Verification of LHP Stability Theory Part II

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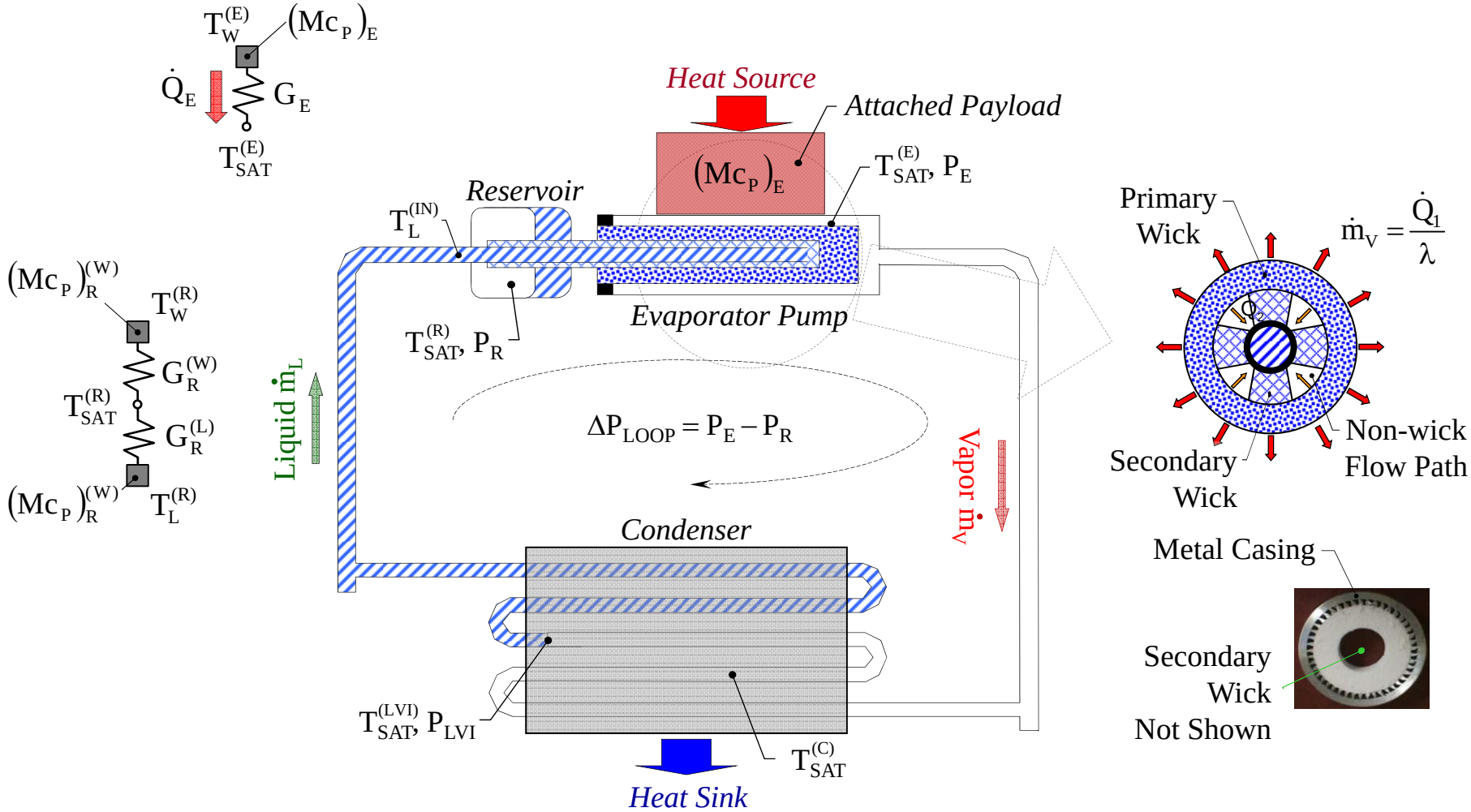
Outline

- Loop Heat Pipe (LHP) Stability Theory
- *Instability* Criterion for High-Frequency Oscillations
- Theory Verification Process
- Model Predictions vs. Test Data
- Summary / Conclusion

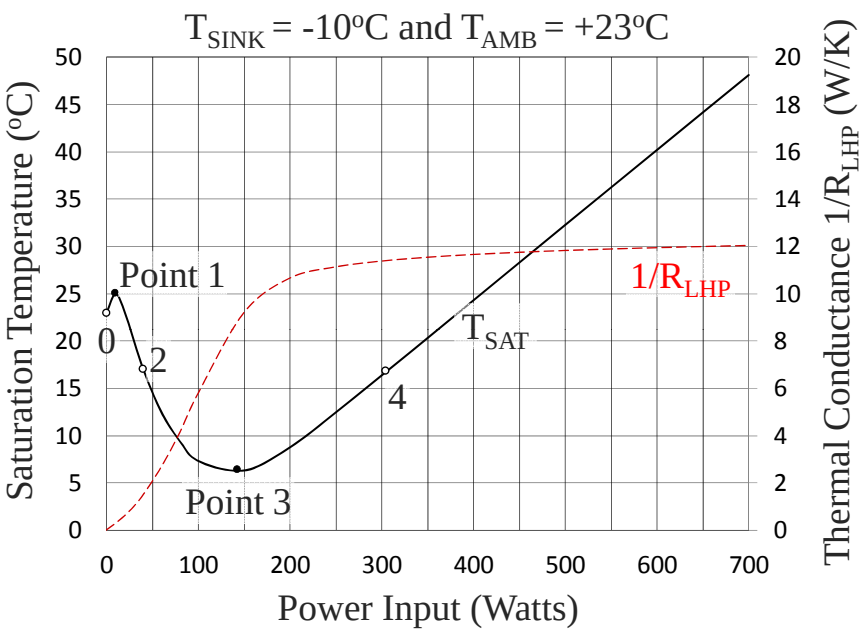
Loop Heat Pipe



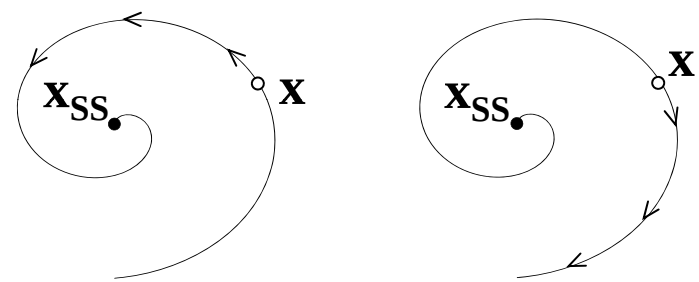
LHP is a capillary-pumped device having no mechanical moving part

LHP Linear Stability Theory

Is LHP state x capable of reaching steady state x_{SS} ?



$$\mathbf{x}(t) - \mathbf{x}_{SS} = \sum_k \mathbf{A}_k e^{\lambda_k t}$$

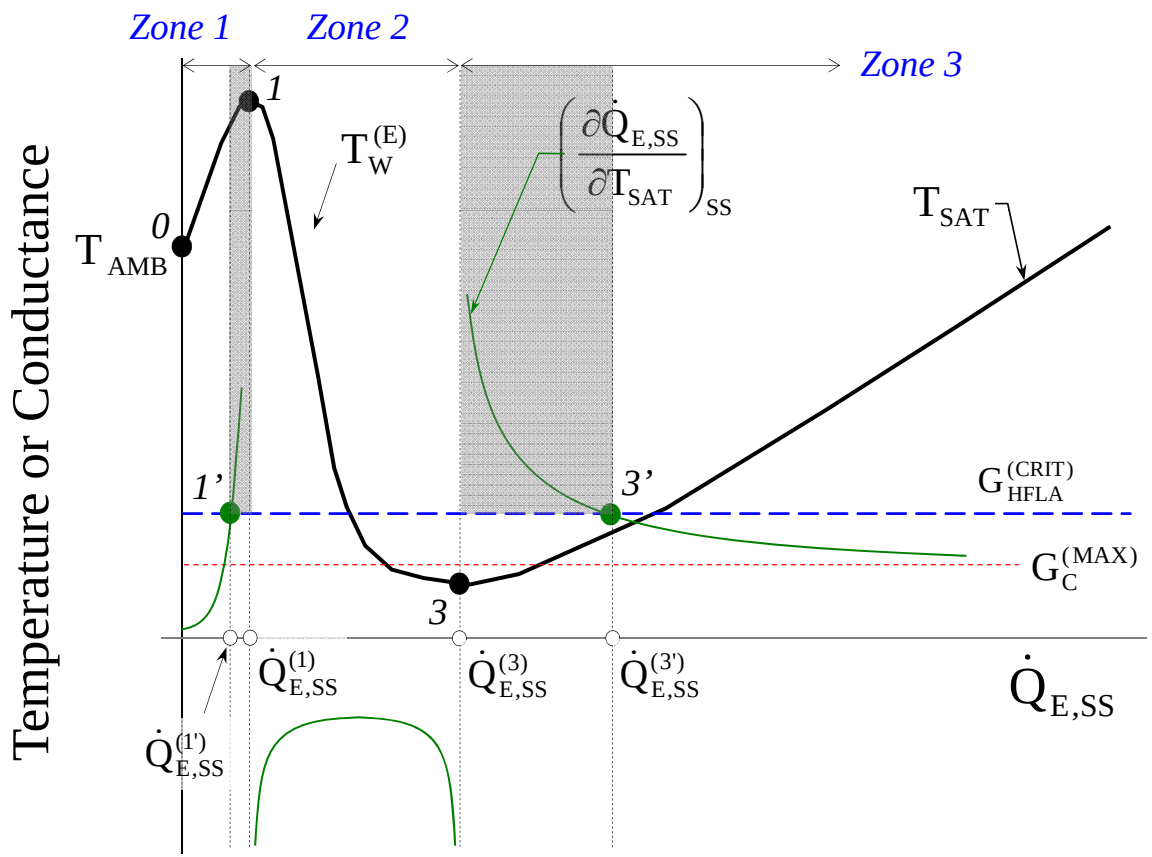


Instability Criterion for High-Frequency/Low-Amplitude Oscillations

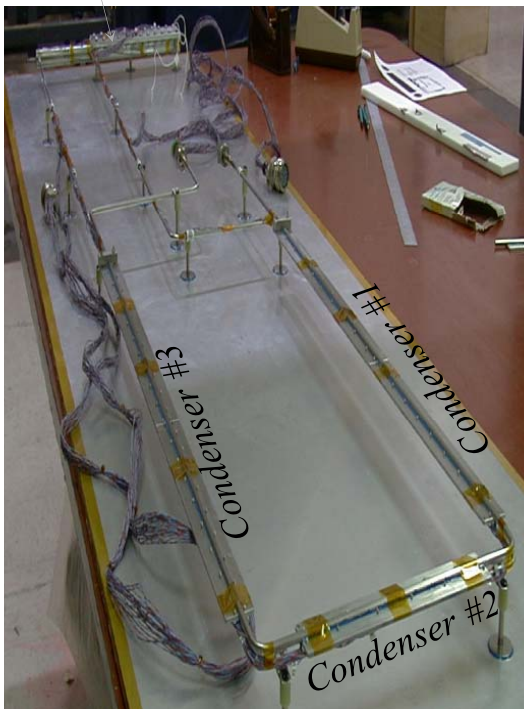
$$\left(\frac{\partial \dot{Q}_E}{\partial T_{SAT}}\right)_{SS} > \frac{G_C^{(MAX)} \dfrac{V_C^{(2\phi)}}{V_C}\left\{1+\eta\left(\dfrac{\rho_L}{\rho_V}-1\right)\left(\dfrac{\dot{Q}_2}{\dot{Q}_E}\right)_{SS}\left[1+\left(\dfrac{\dot{Q}_2}{\dot{Q}_E}\right)_{SS}\right]\right\} + \dfrac{\chi_R}{\chi_V} G_R^{(L)}\left(1-\dfrac{\partial T_L^{(R)}}{\partial T_{SAT}^{(R)}}\right)_{SS}}{1+\left(\eta\dfrac{\rho_L}{\rho_V}-2\right)\left(\dfrac{\dot{Q}_2}{\dot{Q}_E}\right)_{SS}} \equiv G_{HFLA}^{(CRIT)}$$

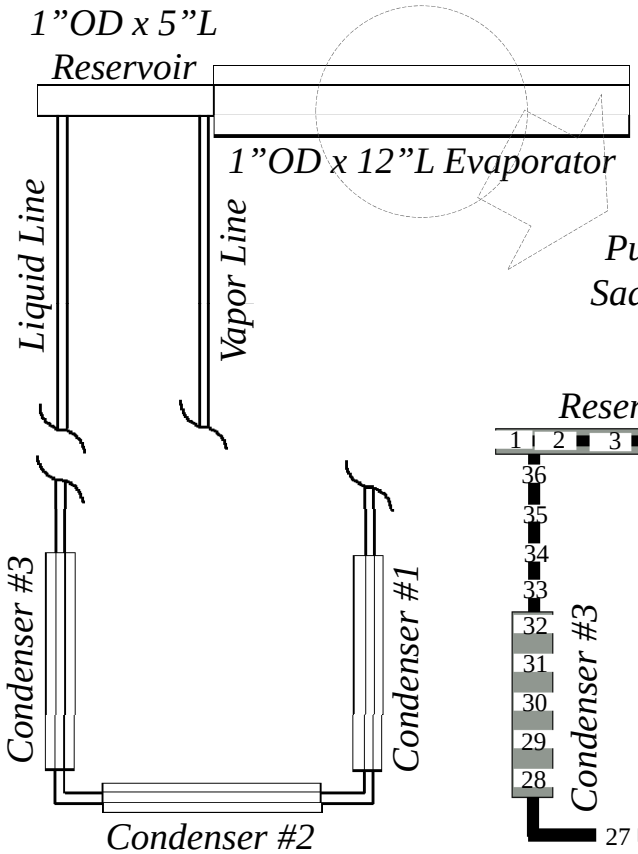
High Frequency Oscillations

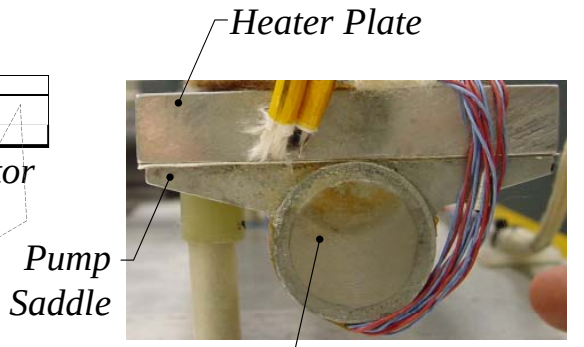
For Unstable LHP Operation: $\left(\frac{\partial \dot{Q}_E}{\partial T_{SAT}}\right)_{SS} > G_{HFLA}^{(CRIT)}$

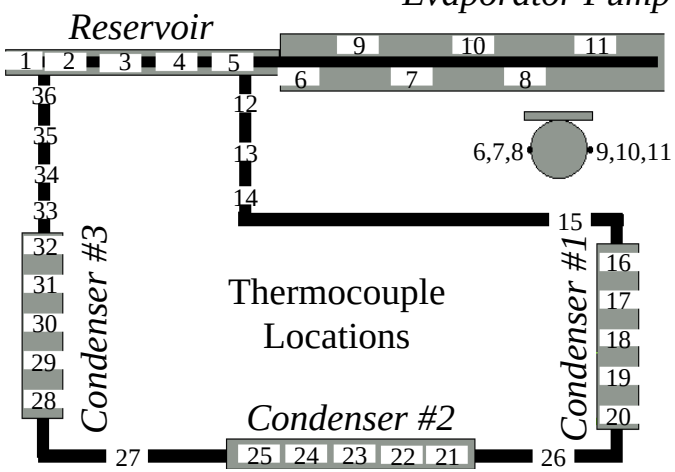


NRL Loop Heat Pipe









NRL Loop Heat Pipe

Dimensions and Properties of LHP Components

Evaporator

Primary Wick

Material:	Sintered Powder Nickel
Outer Diameter:	24.21mm (0.950”)
Inner Diameter:	*9.525mm (0.375”)*
Active Length:	0.3048m (12”)
Max. Pore Radius:	1.3µm
Permeability:	$1.3 \times 10^{-14} m^2$
Effective Conductivity:	*7.80W/m-K*

Casing/Saddle, 1st Wick, and Attached Thermal Mass

Thermal Mass of Heater Plate + Saddle + Casing:	1,575J/K
Thermal Mass-to-Vapor Conductance G_E:	*18.00 W/K*

Vapor Grooves

Number of Channels:	*4*
Hydraulic Diameter:	*0.05”*

Transport Lines

Vapor Line

Outer Diameter:	4.76mm
Wall Thickness:	0.508mm
Length:	1.524m

Liquid Line

Outer Diameter:	4.76mm
Wall Thickness:	0.508mm
Length:	1.96m (incl. bayonet)

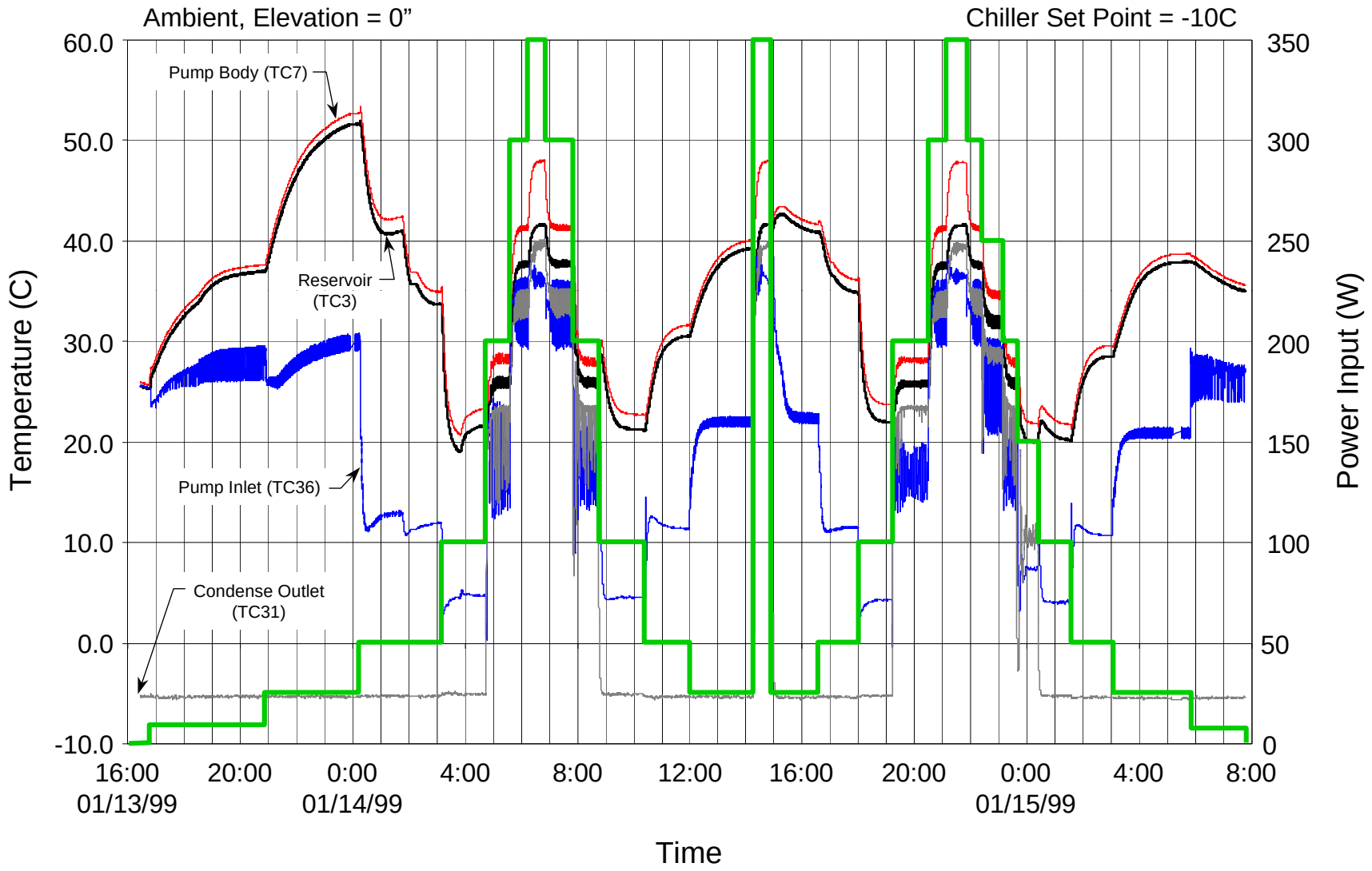
Condenser

Number of Parallel Passes	1
Heat Exchanger Tubing	
Inner Diameter:	3.744mm
Length:	2.032m (80”)
Conductance $G_C^{(MAX)}$:	*6.75W/K*

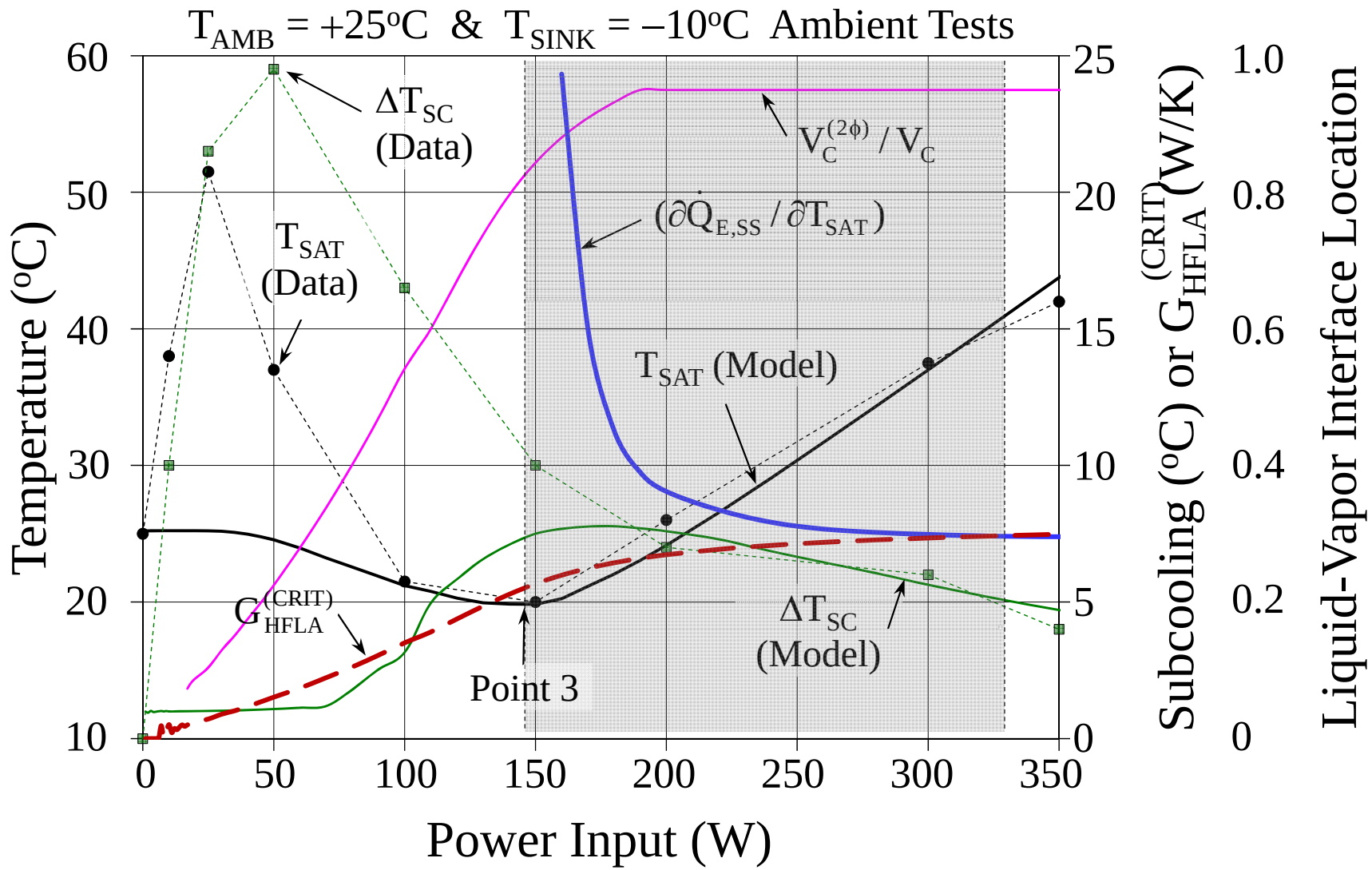
Reservoir

Outer Diameter:	25.4mm
Wall Thickness:	*1.27mm*
Active Length:	0.127m
Thermal Mass $(Mc_P)_R$:	*135.80J/K*
Conductance G_R:	*16.50W/K*

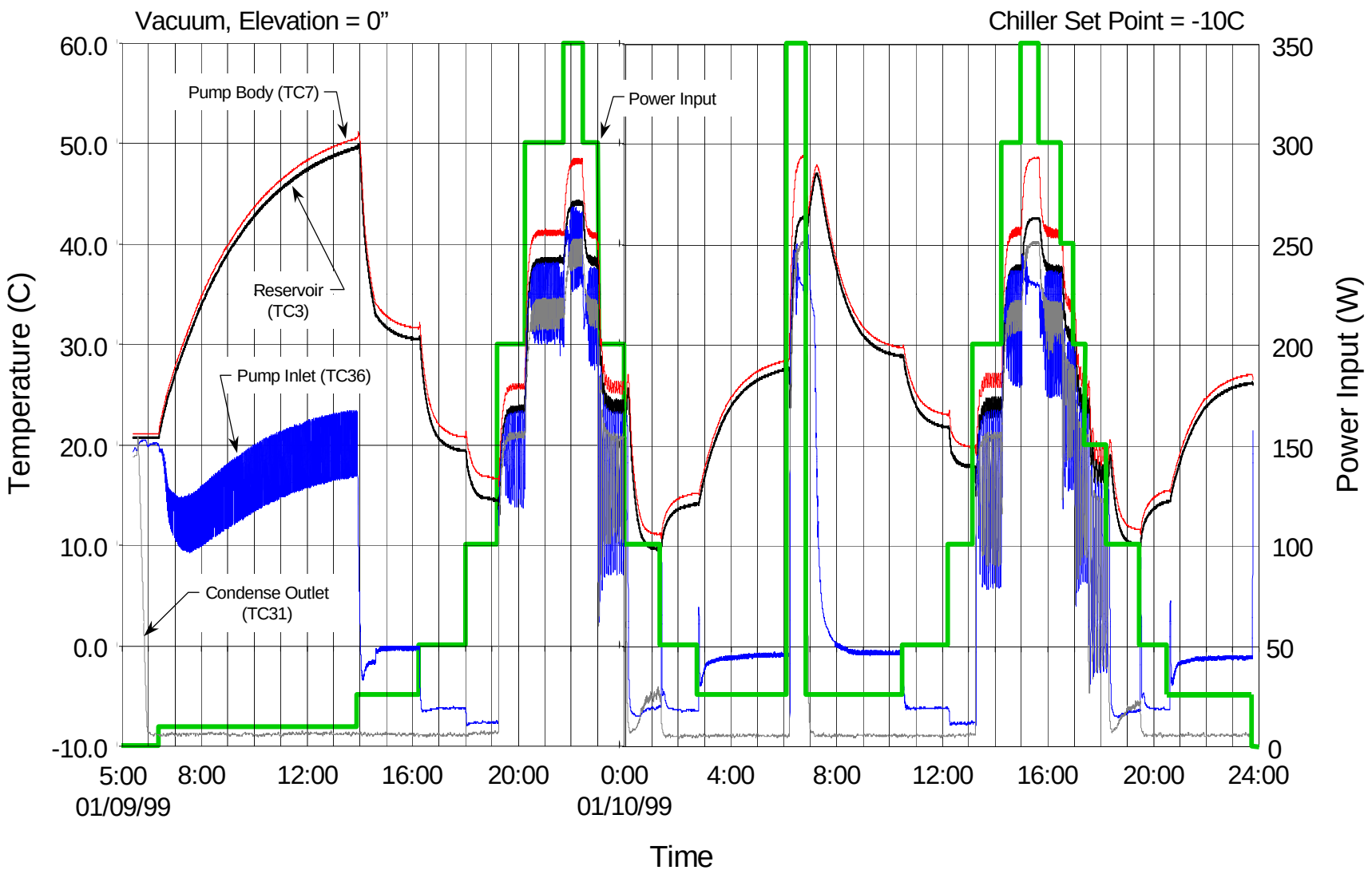
NRL LHP Ambient Tests



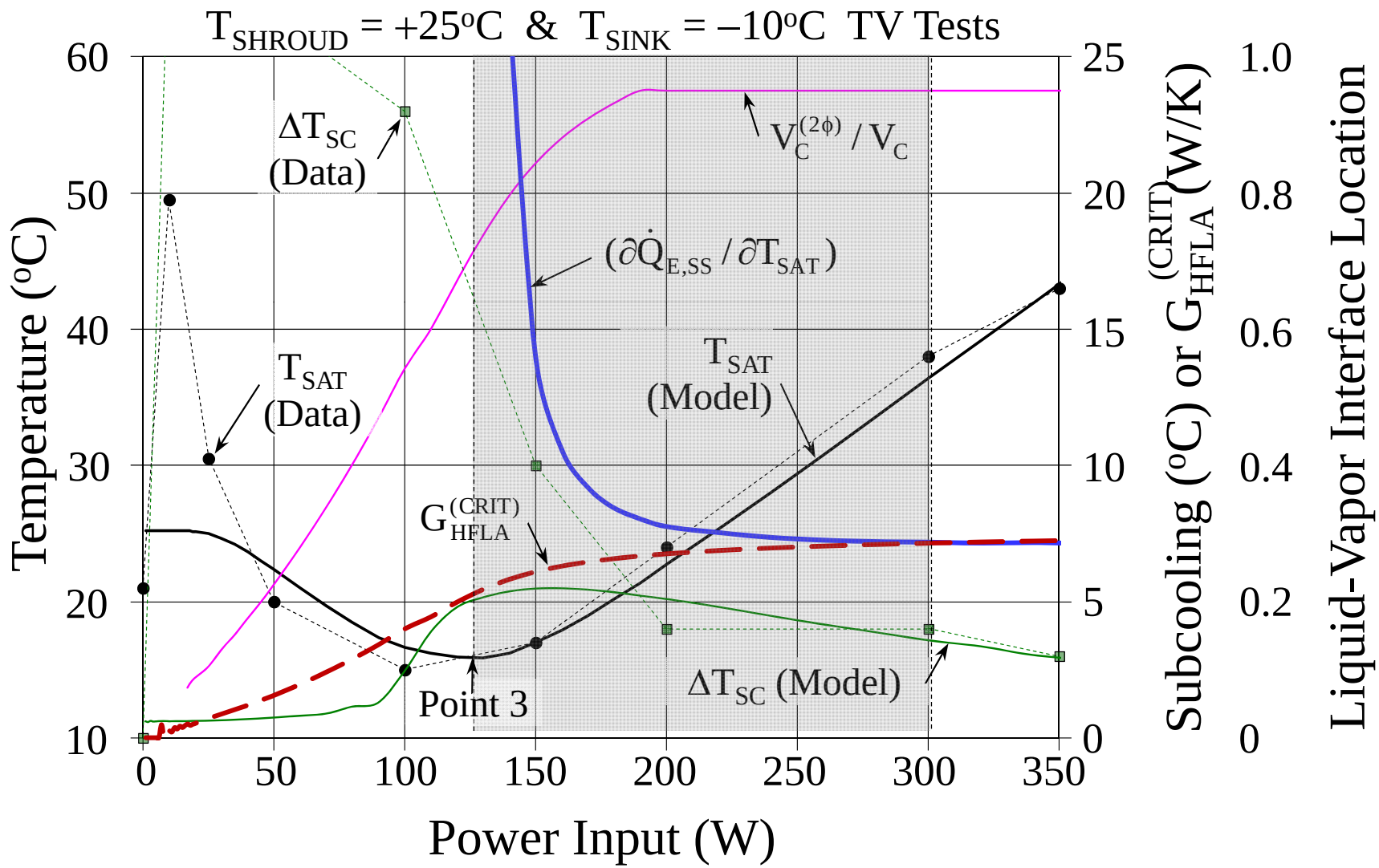
NRL LHP Ambient Instability Prediction



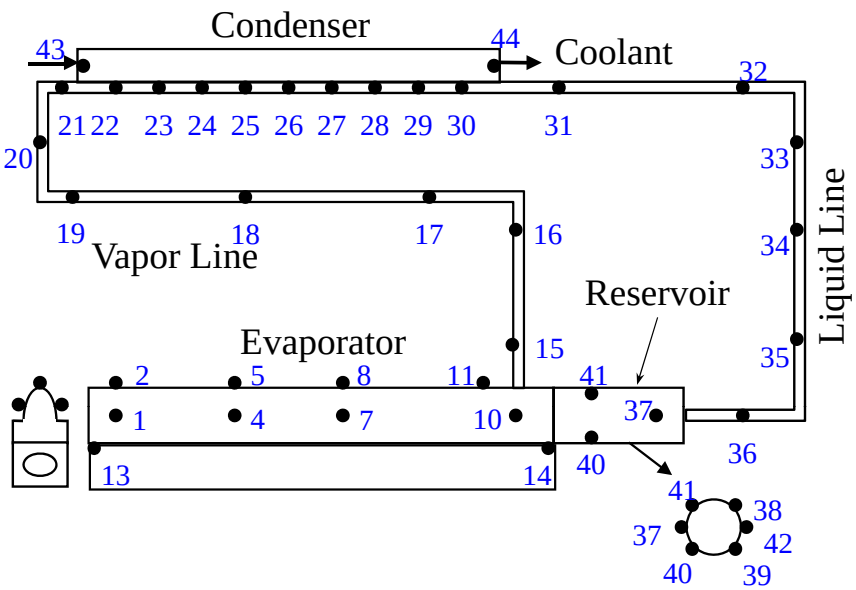
NRL LHP Thermal Vacuum Tests

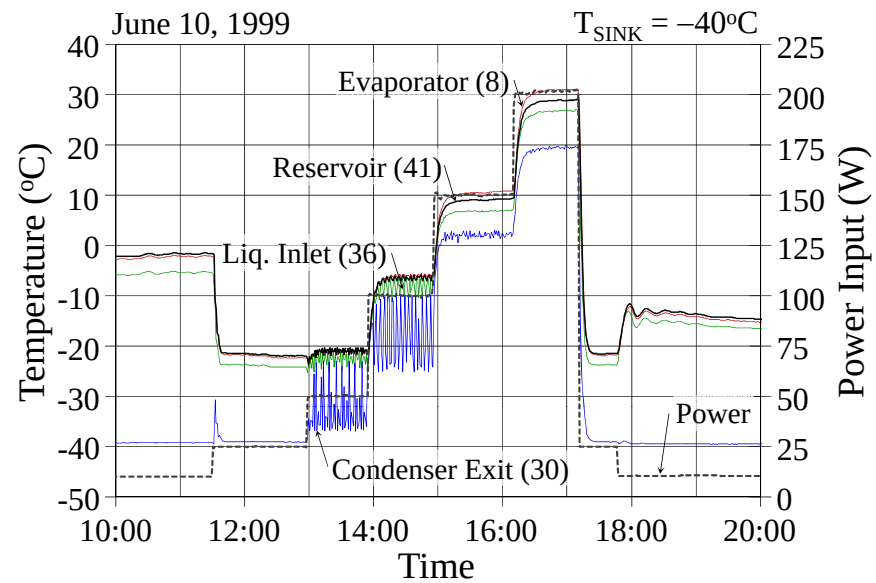


NRL LHP Vacuum Instability Prediction



GSFC Mini Loop Heat Pipe





Dimensions and Properties of LHP Components

Evaporator

Primary Wick

Material:	Sintered Powder Nickel
Outer Diameter:	12.00mm
Inner Diameter:	4.5mm
Active Length:	0.120m
Max. Pore Radius:	1.2µm
Permeability:	$4.0 \times 10^{-14} m^2$
Effective Conductivity:	7.80W/m-K

Transport Lines

Vapor Line

Outer Diameter:	3.175mm
Wall Thickness:	0.1875mm
Length:	0.160m

Condenser

Number of Parallel Passes	1
Heat Exchanger Tubing	
Inner Diameter:	2.800mm
Length:	0.100m
Conductance $G_C^{(MAX)}$:	3.300W/K

Casing/Saddle, 1st Wick, and Attached Thermal Mass

Thermal Mass of Heater Plate + Saddle + Casing:	147.66J/K
Thermal Mass-to-Vapor Conductance G_E:	13.50 W/K

Vapor Grooves

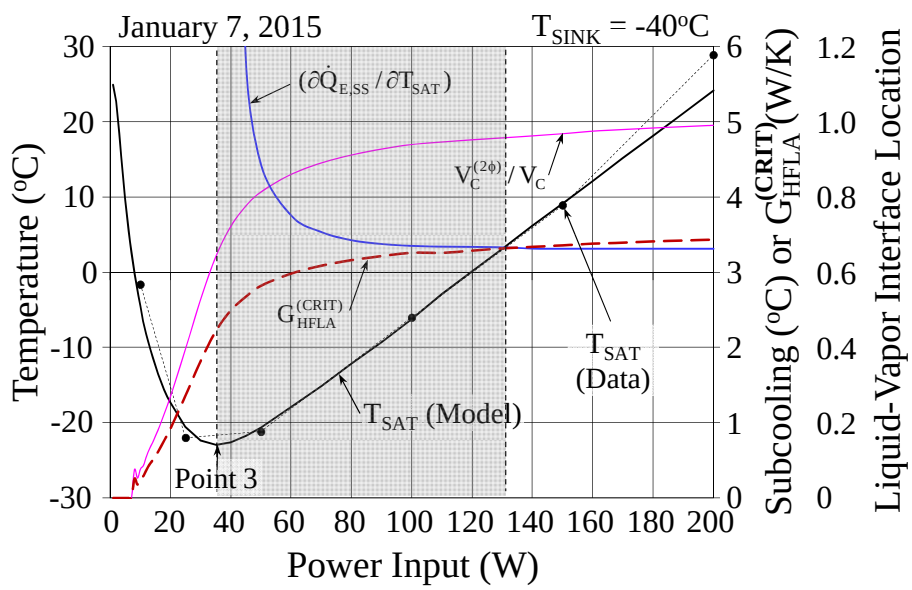
Number of Channels:	4
Hydraulic Diameter:	0.05"

Liquid Line

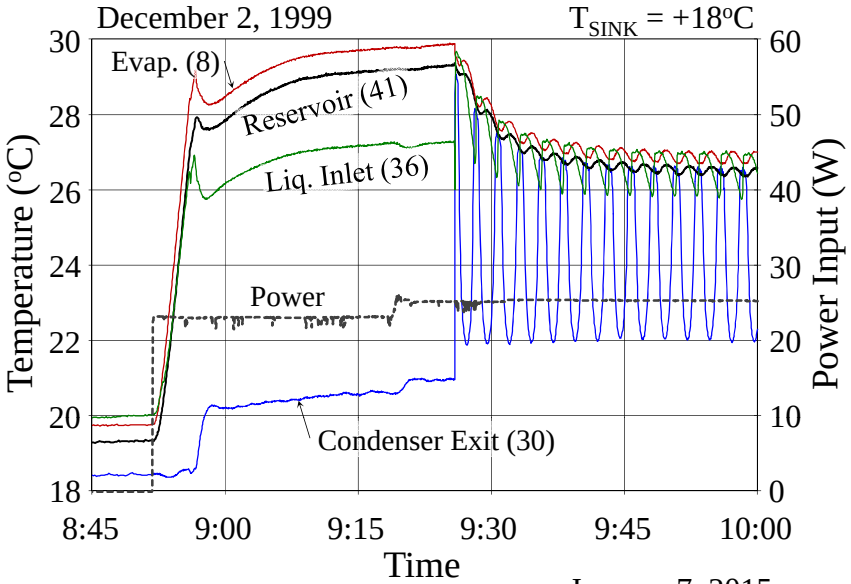
Outer Diameter:	3.175mm
Wall Thickness:	0.1875mm
Length:	0.250m (incl. bayonet)

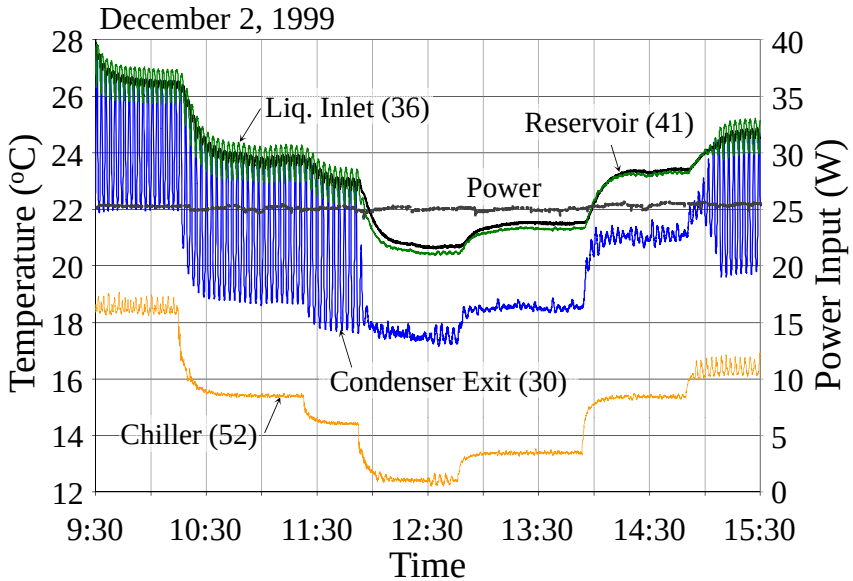
Reservoir

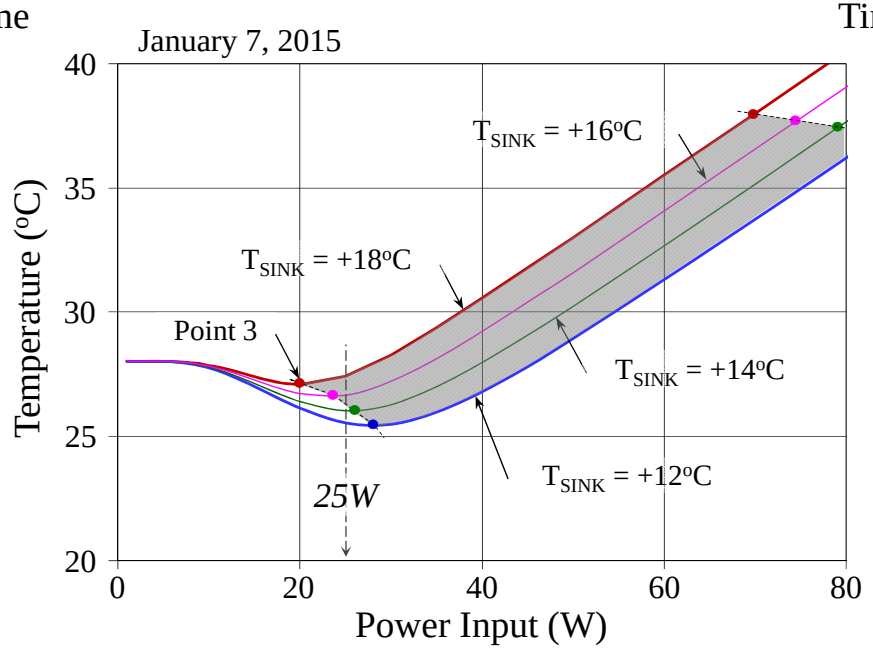
Outer Diameter:	13.0mm
Wall Thickness:	1.00mm
Active Length:	0.030m
Thermal Mass $(Mc_p)_R$:	14.83J/K
Conductance G_R:	8.168W/K



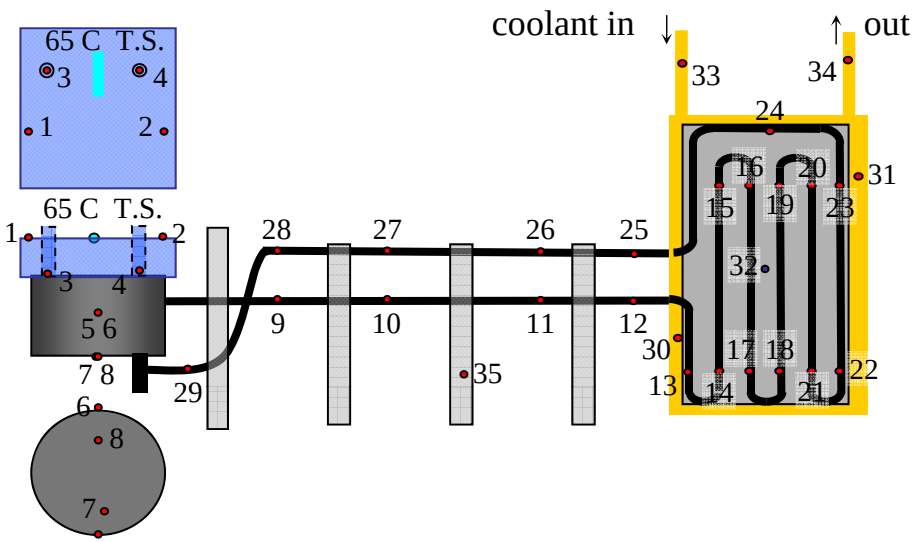
GSFC Mini Loop Heat Pipe

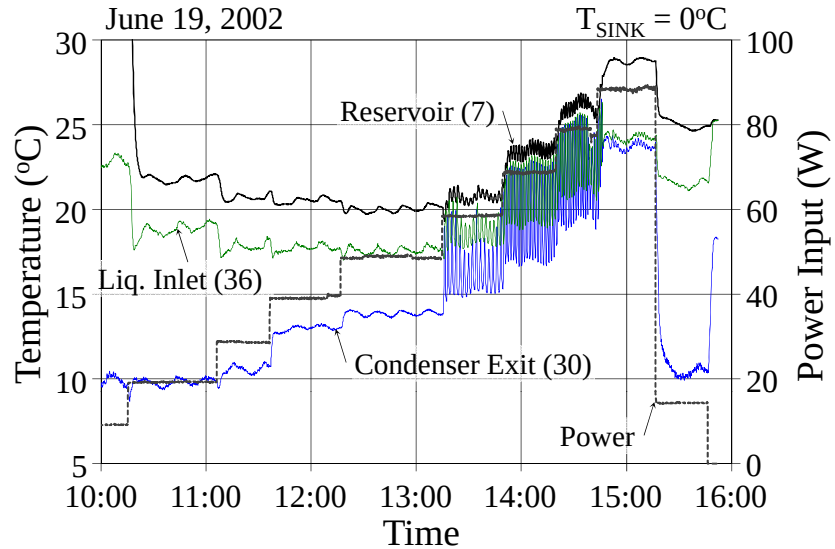






GSFC Flat Loop Heat Pipe





Dimensions and Properties of LHP Components

Evaporator

Primary Wick

Material:	Sintered Powder Nickel
Outer Diameter:	25.00mm
Thickness:	4.00mm
Active Length:	-
Max. Pore Radius:	1.0μm
Permeability:	$1.0 \times 10^{-14} m^2$
Effective Conductivity:	2.50W/m-K

Casing/Saddle, 1st Wick, and Attached Thermal Mass

Thermal Mass of Heater Plate + Saddle + Casing:	75.50J/K
Thermal Mass-to-Vapor Conductance G_E:	7.20 W/K

Vapor Grooves

Number of Channels:	4
Hydraulic Diameter:	0.05"

Transport Lines

Vapor Line

Outer Diameter:	2.000mm
Wall Thickness:	0.1875mm
Length:	0.770m

Liquid Line

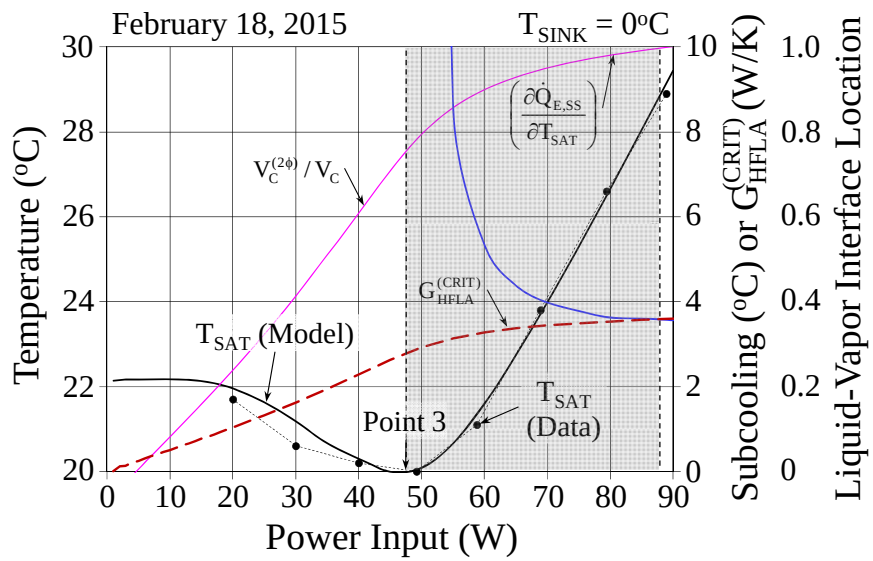
Outer Diameter:	2.000mm
Wall Thickness:	0.1875mm
Length:	0.760m (incl. bayonet)

Condenser

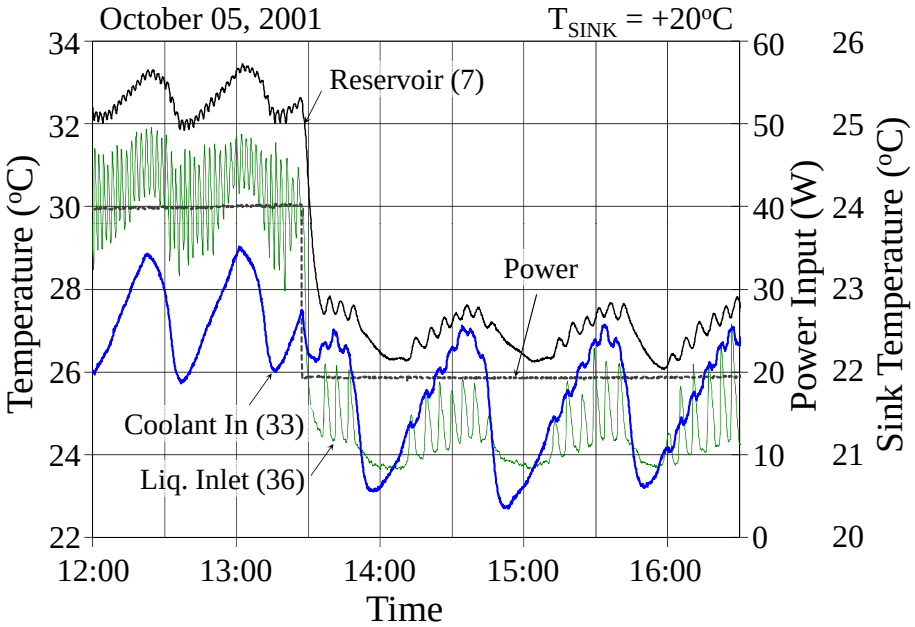
Number of Parallel Passes	1
Heat Exchanger Tubing	
Inner Diameter:	1.625mm
Length:	0.760m
Conductance $G_C^{(MAX)}$:	3.10W/K

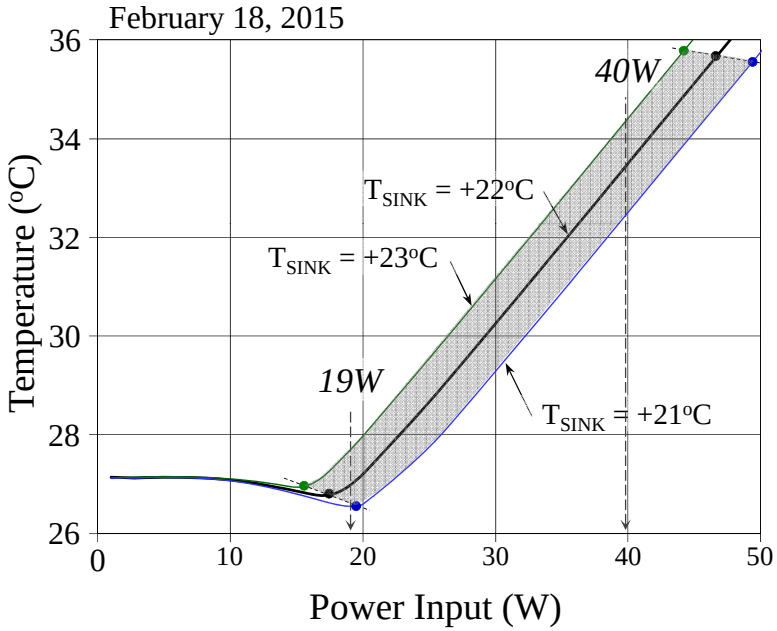
Reservoir

Outer Diameter:	30.00mm
Height:	25.00mm
Active Length:	0.127m
Thermal Mass $(Mc_p)_R$:	65.30J/K
Conductance G_R:	5.50W/K



GSFC Flat Loop Heat Pipe





Conclusion / Summary

- LHP Linear Stability Theory
  - high-frequency/low-amplitude oscillations are caused by direct condensation of vapor in reservoir by return subcooled liquid
  - theory is limited to single-pass condenser LHPs
- Theory Verification
  - model predictions agreed very well with test data from 3 different LHPs
- Path Forward
  - continue with verification when additional data available
  - add multiple parallel evaporators/condensers to theory