Capillary Two-Phase Thermal Devices for Space Applications

Jentung Ku

NASA/ Goddard Space Flight Center

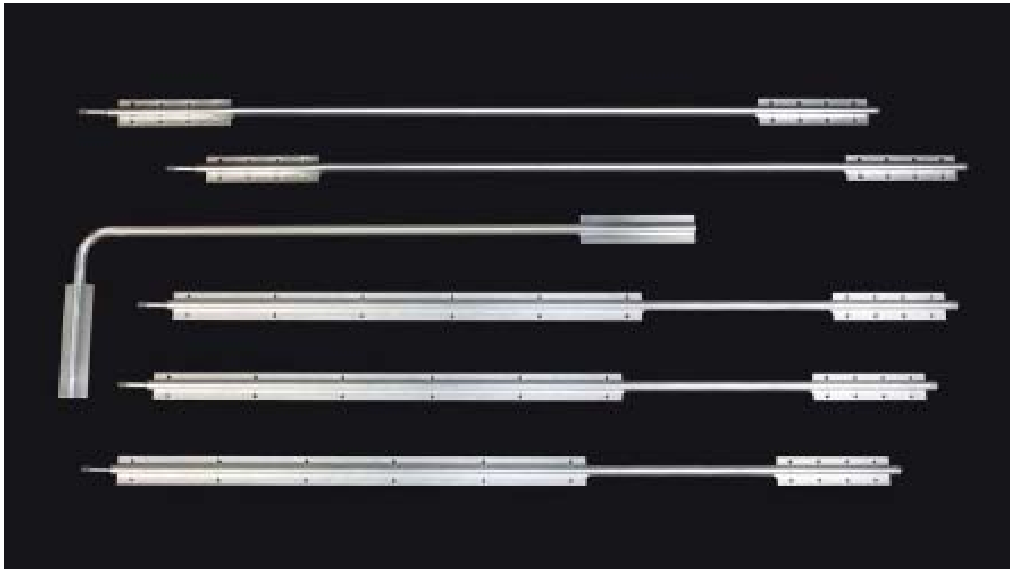
Greenbelt, Maryland

April 2016

Outline

- Introduction
- Heat Pipe Operating Principles
  - Pressure Drops
  - Operating Temperature
- Heat Pipe Operating Characteristics
- Loop Heat Pipe Operating Principles
  - Pressure Drops
  - Operating Temperature
- Loop Heat Pipe Operating Characteristics
- Examples of Space Applications

Heat Pipes - Hardware

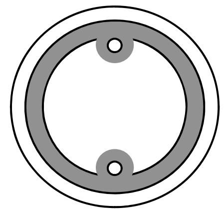


- Metal (aluminum) tube with grooves on the inner surface – cold extrusion
- Grooves are filled with the working fluid (water, ammonia, propylene, etc.)
- Flanges can be added on the outer surface for easy integration with instruments or radiators (The flange is an integral part of the extrusion)
- Various diameters, lengths, and groove sizes

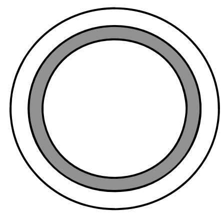
Some Wicks Used in Heat Pipes

- **Many HP hardware variations exist.**
  - **Size**
  - **Length**
  - **Shape**
  - **Wick material**
  - **Wick construction**
  - **Working fluid**

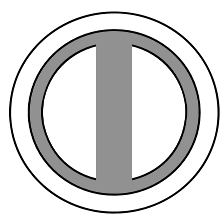
- **Axial Grooves**
  - **Design simplicity**
  - **Reliability**
  - **High heat transport**
  - **High thermal conductance**
  - **Versatility**
  - **Broadly used in aerospace applications**



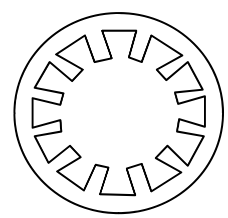
POWDER METAL WITH PEDESTAL ARTERY



CIRCUMFERENTIAL SCREEN WICK



SLAB WICK



AXIAL GROOVES

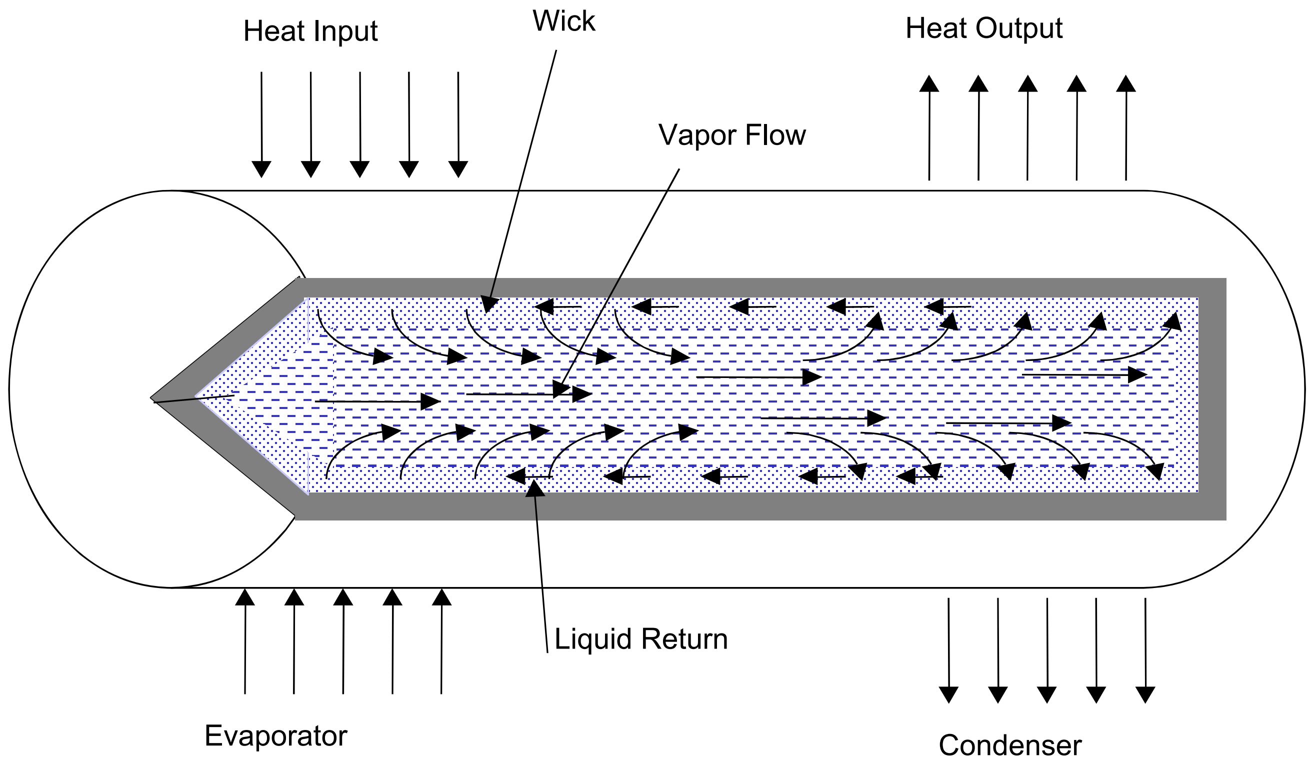
Introduction – Why Heat Pipes?

- Heat pipe is a capillary two-phase heat transfer device.
  - Transports heat from a heat source to a heat sink
  - Works as an isothermalizer

- Why two-phase thermal system?
  - Efficient heat transfer – boiling and condensation
  - Small temperature difference between the heat source and heat sink

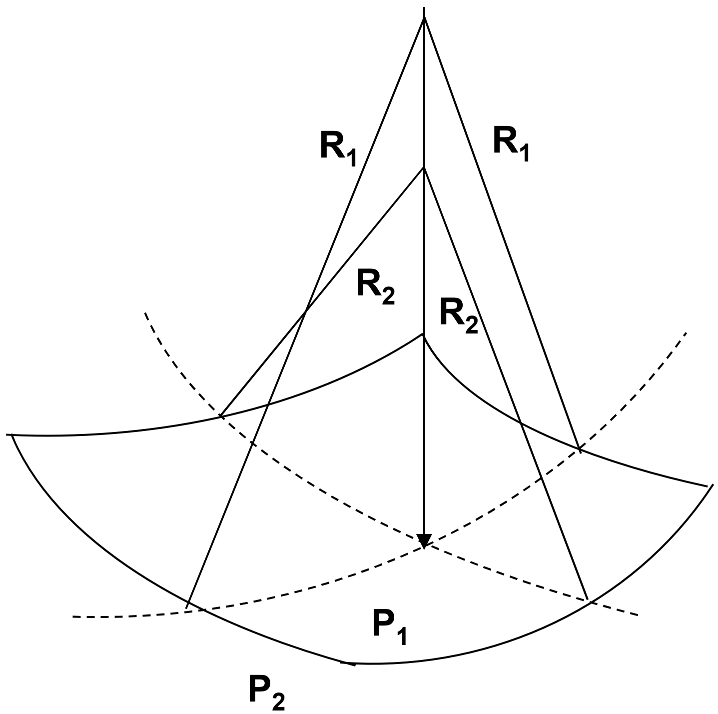
- Why capillary two-phase system?
  - Passive – no external pumping power
  - Self regulating – no flow control devices
  - No moving parts – vibration free

Heat Pipes – Operating Principles



- **Typical use of heat pipe: transports heat from one end (evaporator) to the other (condenser).**
- **Vapor flows from the evaporator to the condenser along the center core.**
- **Vapor condenses at the condenser. Liquid is drawn back to the evaporator by the capillary force along the grooves.**
- **The pressure difference between the vapor and liquid phases is sustained by the surface tension force of the fluid.**
- **Passive – Waste heat provides the driving force for the fluid flow; no external pumping power.**

Differential Pressure Across a Curved Surface



$\Delta P = P_1 - P_2 = \sigma\,(1/R_1 + 1/R_2)$

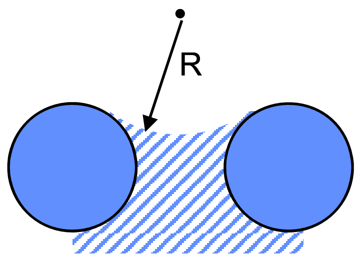
σ: Surface tension; R_1 and R_2: Radii of curvature

Pressure Differential Across a Meniscus

- **A meniscus will be formed at the liquid/vapor interface, and a capillary pressure is developed.**

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

σ: Surface tension; R: Radius of curvature; θ: Contact Angle

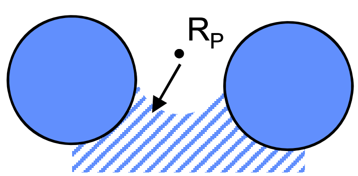


- **The maximum capillary pressure**

$\Delta P_{cap,max} = 2\sigma \cos\theta/R_p$

$R \geq R_p$

R_p : Radius of the pore

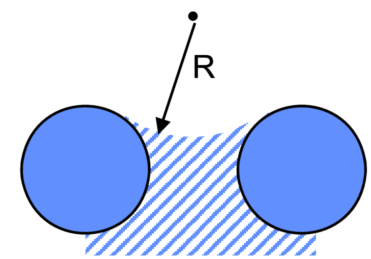


Pressure Balance in Heat Pipes

- **The fluid flow will induce a frictional pressure drop. The total pressure drop over the length of the heat pipe is the sum of individual pressure drops.**

$$\Delta P_{tot} = \Delta P_{vap} + \Delta P_{liq} + \Delta P_g$$

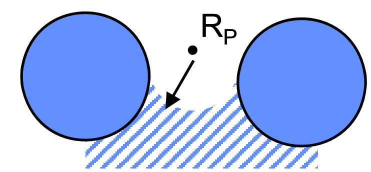
- **The meniscus will curve naturally so that the capillary pressure is equal to the total pressure drop.**



$$\Delta P_{cap} = \Delta P_{tot}$$

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

- **The flow will stop when the capillary limit is exceeded.**



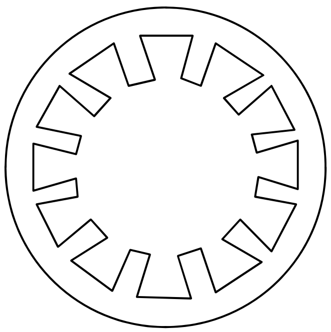
$$\Delta P_{cap,max} = 2\sigma \cos\theta / R_p$$

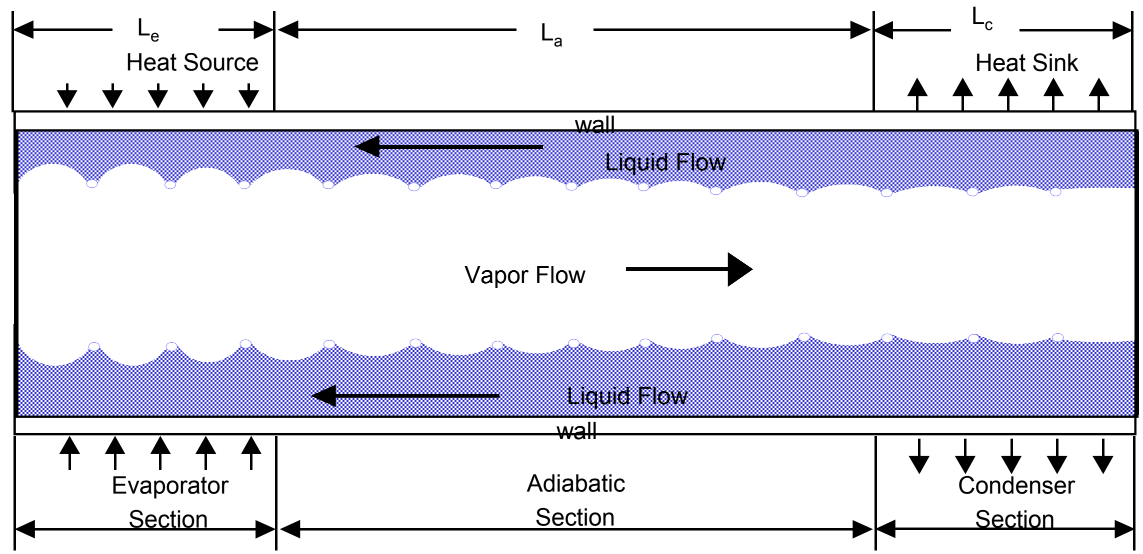
R_p : Radius of the pore

- **For normal operation of heat pipes:**

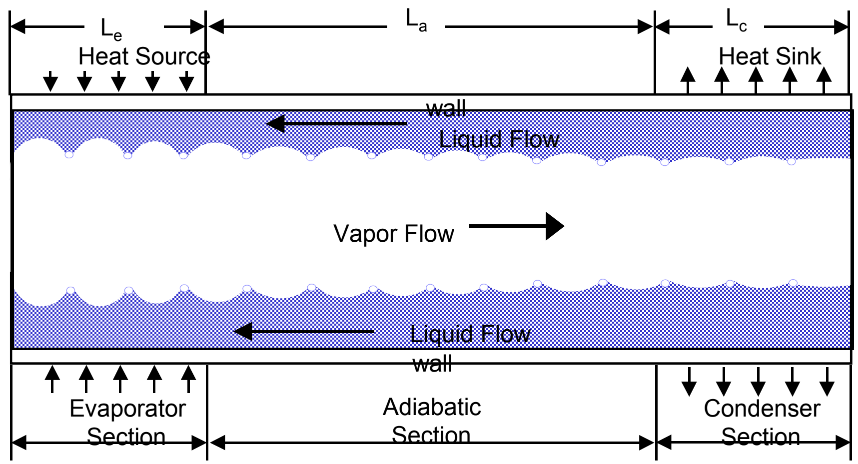
$$\Delta P_{tot} = \Delta P_{cap} \leq \Delta P_{cap,max}$$

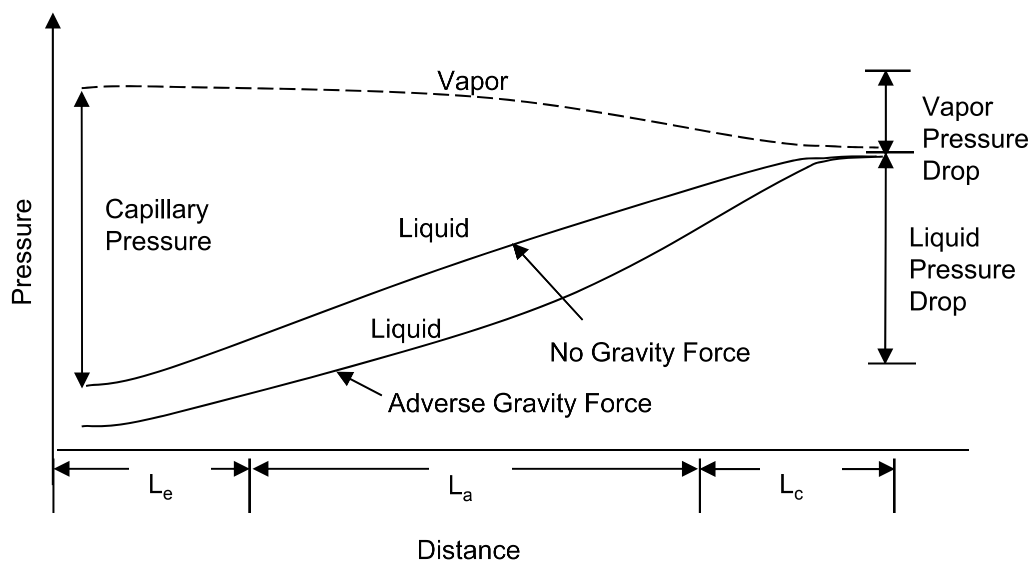
Pressure Differential at Liquid Vapor Interface





Heat Pipes – Pressure Drops

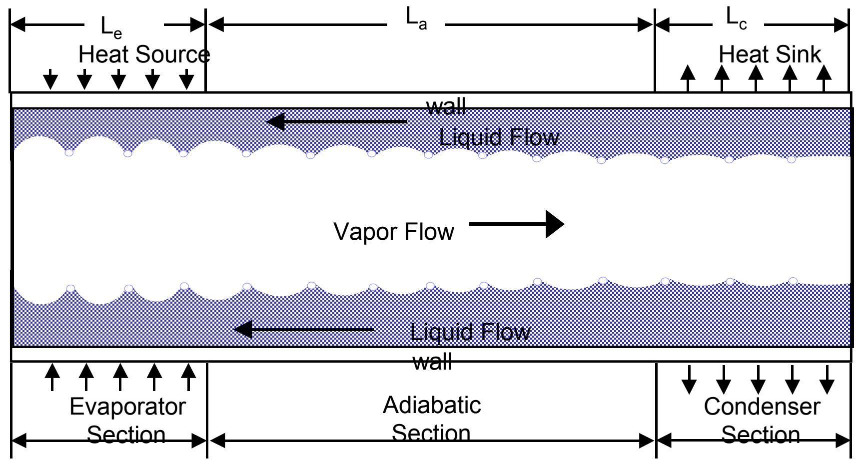


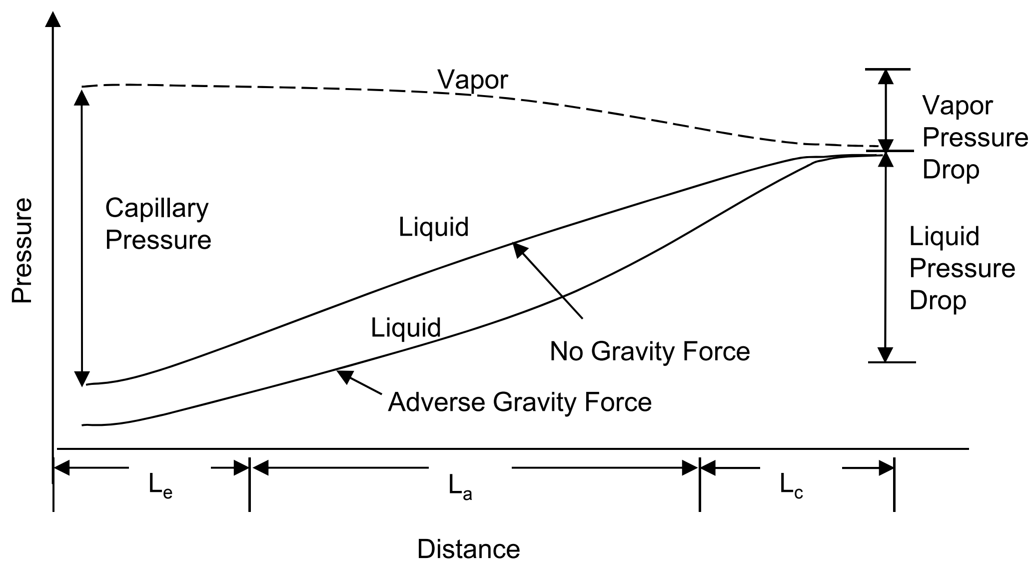


b) Vapor and liquid pressure distributions

- **Vapor pressure drop diagram**
- **Liquid pressure drop diagram**
- **Pressure drop due to gravity head**
- **Pressure differential between vapor and liquid - sustained by capillary force**
- **The highest pressure differential occurs at the very end of the evaporator.**
- **Pressure drops depend on heat load and transport distance.**

Heat Pipes - Heat Transport Limit





b) Vapor and liquid pressure distributions

- **The total pressure drop must not exceed its capillary pressure head.**

  $\Delta P_{tot} = \Delta P_{vap} + \Delta P_{liq} + \Delta P_g$

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

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

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

- **Capillary pressure head:**

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

- **Liquid pressure drop:**

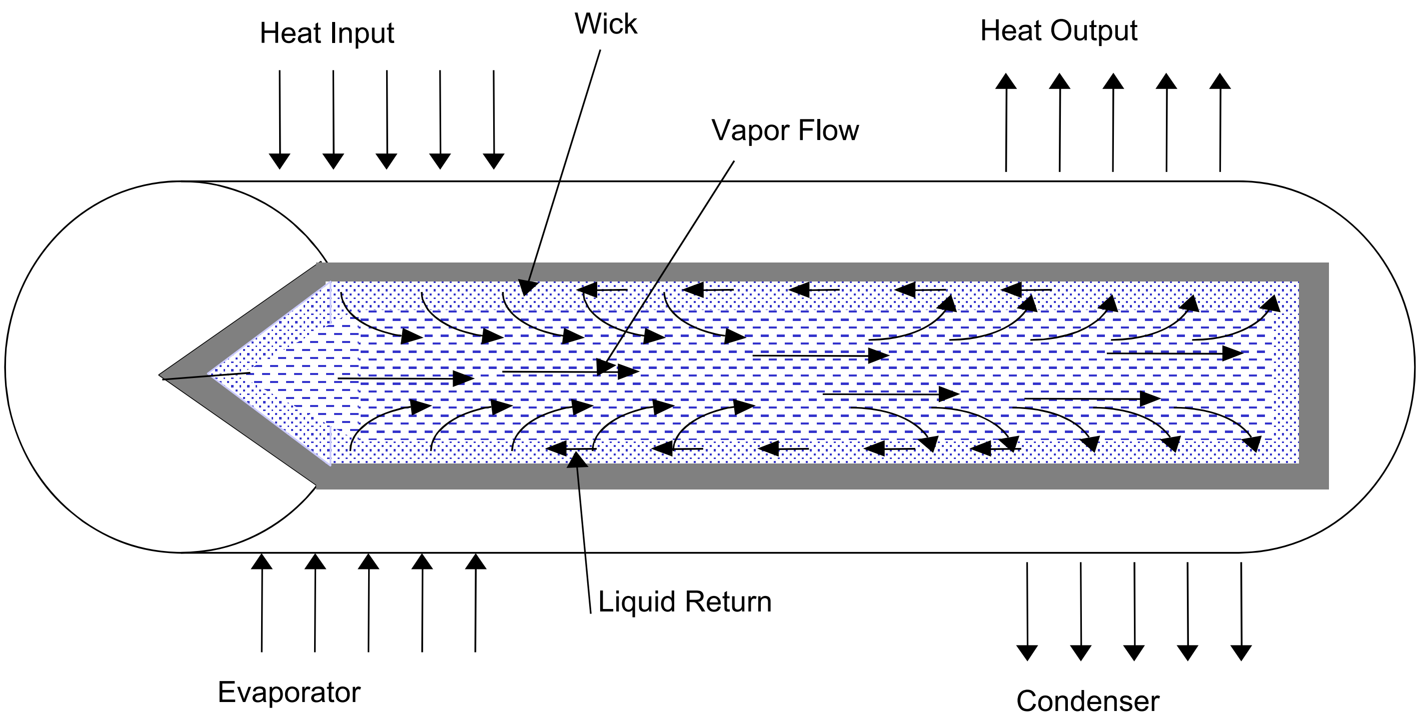
  $\Delta P_{liq} \propto 1/R_p^2$

- **An optimal pore radius exists for maximum heat transport.**

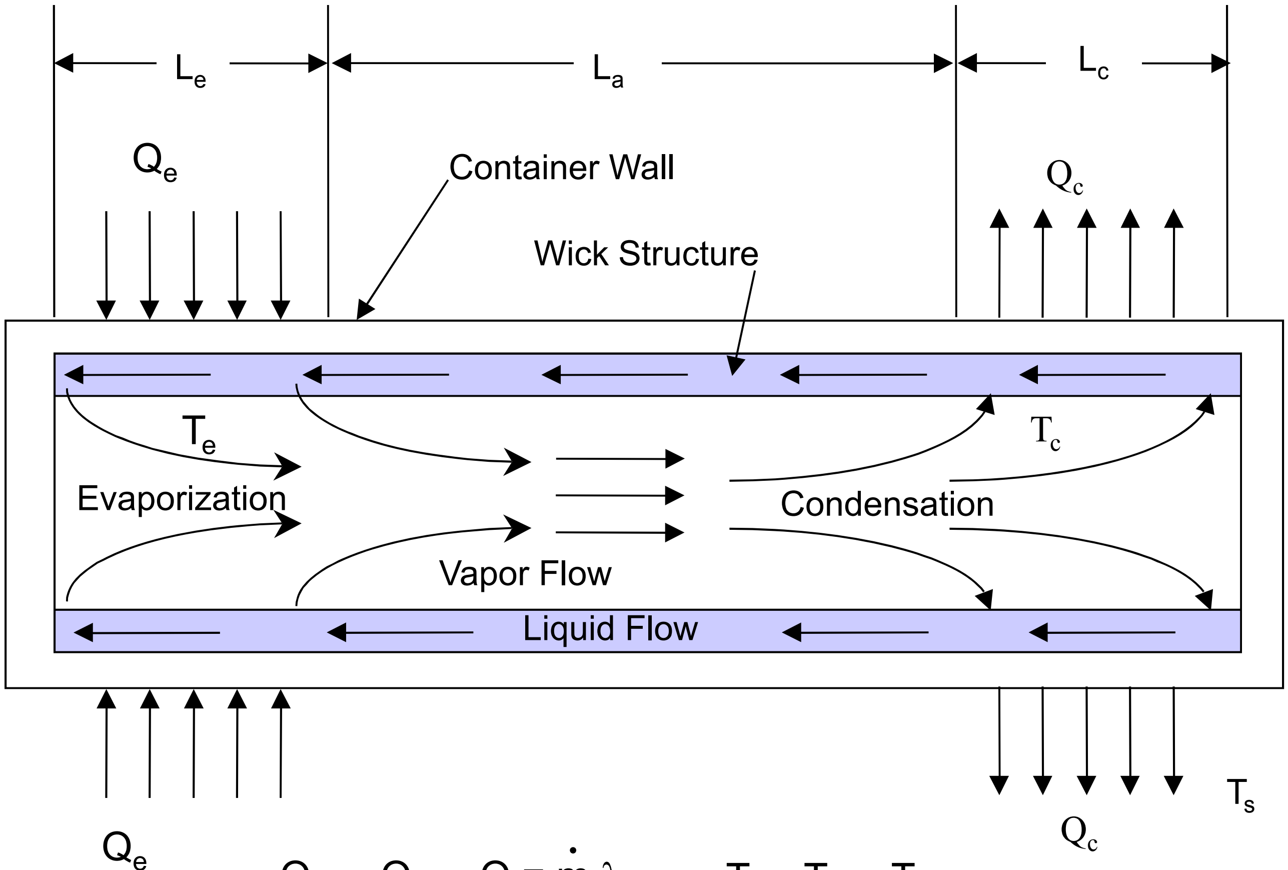
- **Limited pumping head against gravity**

Functional Types Of Heat Pipes

- Three Basic Functional Types
  - Constant Conductance Heat Pipe (CCHP)
  - Variable Conductance Heat Pipe (VCHP)
  - Diode Heat Pipe



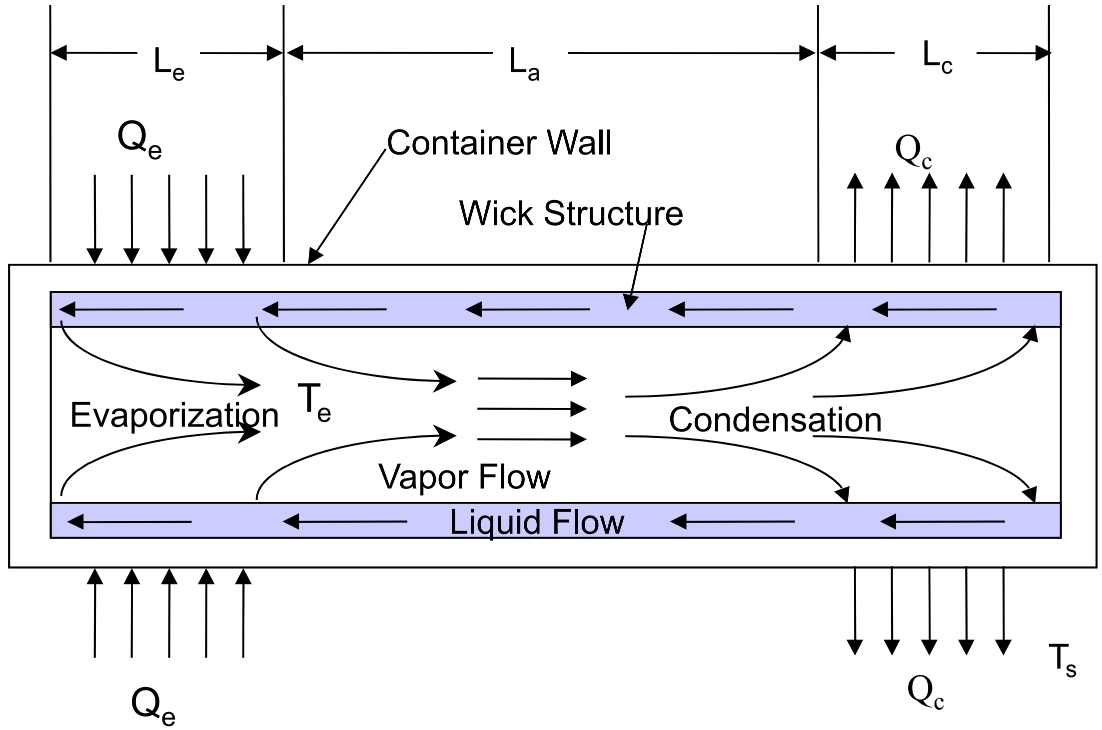
Energy Balance in Heat Pipe

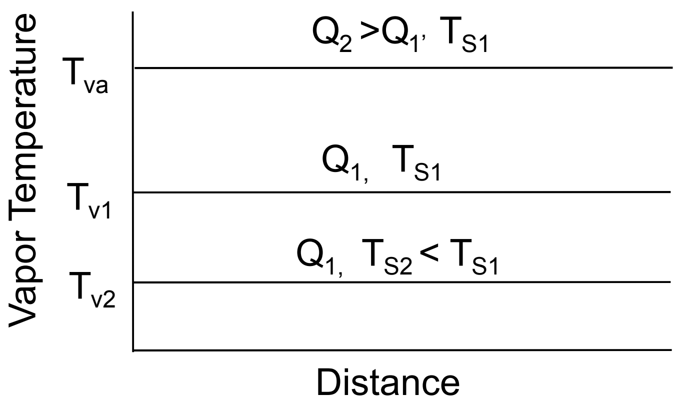


$$Q_e = Q_c \equiv Q = \dot{m}\,\lambda \qquad T_e \cong T_c \equiv T_v$$

L_e = Evaporator length
L_a = Adiabatic length
L_c = Condenser length
$\dot{m}$ = Mass flow rate (liquid or vapor)
λ = Latent heat of vaporization

Thermal Characteristics of a CCHP





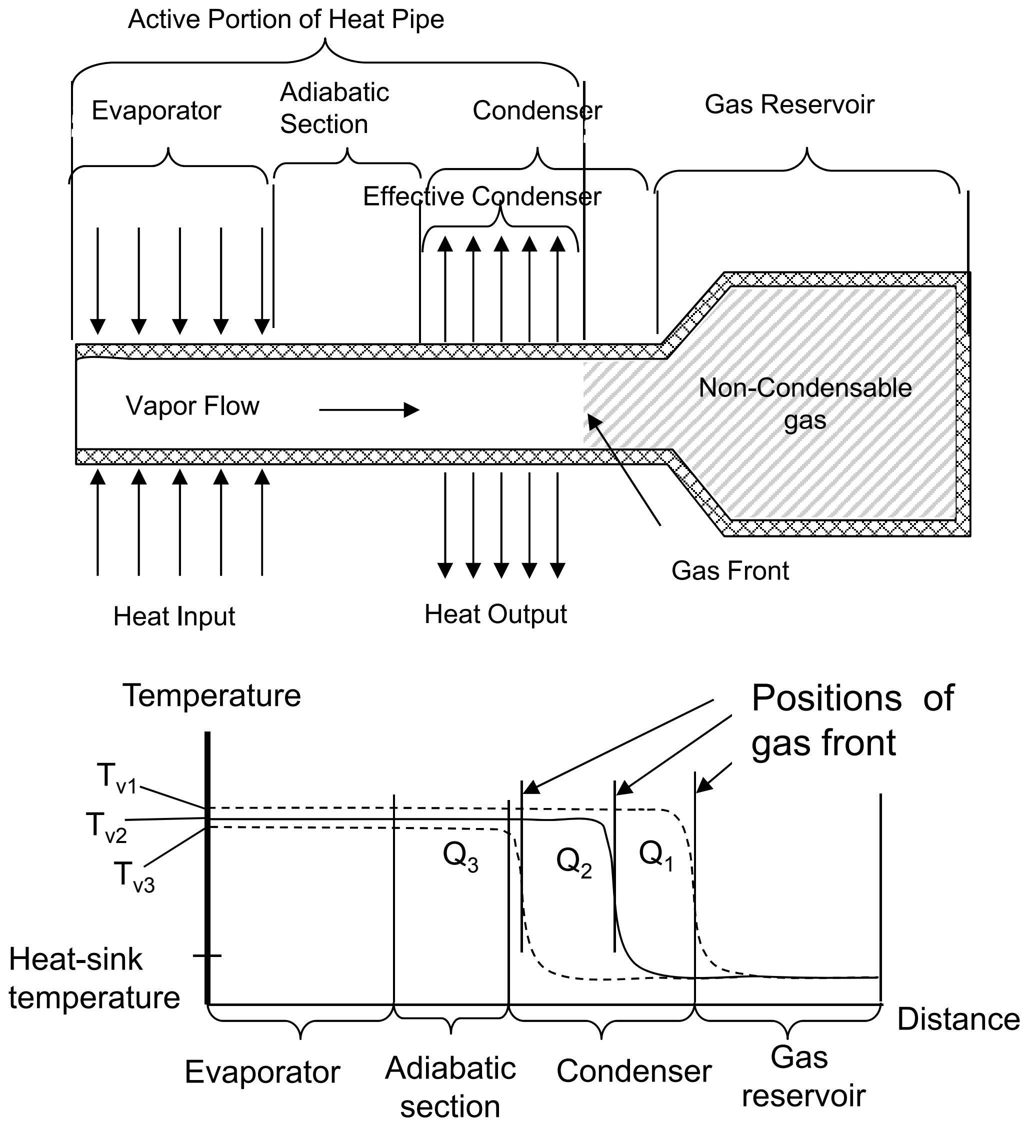
$Q = h(\pi D L_c)(T_V - T_s)$

L_c = constant

$h(\pi D L_c)$ = constant conductance

T_V varies with T_s and Q

Thermal Characteristics of a VCHP



$Q = h(\pi D L_c)(T_V - T_s)$

L_c varies with T_s and Q

so as to keep T_V constant

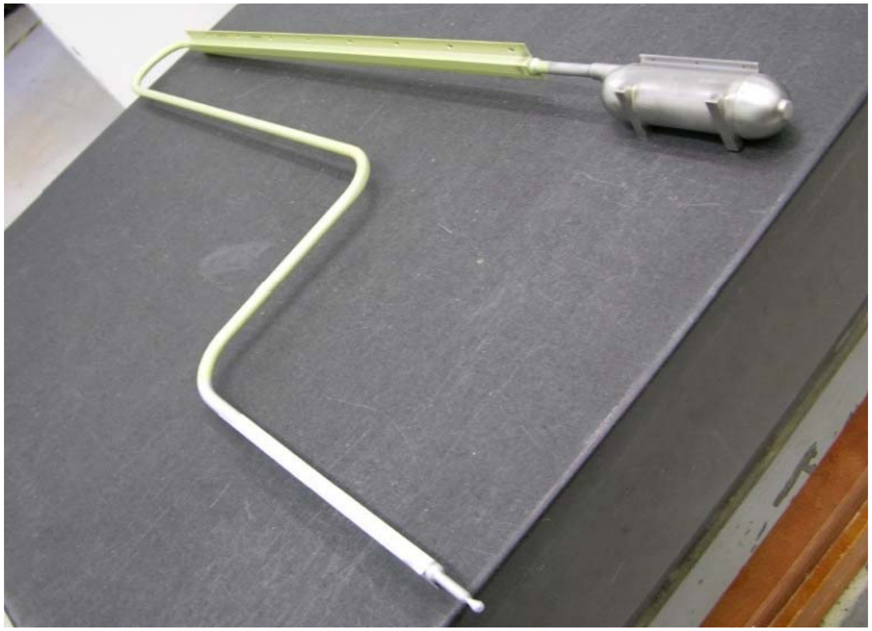
$h(\pi D L_c)$ = variable conductance

Reservoir size is a function of:

- **Range of heat load**
- **Range of sink temperature**
- **Temperature control requirement**

VCHPs

Typical VCHP



OCO-2 VCHPs

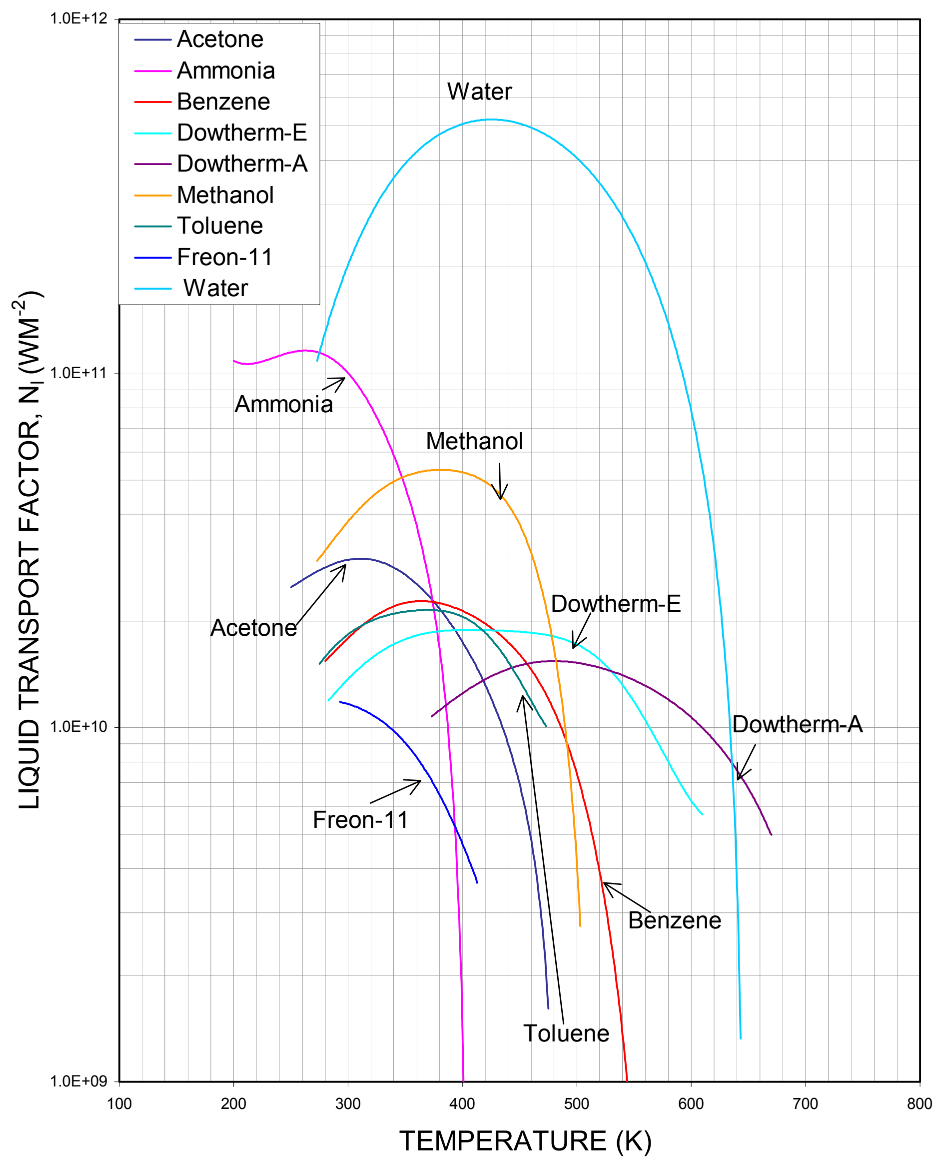
- **Types of VCHPs**
  - **Feedback-controlled VCHP**
  - **Passive VCHP**

Liquid Transport Factor vs Temperature

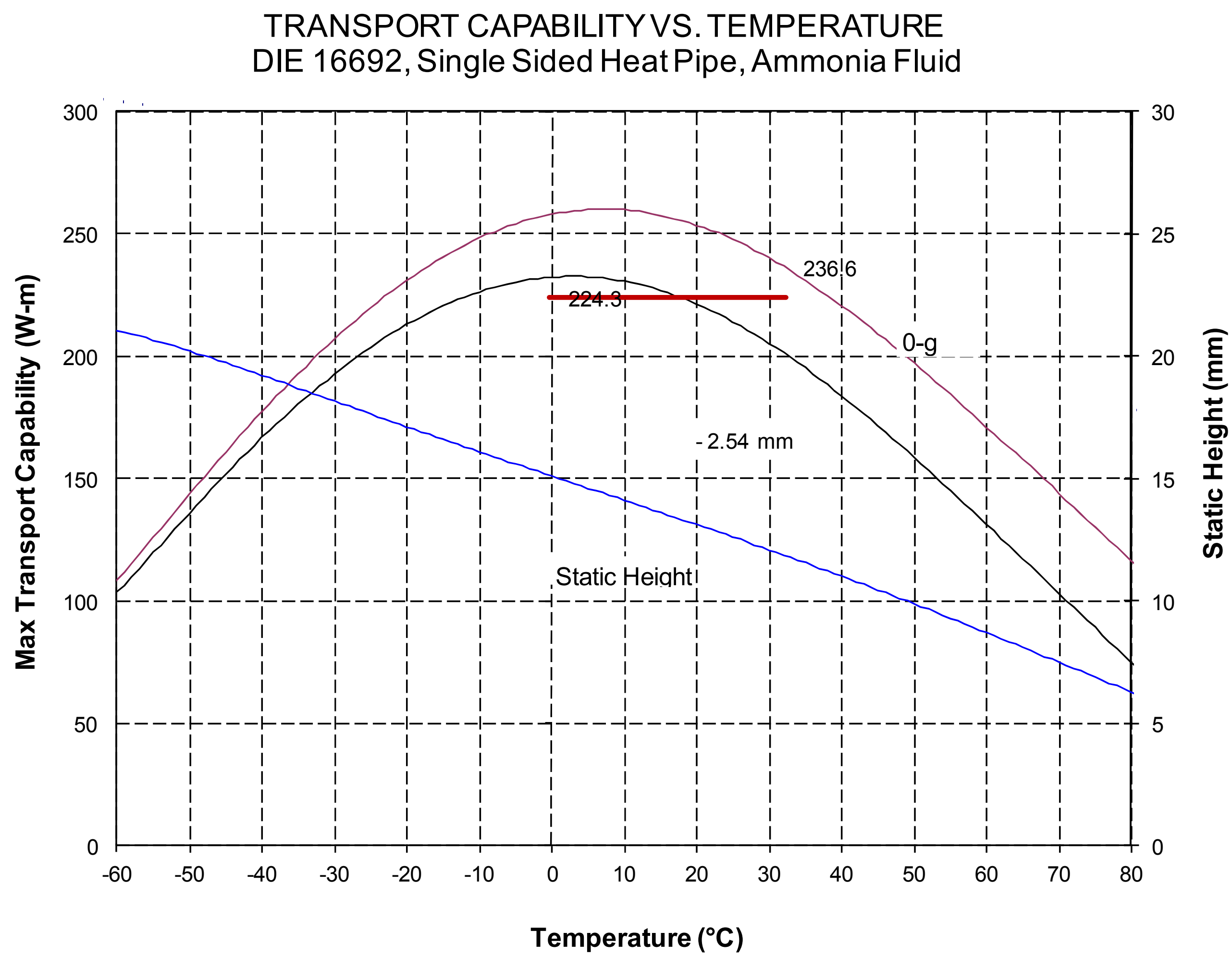
- **A convenient figure of merit is the liquid transport factor, N_l,**

$$N_l = \lambda\sigma\rho_l/\mu_l$$

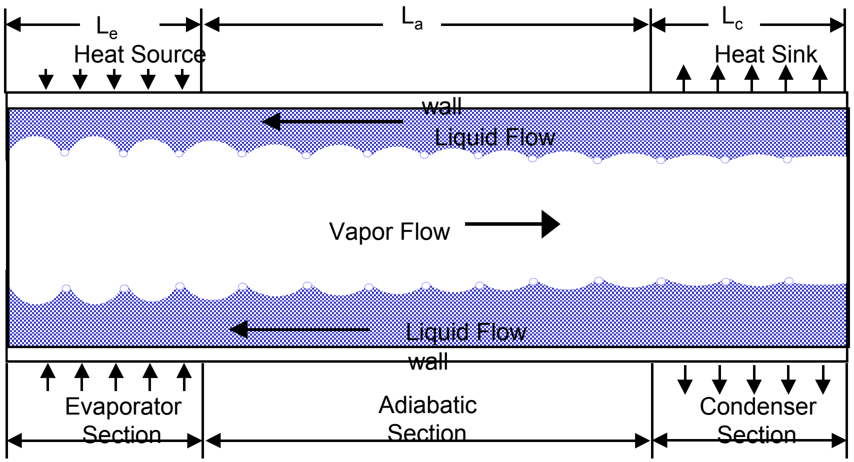
N_l = Latent Heat * Surface Tension * Liquid Density/ Liquid Viscosity

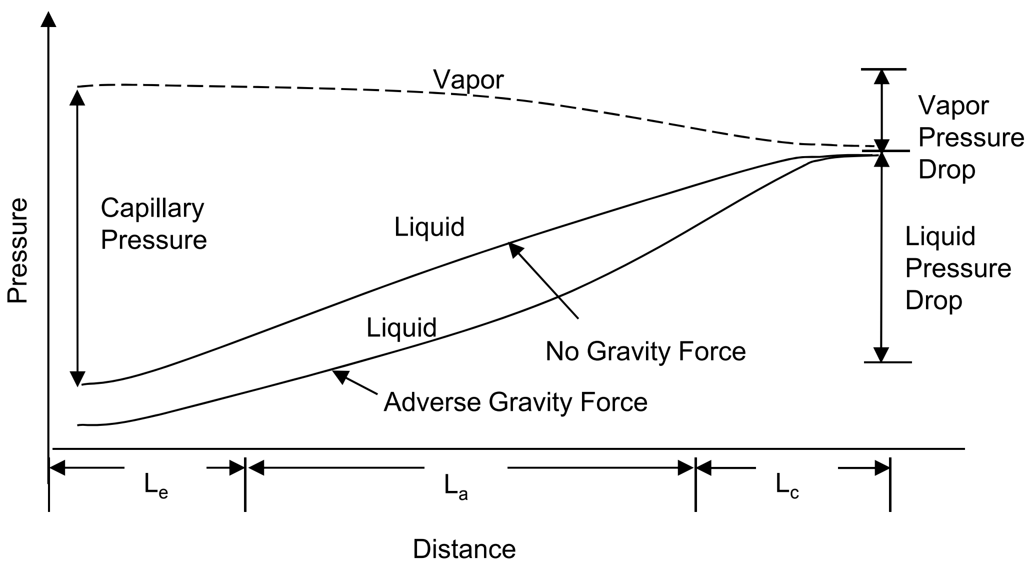


Heat Pipe Performance Curve for Given Heat Pipe Design and Working Fluid (Usually Provided by the Vendor)



Heat Pipes - Heat Transport Limit





b) Vapor and liquid pressure distributions

- **The total pressure drop must not exceed its capillary pressure head.**

  $$\Delta P_{tot} = \Delta P_{vap} + \Delta P_{liq} + \Delta P_g$$
  $$\Delta P_{cap,max} = \sigma \cos\theta / R_p$$
  $$\Delta P_{tot} \leq \Delta P_{cap,max}$$

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

- **Capillary pressure head:**

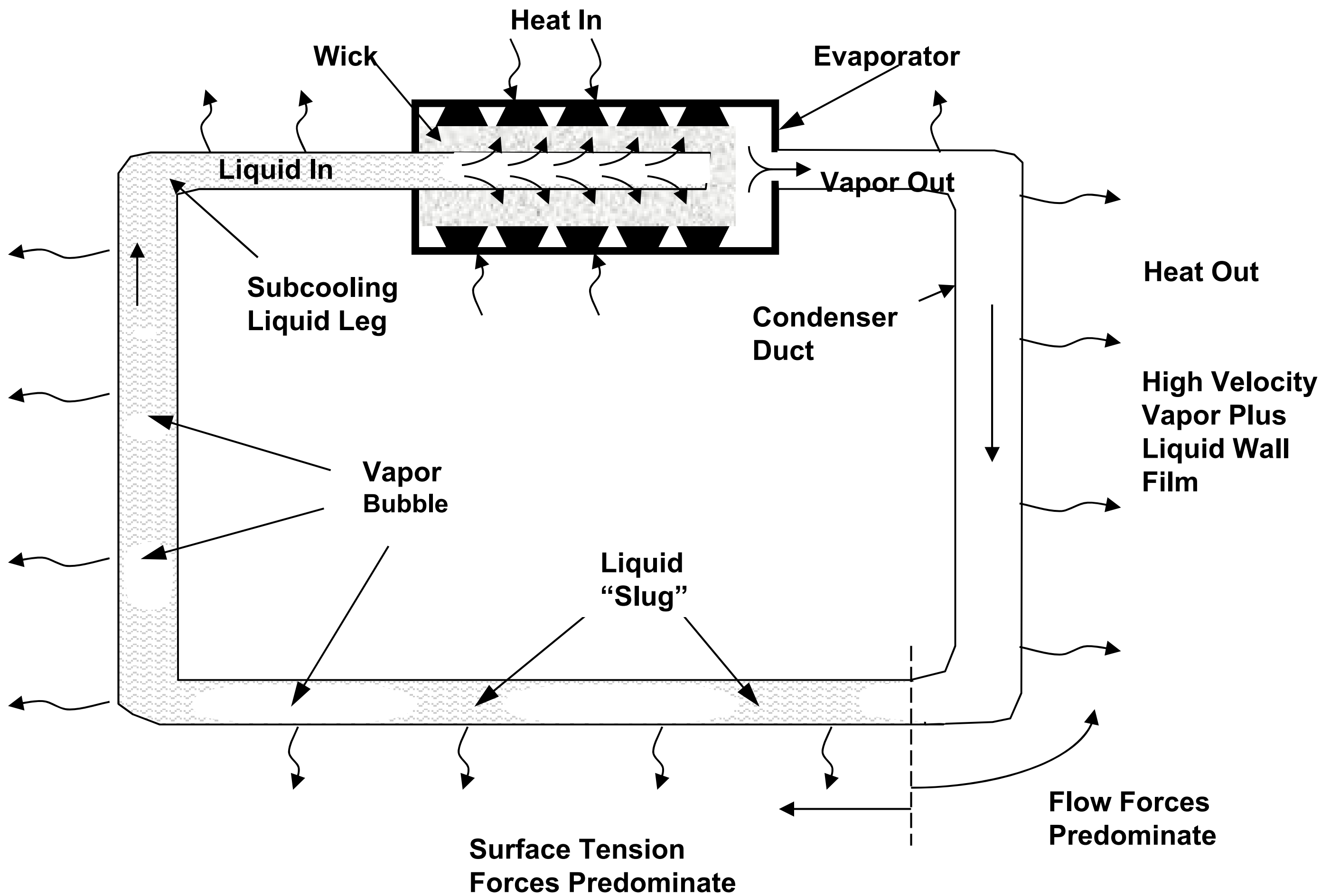
  $$\Delta P_{cap} \propto 1/R_p$$

- **Liquid pressure drop:**

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

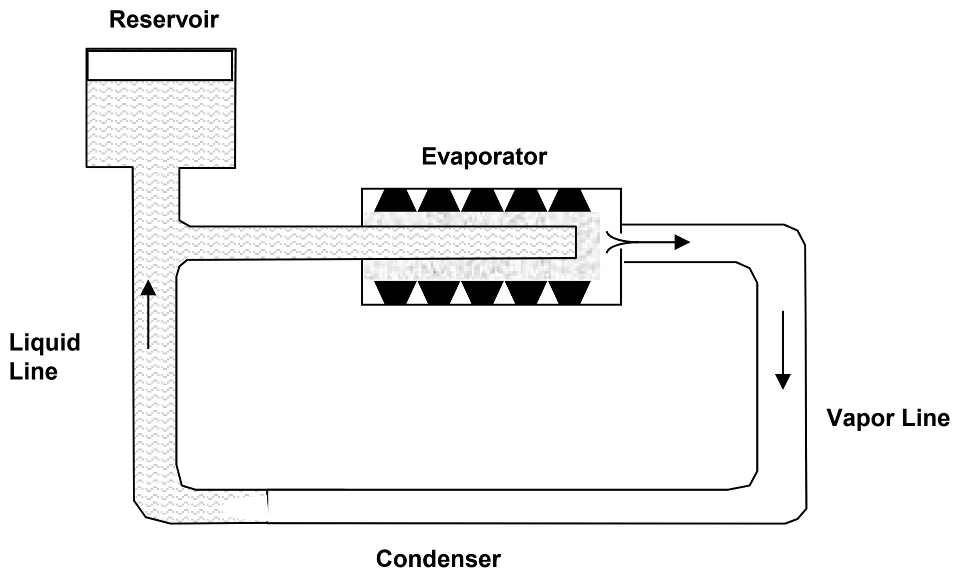
- **An optimal pore radius exists for maximum heat transport.**
- **Limited heat transport capability**
- **Limited pumping head against gravity**

Constant Conductance Capillary Pumped Loop



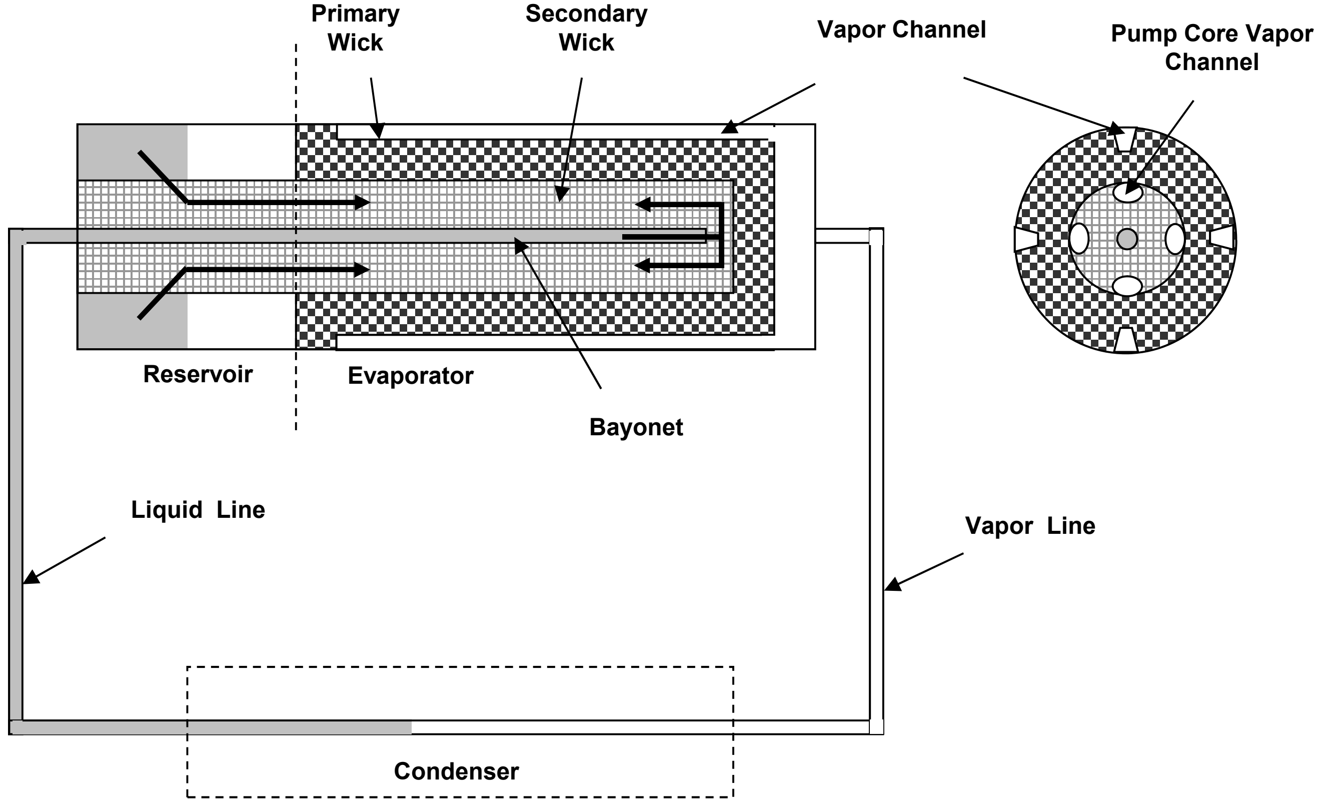
- **Wicks are present only in the evaporator, and wick pores can be made small.**
- **Smooth tubes can be sized independently to reduce pressure drops.**
- **Vapor and liquid flow in the same direction instead of countercurrent flows.**
- **Operating temperature varies with heat load and/or sink temperature.**

Variable Conductance Capillary Pumped Loop



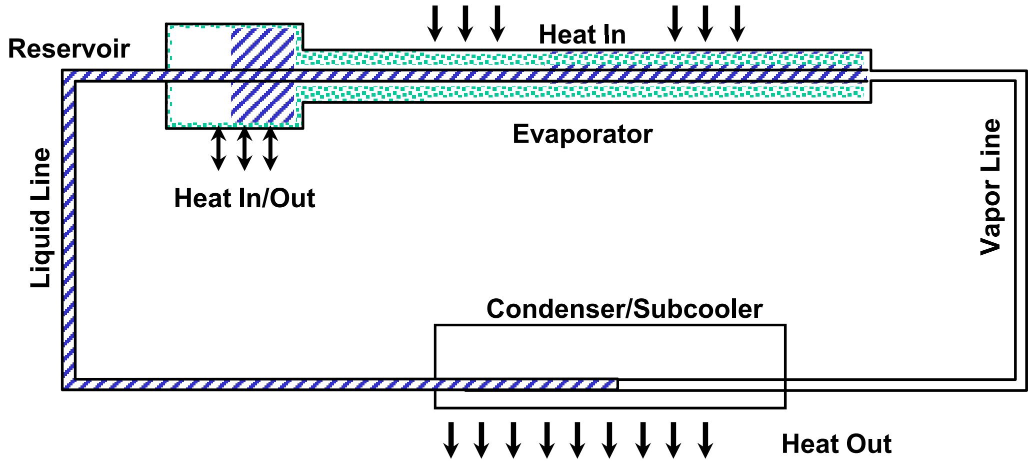
- The reservoir stores excess liquid and controls the loop operating temperature.
- The operating temperature can be tightly controlled with small heater power.
- The loop can be easily modified or expanded with reservoir re-sizing.
- Pre-conditioning is required for start-up.
- Evaporator cannot tolerate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

Schematic of a Loop Heat Pipe



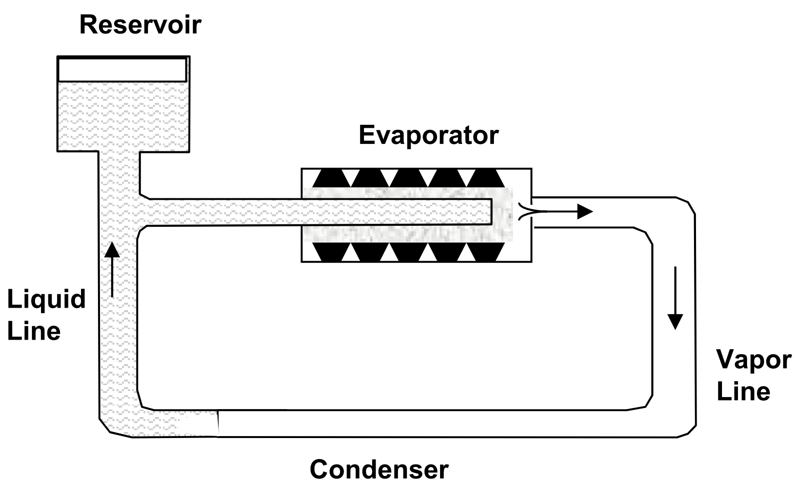
- **Main design features**
  - **The reservoir forms an integral part of the evaporator assembly.**
  - **A primary wick with fine pore sizes provides the pumping force.**
  - **A secondary wick connects the reservoir and evaporator, supplying liquid.**

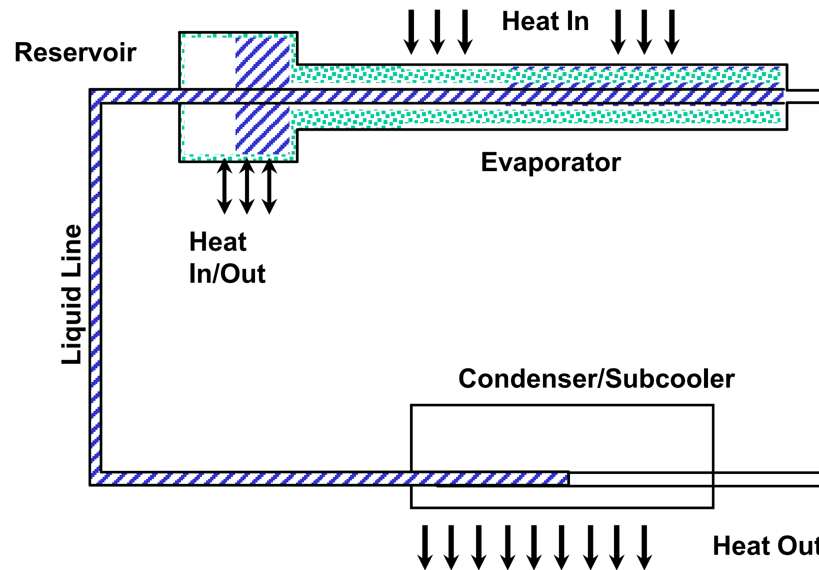
Main Characteristics of LHP

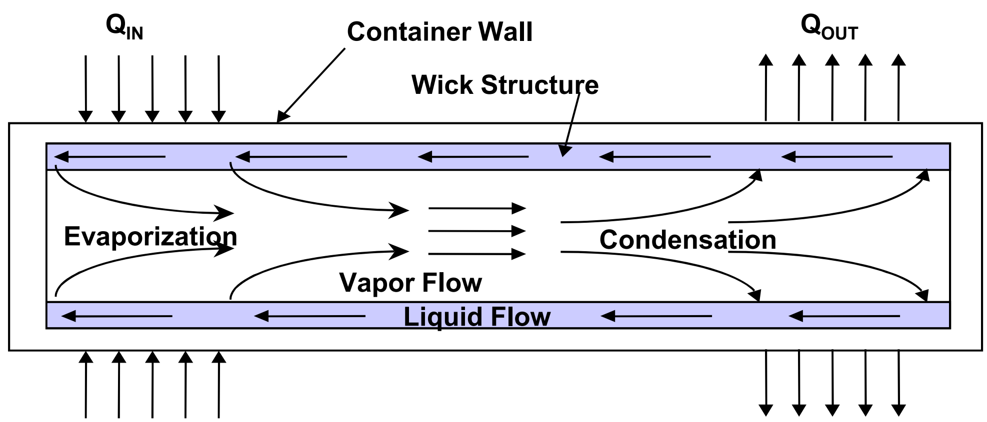


- **High pumping capability**
  - **Metal wicks with ~ 1 micron pores**
  - **35 kPa pressure head with ammonia (~ 4 meters in one-G)**
- **Robust operation**
  - **Vapor tolerant: secondary wick provides liquid from CC to evaporator**
- **Reservoir is plumbed in line with the flow circulation.**
  - **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**

Capillary Two-Phase Thermal Devices







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:

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

- The capillary pressure rise across the wick meniscus:

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

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

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

  r_p= radius of the largest pore in the wick

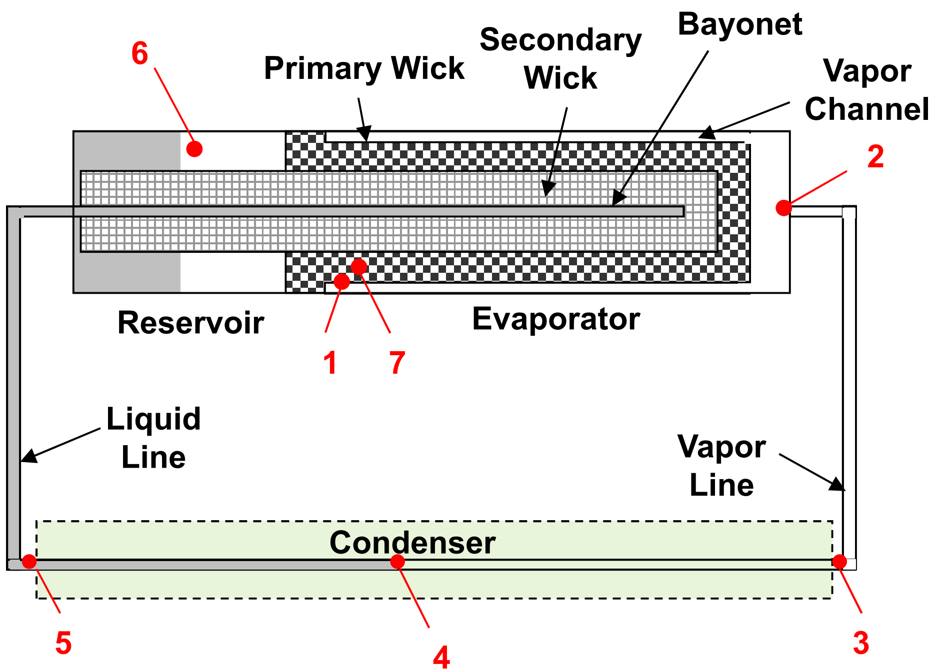
- The meniscus will adjust it radius of curvature so that the capillary pressure rise matches the total pressure drop which is a function of the operating condition:

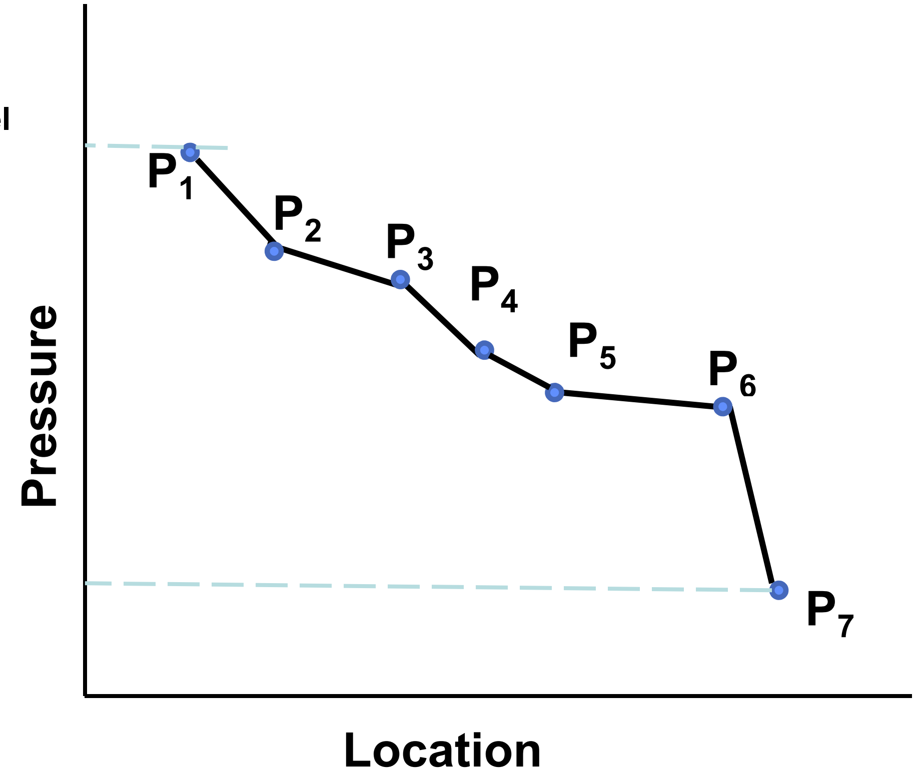
  $\Delta P_{cap} = \Delta P_{tot}$ (4)

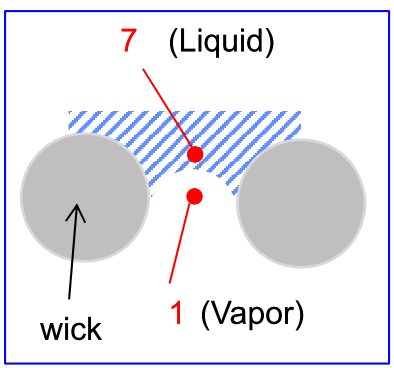
- The following relation must be satisfied at all times for proper LHP operation:

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

Pressure Profile in Gravity-Neutral LHP Operation
Capillary Force Driven



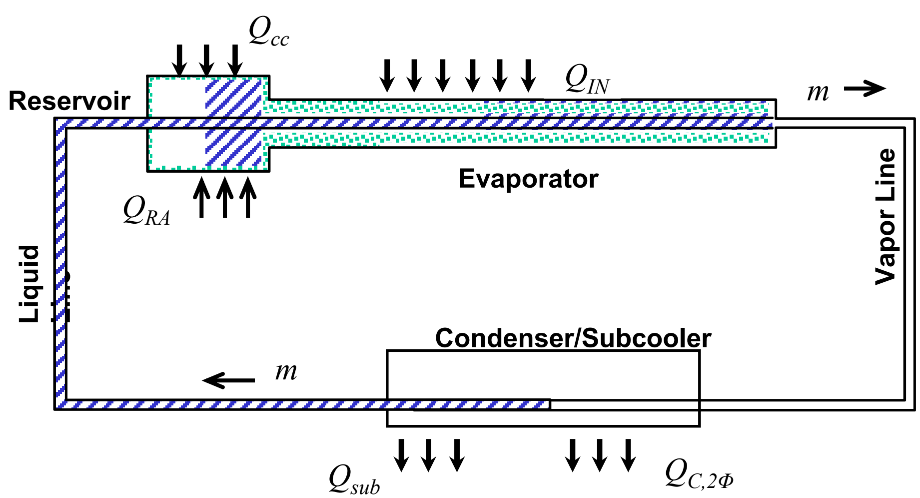


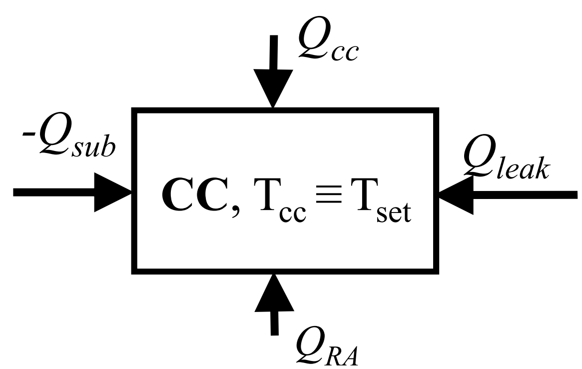


- Evaporator core is considered part of reservoir.
- P_6 is the reservoir saturation pressure.
- All other pressures are governed by P_6
- All pressure drops are viscous pressure drops.

LHP Operating Temperature

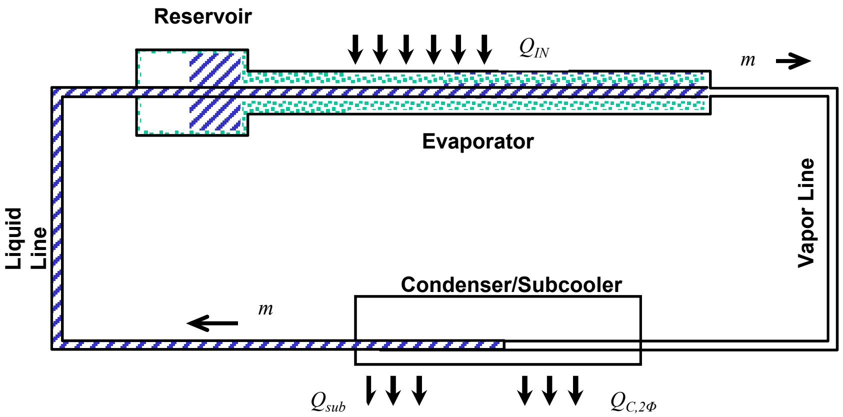
- The LHP operating temperature is governed by the CC saturation temperature.
- The CC temperature is a function of
  - Evaporator power
  - Condenser sink temperature
  - Ambient temperature
  - Evaporator/CC assembly design
  - Heat exchange between CC and ambient
- As the operating condition changes,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

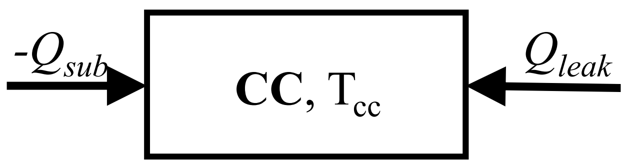


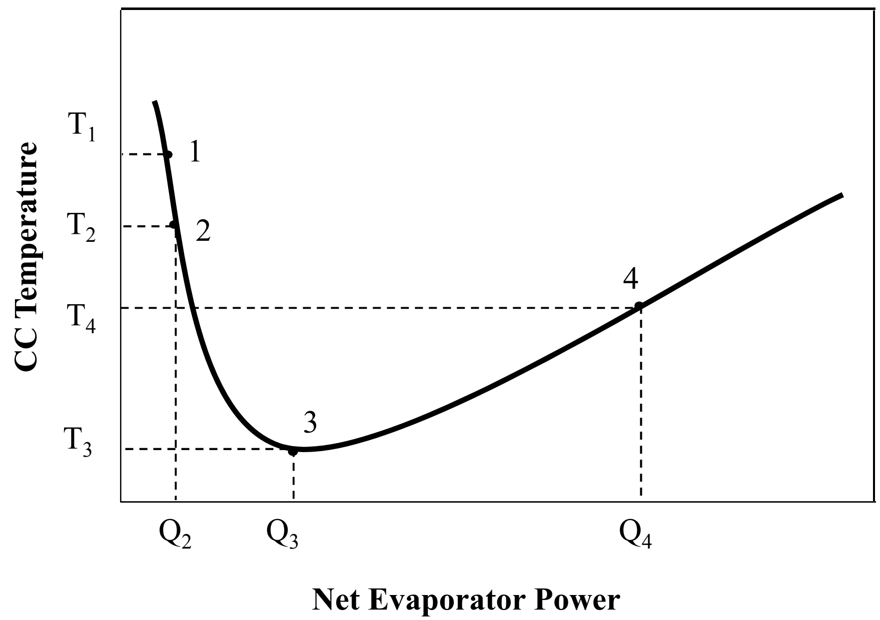


$$Q_{leak} - Q_{sub} + Q_{cc} + Q_{RA} = 0$$

LHP Natural Operating Temperature
No Active Control of CC Temperature







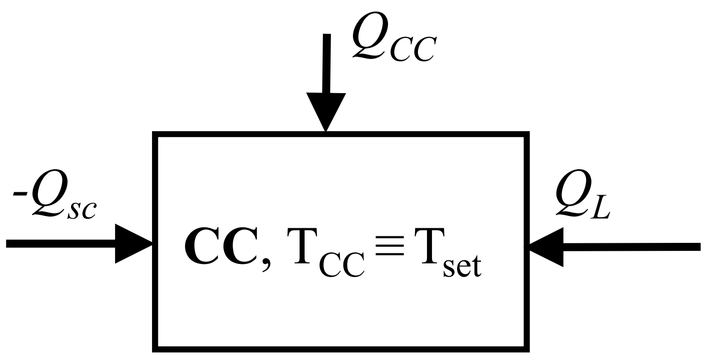
$$Q_{leak} - Q_{sub} = 0$$

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

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

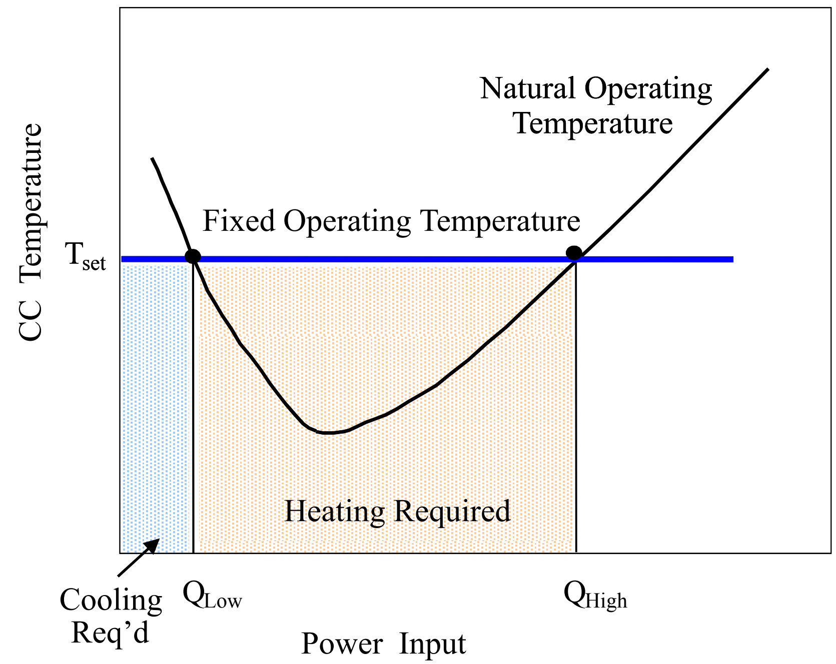
- **For a well insulated CC, T_{cc} is determined by energy balance between heat leak and liquid subcooling.**
- **T_{cc} changes with the evaporator power, condenser sink temperature, and ambient temperature.**

LHP Operating Temperature
CC Temperature Controlled at T_{set}



$$Q_L - Q_{sc} + Q_{cc} = 0$$

$$Q_{cc} = Q_{sc} - Q_L$$

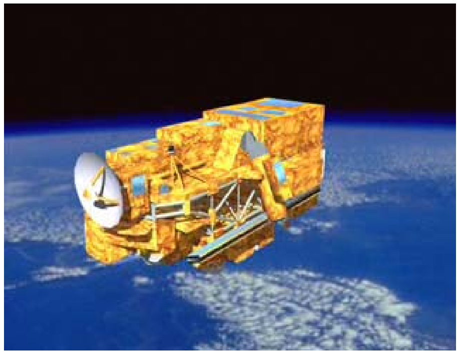


- CC is cold biased, and electrical heaters are commonly used to maintain T_{cc} at T_{set}.
- Q_{CC} varies with Q_{sc}, which in turns varies with evaporator power, condenser sink temperature, ambient temperature and number of coupling blocks.
- Electrical heaters can only provide heating, not cooling,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

LHP Temperature Control Methods

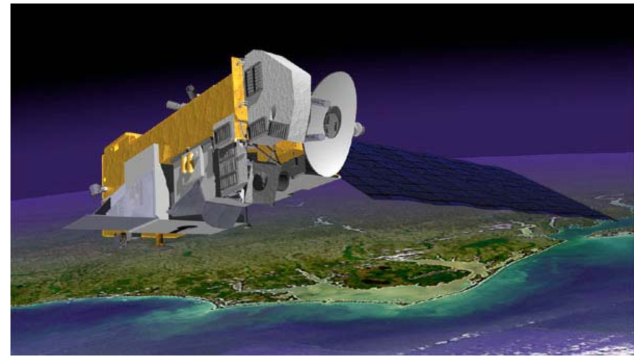
- All methods involve cold-biasing the CC and use external heat source to maintain CC temperature
  - Electric heater on CC only (Aura TES, GOES-R GLM)
  - Electric heater on CC and coupling blocks placed between vapor and liquid lines (ICESat GLAS)
  - Electric heater on CC and VCHP connecting the evaporator 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)

CPL and LHP Flight Applications – NASA Spacecraft

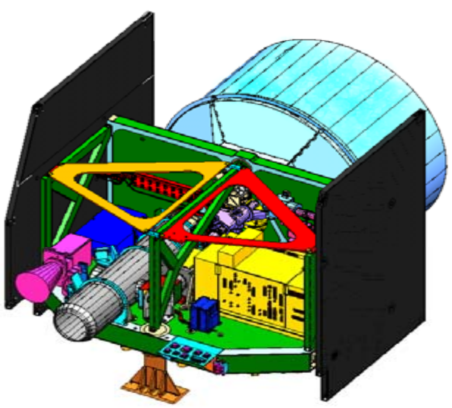


TERRA, 6 CPLs
Launched Dec 1999

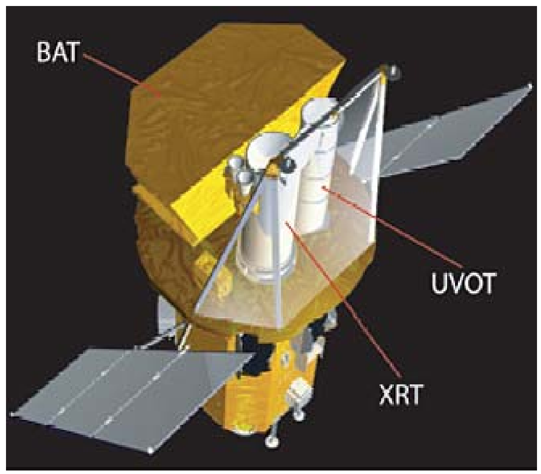
HST/SM - 3B; 1 CPL
Launched Feb 2002



AURA, 5 LHPs
Launched July 2004



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



SWIFT, 2 LHPs
Launched Nov 2004

GOES N-Q, 5 LHPs each
Launched 2006

CPL and LHP Flight Applications – NASA Spacecraft

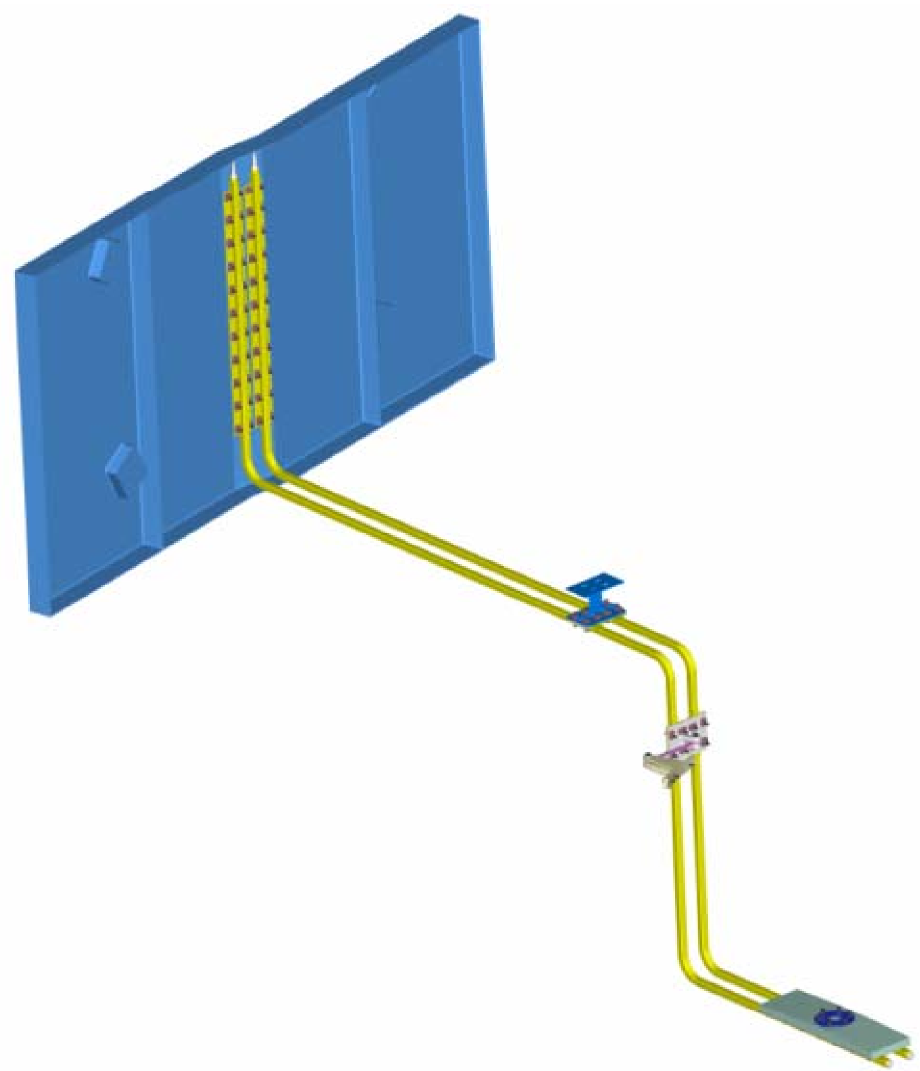
GOES R-U, 4 LHPs each
To be launched

ICESat-2, 1 LHP
To be launched

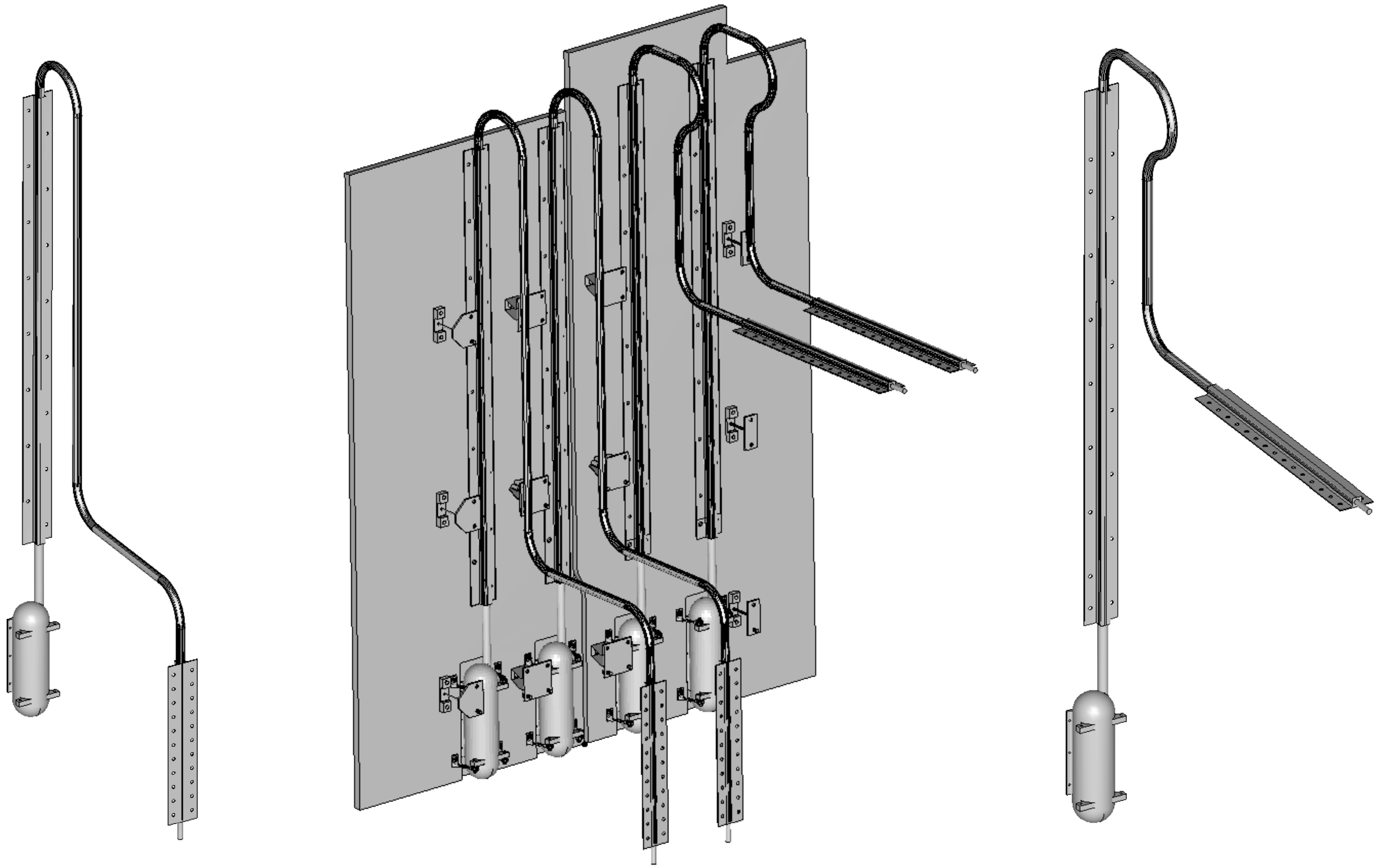
SWOT, 4 LHPs
To be launched

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

Swift XRT Ethane Heat Pipes



Orbiting Carbon Observatory–2 (OCO-2) VCHPs

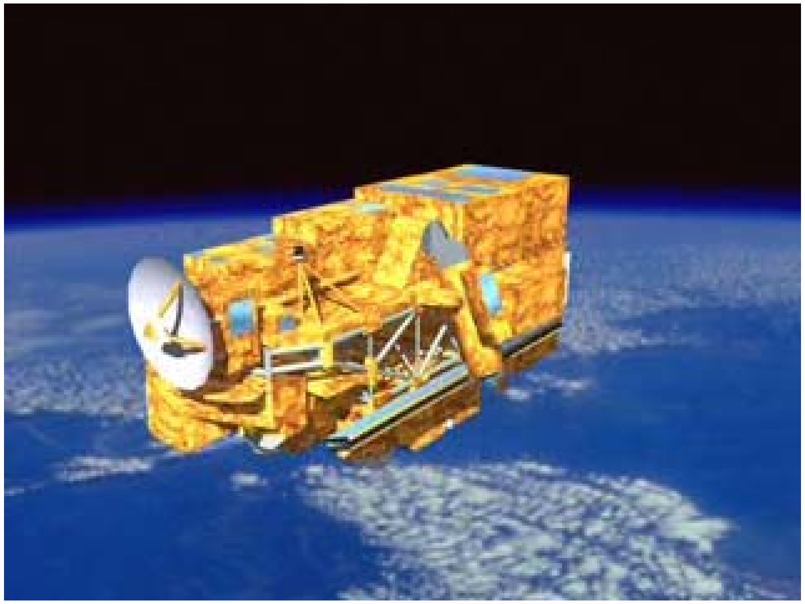


Terra CPLs

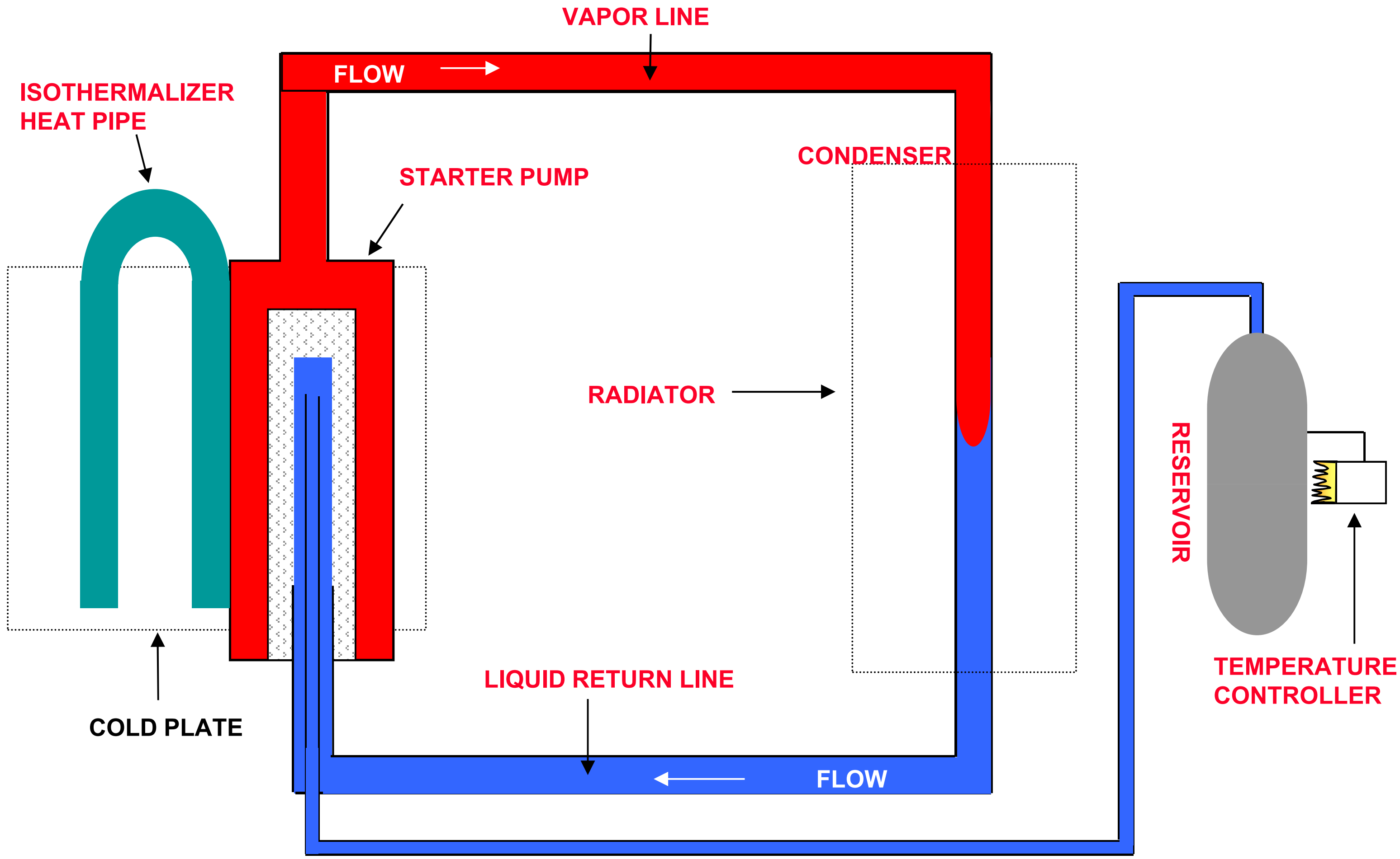
- Over 16 years of successful on-orbit operations

- **Terra launched 12/1999**

- **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**
- **Nominal operations continue**

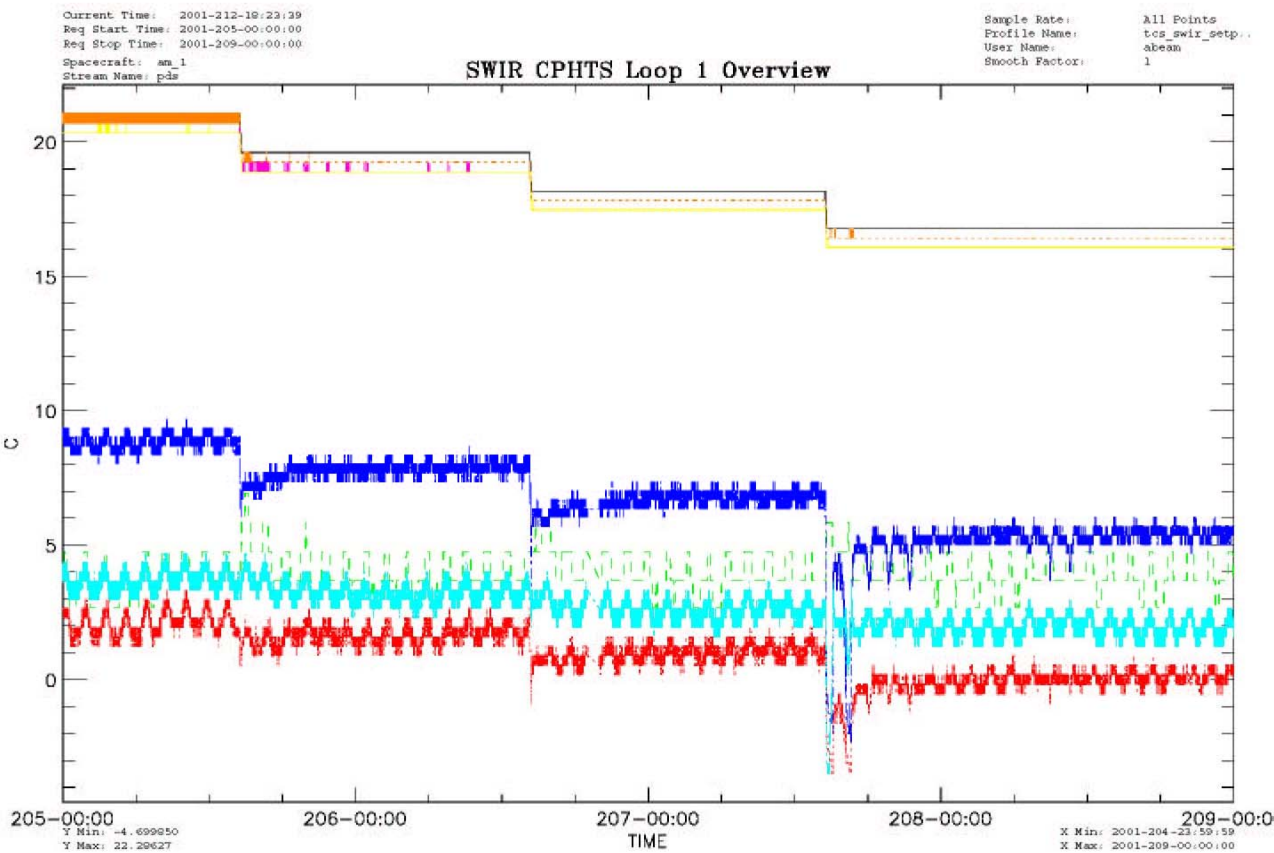


Terra CPL Flow Schematic



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 ^{0}C in 3 steps**



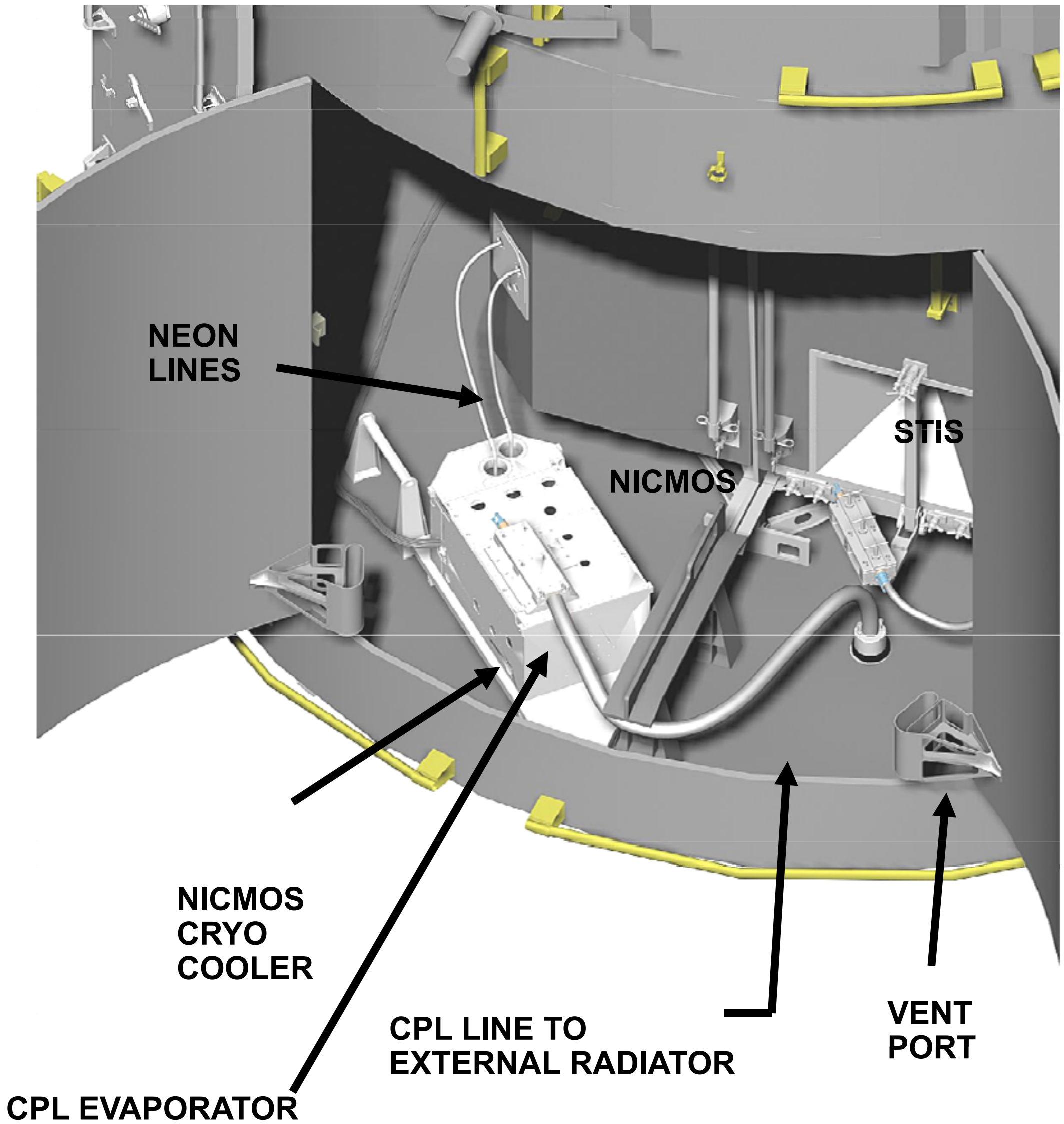
MNEMONIC NAME	E/R	Y-Offset	S/C	SAMPLES	MINIMUM	MAXIMUM	AVERAGE	STD DEV	DESC.
TCS_TR_S_CPPUMP1_MID................	EU			41749	16.779	21.060	18.485	1.5413	SWIR Loop 1 Pump Middle T [C].
TCS_TR_S_LIQLIN1_IN................	EU			41749	-3.4732	3.3144	0.89767	0.99447	SWIR Loop 1 Pump Liquid I [C].
TCS_TR_S_RADSURF_HX1................	EU			5218	2.6645	6.9409	3.9867	0.71790	SWIR Radiator Surface HPH [C].
TCS_TR_S_RESLIN1_IN................	EU			41749	-2.3568	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_FLX................	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

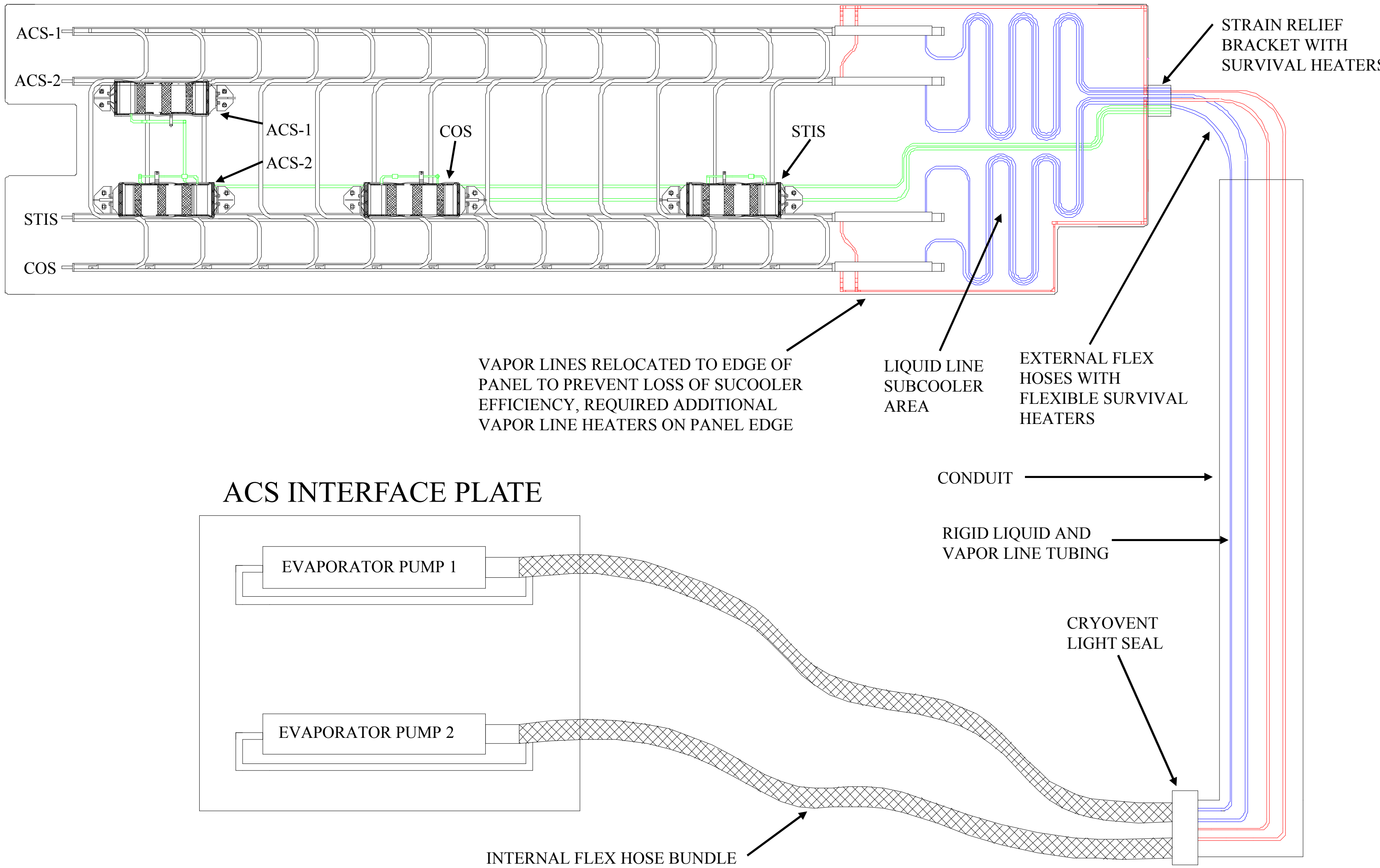
CPL on HST/SM-3B

STS-108, Feb/2002

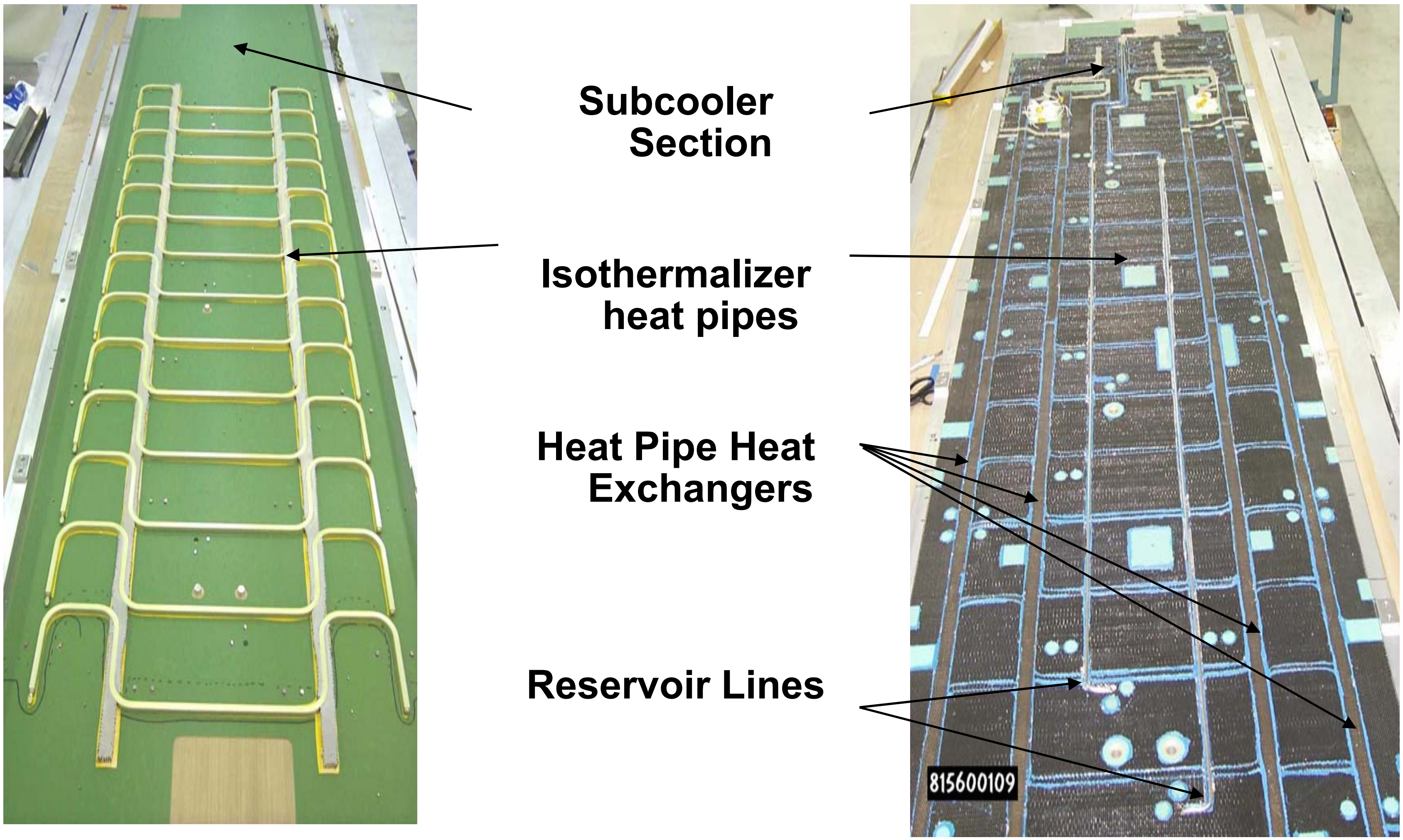


- CPL was added to HST Aft Shroud on SM-3B
- Astronauts fed CPL evaporator through bottom of shroud, attached it to cryo-cooler, and attached new radiator to handrails.
- CPL removes ~ 400 W heat from NICMOS cryocooler which allows the NICMOS sensor to be reactivated.
- Tight temperature control

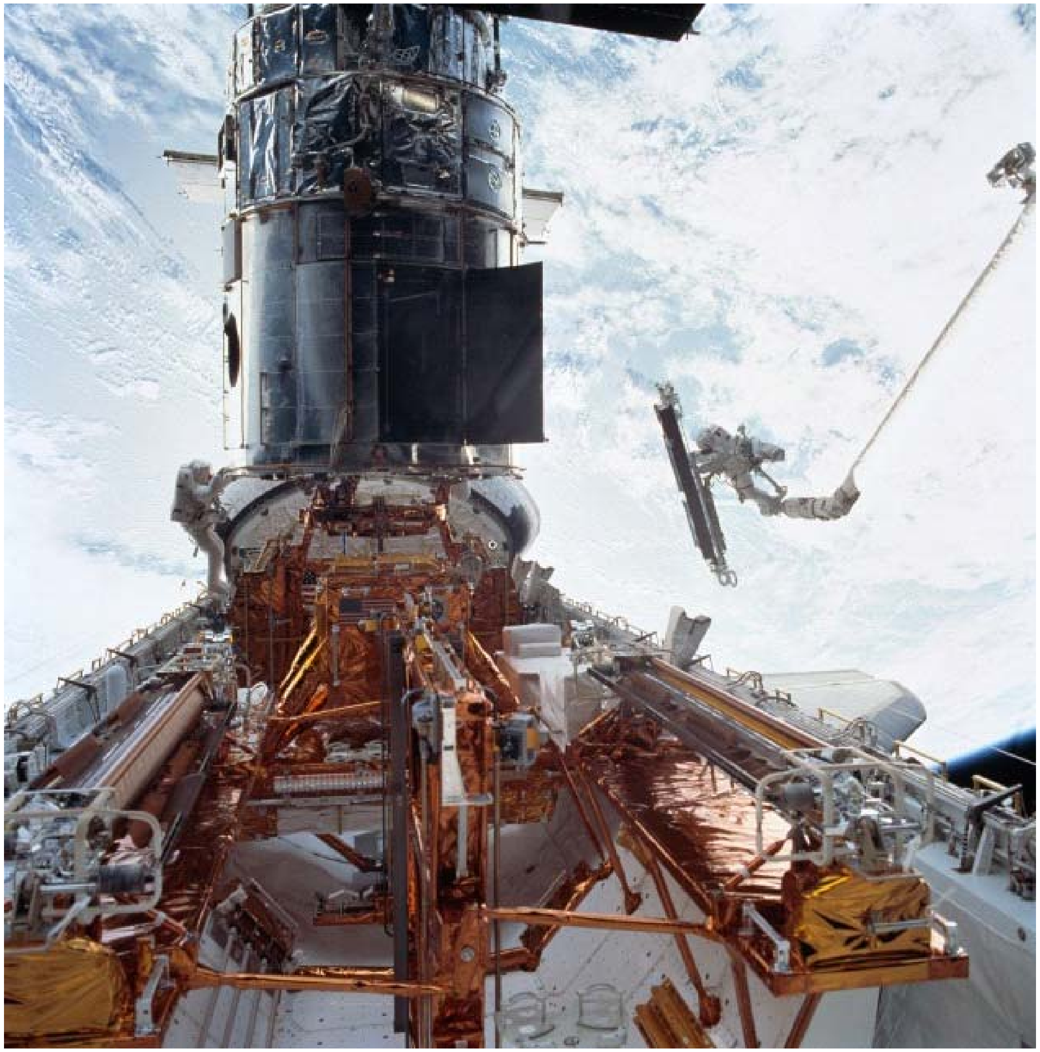
HST ACS CPLs and ASCS Radiator Design



HST CPL/HP Radiator Assembly

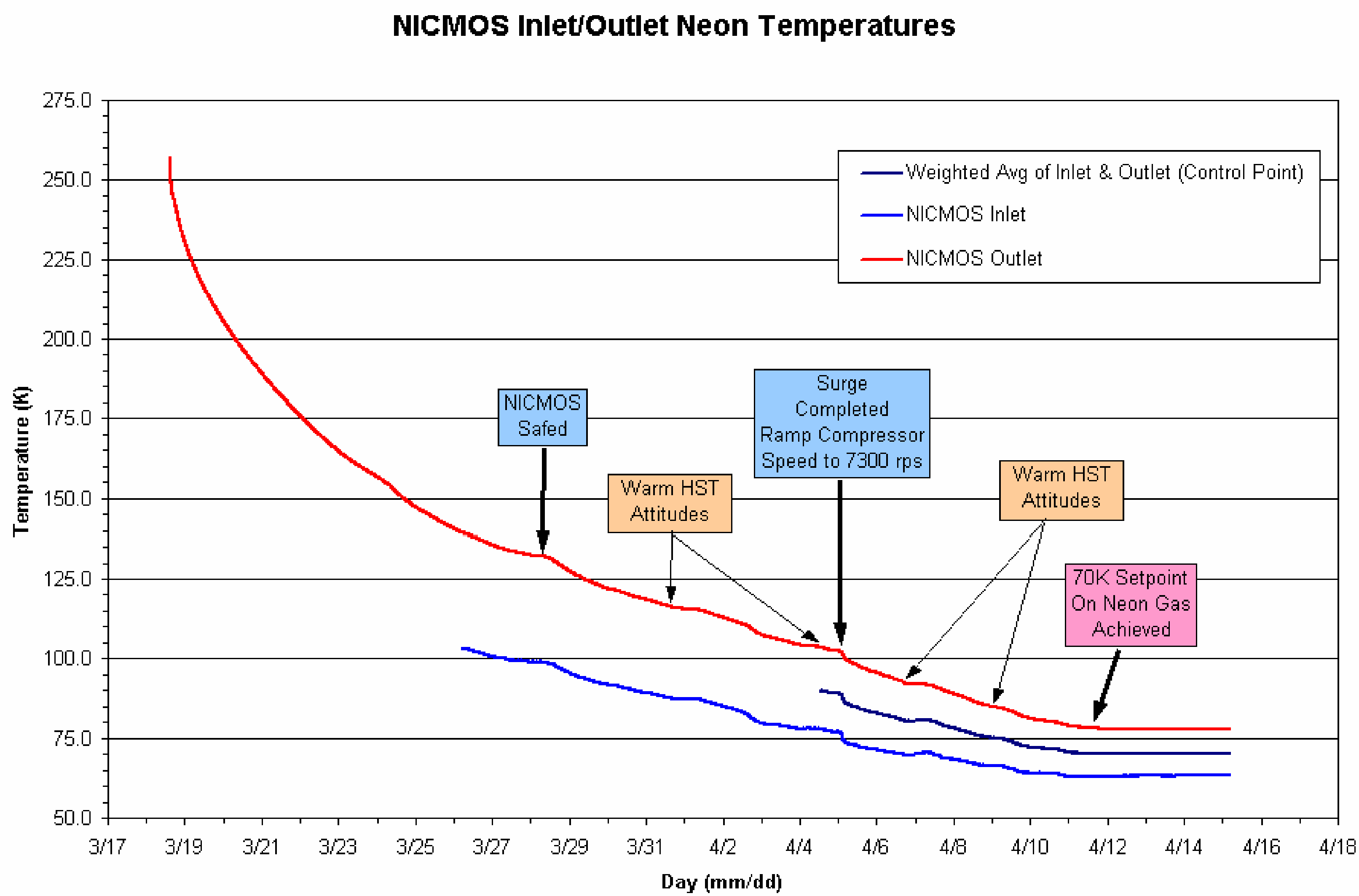


CPL on HST

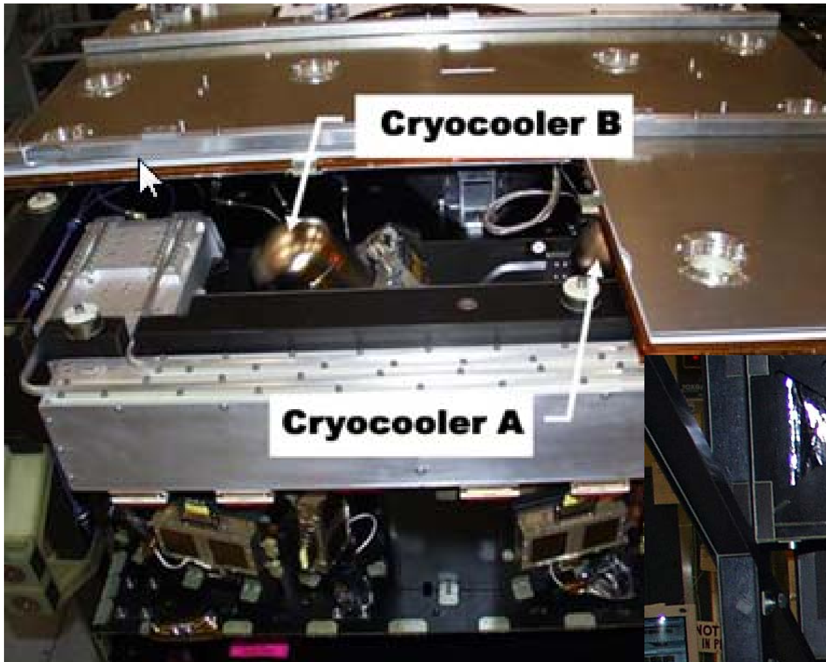


The loop was fully charged and integrated with the radiator on the ground, and was installed to the HST by the astronaut

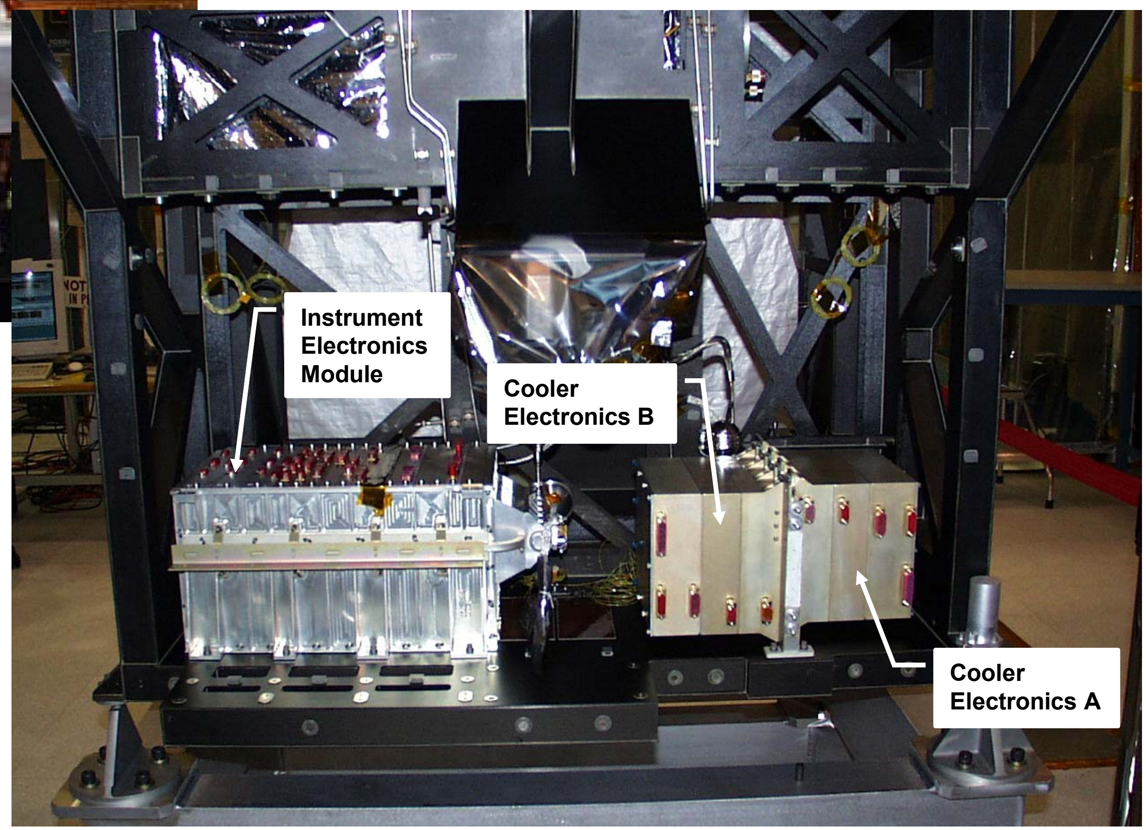
HST NICMOS Temperatures



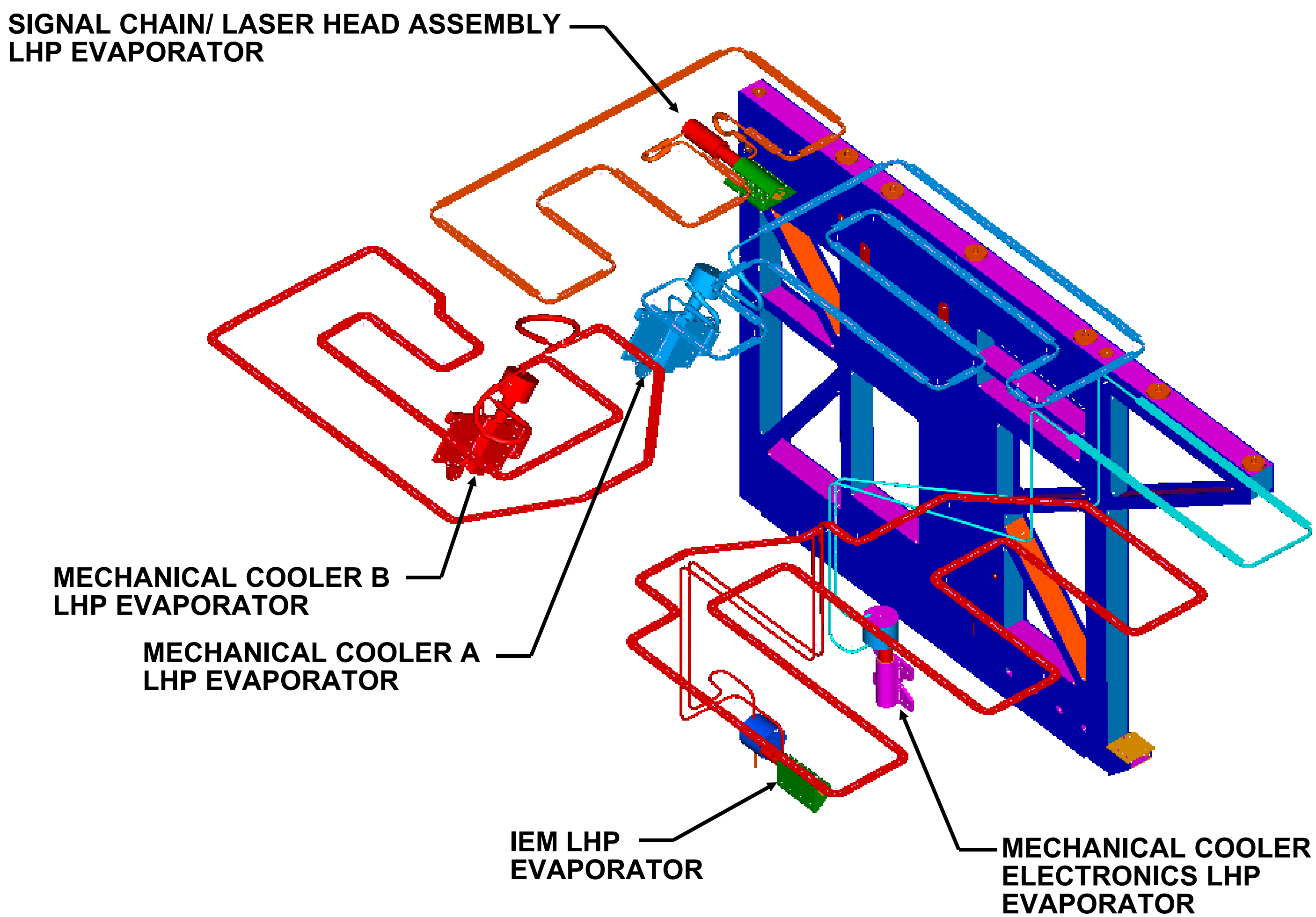
Tropospheric Emission Spectrometer (TES)



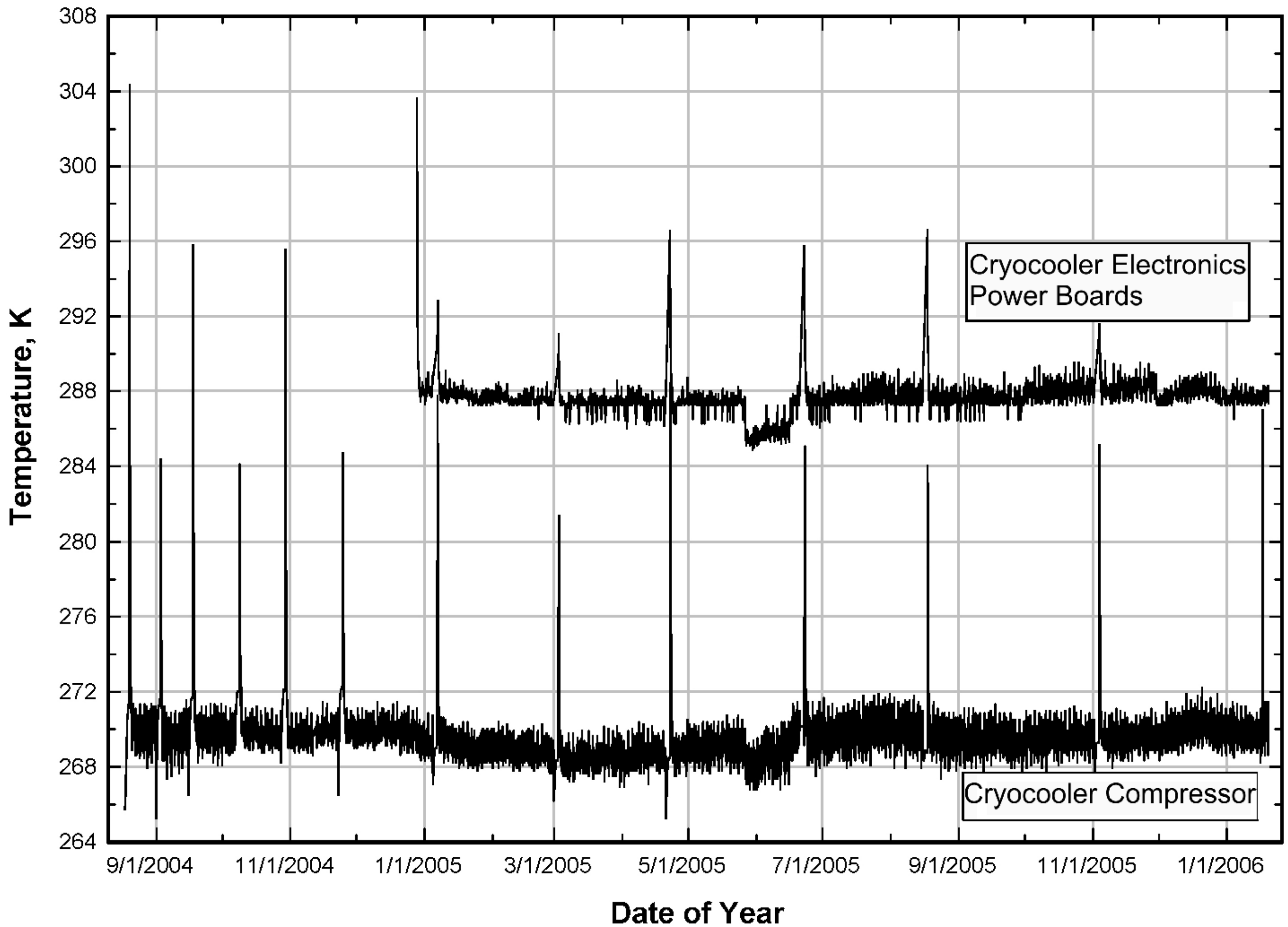
- CCHPs and LHPs manage equipment power dissipation from:
  - 2 Mechanical Cooler Compressors
  - Cooler electronics
  - Signal Chain and Laser Head electronics
  - Integrated Electronics Module (IEM)



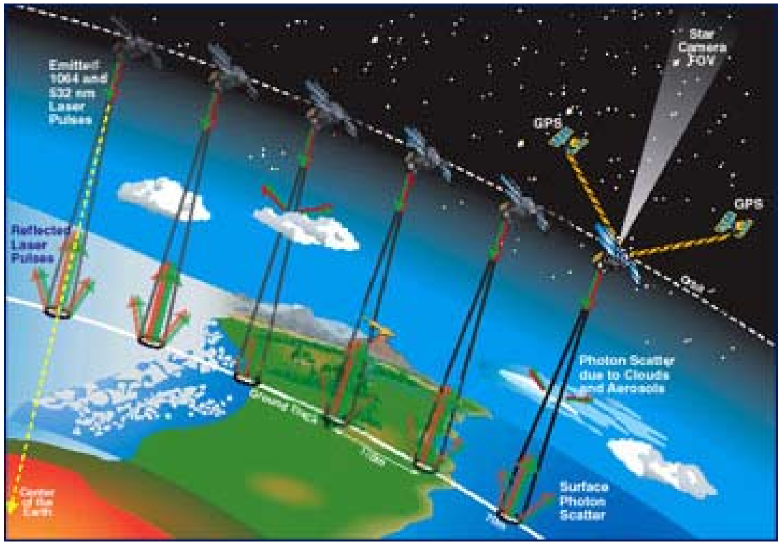
EOS-Aura TES Instrument Loop Heat Pipe Layout

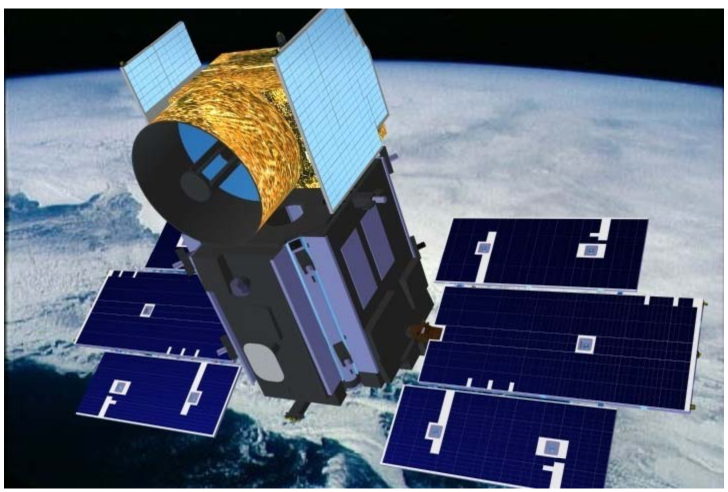


EOS-Aura TES Components Thermal Performance

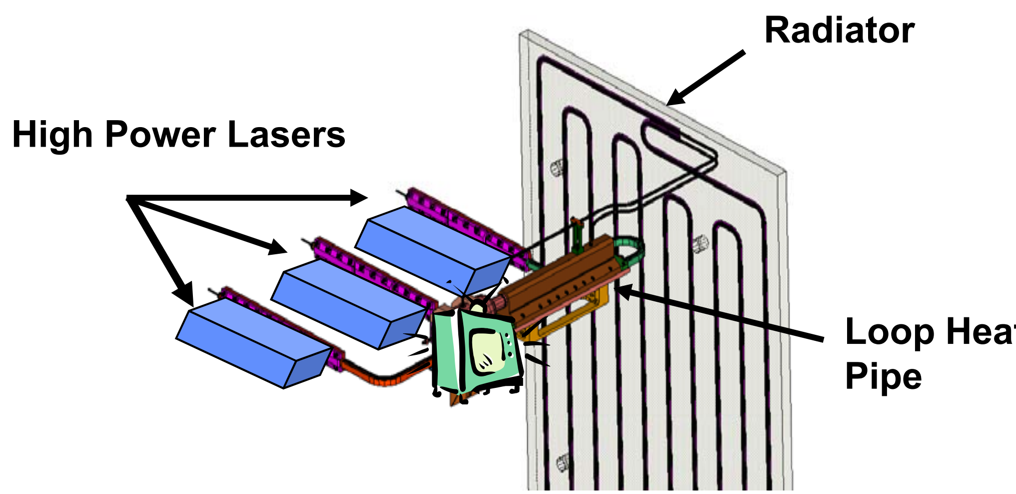


LHPs on ICESat



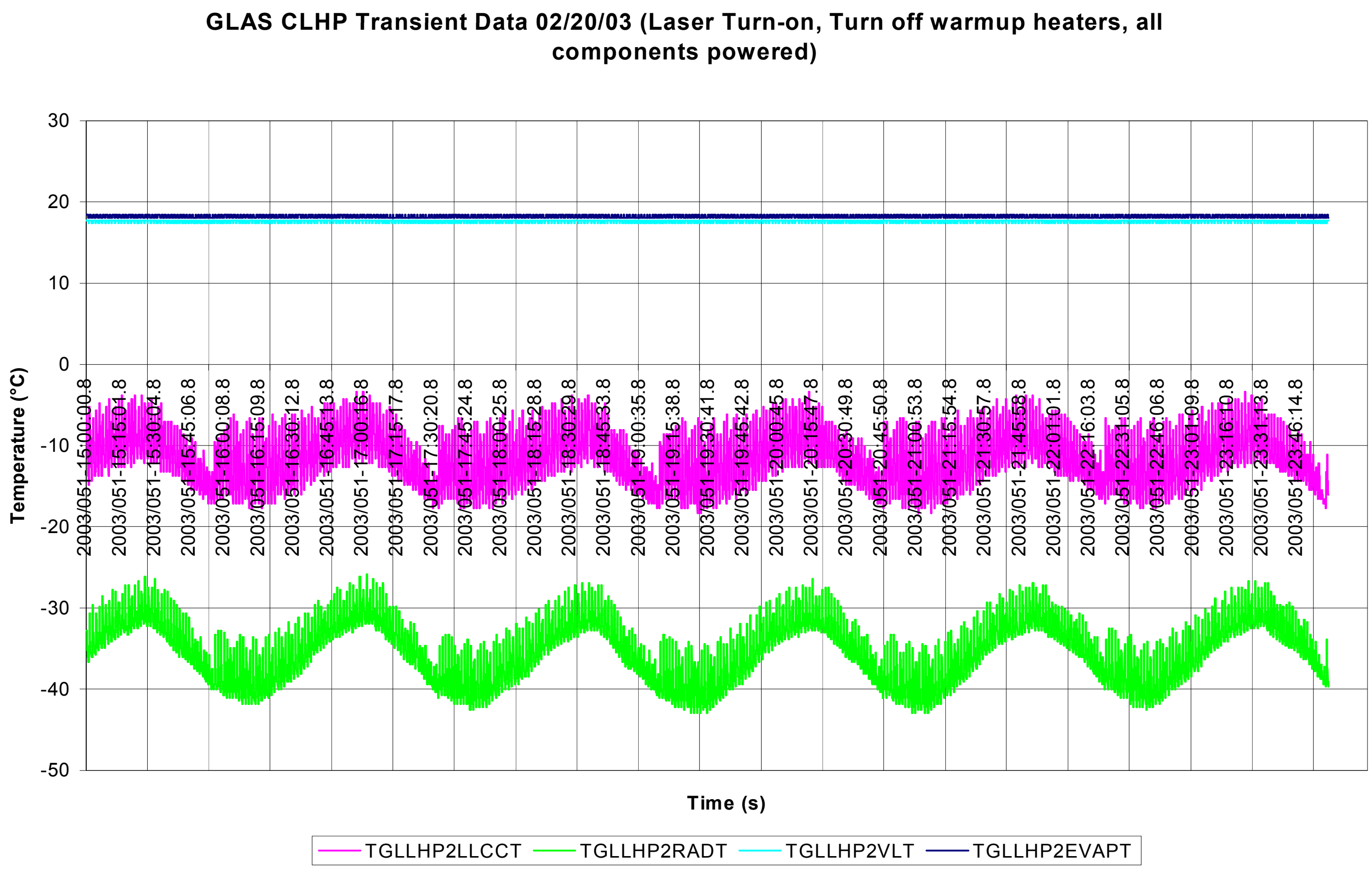


- GLAS has high powered lasers to measure polar ice thickness
- First known application of a two-phase loop to a laser
- 2 LHPs; Laser altimeter and power electronics
  - Propylene LHPs
- Launched January, 2003
- Both LHPs successfully turned on
- Very tight temperature control ~ 0.2 ^{o}C



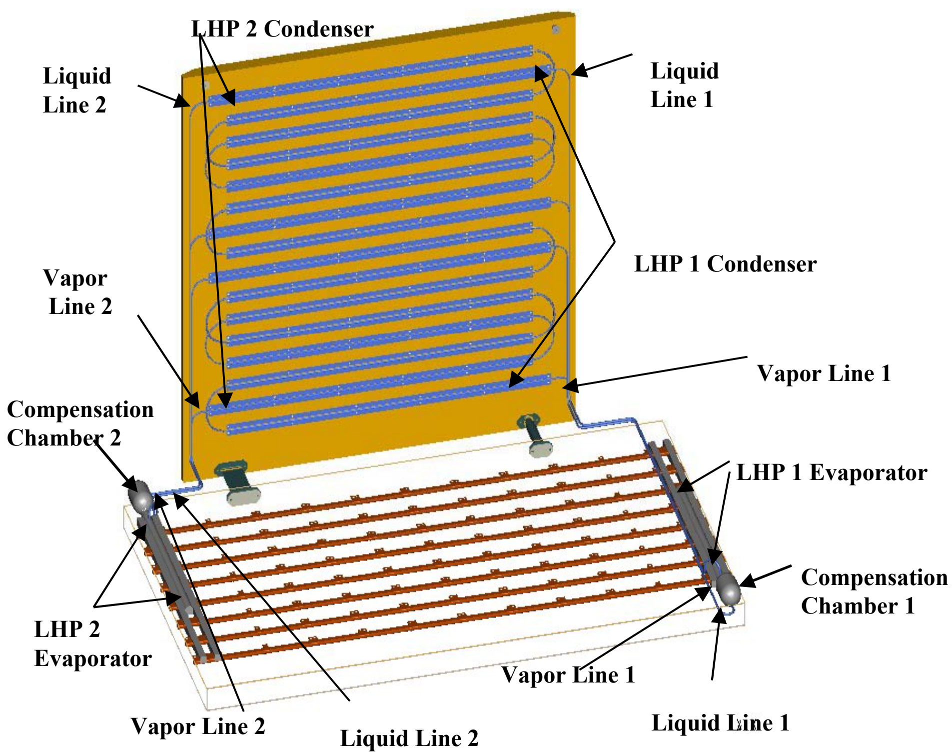
GLAS Laser Temperatures

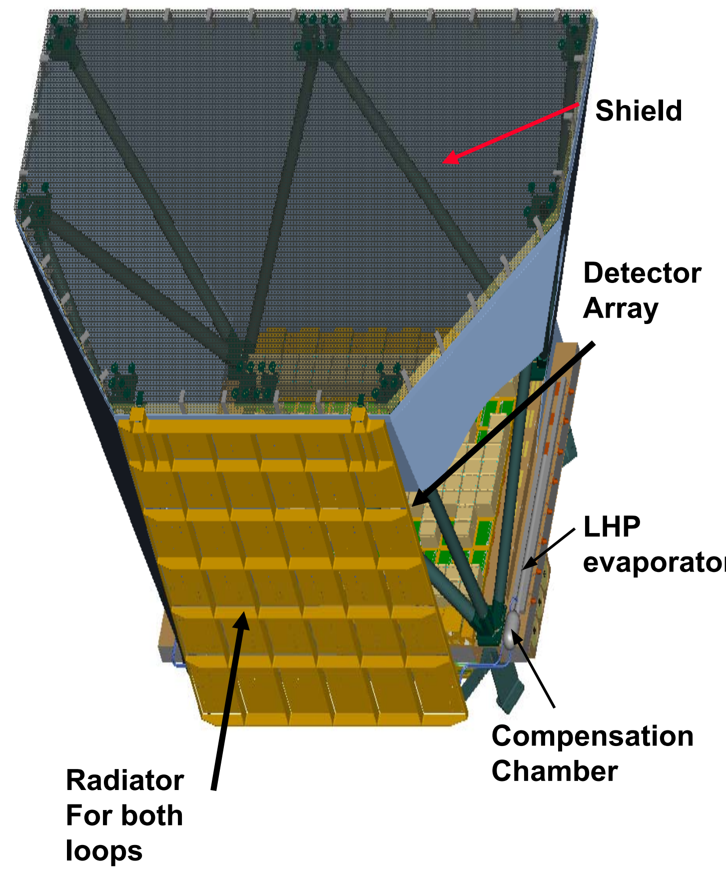
- **LLHP active control is finer than can be measured in the laser telemetry when the LHP is at full 110 W of power**



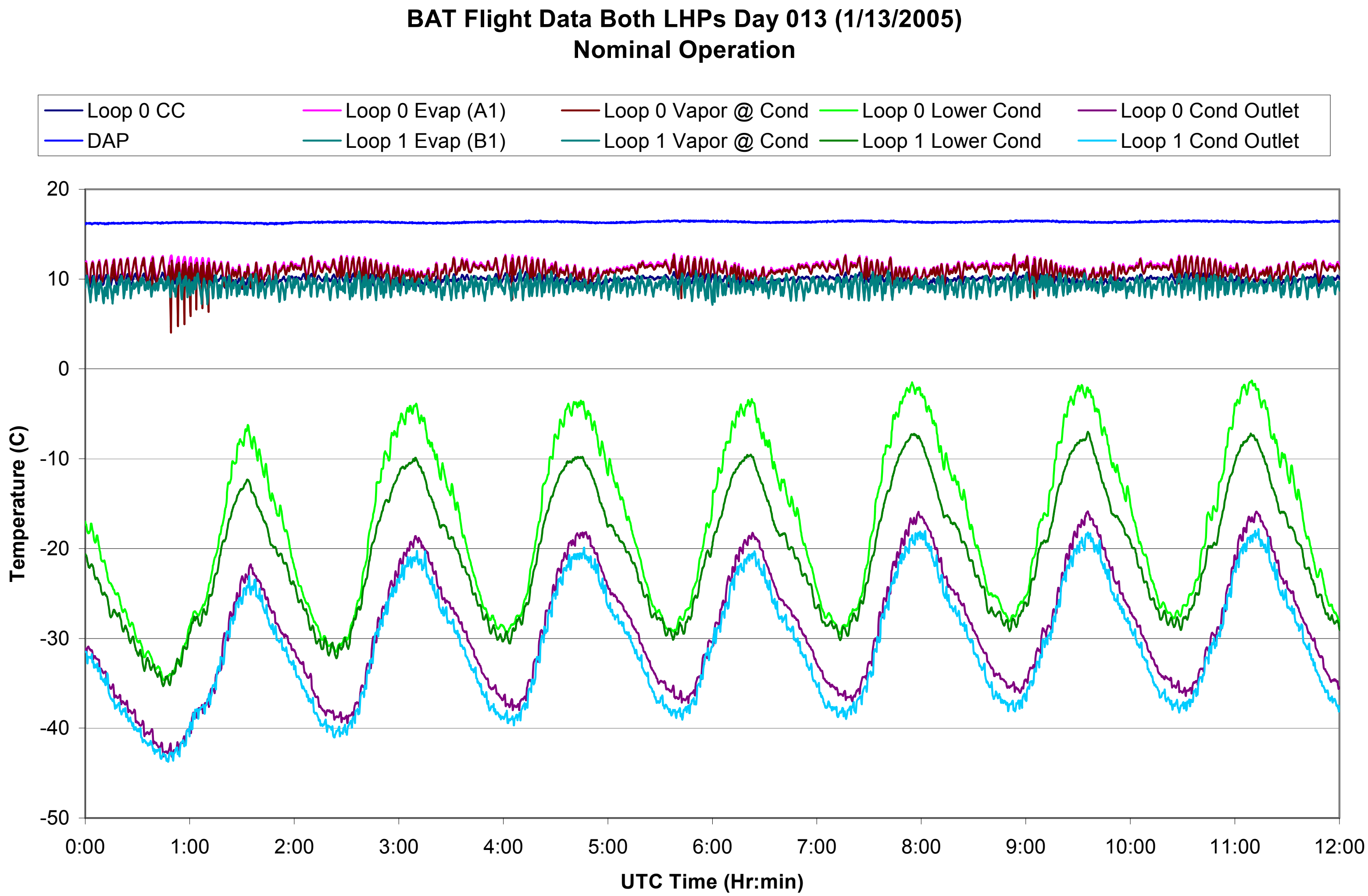
CCHPs/VCHPs/LHPs on SWIFT ABT

- **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**



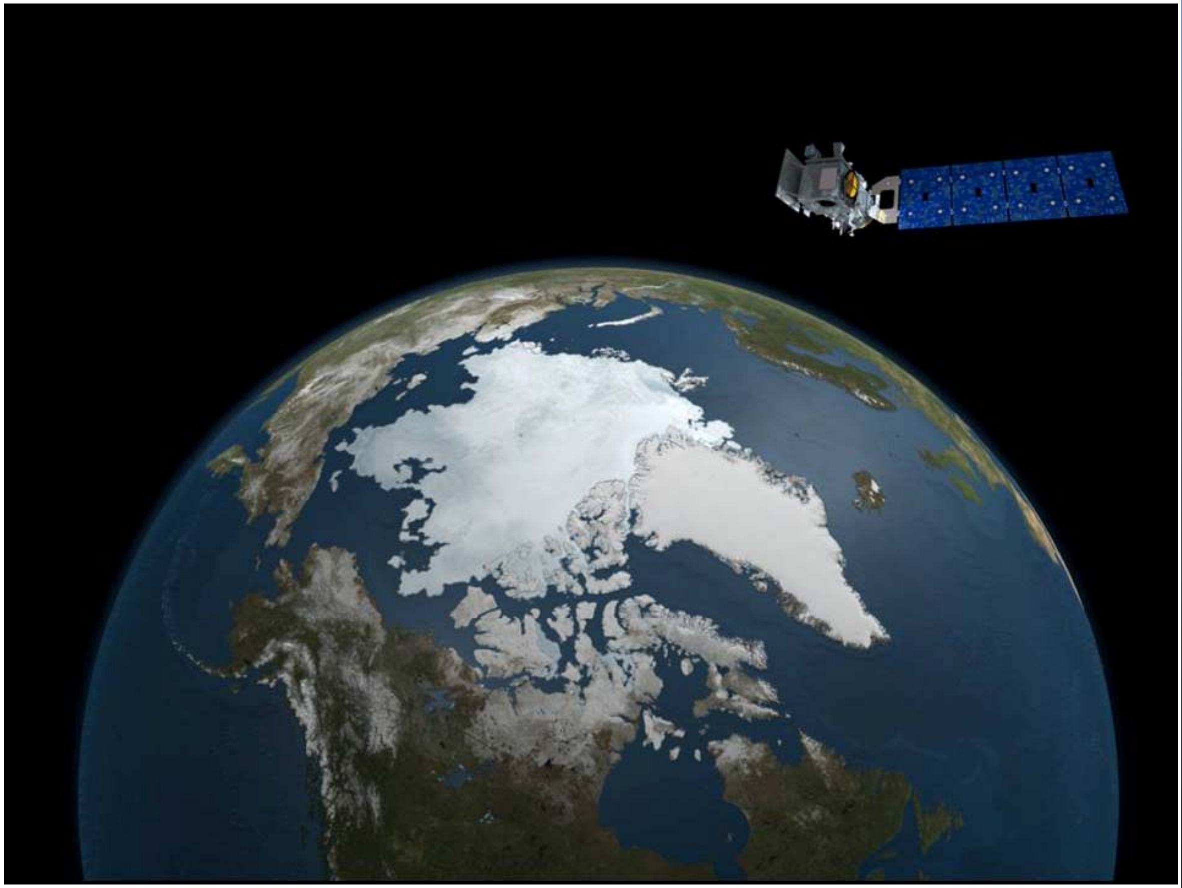


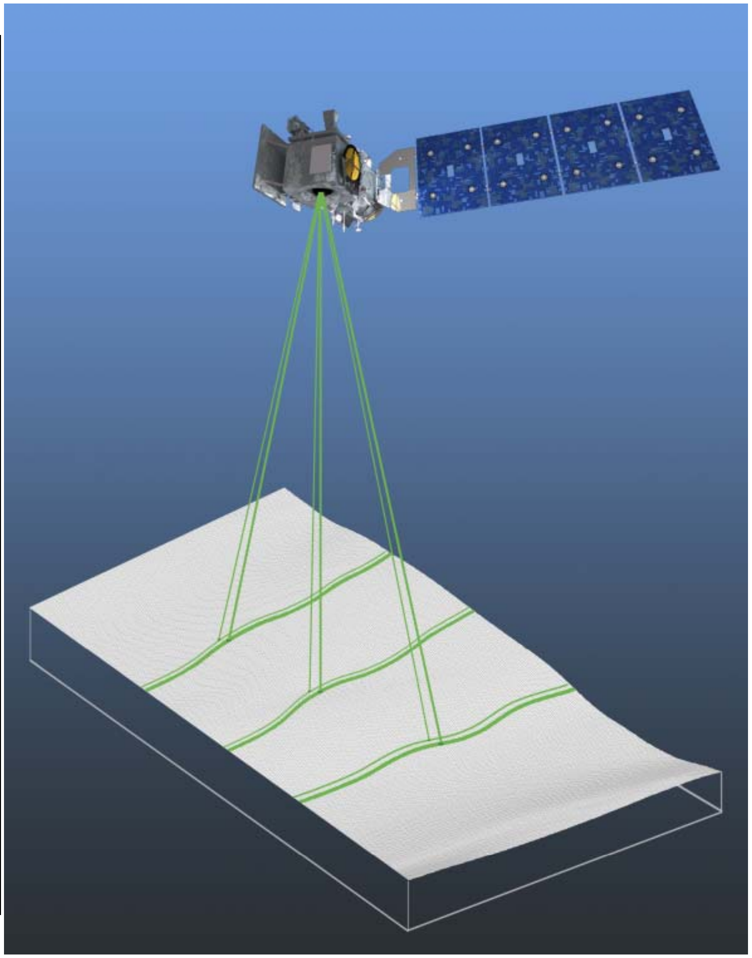
Swift BAT VCHPs and LHPs



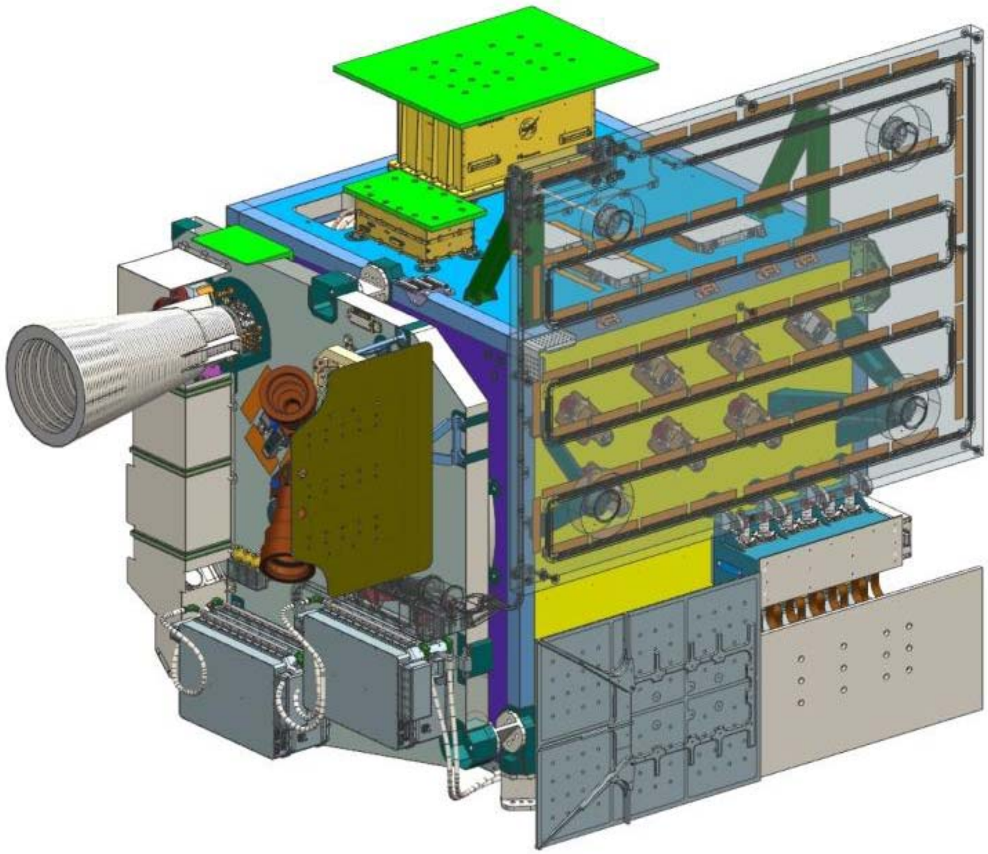
- **Temperature fluctuations of detectors < 0.4 ^{0}C**
- **Frequent spacecraft slews have no noticeable effect on LHP operation.**
- **Flight results verify satisfactory operation of dual LHPs for tight temperature control.**

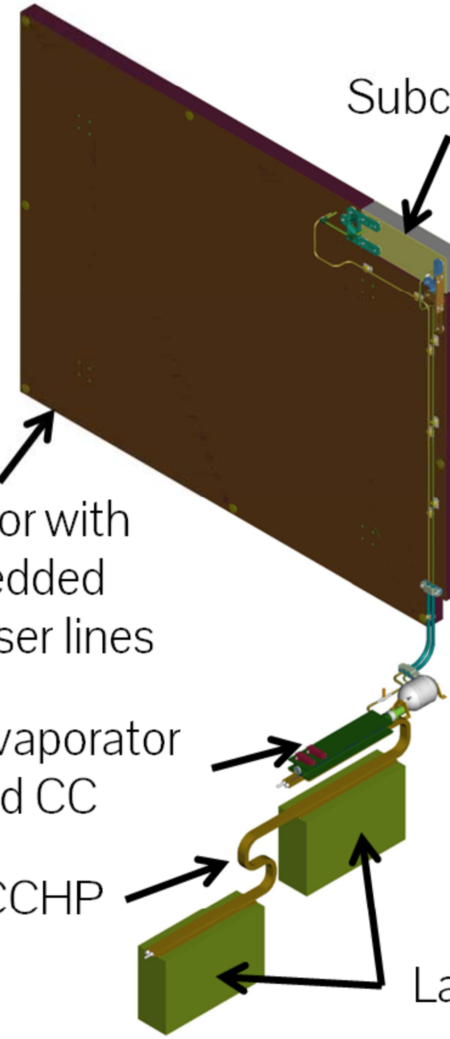
ICESat -2 (Ice, Cloud, and land Elevation Satellite - 2)

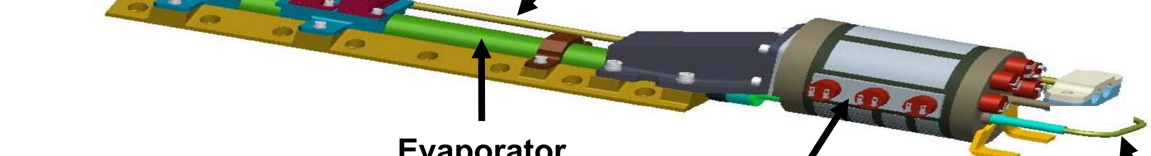




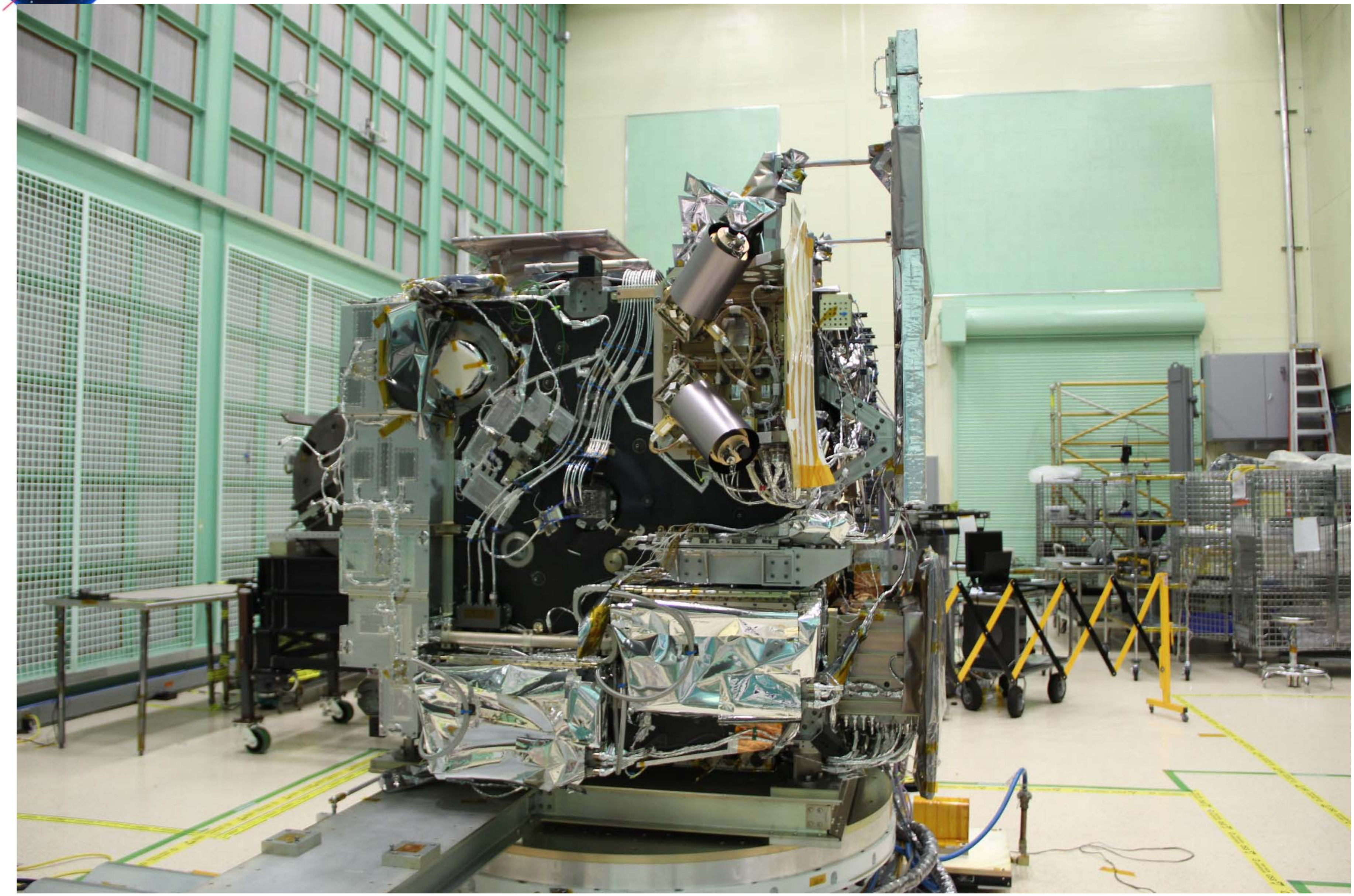
HPs and LHPs on IceSat-2 ATLAS LTCS



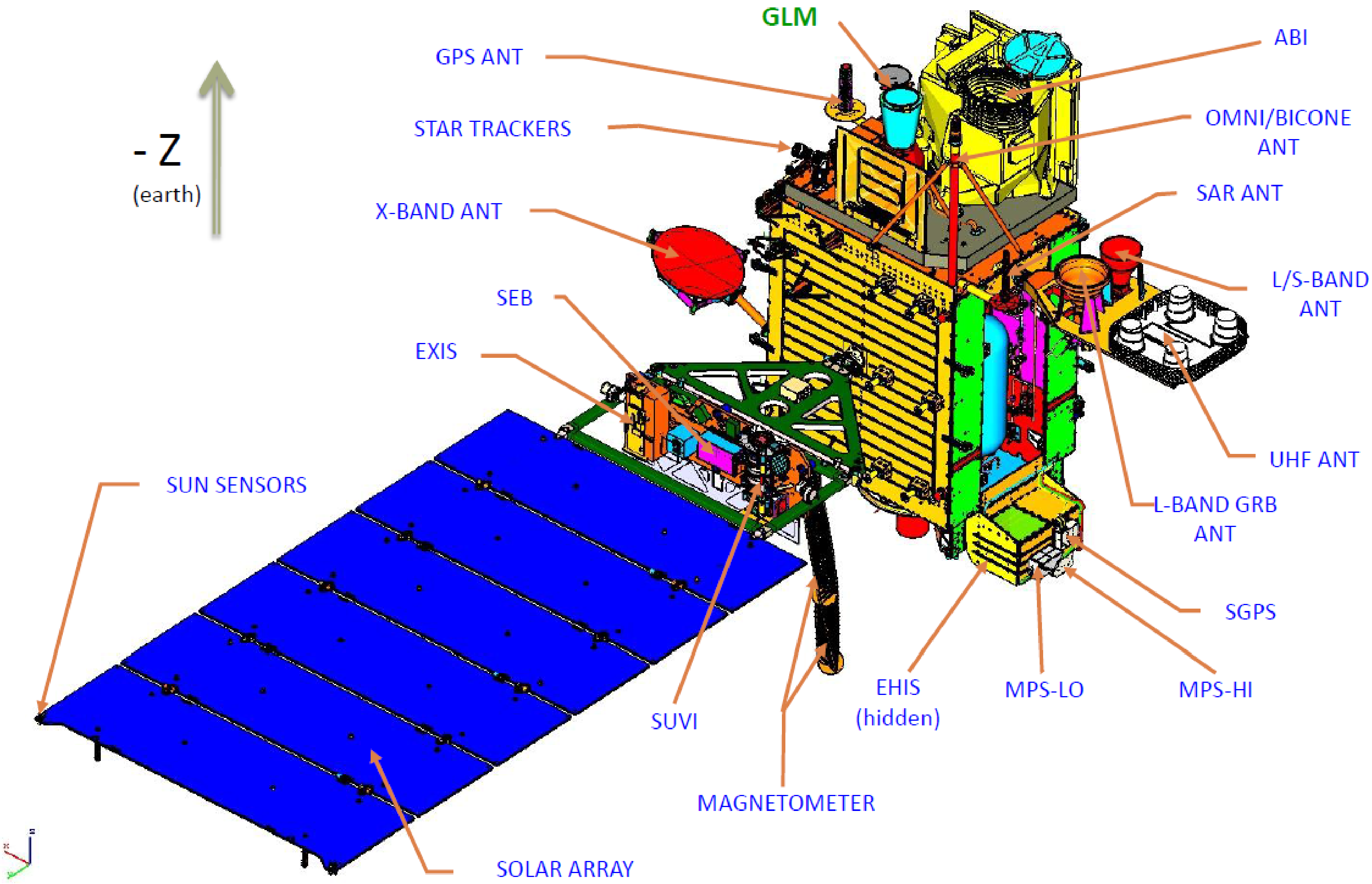




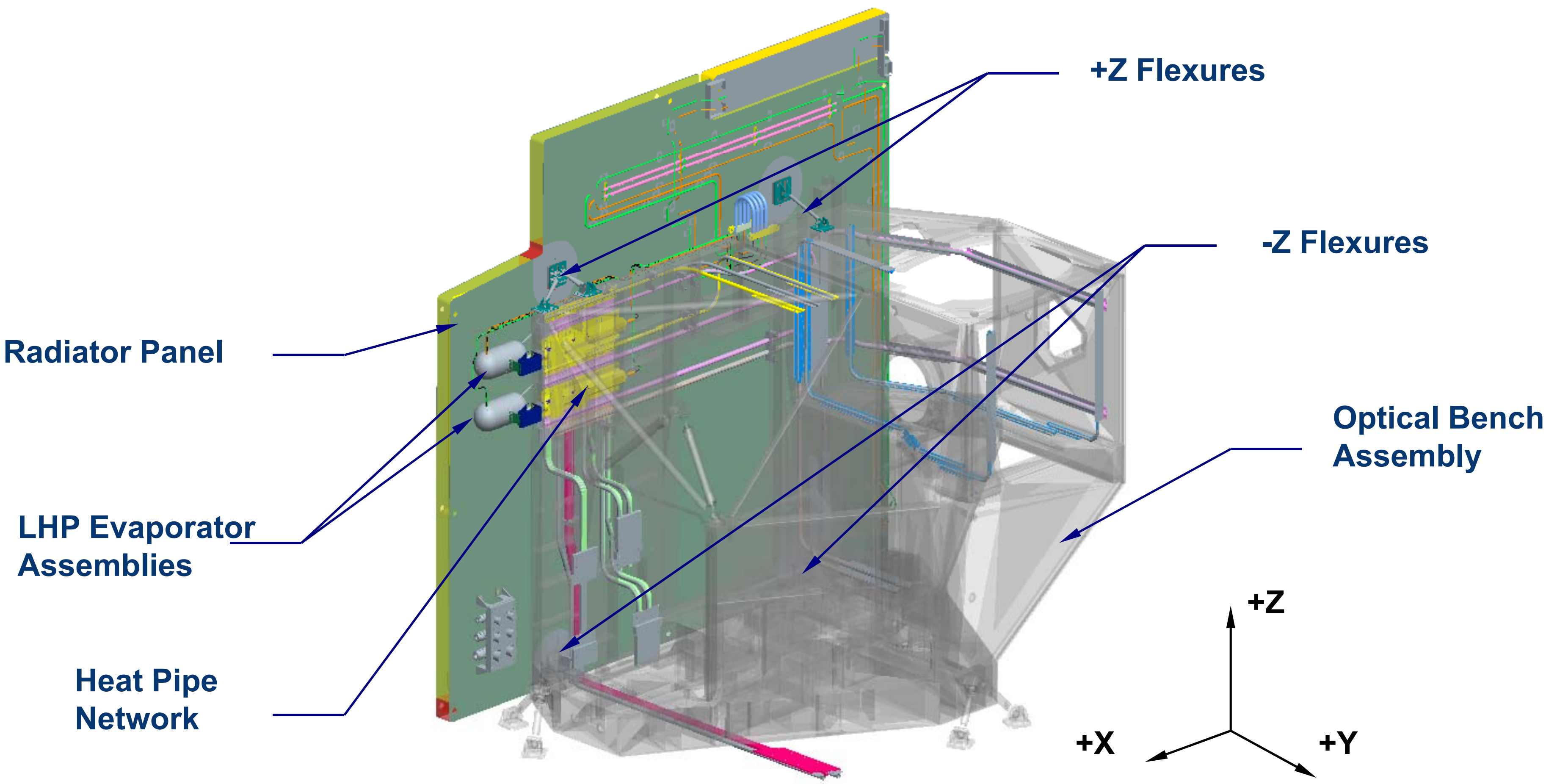
IceSat-2 ATLAS Instrument Flight Hardware



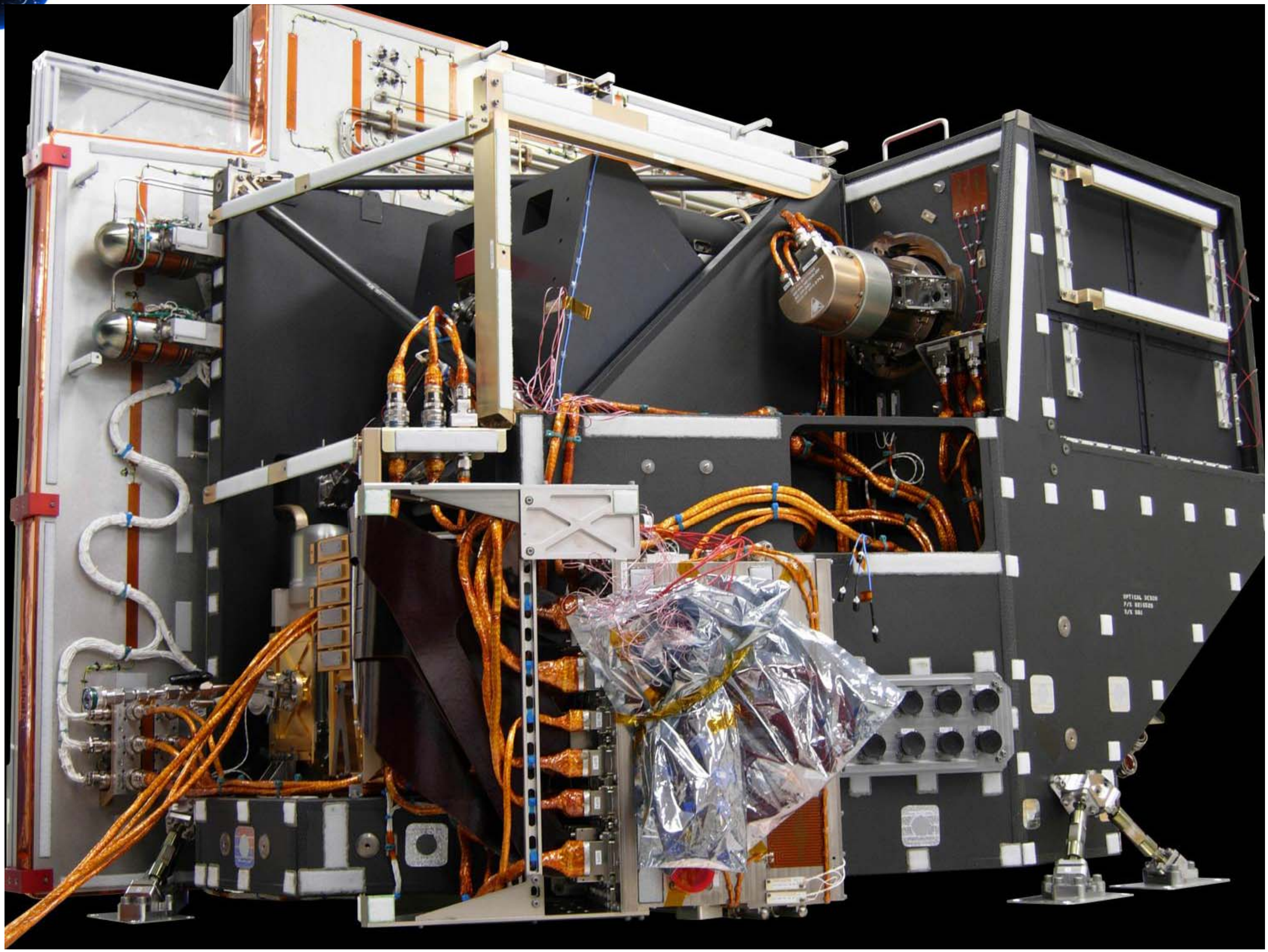
GOES-R Spacecraft Layout



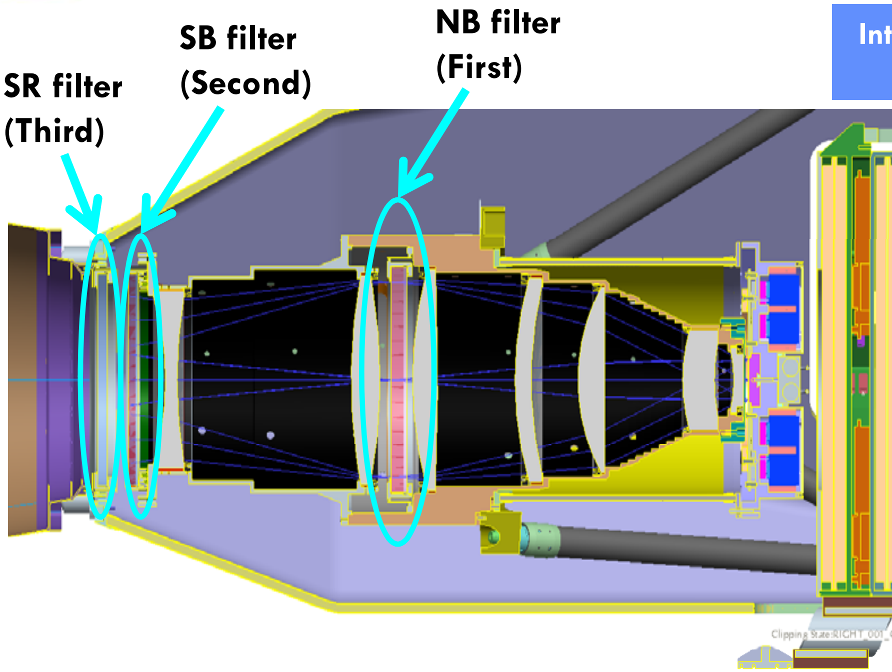
GOES-R ABI HPs/LHPs Assembly

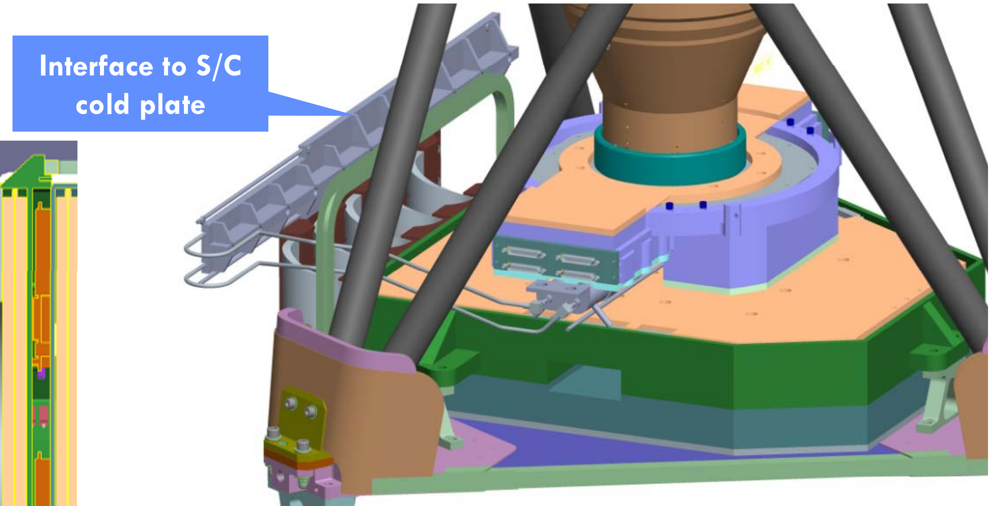


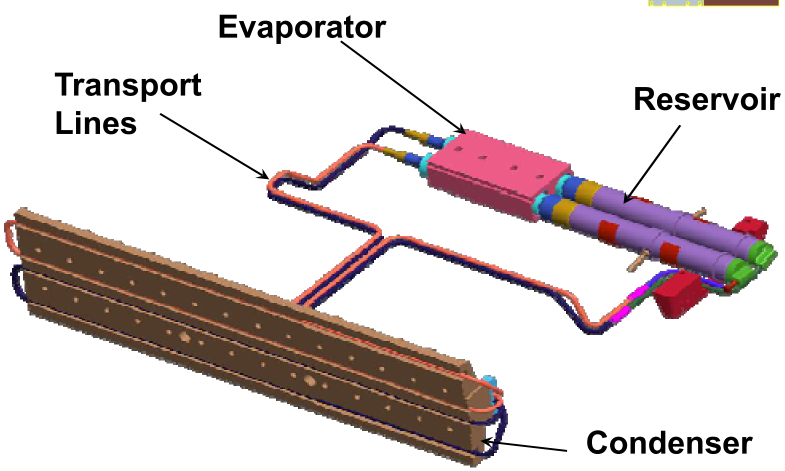
GOES-R ABI HPs/LHPs Assembly

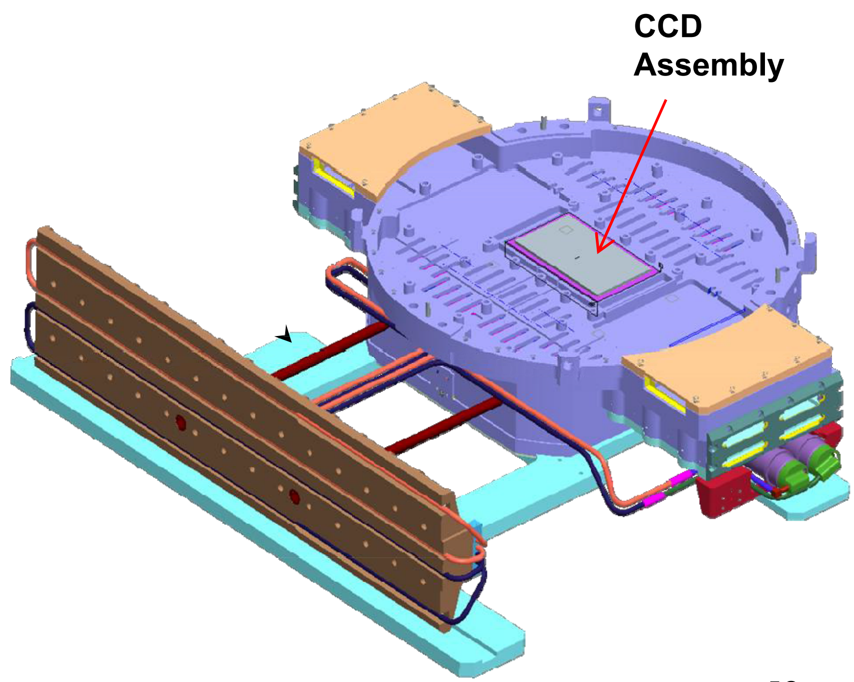


GOES-R GLM LHPs

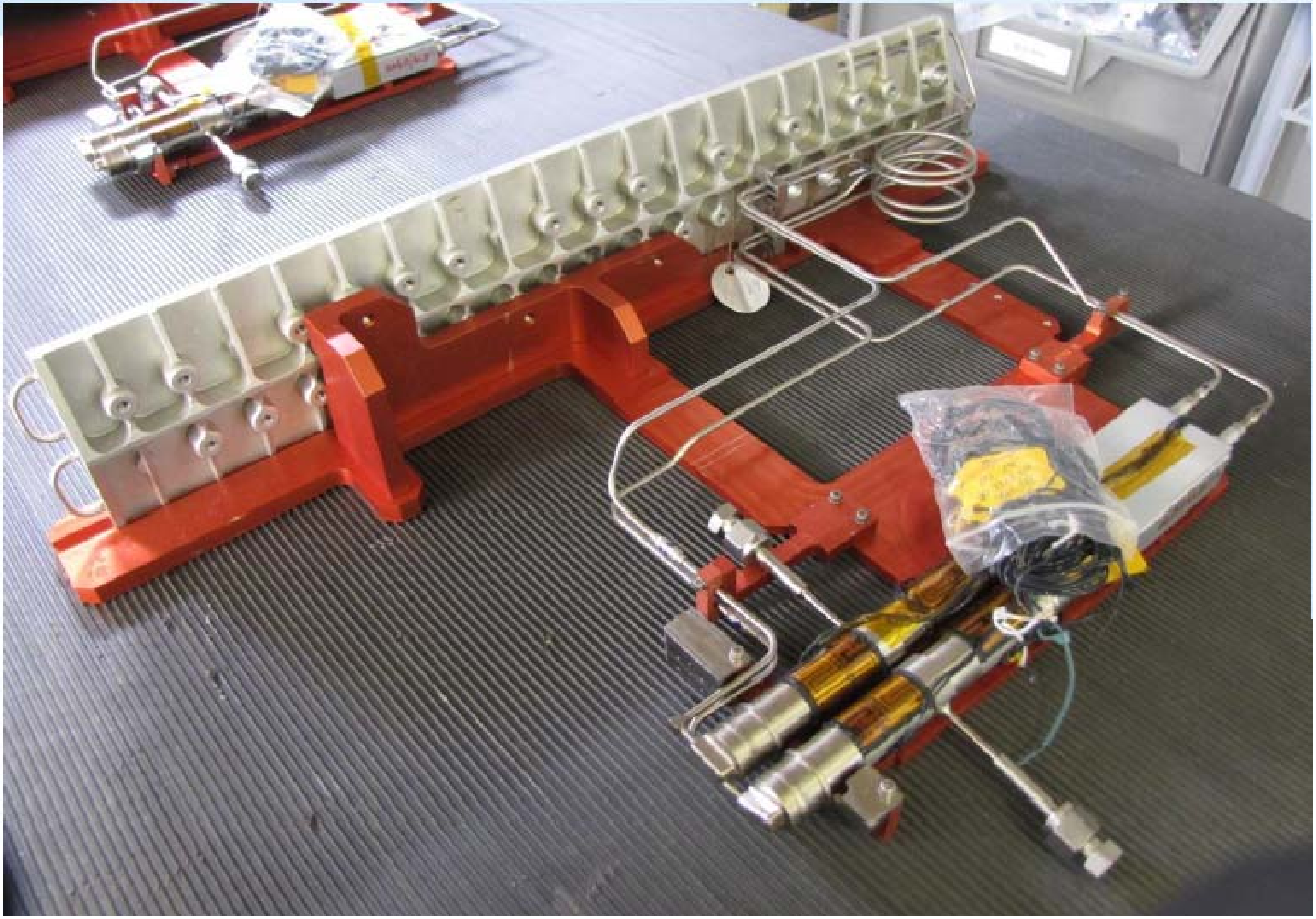








GOES-R GLM LHP Flight Hardware



Questions?