Thermal Margins for Flight Electronics Review and Assessment


Jet Propulsion Laboratory, California Institute of Technology

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Agenda

- Scope of the Investigation
- JPL Thermal Margins
- Comparison of Thermal Margins
- Margins by Domain
  - Qualification / Protoflight
  - Thermal Control System
  - Parts and Derating
  - Reliability
- Integrated Margin and Conservatism
- Observations and Assessment
- Conclusions
The scope of this investigation is limited to

- Electronic assemblies (typically instruments or bus mounted)
- Hot operating conditions
JPL Thermal Margins

Protoflight/Qualification Margin (AFT + 20°C or 70°C, whichever is higher, per Design Principles)

Thermal Design Margin, ≥ 0

Worst Case Hot / Cold Predicted Temperature Range

Thermal Design Margin, ≥ 0

Protoflight/Qualification Margin (AFT - 15°C or -35°C, whichever is lower, per Design Principles)

FA Thermal Reliability Margin (+5°C per Design Principles)

Allowable Flight Temperature Range

Flight Acceptance Temperature Range

FA Thermal Reliability Margin (-5°C per Design Principles)

Protoflight / Qualification Temperature Range

Design & Analysis

Testing
Comparing JPL Margins

- **JPL**
  - 20C Qual/Proto Margin (min = 70C)
  - AFT hot
  - 5C FA Margin
  - 15C Qual/Proto Margin (max = -35C)

- **GSFC and Typical Industry Margin**
  - 10C Qual/Proto Margin
  - Worst Case Prediction
  - 5C FA Margin
  - 5C Uncertainty
  - 5C FA Margin

- **The Aerospace Corporation (1540) Margin (for one of)**
  - 10C Qual/Proto Margin
  - Worst Case Prediction
  - 5C FA Margin
  - 11C Uncertainty (for test correlated models)
  - 5C FA Margin
  - 11C Uncertainty (for test correlated models)

-AFT = Allowable Flight Temperature

- **TFAWS 2012**

- **For a series of satellites**
  - - protoqual
  - - FA

- **GSFC** and **Typical Industry Margin**

- **The Aerospace Corporation (1540) Margin**

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Comparing JPL Margins

- **Qual hot**
  - 20C Qual/Proto Margin (min = 70C)
  - 5C FA Margin
  - Worst Case Prediction

- **Qual cold**
  - 15C Qual/Proto Margin (max = -35C)
  - 5C FA Margin
  - 10C Qual/Proto Margin

- **10C Qual/Proto Margin**
  - 5C FA Margin
  - 5C Uncertainty

- **Worst Case Prediction**

- **11C Uncertainty**
  - (for test correlated models)

- **10C Qual/Proto Margin**
  - 5C FA Margin
  - 10C Qual/Proto Margin
  - 11C Uncertainty
Comparing JPL Margins

- **20C Qual/Proto Margin (min = 70C)**
  - WC hot: 5C FA Margin
  - WC cold: 15C Qual/Proto Margin (max = -35C)

- **10C Qual/Proto Margin**
  - WC hot: 5C FA Margin
  - WC cold: 10C Qual/Proto Margin

- **Uncertainty**
  - 5C Uncertainty
  - 11C Uncertainty (for test correlated models)

- **Worst Case Prediction**
  - WC hot: 10C Qual/Proto Margin
  - WC cold: 10C Qual/Proto Margin

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Bus electronics design temperature range

Bus electronics shall be designed to operate within specification over the temperature range of -35°C to +70°C or AFT temperature limits extended by -15°C and +20°C, whichever is more severe.

"line in the sand"
Historic Background

• Historic background from early Ranger missions:
  – Upper limit of 50C based on max temperature of a white painted surface at full sun exposure between earth and moon
  – Lower limit of 5C based on freezing temperature of Hydrazine
  – Anticipated planetary mission to Venus and potential passage through earth’s shadow resulted in 25 margin
    • -20C/75C, later changed to -20C/70C
Qualification

• The minimum electronics Qual/PF temperature limit of 70°C promotes a robust and reliable hardware design that will lead to successful missions.

• Designing to a 70°C Qual/PF temperature constrains thermal rise from the assembly baseplate to the electronic part junctions, resulting in lower in-flight junction temperatures, than would otherwise result from lower Qual/PF limits.

• It decouples the electronic assembly thermal design from flight system thermal design, allowing both disciplines to proceed with their designs in parallel with little chance for margin deterioration.
- Requirement as stated

- AFT
Thermal Control System

- The thermal control system is designed to maintain the payload and the spacecraft subsystems within their Allowable Flight Temperature [AFT] requirements for all operating modes, in all thermal environments it may be exposed to, throughout the mission lifetime.

- JPL’s standard thermal engineering practice prescribes worst case methodologies for design.

- Uncertainty in absolute temperatures and, consequently, in margins is usually estimated by sensitivity analyses.
Qualification and Thermal Control

- Requirement as stated

- AFT

ΔT (design space) available to heat rejection

- Required Qualification and Junction Temperature, [°C]

- Allowable Flight Temperature, [°C]

For Hot Operating Conditions
Parts and Derating

- Derating prevents small changes in operating characteristics from creating large increases in failure rates.
- Present derating policy is intended to reduce the occurrence of stress related failures and help assure long-term reliability.
- JPL derating guidelines provide derating factors to be applied as a percentage of maximum rated values for critical device parameters.
- The derating factor needed depends on the tolerance of the design to variation in operating parameters.
- A key derating parameter for microcircuits and discrete semiconductors (diodes, transistors, optoelectronics) is junction temperature.
Parts and Derating

- Historically, junction temperature (Tj) derating for silicon microcircuits in ceramic hermetic packages has been limited to between 110°C and 115°C.
- The basis of this calculation can be described as follows:

\[ MTTF \propto e^{-\frac{E_a}{kT}} \]

\( MTTF = \) mean time to failure  
\( E_a = \) activation energy, a constant  
\( k = \) Boltzmann’s constant  
\( T = \) Temperature, [K]

- In order to achieve twice the lifetime, the junction temperature must be lowered such that the MTTF is twice the nominal values.
- For a 125°C max rated Tj device, assuming an \( E_a = 0.6 \) eV, the typical 10-year MTTF can be extended by a safety margin of two by lowering the junction temperature by 15°C to 110°C.
Qualification, Thermal Control and Parts

- Typical Junction Limit
- Requirement as stated
- AFT

Required Qualification and Junction Temperature, [°C]

ΔT (design space) available to heat rejection

Allowable Flight Temperature, [°C]
For Hot Operating Conditions
Packaging

- Packaging designs are dominated by multilayer circuit board technology using mostly packaged and screened electrical components.
- Thermal performance is dominated by heat conduction, with no convection and usually minor radiation transfer.
- The primary margin is in the protoflight temperature used for analysis compared to the allowable flight temperature (AFT).
  - No other margin is intentionally added in the thermal analysis process.
  - But there is likely to be some margin in the power dissipations used for analysis.
Qualification, Thermal Control, Parts and Packaging

- Typical Junction Limit
- Requirement as stated
- AFT

ΔT (design space) available to heat rejection

ΔT (design space) available to packaging

Qualification Margin

Required Qualification and Junction Temperature, [°C]

Allowable Flight Temperature, [°C] For Hot Operating Conditions
Reliability

• Temperature is one of many factors for key reliability design analysis

• These temperatures are based upon Qual/Protoflight temperatures at the thermal control surface (TCS).

• Electronic Parts Stress Analysis (EPSA)
  – Identifies highly stressed parts
  – Commonly, the EPSA is completed first using the assumption of a 20°C rise from the thermal control surface (70°C) to the part case

• Worst-Case Analysis (WCA)
  – Demonstrates margined performance under extreme conditions
  – Assumes a 10°C rise from the thermal control surface (70°C) to the part case for the hot condition

• Temperature rise assumptions used in the EPSA and WCA must be verified and reconciled with the Thermal Analysis once the results are available.
Qualification, Thermal Control, Parts, Packaging and Reliability

- Typical Junction Limit
- Requirement as stated
- AFT
Integrated Margins

- The figure depicts an integrated picture of JPL’s margin. The complexity of the approach becomes readily apparent.

![Diagram showing Integrated Margins with various analysis and operating conditions.](image-url)
Conservatism

- In addition to margins, domains apply conservatism. To the degree that actual flight temperatures are lower than predictions because of this conservatism, actual junction temperatures are lowered by the same amount. The degree of applied conservatism is experience-based and can be fine-tuned if resources permit.

<table>
<thead>
<tr>
<th>Domain</th>
<th>Conservatism</th>
<th>Margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parts</td>
<td>worst case power</td>
<td>Derating/Screening</td>
</tr>
<tr>
<td>Packaging</td>
<td>worst case material properties</td>
<td></td>
</tr>
<tr>
<td></td>
<td>worst case operating conditions</td>
<td></td>
</tr>
<tr>
<td>Qualification</td>
<td>70°C heat sink boundary</td>
<td></td>
</tr>
<tr>
<td>Reliability</td>
<td>worst case voltage/current</td>
<td></td>
</tr>
<tr>
<td>Thermal Subsystem</td>
<td>worst case power</td>
<td></td>
</tr>
<tr>
<td></td>
<td>worst case material properties</td>
<td></td>
</tr>
<tr>
<td></td>
<td>worst case operating conditions</td>
<td></td>
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<tr>
<td></td>
<td>worst case environment</td>
<td></td>
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<tr>
<td></td>
<td>worst case attitude</td>
<td></td>
</tr>
<tr>
<td></td>
<td>worst case configuration</td>
<td></td>
</tr>
</tbody>
</table>
Observations

• Existing margin requirements
  – Are applied in a *one size fits all* fashion
  – Are agnostic to mission class

• Over time, responsibility for elements of the overall thermal design has been segregated into different disciplines and organizations

• The relevant margin elements are
  – *Reliability* (Line In The Sand, aka *LITS*)
  – *Qualification* (AFT + 20°C)
  – *Derating* (of allowable junction temperatures)
Segregation facilitates concurrent design but does not consider uncertainties, risk and margin in a holistic way.

The introduction of a considerable number of new parts to the design, which were not in use when margin requirements were originally established, complicates the situation.

Higher packaging density and resulting heat concentration make it increasingly difficult to keep the chassis to junction temperature rise within the currently required 40°C.
Assessment

• Benefits of a JPL margin reduction
  – vendor hardware qualification will be in family
  – compatibility with the margin approach of the Goddard Space Flight Center (GSFC) is established
  – the inherent risk posture of different mission classes is acknowledged
  – the thermal “headroom” for parts packaging is increased
  – the number of waivers will be reduced
Assessment

- Downside of reduced qualification and reliability margins
  - design or hardware heritage for future use is limited
  - inflight anomalies need to be met with lower margins
  - junction temperatures can potentially increase
Conclusions

• This study has reinforced that robust margins are inherently tied to JPL’s mission success.
• It also has become apparent that today’s diversity of missions will benefit from a more flexible approach to defining margin requirements than the currently practiced *one size fits all* approach.
• The complexity of determining the margin approach over the spectrum of applicable scenarios has so far prevented our institution from converging on a specific set of recommendation.
• This work provides a point of departure for future discussion that is soundly based on past experience and a renewed understanding of the intent and merits of our margin.
Thank you for your attention.

Any questions?
Appendix
<table>
<thead>
<tr>
<th>Characterization</th>
<th>Class A</th>
<th>Class B</th>
<th>Class C</th>
<th>Class D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Priority (Criticality to Agency Strategic Plan) and Acceptable Risk Level</td>
<td>High priority, very low (minimized) risk</td>
<td>High priority, low risk</td>
<td>Medium priority, medium risk</td>
<td>Low priority, high risk</td>
</tr>
<tr>
<td>National significance</td>
<td>Very high</td>
<td>High</td>
<td>Medium</td>
<td>Low to medium</td>
</tr>
<tr>
<td>Complexity</td>
<td>Very high to high</td>
<td>High to medium</td>
<td>Medium to low</td>
<td>Medium to low</td>
</tr>
<tr>
<td>Mission Lifetime (Primary Baseline Mission)</td>
<td>Long, &gt;5 years</td>
<td>Medium, 2-5 years</td>
<td>Short, &lt;2 years</td>
<td>Short &lt; 2 years</td>
</tr>
<tr>
<td>Cost</td>
<td>High</td>
<td>High to medium</td>
<td>Medium to low</td>
<td>Low</td>
</tr>
<tr>
<td>Launch Constraints</td>
<td>Critical</td>
<td>Medium</td>
<td>Few</td>
<td>Few to none</td>
</tr>
<tr>
<td>In-Flight Maintenance</td>
<td>N/A</td>
<td>Not feasible or difficult</td>
<td>Maybe feasible</td>
<td>May be feasible and planned</td>
</tr>
<tr>
<td>Alternative Research Opportunities or Re-flight Opportunities</td>
<td>No alternative or re-flight opportunities</td>
<td>Few or no alternative or re-flight opportunities</td>
<td>Some or few alternative or re-flight opportunities</td>
<td>Significant alternative or re-flight opportunities</td>
</tr>
<tr>
<td>Achievement of Mission Success Criteria</td>
<td>All practical measures are taken to achieve minimum risk to mission success. The highest assurance standards are used.</td>
<td>Stringent assurance standards with only minor compromises in application to maintain a low risk to mission success.</td>
<td>Medium risk of not achieving mission success may be acceptable. Reduced assurance standards are permitted.</td>
<td>Medium or significant risk of not achieving mission success is permitted. Minimal assurance standards are permitted.</td>
</tr>
<tr>
<td>Examples</td>
<td>HST, Cassini, JIMO, JWST</td>
<td>MER, MRO, Discovery payloads, ISS Facility Class Payloads, Attached ISS payloads</td>
<td>ESSP, Explorer Payloads, MIDEX, ISS complex subrack payloads</td>
<td>SPARTAN, GAS Can, technology demonstrators, simple ISS, express middeck and subrack payloads, SMEX</td>
</tr>
</tbody>
</table>

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Minimum Acquisition Cost. Class D is defined as a higher-risk, minimum-cost effort. The characteristics for Class D usually involve some combination of the following features: medium to low national prestige, short life. Low complexity, small size, single string designs, simple interfaces. hard failure modes, no flight spares, lowest cost, short schedule, and a noncritical launch schedule. Vehicle and experiment retrievability or in-orbit maintenance may or may not be possible.
Projects in the Context of Requirements

Thermal Margin Assessment

- CloudSat HVPS
- SeaWinds, QuikScat
- MSL CPA, OCO, SMAP
- SMAP Spin Elect.
- Voyager ISS, MSL, MER
- Juno, MER
- OSTM
- ST7/MIRI
- M3
- MER Radar Electr.
- MER Mini TES
- Viking, Voyager
- Galileo, Casini

Required Qualification and Junction Temperature, [°C] vs. Allowable Flight Temperature, [°C]