Different Types of Heat Pipes

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Thermal & Fluids Analysis Workshop
TFAWS 2014
August 4 - 8, 2014
NASA Glenn Research Center
Cleveland, OH

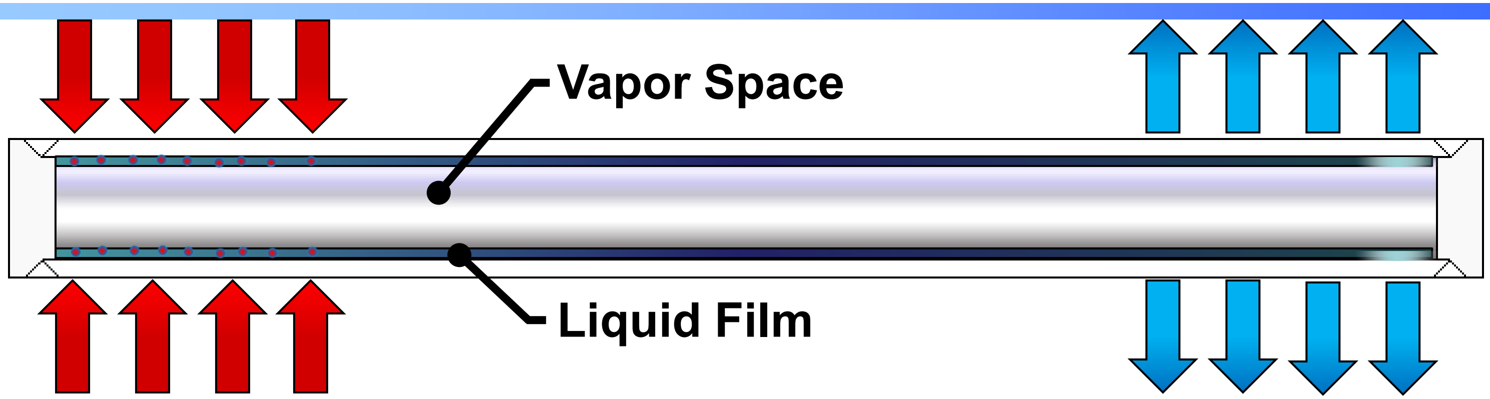
Motivation

- Most heat pipe books discuss standard heat pipes, vapor chambers, and thermosyphons
  - Most of the heat pipes in use are constant conductance heat pipes and thermosyphons (> 99%)
- Specialty books discuss VCHPs for precise temperature control, and diode heat pipes
- Information on non-standard heat pipes is buried in the technical literature
- This presentation is a brief survey of the different types of heat pipes

Presentation Outline

- Constant Conductance Heat Pipes
  - Heat Pipes
  - Vapor Chambers
- Gas-Loaded Heat Pipes
  - Variable Conductance Heat Pipes (VCHPs)
  - Pressure Controlled Heat Pipes (PCHPs)
  - Gas Trap Diode Heat Pipes
- Interrupted Wick
  - Liquid Trap Diode Heat Pipes
- Heat Pipe and VCHP Heat Exchangers
- Alternate Means of Liquid Return
  - Thermosyphons
  - Rotating Heat Pipes

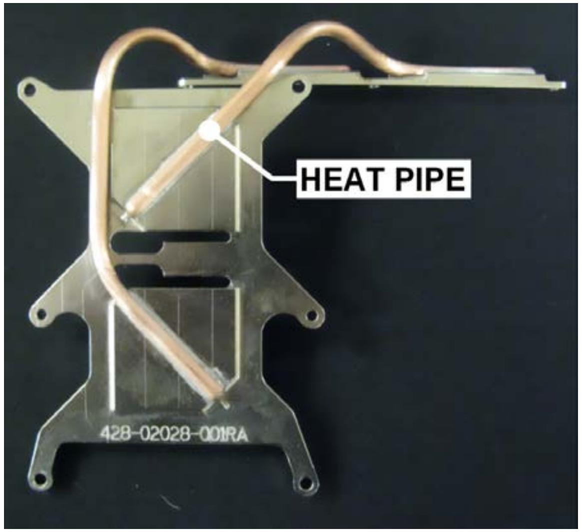
Heat Pipe Basics

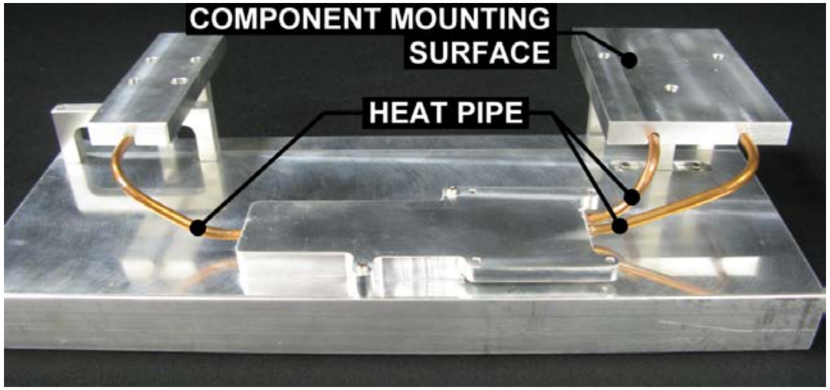


- Passive two-phase heat transfer device operating in a closed system
  - Heat/Power causes working fluid to vaporize
  - Vapor flows to cooler end where it condenses
  - Condensed liquid returns to evaporator by gravity or capillary force
- Typically a 2-5 °C ΔT across the length of the pipe
- k_{eff} ranges from 10,000 to 200,000 W/m-K
- Heat Pipes can operate with heat flux up to 50-75W/cm^2
  - Custom wicks to 500W/cm^2

Standard Heat Pipe "*Use & Benefits*"

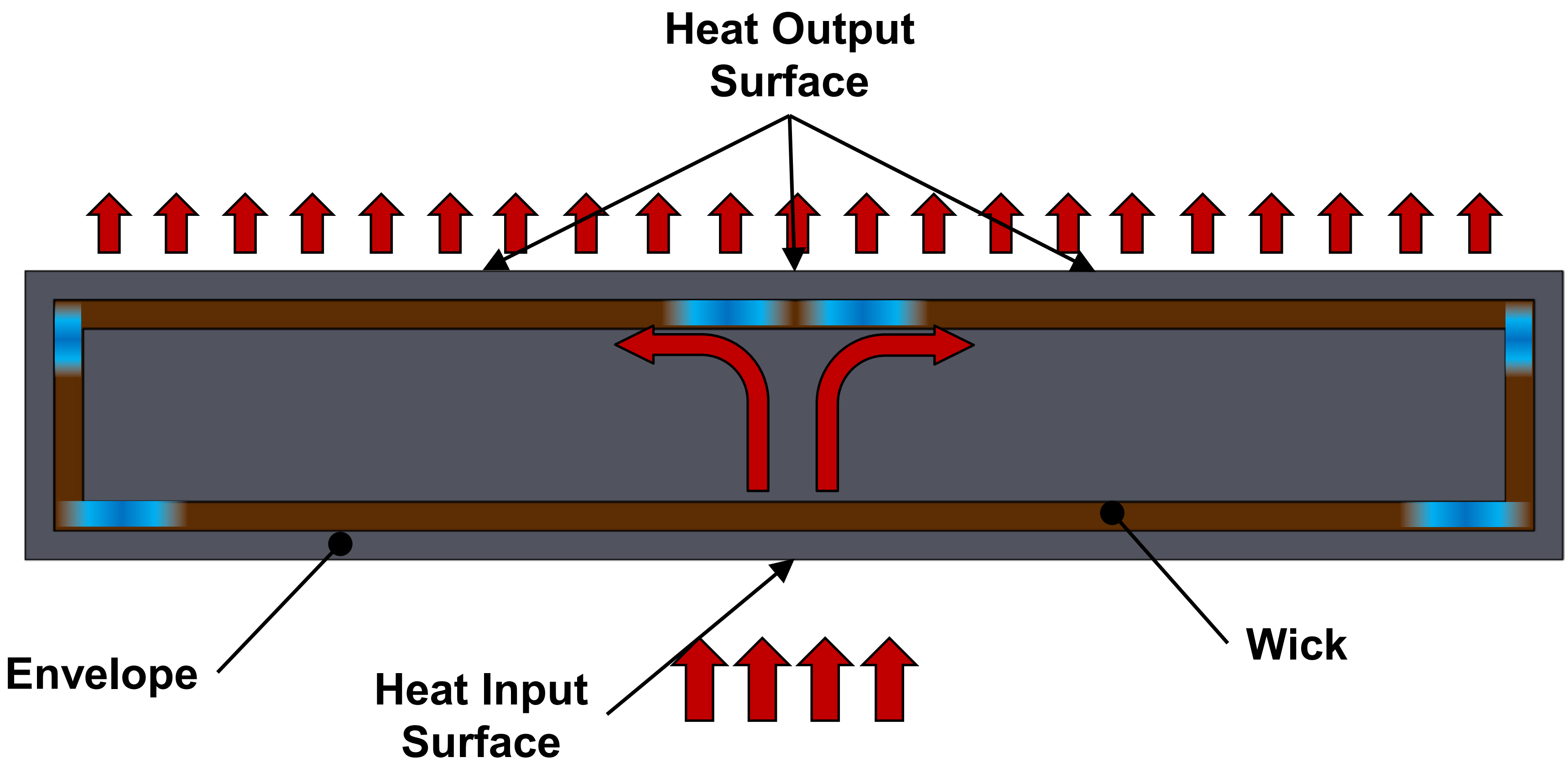
- When to Consider Spot Cooling Heat Pipes
  - Cooling of individual components by transferring heat to an external sink
- Benefits
  - Decrease hot spots to increase maximum power output
  - High Thermal Conductivity
    - 10,000 to 100,000 W/m K
    - Isothermal, Passive
  - Flexibility
    - Can be formed to fit countless geometries
  - Shock/Vibration Tolerant
  - Freeze/Thaw Tolerant





Vapor Chamber

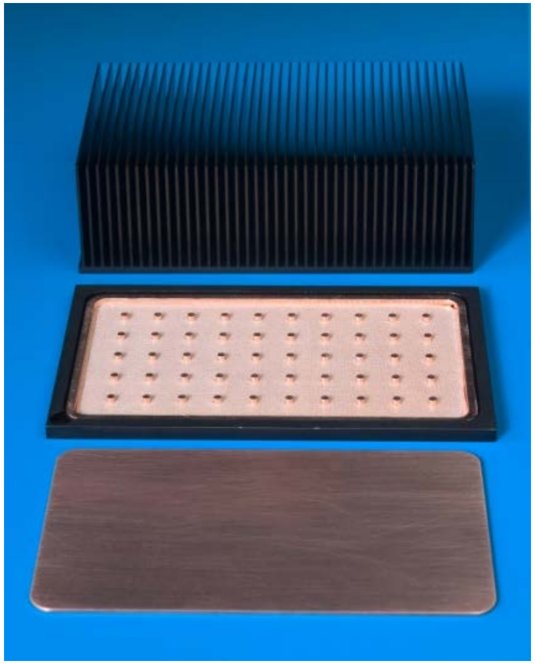
- Vapor Chambers are Planar Heat Pipes for Heat Spreading/Isothermalizing



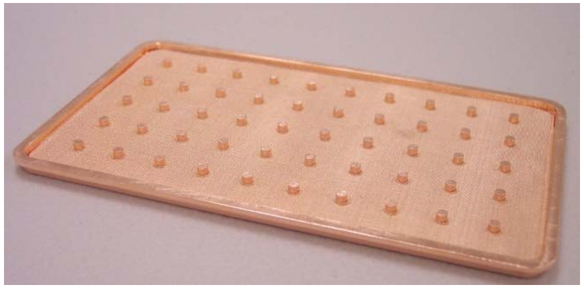
P. M. Dussinger et al., "High Heat Flux, High Power, Low Resistance, Low CTE Two-Phase Thermal Ground Planes for Direct Die Attach Applications," GOMACTech 2012, Las Vegas, NV, March 2012

Vapor Chambers *"Use and Benefits"*

- Benefits
  - Multi-component mounting
  - Thickness from 0.12" (3 mm)
  - Excellent Heat Spreading
    - Resistance < 0.15 °C/W, < 0.08 °C/W for special wicks
  - Excellent Isothermalization
  - High heat flux to low heat flux
  - Ideal for high heat flux/high performance applications
    - Heat flux > 60 W/cm^2, up to 750 W/cm^2 for special wicks



Typical Components



Vapor Chamber Internals

Assembled Vapor Chamber

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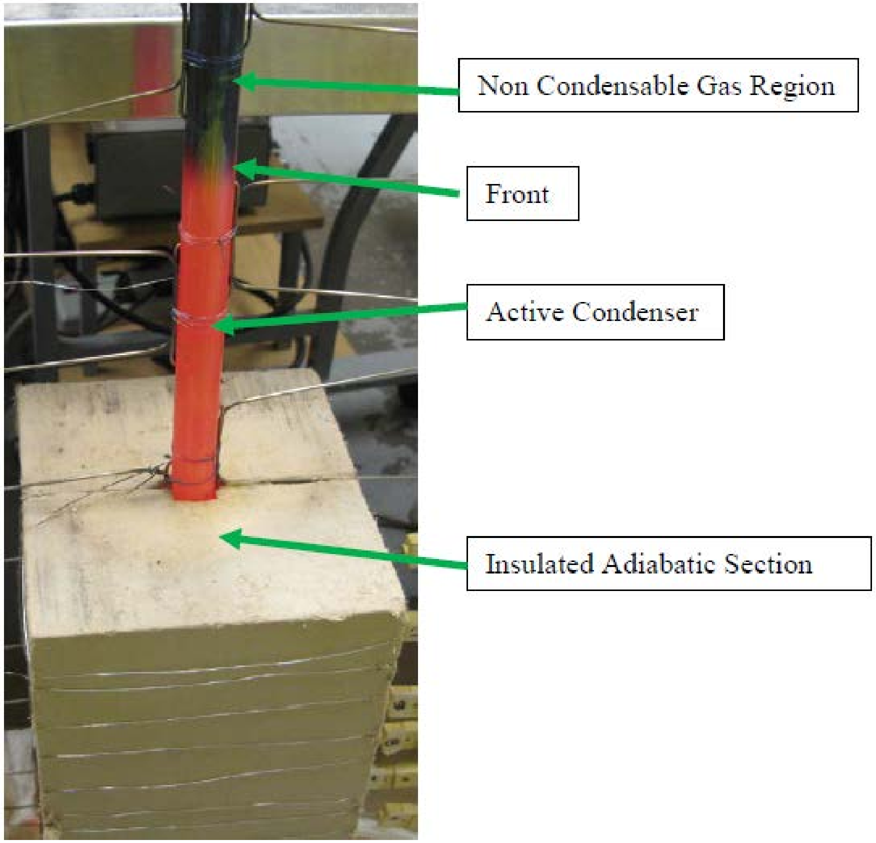
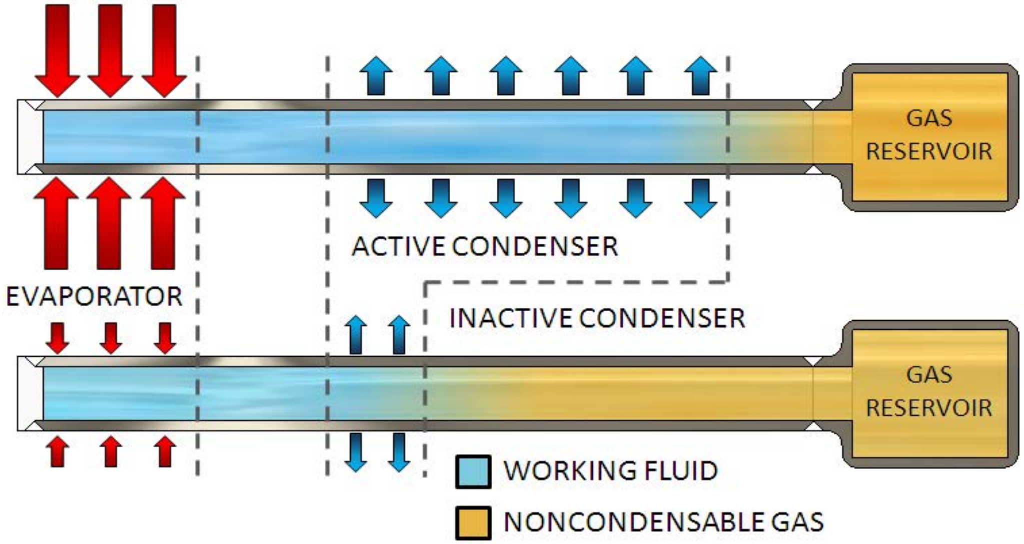
  - Rotating Heat Pipes

Gas-Charged Heat Pipes

- Standard heat pipes are evacuated, then filled with the working fluid
  - Vapor space contains only working fluid vapor
- In Gas Charged Heat Pipes, a Non-Condensable Gas (NCG) is added
  - Noble Gas
  - Typically argon for horizontal heat pipes, helium for vertical
- NCG is driven to the end of the pipe
- VCHPs, PCHPs, Gas-Charged Diodes



Variable Conductance Heat Pipe (VCHP) Operation



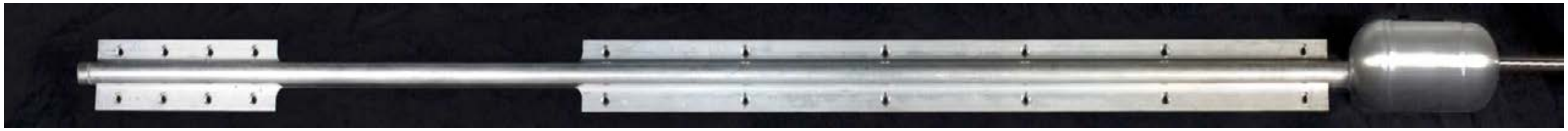
- During operation, the working fluid drives the Non-Condensable Gas (NCG) to the condenser
- The portion of the condenser blocked by NCG is not available for heat transfer by condensation
  - Inactive condenser region
- Remaining condenser is available for heat transfer
  - Active condenser region
- Active and inactive length depend on working fluid pressure

VCHP Applications

- Maintain constant evaporator temperature over varying power and sink temperatures
  - Standard aerospace application
- Dual condensers for radioisotope Stirling applications
  - Radioisotope heat must always be removed
  - Dump heat to secondary condenser when Stirling is turned off
- Variable Thermal Links
- Aid in Start-up and Shut-down from a frozen state
  - Prevents sublimation in water pipes when frozen
  - NASA radiator application
- VCHP Heat Exchangers
  - Provide constant outlet stream temperature, with varying input stream
  - Fuel cell application
  - Discussed below in Heat Exchanger Section

Standard VCHPs for Temperature Control

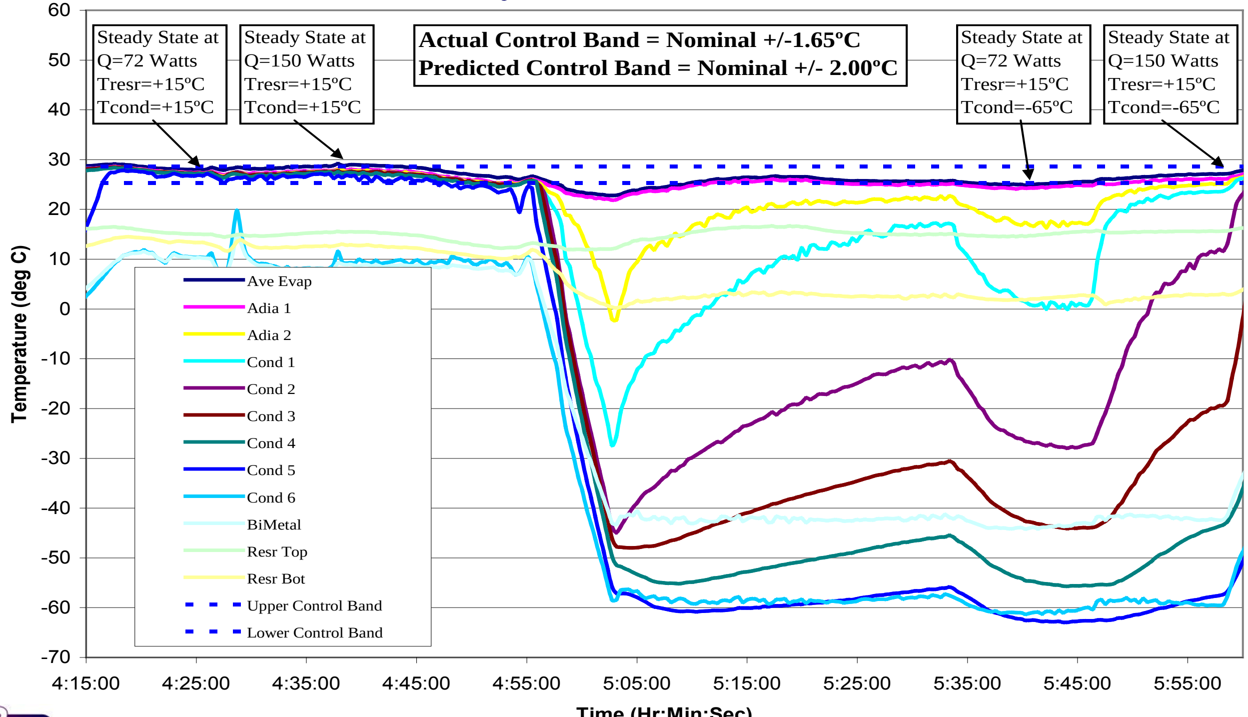
- VCHPs are most often used for temperature control in spacecraft applications



- 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

Standard VCHPs for Temperature Control

- Aluminum/Ammonia Design
- Evaporator controlled to ±1.65ºC
  - Good agreement with the analytical prediction of ±2ºC.
  - Input power was varied from 72 Watts to 150 Watts
  - Sink temperature ranged from +15ºC to -65ºC
  - Reservoir Thermostatically Controlled at 15°C.

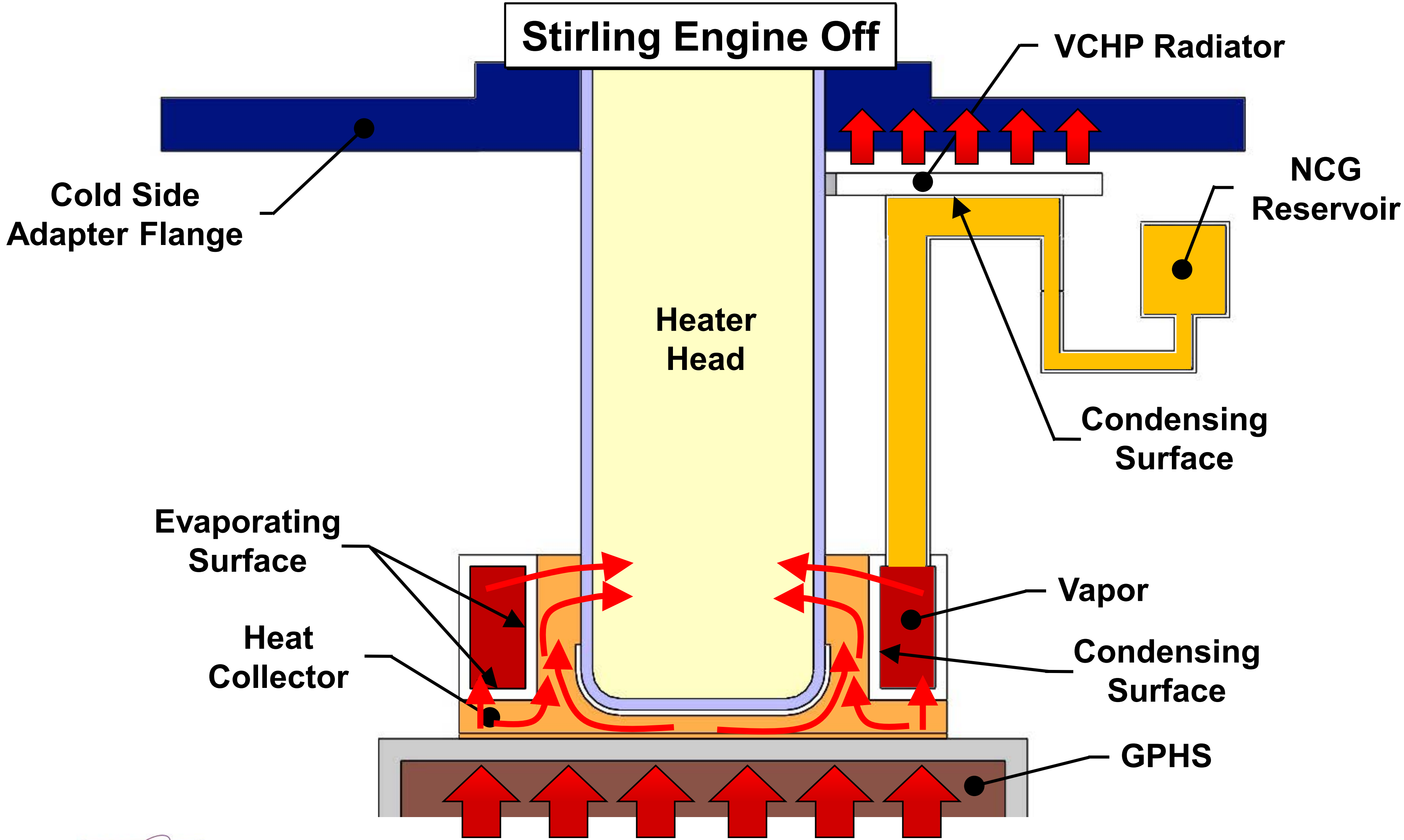


Dual Condenser VCHPs for Radioisotope Stirling

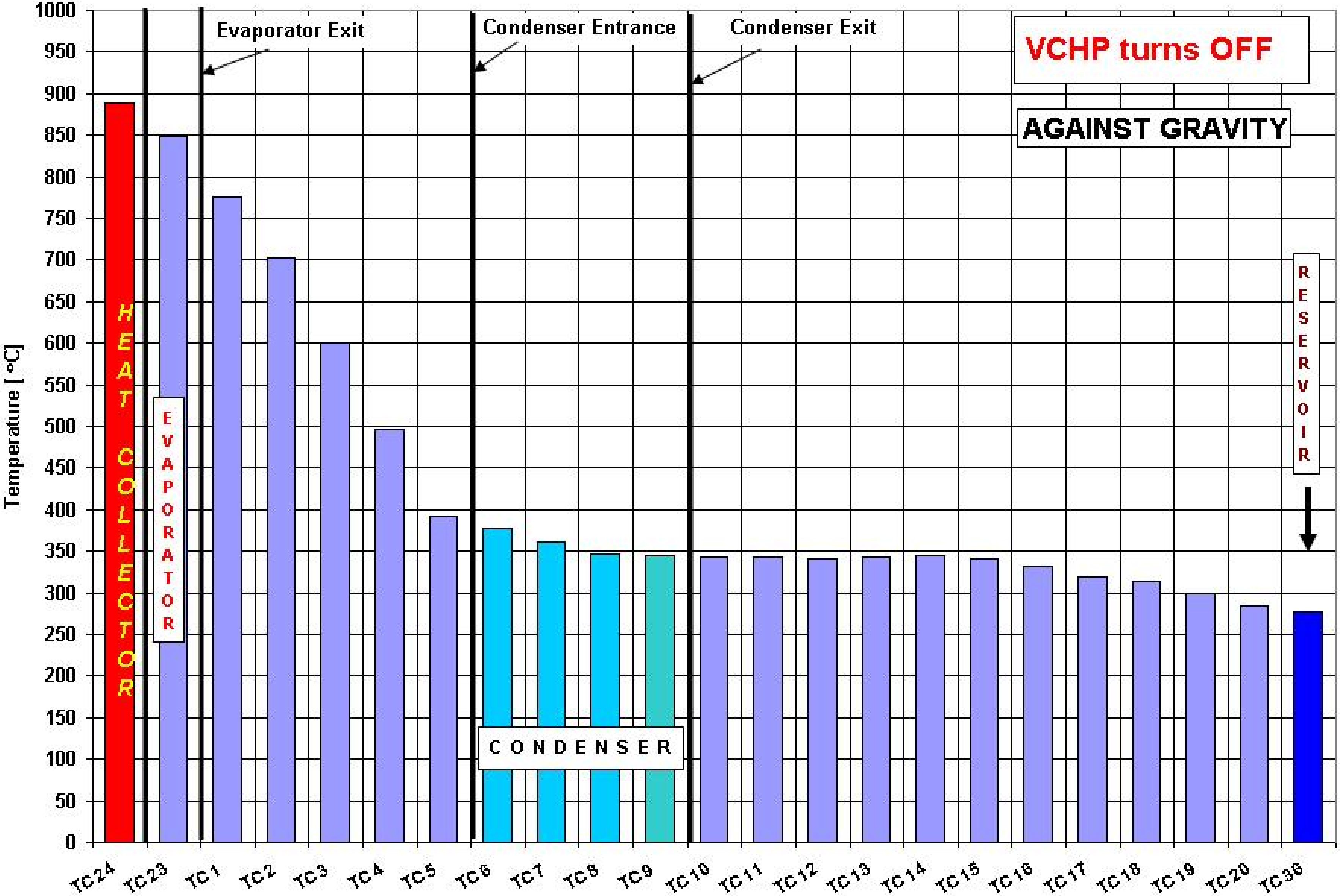
- NASA Glenn is developing the Advanced Stirling Radioisotope Convertor (ASRG) for more efficient space power
  - Uses 250 W General Purpose Heat Sources
  - Radioisotope must be Continually Cooled, or it will melt
- Dual Condenser VCHP
  - Supply Power to Stirling when Operating
  - Radiate to Second Condenser when Stirling off

C. Tarau and W. G. Anderson, "Sodium VCHP with Carbon-Carbon Radiator for Radioisotope Stirling Systems," 15th International Heat Pipe Conference, Clemson, SC, April 2010

Dual Condenser VCHPs for Radioisotope Stirling



Dual Condenser, Against Gravity, 850°C, Insulation → MicroTherm



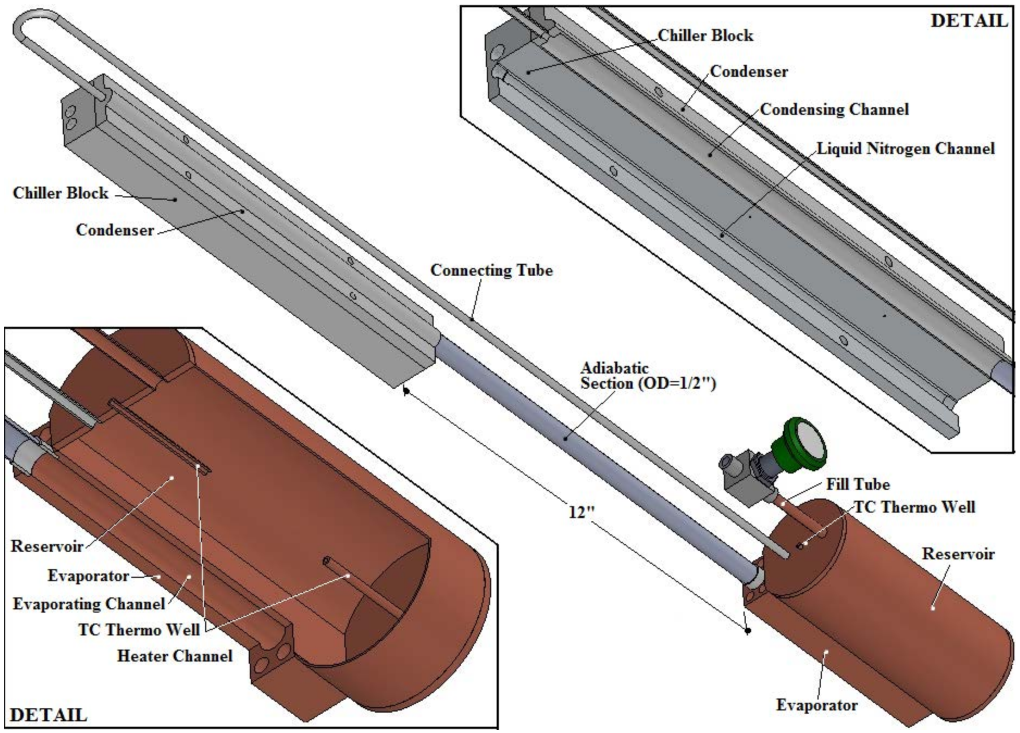
VCHPs for Variable Thermal Links

- VCHPs can also be used for variable thermal links
  - 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
- Variable Thermal Link useful when
  - Variable system loads resulting from intermittent use
  - Large changes in environment temperature
    - Lunar surface temperature range: -140 °C to 120 °C
  - Limited electrical power
    - Lunar Application: 1 W = 5 kg of energy storage and generation
- Applications that can benefit from using VCHPs as variable thermal links include
  - Lunar and Martian Landers and Rovers
  - Research Balloons (fly near Poles in winter)
  - Lunar and Space Fission Reactors

W. G. Anderson et al., "Variable Conductance Heat Pipes for Variable Thermal Links," 42nd International Conference on Environmental Systems (ICES 2012), San Diego, CA, July 15-19, 2012.

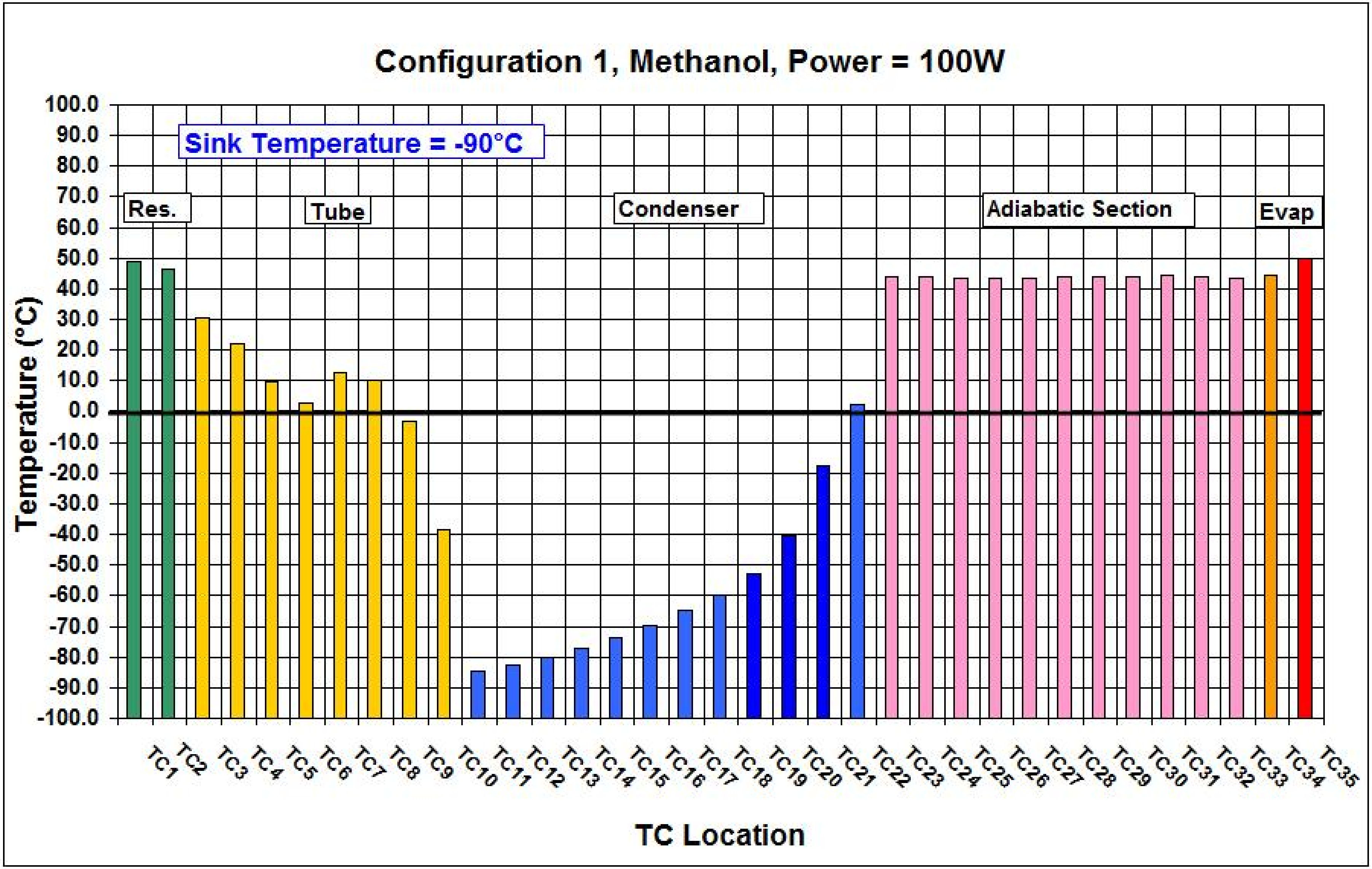
VCHP with Warm Reservoir for Balloons

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



C. Tarau and W. G. Anderson, "Variable Conductance Thermal Management System for Balloon Payloads," 20th AIAA Lighter-Than-Air Systems Technology Conference, Daytona Beach, FL, March, 25-28, 2013

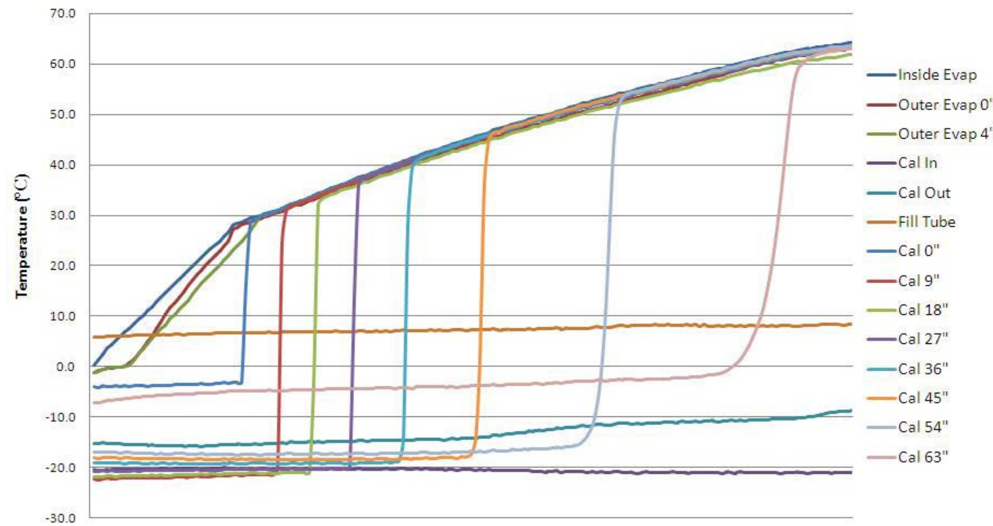
Warm Reservoir VCHP, 100 W Power, Variable Sink



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

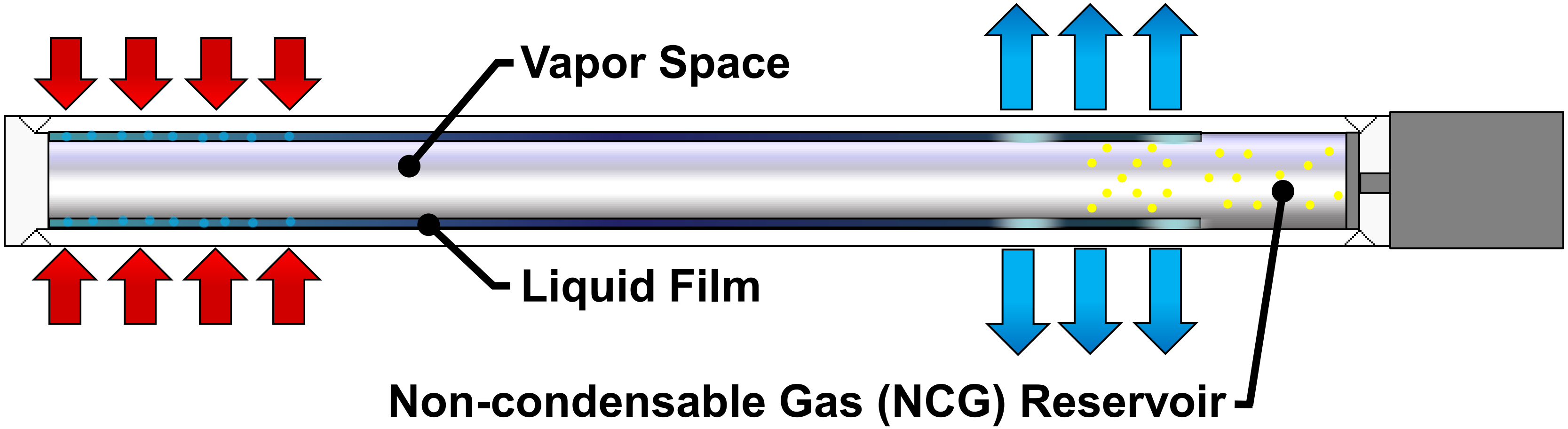
Freeze Thaw Testing – Startup Temperatures



- Titanium/Water VCHP designed for gravity aided operation
- Freeze free liquid in an arbitrary position
- Primary/Secondary Wicks held enough liquid to allow VCHP to operate at correct temperatures with no dryout

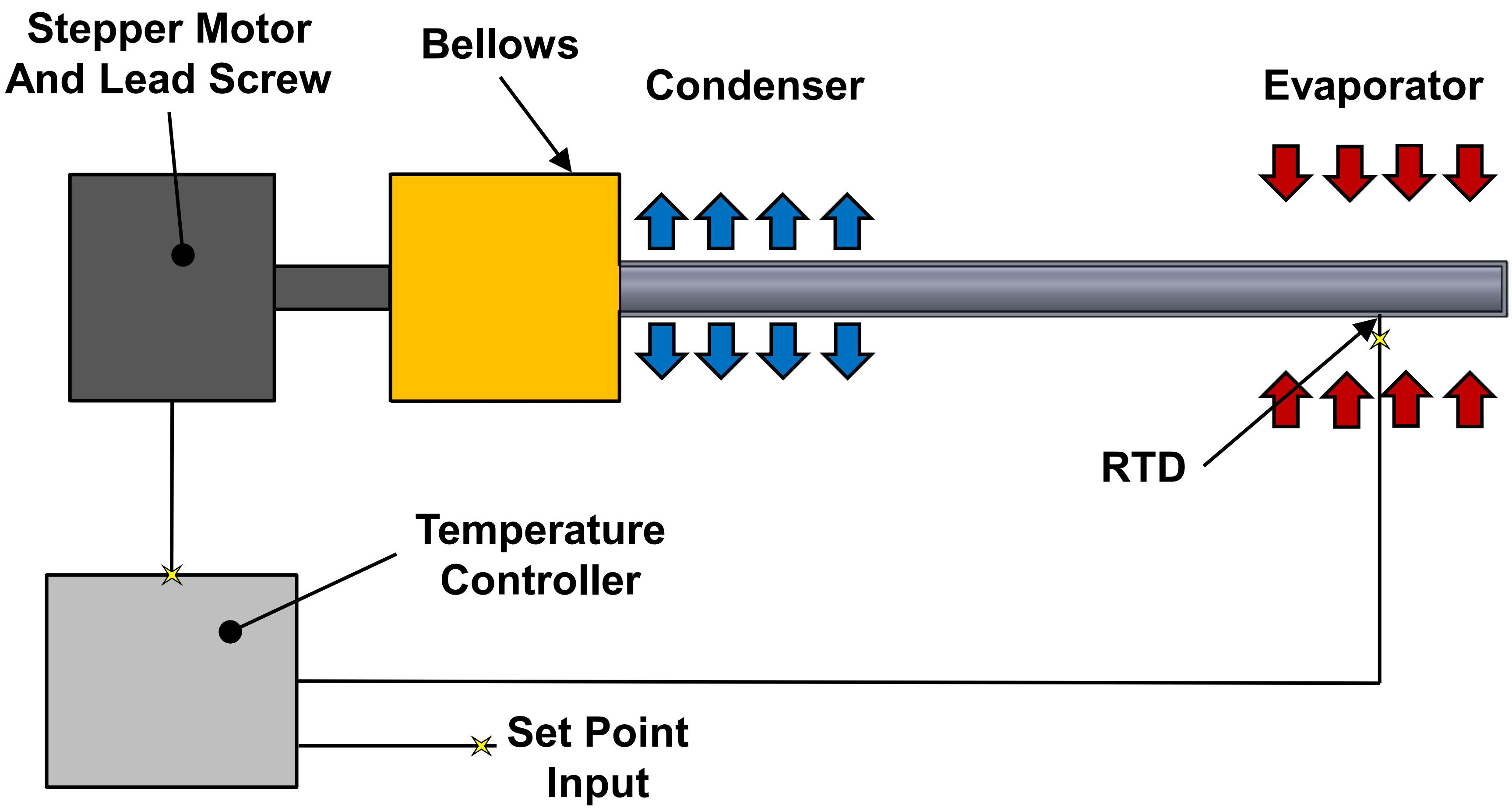
M. Ellis and W. G. Anderson, VCHP Performance after Extended Periods of Freezing, SPESIF, Huntsville, Alabama, February 2009

Pressure Controlled Heat Pipe (PCHP) Operation Summary



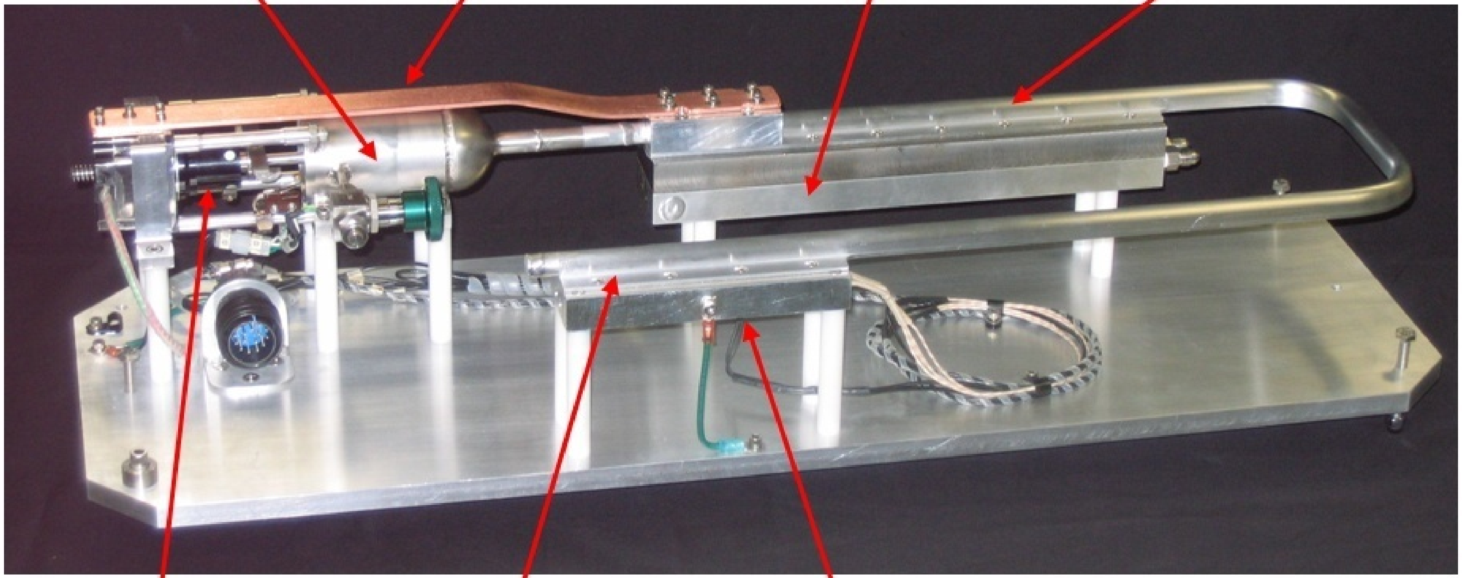
- Heat pipe pressure and temperature set by vapor pressure of working fluid.
  - Reservoir is linked to the vapor space so NCG is at the same pressure
- Vary reservoir volume or amount of gas
  - Actuator drives bellows to modulate the reservoir volume
  - Pump/vacuum pump adds/removes gas
- Used for
  - Precise Temperature Control
  - Power Switching

PCHP for Precise Temperature Control



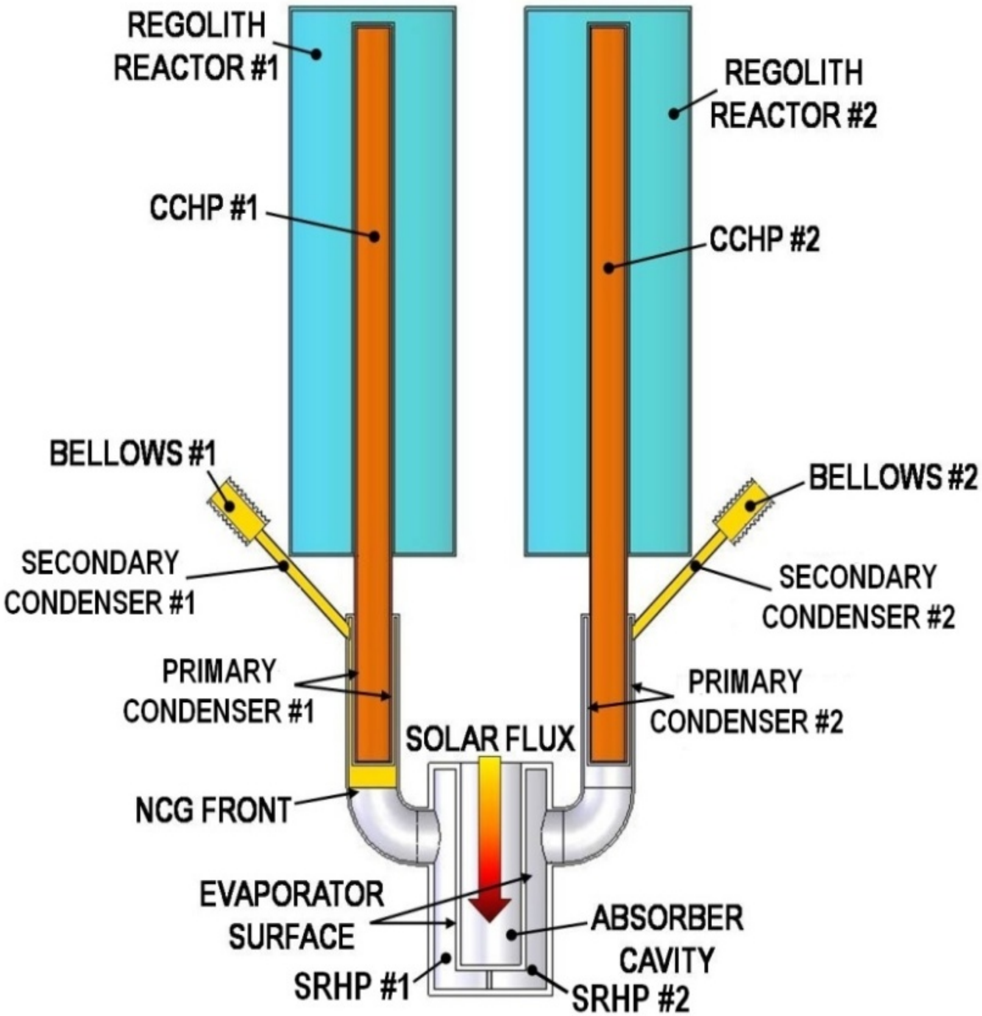
PCHP for Precise Temperature Control

- Deliverable Al/Ammonia PCHP with stainless bellows
- Control temperature to within 8 mK
  - Adjust for varying power or sink conditions



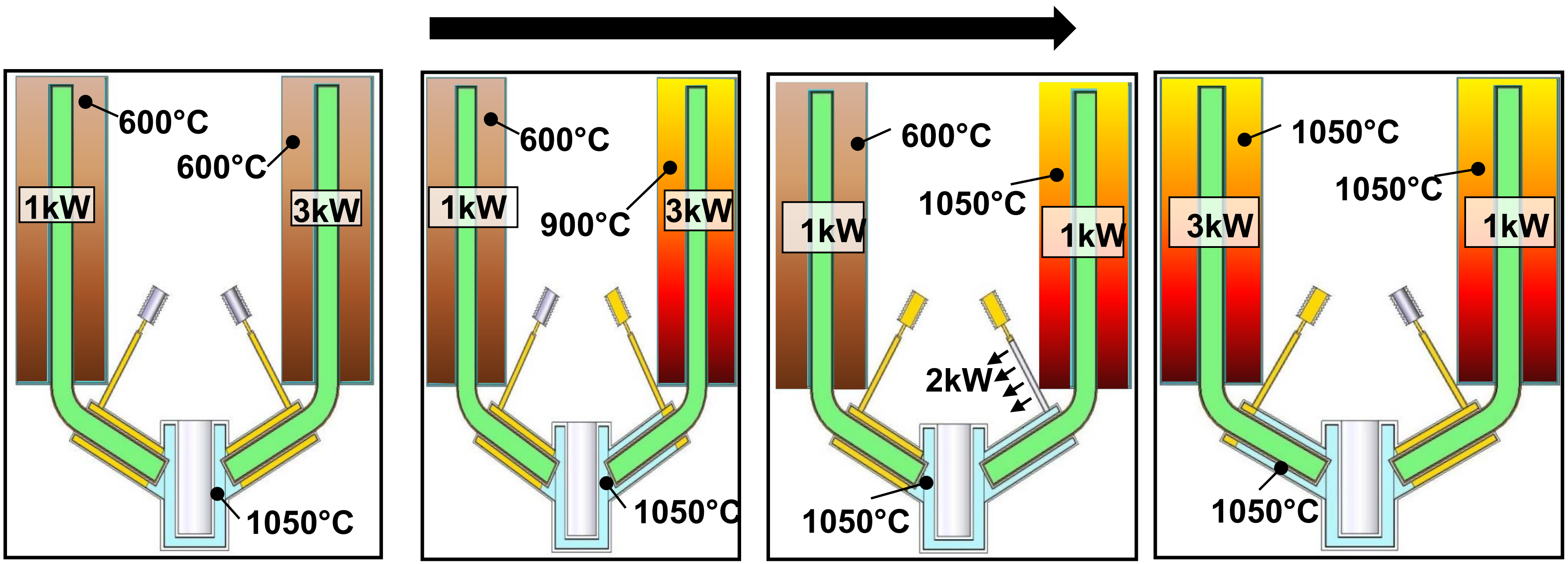
W. G. Anderson et al., "Pressure Controlled Heat Pipe Applications," 16th International Heat Pipe Conference, Lyon, France, May 20-24, 2012

PCHPs for Power Switching – Lunar Regolith



- A single power source (solar concentrator) is used to provide heat to two regolith reactors in order to extract oxygen from lunar regolith
- There are three major stages of processing for each side:
  - RHS (Right Hand Side) Warm Up (constant power)
  - RHS Process (power reduction)/LHS (Left Hand Side) Warm Up (constant power)
  - LHS Process(power reduction)/RHS Warm Up (constant power)
- System utilizes two separate PCHPs equipped with an NCG to regulate the amount of power that goes into each reactor depending on the need
- A secondary condenser is used to dissipate any excess power that is experienced as the NCG front moves closer to the end of the primary condenser

Lunar Regolith Processing Control Sequence



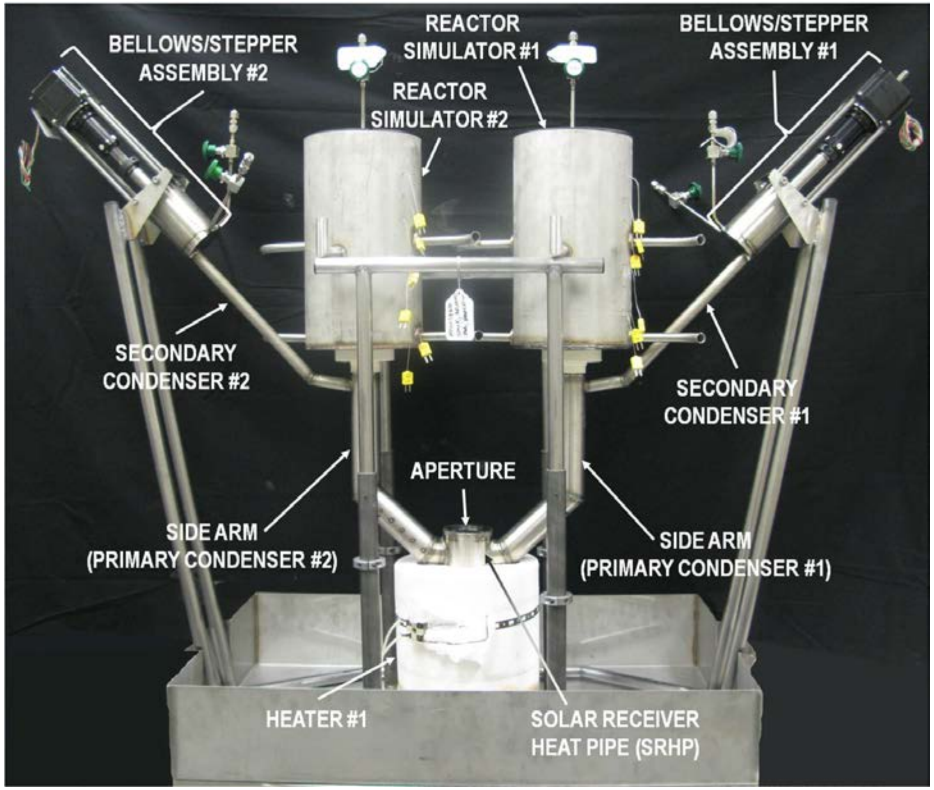
- Reactors loaded w/ regolith
- Bellows to the fully on position (CCHP evaporator “closed”)
- Start heating SRHP
- Gradually retract NCG front on one side and increase power until RHS sidearm is at 600°C. Do the same thing for the left hand side

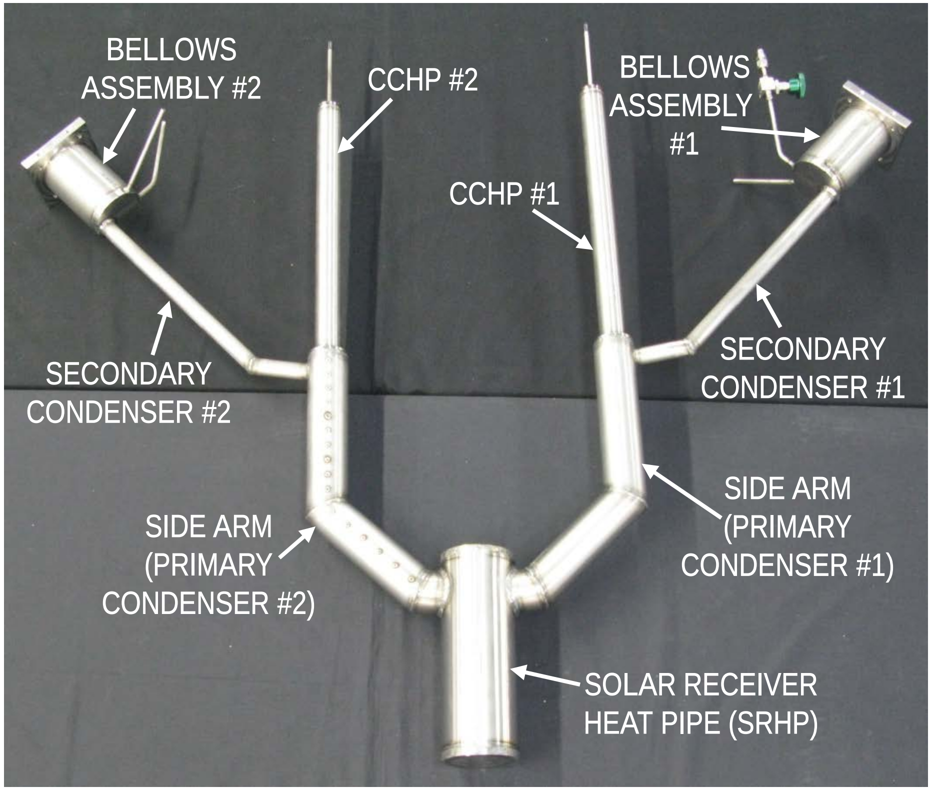
- 3kW directed to RHS, increase regolith from 600°C to 1050°C
- NCG front gradually retracts into reservoir (bellows or piston) exposing entire CCHP evaporator
- Initially at 3kW, but decreases as regolith temperature increases

- Above ~ 900°C unable to accept the full 3kW due to small ΔT between SRHP and regolith
- NCG front retracts into secondary condenser
- At SS, 1kW transfers to regolith to process at 1050°C, 2kW is radiated to space from secondary condenser

- Cold regolith loaded into LHS reactor, gas front blocking entire SRHP condenser
- 3kW radiate from RHS secondary condenser, gas front on RHS will move forward reducing evaporator length and power - NCG front on LHS retracts exposing LHS evaporator transferring power to the LHS reactor

Dual Sided Solar Receiver Heat Pipe Fabrication

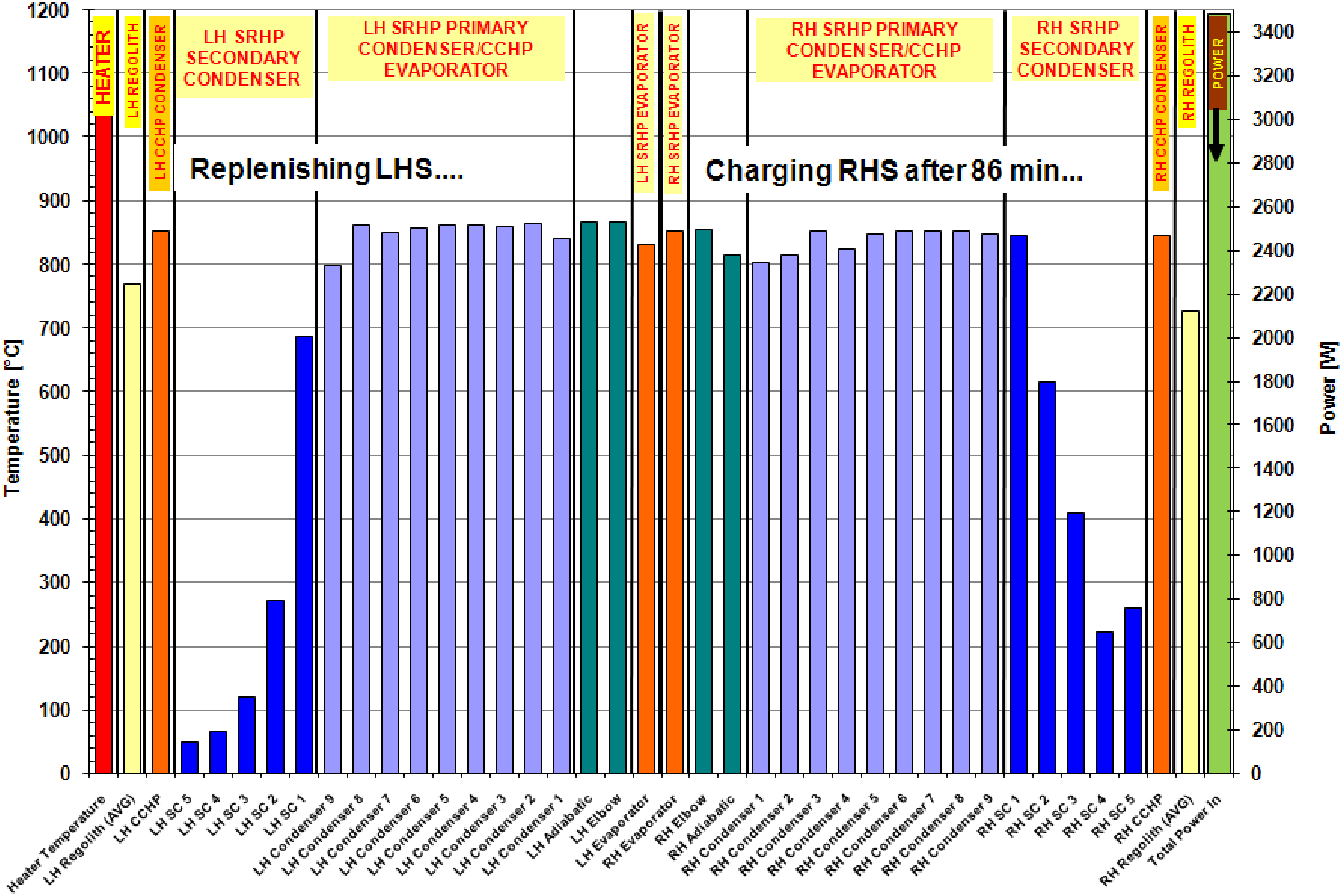




J. Hartenstine et al., "PCHP Solar Receiver for Regolith Oxygen Production with Multiple Reactors," 9th IECEC, San Diego, CA, July 31 - August 3, 2011

Dual Sided Haynes 230 and Sodium Demonstration System

NCG Front Movement – Figure 34 Animation



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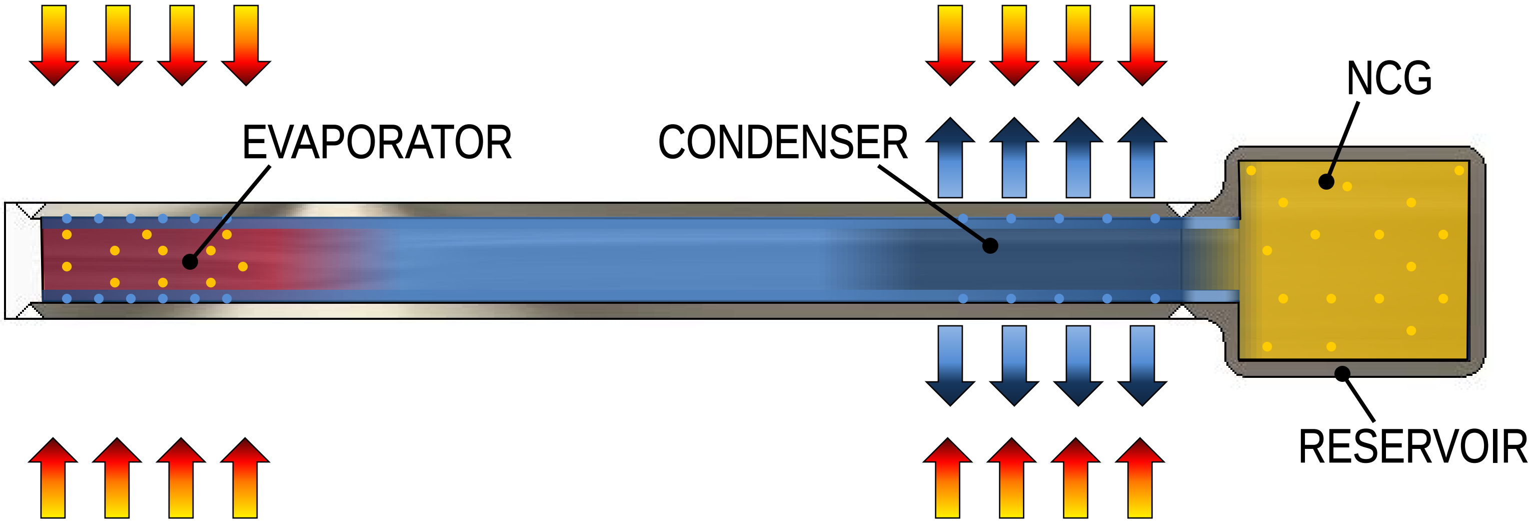
Diode Heat Pipes

- Diode Heat Pipes designed to act like an electronic diode
- Evaporator Hotter Than Condenser
  - Heat Flows
- Condenser Hotter Than Evaporator
  - Blocks Heat From Flowing
- No method to throttle heat in the forward direction
- VCHPs and LHPs will both function as diode if direct sun heats up the evaporator
  - VCHP evaporator blocked by gas
  - LHP condenser fills with vapor
- Thermosyphon also a diode
  - No liquid available if heat from the top

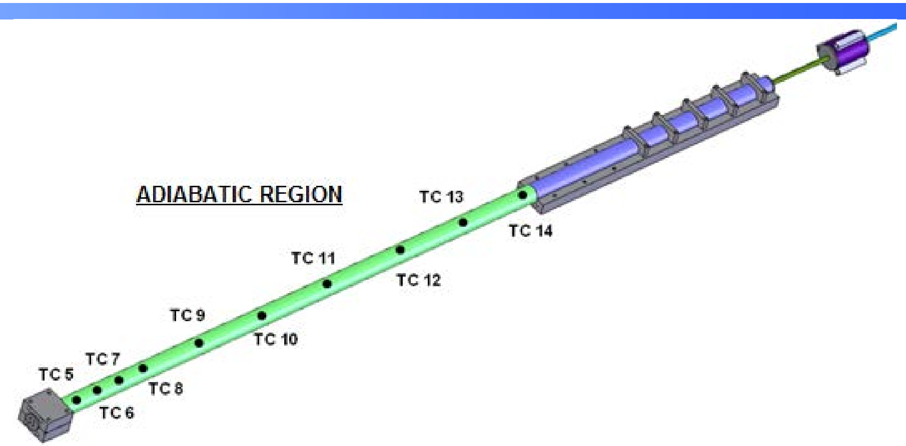
Gas Diode Heat Pipes



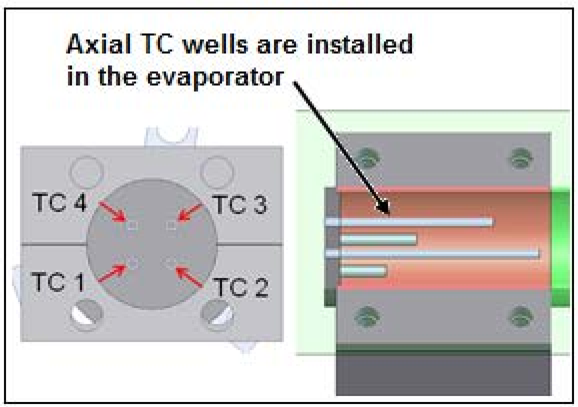
- During normal operation, functions very similar to a VCHP
  - Gas reservoir at condenser end with NCG
  - NCG blocks of parts of the condenser depending on the thermal load
- During reverse operation vapor flows in the opposite direction
  - NCG gas moves to the opposite end of the heat pipe due to the change in pressure
  - NCG gas blocks off what would be the condensing end, effectively “shutting off” the HP

Gas-Trap Diode Heat Pipe Design

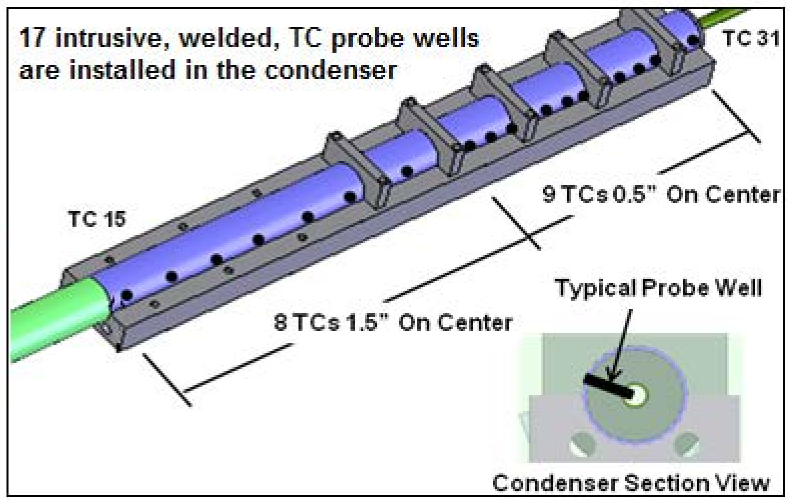
- Thermocouple placement along the DHP.
- Thermo-wells are installed in critical areas (Evaporator and Condenser).



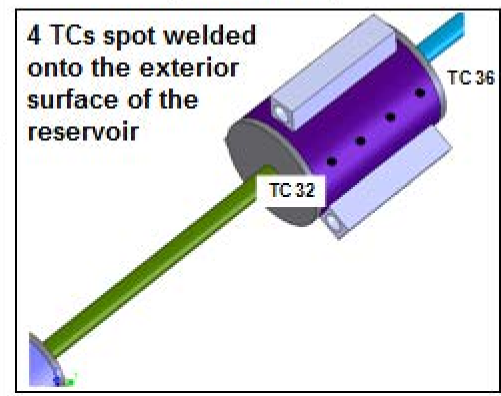
EVAPORATOR



CONDENSER



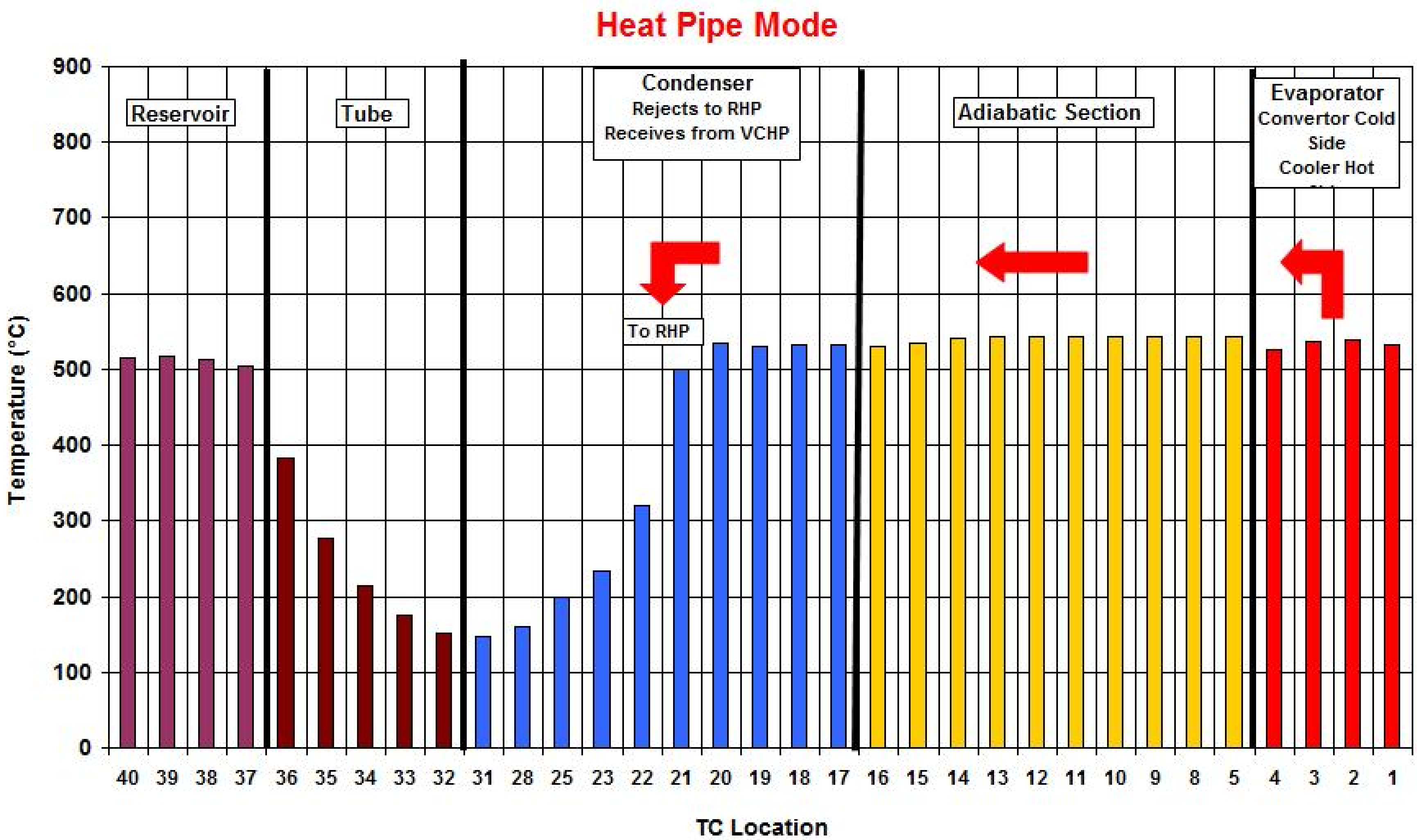
RESERVOIR



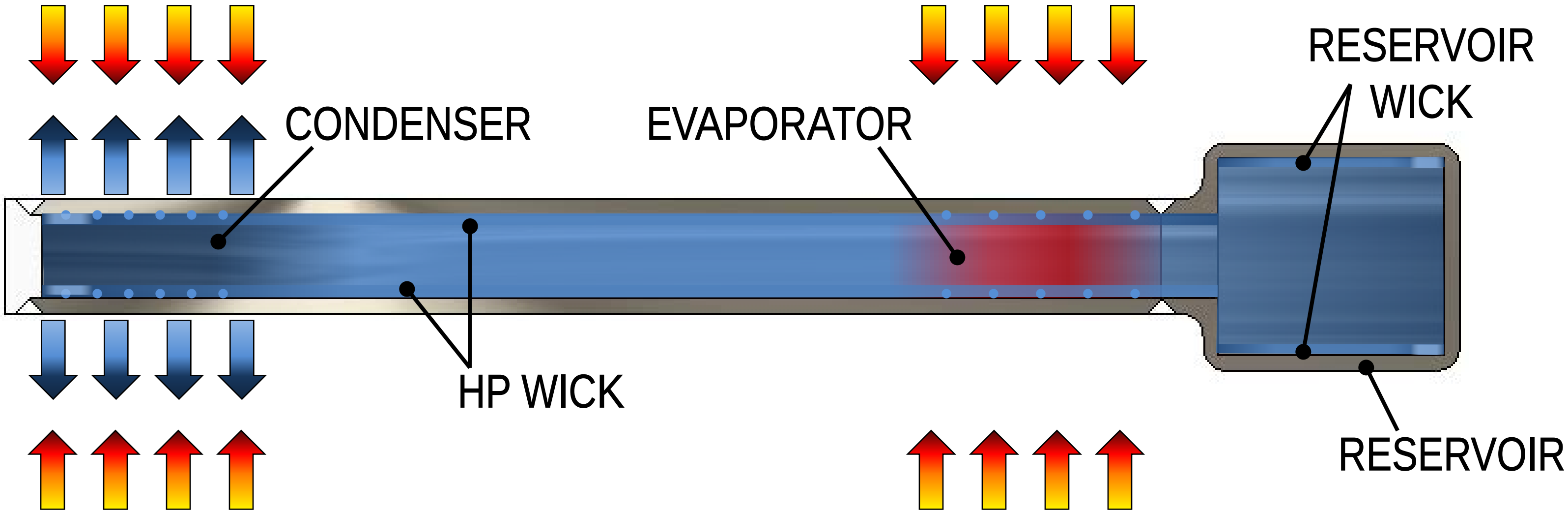
C. Tarau et al., "Diode Heat Pipes for Venus Landers," 9th IECEC, San Diego, CA, July 31 - August 3, 2012.

Diode Heat Pipe Development

- Testing Results for the Thin Reservoir Tube DHP (#1) -



Liquid Trap Diode Heat Pipes



- Wicked reservoir located at evaporator end of HP
  - Reservoir wick does not communicate with HP wick
- In normal operation functions like CCHP
  - Liquid evaporates at hot end, condenses at cold end and returns to hot end via HP wick
- In reverse direction, liquid evaporates at the hot side and condenses in the reservoir and becomes trapped
  - Separate reservoir and heat pipe wick traps the condensate in the reservoir, preventing it from returning to the hot end, effectively "shutting off" the HP

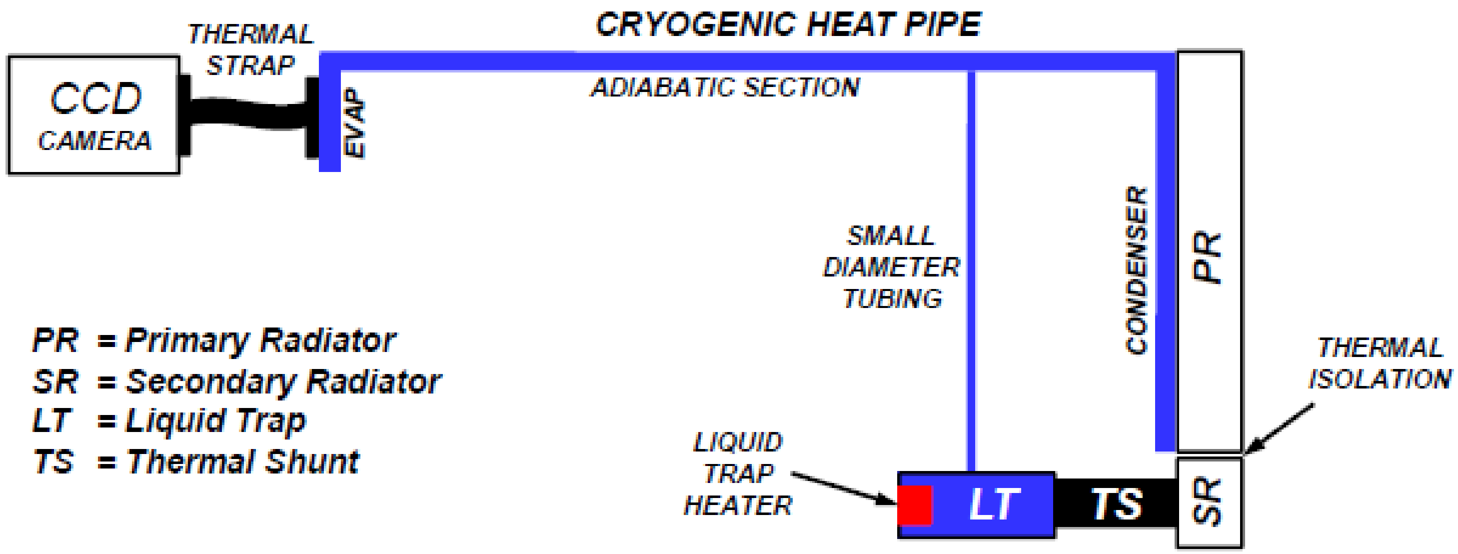
Liquid Trap Diode

- Liquid trap diode developed by David Bugby to link cameras to a cryoradiator
- During normal operation, a heat pipe cools the cameras, transferring heat to the cryoradiator at 140 K
- Periodically, the Cameras must be decontaminated by heating them up
  - Hot-side decontamination temperature: 293 K
  - Need to minimize the hot-side decontamination heater power
  - Need to turn off the heat pipe
- Solution: Cryogenic heat pipe with thermal switching capability provided by a secondary radiator thermally isolated from the primary radiator, a thermally shunted liquid trap, and small liquid trap heater.

- D. Bugby et al., "Cryogenic Heat Pipe Thermal Transport and Switching System," 2010 Spacecraft Thermal Control Workshop"

Liquid Trap Diode

- During normal operation, the small liquid trap heater keeps the liquid trap warm enough so that it is filled with vapor only thus the heat pipe is ON.
- During decontamination, the liquid trap heater is turned off and all the working fluid migrates to the liquid trap turning the heat pipe OFF.



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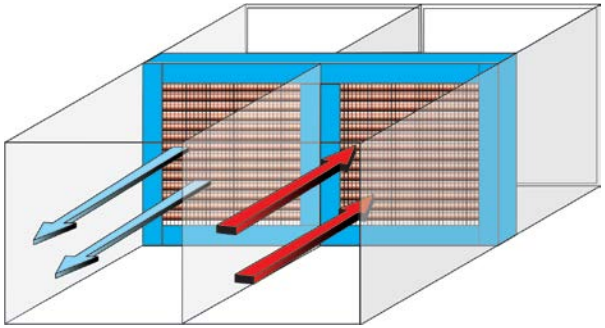
Heat Pipe Heat Exchangers

- Heat Pipe Heat Exchangers are used when the heat exchange occurs between two fluid streams that must be kept separate
  - Often streams are physically remote
- Applications
  1. Cabinet Coolers
     - Heat pipe
  2. Air-to-Air Energy Recovery Heat Exchangers
     - Thermosyphon
  3. Wrap-Around Heat Pipe Heat Exchangers for Dehumidification Energy Recovery
     - Thermosyphon

Air-to-Air Energy Recovery

- Used in places that require large amounts of make-up air
  - Often used in places like hospitals, that require large amounts of fresh air
- Recover energy from outgoing cold air in summer, outgoing warm air in winter
- Gravity Aided Thermosyphons, with a small tilt.

  - Tilt changes with the season
  - Copper or Al
  - R134a working fluid

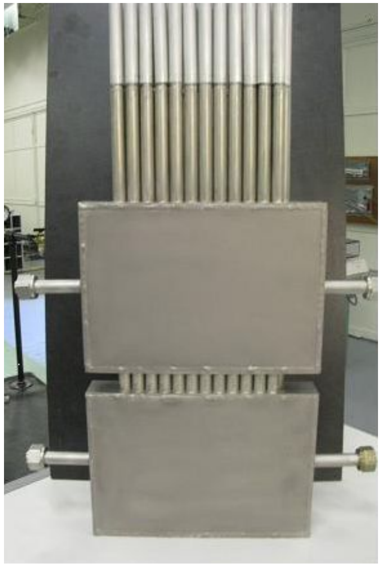


Air-to-Air Energy Recovery – Tiltable

- Heat Pipes tilt between summer and winter, so that the warmest air stream flows through the lowest half of the heat pipe

VCHP Heat Exchangers

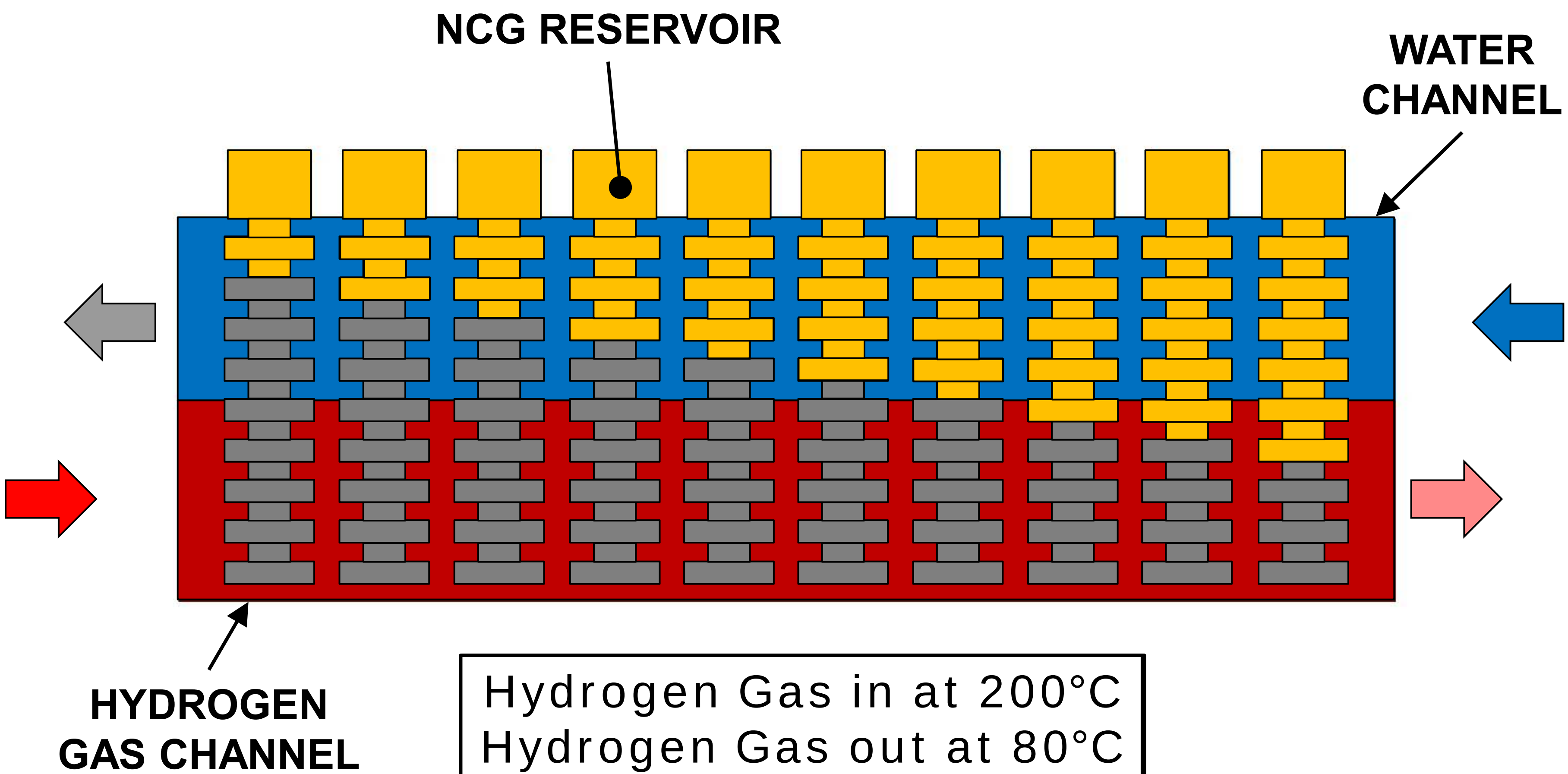
- VCHP heat exchangers are used to provide a nearly constant outlet temperature for one fluid stream, with large variations in inlet flow rate and temperature
- Navy Fuel Cell Application
  - Inlet Temperature from 120 to 400°C
  - Outlet Temperatures must be maintained within ±30°C
  - Changes in electrical load cause changes in reactant flow rates
  - Turndown ratio of 5:1 or greater
- Current control system utilizes bypass valve
  - Requires power
  - Requires higher ΔP



VCHP Heat Exchanger

– D. Sarraf et al., "Passive Thermal Management for a Fuel Cell Reforming Process," 2006 IECEC, San Diego, CA, June 2006.

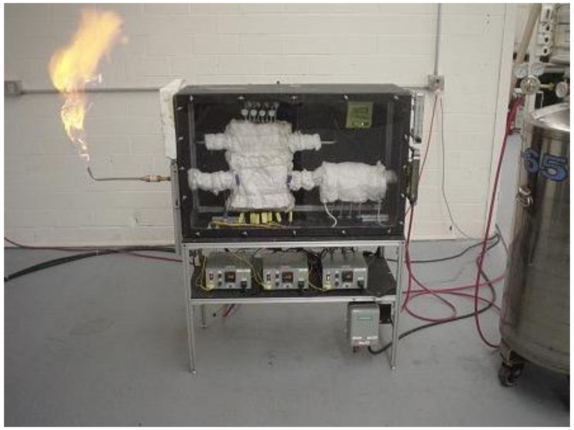
VCHP Heat Exchanger Schematic



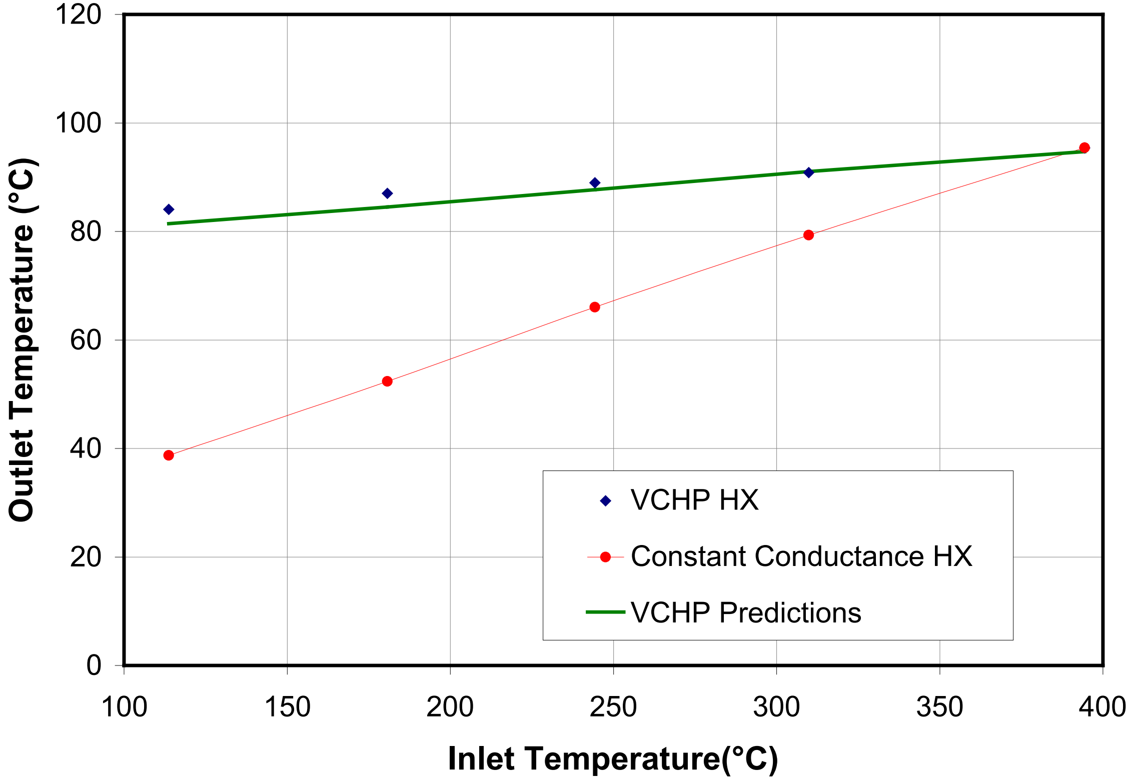
Hydrogen Gas in at 200°C
Hydrogen Gas out at 80°C

- Non-condensable gas front position responds to changes in flow rates and inlet temperatures

Testing Results: High Flow



Test Apparatus



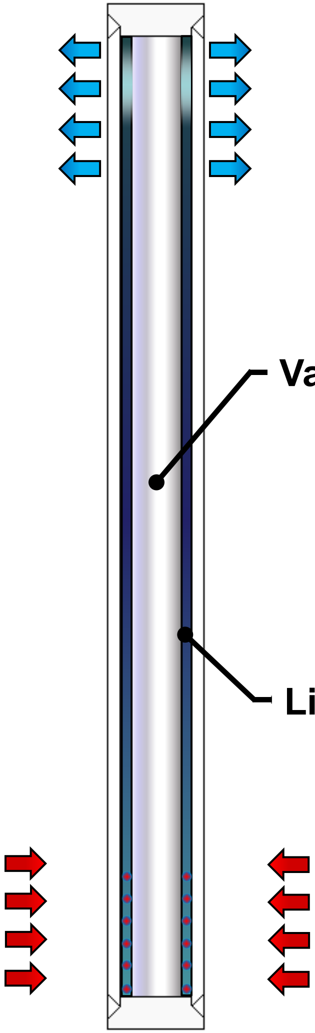
Presentation Outline

- Constant Conductance Heat Pipes
  - Heat Pipes
  - Vapor Chambers
- Gas-Loaded Heat Pipes
  - Variable Conductance Heat Pipes (VCHPs)
  - Pressure Controlled Heat Pipes (PCHPs)
  - Gas Trap Diode Heat Pipes
- Interrupted Wick
  - Liquid Trap Diode Heat Pipes
- Heat Pipe and VCHP Heat Exchangers
- Alternate Means of Liquid Return
  - Thermosyphons
  - Rotating Heat Pipes

Alternate Means of Liquid Return

- All of the heat pipes discussed above have a wick to return liquid from the condenser to the evaporator
  - Allows heat pipe to operate in any orientation
  - Typically screen or sintered for terrestrial
  - Grooved for spacecraft applications
- There are at least 3 other ways to return liquid
  - Gravity
    - Thermosyphons
    - Loop Thermosyphons
  - Centrifugal forces
    - Rotating heat pipes
    - Rotating HiK™ shafts
  - Electrohydrodynamic Forces

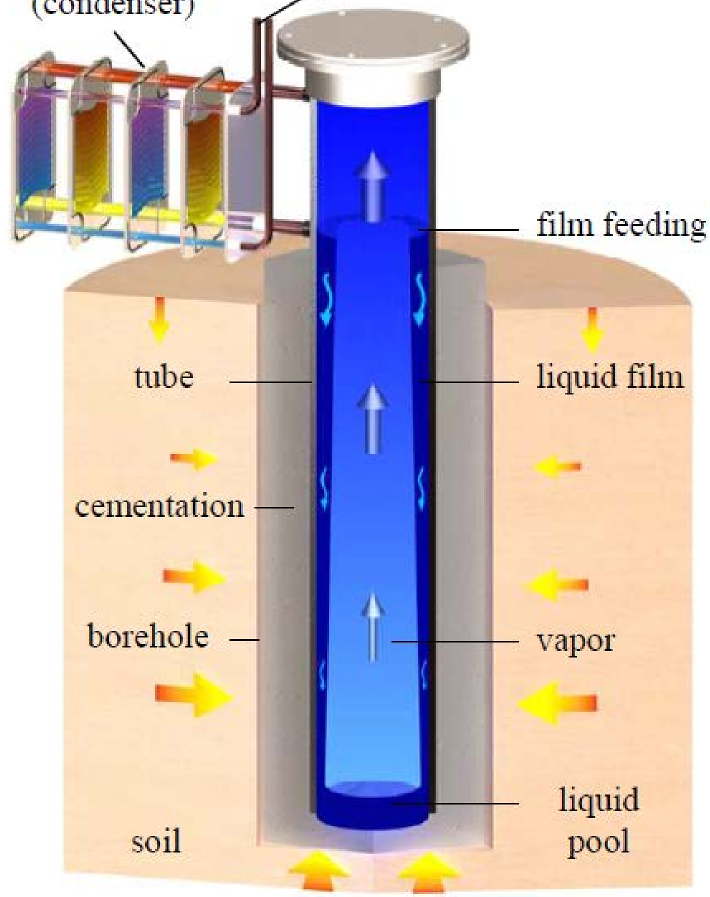
Thermosyphon Operation Summary



- Normal Heat Pipes can operate in any orientation
  - Use capillary forces in the wick to return liquid to the evaporator when the evaporator is elevated above the condenser
- Thermosyphons are gravity-aided heat pipes
  - Evaporator must be located below the condenser
  - Fluid returns to the evaporator by gravity
  - Evaporator normally wicked for start-up
- Higher powers
- Essentially unlimited lengths

Long Thermosyphons - Vertical

- Collect geothermal energy for heating buildings (with heat pump)
- Propane working fluid
- 5.3 cm diameter
- 93 m long
- Fabricate in place – Insert sections and weld as lower into hole
- Camera inserted to view behavior
  - After system start-up, takes several *minutes* for the entire wall to be wetted

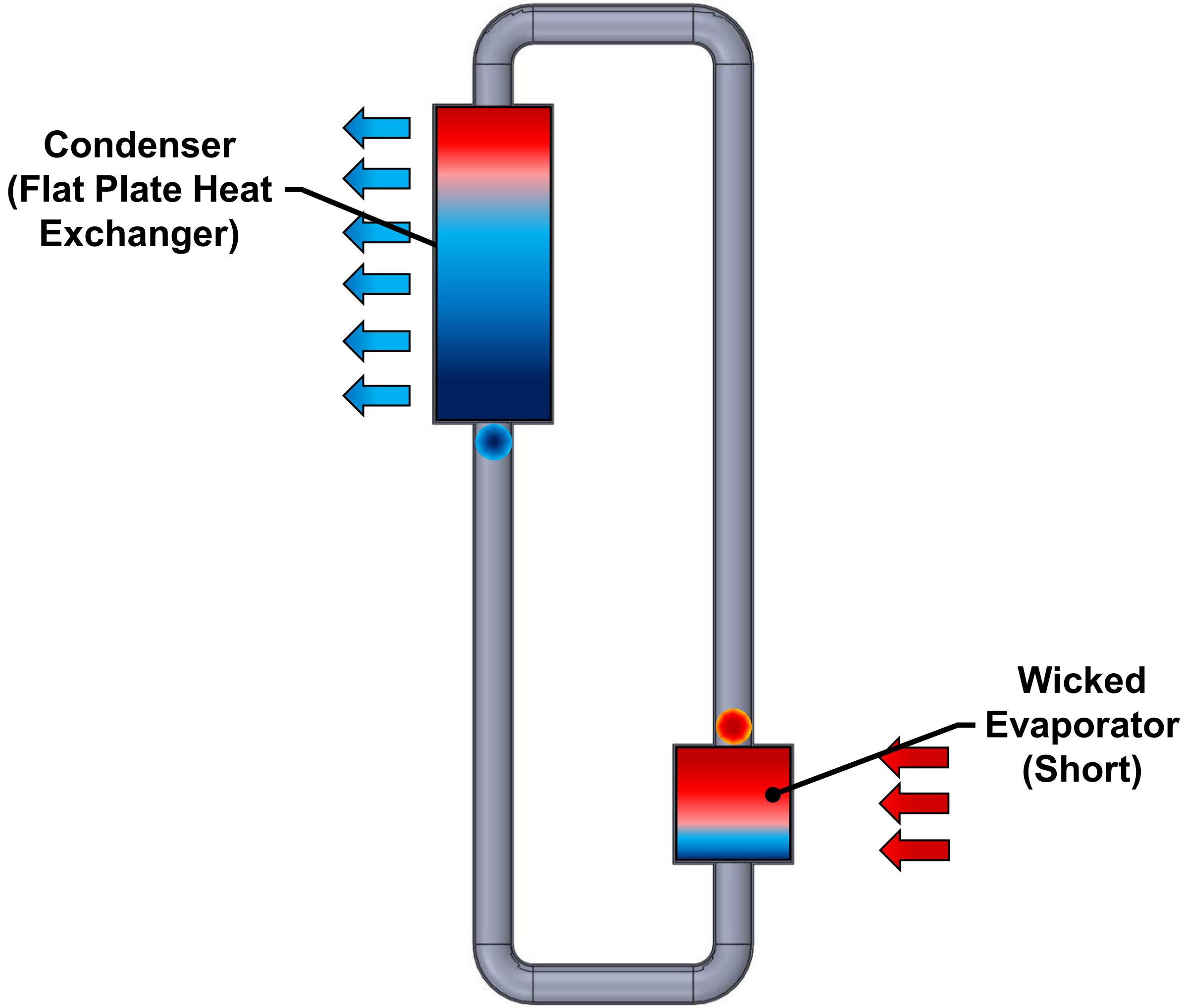


Storch et al., "Wetting and Film Behavior of Propane Inside Geothermal Heat Pipes," 16th International Heat Pipe Conference, Lyon, France, May 20–24, 2012.

Loop Thermosyphons

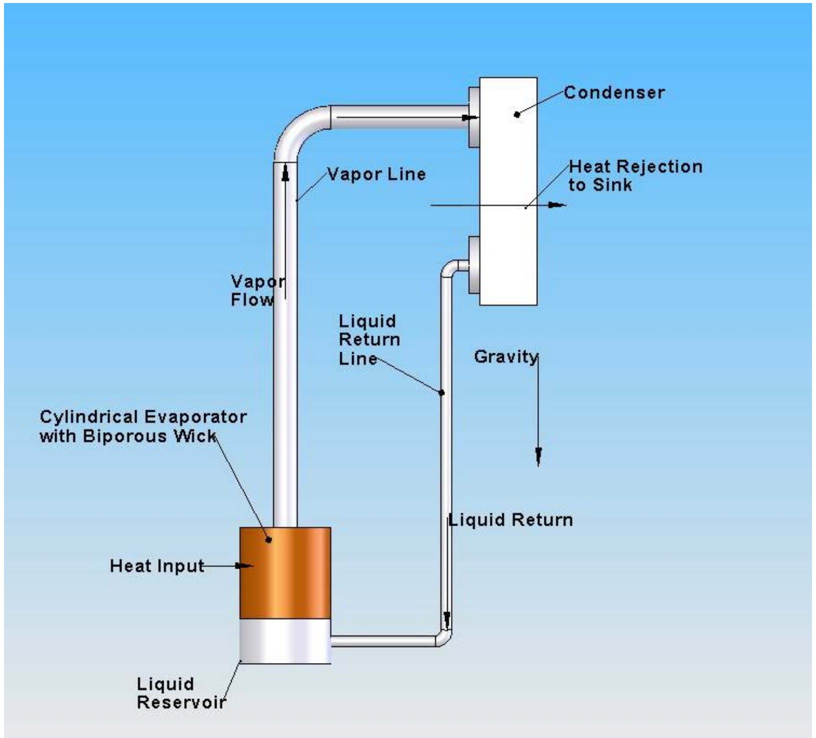
- Maximum power can be limited by the countercurrent vapor and liquid flow in heat pipes and thermosyphons
  - Entrainment limit for heat pipes
    - Vapor velocity so high that shear rips liquid from the wick
    - Can limit at lower temperatures
  - Flooding limit for thermosyphons
    - Vapor velocity so high that shear prevent liquid from draining back down to the evaporator
    - Limits power over a wide range of temperatures
- Loop thermosyphons eliminate the Flooding Limit
  - Vapor and liquid flow in a loop, so shear does not limit power
- Loop thermosyphons are used:
  - Higher power and heat fluxes than regular thermosyphons
  - Nearly horizontal systems, where flooding limit is low

Loop Thermosyphon



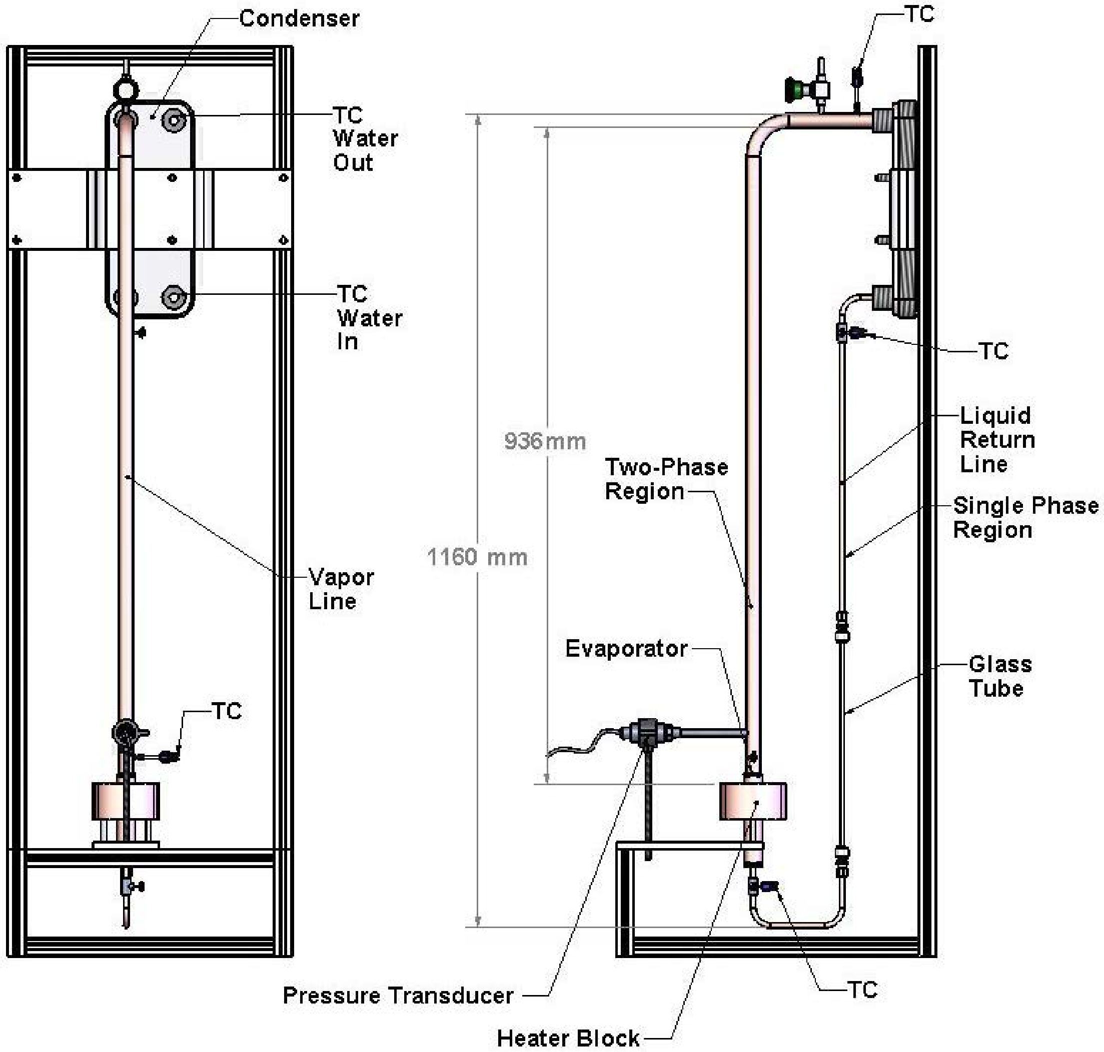
Loop Thermosyphons

- Loop thermosyphon an improvement over pool boiler designs
  - Have liquid pool in the evaporator and relies on pool boiling for the liquid-to-vapor phase change.
  - The pool boiling mechanism is very inefficient (i.e. large superheat ΔT) and cannot handle high heat fluxes (i.e. low CHF).
- Evaporator design includes a porous wick structure in evaporator partially fed by circulating two-phase flow, and capillary forces
  - Very high heat fluxes



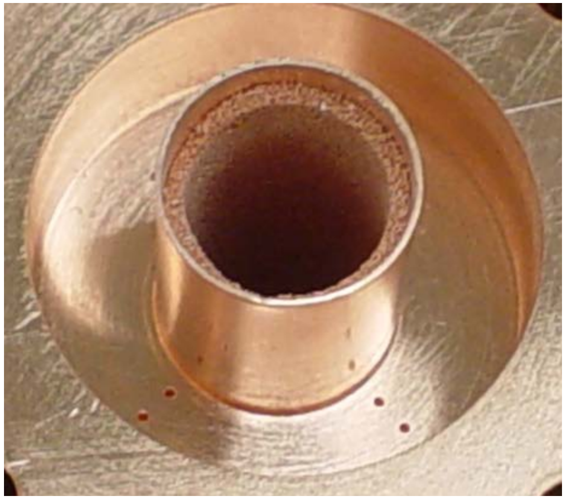
J. Hartenstine et al., "Loop Thermosyphon Design for Cooling of Large Area, High Heat Flux Sources," InterPACK 2007, Vancouver, Canada, July 2007.

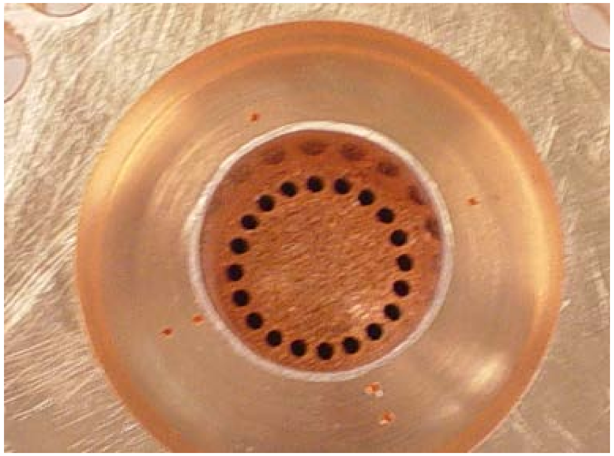
Loop Thermosyphon Design Schematic



Evaporator Wick Structures

- Monoporous Wick Design
  - Annular
  - 2mm thick x 127mm long
  - Monoporous Wick, 2,280W @ 240W/cm^2
- Biporous Wick Design
  - Annular
  - 2mm thick x 127mm long
  - Biporous Wick, 4,390W @ 465W/cm^2
- Composite Design
  - Annular Biporous Copper Powder Layer Attached to Heat Input Surface
  - Integral Secondary Slab Wick for Improved Liquid Transport
  - Circular Array of vapor Vents
  - Biporous Wick with Vapor Vents, 3,488W @ 367W/cm^2



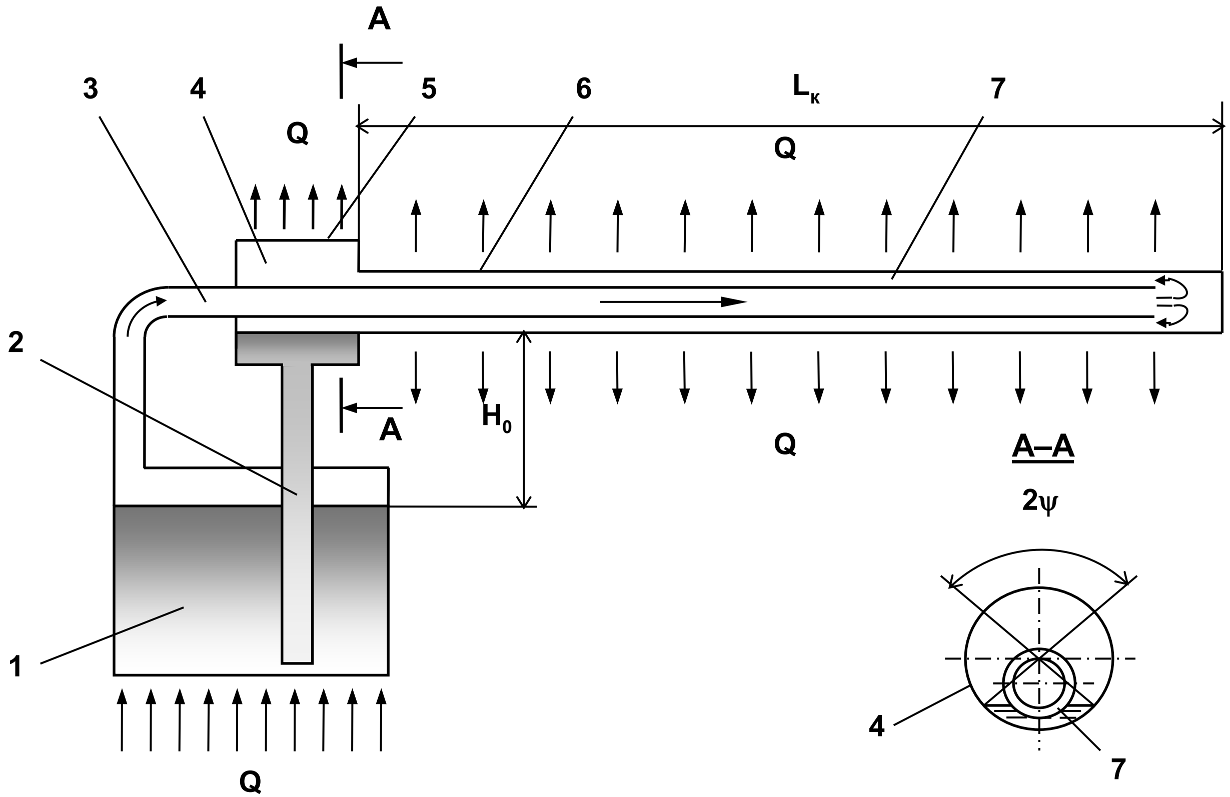


Long Thermosyphons - Horizontal

- Entrainment Limit for thermosyphons decreases as get closer to horizontal
  - No flooding limit data near horizontal
- "Horizontal Vapordynamic Thermosyphons, Fundamentals and Practical Applications"
  - Horizontal heat transfer for tens of meters
  - Vapor flows in an interior tube – tube has high conductivity
  - Condenses in an outer annular tube
  - Gravity returns fluid from the condenser to the evaporator
  - Demonstrated Flexible Condensers
- They say that their design functions without the noise, vibrations, and temperature overshoot typical for conventional thermosyphons with smooth walls

L. Vasiliev and L. Vasiliev Jr. "Horizontal Vapordynamic Thermosyphons, Fundamentals and Practical Applications," 16th International Heat Pipe Conference, Lyon, France, May 20 – 24, 2012.

Vapor-dynamic thermosyphon schematic



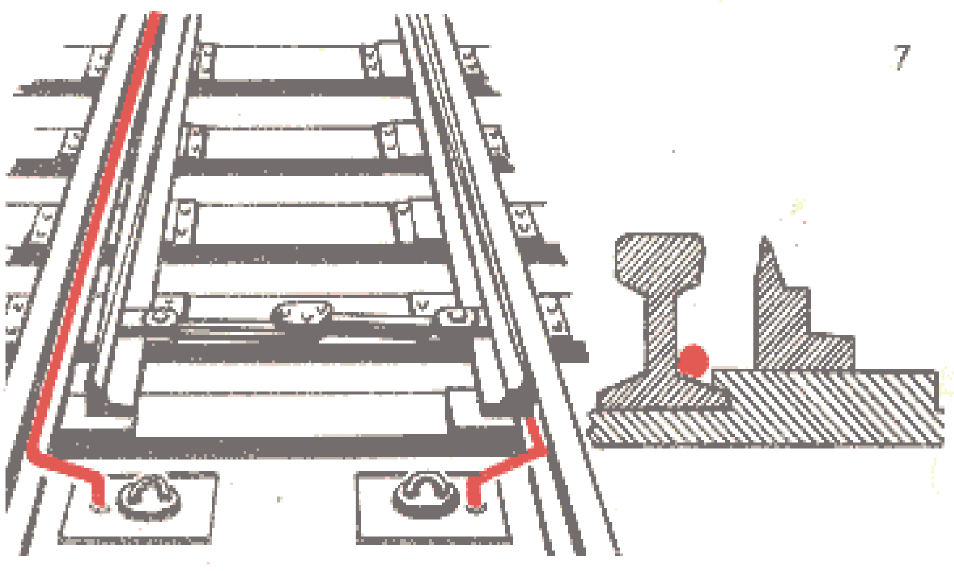
1 – evaporator, 2 – liquid pipe, 3 – vapor pipe, 4 – compensation chamber, 5 – heat sink, 6 – condenser, 7 – annular channel, H_0 – hydrostatic pressure drop

$$\Delta P_t = \Delta P_{evap} + \Delta P_v + \Delta P_{cond} + \Delta P_l$$

Vasiliev, L.L., Morgun V.A., Rabetsky M.I (1985),
US Patent No. 4554966, 26.11.1985

Applications

- **VDT with electric source of energy for snow melting between railway switches**

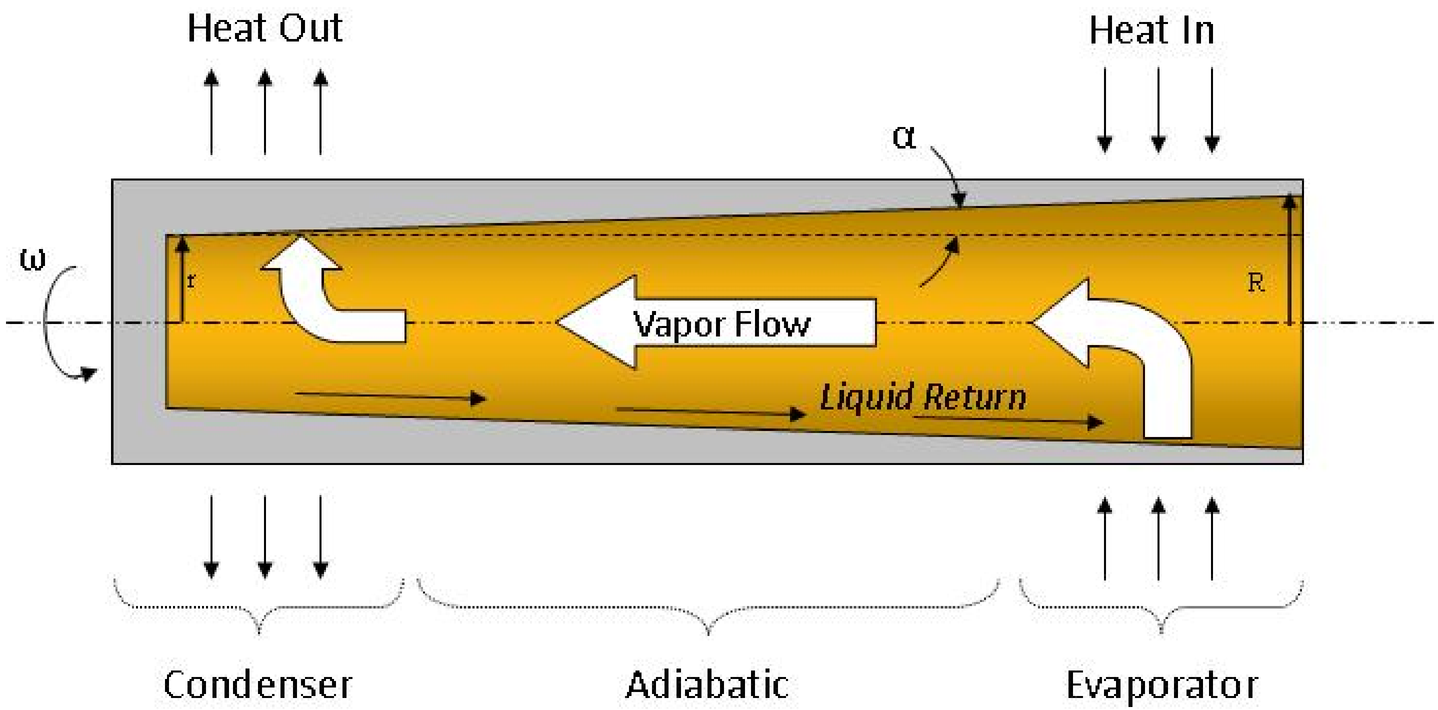


Two VDT for snow melting, length – 4.5 m, heat flow 2 kW.

VDT condenser d = 16 mm. At the ambient temperature minus 7-10 0C, the snowfall intensity of 100-150 mm and wind velocity 5-10 m/s the VDT ensures complete snow thawing between the railway switches during 1 hour.

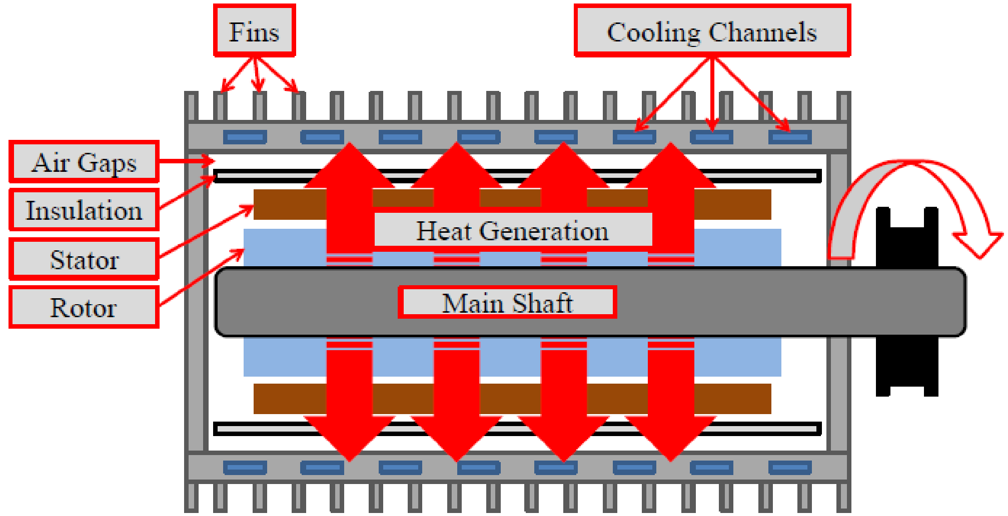
Rotating Heat Pipes

- Wickless, return fluid by centrifugal forces
- Typically tapered to provide return force

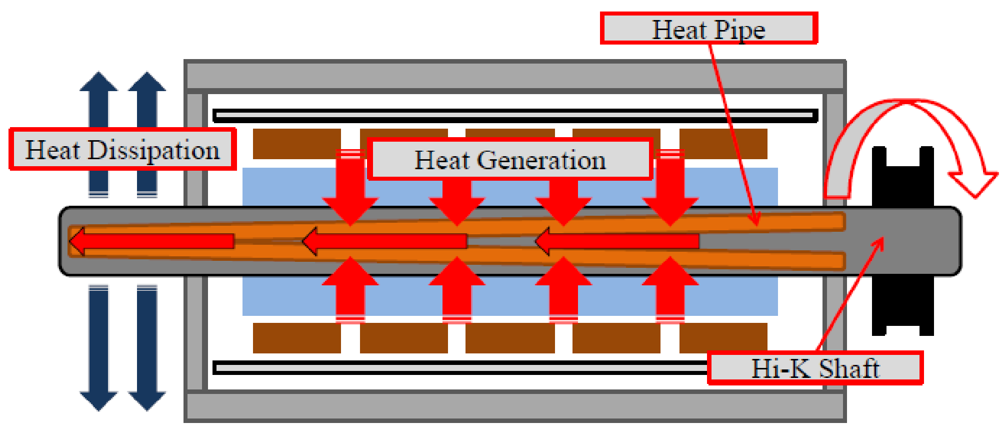


Rotating Heat Pipes

- Difficult to remove heat from engine shaft

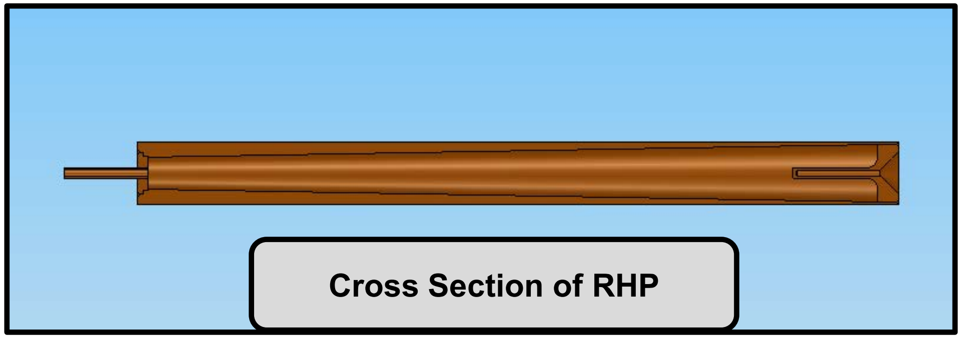


- Rotating heat pipes removes heat outside engine

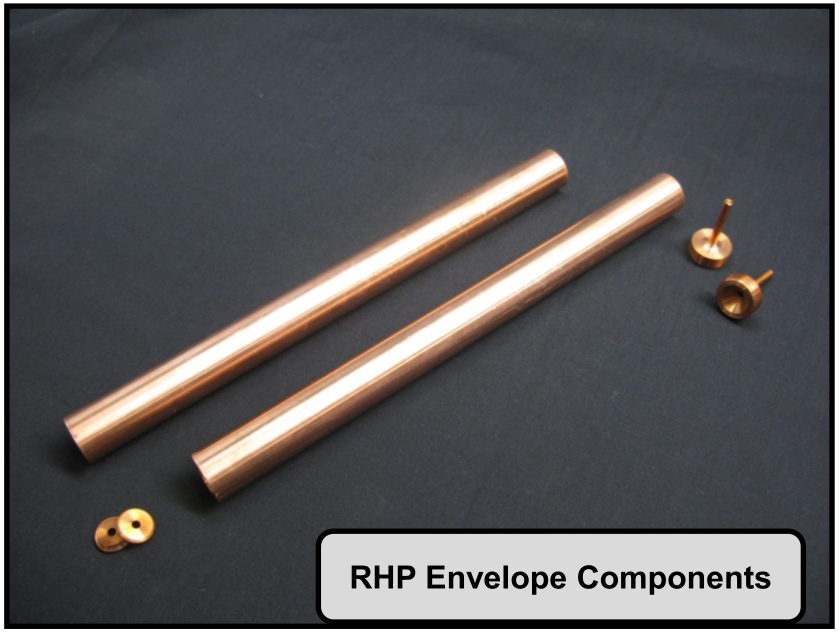


RHP Design and Fabrication

- **Due to freeze/thaw concerns in a wick-less heat pipe, the working fluid selected for the RHP is Methanol.**
- The 1° Rotating Heat Pipe demonstrated a higher than anticipated temperature gradient between the evaporator and condenser.
  - At 2000 RPM and 526 W, the overall RHP ΔT is ~124°C.
- This elevated ΔT in the RHP is caused by:
  - High evaporation and condensation thermal resistance of methanol (compared to water).
  - Conduction through the liquid film layer at both the evaporator and condenser end of the heat pipe (puddle formation with no wick).



Cross Section of RHP



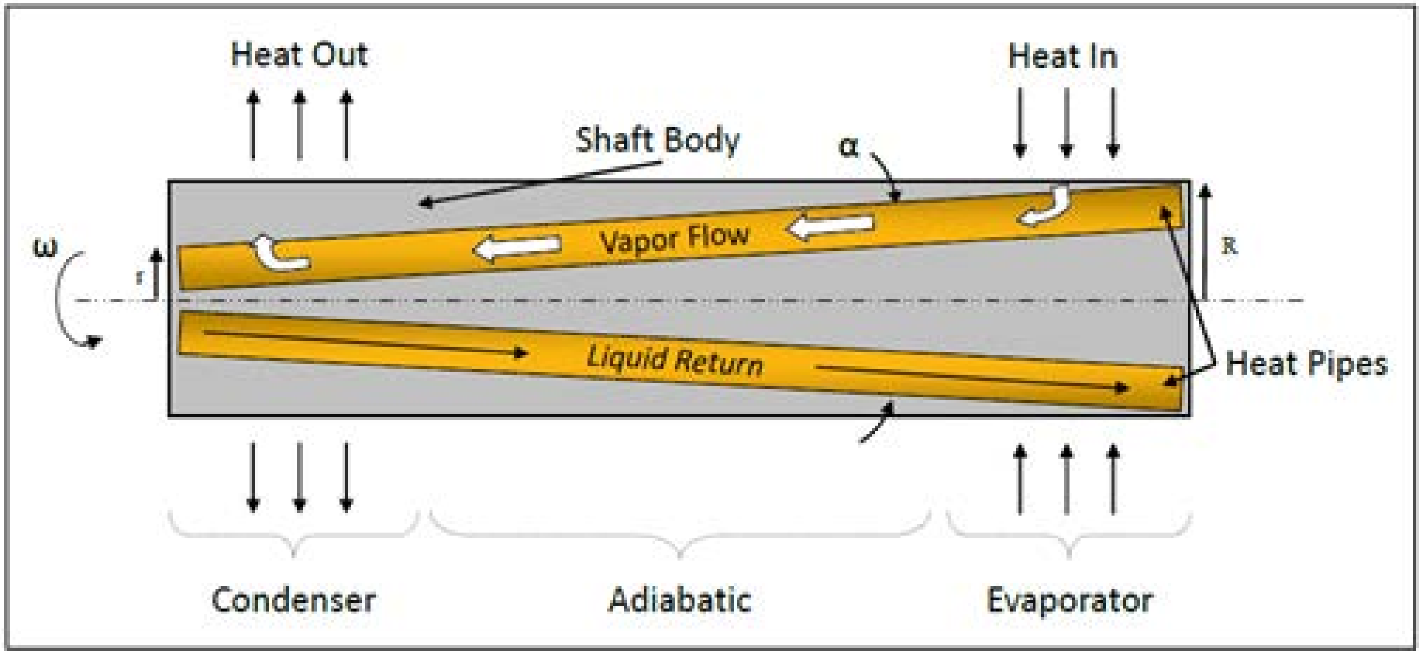
RHP Envelope Components

Rotating Heat Pipe Testing

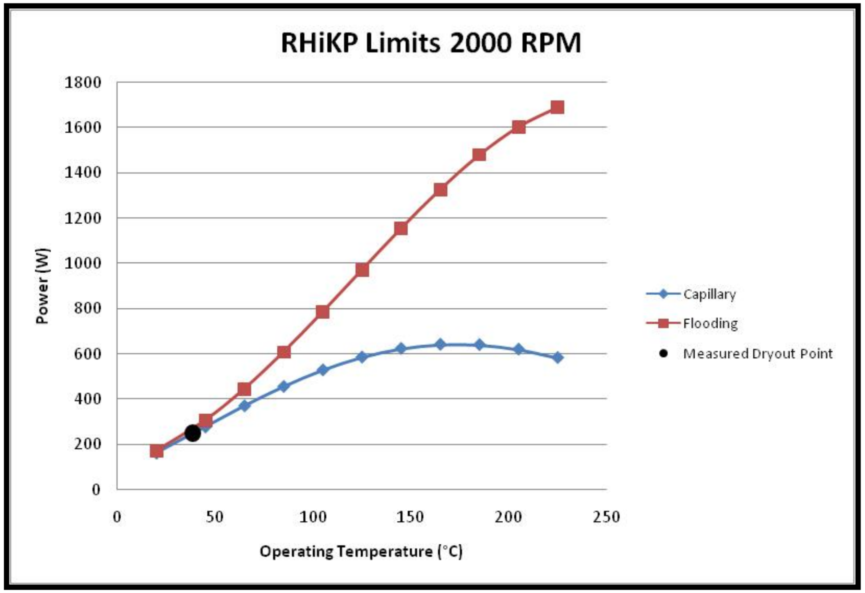
- The 1° Rotating Heat Pipe demonstrated a higher than anticipated temperature gradient between the evaporator and condenser.
  - At 2000 RPM and 526 W, the overall RHP ΔT is ~124°C.
- This elevated ΔT in the RHP is caused by:
  - High evaporation and condensation thermal resistance of methanol (compared to water).
  - Conduction through the liquid film layer at both the evaporator and condenser end of the heat pipe (puddle formation with no wick).
- Maximum temperature limit reached before the RHP could dry out
  - NOTE: NCG at ~140°C with copper-methanol heat pipes
- ACT has switched to Rotating Shafts with Embedded Copper/Water Heat Pipes

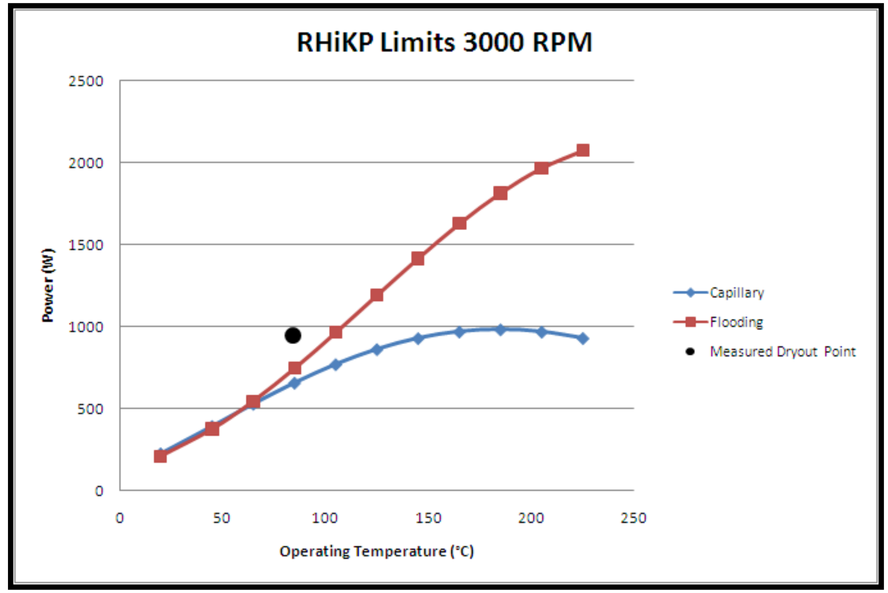
Rotating Shafts with Embedded Heat Pipes

- Rotating heat pipes used methanol for freeze/thaw
- Better choice is to embed heat pipes in the shaft
  - Water as working fluid
  - Higher performance



Rotating Shaft/Embedded Heat Pipe Test Results





Predicted RHiKP Capillary and Flooding Limits. The black dot represents the measured dry out condition.

- 2000 RPM Test Data matched well with prediction
- 3000 RPM Test Data matched well with prediction, but is slightly more conservative
- *NOTE:* At speeds above 3000 RPM, the RHiKP operating limit exceeded the capabilities of the IR Heater – dryout condition could not be reached.

Links

- Heat Pipes
  - CCHPs
  - Embedded Heat Pipes
  - Vapor Chambers
- Variable Conductance Heat Pipes (VCHPs)
  - Temperature Control
  - Dual Condenser
  - Variable Thermal Link
  - Frozen Start-up/Shutdown
- Pressure Controlled Heat Pipes (PCHPs)
  - Precise Temperature Control
  - Power Switching
- Diode Heat Pipes
  - Gas Diode
  - Liquid Trap
- Heat Pipe and VCHP Heat Exchangers
  - Heat Pipe Heat Exchanger
  - VCHP Heat Exchanger
- Alternate Means of Liquid Return
  - Thermosyphons
  - Rotating Heat Pipes
    - Embedded Rotating
- Marcus – Theory and Design of VCHPs
- Thermalpedia – Types of Heat Pipes

Different Types of Heat Pipes

William G. Anderson
Advanced Cooling Technologies, Inc.

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Thermal & Fluids Analysis Workshop
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