Missions in Low $T$ Environments: Architectures, Issues, Failures

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Overview

• Definition
  – Mars
  – Titan
  – Other Cold Places

• Missions operating in low $T$ environments
  – Past, current, future

• Effects of Low $T$ on Probe Architecture & Subsystems
  – Power, Electronics, Structural, Thermal, Mobility
Definition: What (and Where) do we mean by “Low Temperature”? 

- ‘Low $T$’ is regarded as below -55°C (electronics limit)
- May be coupled with deep thermal cycling, e.g. Mars
- ‘Greenhouse effect’ relative to airless worlds
- Atmosphere acts as a heat conduction path – e.g. forced convection during parachute descent
- Heat loss issues may in fact be greater for a mission to an atmosphere than to a less cold, airless body
- The $T$ of a probe element is in general not the same as the natural $T$ of its environment (thermal design, heat capacity, …)
- May also need to avoid overheating, e.g. during cruise or early afternoon
- Moving from low to high $T$ in humid atmosphere may produce condensation on probe
Martian Atmospheric Temperature (1m above surface)

- Mars: -143°C to +27°C (surface); see ref models
  - Large diurnal variation (e.g. Phoenix, Sol 13: -80°C to -32°C)
  - Variations with latitude, topography, surface properties,…
Mars Atmospheric Profile

- See also Mars Climate Database, Mars-GRAM, TES & THEMIS data,...
Mars Atmospheric Profiles from Spirit & Opportunity

Withers and Smith, 2006
• Titan: -178°C (surface), ~-203°C (tropopause ~40km)
  - Small diurnal variation

Fulchignoni et al., 2005
Some Other Cold Places

- Low $T$ challenges also (in fact predominantly) faced by orbiter / flyby spacecraft, airless body landers and cooled optics / focal plane instruments
- Deep Space / Outer Solar System (Pioneer 10/11, Voyager 1,2, New Horizons, Galileo, Cassini, Rosetta, Juno, …)
- Cometary nuclei (Philae) (~-150°C)
- Lunar night (-160°C) & shadowed craters (-230°C)
- Cooled s/c assemblies (e.g. IR telescope optics & focal plane)
- Icy satellites
  - Enceladus: -193°C (equator), -188°C (S pole)
  - Europa: -180°C (surface)
  - Triton: -235°C (surface)
In Situ Missions to Worlds with Atmospheres

Launch date


Programme

US Mars:
- Pioneer Venus
- Pathfinder
- + Soviet/Russian Mars
- MPL/DS-2
- Phoenix
- MER
- MSL
- Beagle 2 +
- ExoMars +

US Other:
- + Pioneer Venus
- + Galileo

HOT

COLD

Europe:
- Huygens

Other:
- ExoMars

Soviet/Venera/VeGa

HOT

COLD
Mars In Situ Missions

- 2MV-3 probe
- M-71 landers (Mars 2,3)
- M-73 landers (Mars 6,7)
- Viking Landers*
- Mars 96 Penetrators*
- Mars 96 Small Stations**†
- Mars Pathfinder
- Sojourner†

- *RTG power & thermal
- †RHUs

- Mars Polar Lander
- DS-2 Mars Microprobes
- Beagle 2
- MER (Spirit & Opportunity)
- Phoenix
- MSL*
- ExoMars†
MER, MPL, Phoenix

- Warm Electronics Box (WEB) underneath an equipment deck
• Forced convection during descent
• Foam insulation (Basotect)
• RHUs
• Minimal sensors exposed
  – HASI TEM, PWA
  – SSP ACC-E, API-V, API-S, PER, THP, REF, DEN
  – DISR apertures
  – GCMS & ACP inlets
• Probe also had to cope with warm Venus flyby
• Higher than predicted heat losses around parts of the probe connected to the outside – thermal model underpredicted losses?
Huygens Thermal Design

Back cover
External MLI: 15 layers
HTP/Prosial: 0.5 to 2.7 mm thick
Al structure 0.8 to 1.6 mm thick

Titanium struts to orbiter
SED + ring: 15 layers of MLI
Labyrinth foils

Front shield exterior
Rear face exterior: MLI 15 to 16 layers
HTP/Prosial: 2.1 mm thick
CFRP/Honeycomb structure
HTP/AQ60: 18.2 mm thick
Front face exterior: MLI 15 to 16 layers

Front shield central section
CFRP/Honeycomb structure
HTP/AQ60: 17.4 mm thick
External MLI 15 layers

J. Garry (after ESA)
Future Missions to Low T Environments

- Mars
  - Sample Return
  - Balloon
  - Polar caps
  - Caves
- Titan
  - Balloon
  - Lander
  - Ocean explorer
- Saturn, Uranus, Neptune entry probes

Effects of Low T on Probe Architecture & Subsystems

- Low $T$ has consequences for many subsystems:
  - Power (Batteries, RTGs, Solar Arrays, Fuel cells, Flywheels, Capacitors)
  - Electronics
  - Communications
  - Structure
  - Thermal
  - Mobility
  - Propulsion
  - …

- Probes convert stored or absorbed energy to heat, RF emission and mechanical work
Effects of Low $T$ on Power

- Increased efficiency at low $T$, so fall off vs. $r$ from Sun goes not as $r^2$ but $r^{1.7}$.
- Lower solar intensity reduces temperature, but forces larger area arrays
  - Practical limit being pushed by LILT (Low Intensity, Low $T$) array technology
  - Beyond that limit, nuclear is only option (RTG, MMRTG, Stirling Cycle RTG)
- Heat from RTGs is a useful by-product in a low $T$ environment, for keeping electronics (and balloon gas) warm
- Batteries stop working at low $T$; current limit is around -40°C (Li-ion) BUT new technologies under development
- See sections 4.3.5 and 5.2.4 of JPL report
- Performance metrics
Figure 4.31: The effects of temperature on the performance of various primary and rechargeable commercial batteries.
Effects of Low $T$ on Electronics

- Sections 4.3.2 and 5.2.2 of JPL report
- Limited commercial demand for components
- Thermal cycling – wear on solder joints
- Performance metrics
Effect of Low $T$ on Structure

- Low $T$ makes many materials brittle
- Differential thermal expansion – degradation of joints
- Implications for
  - Structural components
  - Parachute systems
  - Balloon envelopes
  - Icy satellite penetrators
Effects of Low $T$ on Thermal Design

- Heat loss shortens a mission and/or increases the resources needed to maintain temperature
  - Solar absorbers (e.g. Philae, Beagle 2)
  - Insulation (e.g. Basotect foam in Huygens, aerogel in Sojourner)
  - RHUs ($^{238}$Pu, $^{210}$Po)
  - Electrical power
  - Phase-change materials
Effects of Low $T$ on Mobility

- Mechanisms – operation of gears and bearings below -130°C limited to 1,000,000 cycles, and drive and position sensors limited to -130°C
- Cold electronics can greatly simplify cabling to wheels, etc.
- Sections 4.4.2, 4.4.4, 5.3.2, 5.3.4 of JPL Report
- Performance metrics
Conclusions

• Coping with low $T$ is less challenging than coping with high $T$
  – Heating easier than cooling
• Importance of good models
• Trade-off between Low $T$ technologies (High cost? Lower TRL? Worse performance?) and providing (where feasible) a warm environment (e.g. ebox)
• Current and foreseen architectures still centred around warm compartment for battery & electronics, with insulation and heating
• Many sensors and subsystems need to be outside, however
• What new measurements or probe architectures might be enabled by low $T$ technologies?
• What testing strategy for low $T$ atmospheric environment?