Space Environment Testing

5. Thermal test part 2

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Derivation of test levels and conditions
Temperature margin

- Every simulation is not perfect
- Thermal analysis may have uncertainty up to 11°C
  - US research
- Passive thermal control (surface paint, mirror, etc) may change its property (\(\alpha\), \(\varepsilon\)) during long time in orbit
- Environment condition may vary
- Anything can happen
- A certain margin (10 to 15°C) should be added to the result of thermal analysis
  - Maximum Predicted Temperature (MPT)
  - Maximum Predicted Environment (MPE)
- For qualification purpose, another margin (5 to 10°C) should be added
- Overall, 15 to 25°C margin is added to the thermal analysis result
Margins

MPE: Maximum predicted environment

From ECSS-E-10-03A (2002)
Temperature margin

Fig. 19.1. Unit level predicted and test temperature ranges.


Unit test is carried out as environment stress screening (MIL philosophy)
Temperature margin

Number of cycles

- More cycles effective to detect the latent defects. But how many?
- Differs depending on institutions

<table>
<thead>
<tr>
<th></th>
<th>JERG-2-130 (JAXA)</th>
<th>ECSS-E-ST-10-03C (ESA)</th>
<th>SMC-S-016 (US)</th>
</tr>
</thead>
<tbody>
<tr>
<td>System</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>QT</td>
<td>4 TV cycles</td>
<td>4 TV cycles</td>
<td>8 TV cycles</td>
</tr>
<tr>
<td>AT</td>
<td>4 TV cycles</td>
<td>3 TV + 1 back-up cycles</td>
<td>4 TV cycles</td>
</tr>
<tr>
<td>PFT</td>
<td>4 TV cycles</td>
<td>3 TV + 1 back-up cycles</td>
<td>4 TV cycles</td>
</tr>
<tr>
<td>Unit (Electronics)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>QT</td>
<td>8 TV cycles</td>
<td>8 TV or TC cycles with at least 1 TV cycle</td>
<td>27 TC cycles or 23 TC + 4 TV cycles</td>
</tr>
<tr>
<td>AT</td>
<td>8 TV cycles</td>
<td>4 TV or TC cycles with at least 1 TV cycle</td>
<td>14 TC cycles or 10 TC + 4 TV cycles</td>
</tr>
<tr>
<td>PFT</td>
<td>8 TV cycles</td>
<td>4 TV or TC cycles with at least 1 TV cycle</td>
<td>27 TC cycles or 23 TC + 4 TV cycles</td>
</tr>
</tbody>
</table>

Number of cycles in thermal test (AT) for a satellite system recommended by various test standards

TV: thermal vacuum, TC: thermal cycle
Number of cycles

Figure 5. Thermal cycling test effectiveness
Number of cycles

\[ TE = \frac{F_f}{F_a} \times 100 \]  

where:

\( TE \) = The test effectiveness for the test(s) of interest

\( F_f \) = Total failures found in the test(s) of interest

\( F_a \) = Total failures available to be found including early flight
Figure 6 (b). Thermal cycling test effectiveness versus cycles

THE EFFECTIVENESS OF SATELLITE ENVIRONMENTAL ACCEPTANCE TESTS

With one thermal vacuum test
Thermal vacuum or thermal cycle?
Thermal vacuum/cycle test

• What is difference between thermal vacuum and thermal cycle test?

• The purpose of thermal vacuum test
  1. To check the performance at the high temperature limit in vacuum,
  2. To check the performance at the low temperature limit in vacuum
  3. To check the susceptibility to the temperature cycle in vacuum
  4. To detect latent defects of workmanship/material and design
  5. Mission simulation in flight-representative environment

• The purpose of thermal cycle test
  1. To check the performance at the high temperature limit in vacuum
  2. To check the performance at the low temperature limit in vacuum
  3. To check the susceptibility to the temperature cycle in vacuum
  4. To detect latent defects of workmanship/material and design
  5. Mission simulation in flight-representative environment
Thermal vacuum/cycle test

- Difference is the presence of air

Thermal vacuum is more representative of flight condition
- Thermal vacuum is more expensive (more labor intensive, longer time)
Thermal vacuum (TV) vs thermal cycle (TC)

- Little difference of time in cycling phase
- TV takes longer in test set-up
- TV takes longer before and after the test
  - Vacuum pumping
  - LN2 injection/removal
- TV cannot stop
  - To put on-hold, test article needs to be warmed constantly, otherwise may become too cold
- TV facility is more expensive than TC facility

Time $\approx$ money
Power control unit for a nanosatellite (max 200W)

5.0N・mで締め付け

1.2N・mで締め付け
Temperature distribution

Thermography observation of Power Control Unit temperature distribution
Effect of air

- Consider heat flux between a concentric spheres
- When sphere is filled by air, the heat flux between the two spheres

\[
\frac{Q}{A_1} = \frac{\sigma}{1 + \left( \frac{1}{\varepsilon_2} - 1 \right) \frac{A_1}{A_2}} \left( T_1^4 - T_2^4 \right) + Nu \frac{k_{air}}{r_2 - r_1} (T_1 - T_2)
\]

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

\[Nu = 2 + \frac{0.589 \text{Ra}_{aD}^{1/4}}{\left(1 + (0.469 / Pr)^{9/16}\right)^{4/9}} \approx 2 + 50 (\Delta T)^{1/4} D^{3/4}\]

- Nu: Nusselt number
- Ratio of heat conduction (due to liquid at rest) to heat convection (due to liquid at motion)
- Nu=1 for conduction only
- Ra: Rayleigh number: index of conduction to convection
- Pr: Prandtl number, index of viscosity and heat diffusion \(\sim 0.7\) for air
Effect of air

- Consider heat flux between a concentric spheres
- When sphere is filled by air, the heat flux between the two spheres

\[
\frac{Q}{A_1} = \frac{\sigma}{1 + \left(\frac{1}{\varepsilon_1} - 1\right) \frac{A_1}{A_2}} \left(T_1^4 - T_2^4\right) + Nu \frac{k_{\text{air}}}{r_2 - r_1}(T_1 - T_2)
\]

\[
Nu = 2 + \frac{0.589 R_{\text{ad}}^{1/4}}{\left(1 + \left(0.469 / P_r\right)^{9/16}\right)^{4/9}} \approx 2 + 50(\Delta T)^{1/4} D^{3/4}
\]

\[
R_{\text{ad}} = \frac{g \beta}{\nu \alpha} \Delta T x^3
\]

D=x=r_2-r_1

Assuming 20°C

\[
k_{\text{air}} = 0.0316 \text{ (W/m K)}
\]

\[
g=9.8 \quad \beta = \frac{1}{T} = 3.4 \times 10^{-3} \quad \nu = \frac{\mu}{\rho} = 1.58 \times 10^{-5} \quad \alpha = \frac{k}{\rho C_p} = 2.2 \times 10^{-5}
\]
The effect of air can be described by the following equation:

\[
\frac{Q}{A_1} = \frac{\sigma}{\varepsilon_1} + \left( \frac{1}{\varepsilon_2} - 1 \right) \frac{A_1}{A_2} \left( T_1^4 - T_2^4 \right) + Nu \frac{k_{air}}{r_2 - r_1} (T_1 - T_2)
\]

where:
- \(Q\) is the heat flux
- \(A_1\) is the area of the inner surface
- \(A_2\) is the area of the outer surface
- \(\sigma\) is the Stefan-Boltzmann constant
- \(\varepsilon_1\) and \(\varepsilon_2\) are the emissivities of the inner and outer surfaces, respectively
- \(T_1\) and \(T_2\) are the temperatures of the inner and outer surfaces, respectively
- \(Nu\) is the Nusselt number
- \(k_{air}\) is the thermal conductivity of air
- \(r_1\) and \(r_2\) are the radii of the inner and outer surfaces, respectively

The graph shows the temperature difference as a function of heat flux for different values of \(\Delta r\), the radial distance between the surfaces. The temperatures \(T_1\) and \(T_2\) are indicated for different scenarios.
Effect of air

- The higher heat flux, the more effect of air convection
- Temperature difference of 10°C is practical limit
- For CubeSat (Δr~1 cm), the internal heat generation is less than 1.6 W for ΔT<10°C
- CubeSat can be tested only by thermal cycle
- A satellite bigger than CubeSat requires thermal vacuum to produce representative temperature distance
When TV mandatory?

• For small satellites (e.g. CubeSat) or units with low power dissipation, TV may be replaced by TC

• TV is necessary for the units or small satellites
  – With pressure sensitive parts
  – With hermetically sealed items
  – With high voltage with corona or multipaction concerns
  – With high localized power densities
  – With new design with little or no flight heritage
  – Example: RF unit, Power control unit

• Even if TV is not done, at least a function test in vacuum is necessary
Homework

- Consider concentric sphere with $r_1$ and $r_2$.
  $r_1=0.05$ (m) and $r_2=0.1$ (m)
- The surface emittance is $\varepsilon_1=\varepsilon_2=0.9$
- The temperature $T_2$ is kept at 20 ($^\circ$C)
- Internal heat dissipation $Q$ is 1 (W)
- Calculate the temperature of the internal sphere $T_1$ when there is no air between $r_1$ and $r_2$ and when there is air of 1 (atm) pressure
- Repeat the calculation for the case of $Q=10$ (W) and 100 (W)
Thermal cycle test
Thermal cycle test

- Thermal cycle test is not suitable for the purpose of testing the effects of temperature distribution inside a test article.
- Thermal cycle test is still useful to test:
  - Survivability against thermal stress due to repeated cycles of high/low temperature
    - Solar array, antenna, etc.
  - Functionality at high and low temperatures for a small unit
    - Battery, sensor, etc.
  - Workmanship/material defects as a part of Environment Stress Screening
Thermal cycle chamber

- Can adopt a thermostatic chamber made for terrestrial use
  - Can buy a catalogued product from the market
  - Need to modify if cryogenic temperature is needed
- Easy to handle, automatic temperature control
Thermal cycle test

For electronics units

Fig. 19.4. Typical unit level thermal cycle profile.

Thermal cycle test

Make sure temperature being kept constant (typically within 3°C) during functional test. Temperature tends to increase due to the internal heat dissipation.


Definitions at hot and cold temperature plateaus
Temperature profile terminology

• Temperature stabilization
• Thermal dwell
• Thermal soak
• Thermal test tolerance
Thermal cycle test

For solar array

No functional test in the middle
Check functionality before and after the cycle test
Thermal cycle test

• **It is very important to identify the temperature measurement points**
  
• The points used for the control of environment temperature
  – Usually at mounting points of the unit
  – The interface temperature given from the satellite system
Thermal vacuum test
Temperature profile

- Baking for contamination/discharge prevention
- Discharge check
- Room Temp.
- Pressure

Turn-on

Less than 0.013 Pa

Functional test

Time

Thermal vacuum basic profile (unit)

From JERG-2-130
Thermal vacuum cycle profile

- **Baking**
  - Before starting cycling, raise the temperature to remove any residual gas from the test article
- **Cold/Hot start (turn-on)**
  - Confirm units can be turn-on at storage temperature (different from operational temperature)
- **Functional test**
  - Confirm functionality of test article at low/high (and middle) temperature extreme
  - Maintain the temperature at constant
- **Finish the test with high temperature side**
  - Avoid contamination on test article

Thermal balance test whose purpose is verification of thermal control subsystem may be done together with thermal vacuum test
Operation of heater/shroud system

- Maintaining at a constant temperature during functional test requires control
- Removal of internal heat dissipated
- Temperature control between hot/cold extreme

Without control

To be constant (within 3ºC)

Temperature rate specified
Operation of heater/shroud system

Baseplate (cryogenic)

Remove the dissipated heater via conduction to the baseplate
Operation of heater/shroud system

Temperature reading

Control the temperature by heater power and LN2 flow
Operation of heater/shroud system
Temperature control

- Monitoring of sensitive units during test

Monitor the temperature inside the satellite as much as possible
Either by thermo-couples or internal temperature sensors
Temperature control

- Wide temperature variation inside a satellite
  - Watching only one point may risk the other parts exceeding the temperature limit

- Divide the satellite into several zones
  - Turn-on/off payload or heater to maintain the temperature within acceptable range if necessary

Photo: from Space Systems Loral Web (sslmda.com)
Risk of Paschen discharge

Source: http://commons.wikimedia.org/wiki/File:Paschen_Curves.PNG

Risk of discharge when a high voltage unit is turned on while residual pressure is still high
High voltage units onboard satellites

Ion engine grid

Traveling Wave Tube Amplifier (TWTA)

Up to 1.5kV

Up to 15kV

Wait for a long time before you turn on

Do baking initially to accelerate degassing processes
Outgas (diffusion)

Diffusion of impurities from material

Diffusion: transportation from “dense” to “rare”

Dominated by random motion and collision

\[ \text{Speed of random motion} \sim \sqrt{\frac{\kappa T}{m}} \]

Higher temperature -> more diffusion
Outgas (diffusion)

Temporal profile of impurity density distribution within solid material

From 堀越源一、「真空技術」、東京大学出版会、1976
Outgas (desorption)

Particles (molecules, atoms) are attached to surface by chemical reaction (chemisorption) or van der Waals’s force (physisorption)
Trapped by a potential well of depth ΔE
Particles are detached from the surface with a probability proportional to

$$\exp\left(-\frac{\Delta E}{\kappa T}\right)$$  Arrhenius

The Higher temperature, the more desorption
Outgas (baking)

Chamber pressure

Without baking

Temperature

Heater-on

with baking

Time
Contamination

Solar panel coupon contaminated after test
Boeing 702

http://media.komonews.com/images/070215_boeing_telesat_702.jpg
Boeing 702

http://space.skyrocket.de/doc_sat/hb-702.htm
Contamination

• Particulate contamination
  – Dust, hair, paint flake, etc.

• Molecular contamination
  – Molecules attached to surface
  – Oil vapor, human sebum (sweat, etc.), organic materials, etc.
  – Attach to the surface by losing energy to move freely
Contamination

Free moving particle

vacuum

Solid object

Adsorption

Lose energy to the wall

Solid object

vacuum

It is easier for the particle to lose energy when the wall temperature is low.
While the satellite is heated, the contaminant on the satellite is removed from the surface and trapped at the shroud wall.

While the satellite is cooled, some of the contaminant inside the chamber may attach to the satellite surface.
Contamination

Finish test at hot cycle to prevent reattachment of contaminants.
Gas purge and chamber care

- Water is the major constituent of adsorbed molecules
- After a vacuum test, purge the chamber with nitrogen or dry air to avoid atmospheric vapor entering the chamber
  - Be careful about suffocation (if you use N₂) when you open the chamber door
- Minimize the time exposed to wet atmosphere
  - Shut the chamber door and maintain it in vacuum
- Wear gloves when you work on chamber to avoid your sweat contaminating the chamber surface
- Clean the surface with alcohol
Temperature measurement

A thermocouple measuring circuit

Depends on $T_h - T_c$ and combination of Metal A & B

Need to know $T_c$ precisely

Temperature measurement

<table>
<thead>
<tr>
<th>Type</th>
<th>Temperature range °C (continuous)</th>
<th>Temperature range °C (short term)</th>
<th>Tolerance class one (°C)</th>
<th>Tolerance class two (°C)</th>
<th>IEC Color code</th>
<th>BS Color code</th>
<th>ANSI Color code</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>0 to +1100</td>
<td>−180 to +1300</td>
<td>±1.5 between −40 °C and 375 °C</td>
<td></td>
<td>±0.004×T between 375 °C and 1000 °C</td>
<td></td>
<td>±2.5 between −40 °C and 333 °C</td>
</tr>
<tr>
<td>J</td>
<td>0 to +750 °C</td>
<td>−180 to +800</td>
<td>±1.5 between −40 °C and 375 °C</td>
<td></td>
<td>±0.004×T between 375 °C and 750 °C</td>
<td></td>
<td>±2.5 between −40 °C and 333 °C</td>
</tr>
<tr>
<td>N</td>
<td>0 to +1100</td>
<td>−270 to +1300</td>
<td>±1.5 between −40 °C and 375 °C</td>
<td></td>
<td>±0.004×T between 375 °C and 1000 °C</td>
<td></td>
<td>±2.5 between −40 °C and 333 °C</td>
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<td>R</td>
<td>0 to +1600</td>
<td>−50 to +1700</td>
<td>±1.0 between 0 °C and 1100 °C</td>
<td></td>
<td>±1.5 between 0 °C and 1100 °C</td>
<td></td>
<td>±1.5 between 0 °C and 600 °C</td>
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<tr>
<td>S</td>
<td>0 to +1600</td>
<td>−50 to +1750</td>
<td>±1.0 between 0 °C and 1100 °C</td>
<td></td>
<td>±1.5 between 0 °C and 1100 °C</td>
<td></td>
<td>±1.5 between 0 °C and 600 °C</td>
</tr>
<tr>
<td>B</td>
<td>+200 to +1700</td>
<td>0 to +1820</td>
<td>Not Available</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>T</td>
<td>−185 to +300</td>
<td>−250 to +400</td>
<td>±0.5 between −40 °C and 125 °C</td>
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<td></td>
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<tr>
<td>E</td>
<td>0 to +800</td>
<td>−40 to +900</td>
<td>±1.5 between −40 °C and 375 °C</td>
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<tr>
<td>Chromel/AuFe</td>
<td>−272 to +300</td>
<td>n/a</td>
<td>Reproducibility 0.2% of the voltage; each sensor needs individual calibration.</td>
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</tr>
</tbody>
</table>

In space, T-type (and K-type) is mostly used
Temperature measurement

- Measurement surface and sensor head are insulated by Kapton tape
- Sensor head should be firmly attached to the surface (aluminum tape recommended)
- Sensor cover $\alpha$ and $\varepsilon$ should match with the measurement point
- To minimize the heat leak through thermocouple
  - Thermocouple lead should be attached to the surface to make the lead the same temperature as the measurement point
  - Use small diameter lead
Temperature measurement

Onboard thermistor for cold-junction compensation

Need to know $T_C$ precisely


Contamination measurement

Satellite

Witness plate  TQCM, QCM

Mass measurement  Chemical analysis

In-situ measurement of contaminant accumulation
QCM

Quartz Crystal

Mass increases
Decrease of resonant frequency

http://jp.fujitsu.com/group/fql/services/environment/qcm/
TQCM

- Thermoelectric Quartz Crystal Microbalance
- Maintain the temperature at constant by Peltier device
  - -80°C ~ +100°C
- Need to evaluate contamination effects on satellite surface
  - Not how much contaminant comes out
- Limited supplier
Deployment test

- Deployment such as antenna or solar paddle is the life-critical moment of a satellite
- Deployment is often as soon as after satellite separation
- Temperature may not yet controlled
  - Especially small piggy-back satellites
- Deployment under cold environment may be challenging
  - Stiff material
  - Low lubrication
Deployment test

• Demonstrate a deployment system works under the possible worst case
  – Cold and vacuum (at least either of the two)
  – Microgravity (very difficult to test)
Deployment test
Deployment test
Deployment test

HORYU-II antenna deployment at -50°C (-11°C battery)