HUMIDITY TESTING FOR HUMAN RATED SPACECRAFT

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ABSTRACT

Determination that equipment can operate in and survive exposure to the humidity environments unique to human rated spacecraft presents widely varying challenges. Equipment may need to operate in habitable volumes where the atmosphere contains perspiration, exhalation, and residual moisture.
Equipment located outside the pressurized volumes may be exposed to repetitive diurnal cycles that may result in moisture absorption and/or condensation. Equipment may be thermally affected by conduction to coldplate or structure, by forced or ambient air convection (hot/cold or wet/dry), or by radiation to space through windows or hatches. The equipment's on/off state also contributes to the equipment's susceptibility to humidity. Like-equipment is sometimes used in more than one location and under varying operational modes.

Due to these challenges, developing a test scenario that bounds all physical, environmental and operational modes for both pressurized and unpressurized volumes requires an integrated assessment to determine the "worst-case combined conditions."

Such an assessment was performed for the Constellation program, considering all of the aforementioned variables; and a test profile was developed based on approximately 300 variable combinations.

The test profile has been vetted by several subject matter experts and partially validated by testing. Final testing to determine the efficacy of the test profile on actual space hardware is in the planning stages. When validation is completed, the test profile will be formally incorporated into NASA document CxP 30036, "Constellation Environmental Qualification and Acceptance Testing Requirements (CEQATR)."

This paper described the variables and resulting profile.

KEYWORDS: Humidity testing, human rated spacecraft, qualification and acceptance testing, environmental testing, functional testing, dewpoint, relative humidity, condensation, corrosion, tin whiskers, water vapor, environments, psychrometric, dendrite.

INTRODUCTION

Integrating and launching spacecraft is typically accomplished somewhere coastal and often tropical. External structure and equipment in locations that are not pressurized or purged are subject to widely varying degrees of airborne water vapor and potential condensation. In-transit and storage environments also provide opportunity for water vapor incursion and absorption.

A qualification test is required to verify the design features that protect equipment from the degrading effects of varying concentrations of water vapor and exposure to condensate. These environments are potentially encountered during storage, transportation, ground operations, and flight operations; the testing should correlate to these service life events.

Current humidity test procedures in documents such as MIL-STD-810G, "Department of Defense Test Method Standard, Environmental Engineering Considerations and Laboratory Tests," do not represent these variables and are not compliant with the test like you fly (TLYF) or day in the Life (DITL) paradigms, although significant improvements were made to the latest revision. A test is needed to verify that the failure mechanisms associated with individual or combinations of the variables have been adequately addressed by design or adequately protected against by formalized procedures.

Humidity testing qualifies hardware that may be exposed to high water vapor extremes and accumulation of moisture. High-moisture environments potentially cause the following failure mechanisms:

1. Electrical continuity problems (opens/shorts)
2. Accelerated wear on moving parts
3. Infiltration of plastics and coatings causing substrate corrosion due to entrapped moisture or absorption
4. Dendrite formation
5. Whisker formation
6. Internal and external corrosion
7. Migration of moisture across hermetic seals and accumulation within the equipment due to differential pressure change when the unit is cooler than the surrounding environment

Corrosion, defined as "the destructive attack of a metal caused by either a chemical or an electrochemical reaction with the various elements in the environment," is the primary failure mechanism of high concentrations of moisture. In the most common use of the word, this means a loss of electrons of metals reacting with water and oxygen.

ENVIRONMENTS

The data in Table 1 was extracted from NASA document "Constellation Program Design Specification for Natural Environments (DSNE)," Table 3.1.7-1. Atmospheric humidity is used for defining the thermal and dry/moist conditions acting on the vehicle. The surface psychrometric data are based on hourly surface observations for the Eastern Range from 1957 to 2002. Figure 1 is a representation of the data in Table 1, with the temperature in degrees Fahrenheit.

Table 1. Psychometric Data, Dew Point Temperature
versus Temperature Envelope for KSC

Temperature (°C)(°F)	Dew Point (°C)(°F)	Relative Humidity
(-4)(25)	(-14)(7)	46
(-4)(25)	(-4)(25)	100
(28)(82)	(28)(82)	100
(36)(97)	(28)(82)	62
(40)(104)	(15)(59)	23
(11)(52)	(-14)(7)	16

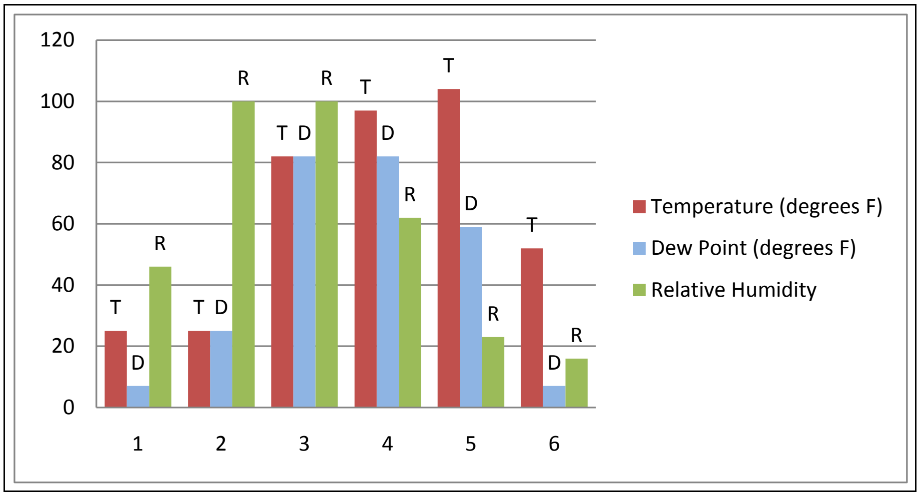

Figure 1.

As shown by this data, the potential variation in airborne moisture at Kennedy Space Center (KSC) is extreme. The saturated vapor density at -4 °C air temperature is 3.8 grams per cubic meter, and is 51 grams per cubic meter for an air temperature of 40 °C. Although very improbable, it shows that short duration extremes are possible. The hot, humid case of 36 °C air temperature and 28 °C dew point results in a relative humidity of approximately 65% with 27grams of water vapor.

However, the real natural humidity environment is not static and is best represented by a diurnal cycle for design and protection purposes. The following cycle is an excerpt from the Shuttle Environmental Requirements and Test Criteria for the Orbiter Vehicle specification (MF0004-014, Revision F, September 30, 2003):

> "The following extreme humidity cycle of 24 hours should be considered in design: 3 hours of 37.2°C (99°F) air temperature at 50 percent relative humidity and a vapor concentration of 22.2 g/m3 (9.7 gr/ft3); 6 hours of decreasing air temperature to 24.40°C (760°F) with relative humidity increasing to 100 percent (saturation); 8 hours of decreasing air temperature to 21.10°C (700°F), with a release of 3.8 grams of water as liquid per cubic meter of air (1.7 grams of water per cubic feet of air), humidity remaining at 100 percent; and 7 hours of increasing air temperature to 37.20°C (99°F) and a decrease to 50 percent relative humidity."

Similar environments exist along the coastal regions of the southern United States as well as equatorial launch sites; therefore, ample opportunity for moisture incursion exists. As shown in the excerpt above, condensation on cooled spacecraft surfaces or in vented equipment can be significant. It has been demonstrated that moisture permeates across virtually any seal, even hermetically-sealed units. Welding is the only demonstrated method of totally preventing moisture transfer. In addition, equipment with organic conformal coating will accumulate moisture within the protective coating over time, creating the potential for corrosive action including electrochemical migration above and under the conformal coating.

Interior environments for human-rated spacecraft are generally controlled to strict operating conditions, but occasionally even those areas are subject to events when control is problematic. Events such as assembly operations, troubleshooting, transport, or loss of purge during power outages are just a few examples. Health of the hardware should not be dependent on subsequent purging or drying processes after exposure to high water vapor environments, since some areas will not be accessible, and residual from the moist environments may result in damage to hardware that is very difficult to locate and repair.

Habitable volumes are carefully managed to ensure minimal water vapor, but when people are present, so is moisture. The average person sweats at almost precisely 98.6 °F (37 °C). The maximum normal rate of perspiration is approximately 1.5 liters per hour. For individuals well acclimated to tropical climates, this rate can increase to 3.5 liters per hour (Guyton 1971). This acclimatization would be expected of astronauts training in Houston and flying from KSC. This level of perspiration severely challenges spacecraft humidity control systems when vigorous exercise is required or stressful situations are encountered. Even when one is unaware of perspiration, an average amount of about 600 grams (0.6 L) per day of "insensate loss" of moisture from the skin can be expected. The volume of water lost in sweat daily is highly variable, ranging from 1 to 8 liters per day. So, as we can see, structure and equipment anywhere on a spacecraft has some level of susceptibility to water vapor and condensate.

In contrast are conditions of very hot and cold extremes that can be encountered during the hardware's lifecycle, with very low water vapor concentrations. Changes in the material properties of the equipment, static electrical/arcing, and lubrication issues are the primary concern under these conditions. These dry environments also challenge the design and protection processes, but are covered during thermal cycle or thermal vacuum testing rather than as part of humidity testing.

The job of hardware design organization is to build in self-protection design features. The job of the operations, logistics, and maintenance organizations is to provide external protective measures. The job of the test engineer is to verify that these measures are adequate.

HARDWARE AND SERVICE LIFE CONFIGURATION

There are three basic categories of equipment at the unit level of testing:

1. Electrical/electronic (vented chassis)
2. Electrical/electronic (hermetically-sealed chassis)
3. Non-electrical/electronic

The electrical/electronic units will have one or more of the following categories of thermal control:

1. Passive
2. Forced-air
3. Cold-plate

Hardware will typically be installed in one of the following operational environments:

1. Internal-controlled
2. Sheltered-uncontrolled
3. External-uncontrolled

The configurations defined above must then be evaluated in the following three modes to determine worst-case test environments:

1. Mission (prelaunch, flight, landing, post landing) - Unpowered
2. Mission (prelaunch, flight, landing, post landing) - Powered
3. Nonoperational (storage, repair, transportation)

DEVELOPING THE COMPREHENSIVE TEST

As part of developing an all-encompassing humidity test profile, a matrix was developed to assess the substantial combinations of service life factors defined above, that need to be addressed in crafting a comprehensive test. A spreadsheet was developed to assist in the process and document the results. All combinations were evaluated to determine if they were a design case or within the envelope of bounding conditions. Some of the factors in making these determinations are defined in the following paragraph.

Units installed in external vehicle applications will be exposed to natural diurnal cycles of high-temperature and high-moisture content followed by decreasing temperatures and the potential for condensing conditions. Also, the transitional periods must be assessed as well as end points since convergence of air temperature and dew point may occur.

Units installed in interior applications, where there is typically human presence, will also see high-humidity environments due to perspiration and exhaled water vapor. In addition, during ground operations, purging conditions may create very dry, warm environments especially when dry nitrogen is used as a purging element for interstitial and non-occupied areas of the spacecraft.

Cold-plate cooled equipment may be susceptible to condensation if, while powered off, cooling is being applied. Equipment or structure that can get colder than the dew point temperature of the surrounding air may also present a condensate dripping hazard to adjacent equipment.

When the assessment and worst-case scenarios were completed, a search of existing procedures was performed. Excerpts from existing standards were integrated with configuration and operational mode-related states to develop the following test profile.

TEST DESCRIPTION

Two profiles are combined for the basic electrical/electronic equipment humidity/moisture test (Static Temperature/Humidity/Bias [THB] test and the Cyclic THB test):

1. The Static THB test provides an environment that assesses the potential for development of dendrites. Functional testing is performed prior to the start of testing. Then the test article (TA) is subjected to high-moisture, high-temperature environments for extended durations while powered and monitored. The TA is then exposed to the high-moisture environment in an unpowered state to represent operationally quiescent periods and the storage and transportation environments.
2. The Cyclic THB test (see note below) assesses the ability of the product to operate reliably under high-humidity environments and potentially condensing conditions (dew point). The cyclic nature of this test increases the potential for electrochemical migration between insulated conductors. It also verifies that hermetic sealing properties are adequate for high-moisture conditions.

   After inspection and functional verification, the article is environmentally cycled while powered and monitored to represent potential service-life exposure. This test determines if intrusion or exposure to elevated atmospheric moisture impacts functional performance. Following completion of the high-humidity cycles, a performance test is performed to demonstrate that no degradation has occurred. A detailed physical inspection determines if corrosion, dendrite, moisture accumulation, or tin whisker growth is present.

   NOTE: Condensation occurs when the temperature of the TA is less than the dew point temperature of the surrounding environment. Condensation does not occur if the article's temperature is 5 °C or greater than the ambient dew point temperature. If the unit is always powered and the delta T is always greater than 5 °C, then there is no value in performing the cyclic test. However, if there are periods of lower power consumption or periods when power is removed, then the cyclic test must be performed.

Simplified versions of these tests are performed for nonelectrical/electronic equipment such as mechanical assemblies and optics. Nonelectrical/electronic TAs are subjected to high-moisture environments to ensure that they will survive service-life exposure to mission and non-mission environments. Corrosion susceptibility to high-moisture content is assessed under high- and low-temperature environments with operability verified by functional test during and after multiple cycles.

The following procedure was developed using input from numerous existing standards such as MIL-STD-810 and IPC-TM-650, "Test Methods Manual."

TEST PROCEDURE

Initial Test Conditions

1. Install the TA in a chamber with the axis consistent with operational orientation and protected from dripping condensation sources unless this is a potential during operational use.
2. The chamber is vented to maintain site ambient pressure. For electrical/electronic units, power and instrumentation is connected and verified prior to test.
3. Apply baseplate or forced-air cooling, if required, at the minimum cooling levels (least amount of cooling) defined by the design specification. Apply power to electrical/electronic units.
4. Adjust the chamber temperature to 22 ± 1 °C and atmospheric moisture content at 10 ± 1 °C dew point (approximate RH of 50%). Allow parameters to stabilize.
5. Perform a functional test to ensure the article is properly operating at room ambient conditions.

The Static Temperature/humidity/Bias (STHB) Static High Moisture Exposure

1. Warm/Moist Ramp Powered
   a. Ramp the chamber conditions from ambient conditions to 40 °C +3/-0 °C.
   b. Raise the atmospheric moisture content to a dew point of 1 °C less than the atmospheric dry bulb temperature (approximate 93% RH, not to exceed 95%), maintaining constant chamber temperature and site ambient pressure. Perform this temperature/humidity ramp at a rate not to exceed the predicted platform rate and ensure that the atmospheric dew point does not exceed the TA temperature, which might cause condensation.
2. Warm/Moist Dwell Powered
   a. Maintain the 40 °C +3/-0 °C and 93 +2/-0% RH for 12 +.25/-0 hours. Monitor for intermittent or anomalous behavior during the 12-hr period.
   b. At the end of 12 hours, perform a functional test.
   c. If the unit is actively cooled, adjust the cooling to maximum cooling mode for power-on conditions, as defined in the design specification. Maintain these conditions for 12 +0.25/-0.0 hours. Monitor for intermittent or anomalous behavior during the 12-hr period.
3. Return to Ambient: Reduce temperature to room ambient at no more than 3 °C ±1 °C per minute average, while simultaneously reducing humidity levels such that condensation does not form while returning the chamber and TA to ambient conditions. Do not disturb or move the TA.
4. Post-test Inspection: Perform a functional test of the unit while the article is still installed in the chamber.
5. Simulate Multiple Exposures: Repeat the cycle (steps 1 thru 4 above) four more times for a total of five cycles.

Cyclic Temperature/Humidity/Bias (CTHB) Operating Under Condensing Conditions

1. Initial Test Conditions: Establish initial test conditions on the TA.
2. Minimum Operating Temperature
   a. Adjust chamber temperature to minimum ground or compartment operating temperature level, as defined in the development specification +0/-3 °C, while maintaining RH at 50% or less.
   b. Allow the temperature to stabilize for at least 1 hr. Continuously monitor the TA for intermittent or off-nominal performance.
3. Cold Atmosphere, Condensing Moisture
   a. While maintaining the chamber atmospheric temperature at the stabilized cold case level, inject moisture into the air stream until saturation occurs and condensation begins to form on the TA.
   b. Continue to add moisture, as required, to maintain condensate on the TA.
   c. Cycle the atmospheric temperature and moisture injection to maintain these conditions for 3 +.25/-0 hours.
   d. Continuously monitor the TA for intermittent or anomalous performance.
4. For baseplate active-cooled units only (Cold atmosphere, condensing moisture-maximum cooling)
   a. While the TA is covered with condensate, decrease the baseplate temperature to maximum cold-case specified while continuing to add atmospheric water vapor to maintain condensate on the TA.
   b. Cycle the atmospheric temperature and moisture injection to maintain these conditions for 3 +.25/-0 hours.
   c. Continuously monitor the TA for intermittent or anomalous performance.
5. Functional Test (cold soaked unit exposed to saturated cold atmosphere while operating): Perform a functional test and monitor for anomalous conditions.
6. Unpowered Cold Soak: Remove power from the TA and maintain atmospheric conditions at the levels established in step 3 above for 3 +.25/-0 hours.
7. Cold Power Up (Cold Start [CS] and cold damp conditions): Apply power to the TA and perform a functional test.
8. Ramp to Warm/Moist Atmosphere (Condensing)
   a. Ramp the chamber conditions to the maximum predicted operating temperature +3/-0 °C.
   b. Increase the atmospheric moisture content of the test chamber to maintain saturation with 100% RH. Perform this temperature/humidity ramp at a rate not to exceed the predicted platform rate. The predicted humidity increase rate shall simulate the worst-case dew point transition from a daily diurnal cycle.
   c. Maintain these conditions for 3 +.25/-0 hours. Continuously monitor the TA for intermittent or anomalous performance (cold, damp unit exposed to a warm, moisture-condensing environment, while operating).

9. Warm Case Power-On/Power-Off Condensing Cycle
   a. Remove power from the TA and maintain active cooling to maximum levels specified in the development specification.
   b. Maintain these conditions for 3 +.25/-0 hours.
   c. Apply power and perform a functional test, monitoring for intermittent or anomalous performance.
10. Warm/Moist to Ambient Condensing Cycle
   a. Ramp the chamber from the maximum operating temperature to room ambient temperature without adjusting moisture levels. Perform this temperature/pressure ramp at the maximum facility rate, not to exceed the predicted platform rate.
   b. Maintain these conditions for 3 +.25/-0 hours. Continuously monitor the TA for intermittent or anomalous performance.
   c. Following the 3-hr soak, perform a functional test monitoring for intermittent or anomalous performance.
11. Simulate Multiple Exposures: Repeat the cycle (steps 1 through 10 above) nine more times for a total of 10 cycles.

Supplementary Requirements

The pass/fail criteria for unit testing are primarily based on compliance with functional test requirements during and after exposure to high-moisture content environments. Visual inspection shall be performed within 1 hour of test completion. When the integrity of the unit may be permanently impaired by access cover removal, this moisture/humidity testing should be performed last in the sequence of testing, or the inspection should be deferred until all other testing is completed.

The following conditions are indicative of design deficiencies and shall be assessed following testing:

1. Dendrite growth (electrical/electronic units) – Inspection and functionality
2. Corrosion – Inspection and functionality
3. Tin whiskers – Inspection and functionality
4. Water intrusion – Verified by precise weight measurement or visual inspection prior to and following humidity testing.

SUMMARY & CONCLUSIONS

This qualification test should thoroughly stress equipment in environments and configurations that may be reasonably expected during its service life. If hardware operates nominally during and after exposure to these high water vapor concentrations and condensate formation, there should be a reasonable expectation that it will continue to so, given nominal protection during use.

REFERENCES

CxP 70023, Constellation Program Design Specification for Natural Environments (DSNE), November 2008.

CxP 70036, Constellation Environmental Qualification and Acceptance Testing Requirements, December 2008.

Guyton, Arthur C., "Basic Human Physiology: Normal Function and Mechanisms of Disease," W.B. Saunders Co., 1971.

Hillman, Craig - Ph.D., White Paper "Qualifying for Moisture-Containing Environments," (no date).

IPC-TM-650, Test Methods Manual.

MF0004-014, Shuttle Environmental Requirements and Test Criteria for the Orbiter Vehicle specification, Revision F, September 2003.

MIL-STD-810G, Department of Defense Test Method Standard, Environmental Engineering Considerations and Laboratory Tests, October 2008.

BIOGRAPHY

Gary B. Johnson currently is employed as a chief engineer for environmental test by the Science Application International Corporation (SAIC). He supports the NASA Constellation Program Office, Systems Engineering and Integration (SE&I) function in this capacity.

Mr. Johnson began his career with North American Aviation on the Apollo program in Laboratories and Test, working primarily propulsion system development testing. He then transitioned to Apollo Test Operations as an Environmental Control Systems test conductor.

Following Apollo, he developed Level 2, 3, and 4 requirements for the Shuttle Environmental Control and Life Support Systems. He authored the "Environmental Requirements and Test Criteria for the Orbiter Vehicle Specification," which served as the authoritative source for all flight and ground environmental design criteria and corresponding qualification and acceptance tests.

As the Shuttle program transitioned from design to flight operations, he was assigned to Support Engineering and Logistics as a project manager. In this capacity, he was responsible for systems management processes and information systems, both institutional and programmatic.

Following Shuttle, he moved to the Johnson Space Center (JSC) supporting International Space Station (ISS) integration activities. On ISS, he was responsible for flight and ground transportation environments definition, with corresponding test oversight.

Mr. Johnson retired from Boeing North American in 1998 after 36 years of service.

He served as the Orbital Sciences JSC site representative from 1998 to 2001 on the X-38 and Orbiter upgrade programs.

Mr. Johnson has a BS degree from LaVerne University and is a member of the following organizations:

- Institute of Environmental Sciences and Technology (IEST)
- Institute of Electrical and Electronic Engineers (IEEE)
- Society of Southwestern Aerospace Professional Representatives Association (SWAPRA)
- Rotary Club of Space Center