Variable Thermal Conductance Link for Lunar Landers and Rovers

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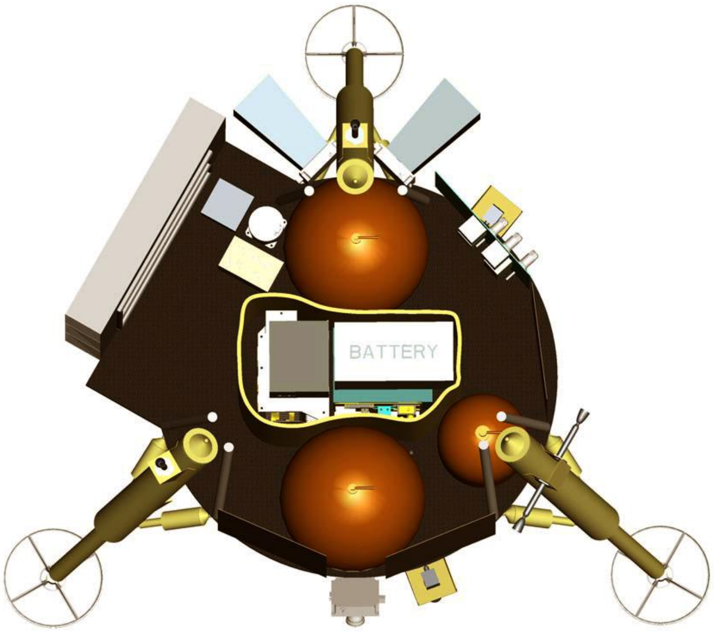
Presentation Outline

- Design Targets
- Variable Thermal Links
- Variable Conductance Heat Pipes
- Loop Heat Pipes
- Conclusions and Recommendations

International Lunar Network Trade Study

- Objective: Develop Variable Thermal Link designs to be used for Thermal Management of the Warm Electronics Box (WEB) on the International Lunar Network (ILN) Anchor Node mission
- Remove ~ 60 W during the lunar day
- Conserve heat to keep the electronics and battery warm during the lunar night



Design Targets

Minimum Electronics Temperature	-10 C (263 K)
Maximum Electronics Temperature	30 C (303 K) May increase to 50 C (323 K)
Power During Lunar Day/Night – Stirling	52 W/52 W
Power During Lunar Day/Night – Solar	60 W/20 W
Power During Transit	Assume Full Power
Trip Length	5 Days, or Several Months
Duration	~ 6 years
Warm Electronics Box Geometry Will be Larger for Solar Option	21.5” x 13” x 15” height
Radiator Dimensions	21” (tall) x 25” (wide)

Solar power controls, Maximum Day and Minimum Night

Design Targets

Maximum Tilt	20 (10 slope, 10 hole)
Maximum Radiator Sink Temperature (Landing)	263 K
Minimum Radiator Temperature	141 K
Minimum Soil Temperature	-173 C (100 K)
Maximum Soil Temperature	116 C (390 K)

- Minimizing power usage at night is extremely important
- 1 W power = 5 kg Batteries!
- 20° tilt means that conventional grooved aluminum/ammonia CCHPs can not be used in the WEB to isothermalize the system
  - Maximum Adverse Elevation: 13.3 inch

Variable Thermal Link

- Three basic elements to the WEB thermal control system
  1. A method to isothermalize the electronics and battery during the lunar night, and to remove heat to a second, variable conductance thermal link during the day (Constant Conductance Heat Pipes (CCHPs)).
  2. A variable thermal link between the WEB and the Radiator
  3. A radiator to reject heat
- Possible Thermal Links
  - Variable Conductance Heat Pipes (VCHPs)
  - Loop Heat Pipes (LHPs)
  - Thermal Switch
  - Pumped loop

Comparison of Thermal Links

- Partially based on Mars Rover Thermal Links from Birur, Pauken, and Novak (2002)

Technology Attributes	Mechanical Heat Switch	VCHP	Mini Loop Heat Pipe	Mechanically Pumped Coolant Loop
Practical Heat Transfer Capacity Range, W	1 to 20	1 to over 100	10 to over 100	25 to over 500
Active/Passive System	Passive	Passive	Passive	Active
Configuration Flexibility	Not flexible, needs to be located close to the heat sink	Flexible	Very flexible, can easily transfer heat over large distances, over a meter	Very Flexible, can transfer heat over an order of magnitude longer distance
Heat Collection Flexibility (at source)	Constrained to small foot print	Constrained to small foot print	Constrained to small foot print	No constraint on foot print
Heat Rejection Flexibility (at sink)	Constrained to small foot print	Constrained to small foot print	No constraint on foot print	No constraint on foot print
Typical mass, kg	0.10 to 0.12	0.3 to 0.5	0.3 to 0.5	4 to 20
Conductance, W/K On	0.4 to 0.5	20	10 to 15	5 to 10
Conductance, W/K Off	0.02 to 0.025	0.01 to 0.04	0.01 to 0.03	0.03 to 0.05
Electric Power, W	None	1-2 for tight thermal control	1 for "off condition" 5 for start up (a few min.)	3 to 10 for "on condition" (including electronics)
Heritage	Excellent (test on Mars)	Excellent for grooved wicks	Excellent for Space	Excellent for Space

Variable Thermal Links

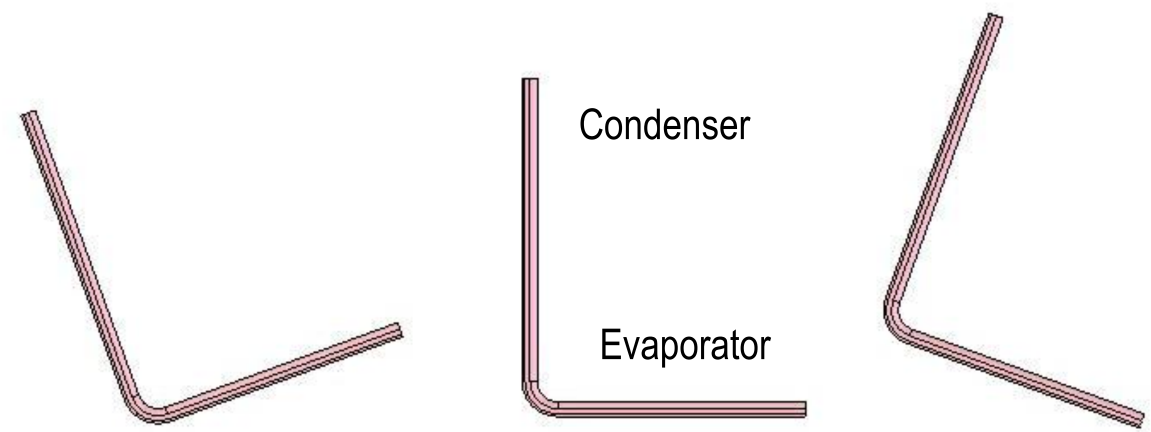
- **Pumped Loop** – Reject
  - Moving Parts/Power
  - Can use passive system
- **Thermal Switch** – Reject
- Thermal switches were used on the batteries for the Mars Exploration Rovers
  - TRL Level 9
- Dropped from further consideration
  - Lower thermal conductance than VCHP or LHP solution
  - ~ 0.5 W/K when on, versus > 10 for VCHPs and LHPs
  - Limited footprint for both heat input and heat rejection
- **VCHPs, LHPs, LHPs with Thermal Control Valve**

VCHP Design Constraints

- Aluminum/Ammonia VCHP
  - Ammonia freezes in condenser section at night
- VCHP differs from normal VCHP in 4 different ways
- Need to operate with fairly large tilts in the evaporator
  - Slope can vary from -20° to +20°
  - ~13 inch adverse elevation across the WEB
  - Grooved CCHPs operate with 0.1 inch adverse tilt
  - Requires non-standard wick
- Tight temperature control not required
  - Have a ~40°C range versus ±1°C for conventional VCHPs
- No power available for reservoir temperature control
  - 1 W = 5 kg
  - External reservoir will cool down to ~140 K
- Require stainless steel section to minimize heat leak when shut down

Wick Design – Maximum Tilt

- Sections of VCHPs or CCHPs that will operate in gravity-aided mode on the Moon will have a grooved wick
  - Only method to carry the power over long distances in space
- Groove only works 0.010 inch against gravity
- Screen wick required for sections that operate against gravity

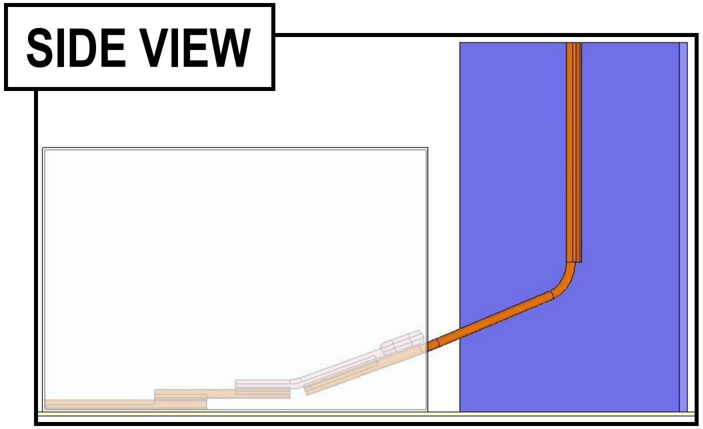


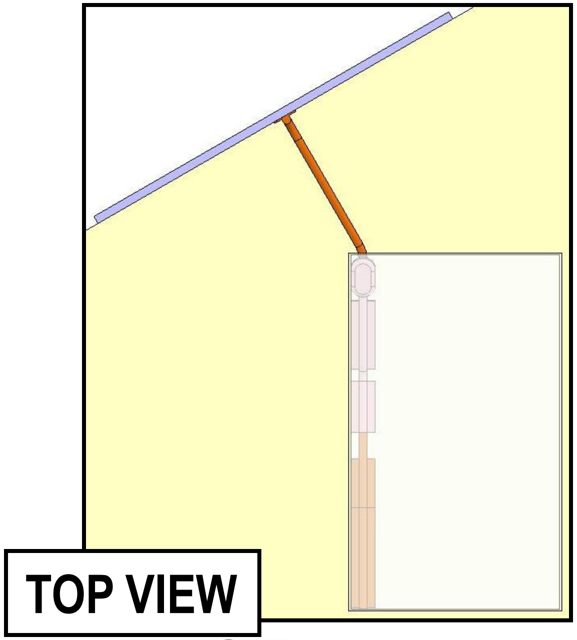
-20°, Evaporator Works Against Gravity

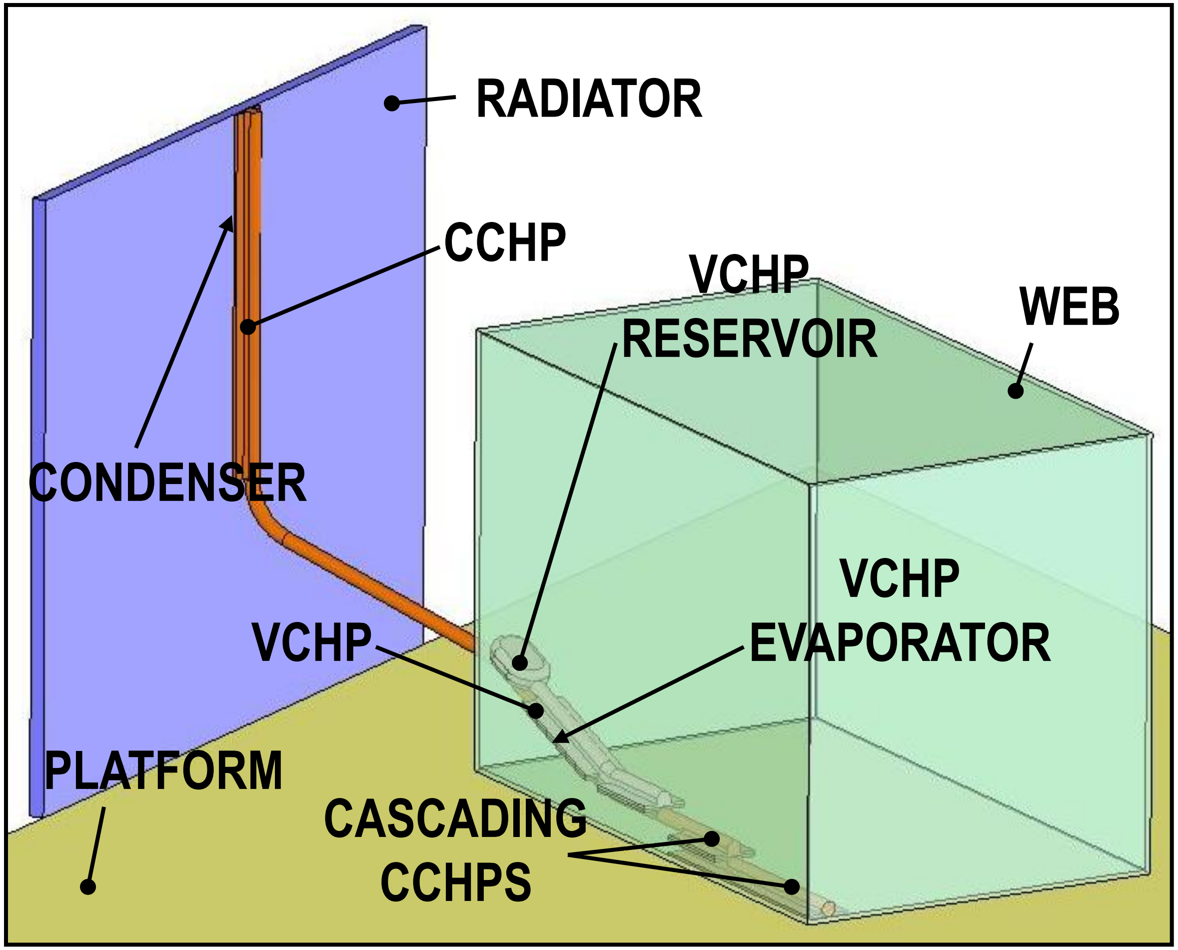
Level, Puddle Flow in Evaporator

+20°, Evaporator Gravity Aided

Concept #1 – Cascading CCHPs and VCHP





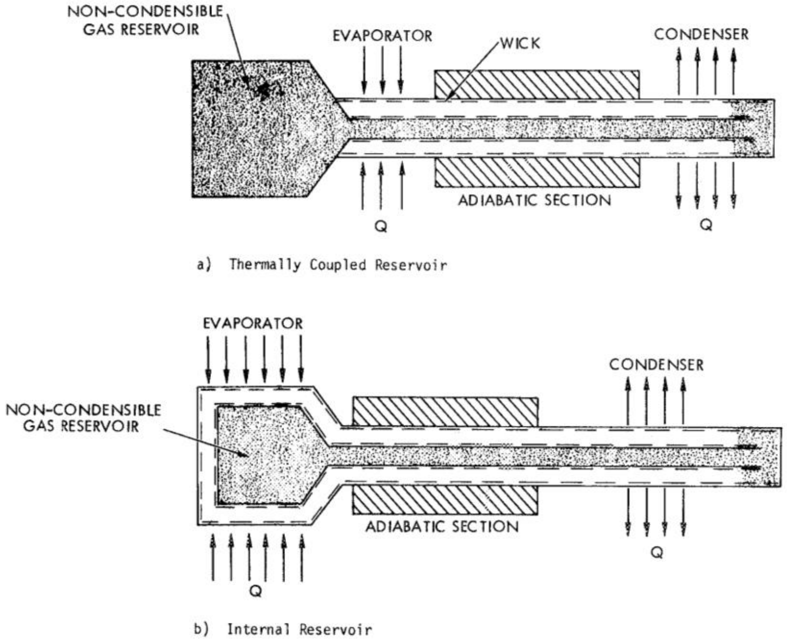


Concept #1 – Cascading CCHPs and VCHP

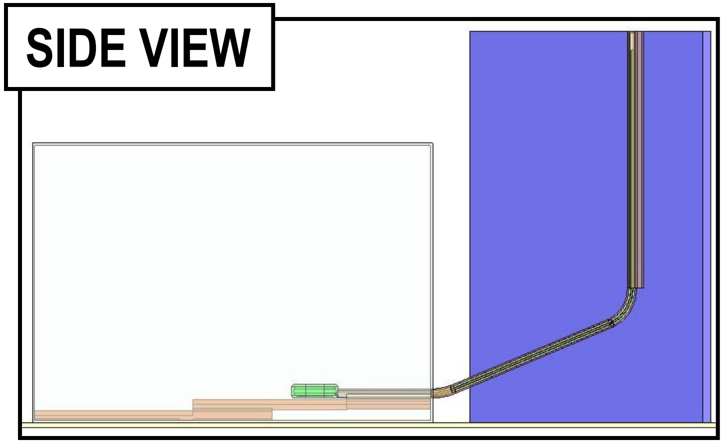
- Internal VCHP, External CCHP
- Design consists of multiple CCHPs and a VCHP
  - Cascading CCHPs located at the interior base of the WEB carry the thermal load across the WEB to the VCHP
  - VCHP is located on the interior of the WEB in order to ensure the NCG reservoir stays warm
  - VCHP carries the thermal load from the cascading CCHPs to the CCHP connected to the radiator
- Diagram shows cascaded heat pipes in WEB on top of each other
  - For ease in explanation
  - Actual heat pipes would be side by side
- Could improve location where attaches to reservoir by slanting the evaporator

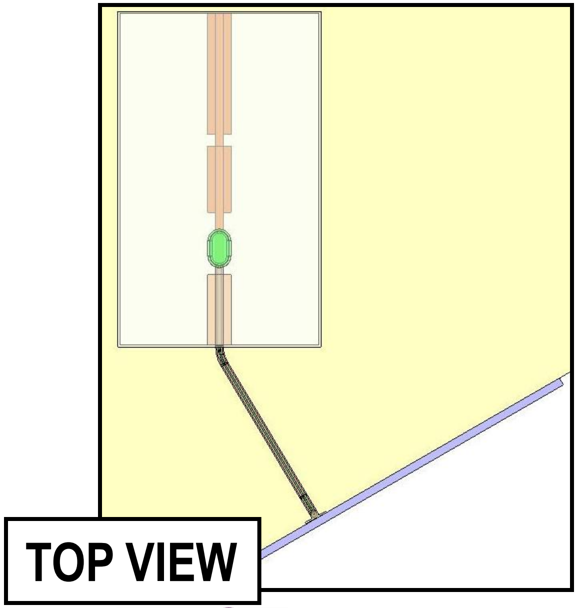
Variable Conductance Heat Pipe

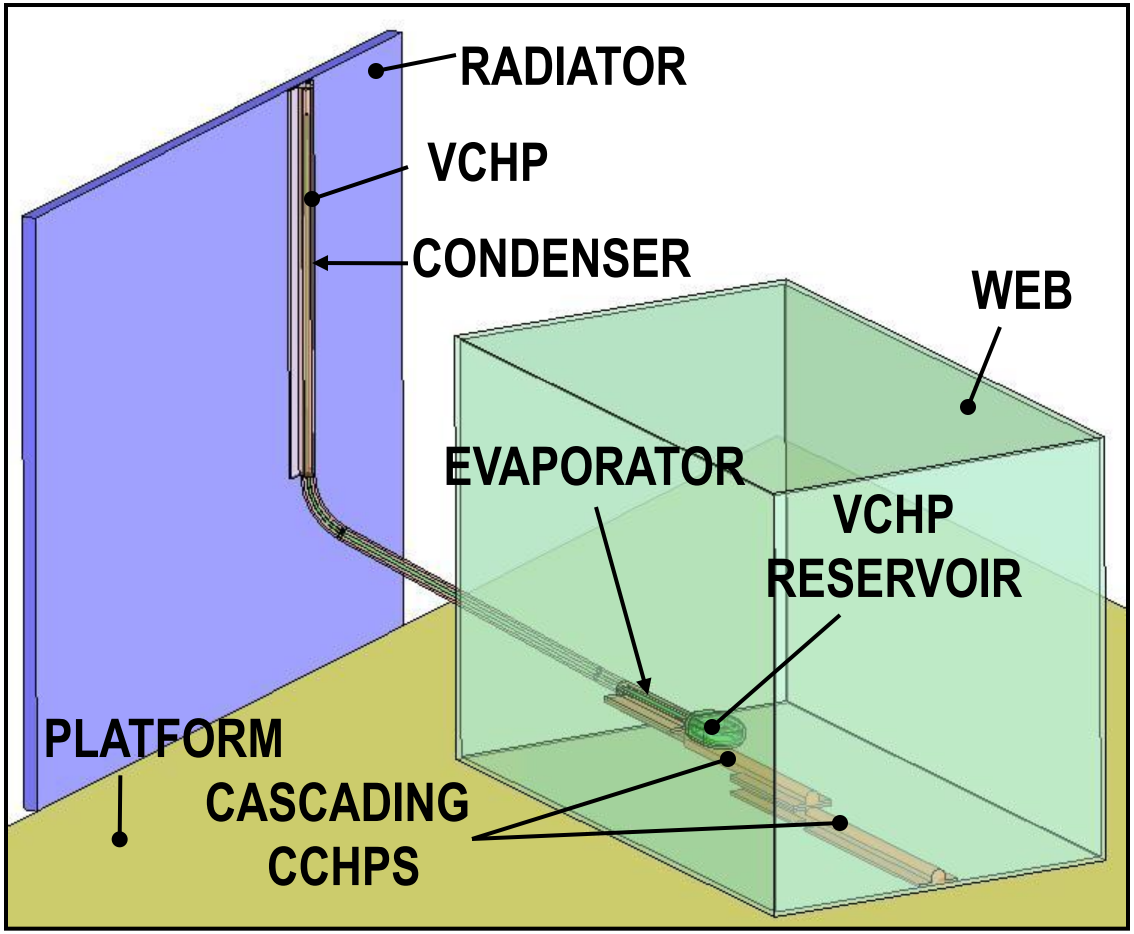
- Reservoir – Temperature must be kept ~ constant
- Two designs maintain a constant reservoir temperature
  - Internal VCHP, External CCHP
  - Reservoir Coupled to Evaporator (Marcus. 1976)



Concept #2 – VCHP with Reservoir at Evaporator End



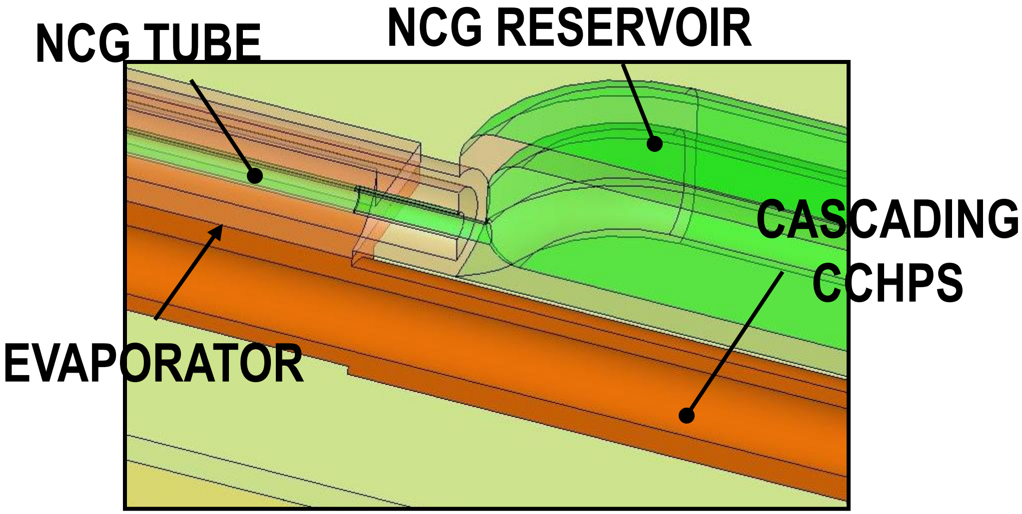


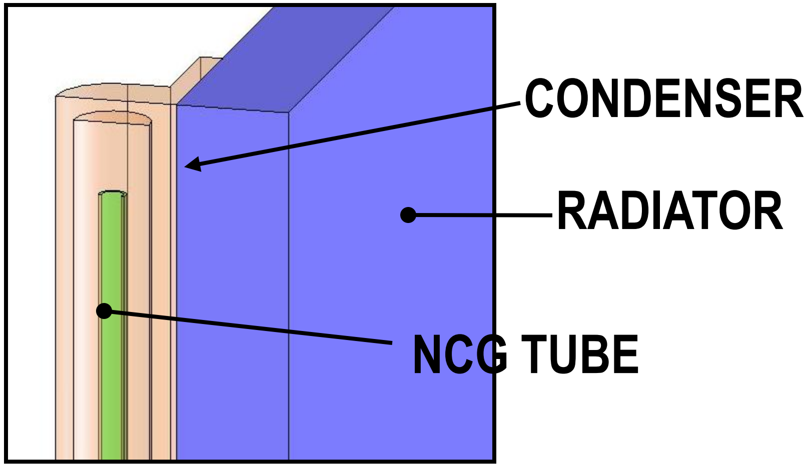


Concept #2 – VCHP with Reservoir at Evaporator End

- VCHP reservoir coupled to evaporator
- Design consists of multiple cascading CCHPS and a VCHP
  - Cascading CCHPs located at the interior base of the WEB carry the thermal load across the WEB to the VCHP
  - VCHP carries the thermal load from the interior of the WEB to the radiator
  - VCHP reservoir is located at the evaporator end to ensure that it stays warm
    - A internal tube travels from the reservoir to the condenser end of the VCHP to deliver the NCG gas
  - One fewer thermal joint than Concept 1
  - More complicated to fabricate if need flexible section
  - Need to consider freeze/thaw of VCHP, unlike Concept 1

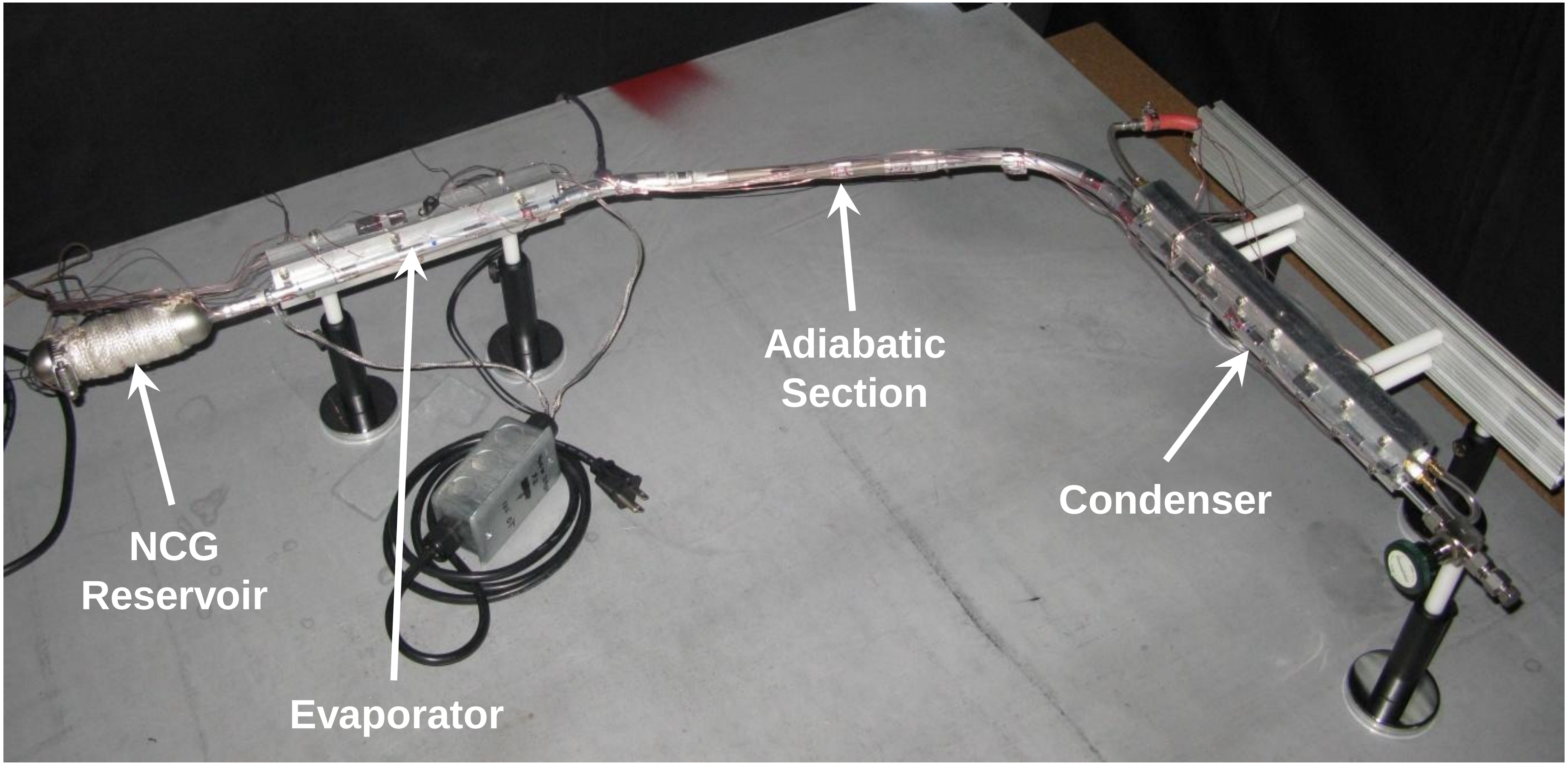
VCHP Design with Reservoir at Evaporator End



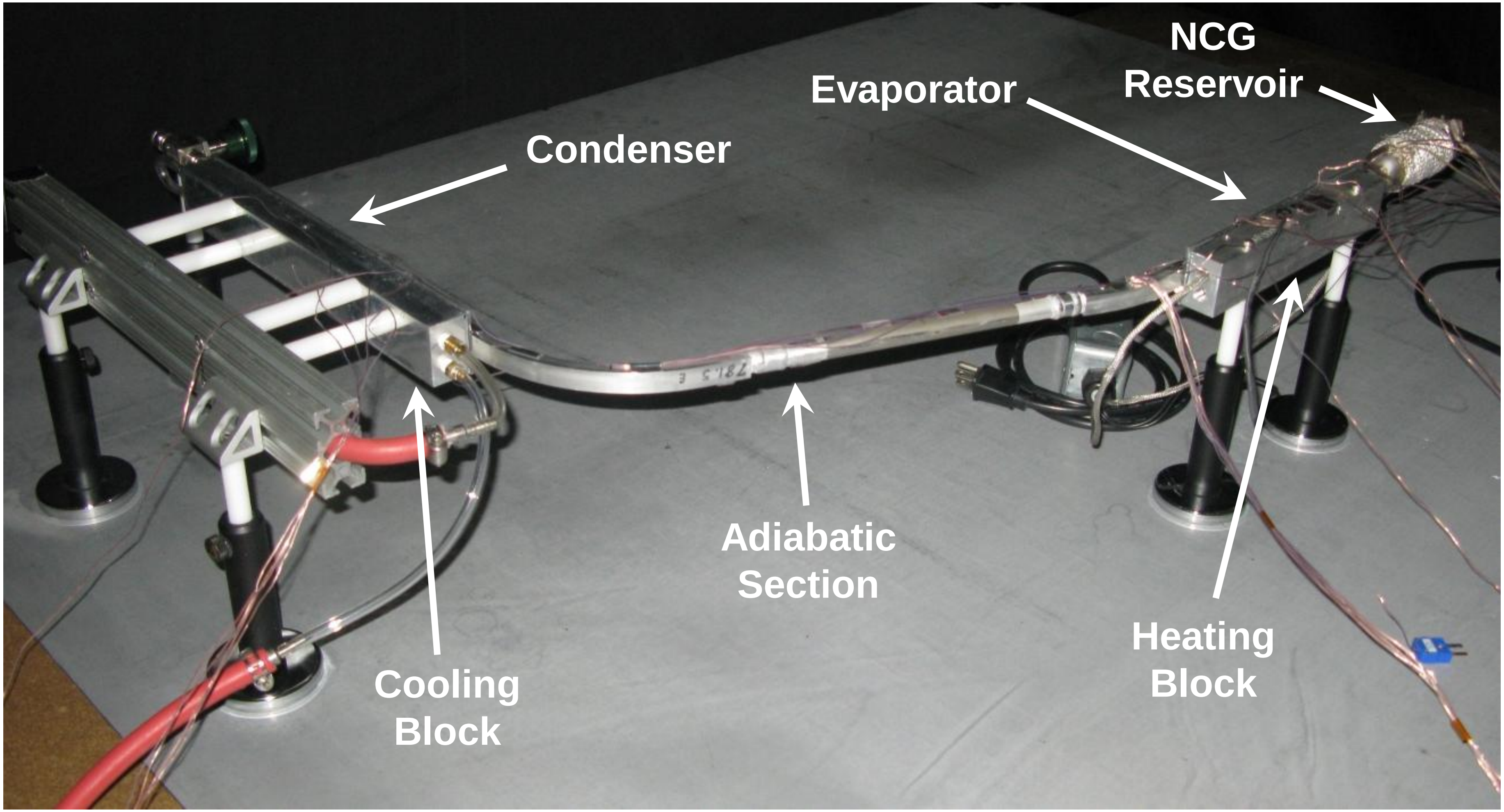


- Reservoir is located at evaporator end instead of condenser end
- Tube connected to the reservoir travels the length of the pipe and ends short of the condenser end
- This tube supplies the NCG to the condensing end of the pipe
- This location ensures the reservoir will be inside the WEB and therefore the temperature can be maintained

VCHP with Internal Radiator

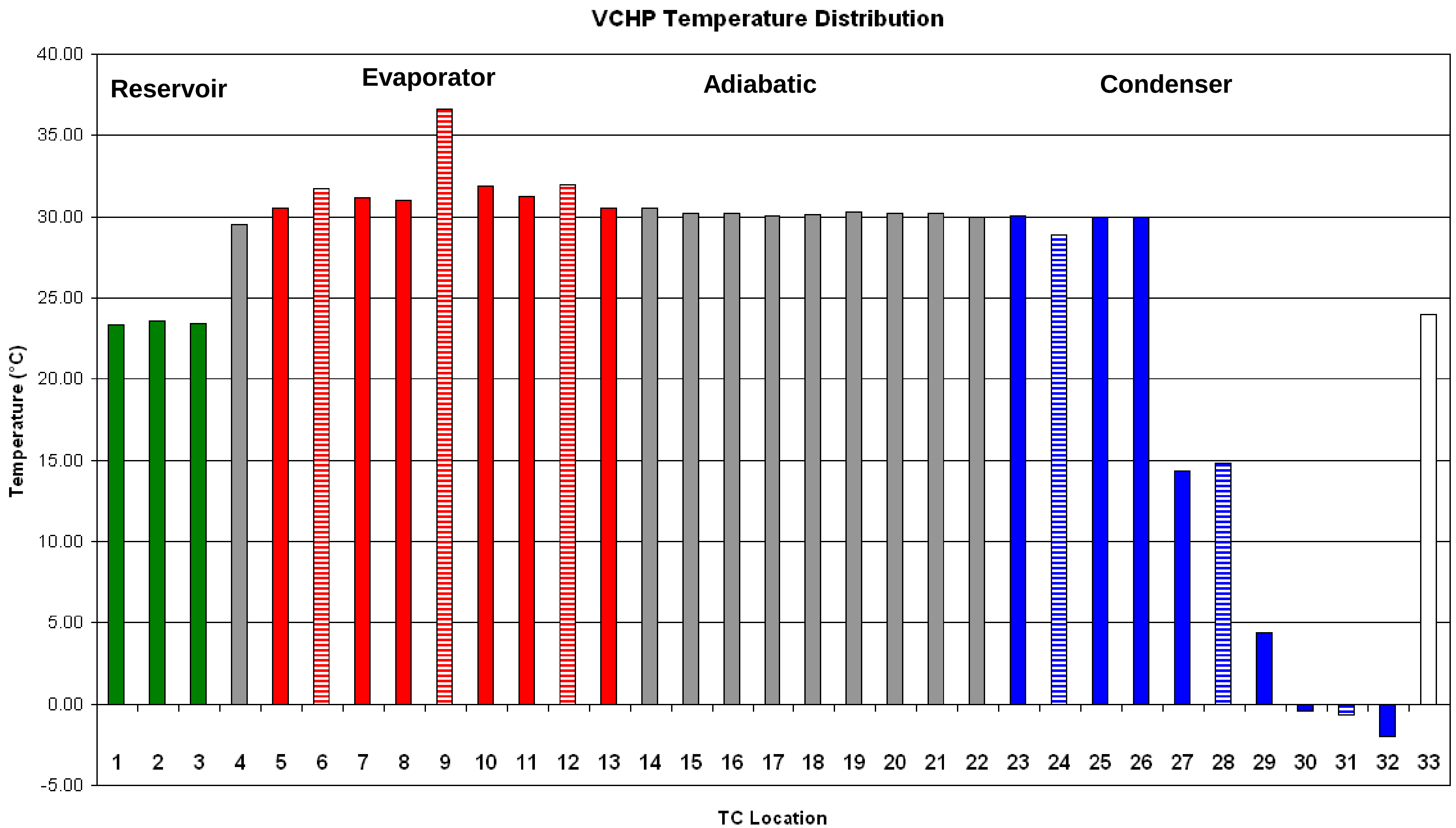


VCHP with Internal Radiator



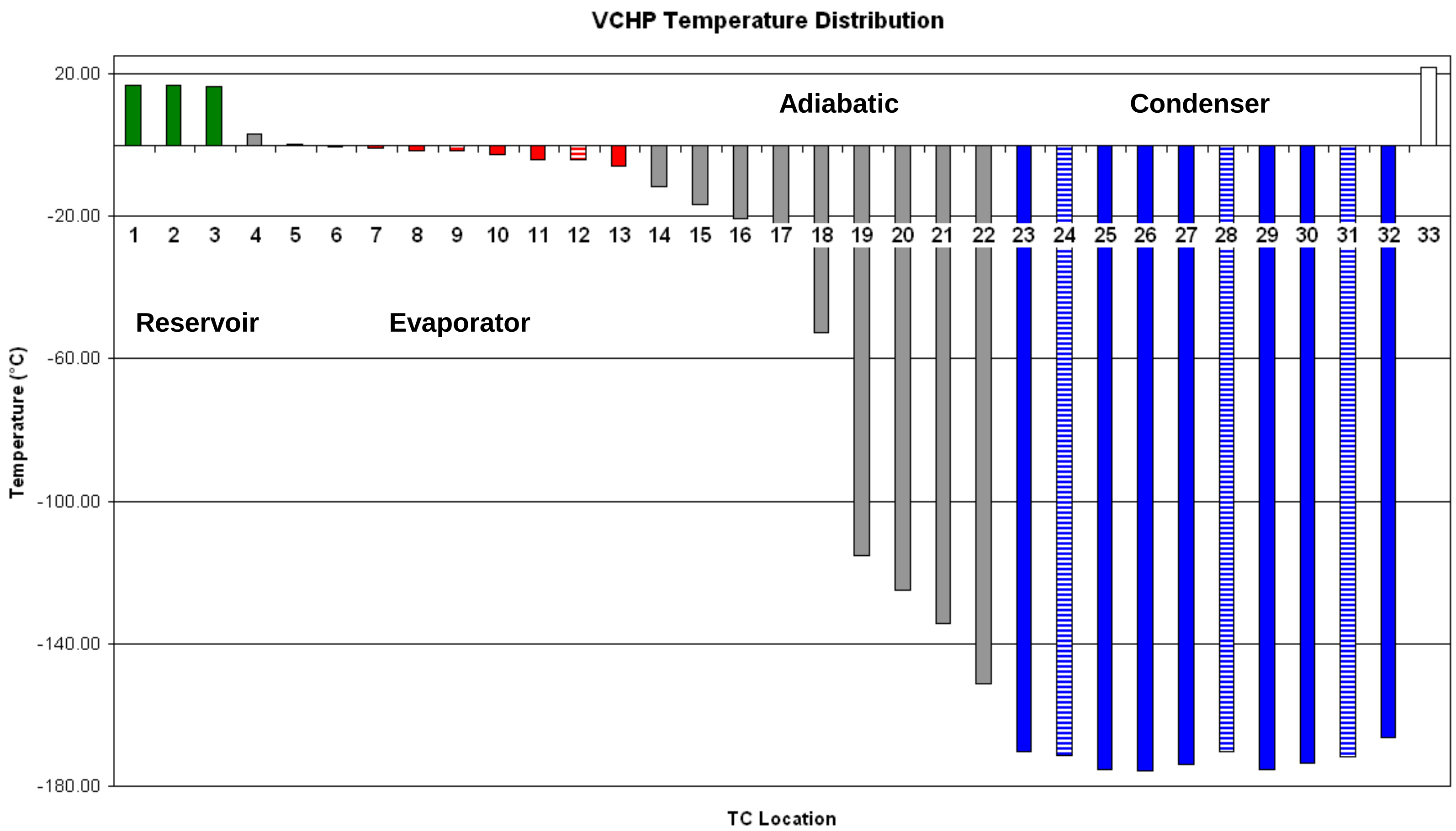
VCHP – Normal Operation

- 30°C Evap., 90 W, Condenser Vertical, Adverse Evaporator Tilt



VCHP – Shutdown

- Shutdown, -177°C Condenser, Heat Inleak, Adverse Evap.



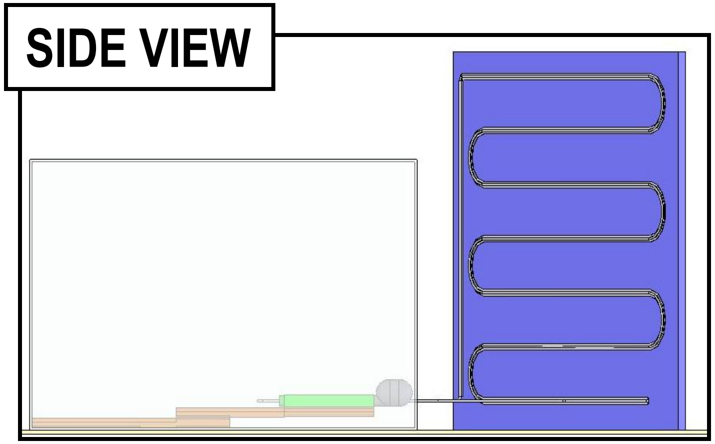
Loop Heat Pipes

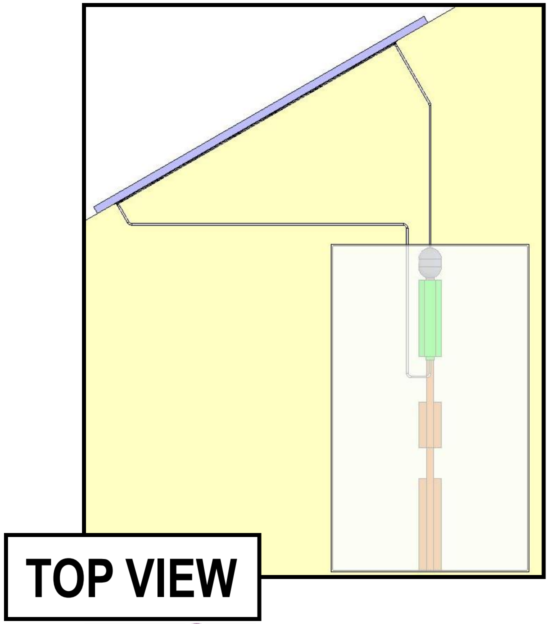
- Advantages
  - Totally Passive
  - Act as Diode when Radiator Hotter
  - Flexible, Bendable, Routable
  - Transports Heat over Large Distances (> 10 m)
  - Insensitive to Tilt (although WEB CCHPs need to consider)
  - TRL Level 9, hundreds of LHPs used in space
  - Tests by JPL on a similar size design
  - Simplifies radiator design
- Disadvantages
  - Order of Magnitude more expensive than a VCHP
  - More complicated to control than VCHP (but routinely done in space)

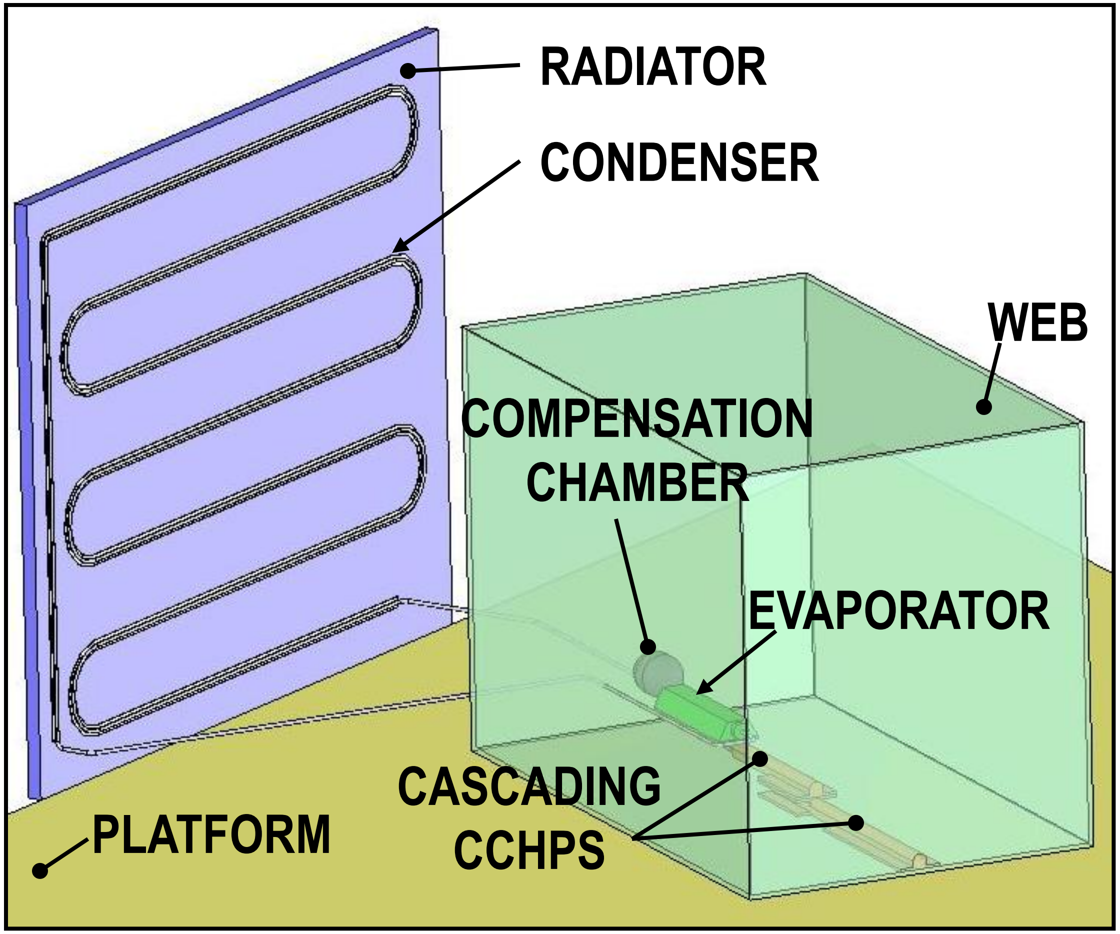
LHP Design Constraints

- LHPs have a limited footprint for heat input
  - Probably 5-6 inch evaporator, based on previous mini-LHP designs
  - Heat Leak Increases as Lengthen Evaporator
- Heat Rejection
  - Better than VCHP to distribute heat to radiator
  - May need liquid that will not freeze
  - Propylene commonly used for spacecraft LHPs when freezing is an issue

LHP Concept – Cascading CCHPs







Loop Heat Pipe

- The LHP concept consists of multiple CCHPs and a single LHP
  - Could use two evaporators in a single LHP
  - Could use two LHPs for redundancy
- Like previous designs, cascading CCHPs are used to carry the thermal load across the length of the WEB.
- The thermal load is then transferred to the LHP evaporator which then transfers it directly to the radiator where it is radiated to space
- Concept shows LHP at one end of the box
- Get better performance from the CCHPs if move LHP evaporator to the middle of the box
  - ΔT through fewer cascaded pipes

LHP Shut-Down

- Need to shut down LHP during the Lunar night
  - Minimize Heat Losses from the WEB
- Standard method uses a heater on the compensation chamber
  - During normal operation, the Compensation Chamber runs at a lower temperature than the LHP evaporator
    - Required to maintain lower pressure in CC
  - Activate heater to shut down
  - Increase saturation temperature and pressure of LHP
  - Cancels the pressure difference required to circulate the sub-cooled liquid from the condenser to the evaporator
- Standard method validated in spacecraft
  - 1 W = 5 kg

LHP Start-Up

- Start-Up heaters sometimes required to start LHP
- Problem occurs when the grooves in the LHP wick are filled with liquid
  - More likely when have previously heated the CC to shutdown the LHP, driving fluid out of the CC.
  - Heat can be conducted into the interior of the wick, raising the entire LHP temperature
    - LHP requires a temperature difference between the CC and evaporator
  - Use heater with concentrated heat flux to blow bubble, clear grooves
  - JPL used about 5 W for their mini-LHP
- Ku has proposed using thermoelectrics instead to pull heat from the CC
  - Similar power
  - Aids in start-up by dropping the Compensation Chamber temperature

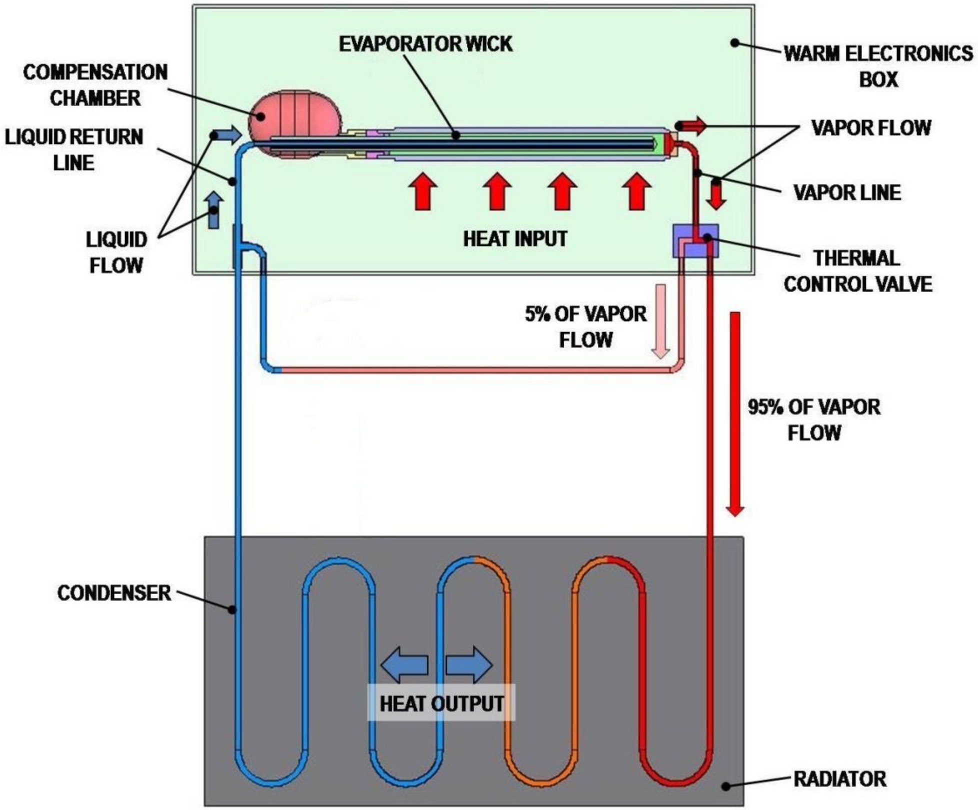
NASA JPL Mini-LHP for Mars Rover

- Developed for Mars Rover
  - Pauken, Birur, and Novak (2002)
  - Similar Size/Power as Anchor Node
- Design
  - Ammonia/Aluminum Evaporator/SS Transport Lines and Condenser
  - Require strong transport lines to withstand pressure of thawing ammonia in condenser
  - Single Evaporator/Single Condenser (other designs also examined)
  - One-half inch dia. sintered nickel wick, ~ 6 inches long
- Start-up heaters on evaporator ~ 5W
- Shut-down heater on compensation chamber ~1 W
- Accommodate ammonia freeze/thaw in condenser
  - -15°C to +70°C in Evaporator
  - -120°C to +65°C at Condenser (Ammonia Freezes at -77°C)

JPL Mini-LHP Qualification Testing

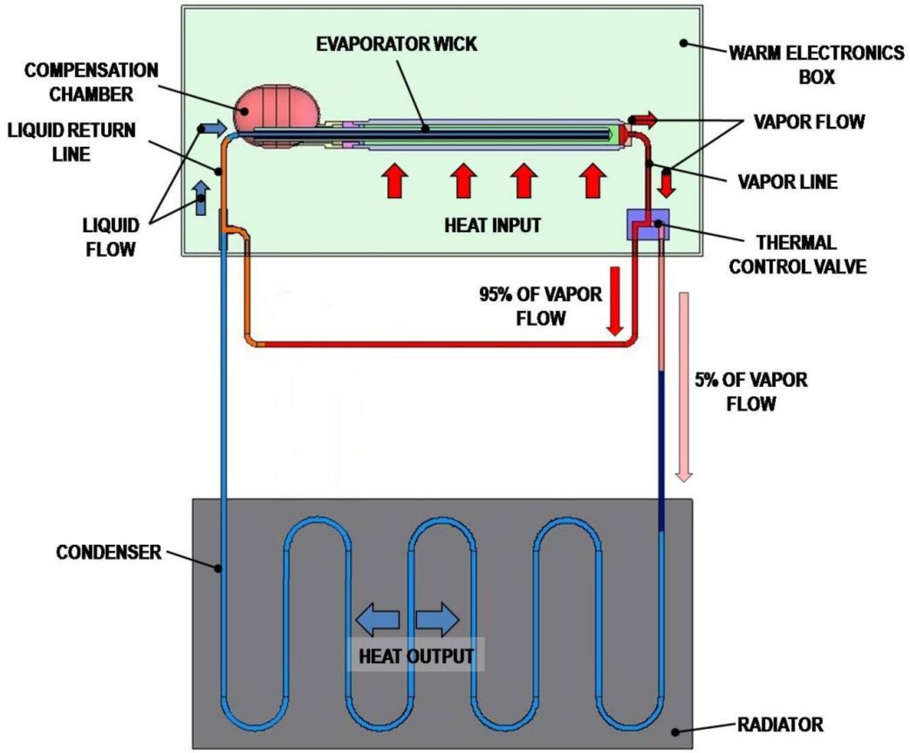
- Not demonstrated on Mars, but extensive series of tests on earth
- Thermal Tests to Demonstrate:
  - Reliable start-up and shut-down
  - Steady state heat transport
  - Transient response to varying evaporator power and varying condenser sink temperatures
- Thermal Cycling
  - 100 freeze-thaw cycles on the condenser
- Mechanical Tests
  - Proof pressure
  - Landing loads on Mars
  - Random vibration
  - Vapor and liquid transport-line flexibility
  - Ammonia leakage

LHP with Thermal Control Valve - Day



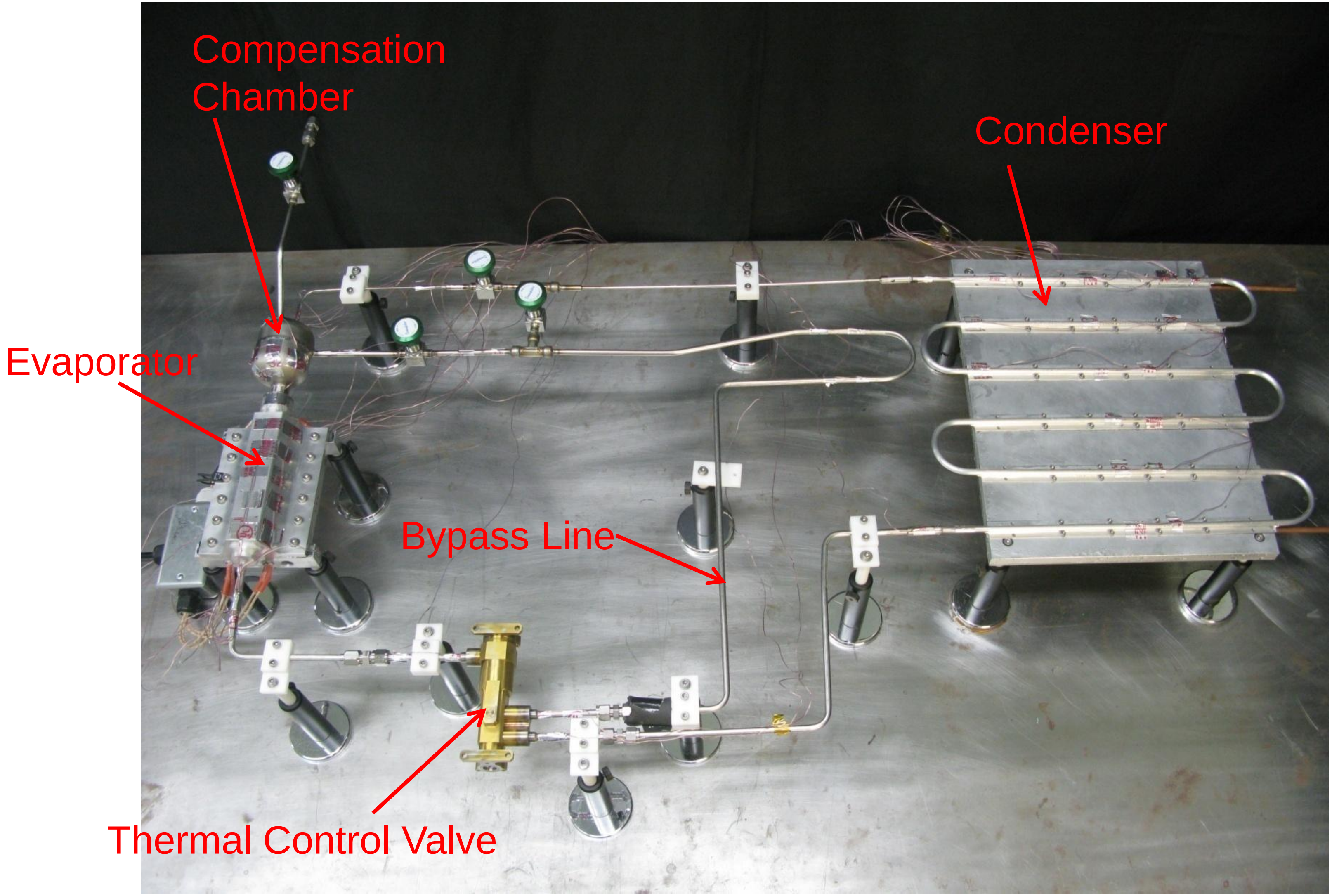
- Eliminate the shutdown power with a thermal control valve
- Lunar Day
  - Vapor will exit the evaporator and enter the TCV
  - Ratio of two outlet vapor streams from valve will change in response to inlet temperature and adjust valve spool accordingly resulting in more flow directed to the radiator as temperature increases

LHP with Thermal Control Valve - Night



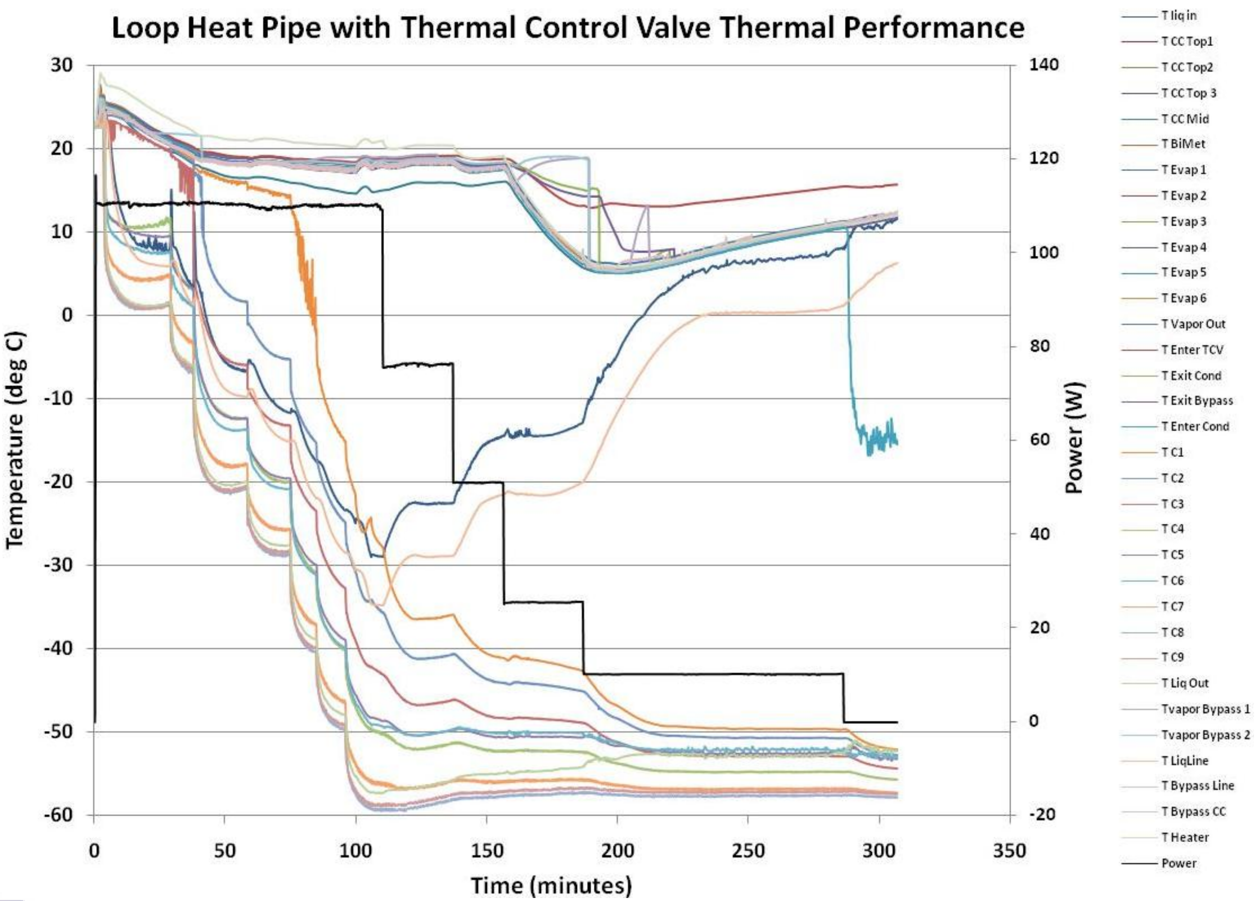
- Design Goal: Thermal link must be as ineffective as possible
- Lunar Night
  - Prevent heat from leaving the WEB to ensure electronics and batteries are kept warm with minimal power
  - As sink decreases, ratio of the two outlet vapor streams from TCV will change in response to inlet temperature
  - TCV will adjust valve spooling resulting in more flow directed away from radiator and through bypass line

LHP with Thermal Control Valve



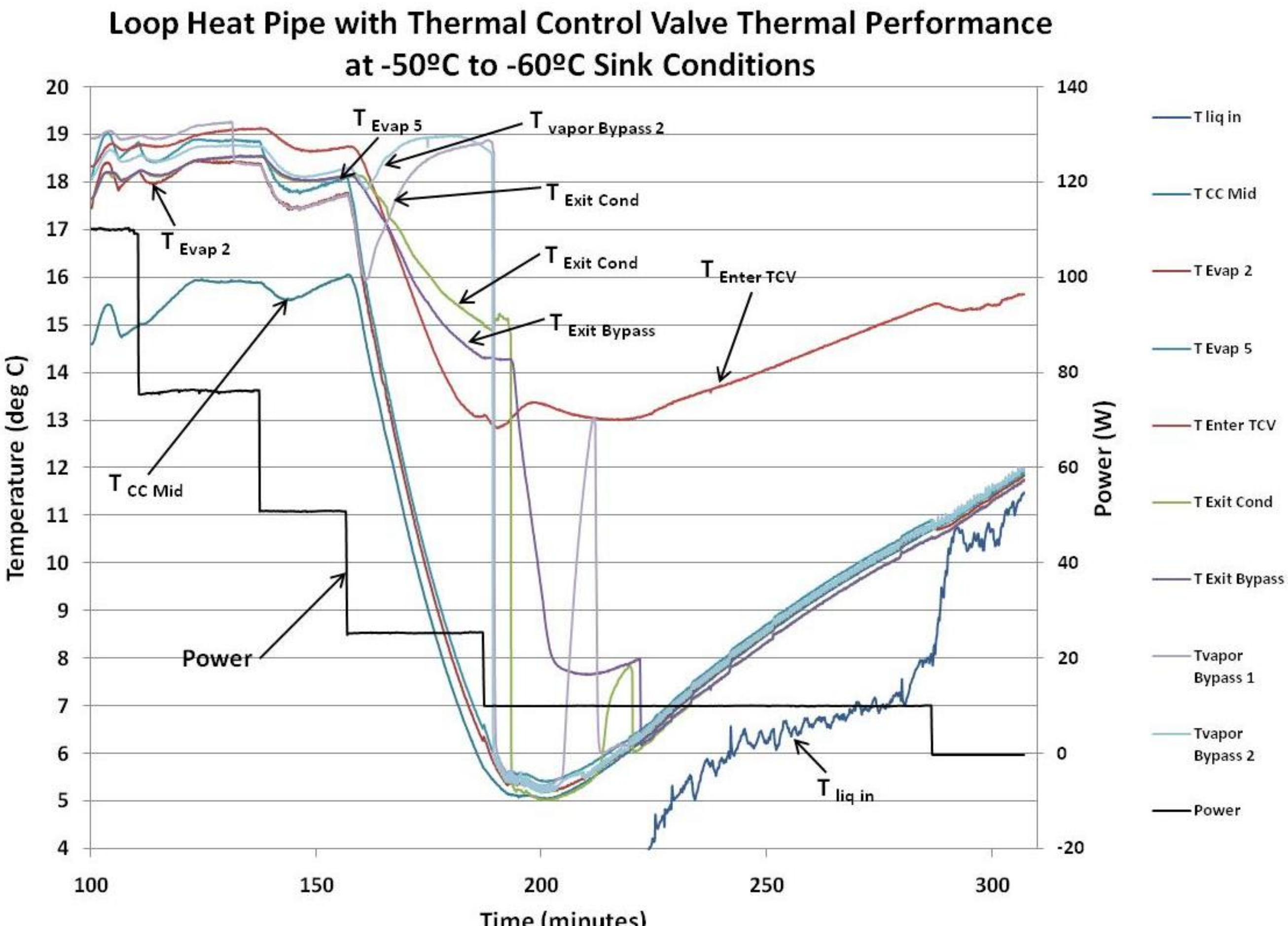
LHP with TCV – Shutdown

- Decrease Condenser Temperature to -60°C
- Decrease Power
- Evaporator Remains above 0°C



LHP with TCV – Shutdown

- Thermal Control Valve works from 20°C to 0°C
- Evaporator and Compensation Chamber ΔT narrows as LHP shuts down



Conclusions

- Have Shown 3 workable designs
- LHP
  - LHPs have a TRL level of 9 – flown in space
  - Require power to shutdown
  - Little experience with vertical radiator
- LHP with Thermal Bypass Valve
  - Testing in Europe
  - Early stages of development at ACT
  - No power to shutdown
- VCHP with Hybrid Wick and Internal Reservoir
  - No power to shutdown
  - Least expensive
  - Lowest TRL level
  - Under development at ACT

Acknowledgements

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