

THE CERTIFICATION OF ENVIRONMENTAL CHAMBERS FOR TESTING FLIGHT HARDWARE

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ABSTRACT

The JPL chamber certification process for ensuring that test chambers used to test flight hardware meet a minimum standard is critical to the safety of the hardware and personnel. Past history has demonstrated that this process is important due to the catastrophic incidents that could occur if the chamber is not set up correctly. Environmental testing is one of the last phases in the development of a subsystem, and it typically occurs just before integration of flight hardware into the fully assembled flight system. A seemingly insignificant –miscalculation or missed step can necessitate rebuilding or replacing a subsystem due to over-testing or damage from the test chamber. Conversely, under-testing might fail to detect weaknesses that might cause failure when the hardware is in service. This paper describes the process that identifies the many variables that comprise the testing scenario and screening of as built chambers, the training of qualified operators, and a general “what-to-look-for” in minimum standards.

KEY WORDS

Thermal, Temperature, Vacuum Chamber, Failsafe, Thermal Cycles, Contamination.

INTRODUCTION

The fundamental purpose of environmental testing is to simulate the launch and in-flight environments to qualify the design of hardware. Environmental testing is typically performed at three levels, the assembly, subsystem and the full-up spacecraft or system level. The assembly and subsystem level are performed in smaller environmental chambers about 100 cu/ft (2.8 cu/m) in size. Full-up spacecraft or system testing is done in larger environmental chambers as large as 38,500 cu/ft (1,090 cu/m). The three types of testing are:

Protoflight

Protoflight (PF) testing is performed on flight hardware, *which is intended to be flown*, and for which there is no previous qualification. Protoflight testing accomplishes the combined purposes of design qualification and flight acceptance. Due to its wider test margins and therefore increased defect detection, PF testing is the preferred method of environmental testing for all flight units. However, where hardware fatigue or wear-out is of a significant concern, a QUAL/FA test program may be necessary in lieu of a PF test program. Hardware with qualification heritage may still be PF tested.

Qualification

Qualification (QUAL) testing is performed on a dedicated Qualification Model of flight hardware (or an Engineering Model if approved for qualification purposes), *which is not intended to fly*, in order to qualify the hardware design for the maximum expected flight environment plus margin, including margin on environmental duration or cycles.

Flight Acceptance

Flight Acceptance (FA) testing is performed on flight hardware and spares only when a protoflight or qualification test is performed on an identical item. If, as determined by a Heritage Review, previous qualification or protoflight test levels of a heritage assembly are adequate for the mission and the heritage design and operations are not modified in a way that negates the previous qualification, then the assembly may be FA tested. However, as mentioned above, PF testing is preferred on all flight units for improved workmanship-defect detection.

Of the many levels of testing that the hardware is subjected to during the lifecycles of the hundreds of sub-assemblies that comprise a spacecraft, one of the final tests is the completed spacecraft being tested in an environmental chamber. This simulates the environment that the spacecraft will experience during the total mission. This environment includes the vacuum of space, the maximum and minimum temperatures that the spacecraft is expected to experience, and the expected solar luminance. The following list includes some of the possible problems that have been experienced when a spacecraft has not been environmentally tested correctly.

- Breakage from over stressing
If the thermal testing has too many thermal cycles at the temperature extremes it can over stress the instrument and its parts.
- Thermal temperature too cold
If the chamber temperature goes below the target temperature, it can damage or destroy the test article or its parts.
- Thermal temperature too hot
If the chamber temperature goes above the target temperature, it can damage or destroy the test article. For example, if the instrument is a transmitter or receiver and it gets too hot or cold while testing, it could degrade the electronic components, thus causing poor performance. This type of failure may not be caught prior to launch, causing a partial failure of the mission.

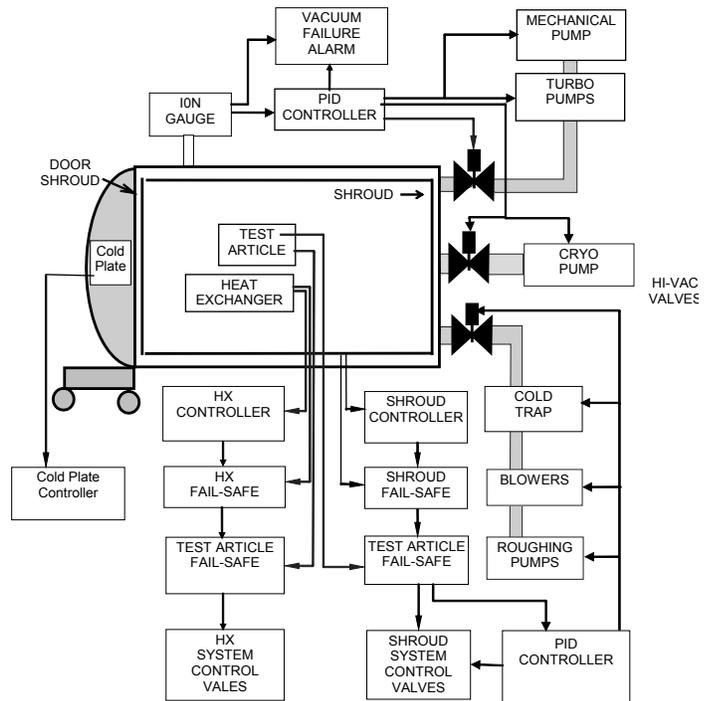
TYPICAL THERMAL AND THERMAL VACUUM CHAMBERS



(a)



(b)



(c)

Figure 1. JPL thermal vacuum chamber showing (a) external view, (b) control area, and (c) functional diagram. Chamber internal testing area 10 ft dia × 10 ft long (3.04 × 3.04 m)

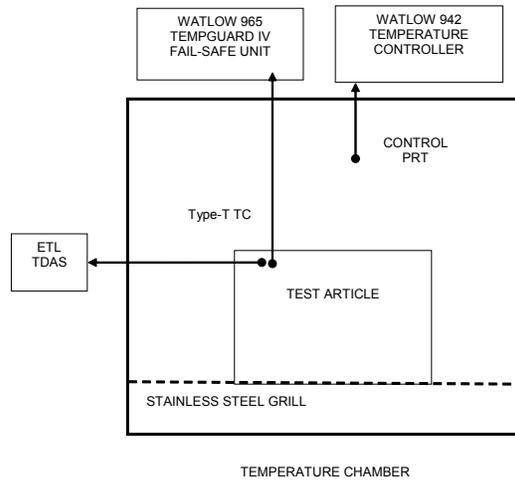


Figure 2. JPL thermal ambient-pressure chamber showing external view (left) and functional diagram (right). Chamber internal testing area 40" × 40" × 40" (101×101 ×101 cm)



Figure 4. Cassini spacecraft in JPL thermal vacuum chamber. Chamber internal area is 25 ft dia × 85 ft high (7.62 × 25.9 m)



Figure 3. JPL thermal vacuum chamber with internal testing area of 27" dia × 36" long (68.58 × 91.44 cm).

THE CHAMBER CERTIFICATION PROCESS

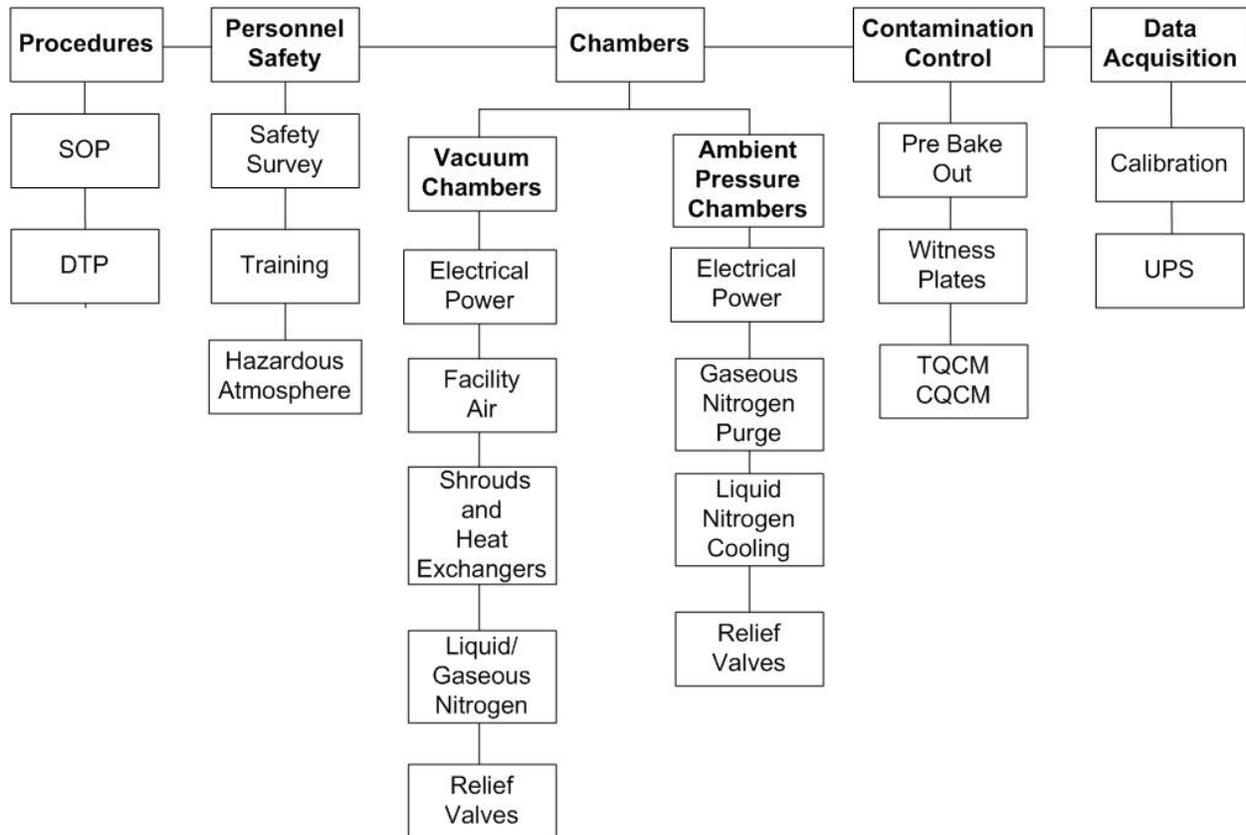


Figure 5. Environmental Test Laboratory chamber survey flow chart.

PROCEDURES

Standard Operating Procedure (SOP)

The environmental chamber SOP contains the information that is directly related to the operation of that chamber. It is written with the assumption that the operators have the basic knowledge of environmental testing and intimate knowledge of the chamber control systems.

- This procedure describes the step-by-step operation of the chamber detailed instructions. These steps need to be organized in sections so that any particular step will be easy to locate in case of an emergency.
- The preventive maintenance procedure is the key to keeping the chamber in good operating condition. This document contains instructions on how to perform the maintenance on each of the chamber's subsystems. Included are tracking instructions and notations about how often maintenance is done, when it was completed, and by whom.

- Chamber Identification allows for operator, customer and product assurance to relate a specific SOP or detailed test procedure (DTP) with the correct chamber.
- A list of trained and certified operators is required for ISO 9001 certification, and these operators need to know their responsibilities as well as being able to demonstrate that they can operate the chamber safely.
- Instructions are required on how to install the test article in the specific chamber. These instructions can be provided by a general handling class for flight hardware or in a specific training program (project specific or subsystem specific). Each chamber is different, so the operators need to know if there are any special handling requirements for the hardware or idiosyncrasies that are related to each specific chamber.
- The emergency response section of the procedure is required to ensure clear instructions in the unlikely event of an emergency. This procedure will help to protect personnel, the test article, and the facilities in the event of earthquake, fire, uncontrolled liquid nitrogen (LN₂) venting, loss of facility power, loss of facility compressed air supply, loss of facility cooling water supply, or anything else that may be an emergency. Periodic review by operating personnel of each section of this procedure will help them in an emergency to overcome any possible stress caused by the emergency. The end result is that the operators are so familiar with the emergency operations that they would react during the emergency in the same calm and competent manner as they do during normal operations.

Detailed Test Procedure (DTP)

This unique procedure describes the details of the testing operation, and a separate DTP is created for each test in each chamber. There are many detailed requirements that can be included in the DTP. Generating the DTP is typically the responsibility of the Cognizant Engineer for the article being tested (also referred to as the Test Article Engineer or TAE); however, many test organizations have a test engineer dedicated to performing this type of work. The following is a list of suggested contents for the DTP

- Assign a test number to keep track for future reference. (ISO Requirement)
- Project and test article name (full name, not just an acronym)
- Appropriate procedure signatures
- List of the test requirements, parameters, and sequences
- List of any unusual security, safety, and cleanliness requirements
- List of test tolerances, alarms, and limits for failsafe devices
- Detailed step-by-step instructions for the performance of the test
- Emergency shutdown procedures to protect the specific test article in case of a chamber anomaly
- Instructions for handling the test article, installing the test fixtures, and removing the test fixtures

PERSONNEL SAFETY

Safety Survey

The safety survey is a vital part of the testing process used to ensure that the facility and personnel are safe. A survey is done by the system safety department to identify any discrepancies from the unique chamber setup. There are two distinct parts to the survey. One is focused on the testing facility, and the second is focused on the testing system. Each part has questions that have to be answered either yes, no, or n/a (not applicable).

A subset of the safety survey is an environmental chamber certification survey performed by the Environmental Testing Laboratory at JPL. This also is also a yes, no, or n/a format, but it is more specific to each test setup with a specific chamber. This survey process is the basis for the writing this paper.

Operator Training

There are multiple levels of training required to run an environmental chamber with flight hardware. First, there is the basic knowledge of chambers and vacuum principles. Second, is how to operate a specific chamber and what to do in an emergency. Finally, the operators need to learn the flight protocols that are specific to the testing of the flight hardware. The certification process requires that the operators demonstrate to the facilitator that they know how to operate the chamber and what to do in an emergency.

Hazardous Atmosphere

There is always a possibility of introducing a hazardous atmosphere when using gaseous nitrogen (GN₂). To eliminate the risk of personnel becoming suffocated, the requirement is to have a calibrated oxygen monitor in the immediate area. Such monitors can be permanently mounted or portable as long as the portable model does not leave the testing area during the duration of the test.

Confined Space

Confined space is important to establish for the safety of the personnel. When personnel are working in a large chamber with the capability to trap GN₂ or other hazardous gases, there is a risk that they could suffocate if they were to enter a confined space with a build-up of hazardous gas or gases.

A confined space is a space that meets the following criteria:

- The space is large enough and so configured that an employee can bodily enter and perform assigned work; and
- Has limited or restricted means for entry and exit (example: tanks, vessels, silos, storage bins, hoppers, vaults and pits); and is not designed for continuous employee occupancy.

A Permit Required Confined Space (PRCS) is a confined space that has one or more of the following characteristics:

- Contains or has the potential to contain a hazardous atmosphere; or
- Contains a material having the potential for engulfing an entrant; or
- Has an internal configuration such that an entrant could be trapped or asphyxiated by inward converging walls or by a floor that slopes downward and tapers to a smaller cross-section; or
- Contains any other recognized serious safety or health hazard.

Oxygen Content % by Volume	Effects and Symptoms (at Atmospheric Pressure)
>23.5	Fire Hazard
20.9	Normal oxygen concentration
19.5	Minimum permissible oxygen level
15–19	Decreased ability to work strenuously. May impair coordination and may induce early symptoms in persons with coronary, pulmonary, or circulatory problems.
12–14	Respiration further increases in rate and depth, poor judgment, lips blue.
8–10	Mental failure, fainting, unconsciousness, ashen face blueness of lips, nausea, and vomiting.
6–8	8 minutes, 100% fatal; 6 minutes, 50% fatal; 4–5 minutes, recovery with treatment.
4–6	Coma in 40 seconds, convulsions, respiration ceases, death.

CHAMBERS

Backup Generator

If there is a power outage, the capability of a backup generator is recommended to supply power to the chamber systems vacuum valves, data acquisition system, and thermal control system. The backup generator is used to give extra time to secure the chamber to a safe condition and not harm the test article.

In addition to the generator, it is recommended to have a UPS (Uninterruptable Power Supply) connected to the chamber control system to facilitate a smooth transition between the power outage and the time it takes to get the backup generator operational.

Backup Air Compressor

The backup air compressor can mitigate a facility air interruption. Most vacuum chambers have pneumatic vacuum valves, and if the air pressure is lost to the valves, they fail in the closed position. In most cases that is a “safe” condition, but there are many instances for which if the chamber vacuum valves close, the chamber pressure starts to increase. If you are in a cold testing phase, the high pressure can cause thermal instability.

Two factors cause this instability. First, there are inherent leaks in the chamber; though probably small, they can add up to a significant leak rate. Second, if there is a large surface area on the test article, it can outgas and contribute a high gas load to the chamber. The ideal configuration is to have the backup compressor start automatically if the primary compressor fails. Make sure that you have a check valve installed between the primary system and the backup systems. Also, install an alarm in the testing area to indicate if the primary air pressure has been compromised.

Shrouds and Heat Exchangers

In a vacuum chamber, shrouds and heat exchangers are the key test hardware items that deliver heat and cold to the test article using the radiative thermal principal for the shrouds and conductive for the heat exchangers. It is imperative that they do not leak especially when using a heat transfer fluid like Syltherm or ethylene glycol. If the chamber has a robust pumping system, it could be pumping the leak volume and therefore not indicate a leak. But, the small amount of fluid being introduced into the chamber will still be contaminating the test article. The best way to leak check the shrouds is to evacuate them with a roughing pump, connect a helium mass spectrometer and spray helium on the outside of the shrouds. The maximum recommended helium leak rate is 1×10^{-8} cc/s.

Liquid and Gaseous Nitrogen

Liquid and gaseous nitrogen is typically used to heat and cool the shrouds and heat exchangers in a vacuum chamber. There are numerous concerns that need to be identified when using them.

- Verify that there is an adequate supply of LN₂/GN₂ to meet the needs of the test. Always check the storage tank level and that there are planned deliveries for the volume that the chamber will use.
- Check that there a liquid-level alarm on the liquid storage tank. Most of time, smaller tanks do not have such an alarm. These days, the liquid nitrogen supplier has a tele-monitoring system to track usage remotely. However, the monitoring system can fail or inclement weather could interrupt the deliveries. Entering the tank level on a log sheet once per shift should be done to make sure that the tank status is known before it is empty.
- The LN₂ plumbing lines need to be insulated properly to make sure that air cannot condense on the pipe. Oxygen can condense out of the air and create a flammable hazard. This hazard results from the fact that the normal boiling point of nitrogen is approximately -320°F (-195°C) while that of oxygen is -297°F (-183°C).
- The LN₂ control system must have a redundant failsafe valve in series with the primary control valve. This protects the system from running away and getting too cold, which could harm the test article. There are two reasons how this could occur, one is ice building up inside the valve that holds the valve open or two, the top of the solenoid plunger mushrooms and sticks opens. The backup failsafe

(normally closed valve) has an independent thermocouple and controller; which if the temperature dropped below a cold threshold value, would close thus stopping the flow of LN₂ and make the system safe.

Ambient Pressure Chamber Purging

Testing in a temperature/ ambient pressure chamber, the protocol is typically to purge with GN₂ (gaseous nitrogen) because it is the most common purge gas in the typical environmental testing area. It is important that the purge volume be enough to keep the moisture out of the testing volume, but at the same time the purge volume should not be too much so that it exposes the operators to a hazardous atmosphere.

A dry run is needed to deal with this issue. The dry run is done at the test temperatures without the test article and preferably with a mass model in the chamber. Multiple runs may be needed to determine the correct GN₂ flow. When the correct flow is determined, there will be no frost anywhere in the chamber or the test article. The best method is to install a manometer that measures pressure (in inches of water) inside the chamber. If there is at least 0.5 inch (1.3 cm) of water pressure, the chamber has positive pressure, and ambient humidity moisture cannot enter the chamber.

Calibration

The temperature controllers and the temperature failsafe controllers are required to be calibrated to ensure that they are reading correctly and function as designed. The calibration protocols are different for each company, but the calibration must be able to be traced to NIST (National Institute of Standards and Technology).

Failsafe

The temperature failsafe is one of the most important parts of the chamber design. If there is a thermal anomaly, the failsafe will shut down the system and make sure that the test article is not damaged.

The process or target test temperature cannot be close to the maximum or minimum test article allowable temperatures. The test article always has a not-to-exceed design temperature, and many times the target temperature is too close that limit. A worst-case scenario of a runaway temperature controller, either too hot or too cold can be disastrous to the test article. Assuming that the failsafe is set correctly, the temperature of the test article would trip the failsafe and then continue to over/under shoot (coasting effect) past the allowable temperatures. The best way to eliminate the problem is to perform a “dry run” using a mass model and simulate a “worst case” runaway scenario. See Figure 6 below.

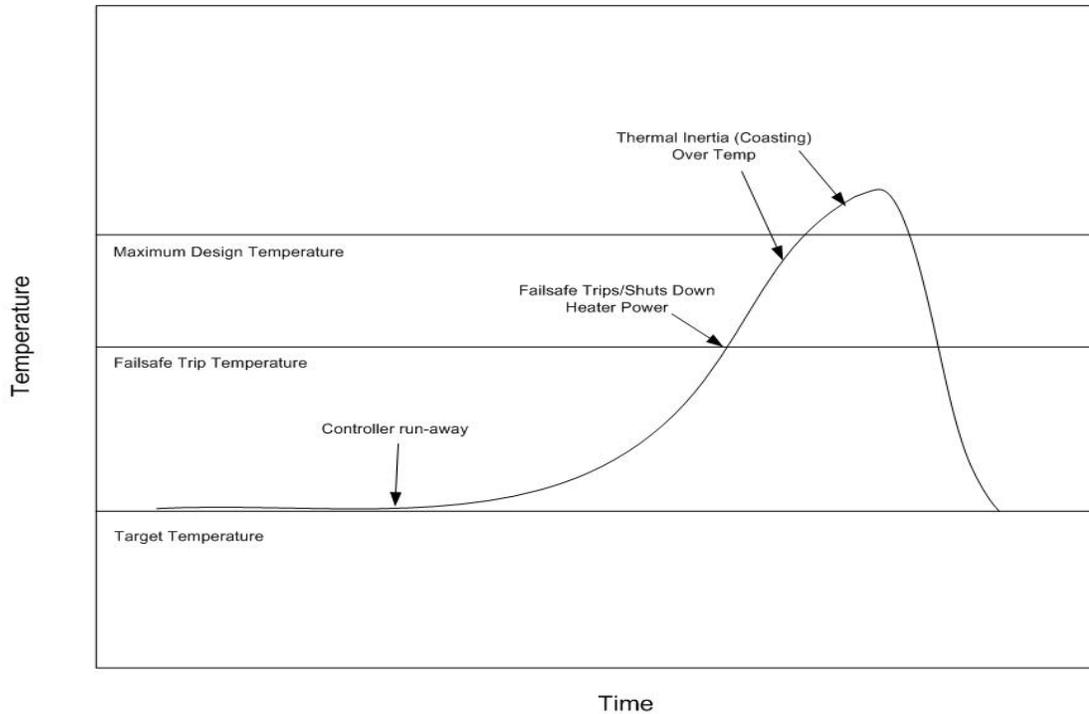


Figure 6. Scenario for failsafe operation

Relief Valve

The relief valve is always required when using LN₂, GN₂, or other pressurized gases. The expansion ratio of liquid nitrogen to gas is 694 times. If there were trapped LN₂ in a plumbing system that warmed enough to evaporate the LN₂, there is a possibility of increasing the pressure beyond the capability of the plumbing specifications and thus causing an explosion that might harm the personnel and damage the equipment. The other requirement is the relief valve needs to be calibrated by verifying that the valve operates at the designated pressure that the label indicates.

CONTAMINATION CONTROL

Contamination Control Requirements

- Define the cleanliness and contamination control requirements for the Project or subsystem based on performance requirements.
- Determine if there are other contamination compatibility requirements for the system levied by the launch vehicle, spacecraft, other instruments on the same platform, or other sources.
- Coordinating with Planetary Protection (PP) activity when mission is PP Class 4A or higher.

Chamber Pre-bake Out

The chamber is required to run a pre test bake out at a higher temperature than the flight hardware will be exposed to. Typically it will be 20°C to 40°C above the target temperature. The length of time of the bake out is relative to the contamination requirements of the project. This eliminates any residual contamination volatiles that might be in the chamber from the last test. Also witness plates are placed in the chamber to quantify what and how much contamination was in the chamber.

Analytical Method for Contamination Witness Plates

Pre-cleaned aluminum witness plates are exposed in the vacuum chamber at representative locations. The plates are rinsed with appropriate solvents to remove any deposited oily residue. The low volatility residue (LVR) rinsed from the witness plates is analyzed using Diffuse Reflectance Infrared Fourier Transform (DRIFT) spectroscopy (1). Blank samples are run along with the samples (2). Fourier Transform Infrared (FTIR) provides chemical functional group information for quantitative analysis and qualitative identification of materials. The analysis complies with IEST-STD-CC1246D (3) and is sensitive to stringent levels (4).

References and Notes Regarding Witness Plates

1. M. S. Anderson et al "Analysis of Semi-Volatile Residues Using Diffuse Reflectance Infrared Fourier Transform Spectroscopy" in *Optical System Contamination: Effects, Measurements, and Control VII*; July 2002, edited by Phillip T. C. Chen and O. Manuel Lee; *Proceedings of the SPIE*, vol. 4774, pp. 251–261, (2002).
2. The rinse blanks are less than 10 percent of the amount in the sample, and this is subtracted from the reported sample amount. High blanks (greater than 10 percent of the sample) are noted in the report. A typical solvent wipe has a detection limit of $\sim 0.005 \mu\text{g}/\text{cm}^2$ of removed residue from a 100 cm^2 sample. Note: this limit is well below the adventitious carbon level (ref. 4). Lower limits are possible using modified methods.
3. The analysis conforms to the Institute of Environmental Science and Technology (IEST), Contamination Control Division Document IEST 1246D "Product Cleanliness Levels and Contamination Control Program". The contamination limits are generally set by Contamination Control Engineering at JPL. A typical limit is "Level A" (IEST-STD-CC1246D), and this is 1 microgram per square centimeter ($\mu\text{g}/\text{cm}^2$). This corresponds to an average film thickness of 100 angstroms (assuming a density of 1.0). In many cases more stringent limits apply (4).
4. Very clean surfaces, $\leq 0.02 \mu\text{g}/\text{cm}^2$, with mono-molecular layers or less are more complex to describe when cleaning or analyzing. Carbon/hydrocarbon-based substances are known to rapidly (within ~ 1 hour) accumulate on most, if not all, freshly exposed surfaces. This "adventitious" carbon is well documented in clean rooms and vacuum systems, and it compositionally varies by environment. Adventitious carbon is a discontinuous layer of approximately ~ 0.2 nanometers thick or $\sim 0.02 \mu\text{g}/\text{cm}^2$ up to $0.1 \mu\text{g}/\text{cm}^2$ (for $\rho = 1$). The last mono-layer fractions may in some cases be strongly adsorbed to the surface as a "corrosion" layer. Therefore, solvent based sampling methods may not remove these fractions, particularly if the

surface is porous. When specifying cleanliness level to less than A/10 IEST-STD-CC1246D ($0.1 \mu\text{g}/\text{cm}^2$) these monolayer effects become more significant. See also: H. Piao and N. S. McIntyre, "Adventitious carbon growth on aluminum and gold-aluminum alloy surfaces," *Surface and Interface Analysis*, 2002; vol. 33, pp. 591–594.

TQCM/CQCM

The best way to determine if the chamber is clean is to install a TQCM (Thermal Quartz Crystal Micro Balance), which is a thermally controlled QCM. TQCMs have an internal Peltier heat exchanger, which can either heat or cool the QCM to aid in both collecting condensables and then boiling them off later.

Another method is to install a CQCM (Cryogenic Quartz Crystal Microbalance), which can operate successfully below the temperatures of liquid nitrogen (as low as -262°C). They have an internal heater, which can be used to keep them at a constant temperature or to boil off surface films from the sensor crystals. Usually smaller in size, CQCMs use less power than other QCMs and are readily adaptable to space environments.

GN₂ Condition

The condition of the GN₂ is very important to make sure it does not harm the test article during chamber purging and/or chamber backfilling. The three variables that need to be monitored are the dew point, the hydrocarbons, and the particulates. The JPL specification (Manufacturing Process Specification FS-504574) requires that the dew point be $<-60^\circ\text{C}$, with the hydrocarbons <25 ppm and the particulates be ≤ 5 microns. To make ensure that the entire GN₂ plumbing system is tested, it is recommended that a test valve on a tee be installed to be a test port at the point of entry into the chamber.

DATA ACQUISITION

The temperature data from the thermocouples are required to be electronically logged and stored on an independent computer.

Calibration

The data acquisition module (the instrument that interfaces the thermocouples and the computer) is required to be calibrated to make sure the data being logged is actually the true temperature.

UPS (Uninterruptible Power Supply)

The data acquisition system needs to be connected to an uninterruptible power supply when running the environmental test to make sure that in case of a power failure the temperature data will still be constantly logged. It is always good to know what the temperature of the test article is in an emergency situation.

SUMMARY AND CONCLUSIONS

The environmental certification program can be a very crucial part of the flight hardware testing process. If done correctly, it can improve the success of each subsystem critical to the mission. Be it instrument sub-assemblies or full-up spacecraft, the protocols are the same; the major differences are the size of the chamber and how it may be controlled or operated. If a group testing flight hardware tries to save time and/or money by not performing the testing in a fully certified chamber, eventually an anomaly will occur, and hardware could be damaged or destroyed.

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BIOGRAPHY

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