Loon LLC

Reliability Requirements Document

2020

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Objectives

This document is meant to serve the following purposes:

1. Provide background information into reliability testing methodology and requirements
2. Document all test SOPs across all subsystems
3. Document reliability specifications including justifications
4. Document reliability targets for the vehicle and each subsystem
5. Provide insight into test-to-field correlation

Reliability Engineering Basics

Why bother with reliability testing?

The primary goals of reliability engineering are to (1) uncover weaknesses in the design, (2) estimate how long a product will successfully perform its intended function under specified conditions before failing, and (3) ensure that the manufacturing processes and assembly lines are consistently producing good parts.

Benefits of a good reliability testing program include:

- Faster and more informed design iteration and downselection
- More robust manufacturing processes
- More intelligent dispatching of flights
- Longer flights!

Accelerated Life Tests

Failures on a real flight may take months to manifest. However, the development cycle does not afford us enough time to wait that long to make design decisions. Therefore the challenge is to precipitate inflight failures in the lab in a matter of days, while taking care to not excite any additional unwanted failure modes. This is made possible by accelerated life tests.

Accelerated tests can involve subjecting a product to a higher usage rate/duty cycle (time compression), higher stress levels than it would experience inflight (overstress), or both. All accelerated life tests have an acceleration factor (AF) through which it is possible to correlate test time to time in flight. The AF in a test with time compression is the ratio between the time in flight to the time in test. The AF in a test with overstress depends on the type of stress and the nature of the expected failure mode.

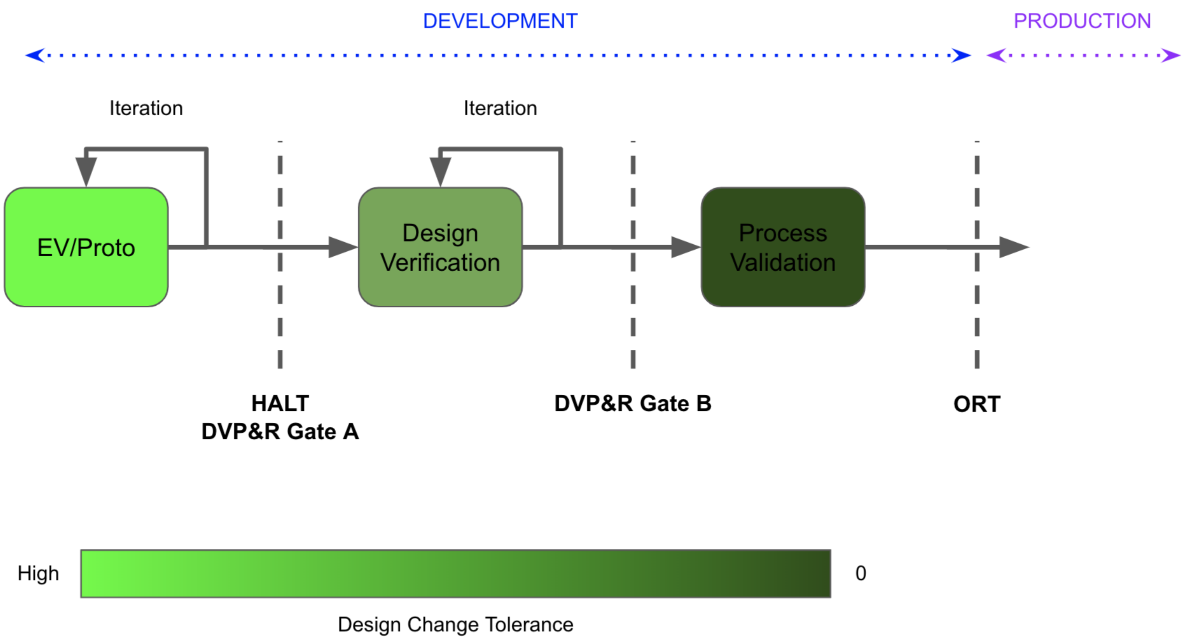
In summary, the main advantage of accelerated life testing is that it enables us to predict how long a real flight will survive after just a few days or weeks of lab testing.

Highly Accelerated Life Tests (HALT)

In HALT, a product is subjected to increasing levels of temperature and vibration stress (first independently and then in combination). The main deliverables of HALT are operational limits and design weak points (by producing multiple failure modes). Any failures in HALT must be followed up by thorough failure analysis to properly determine root cause. While HALT can be a quick and efficient way to evaluate a design, it is not usually possible to correlate test time to flight time. In other words, HALT has no AF.

When should we do reliability testing?

Reliability testing should be done in both the development phase and the production phase.



The development phase can be broken up into 3 stages: engineering validation (EV) or proto builds, design verification (DV), and process validation (PV). Each of these stages must have a customized reliability test criteria (DVP&R), which act as gates before being permitted to advance to the next stage. Failures in reliability tests at these stages can serve as useful information to design engineers and prompt a design iteration. However, any design iterations that happen within a stage also need to have a targeted reliability test plan to qualify them. The tolerance for design changes is relatively high in EV/proto builds, and progressively decreases in DV and PV builds. Lastly, reliability testing is still necessary in the production phase after the design is locked down. This is known as ongoing reliability testing (ORT), and is intended to monitor the production processes and assembly lines. ORT is useful for catching batch issues or quality drifts.

Reliability Statistics

Time-to-failure data from either reliability tests or inflight failures can be fit to a number of different statistical distributions, the main ones being exponential, lognormal, and Weibull. The exponential distribution models a constant failure rate and is useful for random failures. On the other hand, the lognormal distribution is useful for wearout/fatigue failures. However, the most commonly used distribution is the Weibull distribution because of its versatility. The cumulative density function (CDF) of the 2-parameter Weibull distribution is below:

$$F(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}}$$

Here, F(t) represents the cumulative probability of failure from zero till time t. It is also known as the unreliability function. The reliability function then is (1 - unreliability):

$$R(t) = e^{-\left(\frac{t}{\eta}\right)^{\beta}}$$

β is known as the shape parameter, and contains information about the nature of the failure mode. $\beta < 1$ indicates a failure rate that decreases with time (infant mortality), $\beta = 1$ implies a constant failure rate (random failures), and $\beta > 1$ indicates a failure rate that increases with time (wearout/fatigue failures).

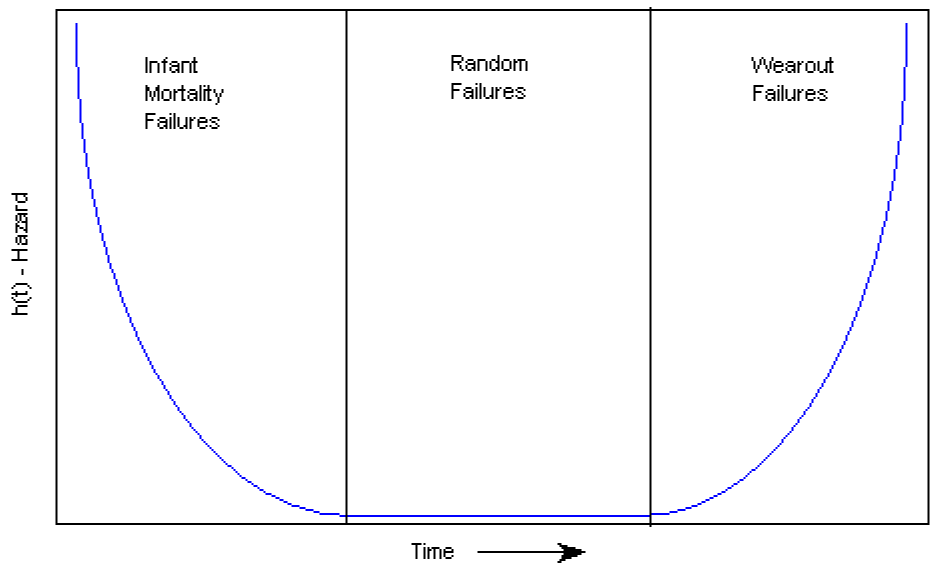
η is known as the characteristic life, and it represents the point at which 63.2% of the population has failed. For a given β, a higher η translates to a higher reliability.

β and η also affect the spread of the distribution. Generally, a higher β or a lower η imply a tighter failure distribution, meaning most failures happen in a well-specified time interval.

Another useful parameter is the hazard rate or instantaneous failure rate, which is the propensity of a product to fail in the next time interval given that it has survived so far. If the failures follow a 2-parameter Weibull distribution, the hazard rate can be expressed as:

$$h(t) = \frac{\beta}{\eta^{\beta}} t^{\beta - 1}$$

The hazard rate may be especially useful to a broader audience because it allows us to quantify the risk of a vehicle, which can be used to guide deployment and flight operations. Many products have hazard rates that follow the “bathtub curve”:



For most products, the hazard rate is high at the beginning (infant mortality failures due to manufacturing defects), lower in the center (random failures in the useful life stage), and high at the end (wearout failures).

Non-Parametric Methods

Weibull (and lognormal) distribution serves as useful parametric methods to fit failure data for a single failure mode. A rule of thumb to bear in mind - each failure mode is best represented by a distinct set of model parameters. Therefore, in the case when failure data involve multiple failure modes, a parametric method may no longer be appropriate.

Non-parametric methods provide a modeling option without assuming an underlying distribution. Compared to parametric models, there are a few keys advantages in using a non-parametric approach:

1. Simplicity in model methodology and inference
2. Avoids potentially significant errors due to incorrect assumptions
3. Model complexity increases with number of observations

Non-parametric Survival Function Estimator

The Kaplan-Meier estimator of the survival function has the following form:

$$\hat{S}(t) = \prod_{i:\, t_i \leq t} \left(1 - \frac{d_i}{n_i}\right)$$

t_i: *time when at least one event occurred*

d_i: $number\ of\ events\ (e.g.\ failed\ units)\ at\ time\ t_i$

n_i: $number\ of\ units\ known\ to\ have\ survived\ up\ to\ time\ t_i$

The Hardware Reliability team utilizes the Kaplan-Meier estimator for the following applications:

- Compare reliability improvements across engineering design iterations
- Assess reliability at targeted durations for population with potentially multiple failure modes

There are a few disadvantages with non-parametric methods, the most important one being that the model estimates have much wider confidence bounds. The higher uncertainty is due to the model not being restricted to fixed constraints (also known as assumptions). Therefore, it is often more appropriate to adopt a non-parametric method only when there is sufficient sample size. **An approach adopted by the Loon Hardware Engineering team is as follow:**

- Due to low sample size and lab failures are often studied in depth, reliability test results are recommended to be modeled using parametric methods
- Apply non-parametric methods for production fleet field data as long as large sample size is available given that root-cause of failure mode is often not able to be determined

A detailed example of the Kaplan-Meier method is presented here as an educational resource.

Non-parametric Hazard Rate Estimator

For cases when the hazard rate function needs to be estimated instead of the survival function, the **Nelson-Aalen estimator,** shown below, serves as the non-parametric method of choice.

$$\hat{H}(t) = \prod_{i:\, t_i \le t} \frac{d_i}{n_i}$$

d_i: $number\ of\ events\ (e.g.\ failed\ units)\ at\ time\ t_i$

n_i: $number\ of\ units\ known\ to\ have\ survived\ up\ to\ time\ t_i$

There are two extensions to the Nelson-Aalen estimator that will provide more practicality to hazard rate estimates:

- Estimate instantaneous risk at time *t*: A kernel function applied to the hazard function results in hazard rate estimates that can be interpreted as instantaneous risk of failure. The method is an informative tool in assessing the relative instantaneous failure risk at time *t* across the unit duration.

- Estimate total incurred risk up until time *t*: Summing the hazard rate results in the cumulative hazard rate, and can be interpreted as the total risk of failure up until time *t*

Competing Failure (CFM) and Mixed Failure Model (MFM)

Non-parametric methods are suitable when the acquired failure data does not provide more information aside from duration (or cycle units). However, with additional information, there are alternative modeling approaches that may be more suitable than non-parametric methods.

Competing Failure Model (CFM)

Assuming that cause for all failed units are available, system reliability may be modeled by combining multiple reliability functions with each function representing a distinct failure mode. Given a system subjected to *k* failure modes, the overall reliability for the system can be modeled as follow using CFM:

$$R(t) = \prod_{i=0}^{k} R_i(t)$$

$R_i: Reliability\ for\ i^{th}\ failure\ mode$

Each R_i can be modeled using various parametric forms and combined to create a more accurate model.

Mixed Failure Model (MFM)

Failure data may include subpopulations based on subsystem version, manufacturing process, usage environment, etc. MPM provides a form to fit the overall reliability function as the weighted sum of the reliability of each subpopulation:

$$R(t) = \prod_{i=1}^{m} p_i R_i(t)$$

$p_i: Proportion\ of\ population\ from\ subpopulation\ i$

$R_i: Reliability\ for\ i^{th} subpopulation$

Mixed Weibull Analysis (MWA) is a special case of the MPM where all reliability functions R_i is modeled using Weibull distribution. The resulting distribution R is then a continuous function composed of multiple Weibull distributions, and can be used to model the bathtub curve using the following equation:

$$R_{MW}(t) = \sum_{i=1}^{S} \frac{N_i}{N} e^{-(\frac{t}{\eta_i})^{\boldsymbol{\beta}_i}}$$

$S: Number\ of\ failure\ modes\ present$

MWA selects the parameters N_i, β_i, η_i using maximum likelihood estimation (MLE) and only requires the number of failure modes S to be specified.

In summary, CFM, MPM and MWA are useful to fit multimodal failure data (data with multiple failure modes). CFM is suitable when failure modes can be confidently assigned to each failed unit. If failure modes cannot be assigned or failure analysis is not possible, MPM/MWA may be used to model the overall reliability of the system.

Handling Small Sample Size

In cases when analysis is performed on small datasets with zero or very low number of failures, it is difficult to characterize reliability or failure distribution into a useful result. Assuming increasing the sample size is not feasible, there are a couple options to conduct an informative analysis but it requires incorporating additional assumptions to the model.

- Fixed Parameter Model: One of the Weibull parameters (β, η) are fixed and the observed data is used to estimate the other unconstrained parameter. The fixed value may be selected based on prior failure information or assumed based on the targeted failure mode.
- Weibayes: Instead of fixing one of the Weibull parameters to be a constant, Weibayes assign prior distributions to one or more parameters and using Bayes Theorem and iteratively computes the posterior distribution of the model parameters. An advantage for this approach is that the prior distributions may be defined to reflect the level of uncertainty of the parameters.

Both Fixed Parameter Model and Weibayes methods are available in JMP.

Sample Size Determination

A statistical approach to select the appropriate sample size for a reliability test is to use the binomial distribution. When seeking to determine the sample size needed to demonstrate a specified reliability target at a given confidence level, the non-parametric binomial distribution is often used:

$$1 - CL = \sum_{i=0}^{f} \binom{n}{i} (1 - R)^{i} R^{n-i}$$

where CL is the confidence level, f is the number of failures, n is the sample size, and R is the reliability.

If we want to calculate the required sample size assuming none of the units will fail in the test (f = 0), the equation simplifies to:

$$1 - CL = R^{n}$$

Reliability Targets

Equipment & Fixtures

Environmental Testing:

Chambers	Loon #	Qty.	Table size & Vol.	Temp. Range	Humidity Range	Vibration Capability	Pressure Capability	Max Cooling Ramp Rate
Chamber 1	R21 R22	2	48”x48” 90.1 cu.ft.	-100°C to 200°C	N/A	N/A	N/A	70°C/min
Chamber 2	R23	1	36”x36” 40.1 cu.ft.	-100°C to 200°C	N/A	5 - 75 gRMS	N/A	70°C/min
Chamber 3	R08	1	24”x24”x24” 8 cu.ft.	-70°C to 180°C	10%-98%	N/A	N/A	3.9°C/min
Chamber 4	R09 R10	2	30”x30”x30” 30 cu.ft.	-68°C to 180°C	10%-98%	N/A	N/A	4.0°C/min
Chamber 5	R15	1	38”x38”x38” 32 cu.ft.	-68°C to 180°C	N/A	N/A	N/A	5.4°C/min
Chamber 6	R16 R17 R18	3	40”x39”x38” 34.8 cu.ft.	-70°C to 180°C	10%-98%	N/A	N/A	9.6°C/min
Chamber 7	Mr. Freeze	1	48”x48”x48” 64 cu.ft.	-73°C to 177°C	N/A	N/A	55 hpa to ambient	10°C/min
Chamber 8	MCSK	1	48”x48”x48” 64 cu.ft.	-87°C to 177°C	N/A	N/A	55 hpa to ambient	70°C/min
Chamber 9	Mega TRON	1	48”x96”x48” 96 cu.ft.	-73°C to 177°C	N/A	N/A	55 hpa to ambient	10°C/min
Chamber 10	R14	1	39"x31"x39" 28 cu. ft.	-70°C to 180°C	10%-95%	N/A	N/A	13.5°C/min
Chamber 11	R24	1	N/A	-100°C to 200°C	N/A	N/A	N/A	15°C/min

Example Chamber:

- UV source - Xenon arc lamp
- Quartz inner, Boro-S outer: “Weathering tests with somewhat more and shorter UV than sunlight.”
- Lowest achievable chamber conditions:
    - Chamber set temperature: 30°C.
        - Results in values ranging from 30-35°C

    - Black panel set temperature (used to estimate rack temperature): 35°C.
        - Results in values ranging from 35-42°C
    - Set relative humidity: 25%.
        - Results in values ranging from 25%-35%.
- Current UV exposure recipe uses the above setpoints, and 8 hours/4 hours on/off exposure cycles.
    - Typical exposure duration for PE01 seals, 1-6 weeks.
        - Beyond that the seals are heavily degraded.
- Theoretical PE01 UV Absorption in Chamber vs In-Flight
    - In reality, PE01 seals treated in chamber tend to degrade 2x the rate they do in-flight.

Mechanical Testing:

- Universal Instron Systems
    - Tension and compression testing (4 point bend also available)
    - Temperature chamber range: -100°C to 350°C
    - Crosshead speed rage: 0.001 to 1,000 mm/min
    - Load cell limits: 100 N, 5 kN, 30kN
    - 3,000 mm/min also available up to 5kN
- Torsional Instron System
    - Static torsional testing
    - Option to use thermostream and temperature box to test at temperature
- Hysteresis Dynamometer

Dynamic Testing:

Dorne

Vertical Electrodynamic Shaker - VR4600

Mechanical Lab at 2081

Horizontal Electrodynamic Shaker - SAI30F-H560B-24/ST

Vertical Electrodynamic Shaker - SAI90-K170-24C

Electrical Testing:

Data Acquisition/Switch Unit

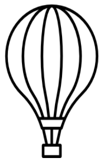
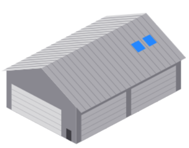
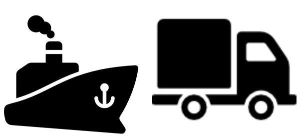
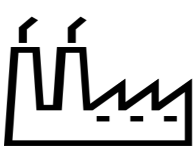
Oscilloscopes

True-rms multimeters

Vector Network Analyzers

Test Coverage

Stresses affecting reliability

 In-Flight	• HALT • Thermal characterization • Thermal cycling/shock • Cold soak • Heat soak • Water ingress • UV • VTCE • PTCE/HTOE • Burst Load • EMI/EMC • Lightning Induced Transients Testing
 Launch cart	• Mechanical shock • Dew test
 Hatchery	• Storage • ESD
 Shipping/Transport	• Transport Vibration • Handling Test • Salt Fog
 Manufacturing	• ESD

Test Coverage Matrix

	ACS	Avionics	Balloon	Comms Node	B2X	LTE	PDRA	Ground Station
Thermal Characterization	✓	✓	?	✓	✓	✓	✓	✗
HALT/VTCE	✓	✓	✗	✓	✓	✓	✓	✓
Cold Soak	✗	✗	?	✓	✓	✓	?	✗
Heat Soak	✗	◎	?	✓	✓	✓	✓	✗
Altitude/Pressure Cycling	✗	?	✗	✗	✓	✗	?	✗
Storage	✓	✓	✓	✓	✓	✓	✓	✗
Dew Test	✗	✗	✗	✓	✓	✓	✓	✗
Salt Fog	✗	✗	✗	✓	✗	✗	✗	◎
Water ingress	✗	✗	✗	✗	✗	✗	✓	✗
Transport Vibration	✓	✓	✗	✓	✓	✓	✓	✓
Transport Shock/ Handling	?	?	✗	◎	◎	◎	?	◎
Burst Load	✓	✗	✓	✗	✗	✗	✓	✗
Mechanical Shock	✗	✓	?	✓	✓	✓	✓	✗
Thermal Shock / Thermal Cycling	✓	✓	✗	✓	✓	✓	✓	✓
UV	✗	✗	✓	✗	✗	✓	?	◎
PTCE/HTOE	✓	✓	✗	✓	✓	✓	✓	✗
EMI/EMC/ESD	?	✓	✗	✓	✓	✓	✓	✗
Lightning Induced Transients Testing	?	✓	✗	✗	✗	✗	✓	✗

Legend:

✓ : test is currently done
☓ : test is currently not done
? : test is sometimes done (evaluated on a case-by-case basis by reliability engineer)
◎ : target to start implementing test (currently not done)

Specs

Reliability Test Specs

Thermal Characterization

Test Parameters:

-85 °C / 100 hPa (w/o load -- cold case)
-60 °C / 60 hPa (w/ load -- hot case)

Justification:

Without an electrical load, the UUT will experience a colder temperature, resulting in higher pressure. The test temperatures and pressures in the two test cases are based on the worst case estimates calculated from the vehicle's operating altitude range.

Storage Test

Test Parameters:

Truck transit (Induced B3 profile: up to 71C, up to 80%RH - 6 cycles) → Ocean transit (Induced B1 profile: 27C, up to 100% RH - 4 cycles) → Warehouse/dock (Induced B2 profile: up to 63C, up to 75%RH - 22 cycles). See MIL-STD 810G section 507.5 for profiles and table of setpoints.

Justification:

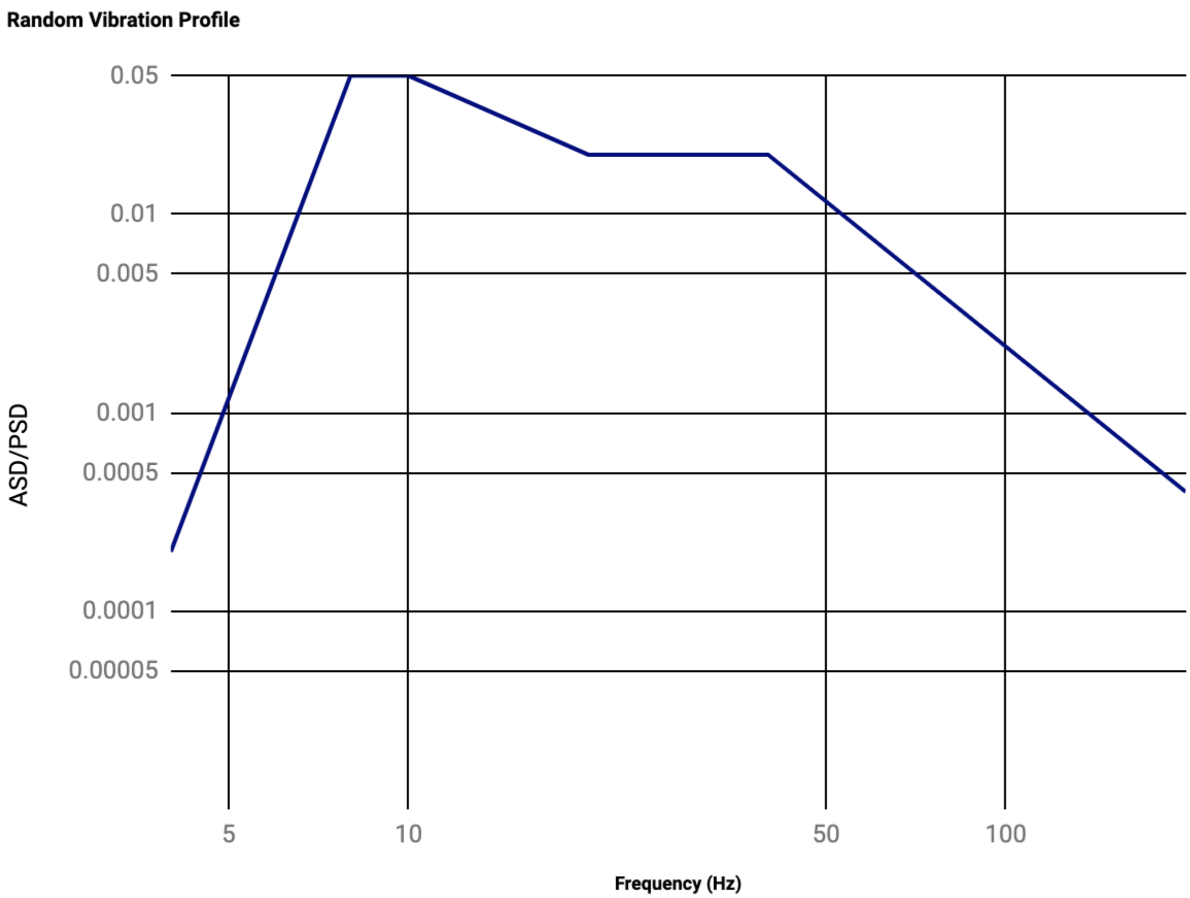
A UUT can be exposed to 3 different storage conditions. First, it is stored in a truck as it is transported to the shipping dock. Next, it is stored in a ship as it is transported overseas. Lastly, it is stored in a warehouse/dock until it is ready for assembly. Since each of these conditions subject the UUT to different temperatures and humidities, it is necessary to test under all 3 conditions.
The specific temperature/humidity setpoints for these 3 conditions are from MIL-STD 810G section 507.5, and the justification is as follows. Induced B3 profile (used to mimic truck transit) simulates a hot & humid environment, when the UUT receives heat from solar radiation with little/no cooling. Induced B1 profile (used to mimic ocean transit) primarily simulates a high humidity (> 95% RH) environment with a constant temperature. Finally, induced B2 profile (used

to mimic warehouse/dock storage) simulates a variable temperature/humidity environment for a longer period of time as in a warehouse.

Transport Vibration

Test Parameters:

The random vibration profile is as follows:



Frequency (Hz)	Power Spectral Density (g^2/Hz)
4	0.0002
8	0.05
10	0.05
20	0.02

40	0.02
200	0.0004
Overall g rms	1.166
Stroke (in.)	0.40

Note: As per ASTM D4169, handling tests (environmental preconditioning, package drop test, rotational drop test, tip test, side impact, etc.) are also done, but test specifications are currently under review for future test optimization.

Justification:

The average vibration values were recorded for a UUT transported from Mountain View to Puerto Rico (Puerto Rico is assumed to be the worst case due to rougher roads). In the future, an up-to-date industry standard (such as ISTA standard) may be considered as an alternative.

Mechanical Shock

Test Parameters:

- Part A:
  - Shock pulse magnitude: 14g sawtooth
  - Shock pulse duration: 15ms
  - # of shocks: 3 shocks per direction (+/-X, +/-Y, +/-Z)
- Part B:
  - Shock pulse magnitude: 10g half sine
  - Shock pulse duration: 11ms
  - # of shocks: 3 shocks per direction (+/-X, +/-Y, +/-Z)

Justification:

- Part A simulates launch. The profile used was derived as follows: a payload was instrumented with accelerometers (on gimbals) and the shock profiles were measured during various stages of launch (pushed around on the prep cart, pushed around on the launch cart, tethered launch) at WMC. SRS analysis revealed that the 14g sawtooth 15ms pulse was the best fit to mimic the shock experienced by the payload during real launch.
- Part B simulates balloon burst. The 10g magnitude comes from the design requirement that everything below the mechanical fuse should not experience more than 10g during balloon burst.

Thermal Shock/Cycling

Test Parameters:

- Temperature range: determined by RE
- Ramp rate: determined by RE. Ramp rate for thermal shock (usually ≥ 50C/min) should be higher than for thermal cycling (usually ≤ 20C/min).
- Dwell time: Long enough for UUT temperature to stabilize
- Cycles: determined by RE

Justification:

- Temperature range: This depends on several factors.
    - Location of component: If the UUT is thermally insulated from the surroundings, or if it is in close proximity to a warm component on the vehicle, it would not be tested to temperatures as low as -90C.
    - Presence of heaters: If the UUT has heaters to prevent it from approaching ambient temperatures, it would not be tested to temperatures much lower than the heater setpoint.
    - Operating temperature and heat dissipation: If the UUT generates heat while running and is inefficient at dissipating the heat, the high temperature limit would be closer to the upper limit.
- Ramp rate: The ideal ramp rate is as fast as possible without causing damage to any components (such as ceramic components) that are sensitive to fast temperature ramps. This would result in maximum thermal stresses due to CTE mismatches and precipitate failures in the shortest time frame. Any UUTs with ceramic components should be put through thermal cycling instead of thermal shock, which has more gradual temperature ramps that are more representative of real flights.
- Dwell time: The ideal dwell time is as short as possible while still allowing the temperature of the UUT to completely equilibrate with the chamber temperature. Thus the thermal mass of the UUT needs to be taken into account when choosing the dwell time.
- Cycles: The number of cycles needs to be equivalent to a certain number of days in flight that is greater than our reliability target by some margin. This needs to be evaluated on a case by case basis, and is dependent on the criticality of the component and the impact of failure. A rule of thumb is 2x the design life.

PTCE/HTOE

Test Parameters:

- Temperature range: minimum to maximum operating temperature of UUT
- Ramp rate: < 10C/min recommended, but determined by RE
- Dwell time: determined by RE
- Operational state: off when chamber is cold, on at maximum power when chamber is hot
- Cycles: determined by RE

Justification:

- Temperature range: Low temperature limit is the lowest temperature that the UUT is expected to experience in the field. While some subsystems have heaters to avoid reaching worst case ambient temperatures (-90C), the power budget needs to be factored in. If these subsystems are turned off due to insufficient available power, they may reach ambient temperatures. Therefore it may still be worth testing to -90C. High temperature limit is the maximum temperature the UUT will reach when running at full power. However, some subsystems (such as ACS, Avionics, etc.) are also run on the ground prior to launch. For these, there are 2 high temperature states: (1) running at max power on the ground, and (2) running at max power in flight at night. Therefore the RE must set the high temperature limit such that both these cases are covered.
- Ramp rate: The ramp rate is much lower than in thermal cycling/shock in order to avoid saturating the results with thermal fatigue failures (which would anyway be caught in thermal cycling/shock) and catch any additional failure modes from operating the UUT at high or low temperatures.
- Dwell time: The dwell time is based on the time to reach thermal steady state. This depends on the thermal mass of the UUT, location of the UUT on the system, how exposed the UUT is to the ambient temperature, and how much heat the UUT generates when it runs. Many of these can be learned through thermal characterization, which would be conducted before this test.
- Operational state: When the chamber is cold, the UUT is off to keep its temperature as low as possible. Once the chamber is hot, the UUT is powered on with maximum power draw to elevate its temperature as much as possible.
- Cycles: The number of cycles needs to be equivalent to a certain number of days in flight that is greater than our reliability target by some margin. This needs to be evaluated on a case by case basis, and is dependent on the criticality of the component and the impact of failure. A rule of thumb is 2x the design life.

UV

Test Parameters:

- Lamp: Xenon
- Irradiance (outdoor): 0.35 W/m^2 @ 340nm
- Chamber Temperature: 38°C
- Black panel (rack) temperature: 55°C
- Relative Humidity: 55%
- Filters: borosilicate for inner and outer filters
- Water spray: off
- Duration: 1500 hours

Justification:

- Lamp: Xenon arc lamp simulates full-spectrum sunlight in a chamber, and has better correlation to natural sunlight than fluorescent lamps
- Irradiance (outdoor): An irradiance of 0.35 W/m^2 was chosen because this aligns with the irradiance of natural sunlight of 340nm. Ultraviolet light consists of wavelengths between 10nm and 400nm. However, 340nm is chosen because it is in the range of Ultraviolet A (UVA) light, which is not absorbed by the ozone layer. However, this reference data does not account for the high altitude of the balloon and the low temperatures in the stratosphere.
- Chamber Temperature: UV degradation occurs faster at higher temperatures. Hence, a chamber temperature of 38C is very conservative and allows for acceleration of the test, as a real flight would not reach temperatures this high.
- Black panel (rack) temperature: The black panel temperature provides an estimate of the maximum sample temperature. If the sample is overheated during the UV test, this may result in undesirable failure modes. Hence, the black panel temperature is capped at 55C, ensuring the samples do not get hotter than 55C.
- Filters: Filters help obtain the desired spectral power distribution. Borosilicate is the most commonly used filter to simulate the spectral power distribution of natural sunlight. However, previous studies have indicated that a different combination of filters may be necessary to achieve a higher total UV irradiance that more closely approximates the total UV irradiance at the average flight altitude.
- Water spray: Used to simulate any weathering conditions such as rain/moisture. Since these are not significant factors in flight, the water spray is turned off during this test.
- Duration: With the given test settings, previous studies have shown that 1500 hours of test roughly simulates 50 flight days assuming 14 hours of sunlight per day. This spec needs to be revisited for each subsystem, accounting for its location on the vehicle and exposure to sunlight.

Dew Test

Test Parameters:

- Cold chamber:
  - Temperature: -30C
  - Humidity: uncontrolled
  - Dwell time: as long as it takes for UUT temperature to stabilize to within 3C of the chamber temperature
- Warm chamber:
  - Temperature: 25C
  - Humidity: 95% RH
  - Dwell time: 60 mins
- Operational state: powered
- Orientation: all orientations as in field
- Cycles: 3

Justification:

Since the goal of this test is to consistently generate dew on the UUT, the temperature of the cold chamber can be as low as possible, as long as it does not breach any design limit. The lower this temperature, the lower the necessary dwell time. The temperature of the warm chamber is room temperature, and the humidity is kept high to induce dew formation. The UUT is powered in order to induce self heating and to monitor the health of the UUT after condensation takes place.

Salt Fog

Test Parameters:

- Salt solution: 5% NaCl
- pH: 6.5 - 7.2
- Chamber temperature: 35C
- Fogging rate: 1-2 mL per 80 cm^2 of collecting area per hour
- Duration: 24 hours (based on initial results, additional 24 hours may be requested)

Justification:

Refer to the ASTM B117 standard. This test should only be run if the RE determines there is a strong need to do so (examples: if the UUT will be on a cruise ship, or if it will go through extended ocean transport). While these test parameters may result in much harsher conditions than the UUT will experience in the field, the salt fog test can be used as an A-B comparison test.

Heat Soak

Test Parameters:

- Temperature range: 25C (min) to 60C (max)
- Temperature ramp rate: 35C in 1 hour
- Humidity range: 25% RH (min) to 90% RH (max)
- Humidity ramp rate: 65% RH in 1 hour
- Dwell time: 72 hours
- Operational state: non-operational for materials or mechanical structures, operational for electronic components

Justification:

- These parameters conform to industry test standards, but may be revisited in the future depending on the subsystem under test.

Cold Soak Survival

Test Parameters:

- Temperature range: 25C to -80C
- Temperature ramp rate: 105C in 1 hour
- Humidity range: uncontrolled
- Dwell time: 72 hours
- Operational state: powered

Justification:

- Temperature range: -80C is close to the coldest ambient temperature that a flight will experience.
- Temperature ramp rate: Temperature is reduced gradually in order to avoid saturating the results with thermal shock related failures.
- Humidity range: uncontrolled
- Dwell time: 72 hours
- Operational state: powered

Turbuckets (Combined PTCE/HTOL/LTOL)

Test Parameters:

- State 1: Cold Boot - Lower Operational Limit Testing ("Cold Morning Starts")
    - Low temperature setpoint: -100C
- State 2: PTCE - Endurance Testing over Operational Range ("Daily Flight")
    - Low temperature setpoint: -100C
    - Low temperature dwell time: 4 hours
    - High temperature setpoint: 20C
    - High temperature dwell time: 30 mins

Justification:

- State 1: Cold Boot - Lower Operational Limit Testing ("Cold Morning Starts")
    - Low temperature setpoint: this is the coldest ambient temperature an ACS experiences in flight.
- State 2: PTCE - Endurance Testing over Operational Range ("Daily Flight")
    - Low temperature setpoint: this is the coldest ambient temperature an ACS experiences in flight.
    - Low temperature dwell time: the bulk of the test is carried out at this worst case ambient temperature. This is because this test involves continuous descend cycles, which increases the shroud temperature. In order to sufficiently accelerate this test, it is necessary for the chamber temperature to be as low as possible (worst case ambient of -100C) so that the overheat error is not constantly triggered when the UUT heats up during descend cycles. This is why the UUT needs to dwell at -100C for the majority of this test.
    - High temperature setpoint: this represents the highest ambient temperature typically experienced by an ACS in flight. However, recent inflight ACS temperature distributions suggest that the high temperature setpoint may need to be raised to 40C in the future.
    - High temperature dwell time: the high temperature dwell time is just long enough for the UUT temperature to stabilize in response to the increase in chamber temperature.

EMI/EMC Test

Following DO-160 + CISPR25 with Loon custom limits

Test Parameters:

- Mode: Radiated Emissions
- Frequency Range: 300-3000 MHz
- Resolution bandwidth:
    - 100 kHz from 300-1000 MHz

    - 300 kHz from 1000-3000 MHz
- Step size:
    - 50 kHz from 300-1000 MHz
    - 150 kHz from 1000-3000 MHz
- Measurement time:
    - 10 ms from 300-1000 MHz
    - auto from 1000-3000 MHz
- Antenna orientations tested: horizontal & vertical
- Distance from antenna to UUT: 1m
- Baseline scan: Ambient (empty chamber, no UUT)

Justification:

- Mode: Radiated Emissions is chosen because the primary goal of this test to measure the level of electromagnetic radiation that is emitted by a UUT across a broad frequency range to determine the potential interference on other subsystems on the vehicle (especially LTE, which is the most sensitive to interference).
- Frequency Range: 300-3000 MHz range covers most of the frequencies our subsystems are sensitive to.
- Resolution bandwidth / step size / measurement: Lower resolution bandwidth, smaller step size, and longer measurement time all correspond to higher overall resolution. Since the subsystem that is most vulnerable to radiated emissions is LTE, and since LTE operates at a range between 700-1000 MHz, below 1000 MHz the test resolution bandwidth is low, the step size is small, and the measurement time is long. After clearing 1000 MHz, the test resolution bandwidth, step size, and measurement time are relaxed to save testing time.
- Antenna orientations tested: Both horizontal and vertical orientations are tested to account for different polarizations of the emitted radiation.
- Distance from antenna to UUT: Following industry standard.
- Baseline scan: The empty chamber itself has a distinct radiated emissions spectrum. Therefore the test is first done with no UUT to obtain a baseline scan, against which the UUT spectrum is evaluated.

ESD Test

Following modified DO-160 standard

Test Parameters:

- Test mode: contact
- Pulse voltage: 15kV
- Test locations: to be defined by RE
- # of pulses: 10 in each of the selected locations and in both positive and negative voltage polarities (10 positive and 10 negative)

Justification:

- Test mode: contact testing is chosen because this test is meant to assess the risk of a human hand touching the UUT during assembly/storage/transport. However, non-contact testing may also be useful in some situations where the goal is to determine where the discharge will arc to on the UUT.
- Pulse voltage: in some cases the peak voltage of a static discharge from human hand contact can be as high as ~12kV. 15kV is selected to add some buffer.
- Test locations: The test locations chosen should be all locations (conductive or non-conductive) on the UUT that can potentially be directly touched by human hands during transport, assembly or launch.
- # of pulses: Some circuits are more vulnerable to either positive or negative voltages, so both are tested. The discharge is repeated 10 times per polarity to account for potential cumulative damage.

Lightning Induced Transients Testing (Pin Injection)

Following modified DO-160 standard

Test Parameters:

- Test waveform set A (4/1, level 3):
    - Peak open circuit voltage: 300V

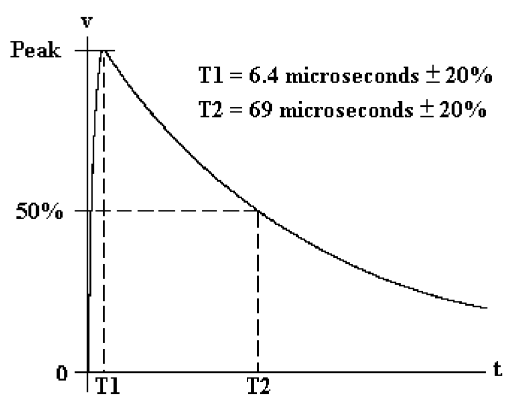


Figure 22-4 Voltage Waveform 4

    - Peak short circuit current: 60A

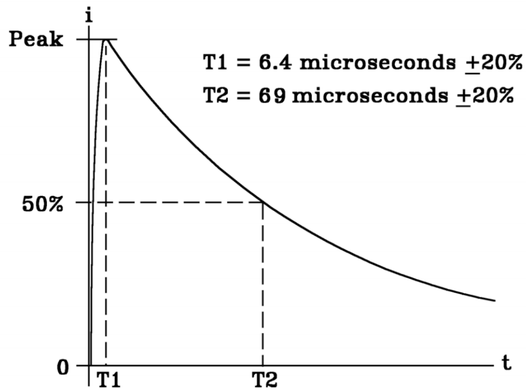


Figure 22-1 Current Waveform 1

Justification:

- These were the current and voltage waveforms that were most representative of the transients experienced by a circuit on a flight vehicle during a lightning event.

Burst Load

The burst rig is set up such that it is able to accelerate the load ring and associated hardware at over 400g, which is the absolute worst-case acceleration experienced during a worst-case burst . The main objective of this test is to ensure there is no risk of TFOA (things falling off aircraft). As long as no TFOA is seen, the test is successful.

Altitude/Pressure Cycling

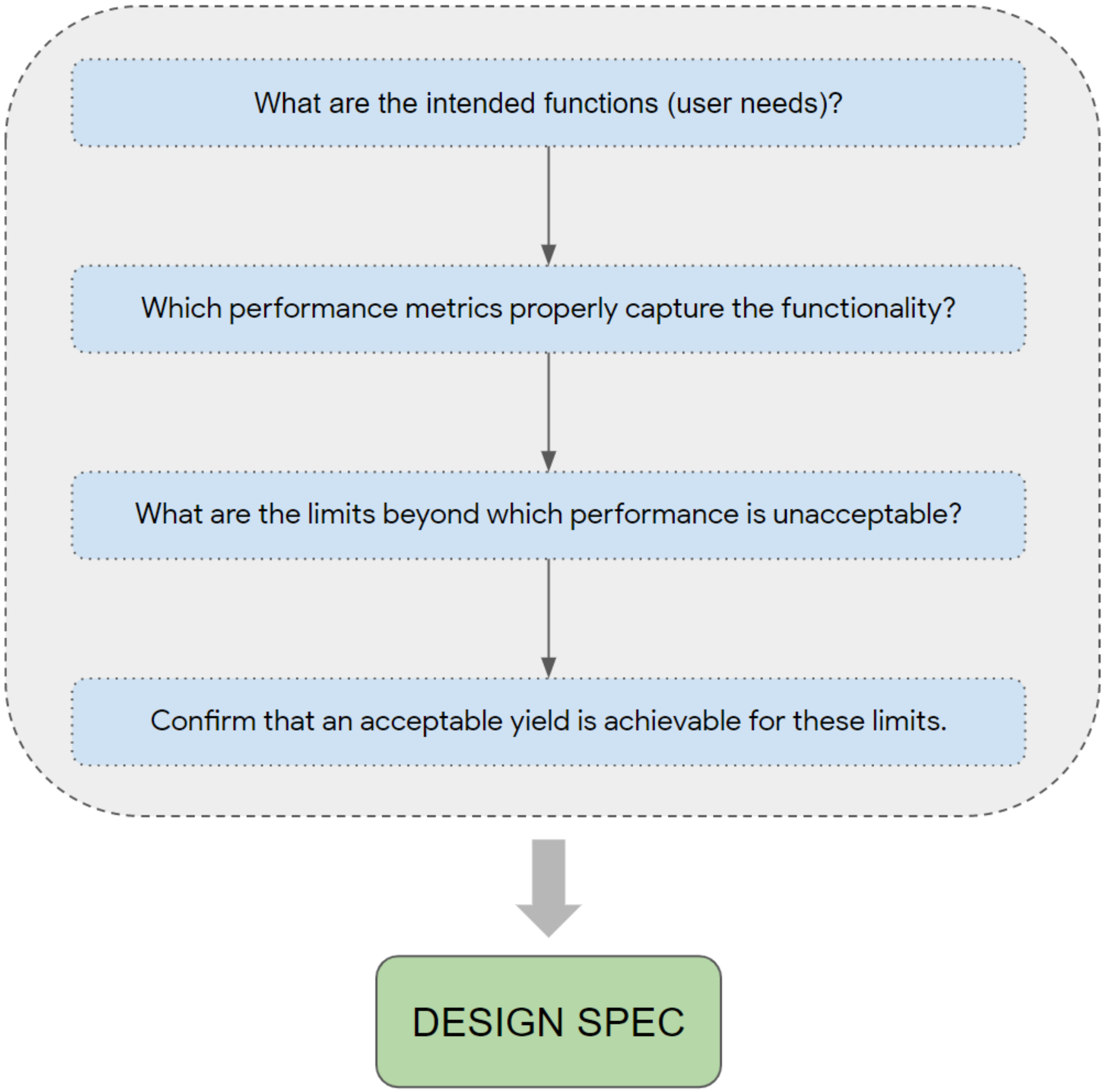
Test under development

Water Ingress Test

Test under development

Design (T0) Specs

Guidelines for developing design specs:



Pass/Fail Criteria

Guidelines to determine pass/fail criteria:

A unit is considered a failure if one of the following conditions are true:

- During test:
  - A parametric value drifts outside of the defined spec limits
  - An error code is generated at an unexpected part of the test
- Before or after test:
  - There is a failure in a functional test
  - Cracks or fractures are observed on the unit

Reliability Tests

Thermal Characterization

Purpose: This is a prototype level test to verify intended functionality at harsh flight conditions: assess start performance at cold, friction at cold, functionality with low convection.

Relevant Subsystems: All

Operational State: Operational

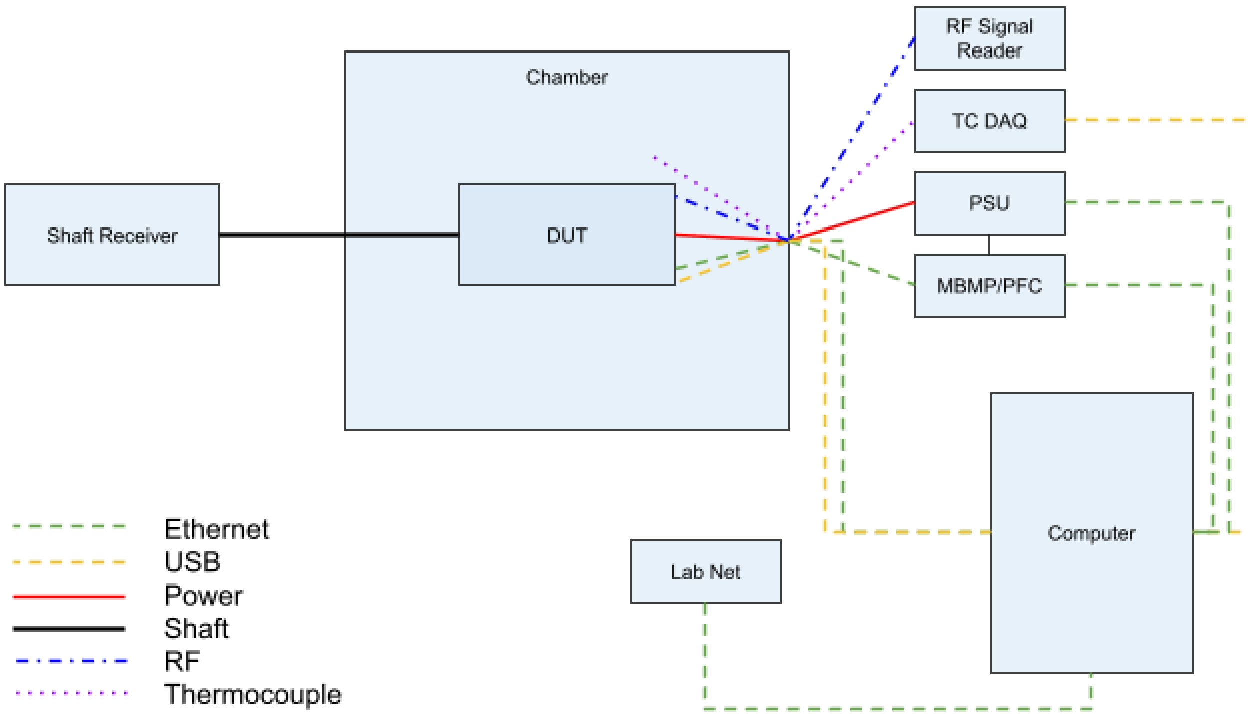
Equipment Required: There are various tools available to use during a thermal characterization test. Depending on test requirements, any of these tools may be implemented.

- Altitude chamber with wall passthroughs to control pressure and temperature
  - Environmental Control
    - Pressure
    - Temperature
  - Chamber Passthroughs
    - Ethernet
    - USB
    - Thermocouple
    - Power
    - RF
    - Shaft
    - 4x1 for loon hardware
- Data Logging and Viewing Tools
  - Thermotron Listener
  - Debug Pipeline
  - TempLogger & Thermocouple DAQ

- PSULogger
- Grafana

Total Test Duration: 1-2 days

Test Setup: This test is usually performed in the altitude chamber. It is set up with a PSU, TC DAQ, MBMP, and has all the passthroughs available. Also, this chamber is LN2 enabled, so temperatures below -70C are possible. Here is a basic diagram of all test modules that can be used:



SOP/Test Profile:

1. Perform visual and functional inspections on UUT at T0.
2. Assemble test setup as needed.
    a. Install and instrument UUT in chamber
    b. Prepare connections outside of chamber
    c. Start any data logging tools that are required (see above)
3. Determine which corner case will be tested. UUT will be soaked at and then tested at one or both of the following flight corner cases:
    a. HOT case: T = -60C, P = 60 hPa (UUT will be hottest)
    b. COLD case: T = -85C, P = 100 hPa (UUT will be coldest)
4. Set the chamber temperature and pressure to the desired case from #2
    a. Ramp up to 10 C/min and up to 100 hPa/min
5. Pre-soak UUT at the intended case until it has reached steady state. For some systems, it may be necessary to utilize on-board heaters to maintain minimum temperatures.

6. Begin characterization test. Start the UUT's duty cycle at the selected flight condition case for the test. Again, run until it reaches a steady state.
7. Once steady state has been reached, stop data logging scripts
8. Power off UUT
9. Bring chamber back to ambient conditions
10. Disassemble test
11. Perform visual and functional inspections on UUT post-test and record any delta.

Highly Accelerated Life Test (HALT)

Purpose: Quickly discover operational limits and design weak points. Determine the effects of extremely high and low temperatures as well as vibration on the performance and functionality of the unit.

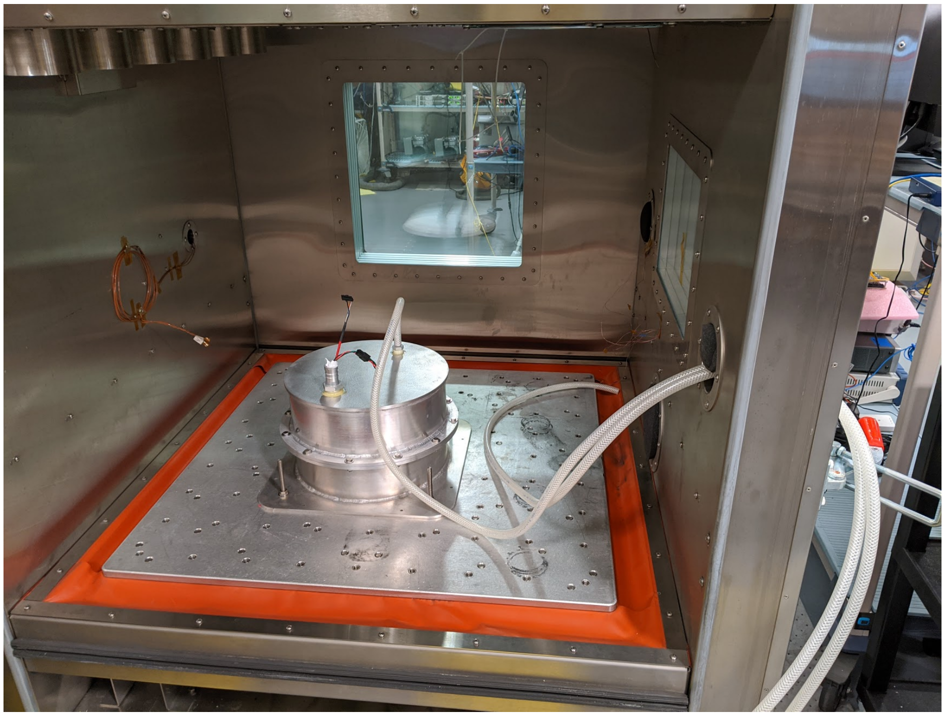
Relevant subsystems: ALL (including any boards, sensors or modules/subsystems)

Operational state: Operational

Equipment required:
- HALT chamber (R23)
- Vibration fixture for DUT (T-cell for ACS)
- PSU
- Vacuum pump if testing ACS
- Loonix gadget or rel pi
- MBUP, PFC, and any additional boards necessary for operation of DUT
- Thermocouple + Labjack (optional)

Total test duration: until failure (target < 5 days)

Test Setup:



example HALT setup for ACS in T-cell

SOP / Test Profile:

1. Establish the lower operational thermal limit
   a. RE to define start/end temp and dwell time at each temp for cold regime.
   b. Start at the start temp and step down by 10C till end temp is reached or till there is a soft failure, dwelling at each step. When a soft failure is reached, step up by 10C, dwell, and then step back down by 10C to see if soft failure returns. If soft failure does not return, continue stepping down in temperature towards end temp. If soft failure does return, step up by 5C, dwell, and see if there is soft failure.
2. Establish the upper operational thermal limit
   a. RE to define start/end temp and dwell time at each temp for warm regime.
   b. Start at the start temp and step up by 10C till end temp is reached or till there is a soft failure, dwelling at each step. When a soft failure is reached, step down by 10C, dwell, and then step back up by 10C to see if soft failure returns. If soft failure does not return, continue stepping up in temperature towards end temp. If soft failure does return, step down by 5C, dwell, and see if there is soft failure.
3. 10x thermal shock cycles between the lower and upper operational thermal limits. Dwell times and ramp rate to be determined by RE.
4. Random vibration at the following levels of Grms [5, 10, 15, 20, 25, 30, 35, 40, 50] at room temperature. Dwell time at each setpoint: 10 minutes.
5. Combined random vibration and thermal shock cycles at uncontrolled ramp rate at Grms [5, 10, 15, 20, 25, 30, 35, 40, 50] and temperature limits found in steps 1-2. The dwell time at each setpoint: 30 minutes.

Additional notes:

- After each unit fails, thorough failure analysis is required to determine root cause. It should be noted that engineering judgment is needed to determine which failure modes have to be addressed. For example, a failure that occurs due to exceeding the expected temperature/vibration ranges is not representative of performance in flight and so would not need to be fixed, but can still provide valuable information of the margin in the design.

Salt Fog

Purpose: Create and maintain a salt fog environment and test the corrosion resistance of materials and coatings. The environment (% NaCl fog, pH, and temperature) produces an environment similar to coastal conditions along the ocean and is known to cause corrosion, oxidation and coating delamination for many materials.

Relevant subsystems: Comms, Ground Station

Operational state: Non-operational

Equipment required:

- Q-Fog chamber

Total test duration: 1-2 days

Test Setup:
UUT in salt fog chamber. The UUT orientation should match its actual use orientation where applicable. All harnesses should be connected, and openings should be plugged where necessary to avoid unwanted ingress.

Example DS10 setup in salt fog chamber

SOP / Test Profile:

1. Setup the salt fog chamber with the specified settings.
2. Inspect samples for any preexisting pitting, discoloration, corrosion, or coating damage.
3. Place samples in the specified orientation in the salt fog chamber, allowing adequate space between samples for fog circulation. Hang the samples with fishing line whenever possible to prevent contact with other materials and samples inside the salt fog chamber.
4. Run the test for the specified time and then purge the chamber.
5. Remove samples and clean with DI water and a clean paper towel.
6. Allow samples to completely air dry.
7. Inspect for corrosion, pitting, or other types of damage. Compare to an untested control sample in order to understand corrosion initiation sites. Inspect mechanical assemblies for proper function.
8. Photograph test samples to document any oxidation, corrosion, or surface damage.

Storage Test

Purpose: Expose UUT to potential damage resulting from temperature & humidity conditions during transport and storage.

Relevant subsystems: All

Operational state: Non-operational

Equipment required:

- Any environmental chamber

Total test duration: 35 days

Test Setup:
UUT with all packaging to mimic storage conditions as closely as possible. Any environmental chamber with temperature/humidity controls can be used for this test.

SOP / Test Profile:

9. Truck transit: Induced B3 profile (up to 71C, up to 80%RH) - 6 cycles (see MIL-STD 810G section 507.5 for table of setpoints)

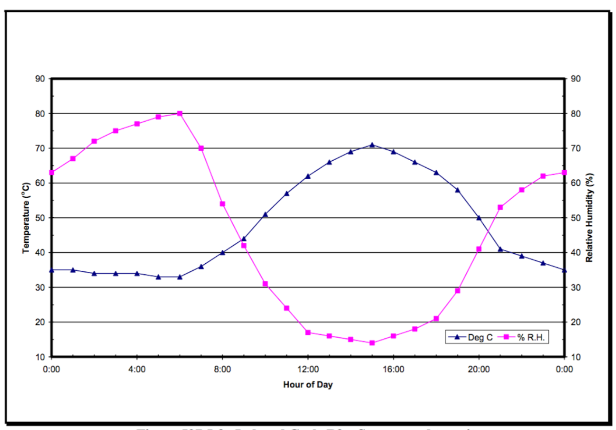


Figure 507.5-3. Induced Cycle B3 – Storage and transit.

10. Ocean transit: Induced B1 (27C, up to 100% RH) - 4 cycles (see MIL-STD 810G section 507.5 for table of setpoints)

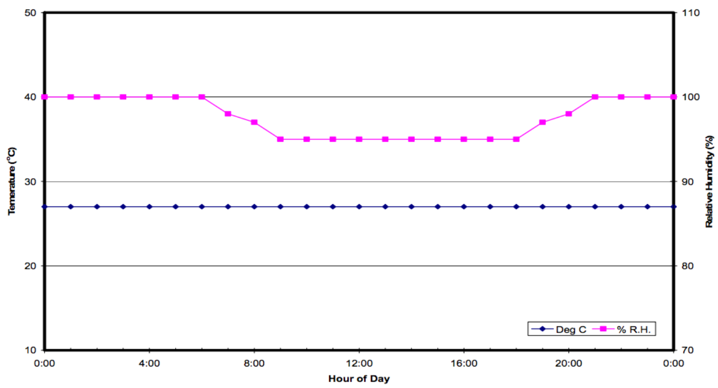


Figure 507.5-1. Induced Cycle B1 – Storage and transit.

11. Warehouse/dock storage: Induced B2 (up to 63C, up to 75%RH), number of cycles = 22 (see MIL-STD 810G section 507.5 for table of setpoints)

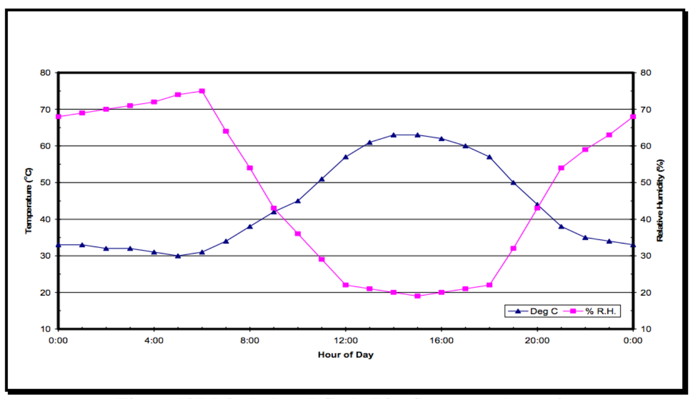


Figure 507.5-2. Induced Cycle B2 – Storage and transit.

Transport Vibration

Purpose: Evaluate robustness of UUT in package/pallet to dynamic stresses during transport.

Relevant subsystems: All

Operational state: Non-operational, packaged

Equipment required:

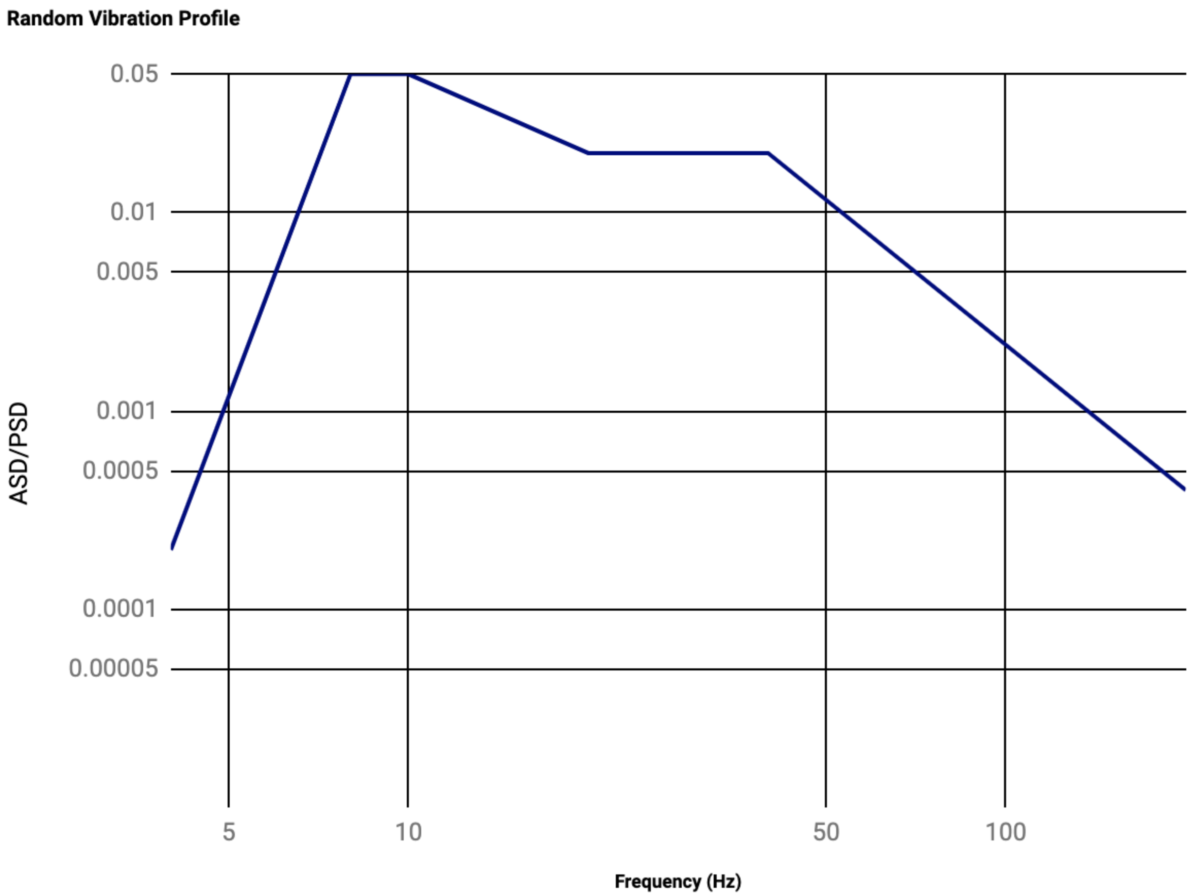
- None at RLS - test run in Nefab

Total test duration: 1-2 days

Test Setup:
UUT in packaging and stacked/palletized as shipped.

SOP / Test Profile:

1. Rigidly mount the UUT in packaging to the vibration table such that it moves along the x axis.
2. Mount a triaxial accelerometer on the package UUT in the appropriate orientation. The accelerometer should be mounted to the rigid part of the assembly, closest to the most fragile components. If needed, multiple accelerometers may be used for this purpose.
3. Run the random vibration profile (see below) for 60 mins:



4. Repeat for y and z axes.

Mechanical Shock

Purpose: Test robustness of the UUT against mechanical shock induced on the launch cart and during burst.

Relevant subsystems: Avionics, Comms, LTE, PDRA

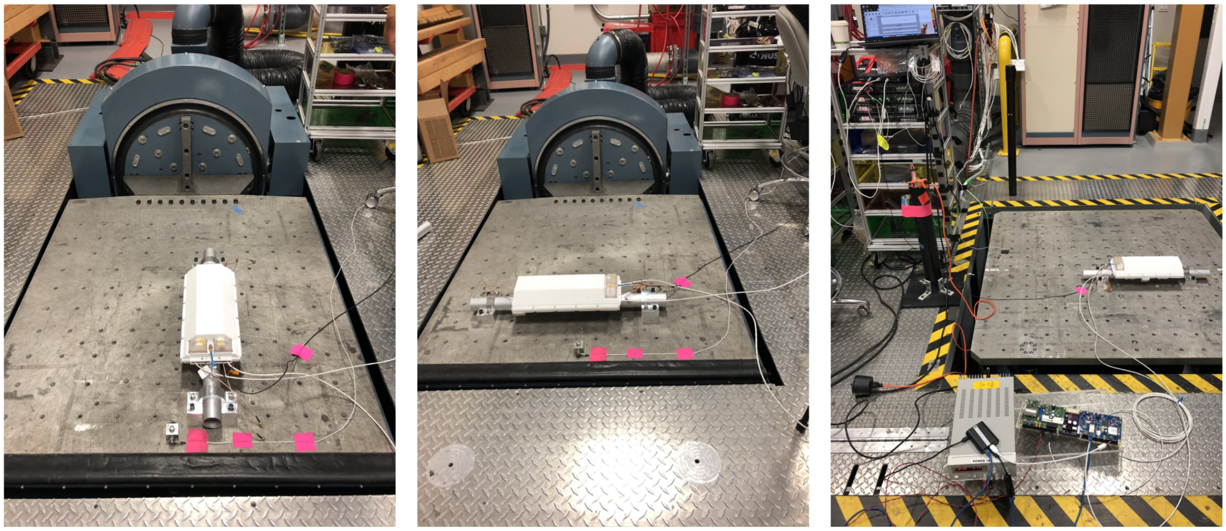
Operational state: operational

Equipment required:

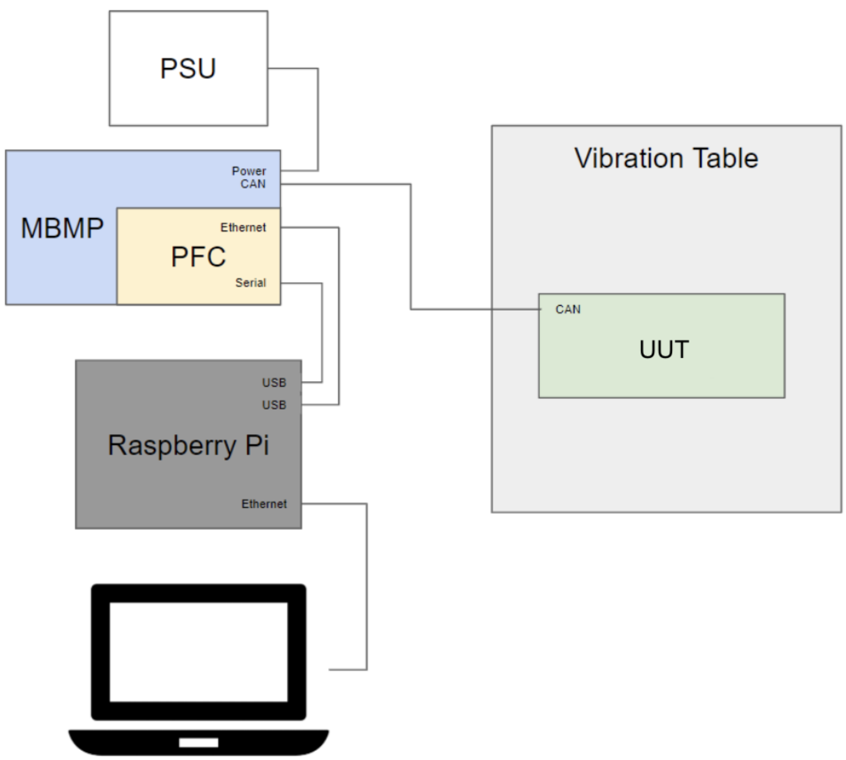
- Vibration/shock table that is large enough to mount UUT and capable of achieving desired parameters
- 1x shock/vibration fixture to mount UUT to table
- 1x uniaxial accelerometer (additional accelerometer is needed if transmissibility of fixture is to be determined or if additional areas of a large/complex assembly need to be monitored)

Total test duration: ~ 1 day

Test Setup:
UUT should be powered and mounted onto the appropriate shock/vibration fixture. This fixture should be bolted to the shock/vibration table in the correct test orientation. The accelerometer should be glued onto the UUT in the correct orientation. If it is necessary to understand how well the fixture transmits the shock pulse to the UUT, an additional accelerometer may be glued onto the fixture in the same orientation as on the UUT. Additionally for complex fixtures, a separate fixture survey (test run without the UUT, only the fixture with the accelerometer) is recommended to evaluate the fixture and to avoid damaging the UUT.



example of EFC assembly mounted in X (left), Y (center), Z (right) orientations



block diagram of setup

SOP / Test Profile:

1. Perform visual and functional inspections on UUT at T0.
2. Ensure UUT is powered and debug pipeline is set up.
3. Mount unit and accelerometer for X axis shock.

4. Perform Part A shock pulse (14g sawtooth, 15ms duration) in -X/+X 3 times each.
5. Repeat steps 3 and 4 for Y and Z axis shock.
6. Repeat steps 3-5 with Part B shock pulse (10g half sine, 11ms duration).
7. Perform visual and functional inspections on UUT after test and review shock profile logs.

Thermal Shock/Cycling

Purpose: Evaluate robustness of UUT to thermal fatigue and uncover any failures driven by thermal mismatch.

Relevant subsystems: All

Operational state: Decided on a case by case basis. Default is non-operational, but if the intent is to monitor the performance or degradation of any variable in response to thermal shock, the test can be operational.

Equipment required:
- Environmental chamber capable of fast ramp rates. Thermostream can also be used if samples are small enough to fit in the chamber.
- Elevator chamber can also be used if available.

Total test duration: 5 days

Test Setup:
If test is non-operational, UUTs can be placed directly on the racks in the chamber. If the test is operational, UUT must be connected to PFC & MBUP with debug pipeline set up. Additionally, all auxiliaries (such as pressure sensors, GPS, Inmarsat, etc.) that need to be validated should be properly connected and instrumented.

SOP / Test Profile:
8. Perform visual and functional inspections at T0.
9. Place UUTs in chamber (set up debug pipeline if test is operational) and subject them to thermal shock with the following parameters:
    a. Temperature range: defined by RE
    b. Ramp rate:
        i. If performing thermal shock, ramp rate is as fast as possible
        ii. If performing thermal cycling, ramp rate to be defined by RE
    c. Dwell time: defined by RE
    d. Cycles: 200
10. Redo visual and functional inspections every 100 cycles. Record any delta.

PTCE/HTOE

Purpose: Evaluate robustness of UUT against a lifetime of temperature cycling caused by exposure to ambient temperatures combined with self-heating during operation.

Relevant subsystems: LTE, PDRA, Comms, Avionics, ACS

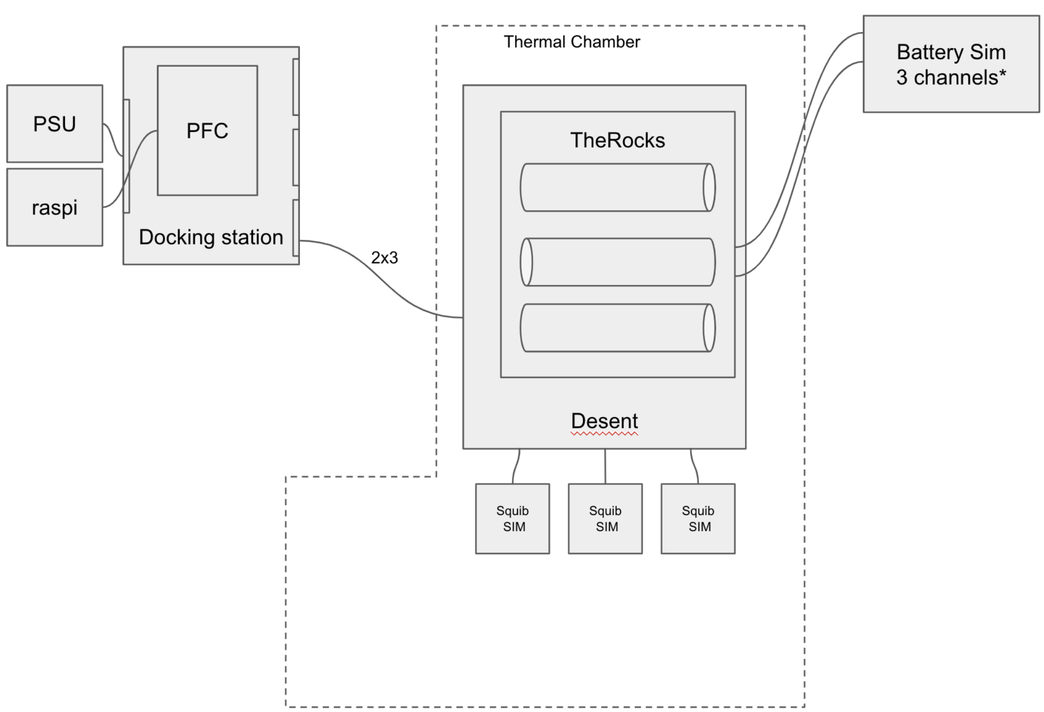
Operational state: operational

Equipment required:

- Environmental test chamber
- Power supply
- RasPi/Gadget for each UUT

Total test duration: ~60 days

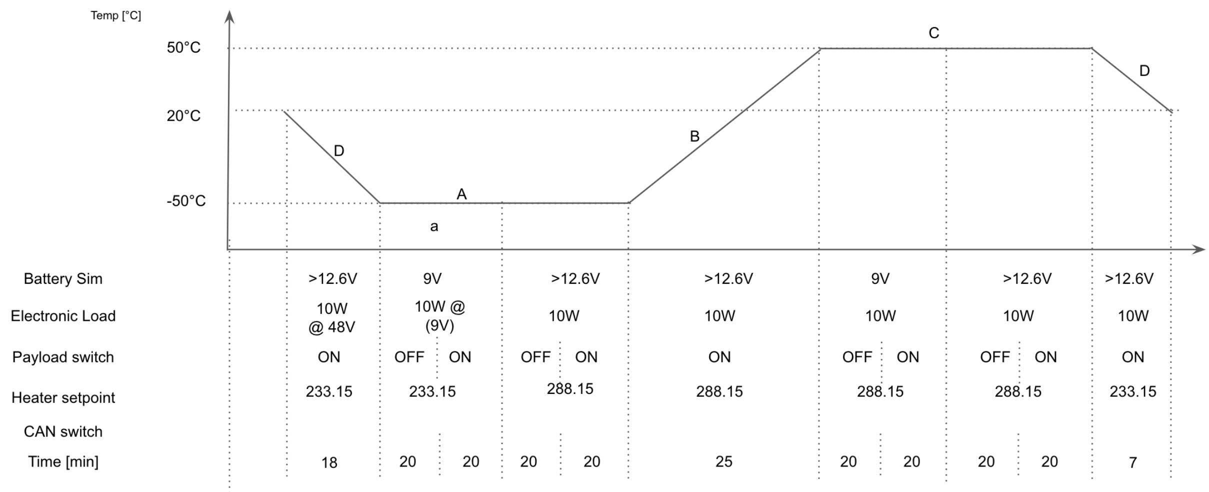
Test Setup:
UUT should be operational with debug pipeline set up. All necessary auxiliaries (pressure sensors, GPS, Inmarsat, etc.) should be properly connected. Battery simulators and squib simulators should be used where appropriate.



Example block diagram of PTCE setup for Descent board

SOP / Test Profile:

1. Perform visual and functional inspection of UUT at T0.
2. Setup UUT in chamber as per block diagram (to be provided by the RE) with power on.
3. Run the PTCE/HTOE test with the temperature profile provided by the RE (example test profile below).
4. Perform visual and function inspection of UUT post-test and record any delta.



Example PTCE/HTOE test profile

UV

Purpose: Evaluate any material degradation on UUT due to UV exposure.

Relevant subsystems: LTE, PDRA, Ground Station

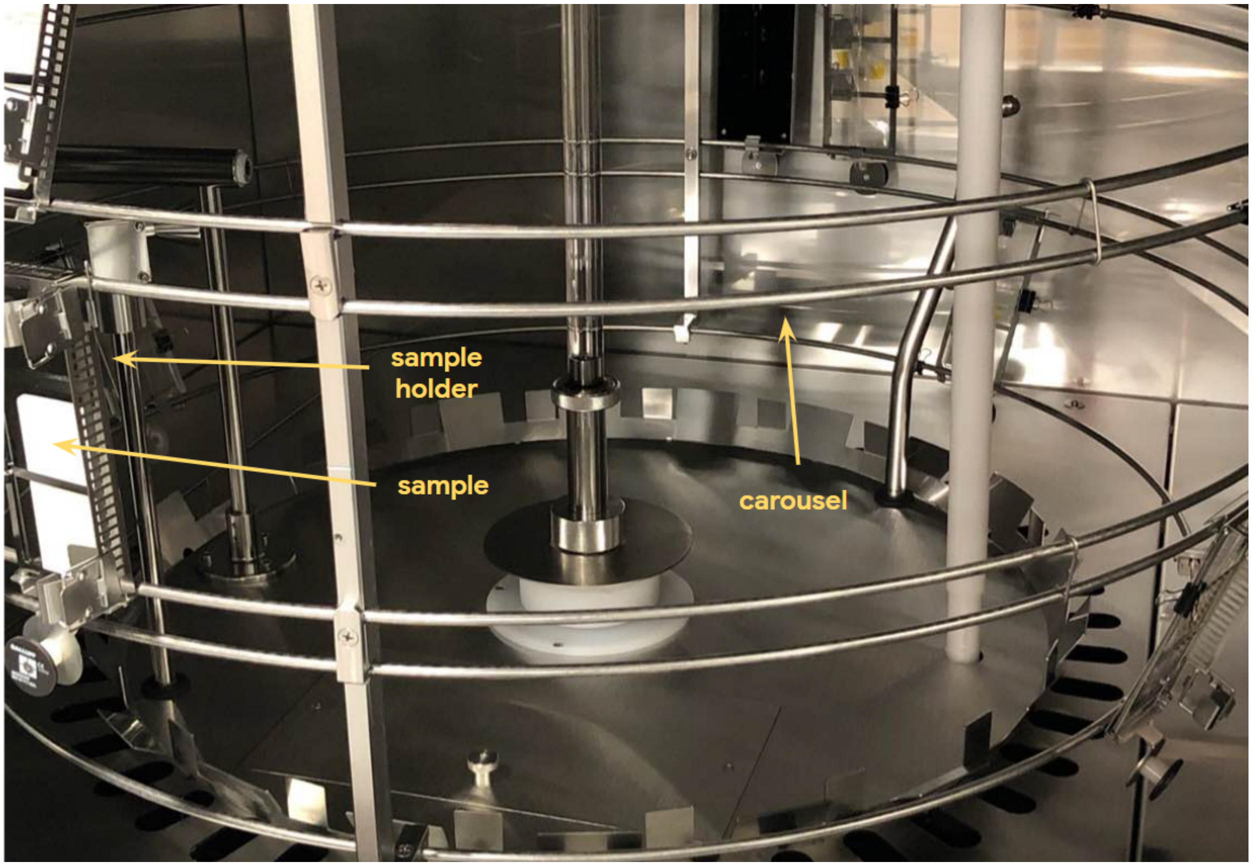
Operational state: Non-operational, often coupon level

Equipment required:

- Atlas UV chamber with filtered Xenon lamp simulating broadband sun exposure (infrared through visible spectrum to ultraviolet)

Total test duration: 63 days

Test Setup:
Determined on a case-by-case basis according to part of UUT being tested and its intended function. Test is mostly done at material/coupon level but can be done at enclosure level if enclosure fits in the UV chamber.



example of sample mounting inside UV chamber

SOP / Test Profile:

1. Perform T0 inspection of part being tested. The inspection method depends on the function of the part being tested, but examples include:
    a. Tensile testing if testing load bearing material
    b. Thermal cycling followed by crack inspection
    c. Water ingress testing if testing seals/gaskets
2. Secure the sample/UUT to sample holder (using wire) and mount the sample holder onto carousel in UV chamber with the surface of interest facing inwards toward the light source. If the sample/UUT does not fit in the sample holder, secure it directly onto carousel in UV chamber using wire.
3. Run UV test for 1500 hours with the following settings:
    a. Irradiance (outdoor): 0.35 W/m^2 @ 340nm
    b. Chamber Temperature: 38°C
    c. Rack Temperature (Black panel): 55°C
    d. Relative Humidity: 55%
4. If sample size is sufficient, take one sample out of the chamber at each intermediate checkpoint (100, 250, 500, 1000 hours). If sample size is a constraint, take out sample only at the end of 1500 hours. After taking out each sample, redo the same inspection that was done at T0 and record any delta.

Dew Test

Purpose: Evaluate robustness of UUT against moisture condensation when the UUT temperature is lower than the dew point of the ambient air.

Relevant subsystems: Comms, LTE, PDRA

Operational state: operational

Equipment required:
- 2x environmental test chambers

Total test duration: 2 days

Test Setup:
UUT should be operational and powered. Test can be done at component/board level or at assembly level - to be determined by RE.

SOP / Test Profile:
1. Perform functional/visual inspections before test. Inspection methodology to be determined by RE.
2. Preset two environmental chambers:
   Cold Chamber: -30°C, Uncontrolled RH
   Warm Chamber: 25°C, 95% RH
3. Place UUT in cold chamber.
4. Dwell in the cold chamber until UUT is within 3°C of the chamber temperature.
5. Transfer UUT to warm chamber in an orientation the UUT is expected to be used in the field. If there is more than one expected orientation, repeat the dew test for every orientation.
6. Redo functional/visual inspection at 0, 30, and 60 minute dwell times. This completes 1 cycle.
7. Repeat for a total of 3 cycles.

Heat Soak

Purpose: Evaluate robustness of UUT against prolonged exposure to a high temperature and high humidity environment.

Relevant subsystems: Comms, LTE, Avionics, PDRA

Operational state: non-operational for materials or mechanical structures, operational for electronic components

Equipment required:

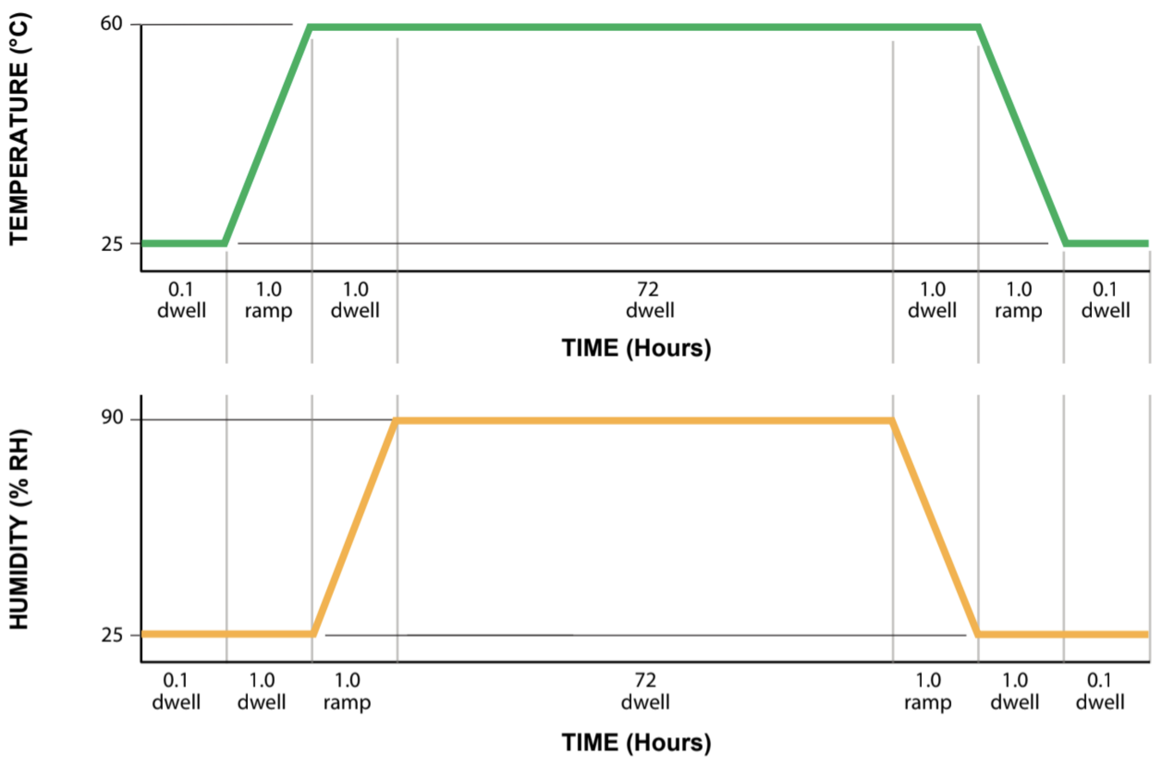
- Environmental test chamber

Total test duration: 3-4 days

Test Setup:
UUT placed in chamber.

SOP / Test Profile:

1. Perform functional/visual inspections before test. Inspection methodology to be determined by RE.
2. Place UUT in chamber.
3. Ramp chamber temperature and humidity according to the profile below:



4. Perform functional/visual inspections after test and record any delta.

Cold Soak Survival

Purpose: Evaluate robustness of UUT against prolonged exposure to a low temperature environment.

Relevant subsystems: Comms, LTE, PDRA

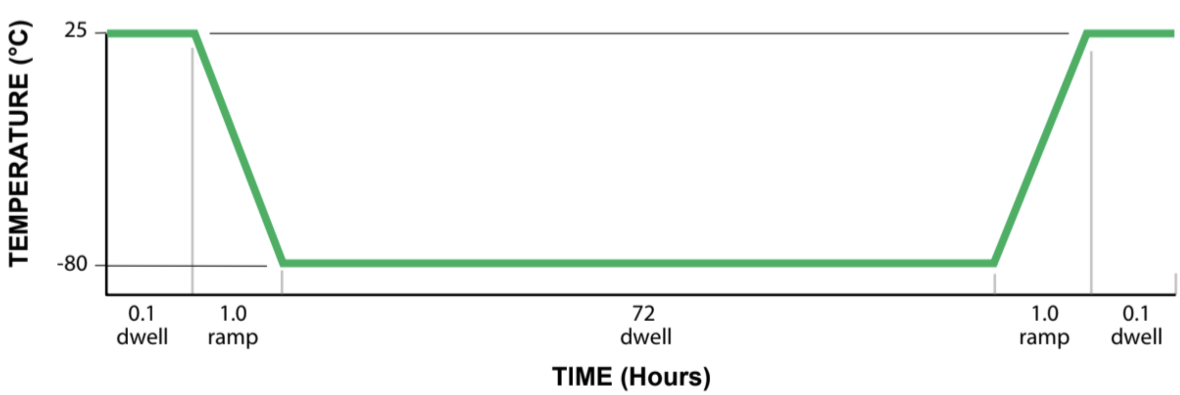
Operational state: operational

Equipment required:
- Environmental test chamber

Total test duration: 3-4 days

Test Setup:
UUT powered and placed in chamber with debug pipeline set up.

SOP / Test Profile:
1. Perform functional/visual inspections before test. Inspection methodology to be determined by RE.
2. Place UUT in chamber, ensuring power is on and debug pipeline is set up.
3. Ramp chamber temperature according to the profile below:



4. Perform functional/visual inspections after test and record any delta.

EMI/EMC Test

Purpose: Evaluate level of radiated emissions from a UUT and determine the impact to other subsystems on the vehicle.

Relevant subsystems: ACS, Avionics, Comms, LTE, PDRA

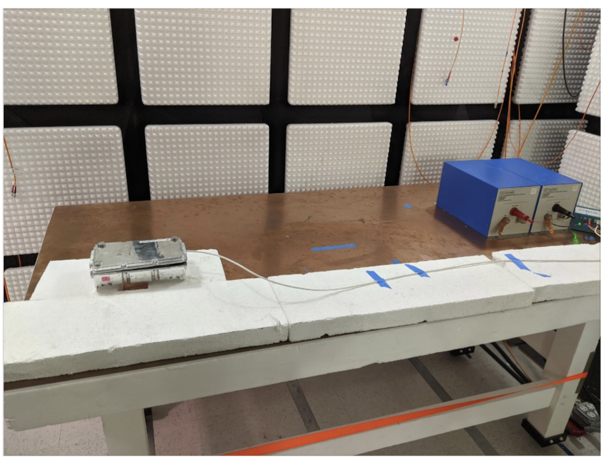
Operational state: Operational

Equipment required:
- Anechoic chamber w/ antenna
- Line impedance stabilizer networks

Total test duration: ~ 1 day

Test Setup:
Ambient scan: empty chamber (no UUT), measurements taken with horizontal and vertical antenna orientations

Other scans: UUT on and drawing max power, measurements taken with horizontal and vertical antenna orientations




Example of Descent assembly set up in anechoic chamber

SOP / Test Profile:
1. Perform visual and functional inspections of UUT at T0.
2. Ensure UUT is prepared for EMI/EMC test:
    a. If any battery/board heaters need to be toggled during the test, have the relevant firmware commands ready
    b. Terminate Iridium/Inmarsat/Transponder/GPS antennas with 50 ohm load
3. Set up UUT and run tests according to test matrix (example of test matrix below):

Filename	EUT Configuration Notes	Frequency Range MHz	RBW Khz	Step Size KHz	Meastime Ms	Antenna Orientation	Description Of Test
Scan1 300-3000 MHz Horizontal Ambient	Empty Chamber	300-1000 1000-3000	100 300	50 150	10 auto	Horizontal	Ambient Radiated Peak & Avg
Scan2 300-3000 MHz Horizontal Ambient	Empty Chamber	300-1000 1000-3000	100 300	50 150	10 auto	Vertical	Ambient Radiated Peak & Avg
Scan3 300-3000 MHz Horizontal Active	Descent ON	300-1000 1000-3000	100 300	50 150	10 auto	Horizontal	Radiated Peak & Avg
Scan4 300-3000 MHz Vertical Active	Descent ON	300-1000 1000-3000	100 300	50 150	10 auto	Vertical	Radiated Peak & Avg

Example of EMI/EMC test matrix with Descent assembly

ESD Test

Purpose: Evaluate the robustness of a UUT against electrostatic discharge from human contact during assembly, storage or transport.

Relevant subsystems: ACS, Avionics, Comms Node, B2X, LTE, PDRA

Operational state: Non-operational

Equipment required:

- ESD generator with a discharge resistor of 330 ohms (±20%) and an energy storage capacitor of 150 pf (±20%). The ESD generator should also be capable of generating a pulse of 15kV in both positive and negative polarities.

Total test duration: ~ 1 day

Test Setup:
The ESD generator should be held perpendicular to the UUT. The discharge return cable of the generator should be grounded to the ground plane and kept at a distance of at least 0.2m from the UUT and its cabling.

SOP / Test Profile:

1. Perform visual and functional inspections of the UUT at T0.
2. Move the ESD tip towards a pre-defined test point on the UUT until contact is made.
3. After discharge, remove ESD tip from the test point and allow it to recharge.
4. Perform steps 2 & 3 10 times with positive voltage and 10 times with negative voltage.
5. Repeat step 4 for all chosen test points.
6. Perform functional/visual inspections after test and record any delta.

Lightning Induced Transients Testing (Pin Injection)

WARNING: THIS TEST INVOLVES HIGH VOLTAGES AND CURRENTS THAT CAN BE LETHAL. EXTREME CARE SHOULD BE TAKEN WHEN PERFORMING THIS TEST. Before running this test, the operator must pass the required safety training and perform the safety pre-check.

Purpose: Verify that the UUT can survive lightning induced transients during flight.

Relevant subsystems: Avionics, PDRA

Operational state: Non-operational

Equipment required:

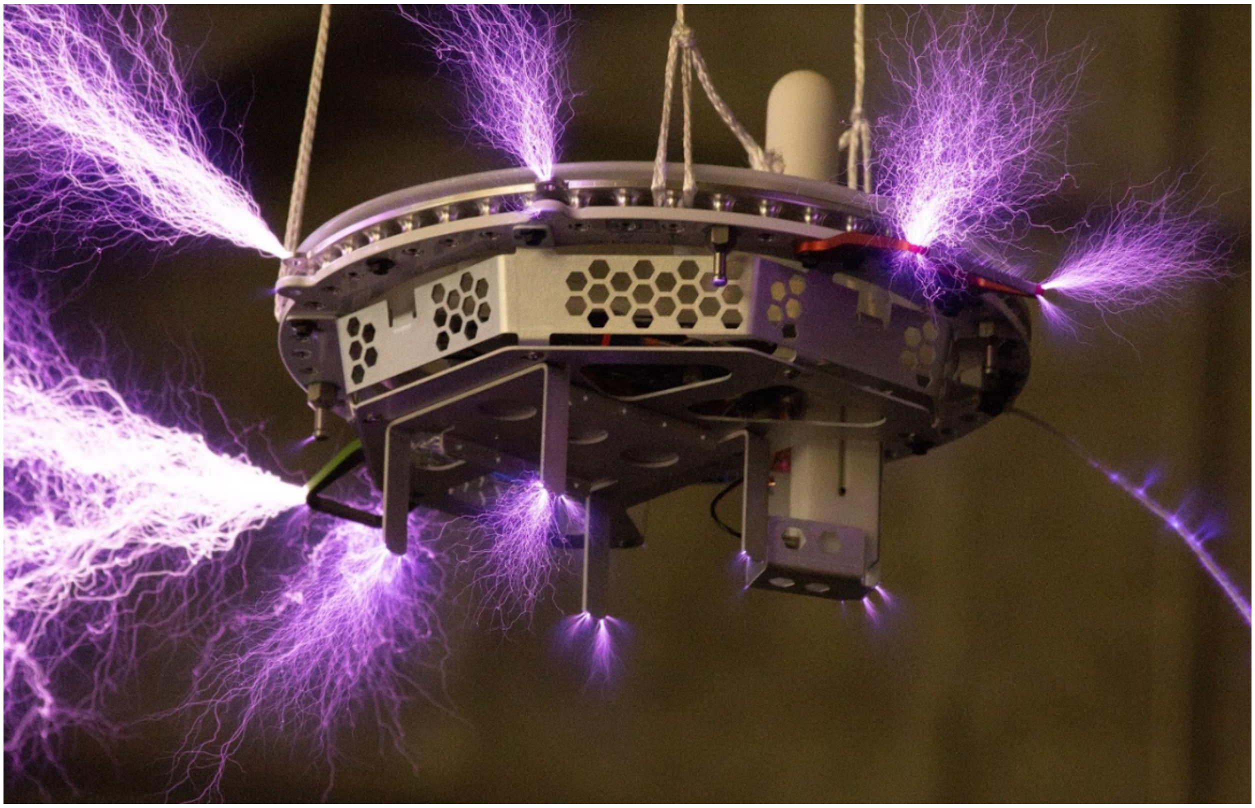
- AVI3000 transients generator
- Line impedance stabilization networks (LISNs)
- Measurement probes and injection transformers

Total test duration: ~ 1 day

Test Setup:
The UUT should be set up on a ground plane. In accordance with DO-160, this should be a copper, brass, or aluminum ground plane - at least 0.25mm thick for copper/aluminum and at least 0.5mm thick for brass. The area should be at least $2.5m^2$ with a minimum depth of 0.75m.

SOP / Test Profile:

1. Perform visual and functional inspections on UUT at T0.
2. Perform safety pre-check.
3. Ensure that the green safety light is lit (press the big red stop button if necessary)
4. Open the plexiglass cover and set up the test as necessary
    a. Test waveform set A (4/1, level 3):
        i. Peak open circuit voltage: 300V
        ii. Peak short circuit current: 60A
5. Close the plexiglass cage.
6. Twist the red stop button to disengage the safety interlock. The green light should turn off and the red light should turn on.
7. Use a laptop plugged into the Ethernet switch to start the test.
8. When the test is complete, press the red stop button to engage the safety interlock
9. When the green light is lit, you may now open the plexiglass cage and touch the UUT.
10. Perform functional/visual inspections after test and record any delta.



Example of Lightning Induced Transient testing on Apex Inmarsat

Turbuckets (Combined PTCE/HTOL/LTOL)

Purpose: Evaluate expected life of ACS in flight, with a focus on operating under flight equivalent conditions (temperature, pressure, aerodynamic loads).

Relevant subsystems: ACS

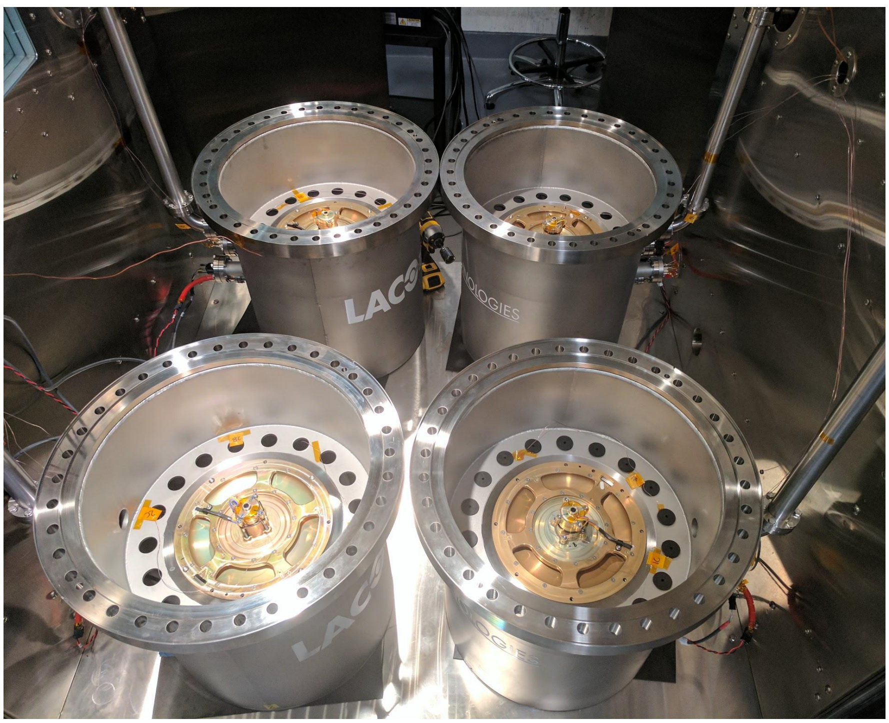
Operational state: Operational

Equipment required:

- Environmental chamber (R22)
- Turbuckets
- PSU
- Vacuum pump
- Loonix gadget or rel pi
- MBUP, PFC, ACS5 boards
- Thermocouple + Labjack (optional)

Total test duration: ~ 2 months

Test Setup:
A compressor subsystem sits in a vacuum chamber, which in turns sits inside a LN2 cooled temperature chamber. 4 of these test stands exist in the chamber. The compressor is mounted in the middle of the chamber, with a ring of orifices providing the necessary backpressure. Pressure in the chamber can be adjusted to simulate different altitudes and air densities.



Inside the Turbuckets, populated with compressors

SOP / Test Profile:
The test profile for the turbucket consists of combinations of ascend and descends, initially conducted at ~12% duty cycle to achieve extremely low temperature thermal cycles. Given that the current expected mode of failure may or may not have strong temperature correlation, and suggests a constant failure rate, duty cycle now increased to accelerate testing (40-50%), with periodic cold soaks to assess lower operating limit issues. Evaluations of distribution of stator/shroud temperatures versus flight appear to be comparable. Below are the two operational states for the test - State 1 is assessed every 50 cycles of State 2, roughly corresponding to the completion of 95% percentile single flight day operation:

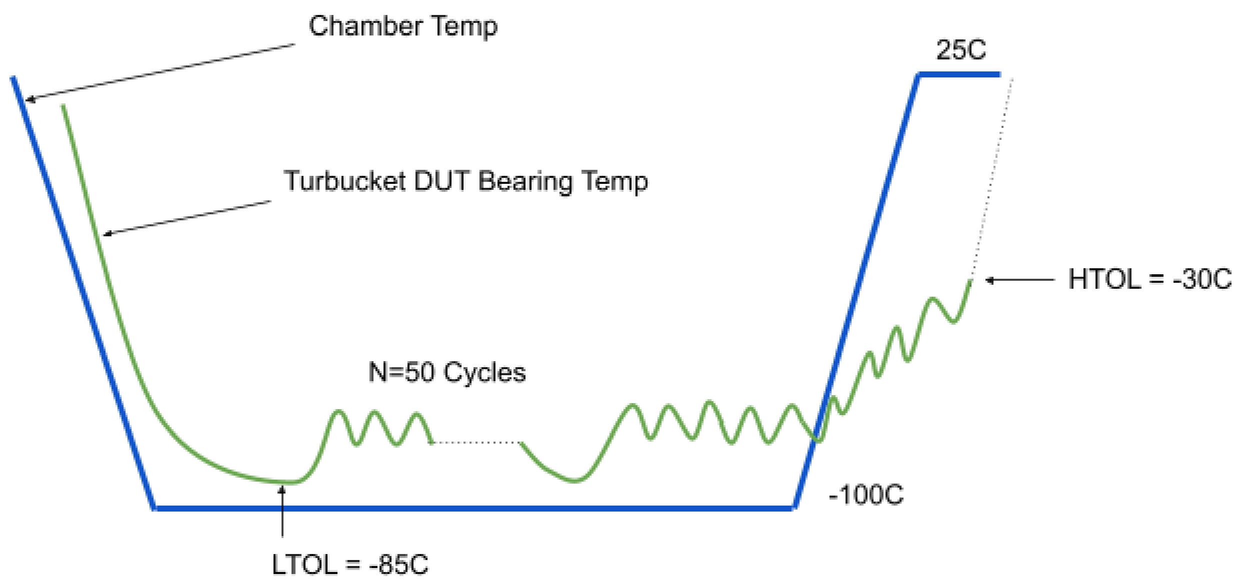
<u>State 1: Cold Boot - Lower Operational Limit Testing (“Cold Morning Starts”)</u>

- Chamber ramp from 20C to -100C, 25C/min
- Set a “Cold Boot” flag in database logging
- Wait for -85C stator temperature
- Soak another five minutes (bearings)
- Turn off Temperature/Valve reading on DAQ
- Ascend Cycle on valve (30 cycles, 5 second dwell)
  - Measure Valve vibe three times
  - Turn on Temperature/Valve reading on DAQ (hall effect)
  - Turn off Temperature/Valve reading on DAQ
- Descend full power for 1 minute
  - Measure Compressor vibe
  - Turn on Temperature Measurement
- Clear Cold Boot flag in database logging

<u>State 2: PTCE - Endurance Testing over Operational Range (“Daily Flight”)</u>

- Chamber on ~5 hour cycle (30 minute dwell at 20C, 4 hours at -100C, 25C ramp)
- Wait for Temp to -40C
  - Turn off Temperature reading on DAQ
  - Descend full power 30 seconds
  - Measure Vibration (20Hz-2.5kHz) 5 times (MEMS accel - currently not in use, will be updated to include cryogenic IEPE accels)
  - Turn on Temperature Measurement
- Repeat Descend Cycles until stator temp >-40C

1. Start State 1, wait for LTOL
2. Perform 50 Cycles @ State 2 (PTCE)
3. Go to Step 1, repeat until HTOL is reached



Turbucket Test Profile

Burst Load

Refer to burst load document.

Altitude/Pressure Cycling

Test under development

Water Ingress Test

Test under development

Acceleration Factor Calculations

Thermal Characterization

N/A - this is not an accelerated life test.

Storage Test

AF from time compression: 1
AF from overstress: unknown - no data collected that shows what temperatures/humidities UUTs experience during transportation and storage

Transport Vibration

AF from time compression: Depends on what part of the UUT the test targets. The AF from time compression can be estimated based on the SN curve of the material expected to fail in this test.
AF from overstress: Can be estimated from calculating the margin in the test (how much the PSD of the test profile exceeds the real vibration profile measured during transport).

UV

AF from time compression: A rough AF can be calculated based on the irradiance settings on the UV chamber and the corresponding total radiant exposure on the sample.

Irradiance is measured in W/m^2. Radiant exposure can be obtained by integrating irradiance over time. Then the units for radiant exposure are $W/m^2 * s = J/m^2$. Considering the fact that radiant exposure is normally measured in kJ/m^2 and that UV tests are timed in hours, the conversion factor becomes: $kJ/m^2 = W/m^2 * 3600\ sec/hr * 0.001 kJ/J$.

Caveats:

- All assumptions made for calculating AF are based on data at ground level. The effect of higher exposure at flight altitudes has not been factored in.
- The effect of low temperatures in material degradation has not been considered.
- The amount of UV exposure is highly dependent on where the part is on the flight vehicle and whether or not it is shielded. This has not been considered in the UV test.
- Day/night cycles, seasonal effects, geographical effects, and atmospheric variations will all contribute to variability in spectral power of sunlight.
- Filtered Xenon light is not an exact match to natural sunlight

- Xenon light and filters age, which may contribute to test variability

AF from overstress: unknown. Depends on:
- What material is being tested
- Where on the vehicle it is located
- What the failure mechanism is

Mechanical Shock

AF from time compression: difficult to quantify. This depends on several factors, including how many shock events are experienced by the UUT during launch and burst in a real flight, which is not known.

AF from overstress: difficult to determine. The shock test profile was derived from adding some margin to the measured shock pulses during launch. However, quantifying this margin is not a straightforward exercise. Furthermore, the dampening of the test pulse by the fixture would also affect the overstress acceleration factor, but is also not accounted for.

Thermal Shock/Thermal Cycling/PTCE

AF from time compression: The acceleration factor from time compression is the ratio of the number of temperature cycles the UUT experiences in the test to the number of cycles the UUT experiences on a typical day in flight:

$$AF_{time\ compression} = \frac{N_{test}}{N_{flight}}$$

AF from overstress: The goal of these tests is to precipitate thermal fatigue failures due to repeated thermal stresses from a mismatch in the coefficient of thermal expansion. In this case, the AF can be calculated using the Coffin-Manson model:

$$AF_{overstress} = \left(\frac{\Delta T_{test}}{\Delta T_{flight}}\right)^{m}$$

where ΔT_{test} is the temperature range in the test, ΔT_{field} is the maximum temperature range in flight, and m is the fatigue or Coffin-Manson exponent. m is material dependent and needs to be empirically determined for any failures seen in our test. The most commonly used value for m is 2.7, which was derived for lead-free solder.

Total AF: The total effective acceleration factor is the product of the acceleration factor from time compression and the acceleration factor from overstress:

$$AF = \frac{N_{test}}{N_{flight}}\left(\frac{\Delta T_{test}}{\Delta T_{flight}}\right)^{m}$$

Caveats:

- The AF calculated is highly dependent on the Coffin-Manson exponent, which was originally determined empirically for lead-free solder. If applying this model for any material other than lead-free solder, it is necessary to experimentally determine the appropriate Coffin-Manson exponent.

HTOE

Total AF: Although HTOE is often run in conjunction with PTCE, they target two different failure mechanisms. While PTCE induces thermal fatigue failures, HTOE is meant to target chemical degradation due to high temperature operation. Thus for HTOE, the Arrhenius model is used to calculate the AF:

$$AF = exp\left(\frac{E_a}{k}\left(\frac{1}{T_{flight}} - \frac{1}{T_{test}}\right)\right)$$

More generally, given that there are a range of discrete temperature readings that a vehicle has experienced in flight given by T_i at times t_i, the total AF becomes:

$$AF = \frac{1}{\left(\frac{p_i}{AF_i}\right)}$$

Where $p_i = \frac{t_i}{\Sigma t_i}$, which represents the fraction of time spent in the i^{th} state, and $AF_i = exp\left(\frac{E_a}{k}\left(\frac{1}{T_i} - \frac{1}{T_{test}}\right)\right)$.

When running HTOE and PTCE together, the test duration should be such that it meets the reliability target at stated confidence for each of the two failure mechanisms.

Dew Test

AF from time compression: Difficult to determine. There are several factors that affect this:

- # of times a vehicle goes through clouds in its lifetime
- # of night-to-day transitions an average flight experiences in its lifetime (in flight and in storage/transport)
- How insulated the UUT is
- How well the UUT is protected against moisture ingress

AF from overstress: The goal of the dew test is to bring about material failures related to condensation because of a sudden increase in temperature and humidity. The most common model that is used for this purpose is the Peck Model, which has the following AF:

$$AF_{overstress} = \left(\frac{RH_{test}}{RH_{flight}}\right)^{n} exp\left(\frac{E_a}{k}\left(\frac{1}{T_{flight}} - \frac{1}{T_{test}}\right)\right)$$

where RH_{test} and RH_{flight} are the relative humidity in test and flight respectively, n is the humidity exponent, E_a is the activation energy (a measure of the energy required to trigger the chemical degradation), k is the Boltzmann constant (8.617385×10^{-5} eV/K), and T_{flight} and T_{test} are the temperatures in flight and test respectively.

Caveat:

- The AF calculated is highly sensitive to the values used for activation energy and humidity exponent. These are both material specific parameters, and so would need to be determined based on the material that exhibits the failure. Commonly used values for E_a and n are 0.7 and 2.7 respectively, but these values are for semiconductor epoxy packages. If applying this model for other materials, it is necessary to experimentally determine the appropriate values for E_a and n.

Heat Soak

AF from time compression: Difficult to determine. There are several factors that affect this:

- Total amount of time the UUT spends in a high temperature and high humidity environment over its lifetime
- How insulated the UUT is
- How well the UUT is protected against moisture ingress

AF from overstress: The high temperature and high humidity in this test causes chemical degradation of materials in the UUT. Therefore, the appropriate model to determine the AF is the Peck Model:

$$AF_{overstress} = \left(\frac{RH_{test}}{RH_{flight}}\right)^{n} exp\left(\frac{E_a}{k}\left(\frac{1}{T_{flight}} - \frac{1}{T_{test}}\right)\right)$$

where RH_{test} and RH_{flight} are the relative humidity in test and flight respectively, n is the humidity exponent, E_a is the activation energy (a measure of the energy required to trigger the chemical degradation), k is the Boltzmann constant (8.617385×10^{-5} eV/K), and T_{flight} and T_{test} are the temperatures in flight and test respectively.

Caveat:

- The AF calculated is highly sensitive to the values used for activation energy and humidity exponent. These are both material specific parameters, and so would need to be determined based on the material that exhibits the failure. Commonly used values for E_a and n are 0.7 and 2.7 respectively, but these values are for semiconductor epoxy packages. If applying this model for other materials, it is necessary to experimentally determine the appropriate values for E_a and n.

Cold Soak Survival

AF from time compression: Difficult to determine. There are factors that affect this include:

- Total amount of time the UUT spends in a low temperature environment over its lifetime
- How insulated the UUT is

AF from overstress: The overstress AF depends on the specific failure mode. Several different failure modes can be experienced during the cold soak survival test:

- Temperature swings during self heating at low temperature (or cold starts for motors) combined with CTE mismatches causing thermal fatigue failures. In this case, the Coffin-Manson model should be used to calculate the AF:

$$AF_{overstress} = \left(\frac{\Delta T_{test}}{\Delta T_{flight}}\right)^{m}$$

- Thermal fatigue of some components causing mechanical fatigue failures on components. For example, this can be seen when a PCBA is subjected to cold soak. Due to nonuniform trace direction and density, as well as CTE differences between copper and FR4 (or other PCB laminate materials) PCBAs naturally warp when heated or cooled. This bending stresses components and can lead to solder fatigue or component package failure. An appropriate model for this type of failure mode would need to account for the thermal characteristics of the UUT and the geometry of the UUT and relate that to mechanical fatigue of certain components on the UUT. This kind of model would likely require an in-depth FEA.
- Most materials become brittle at low temperatures, making them more susceptible to cracking if any mechanical load is then applied. The failure mode in this case is a

change in some material parameter in response to temperature (such as Young's modulus, yield strength or fracture toughness), which would need to be accounted for by any model that is used for this failure mode.

- IC components can experience a phenomenon known as hot carrier injection, which can lead to higher rates of IC degradation when the temperature is low. Hot carrier injection (or charge trapping) refers to the phenomenon when electrons experiencing a strong electric field (as in a MOSFET) gain enough kinetic energy to tunnel across the insulating oxide layer, causing them to get trapped in normally forbidden regions such as the floating gate, where they can cause damage. Once the electric field is removed, charge detrapping normally begins to occur, where the thermal energy of the trapped electrons causes them to decay back out of the oxide layer. However at cold temperatures, the detrapping rate is decreased because the trapped electrons have less thermal energy. These electrons are now trapped much longer in forbidden regions of the MOSFET, and so are able to do more damage. An appropriate model for this failure mode would require knowledge of the kinetics of charge trapping and detrapping at different temperatures as inputs, which requires extensive electrical characterization.

9.2 Cold Soak Survival (Operational)

For operational components and modules this should be operational test. For all others this is a non-operational test.

9.2.1 Preconditioning

None

9.2.2 Required Inspection

Perform a baseline inspection on the UUT before and after the procedure.

Functional test of UUT before and after procedure.

9.2.3 Parameters

- 72 hour dwell
- Low Temperature: –80°C
- Humidity: Uncontrolled

Turbuckets (Combined PTCE/HTOL/LTOL)

Refer to another document.