GODDARD SPACE FLIGHT CENTER

The New Millennium Program
ST8 Thermal Loop Experiment

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Outline

- Overview of NMP Space Technology 8 (ST8) Project and Thermal Loop Experiment
- Description of Thermal Loop Experiment
- Summary of Thermal Loop TRL 4 Validation Results
- Summary of Thermal Loop TRL 5 Validation Results
- Thermal Loop Protoflight Unit for TRL 7 Validation
- Thermal Loop Development Status
- Summary and Conclusion

Thermal Loop Experiment Description and Objective

- Thermal Loop experiment is an advanced thermal control system consisting of a miniature loop heat pipe with multiple evaporators and condensers designed for future small system applications requiring low mass, low power, and compactness.

- The TL technology will benefit future systems by outperforming conventional satellite thermal management approaches based solely on MLI, auxiliary heaters, conventional conduction heat sinks, louvers, conventional heat pipes, and radiators while providing flexibility in system testing configuration and component placement.

- The objective is to validate in space a miniature loop heat pipe thermal control system capable of reliable start-ups, steady operation, heat load sharing, and tight temperature control between 273K and 308K.

Thermal Loop is Part of ST8 Mission

- The Thermal Loop technology will be validated as part of the New Millennium Program Space Technology 8 (ST8) mission.
- ST8 is a JPL managed project with the purpose to advance the maturity of four technologies from “validated in a laboratory environment” (TRL 4) to “demonstrated in a space environment” (TRL 7).
- The four experiments will be integrated on an Orbital Sciences Corporation (OSC) spacecraft bus.
- ST8 is a seven month mission including one month of checkout
- Launch will be on the Pegasus XL, currently scheduled for February 28, 2009.

Thermal Loop Companion Technology Experiments

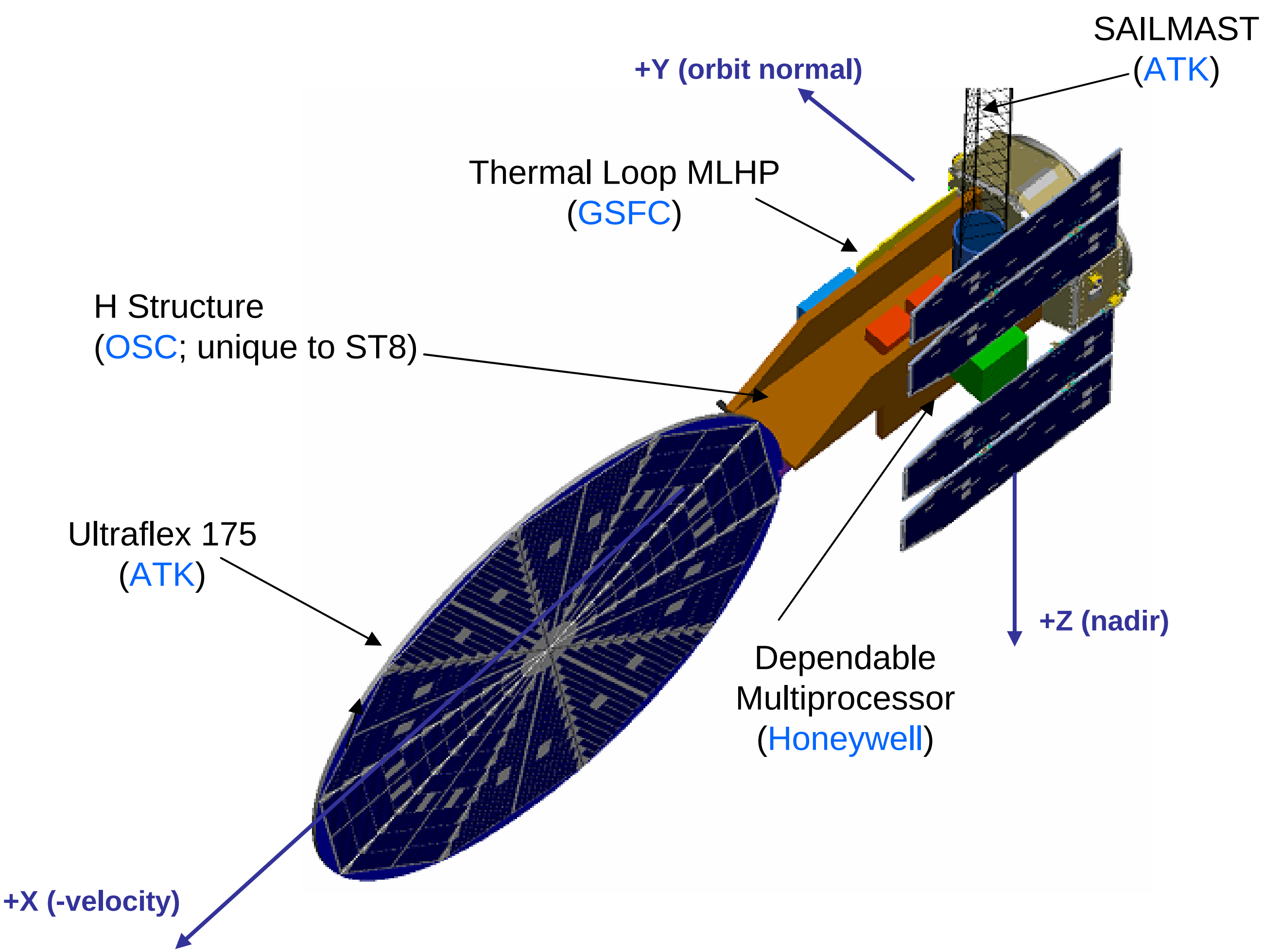
- **Dependable Multiprocessor:** COTS component based processor with real-time environment sensing, fault tolerant control algorithms, and rad-hard system infrastructure to provide an environmentally-adaptable, high-performance, and reliable on-board processing platform (Honeywell)

- **SAILMAST**: A 40 meter coilable and deployable gossamer truss with fewer parts and approximately twice as slender as current state-of-the-art trusses (ATK Space Systems)

- **UltraFlex**: An ultra-lightweight accordion-fanfold flexible-blanket solar array that deploys into a tensioned/rigid pre-loaded structure (ATK Space Systems)

Note: All four ST8 technology experiments will operate independently during validation.

ST8 Spacecraft Overview



- OSC single string S/C
- Heritage from MicroStar (avionics) and LeoStar (structure)
- Pitch momentum bias: 1 reaction wheel and 3 magnetic torquers
- No propulsion system
- Attitude sensed with: fine sun sensor, coarse sun sensors, earth horizon sensor, magnetometers
- S-band omni antennas
- Sun-synch. polar orbit
- Perigee: 320km
- Apogee: 1300km
- Inclination: 98.96 deg

Thermal Loop Level 1 Requirements

Technology Validation

1 Operate in space a miniature, multi-evaporator loop heat pipe for small system applications capable of 80% start-up success rate on a minimum of 20 start-ups.

Develop an analytical model which can predict the loop’s critical temperatures during steady state and transient operation.

Full Success Criteria

2 Operating temperature of the Loop measured at the compensation chamber shall be within ±3K of the desired set point temperature over 273K to 308K range.

3 Heat load share two loads in the range of 0 to 75 W while the loads either remove or add heat to the system.

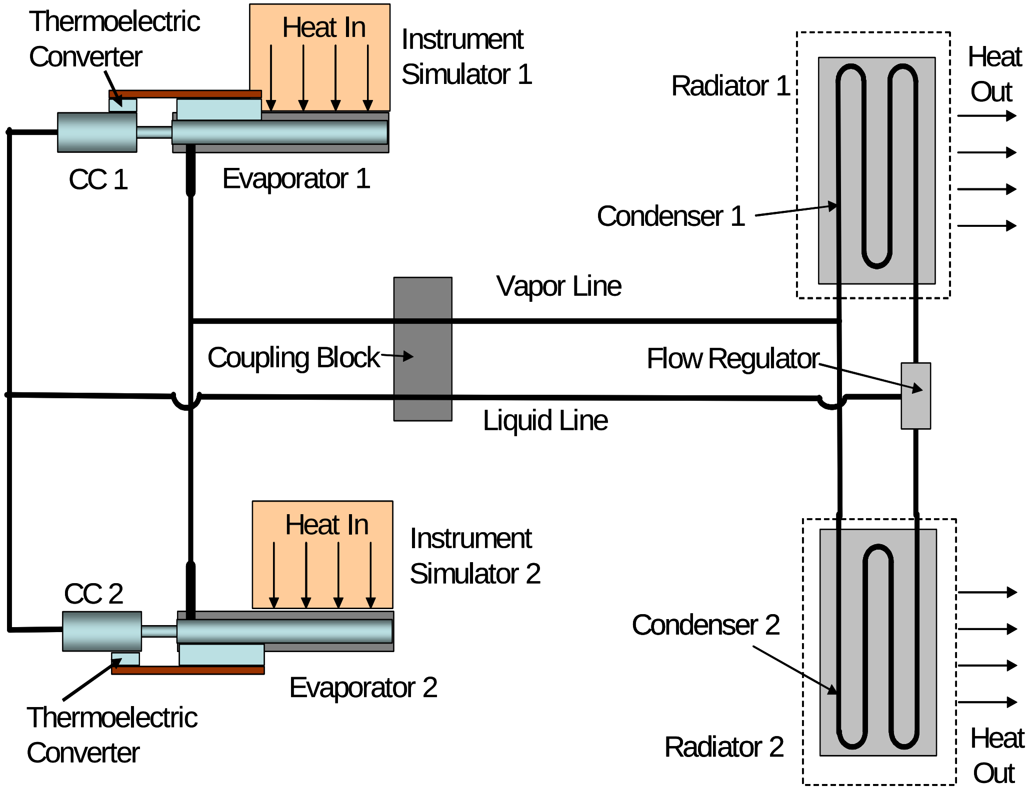
Minimum Success Criteria

2a Operating temperature of the Loop measured at the compensation chamber shall be within ±5K of the desired set point temperature over 273K to 308K range.

3a Heat load share two loads in the range of 0 to 50 W while the loads either remove or add heat to the system.

Thermal Loop Concept Description

- **Miniature Loop Heat Pipe**
  - Two parallel evaporators
  - Two parallel condensers
  - Compensation Chamber (CC)
    - Fluid reservoir
  - Flow Regulator
    - Prevents vapor blow through when only one condenser is fully utilized
  - Working Fluid
    - Anhydrous ammonia
- **Instrument Simulators**
  - Simulate instruments or electronic box
- **Thermoelectric Converters (TECs)**
  - Maintain CC saturation temperature
  - Variable set point control
- **Coupling Blocks**
  - Reduce control heater power requirements by transferring heat from vapor to return liquid



Technical Advances and Benefits

State-of-the-Art	*ST8 Technical Advance*
LHP has a single evaporator	**LHP has multiple evaporators (Thermal Loop will have two evaporators for demonstration)**
Requires supplemental heaters to maintain temperatures of off-instruments	**Heat load sharing among evaporators eliminates or reduces supplemental heater powers**
LHP has 25mm wick	**LHP has 6.35mm wick - reduced volume and mass**
Top-level transient model for LHPs with a single evaporator **No scaling rule has been established**	**Detailed transient model for LHPs with multiple evaporators** **Scaling rules will be established**
Relies on starter heater on evaporator for start-up **Power required: 20W to 40W**	**Uses TECs on CCs to ensure successful start-up** **Power required: less than 5W**
Control heater on CC for temperature control - cold biased, heating only, no cooling, **Heater power: 5W to 20W**	**TECs on CCs and coupling block on transport lines for temperature control - heating and cooling** **Heater power: 0.5W to 5W**

The Thermal Loop experiment combines the functions of variable conductance heat pipes, thermal switches, thermal diodes and advances beyond the state-of-the-art LHPs, making it versatile, robust, reliable, and more volume, mass, and power efficient.

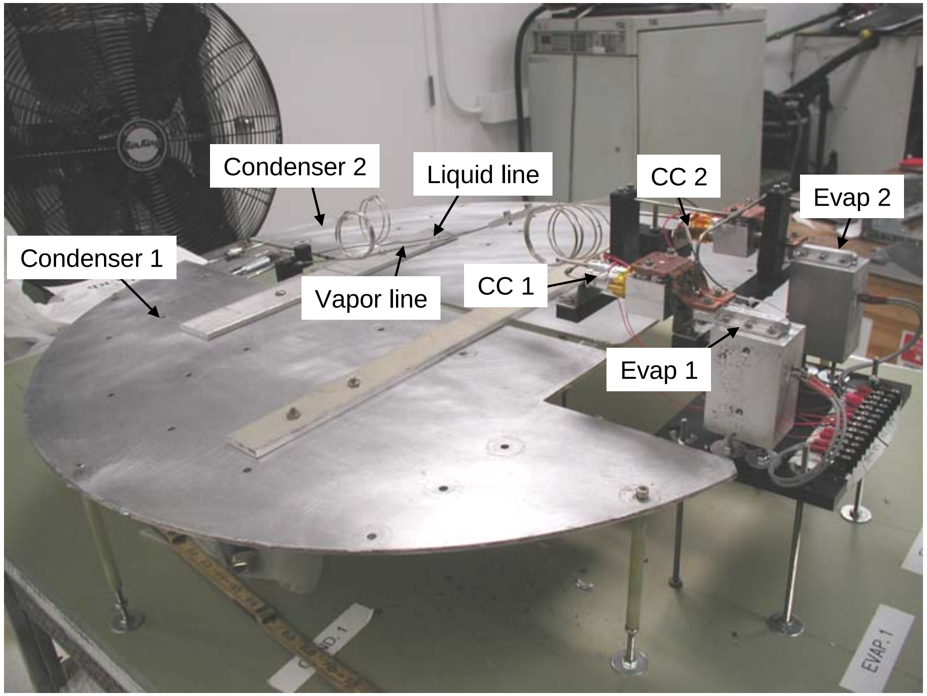
Rationale for Flight Experiment

- The operation of two-phase fluid systems is greatly affected by gravity. The zero-G operation of the LHP cannot be effectively simulated in a one-G environment.
  - Fluid distribution and flow regimes within the LHP components are dependent on the gravity environment.
  - Fluid distribution in the evaporator is critical in determining LHP start-up behavior and subsequent loop operating temperature.
- Thermal Loop includes numerous innovative components, including ¼ inch (6.35 mm) diameter wick evaporators, TECs for start-up and operating temperature control, and multiple evaporators, that have never been proven in space, and whose zero-G operation could have unexpected characteristics.
- Long duration 0-G tests of the LHP are required because of the slow thermal response of the system – drop tower and KC-135 tests are not adequate
- Flight validation is imperative in order to reduce risks for first users.
- Flight data is required to correlate analytical model and provide confidence in its use for future programs.

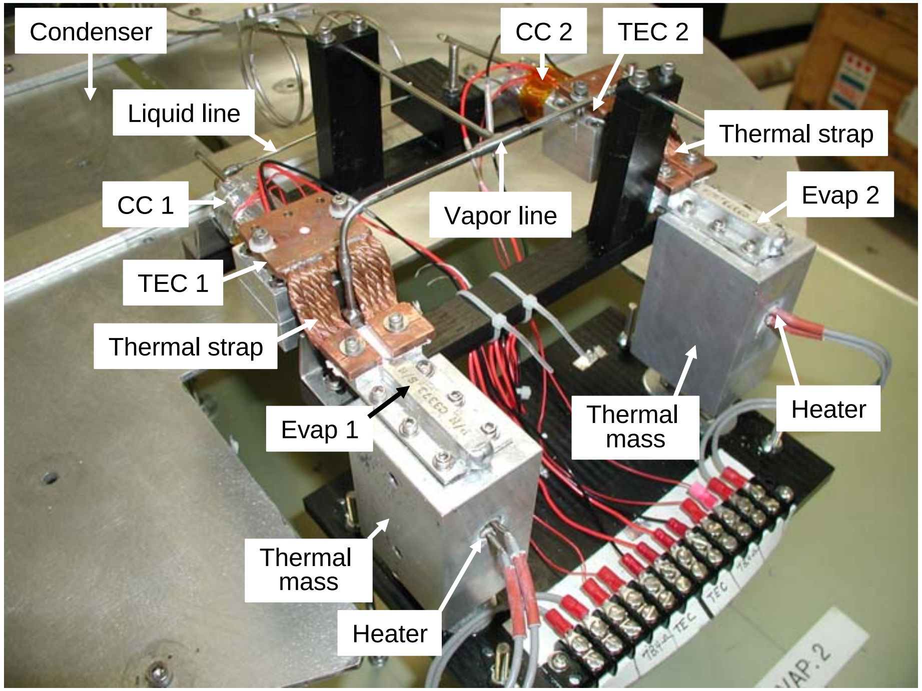
Thermal Loop TRL 4 and TRL 5 Validation

- NMP TRL 4 Definition
  - Component and/or breadboard validated in a laboratory environment
- NMP TRL 5 Definition
  - Component and/or prototype validated in a relevant environment
- Thermal Loop experiment used a breadboard for TRL 4 and 5 validation.
  - TRL 4 - breadboard tested in a laboratory environment
  - TRL 5 – breadboard tested in a thermal vacuum environment
  - An LHP analytical model was developed to replicate the results of laboratory and thermal vacuum tests.

Thermal Loop Breadboard - Pictures

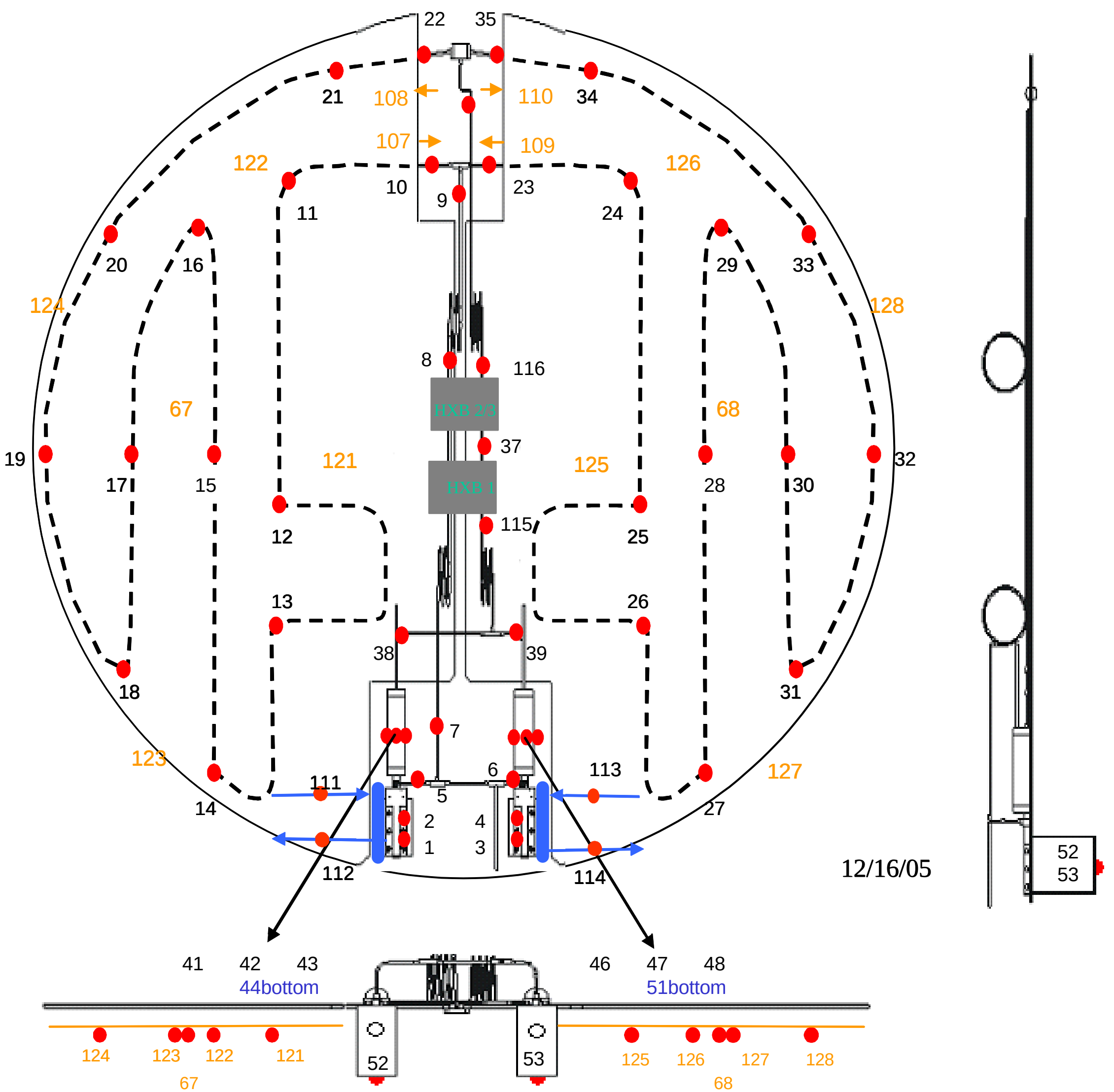


Overall View



Close View of Evaporator/CC Section

Thermal Loop Breadboard – Schematic and TC Locations



Thermal Loop Breadboard Design Summary

- Evaporator (Aluminum 6061)
  - O.D. : 9mm
  - Length: 52mm
  - Thermal mass attached: 400 g aluminum (each)
- Primary Wick (Titanium)
  - O.D.: 6.4mm
  - I.D. : 3.2mm
  - Porosity: 0.35
  - Pore radius: 1.39 μm (E1)
1.47 μm (E2)
  - Permeability: 0.11E-13m^2 (E1)
0.09E-13m^2 (E2)
  - Thermal conductivity: 7.8 W/m-K
- Secondary Wick
  - Porosity: 0.67
  - Pore radius: 68.7 μm
  - Permeability: 68.7E-13m^2
- Bayonet tube (SS 304L)
  - O.D.: 1.1 mm
  - I.D.: 0.79 mm
- Reservoir (SS 304L)
  - O.D.: 22.2 mm
  - I.D.: 21.2 mm
  - Length: 72.4 mm
- Vapor Line (SS 304L)
  - O.D.: 2.38 mm
  - I.D.: 1.37mm
  - Length: 914 mm
- Liquid Line (SS304L)
  - O.D. 1.59 mm
  - I.D.: 1.08 mm
  - Length: 914 mm
- Condenser (SS 304L)
  - No. of parallel lines: 2
  - O.D.: 2.38 mm
  - I.D.: 1.37 mm
  - Length: 2540 mm (each)
- Flow Regulator
  - Pore radius: 10.1 μm
  - Permeability: 0.2 E-13 m^2
  - Flow Area: 98 mm^2
- Working Fluid
  - Ammonia
  - 29.3 grams
- LHP Mass
  - 316.6 grams

Summary of TRL 4 Validation Results

- The Thermal Loop breadboard was tested in a laboratory environment.
- The laboratory test demonstrated more than 1200 hours of LHP operation under a wide range of operating conditions.
- Test configuration
  - Five configurations: horizontal, upside down, sideways, 45-degree tilt, vertical
- Start-up
  - More than 160 start-ups were performed. All were successful.
  - CC temperature: 0, 1 or both CCs were controlled at temperatures between 288K and 313K
  - Heat load between 5W and 100W to only one of the evaporators
  - Heat load to both evaporators: 1W/1W, 5W/5W, 10W/10W, 5W/50W, 50W/50W, and more
  - Temperatures of the two chillers: 243K to 293K, independent of each other
- Operation
  - The LHP operating temperature was controlled within ±0.5K of the desired set point between 288K and 313K in all tests.
  - Demonstrated heat transport capability of more than 100W
  - Stable LHP operation at all times over the full range of heat loads and sink temperatures
  - Demonstrated heat load sharing between the two evaporators
- Analytical Model
  - The model predicted all critical temperatures to within ± 5K during start-up and operation

Summary of TRL 5 Validation Results

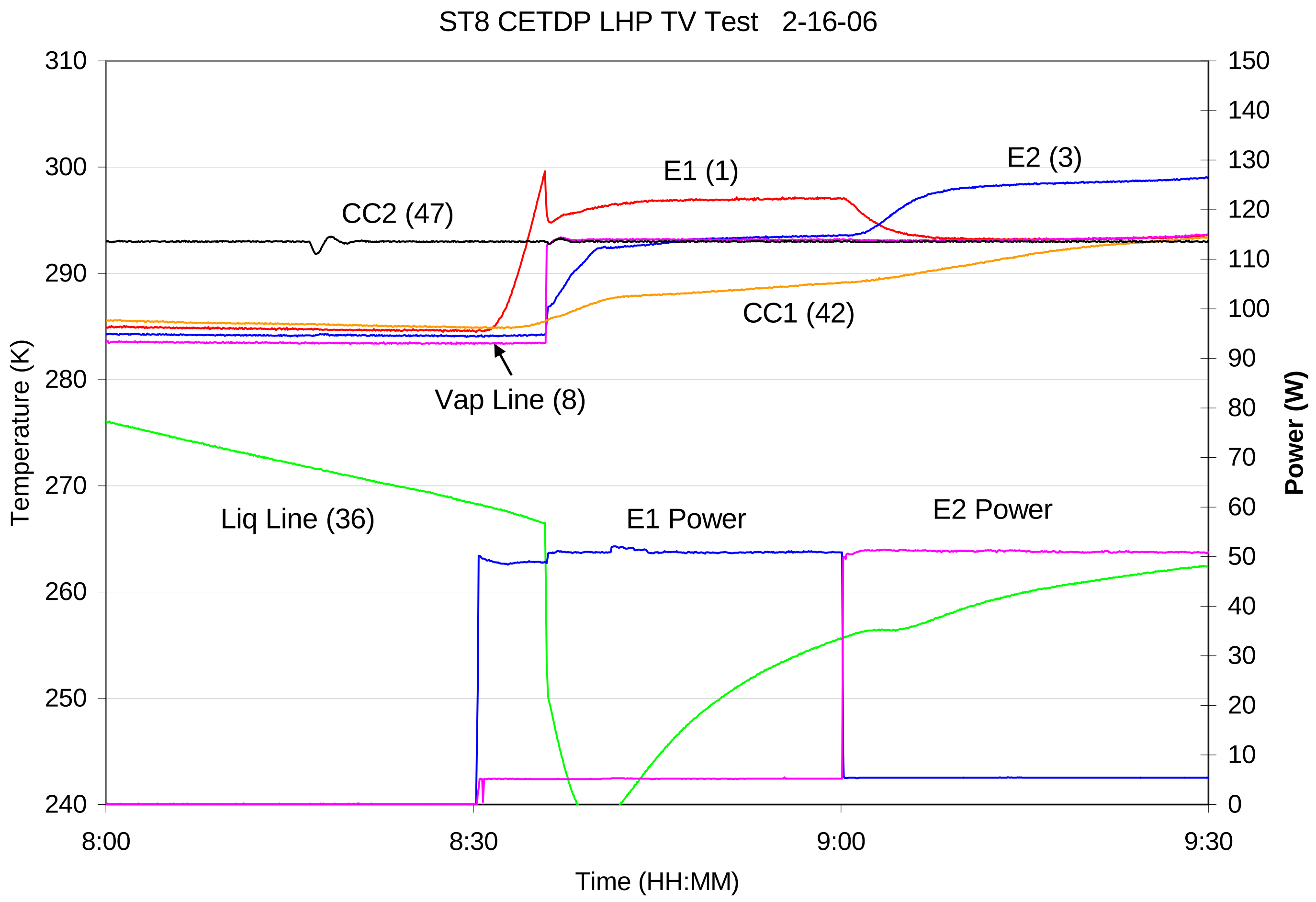
- The MLHP breadboard was tested in a thermal vacuum environment.
- The thermal vacuum test demonstrated more than 500 hours of LHP operation under a wide range of operating conditions.
- Start-up
  - Fifty-one start-ups were performed. All were successful.
  - CC temperature: 0, 1 or both CCs were controlled at 258K, 273K, 283K, 288K, 293K, 298K, 303K, and 308K
  - Heat load between 5W and 50W to only one of the evaporators
  - Heat load to both evaporators: 5W/5W, 10W/10W, 5W/50W, 50W/5W, and more
  - Temperatures of the two condenser sinks: 203K/203K, 203K/243K, 273K/243K, and more
- Operation
  - The LHP operating temperature was controlled within ±0.5K of the desired set point between 258K and 308K in all tests.
  - Demonstrated heat transport capability of more than 100W
  - Stable LHP operation at all times over the full range of heat loads and sink temperatures
  - Demonstrated heat load sharing between the two evaporators
- Analytical Model
  - The model predicted all critical temperatures to within ± 5K during start-up and operation

* This presentation will only highlight the TRL 5 validation results.

Thermal Loop TRL 5 Validation Test - Start-up

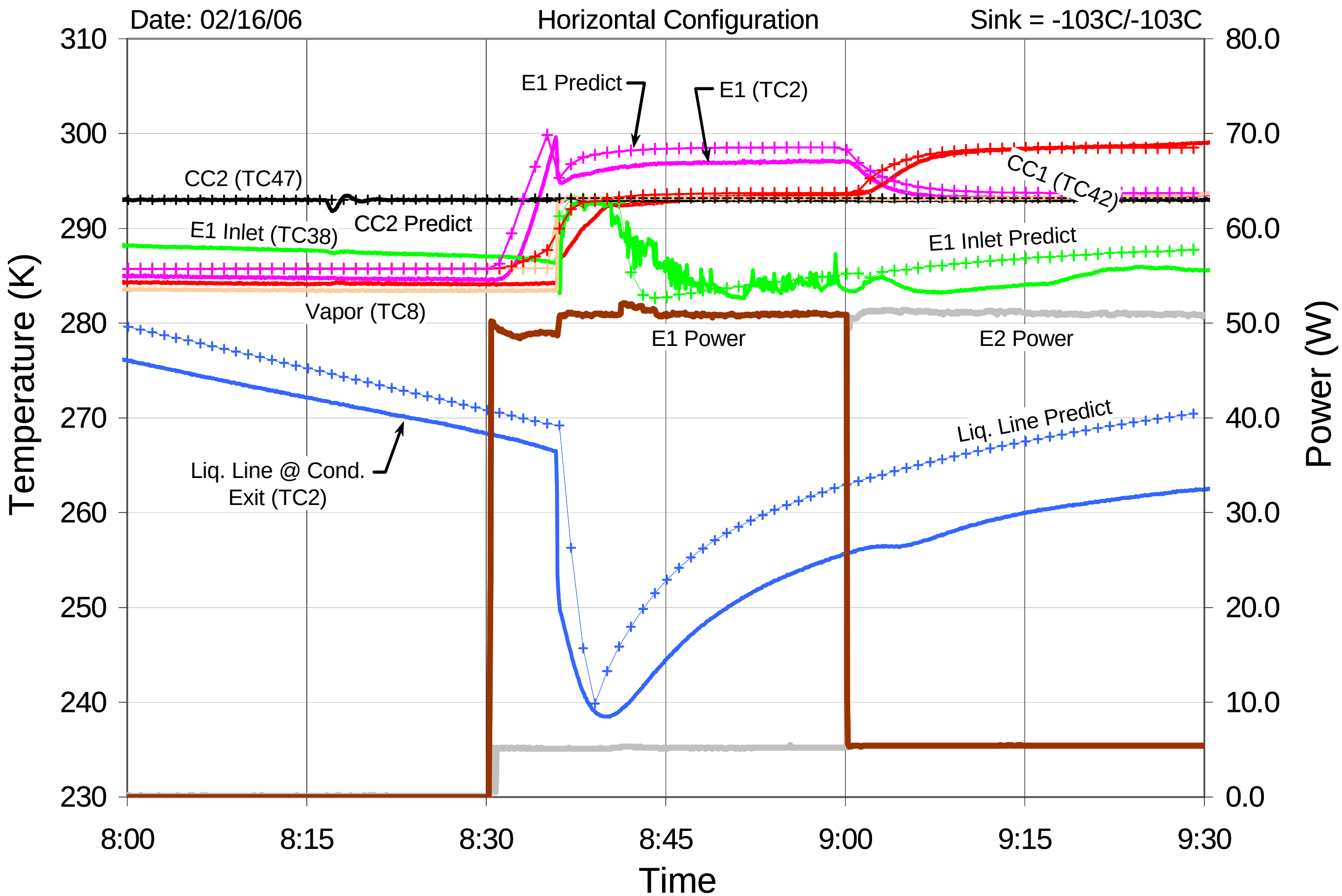
No control/293K, 50W/5W

- E1 was flooded prior to start-up – this is Condition 3.
- E1 reached set point temperature first and started the loop with 7K superheat.



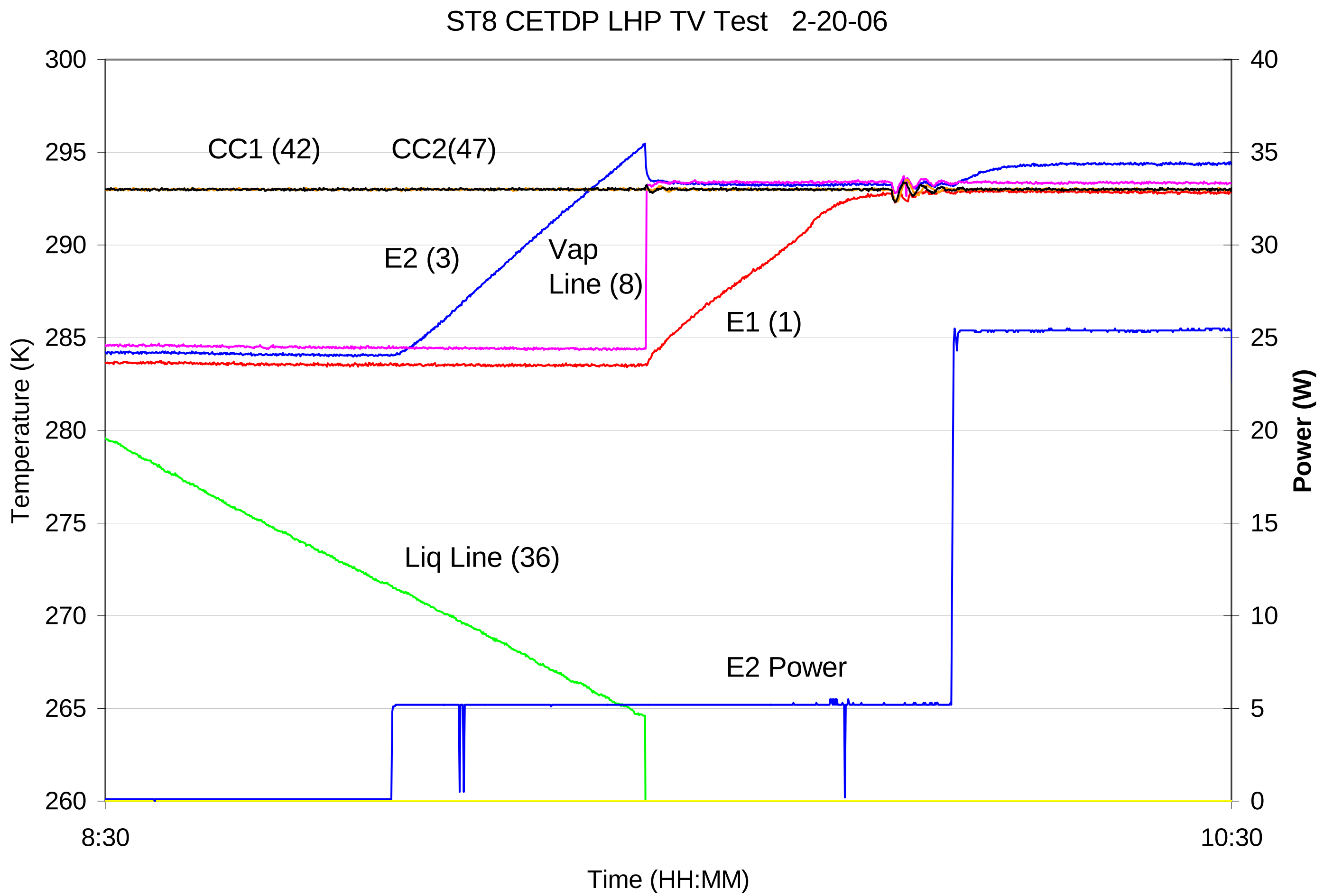
Thermal Loop TRL 5 Validation Results – Comparison of Predictions with Test Data

- CC1/CC2 = NC/293K, C1/C2 sinks =173K/173K, E1/E2 power = 50W/5W, 5W/50W
- Input data: superheat = 7K
- **The model predicts loop critical temperatures within ±5K.**



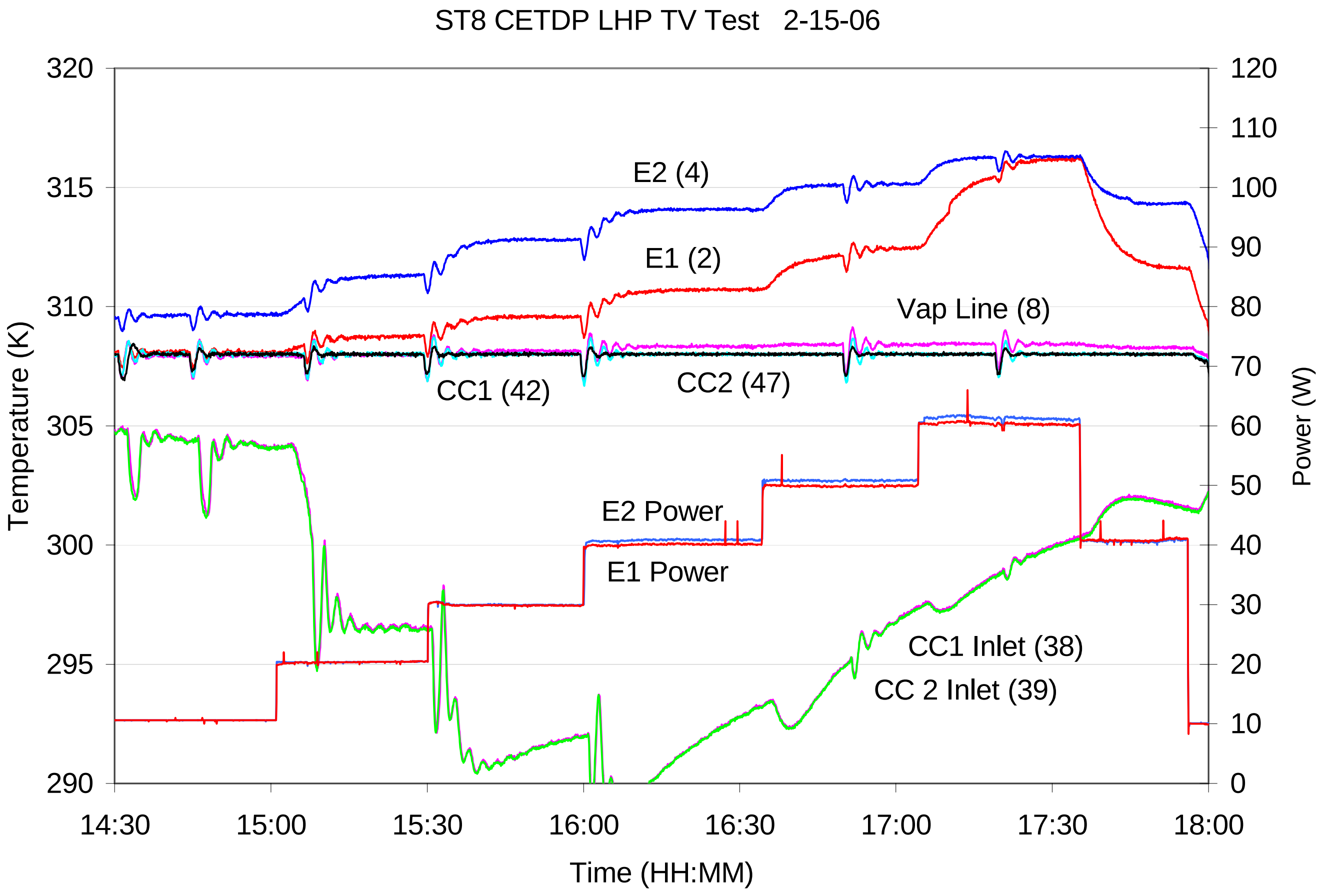
Thermal Loop TRL 5 Validation Test - Start-up
293K/293K, 0W/5W

- 2.5K superheat on E2 at start-up
- E1 shared heat after loop started.



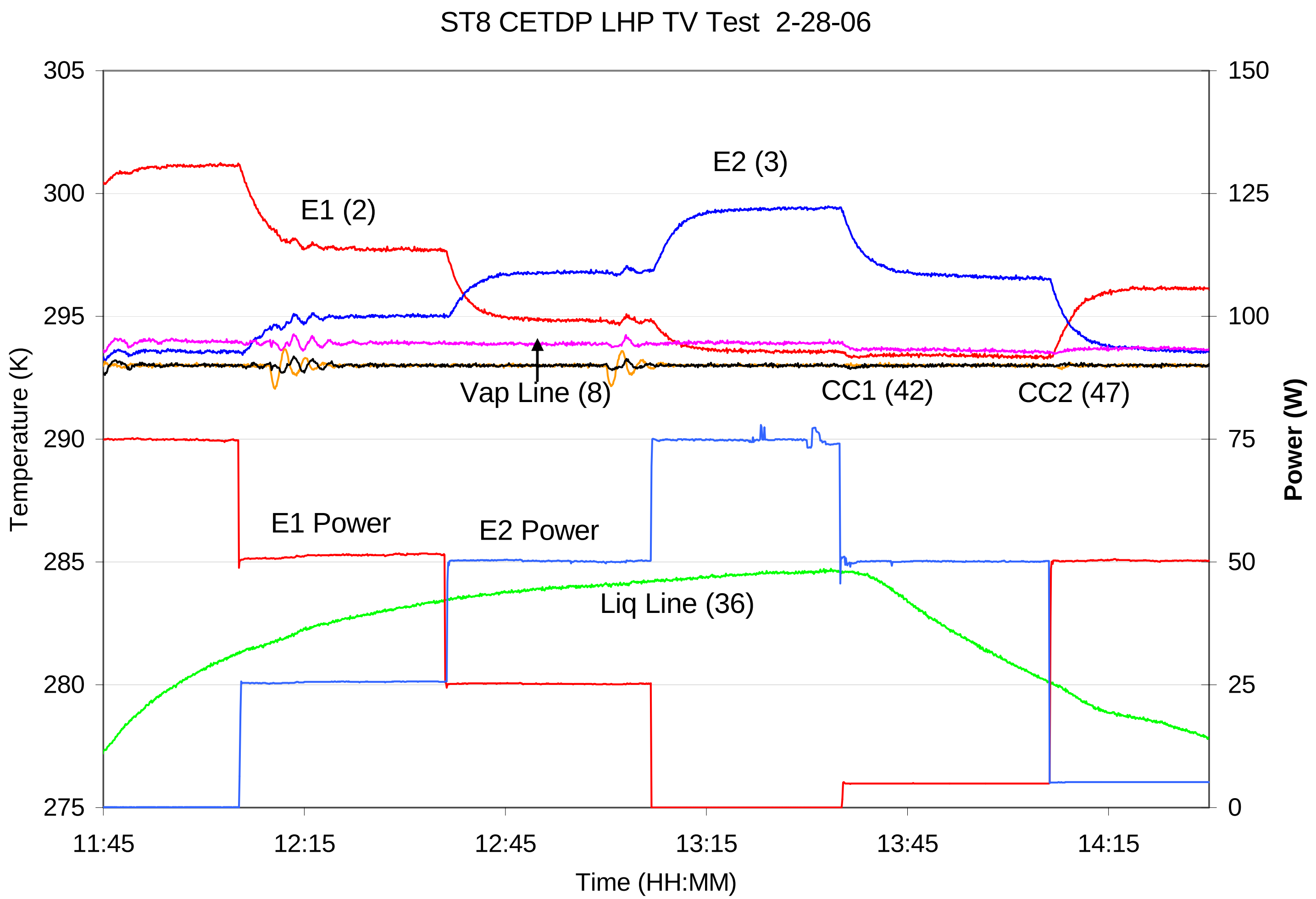
Thermal Loop TRL 5 Validation Test - Power Ramp Up

- CC1/CC2 = 308K/308K, C1/C2 sink = 123K/123K
- E1/E2 Power: 10W/10W, 20W/20W, 30W/30W, 40W/40W, 50W/50W, 60W/60W, 40W/40W
- **Loop demonstrated more than 100W heat transport**.
- Loop operating temperature was controlled within ±1K of the 308K set point temperature.
- The vapor line temperature was the same as the set point temperature.



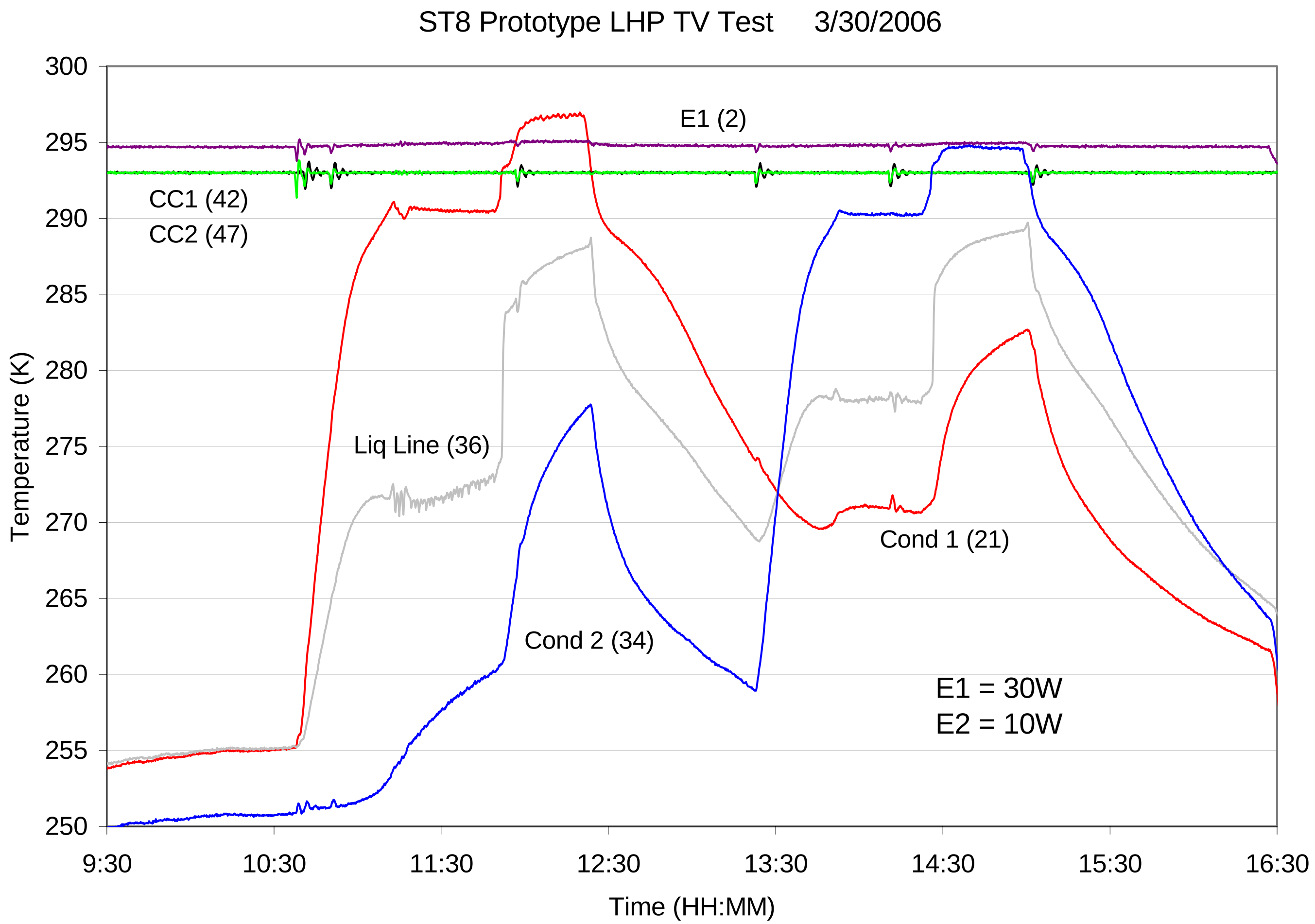
Thermal Loop TRL 5 Validation Test - Power Cycle

- CC1/CC2= 293K/293K, C1/C2 sink = 173K/173K
- E1/E2 power = 75W/0W, 50W/25W, 25W/50W, 0W/75W, 5W/50W, 50W/5W
- **The loop operating temperature was maintained within ±1K of the 298K set point temperature**.



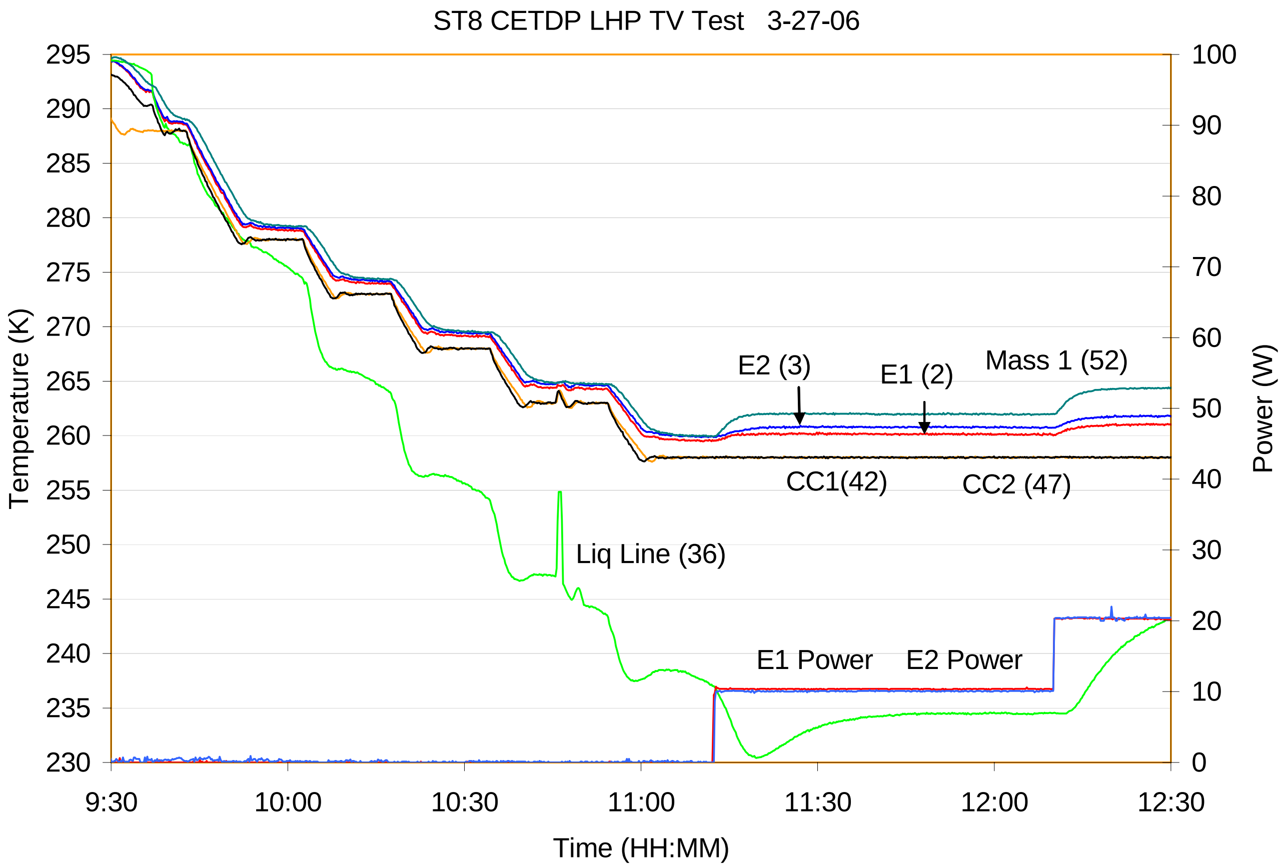
Thermal Loop TRL 5 Validation Test - Flow Regulator Test

- E1/E2 power = 30W/10W constant. CC1/CC2 = 293K/293K
- C1/C2 sink = 223K/223K, 293K/223K, 298K/223K, 223K/223K, 223K/293K, 223K/298K 223K/223K,
- **Both sides of the flow regulator worked properly to stop vapor.**



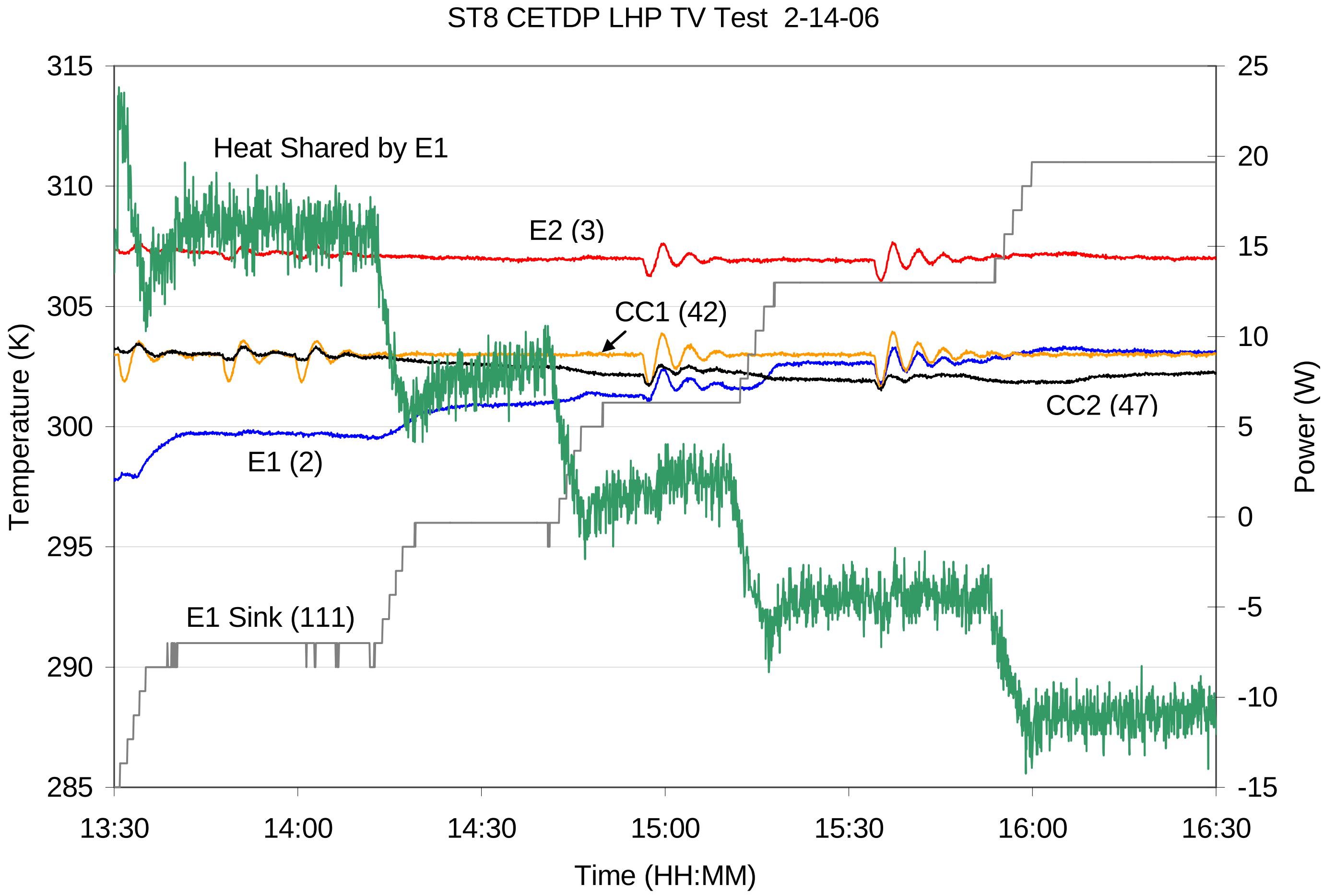
Thermal Loop TRL 5 Validation Test - Operation at 258K

- C1/C2 sink = 203K/203K. No heat load to E1/E2.
- CC1/CC2=293K/293K, 288K/288K, 283K/283K, 278K/278K, 273K/273K, 268K/268K, 263K/263K, 258K/258K
- At 258K/258K, E1/E2 power = 10W/10W and 20W/20W
- **TECs enabled CC1/CC2 to control the loop saturation temperature below its natural operating temperature.**



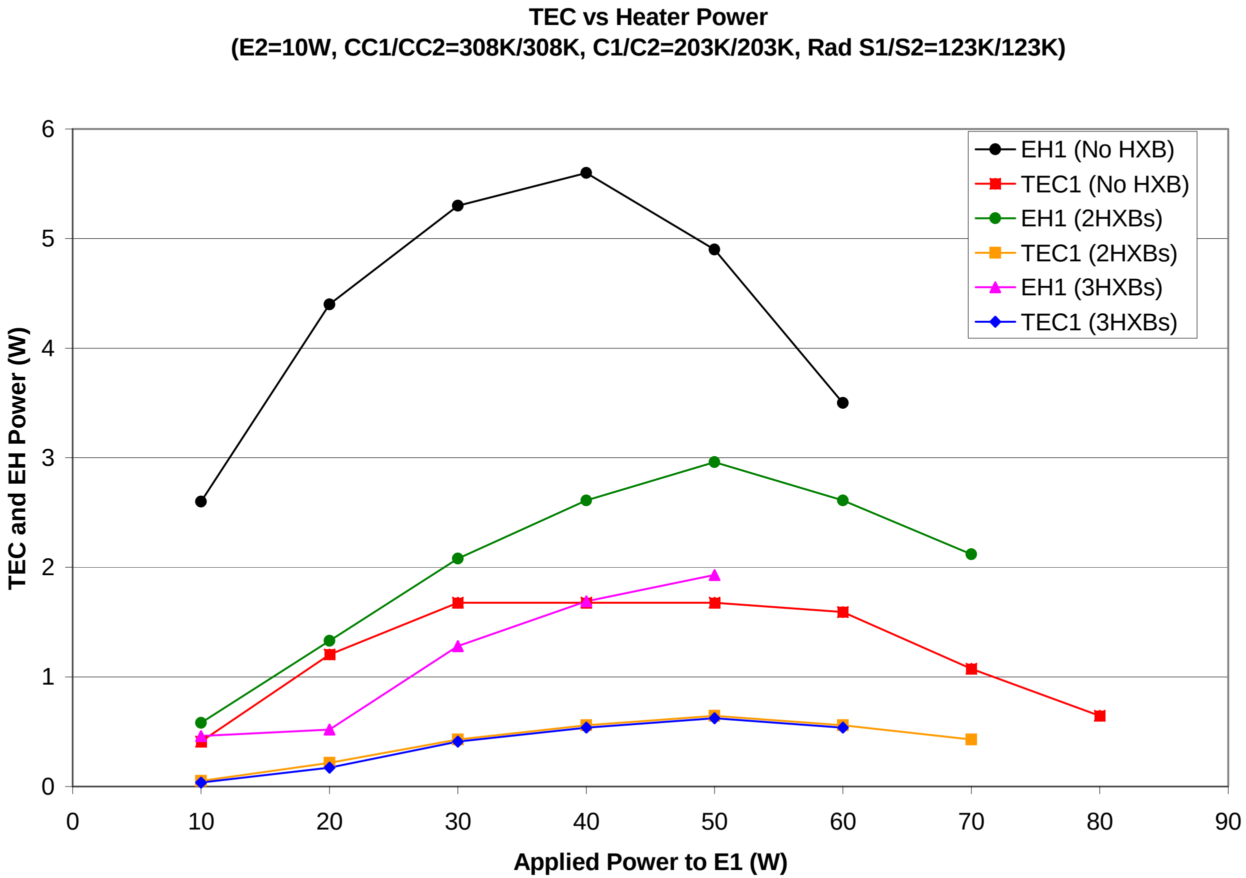
Thermal Loop TRL 5 Validation Test - Heat Load Sharing

- CC1/CC2 = 303K/NC, E2 power = 50W constant, C1/C2 sink = 203K/243K
- E1 coolant flow rate = 0.15 gpm
- E1 coolant temperature = 283K/288K/293K/298K/303K/308K
- As coolant temperature reached 303K and 308K, E1 received heat from the coolant and was in its normal operation (shared negative heat)



Thermal Loop TRL 5 Validation Test – TEC Power versus Electrical Power

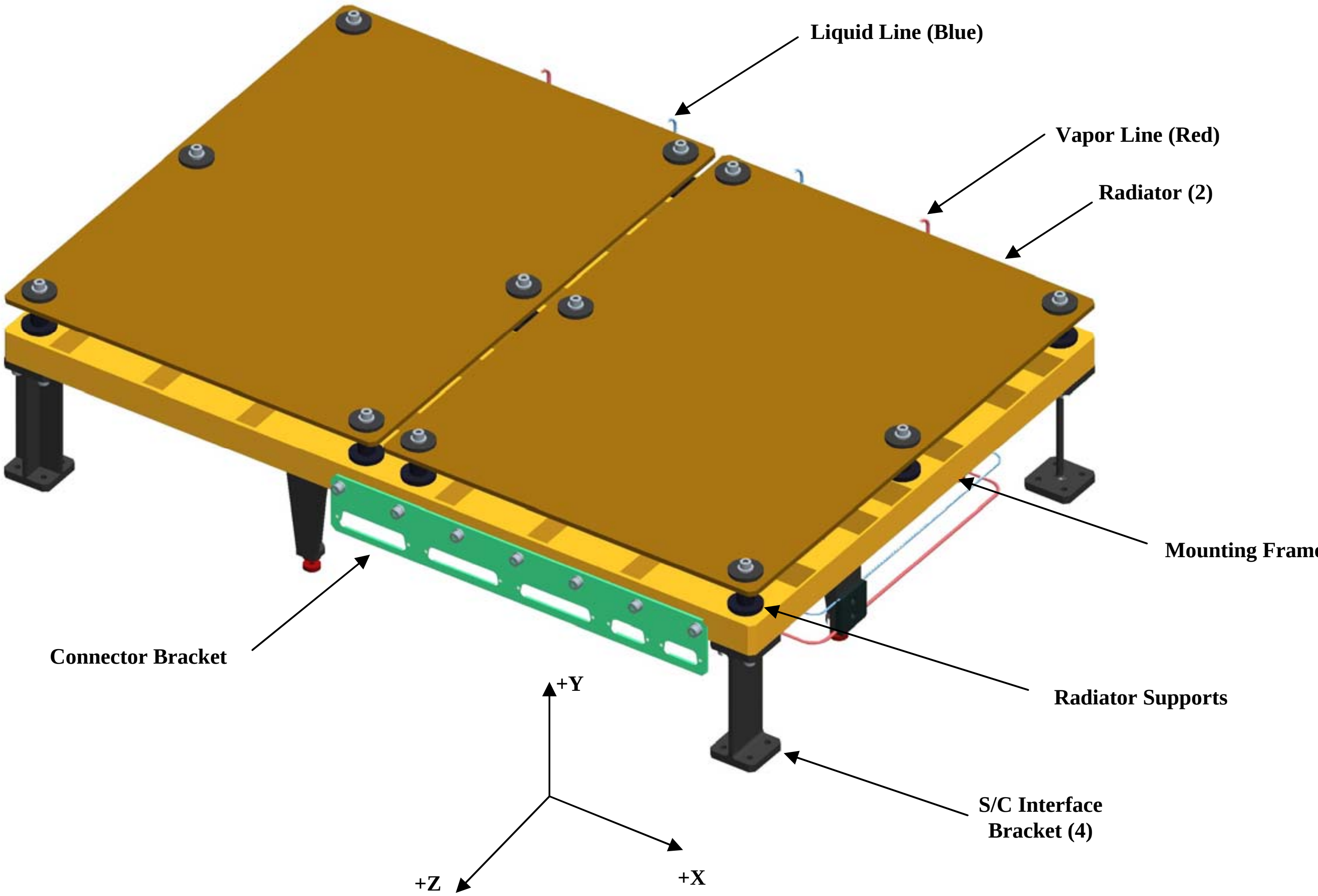
- **TECs reduced control heater power by more than 60% compared to electrical heaters.**
- Coupling blocks were also effective in reducing the control heater power.
- Combination of coupling blocks and TECs yielded significant power savings.
- Ambient tests under various sink temperatures and 0, 2, 3, 4 blocks showed similar power savings.



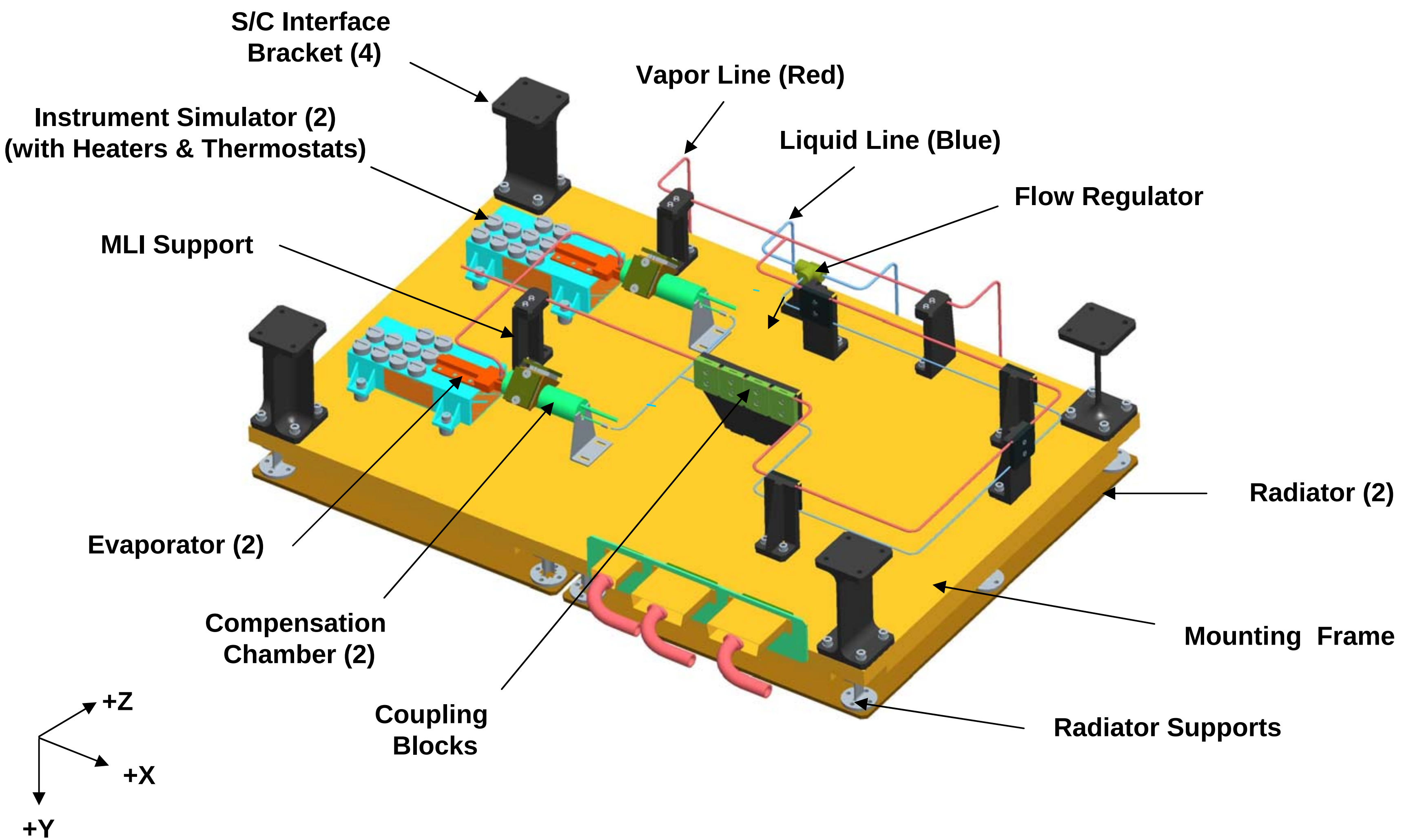
Thermal Loop Experiment Key Dates

✓ TRB Briefing #1	May 6, 2005
✓ E-SRR	June 17, 2005
✓ TRB Briefing #2	August 9, 2005
✓ E-Delta SRR	August 24, 2005
✓ ST8 PMSR	Jan 10-12, 2006
✓ TRB Briefing #3	May 9, 2006
✓ E-PDR	May 25, 2006
✓ ST8 PDR	July 25-27, 2006
• ST8 Confirmation Review	Sept 19, 2006
• E-CDR	Feb 7, 2007
• ST8 CDR	June 12-13, 2007
• E-PER	Aug tbd, 2007
• E-PSR	April tbd, 2008
• TL Experiment Delivery	May 16, 2008
• ST8 Launch Readiness	Feb 28, 2009

Thermal Loop Experiment: MLHP Module for TRL 7 Validation
(Top View)



Thermal Loop Experiment: MLHP Module for TRL 7 Validation
(view from S/C)



Summary and Conclusion

- Thermal Loop experiment will validate in space a miniature loop heat pipe technology with the following capabilities:
  - Turn-key start-up without lengthy pre-conditioning
  - Fine temperature control at any temperature between 273K and 308K
  - Control temperature can be varied while operating
  - Thermal bus for multiple instruments or heat dissipating locations
    - Any power distribution between two heat sources up to the maximum total load, including negative loads (heat load sharing) for one load.
  - 100W+ heat transport limit
  - Heat dissipation to radiators exposed to different thermal environments.
    - Will continue to operate as long as one radiator can dissipate entire load, even if other radiator has a net heat gain.
  - An analytical model capable of predicting steady state and transient behaviors of LHPs
- Comprehensive ground and flight tests to verify zero-G and one-G performance, and to validate analytical model capabilities and scalability.
- The Thermal Loop has attained TRL 5. Development of protoflight unit for TRL 7 validation is under way.