Creating the Test 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 eight human test subjects could safely live and work for at least 11 days in the same conditions (e.g., reduced pressures, oxygen concentrations, and so on) 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 18 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
DAQ	=	Data Acquisition Unit
DCS	=	Decompression Sickness
EC4	=	Systems Test Branch of the Crew and Thermal Systems Division at Johnson Space Center
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
HHFB	=	Habitability and Human Factors Branch

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HVAC	=	Heating, Ventilation, and Air Conditioning
ISS	=	International Space Station
JSC	=	Johnson Space Center
LED	=	Light Emitting Diode
NFPA	=	Nation Fire Protection Association
MUCB	=	Materials Usage Control Board
O_2	=	Molecular oxygen
PDR	=	Preliminary Design Review
PBD	=	Performance Based Design
PLC	=	Programmable Logic Controllers
PI	=	Principal Investigator
PPE	=	Personal Protective Equipment
PTZ	=	Pan Tilt Zoom
RV	=	Relief Valve
SDS	=	Safety Data Sheets
SOLR	=	Special Operations Long Range
SPL	=	Sound Pressure Level
TD	=	Test Director
TRR	=	Test Readiness Review
URR	=	User Readiness Review

I. Introduction

Since the days of Projects Gemini and Apollo, Extravehicular Activities, or EVAs, have evolved in practice, and the spacesuits that have supported those activities have evolved as well. General spacesuit design since that era has striven to optimize for mobility, crew person comfort, and particular resources available on the supporting vehicle, while simultaneously minimizing the risks of embolisms 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. With the advent of the Shuttle program, the longer-term missions made it crucial to design Environmental Control and Life Support Systems (ECLSS) in vehicles that mimicked Earth sea-level conditions (21% oxygen/78% nitrogen/1% trace gases) atmosphere at 14.7 psia (101.35kPa)) 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.

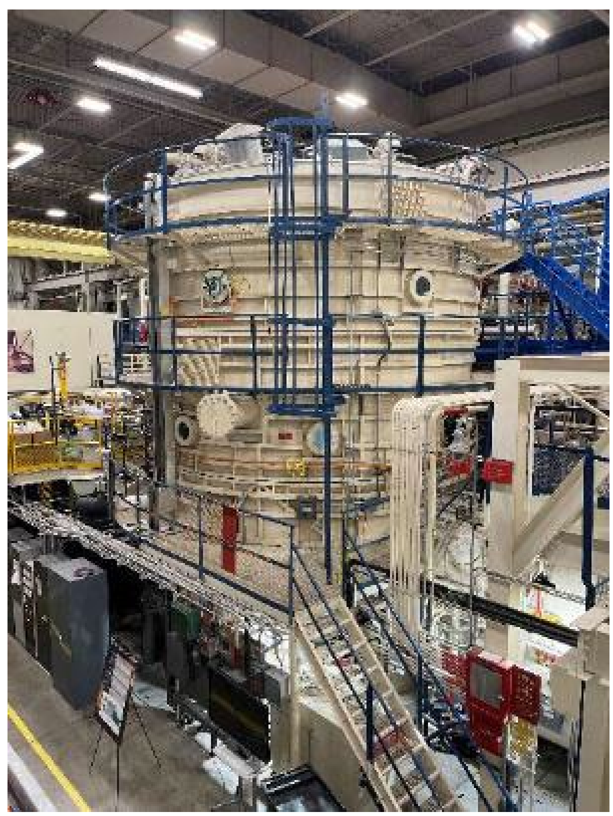

Figure 1. JSC CTSD 20 FT Chamber

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. The advent of our current NASA programs that carry with them the exciting goals of establishing permanent habitats on the Moon in the near future brought with them the necessity 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 on 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 equilibriate 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 Systems Division (JSC CTSD) has a long and extensive history in conducting crewed testing in its human-rated vacuum facilities, and as a part of its inventory of those facilities, there is a vacuum chamber with a long, successful history of supporting extensive, long-term crewed testing. This chamber, the JSC CTSD 20 FT Chamber, was selected due to its size and existing systems that could be modified in a fairly reasonable amount of time to provide critical study data before fast-approaching key milestone decision dates for NASA's 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 (6.1 m) in diameter and 27.5 feet (8.4 m) in height, located in Building 7 of JSC in Houston, Texas. It was originally built in 1964 by the Chicago Bridge and Iron Company as a two 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 third floor was added to the chamber in anticipation 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 closed-loop ECLSS 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 JSC. 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.

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, established the content for exploration atmospheres as 8.2 psia (56.54 kPa) and 34% oxygen. The H-3PO Laboratory scientists were searching for a vacuum chamber that could support an 11-day study for 8 test subjects exposed to the proposed 8.2 psia (56.54 kPa)/34% oxygen exploration atmosphere environment. During this study, the test subjects would perform simulated EVAs. This would involve subjects breathing 85% oxygen supplied through oxygen masks while the chamber was at a pressure of 4.3 psia (29.65 kPa), simulating the pressure they would be working in while in a spacesuit at EVA. The subjects would perform tasks during the EVA to simulate actions and stress loads that astronauts would encounter while on a planetary surface EVA. The 11 days would consist of an initial pumpdown to 8.2 psia (56.54 kPa) (on day 1) followed by 48 hours of climatization at 8.2 psia (56.54 kPa)/34% oxygen conditions. On day 3, the first 6-hour EVA would take place followed by a return to 8.2 psia (56.54 kPa)/34% conditions. Non-EVA days would alternate with EVA days throughout the rest of the test, exposing the test subjects to five 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. Modifications of several existing chamber systems would need to be made for the 20 FT Chamber to adequately host the Exploration Atmosphere study. When it became clear to the H-3PO laboratory that significant funding would be required 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 necessary upgrades. As is typical in a government environment, the funding request process would take a few years to complete. Funding was finally secured for the upgrade projects late in FY18, at which time planning and designing of the necessary 20 FT chamber upgrades began in earnest.

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, in turn, would drive the requirements for 20 FT Chamber upgrades and installation of any new required systems the chamber did not already possess. Out of those discussions, the basic requirements were generated. Those requirements are reflected in Table 1.

Table 1. JSC CTSD 20 FT Chamber Defined Exploration Atmosphere Study Requirements

20 FT Subsystem	Exploration Atmosphere Study Requirement
Manlock (existing Human-Rated chamber airlock system)	Enable routine transfer of test subjects and materials in and out of the main chamber.
Transfer Lock (existing small air lock on side of chamber used for small item transfer)	Enable routine transfer of materials in and out of the main chamber.
Chamber Sound Pressure Levels (SPLs)	Limited to a degree where test subjects could live and work in the chamber without hearing protection during non-EVA periods.
Air Revitalization System (ARS) (new chamber system)	Maintain CO_2 levels throughout the chamber within acceptable limits as well as trace contaminant control.
Audio Communications System (existing chamber system requiring major upgrades)	Hardline audio capability for all test team members and test subjects, Doppler Techs, and rescue personnel during routine operations and durng operations when the test subjects and Doppler Techs are on breathing masks; an intercom system that allows 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 are not on masks; and wireless communications capability during sea-level activities to facilitate test preparations.
Breathing Gas System (new chamber system)	Provide a minimum of nine breathing mask stations inside the main chamber capable of providing 85% or 100% oxygen breathing gas and a minimum of three breathing mask stations in the Manlock capable of supplying 100% oxygen breathing gas. Also required to provide a minimum of eight walk around oxygen bottles within the Main Chamber to support chamber operations for a minimum of 15 minutes in the event of contingencies.
Crew Living and Working Quarters (new chamber system)	Required outfitting of chamber with crew quarters for all participating crew members, hygiene areas, a conference area for meetings and meals, and a work area to conduct EVA operations and exercise when not at EVA.
Food Storage and Preparation System (new chamber system)	Provide a means to store and prepare food and water.
Crew Health Monitoring System (new chamber system)	Support health monitoring equipment and to supply health monitoring data to the Principal Investigator and medical personnel.
Waste Collection System (new chamber system)	Provide the ability for human waste collection during non-EVA operations and EVA operations; to provide the ability to maintain general human hygiene throughout the course of the study; and to provide a means for trash and dry waste storage and removal throughout the study.
Data Collection System (existing chamber system requiring major upgrades)	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.
Chamber and Manlock Vacuum Systems (existing chamber system requiring major upgrades)	Capable of depressurizing the main chamber and manlock from Sea Level (14.7 psia or 101.35 kPa) to 8.2 psia (56.54 kPa) in about 15 minutes and from 8.2 psia (56.54 kPa) to 4.3 psia (29.65 kPa) in about 15 minutes to simulate expected spacecraft/spacesuit performance as well as repressurizing back from 4.3 psia (29.65 kPa) to 8.2 psia (56.54 kPa) in about 15 minutes and from 8.2 psia (56.54 kPa) to Sea Level (14.7 psia or 101.35 kPa) in about 15 minutes again to simulate expected spacecraft/spacesuit performance. The manlock is required to have the capability of depressurizing and repressurizing between Sea Level and 8.2 psia (56.54 kPa) independently while the Main Chamber is at 8.2 psia (56.54 kPa) and between 8.2 psia (56.54 kPa) and 4.3 psia (29.65 kPa) independently while the Main Chamber is at 4.3 psia (29.65 kPa). The vacuum system is also required to automatically maintain pressure at both 8.2 psia (56.54 kPa) and 4.3 psia (29.65 kPa) to ensure stable conditions during EVA and non-EVA operations.
Emergency Management System (EMS) (existing chamber system requiring major upgrades)	Have the capability 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.
HVAC System (existing chamber system requiring major upgrades)	Maintain chamber humidity at prescribed levels, chamber temperatures on all three levels at prescribed levels, and ventilation capable of circulating internal chamber air throughout all three levels at high enough rates to allow oxygen injection into the chamber while preventing oxygen specific accumulations in any chamber areas.
Lighting System (existing chamber system requiring major upgrades)	Provide general lighting on all three levels that could be adjusted as necessary in different areas for normal operations, sleep periods, and visual acuity testing.
Power Distribution System (existing chamber system requiring major upgrades)	Accommodate all necessary test requester hardware to support the study which would incorporate protection from arcing in an enriched oxygen environment.
Oxygen Injection System (new chamber system)	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.
Video System (existing chamber system requiring major upgrades)	Monitor all levels of the chamber and record video throughout the entire study.
Enriched Oxygen Atmosphere Compatibility	Everything inside the chamber must be compatible with an enriched oxygen environment all the way up to an internal chamber atmosphere with 36% oxygen content

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. Of special note, a very unique challenge for all these system projects presented itself at the onset of all these projects due to sheer timing. The main efforts for these projects began shortly before the COVID pandemic shutdowns. Once the pandemic lockdowns began in Mid March of 2020, access to JSC was limited to essential personnel only, and initial design work had to be performed remotely via telework. Once restrictions were lifted to the point where enough of the workforce was allowed back onsite to perform buildup work, individual hazard analyses detailing measures to minimize transmission for all work were required to be written prior to the work being performed. Additional PPE was required to be worn that wasn't required in normal conditions, and sanitation protocols were enacted before and after work was performed. All personnel working onsite at JSC were tracked to assist with contact tracing required at the time. Those additional protocols significantly slowed the upgrade processes, and lasted into 2021 before being gradually relaxed throughout 2021 into the first half of 2022 when the first crewed vacuum test occurred.

A brief summary of each of the major chamber system projects and their accompanying unique challenges 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 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 (.005093 cubic meters per second per square meter) 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 minimum 2.0 gpm/sq ft (.001358 cubic meters per second per square meter) 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 first, second and third level fire suppression system was required along with providing a fire suppression water supply to all three levels independently. Supply piping to the 20 FT chamber would also have to be increased from 6 in (15.24 cm) to 8 in (20.32 cm), and the new piping would need to accommodate the new habitat designs on the second and third levels. A new structural platform was built to support and provide access to two 8 in deluge valves for each chamber level and manlock. To ensure the 2.0 gpm/sq ft (.001358 cubic meters per second per square meter) requirement would be met in all the chambers, the existing fire suppression

Figure 2. JSC Building 7 Fire Booster Pump

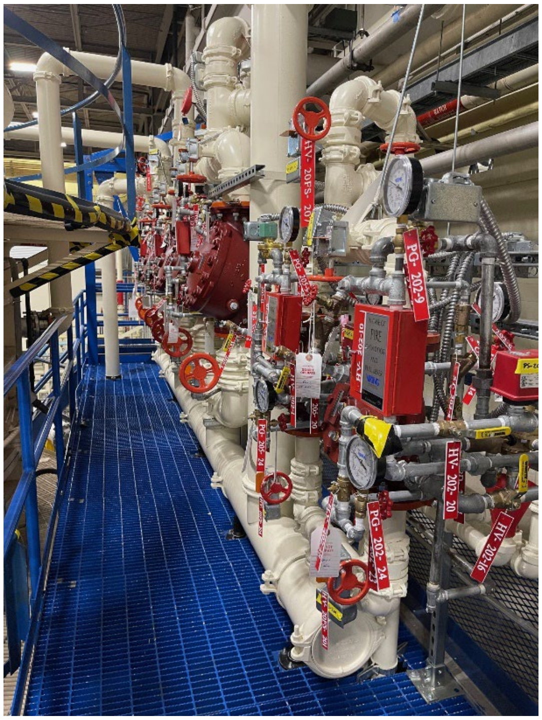

Figure 3. 20 FT Fire Manifold

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 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 two 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, which serve to implement predetermined actions in the cases of various prescribed emergencies that may be encountered during testing. While many components were already in place from the existing chamber system, many other components needed to be added to accommodate the requirements for the Exploration Atmospheres Study, and to communicate with the upgraded fire suppression system allowing integration and coordination of EMS actions between the two systems. A major challenge during this upgrade stems from the fact that the 20 FT Chamber shares its vacuum system with CTSD's Space Station Airlock Test Article (SSATA), which is the primary facility where astronauts train in a spacesuit at vacuum before they go on their orbital missions. The facility engineers had to develop proper system interlocks had to be developed then integrated with existing SSATA chamber vacuum controls such that the controls of the SSATA Chamber during SSATA Chamber testing could not be overridden or negated by the controls in the 20 FT Chamber, and vise-versa during 20 FT Chamber testing. This work had to be planned not only around COVID restrictions, but also the busy astronaut training schedule the SSATA chamber routinely accommodates. Despite these major challenges to the EMS system upgrades, in general the 20 FT Chamber EMS is a similar system to what other CTSD chambers have, and because of the extensive knowledge and experience of the facility engineers who routinely maintain and run those other chamber systems, most of the necessary changes to the 20 FT chamber EMS were fairly straightforward. The interlock implementation did take a few iterations of trial and error before it worked as designed, but overall the challenges it had presented were not very different than implantation in other EMS systems. 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 in the 20 FT Chamber system. Every CTSD EMS has dual EMS Programmable Logic Controllers (PLC), 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 refurbishment began with reactivation of system components to verify they still performed in accordance with design specifications. Next, preliminary vacuum functionals of the chamber were performed. During these functionals, it was discovered that the original primary Beach-Russ RP-1000 vacuum pump would overheat while maintaining 8.2 psia (56.54 kPa). As a result, the original pumps were replaced with Busch vacuum pumps. While the Busch pumps were not large enough to change chamber pressure at the required

Figure 5. New 20 FT Busch Vacuum Pumps

rates they were capable of maintaining higher chamber pressures without overheating. New rate valves were also installed for the main chamber, and the vacuum piping servicing the manlock was reconfigured to tie in to the new Busch pumps. Once the mechanical upgrades had been successfully installed and tested, 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 ensure 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 (56.54 kPa) and 4.3 psia (29.65 kPa). Of note on repressurization is that there are no repressurization pumps in the 20 FT system. For repressurization, a repressurization valve is throttled to bring in outside air at a desired rate. 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. After completion and checkout of all the upgrades, the 20 FT vacuum system met or exceeded all Exploration Atmosphere Study requirements.

D. Oxygen System

The 20 FT did not previously have an installed oxygen system that was active or fit for use. A new chamber oxygen distribution system was purpose built for the Exploration Atmosphere Study from the ground up. The system was designed to supply a mixture of 85% oxygen (balance nitrogen) for test subject mask breathing during simulated EVA activities and 100% Aviators Breathing Oxygen (ABO) for mask breathing and chamber atmosphere control. To avoid the possibility of dilution, due to leakage or misconfiguration, the ABO and 85% oxygen systems are independent parallel supplies. Separation of the 85% oxygen supply system is also advantageous when new studies request different breathing gas concentrations, only requiring a source change. Originally the ABO system was designed using the existing building oxygen distribution system as a gas source. Toward the completion of the 20 FT oxygen system buildup and acceptance testing, it was discovered that as part of an independent project the building oxygen distribution system was redesigned to support the future needs of testing in CTSD but, the redesign introduced flow restrictions that would prevent the 20 FT system from meeting the requirement to transition from site pressure to 8.2 psia (56.54 kPa) in 15 minutes with a chamber atmospheric concentration of 34% oxygen. To meet test requirements, the 20 FT 100% system was redesigned to be supplied by its own tube trailer independent of the building distribution system. Within the chamber, ten stations for both ABO and 85% oxygen were provided on the first level of the main chamber, five of each on opposite sides of the chamber from one another. Additionally, the manlock was provided with four ABO oxygen stations. 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 and the CTSD Materials Usage Control Board (MUCB).

Figure 4. 20 FT Oxygen Panel

Planned simulated EVA activities drove several design considerations that may not typically apply to oxygen mask selection. A requirement for the mask wearer to hydrate without mask removal due to the long duration (six hours at the simulated EVA pressure of 4.3 psia (29.65 kPa)) was imposed by the JSC medical team. Historically, CTSD has used Gentex® MBU-12/P masks for operations up to 18k ft (5486.4 m) altitude, conditions which allow the mask to be briefly removed for drinking, or FAS masks, with integrated drink facility, when operating at 4.3 psia (29.65 kPa) in the Dual Glovebox facility. The FAS was a mask produced by Gentex® for the German military for nuclear, biological, and chemical protection and is no longer in production. Oxygen to these masks is supplied by a CRU-73, or similar, panel mount regulator and 7/8" (2.22 cm) inner diameter convoluted hose at a pressure of roughly 1 inH_2O (0.249 kPa). Umbilical management of existing hardware was deemed impractical due to size and weight, the planned simulated EVA activities required more freedom of movement and thus longer oxygen supply hoses than any previous test. Parachutist oxygen masks with mask mounted demand regulators were identified as an alternative to the discontinued MBU-12/P and FAS. The SOLR® Oxygen Mask from Airborne Systems has an altitude limit of 35,000 ft (10668 m) and was able to be purchased with a drink port option from the manufacturer. The mask mounted demand regulator is supplied by a 25 ft (7.62 m) long ¼" (.635 cm) diameter hose, but because the regulator supply pressure is 80 psig (652.934 kPa), umbilical length does not result in excessive pressure drop that would impact a CRU-73 supplied mask with similar length umbilical. Mobility was significantly improved by the weight reduction and flexibility of the ¼" (.635 cm) diameter hose compared to the 7/8" (2.22 cm) inner diameter convoluted hose. Airborne Systems SOLR® 3000 bailout bottles were used as the emergency oxygen supply for each test subject and provided automatic seamless oxygen delivery in the event of facility supply disruption or inadvertent disconnection. The facility oxygen system and SOLR® equipment were 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. A major challenge that had to be overcome during the controls system installation was that it happened that during the controls software development, compliance with NASA Software Engineering requirements, NASA NPR 7150.2, was enforced for the first time in the CTSD organization. This impacted all software packages for not only the Iconics® control systems software that CTSD uses for all of its test facilities, but also for the PLC control software, EMS PLC software, and data system. Successful compliance was ensured through close coordination between the facility control engineers and the local JSC Software Assurance group at every step of the software development process. Another challenge encountered during software vacuum controls development was the fact that the existing chamber vacuum valves were large in size and primarily designed for coarse control. The facility engineers were able to develop and implement finely tuned PID control loops that were able to operate the valves in a precise enough manner to meet the Exploration Atmosphere pressure control limits. The control system was successfully acceptance tested and met all Exploration Atmosphere requirements prior to the Integrated URR.

Figure 6. 20 FT Control Room

F. Data and Instrumentation

The chamber instrumentation was provided in adherence to the Exploration Atmosphere requirements. Table 2 summarizes the instrumentation throughout the 20 FT Chamber Complex. Data is shared between facility DAQ and the chamber control system. All instrumentation was individually tested through end to end checkouts and verified through chamber control acceptance testing. During the chamber acceptance testing, the test team experienced slow performance issues and lock up of the data trend graphs shown on the screen. This was found to be the result of the heavy data monitoring load for this particular chamber and test combined with antiquated servers that needed updating. After trying various server solutions, the system server was finally upgraded to a high perfomance physical server which mostly solved the performance issues, but periodic refreshing of data trends that buildup large amounts of historical data over several days was still required to completely address the problem.

Table 2. JSC CTSD 20 FT Chamber Instrumentation

Oxygen and CO2 Monitoring	Six Oxigraf® O_2 and CO_2 analyzers installed around the outside of the main chamber and one on the manlock.
Chamber Vacuum Monitoring	Seven MKS® baratrons, three for BR1 and BR2 pumps, two for main chamber and two for manlock.
Humidity Monitoring	Two Vaisala® dew point analyzers installed on the first and third levels with humidity calculated from dew point and temperature.
Temperature Monitoring	Six free air thermocouples, two on each level of the Main Chamber.
System Pressure Monitoring	Thirteen Honeywell® pressure transducers total, twelve in the 85% oxygen panel and 100% O_2 panels and one for the Main Chamber.
Drain Tank Overflow Monitoring	One Idec® LED Signalight Tower installed on the HVAC drain tank, and two float switches in the tank connected to the LED tower and facility DAQ.

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® Industrial Lighting for hazardous locations (NFPA 70 Class I Division 2 lighting) was selected and installed throughout the chamber. These lights are rated at 10V and protected by fastblow fuses. They are not explosion proof, but are rated for IP 67 level water protection in case of a water flow from the fire suppression system. 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 NFPA 99. All receptacles installed inside the chamber were hospital grade GFI recepctacles with metal outdoor covers. They are all waterproof and lockable so that electrical items cannot 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, a comprehensive communications system was installed throughout the 20 FT Chamber. A summary of the communication stations is provided in Table 3. Subjects on mask have three connection points (mask panel, bottle, helmet liner). 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 two-way communication. Two Doppler analog-to-digital converters to Clear-Com matrix were installed to tranmit the doppler signals out of the chamber. All communications system stations were verified for their intended functionality during a comprehensive communications acceptance test prior to Integrated URR.

Table 3. JSC CTSD 20 FT Chamber Communications Stations

20 FT First Floor	Ten personal communications stations, (8 for Exploration Atmosphere participants plus 2 spares), each capable of private communications with the Test Directors and Medical Officer. One Public Announcement Speaker (replaced with squawk box before subsequent tests).
Manlock	Four personal communications stations, (For Crew Transfers, visitor transfers, and lock observers if/when necessary), each capable of private communications with the Test Directors and Medical Officer.
20 FT Second Floor	One communication headset station capable of private communications with the Test Directors and Medical Officer. One Public Announcement Speaker (replaced with squawk box before subsequent tests).
20 FT Third Floor	One communication headset station capable of private communications with the Test Directors and Medical Officer. One Public Announcement Speaker (replaced with squawk box before subsequent tests).

I. Video System

To adequately monitor activities on all three levels of the 20 FT Chamber, analog cameras for real-time (low latency) monitoring were installed with the first floor 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 of the old 32-in screens in the front of the control room were replaced with updated 43-in 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 CO_2 levels inside the Main Chamber to a 1 hour average not to exceed 3.0mmHg during operations between 8.0 psia (55.16 kPa) and 14.7 psia (101.35 kPa). Additionally, the system 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. Four of these units were installed on a mounting bracket located on the first level of the 20 FT. Three units were identified for CO_2 scrubbing and used Soda Lime adsorbent for the canister material. The fourth 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 two studies conducted in the chamber, two additional units were installed, one on the second level and one on the third level to increase CO_2 scrubbing capacity while minimizing response time based on observed performance during the first chamber studies.

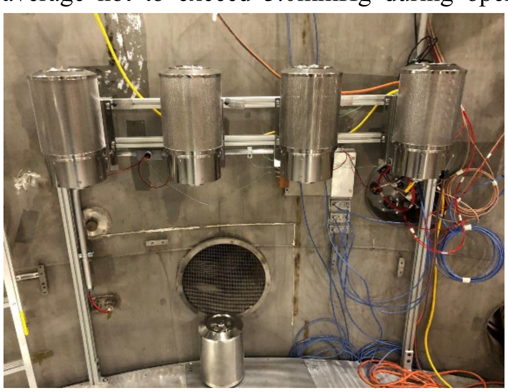

Figure 7. 20 FT Air Revitalization System, 1st Floor

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 recreational vehicle (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

Figure 8. 20 FT 2nd Floor Laveo® Dry Flush Toilet

“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 safetydata sheets for every part of the toilet unit in order to approve the system for vacuum and an enriched oxygen environment. One 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, three more units were purchased. Two were installed on the second level of the 20 FT chamber and hardwired into the power system. The third toilet was installed on the first level of the 20 FT primarily for use during EVAs, and that toilet was left in its original factory configuration utilizing an internal, rechargable 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

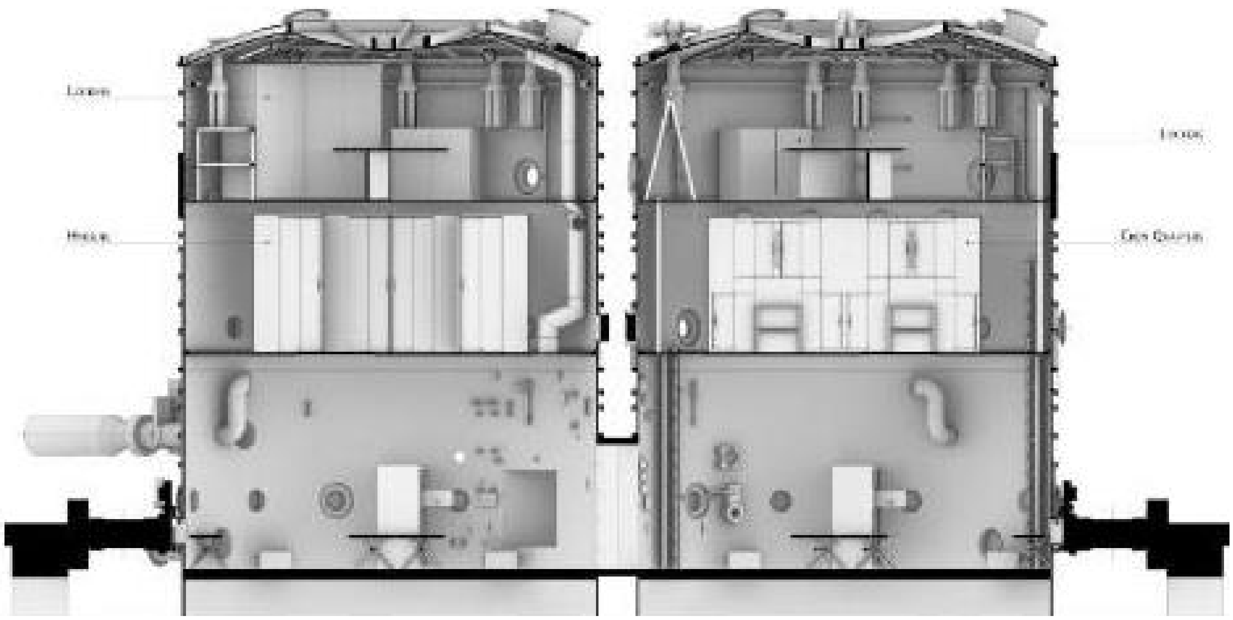

Figure 9. 20 FT Chamber Overall Inside Layout

considerations. HHFB was specifically tasked to design and outfit the second and third 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 eight 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 second level and a general meeting/galley area on the third 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. More than 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

Figure 10. 20 FT 1st Floor

Figure 11. 20 FT 2nd Floor

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. After basic 20 FT system builds such as the upgraded Fire Suppression System were completed on the second and third levels, HHFB began their construction of the habitat areas. Those areas were completed with the exception of a few of the door installations by the Integrated URR. Figure 9 shows the final overall layout, and Figures 10, 11 and 12 show the final habitat configurations. The final floor area on both the first floor and the third floor is 314 square ft (29.17 square meters). The final floor area on the second floor is 407.78 square ft (37.88 square meters) which includes the area of the crew quarters.

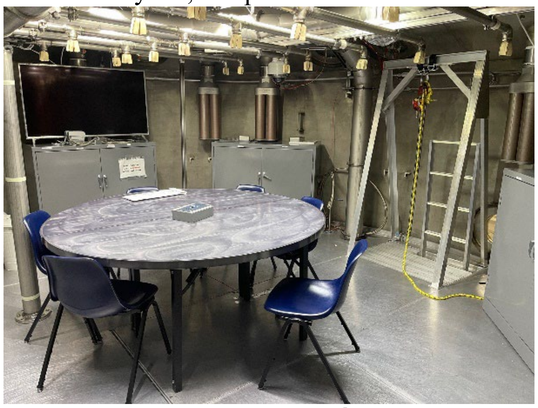

Figure 12. 20 FT 3rd Floor

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 to 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 17, 2021, after all actions constraining 20 FT Integrated Acceptance Testing had been completed. A 20 FT URR Closeout Meeting was completed on November 1, 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. The 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 were 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 despite the many challenges the engineers faced while designing and building up the systems. Also obvious to the URR Board was that the engineers throughout the process always kept in mind and diligently worked towards specifically meeting 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 1, 2021, closeout meeting, including the successful completion of the chamber Integrated Acceptance Test.

The chamber Integrated Acceptance Test was conducted over the course of 4 weeks, and aggressively operated all chamber systems together to ensure that the chamber met all H3PO Laboratory requirements for the Exploration Atmosphere study. This was the first time the chamber would be run as a whole in a test environment since all the new upgrades and system were installed. Not only did it test the systems, but it provided an opportunity to the test team to run checklists and test procedures for the first time and flush out any procedural issues before running actual crewed tests. It also had to be conducted around other testing that was running concurrently as well as the final vendor acceptance test of the new Fire Suppression System. 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 (56.54 kPa) and 34% oxygen concentration, the facility systems as designed and chamber materials as approved could accommodate other habitat conditions as long as they did not approach the 40% oxygen concentration level established by the PBD and go below the specified 4.3 psia (29.65 kPa) 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 did not 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 (56.54 kPa), and 4.3 (29.65 kPa) 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% oxygen. 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% oxygen. 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 crewed study. A full crew complement of six test subjects and two Doppler Technicians entered the chamber and simulated the first several days of the 11-day study with the Main Chamber door closed, including one 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 EVA stations (all located on the 20 FT first floor) 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. While the 20 FT systems were working as designed and tested during this testing phase, 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 found that they needed to gain more experience with the systems, test hardware, and test procedures in order to ensure that the 11-day crewed 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.

The first event of this new ramp up plan would begin 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 toward 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 was proposed to be 3–5 days in length and the second one was proposed to be 5–7 days in length), 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 9, 2022. This last test in the Operations Validation phase successfully checked out all chamber systems at 8.2 psia (56.54 kPa) and 4.3 psia (29.65 kPa) with two 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 two 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.

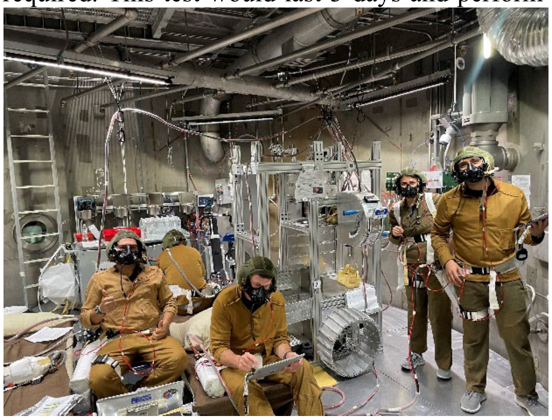

Figure 13. 20 FT EA Study Crewed EVA Simulation- 20 FT 1st Floor

The 3-day test was successfully conducted May 9–12, 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. Five 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 6, 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 (56.54 kPa) and 34% oxygen concentration was successfully completed on June 17, 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 (56.54 kPa) 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 commercial flight profile culminating with a 2-hour simulated EVA. This test was successfully performed December 18–20, 2022, and demonstrated the 20 FT chamber's 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 (56.54 kPa)/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. Several chamber modifications were made prior to this next series based on observations from the first 11 day crewed study. As noted in the section describing the Air Revitalization System above, CO_2 scrubbing units were added on the 2nd floor and 3rd floor to help better manage CO_2 levels throughout the chamber. The chamber oxygen injection system was outfitted with larger lines to increase capacity and allow it to achieve chamber oxygen levels in keeping with the original requirements. It had been observed in the first test that the system as originally built could not raise the chamber oxygen percentage in the desired 15 minute timeframe. Finally, a separate oxygen injection line was installed in the manlock as it was observed during the first study that natural mixing from the chamber was not adequate to bring the manlock oxygen level to 34% in a reasonable amount of time after transfer operations.

A 3-day test was conducted May 1–4, 2023, followed by a full 11-day Exploration Atmosphere 8.2 psia (56.54 kPa)/34% habitat atmosphere study June 12–23, 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 (56.54 kPa)/34% oxygen concentration provided the H-3PO Laboratory personnel sufficient data to validate the prebreathe protocol at those conditions.

The third Exploration Atmosphere Prebreathe Protocol 11-day test was performed November 6–17, 2023. This time a new prebreathe protocol was the focus of the study utilizing a habitat atmosphere of 9.6 psia (66.19 kPa)/28.5% oxygen content and a test subject prebreathe O_2 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 fourth Exploration Atmosphere Prebreathe Protocol study is scheduled for September 2024, and a CO_2 sensitivity study is planned for early 2025.

X. Conclusion

As they say, space is hard. In many respects, simulating space and space habitats on Earth is no less challenging. Evolving the JSC CTSD 20 FT Chamber to its current state as a world class premier testing and research facility in the area of human expeditionary space habitat atmospheres was a long and difficult process in many respects due to the many unique and unyielding requirements placed upon it by the sheer reality of what was needed in order to ensure future astronauts will be able to more efficiently and safely work outside of planned space habitats. Overall, despite the challenges encountered and overcome, the 20 FT Chamber's demonstrated capabilities throughout the past 2 years have outperformed their original design goals, making the JSC CTSD 20 FT Chamber a one-of-a-kind testing facility that both Government and commercial partners are looking to in order to help further planetary exploration.

Acknowledgments

We would like to thank Jonathan Homan, Eric Chan, John Tatum, Shelby Rode, Kai Cui, Jose Cervantes, Chris Horne, Gerardo Vargas, David Arnold, Andrew Francis, Luca Callini, Dr. Andrew Abercromby, Dr Alejandro Garbino, and Dr. Monica Lew. In addition, we would like to the thank everyone in the Systems Test Branch of the Crew and Thermal Systems Division and in the H-3PO Laboratory of the Biomedical Research and Environmental Sciences Division at NASA JSC for their hard work in making these crewed Exploration Atmosphere study tests in the 20 FT Chamber possible.

References

[1]W.H. Gerstenmaier, Memorandum from the Associate Administrator for Human Exploration and Operations: Exploration

[2]Andrew F.J. Abercromby, Johnny Conkin, Michael L. Gernhardt, "Modeling a 15-min extravehicular activity prebreathe protocol using NASA's exploration atmosphere (56.5kPa/34% O2)," *Acta Astronautica*, Vol. 109, 2015, pp. 76–87.

[3]NFPA, "Standard for Hypobaric Facilities," NFPA 99B, 2018.

[4]Beeson, H, Forsyth, E, & Hirsch, D. "Total Water Demand for Suppression of Fires in Hypobaric Oxygen-Enriched Atmospheres." Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres: Eighth Volume. Ed. Chou, T, Royals, W, & Steinberg, T. 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959: ASTM International, 1997.

[5]Callini, G "A Tale of Two Chambers: Iterative Approaches and Lessons Learned from Life Support Systems Testing in Altitude Chambers," NASA Johnson Space Center, , 2016.

[6]"Exploration Atmosphere & Prebreathe Protocol Validation-Test Requirements, CTSD-ADV-1603 Rev 2." In: NASA Test Requirements Document, 2021.

[7]"20 FT Chamber – Exploration Atmosphere Pre-breathe Protocol Validation Test Detailed Test Procedures, CTSD-ADV-1937 Rev C." In: NASA Detailed Test Procedure, 2023.

[8]NASA, "Standard for Fire Protection and Life Safety," NASA-STD-8719.11, 2008.

[9]NASA, "JSC Safety And Health Requirements," JPR 1700.1, 2018.

[10]NASA, "NASA Software Engineering Requirements," NPR 7150.2, 2022.