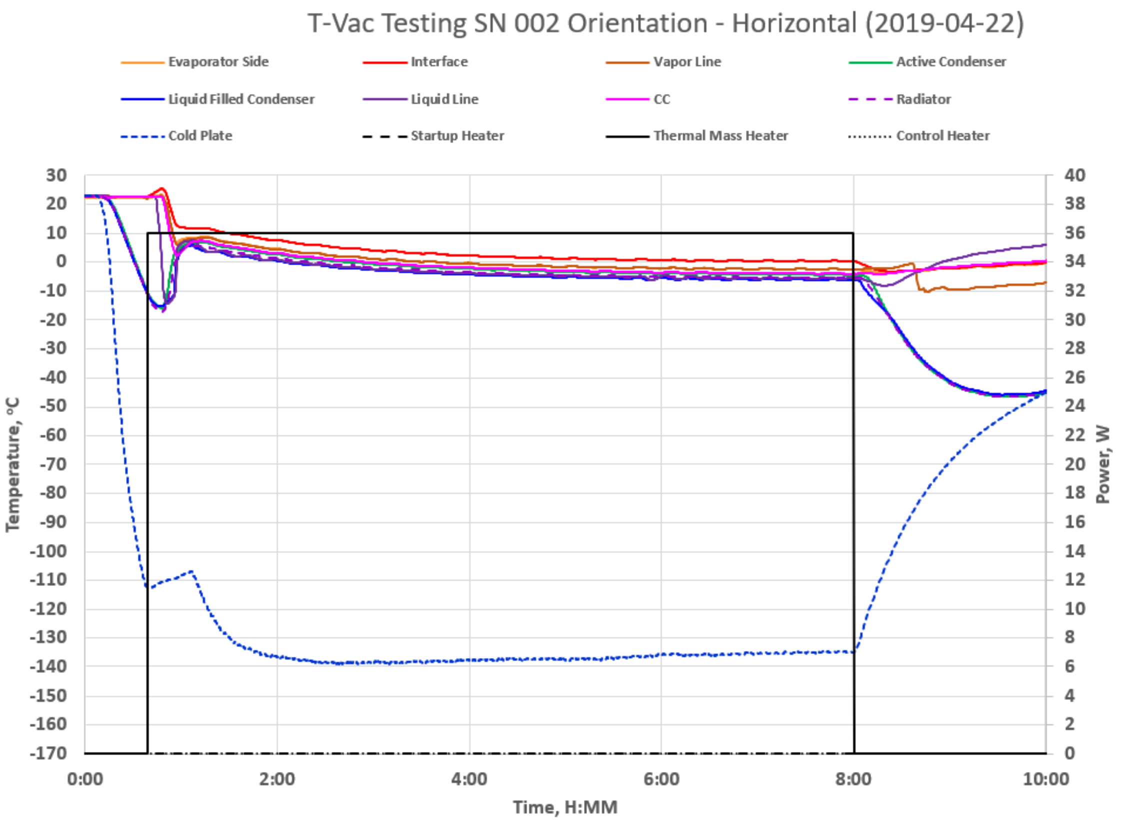


Phase II. Boiling and beginning of flow
Evaporator temperature will be coming down.
Vapor line and CC temperatures follow the evaporator.
Condenser, liquid line and radiator temperatures increase and approach the compensation chamber temperature.

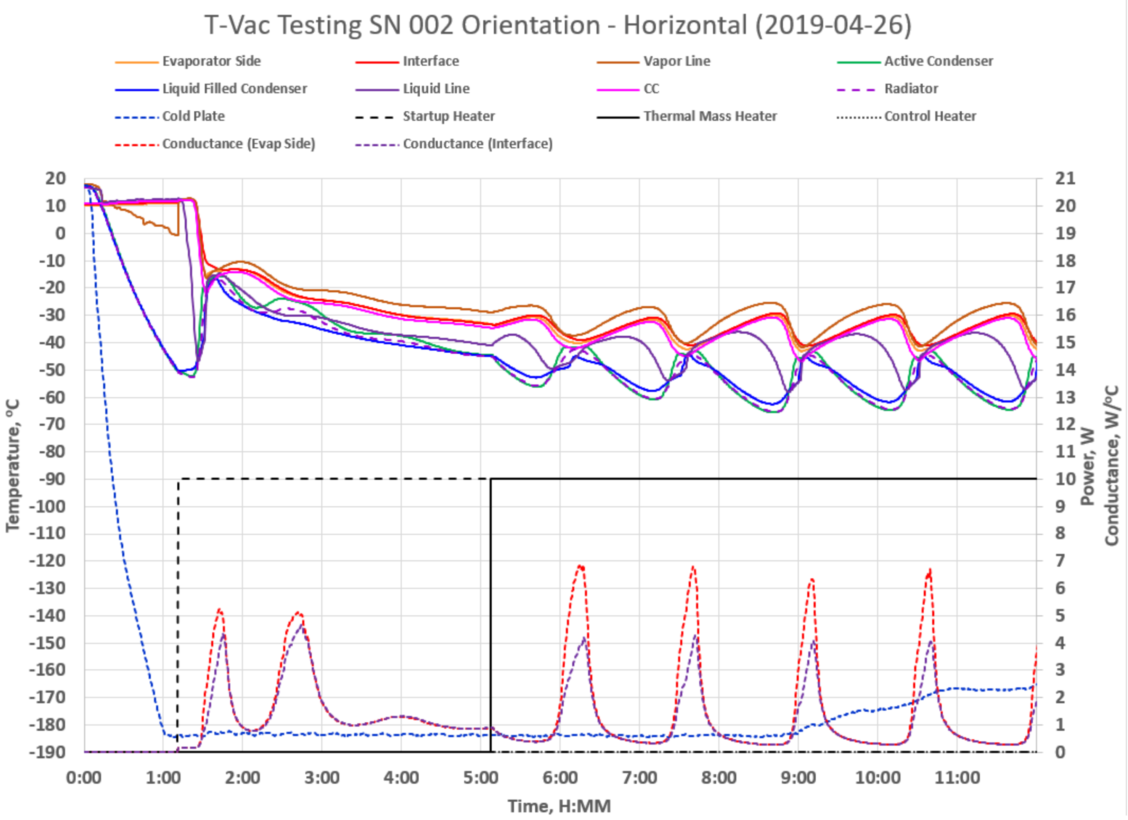


LHP Startup (Phase III)

Phase III. Approaching steady-state
All temperatures monotonically approach steady values.

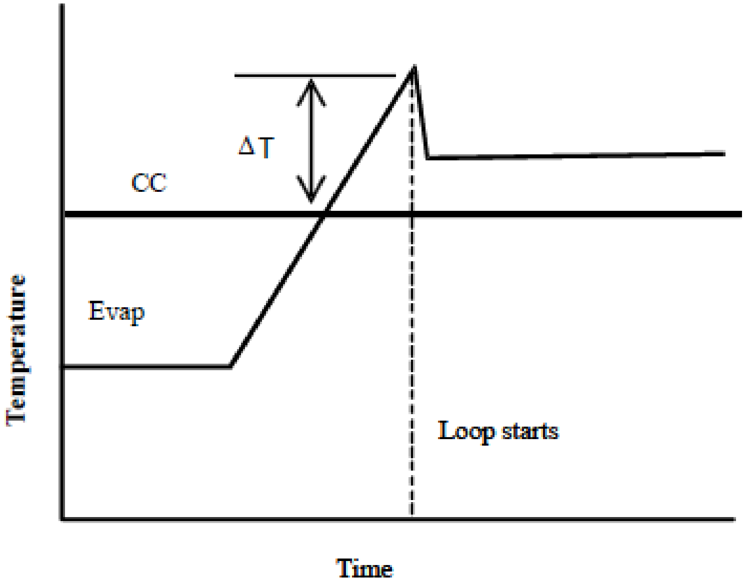


Phase III. Oscillatory behavior
Occurs at low power.
Observed on PACE OCI LHPs at 10W.

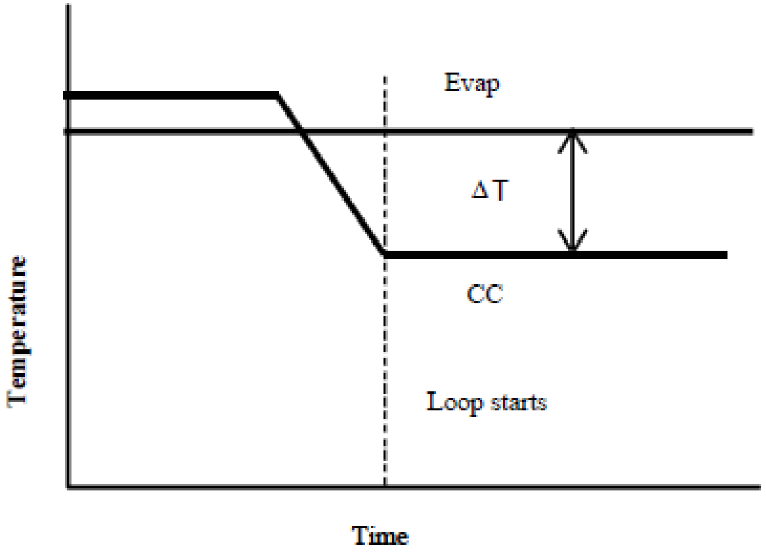


LHP Startup Assistance

- A minimum amount of power is required for start-up under certain conditions.
- 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.



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

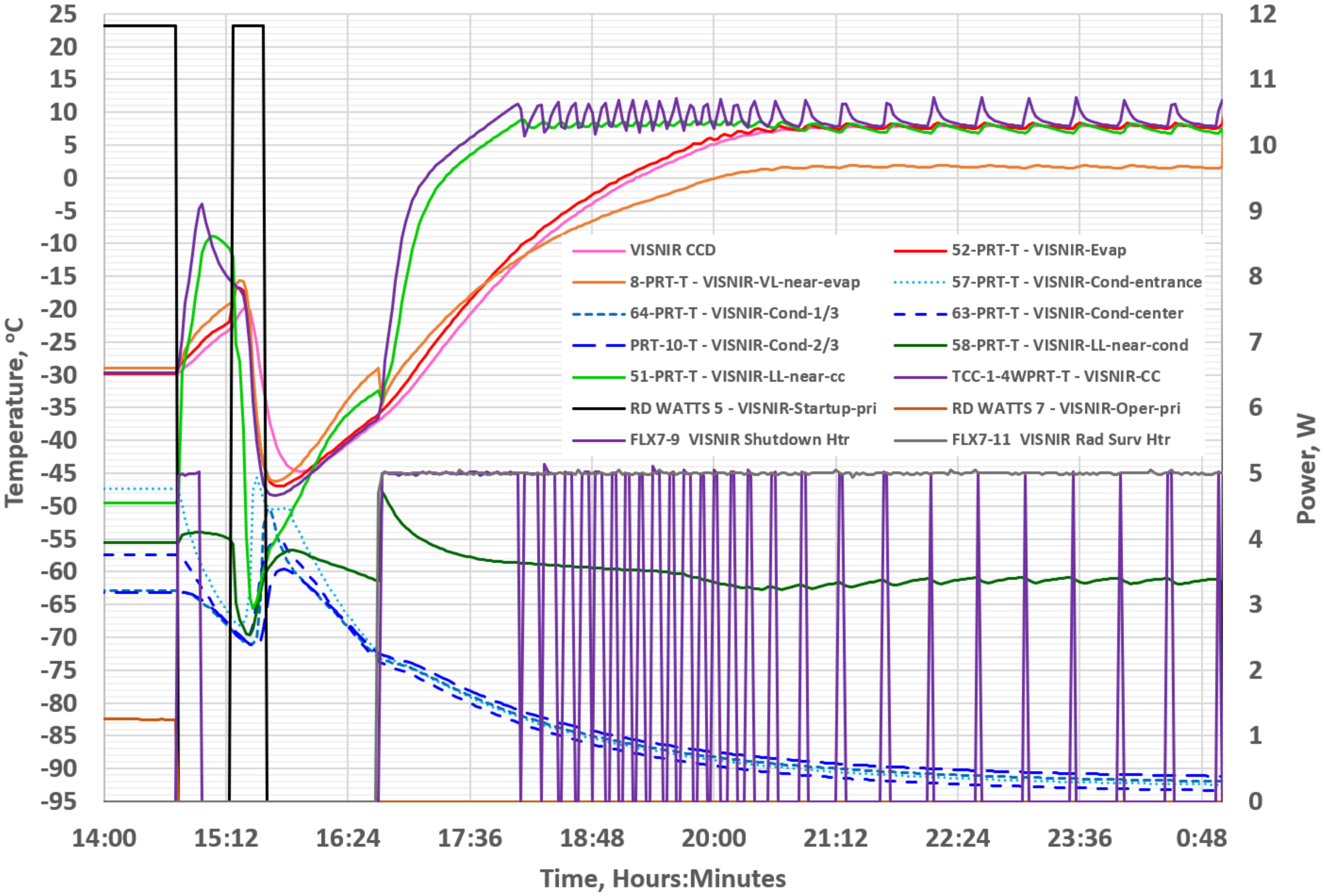


TEC lowers the CC temperature

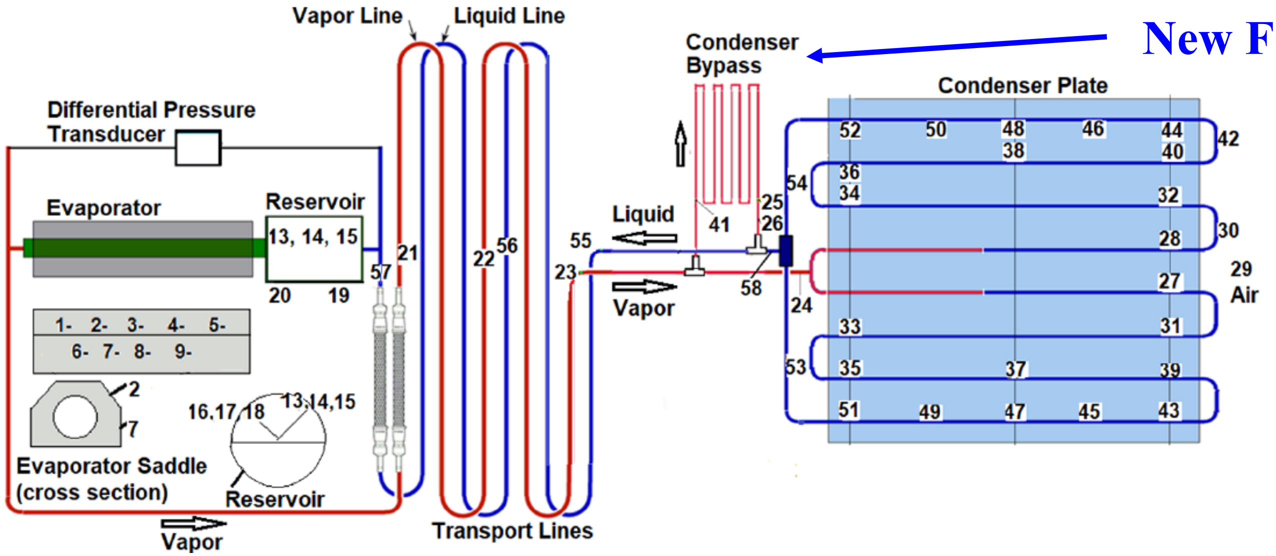
LHP Shutdown

- 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 and $T_{cc} > T_{evap}$
  - 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.

Shutdown of PACE OCI LHP (Ref. 23)

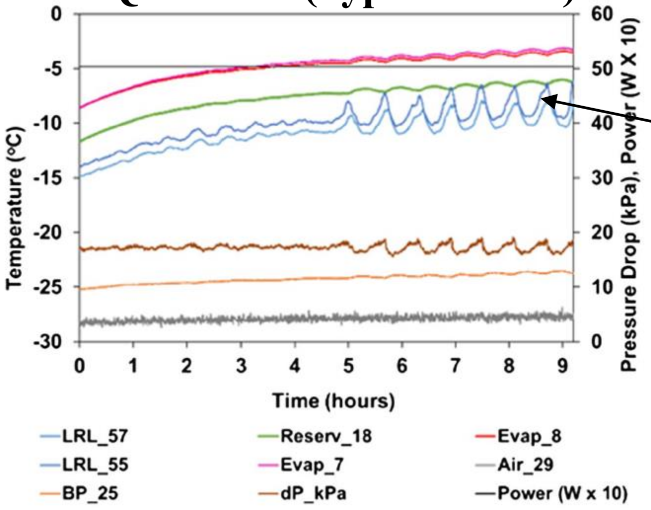


Stabilized LHP Architecture for Reliable Operation Under High-Power Transients (Ref. 17)



New Feature

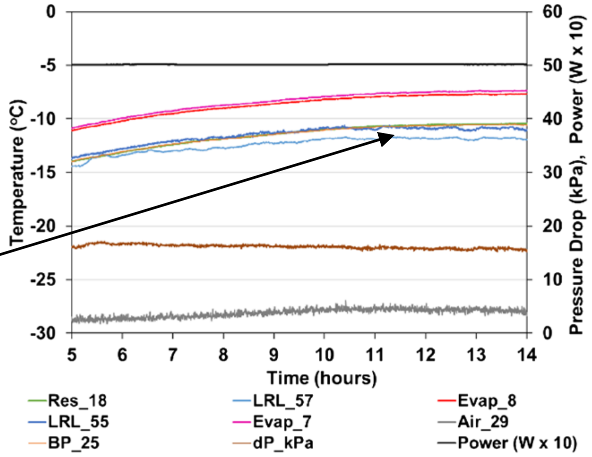
Q = 500W (bypass closed)



Temperature Oscillations

No Oscillations

Q = 500W (bypass open)



Design Recommendations

- **First consider the simplest and safest system.**
  - The CCHPs are simplest.
  - LHPs are simpler and more robust than CPLs
    - CPLs provide advantages in cryogenic applications
      - Reservoir can be located near condenser

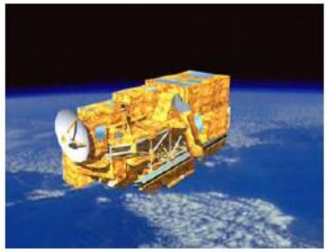
- **Performance margins are needed.** Recommendations:
  - Power capacity margin ≥ 30%
  - Thermal conductance margin ≥ 20%

  Note that conductance will degrade over time.

- **Redundant system is desirable.**
  - To avoid a single point of failure despite the fact that two-phase systems are very reliable.

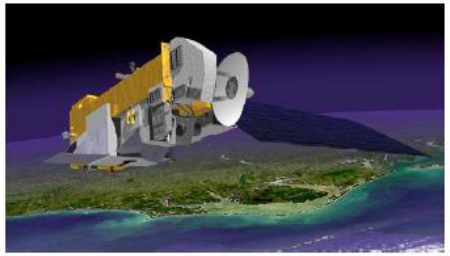
- **Ground testing is paramount.**
  - Repeatability and consistency of the test results lead to success.

CPLs and LHPs on NASA Spacecraft

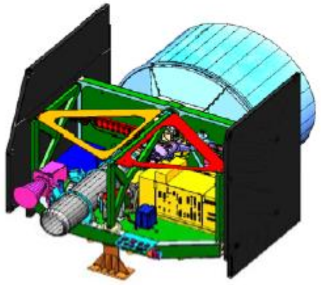


TERRA, 6 CPLs
Launched Dec 1999

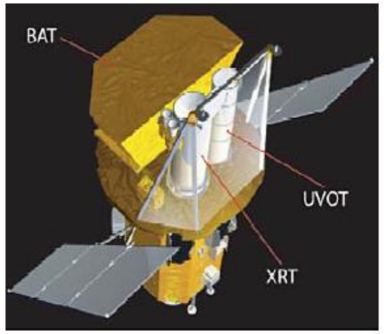
HST/SM - 3B; 1 CPL
Launched Feb 2002



AURA, 5 LHPs
Launched July 2004



ICESat, 2 LHPs
1/13/2003 to 8/14/2010

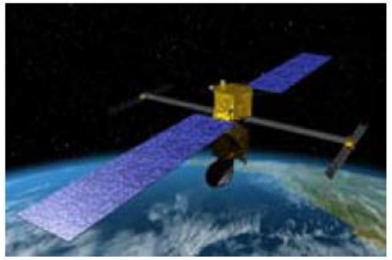


SWIFT, 2 LHPs
Launched Nov 2004

GOES N-Q, 5 LHPs each
Launched 2006

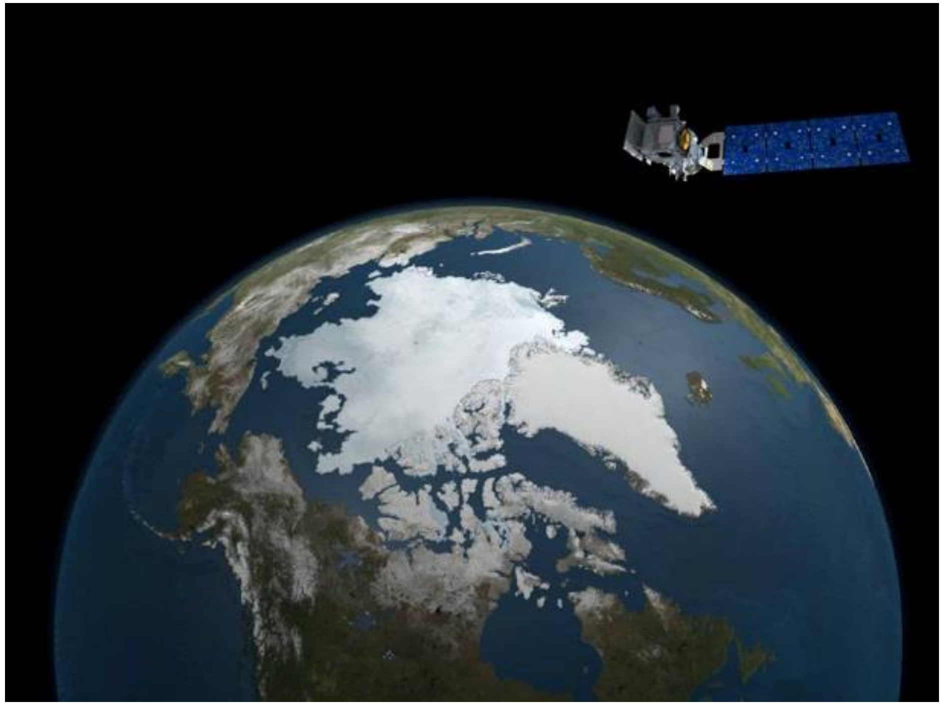
GOES R-U, 4 LHPs each

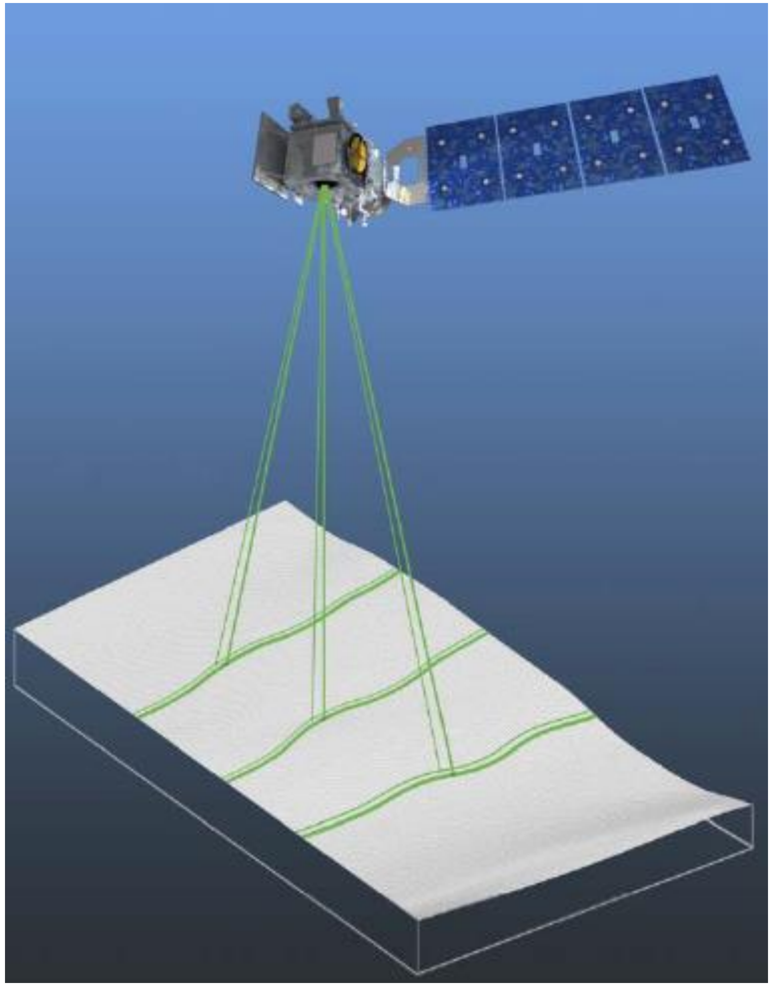
ICESat-2, 1 LHP



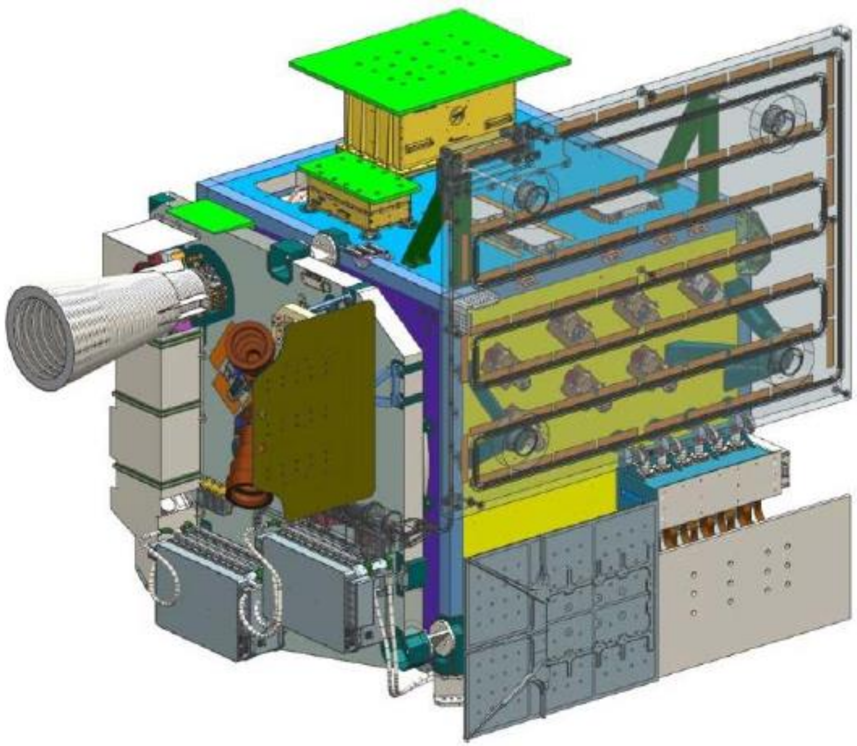
SWOT, 4 LHPs

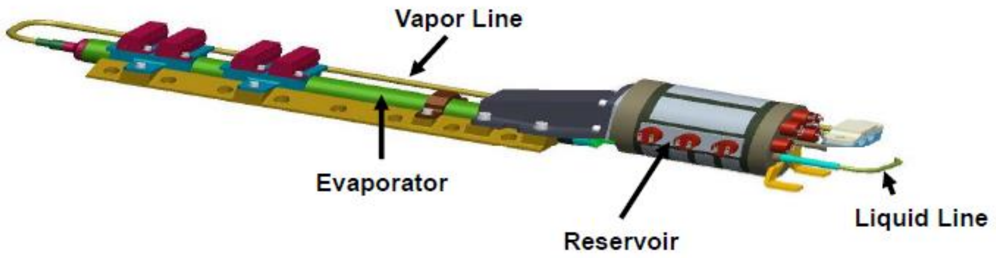
ICESat-2 (Ice, Cloud, and land Elevation Satellite-2)

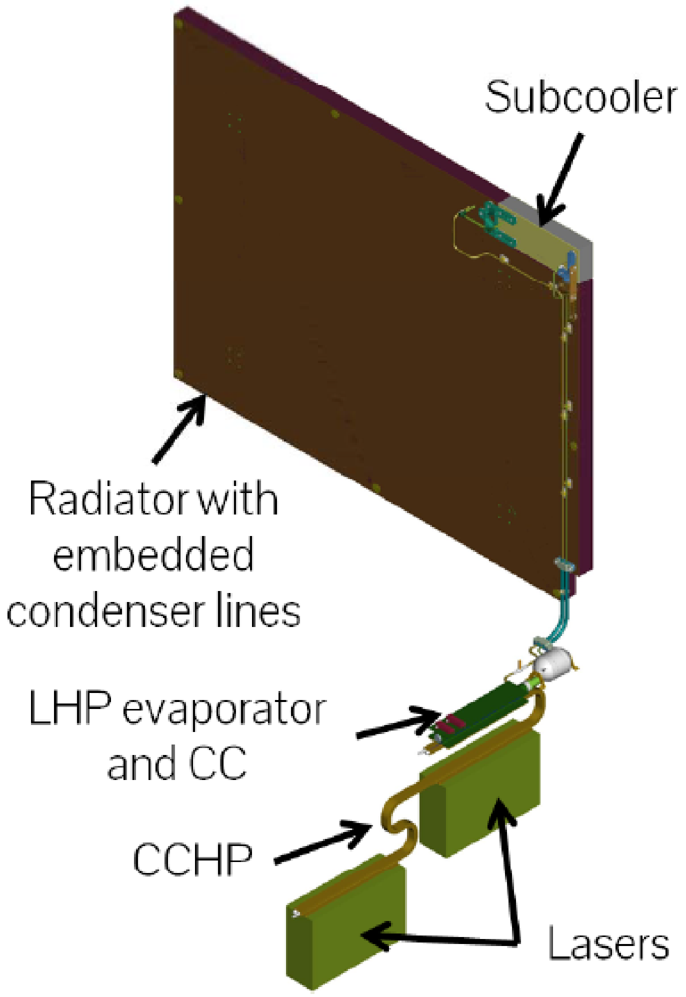




HPs and LHPs on IceSat-2 ATLAS LTCS

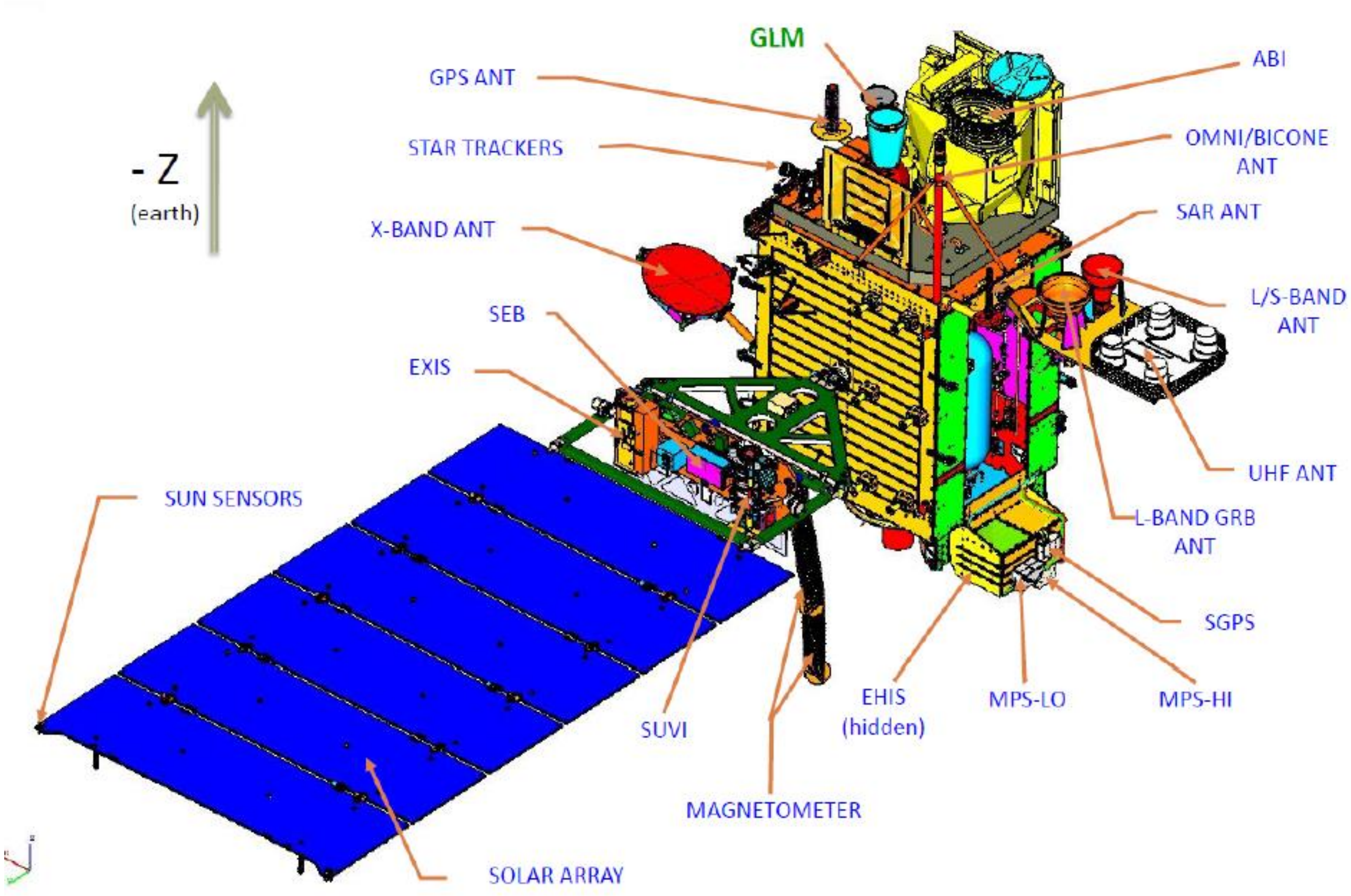




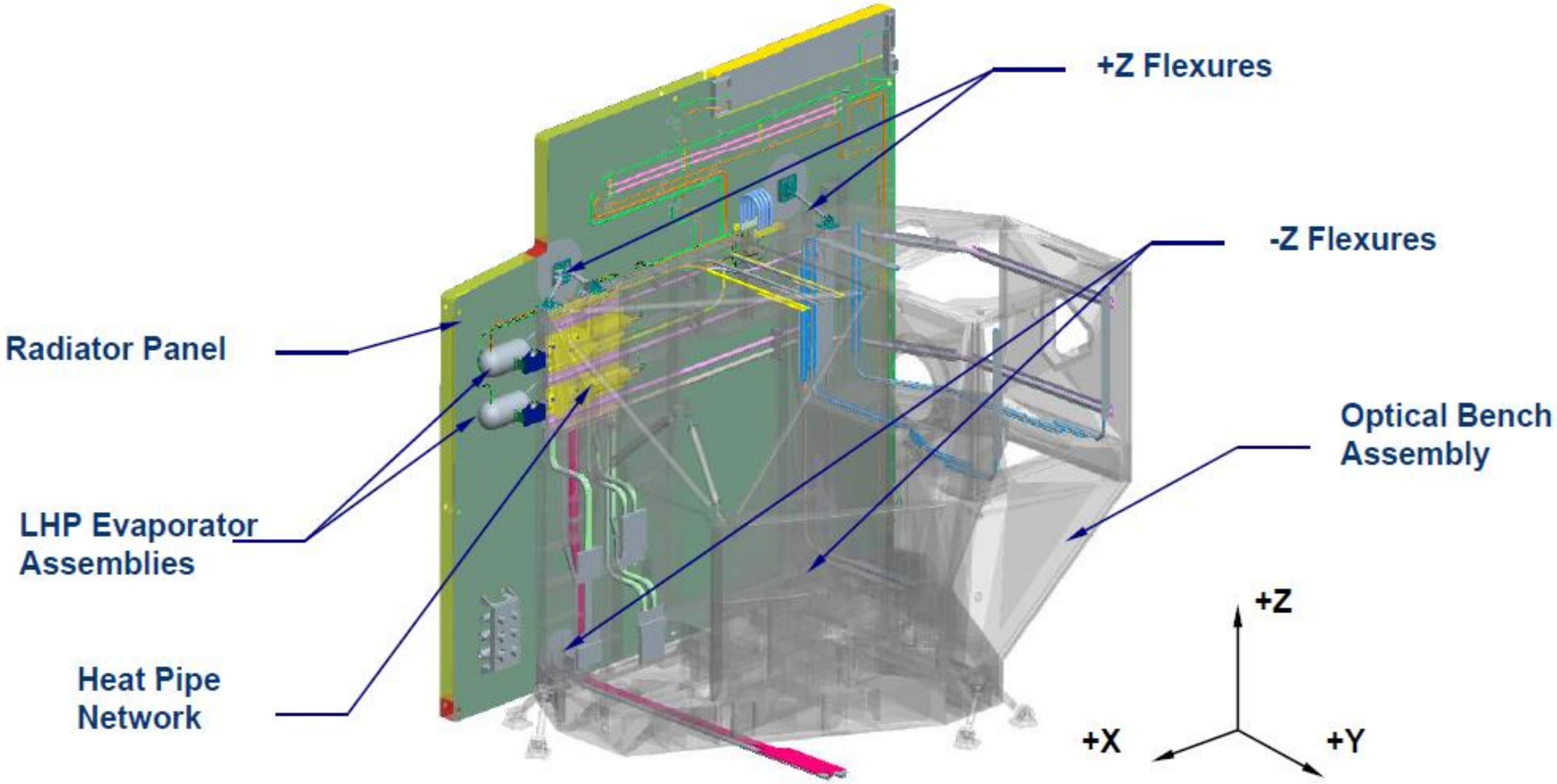


IceSat-2 ATLAS Instrument Flight Hardware

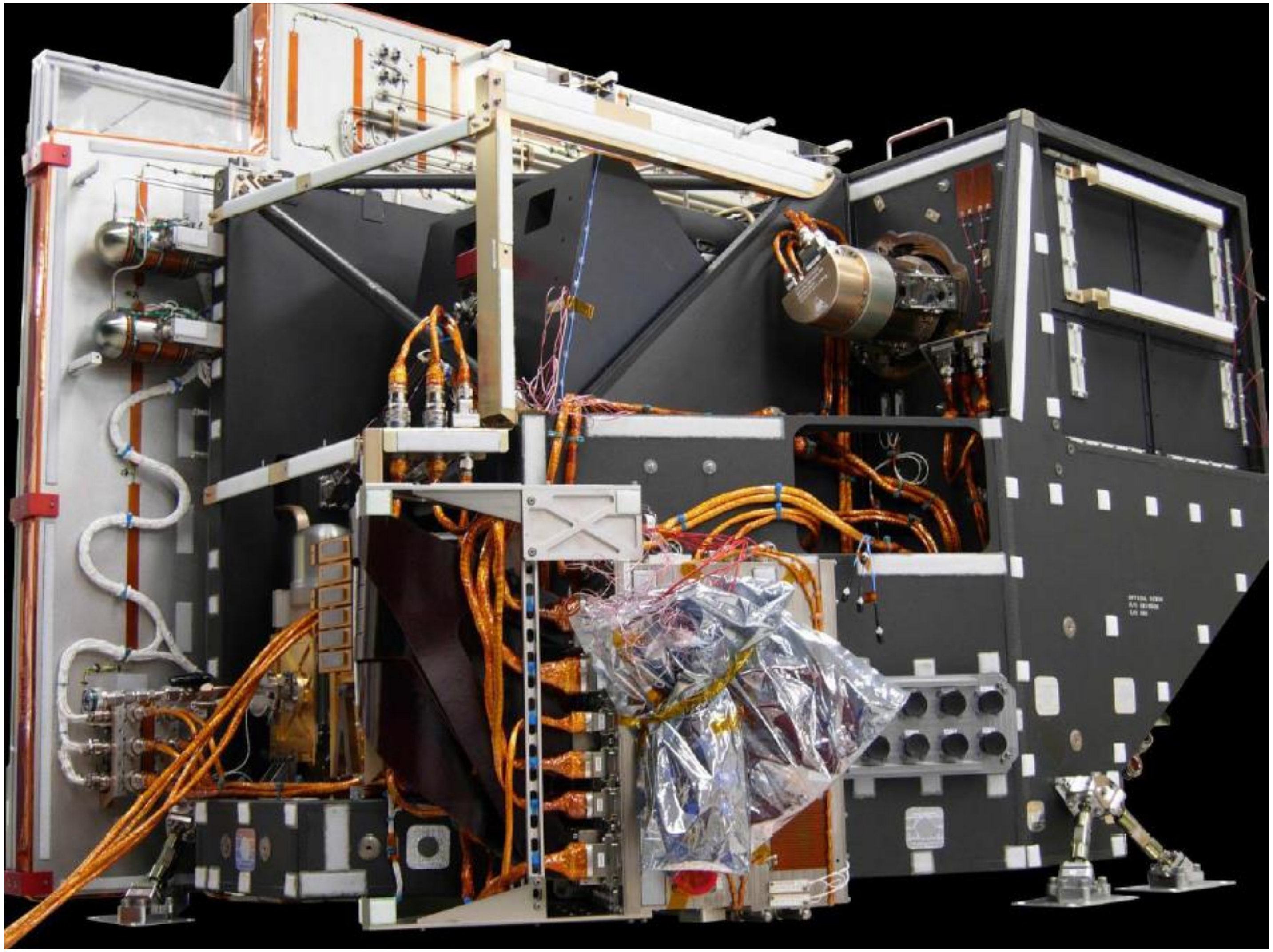
GOES-R Spacecraft Layout



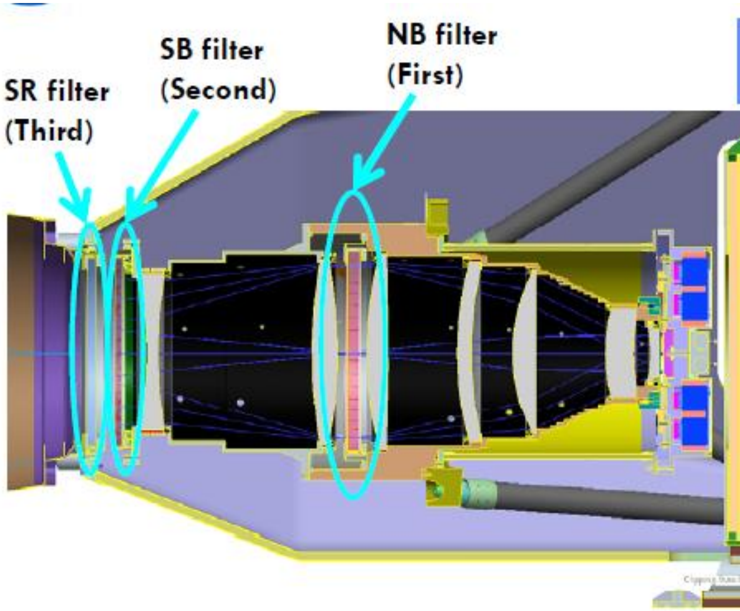
GOES-R ABI HPs/LHPs Assembly

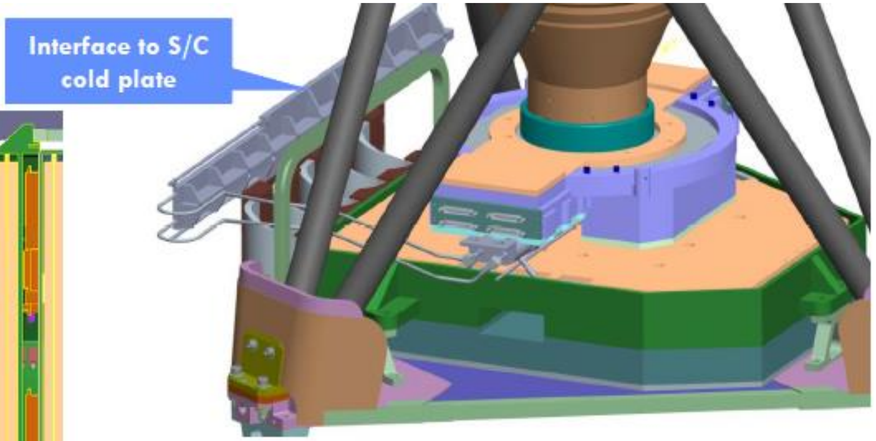


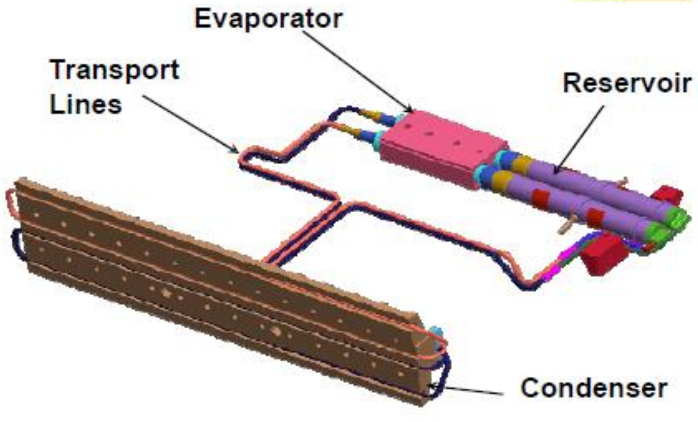
GOES-R ABI HPs/LHPs Assembly

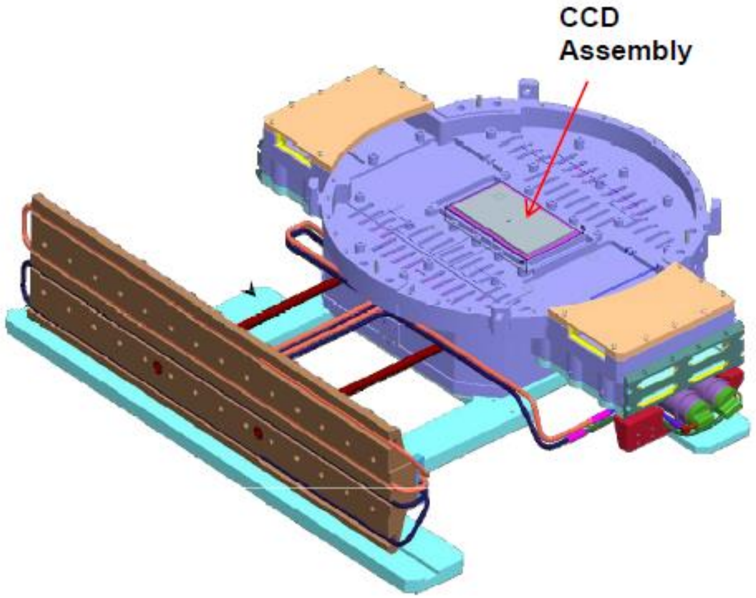


GOES-R GLM LHPs

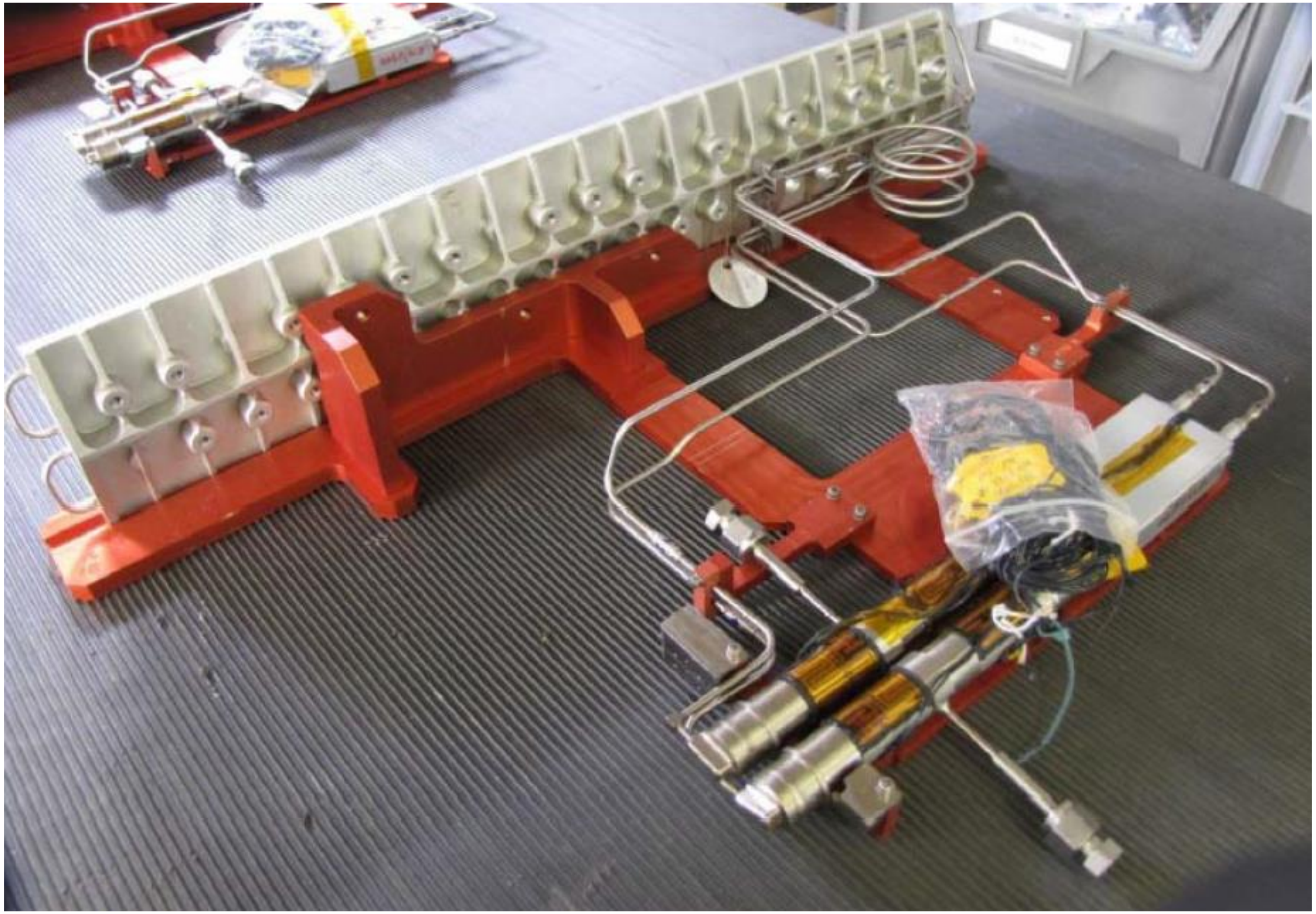








GOES-R GLM LHP Flight Hardware



Abbreviations

- AGHP – Axial Grooved Heat Pipe
- CCHP – Constant Conductance Heat Pipe
- CLHP – Cryogenic Loop Heat Pipe
- CPL – Capillary Pumped Loop
- HEX – Heat Exchanger
- HP – Heat Pipe
- LEO – Low Earth Orbit
- LHP – Loop Heat Pipe
- OHP – Oscillating Heat Pipe
- PHP – Pulsating Heat Pipes
- SC – Spacecraft
- TCS – Thermal Control System
- TPS – Two-Phase System
- TRL – Technical Readiness Level
- VC – Vapor Chamber
- VCHP – Variable Conductance Heat Pipe

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