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 \( T_S \)

\[
Q = mC_p \frac{dT}{dt} \quad Q = Q_D + G(T_S - T)
\]

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

\[
T = T_{SS} - \Delta T
\]

• Steady state is defined as when the assembly \( \frac{dT}{dt} = 0 \), so the dissipated heat equals the heat conducted to the sink

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

\[
\frac{dT}{dt} = \frac{G\Delta T}{mC_p}
\]
• 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 $T_S$

$$Q = mC_P \frac{dT}{dt} \quad Q = Q_D + A\sigma (T_S^4 - T^4)$$

• The same definition of $T_{SS}$ and $\Delta T$ applies to this derivation

• $T^4$ was expanded and it was assumed that $T_{SS} > > \Delta T$, giving:

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

• 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

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

• Conservation of every can then be rewritten as

$$\frac{dT}{dt} = \frac{4A\sigma \Delta T}{mC_P} \left( T_S^4 + \frac{Q_D}{A\sigma} \right)^{3/4}$$
Theory: Steady State Predictions

• Thermal stabilization criteria are selected to acknowledge that you will never reach true steady state ($\Delta T$ 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.

\[
\frac{dT}{dt} = \frac{G\Delta T}{mC_p} \quad \quad \quad \quad \quad \frac{dT}{dt} = \frac{4A\varepsilon\sigma\Delta T}{mC_p} \left( T_s^4 + \frac{Q_D}{A\varepsilon\sigma} \right)^{3/4}
\]

• By solving for $\Delta T$ 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 ($T$, $dT/dt$).

\[
T_{SS} = T + \frac{mC_p \frac{dT}{dt}}{G} \quad \quad \quad \quad \quad T_{SS} = T + \frac{mC_p}{4A\varepsilon\sigma \left( T_s^4 + \frac{Q_D}{A\varepsilon\sigma} \right)^{3/4}} \frac{dT}{dt}
\]
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)
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.
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 mC₀.
- 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