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Enabling Space Environment Simulation for Commercial Vehicles

Ariel Tello[1]
Amentum Space Missions Division, Houston, TX 77058, USA

Steven Del Papa[2]
NASA Johnson Space Center, Houston, TX 77058, USA

NASA Administrator Jared Isaacman has stated multiple times since taking office that "NASA works on what industry can't." Recently, the Crew and Thermal Systems Division's (CTSD) System Test Branch (STB) at NASA Johnson Space Center (JSC) demonstrated its unique ability to subject large commercial spacecraft to thermal vacuum conditions that provide commercial customers critical data in evaluating their vehicles for spaceflight through the 15-day thermal vacuum test of the Blue Origin MK1 Lunar Lander inside the JSC Space Environment Simulation Test Laboratory Chamber A. Thermal vacuum testing on this scale is difficult to replicate and not cost effective for industry to reproduce privately. Thus, using NASA's already existing facilities to assist commercial customers in testing their developmental spacecraft makes sense from a cost and schedule perspective, especially with the current timeline NASA has set for the Artemis Program. The MK1 vehicle, a single-launch lunar cargo vehicle capable of delivering 3 metric tons to the lunar surface, was exposed to an environment simulating anticipated spaceflight conditions during the test to characterize performance of active and passive vehicle thermal control systems as well as validate thermal models. Using the heater cage designed and built by the Systems Test Branch, the vehicle was subjected to 1 thermal cycle over 15 days consisting of four thermal balances and two performance tests, providing data that will assist with final preparations for launch on an upcoming New Glenn vehicle mission. This paper will discuss test background, test operational preparations, conduction of the test, and post test operations.

Nomenclature

CDR	=	*Critical Design Review*
cfm	=	*cubic feet per minute*
CTSD	=	*Crew and Thermal Systems Division*
EC2	=	*Design and Analysis Branch of the Crew and Thermal Systems Division at Johnson Space Center*
EC4	=	*Systems Test Branch of the Crew and Thermal Systems Division at Johnson Space Center*
EMS	=	*Emergency Management System*
ES4	=	*Materials and Processes Branch of Structural Engineering Division at Johnson Space Center*
FOD	=	*Foreign Object Debris*
GSE	=	*Ground Support Equipment*
H2O	=	*Water*
JSC	=	*Johnson Space Center*
JWST	=	*James Webb Space Telescope*
LN2	=	*Liquid Nitrogen*
MUCB	=	*Materials Usage Control Board*
PDR	=	*Preliminary Design Review*
SESL	=	*Space Environment Simulation Laboratory*
STB	=	*Systems Test Branch*
TRR	=	*Test Readiness Review*
TVAC	=	*Thermal Vacuum*
URR	=	*User Readiness Review*

[1] Test Director, NASA Johnson Space Center, 2101 NASA Parkway, Mail Code: EC4, Houston, Texas 77058
[2] Test Director and Test Operations Lead, NASA Johnson Space Center, 2101 NASA Parkway, Mail Code: EC4, Houston, Texas 77058.

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I. Introduction

THE increase in large commercial spacecraft has come with the growing supporting programs that help enable a strong space economy. NASA has been at the forefront of enabling the space industry by ameliorating the challenges that come with spaceflight which enables industry to overcome challenges. The Crew and Thermal System's Division System Test Branch has maintained and improved the JSC Space Environment Simulation Test Laboratory Chamber A since its inception during the Apollo era.

Background Section

Chamber A, part of NASA's Space Environmental Simulation Laboratory at Johnson Space Center (JSC), has a rich legacy stretching back to its commissioning in the 1960s for Gemini and Apollo spacecraft. Built in 1965, it supported testing of Apollo modules, spacesuits, Skylab systems, and the Apollo/Soyuz docking module (Figure 1). In recent years it has embraced commercial partnerships: in the summer of 2024, it hosted Vertical Solar Array Technology (VSAT) prototypes by Honeybee Robotics (a Blue Origin company) and Astrobotic Technology to assess lunar solar-array deployment and performance under simulated lunar conditions. These commercial tests build upon Chamber A's evolving role—now enhanced for extremely low temperatures and deep-space simulation to support not just NASA programs like JWST but also enable new commercial lunar infrastructure development.

The James Webb Space Telescope (JWST) test campaign in Chamber A (Figure 2) catalyzed the modernization of the chamber to meet its deep-space, low-contamination requirements. Existing systems were upgraded to support months-long, 20 K helium-shrouded testing. Legacy solar-simulation hardware was removed and replaced with new LN_2 and 20 K helium thermal shrouds, along with efficient thermo-siphon fluid systems, updated high-vacuum pumping (cryo and turbo pumps), and clean, emergency-power-backed infrastructure to prevent hydrocarbon contamination. A pivotal facility enhancement was the construction of a dedicated ISO Class 7 cleanroom directly attached to Chamber A's 40-foot door. This cleanroom, supported by independent airflow systems (filter fan units, HEPA and charcoal filtration), temperature and humidity controls, and positive-pressure protocols, sustained contamination at or below JWST's particulate and molecular limits during both assembly and testing[(1)].



Figure 1: Chamber A with Block 1 Apollo Command and Service Module 008 (CSM-008)

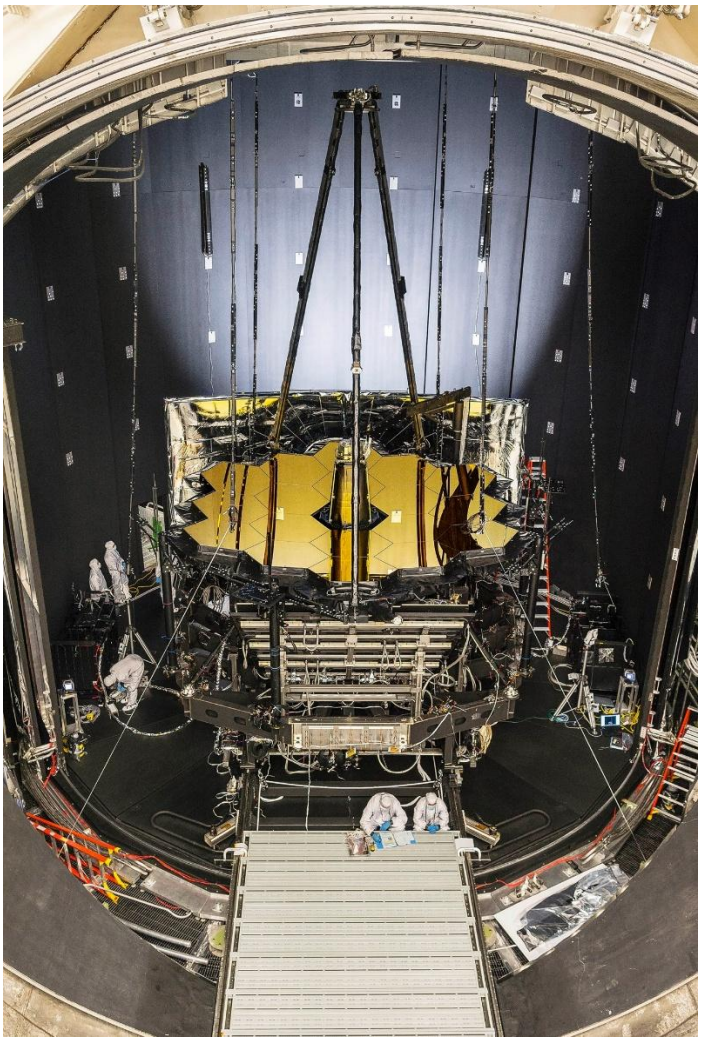


Figure 2: NASA's James Webb Space Telescope sits inside Chamber A at NASA's Johnson Space Center, Houston

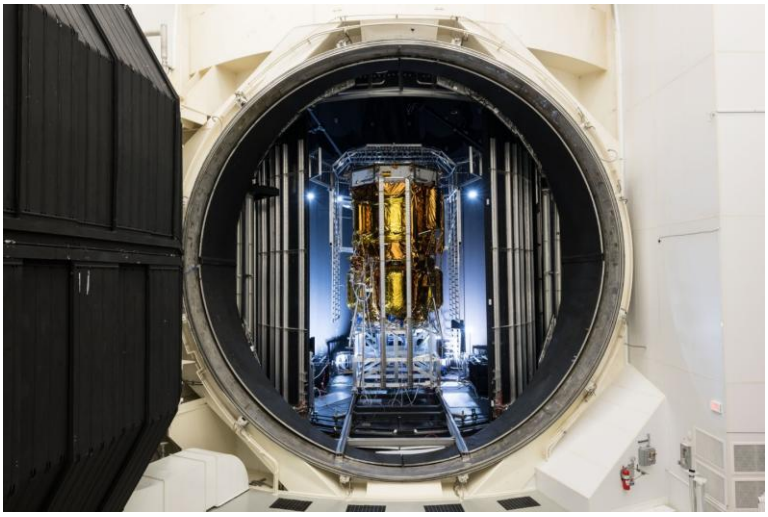


Figure 3: Blue Origin's MK1 Vehicle configured inside Chamber A

II. Test Operational Preparations

Facility preparations, material reviews, and logistical coordination was the primary work load for ensuring that the test is conducted safety and is meeting the customer's test objectives. Technical expertise from different internal NASA branches such as the Design and Analysis Branch (EC2) for thermal analysis, the Structures Branch (ES2) for structural planning and material reviews, and the Materials and Processes Branch (ES4) for contamination and outgassing analysis. The primary effort of the Systems Test Branch (EC4) was maintaining the test objectives between the customer and our internal expertise as well as preparing the facility for the vehicle.

A. Integration Coordination

The coordination for the build-up and integration for the test was significant that build-up of the test dedicated a project-forward approach to identify risk, mature requirements, and identify all required interfaces for the test. The project reviews included Critical Design Review (CDR), Preliminary Design Review (PDR), Facility Readiness Reviews (FRR), and Test Readiness Review (TRR). These checkpoints ensured all technical parameters, design elements, facility modifications, and operational plans satisfied both NASA and customer requirements.

Technical Interchange Meetings (TIMs) and weekly tag-ups provided additional opportunities for stakeholders from NASA and the commercial partner to review deliverables, schedule progress, interface definitions, and open technical questions. This continuous communication helped reduce integration risk and ensured transparency throughout the build-up phase.

The integration period was critical for verifying that the test configuration would perform as intended and meet the established test objectives through rigorous project gate phases and deliverables. EC4's expertise in complex system integration and test operations played a key role in bridging gaps between participating organizations, helping resolve ambiguities early, strengthening technical rigor, and ensuring the final test set-up was both reliable and fully mission-ready.

B. Heater Cage

EC4 designed, fabricated, and installed the heater cage (Figure 4) in Chamber A based on the provided test objectives, incorporating multiple heater bars controlled by 33 zones. EC2 supported the design effort to ensure customer requirements were met and that each zone included a sufficient number of heater bars.

The structure underwent comprehensive structural reviews, with stress analyses performed for two configurations: the heater cage staged inside Chamber A and the heater cage rolled outside the chamber in the cleanroom. These analyses evaluated multiple load cases, including the thermal environment, personnel loading, and conditions associated with assembly and disassembly.

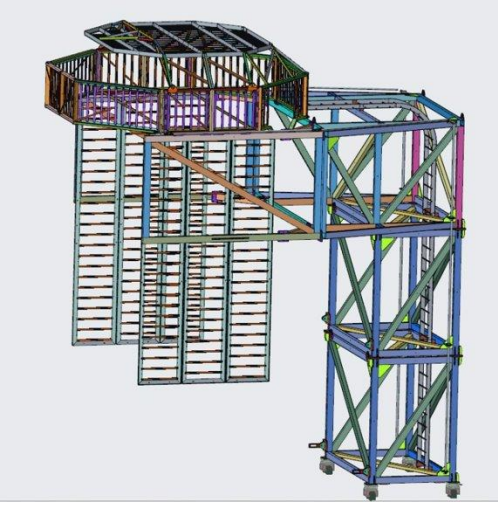


Figure 4: Heater Cage for Blue Origin MK-1 TVAC Test

C. Cleanroom Operations

For the purposes of cleanliness, the chamber and the cleanroom are an integrated facility and subject to identical contamination control requirements. The cleanroom and chamber are designed to operate at ISO Class 7 (per ISO 14644-1), but was held to a less restrictive ISO Class 8 requirement for this specific test. The chamber has an adjustable air flow rate between 0 and 50,000 cfm that enters through the top of the chamber and exits through the bottom of the chamber. The cleanroom has an air flow rate that provides a minimum of 40 air changes per hour. A positive pressure of at least 0.05 inches of H2O is maintained during normal operations. The temperature is maintained at 20±3°C (68±5°F) with a relative humidity of 50±10%. All interior surfaces, test hardware, and supporting equipment is visibly cleaned and qualitatively verified to be free of all particulate and non-particulate material[3]. Materials that are prone to producing particulates and volatiles such as wood, cardboard, silicone, etc. are prohibited. Personnel entering the cleanroom would fully gown up in the gowning area and then pass through an air shower prior to entering the clean room. FOD prevention was enforced through a "clean as you go" policy and regular "FOD walks".

D. Facility and Test Readiness

Requirement reviews were conducted for the test profile, test rules, and test protocols. The test rules defined key parameters such as thermocouple critical temperature limits, emergency scenarios, anomaly response posture, and conditions for stopping the test. Critical temperatures represent thresholds that must not be exceeded to prevent hardware damage; Test Directors actively monitor these limits and direct technicians as needed to ensure they are not reached.

In parallel, materials reviews ensured all non-metallics and submitted materials were compatible with chamber environments and met facility usage requirements. These reviews were carried out by the Materials Usage Control Board (MUCB), which includes materials specialists from EC4 and ES4, representatives from occupational health and toxicology, the EC4 Branch Chief, and the MUCB chair. All submitted materials received comprehensive evaluation and formal approval from this board.

A Facility Readiness Review (FRR) verified full functional capability of the test facility. This included running both the coldest and hottest test cases, confirming overall facility performance, verifying heater-cage functionality, and checking the health of thermocouples and thermal coupons.

The Test Readiness Review (TRR) confirmed that the test setup was fully completed and that all required documentation such as the Detailed Test Procedure, Hazard Analysis, Material Usage Log, and site-pressure functional checks had been finalized and approved. The TRR also verified that all personnel from JSC and Blue Origin had the proper training. The TRR chair members reviewed the entire test setup, test rules, test profile, and any outstanding documentation to ensure all materials were complete, signed, and ready before authorizing test execution.

III. Test Conduct

During the test campaign, expectations were set for both parties to ensure that the safety of the facility, vehicle and test personnel is upheld. EC4 Test Directors led Test Team Briefings (TTBs) which communicated the expected test conduct for communications, test emergencies procedures, test set-up, thermal profile, and the test schedule. The Test Director was responsible for the overall conduct and safety of the test facility, the execution and maintenance of chamber thermal and vacuum profiles, and direction of the facility test team members. With the large number of test personnel for this test, communication for test was concentrated to the EC4 Test Director and the Test Conductor from Blue Origin.

A. Test Team Expectations

The Blue Origin Test Team was responsible for maintaining vehicle safety throughout the duration of the test and ensuring proper execution of vehicle functional operations. Vehicle functional test were conducted throughout the test and communications were maintained with EC4 Test Directors to maintain alignment with facility operations and to ensure that all data collected remained representative of intended thermal conditions.

The Blue Origin Test Conductor is responsible for knowing the facility and test environment sufficiently well to lead the Blue Origin team during nominal operations and must ensure that sufficient expertise is possessed by the team members for the safe conduct of the involved operations. The Test Conductor typically leads the team through the written procedures and will ensure that data reduction and analysis functions are properly staffed. The Test Conductor will coordinate closely with the Test Article's Responsible Engineer in all matters regarding the test article, facility readiness, and test data delivery. The Test Conductor responds to all off-nominal situations that arise on the test stands that are not personnel-safety-critical emergencies.

B. Facility Monitoring

The heater cage used for the TVAC test was divided into multiple thermal zones, with each zone consisting of several heater bars (Figure 5) arranged to deliver controlled and distributed thermal input to the vehicle. Each zone was independently regulated through a dedicated PCC channel, enabling fine adjustment of thermal loading throughout the test. For every vehicle thermal target, baseline heater settings were established using thermal predictions developed by the Design and Analysis Branch (EC2). To prevent temperature overshoot, heater power was increased gradually until each zone reached its calculated PCC percentage baseline. After the system stabilized at these baseline settings, additional adjustments were made as necessary to individual PCC zones to achieve and maintain the desired vehicle temperature profile.



Figure 5: Heater Bar

C. CQCM/RGA Monitoring

The Cryogenic Quartz Crystal Microbalance (CQCM) and Temperature controlled Quartz Crystal Microbalance (TQCM) are precision instruments for measuring surface contamination as a function of temperature in a space simulation chamber. They use a quartz crystal oscillator to measure mass loading while the set temperature of the crystal is automatically controlled. The CQCM/TQCM output provides a real-time measurement of the outgassing deposition rate, typically in units of Hertz/hour. These measurements can be combined with analytical modeling to determine the CQCM/TQCM sensitivity and provide a total outgassing rate in units of grams/second. CQCMs are rated for cryogenic temperatures while TQCMs are only rated for higher temperatures and normally used in thermal-vacuum bakeouts. For this test, two CQCMs with cryogenic conditioning were mounted in close proximity to the test article. A third CQCM was mounted on the 3rd level of the helium shroud where Chamber A CQCMs are normally placed. All 3 CQCMs were cryogenically conditioned and controlled to 243K (-30°C) by mounting to a cold plate with LN2 lines welded to the plate (Figure 6). These providing data to measure the outgassing rates. Additionally, one TQCM was mounted on LN2 Scavenger Panel 1 for any warm temperature QCM measurements.

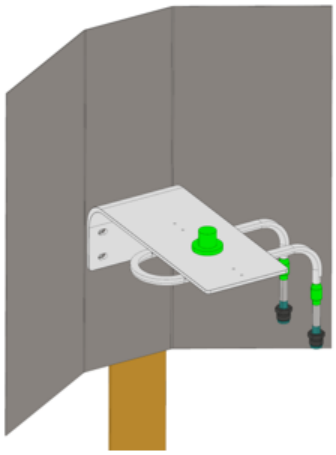


Figure 6: CQCM installed on the cold plate with LN2 lines

IV. Post Test Operations

After the conclusion of testing, routine operations were performed in order to ensure that the chamber is safe to enter for post-test inspections of both the vehicle and the chamber. Personnel from EC4 and ES4 conducted comprehensive contamination assessments of Chamber A to verify environmental cleanliness, confirm compliance with contamination-control requirements, and document the facility's return to baseline conditions. These activities provided essential validation of post-test readiness and ensured that Chamber A remained fully prepared to support subsequent government and commercial test campaigns.

A. Facility Assessments

Pre-TVAC control samples were collected from the chamber cryopans, and witness samples were deployed to evaluate non-volatile residue (NVR) collection and optical properties characterization. Post-TVAC liquid condensate and residue was collected from the cryopans (Figure 7), and the NVR/optical witness samples were retrieved. Preliminary chemical analysis was performed by the JSC ES4 Analytical Chemistry Lab of the control and condensate. The major constituents found were 1,2-Propanediol (propylene glycol), Nylon-6, Benzoic Acid, and Hydroxyphenyl phosphonic acid (Figure 8). The propylene glycol response is consistent with the use of a 50/50 propylene glycol/water mixture that was used in the GSE support hardware for the MK-1 during the TVAC test.

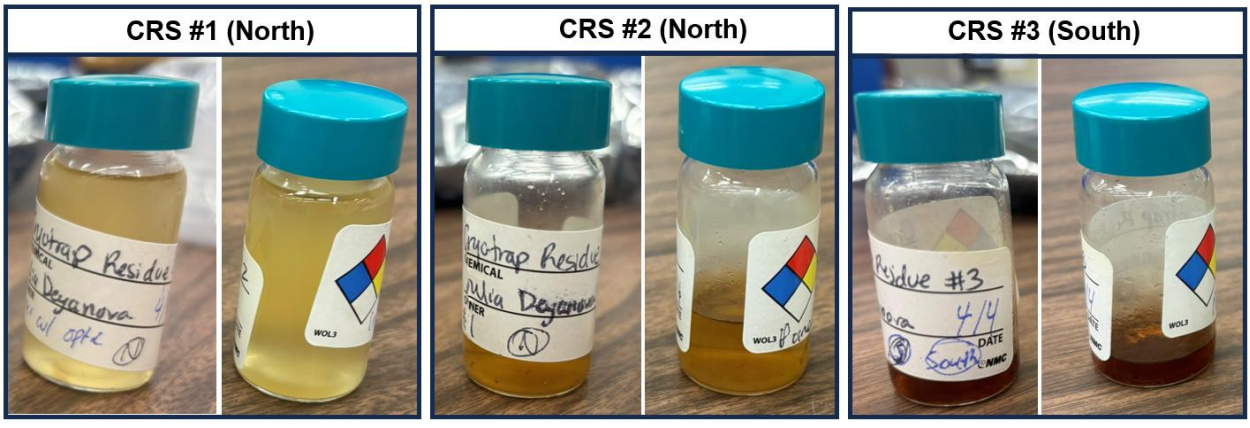


Figure 7: Cryotrap Residual Samples Collected

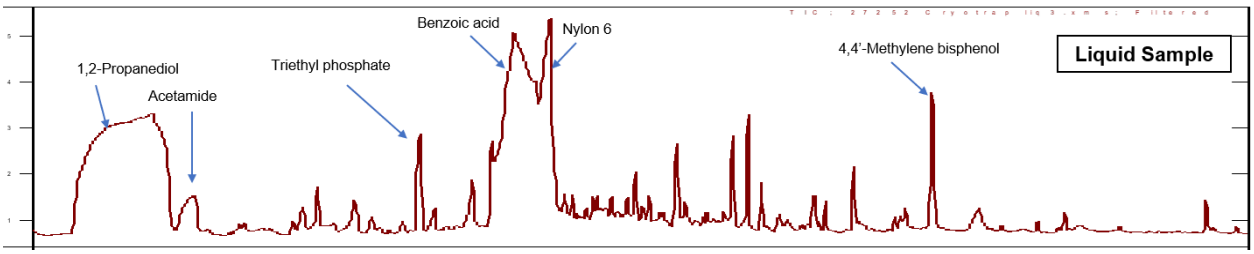


Figure 8: Gas Chromatography–Mass Spectrometry (GC-MS) of CRS #3 (North) Sample

V. Conclusion

The Blue Origin MK1 thermal vacuum (TVAC) test campaign demonstrated Chamber A's capability to support complex commercial test operations through a successful 15-day test enabled by months of meticulous planning, targeted facility modifications, and coordinated expertise from multiple NASA organizations. The campaign validated Chamber A's ability to deliver simulated space environments through its thermal vacuum capabilities while accommodating unique vehicle requirements via collaboration, integration, and operational processes. Building on these outcomes, Chamber A is positioned as a facility ready to accept a wide variety of testing from both NASA programs and commercial customers, providing a robust national resource for large-scale environmental verification and advancing the broader commercial spaceflight enterprise.

Acknowledgments

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