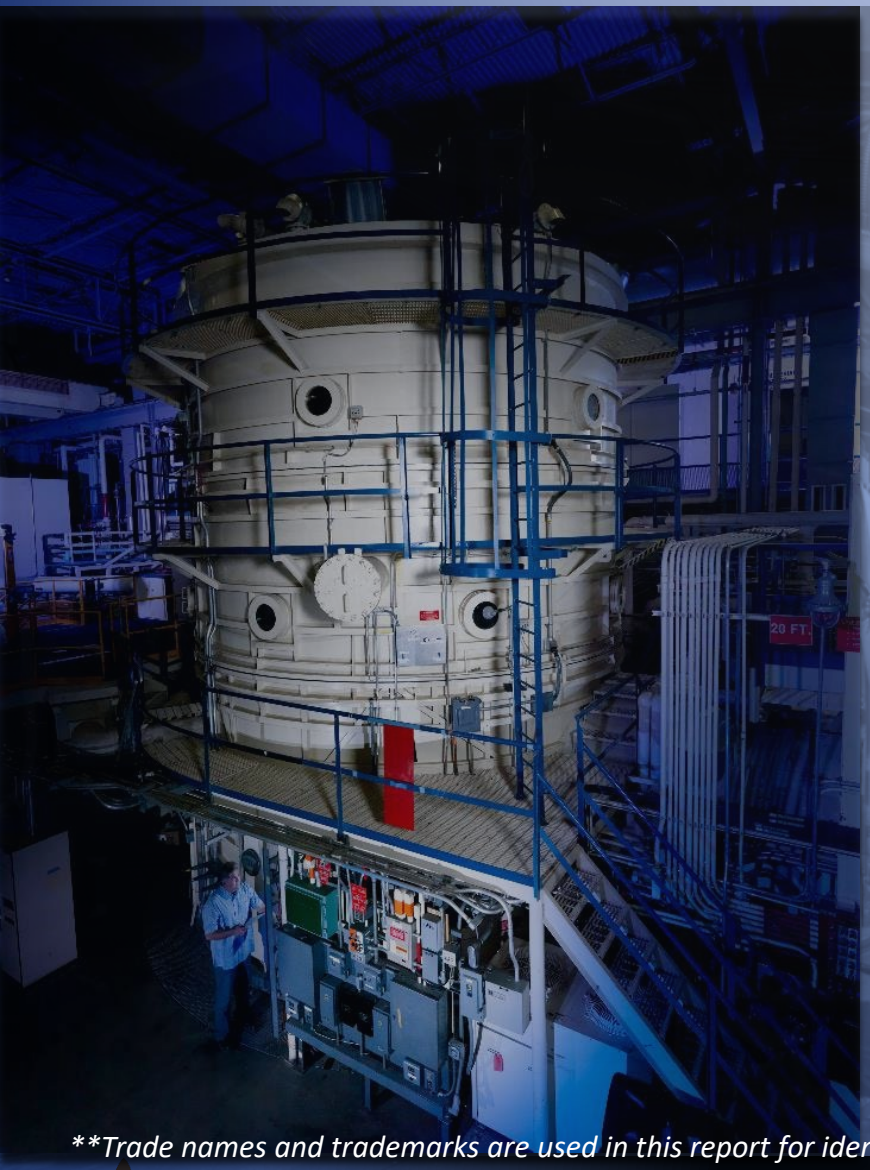

Creating the Test Environment for Exploration Habitats

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ICES
ENABLING EXPLORATION

Introduction

- **Extravehicular Activities (EVAs) have evolved since the days of Projects Gemini and Apollo**
  - Gemini and Apollo capsule cabins were 100% oxygen and required no prebreathe prior to EVA
  - Shuttle atmosphere (and later ISS atmosphere) mimicked Earth sea-level conditions (21% oxygen/78% nitrogen/1% trace gases at 14.7 psia/101.35kPa)
  - Requires 4 hour prebreathe at 100% oxygen to minimize risk of Decompression Sickness (DCS)
- **Current NASA programs have the ultimate goal of establishing permanent habitats on the moon in the near future**
  - More frequent Extra-Vehicular Activities will be required as part of daily work routine for these habitats
  - EVA prebreathe times need to be shortened from currently accepted 4-4.5 hours.

Introduction

- **New Prebreathe Protocols need to be established to support the shorter prebreathe times/more frequent EVAs required for lunar/planetary habitats**
  - New prebreathe protocols require studies to validate those protocols for EVA use.
  - Studies of this kind require a human rated vacuum chamber suited for providing both a simulated lunar habitat environment and a simulated EVA suit pressure for conducting simulated EVAs.
- **The Crew and Thermal System Division (CTSD) 20 FT Human-Rated Vacuum Chamber at NASA Johnson Space Center is uniquely qualified to serve as host to the required prebreathe protocol studies**

Brief 20 FT Chamber History

- **3 Story Vacuum Chamber 20 FT (6.1m) in diameter/27.5 FT (8.4m) in height located in Building 7 of NASA Johnson Space Center**
  - Originally built in 1964 as a 2 story vacuum chamber to support crewed testing for Gemini and Apollo Programs
  - Later used in 1970s for extended duration tests supporting Skylab
  - 3rd story added in 1980s in anticipation of testing supporting proposed U.S. Space Station
  - Served as test platform for closed loop ISS ECLSS development testing during 1990s
  - Served as high fidelity Mars/Lunar surface habitat analog during early 2010s
  - Selected for EVA Protocol Validation Test Studies in latter 2010s

JSC CTSD 20 FT Chamber

Prebreathe Protocol Study Selection of 20 FT Chamber

- **Discussions for a proposed Exploration Atmosphere Study between CTSD and JSC's Human Physiology, Performance, Protection, and Operations (H-3PO) Laboratory began in 2013-2014 timeframe**
  - Spurred by 2013 Memo from then Associate Administrator Gerstenmaier adopting 8.2 psia (56.54 kPa)/34% oxygen for future exploration habitat atmospheres to support higher frequency EVAs
  - 11 Day Study proposed to include initial pumpdown to habitat atmosphere of 8.2 psia (56.54 kPa)/34% Oxygen, a 48-hour acclimatization period, a 6-hour simulated EVA, then a return to the 8.2 psia (56.54 kPa)/34% Oxygen conditions. The process would continue alternating Non-EVA days with EVA days to get a total of 5 simulated EVAs during the 11-day test period
  - 20 FT became clear candidate during these initial conversations, but significant upgrades would be required
  - H3PO Laboratory put discussions about the study on hold until they could secure proper funding
  - Funding was secured in FY18, allowing initial 20 FT upgrade planning and designing to start in earnest

Defining 20 FT Requirements and Upgrade needs for Prebreathe Protocol Studies

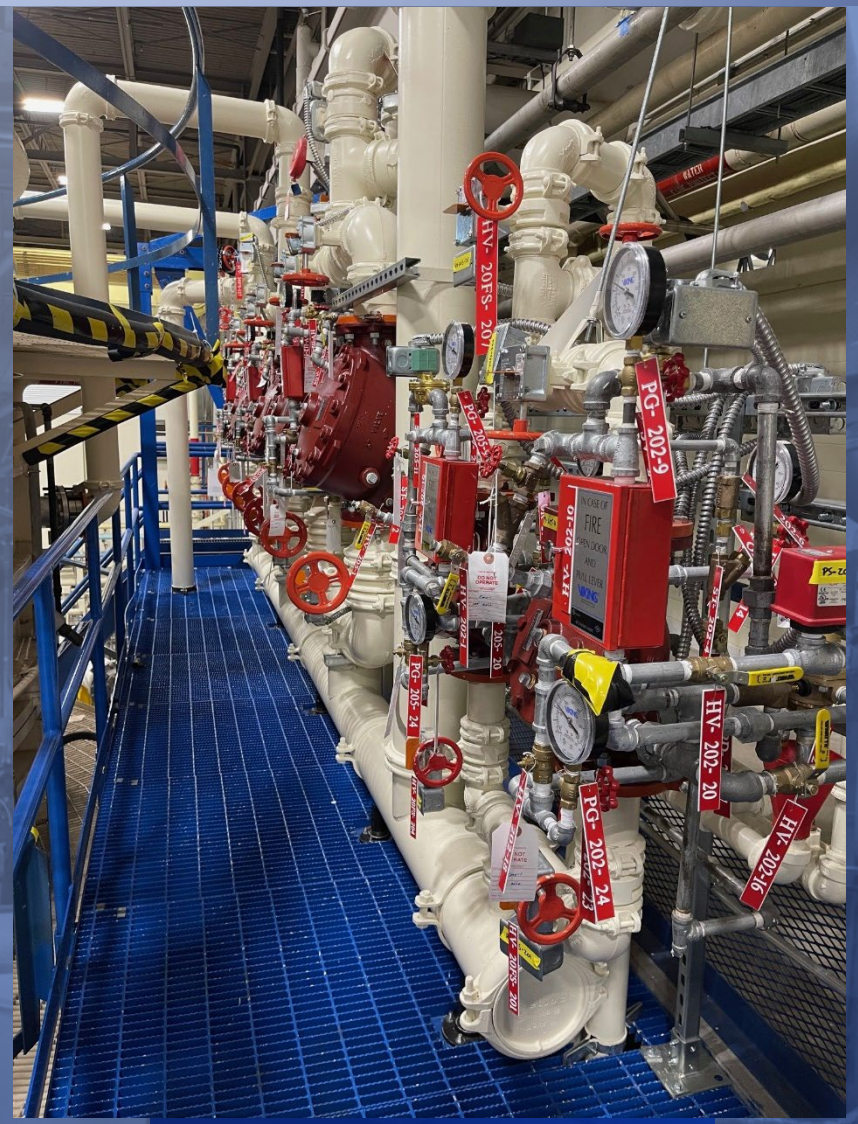
- **Initial Upgrade planning commenced in mid-2018 with the surveying of all chamber facility systems and determination of what systems would need to be upgraded and if there were new systems that needed to be installed**
  - 2 systems were found to satisfy requirements (Manlock and Transfer Lock)
  - 8 systems required significant upgrades (Comm, Data, Vacuum, Emergency Management, HVAC, Lighting, Power, and Video)
  - 7 new systems were required to be installed (Air Revitalization, Breathing Gas, Crew Quarters, Crew Health Monitoring, Food Storage/Prep, Waste Collection, and Oxygen Injection)
  - Individual projects were begun on each of these systems in late FY18/early FY19
  - Project progress was significantly hampered during COVID pandemic beginning in March 2020, but CTSD personnel adapted and continued the work with COVID protocols in place
  - The COVID protocols continued into 2021 before being gradually relaxed throughout 2021 into 2022

Fire Suppression System (FSS) Upgrades

- **Fire Suppression System had been in place for several decades, and there was general concern among the CTSD engineering staff that the system didn't meet national and JSC standards**
  - Performance Based Design study by Jacobs Engineering commissioned to identify deficiencies related to all applicable codes for all CTSD Building 7 crewed chambers
  - For the 20 FT Chamber, study concluded that it was an NFPA 99B, Class E, oxygen enriched atmosphere chamber per code
  - Study established code equivalent design per NASA STD 8719.11 which established 40% oxygen content as the maximum chamber oxygen concentration and requiring 2.0 gpm/sq ft (.0014 $(m^3/s)/m^2$) water density for existing deluge system as sufficient to meet PBD equivalent design requirements
  - To meet design requirements in 20 FT, a complete reconfiguration of the existing fire system on all 3 levels took place
    - Fire Suppression water supply had to be routed to all 3 levels independently
    - New configuration needed to accommodate new habitat on 2nd level
  - Supply piping to the chamber had to be increased from 6 in (15.24 cm) to 8 in (20.32cm)
    - New platform was built to support new supply piping and provide access to two 8 in deluge valves for each chamber level
  - Vertical in-line electrical fire pump was added to existing CTSD Building 7 highbay fire suppression system header to ensure 2.0 gpm/sq ft (.0014 $(m^3/s)/m^2$) requirement was met in all CTSD Building 7 chambers

Fire Suppression System (FSS) Upgrades

JSC Building 7 Fire Booster Pump



20 FT Fire Manifold

Emergency Management System (EMS) Upgrades

- **Emergency Management System (EMS) is similar in design and function to other CTSD crewed chamber EMS, serving to implement predetermined actions in cases of various prescribed emergencies that may be encountered during testing**
  - Operates with 2 Programmable Logic Controllers (PLCs) each on independent power and programmed with same operating code with separate output field devices for redundancy
  - Many components were already in place from the existing chamber system, but many additional components had to be added to accommodate Exploration Atmosphere Study requirements as well as communicate with upgraded Fire Suppression System
  - 20 FT Chamber shares vacuum system with CTSD Space Station Airlock Test Article (SSATA) which required development of system interlocks
    - Interlocks ensured that SSATA vacuum control couldn't be overridden during SSATA testing by 20 FT controls and vice versa during 20 FT testing
  - SSATA is primary facility where astronauts train at vacuum in a spacesuit practicing ISS Airlock procedures before their missions, and these training sessions occur fairly regularly
    - Interlock installation had to be worked on a not-to-interfere basis with these trainings as well as implemented under restrictive COVID protocols

Vacuum System Upgrades

- **During preliminary vacuum system functionals that occurred soon after 20 FT vacuum system was reactivated, it was discovered that existing Beach-Russ RP 100 vacuum pumps would overheat while maintaining the required 8.2 psia (56.54 kPa) habitat environment pressure**
  - Required replacement of original pumps with Busch vacuum pumps
    - Capable of maintaining higher chamber pressures without overheating
  - Vacuum piping servicing Manlock was reconfigured to tie into new pumps
  - Tied into new facility control system for remote control
  - Interlock added to ensure main chamber remains at equal or lower pressure than Manlock
  - Note that these pumps are for depressurization only; chamber repressurization is achieved through use of throttling valve

New 20 FT Busch Vacuum Pumps

Oxygen System Installation

- **As 20 FT had no installed oxygen system prior to selection for the Exploration Atmosphere study, a new chamber oxygen distribution system was purpose built for the study from the ground up**
  - Designed to supply 85% oxygen for test subject mask breathing during simulated EVAs and 100% Aviators Breathing Oxygen (ABO) for mask breathing and chamber oxygen concentration control
  - Originally designed to feed off of overall building supply, but due to redesign of building supply system, had to be modified to feed off of independent tube trailer in order to continue to meet test requirements
  - 10 total stations for both 85% oxygen and ABO installed, 5 stations for each installed opposite each other on 20 FT 1st floor
  - 4 ABO stations installed in Manlock
  - Due to the requirements imposed by the simulated EVAs to be conducted during studies, the Airborne Systems parachutist SOLR® oxygen masks with mask mounted demand regulators were chosen as the oxygen mask to be used in the chamber
  - Airborne Systems SOLR® 3000 bailout bottles were chosen to be worn on test subjects as emergency oxygen supply

20 FT Oxygen Panel

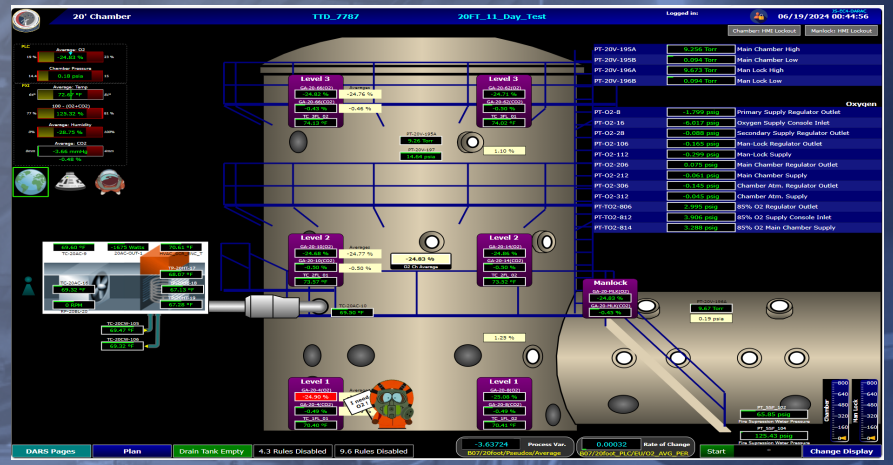
Chamber Control System Installation

- **Per Exploration Atmosphere study requirements, a chamber control system was designed to provide control and indications for all 20 FT facility systems through interfaces in 20 FT Control Room**
  - Provides central control of critical 20 FT systems including vacuum/repress, chamber atmospheric oxygen concentration, HVAC and positive pressure blowers
  - Designed so that chamber and manlock pressures and oxygen concentrations can be both manually controlled or programmed to specific set points by operator and automatically controlled to those setpoints
  - Designed to comply with NASA Software Engineering Requirements Document NPR 7150.2
  - PID control loops were developed to operate existing coarse control valves in precise manner to hold pressures to defined pressure control limits

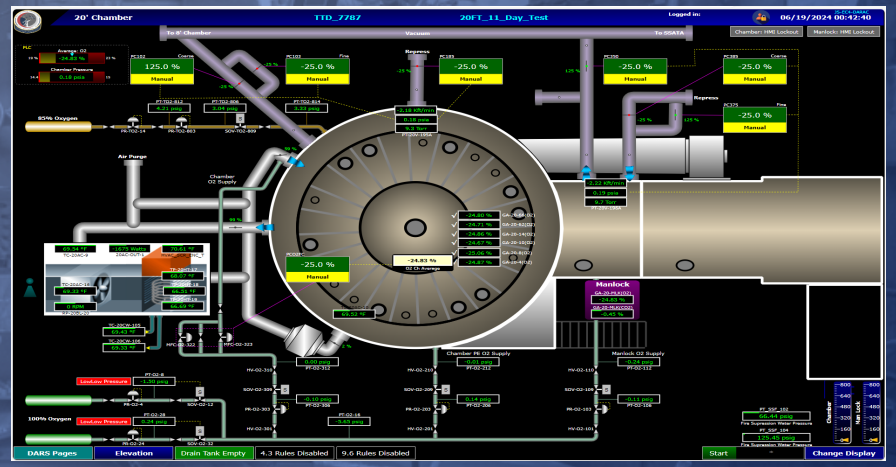
20 FT Control Room

Data/Instrumentation System Upgrades

- **Instrumentation and data collection were implemented in accordance with Exploration Atmosphere Requirements**
  - 7 total Oxygraf® O_2/CO_2 analyzers used for O_2/CO_2 monitoring
  - 7 MKS® baratrons used for vacuum monitoring
  - 2 Vaisala dewpoint analyzers used for humidity calculation
  - 6 thermocouples, 2 on each level used for temperature monitoring
  - 13 Honeywell ® pressure transducers used for system pressure monitoring
  - Data displayed constantly on facility data system and recorded
    - During facility acceptance testing, heavy data monitoring load for this chamber resulted in slow performance and lock up of data trend graphs, necessitating upgrading of data system servers



20 FT Main Data Screen Plan View



20 FT Main Data Screen Elevation View

Lighting and Power System Upgrades

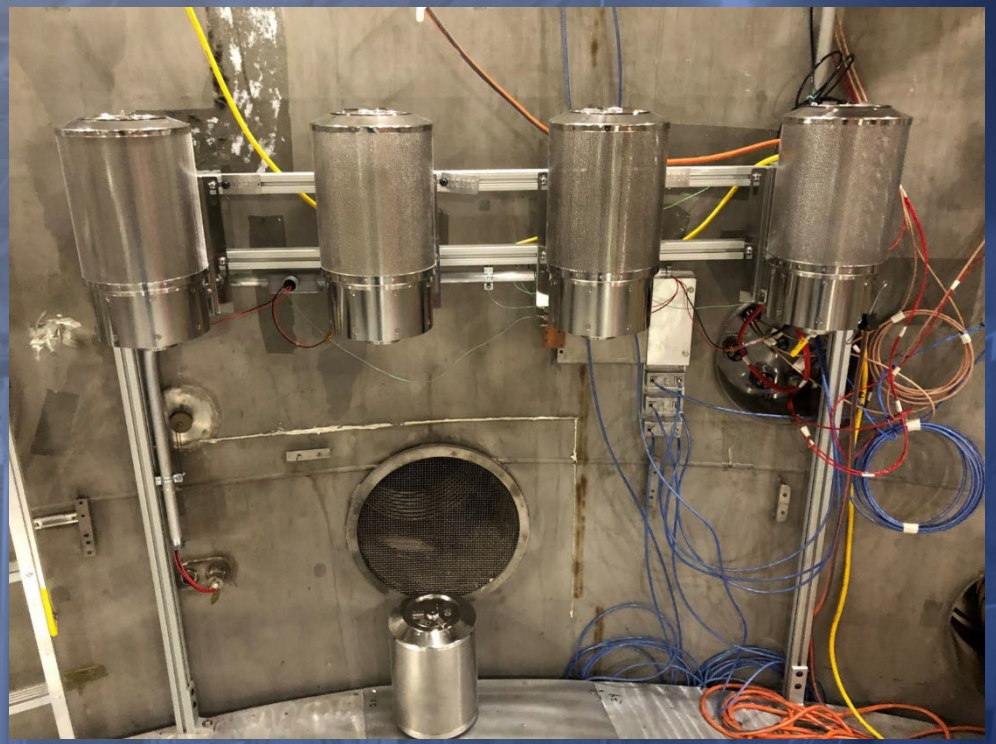
- **Lighting system was required to maintain correlated color temperature between 2700 and 6500K and have ability to be adjusted through dimmer switches located outside chamber**
  - Nemalux® Industrial Lighting for hazardous locations (NFPA 70 Class I Division 2 lighting) selected to satisfy this requirement and installed throughout chamber
  - Lighting on/off dimmer switches installed on panel outside 20 FT chamber and are adjusted to specified daytime and nighttime levels during test
  - Fiber optic lighting installed throughout chamber for emergency lighting
    - Satisfied requirement for emergency lighting power to come from outside chamber
- **Power Distribution System built to supply power to all test-requester provided equipment while maintaining adherence to NFPA 99**
  - All receptacles inside chamber are hospital-grade GFI receptacles with lockable, waterproof metal covers
    - Locked during testing to prevent unplugging of hardware/minimize risk of arcing

Comm and Video System Upgrades

- **Comprehensive communications system installed throughout chamber to satisfy Exploration Atmosphere study requirements**
  - 1st Floor: 10 personal comm stations each capable of private comms with Test Directors and Medical personnel plus 1 PA speaker (replaced with squawk box after first EA study)
  - Manlock: 4 personal comm stations each capable of private comms with Test Directors and Medical Personnel
  - 2nd Floor and 3rd Floor: 1 comm headset station each capable of private comms with Test Directors and Medical personnel plus 1 PA speaker (replaced with squawk box after first EA study)
- **Analog cameras for real-time (low latency) monitoring were installed on all 3 levels of the 20 FT Chamber to adequately monitor activities**
  - HD cameras installed at chamber viewing portals outside chamber for emergency viewing after power kill event
  - Digital and analog audio and video recording system installed to capture chamber operations

Air Revitalization System Installation

- **Air Revitalization System installed in chamber to remove CO_2 and trace contaminants**
  - COTS scrubber units from IHC Hytech® selected to satisfy CO_2 and trace contaminant removal requirements
    - CO_2 requirement: 1 hr average not to exceed 3.0 mmHg during non-EVA operations
    - Scrubber units consist of base with fan with refillable canisters installed on base
  - 3 units utilizing canisters filled with soda lime adsorbent installed on 1st Floor for CO_2 scrubbing
  - 1 unit utilizing canister filled with proprietary blend of carbon molecular sieve and catalyst for trace contaminant installed in line with 3 CO_2 scrubbing units
  - After 1st Exploration Atmosphere study, 2 additional CO_2 scrubbing units were installed, one on 2nd Floor and one on 3rd Floor, to increase CO_2 scrubbing capacity



20 FT Air Revitalization System, 1st Floor

Waste and Hygiene System Installation

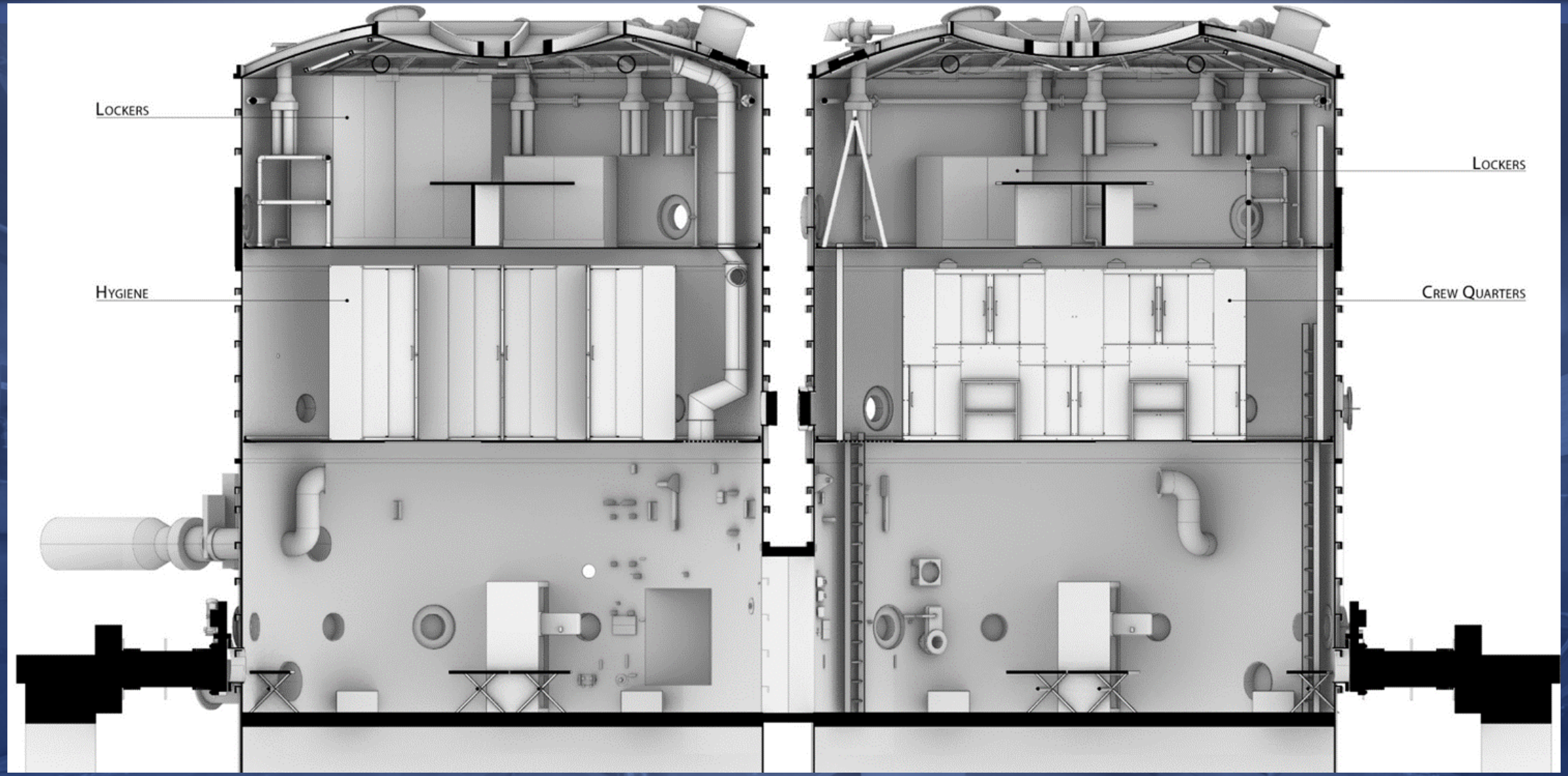
- **Hand wipes approved for enriched oxygen environment for personal hygiene and Laveo® dry flush toilet system typically used for camping and recreational vehicle purposes chosen for human waste management**
  - Original vision for waste and hygiene was to install full vacuum-compatible plumbing system, but was found to be extremely cost prohibitive
  - Laveo® system uses special mylar bag mechanically twisted by toilet to isolate waste each time system “flushed”
    - Completely self contained
    - 1 unit installed on 1st Floor powered by battery for use during simulated EVAs
    - 2 units installed on 2nd Floor powered by facility power

20 FT 2nd Floor Laveo® Dry Flush Toilet

Habitation System Installation

- **JSC Habitability and Human Factors Branch (HHFB) hired to design and build 20 FT habitation system due to extensive experience with designing space habitats and crew systems**
  - General requirements were to design and build 8 crew quarters each with individual lighting, ventilation and storage plus waste and hygiene areas on 20 FT Chamber 2nd Floor and general meeting/galley area on 20 FT Chamber 3rd Floor
  - HHFB solicited extensive inputs from both H-3PO Laboratory personnel, CTSD personnel, and fire/rescue personnel while designing habitation areas
  - Initially developed 20 preliminary habitat designs, then internally down selected to several top designs
  - Top designs presented to H-3PO and CTSD personnel for final design selection
  - Virtual models of chosen design developed and shared with H-3PO and CTSD personnel for further refinement of design
  - Sample Crew Quarters built in HHFB facility to confirm loading requirements
  - Completed construction of habitat areas after other basic 20 FT Chamber system builds were completed

Habitation System Installation



20 FT Chamber Overall Inside Layout

Habitation System Installation

20 FT 1st Floor

20 FT 2nd Floor

Habitation System Installation

20 FT Crew Quarters Interior

20 FT 3rd Floor

Integrated Chamber URR and Acceptance Testing

- **Integrated User Readiness Review (URR) Board commissioned by Director of JSC Engineering Directorate to evaluate 20 FT Chamber readiness to support crewed testing capabilities before proposed Exploration Atmosphere Studies could take place**
  - Individual URRs and Acceptance Tests were completed on each upgraded/installed system prior to Integrated Chamber URR
  - Integrated URR took place in June 2021 and thoroughly reviewed each individual system URR to ensure integrated chamber system met all required testing capabilities to support proposed Exploration Atmosphere studies
  - Board generated 12 action items to be completed prior to Integrated Acceptance Testing and overall URR Board closeout
  - Integrated Acceptance Testing was completed over course of 4 weeks in late September 2021-mid October 2021
    - First time chamber was run in test environment with all new and upgraded systems online
  - A final URR closeout meeting was convened on November 1st 2021 to verify all URR Action Items were satisfactorily completed
  - Chamber was approved for crewed Exploration Atmosphere tests at conclusion of URR closeout meeting

Crewed and Uncrewed Operations Validation Testing

- **Immediately following URR Closeout in November 2021, uncrewed Operations Validation Testing at sea-level and vacuum as well as crewed testing at sea-level to validate chamber operations with test requester hardware as well as procedures Test Subjects during Exploration Atmosphere Studies would follow**
  - Uncrewed vacuum operations followed depress/repress rates set forth in Exploration Atmosphere test requirements and verified operation of test requester hardware at vacuum and 34% oxygen atmosphere conditions
  - Acoustic measurements were taken to ensure normal chamber operations exceeded safe sound levels for Test Subjects
  - Sea-level crewed Operations Validation Testing served as dress rehearsal for test procedures to be followed during first 11 day Exploration Atmosphere Study
    - Full crew complement of 6 Test Subjects and 2 Doppler Technicians simulated first several days of 11 day study
    - Flushed out minor issues with procedures and test equipment
  - Out of initial Operations Validation Testing, H-3PO and CTSD personnel realized that due to complexity of Exploration Atmosphere Study, a “ramp up” to a full 11 day study was warranted
    - Began with 1 Day crewed Operations Validation Test at vacuum in February 2022
      - First time since mid-1970s that crewed vacuum testing had occurred in 20 FT Chamber
    - Provided opportunity to actually operate equipment inside chamber at vacuum
    - Successful completion paved way for longer crewed tests during months that followed

First 11 Day Exploration Atmosphere Study

- **First 11 Day Exploration Atmosphere Study was completed June 6th – June 17th 2022 after a ramp up 3 – Day test in early May 2022**
  - Original ramp up plan called for a 3-5 day test followed by a 5-7 day test before the full 11 day study
  - 3 day test in early May executed the planned activities for the first 3 days of the 11 day study (Initial pumpdown to habitat atmosphere/48 hour equilibration period/6 hour simulated EVA)
  - 3 day test went so well that combined test team determined intermediate 5-7 day test not necessary
  - Full 11 Day study in June planned with caveat that if issues arose preventing full completion, test would be terminated early and issues addressed before another attempt was made several months later
  - Despite new minor procedure and equipment issues encountered, full 11 day study was completed and vital data obtained towards validating 8.2 psia (56.54 kPa) and 34% oxygen habitat atmosphere
  - Proved 20 FT Chamber capability as habitat atmosphere study testbed

20 FT EA Study Crewed EVA Simulation – 1st Floor

Subsequent 20 FT Studies and Future Work

- **Several crewed 20 FT Chamber habitat environment studies have taken place since completion of first 11 day Exploration Atmosphere Study**
  - Commercial partner study in December 2022 to evaluate DCS risk for potential participants in proposed future commercial EVA
  - 2nd 3 day precursor test in May 2023 and 2nd full 11 Day Exploration Atmosphere Study June 12-23 2023 using 8.2 psia (56.54 kPA) and 34% oxygen concentration habitat atmosphere
    - Completed data collection to fully validate 8.2 psia (56.54 kPA)/34% Oxygen concentration habitat atmosphere
    - Implemented chamber improvements including expanded oxygen injection capability to chamber and manlock as well as expanded CO_2 scrubbing capability
  - 3rd 11 day Exploration Atmosphere Study November 6-27 2023
    - Began validation study for 9.6 psia (66.19 kPa)/28.5% exploration habitat atmosphere
    - Conducted without precursor 3 day test due to test team comfort with chamber operations and recency of previous 11 day test
  - 4th Exploration Atmosphere Study planned for September 2024
  - 5th Exploration Atmosphere Study planned for February 2025
  - CO_2 Sensitivity Study planned for July 2025
  - 6th Exploration Atmosphere Study planned for September 2025

Conclusion

- **Simulating Space (and Space Habitats) is hard!**
  - 20 FT Chamber was evolved into a world class premiere testing and research facility through long and difficult process due to many unique and unyielding requirements imposed by Exploration Atmosphere requirements
  - Despite challenges encountered and overcome, 20 FT Chamber systems have outperformed original design goals during past 2 years of testing
  - Chamber has established itself as a one-of-a-kind testing facility solicited by government and commercial partners to conduct studies that will help further planetary exploration

Creating the Test Environment for Exploration Habitats

QUESTIONS?