TFAWS Passive Thermal Paper Session

Thermal Design and Qualification Testing of the Ka-Band Radar Interferometer (KaRIn) Instrument Thermal Pallets

Louis A. Tse , Ruwan P. Somawardhana
Jet Propulsion Laboratory/California Institute of Technology, Pasadena, CA, 91109

Presented By
Louis A. Tse

Thermal & Fluids Analysis Workshop
TFAWS 2019
August 26-30, 2019
NASA Langley Research Center
Hampton, VA

Outline

- Background
- KaRIn Instrument Thermal Design
- Thermal Test Objectives
- Results
- Lessons Learned
- Conclusion

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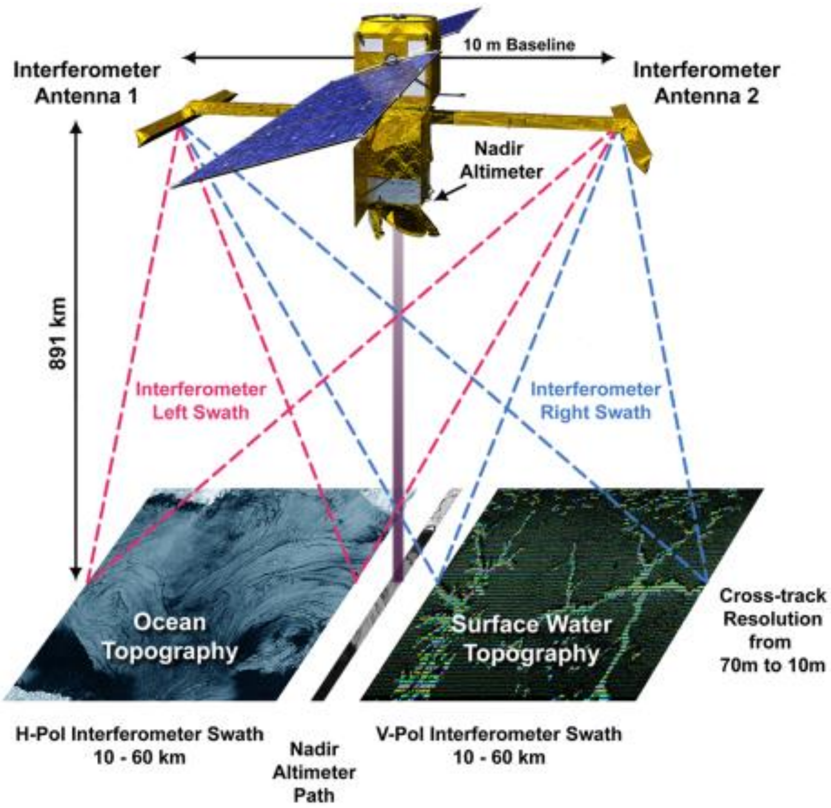
Background

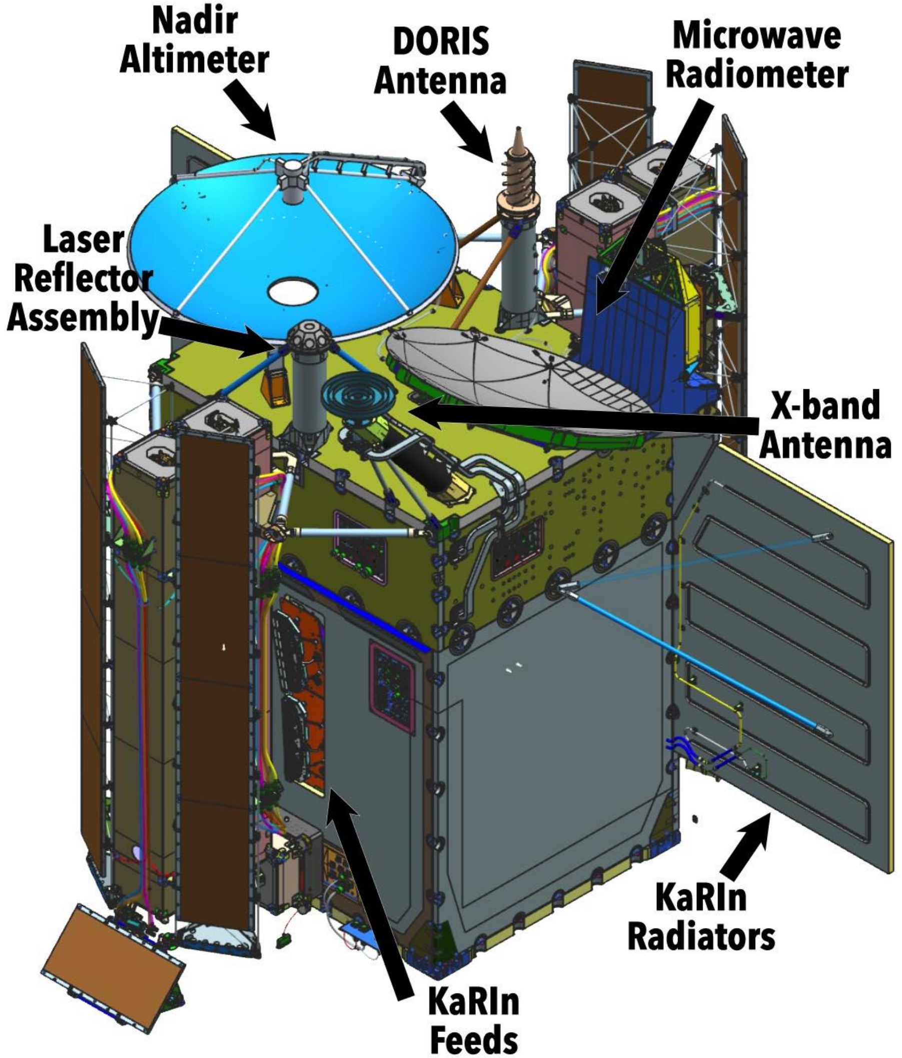
- SWOT will make first-ever global survey of Earth’s surface water
- Will survey at least 90% of the globe, studying Earth's lakes, rivers, reservoirs and oceans
- Aims to improve ocean circulation and climate models, and aid in global freshwater management
- Additional instruments:
  - Conventional Jason-class altimeter for nadir
  - AMR-class radiometer for wet-tropospheric delay corrections



[1] H. Fang, et al., “Thermal Deformation and RF Performance Analyses for the SWOT Large Deployable Ka-Band Reflectarray,” in *51st AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference 18th AIAA/ASME/AHS Adaptive Structures Conference 12th*, 2010, p. 2502

SWOT Payload

- **KaRIn**
  - Using JPL-developed instrument technology, radar interferometry, KaRIn will measure ocean and surface water levels over a 120-km (75-mi) wide swath with a ~20 km (~12 mi) gap along nadir
- Jason-class Altimeter
- DORIS Antenna
- Advanced Microwave Radiometer (AMR)
- X-band Antenna
- Laser Reflector Assembly
- Global Positioning System (GPS) Receiver



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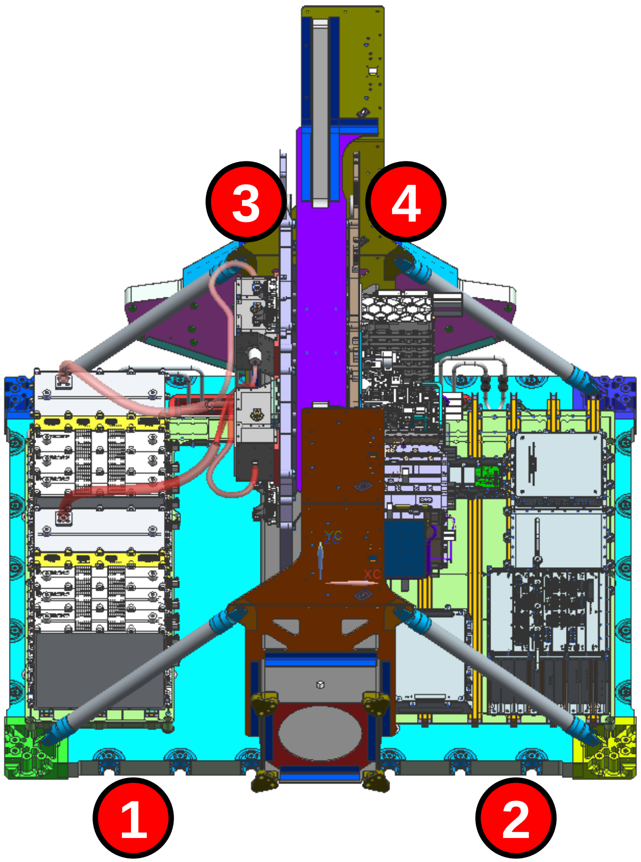
KaRIn Thermal Pallet Design

Design needs

- Acute space constraints
- High electronics dissipative heat (greater than 1,000 W)
- Limited survival power

Thermal design

- Four zones, each utilizing a thermal pallet with embedded constant conductance heat pipes (CCHPs) and one loop heat pipe (LHP) with variable conductance

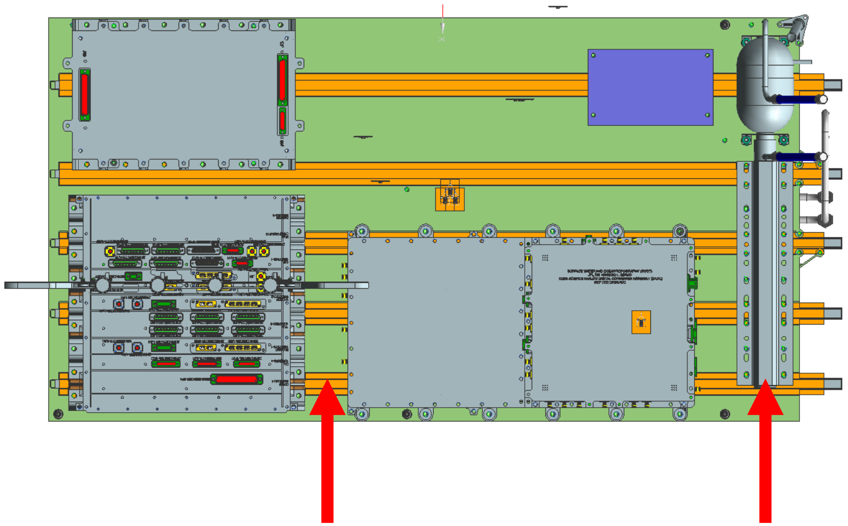


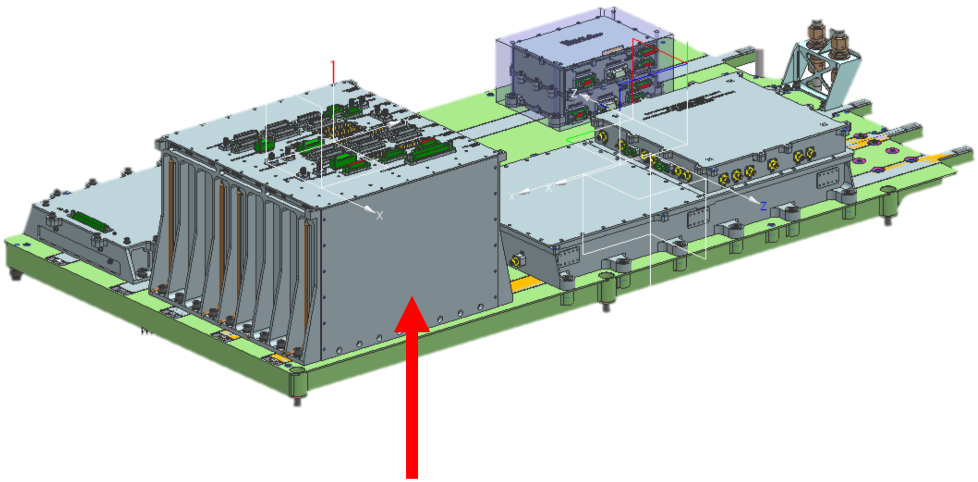
Challenges

- Depending on LHP boundary conditions, high and low frequency oscillations have been reported
- Related to heat source fluctuations, improper radiator sizing, and varying heat sink temperatures[2]

[2] Somawardhana, Ruwan. "Thermal Stability Testing of Two-Phase Thermal Control Hardware for the Surface Water Ocean Topography Mission." 46th International Conference on Environmental Systems, 2016.

KaRIn Thermal Pallet Diagram



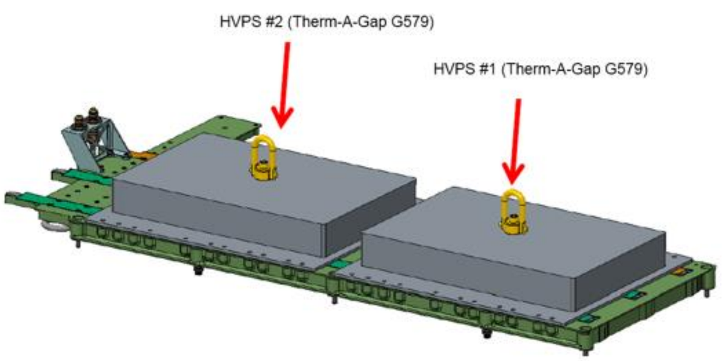


- Aluminum-ammonia constant-conductance heat pipes
- Bonded into pallet with 0.2 mil thick Nusil CV-2946

- Loop heat pipe evaporator (to radiator)
- Grafoil HT-1220 interface material

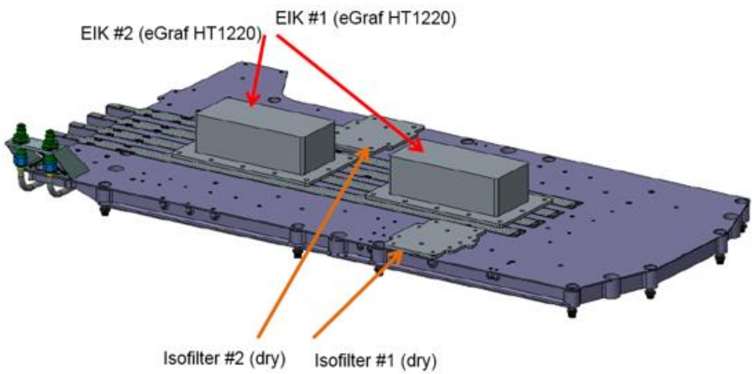
- Electronics boxes
- Varying interface materials (bare metal contact, Therm-A-Gap G579, Grafoil HT-1220)

Electronics Power



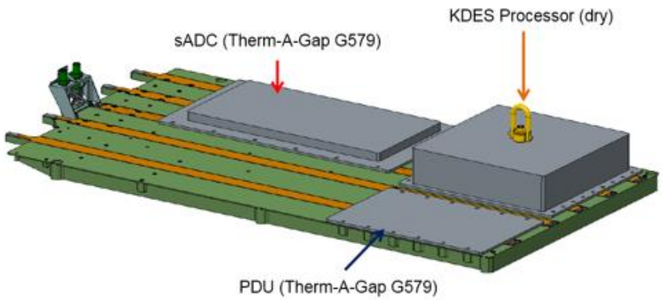
143.8 W

HVPS Pallet



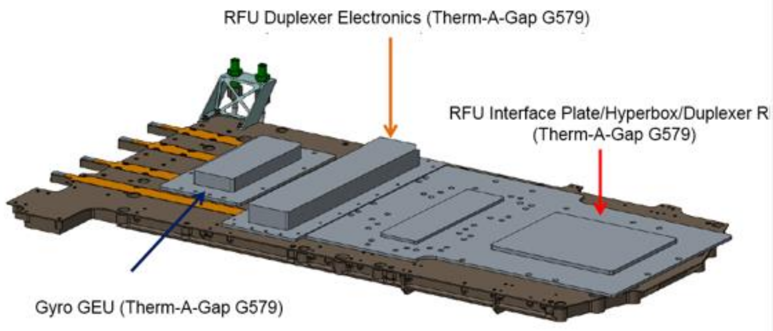
302.0 W

EIK Pallet



245.0 W

KDES Pallet



282.5 W

RFU Pallet

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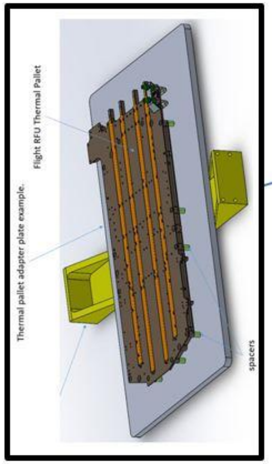
Thermal Test Objectives

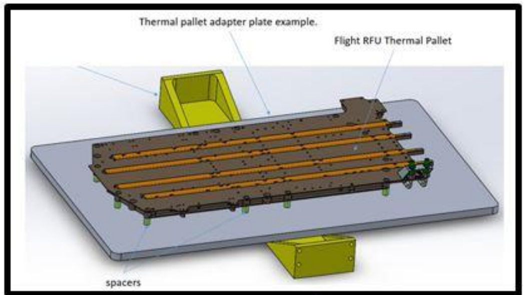
1. **Validate thermal design by direct empirical testing**
   - Can this hardware be used for flight? Verify it meets allowable flight temperature (AFT) limits
2. **Assess operational impacts in Vertical orientation**
   - Utilize CCHP start-up behavior to inform payload-level test campaign
3. **Thermal characterization of Thermal Pallet under various conditions**
   - Use test data to correlate on-orbit model of the Thermal Pallets, for Hot vs. Cold conditions, prime vs. redundant electronics powered on, Horizontal vs. Vertical orientation

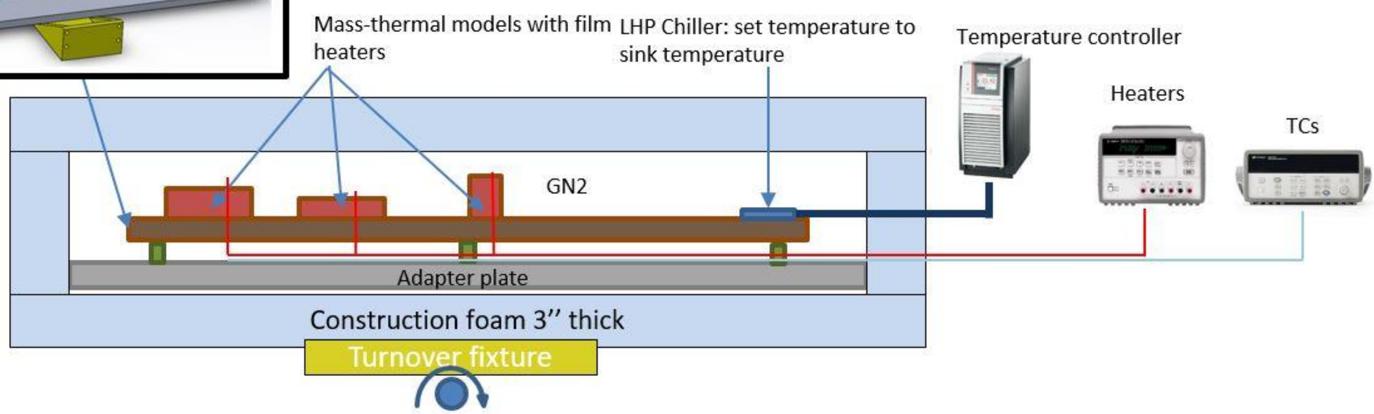
Thermal Test Setup Diagram

Vertical



Horizontal

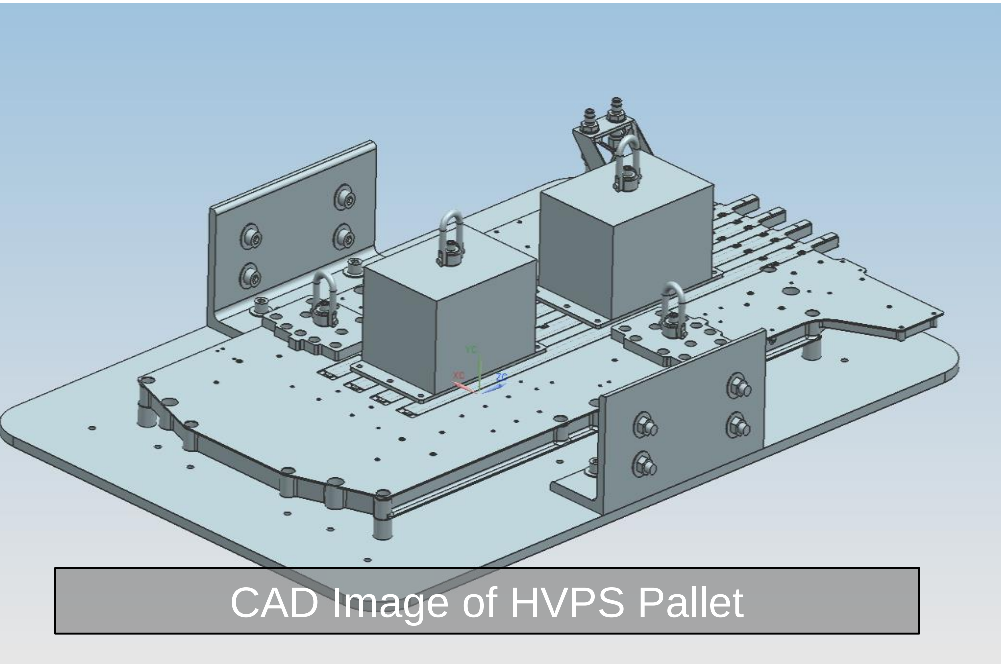




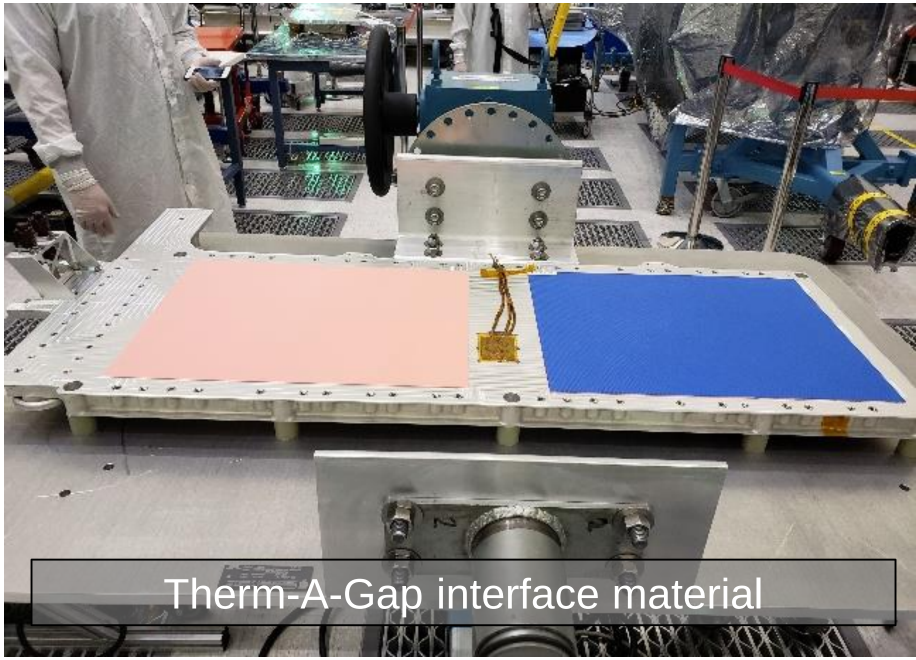
Test Setup

- Thermal Pallet installed on rotating turnover fixture, to test orientation
- Mass-thermal models (MTMs) with flight interface material and film heaters simulate electronics dissipation and thermal mass, for steady-state and transient data
- Temperature controller with Novec 7500 fluid used to establish boundary condition
- Assembly is encapsulated with 3'' thick construction foam to minimize environmental heat loss

Thermal Pallet Test Integration



CAD Image of HVPS Pallet

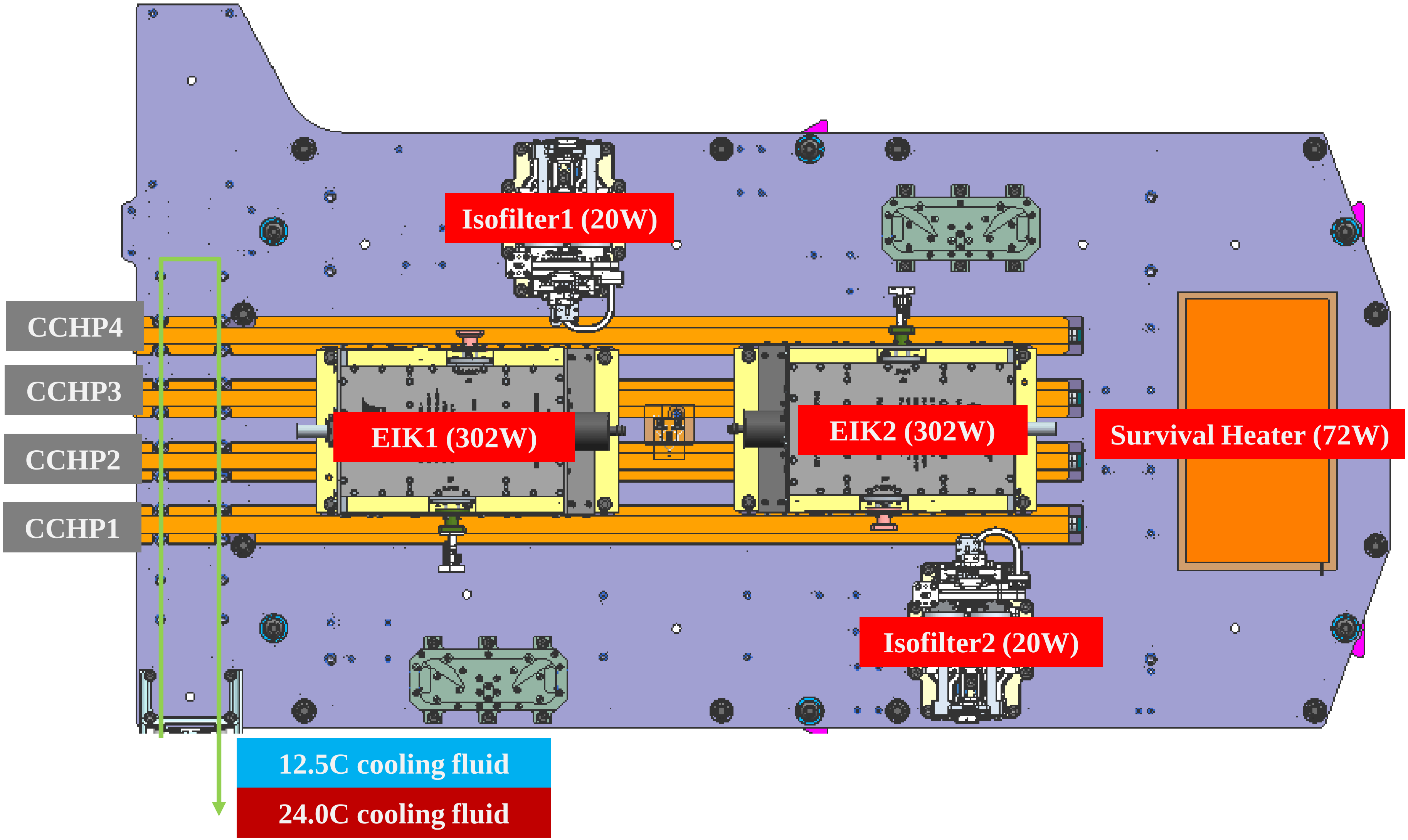


Therm-A-Gap interface material

HVPS Pallet with MTMs installed

Construction foam box, with top removed

Electron Interaction Klystron (EIK) Thermal Pallet Diagram



Test Matrix (EIK Pallet)

Case No.	Orientation	Sink Temp	Power (W)	Heater Order	CCHP Start
1a	Horizontal	Hot	302	1. MTM2	CCHP1, CCHP2, CCHP3, CCHP4
1b	Horizontal	Cold	302	1. MTM2	CCHP1, CCHP2, CCHP3, CCHP4
2a	Horizontal	Cold	302	1. MTM2	CCHP1, CCHP2, CCHP3, CCHP4
2b	Horizontal	Hot	302	1. MTM2	CCHP1, CCHP2, CCHP3, CCHP4
3a	Horizontal	Hot	302	1. MTM1	CCHP1, CCHP2, CCHP3, CCHP4
3b	Horizontal	Cold	302	1. MTM1	CCHP1, CCHP2, CCHP3, CCHP4
4a	Vertical	Cold	302	1. MTM1	CCHP1, CCHP2, CCHP3, CCHP4
4b	Vertical	Cold	374	1. MTM1, 2. Surv.	CCHP1, CCHP2, CCHP3, CCHP4
5a	Vertical	Hot	302	1. MTM1	CCHP1, CCHP2, CCHP3, CCHP4
5b	Vertical	Hot	374	1. MTM1, 2. Surv.	CCHP1, CCHP2, CCHP3, CCHP4
6a	Vertical	Cold	72	1. Surv.	CCHP1, CCHP2, CCHP3, CCHP4
6b	Vertical	Cold	374	1. Surv., 2. MTM2	CCHP1, CCHP2, CCHP3, CCHP4
7a	Vertical	Cold	302	1. MTM2	CCHP1, CCHP2, CCHP3, CCHP4
7b	Vertical	Cold	374	1. MTM2, 2. Surv.	CCHP1, CCHP2, CCHP3, CCHP4
7c	Vertical	Cold	410	1. MTM2, 2. Surv., 3. Start-up	CCHP1, CCHP2, CCHP3, CCHP4
8a	Vertical	Cold	72	1. Surv.	CCHP1, CCHP2, CCHP3, CCHP4
8b	Vertical	Cold	108	1. Surv., 2. Start-up	CCHP1, CCHP2, CCHP3, CCHP4
8c	Vertical	Cold	410	1. Surv., 2. Start-up, 3. MTM1	CCHP1, CCHP2, CCHP3, CCHP4
9a	Vertical	Cold	72	1. Surv.	CCHP1, CCHP2, CCHP3, CCHP4
9b	Vertical	Cold	108	1. Surv., 2. Start-up Film	CCHP1, CCHP2, CCHP3, CCHP4
9c	Vertical	Cold	410	1. Surv., 2. Start-up, 3. MTM1	CCHP1, CCHP2, CCHP3, CCHP4

Test results from three cases, with varying outcomes, will be presented.

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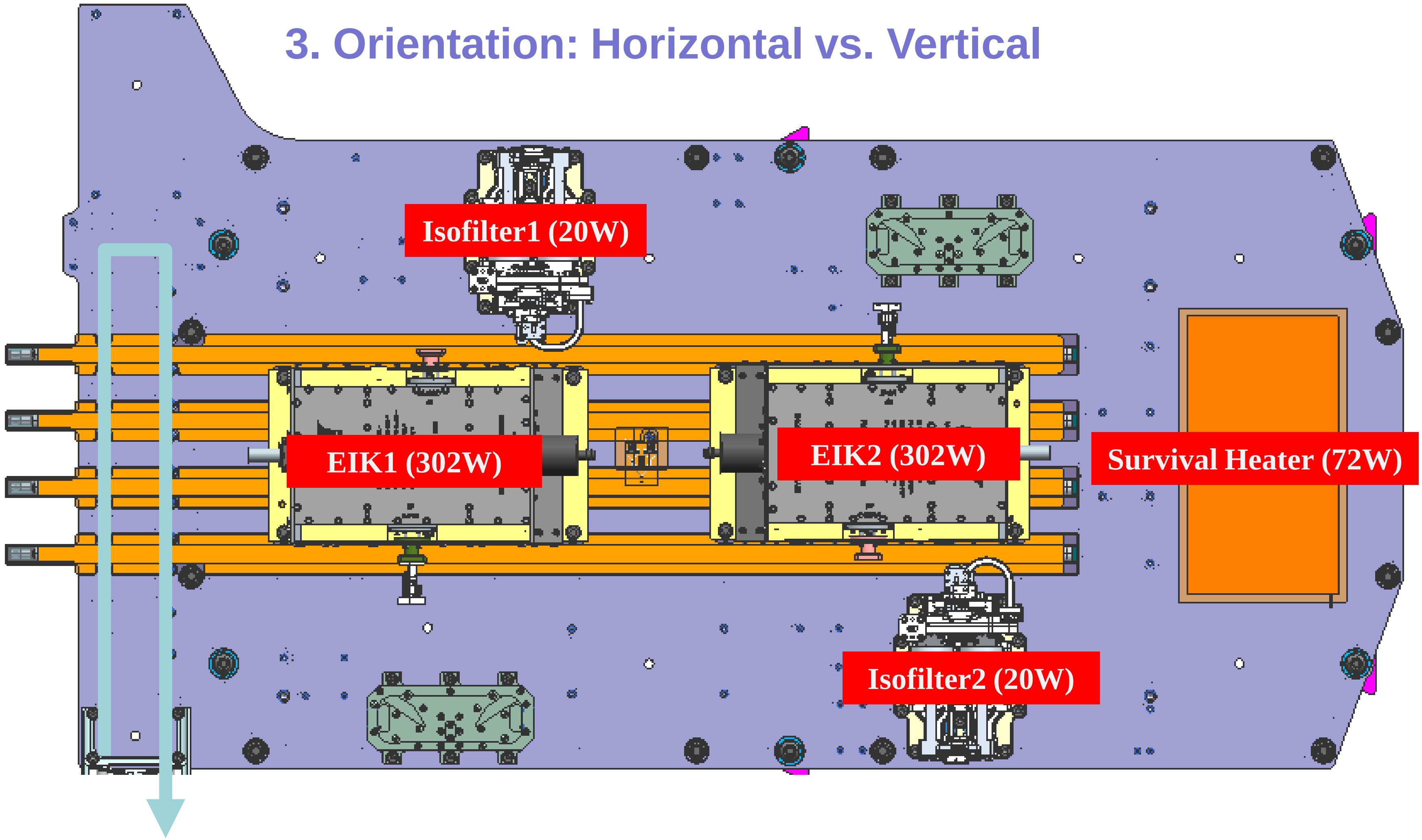
Selected Parametric Studies

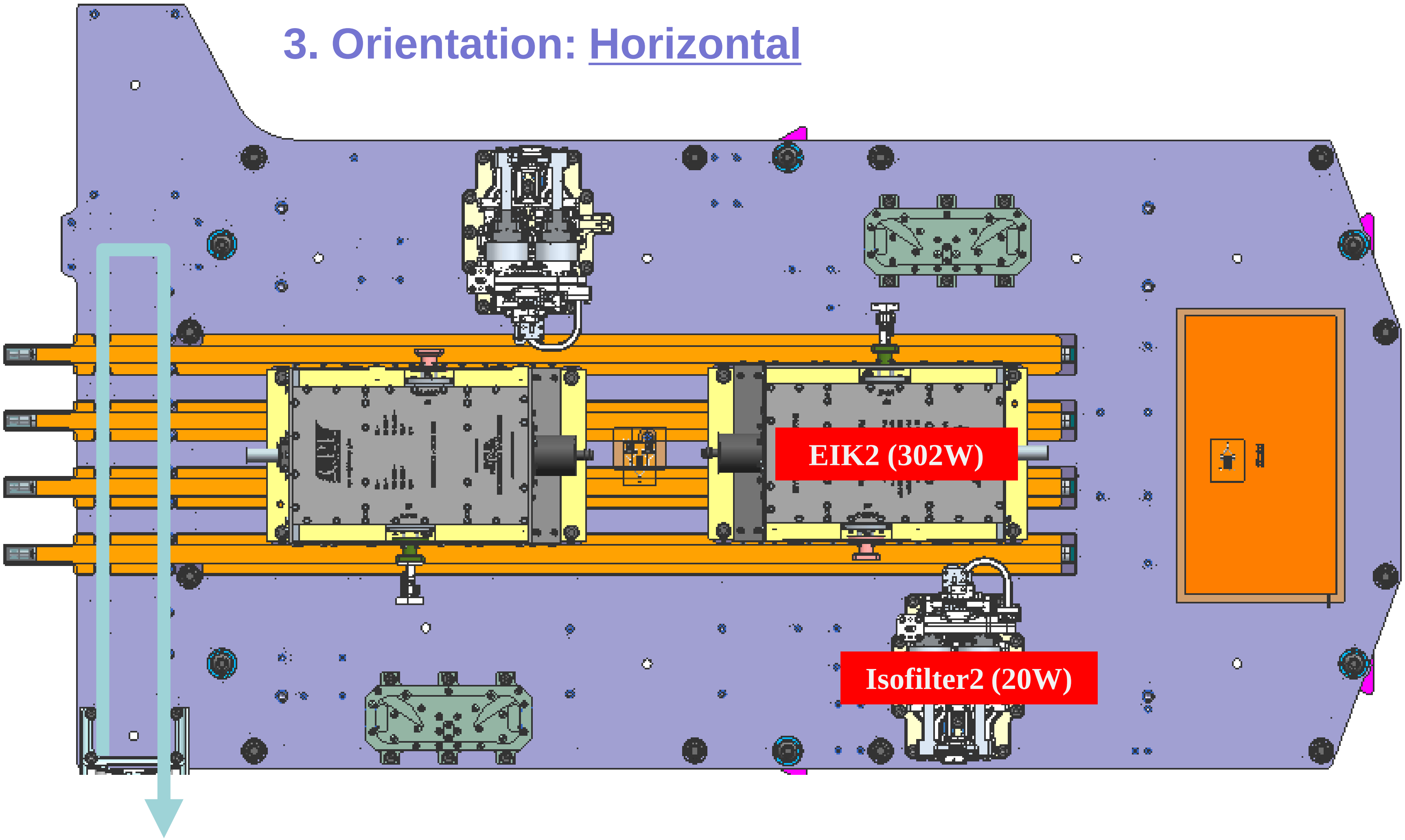


1. Sink Temperature: Hot vs. Cold

2. Power Mode: Prime (1) vs. Redundant (2) Chain

Case 1: Horizontal, Hot/Cold, MTM2

3. Orientation: Horizontal



1. Sink Temperature: Hot, then Cold

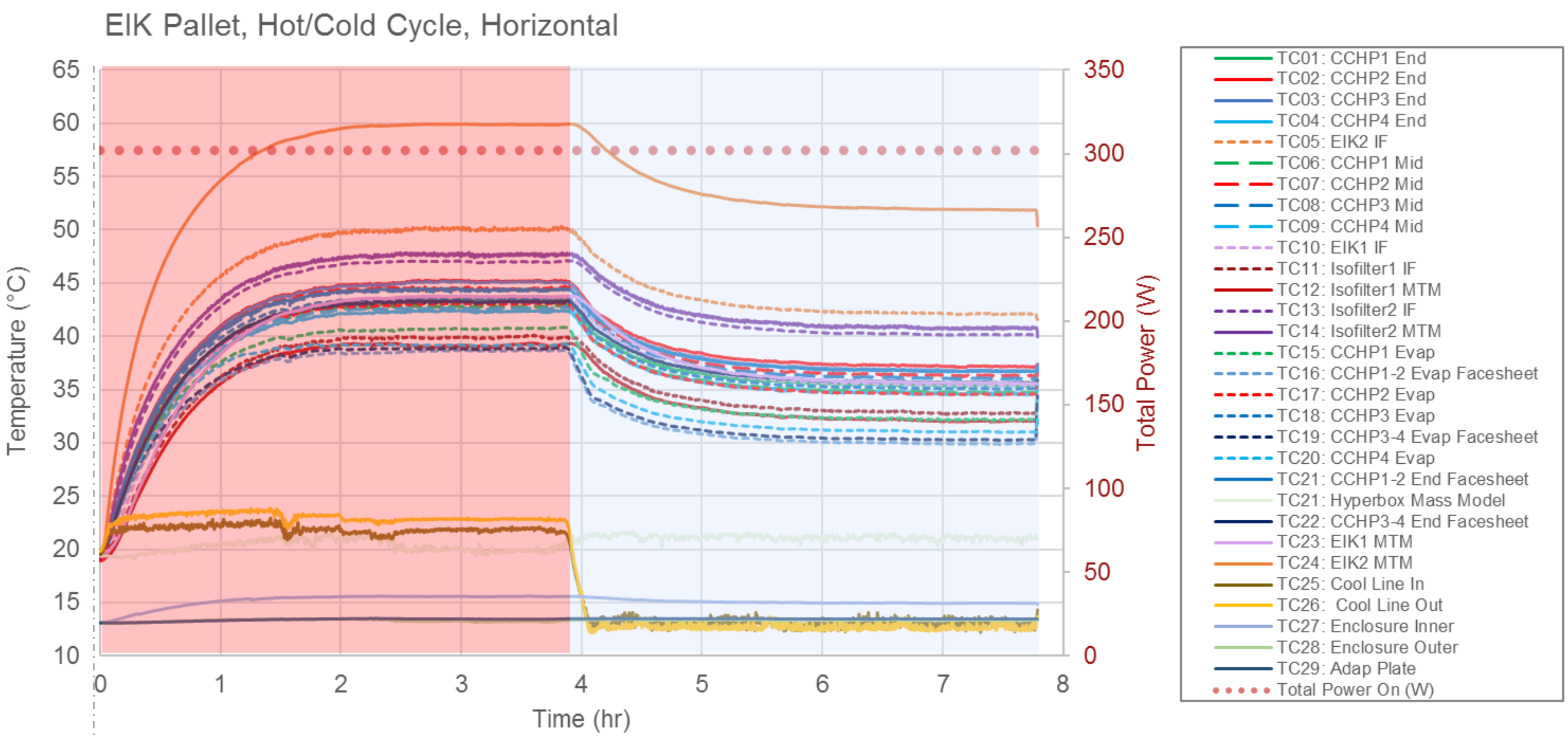
2. Power Mode: Redundant (2) Chain

Case 1 Summary: Horizontal, Hot/Cold, MTM2

Test Summary

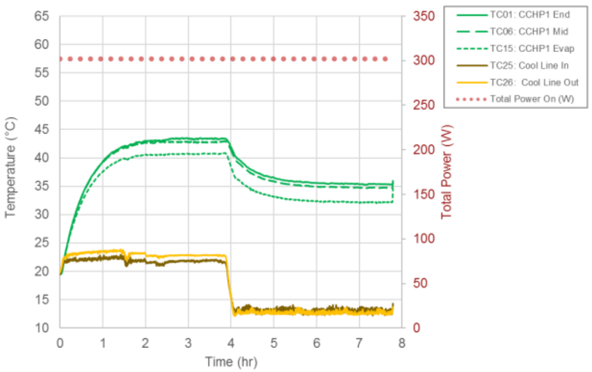
- **Objective:** for Horizontal Hot/Cold case, will CCHPs start solely with MTM power? Will sudden change in sink temperature cause CCHPs thermal instability?
  - Answer: Yes.
- **Findings:**
  - CCHPs start with solely MTM power
  - CCHPs are not affected by sudden change in sink temperature

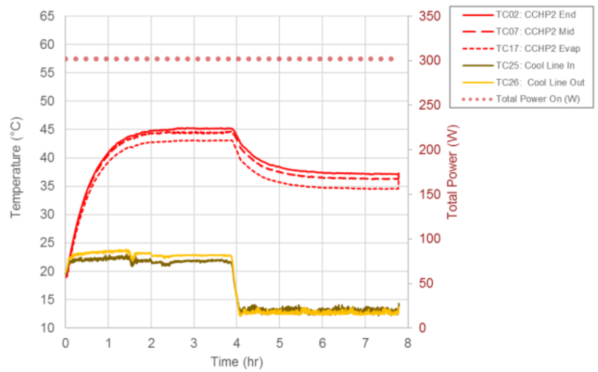
Case 1: All Temperatures

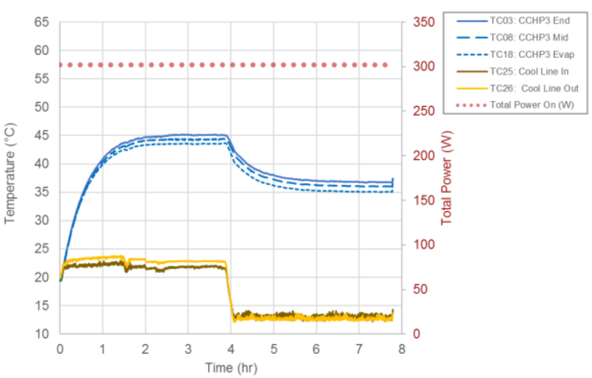


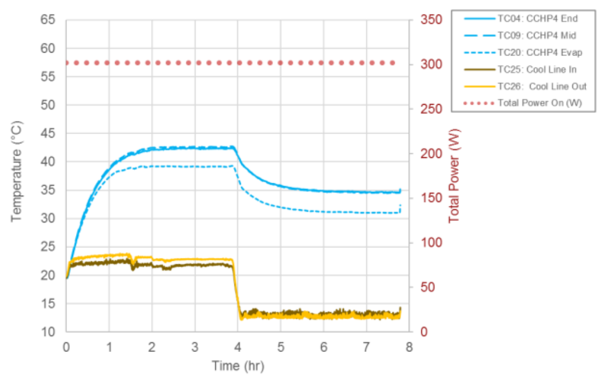
MTMs turned on (302W)

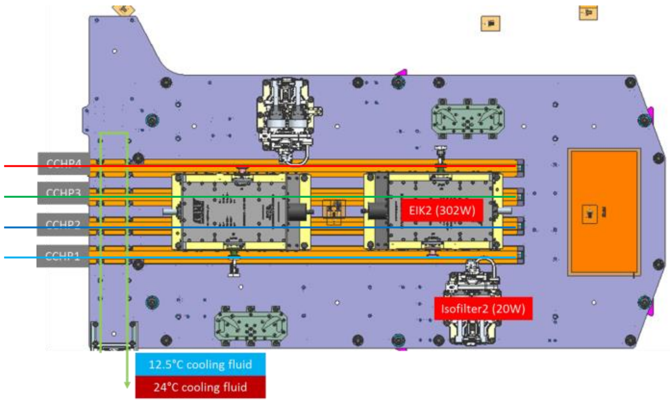
Case 1 Plots: CCHPs









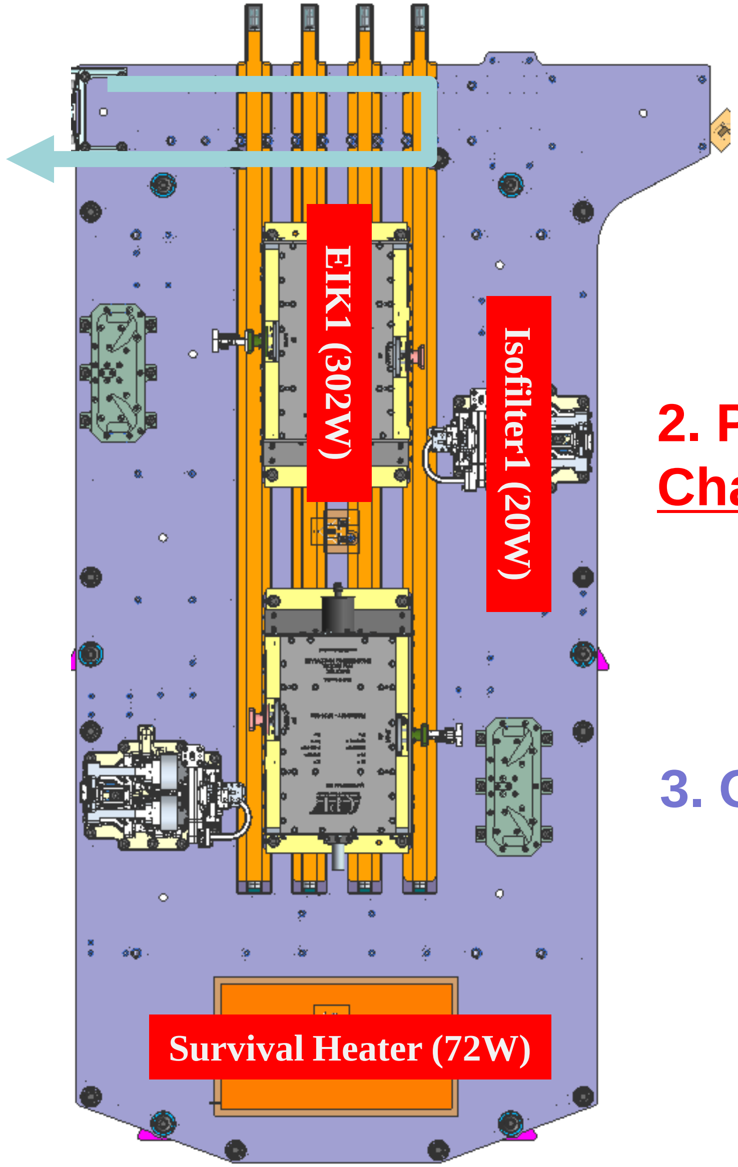


Note: all CCHPs started

	Hot Cycle				Cold Cycle			
CCHP SS Temperature	End	Mid	Evap	ΔT	End	Mid	Evap	ΔT
CCHP1	43.4	42.8	40.7	2.7	35.4	34.7	32.2	3.2
CCHP2	45.2	44.4	43.1	2.1	37.2	36.3	34.6	2.6
CCHP3	45.1	44.3	43.5	1.6	36.8	36.0	35.1	1.7
CCHP4	42.3	42.6	39.2	3.2	34.7	34.6	31.0	3.6

Case 4: Vertical, Cold, MTM1

1. Sink Temperature: Cold



2. Power Mode: Primary (1) Chain

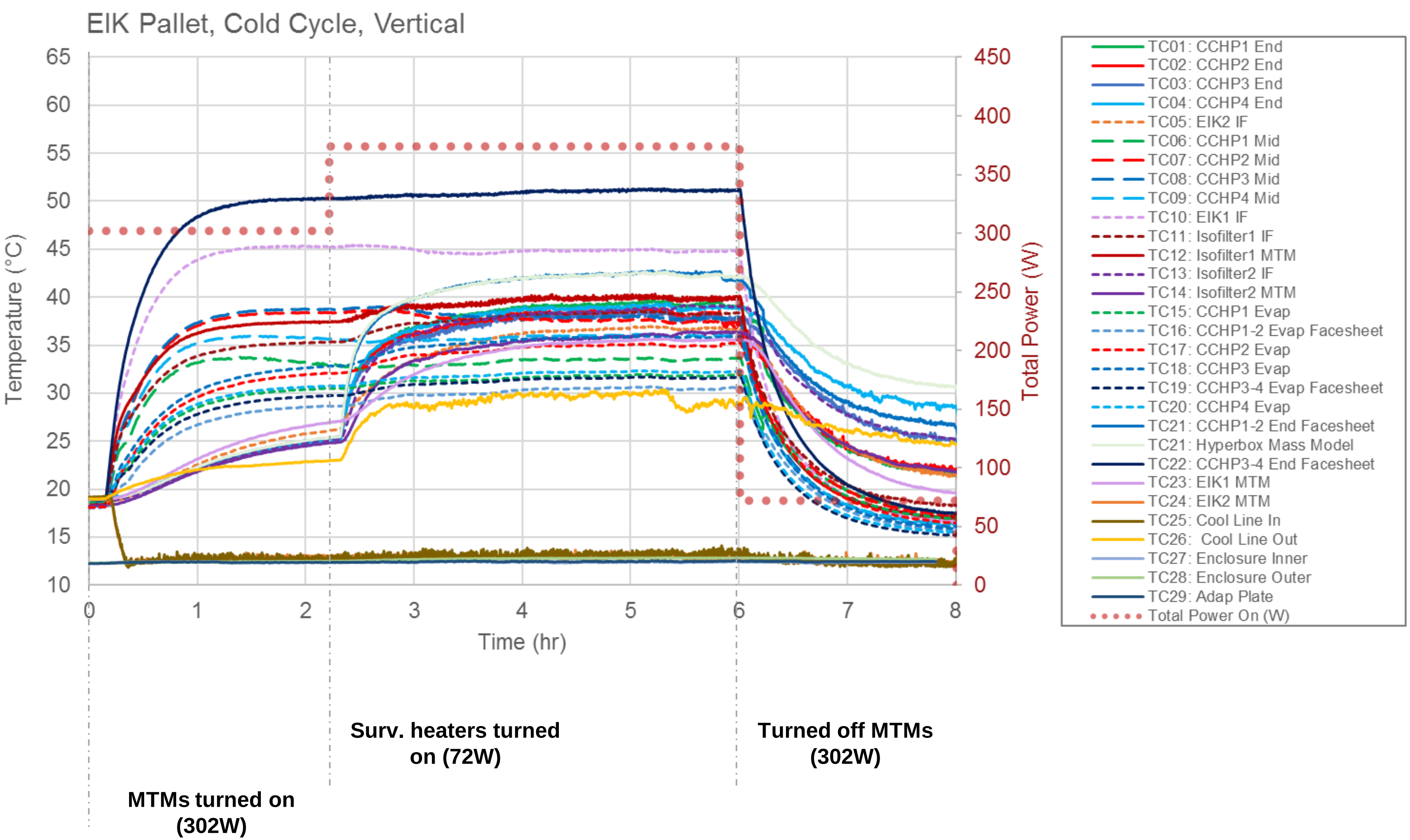
3. Orientation: Vertical

Case 4 Summary: Vertical Cold, MTM1

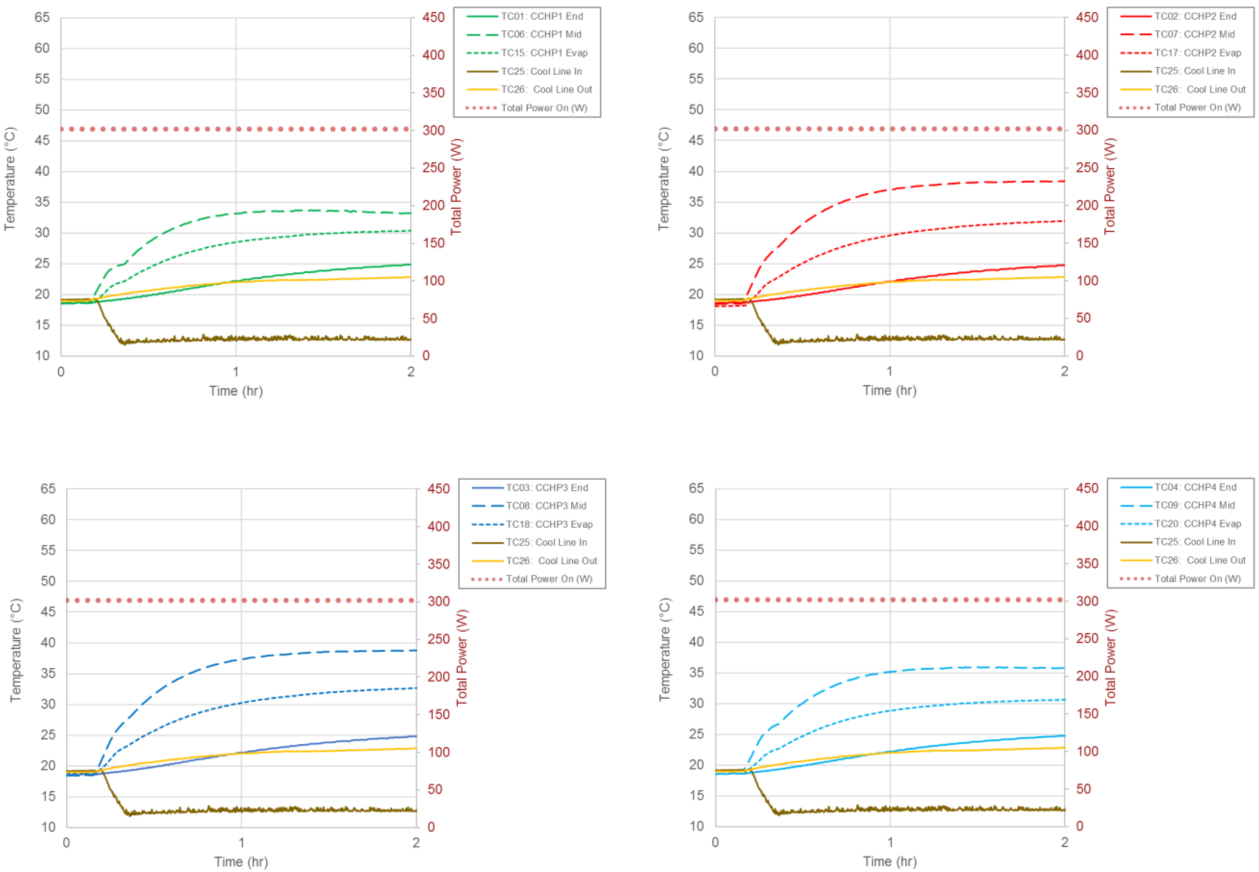
Test Summary

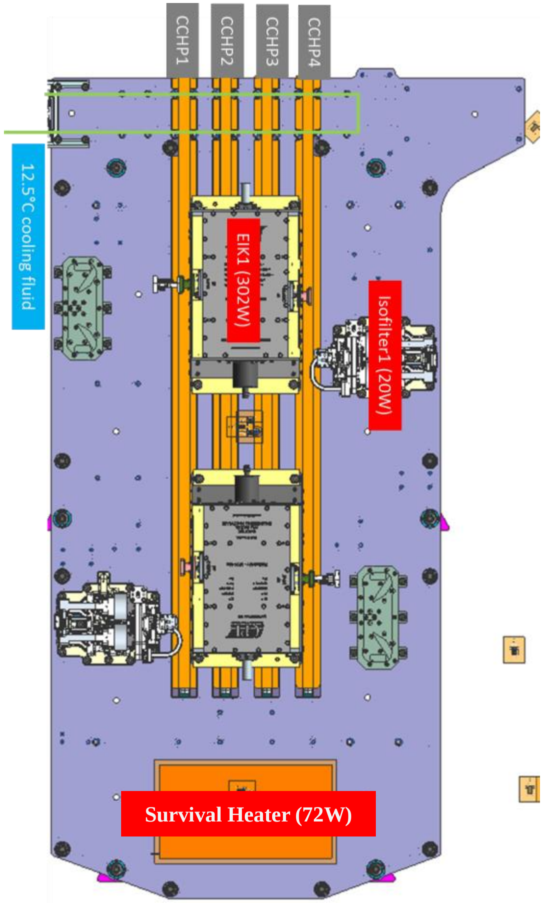
- **Objective:** for Vertical Cold case, will CCHPs start solely with MTM power closest to LHP Evaporator?
  - Answer: No.
- **Findings:**
  - No CCHPs started, even with 1) MTM1 power and 2) survival heater power.

Case 4 Plots: All



Case 4a Plots: CCHPs



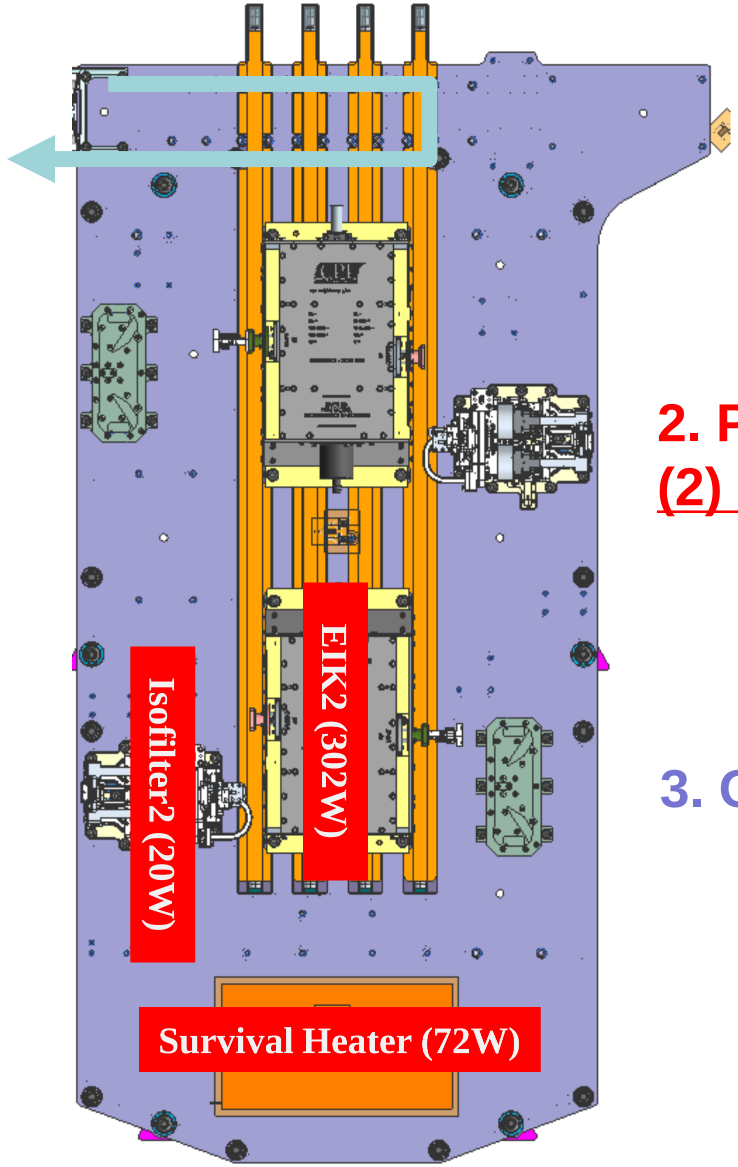


	Cold Cycle			
CCHP SS Temperature	End	Mid	Evap	ΔT
CCHP1	39.3	33.5	31.8	7.5
CCHP2	38.1	37.5	34.9	3.2
CCHP3	37.8	37.8	35.8	2.0
CCHP4	38.9	36.0	32.2	6.7

Note: no CCHPs started

Case 4: Vertical, Cold, MTM2

1. Sink Temperature: Cold



2. Power Mode: Redundant (2) Chain

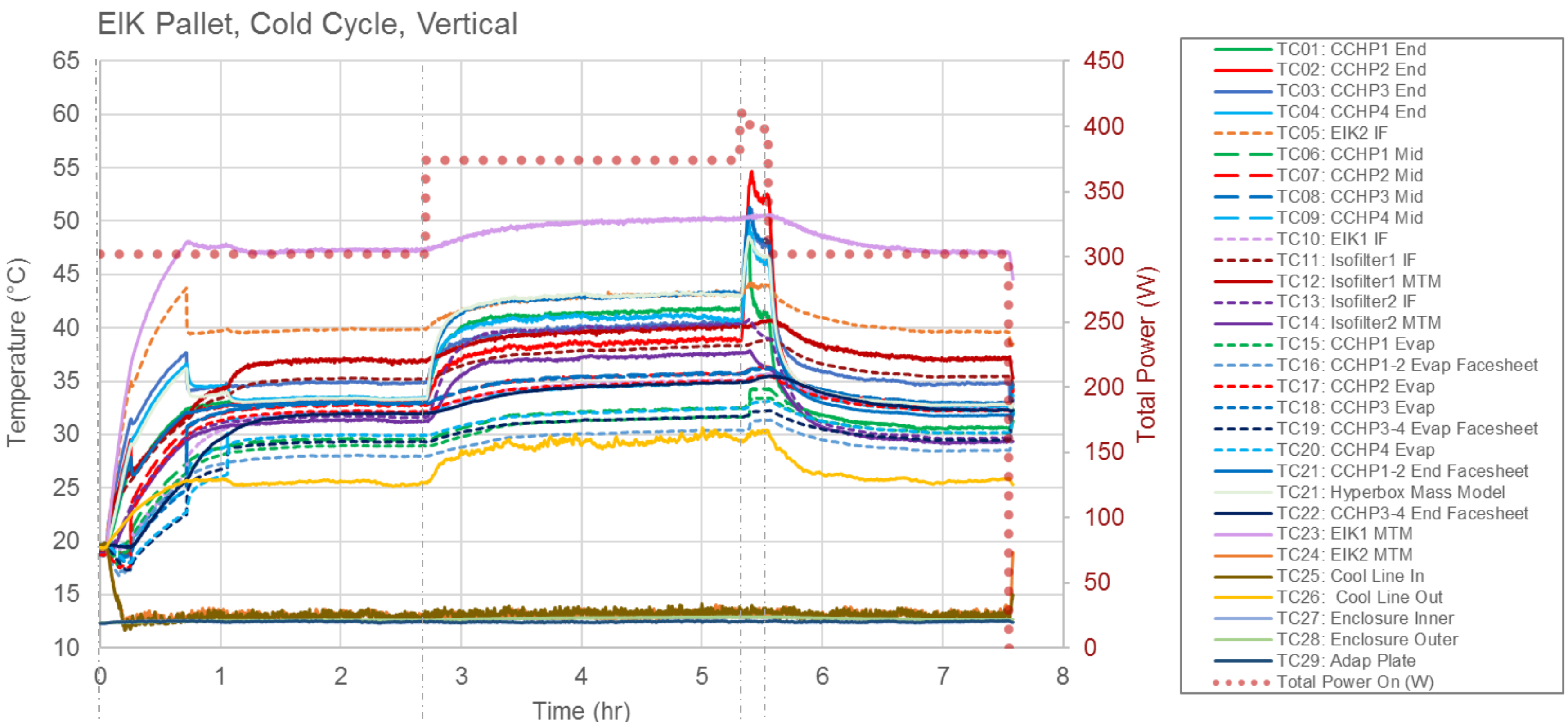
3. Orientation: Vertical

Case 7 Summary: Vertical Cold, MTM2

Test Summary

- **Objective:** for Vertical Cold case, will CCHPs start with solely MTM2 power?
  - Answer: No.
- **Findings:**
  - All CCHPs started with 1) MTM2 power, 2) survival heater power, and 3) start-up heater power.
  - Recommendation: heater order should be 1) survival power, then 2) MTM2 power

Case 7 Plots: All Temperatures



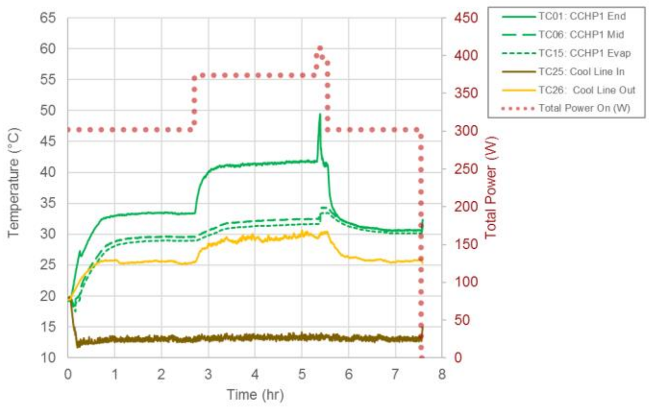
1. MTMs turned on (302W)

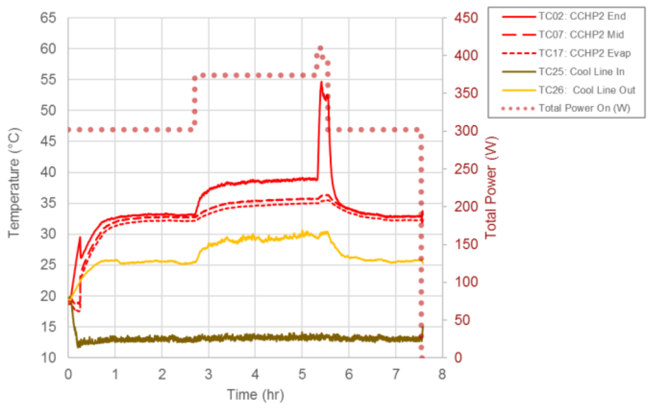
2. Survival heaters turned on (72W)

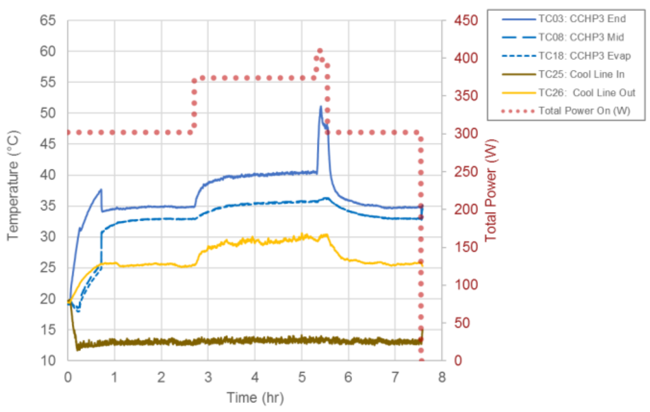
3. Start-up heaters turned on (36W)

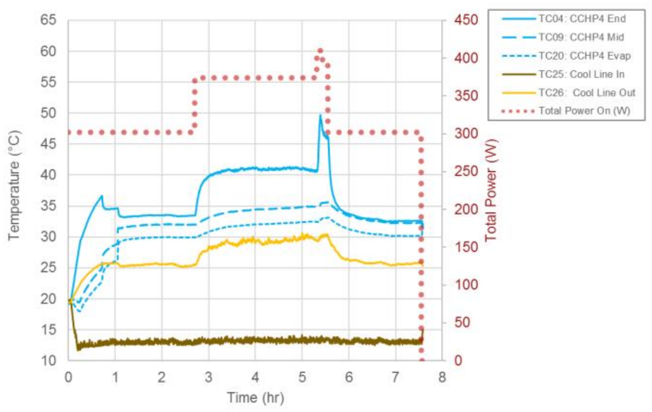
4. Start-up heaters (36W) and survival heaters (72W) turned off

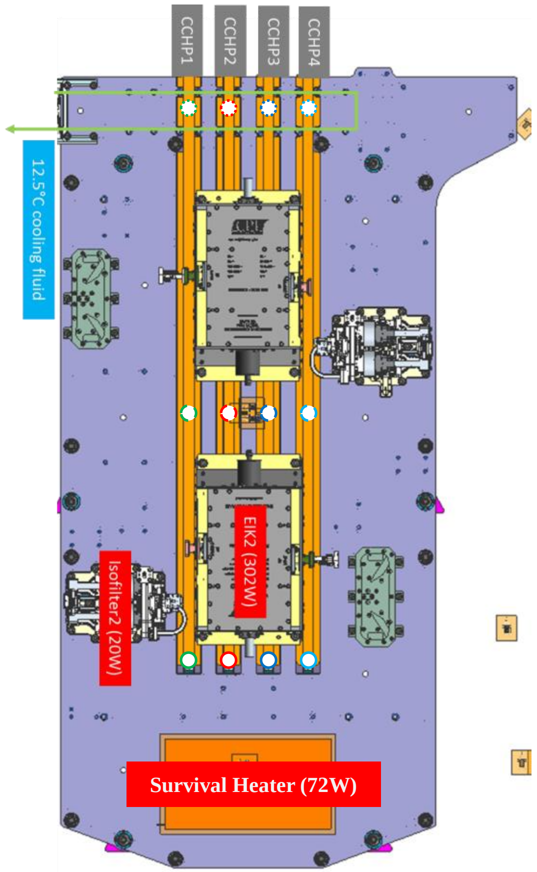
Case 7 Plots: CCHPs











	Cold Cycle			
CCHP SS Temperature	End	Mid	Evap	ΔT
CCHP1	30.6	30.7	30.2	0.5
CCHP2	32.9	32.9	32.3	0.6
CCHP3	34.8	33.0	33.0	1.8
CCHP4	32.6	32.3	30.2	2.4

Note: all CCHPs started

Flight Model Correlation Parameters

Model Correlation

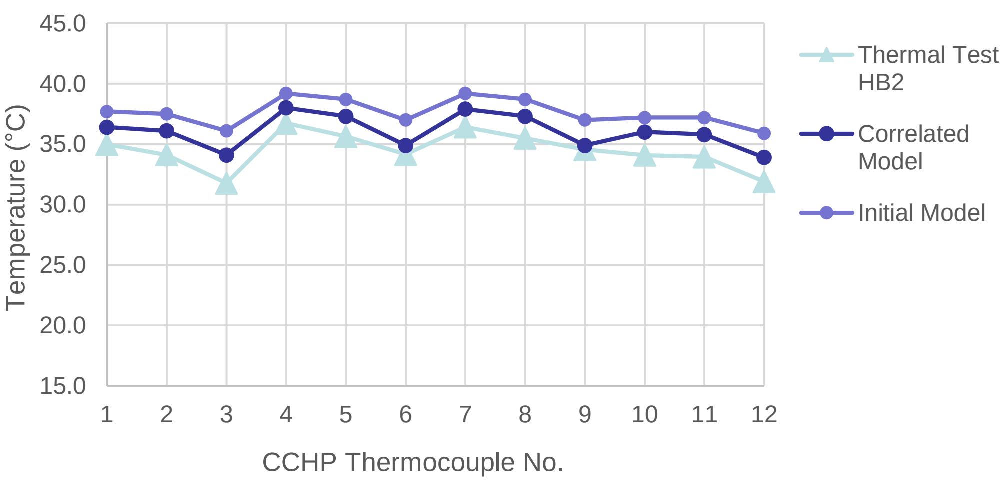
- **Objective:** use empirical and manufacturer data to correlate heat transfer parameters, minimizing root mean square error over all four pallets and 28 total test cases.

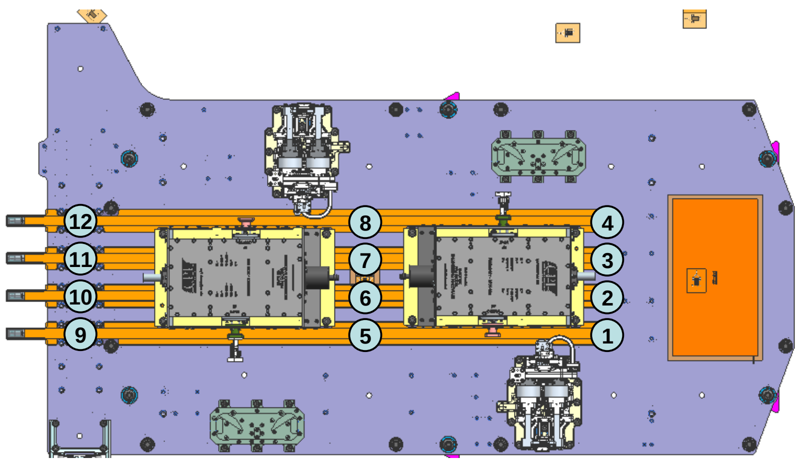
Correlated parameters	Initial Model Value	Correlated Model Value	Notes
CCHP bondline thermal conductivity, k	1.1	1.3	Varied between 0.5 – 2.0 W/m-K to correlate test data. Manufacturer data specifies 1.49 W/mK.
CCHP conductance	2.0	4.0	Varied between 1.0 – 5.0 W/in˚C to match test data. Manufacturer data specifies 2.0 – 3.5 W/in˚C. Prior correlated test values were 4.0 – 6.0 W/in˚C.
Convective heat transfer coefficient with ambient, h	5.0	2.0	Varied between 1.0 – 5.0 W/m^2C as best estimated value for enclosure, from approximate hand calculation.
Ambient temperature	21.0	23.7	Lower and upper bounds as measured in test.
Boundary condition sink temperature	12.5	17.5	Lower and upper bounds as measured in test.

Correlated Values

Results

- **RMS error:** initial model showed RMS error = 11C, final correlated model showed RMS error = 7.5C
  - Correlation to lower RMS achievable, but maintained to keep margin
- **Final values:**
  - CCHP conductance correlated to upper bound of manufacturer reported value range, and bondline conductivity correlated to manufacturer reported value





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Lessons Learned

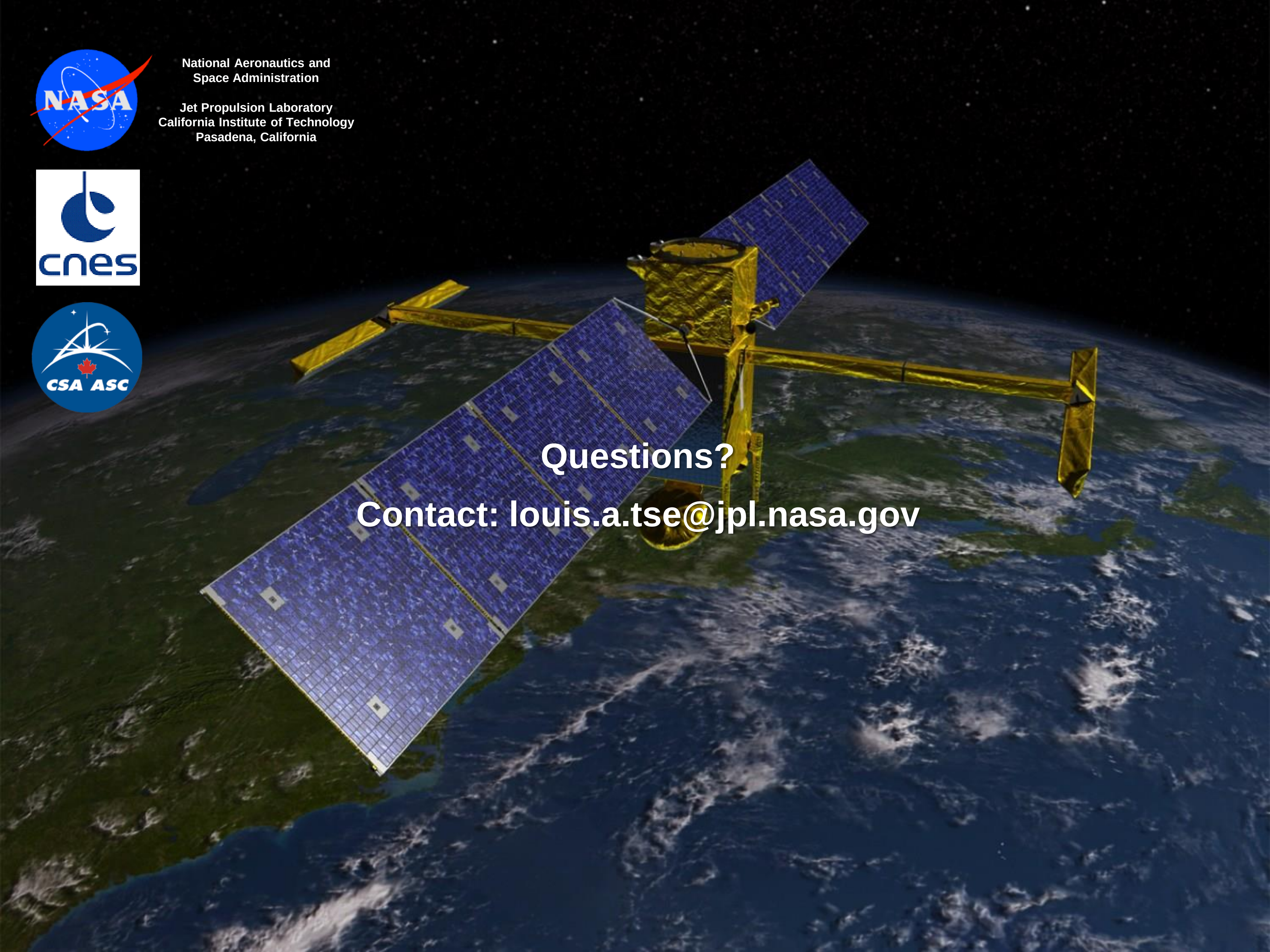
- **Effect of Sink Temperature:** it is more challenging to start CCHPs for lower sink temperature
- **Effect of Orientation:** in the Vertical orientation, there is likelihood that CCHPs are already active, but operating in degraded mode due to parasitic heat leaks
- **Effect of Start-up:** it is advisable to consider interaction effect between CCHPs. When a single CCHP starts, it is typically signified by sharp temperature change axially.
  - However, this often makes it more challenging for subsequent CCHPs to start because heat is then transported through started CCHPs rather than non-started CCHPs (typically signified by a much-less-sharp temperature change axially)

Conclusion

- KaRIn Thermal Pallets were tested under operational flight-like power, and verified AFT requirements can be met
- Operational impacts were determined for CCHP start-up, for the payload-level Thermal Balance test campaign
- Future work:
  - Thermal testing at the next assembly level (entire KaRIn payload) will be conducted to accomplish Thermal Balance and correlate on-orbit model

National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California



Questions?

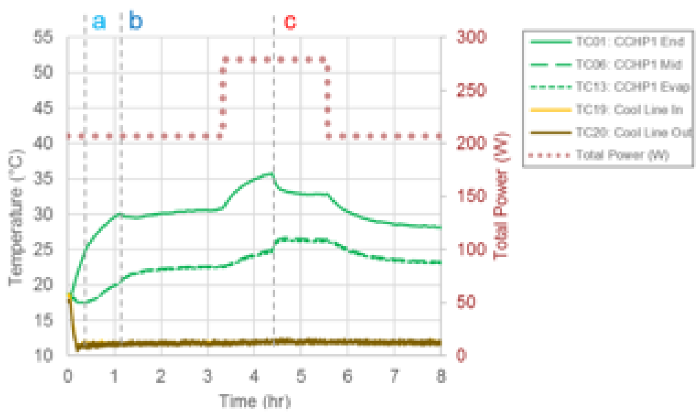
Contact: louis.a.tse@jpl.nasa.gov

Back-up Slides

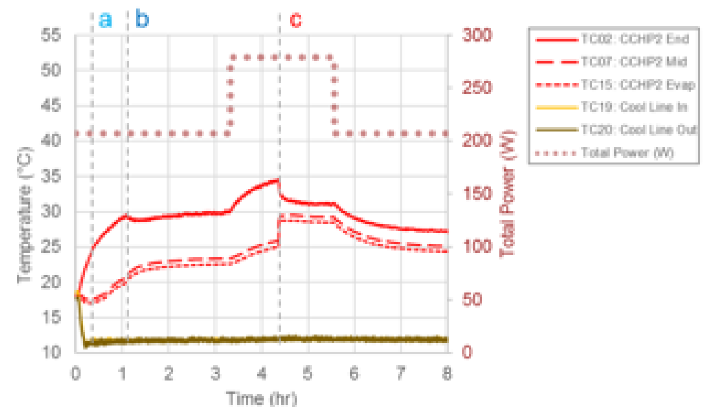
CCHP Interaction

Case 4: Vertical, Cold, MTMs

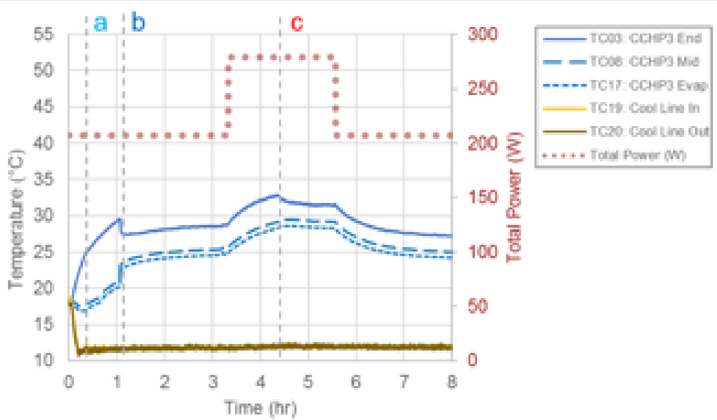
CCHP1



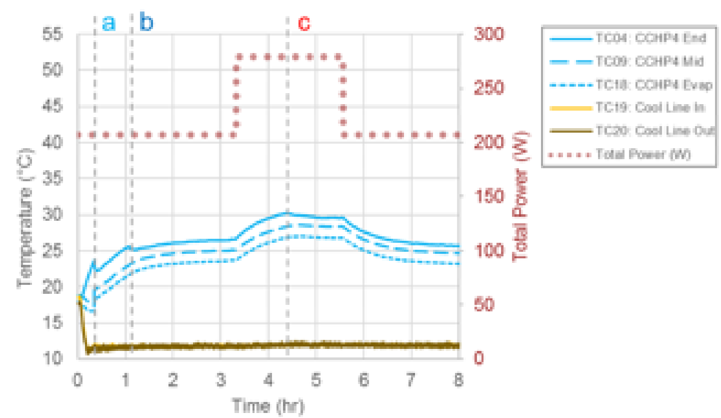
CCHP2



CCHP3

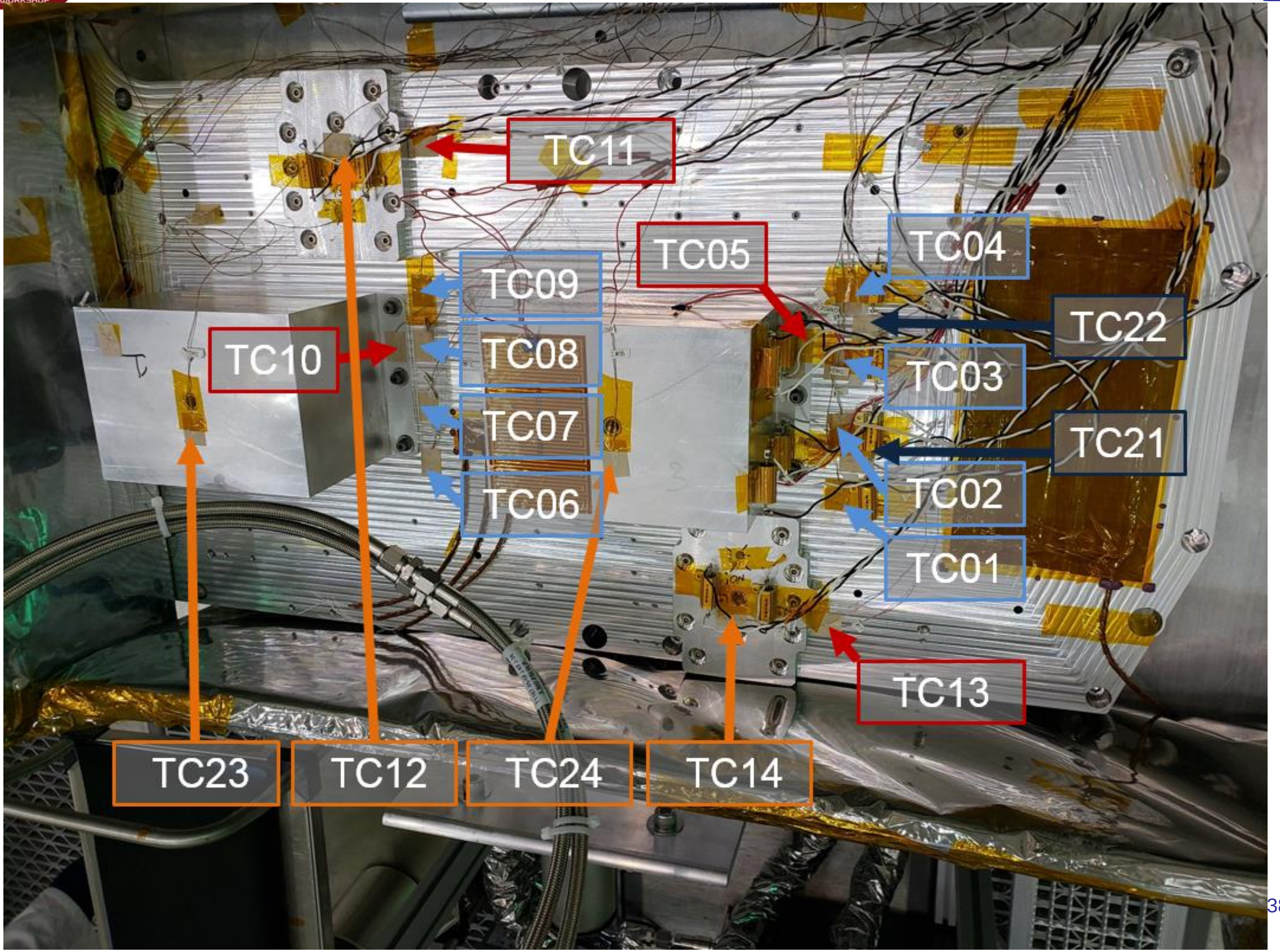


CCHP4

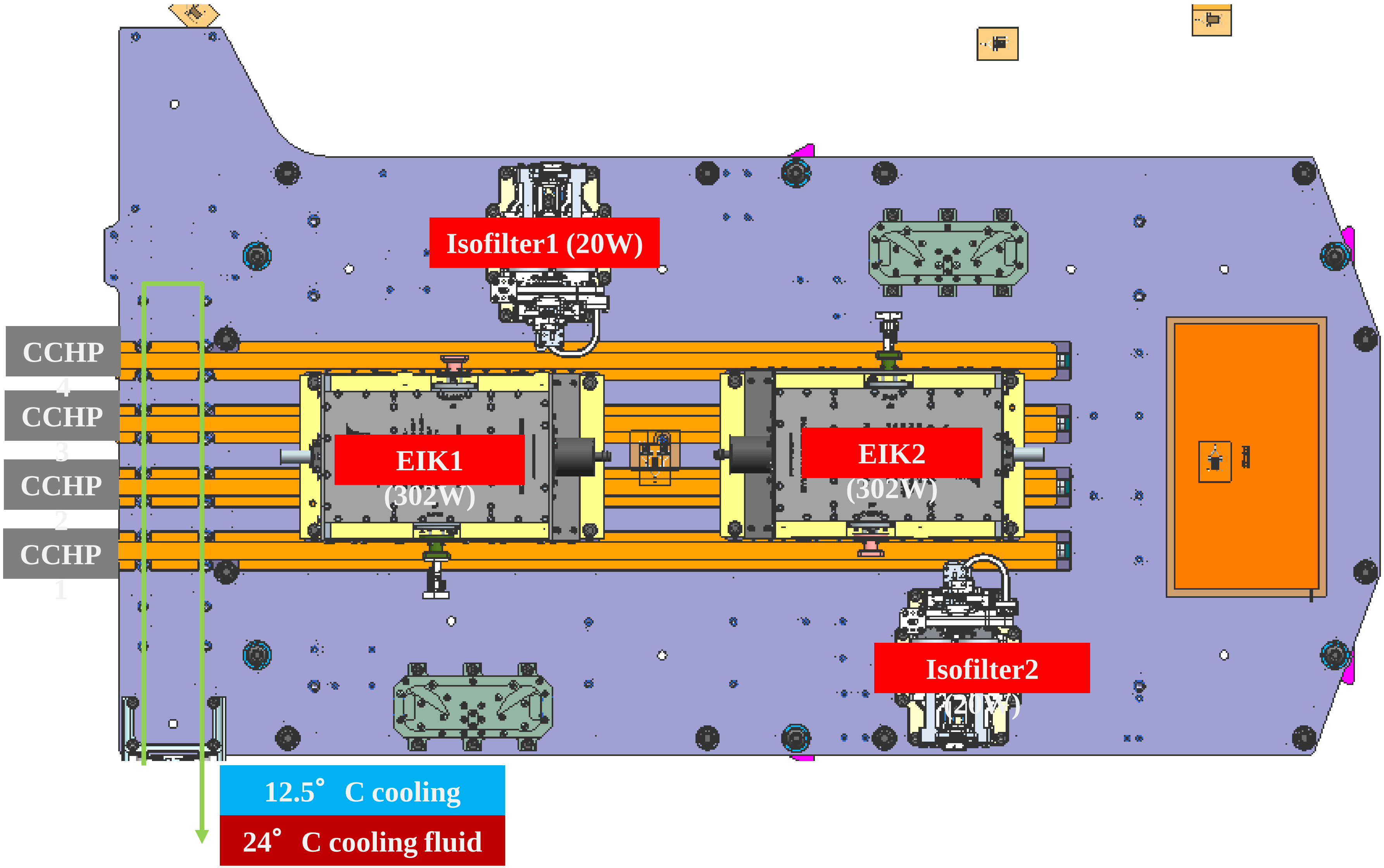


a: CCHP4 started
b: CCHP3 started
c: CCHP2 started

EIK Thermal Pallet Instrumentation

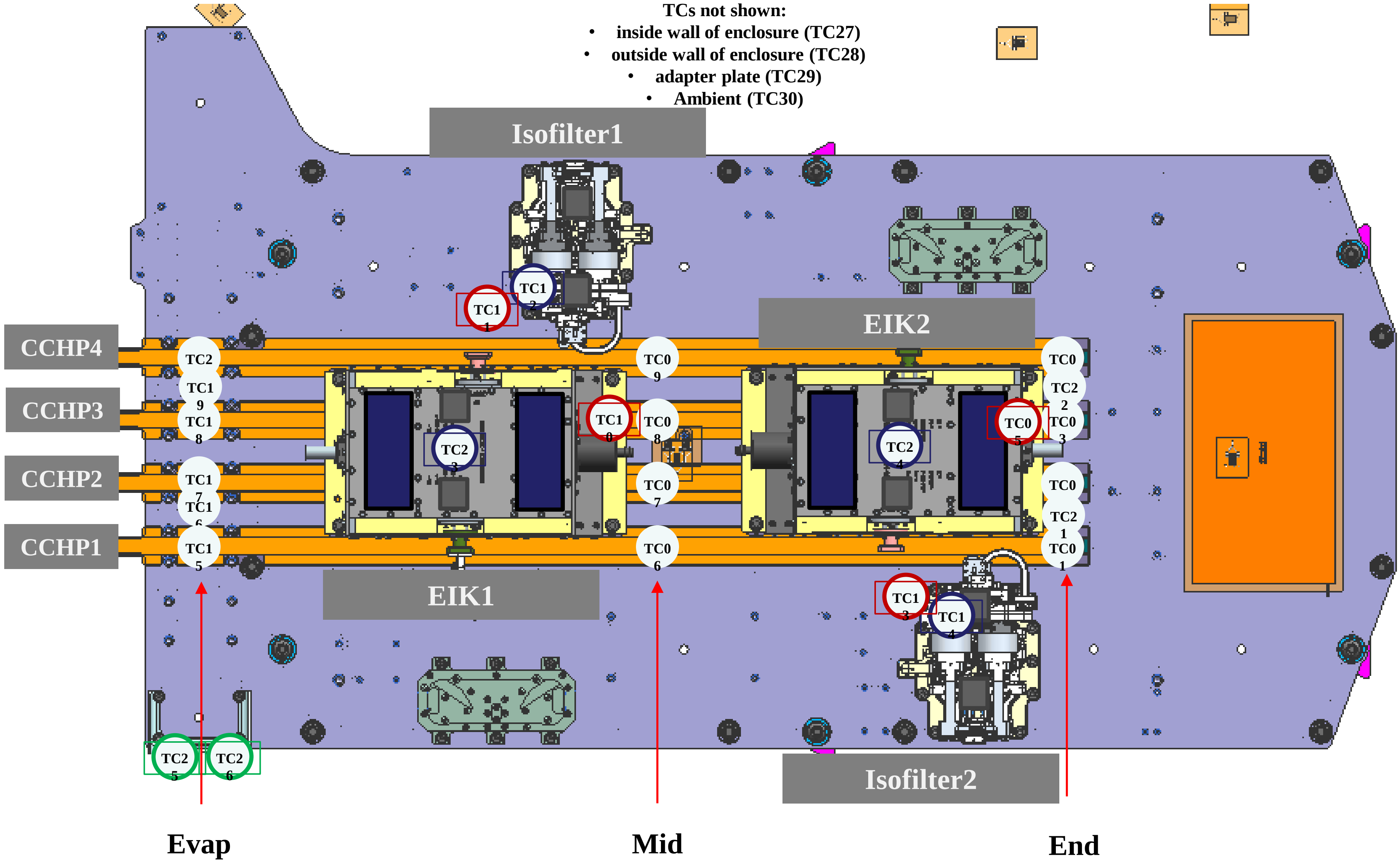


EIK Test Case Figure Diagram

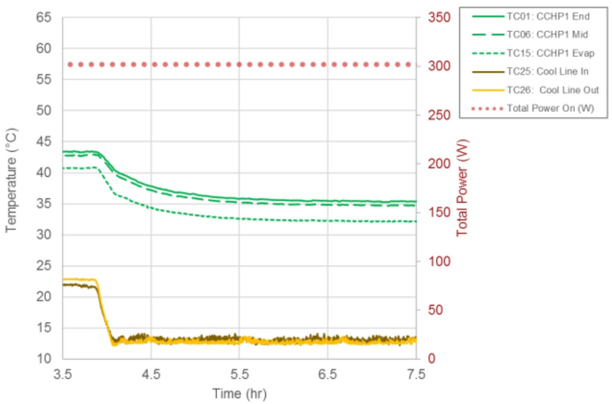


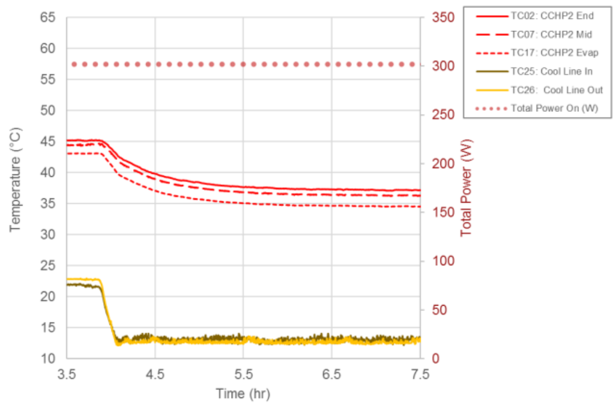
EIK Pallet: TCs and heaters

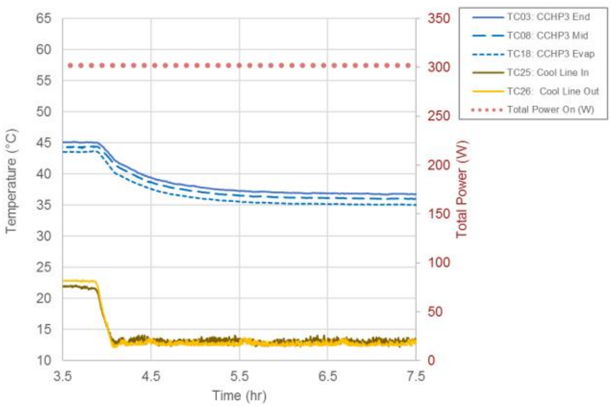
TCs not shown:
- inside wall of enclosure (TC27)
- outside wall of enclosure (TC28)
- adapter plate (TC29)
- Ambient (TC30)

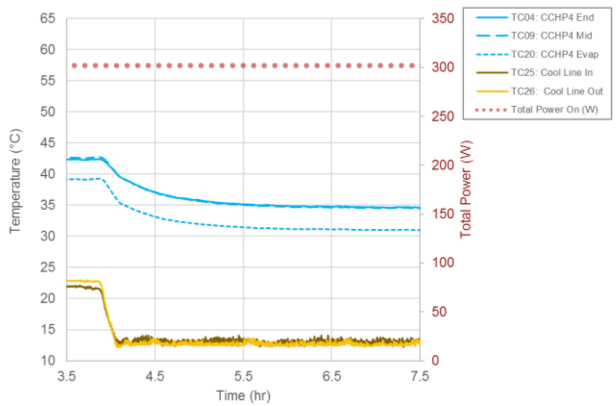


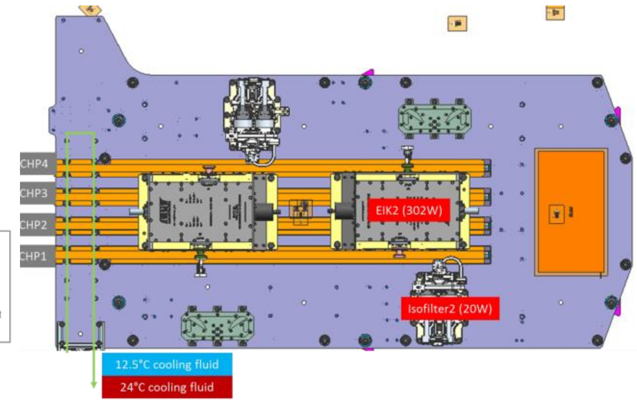
Case 1b Plots: CCHPs











Note: all CCHPs started

	Hot Cycle				Cold Cycle			
CCHP SS Temperature	End	Mid	Evap	Diff	End	Mid	Evap	Diff
CCHP1	43.41	42.76	40.74	2.66	35.37	34.74	32.18	3.19
CCHP2	45.18	44.41	43.06	2.12	37.17	36.32	34.56	2.61
CCHP3	45.11	44.31	43.54	1.56	36.78	36.04	35.09	1.70
CCHP4	42.34	42.63	39.17	3.17	34.66	34.56	31.04	3.62