Application of a Physics-Based Stabilization Criterion to Flight System Thermal Testing

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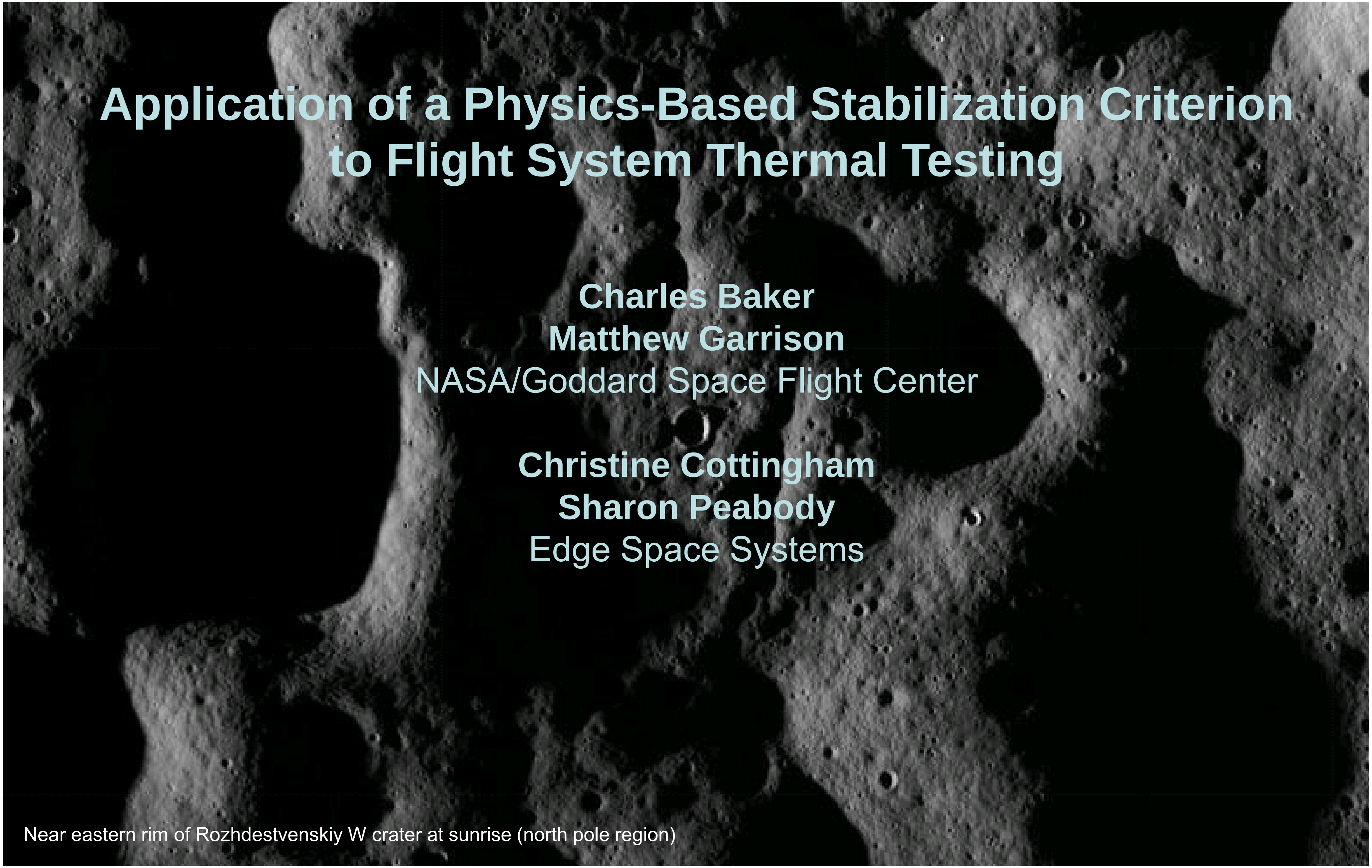
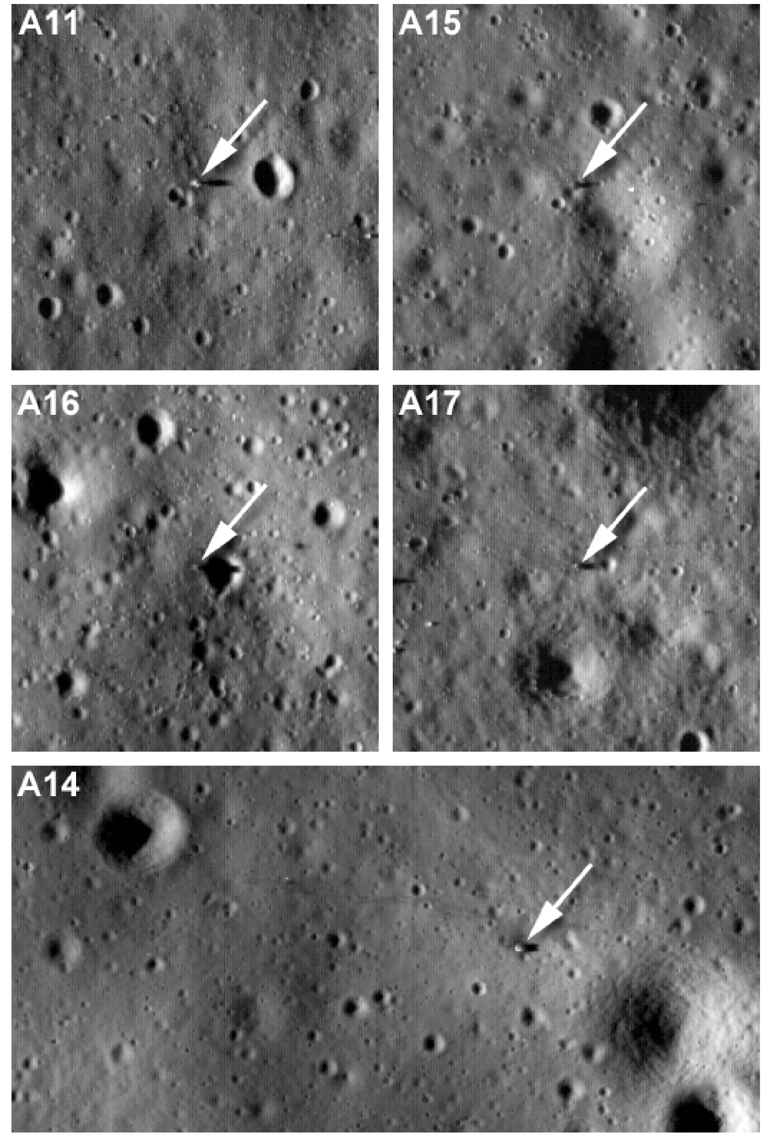


Near eastern rim of Rozhdestvenskiy W crater at sunrise (north pole region)

AGENDA

- Derivation of Theory
- LRO Subsystem Testing
    - Description
    - Application of Theory
- LRO Orbiter-Level Testing
    - Description
    - Application of Theory
- Conclusions



Theory: Origins and Assumptions

- Theory presented here is a simplified form of the general stability criteria derived by Rickman and Ungar (see reference in paper)
- Analysis makes the following assumptions:
  - The entire test assembly temperature changes at the same rate, dT/dt
  - The test assembly interfaces to a constant-temperature sink by either radiative or conductive heat transfer, with all other heat losses and gains negligible
  - The heat dissipated within the test assembly is constant
  - The sink temperature is constant
  - The radiative or conductive interface to the sink is known (or a prediction is known, to be refined during the test)
  - Temperatures are in an absolute scale
  - For radiation-dominated cases, temperatures are much larger than absolute zero
- For complex systems, this theory can apply to each thermal control system individually

Theory: Conduction-Dominated Systems

•Assume conservation of energy, where the heat into the single-node test assembly is the sum of the dissipated power (Q_D) and the heat conducted from the sink at T_S

$$Q = mC_p \frac{dT}{dt} \qquad Q = Q_D + G(T_S - T)$$

•The assembly temperature can then be broken into a steady-state temperature (T_{SS}) and the difference between the current temperature and steady state (ΔT)

$$T = T_{SS} - \Delta T$$

•Steady state is defined as when the assembly dT/dt = 0, so the dissipated heat equals the heat conducted to the sink

•When combined with the conservation of energy equation, this gives:

$$\frac{dT}{dt} = \frac{G\Delta T}{mC_p}$$

Theory: Radiation-Dominated Systems

- Assume conservation of energy, where the heat into the single-node test assembly is the sum of the dissipated power (Q_D) and the heat conducted from the sink at T_S

$$Q = mC_p \frac{dT}{dt} \qquad Q = Q_D + A\varepsilon\sigma\left(T_S^4 - T^4\right)$$

- The same definition of T_{SS} and ΔT applies to this derivation
- T^4 was expanded and it was assumed that $T_{SS} >> \Delta T$, giving:

$$Q = Q_D + A\varepsilon\sigma\left(T_S^4 - T_{SS}^4 + 4T_{SS}^3\Delta T\right)$$

- Using the steady state definition, the heat into the single-node assembly can then be expressed as a function of all known or defined values

$$Q = 4A\varepsilon\sigma\left(T_S^4 + \frac{Q_D}{A\varepsilon\sigma}\right)^{3/4}\Delta T$$

- Conservation of every can then be rewritten as

$$\frac{dT}{dt} = \frac{4A\varepsilon\sigma\Delta T}{mC_p}\left(T_S^4 + \frac{Q_D}{A\varepsilon\sigma}\right)^{3/4}$$

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Theory: Steady State Predictions

- Thermal stabilization criteria are selected to acknowledge that you will never reach true steady state (ΔT never equals 0)
- The conduction- or radiation-dominated solutions for dT/dt can be used to set a maximum temperature rate-of-change to balance at an acceptable error from steady state

$$\frac{dT}{dt} = \frac{G\Delta T}{mC_p} \qquad \frac{dT}{dt} = \frac{4A\varepsilon\sigma\Delta T}{mC_p}\left(T_S^4 + \frac{Q_D}{A\varepsilon\sigma}\right)^{3/4}$$

- By solving for ΔT and substituting into the definition of TSS, we can reach a form that can predict the steady-state temperature based on only known parameters and current measurements (T, dT/dt)

$$T_{SS} = T + \frac{mC_p}{G}\frac{dT}{dt} \qquad T_{SS} = T + \frac{mC_p}{4A\varepsilon\sigma\left(T_S^4 + \frac{Q_D}{A\varepsilon\sigma}\right)^{3/4}}\frac{dT}{dt}$$

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Validation of the Theory

- Previous work (Rickman and Ungar) compared the derived results against test data for a very simplified test setup
  - Heaters on a small aluminum cube suspended in a thermal vacuum chamber with a single large conductive coupling
- To see whether this theory is valid on flight systems, or under what circumstances it works, it was applied after the fact to three thermal vacuum tests for LRO
  - The ITP Test, which was conduction-dominated and of medium complexity
  - The Radiator Test, which was radiation-dominated and of medium complexity
  - The Orbiter Test, which was radiation-dominated and of high complexity
- In order to validate the theory, we should be able to predict steady-state temperatures before we reach them and show that derived temperature stabilization criteria give the anticipated steady state temperature error
- Only looked at thermal balances with stable power dissipations (no heater cycling)

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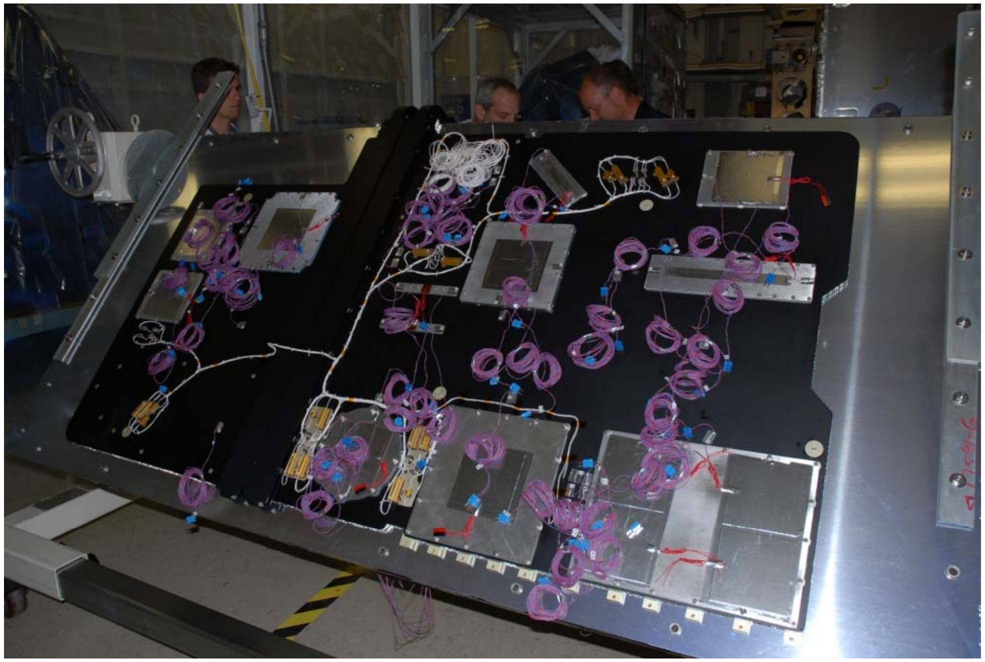
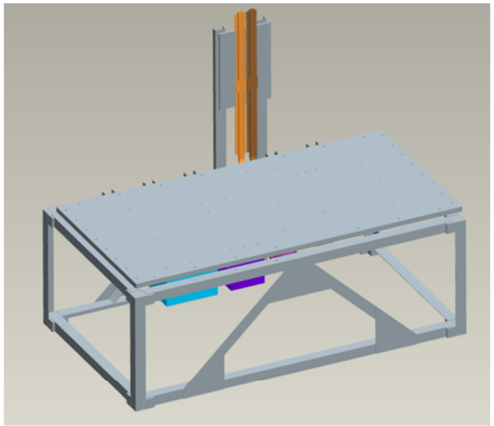
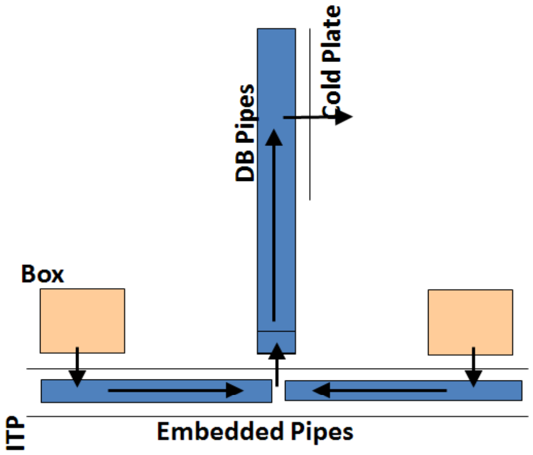
Conduction-Dominated Test Description

- Box simulators were mounted to a flight embedded-heat pipe avionics panel, called the isothermal panel
- Two flight dual-bore header pipes coupled the ITP to a GSE cold plate
- All heat pipes were either horizontal or in reflux
- Multiple hot and cold thermal balances were done to simulate flight-like cases
- The test used a stability criterion of 0.3°C/hr, which is 1% of the max system power divided by the mC_P
- This theory gives a stability criterion of 1.0°C/hr with a goal of balancing no more than 1°C away from steady state







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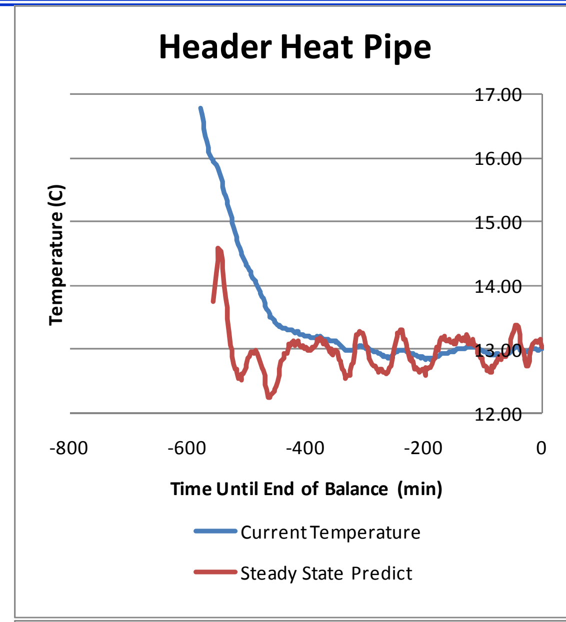
Conduction-Dominated Test Results

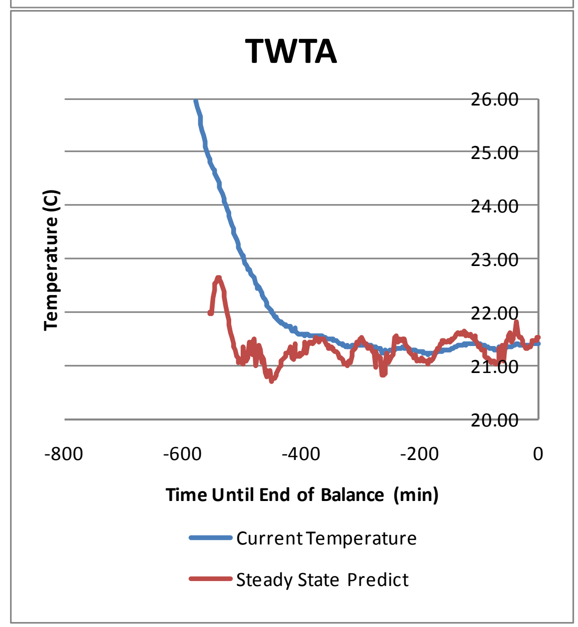
•Components reached 1% thermal stabilization criterion at -318 minutes

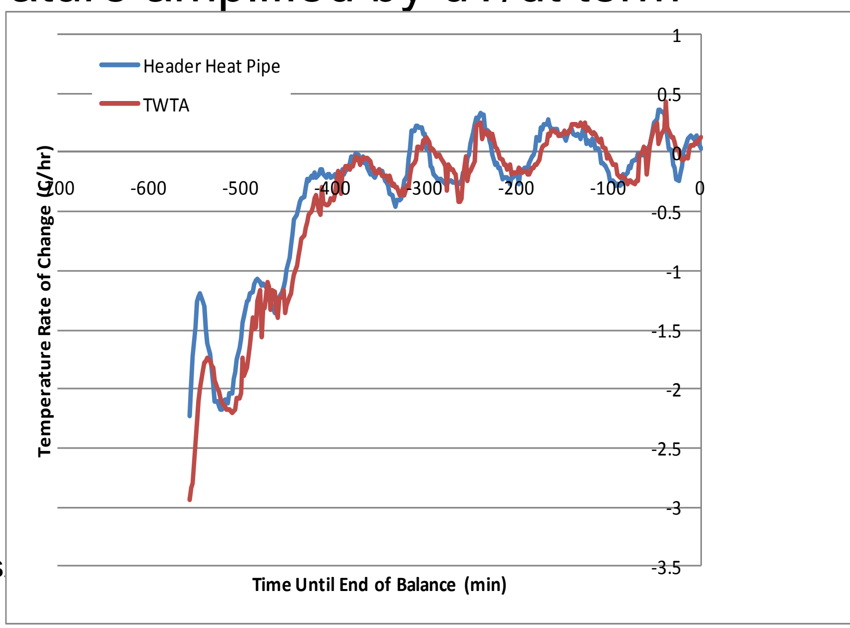
•Our criterion was met at time -440 minutes when the header was 0.3°C away from steady state and the TWTA was 0.4°C away (would save 2hrs per balance)

•Both components' steady state predictions reached the true value by time -500 minutes

•Noise in predictions is due to fluctuations in sink temperature amplified by dT/dt term

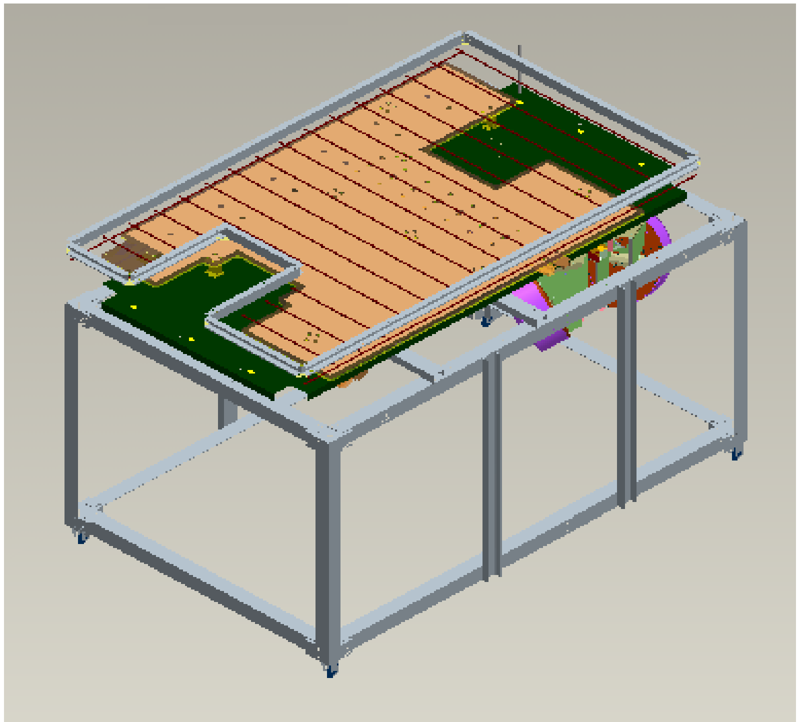


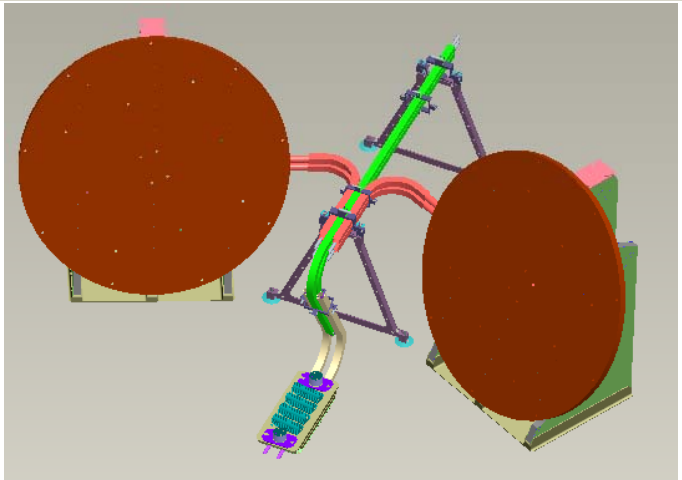




Radiation-Dominated Test Description

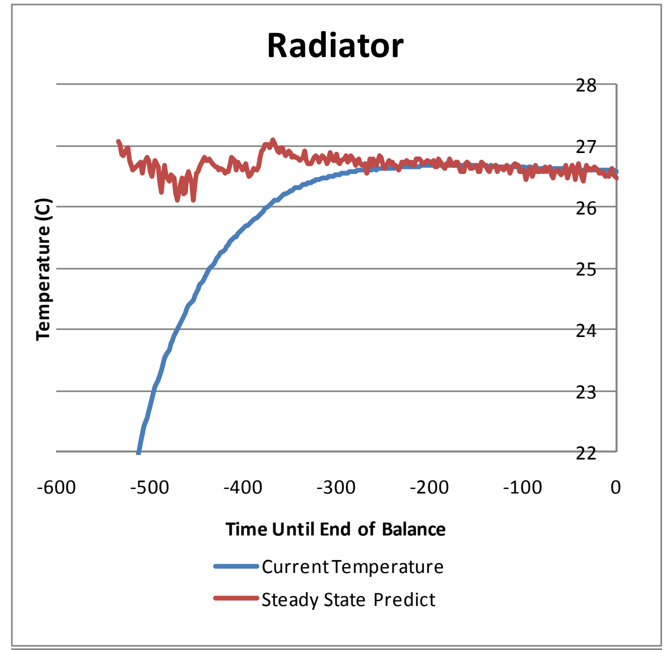
- The flight dual-bore header pipes from the previous test were attached to the flight radiator and flight RWA heat pipe assembly to complete the other end of this thermal control system
- The ITP heat load was replaced with GSE heaters on the header pipes
- The radiator viewed the chamber shroud through a CalRod array used to do orbital transient simulations only
- The test used a stability criterion of 0.6°C/hr, which is 1% of the max system power divided by the mC_P
- This theory gives a stability criterion of 0.9°C/hr with a goal of balancing no more than 1°C away from steady state

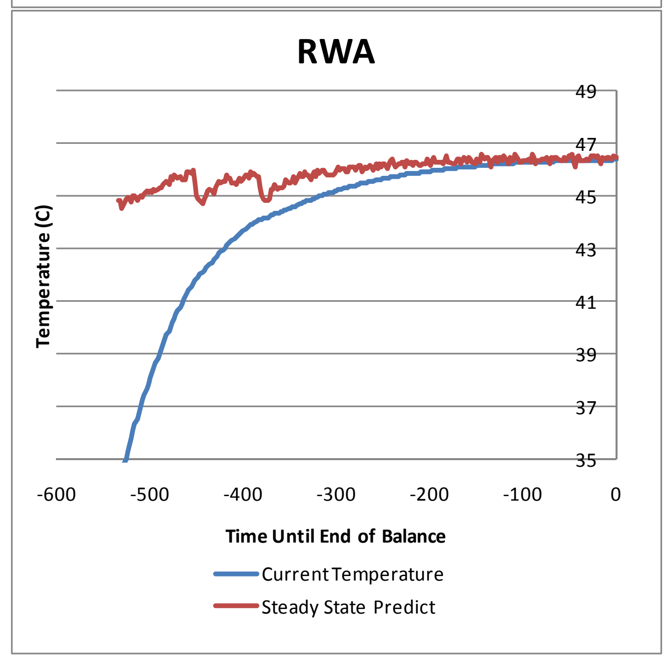


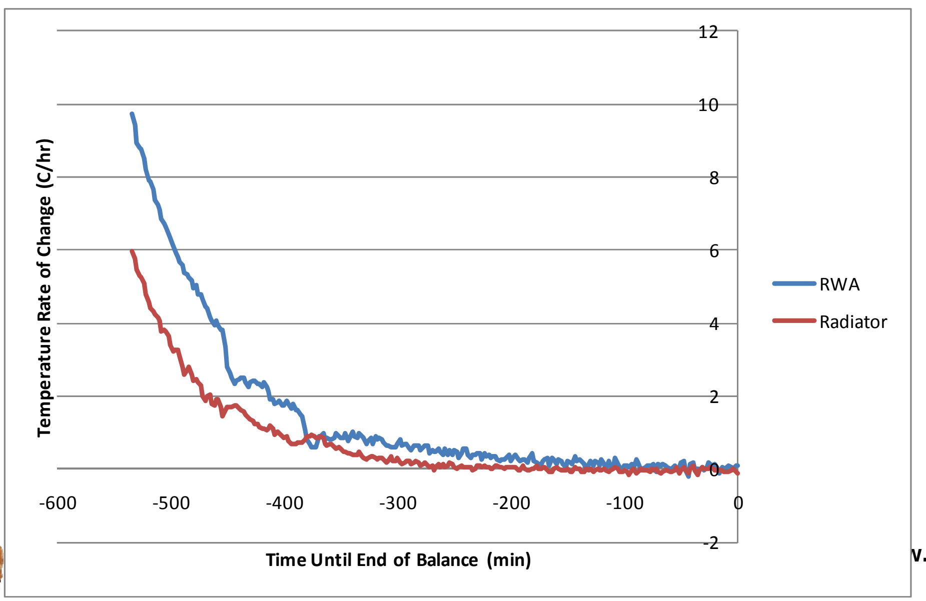


Radiation-Dominated Test Results

- Components reached 1% thermal stabilization criterion at -272 minutes
- Our criterion was met at time -332 minutes when the RWA was 0.9°C away from steady state and the radiator was 0.2°C away (saves 1hr per balance)
- Both components' steady state predictions reached the true value almost instantly (9 hrs prior to balance)
- Lower noise is because of the relatively weaker coupling to any fluctuations in the sink temperature





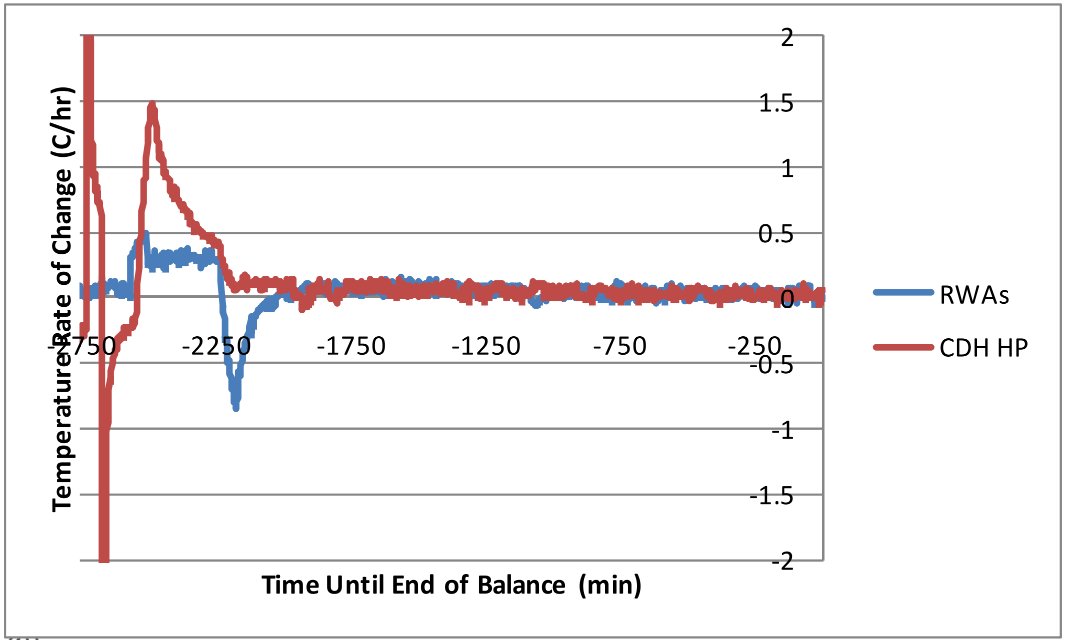


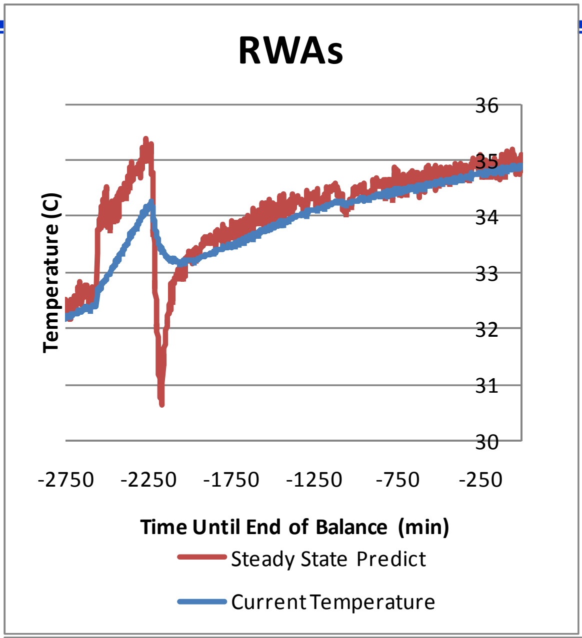
Orbiter-Level Test Description

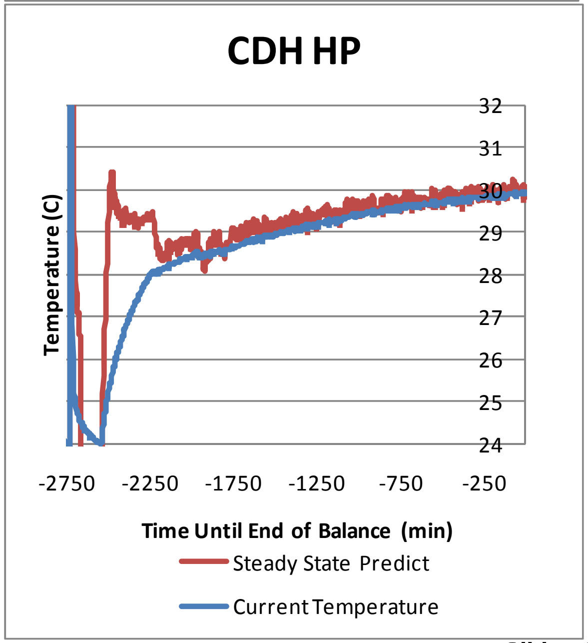
- The full flight thermal orbiter is built up, which is the most complex test investigated here (extra couplings not along the primary heat rejection path, fluctuations in power dissipation, etc)
- Each subsystem had a different thermal stabilization criterion:
    - Electronics stability criterion was 0.3°C/hr, which is 3% of the max system power divided by the mC_P
    - RWA stability criterion was 0.2°C/hr, which is 3% of the max system power divided by the mC_P
- This theory gives a stability criterion of 0.3°C/hr with a goal of balancing no more than 1°C away from steady state

Orbiter-Level Test Results

- Temperature rate-of-change stays below all convergence criteria for 33 hours despite constant temperature change
- Predicted steady state temperature never converges on a final balance condition
- This is due to heat exchange with other orbiter masses not included in the theory, which were carefully isolated during the subsystem-level tests







Summary

- The theory shown here can provide thermal stability criteria based on physics and a goal steady state error rather than on an arbitrary "X% Q/mC_P" method
- The ability to accurately predict steady-state temperatures well before thermal balance is reached could be very useful during testing
- This holds true for systems where components are changing temperature at different rates, although it works better for the components closest to the sink
- However, the application to these test cases shows some significant limitations:
    - This theory quickly falls apart if the thermal control system in question is tightly coupled to a large mass not accounted for in the calculations, so it is more useful in subsystem-level testing that full orbiter tests
    - Tight couplings to a fluctuating sink causes noise in the steady state temperature predictions

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