VCHPs for Variable Thermal Links

W.G. Anderson, M.C. Ellis, J.R. Hartenstine,
C.J. Peters, C. Tarau, & K.L. Walker
Advanced Cooling Technologies, Inc.

Presented By

Calin Tarau

Thermal & Fluids Analysis Workshop
TFAWS 2012
August 13-17, 2012
Jet Propulsion Laboratory
Pasadena, CA

Presentation Outline

- Variable Conductance and Gas-Loaded Heat Pipes
- Aluminum/Ammonia VCHPs for Lunar Landers and Rovers
- VCHPs for Balloon Thermal Management
- Titanium/Water VCHPs for Nuclear Fission Space Radiators
- Conclusions and Recommendations

Standard VCHPs for Temperature Control

- VCHPs are most often used for temperature control in spacecraft applications

- Standard VCHP has an evaporator, a condenser, and a reservoir for Non-Condensable Gas (NCG)
- Cold-biased reservoir is located next to the condenser.
- Electrical heaters control the reservoir temperature
- Typically maintain evaporator temperature control of ± 1-2 °C over widely varying evaporator powers and heat sink temperatures
- Roughly 1-2 W electrical power required for the reservoir heaters

Variable Thermal Links

- VCHPs and Gas-Loaded Heat Pipes can also be used for variable thermal links, and to aid in start-up from a frozen state
  - Gas loaded heat pipe similar to a VCHP, but “reservoir” is an extension of the condenser
- Variable thermal link
  - Maintain evaporator temperature range in a fairly broad temperature range with large variations in sink temperature
  - Transmit heat readily during hot sink conditions
  - Minimize heat transmission during cold sink conditions
- Applications that can benefit from using VCHPs as variable thermal links include
  - Lunar and Martian Landers and Rovers
  - Research Balloons
  - Lunar and Space Fission Reactors
- The above applications can allow relatively wide temperature swings, but need to minimize or eliminate electrical heater power

Variable Thermal Links

- Applications that require variable thermal links generally have the following factors
- Variable system loads resulting from intermittent use
  - Desire to power down systems between missions
  - Results in large turn down ratios
- Large changes in environment temperature
  - Lunar surface temperature range: -140 °C to 120 °C
  - Mars equatorial, near-surface temperature range: -100 °C to 0 °C
  - Research balloons: air temperatures ranging from -90 °C to +40 °C
- Limited electrical power
  - Lunar applications must survive the 14-day-long Lunar night
  - 1 W = 5 kg of energy storage and generation
  - Research balloons have similar constraints
    - Fly near poles in winter

Freeze/Thaw and Startup

- Many applications with variable thermal links also need to consider freeze/thaw and start-up from a frozen state
- Fortunately, the NCG in the heat pipe also helps when the pipe is frozen, and during start-up
- NCG gas in the heat pipe suppresses fluid movement when a portion of, or the entire pipe is frozen
  - With a warm evaporator, prevents vapor from freezing in the condenser, starving the evaporator of working fluid
  - For water heat pipes and thermosyphons, minimizes sublimation of the water from the evaporator to the condenser when the entire pipe is frozen
- NCG also aids start-up from the frozen state by providing a back pressure in the heat pipe condenser during start-up
  - Short Effective Condenser Length
  - Commonly used trick for alkali metal heat pipes

Reservoir Location and Connections

- Variable thermal link VCHPs can have 3 different reservoir configurations

1. Reservoir located near the evaporator, with an internal line
   - Warm reservoir, tighter temperature control
   - More expensive to fabricate, may aid in routing
2. Reservoir located near the evaporator, with an external line
   - Warm reservoir, tighter temperature control
3. Reservoir at the end of the condenser
   - Conventional geometry , easiest and cheapest to fabricate
   - Cold reservoir, sets a minimum allowable ΔT

- Following 3 programs demonstrate the 3 different configurations

Presentation Outline

- Variable Conductance and Gas-Loaded Heat Pipes
- Aluminum/Ammonia VCHPs for Lunar Landers and Rovers
- VCHPs for Balloon Thermal Management
- Titanium/Water VCHPs for Nuclear Fission Space Radiators
- Conclusions and Recommendations

ILN Anchor Node Design Targets

Electronics Temperature	-10°C (263 K) to 50°C (303 K)
Radiator Load	94 W on Moon 117 W during Cruise
Maximum Tilt	20° (10° slope, 10° hole)
Max./Min. Radiator Sink	263 K/141 K

- 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
- 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

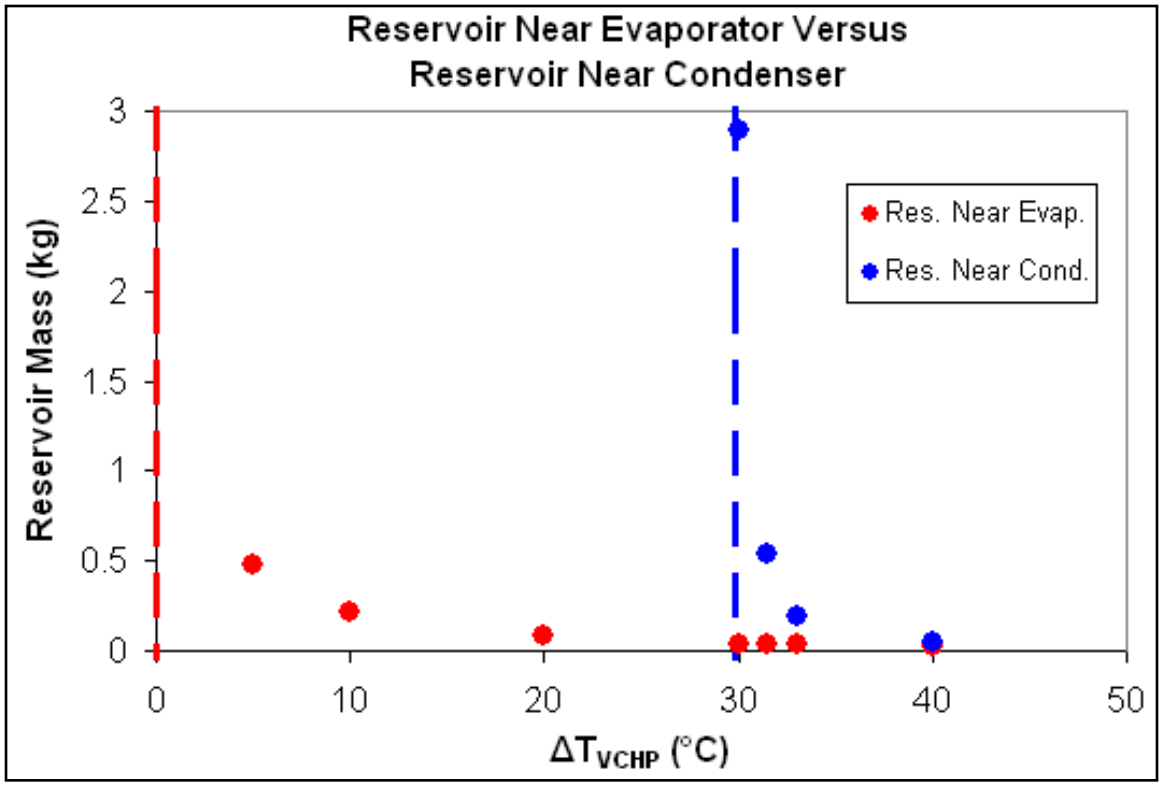
VCHP Design Constraints

- VCHP developed for this program differs from normal VCHP in 5 different ways

1. Need to operate in space, and on the Lunar surface
2. 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
3. Tight temperature control not required
   - Have a ~40°C range versus ±1°C for conventional VCHPs
4. No power available for reservoir temperature control
   - 1 W = 5 kg
   - External reservoir will cool down to ~140 K
5. Need to minimize heat leak when shut down

ILN Anchor Node – NCG Reservoir Adjacent to Evaporator

- Standard reservoir location has poorer thermal control

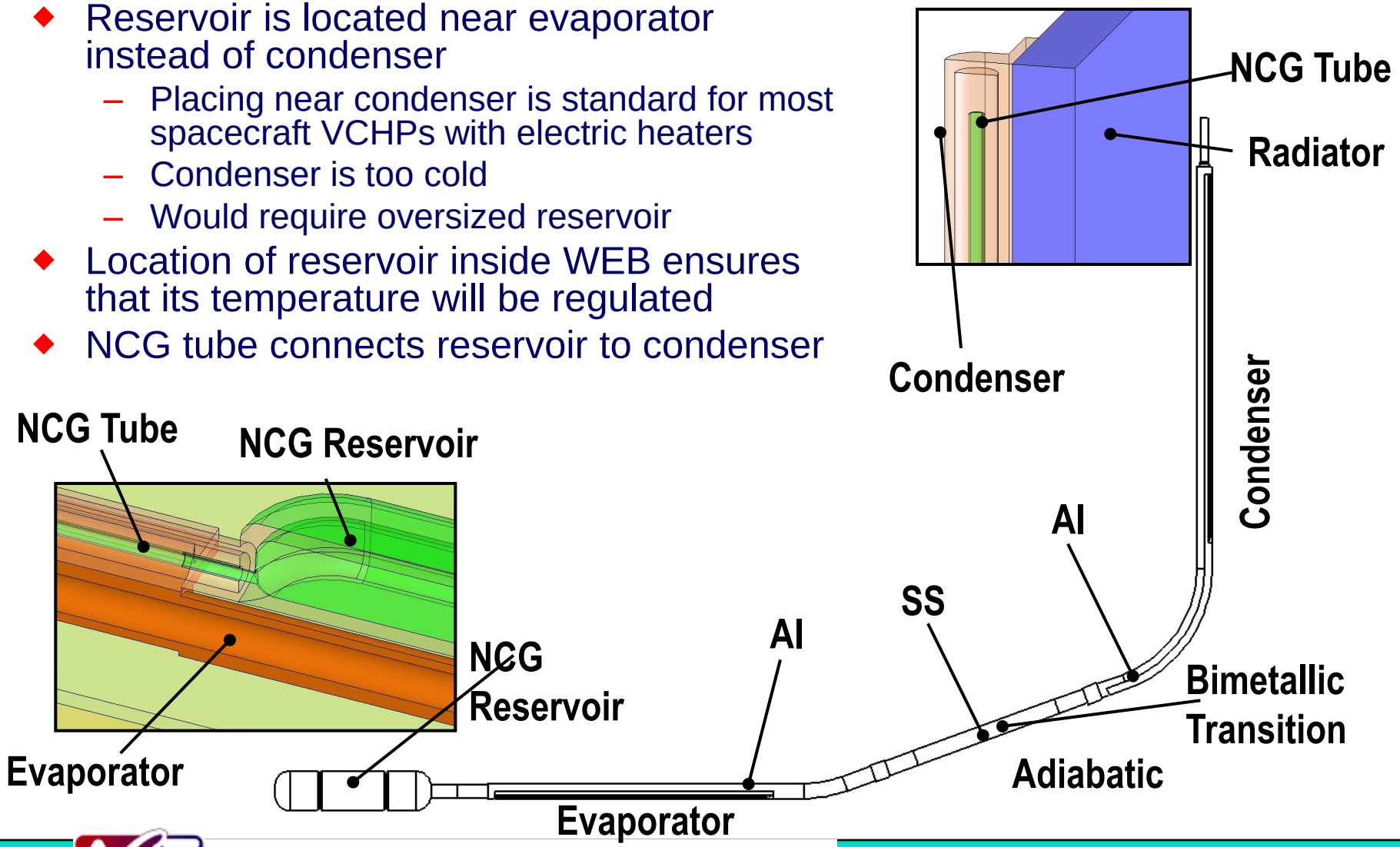


Vertical Asymptotes

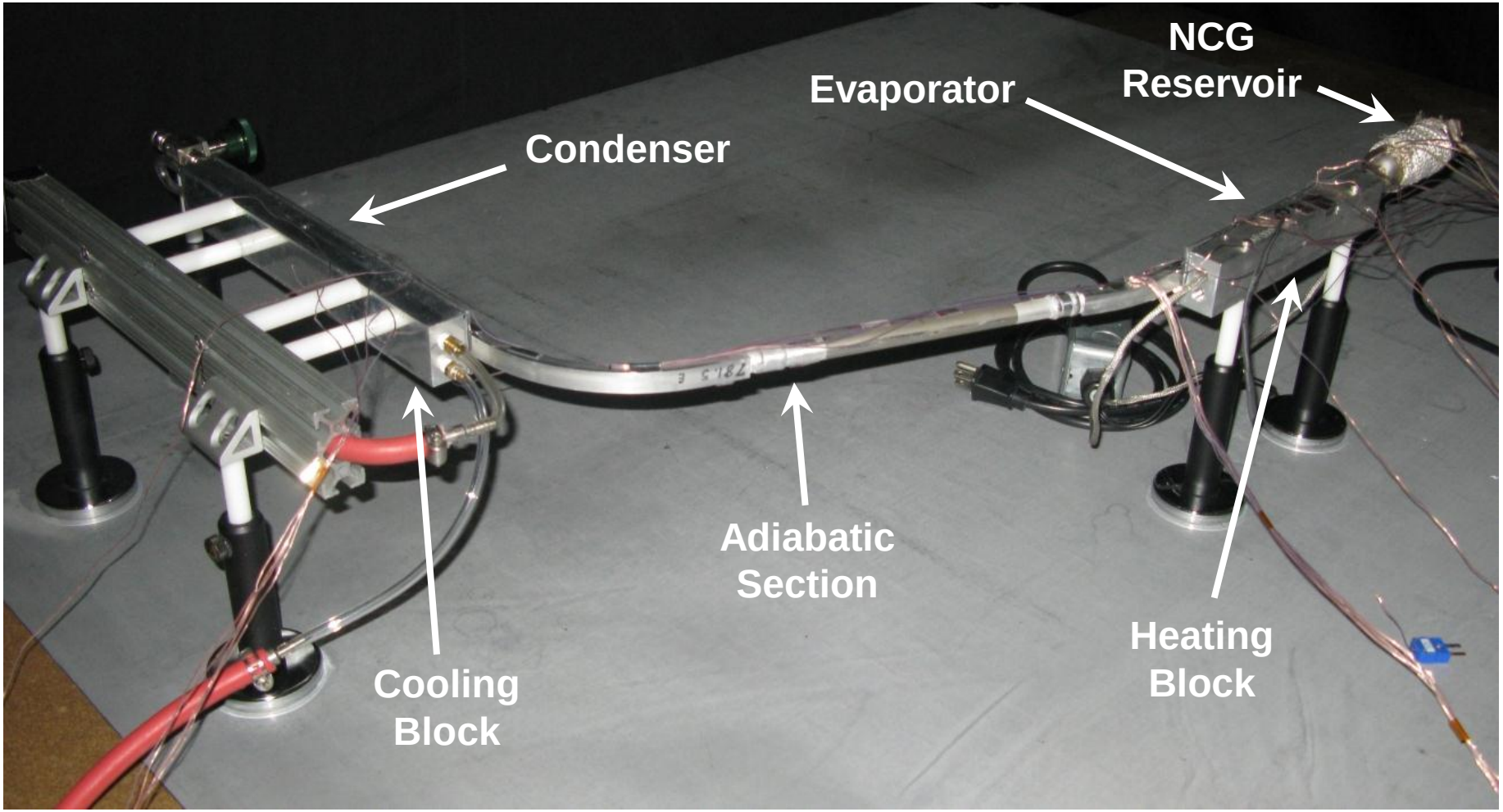
1. Reservoir Near Evaporator: 0 K
2. Reservoir Near Condenser: ≈29.78 K

Overall Design – NCG Reservoir Adjacent to Evaporator

- Reservoir is located near evaporator instead of condenser
  - Placing near condenser is standard for most spacecraft VCHPs with electric heaters
  - Condenser is too cold
  - Would require oversized reservoir
- Location of reservoir inside WEB ensures that its temperature will be regulated
- NCG tube connects reservoir to condenser



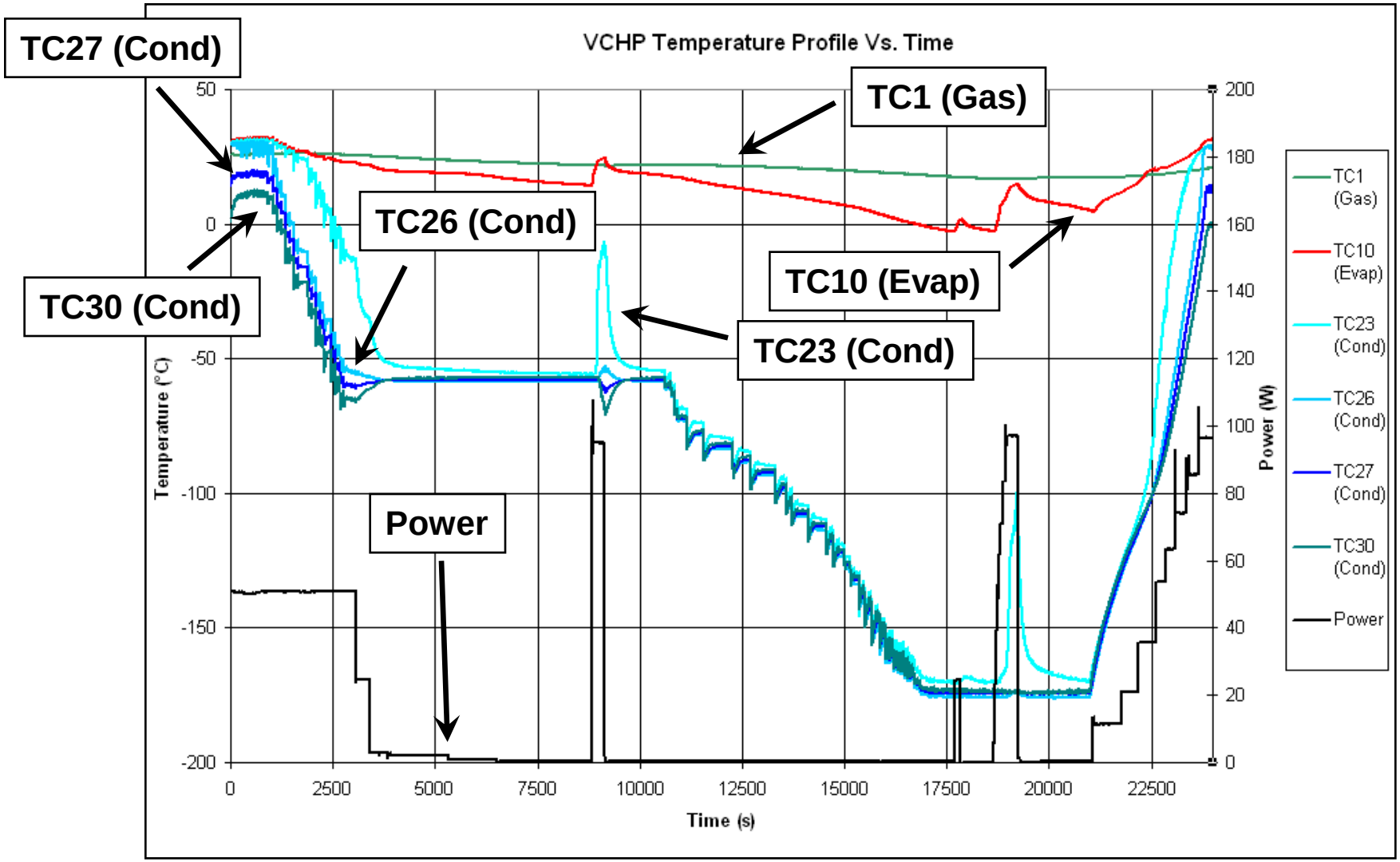
VCHP with Internal Reservoir



VCHP Testing – Lunar Freeze/Thaw

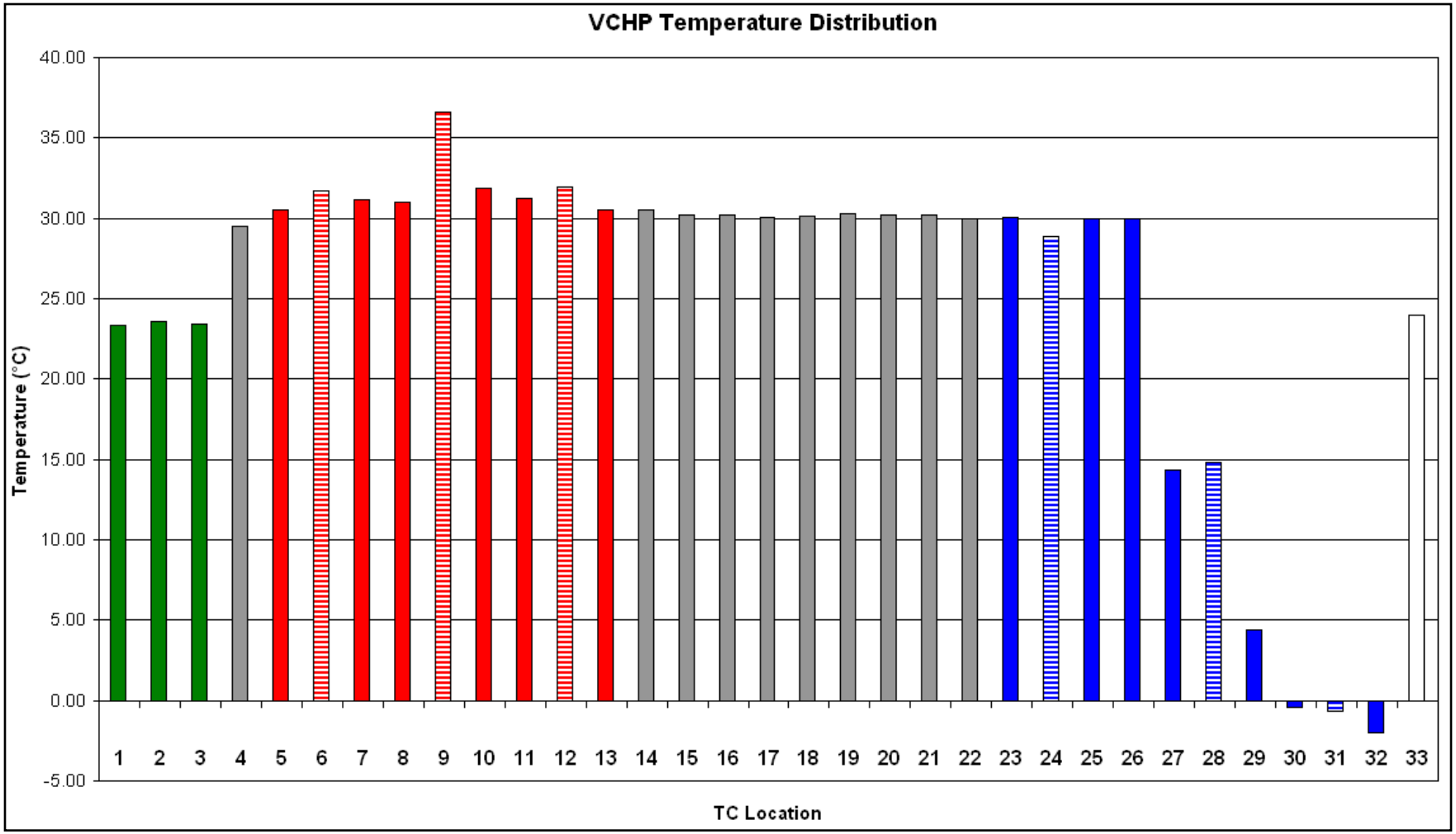
- Purpose
  - Demonstrate ability to shut down
  - Demonstrate ability to startup and operate for brief periods of time when cold
  - Determine overall thermal conductance
- Procedure
  - Vary sink conditions to simulate lunar cycle
    - -60ºC (liquid) and -177ºC (frozen)
  - Several orientations
    - -2.3º & +2.3º
    - Condenser nearly vertical
    - Adiabatic and condenser sections gravity aided
  - 25ºC initial evaporator temperature
  - Measure performance
    - Evaluate temperature gradients across heat pipe; conductances; input power

VCHP Testing – Lunar Freeze/Thaw Results



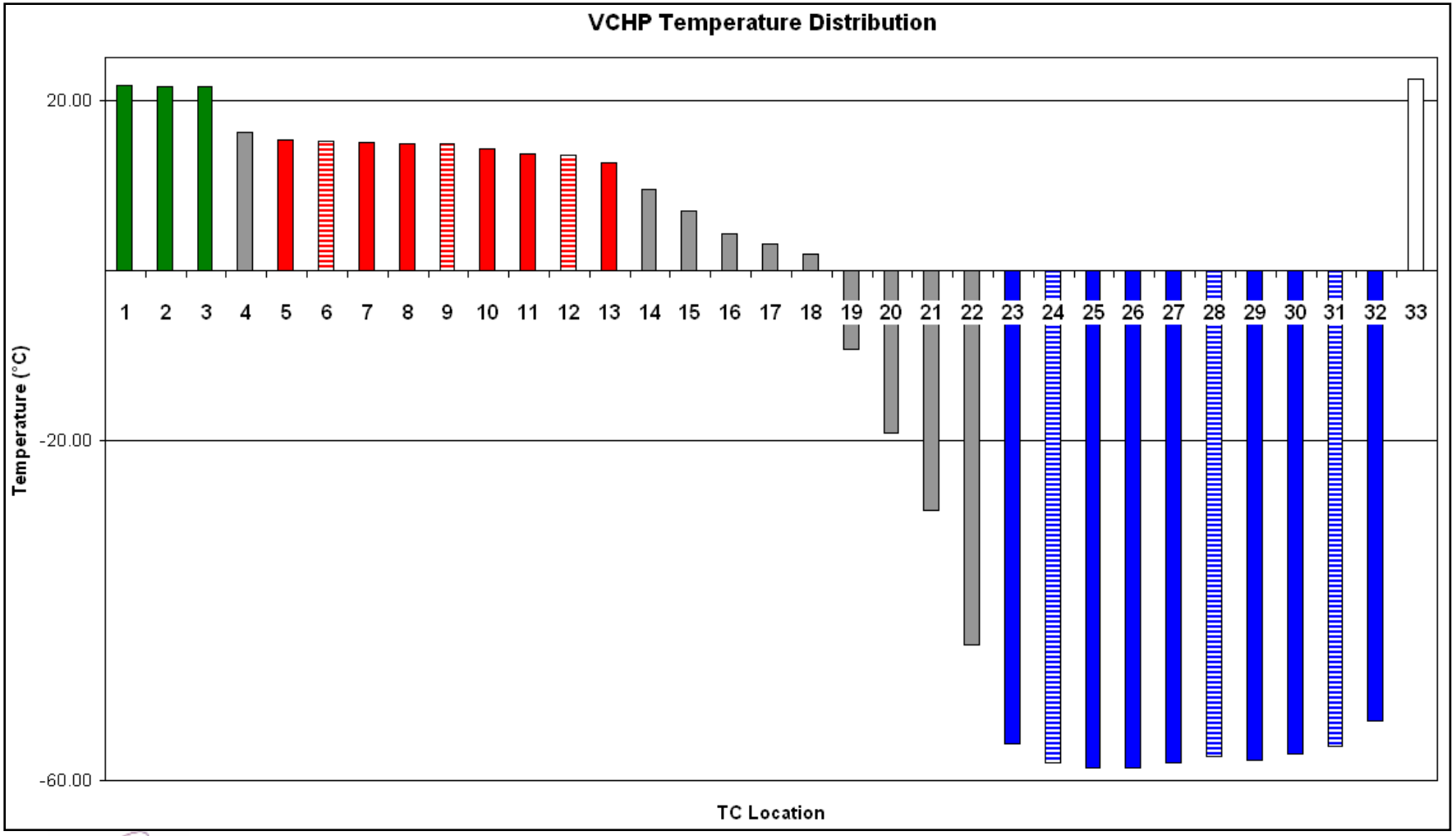
VCHP Testing – Lunar Freeze/Thaw Results

VCHP Operation (25 °C, 95 W, -2.3°)



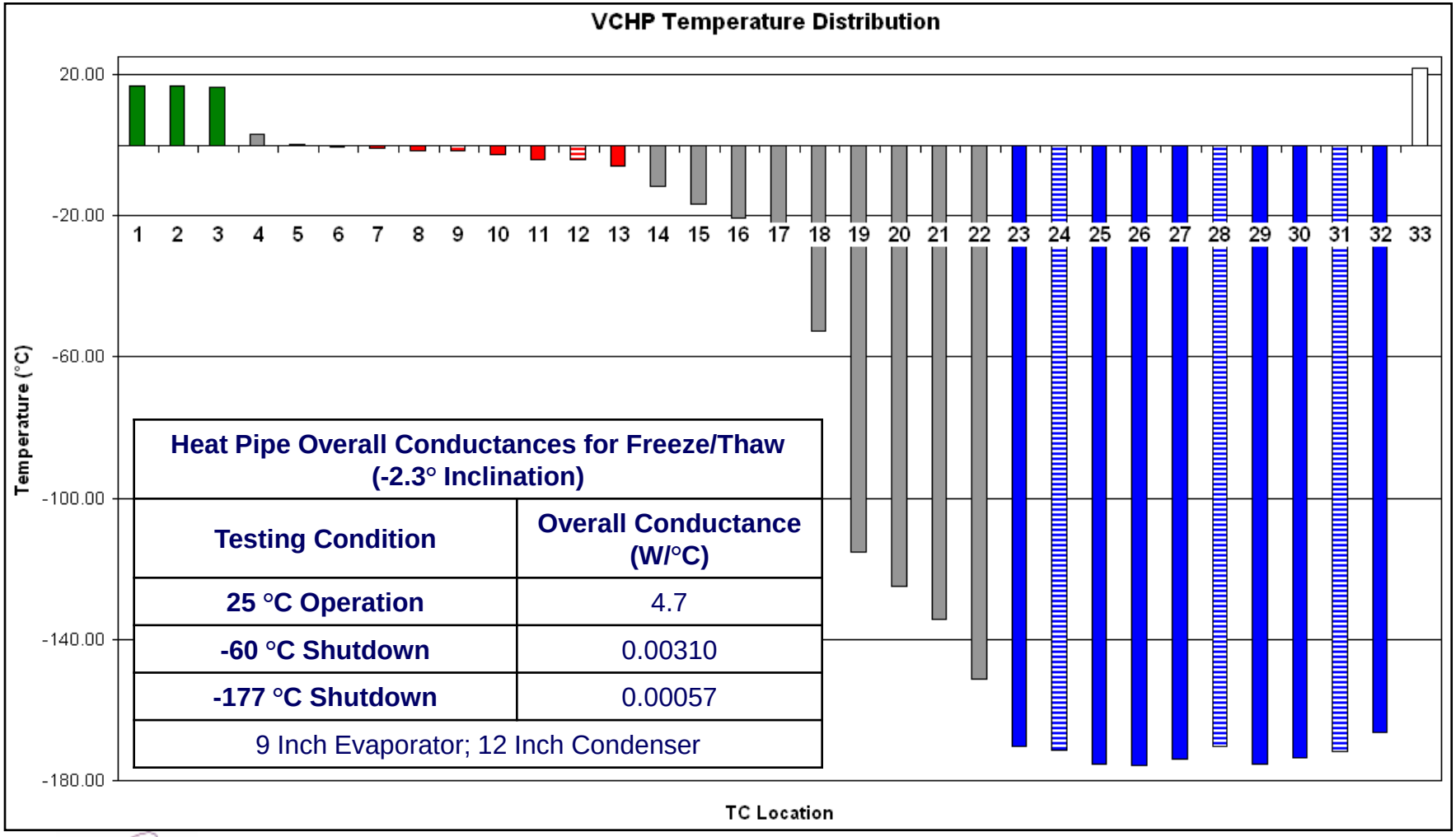
Task 3. VCHP Testing – Lunar Freeze/Thaw Results

VCHP Cold Shutoff (-60 °C, 0.2 W, -2.3°)



VCHP Testing – Lunar Freeze/Thaw Results

VCHP Very Cold Shutoff (-177 °C, 0.1 W, -2.3°)



Heat Pipe Overall Conductances for Freeze/Thaw (-2.3° Inclination)	
Testing Condition	**Overall Conductance (W/°C)**
25 °C Operation	4.7
-60 °C Shutdown	0.00310
-177 °C Shutdown	0.00057
9 Inch Evaporator; 12 Inch Condenser	

Al/NH_3 VCHP Testing – Lunar Freeze/Thaw Results

- VCHP can undergo freeze/thaw cycles without performance degradation
- Effectively shuts off at cold temperatures and reduces heat transfer
- VCHP can experience short-duration full-power bursts during -60 °C and -177 °C cold shutdown
- Evaporator stays within -10 °C to +50 °C temperature range with no power except heat in-leak

Presentation Outline

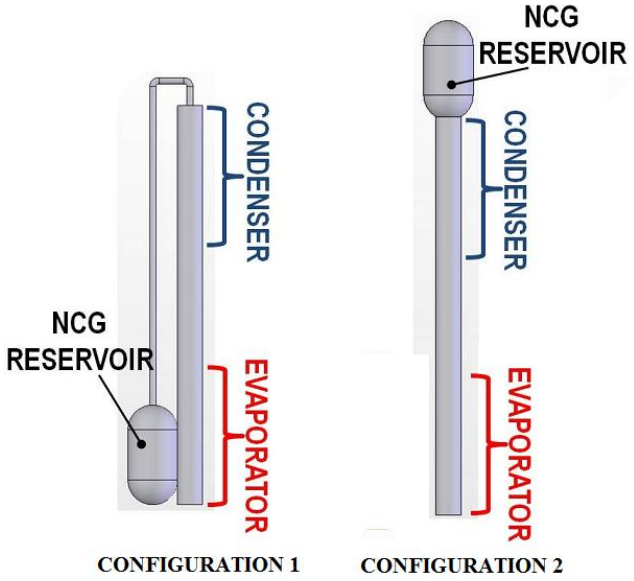
- Variable Conductance and Gas-Loaded Heat Pipes
- Aluminum/Ammonia VCHPs for Lunar Landers and Rovers
- VCHPs for Balloon Thermal Management
- Titanium/Water VCHPs for Nuclear Fission Space Radiators
- Conclusions and Recommendations

Motivation – VCHPs for Balloons

- Payloads of terrestrial high altitude balloons need a Thermal Management System (TMS) to:
  - **Reject waste heat**
  - **Maintain a stable temperature** as the heat sink (air) temperature swings between -90°C to 40°C
  - If active, the TMS should use **minimum power**
  - Low budget imposes a **low cost** TMS
- Current solution: copper constant conductance heat pipes (CCHPs) move the waste heat over long distances
  - **Problem:** Conductance cannot effectively be reduced under cold operating or cold survival environment conditions without expending significant energy in an active heater to keep the condenser warm.

VCHPs with Cold and Warm Reservoir

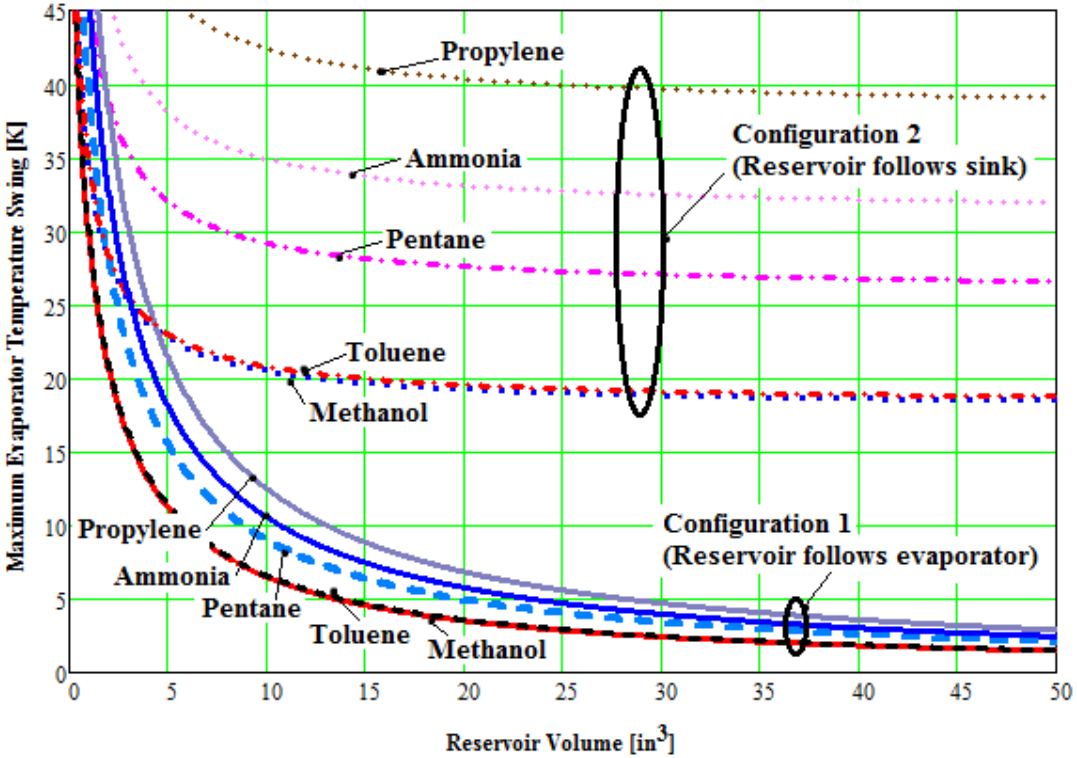
- VCHP required to passively maintain a relatively constant evaporator (payload) temperature while the sink temperature varies between -90 and 40°C
- Two potential VCHP evaporator – condenser – reservoir arrangements were tested



Parameter	Value
VCHP Total Length [in]	30
VCHP OD [in]	0.5
VCHP ID [in]	0.46
Evaporator Length [in]	6
Condenser Length [in]	12
Adiabatic Zone Length [in]	12
Reservoir OD [in]	2.5
Reservoir Length [in]	6
Condenser – Reservoir Connecting Tube Length [in]	3…24

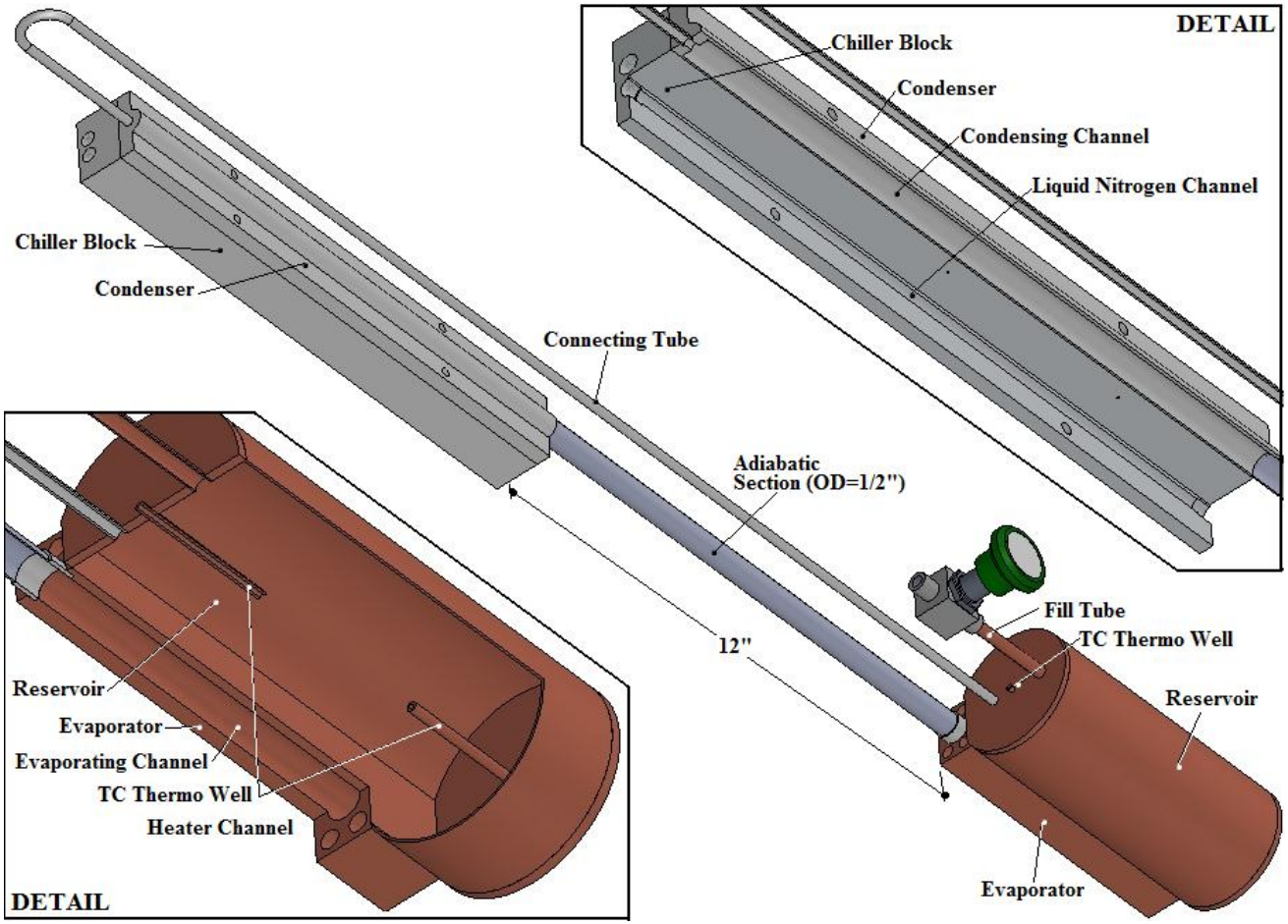
VCHP Performance dependence on Configuration / Working Fluid / Reservoir Size

- Maximum evaporator temperature swings (as the sink temperature sweeps the entire range) as a function of reservoir size.
  - Configuration 1 (warm reservoir) can reach relatively tight temperature control with reasonable reservoir size
  - Methanol and toluene show best temperature control



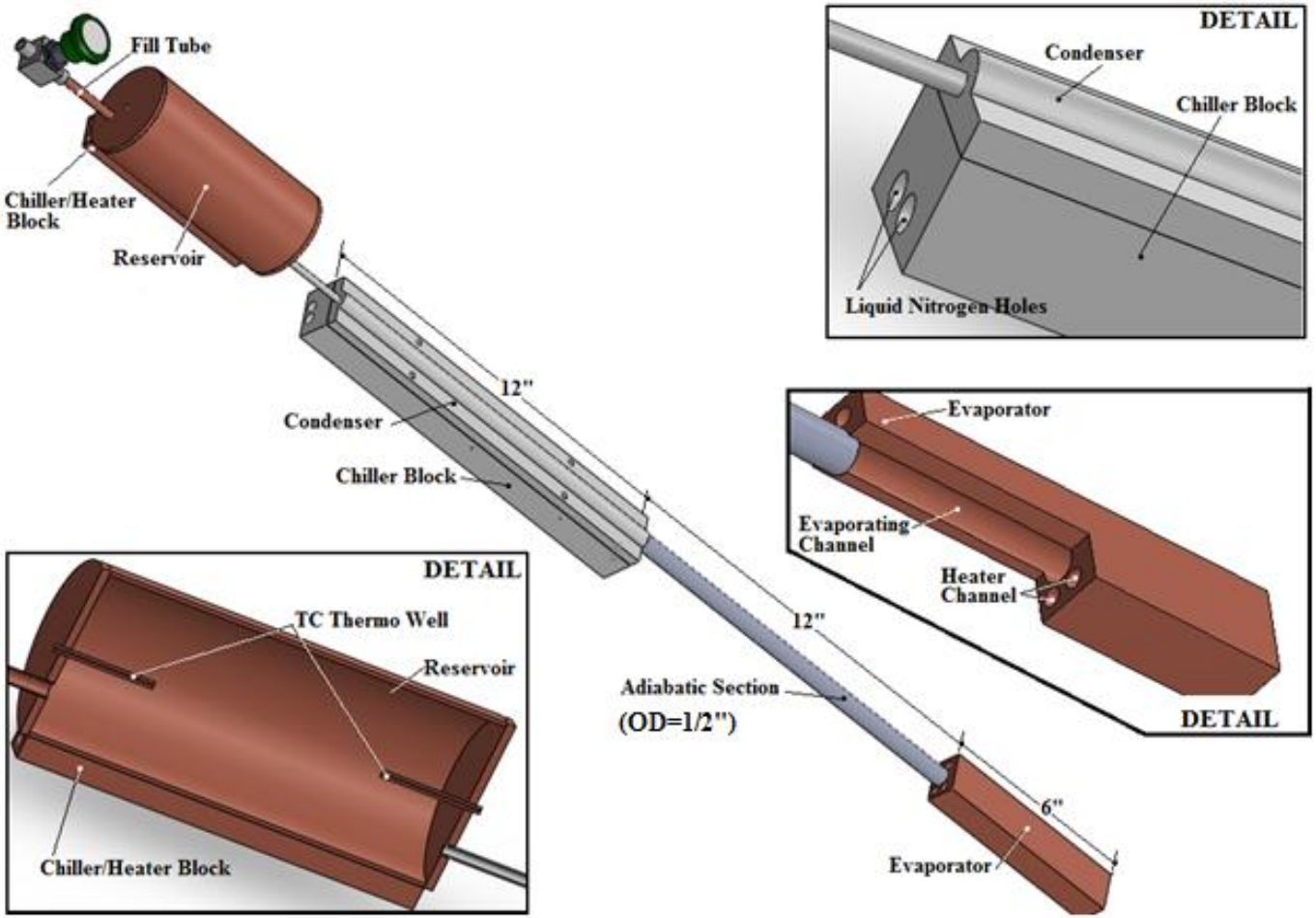
Proof-of-Concept VCHP Design

- Based on flat front theory model two reduced scale systems were designed:
  - Configuration 1 – Reservoir attached to evaporator



Proof-of-Concept VCHP Design

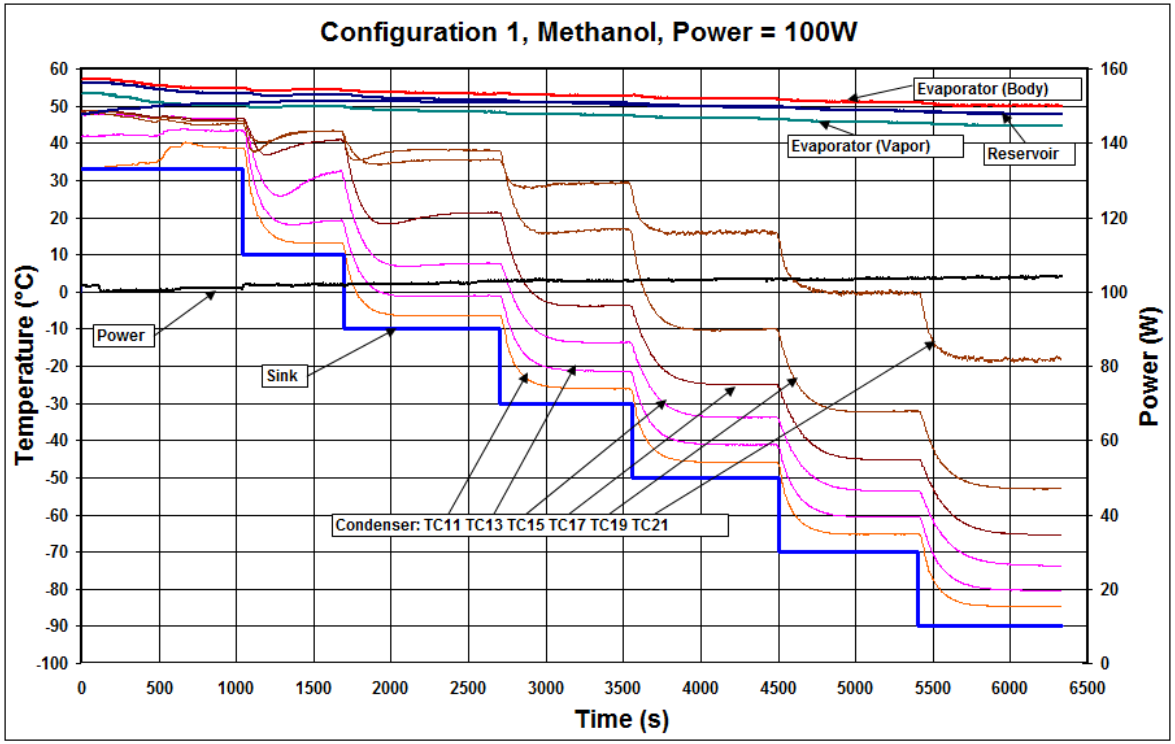
– Configuration 2 – Reservoir attached to condenser



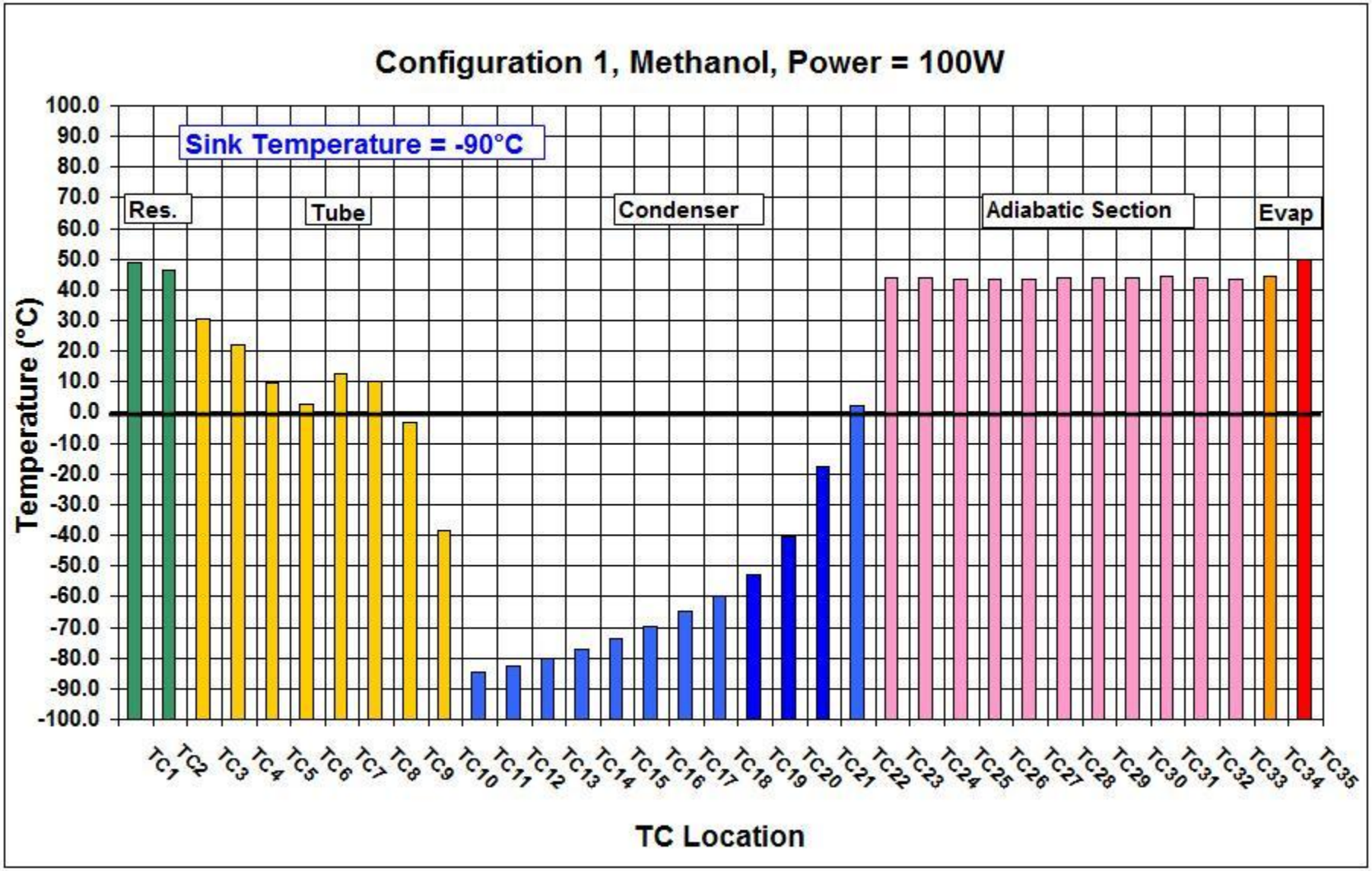
Build and Test Proof-of-Concept VCHP

VCHP Configuration 1 (Methanol) – Thermal Control Test

- Constant Power (100 W)
- Variable Sink Temperature
- Evaporator Temperature dropped by only ~ 5°C as the sink temperature went from +30°C to -90°C



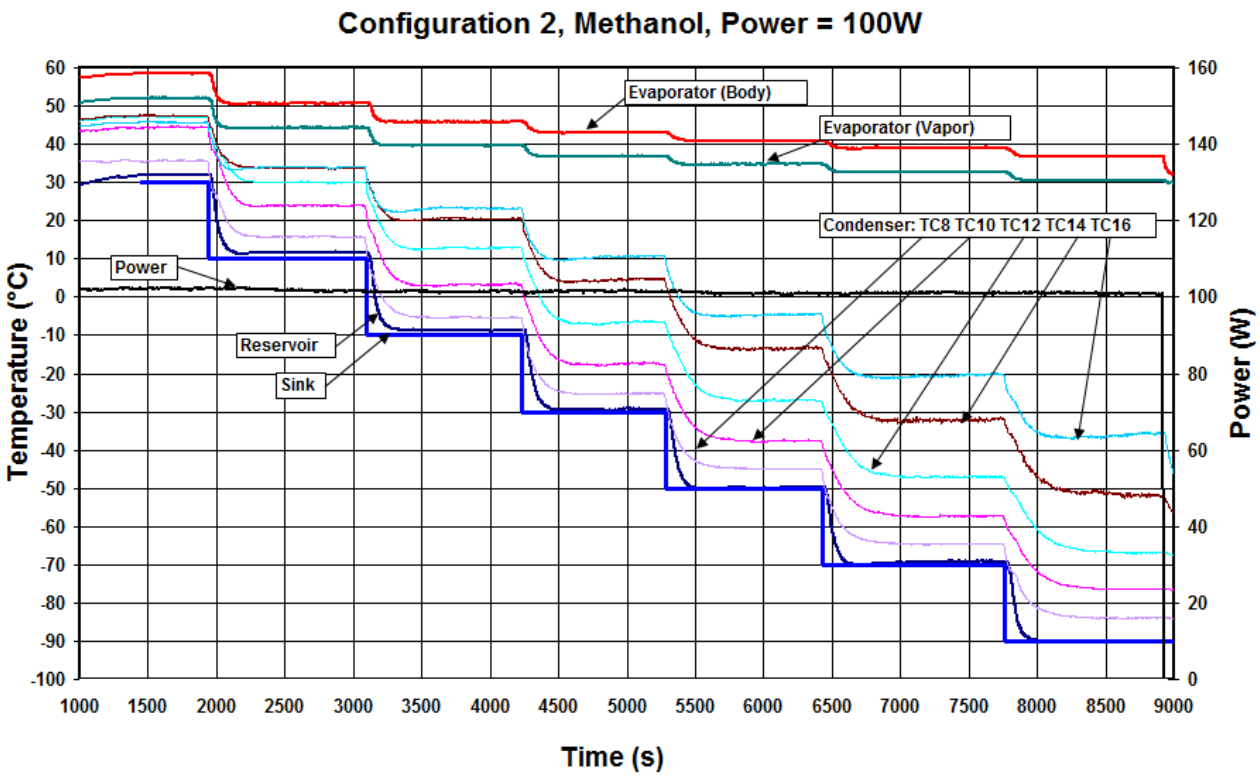
VCHP Testing (Conf. 1 with methanol): constant power (100 W) and variable sink temp.



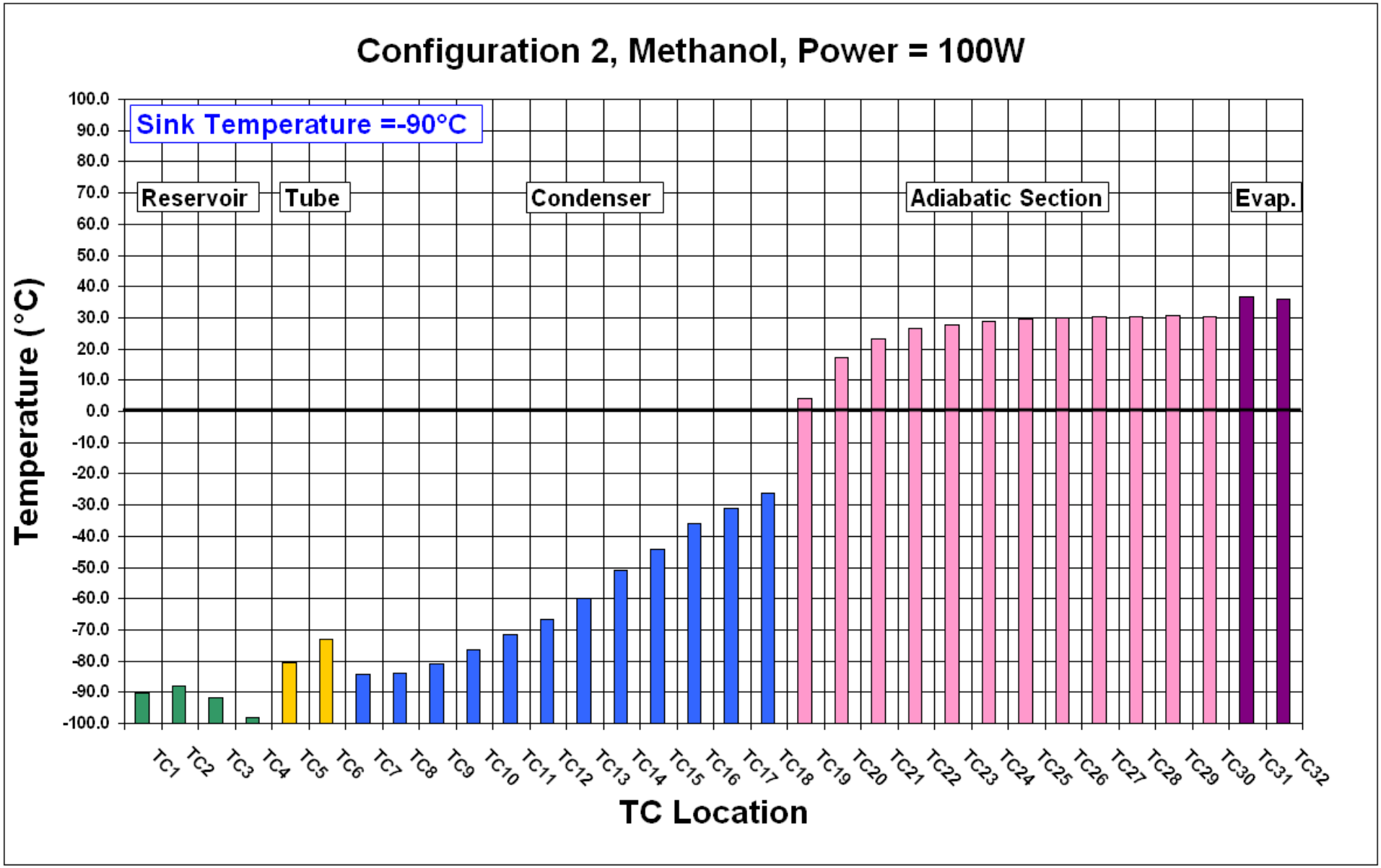
Build and Test Proof-of-Concept VCHP

VCHP Configuration 2 (Methanol) – Thermal Control Test

- Constant Power (100 W)
- Variable Sink Temperature
- Evaporator Temperature dropped by only ~ 21°C as the sink temperature went from +30°C to -90°C



VCHP Testing (Conf. 2 with methanol): constant power (100 W) and variable sink



Balloon VCHP Conclusions

- Two VCHP configurations (hot and cold reservoir) were designed, fabricated and successfully tested
- Three working fluids each:
  - Methanol
  - Toluene
  - Pentane
- Experimental results are consistent with analytical modeling
- Both configurations provide a variable thermal link without electrical power
  - Warm reservoir VCHP has a 4.8ºC temperature control band
  - As expected, the cold reservoir control band is larger, at 21ºC

Presentation Outline

- Variable Conductance and Gas-Loaded Heat Pipes
- Aluminum/Ammonia VCHPs for Lunar Landers and Rovers
- VCHPs for Balloon Thermal Management
- Titanium/Water VCHPs for Nuclear Fission Space Radiators
- Conclusions and Recommendations

Ti/Water VCHP Radiator Program Objectives

- Develop a VCHP radiator to maintain stable heat rejection in the Lunar and Martian environment.
- Demonstrate the VCHP design's ability to
  - Passively adjust heat rejection with changes in sink temperature or input power.
  - Control freezing behavior to isolate frozen fluid in the evaporator
    - Allows for reliable restart
  - Arrest working fluid migration to a frozen condenser
    - Allows for reliable restart after long freeze times, or when fluid is frozen during transit
- Significant project goals
  - Extend freeze/thaw tolerant design to include arbitrary fluid location.
  - Perform CTE testing of a small-scale panel for expected thermal cycles.
  - Design, fabricate and test a VCHP radiator prototype

Ti/H_2O Radiator Design Requirements

Parameter	Value
Location	Lunar Equator Shackleton Crater
Sink Temperature	101 to 314K 114 to 212K
Operating Temperature	370 to 400K
Thermal Energy Rejected	70kW
Individual Thermosyphon Power	≈500 W
Heat Pipe Working Fluid	Water
Heat Pipe Envelope	Titanium Alloy
Orientation	Gravity Aided
Evaporator Length	15.2 cm (6 in.)
Condenser Length	2m (78 in.)
Tilt	±5°

Freeze/Thaw and Start-up

- Continued cooling of the condenser section significantly increases the start up time to normal operation.
- As a heat pipe approaches thermal equilibrium with temperatures below freezing, the condenser freezes before the evaporator.
- Three start up conditions can exist after freezing:
  1. Dry evaporator. Condenser is usually plugged with ice as all the working fluid is frozen in this section. Restart is not possible under freezing conditions.
  2. An insufficient amount of working fluid remains in the evaporator. Restart results in dry out of the evaporator and is not possible under freezing conditions.
  3. A sufficient amount of working fluid remains in the evaporator. Restart results in thawing of the condenser section and is possible under freezing conditions.

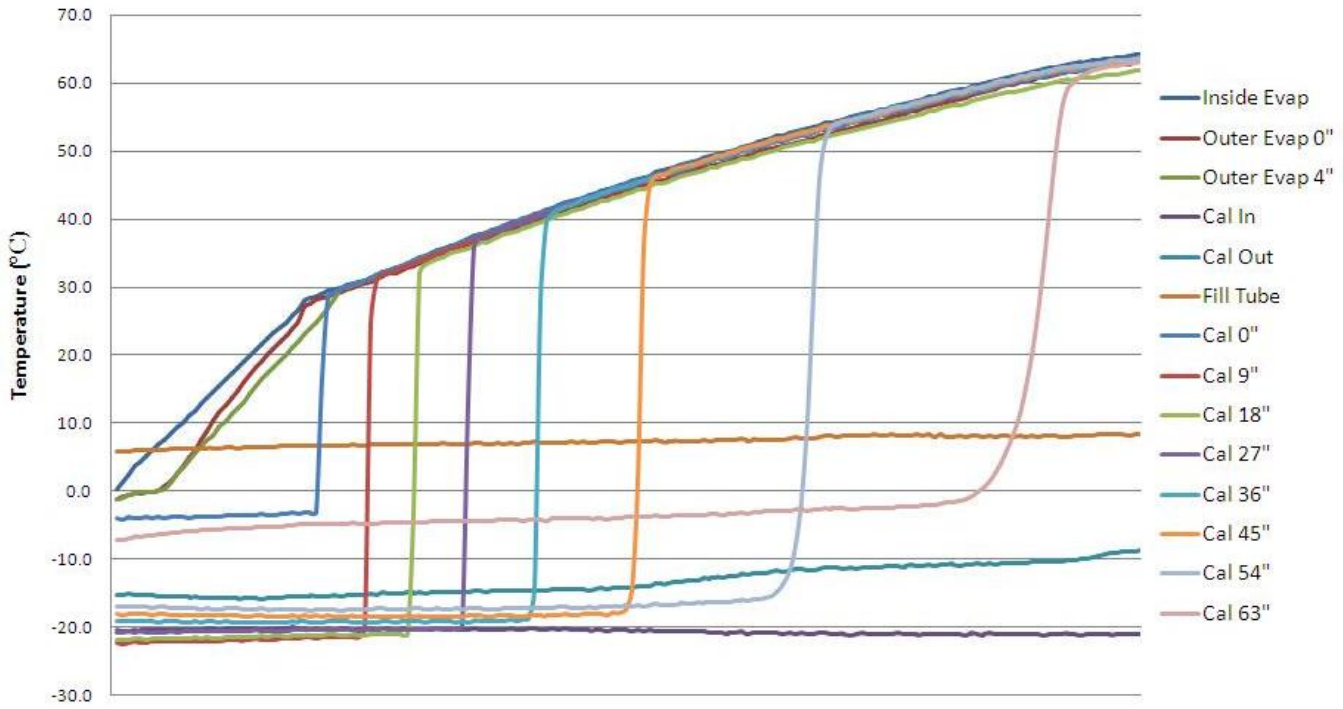
Freeze/Thaw and Start-up

- Presence of a non-condensable gas improves the freezing profile.
  - Shuts down condenser as the pipe is frozen
  - Maintains a higher working fluid temperature as freezing is approached
    - Compared to a Constant Conductance Heat Pipe (CCHP).
  - Restricts vapor movement in the condenser
    - Driving mechanism is diffusion only.
- Restart chances increase with non-condensable gas mass.
  - Condenser shuts down faster and working fluid temperatures remain higher.
- Large condenser to evaporator length ratios improve restart chances.
  - Less likely that the condenser will be blocked by freezing working fluid.

VCHP for Freeze/Thaw Testing

- Titanium/Water VCHP designed for gravity aided operation
- Primary and secondary wick added in evaporator
- Gas Gap calorimeter for heat removal

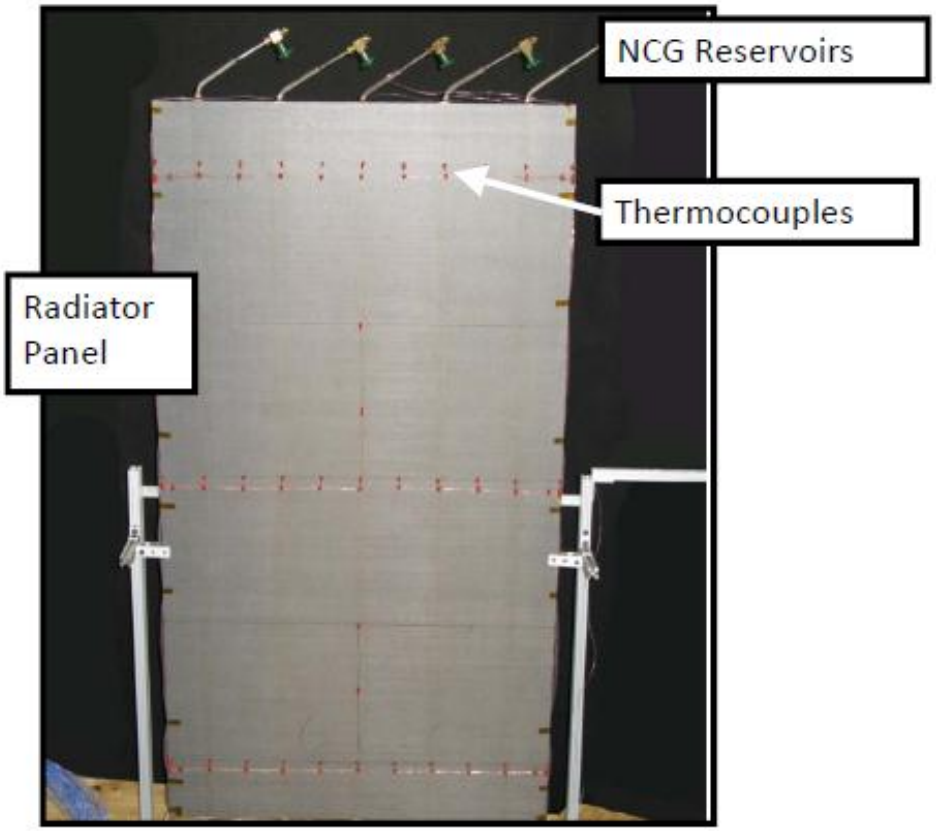
Freeze Thaw Testing – Startup Temperatures



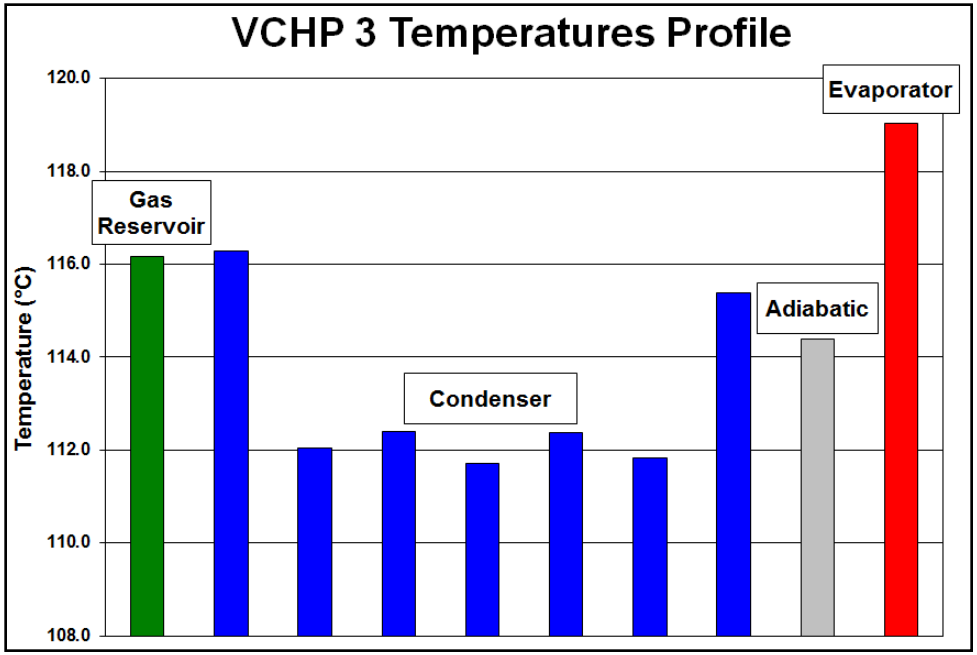
- Successful startup at all positions with similar profiles
- Freeze free liquid in an arbitrary position
- Primary/Secondary Wicks held enough liquid to allow VCHP to operate at correct temperatures with no dryout
- Results show expected performance

VCHP Radiator Panel

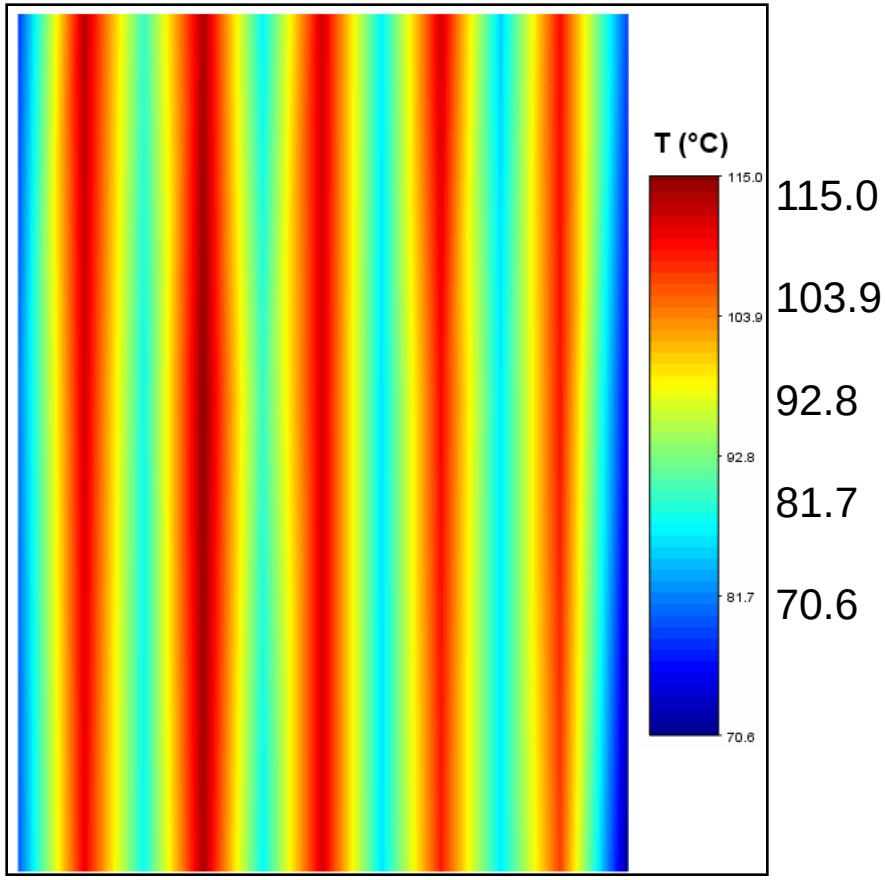
- Full Size Radiator Panel with 5 VCHPs was fabricated and tested
- Reservoir bent to minimize overall panel size



Full-Scale Heat Throughput Test



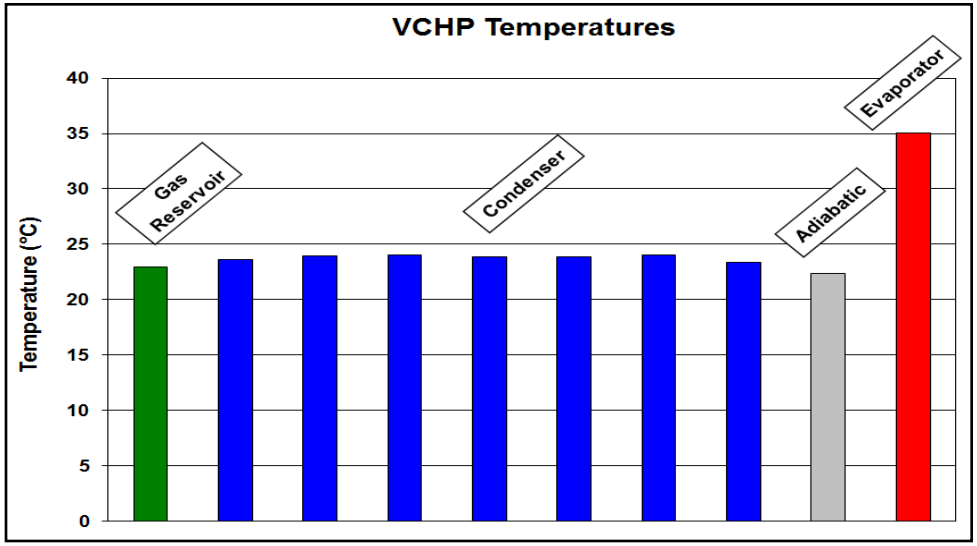
Radiator Facesheet Temperatures

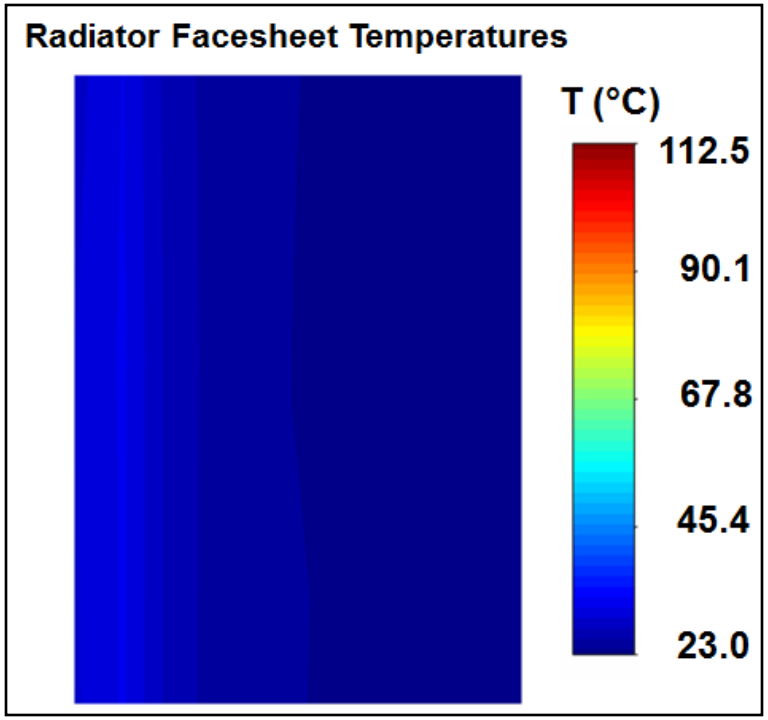


- Q = 3.0 kW – entire radiator panel
- ΔT ≈ 3 °C – evaporator to condenser
- ΔT ≈ 4 °C – condenser to facesheet
- ΔT ≈ 45 °C – across radiator facesheet

Shutdown

- VCHPs shut the radiator panel shut off when temperature was lowered to 25-30°C
- Currently Undergoing Thermal Vacuum testing at NASA Glenn
  - Operation
  - Freeze/Thaw





Ti/H2O VCHP Radiator Conclusions

- The Ti/water VCHPs have been shown to withstand multiple freeze/thaw cycles
  - NCG suppressed liquid loss with a warm evaporator
- A wick design was developed that ensures the heat pipe will restart even when the excess working fluid freezes in an arbitrary location during transit
  - Verified by freeze/thaw experiments on several VCHPs
- Full-scale radiator panel was fabricated and tested for nominal operation and VCHP shutdown
  - During nominal operation, the panel ran at 120 °C (evaporator temperature) and was able to transport 3.8 kW
  - During shutdown, the system stopped rejecting heat to the environment and the radiator surface equilibrated to the ambient temperature

Overall Conclusions

- VCHPs and Gas-Loaded Heat Pipes can be used for variable thermal links, and to aid in start-up from a frozen state
- Applications that can benefit from using VCHPs as variable thermal links allow relatively wide temperature swings, but need to minimize or eliminate electrical heater power
  - Lunar and Martian Landers and Rovers
  - Research Balloons
  - Lunar and Space Fission Reactors
- Common factors include
  - Variable system loads resulting from intermittent use
  - Large changes in environment temperature
  - Limited electrical power
- Many applications with variable thermal links also need to consider freeze/thaw and start-up from a frozen state
  - NCG aids start-up from the frozen state by providing a back pressure in the heat pipe condenser during start-up

Acknowledgements

- The aluminum/ammonia VCHP program was sponsored by NASA Marshall Space Flight Center under Purchase Order No. NAS802060. Jeffery Farmer was the Technical Monitor.
- The balloon VCHP program was sponsored by NASA Goddard Space Flight Center under Purchase Order No. NNX11CF08P. Deborah Fairbrother was the technical monitor.
- The titanium/water VCHP program was sponsored by NASA Johnson Space Center under Purchase Order No. NNX08CC11P. Lee Mason of NASA Glenn Research Center was the technical monitor. The GFRC radiator was fabricated by Ted Stern of Vanguard Space Technologies
- 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.

VCHPs for Variable Thermal Links

W.G. Anderson, M.C. Ellis, J.R. Hartenstine,
C.J. Peters, C. Tarau, & K.L. Walker
Advanced Cooling Technologies, Inc.

Presented By

Calin Tarau

Thermal & Fluids Analysis Workshop
TFAWS 2012
August 13-17, 2012
Jet Propulsion Laboratory
Pasadena, CA