TFAWS Active Thermal Paper Session

Ammonia and Propylene Loop Heat Pipes with Thermal Control Valves – Thermal/Vacuum and Freeze/Thaw Testing

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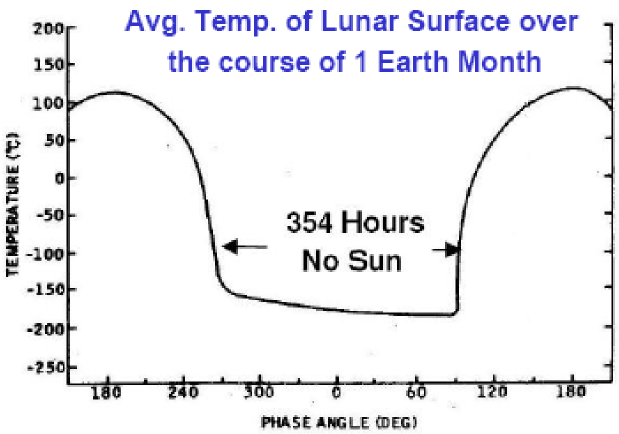
Presentation Agenda

- Motivation
- Design Targets
- Loop Heat Pipe Operation, Thermal Control Valve Integration
- Ammonia Freeze/Thaw
  - Condenser Drainage
  - Freeze/Thaw Testing
- Ammonia LHP with TCV
- Propylene LHP with TCV
- Conclusions
- Acknowledgements

Motivation

- Develop an Loop Heat Pipe with Thermal Control Valve to provide a Variable Thermal Link that passively adapts to changing power and sink conditions
- The lunar environment presents a number of challenges to the design and operation of radiator panels
  - During the day, the heat rejection sink can be 330K
  - At night or in dark craters it can drop down to 50K. Need to conserve heat to keep the electronics and battery warm during the lunar night
  - Instruments and equipment need to be maintained within -20ºC to 40ºC throughout the large diurnal temperature swings.



Design Targets: ILN Anchor Node

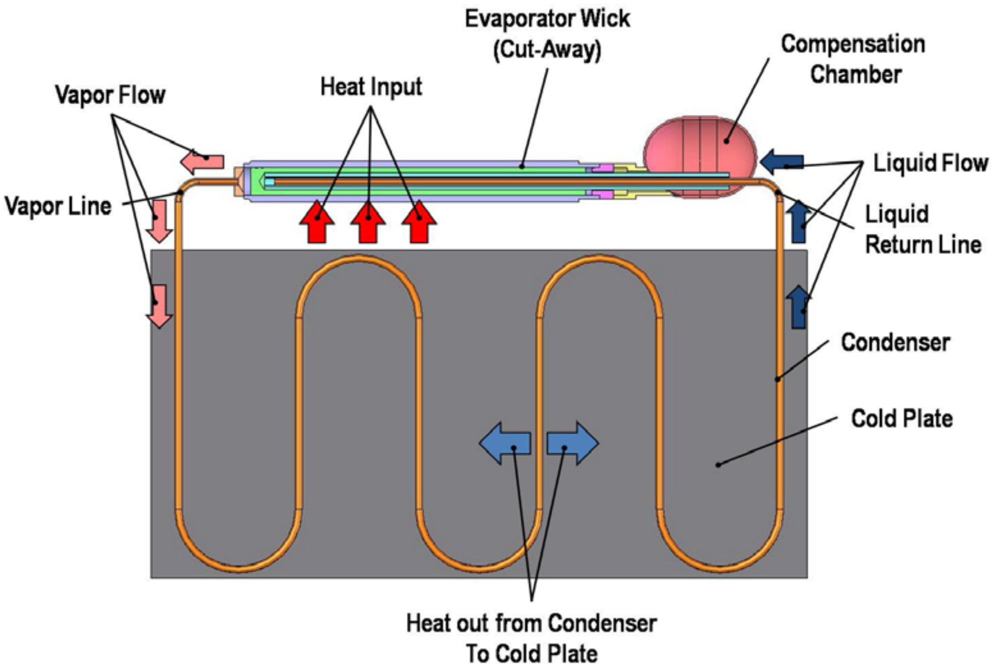
Minimum Electronics Temperature	-10°C (263 K)
Maximum Electronics Temperature	30°C (303 K)
Power During Lunar Day/Night – Stirling	52 W/52 W
Power During Lunar Day/Night – Solar	60 W/20 W
Power During Transit	Assume Full Power
Trip Length	5 Days, or Several Months
Duration	~ 6 years
Warm Electronics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

Solar power controls, Maximum Day and Minimum Night

- Minimizing power usage at night is extremely important
- 1 W power = 5 kg Batteries and solar cells! (more for propulsion)

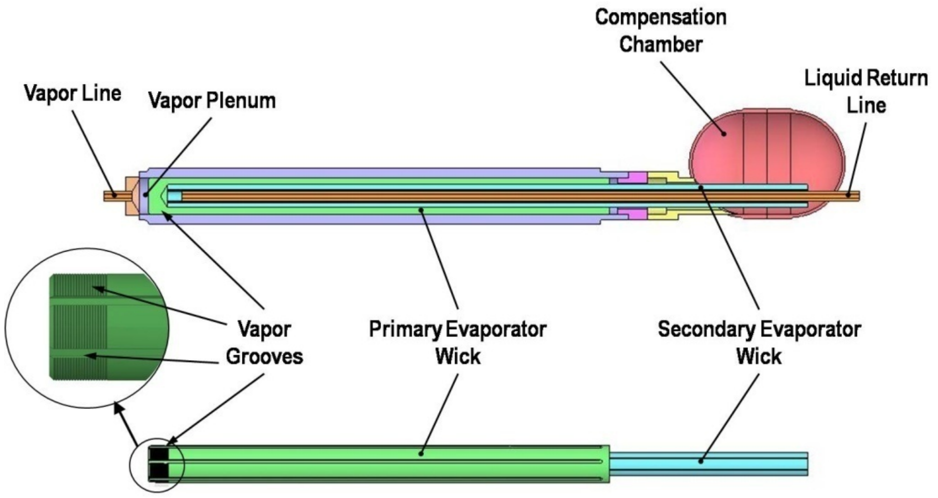
Loop Heat Pipe (LHP) Operation

- LHPs are high thermal conductance devices that are self-contained and passive
- Heat enters the evaporator and vaporizes the working fluid at the wick outer surface
- The vapor is collected by a system of grooves and headers
- The vapor flows down the vapor line to the condenser where it condenses as heat is removed by the cold plate
  - Most of the condenser is filled with a two-phase mixture



Loop Heat Pipe (LHP) Operation

- Heart of the LHP is the evaporator and compensation chamber
  - These contain the primary and secondary wicks
- Compensation chamber (CC) is located adjacent to the evaporator and operates at a lower temperature
  - Creates a lower pressure of the saturated fluid in the CC
  - Lower pressure allows the condensate to flow from the condenser through the liquid return line to the CC
  - Fluid then flows into a central bayonet where it feeds the wick



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 batteries for a Lunar application**
- Eliminate shutdown power with thermal control valve

TCV Integration into LHP

- Thermal Control Valve (TCV) first proposed by Goncharov et al. for precise temperature control
- Previous Valves:

◆ 2-Way – Goncharov

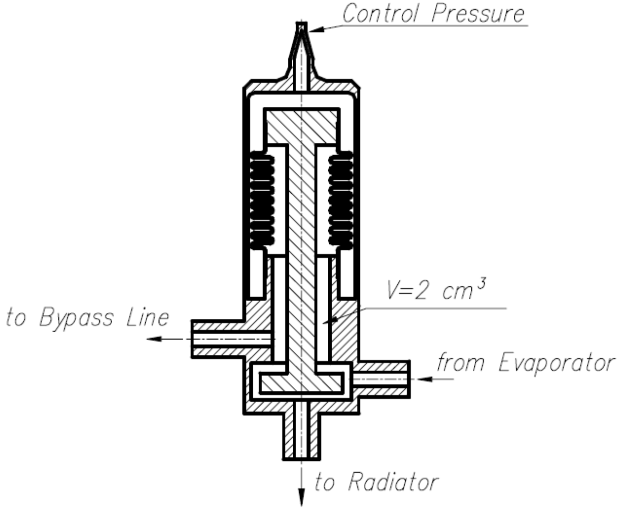
◆ Passive, pressure-controlled

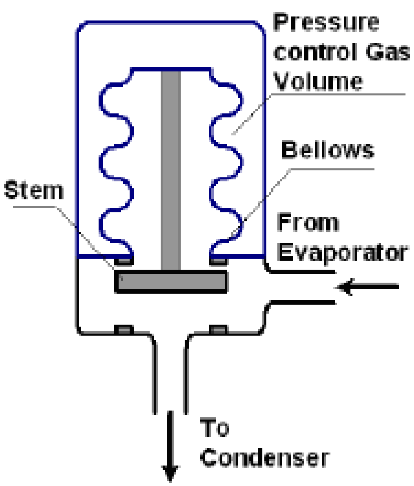
◆ Sealed bellows surrounded by Ar

◆ Mishkinis et al

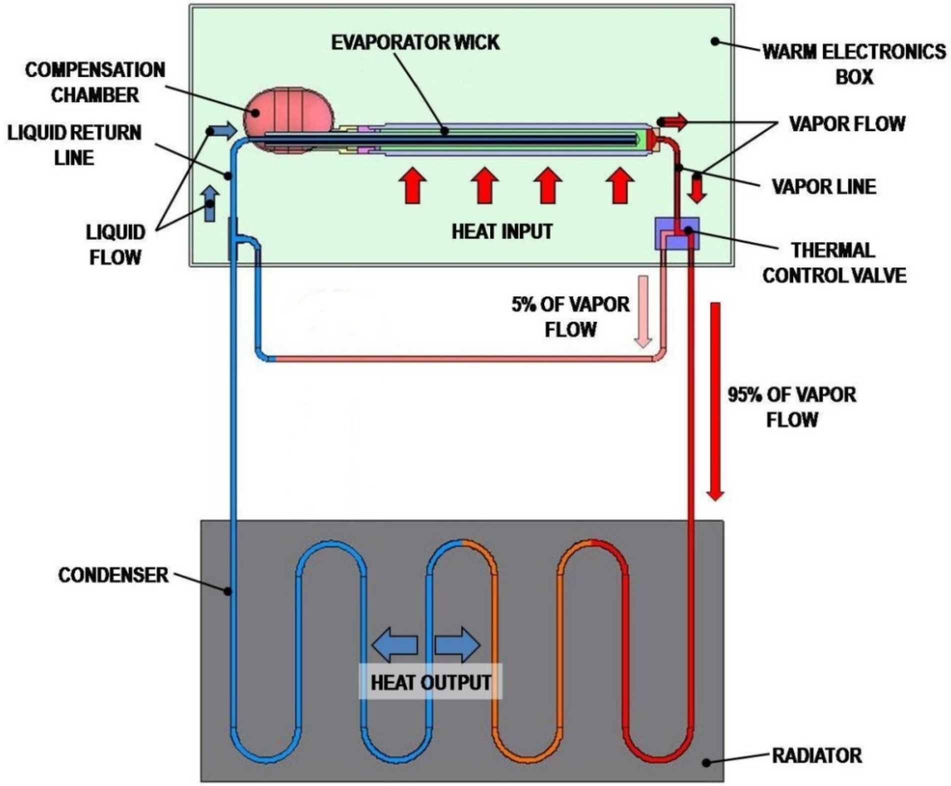
◆ Pressure-controlled single outlet valve

◆ Gradually shut off flow



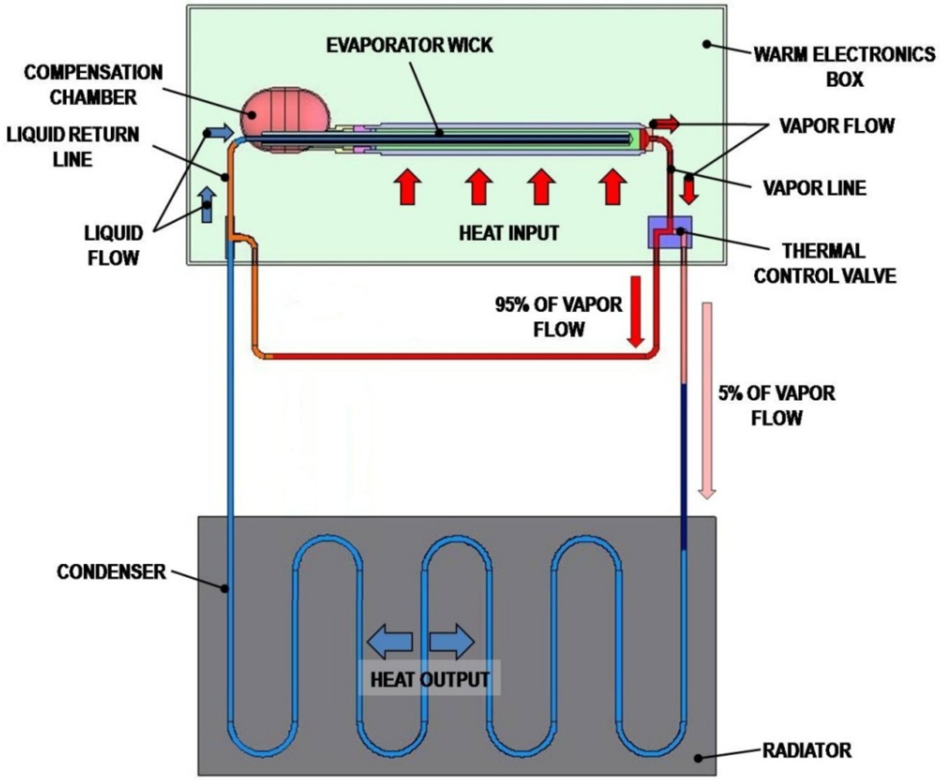


LHP with TCV – Lunar Day Operation



- During Lunar day operation the LHP must remove the waste heat from the WEB and transport it to the radiator
- 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

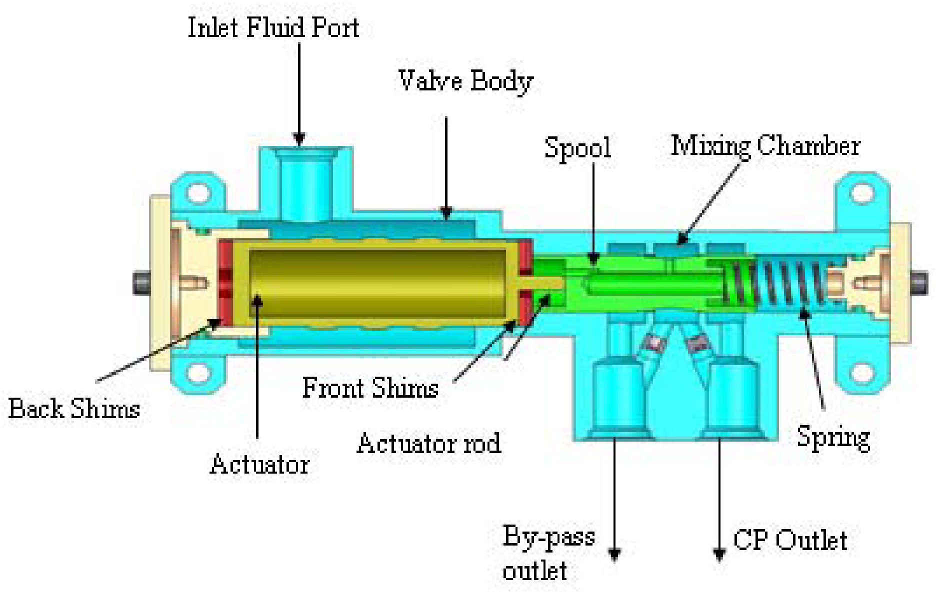
LHP with TCV – Lunar Night Operation



- During Lunar night operation the LHP must provide a thermal link as ineffective as possible
  - 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
- Hot vapor will flow through the bypass line
  - Increase in temperature and associated saturation pressure will stop LHP circulation
  - Small portion of vapor could enter the radiator, but vapor will sub-cool or possibly freeze in the lines

TCV Design and Manufacturing

- The Thermal Control Valve was designed and manufactured by Pacific Design Technologies, Inc. for ACT
  - Currently used in the pumped thermal loop for the Mars Science Laboratory
- Wetted materials in the TCV are all stainless steel
- Working fluid pressure has minimal effect on valve opening

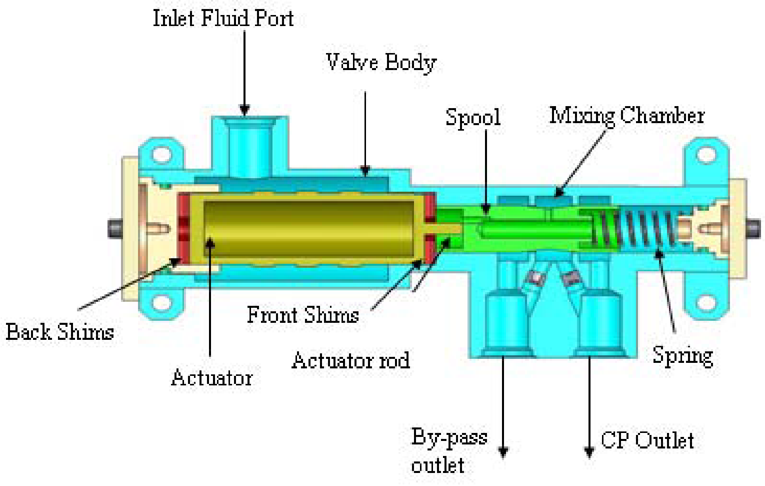


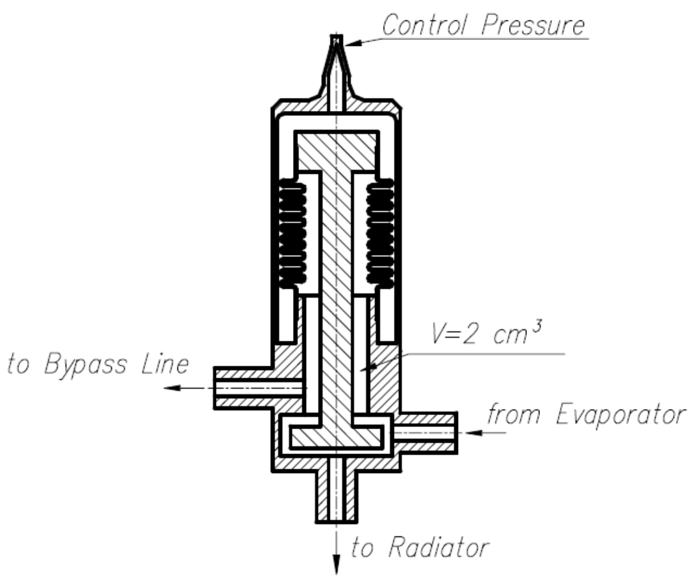
Valve/Vapor Inlet Temperature (ºC)	Outlet A to Condenser (%)	Outlet B Bypass Condenser (%)
≤ 0ºC	Minimize	Maximize
0ºC to +20ºC	Increase in Flow to Condenser with Increasing Temperature	Decrease in Flow to Bypass with Increasing Temperature
≥ +20 ºC	Maximize	Minimize

Comparison with previous LHPs with TCV

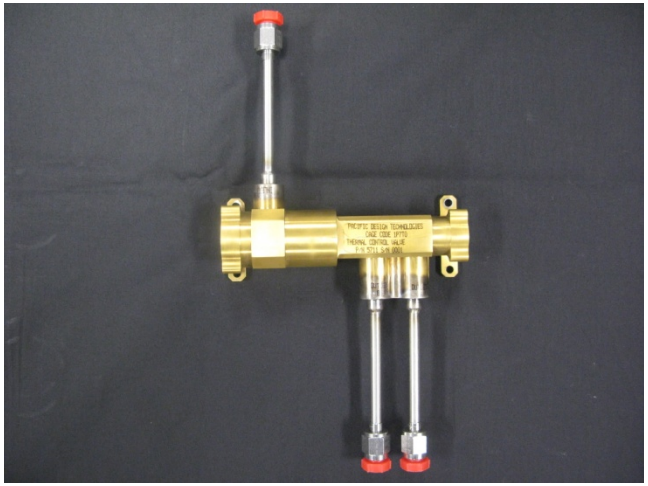
- Two changes were made from previous designs
  - May eliminate oscillations seen in previous systems

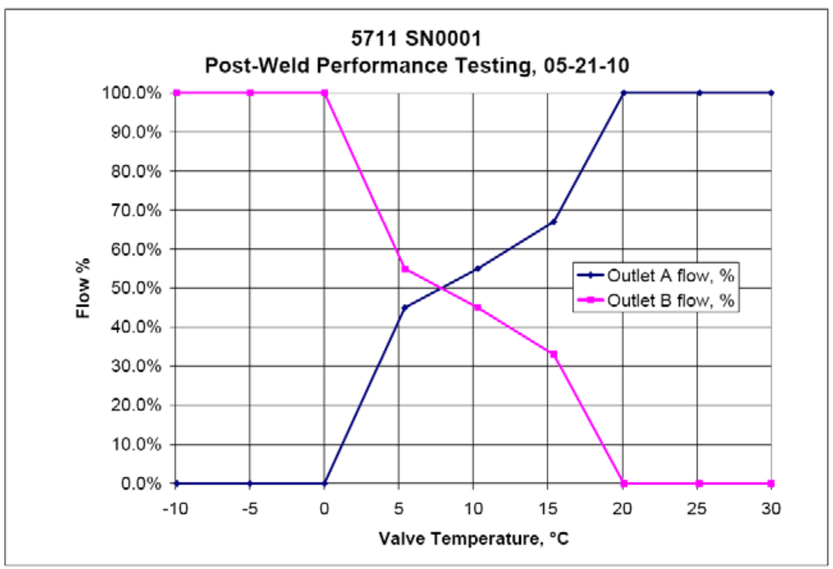
1. TCV is not dependent on system pressure
   - Easier to set up oscillations with pressurized bellows
2. Bypass vapor can go directly into the Compensation Chamber
   - Eliminates large vapor volume introduced into liquid return line, interfering with low liquid volumes





Thermal Control Valve





- TCV pre-weld and post-weld performance was tested by PDT prior to delivery using gaseous nitrogen
- Results from pre-weld and post-weld performance testing are as expected
  - Temperature drops from 20ºC to 0° C, the ratio of flow switches so the flow transfers from outlet A to outlet B.
  - This continues until approximately 20° C where outlet A now has nearly 100% of the flow and outlet B has nearly 0% of the flow

Ammonia Freeze/Thaw

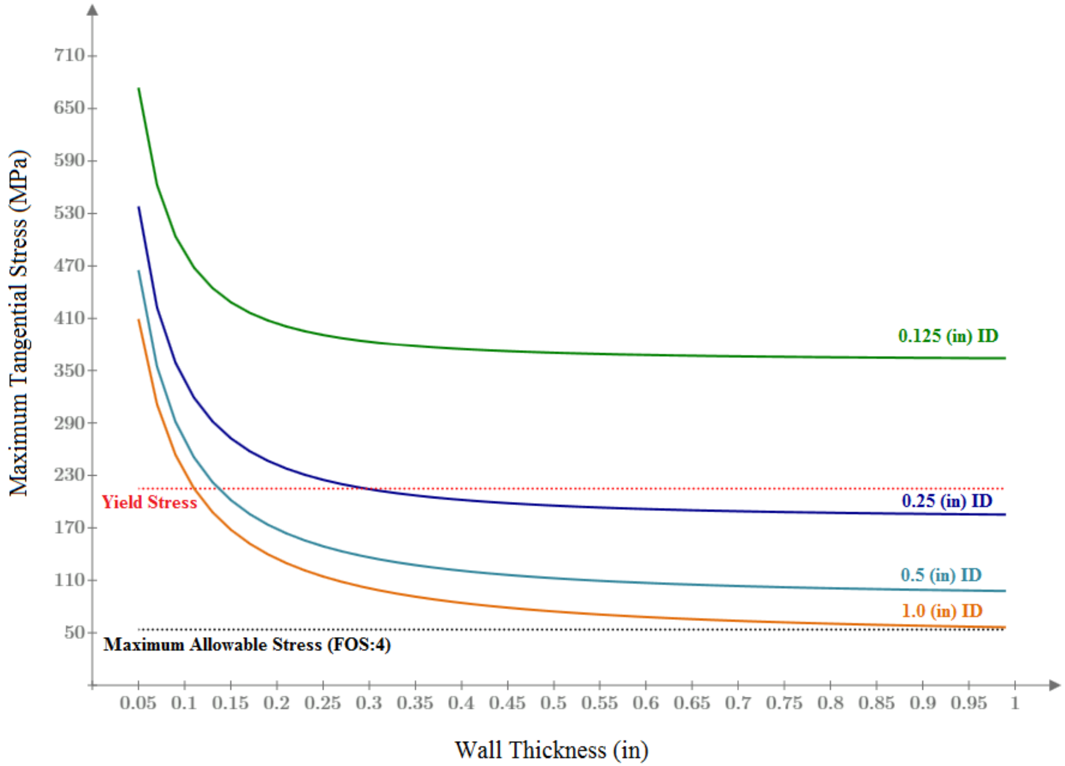
- Sink temperature on Moon and Mars low enough at night for ammonia to freeze in condenser
  - Ammonia contracts when it freezes, expands when it thaws
    - Opposite of water
  - If completely full of ammonia ice, condenser could be damaged by expansion during thaw
- Previous LHPs in space have heaters to prevent the ammonia from freezing in the condenser
  - Not satisfactory for Moon or Mars, due to longer shut-off times
- JPL believed that a vertical LHP condenser could be successfully frozen and rethawed
  - Possible for small amount of liquid to drain in an inactive, vertical condenser

JPL LHP and Freeze/Thaw Testing

- JPL developed a LHP for Mars, and did all of the Earth-based testing necessary to qualify it.
  - Ammonia working fluid, aluminum evaporator, 1.3 cm (0.5 inch) diameter primary wick, stainless steel lines and condensers
  - 1 W to shut down
- Tests included
  - Thermal Performance
  - Shock and Vibration, including Martian landing
  - Proof-pressure
  - Liquid and vapor line flexibility
- Freeze/Thaw tests
  - Vertical evaporator
  - Thick walled stainless steel tubes to withstand ammonia expansion
  - Successfully underwent 100 freeze/thaw cycles

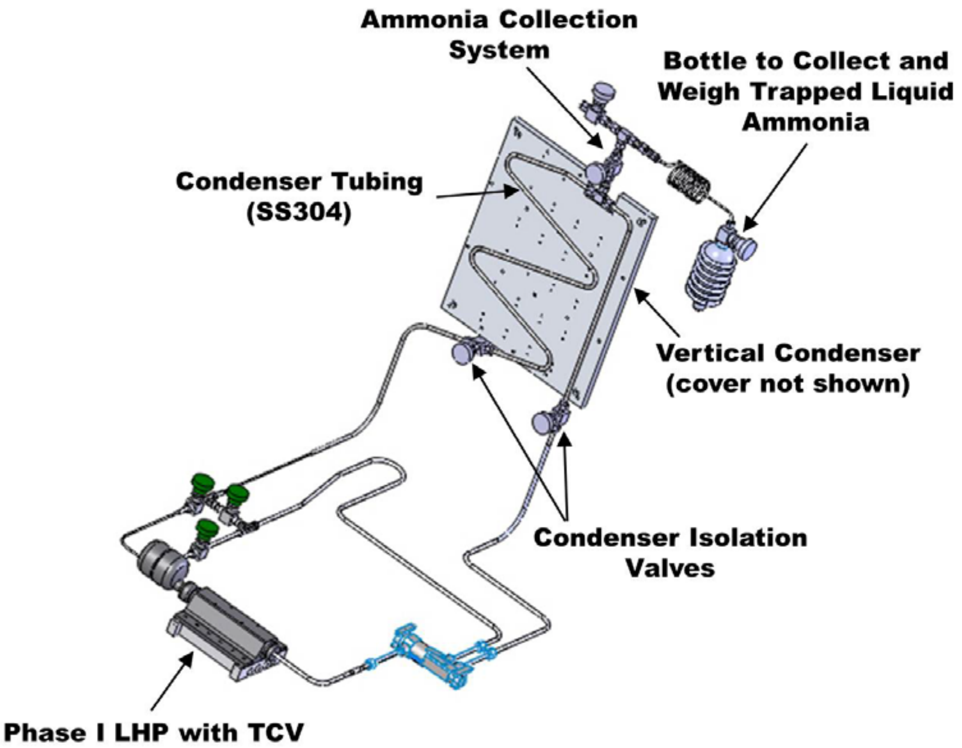
Stresses During Thaw

- Calculated Stresses are extremely high during thawing
  - Assume entire tube filled with ammonia ice
  - Since deformation not observed during JPL freeze/thaw tests, condenser must have some voids



Condenser Drainage Testing

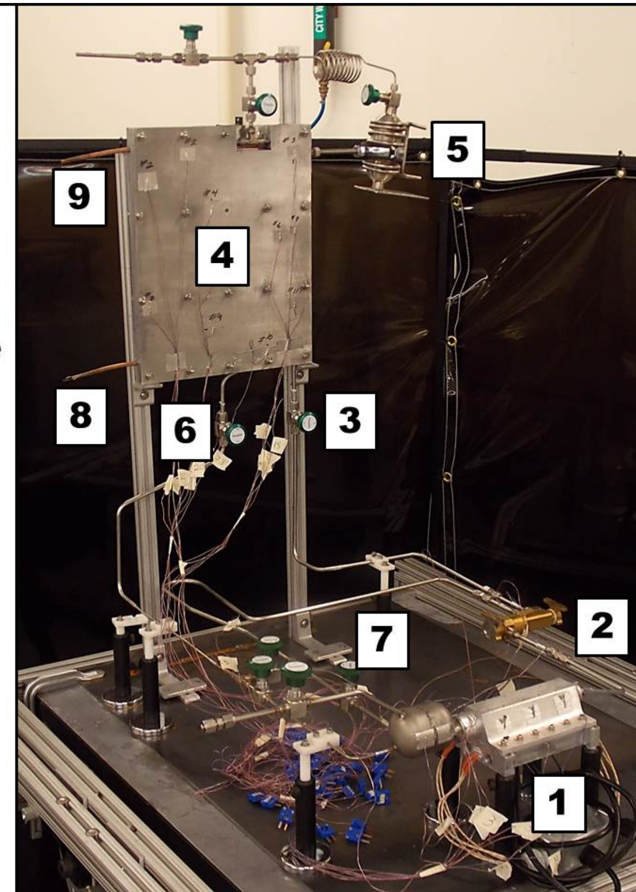
- JPL tests indicated that there was some vapor in the frozen condenser
- Fabricated LHP with TCV with a radiator designed to determine the amount of ammonia in an inactive condenser, just before freezing
- Tubing angled at 32º so that will drain in a 14º tilted environment
- To determine ammonia mass in condenser, close valve to trap ammonia
- Drive ammonia into a bottle and weigh



Condenser Drainage Testing

- Operate at 110W with a condenser set point of -60° C. until steady state
- Decrease power to 0 W, operate for 2.5 hours
- Isolate the condenser by closing the valves
- Transfer the trapped ammonia in the condenser to the ammonia capture bottle
- Weigh the bottle to determine the amount of ammonia in the condenser.

1 – Evaporator
2 – TCV
3 – Vapor Inlet Isolation Valve
4 – Condenser
5 – NH_3 Capture Bottle
6 – Liquid Outlet Isolation Valve
7 – Bypass Line
8 – Coolant Inlet
9 – Coolant Outlet



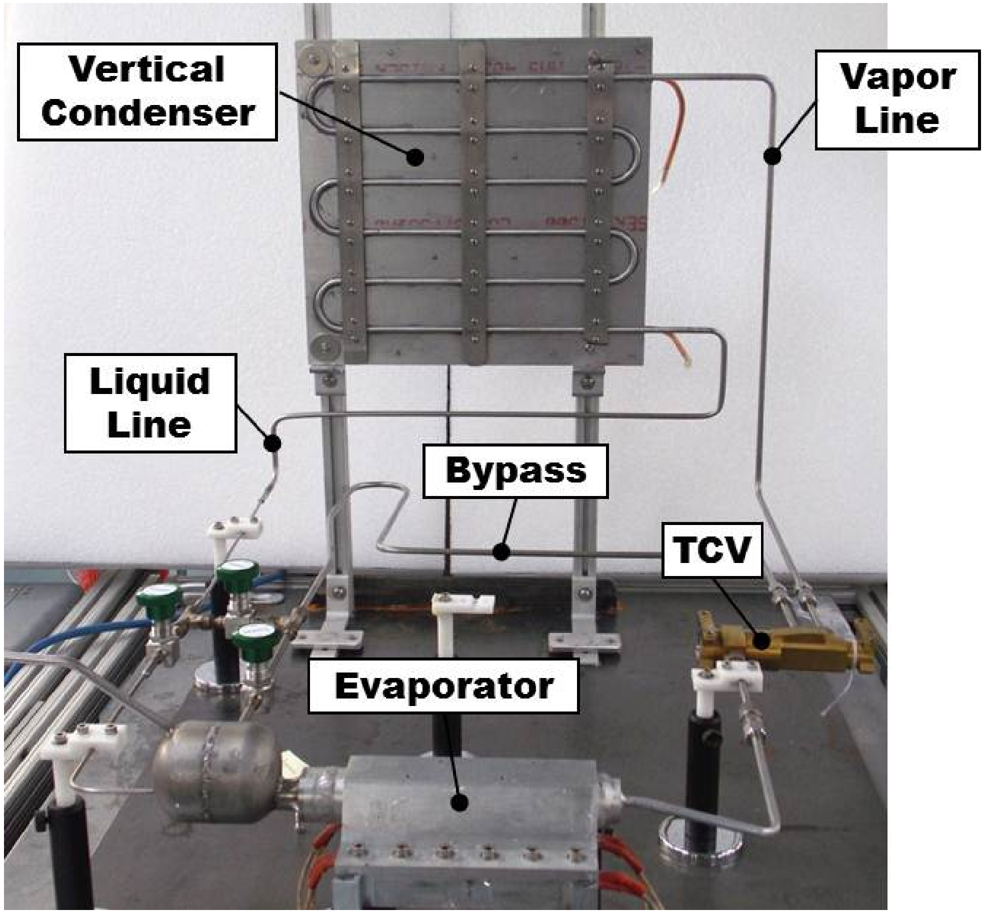
Condenser Drainage Testing Results

- Roughly 4% vapor volume in the inactive condenser
- Small amount of drainage appears to provide sufficient voids to prevent damage during thawing, discussed below

LHP Condenser Tilt	Power Input Applied	Cooling Method	Percentage of Condenser Full of NH_3
Level	110W to 0W	Dynalene in cond top - 60°C	95.89%
Level	110W to 0 W	Dynalene in cond top - 60°C	95.50%
Level	110W to 0 W	Dynalene in cond top - 60°C	95.89%
Level	110W to 0 W	Dynalene in cond top - 10°C	92.18%

Ammonia Freeze/Thaw LHP Test Assembly

- Fabricated freeze/thaw LHP with TCV test assembly
- Condenser has 304 Stainless Steel tubing
  - Allows more deformation before bursting than Al
  - 0.25in (0.64cm) O.D.
  - t_{Wall} of 0.035in (0.089cm)
  - Standard for LHP condenser tubing
- Feed Liquid Nitrogen into condenser cold plate



Ammonia Freeze/Thaw LHP Test Procedure

- Start LHP at a condenser temperature of 20°C and 100W of power input provided to evaporator.
- Cool the condenser in steps to -65°C while maintaining a constant 100W power input to the evaporator.
- Allow the LHP to operate at 100W for 1 hour to achieve steady state. Condenser at -70°C.
- Shut down the LHP by reducing power in 25W intervals (achieving steady state each interval) to 0W.
- Allow LHP to reach steady state at 0W.
- Freeze the condenser by reducing the LN controller temperature
- Allow 1 hour at -120°C to assure complete freeze.
- Warm up the condenser
- Warm-up was performed without additional heat input.

Ammonia Freeze/Thaw LHP Test Results

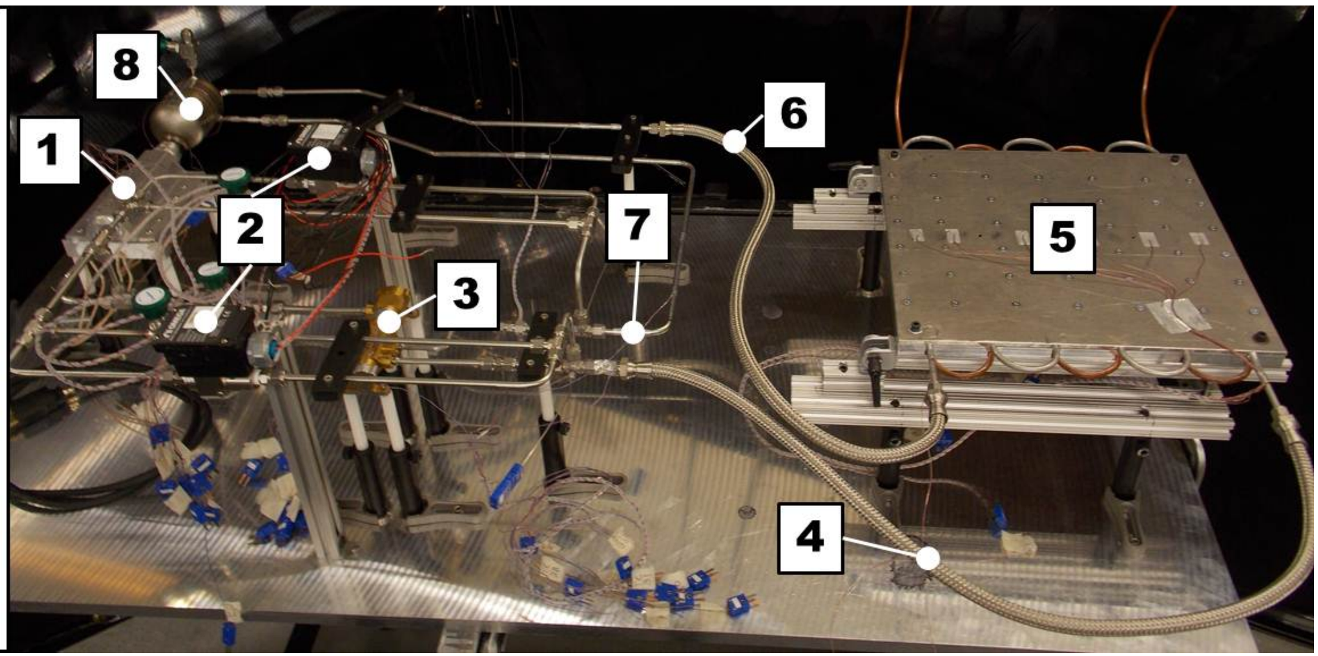
- Conducted 9 freeze/thaw cycles
- Measure geometry of condenser before testing, and after every cycle at 67 locations.
- Minimal distortion observed
- Change of 0.007 inches (0.018cm) in three locations, other locations less than 0.005 inch (0.013cm)

Cycle No	Cooling Direction	Freezing Procedure	Warming Procedure
1	LN top to bottom	Rapid freeze to -120°C, -120° 1hr	Power off, Insulation loosened
2	LN top to bottom	Rapid freeze to -120C, -120°C 1hr	Power off insulation in place
3	LN top to bottom	Rapid freeze to -120°C, -120°C 2 hr	Power off insulation in place, Restart LHP at 50 W when condenser warms to -60C
4	LN top to bottom	Rapid freeze to -120°C, -120°C 2 hr	Power off insulation in place
5	LN top to bottom	Rapid cool to -120°C, -120°C 2 hr	Power off insulation in place
6	LN top to bottom	Slow freeze A	Power off insulation in place
7	LN bottom to top	Slow freeze A	Power off insulation in place
8	LN bottom to top	Slow freeze B	Power off insulation in place
9	LN bottom to top	Slow freeze B	Power off insulation in place

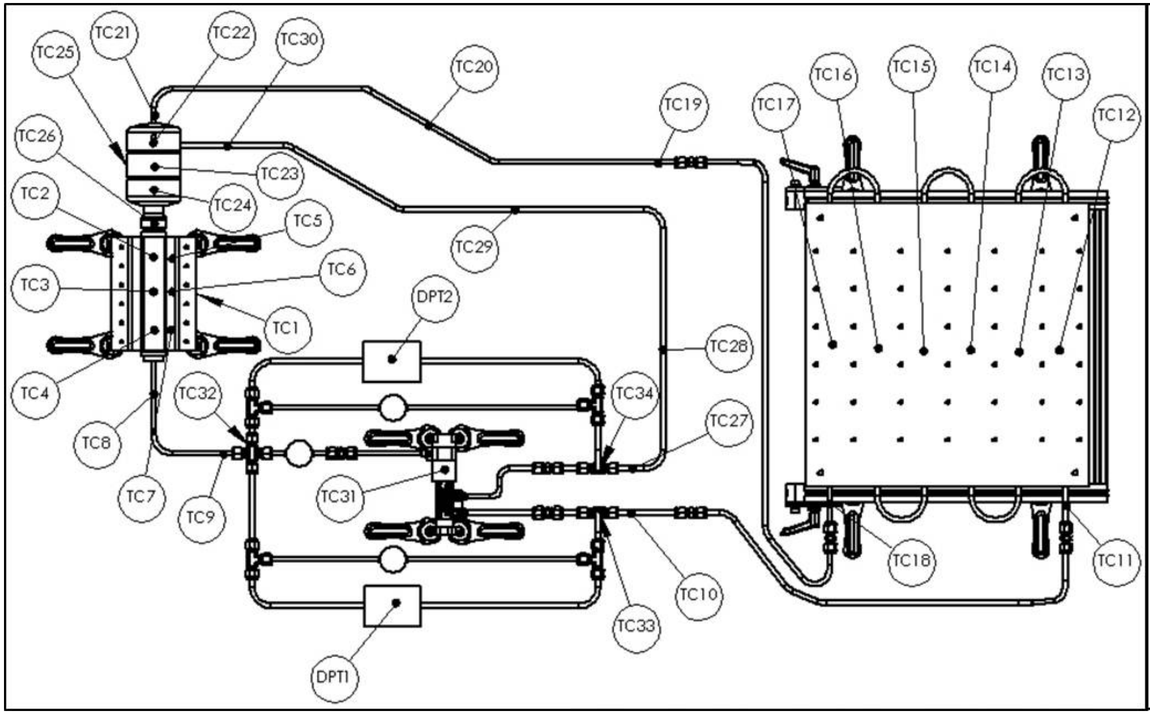
Ammonia LHP with TCV

- Valves around TCV so that it can be bypassed
- Flexible lines allow testing with vertical or horizontal radiator

1 – EVAPORATOR
2 – DPTs
3 – TCV
4 – FLEXIBLE VAPOR LINE
5 – CONDENSER
6 – FLEXIBLE LIQUID LINE
7 – BYPASS LINE
8 – CC



Ammonia LHP Thermocouple Map

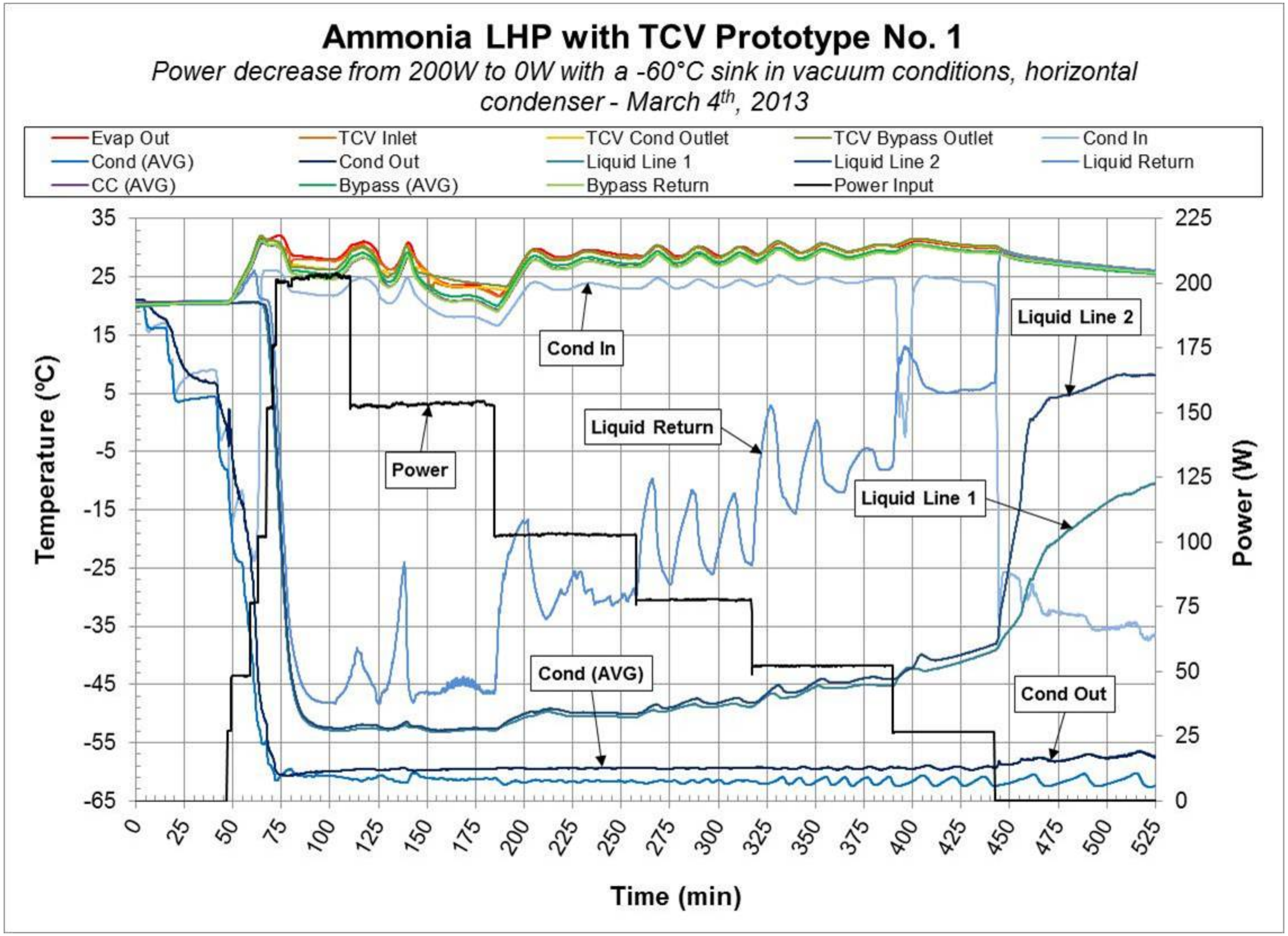


TC1 – Heater Block
TC2 – Evap Top 1
TC3 – Evap Top 2
TC4 – Evap Top 3
TC5 – Evap Side 1
TC6 – Evap Side 2
TC7 – Evap Side 3
TC8 – Evap Out
TC9 – Evap Before Split
TC10 – TCV Out Cond
TC11 – Cond In
TC12 – Cond 1
TC13 – Cond 2
TC14 – Cond 3
TC15 – Cond 4
TC16 – Cond 5
TC17 – Cond 6
TC18 – Cond Out
TC19 – Liquid Line 1
TC20 – Liquid Line 2
TC21 – Liquid Return
TC22 – CC Top 1
TC23 – CC Top 2
TC24 – CC Top 3
TC25 – CC Side
TC26 – Evap bimetallic
TC27 – TCV Out Bypass
TC28 – Bypass 1
TC29 – Bypass 2
TC30 – Bypass Return
TC31 – TCV Body
TC32 – TCV Inlet
TC33 – TCV Cond Outlet (Intrusive)
TC34 – TCV Bypass Outlet (Intrusive)
DPT1 – DPT Cond
DPT2 – DPT Bypass

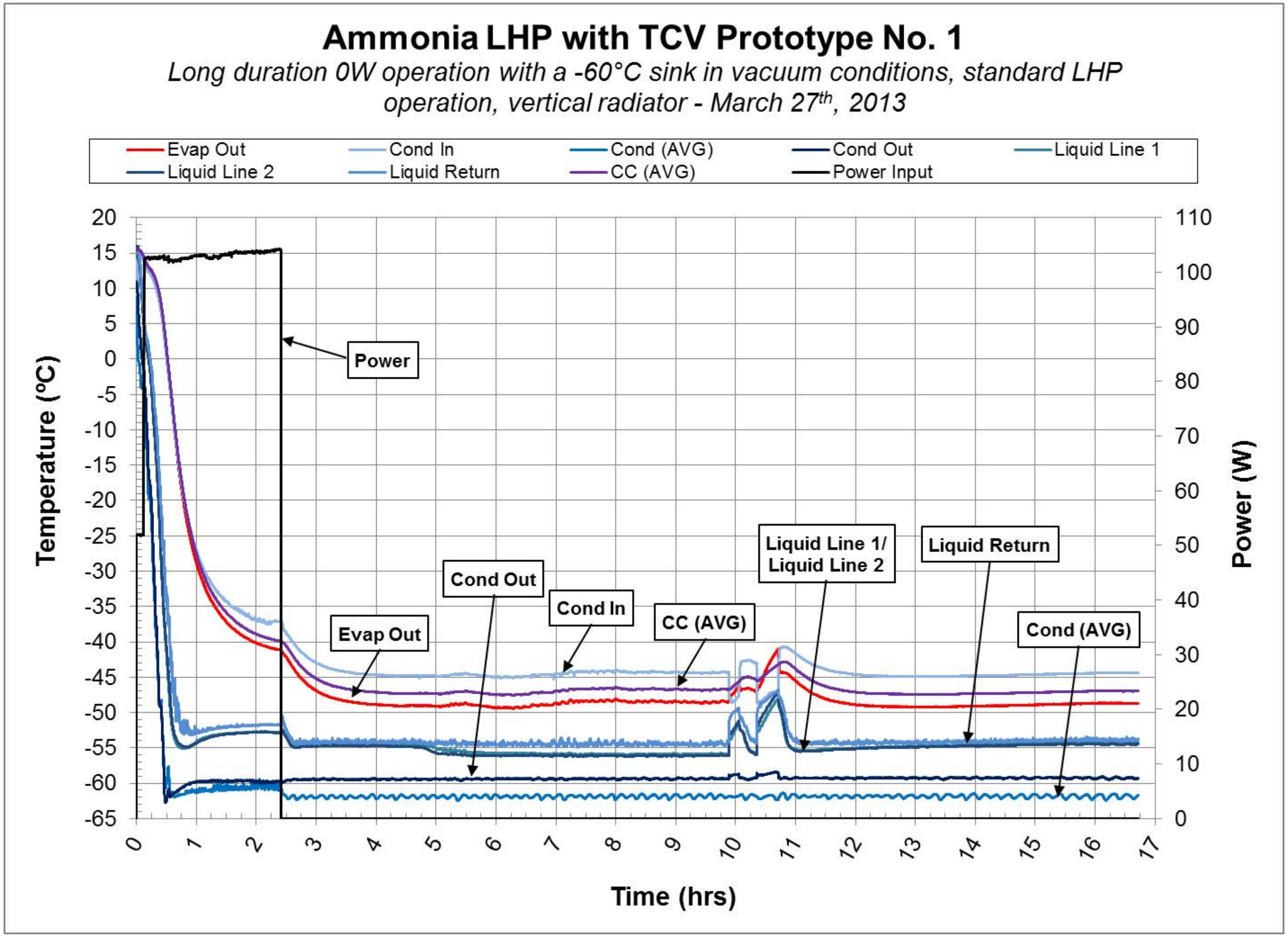
Ammonia LHP with TCV testing

- Tested in a vacuum chamber
  - No cold walls
- Instrumented with 2 Differential Pressure Transducers across the TCV inlet/outlets
- Electrically heated with 4 cartridge heaters
- Condenser assembly mounted to test stand, allowing vertical and horizontal operation
  - Minimal radiation heat transfer to condenser
- Cooling for the condenser was provided using embedded copper tubing in the condenser assembly that is fed liquid nitrogen (LN).
  - LN excites oscillations as it cycles on and off

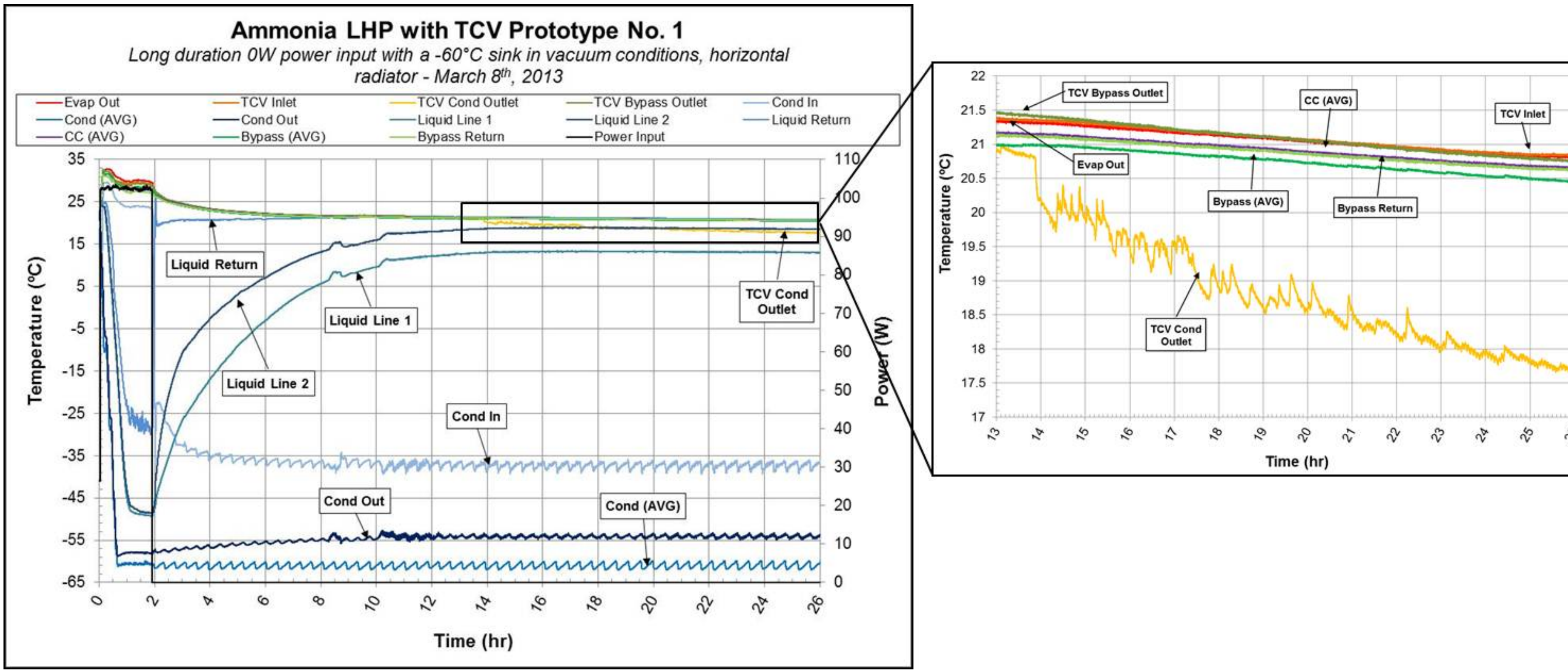
NH_3 LHP with TCV – Stepped Power Decreases



NH_3 LHP without TCV – Long Duration



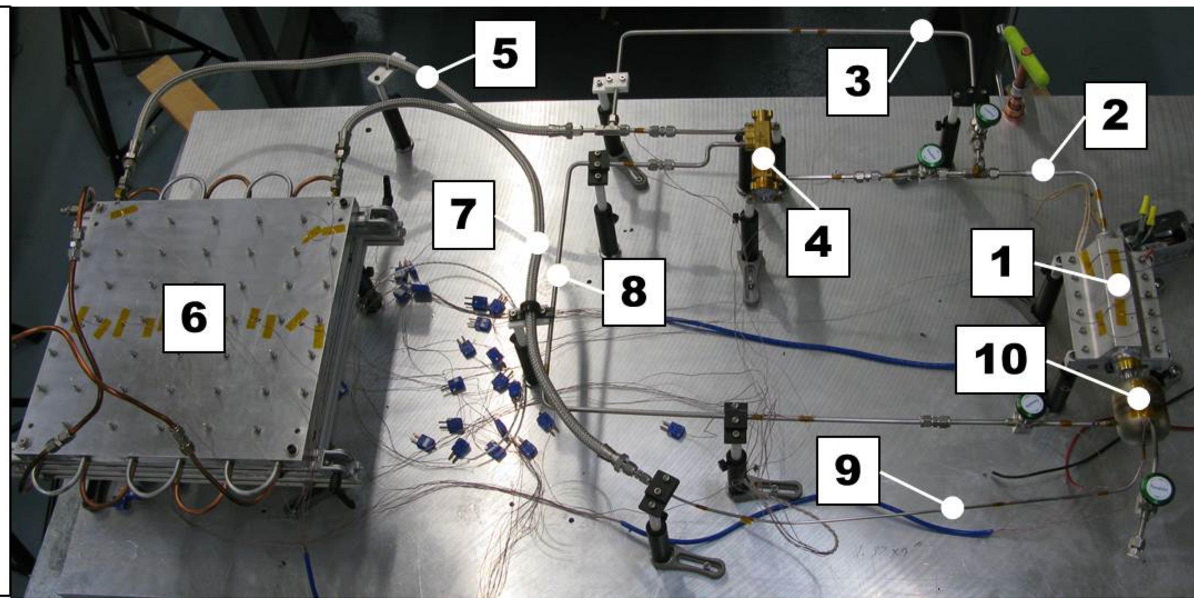
NH_3 LHP with TCV – Long Duration



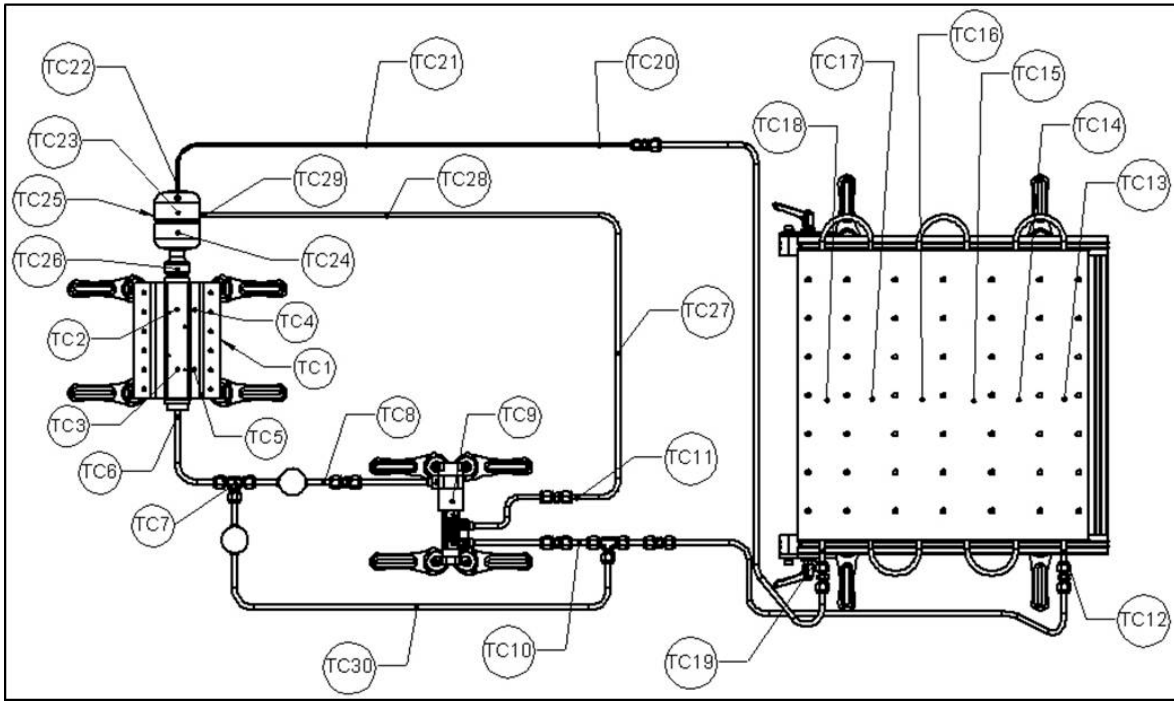
Propylene LHP with TCV

- Valves around TCV so that it can be bypassed
- Flexible lines allow testing with vertical or horizontal radiator

1 – EVAPORATOR
2 – VAPOR OUTLET
3 – TCV BYPASS
4 – TCV
5 – FLEXIBLE VAPOR LINE
6 – CONDENSER
7 – FLEXIBLE LIQUID LINE
8 – BYPASS LINE
9 – LIQUID RETURN
10 – COMPENSATION CHAMBER

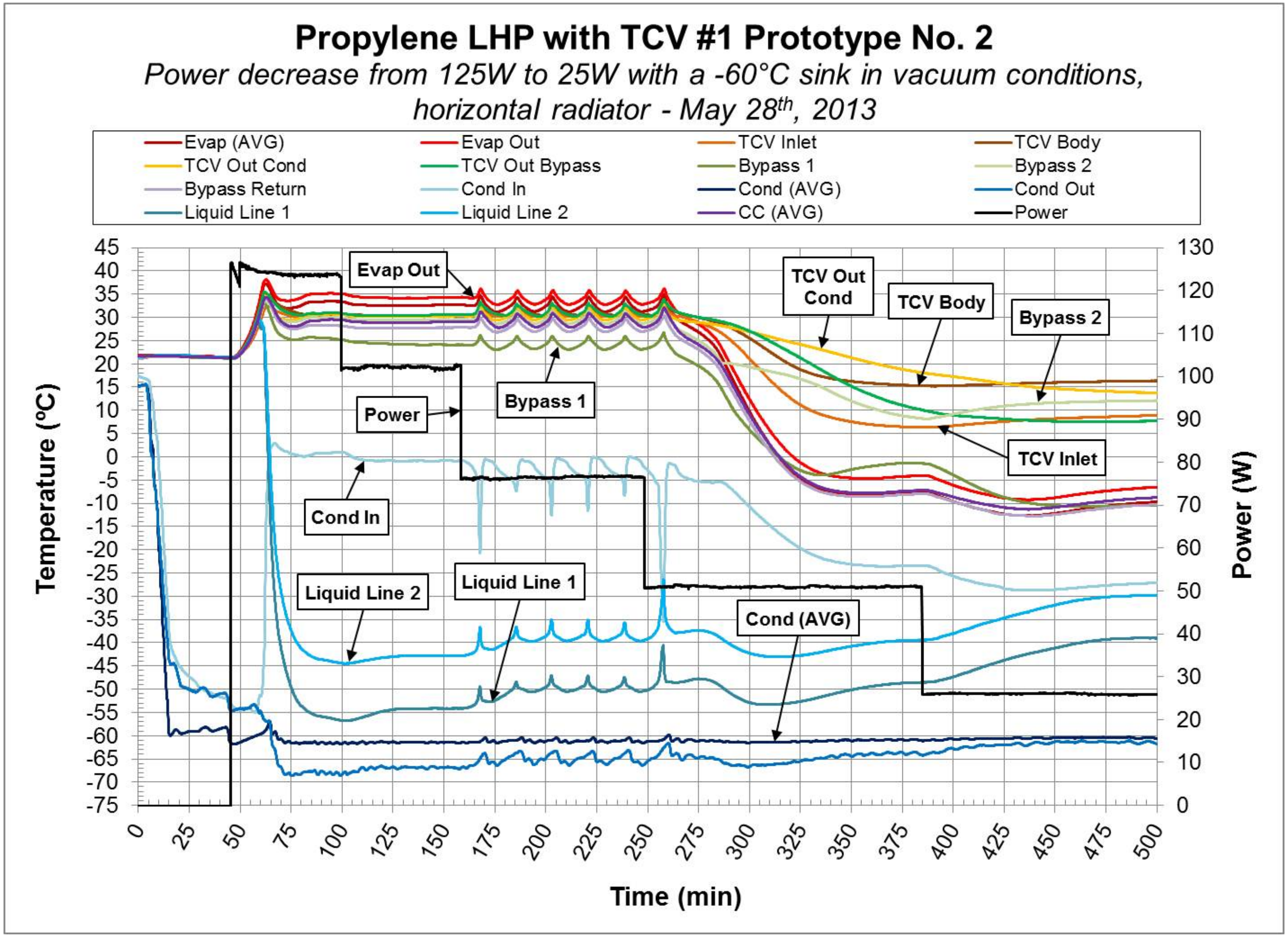


Propylyene LHP Thermocouple Map



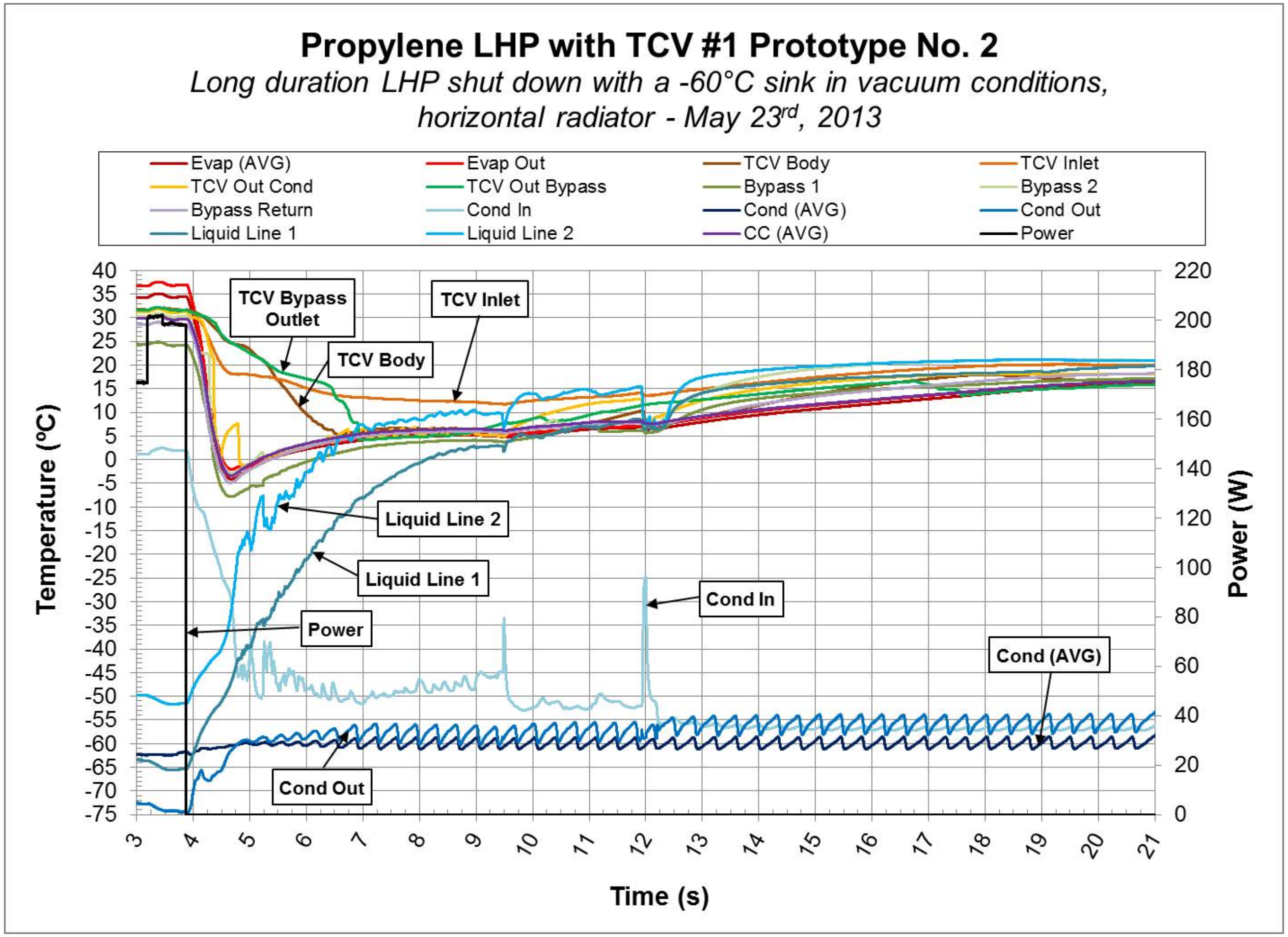
TC1 – Heater Block
TC2 – Evap Top 1
TC3 – Evap Top 2
TC4 – Evap Side 1
TC5 – Evap Side 2
TC6 – Evap Out
TC7 – TCV Inlet (Intrusive)
TC8 – TCV Inlet
TC9 – TCV Body
TC10 – TCV Cond Outlet
TC11 – TCV Bypass Outlet
TC12 – Cond In
TC13 – Cond 1
TC14 – Cond 2
TC15 – Cond 3
TC16 – Cond 4
TC17 – Cond 5
TC18 – Cond 6
TC19 – Cond Out
TC20 – Liquid Line 1
TC21 – Liquid Line 2
TC22 – Liquid Return
TC23 – CC Top 1
TC24 – CC Top 2
TC25 – CC Side
TC26 – Bimetallic Transition
TC27 – Bypass 1
TC28 – Bypass 2
TC29 – Bypass Return
TC30 – Vapor LHP Only

Propylene LHP with TCV – Stepped Power Decreases



Propylene LHP with TCV – Long Duration

- Briefly dropped below goal of 10° C when power was shut off



Conclusions

- Loop Heat Pipe with Thermal Control Valves were developed to provide a variable thermal link over a wide range of environmental thermal conditions for future lunar missions
  - Above the 20ºC maximum temperature set point, a majority of the vapor was routed to the condenser
  - Between 0ºC and 20ºC, a portion of the flow was bypassed to the compensation chamber
  - Below 0ºC, a majority of the flow is bypassed.
- Developed for Lunar and Martian Landers and Rovers
  - Shut off passively, without electrical power
  - 1W = 5 kg batteries
- Examined LHPs with ammonia and propylene working fluids
  - Ammonia is a better working fluid, but freezes at -77ºC

Conclusions

- Examined freeze/thaw behavior in ammonia LHPs with vertical condensers
- Condenser drainage tests were conducted with a vertical condenser
  - Tubing angled so that will drain in a tilted environment
  - Roughly 4% vapor volume in the inactive condenser
  - Small amount of drainage appears to provide sufficient voids to prevent damage during thawing
- Freeze/thaw tests were conducted on an ammonia LHP with TCV
  - Stainless steel condenser tubing
  - Vertical Radiator, liquid nitrogen cooled cold plate
  - 9 freeze/thaw cycles
  - Minimal distortion observed
  - Change of 0.007 inches (0.018cm) in three locations, other locations less than 0.005 inch (0.013cm)

Conclusions

- Developed LHPs with ammonia and propylene working fluids
- Target power of 100 W, maximum power of 200 W
- With constant power, the LHP with TCV can maintain the evaporator temperature as the condenser sink temperature drops
  - Simulates behavior during eclipse for satellite application
- Both systems demonstrated that an LHP with TCV is capable of maintaining an elevated evaporator temperature under cold sink and low power operation
  - Thermal vacuum chamber, liquid nitrogen chilled cold plate
  - Ammonia LHP was more stable
  - Evaporator temperatures in the propylene LHP with TCV dropped below the operating temperature design requirements for an extended period of time.
- Next Step: Additional thermal vacuum chamber testing of the ammonia LHP with TCV at NASA Marshall

Acknowledgements

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- Any opinions, findings, and conclusions or recommendations expressed in this presentation are those of the authors and do not necessarily reflect the views of the National Aeronautics and Space Administration.

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