

Creating the Environment for Exploration Habitats

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The Crew and Thermal Systems Division's (CTSD) 20 Foot Chamber has undergone significant modifications to support NASA's future human exploration missions to the Moon, Mars, and beyond. Existing chamber systems such as Vacuum/Repress, Heating Ventilation and Air Conditioning (HVAC), and Fire Suppression System (FSS), were upgraded, while new systems such as Air Revitalization and Gas Distribution were added. In addition, the chamber was outfitted with crew quarters, hygiene areas, storage, and workspaces. Teams across the Johnson Space Center (JSC) worked together to overcome the logistical and operational challenges of the planned test parameters. The ultimate goal was to create an analog testbed in which a maximum of 8 human test subjects could safely live and work for at least 11 days in the same conditions (reduced pressures, Oxygen concentrations, etc.) as those expected inside a base spacecraft. This would allow researchers to study the effects of such environments on humans and to validate proposed Prebreathe Protocols to enable the safe performance of surface extravehicular activities (EVAs). Over the last eighteen months, the CTSD Systems Test Branch has performed six tests of varying lengths and atmospheres for both NASA and commercial partners. To date, researchers now have collected data on 48 test subjects in the course of 42 days and over 130 simulated EVAs. This paper will discuss the history of the 20 Foot Chamber, its long road to becoming an analog testbed for human exploration, and the capabilities that make it a unique, world class facility for NASA and commercial human exploration missions. It will provide an overview of past and future testing, and the lessons learned along the way.

Nomenclature

ARS	=	Air Revitalization System
AMS	=	Atmosphere Monitoring System
CO ₂	=	Carbon Dioxide
CDR	=	Critical Design Review
CTSD	=	Crew and Thermal Systems Division
EVA	=	Extravehicular Activity
ECLSS	=	Environmental Control and Life Support Systems
EMS	=	Emergency Management System
H-3PO	=	Human Physiology, Performance, Protection, and Operations Laboratory
HESTIA	=	Human Exploration Testbed for Integration and Advancement
HVAC	=	Heating, Ventilation, and Air Conditioning
JSC	=	Johnson Space Center
O ₂	=	Molecular Oxygen
PDR	=	Preliminary Design Review

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<i>PBD</i>	=	Performance Based Design
<i>PI</i>	=	Principal Investigator
<i>SDS</i>	=	Safety Data Sheets
<i>SPL</i>	=	Sound Pressure Level
<i>TRR</i>	=	Test Readiness Review
<i>URR</i>	=	User Readiness Review

I. Introduction

Since the days of Projects Gemini and Apollo, Extravehicular Activities, or EVAs have evolved in practice, and the space suits that have supported those activities have evolved as well. General spacecruit design since that era has always generally striven to optimize for mobility, crew person comfort, particular resources available on the supporting vehicle, while simultaneously minimize the risks of embullisms and Decompression Sickness (DCS). In the early programs, the vehicle cabins were 100% oxygen environments, so no prebreathe protocols were required, either in orbit or before lunar EVAs. However, with the advent of the shuttle program, the longer term missions made it crucial to design Environmental Control and Life Support Systems (ECLSSs) in vehicles that mimicked earth sea-level conditions (21% oxygen/79% nitrogen atmosphere at 14.7 psia) to mitigate the risks associated with a 100% oxygen environment as well as oxygen toxicity. This brought with it the need to develop microgravity prebreathe protocols to minimize the risks of DCS during EVAs, which have generally been 4 hours on orbit. However, because space missions over the past 45 years have been limited to low earth orbit, the associated EVAs and the prebreathe protocols that preceded them were established for a microgravity environment only. With the advent of current programs with goals of establishing permanent habitats on the moon in the near future, it became necessary to begin studies of different habitat atmospheres and oxygen content that could help to lower the necessary prebreathe times from the currently accepted 4 hour time used in orbit. These studies would require a human rated vacuum chamber suited to effectively and safely providing both a simulated habitat environment where test subjects could equilibrate for an extended period and a simulated spacesuit pressure environment to allow them to simulate EVAs after the equilibration period. The Systems Test Branch of Johnson Space Center's Crew and Thermal System Division has a long and extensive history in conducting crewed testing in its human rated vacuum facilities, and as part of its inventory of those facilities, it has a vacuum chamber with a long history of supporting extensive, long term crewed testing. It was selected to support these proposed studies with different habitat atmospheres due to its size and existing systems that could be modified to support these studies within a budget and timeframe that could provide study data before key milestone decision dates for the upcoming lunar missions.

II. Brief History of the JSC CTSD 20 FT Chamber

The JSC CTSD 20 Foot Chamber is a 3 story vacuum chamber 20 feet in diameter located in Building 7 of Johnson Space Center in Houston, TX. It was originally built in 1964 by the Chicago Bridge and Iron Company as a 2 story vacuum chamber to conduct crewed testing in support of the Gemini and Apollo Programs. Later in the 1970s, it was used for extended duration tests in support of the Skylab Program. In the late 1980s, a 3rd floor was added to the chamber in antipation of potential testing that would come as a result of the proposed U. S. space station at the time. During the 1990s, it served as a test platform for 30 day, 60 day, and 90 day sea level pressure ECLSS closed loop testing supporting International Space Station (ISS) development as well as general life support technology development. During the 2010s, the 20 Foot Chamber served as the Habitat Element of the Human Exploration Testbed for Integration and Advancement (HESTIA), a high fidelity Mars/Lunar surface analog with various elements distributed across Johnson Space Center. In the latter half of the 2010s, it was selected to host the Exploration Atmosphere and EVA Protocol Validation Test Program, the program spearheading the studies for new prebreathe protocols supporting lunar and Mars surface EVAs.



Figure 1. JSC CTSD 20 FT Chamber

III. Proposing a Test Bed for Exploration Habitat Atmospheres

The Human Physiology, Performance, Protection and Operations (H-3PO) Laboratory of JSC's Biomedical Research and Environmental Sciences Division began discussions with the CTSD Systems Test Branch about performing its proposed Exploration Atmosphere Study back in the 2013-2014 timeframe after the 2013 memo from Associate Administrator for Human Exploration and Operations William Gerstenmaier establishing the content for exploration atmospheres as 8.2 psia and 34% oxygen content. The H-3PO Laboratory scientists were looking for a vacuum chamber that could support an 11 day study for 8 test subjects subjected to the proposed 8.2 psia/34% exploration atmosphere environment as well as simulated EVAs where the subjects would be on oxygen masks supplying them with 85% oxygen while the chamber was at a pressure of 4.3 psia to simulate the pressure they would be working in while in a space suit at EVA. The subjects would perform tasks during the EVA to simulate actions and stress loads that astronauts would encounter while on a planetoid surface EVA. The 11 days would consist of an initial pumpdown to 8.2 psia on day 1 followed by 48 hours of climatization at 8.2 psia/34% oxygen conditions. On day 3, the first 6 hour EVA would take place followed by a return to 8.2 psia/34% conditions. Non EVA days would alternate with EVA days throughout the rest of the test, exposing the test subjects to 5 EVAs over the course of the test.

During those preliminary conversations, the CTSD 20 FT chamber became a clear candidate for this study as it was already a human rated vacuum chamber and had a volume and basic configuration that made it well suited to house test subjects for the proposed 11 day studies. It already had basic infrastructure that could support this testing, but the chamber as it was configured at the time could not support the proposed Exploration Atmosphere study. It would take modifications of several existing chamber systems for it to adequately host the study. When it became clear to the H-3PO laboratory that it would take significant funding to upgrade the chamber to suit their needs, talks with the CTSD Systems Test Branch were put on pause while the H-3PO laboratory went back to secure funding for the upgrades. That process would take a few years. Funding was finally secured for the upgrade project late in FY18, and it was then when planning and designing of the necessary chamber upgrades began.

IV. Identifying Chamber System Upgrades

The newly formed CTSD-H-3PO team soon began to work together to define the specific requirements for the proposed Exploration Atmosphere study which would drive the requirements for 20 FT Chamber upgrades and installation of any new required systems the chamber didn't already possess. Out of those discussions, the following basic requirements were generated:

- The existing Manlock would need to support routine transfer of test subjects and materials in and out of the chamber.
- The existing Transfer Lock would need to support routine transfer of test subjects and materials in and out of the chamber.
- Sound Pressure Levels (SPLs) would need to be limited so that test subjects could live and work in the chamber without hearing protection during non-EVA periods.
- The chamber would need to have an Air Revitalization System (ARS) that could maintain CO2 levels throughout the chamber within acceptable limits as well as trace contaminant control.
- The chamber would need to have an Atmosphere Monitoring System (AMS) that would be able to measure CO2 levels, humidity, oxygen levels, pressure, and temperature throughout the 3 levels of the chamber at all operating pressures throughout testing.
- The chamber would need an audio communication system that had hardline audio capability for all test team members and test subjects, Doppler Techs, and rescue personnel during routine operations and during operations when the test subjects and Doppler Techs were on breathing masks; an intercom system that would allow communications on each floor within the Main Chamber during non-EVA activities; private audio communication capability between test subjects/Doppler Techs and the Test Directors and between test subjects/Doppler Techs and medical personnel while both on masks and during periods when crewmembers were not on masks; an wireless communications capability during sea-level activities to facilitate test preparations.
- The chamber would need to provide a minimum of 9 breathing mask stations inside the main chamber capable of providing 85% or 100% oxygen and a minimum of 3 breathing mask stations in the Manlock capable of supplying 100% oxygen. The facility was also required to provide a minimum of 8 walk around oxygen bottles within the Main Chamber to support chamber operations for a minimum of 15 minutes in the event of contingencies.

- The chamber would need to be outfitted with crew quarters for all participating crew members as well as hygiene areas a conference area for meetings and meals, and a work area to conduct EVA operations and exercise when not at EVA.
- The chamber would need to provide a means to store and prepare food and water.
- The chamber would need to be able to support health monitoring equipment and supply health monitoring data to the Principal Investigator and medical personnel.
- The Chamber would need to provide the ability for human waste collection during non-EVA operations and EVA operations as well as the ability to maintain general human hygiene throughout the course of the study. A means for trash and dry waste storage and removal throughout the study were also required.
- The chamber would need to provide normal data collection, processing, storage, and retrieval services as well as be able to route sensitive medical data gathered from test subjects only to qualified test personnel.
- The chamber would need to be capable of depressurizing the Main Chamber and Manlock from Sea Level to 8.2 psia in about 15 minutes to simulate expected spacecraft performance as well as repressurizing back to Sea Level. The manlock would need the capability to depressurize and repressurize between Sea Level to 8.2 psia independently while the Main Chamber was at 8.2 psia.
- The chamber would need to be capable of depressurizing the Main Chamber and Manlock from 8.2 psia to 4.3 psia in about 15 minutes to simulate expected spacecraft/spacesuit performance as well as repressurizing back to 8.2 psia in about 15 minutes again to simulate expected spacecraft/spacesuit performance. The manlock would need the capability to depressurize and repressurize between Sea Level to 4.3 psia independently while the Main Chamber was at 4.3 psia.
- The chamber would need an Emergency Management System (EMS) that was capable of providing emergency fire spray, emergency repressurization, fluid systems shut off, power shut off, and emergency lighting in the event of emergencies. Emergency responses in the EMS would be tailored to the specific types of emergencies encountered.
- The chamber would need to provide an HVAC system capable of maintaining chamber humidity at prescribed levels, chamber temperatures on all 3 levels at prescribed levels, and ventilation capable of circulating the internal chamber air throughout all 3 levels at high enough rates to allow oxygen injection into the chamber while preventing oxygen specific accumulations in any chamber areas.
- The chamber would need to provide general lighting on all 3 levels that could be adjusted as necessary in different areas for normal operations, sleep periods, and visual acuity testing.
- The chamber would need a power distribution system to accommodate all necessary test requester hardware to support the study which would incorporate protection from arcing in an enriched oxygen environment.
- The chamber would need the ability to inject oxygen into the main chamber atmosphere to elevate the oxygen level to the desired 34% habitat atmospheric content and also to automatically maintain that level during non-EVA operations.
- The chamber would need the capability to automatically maintain pressure at both 8.2 psia and 4.3 psia to ensure stable conditions during EVA and non-EVA operations.
- Everything inside the chamber would need to be compatible with an enriched oxygen environment all the way up to an internal chamber atmosphere with 36% oxygen content.
- The chamber would need a video system capable of monitoring all levels of the chamber and recording video throughout the entire study.

Once these basic requirements were established by the H-3PO Laboratory and accepted by the CTSD Systems Test Branch, individual projects were established by the Systems Test Branch to build any new systems necessary and implement upgrades to existing systems.

V. Implementing Chamber System Upgrades

Each system was assigned its own individual project and project team, and whether or not it was a new or upgraded system, each system project went through a thorough PDR-CDR-URR-Acceptance Testing process individually. A brief summary of each of the major chamber system projects follows:

A. Fire Suppression System

The existing 20 FT chamber fire suppression system had been in place for a long time. CTSD Systems Test Branch facility engineers had been concerned for a long time that the crewed chambers in the CTSD Systems Test Branch could not meet national consensus codes and standards, as well as NASA/JSC requirements for fire protection. With

the advent of the upgrade of the 20 FT chamber for Exploration Atmosphere studies, the 20 FT fire suppression system was especially inadequate for the fire suppression needs of the chamber in the event of an emergency. As a result, the Systems Test Branch commissioned Jacobs Engineering to perform a Performance Based Design (PBD) study of the JSC Building 7 crewed chambers to identify deficiencies related to applicable codes and standards and to derive a PBD that ensured an acceptable level of safety during test operations. The study concluded that the chamber was designated an NFPA 99B, Class E, oxygen enriched atmosphere based on the Exploration Atmosphere requirements, necessitating 7.5 gpm/sq ft water spray density per code. The existing CTSD Building 7 fire protection water supply was unable to provide the required water density. The PBD developed out of the study established alternative requirements to meet code equivalent design per NASA STD 8719.11 and established 40% as the maximum chamber oxygen concentration. The PBD further established a 2.0 gpm/sq ft water density for existing deluge systems inside the chambers as sufficient. To satisfy the PBD in the 20 FT chamber, a complete reconfiguration of the 2nd and 3rd level fire suppression system was required along with providing a fire suppression water supply to all 3 levels independently. Supply piping to the 20 FT chamber would also have to be increased from 6 in to 8 in, and the new piping would need to accommodate the new habitat designs on the 2nd and 3rd levels. To ensure the 2.0 gpm/sq ft requirement would be met in all the chambers, the existing fire suppression system header at the northwest corner of the CTSD Building 7 highbay was complemented with the addition of a permanent vertical in-line electrical fire pump co-located with the main fire suppression system header. Western States Fire Protection was contracted out to install the new pump system and program the system alarms, and the system was approved by the NASA/JSC local fire protection organization. Western States Fire Protection completed their own acceptance testing to verify conformance of their installed systems with their contract, and the integrated fire suppression system acceptance testing was successfully completed under the EMS acceptance test, although the 2 systems are considered separate, independent systems that exchange information.

B. Emergency Management System

The chamber Emergency Management System is similar in design and function to the other CTSD crewed chamber emergency management systems. Many components were already in place from the existing chamber system, other components needed to be added to accommodate the requirements for the Exploration Atmospheres Study. Additionally, the EMS needed to add the capability to communicate with the upgraded fire suppression system to integrate and coordinate EMS actions between the 2 systems. Because in general it was a similar system to what other CTSD chambers had, and because of the extensive knowledge and experience of the facility engineers who routinely maintain and run those other chamber systems, the necessary changes to the 20 FT chamber EMS was fairly straightforward. JSC's Safety Handbook JPR 1700.1 that governs safety protocols for the entire JSC site explicitly defines the basic requirements for all onsite emergency management systems, and all those requirements were met or exceeded. Every CTSD EMS has dual EMS Programmable Logic Controllers (PLCs) each on their own power source for redundancy; one from emergency power and one from constant power. Additionally each PLC is programmed with the same operating code with separate output field devices to provide as complete independent redundancy as possible allowing for partial or total failure of one PLC system while still ensuring the emergency actions are automatically carried out in the other system. The test requirements dictated the various EMS actions in various emergency situations, and the EMS matrix was programmed to carry out those actions accordingly. Facility Test Directors verified and concurred with the EMS matrix to ensure that it followed the emergency test procedures as they understood them. The integrated EMS-Fire Suppression System acceptance test was successfully completed with only minor issues that were corrected in the subsequent weeks.

C. Vacuum System

The chamber vacuum system didn't require a major upgrade. Inactive components were made active and verified to be within current standards. Additionally, the system was tied into the new facility control system for remote control through pneumatics and control signals as well as integrated into backup compressed air and power systems. Additionally, an interlock was added to the controls programming in order to prevent the Main Chamber remains at equal or lower pressure than the manlock. Once the vacuum system as a whole had been verified as conforming with current pressure systems standards, a manual acceptance functional was conducted to verify the Main Chamber and Manlock vacuum systems could meet all Exploration Atmosphere study vacuum requirements including leak rates, depressurization and repressurization rates, and pressure sustainment at 8.2 psia and 4.3 psia. The vacuum acceptance test was performed manually due to the fact the facility control system was not completed at the time the vacuum system was ready for acceptance testing, so remote control of the vacuum system would be confirmed through the

Controls Acceptance Test. The 20 FT vacuum system met or exceeded all Exploration Atmosphere Study requirements.

D. Oxygen System

The chamber oxygen systems were built specifically for the Exploration Atmosphere Study. The 20 FT did not previously have an installed oxygen system. Airborne Systems SOLR masks were chosen for their mask mounted regulator design to maximize mobility within the chamber. Airborne Systems SOLR Bailout Bottles were chosen as the emergency oxygen sources due to their designed compatibility with the SOLR masks. The 100% Oxygen system was built completely separate from the 85% Oxygen system to avoid the possibility of leakage or dilution. This would be especially advantageous later when new studies desired breathing air concentrations other than 85%. The 85% oxygen system was tied into its own tube trailer while the 100% Oxygen system was originally tied into the existing building oxygen distribution system. Later on as the building oxygen distribution system was redesigned to accommodate future testing, the 20 FT 100% system was redesigned to be supplied by its own tube trailer completely separated from the building distribution system. 10 stations for both 100% oxygen and 85% oxygen were provided in the chamber's 1st level, 5 of each on opposite sides of the chamber from one another. Additionally the Manlock was provided with 4 100% oxygen stations. The 100% system was designed to provide breathing air to the breathing air manifolds, the manlock and the chamber oxygen distribution system. The oxygen systems were designed and built in accordance with applicable codes and regulations, and were reviewed through a thorough Oxygen Compatibility Assessment from the White Sands Test Facility. The system was successfully acceptance tested and met all Exploration Atmosphere requirements prior to the Integrated URR.

E. Chamber Controls, Manual and Automatic

The chamber control system per the Exploration Atmosphere study requirements was designed to provide control and indications for all 20 FT facility systems through interfaces in the 20 FT Control Room. It provides for central control of critical 20 FT systems including vacuum/repress, chamber atmospheric oxygen concentration, HVAC, and positive pressure blowers. It also provides for automatic facility pump and valve interlock protection. It was designed so that chamber and manlock pressures as well as oxygen concentrations could be manually controlled by the operators or programmed to specific set points by the operator and automatically controlled to those setpoints. The operator control panels in the control room were designed to be similar in operation and layout to corresponding operator stations in other CTSD human rated chambers to facilitate operator familiarization and certification. The system was successfully acceptance tested and met all Exploration Atmosphere requirements prior to the Integrated URR.

F. Data and Instrumentation

The chamber instrumentation was provided in adherence to the Exploration Atmosphere requirements. Specifically, 7 Oxigraf O2 and CO2 analyzers were installed, 6 around the outside of the main chamber and 1 on the Manlock. Data is shared between facility DAQ and chamber control system. 7 MKS Baratron's which include 3 for BR1 & BR2 pumps, 2 for main chamber, and 2 for man lock were installed for pressure monitoring. Main chamber data was designed to be shared between the facility DAQ and chamber control system. 2 Vaisala dew point analyzers were installed on the 1st and 3rd levels for humidity calculations. 6 free air thermocouples, 2 on each level, were installed in the Main Chamber for temperature monitoring. 13 Honeywell pressure transducers which included 12 for 85% oxygen panel and 100% O2 panels and 1 for the Main Chamber. 1 Idec LED Signalight Tower was installed on the HVAC drain tank, and 2 float switches were installed in the tank connected to the LED tower and facility DAQ. All instrumentation was individually tested through end to end checkouts and verified through chamber control acceptance testing.

G. Lighting and Power System

The chamber lighting system was required to maintain a correlated color temperature between 2700 and 6500 K. and have the ability to be adjusted through dimmer switches located outside the chamber to specified daytime and nighttime levels. NEMALUX for Hazardous Locations were selected and installed throughout the chamber. Lighting on/off dimmer switches were installed on a panel on the northwest side of the 20 FT Chamber. Fiber Optic lighting was used as emergency lighting to satisfy the requirement that emergency light power had to come from outside the chamber. The power distribution system inside the chamber was built to supply power to all test requester provided equipment while maintaining adherence to NFPA99. All receptacles installed inside the chamber were waterproof and lockable so that electrical items could not be unplugged during testing, minimizing the risk of arcing in an oxygen

enriched atmosphere. The lighting and power systems successfully met Exploration Atmosphere study requirements during acceptance testing prior to the Integrated URR.

H. Audio Communications System

In response to Exploration Atmosphere study communication requirements, 10 connections were installed on the first level which included 6 Test Subjects, 2 Doppler Technicians, and 2 spares. Subjects on mask have 3 connection points (mask panel, bottle, helmet liner). Additionally, 4 connections were provided in the man lock to include 2 Lock Observers and 2 spares. 3 PA speakers were provided, 1 per level. During subsequent tests the PA speakers were replaced with squawk boxes because the PA speakers were not heard very well during operations and squawk boxes provided 2 way communication. 2 Doppler analog to digital converters to Clear-Com matrix were installed to transmit the doppler signals out of the chamber. Communications headset stations on 2nd and 3rd floor were provided for normal communications outside the chamber and private conversations when needed during non-EVA operations. All communications system stations were verified for their intended functionality during a comprehensive communications acceptance test prior to Integrated URR.

I. Video System

To adequately monitor activities on all 3 levels of the 20 FT Chamber, analog cameras for real-time (low latency) monitoring were installed with the level 1 PTZ camera under TD control. HD cameras were installed for increased coverage inside the chamber. HD cameras in the chamber portals were installed to serve as emergency cameras that would not be turned off during a power kill event. All the old 32 inch screens in the front of the control room were replaced with updated 43 inch screens to maximize use of available overhead monitor space, and an additional large screen TV was installed on the Control Room wall to monitor the HD cameras. A digital and analog audio and video recording system was also installed to capture chamber operations. All video requirements were met during acceptance testing prior to the Integrated URR.

J. Air Revitalization System

The chamber air revitalization system was required to maintain CO₂ levels inside the Main Chamber to a 1 hour average not to exceed 3.0mmHg during operations between 8.0 and 14.7 psia. Additionally, it needed to provide a means for trace contamination control within the Main Chamber for the entirety of the test. To achieve this, commercial scrubber units from IHC Hytech were purchased that utilized a base with a fan and refillable canisters installed on the base. 4 of these units were installed on a mounting bracket located on the first level of the 20 FT. 3 units were identified for CO₂ scrubbing and used Soda Lime adsorbent for the canister material. The 4th unit utilized a proprietary blend of carbon molecular sieves and catalyst for trace contaminant control. Acceptance testing showed that the units adequately met specified Exploration Atmosphere requirements. After the first 2 studies conducted in the chamber, 2 additional units were installed, 1 on the 2nd level and 1 on the 3rd level to increase CO₂ scrubbing capacity while minimizing response time based on observed performance during the first chamber studies.

K. Waste and Hygiene

The original vision for the waste and hygiene system was to install a full vacuum compatible plumbing system complete with sinks, showers, and toilets. Several meetings were held with commercial vacuum toilet vendors that routinely sold their products to airlines. After preliminary research into installing such a system, it became readily apparent that under the resource constraints associated with the overall chamber facility upgrades, a full vacuum compatible plumbing system was not feasible. Hand wipes approved for use in the enriched oxygen environment would suffice for personal hygiene, but the problem remained that some type of human waste collection system was needed, and it needed to be completely self-contained since there would be no chamber plumbing. The System Test Branch 20 FT project managers turned to camping and RV toilets as possible solutions to the problem. While researching various camping and RV toilet systems, the project management team discovered the completely self contained Laveo dry flush toilet system, which uses a special mylar bag that is mechanically twisted by the toilet to isolate waste every time the system is “flushed.” It was completely self contained, and the toilet mylar bags were easy to install, use, uninstall, and dispose in larger, chamber approved plastic bags. The vendor was very cooperative in providing all the necessary materials information and safety data sheets for every part of the toilet unit in order to approve the system for vacuum and an enriched oxygen environment. 1 unit was purchased initially to test in a smaller CTSD vacuum chamber to verify its ability to operate at the proposed 20 FT study conditions, and it worked in that preliminary vacuum test with no issues. Subsequently, 3 more units were purchased. 2 were installed on the 2nd level

of the 20 FT chamber and hardwired into the power system. The third toilet was installed on the 1st level of the 20 FT primarily for use during EVAs, and that toilet was left in its original factory configuration utilizing an internal, rechargeable battery.

L. Habitation System

To build the new chamber habitat facilities, the H-3PO Laboratory enlisted the services of the Habitability and Human Factors Branch (HHFB) of JSC's Human Systems Engineering and Integration Division due to its extensive experience in developing designs for space habitats and crew systems based on optimization of human factor considerations. HHFB was specifically tasked to design and outfit the 2nd and 3rd levels of the 20 FT based on the habitability requirements for the chamber set by the H-3PO laboratory. The general requirements were to design and build 8 crew quarters each with individual lighting, ventilation, and storage and waste/hygiene areas with storage and waste control provisions in each hygiene area on the 2nd level and a general meeting/galley area on the 3rd level. HHFB solicited detailed inputs from H-3PO laboratory personnel, CTSD Systems Test Branch personnel, and fire/rescue personnel to assist in their design of the habitat areas. Over 20 habitat designs were initially developed, then down selected to several top designs. These top designs were presented to H-3PO laboratory personnel and CTSD Systems Test Branch Personnel for selection of the final design concept. Virtual models of the design were loaded into HHFB's virtual reality lab, and personnel from both H-3PO and Systems Test Branch were allowed to virtually tour the model to provide additional feedback to HHFB that allowed for further habitat design refinement. Once the design was finalized for the Crew Quarters, a sample crew quarters was built in the HHFB facilities in order to load test the design to confirm that the proposed crew quarters structure would support the general test subject pool, which it did. Once basic systems builds such as the upgraded Fire Suppression System was completed on the 2nd and 3rd levels, HHFB began their construction of the habitat areas, and those areas were completed with the exception of a few of the door installations by the Integrated URR.

VI. Integrated Chamber User Readiness Review and Acceptance Testing

After the successful completion of the individual system user readiness reviews and acceptance tests at the CTSD Systems Test Branch level, an integrated User Readiness Review Board was commissioned by the Director of the JSC Engineering Directorate to evaluate the 20 FT chamber as a whole to ensure that as an integrated facility it safely and effectively met all required testing capabilities to support the proposed Exploration Atmosphere Studies. The initial board was conducted from June 16-17, 2021. Out of that board, a list of actions to be completed prior to both 20 FT Integrated Acceptance Testing and overall URR Board Closeout was assigned. A Test Readiness Review for the 20 FT Chamber Integrated Acceptance Test was completed on September 17th, 2021 after all actions constraining 20 FT Integrated Acceptance Testing had been completed. A 20 FT URR Closeout Meeting was completed on November 1st, 2021 once all assigned 20 FT URR Actions had been completed. The URR Board was provided access to an extensive library of CTSD references and procedural documents that outlined standard operating procedures and maintenance protocols for facilities owned and operated by the CTSD Systems Test Branch. 20 FT subsystem User Readiness Review data from the individual facility systems were also made available to the integrated URR board. The data provided to the URR Board both before and during the initial 20 FT URR meeting was both extensive and thorough. It was obvious at the URR Board that a lot of work had gone into upgrading the facility in many areas, and that the upgrades had all been performed in a methodical and well thought out manner, always keeping in mind and diligently working to meet the demanding testing requirements set forth in the Exploration Atmosphere & EVA Prebreathe Protocol Validation Test Requirements Document. After thorough review of the data presented before and during the 20 FT URR, the 20 FT URR Board assigned 12 actions that EC4 was required to complete prior to final URR, and those actions were all completed to the satisfaction of the URR board by the November 1st 2021 closeout meeting, including the successful completion of the chamber integrated acceptance test where over the course of 4 weeks, the chamber systems were aggressively operated together to ensure that the chamber met all H3PO Laboratory requirements for the Exploration Atmosphere study. As with any new complex system, minor issues were encountered that were noted and corrected after the completion of the integrated chamber testing. The URR Board further recognized that although the chamber was reconfigured to support the specific test parameters for the first Exploration Atmospheres Study with a habitat atmosphere of 8.2 psia and 34% oxygen concentration, the facility systems as designed chamber materials as approved could accommodate other habitat conditions as long as they didn't approach the 40% oxygen concentration level established by the PBD and go below the specified 4.3 psia pressure requirement for the initial Exploration Atmosphere study EVAs, The URR Board in their approval made it clear that these were

the limits that they were approving, but studies could be conducted in the chamber with other atmospheric conditions as long as they didn't violate those limits. The completion of the URR Board and chamber integrated testing officially approved the chamber for crewed Exploration Atmosphere tests, but additional Operations Validation Testing would need to occur to ensure that H3PO Laboratory equipment and procedures would work in the chamber. Thus in the following month both crewed and uncrewed Operations Validation Testing occurred.

VII. Crewed and Uncrewed Operations Validation Testing

Beginning the week after the URR closeout meeting, uncrewed Operations Validation Testing began on the chamber both at sea-level conditions then at vacuum conditions. The objective of the Operations Validation Testing was to perform operational checkouts of test hardware slated for use during the Exploration Atmosphere Prebreathe study. It included checkouts of available test hardware with the chamber/manlock at sea level, 8.2 psia, and 4.3 psia. To the greatest extent possible, the test followed the depress/repress rates set forth in the Exploration Atmosphere Prebreathe Validation Test Requirements. Some test cases required the chamber atmosphere control system to achieve and control the oxygen concentration to 34% O₂. Additionally, acoustics measurements were taken. The test series began with checkout of the test hardware at site pressure. Following this checkout, all test hardware was powered off and the chamber taken through a test pressure profile. Once back at site pressure, all test hardware was powered back on and evaluated to confirm survivability at reduced pressure. The next checkout involved all hardware powered on at reduced pressure. Again, test hardware was evaluated at the conclusion of this stage of checkout. The final checkout was performed with the chamber oxygen concentration set to 34% O₂. All test hardware successfully performed at site pressure and vacuum/enriched oxygen conditions with very minor issues that were able to be corrected. This success paved the way for immediate crewed Operations Validation testing at Sea Level the following week. The sea-level crewed Operations Validation Testing served as a dress rehearsal of the test procedures that would be used during the first 11 day study. A full crew complement of 6 test subjects and 2 Doppler Technicians entered the chamber and simulated the first several days of the 11 day study with the Main Chamber door closed including 1 overnight stay in the chamber and a full simulated EVA. This dress rehearsal of the EVA demonstrated the complex choreography of EVA tasks at different stations and provided important feedback to the H-3PO Laboratory personnel on their EVA procedures that allowed them to make significant refinements prior to the actual Exploration Atmosphere study. Additionally, it became apparent during the sea level Operations Validation Testing that while the 20 FT systems were working as designed and tested, minor issues with both chamber equipment and test requester equipment became apparent and needed tweaking. Additionally, both the Systems Test Branch test personnel as well as the H-3PO laboratory personnel needed to gain more experience with the systems, test hardware, and test procedures in order to ensure that the 11 day study would be conducted successfully. Thus, upon the completion of the sea-level Operations Validation Testing, management from both the Systems Test Branch and the H-3PO Laboratory agreed to a "ramp up" plan to the full 11 day study beginning with 1 more day of Operations Validation Testing at actual vacuum conditions with crewmembers in the chamber. Following successful completion of that 1 day crewed Operations Validation at vacuum, the combined test team would work towards a series of crewed vacuum 20 FT testing that would conduct the planned activities of the first several days of the full 11 day study. Ideally, these tests would be conducted with the actual crew members selected to participate in the full 11 day study in order to give them experience with the chamber systems and test procedures as well. Upon the completion of these ramp up tests, the first one proposed to be 3-5 days and the second one 5-7 days, the combined test team would be confident that the full 11 day study could be conducted with minimized risk of completion. Due to other crewed testing in the CTSD facilities during the December 2021 and January 2022, the final 1 day crewed Operations Validation test at vacuum was not able to be conducted until February 9th of 2022. This last test in the Operations Validation phase successfully checked out all chamber systems at 8.2 psia and 4.3 psia with 2 crewmembers inside. It was the first 20 FT crewed vacuum test since the Skylab program in the mid 1970s, and laid a firm foundation for the ramp up to the full 11 day study.

VIII. First 11 Day Exploration Atmosphere Study

After completion of the crewed Operations Validation testing, preparations immediately began for the proposed 2 precursor tests to the 11 day study. Procedures were further refined based on lessons learned from the 1 day crewed Operations Validation Test, and minor chamber issues were addressed. As preparations proceeded, the test team grew more confident in the operation of the chamber, and concluded that only one precursor test would be required. This test would last 3 days and perform the first 3 days of the proposed 11 day Exploration Atmosphere testing schedule through the first EVA. After successful completion of this 3 day test, final adjustments to procedures and equipment would be made and a full 11 day Exploration Atmosphere Study would be attempted, understanding that if operations

during that test did not go optimally and the full 11 days would have to be cut short, the test team would proceed with terminating early, incorporate any lessons learned as a result of the early termination, and schedule another test several months later that would ideally go the entire 11 days. The 3 day test was successfully conducted May 9th through the 12th, 2022 and all operations through EVA 1 were successfully completed. The combined test team's experience with the chamber over the previous 9 months allowed for smoother test operations each time while still encountering minor equipment and procedural issues that needed to be addressed prior to the full 11 day study. 5 weeks were scheduled between the 3 day test and the 11 day study in order to give the test team adequate time to address final issues while still keeping full 20 FT operations fresh in everyone's focus before other scheduled CTSD testing diverted the team's attention. The 11 day test was started on June 6th 2022 still with the caveat that if need be the team could terminate test early and reschedule after any additional lessons learned were incorporated into procedure. However, every lesson learned incorporated up to that point proved to be adequate, and the entire first 11 Day Exploration Atmosphere Crewed Vacuum Test utilizing a habitat atmosphere of 8.2 psia and 34% oxygen concentration was successfully completed on June 17th 2022 much to the excitement and relief of the combined H-3PO Laboratory-CTSD Systems Test Branch team. There were still many new small procedural and equipment issues that came up during the test that would need to be addressed later, but none were big enough issues to warrant test termination. The team proved that the 20 FT Chamber was now capable of fully serving as a habitat atmosphere study testbed.

IX. Subsequent 20 FT Studies and Future Work

Following the very successful completion of the first 11 day Exploration Atmospheres test with a habitat atmosphere of 8.2 psia and 34% oxygen concentration, a commercial partner became aware of the 20 FT chamber capabilities and approached JSC management with the desire to perform a 3 day DCS risk study for potential participants in a proposed future commercial EVA. The test was conducted at various sub-atmospheric pressures with elevated oxygen levels which mimicked the proposed flight profile culminating with a 2 hour simulated EVA. This test was successfully performed 18-20 December 2022 and demonstrated the 20 FT chambers ability to provide different habitat atmospheres even though the original focus was designing the chamber to meet the needs of the specific 8.2 psia/34% habitat atmosphere conditions. The second cycle of Exploration Atmosphere tests took place almost exactly a year after the first set of Exploration Atmosphere tests. A 3 day test was conducted from 1 to 4 May 2023 followed by a full 11 day Exploration Atmosphere 8.2psia/34% habitat atmosphere study from 12 to 23 June 2023. Once again, the chamber and the combined test team performed well and successfully completed the full 11 day test. This second 11 day test at 8.2 psia/34% oxygen concentration provided the H-3PO Laboratory personnel sufficient data to validate the prebreathe protocol at those conditions. The 3rd Exploration Atmosphere Prebreathe Protocol 11 day test was performed 6-17 November 2023. This time a new prebreathe protocol was the focus of the study utilizing a habitat atmosphere of 9.6 psia/28.5% oxygen content and a test subject prebreathe O2 concentration of 95% instead of 85% utilizing the 85% oxygen system. To provide 95% oxygen to the 85% system, a tube trailer with 95% oxygen was ordered and hooked up rather than at tube trailer with 85% oxygen. This demonstrated further flexibility the chamber can provide. This time, since a full 11 day test had been completed within 6 months, a precursor 3 day test for this November test was deemed unnecessary, but the 3 day test was replaced with a more comprehensive sea level training period 3 weeks before the test than what had taken place before at sea level with a 3 day test incorporated into the 11 day test ramp up. A 4th Exploration Atmosphere Prebreathe Protocol study is tentatively scheduled for September 2024, and a CO2 sensitivity study is planned for early 2025.

X. Conclusion

In conclusion, the JSC CTSD 20 FT Chamber has been evolved into a a world class premier testing and research facility in the area of human expeditionary space habitat atmospheres. Its demonstrated capabilities throughout the past 2 years have outperformed its original design goals, and make it a one of a kind testing facility that both government and commercial partners are looking to in order to help further planetary exploration.

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