Variable Conductance Heat Pipes with Unheated Reservoirs

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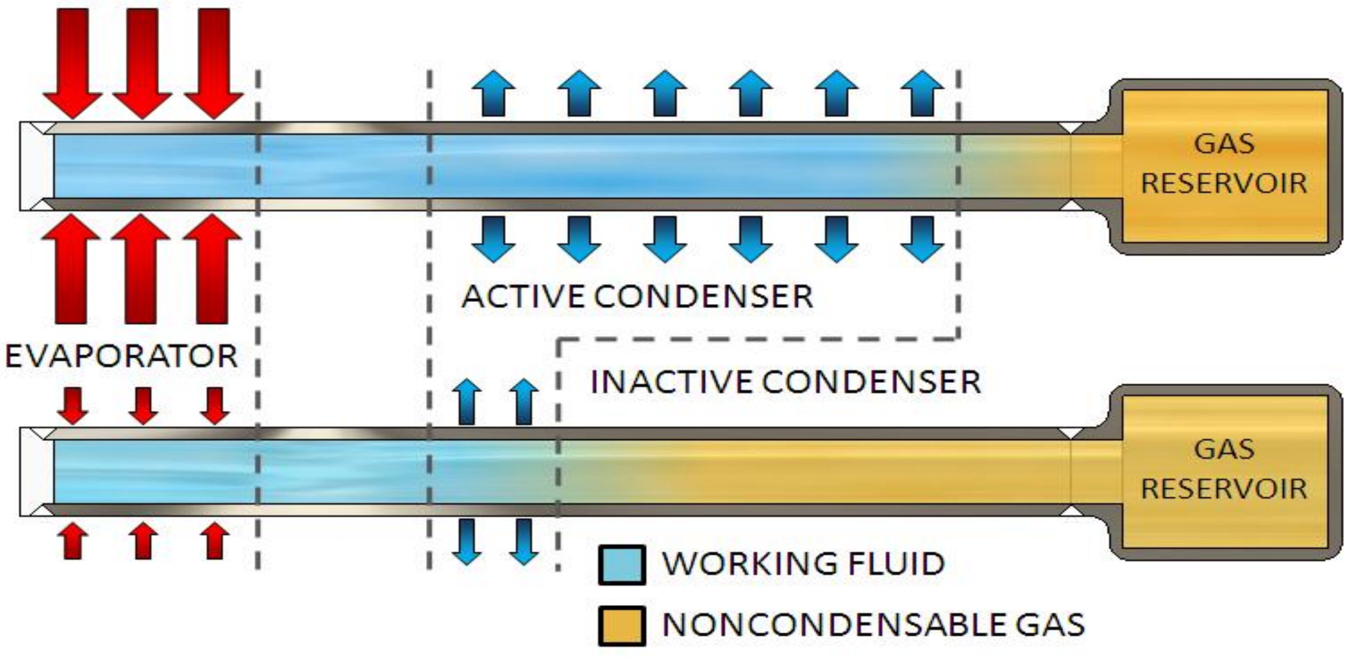
Presentation Agenda

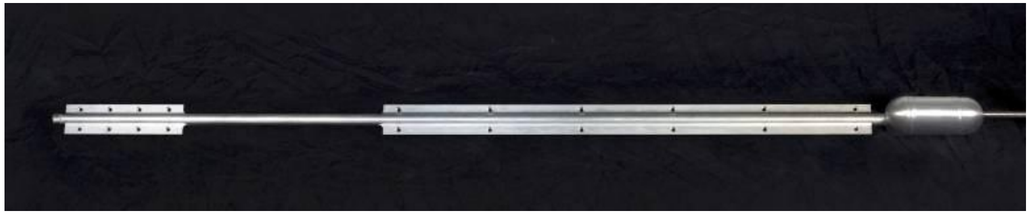
- Variable Conductance Heat Pipes
- Heated versus Unheated Reservoirs
- VCHP Radiator for Lunar and Martian Fission Power Systems
  - Background
  - Radiator Evaporator Trade Study
  - Freeze/Thaw Testing
  - Full Length Panel Fabrication and Testing
- VCHPs with Unheated Reservoirs Located Near the Evaporator
  - Trade Study
  - Design
  - Fabrication and Testing
- Conclusions
- Acknowledgements

Variable Conductance Heat Pipes (VCHPs)

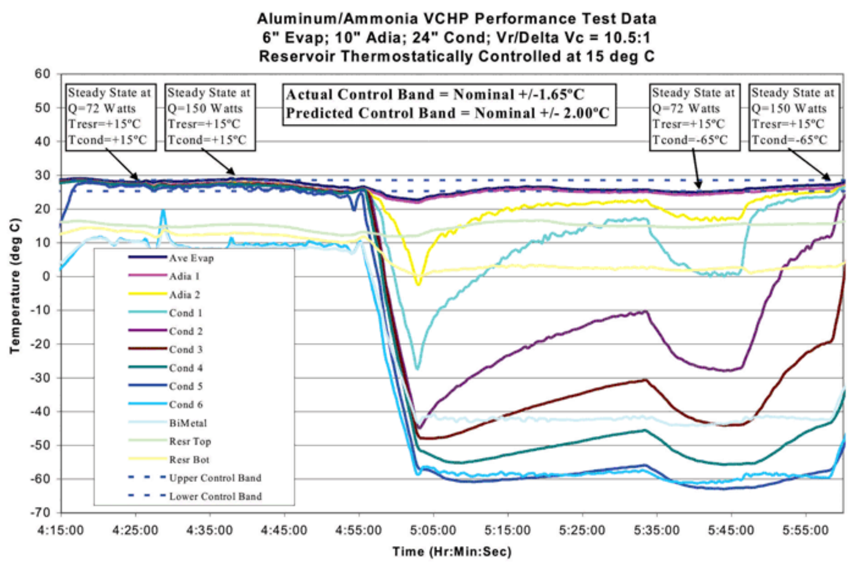


- At high heat load the temperature dependent saturation pressure of the working fluid is high and compress the non-condensable gas into the reservoir.
- At lower heat input the working fluid temperature and pressure is lower, and the non-condensable gas expands into the condenser.

VCHPs for Precise Temperature Control



- Typical VCHP used for precise temperature control
  - Stainless steel reservoir at the end of the condenser
  - Cold biased, Electrically heated
  - Typically can control temperatures to ±1 to 2° C



Other VCHP Applications

1. Variable Thermal Links
2. Frozen Start-up
3. Over-Temperature Protection (discuss in separate TFAWS presentation)

- Reservoirs normally not electrically heated
  - Cold reservoir at condenser
  - Warm reservoir at evaporator
- Looser temperature control band, but eliminate need for electrical heaters and control
- Two Examples discussed
- VCHP Radiator for Lunar and Martian Fission Power Systems
  - 2 m long thermosyphons with unheated reservoirs
- VCHP Variable Thermal Links for Balloon Instrumentation
  - Warm reservoir near evaporator versus cold reservoir near condenser

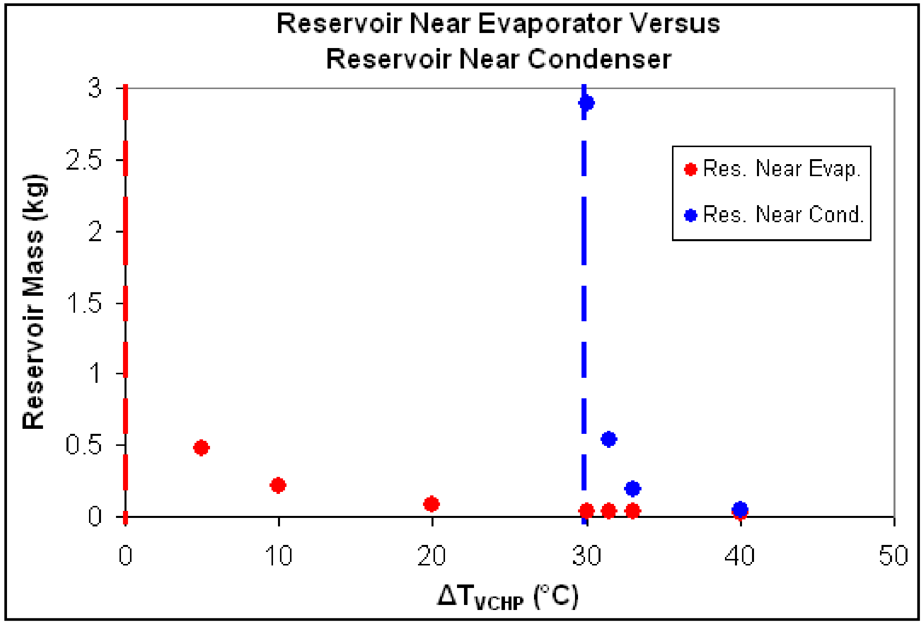
Reservoir Location and Connections

- 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
   - Variable Thermal Links for Balloon Instrumentation
3. Reservoir at the end of the condenser
   - Conventional geometry , easiest and cheapest to fabricate
   - Cold reservoir, sets a minimum allowable ΔT
   - VCHP Radiator Program, Variable Thermal Links for Balloon Instrumentation

Cold versus Warm Reservoirs

- For large ranges in sink temperature, unheated reservoirs only allow coarse temperature control
  - VCHPs work by having the NCG expand as the vapor pressure drops
  - With an unheated reservoir, the drop in reservoir temperature also causes the gas to contract
  - Requires minimum ΔT for temperature difference between hot and cold sinks
- Example below for an Al/NH_3 Lunar VCHP with a minimum ΔT of ~ 30 K

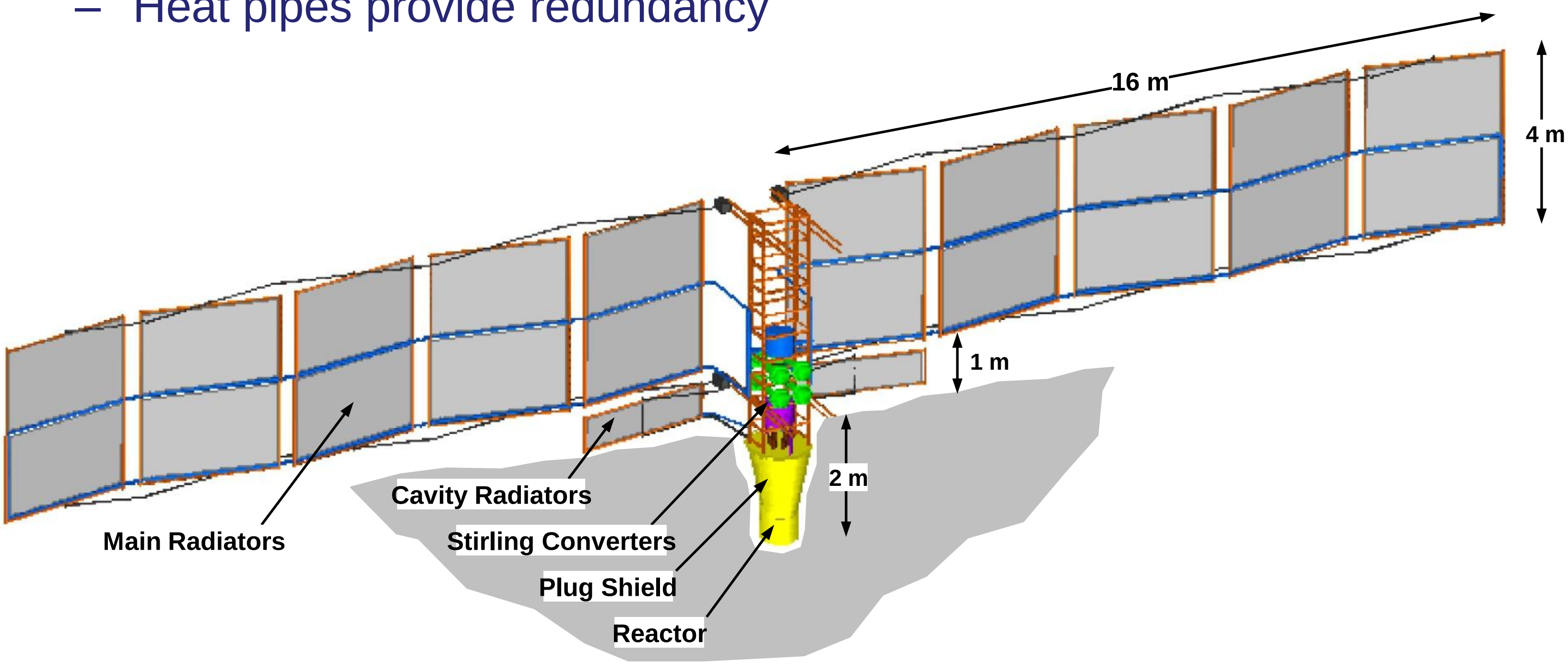


VCHP Radiator – Technical Challenges

- The Lunar and Martian environments present challenges for thermal management systems.
  - 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
- Conventional radiators are sized to operate at the highest temperature.
  - Sink temperature reduction results in higher heat rejection
    - Control system necessary to prevent system instability
- During low or no power operation, working fluid will likely freeze.
  - Potential damage to radiator and uncertain restart behavior.
- Develop freeze-tolerant Variable Conductance Heat Pipe (VCHP) Radiator

Lunar Fission Surface Power Concept

- NASA Glenn Concept
- Reactor delivers power to Stirling Convertors
- Secondary loop transports waste heat
  - Water selected as the working fluid
- Waste heat rejected by heat pipe radiator panels
  - Heat pipes provide redundancy



Geng, Mason, Dyson, and Penswick, STAIF 2008

Technical Challenges

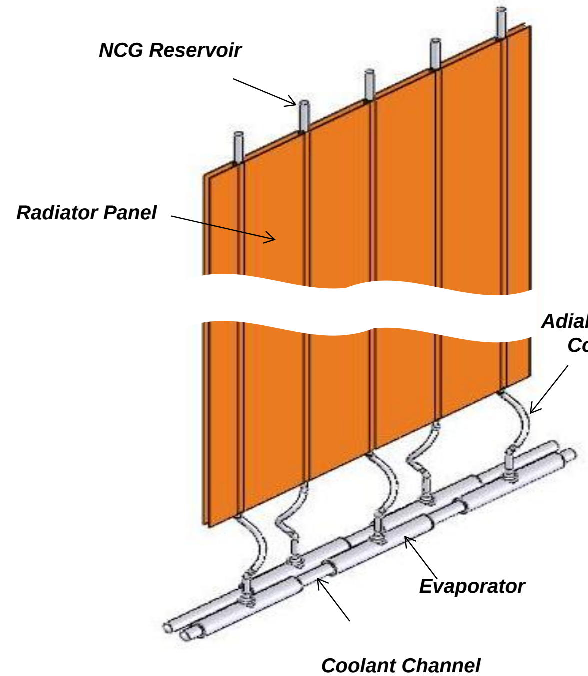
- The VCHP radiator needs to do the following:
  - Operate in the temperature range from 370 to 400 K
    - Too hot for ammonia
  - Minimize mass
  - Accommodate the Coefficient of Thermal Expansion (CTE) mismatch between the titanium heat exchanger and the Graphite Fiber Reinforced Composite (GFRC) panel face sheets.
  - Allow the heat pipes to continue to operate with minimum temperature drop as the power is reduced
  - Startup with free water frozen in an arbitrary position during transit to the moon
  - Survive multiple freeze/thaw cycles.

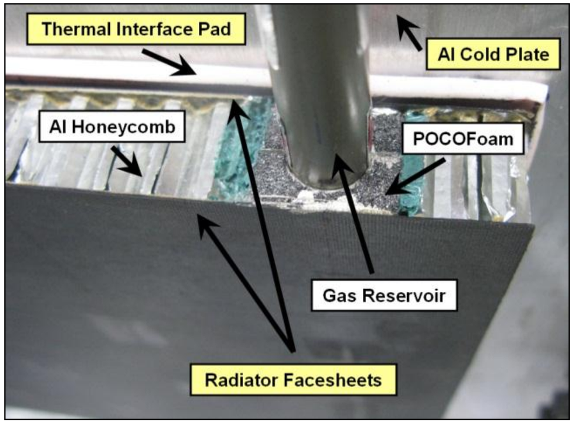
Technical Challenge – Freeze/Thaw

- While not operating, the heat pipes will be exposed to low temperatures
  - Power down on the Lunar or Martian surface
  - Transit to mission site
- As a heat pipe freezes
  - Since input occurs at the evaporator, the condenser freezes first
  - Warm working fluid continues to transport thermal energy to the condenser
  - Finally, the evaporator freezes
  - Most, if not all, of the working fluid is deposited in the condenser
    - The heat pipe cannot restart
- As a VCHP freezes
  - The working fluid pressure decreases allowing the NCG to expand
    - The condenser de-activates as temperature drops
    - NCG confines the working fluid to the evaporator
  - When the VCHP freezes, the majority of the working fluid resides in the evaporator
    - Restart is possible

Radiator Panel Features

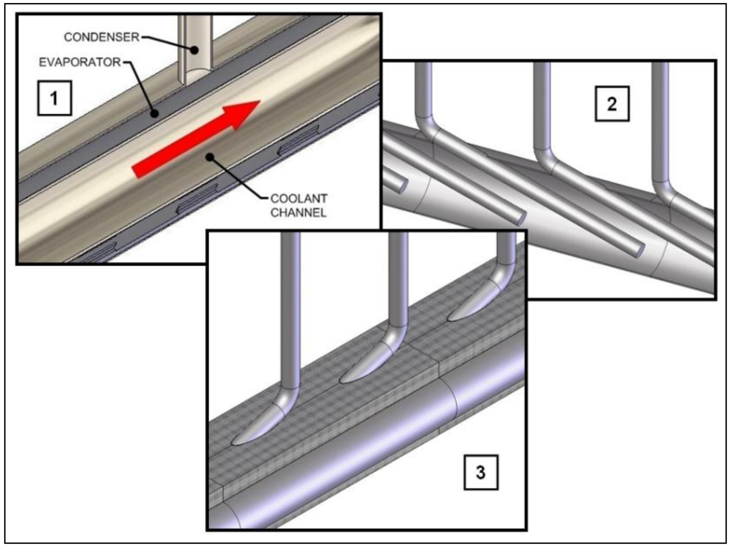
- Titanium/water thermosyphons
- High conductivity foam saddles for CTE mismatch
- High conductivity GFRC fins
- Aluminum honeycomb to provide stiffness to the structure
- Titanium heat exchanger
- Annular heat pipe evaporator
- Coiled adiabatic section to accommodate the C.T.E. mismatch
- Wick design to allow the heat pipe to operate when tilted, and to start-up from a frozen state when the excess water is frozen in an arbitrary position.

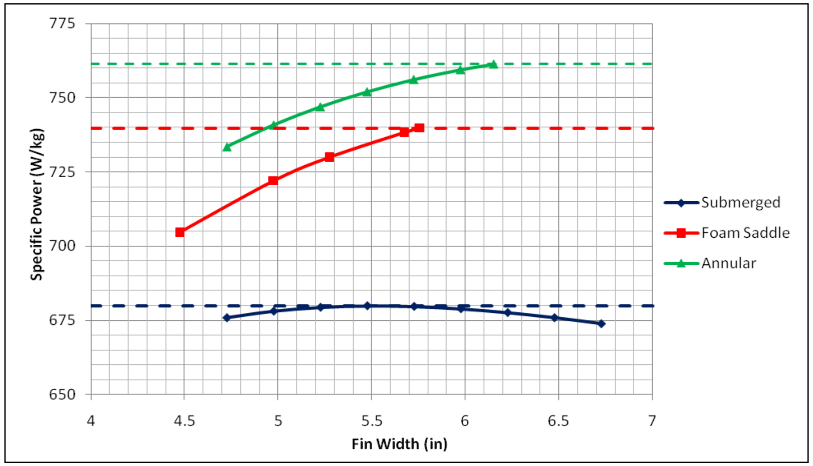




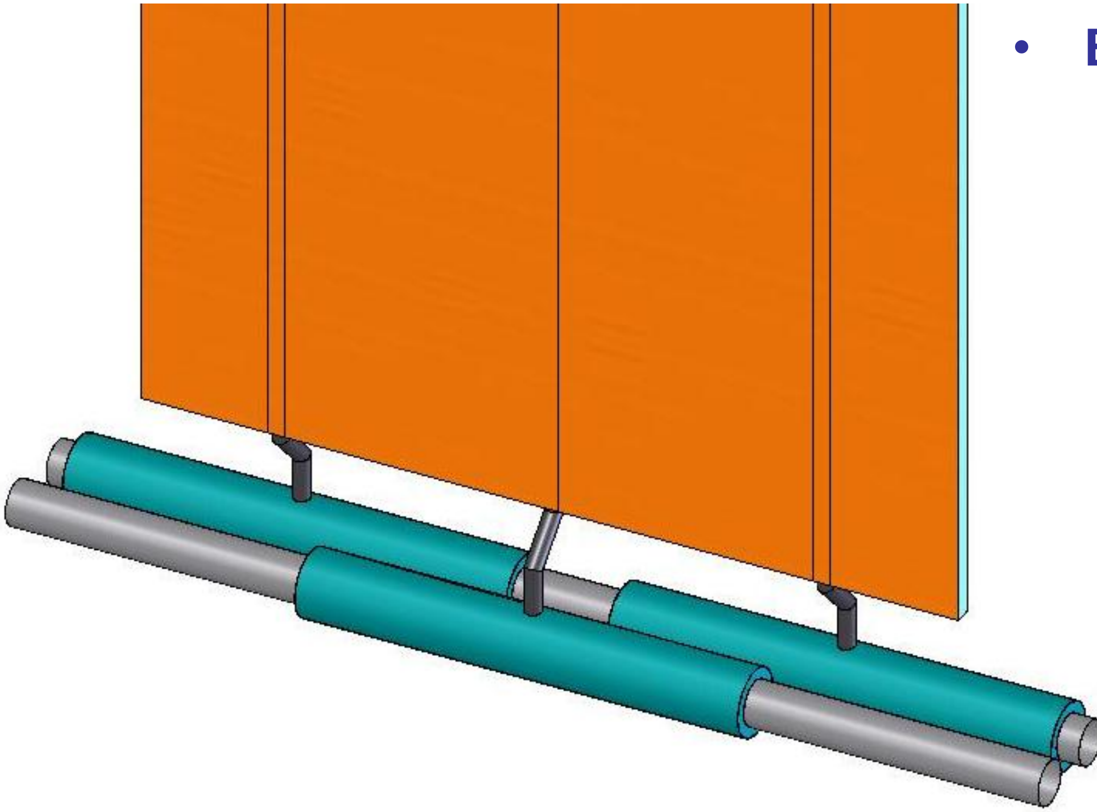
Radiator Trade Study – Heat Exchanger

- Water heat exchanger between coolant line and VCHPs
  - Annular Evaporator
  - POCO Foam Saddle
  - Submerged Evaporator
- Conduct trade study for each design to reach the highest specific power.
- Annular evaporator has highest specific power
  - Larger evaporator area
  - Provides micro-meteorite protection





Dual Coolant Channels

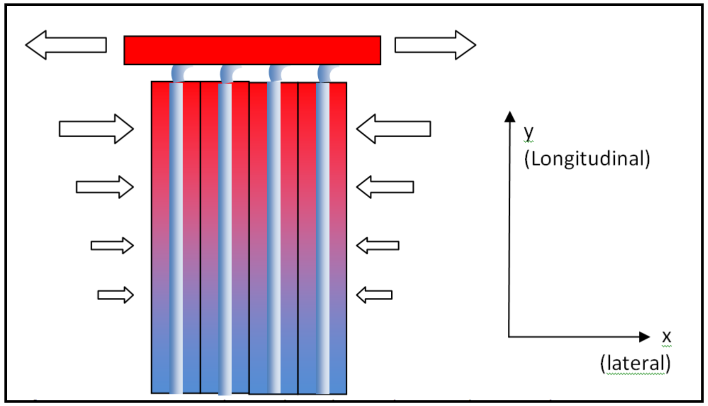


- **Benefits to Annular Design**
  - MMOD Protection
  - Larger primary Wick Area
  - Utilizes dual coolant channels to allow evaporator length to exceed distance between VCHPs
  - Weld Failure would not make the entire design fail.

- Most important benefit is the much larger evaporator area
  - Reduces temperature drop through the VCHP
- After the trade study, a VCHP radiator was fabricated and tested

CTE Mismatch

- Ti CTE: 8.6 μm/m K, GFRC matches CTE along heat pipe axis
- Negative CTE in GFRC perpendicular to heat pipes
- Coiled Adiabatic to accommodate CTE mismatch



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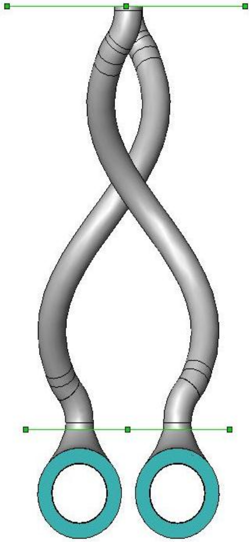

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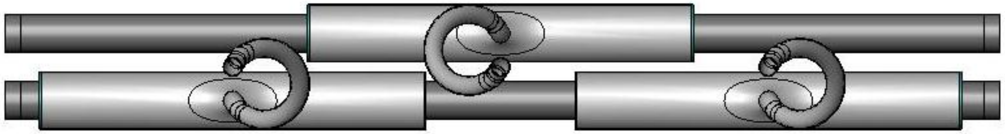

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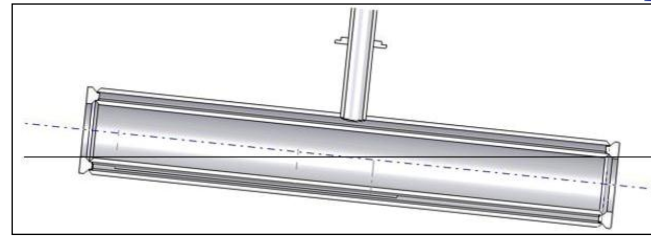
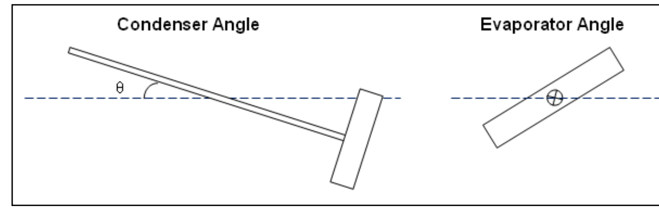
Freeze/Thaw and Start-up

- 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

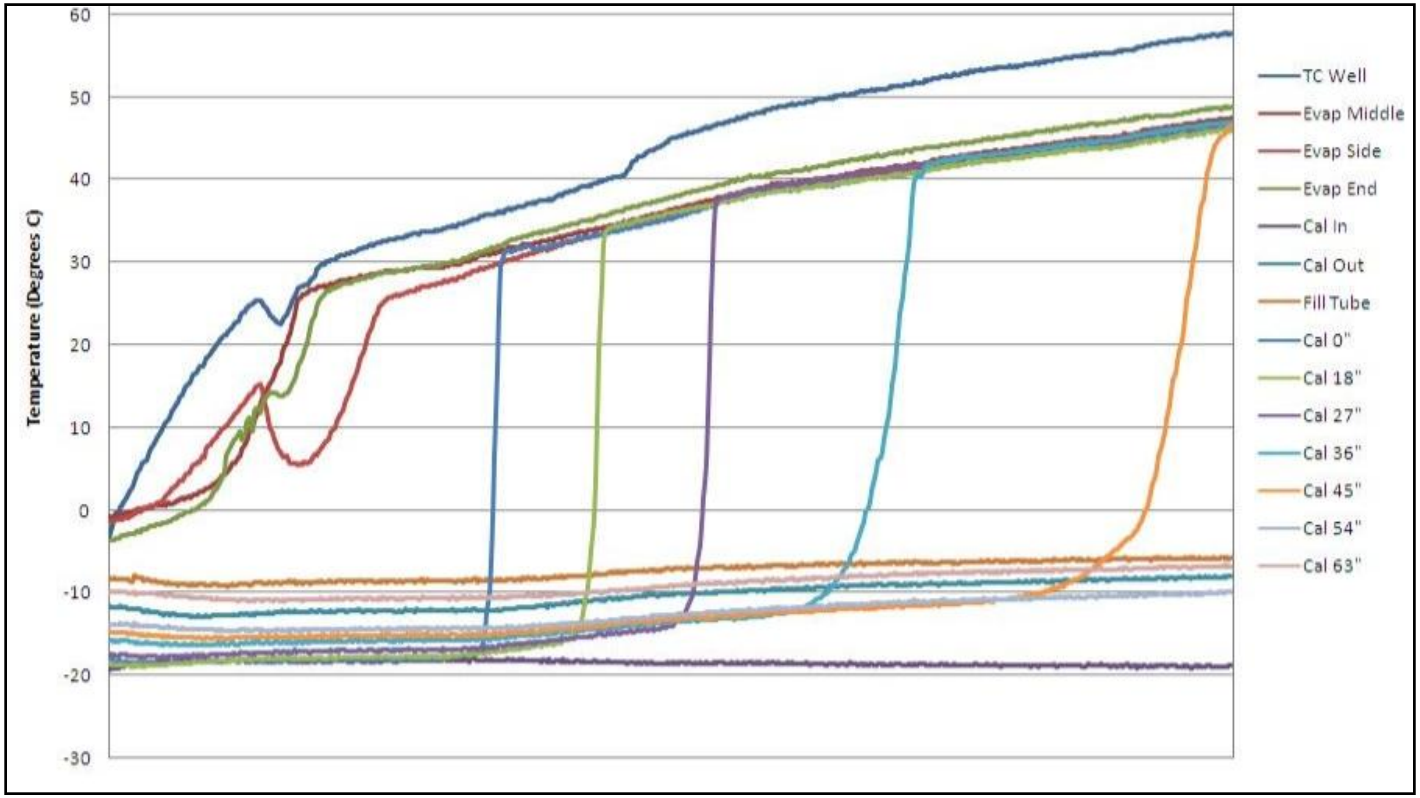
- Titanium/Water VCHP with annular evaporator
- Primary and secondary wick added in evaporator to allow for operating in a tilted environment
- Freeze excess liquid in arbitrary position





Test Run	Condenser Angle	Evaporator Angle
1. Normal Operating Position	90°	-
2. Slightly Gravity Aided	10°	0°
3. Horizontal	0°	0°
4. Slightly Against Gravity	-10°	0°
5. Half Against Gravity	-45°	0°
6. Upside Down	-90°	-
7. Rotated Horizontally	0°	90°
8. Rotated Slightly Horizontally	0°	10°
9. Rotated Half Horizontally	0°	45°
10. Combination	-10°	10°
11. Combination 2	-45°	45°

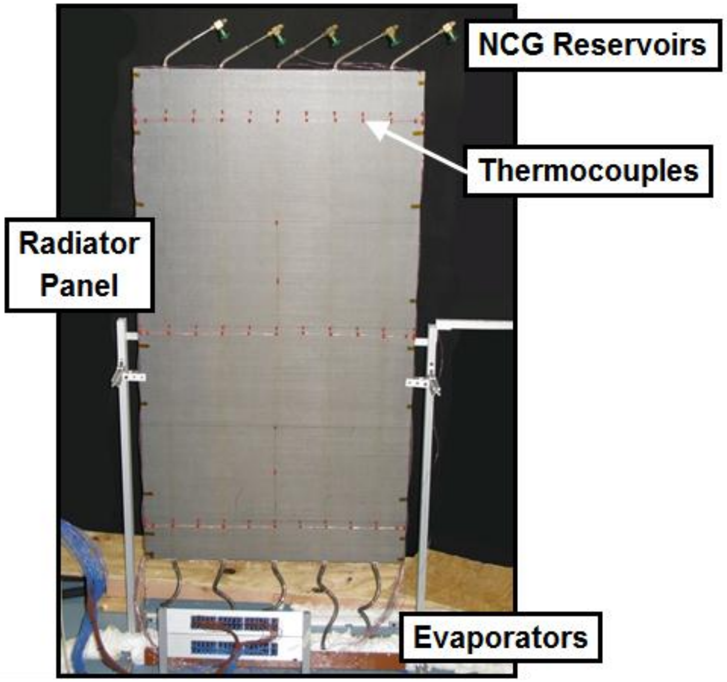
Freeze Thaw Testing – Startup

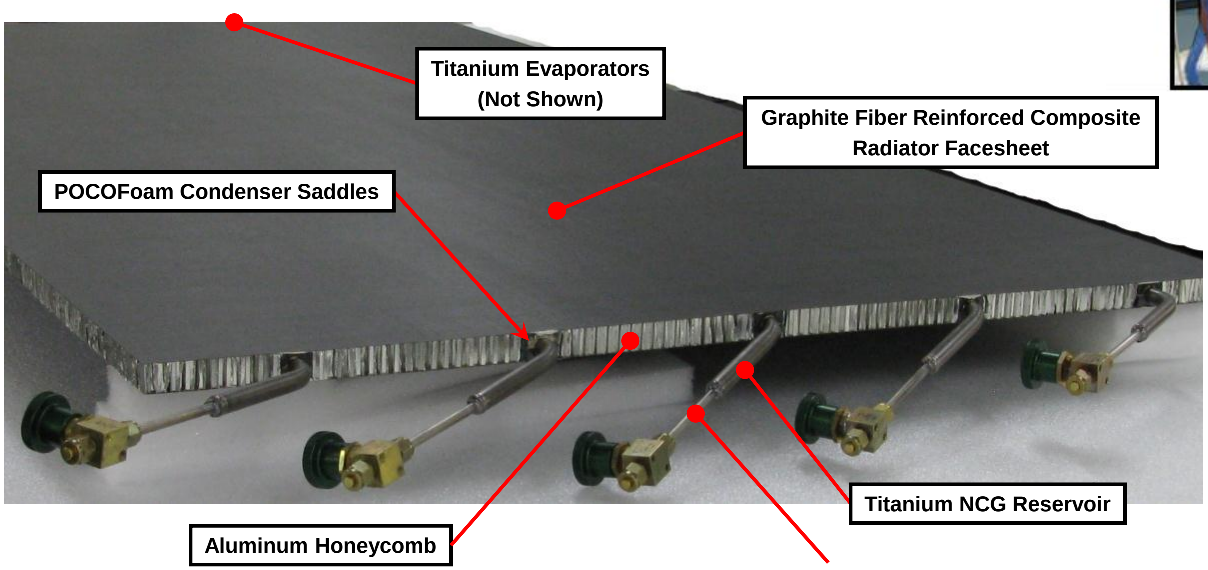


- Successful startup at all positions with similar profiles
- Freeze free liquid in an arbitrary position
- Primary/Secondary Wicks held enough liquid to allow VCHP to operate at correct temperatures with no dryout
- Results above for a 15 day freeze (lunar night)

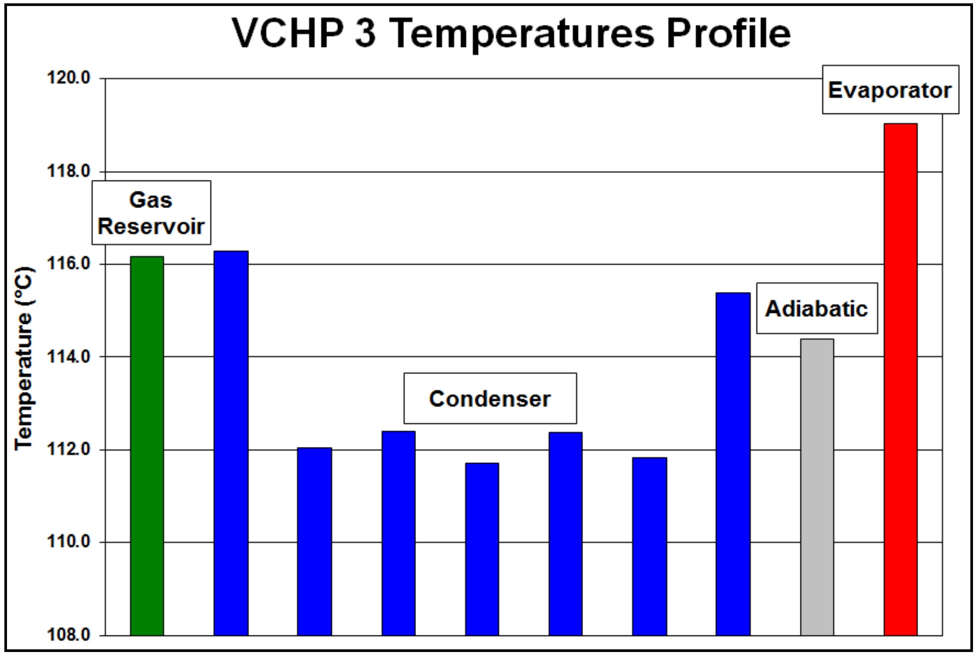
VCHP Radiator Panel

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

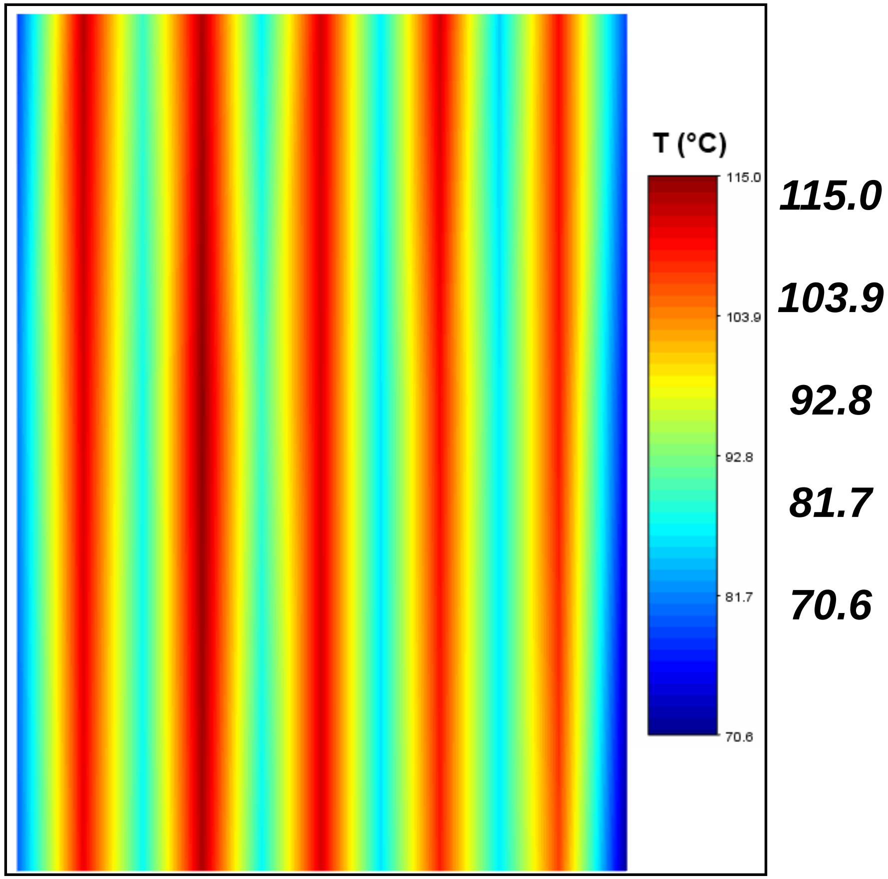




Full-Scale Heat Throughput Test



Radiator Facesheet Temperatures

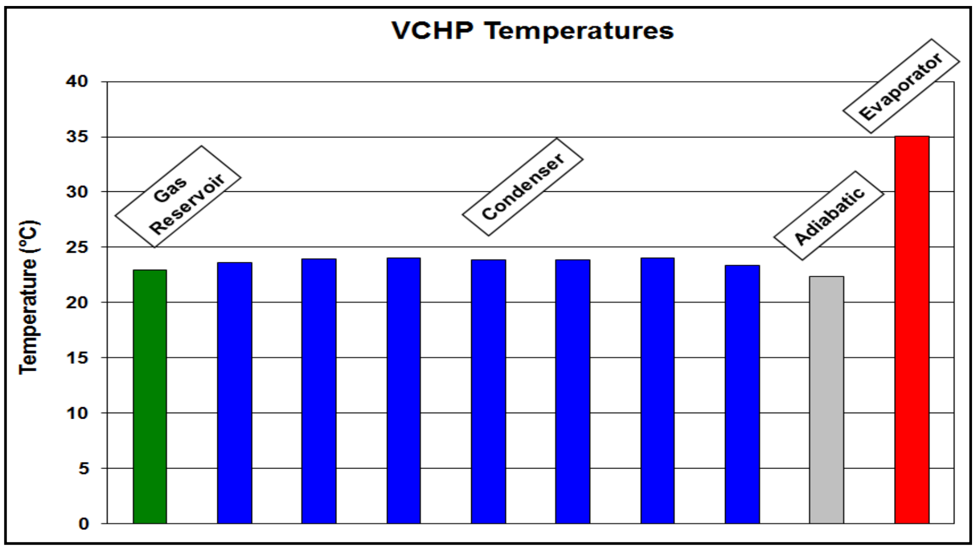


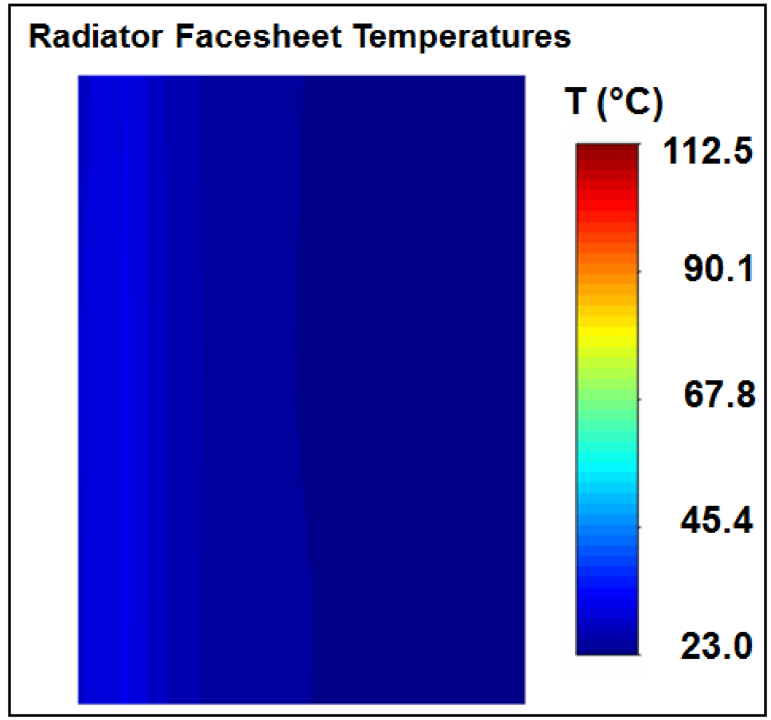
- ***Q = 3.0 kW – entire radiator panel***
- ***ΔT ≈ 3 ˚ C – evaporator to condenser***
- ***ΔT ≈ 4 ˚ C – condenser to facesheet***
- ***ΔT ≈ 45 ˚ C – across radiator facesheet***

Shutdown

- VCHPs shut the radiator panel shut off when temperature was lowered to 25-30° C
- VCHP Radiator was then thermal vacuum tested at NASA Glenn*
  - Operation
  - Freeze/Thaw

*Jaworske et al., "Heat Rejection from a Variable Conductance Heat Pipe Radiator Panel", NETS 2012





VCHP Radiator Conclusions

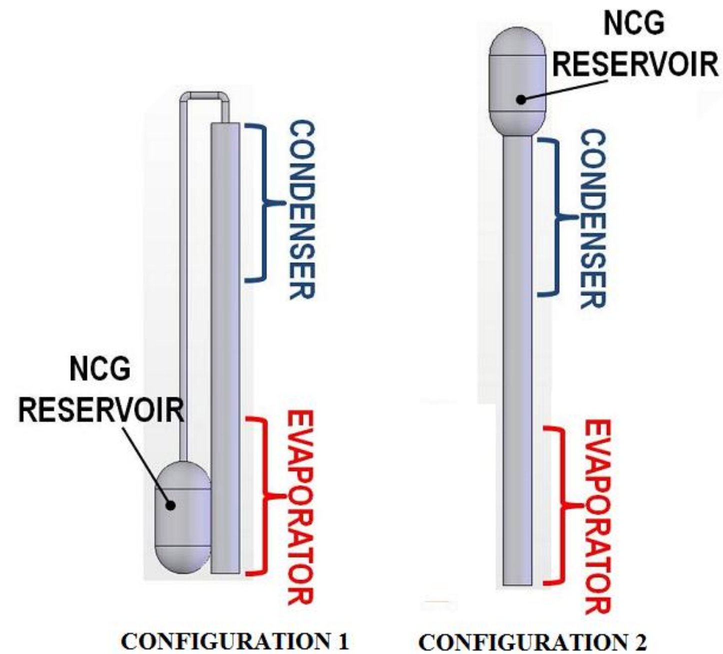
- A VCHP radiator was developed with titanium/water thermosyphons, and unheated reservoirs
  - GFRC panels, POCO foam saddles, aluminum honeycomb
  - Annular heat pipe evaporator
  - Coiled adiabatic section to accommodate the C.T.E. mismatch
  - Wick design to allow the heat pipe to start-up from a frozen state when the excess water is in an arbitrary location
- Full-length VCHP radiator was fabricated
  - Rejected 3 kW with a fully open condenser at operating conditions
  - Shut down and blocked condenser when coolant temperature lowered to 25ºC
  - Demonstrated ability to start-up after multiple freeze/thaw cycles
- Future Work
  - Recently started a Phase I program to examine single facesheet designs, eliminating the POCO foam saddles

VCHPs for Balloon Instruments – Motivation

- Terrestrial high altitude balloons operate for weeks with minimal electrical power
- Payloads 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.
- *New Solution:* A **Variable Conductance Heat Pipe** (VCHP) will passively adjust thermal resistance to maintain instrument's temperature within the required range while heat sink and/or power vary.

Potential VCHP Configurations

- A low-cost VCHP that is capable of passively maintaining a relatively constant evaporator (payload) temperature while the sink temperature varies between -90 and 40° C
- Two potential VCHP evaporator – condenser – reservoir arrangements have been considered
  - Cold reservoir near the condenser
  - Warm reservoir near the evaporator



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 Benefits

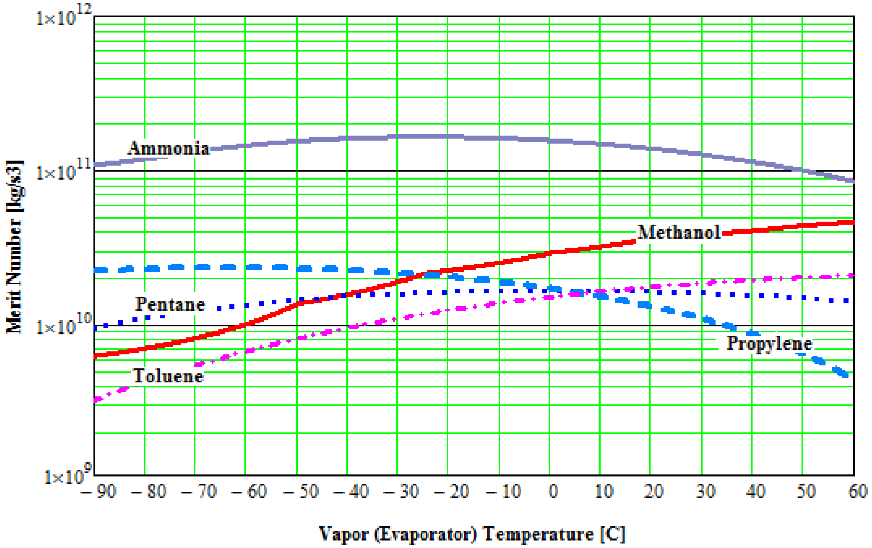
- Potential Benefits, based on a preliminary investigation:
  - Payload protection against low temperatures
  - Passive thermal control
  - No power required
  - Reliable
  - Relatively tight payload temperature control,
    - ~ 5° C with methanol and warm reservoir while the ambient sweeps the entire range of -90° C to +40° C
    - Can be further improved by optimizing the VCHP geometry (reservoir and tubing size) & by using a working fluid with an even more suitable vapor pressure curve
  - Low cost (low cost materials, simple geometry, high manufacturability, non-exotic fluids)
  - Low mass
  - Compact, simple and flexible geometry

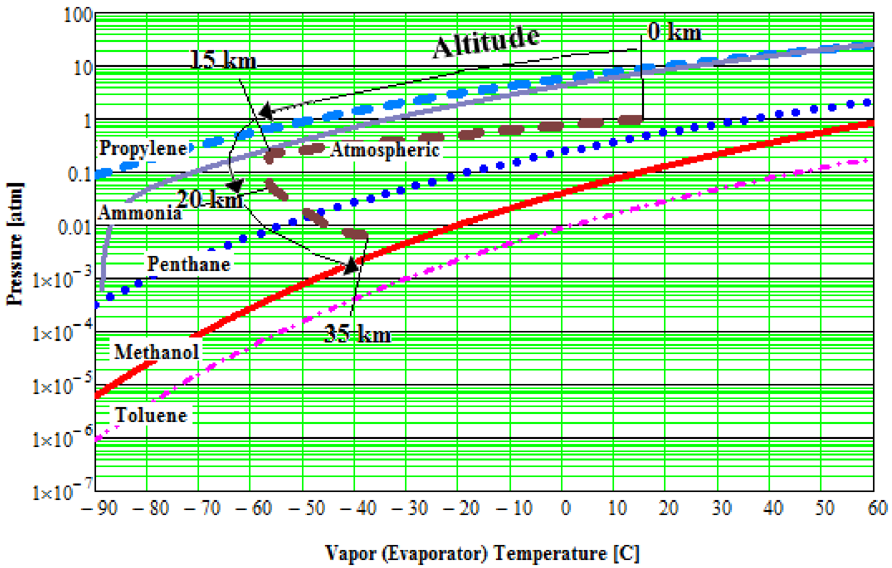
Envelope, Working Fluids & NCG Selection

- The criteria in choosing the envelope and wick materials for this particular application would be:
  - Compatibility with the working fluid
  - Low price
  - Low thermal conductivity (to better control the heat flow)
  - High structural strength (to allow thin walls that in turn allow low mass and better control of the heat flow)
  - Manufacturability (low cost fabrication price)
- A fluid must be chosen that is compatible with the VCHP envelope & wick for a potentially long operating life
  - Potential working fluids: methanol, toluene, pentane, propylene and ammonia
  - NCG: Argon, Neon, Helium

Envelope Material	Compatible	Incompatible
Titanium	Water Methanol Ethanol	Acetone Ammonia
Stainless Steel	Methanol Ethanol Pentane Toluene	
Copper	Acetone Methanol Water Toluene	Ammonia
Aluminum Nickel Stainless Steel	Ammonia Benzene Naphthalene n-Pentane Toluene	Water Alcohols Acetone

Envelope, Working Fluids & NCG Selection

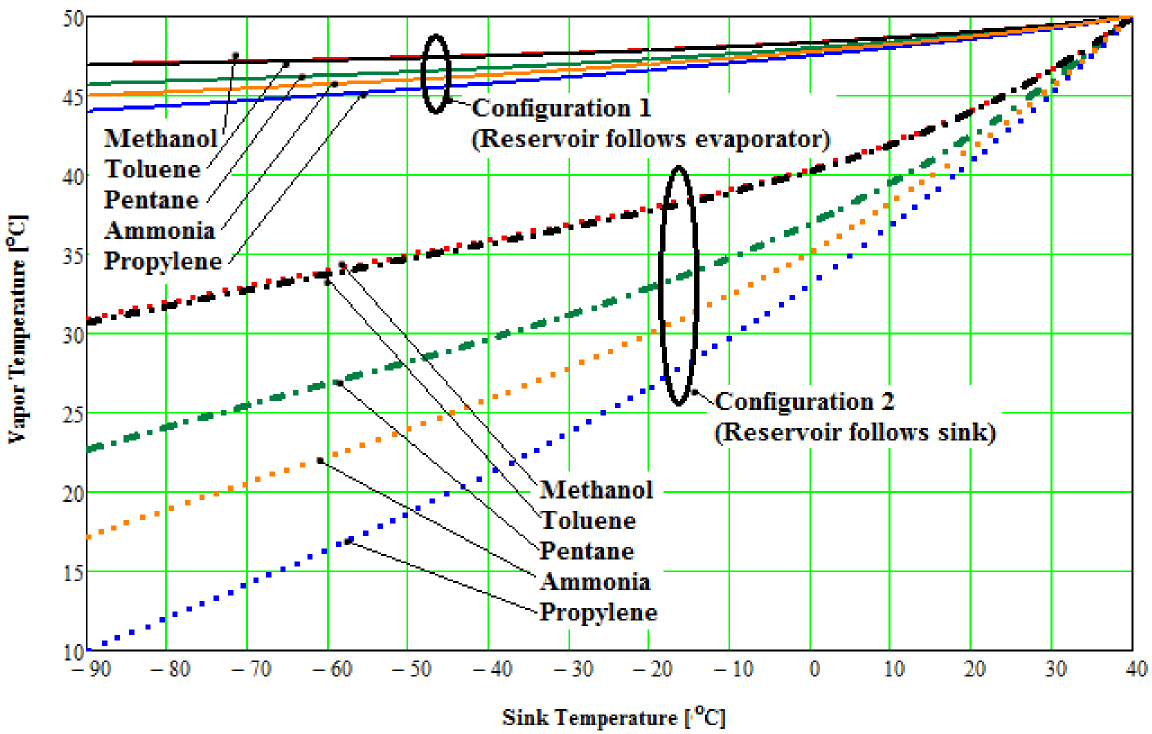




- The results of the down selection show that stainless steel should be used as the envelope & wick materials
  - Working fluids that are compatible with this material are methanol, pentane and toluene
- Assuming that the vapor temperature (payload temperature) will always be within the range of -5 to 50° C, methanol shows slightly better heat transfer properties
- The pressure differences for pentane and methanol vary over the altitude and payload temperatures
  - In a worst case scenario, methanol shows a small advantage

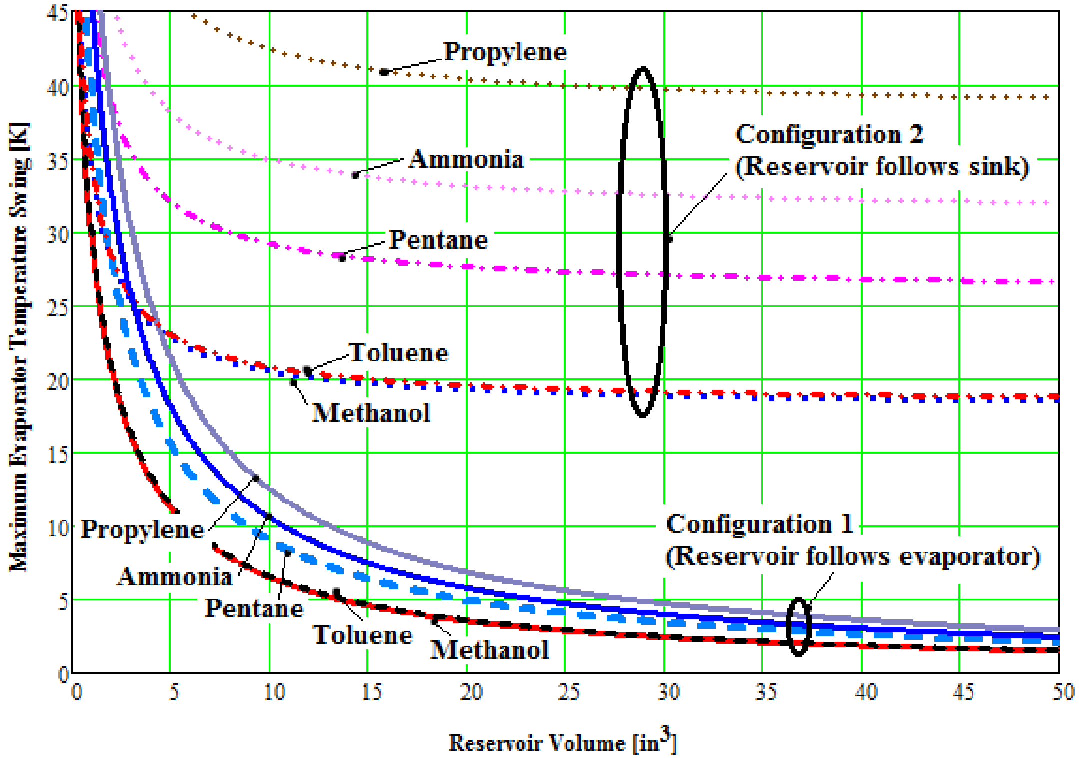
Performance Depends on Configuration/Fluid/Reservoir Size

- Evaporator temperatures variation as the sink temperature sweeps the entire Heat Sink Temperature Interval
  - Warm Reservoir (Configuration 1) shows tighter temperature control than Configuration 2
  - Methanol and toluene show best temperature control



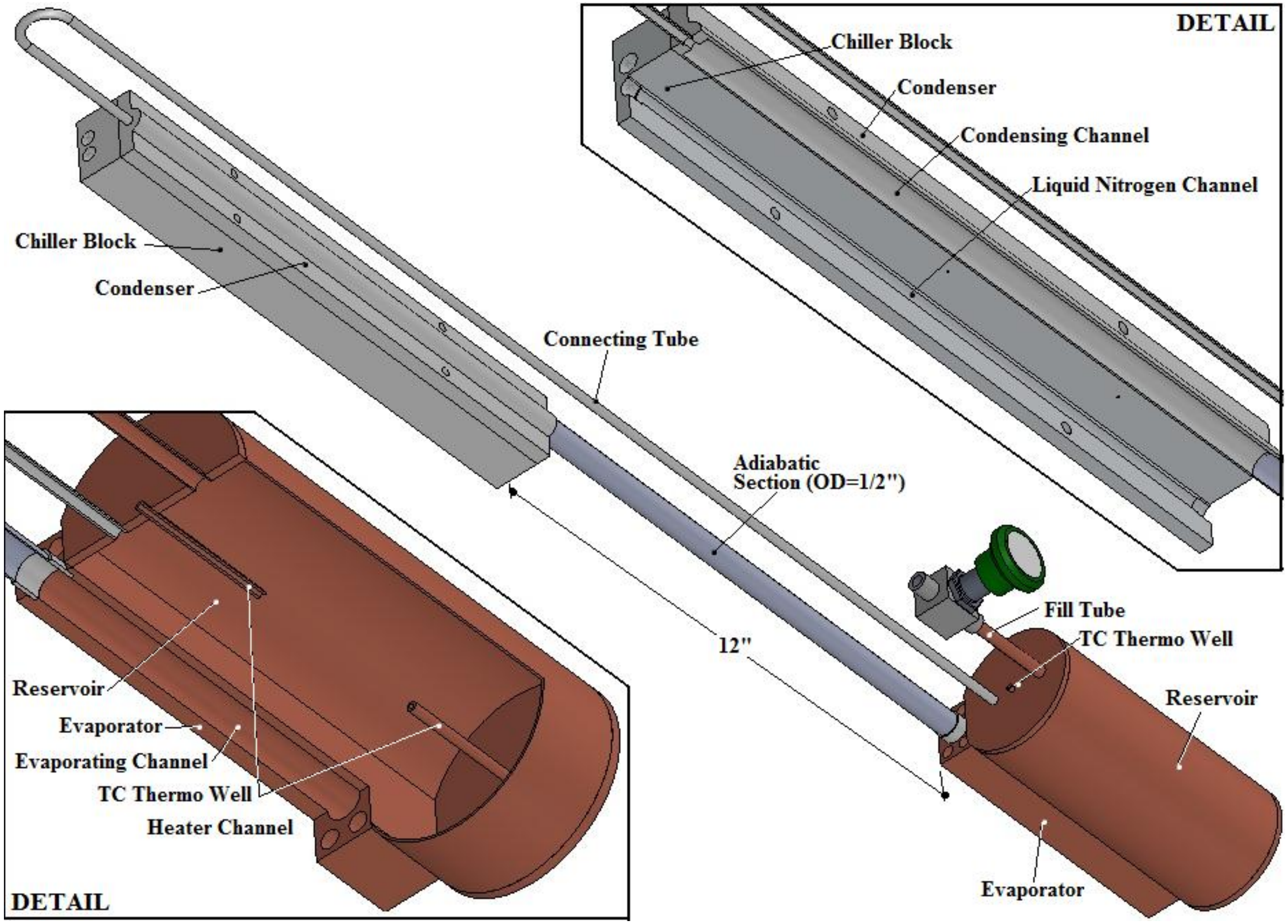
VCHP Performance vs. Reservoir Size

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



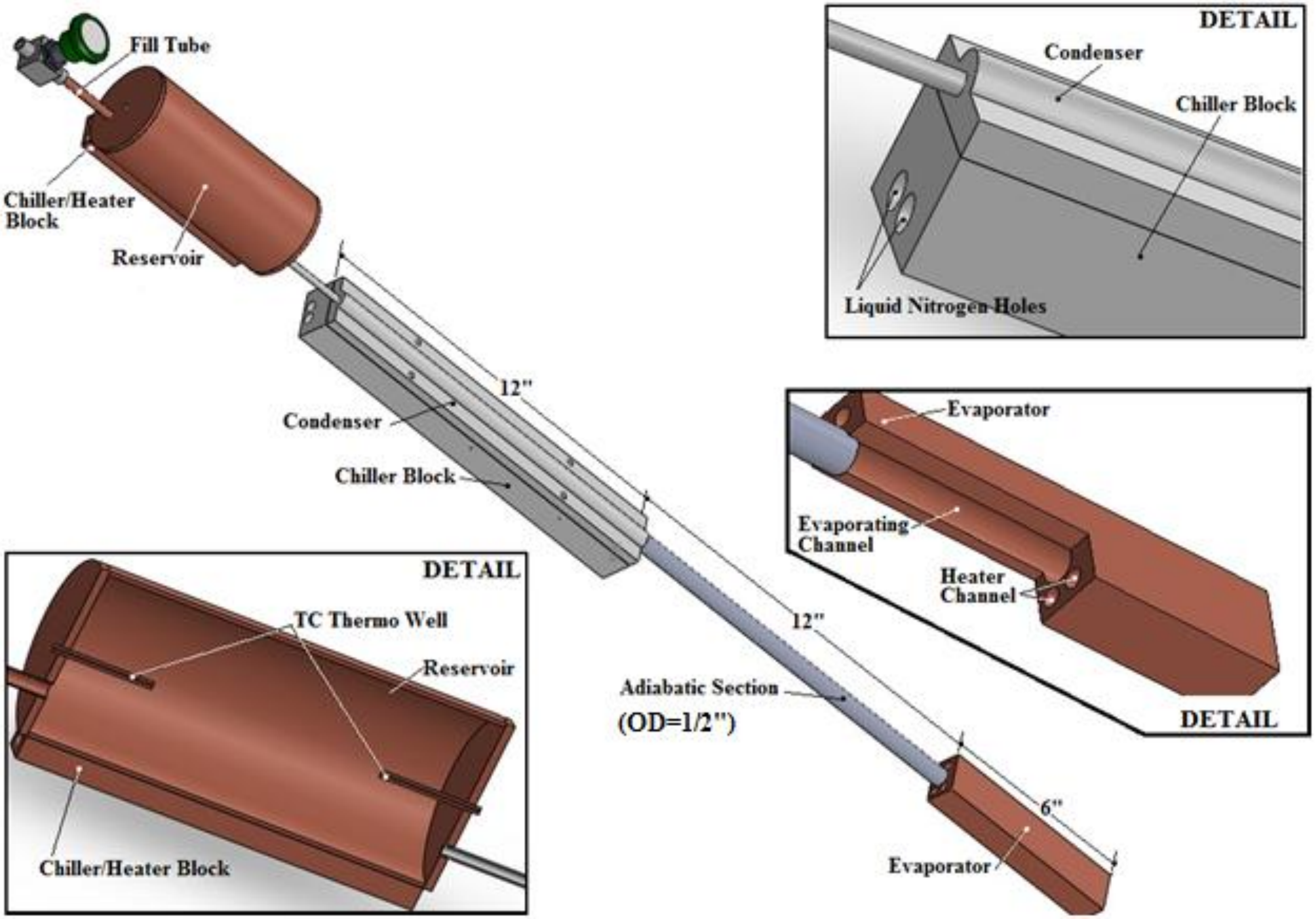
Proof-of-Concept VCHP Design

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



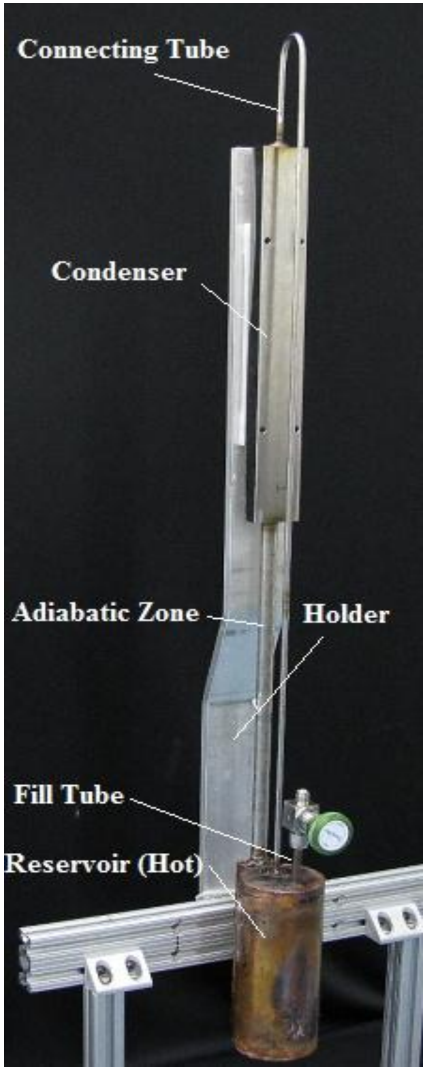
Proof-of-Concept VCHP Design

– Configuration 2 – Reservoir attached to condenser

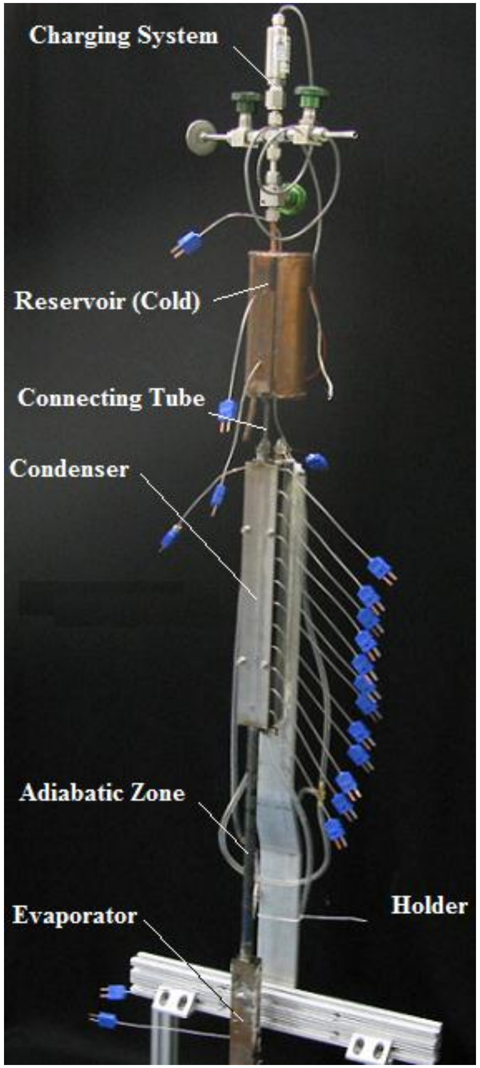


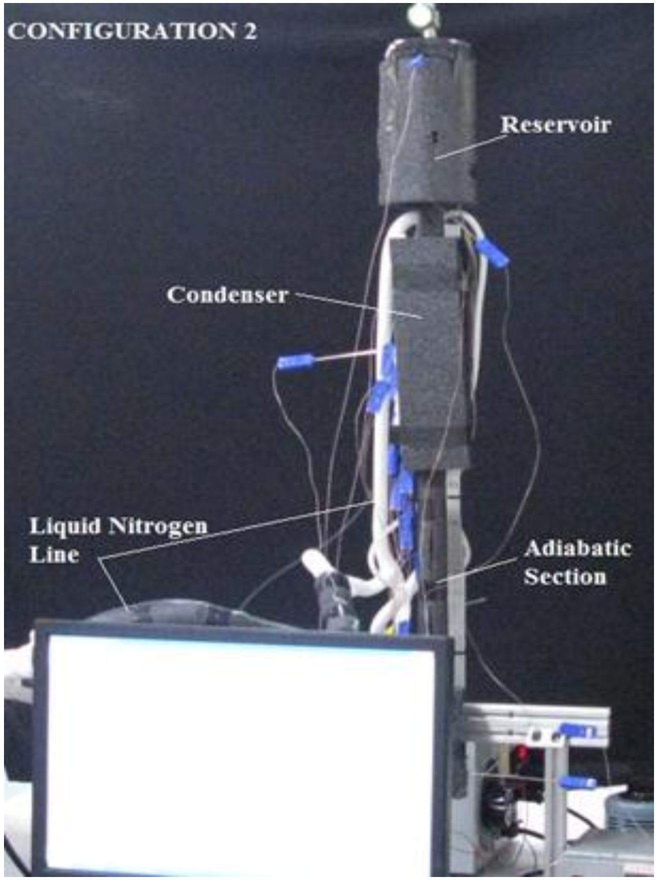
Testing Setup

- Configuration 1



- Configuration 2



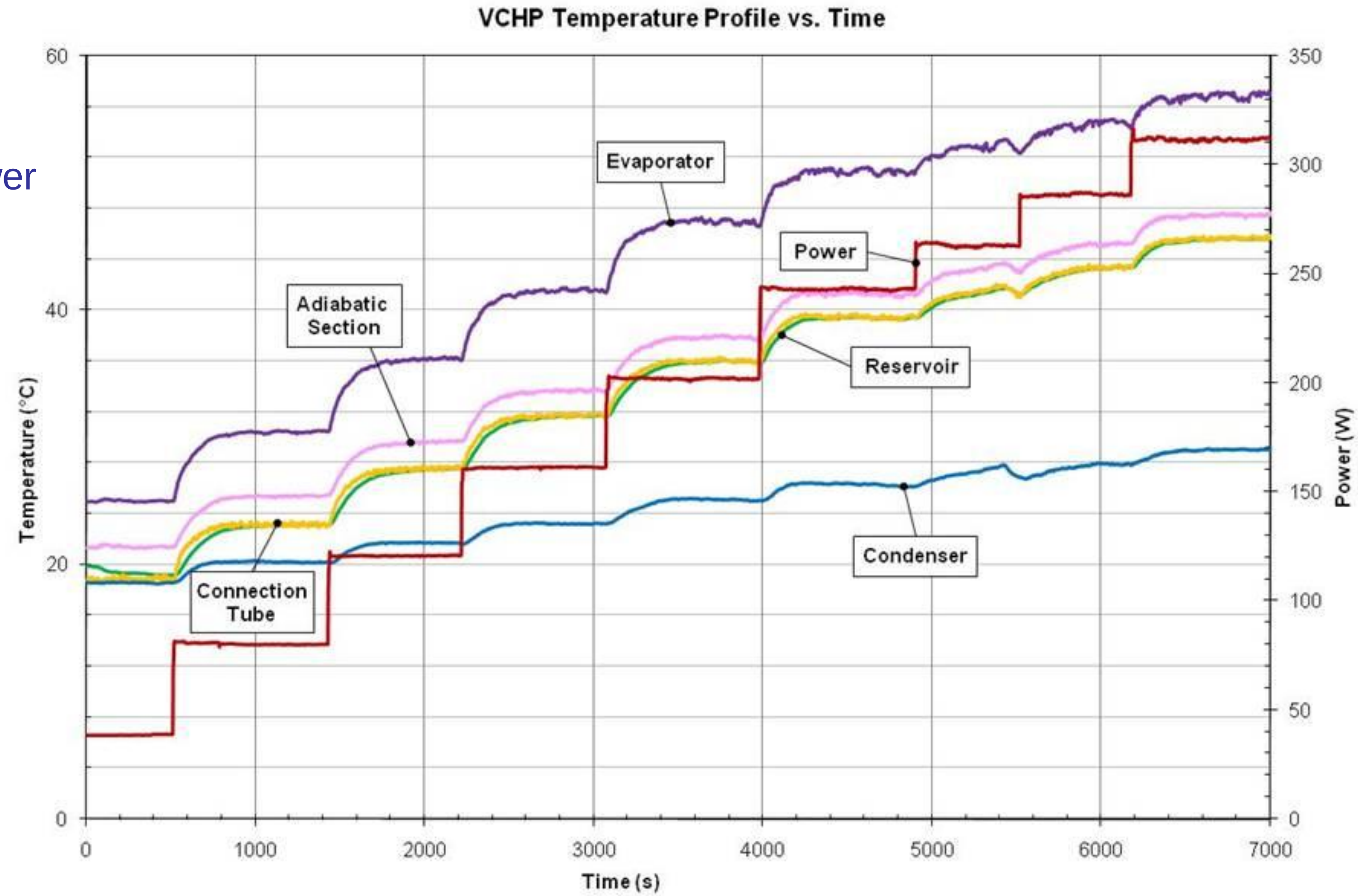


Experimental Results

- Each VCHP configuration was tested with all three working fluids:
  - Methanol
  - Toluene
  - Pentane
- Three types of tests were conducted:
  - Power test *(only configuration 2 with methanol)*
  - Thermal control test *(all combinations)*
  - Survival test *(only configuration 2 with toluene)*
    - Sink temperature = -90°C
    - It shows a very long survival time – temperature dropped from 48°C to 20°C in ~ 13000 sec.
- Configuration 1 (Warm Reservoir) provides the best temperature control
- All the results show very good agreement with the predictions

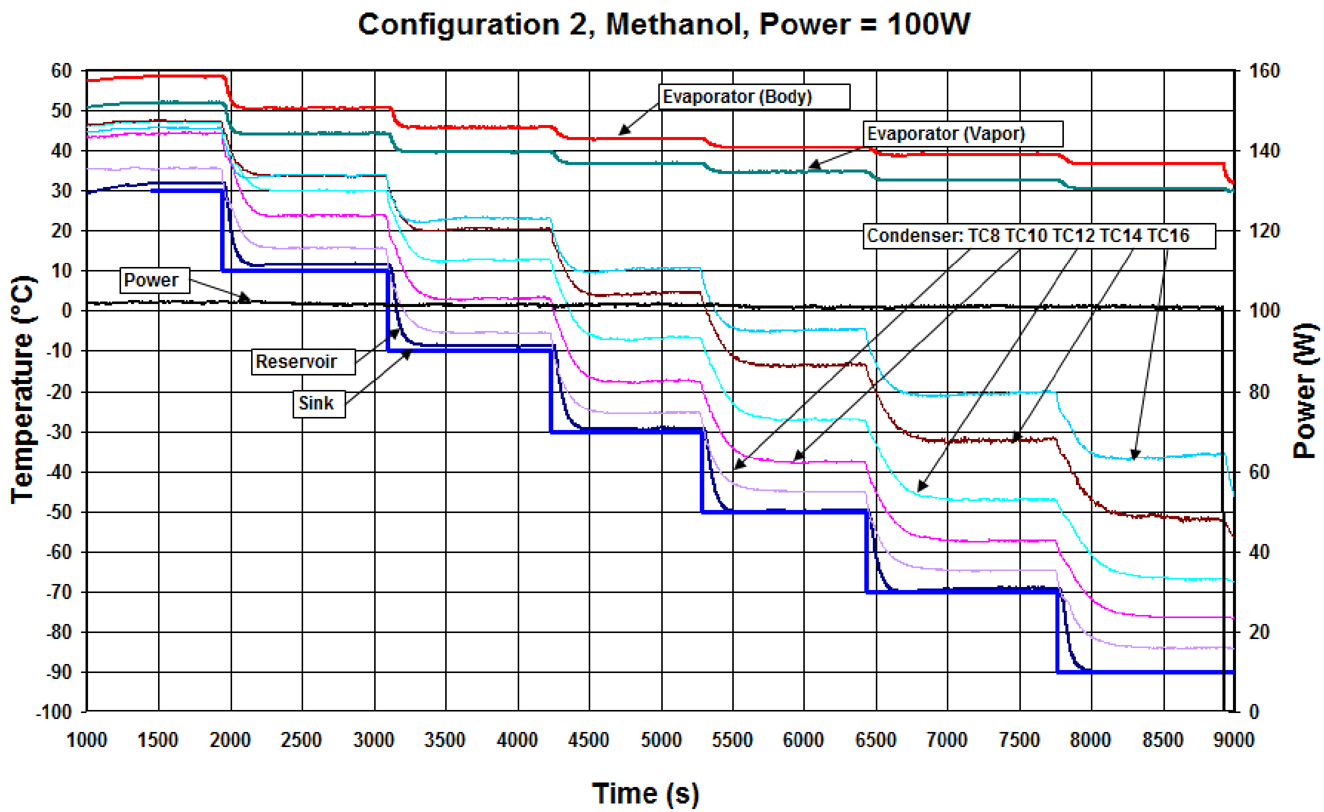
VCHP Cold Reservoir (Methanol) – Power

- 300 W – maximum power

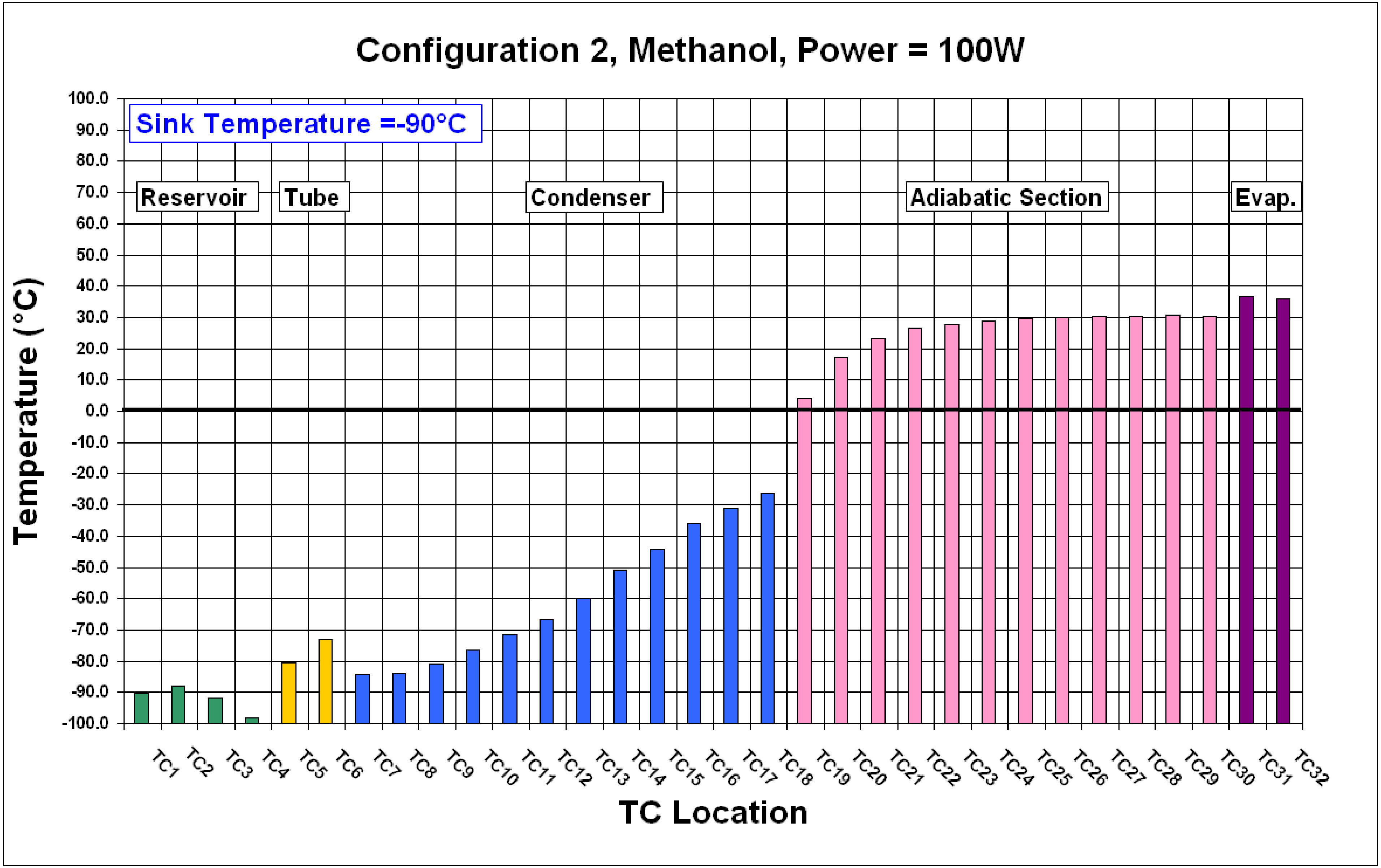


Cold Reservoir (Methanol) – Thermal Control

- 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

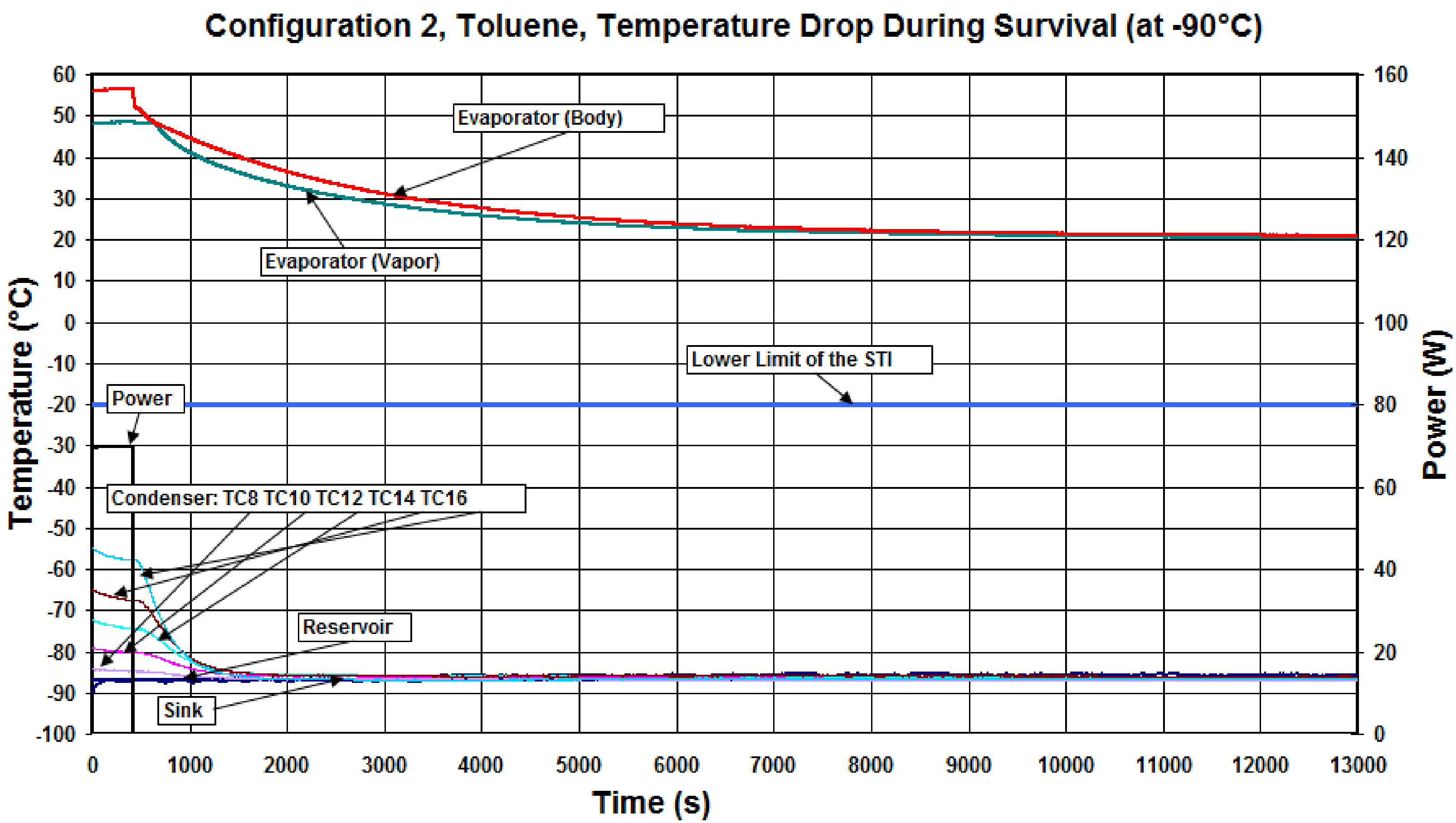


Cold Reservoir (Methanol): Constant power (100 W), Variable Sink

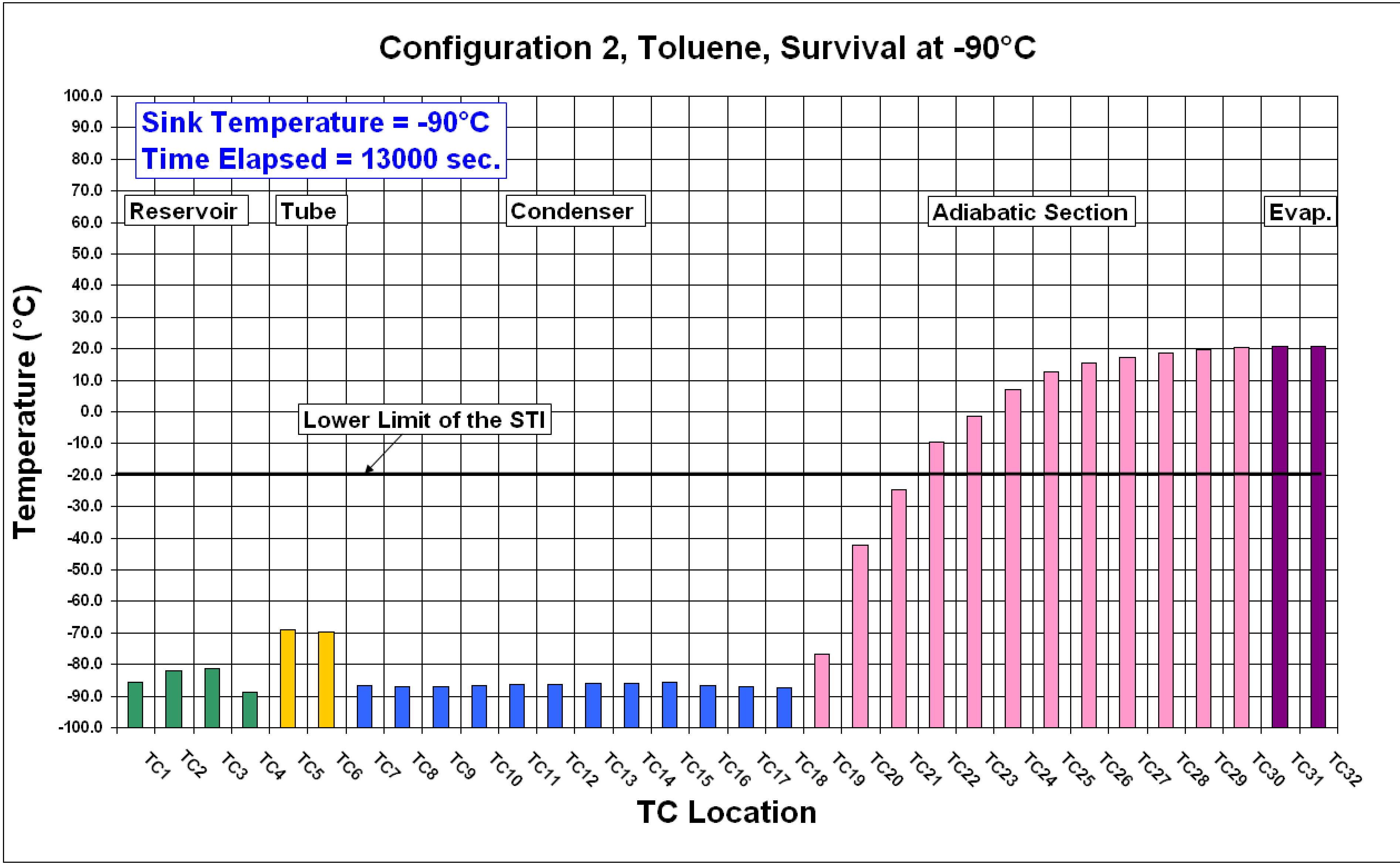


Cold Reservoir (Toluene): Survival Test

- Power = 0 W (neglects heat leak from ambient)
- Sink Temperature = -90ºC

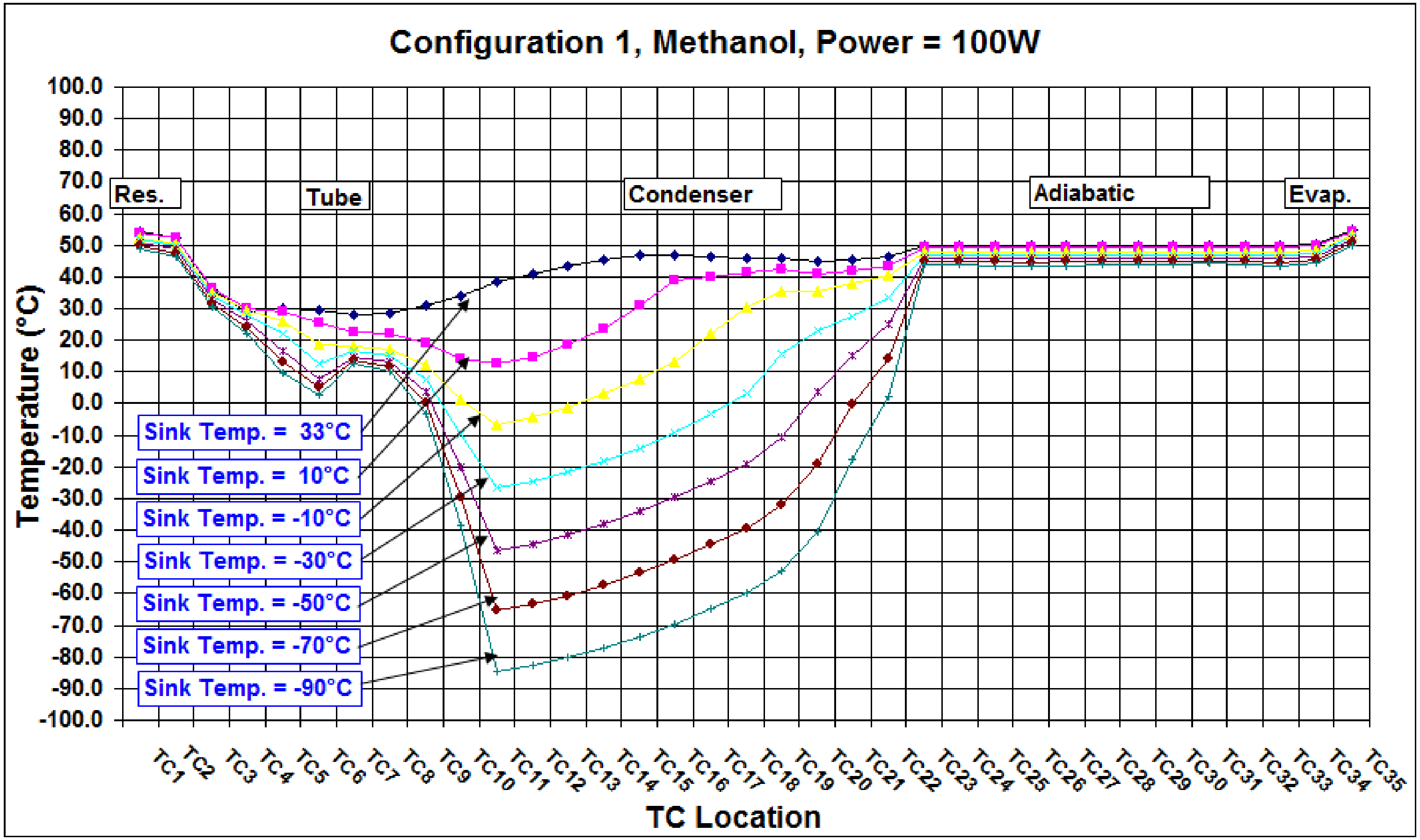


Cold Reservoir (Toluene): Survival Test

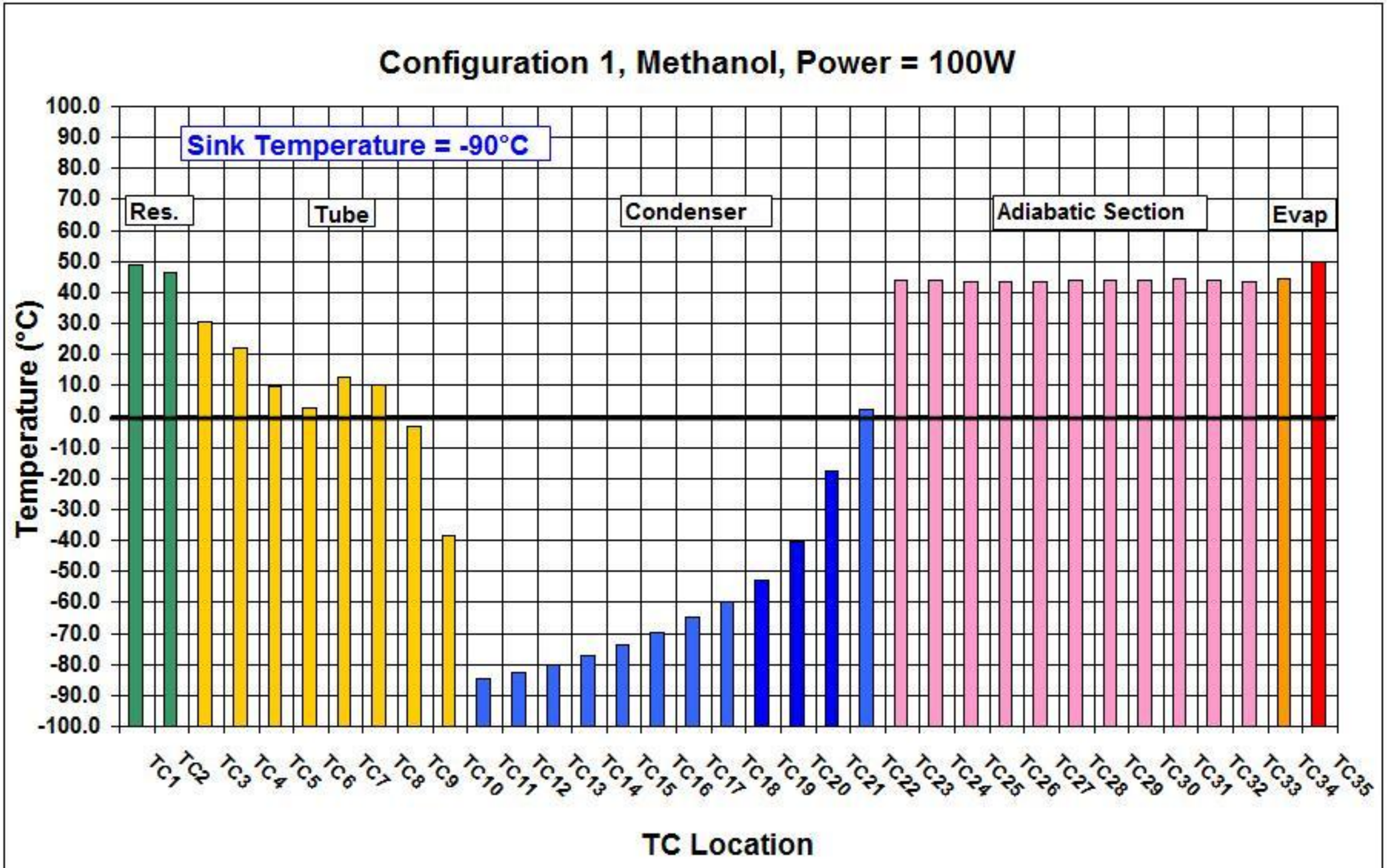


Warm Reservoir (Methanol) – Thermal Control

- Steady State Temperature Profiles
- Constant Power (100 W)
- Variable Sink Temperature

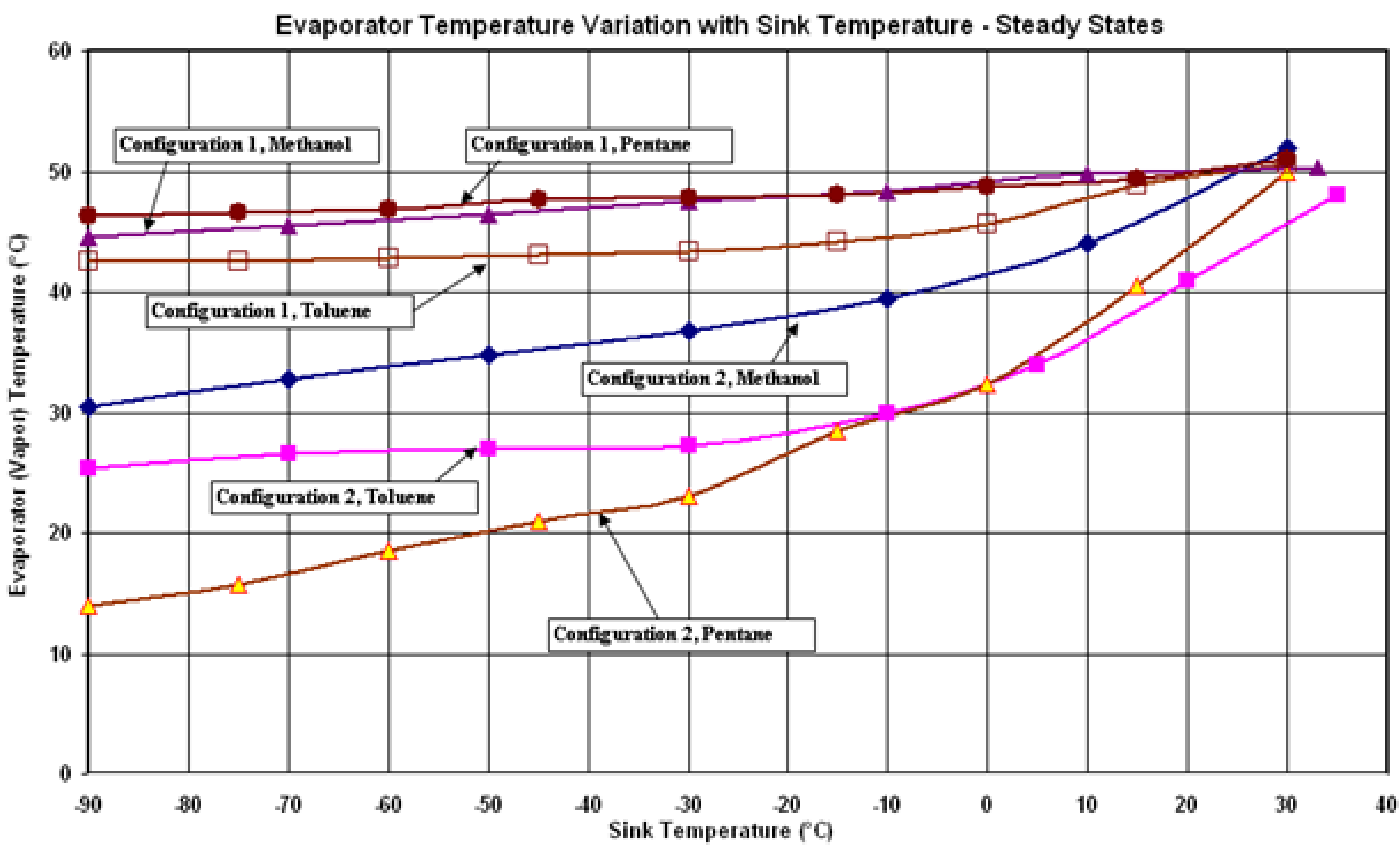


Warm Reservoir (Methanol): Constant power (100 W), Variable Sink



Control with Variable Sink Temperature

- Evaporator Temperature Change as Sink Sweeps the HSTI
- Constant Power (100 W for Methanol and 70W for Toluene and Pentane)
- Variable Sink Temperature



Balloon VCHP Experimental Results

- Six Configurations were Tested:
  - Configuration 1 (Warm) with methanol, 4.8°C temperature control band
  - Configuration 1 (Warm) with toluene, 6.2°C temperature control band
  - Configuration 1 (Warm) with pentane, **3.7°C** temperature control band
  - Configuration 2 (Cold) with methanol 21°C temperature control band
  - Configuration 2 (Cold) with toluene 23°C temperature control band
  - Configuration 2 (Cold) with pentane 36°C temperature control band
- Survival test was carried only for Configuration 2 with toluene
  - Sink temperature = -90°C
  - It shows a very long survival time – temperature dropped from 48°C to 20°C in ~ 13000 sec.
- Configuration 1 (Warm Reservoir) provides the best temperature control
- All the results show very good agreement with the predictions

Working Fluid →	**Methanol**		**Toluene**		**Pentane**	
Configuration	Predicted	Measured	Predicted	Measured	Predicted	Measured
VCHP Configuration 1	47..50°C	45.3..50°C	46.9..50°C	43..50°C	45.2..50°C	46.3..50°C
VCHP Configuration 2	30.8..50°C	30.4..50°C	30.3..50°C	26.2..50°C	17.4..50°C	14..50°C

Conclusions

- In addition to precise temperature control, VCHPs can be used for:
  - Variable Thermal Links
  - Frozen Start-up
  - Over-Temperature Protection
- Reservoirs normally not electrically heated
  - Cold reservoir at condenser
  - Warm reservoir at evaporator
- Two applications were discussed
  - VCHP Radiator for Lunar and Martian Fission Power Systems
    - 2 m long titanium/water thermosyphons, cold reservoir
    - Successfully demonstrated shut down and freeze/thaw
  - VCHP Variable Thermal Links for Balloon Instrumentation
    - Heat sink range of 130° C (-90° C to 40° C)
    - Warm reservoir near evaporator had a ΔT of 3.7° C
    - Cold reservoir near condenser had a ΔT of 21° C

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Variable Conductance Heat Pipes with Unheated Reservoirs

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