Space Environment Testing

4. Thermal test part 1

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Effects of thermal environment on satellite system and units
Thermal environment (Day)

Sunlight -> >100°C

Albedo (reflection)

IR emission
Thermal environment (night)

$>-100^\circ \text{C}$

IR emission
Thermal environment in space

Example from HORYU-II flight data
Environmental requirements of typical electronics

- Operating ambient temperature: 0° to 35° C
- Non-operating temperature: −20° to 45° C
- Relative humidity: 5% to 95% noncondensing
- Maximum operating altitude: 3000 m

Environmental requirements of typical electronics

Industrial Grade Lap-top Computer
Operating ambient temperature: -20 ~ +50°C

Standard type Lap-top Computer
Operating ambient temperature: +10 ~ 35°C
Non-operating temperature: -25 ~ +45°C
Environmental requirements of car electronics

Automobile electronics are required to operate between -40 and 120 °C

From ISO-16750-4: Road vehicles — Environmental conditions and testing for electrical and electronic equipment — Part 4: Climatic loads
Electronics Parts Grade

- Space
- Nuclear, Aerospace
- Automobile
- Industry
- Commercial (Consumer)
## Temperature range of satellite units

<table>
<thead>
<tr>
<th>subsystem/equipment</th>
<th>Temperature range</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Non-active</td>
</tr>
<tr>
<td>receiver</td>
<td>-30/+55</td>
</tr>
<tr>
<td>TWT</td>
<td>-30/+55</td>
</tr>
<tr>
<td>Antenna</td>
<td>-170/+90</td>
</tr>
<tr>
<td>Battery</td>
<td>-10/+25</td>
</tr>
<tr>
<td>Shunt dissipator</td>
<td>-45/+65</td>
</tr>
<tr>
<td>Earth, Sun sensor</td>
<td>-30/+55</td>
</tr>
<tr>
<td>Rate gyro</td>
<td>-30/+55</td>
</tr>
<tr>
<td>Wheel</td>
<td>-15/+55</td>
</tr>
<tr>
<td>Solid apogee motor</td>
<td>+5/+35</td>
</tr>
<tr>
<td>Propellant tank</td>
<td>+10/+50</td>
</tr>
<tr>
<td>Thruster</td>
<td>+10/+120</td>
</tr>
<tr>
<td>Firing bolt</td>
<td>-170/+55</td>
</tr>
<tr>
<td>Separation mechanism</td>
<td>-40/+40</td>
</tr>
</tbody>
</table>
Temperature effects on electronics

- Semiconductor characteristics depend on temperature
  - Things that worked at room temperature may not work at high or low temperatures
  - Especially if different units have different temperatures

Forward current (I_F) and Forward voltage (V_F)

Temperature distribution

Temperature difference even on the same PCB. What if components are separated in vacuum?
Temperature difference

Two components at different temperatures need to work together as a system.
Failure mechanism

Brittle Failure

Ductile Failure

Fatigue Failure
Thermal stress

- Thermal cycle (hot and cold temperature) give thermal stress

<table>
<thead>
<tr>
<th>Material</th>
<th>Coefficient of Thermal expansion (10⁻⁶/°C)</th>
<th>Young’s modulus (GPa)</th>
<th>Tensile strength (Mpa)</th>
<th>ΔL with L=100mm and ΔT=100°C (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FR-4</td>
<td>50~70</td>
<td>22~25</td>
<td>250~330</td>
<td>0.5~0.7</td>
</tr>
<tr>
<td>Sn/Ag/Cu Solder</td>
<td>21</td>
<td>31</td>
<td>35</td>
<td>0.2</td>
</tr>
<tr>
<td>Sn/Pb Solder</td>
<td>24</td>
<td>22</td>
<td>41</td>
<td>0.24</td>
</tr>
<tr>
<td>Cu</td>
<td>17</td>
<td>130</td>
<td>205</td>
<td>0.17</td>
</tr>
<tr>
<td>Al (Aldrey)</td>
<td>23</td>
<td>70</td>
<td>370</td>
<td>0.23</td>
</tr>
<tr>
<td>Ag</td>
<td>19</td>
<td>83</td>
<td>125</td>
<td>0.19</td>
</tr>
<tr>
<td>Invar (36)</td>
<td>2</td>
<td>140~150</td>
<td>450~590</td>
<td>0.02</td>
</tr>
<tr>
<td>Polyimide</td>
<td>10~45</td>
<td>3~7</td>
<td>150~230</td>
<td>0.1~0.45</td>
</tr>
<tr>
<td>CFRP</td>
<td>0.3</td>
<td>118</td>
<td>1230</td>
<td>0.003</td>
</tr>
<tr>
<td>Al2O3</td>
<td>6.8</td>
<td>340</td>
<td>-</td>
<td>0.068</td>
</tr>
</tbody>
</table>

\[ \sigma = \varepsilon E = \frac{\Delta L}{L} E \]

Stress \( \sigma \), Strain \( \varepsilon \),
Young’s modulus \( E \)

Data source
http://www.hitachi-chem.co.jp/japanese/products/bm/801/001.html
http://www.mgc.co.jp/seihin/h/btprint/lineup/fr4.html
http://www.zairyo-ya.com/info/zaiseiki_sii_2.html
http://home.hiroshima-u.ac.jp/~er/Rmin_GL_047.html
http://www.toyobo.co.jp/serihin/xf/polyimide/
http://www.hitachi-m-admet.com/industrial/carbonfiber_byo02.html
http://www.toishi.info/sozai/ni/invar.html
Thermal stress

Small thermal expansion
Large thermal expansion
Solder ball suffer fatigue failure

LSI package
Solder ball
PCB

http://techon.nikkeibp.co.jp/article/WORD/20070803/137439/?rt=nocnt
Thermal stress

15 years in GEO requires thermal stress less than 200 MPa

15 years in GEO

5 years in LEO

From Wikipedia
Thermal stress

- 200MPa thermal stress means
  \[ \sigma = \varepsilon E = \frac{\Delta L}{L} E < 200 \text{(MPa)} \]
- For Al, \( E = 70 \text{(GPa)} \)
- \( \Delta L/L \) must be less than 0.0029

\[ \Delta L \text{ is determined by the difference of coefficient of thermal expansion} \]

Lead length (L) must be significantly long to reduce \( \Delta L/L \)

Example: blocking-diode board of solar panel

From M. Bodeau J. Spacecraft and Rocket, Vol.50, 2013
Thermal stress

Be careful about thermal stress on interconnect and solar cell
Thermal stress

Space Flyer Unit (1995)

Photo by NEC/JAXA

Cable disconnection due to thermal stress
Thermal shock

ADEOS (MIDORI) (1996)

Breakage of solar paddle at the exit of eclipse terminated the mission in 6 months after launch.
Cold brittleness

• Metal is brittle at low temperature

From “Terminator 2” TriStar Picture, 1991
During WWII, Liberty ships were built with welding instead of riveting. Ships disintegrated in cold water due to brittle fracture at welded parts.

Photo from http://www-g.eng.cam.ac.uk/125/1925-1950/tipper3.html
Metal and low temperature

- Tin (Sn) is a major constituent of solder
- Tin at low temperature transition to gray tin, known as “Tin pest”
- Gray tin expands and disintegrates
- Catalyze itself, i.e. more tin pest faster transition, like disease
- Transition starts from +18°C or below (mostly -10°C due to impurity)
- Transition highest at -48°C

Picture from Wikipedia
Tin Pest

Naomi Uemura (1984.2.13, Mt. McKinley)

Scott's party at the South Pole

Napoleon’s Moscow campaign

Loss of transceiver

Loss of oil due to leakage from soldered cans

Uniform buttons are lost
Lubrication at low temperature

Fig. 13  No-load back-driving torque of Unit 1 (Maplub SH050a) as function of temperature (in vacuum)

Lubrication of vacuum grease decrease at lower temperature

From I. Schafer et al., “SPACE LUBRICATION AND PERFORMANCE OF HARMONIC DRIVE GEARS”
Battery structure

http://www.diracdelta.co.uk/science/source/l/i/lithium%20ion%20battery/source.html#.U18kKlzskRc
Battery at low temperature

- Increase of internal impedance

Dependence of lithium-ion battery discharge characteristics on temperature

Source: http://antenna1st.com/html/lithium_point7.html
Battery at low temperature

Ion conductivity depends on temperature. The lower the temperature, the lower the conductivity.
Temperature effects on electronics

- Degradation
  - Shorter lifetime at higher temperature

Degradation is a certain form of change of state

Arrhenius equation $K = A \exp\left(-\frac{\Delta E}{kT}\right)$

- $K$: reaction rate
- $\Delta E$: activation energy
- Higher temperature
- Larger reaction rate
- Higher chance of state change
Battery at high temperature

- Chemical reaction is accelerated
- Degradation proceeds faster
- Self-discharge increases

http://www.mpoweruk.com/performance.htm

Dendrite growth at electrode

Temperature effects on electronics

• Degradation
  – Shorter lifetime at higher temperature

Example: short-circuit of capacitor

Migration of defects/impurity ions finally leads to short-circuit

This process is accelerated at high temperature
Migration

- Thin water film around electrodes
  - Condensation of air moisture
  - Sweat and/or spit during handling
- Dissolving of metal ions into the water layer
- Migration toward the opposite electrode
- Short-circuit

Very slow process, but accelerated at high temperature

http://jp.fujitsu.com/group/fqi/services/analysis/method/epma/
Thermal tests
Purpose of thermal tests

• Demonstration
  – Test article can survive space environment
  – Test article can operate properly in space environment
    • Turn-on at low and high temperatures
    • No functional deterioration over the temperature range
  – Flight model was manufactured properly
    • Environment stress screening for unit acceptance

• Measurement
  – Validate thermal analysis
Type of thermal tests

• Thermal cycle tests
  – Can survive thermal stress due to cycling
  – Performance at high and low temperatures

• Thermal vacuum tests
  – Performance under flight representative conditions

• Thermal balance tests
  – Verify thermal control subsystem to maintain the satellite within the required temperature range
  – Correlation of thermal analytic models

• Burn-In tests
  – Operate unit (mostly electronics) for long time at an elevated temperature, cycles, or elevated voltage

• Environment Stress Screening (ESS)
  – Similar to Burn-in, but with thermal cycling
Burn-in test

- Semi-conductor failure rate is accelerated at high temperature.
- Let defect parts fail in early stage if there are any
  - Detection of inherent defect parts
- Make sure the tested unit is in constant failure mode
Environment Stress Screening

• Adopted in US military program
  – Originally from Apollo program

• Usually applied to acceptance of electronics components

• Add stress to the flight model
  – Random vibration
  – Thermal cycle
  – More severe than AT level but less than QT level

• The best way to detect the latent defects is to “Shake and Bake”
Defects detected by ESS

- Parameter drifts
- Printed circuit board shorts and opens
- Incorrect parts installation
- Wrong parts installation
- Contaminated parts
- Hermetic seal failures
- Foreign material contamination
- Cold solder joints
- Defective parts

Some of these may be detected by Functional test or Burn-in

From D. B. Kececioglu, et al., *Environment Stress Screening*, DEStech Publications, 2003,
## ESS vs Burn-in

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Burn-in</th>
<th>ESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>Operating or accelerated</td>
<td>Cycled from high to low operating</td>
</tr>
<tr>
<td>Vibration</td>
<td>Sinusoidal (if used)</td>
<td>Random, normally 20 ~ 2,000Hz</td>
</tr>
<tr>
<td>Temperature rate of change</td>
<td>Usually constant, but sometimes cycled</td>
<td>5 °C per minute minimum</td>
</tr>
<tr>
<td>Length of time</td>
<td>Normally 168 hours or less</td>
<td>• 10 or 5 minutes perpendicular to each axis of orientation for vibration, and • 10 to 20 cycles for temperature cycling</td>
</tr>
</tbody>
</table>

From D. B. Kececioglu, et al., *Burn-In Testing*, DEStech Publications, 2003,  
ESS can be shorter than Burn-in
Thermal design and verification

1. Mission definition
2. Orbit determined
3. Satellite configuration determined
4. Thermal analysis
5. Thermal balance test (system)
6. Derivation of temperature profile
7. Thermal vacuum/cycle test (unit/subsystem)
8. Thermal vacuum/cycle test (system)

ESS or Burn-in are conducted as a part of acceptance test of units.
Thermal balance test
# Thermal balance test

<table>
<thead>
<tr>
<th></th>
<th>Verification of thermal control subsystem</th>
<th>Correlation of thermal analytic models</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Purpose</strong></td>
<td>Simulate in-orbit conditions as much as possible</td>
<td>Remove air convection effects</td>
</tr>
<tr>
<td><strong>Test condition</strong></td>
<td>Include worst hot/cold cases in orbit</td>
<td>Suitable to evaluate the thermal analysis model</td>
</tr>
<tr>
<td><strong>Vacuum</strong></td>
<td>Mandatory</td>
<td>Mandatory</td>
</tr>
<tr>
<td><strong>Cold surrounding</strong></td>
<td>Mandatory</td>
<td>Desirable, but can be done without it</td>
</tr>
<tr>
<td><strong>Sun simulation</strong></td>
<td>Try to simulate as much as possible</td>
<td>Can be any method, but heat input must be characterized quantitatively</td>
</tr>
</tbody>
</table>
Thermal control subsystem

- Insulation
- Coating
- Heat-sink
- Thermal louver
- Heat-pipe
- Heater
- Sun-shade
- others

Thermal louver
“window blind in space”

Heat-pipe


Thermal balance test

James Webb Telescope
Operational temperature less than -223°C
Thermal balance test

BeppiColombo

10 Solar thermal balance test
Thermal balance test

If the purpose is to verify the thermal control system, the heat sink (deep space) and the heat source (the sun) should be as flight representative as possible.

Deep space (3K)

Sun

1.4kW/m²
Thermal balance test

13mØ Space Chamber

System Architecture

http://aerospacebiz.jaxa.jp/jp/images/facilities/13m_space_chamber.gif
Thermal balance test (heat source)

Use of solar simulator
Thermal balance test (heat source)

Sheet-heater on external panels
Thermal balance test (heat source)

Use of Infrared lamps

## Thermal balance (heat source)

<table>
<thead>
<tr>
<th></th>
<th>Solar simulator</th>
<th>IR lamp</th>
<th>Sheet heater</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pros</strong></td>
<td>The most flight</td>
<td>Can be used to a flight model</td>
<td>Affordable</td>
</tr>
<tr>
<td></td>
<td>representative</td>
<td>Affordable</td>
<td></td>
</tr>
<tr>
<td><strong>Cons</strong></td>
<td>The most expensive</td>
<td>Needs to hang lamps inside a chamber</td>
<td>Cannot be used to a flight model</td>
</tr>
</tbody>
</table>
Thermal balance test (heat sink)
Thermal vacuum chamber

Ideally, it is better to have shroud size 3x bigger than satellite

Satellite (0.5m)

Shroud (1.5m diameter)
How shroud works?

Heat of evaporation

Primary cooler: LN2

Temperature limit: -196°C (LN2)

Liquid cooling

Primary cooler: Silicon oil
Secondary cooler: LN2 or chiller

Temperature limit: -85°C (Silicon oil)
How shroud works

- Liquid Nitrogen (LN2)
  - Boiling temperature -196 °C
  - Heat of evaporation 5.56kJ/mol (199kJ/kg)
  - Density 0.809kg/l (LN2) 1.26g/l (GN2)
  - Mass 28g/mol

- With 1 liter of LN2, heat of evaporation is 161kJ
- To remove the heat of 100W, the required LN2 is
  \[
  \frac{100}{161 \times 10^3} = 2.23 \text{ l/hour} = 1.8kg/hour
  \]
- To cool the shroud of 100kg to -170°C from 20°C
  Steel 0.435 J/g/K -> 8.3x10^6 J
  42kg of LN2
How shroud works

Supply of LN2 is important
How shroud works

Supply of LN2 is important

4900 liter
Radiation heat transfer

Heat transferred from satellite to shroud via radiation (W)

\[ Q_{\text{shout}} = \frac{A_1}{1 + \frac{A_1}{A_2} \left( \frac{1}{\varepsilon_1} - 1 \right)} \sigma \left( T_1^4 - T_2^4 \right) \]

- \( A_1 \): area of satellite
- \( A_2 \): area of shroud
- \( \varepsilon_1 \): emissivity of satellite
- \( \varepsilon_2 \): emissivity of shroud

In space, \( A_1/A_2 << 1 \), \( T_2 = 3 \text{(K)} \)

\[ Q_{\text{orbit}} = \varepsilon_1 A_1 \sigma \left( T_{\text{orbit}}^4 - 3^4 \right) \]

- \( T_{\text{orbit}} \): satellite temperature in orbit

Deep space environment serves as radiative heat sink.
Effective emittance

• Effective emittance between two plates of $\varepsilon_1$ and $\varepsilon_2$ is given by

$$\varepsilon_{12} = \frac{\varepsilon_1 \varepsilon_2}{\varepsilon_1 + \varepsilon_2 - \varepsilon_1 \varepsilon_2}$$
Radiation heat transfer

In the test, we make the heat input to the satellite the same as in orbit

\[ Q_{shroud} = Q_{orbit} \]

Temperature in the shroud, \( T_1 \), becomes higher than in orbit, \( T_{orbit} \)

\[
T_1 = \left( 1 + \varepsilon_1 \frac{A_1}{A_2} \left( \frac{1}{\varepsilon_2} - 1 \right) \right) T_{orbit}^4 + T_2^4 \right)^{1/4}
\]

Temperature difference due to presence of shroud

\[
\Delta T = T_1 - T_{orbit} = \left( 1 + \varepsilon_1 \frac{A_1}{A_2} \left( \frac{1}{\varepsilon_2} - 1 \right) \right) T_{orbit}^4 + T_2^4 \right)^{1/4} - T_{orbit}
\]
Shroud size

- We assume
  - $\epsilon_1 = 0.1$ or $0.9$
  - $\epsilon_2 = 0.9$ (almost black)
  - $T_{\text{orbit}} = 300$ (K)
  - $T_2 = 100$ (K)
    - LN$_2$ temperature

To have a good simulation of dark space, we need the area ratio of 0.3 or less

$$A_1 / A_2 < 0.3$$

$A_1$: area of satellite
$A_2$: area of shroud
# Thermal balance (heat sink)

<table>
<thead>
<tr>
<th>Pros</th>
<th>Evaporation (LN2)</th>
<th>Liquid (Silicon oil)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Can reach low temperature (-170°C or lower)</td>
<td>More uniform temperature distribution</td>
<td></td>
</tr>
<tr>
<td>No need of secondary system</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cons</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Less uniform temperature distribution</td>
<td>Oil becomes very viscous at low temperature. Practical limit ~ -85°C</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Need secondary system, more complex</td>
<td></td>
</tr>
</tbody>
</table>
Requirement on vacuum pressure

- Free molecular flow

\[ K_n = \frac{\lambda}{L} > 1 \]
\[ \lambda = \frac{1}{n\sigma} \]

\( K_n \): Knudsen number
\( \lambda \): Mean free path
\( n \): number density
\( \sigma \): collision cross section
\( L \): Typical length

Air molecules do not collide. Viscosity is neglected

For air
\[ \sigma = \pi D^2 = 4.3 \times 10^{-19} \text{ (m}^2) \]
\[ D = 0.37 \text{ (nm)} \]

Weighed average of N2 and O2

\[ K_n = \frac{\lambda}{L} = \frac{1}{n\sigma L} = \frac{kT}{P\sigma L} = 0.01 \frac{1}{pL} \]

\[ p < \frac{0.01}{L} \]

For \( L=10 \text{ (m)} \), \( p<10^{-3} \text{ (Pa)} \)
Requirement on vacuum pressure

Heat flux carried by free molecular flow

\[
\Gamma = \frac{1}{4} n v \left( \frac{5}{2} kT \right) = \frac{1}{4} n \sqrt{\frac{8kT}{\pi m}} \frac{5}{2} kT
\]

\[
m = 4.8 \times 10^{-26} \text{ (kg)}
\]

\[
\frac{5}{2} kT \quad \text{Energy of each molecule (diatomic)}
\]

Assume particles bounce back with \( T_w \)

\[
\frac{Q}{A} = \frac{5}{8} n \sqrt{\frac{8k}{\pi m}} k \left( T^{3/2} - T_w^{3/2} \right) = \frac{5}{8} \sqrt{\frac{8k}{\pi m}} p \frac{1}{T} \left( T^{3/2} - T_w^{3/2} \right) = 17 p \frac{1}{T} \left( T^{3/2} - T_w^{3/2} \right)
\]

Satellite body
Requirement on vacuum pressure

Heat flux carried by free molecular flow

\[
\frac{Q}{A} \bigg|_m = 17 p \frac{1}{T} \left( T^{3/2} - T_W^{3/2} \right)
\]

Heat flux carried by radiation

\[
\frac{Q}{A} \bigg|_r = \frac{\varepsilon_1 \varepsilon_2 \sigma}{\varepsilon_1 + \varepsilon_2 - \varepsilon_1 \varepsilon_2} \left( T^4 - T_W^4 \right)
\]

\[\sigma = 5.67 \times 10^{-8} \text{ (Wm}^{-2}\text{K}^{-4})\]

Satellite body

Heat flux carried by free molecular flow should be negligible compared to the heat flux carried by radiation
Requirement on vacuum pressure

Gas transfer

\[ \frac{Q}{A} = 17p \frac{1}{T} \left( T^{3/2} - T_W^{3/2} \right) \]

Radiation transfer

\[ \frac{Q}{A} = \frac{\varepsilon_1 \varepsilon_2 \sigma}{\varepsilon_1 + \varepsilon_2 - \varepsilon_1 \varepsilon_2} \left( T^4 - T_W^4 \right) \]

\( \varepsilon_1 \): wall

\( T_2, \varepsilon_2 \): body

Emissivity of a satellite is usually between 0.1 and 0.9

To neglect the effect of heat transfer due to residual gas, chamber pressure needs to be less than 0.001 (Pa)
Thermal balance test

• We modify the input parameters of the thermal analytic model
  – **Conduction**
  – Emittance
  – View factor
  – Others

• so that the TMM prediction matches with the measurement

\[
m_i C_i \frac{dT_i}{dt} = Q_{\text{external},i} + Q_i - \sigma \varepsilon_i A_{\text{space},i} T_i^4 - \sum_{j=1}^{n} h_{ij}(T_i - T_j)
\]

\[
-\sigma \sum_{j=1}^{n} A_i F_{ij} \varepsilon_{ij} (T_i^4 - T_j^4)
\]

11.19
Conduction paths

• Heat conduction through joints is very difficult

Heat conduction through these interface depends on surface condition, how firmly they are attached, etc
Thermal balance test

- There are many uncertainties in the analysis
  - Ex: Conduction between parts
- Need to find the right parameters through comparison with the test results
- Once the parameters are given, the temperature ranges in all aspects of the mission can be predicted

Use thermal model

Test result analysis
Thermal balance test

- If the purpose of the thermal balance test is to obtain measurement data to correlate with thermal analysis
- The environment temperature (shroud or chamber wall) should be uniform and constant to make the analysis easy
  - Fixed boundary condition
- The cooling environment is not mandatory
  - Desirable to have a wide temperature range for comparison with analysis
- The heat input condition needs to be known precisely

Heater attached to the external panel

How much of the heat is transferred to the plate needs to be accurately known