Thermal Vacuum Testing: Test Preparation

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Abstract - *Thermal vacuum testing involves subjecting hardware intended for use in space to a simulated space environment in order to determine its success or failure in such an environment or to verify the accuracy of analysis, while not having to actually risk going into the real world environment. Proper planning and forethought must go into any test before it is executed. This paper covers various guidelines to follow when testing in a thermal vacuum environment. This paper also addresses various pitfalls test requesters find themselves in when preparing for such a test. The intent of this paper is to encourage test teams to develop smart and efficient tests and test practices to accurately determine the success or failure of space related hardware and exercise mathematical models in a simulated real world environment.*

Keywords: Thermal vacuum test, test requester, test article, test team.

1 Introduction

The purpose for Thermal Vacuum Testing of space related hardware is to uncover design deficiencies and workmanship flaws while in a simulated space environment. It is also used to judge the accuracy of mathematical models by comparing analysis to actual test data from a controlled simulated environment. Understanding why you are testing and what test method to employ is critical to the success of any test. There are three main methods used in certifying that a design or actual hardware is safe for regular use in any environment: analysis, testing in simulated environments and real world results [1][2].

Analysis is the process of breaking a complex topic into small parts to gain a better understanding. Proper analysis is very mathematically intensive, but can save a lot of effort out of guess work. This method is by far the safest method in that everything is on paper or on a computer. The drawback is that complex analysis may be time consuming and yield few tangible results. Analytical models may also have the risk of not being realistic when applied to real world applications.

Simulated environments offer the closest experience to real world conditions. For space hardware, real world conditions include the natural environment of Earth, Earth's upper atmosphere, regions beyond the influence of Earth and its atmosphere and outward to deep space. Because all space hardware is currently developed, built, and launched from Earth the influence of Earth's natural environment on hardware must still be taken into consideration. Hardware designers must make sure their hardware can survive the many hours or days sitting on the launch pad prior to clearance for takeoff. Launch sites could be in the hot humid regions of the equator or the frigid cold of northern winters. Then it must survive the rigors of the launch itself, not just the forces and eventual loss of gravity, but also the immediate drop in pressure and changes in temperature. After a successful launch, space hardware may be subjected to temperature gradients ranging from -250 °F to +250 °F in low earth orbit and lower than -370 °F towards deep space. Also, the effects of solar and cosmic radiation come into play as you leave the protection of Earth's atmosphere [1][2].

During actual mission operations anything can happen. Data from real world operations or incidents is often incorporated with analytical results and simulations to modify designs or create new types of hardware. The information can also be used to modify or correct the original test methods so that the event can be accurately reproduced for further study.

Real world recorded data may contain events that are rare and unlikely to re-occur. However, the fact remains that what happened really did happen and the design and test teams must come to a conclusion on how they will respond to that information. A good design shows that you have prepared for the worst.

This paper focuses on testing in simulated environments and, in particular, using thermal vacuum to simulate space. In the following sections test chambers, processes, and instrumentation are discussed including highlights of testing pitfalls and practical advice. This is followed by discussion of key points to be aware of about test preparation and conclusions.

2 Testing in Simulated Environments

NASA employs three main types of tests in simulated space environments: Evaluation, Qualification, and Acceptance testing. Qualification testing subjects the hardware to the most extreme conditions expected during actual operation. Acceptance testing is used to prove the hardware can operate under its stated operating conditions for a given amount of time. Evaluation testing is primarily experimental testing. Evaluation testing may prove the accuracy of analysis under controlled conditions, help a design team gain familiarization with operations of the test hardware, or simply test theories or methods. NASA requires space hardware to pass both qualification and acceptance testing to be certified for use in space. It is important to note that such testing can put a strain on the test hardware. Depending on its use, costs, and availability some hardware is only used for testing while an identical but separate unit is sent into space. Other times there is only one (or a few) unit(s) available which must go through testing and launch, so special attention must be made to test the unit without placing unnecessary strain on it. This is when you go back and review data from your analysis and review the materials properties (under test and ambient conditions) to find and prevent problems such as fatigue, fractures or any other type of deterioration.

An additional type of process done in a thermal vacuum chamber is a bake out. A bake out is a process in which impurities embedded in the construction material of space hardware or support hardware such as gases, moisture, solvents, and other substances originating from the manufacturing process are forced out by heating it within a vacuum chamber. In the vacuum of space these impurities could outgas and cling to sensitive instrumentation, therefore a bake out is performed to minimize these hazards.

Simulating environments to satisfy the conditions of a test requires specialized equipment, usually a chamber. At NASA Johnson Space Center, the Crew and Thermal Systems Division uses three basic types of chambers: humidity, thermal, and thermal vacuum chambers.

2.1.1 Humidity and Thermal Chambers

Humidity chambers closely resemble industrial refrigerators; many have view ports equipped with wiper blades to inspect the progress of a test without opening the chamber door. A humidity chamber is used when a test involves subjecting hardware to elevated and/or specifically controlled moisture levels. A typical test scenario of an elevated humidity test would be the determination of whether a particular electronic component will operate after hours of sitting in the Space Shuttle Orbiter's unpressurized cargo bay during a typical summer in Florida. A controlled humidity test scenario may be to investigate the affects of corrosion on a new Extravehicular Activity (EVA) tool that is expected to be stored inside the International Space Station (ISS) for a number of years.

Thermal chambers could be best described as the combination of a freezer and convection oven. These units are commonly computer controlled, because the nature of the test involves controlled cycling of temperatures through various preplanned temperature profiles. For a test involving a thermal chamber, the test requester is usually interested in knowing if their hardware can survive and operate while exposed to the temperature extremes and temperature swings of space. Glove ports are built into the chamber door to allow protected access into the chamber to manipulate the test article and perform various test functionals while maintaining test temperatures.

2.2 Thermal Vacuum Chambers

Thermal vacuum chambers are vacuum chambers that have been equipped with a means of controlling the temperature of the test hardware inside. Because the amount of air inside a vacuum chamber can be reduced down to the molecular level the primary means of heating and cooling is done by radiant energy and conduction. Convection still occurs but because so little gas is floating around, its affects (in most cases) are negligible.

2.2.1 Producing a Vacuum

A vacuum chamber uses a series of devices to reduce the pressure of gas molecules within an enclosed volume below ambient pressure. Vacuum pressures fall into four categories [3]:

- Low (Rough) vacuum: 760 Torr to 1 Torr
- Medium vacuum: 1 Torr to 10^{-3} Torr
- High vacuum: 10^{-3} Torr down to 10^{-7} Torr
- Ultra High vacuum: 10^{-7} Torr and below

Vacuum pumps are designed to operate within a specific pressure range and the type of pumps can be broadly grouped into four main categories [3]:

- Positive displacement pumps
- Non-positive displacement pumps
- Molecular pumps
- Entrapment pumps

The initial process starts by pumping down the chamber through the low and medium vacuum ranges using a positive displacement pump. Examples include rotary vane pumps, diaphragm pumps, liquid ring pumps, piston pumps, scroll pumps, screw pumps, and a number of other variations. Non-positive displacement pumps are used as exhausters for vacuum systems by maintaining a constant vacuum as the volume of air changes with the number of operators. This produces a high flow capacity even though the vacuum level is not very high [3].

The high vacuum levels are achieved by molecular pumps and entrapment pumps. Diffusion pumps and turbomolecular pumps are both examples of molecular pumps. The pumps are designed to 'knock' gas molecules from the vacuum side of the pump to the exhaust side. To achieve this diffusion pumps use jets of oil to blow out molecules, while turbomolecular pumps use high speed fans. Molecular pumping is only possible below pressures of around 7.5 Torr where molecular flow occurs. Examples of entrapment pumps include ion pumps, cryopumps, sorption pumps and non-evaporative getter pumps. These all operate by trapping gases in a solid or absorbed state [3].

It is common practice in space hardware testing to use shrouds, which line the inner wall of the vacuum chamber, as cryopumps. The shrouds have tubes built into them where cryogenic fluid such as liquid nitrogen flows through at -320 °F. The temperature is so cold that gas molecules and vapors stick to it causing the chamber pressure to drop to high or even ultra-high vacuum. Shrouds also absorb thermal radiation causing the test articles to get very cold easily approaching under -200 °F within several hours (depending on size and material). When using a shroud, special care must be taken to control the temperatures of not only the test article, but also instrumentation [3].

It is highly advisable to have a materials expert available to review the type of materials going into a thermal vacuum chamber. Certain materials may break down at low pressures and coat everything inside a chamber (manufacturing processes that involve coating (plating) use this to their advantage), or it may release toxic fumes [1]. Also, one should review or contact manufacturers or suppliers on the tolerance levels (both pressure and temperatures) of instrumentation before using it in a thermal vacuum chamber.

2.2.2 Corona

Worth noting is a mysterious "corona" effect on charged electrical components while at vacuum between 50 to $5x10^{-4}$ Torr. Years ago this corona effect was observed during testing as it burned out circuit boards inside and outside vacuum chambers and has even ruined a whole military satellite that was powered while the vacuum chamber it was tested in was being pumped down to full vacuum. What we do to avoid "corona" now is obviously effective – in-chamber voltage is maintained below 80 volts when chamber pressure is between 50 and $5x10^{-4}$ Torr. To understand how this can happen in the first place consider the following.

What we call corona is described in other industries that use vacuums in their manufacturing processes as "metal vapor arcing." In processes that create thin films on materials such as sputtering where an electric current (or magnetic field) is applied to an alloy "source," its surface will actually begin to erode and atoms/particles of that alloy will float away and coat anything within the vacuum chamber particularly the "target" component. Between this source and target you may actually have enough transfer of material to form a vapor (or plasma). If enough electrical charge has built up on either side (or chamber wall) it is possible to have an electrical arc travel through the vapor -- producing what we call corona. Another example is metal such as wires heating up - this can form a metal vapor in a vacuum. Metals are not the only materials. Gases or other nonconductive material may become conductive once in a certain vapor or plasma state and if an electric current is present, arcing may occur. It is still largely a random event - but it happens with enough frequency that there are actually devices industries use to anticipate the possibility of arcing so they can adjust current or power down before it occurs [1][4][5].

2.2.3 Heating and Cooling Methods

To setup a test in a thermal vacuum chamber, some analysis may be required to determine the best methods of heating and cooling the test article. The method must not only handle the calculated heat load, but must provide the best thermal control throughout the duration of the test. Infra-red (IR) lights use radiant energy to heat test articles in a vacuum. The great feature about IR lamps is that energy from the lamps appears fairly uniform on the surface of the hardware. Anything within visible view can be heated directly by an IR lamp. Wider areas may require multiple IR lamps laid out in an array to cover a larger surface area. Units such as strip heaters (bar heaters) are primarily used to heat a conductive path such as an aluminum heater plate for direct contact heating. This is great for applying heat to areas not within direct view. They often have a slow response time due to the time required for heat energy to travel through the heater plate material. It is highly suggested that IR lamps and strip heaters be connected to a variable controller to adjust their power output to control temperatures and heat rate.

Figure 1 through Figure 3 show examples taken from an actual Space Shuttle Orbiter tile repair test where the tile exterior needed to be thermally cycled from -209° F to +273° F for 30 cycles at 90 minutes per cycle. To simulate the Space Shuttle in space, the samples of tile were placed in a thermal vacuum chamber. A separate heat load was applied to the underside of the tile versus the tile exterior. This simulated the Space Shuttle's internal temperature just below the tile (25° F) (Figure 3) and the temperatures experienced by the exterior face of the tile including a repair patch (overlay) during its orbital periods (Figure 1 and Figure 2) [6].

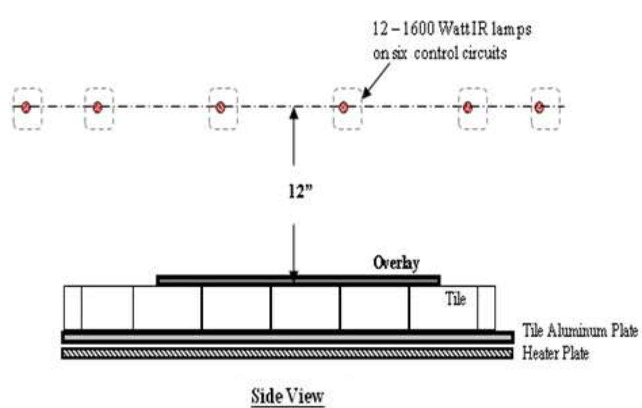

Figure 1. Side view of IR lamp locations.

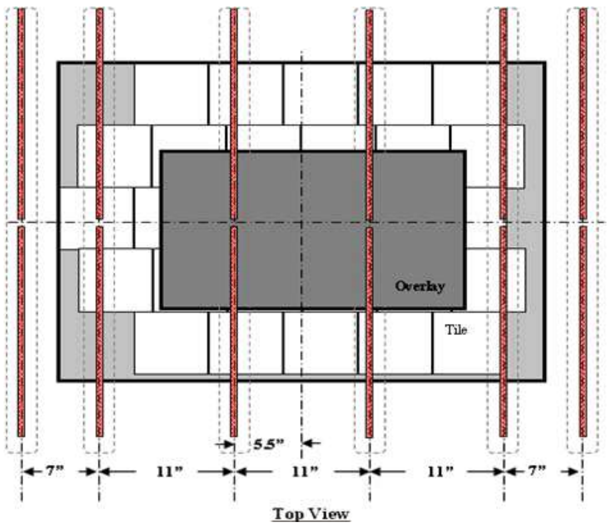

Figure 2. Top view of IR lamp locations.

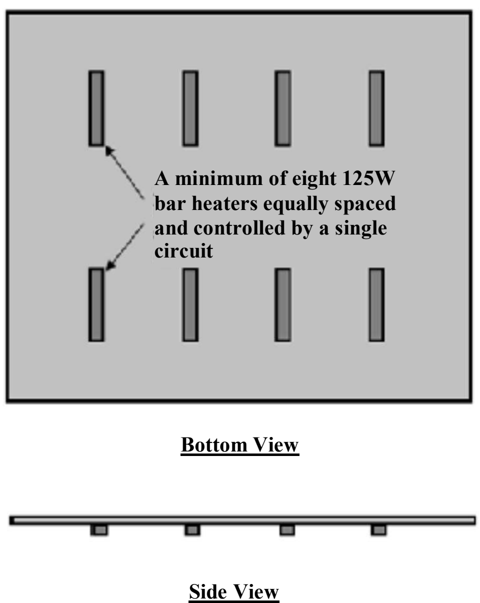

Figure 3. Bottom and top view of strip heater layout.

Another option for thermal control is using a fluid or gas in a convective loop such as a water, GN2, or LN2 loop. In practice a copper tube with a flowing fluid or gas is bent in a coil (or appropriate pattern) and pressed against a surface that will be thermally conditioned. The tubing will go through the chamber wall penetrations to an outside supply and return. The advantage to this method is that the fluid can be conditioned to the desired temperature before it enters the chamber. This provides a higher degree of temperature control of the test article inside by being able to heat and cool a unit from the same lines. With electric heating (IR lamps, strip heaters, etc.) overshooting a desired temperature set-point requires waiting until the test hardware slowly loses radiant energy to return to test conditions.

It is important to know and understand how test hardware temperature is being controlled. On most occasions, test temperatures and temperature ramp rates are determined based on what the hardware will experience during real life operations. The heating and cooling methods used for the test must be able to support the test requirements. Heating or cooling something too quickly, or unevenly, can create unwanted thermal stresses and fatigue in the material of the hardware. Also, significant time and money could be wasted if temperatures are too difficult to control based on unreasonable expectations on test temperatures or temperature ramp rate, poor choice of heating and cooling methods, poor choice or layout of instrumentation to view actual temperatures within the chamber, and nonworking or expired calibration of instrumentation and test equipment.

Operator error is always a factor, even in the field of testing. Having the latest test equipment and facilities is nothing without the skill and experience of a qualified test team.

2.2.4 Instrumentation

As mentioned earlier, poor choice or layout of instrumentation and expired instrument calibration can invalidate the results of tests. It is up to the engineers and scientists working on a test to know what they want measured, what is the full range (temperature, pressure, flow, etc.) they expect the instrumentation to encounter, what type of instrumentation is appropriate, what and where to instrument, and what is the instrument's tolerance after calibration. Consulting a subject expert on instrumentation such as a thermal analyst can assist this process, however, stay focused on what information is critical to your test. Completely covering test hardware with instrumentation such as thermocouples, in an effort to completely recreate an analytical computer model, is not a good way to proceed with testing. Each piece of instrumentation added draws away from the experience of a simulated environment in a very small way that could quickly add up to big changes (e.g., flow meters will cause some degree of flow restriction and thermocouples will affect surface temperatures).

3 Test Preparation

Understand the nature of the test and what thermal vacuum testing is about when preparing to send your hardware for thermal vacuum testing.

Depending on how a test is performed some supporting structure or electronics may have to be designed to support the test hardware, instrumentation, and heating and cooling units. We refer to this as the buildup. Test buildups are a project in their own right due to the amount of effort that goes into engineering the platform and figuring out how the hardware can be positioned while observing safety over people, test hardware, and equipment. The buildup should also be thermally separated from the test hardware (and chamber shroud) to avoid thermally interfering with the test itself. Wiring should be neatly bundled and labeled to aid in troubleshooting (if necessary). The very nature of testing is expecting something to go wrong; if it does, you want to be able to quickly rule out problems with the buildup. A clean, well organized buildup can assist in that effort. Also, when planning for a test, allow sufficient time to develop and construct the buildup.

Test preparation begins shortly after design of the hardware has started. Throughout the design process, project managers need to continually address the question of how they are going to test their design. This should lead to developing a comprehensive test plan. Testing is an expensive and time consuming process. Creating a test plan lowers the overall cost of testing, because many of the issues that lead to mistakes, changes, reworks, and rescheduling can be worked out well before the actual test process begins. Preplanning allows time for questions to be asked for clarification rather than at the last minute when decisions need to be made and time is limited. Limited time often leads to compressed schedules. Those hit the hardest are the technicians often assigned to fabricate and prepare test facilities at short notice. This has the potential to lead to accidents when combined with the confusion resulting from numerous changes and reworks due to poor planning. Safety is a very big concern.

3.1 Familiarization with Test Hardware

Project leads that have a dedicated test team must keep them well informed of the new hardware under development which will eventually require testing. It creates numerous fundamental problems when a test team is not familiar with the test article they have sent out for testing.

Know where you are most likely to fail or have problems and determine courses of action before test begins. Courses of action include knowing what adjustments can be made during a test. This involves being familiar with the test setup to know what is influencing the results of the test and can it be manipulated to bring the situation back to test conditions. If the problem is suspected to be with the test hardware some troubleshooting methods are necessary to narrow down the source of problem before the test is terminated. A test team should develop a general troubleshooting guide for their hardware so in the event something happens during test they are prepared to address the issues in a logical fashion to discover the cause of the problem and determine a solution. Problems during a test are not all ways bad. A well planned test that ended in failing the test hardware for certification means that design or workmanship flaws were found under simulated conditions and prevented during real world operations.

3.2 Rigging Results

From a strictly testing point of view, success or failure of a test article during a test is all a part of the job. Something useful was learned by either experience. However, for the program directors and design team, failure leads to delays in a schedule and many more hours of work. In the presence of impending failure of a certification test, there always lies the temptation to adjust or rewrite test conditions to produce a passing state for the hardware being tested. Although the paper trail may even be rewritten to support such actions the bigger question is – Will this hardware fail when it is used as intended? A bad design supported by a poor test does not lead to assured success. As in all professions, integrity should come first. There may be many people depending on the hardware working as intended and taking confidence in the fact that the equipment they are using has passed through rigorous testing. Test data can also be accessed and used as reference material years later, either in an investigation or for additional information to support a new design. It is extremely important for all parties involved in a test to be open and honest regarding the information filed into a test folder and the results the data reveals.

4 Conclusions

This paper presents information on the use and preparation of simulated environments to test space hardware, in particular the use of a thermal vacuum chamber. Because the space environment and its effects on hardware is foreign to our earth based experiences and intuition, there are several points of advice described in this paper. The main attributes of the environment of space are the absence of air and exposure to radiation and extreme temperature differences on material surfaces. The reader is informed that materials may behave in unexpected manners while under space conditions so proper materials selection for hardware is critical. The mystery of the corona arching was explained. Also, various methods were discussed on controlling the simulated space environment such as heating and cooling methods, instrumentation, and tips on supporting test buildup.

When developing any test one must ask – "Does this test make sense?" "Is this test going to answer the questions regarding the operability of a lunar tool (for example) under the conditions it is expected to operate?" Once you are familiar with the test hardware, how it operates, and the conditions it must operate under, the test must provide the simulated conditions for it to operate in. The simulated conditions must mimic the actions, forces, pressures, and temperatures the hardware could be exposed to. Failure modes were discussed to encourage test teams to be proactive in their methods of resolving problems and understanding that valuable information can be learned in both failures and success of test hardware. Finally, a warning is given on the practice of test manipulation in order to "pass" hardware through testing to meet a project deadline. It is the hope of the writer that those involved in testing learn to avoid those mistakes and adhere to a higher standard of testing.

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