

ECLSS Trace Contaminant Control Testing

Daniela Barajas Ivey¹, Andrew Irby², Phoebe Henson³, Grady Hofstetter⁴, and Enrique Portillo⁵
Vast, Long Beach, California 90806, USA

Jennifer G. Williams⁶, Stanton Woodard⁷, Trent Tran⁸, Adrian L. Johnson⁹, Robert L. Newton¹⁰
NASA Marshall Space Flight Center, Huntsville, Alabama 35812, USA

and

Jay L. Perry¹¹
Life Support Systems Consultant, Madison, Alabama 35758, USA

Vast is focused on designing and launching next-generation commercial space stations in Low Earth Orbit (LEO) with induced artificial gravity. A key aspect of any long-duration space station is maintaining a safe, healthy cabin environment. Among the functions toward this end is the trace contaminant control (TCC) system, which ensures that levels of gaseous compounds emitted by human metabolism, hardware offgassing, and vehicle systems operations remain within safe limits. This paper details the testing of a commercial TCC system that was executed using in-house Vast capabilities in partnership with both commercial vendors and the NASA Marshall Space Flight Center's (MSFC) Environmental Control and Life Support Systems Development Branch. Subscale chemical challenge performance testing was completed onsite at Vast and system-level multi-component challenge testing was completed at MSFC. Results demonstrate that the Vast TCC system is able to maintain a safe and healthy atmosphere for the Haven-1 mission for the designed loads.

Nomenclature

<i>ARS</i>	=	Air Revitalization System
<i>ATCO</i>	=	Ambient Temperature Catalytic Oxidizer
<i>CLD</i>	=	Commercial Low Earth Orbit Destinations
<i>COTS</i>	=	Commercial off-the-shelf
<i>ECLSS</i>	=	Environmental Control and Life Support System
<i>GCMS</i>	=	Gas Chromatography Mass Spectrometry
<i>GSE</i>	=	Ground Support Equipment
<i>HEPA</i>	=	High Efficiency Particulate Air
<i>ISS</i>	=	International Space Station
<i>LEO</i>	=	Low Earth Orbit

¹ Life Support Systems Engineer, Station Engineering, 2851 Orange Ave, Long Beach, CA 90806.

² Principal Life Support Systems Engineer, Station Engineering, 2851 Orange Ave, Long Beach, CA 90806.

³ Principal Life Support Systems Engineer, Station Engineering, 2851 Orange Ave, Long Beach, CA 90806.

⁴ Test Engineer, ECLSS, Station Engineering, 2851 Orange Ave, Long Beach, CA 90806.

⁵ Director, ECLSS, Station Engineering, 2851 Orange Ave, Long Beach, CA 90806.

⁶ AST Technical Management/ECLSS Chemist, NASA, Environmental Control and Life Support Systems Branch, NASA MSFC, ES62.

⁷ ECLSS Chemist, GeoControl Systems, Environmental Control and Life Support Systems Branch, NASA MSFC, ES62

⁸ ECLSS Test Engineer, Environmental Control and Life Support Systems Branch, NASA MSFC, ES62

⁹ Air Chemist, Amentum, Environmental Control and Life Support Systems Branch, NASA MSFC, ES62

¹⁰ ECLSS Architecture Team Lead, Environmental Control and Life Support Systems Branch, NASA MSFC, ES62

¹¹ Life Support Systems Technical Consultant, 125 Southwood Drive, Madison, AL 35758.

<i>LOD</i>	=	Limit of Detection
<i>MFC</i>	=	Mass Flow Controller
<i>Micro-GC</i>	=	micro-Gas Chromatography analyzer
<i>MSFC</i>	=	Marshall Space Flight Center
<i>RH</i>	=	Relative Humidity
<i>ppm</i>	=	parts per million
<i>ppb</i>	=	parts per billion
<i>SCFM</i>	=	Standard Cubic Feet per Minute
<i>SIFT-MS</i>	=	Selected Ion Flow Tube Mass Spectrometry
<i>SMAC</i>	=	Spacecraft Maximum Allowable Concentration
<i>TCC</i>	=	Trace Contaminant Control
<i>VOC</i>	=	Volatile Organic Compound

I. Introduction

FOUNDED in 2021, Vast is developing humanity’s next-generation space stations, and pioneering the path to long-term living and thriving in space. Vast’s Haven-1, scheduled to be the world’s first commercial space station, is currently in development toward an expected launch in 2026. Haven-2, built on the heritage of Haven-1, is a proposed successor to the International Space Station (ISS), designed to serve NASA’s Commercial Low Earth Orbit Destinations (CLD) program as a micro-gravity laboratory in space. Vast-developed Environmental Control and Life Support System (ECLSS) consists of the Air Revitalization System (ARS), the Pressure Control System, and the Waste Management System. The trace contaminant control (TCC) system resides within the ARS. Active TCC maintains gaseous chemical compound and fine dust (≤ 10 microns) concentrations in the air to acceptable levels for human health, either by removing them from the air or by converting them into harmless compounds. TCC is essential for extended human habitation in any closed environment, as both human metabolic processes and spacecraft materials of construction continuously emit gaseous chemical compounds into the cabin environment regardless of efforts to limit their emissions rates via passive means such as materials selection and control. Some gaseous contaminants that are actively tracked in space¹ may be detectable by composite odor—such as toluene and xylenes which are among the compounds responsible for the composite “new car smell” odor. Humans metabolically produce gaseous contaminants as well of which some of the most recognizable via odor include hydrogen sulfide and ammonia. While nearly all gaseous trace species present in a crewed spacecraft cabin are typically well below their individual odor threshold concentrations, they may interact to form a composite odor that may be characteristic of the habitat.

Vast is concerned with gaseous trace chemical contaminant accumulation that may become hazardous to human health as well as fine dust that can, depending on its size, cause respiratory damage and interfere with sensitive electronics in space. Unlike CO₂ and suspended particulate matter which are harmful to human health at higher concentrations in the air, these contaminants are found in trace quantities in the air that may be harmful to humans at parts per billion (ppb) to tens of parts per million (ppm) concentrations. Exposure to certain compounds individually or as a complex mixture can cause eye, skin, and/or respiratory tract irritation, headaches, seizures, loss of consciousness, or death depending on the concentration and exposure duration. To mitigate these deleterious health risks to the crew, an active TCC system employs a combination of unit operations employing chemisorption, physisorption, and catalytic scrubbing to remove targeted chemical contaminant species from the cabin environment.

The design of an active TCC system and the mode in which it is tested is driven by two primary mission architectural characteristics—mission duration and crew size. Trace contaminant control consideration is needed for crewed missions on the order of days. Table 1 compares TCC system requirements for short-duration crew transport vehicles and continuously crewed stations. Haven-1 falls between these extremes, designed for up to 20 days of one continuous mission, and rated to at least 40 days total crew time on station with up to one year between missions. The TCC system components required and their design depend on the contaminants to be controlled, their emission rates, and their respective Spacecraft Maximum Allowable Concentrations (SMAC)². The Haven-1 TCC system includes the following:

- 1) Pleated media scrubbers to manage volatile organic compounds (VOC), ammonia, and aldehydes.
- 2) Packed media bed scrubbers to manage low molecular weight VOCs.
- 3) Ambient temperature catalytic oxidizer to manage carbon monoxide.

Based on the Haven-1 habitat’s total lifetime, active control of hydrogen and methane are not needed, though future missions with longer durations will require high temperature catalytic oxidation to prevent their hazardous buildup to lower explosive limits.

Table 1. TCC system components required for various mission durations.

Mission	Mission Duration	SMAC	System Components
Dragon	5 days crewed 4 crewmembers	7-day	Ammonia ion exchange filter Activated carbon (non-regenerative) HEPA filter ³
Haven-1	≤1 year uncrewed ≤20 days continuously crewed ≤40 days total crewed 4 crewmembers	Ingress: 24-hour Crewed: 30-day	Ammonia ion exchange filter Activated carbon (non-regenerative) Impregnated activated carbon (non-regenerative) Ambient temperature catalytic oxidizer
ISS ¹	>180 days crewed up to 13 crewmembers	180-day	Impregnated activated carbon (non-regenerative) Activated carbon (regenerative and non-regenerative) High temperature catalytic oxidizer

When evaluating the performance of a TCC system, both subscale testing and system level testing are utilized as necessary. Subscale testing is useful to accomplish the following:

- 1) Providing a proof of concept for each scrubber with single component contaminant fluid flow.
- 2) Proving scaled-down performance to confirm full-scale sizing.
- 3) Understanding airflow and mass contact given the geometries of a system.
- 4) Determining potential poisons to each scrubber.
- 5) Developing any data sets needed for isotherms of in-house developed empirical formulas to fully characterize a scrubbing system.

Assembly level testing is informed by subscale testing and is typically performed to understand the following:

- 1) The system performance in a multi-component chemical challenge environment that mimics a crewed spacecraft or habitat cabin. The testing allows for noting interactions between chemical challenge compounds and the TCC system as well as providing insight regarding interactions challenge compounds.
- 2) The interaction of a TCC system with cabin environmental characteristics, notably humidity, temperature, pressure, and cabin ventilation and process airflow. These characteristics may be affected by the TCC system and they may also affect the TCC system performance.

Vast has performed both subscale and assembly level chemical challenge testing on the TCC system for Haven-1 to validate the system's efficacy in maintaining a safe and healthy atmosphere for Haven-1 astronauts visiting the station. These methods have been successfully utilized across many crewed space exploration programs ranging from Skylab to Spacelab, to the International Space Station (ISS) as well as for ECLS technology development for deep space exploration missions.⁴⁻¹¹ These programs pioneered testing techniques pertaining to external mixing volumes and test article integration into chambers to emulate the cabin environment as well as automating gas sampling and analytical methods to provide near real-time test data to better understand cabin concentration dynamics, fate of trace species within a crewed spacecraft cabin, and the interaction of the TCC system with the cabin environment. The testing approach utilized by Vast builds on the experience gained from these flight programs and technology development initiatives, particularly the testing methodology utilized for developing and verifying the ISS Trace Contaminant Control Subassembly (TCCS) and understanding the fate of gaseous contaminants in a crewed cabin environment.^{7,8,9} Vast has employed NASA's unique test chamber facilities and tailored these heritage methodologies to improve them by incorporating contemporary near real-time chemical analysis techniques.

II. Trace Contaminant Control Testing Approach

Vast's progressive system level testing approach generally involves evaluating subassemblies and subsystems individually for coarse development and tuning followed by integrating them into a ground-based module that is representative of the Haven-1 station's pressurized volume for assembly level verification.

A. Subscale Testing

The TCC system subscale testing addressed the process flow, airflow, and media performance technical areas that are key to the detailed design at full scale.

1. Subscale Airflow Testing

The pleated filters within the Haven-1 TCC system were tested for adequate airflow uniformity at target operating conditions using a functionally and geometrically representative ducting system (Fig. 1). This testing is detailed in Ref. 12, with results relevant to the TCC system chemical testing outlined in Section III of this paper.

2. Subscale Chemical Testing

The TCC system's packed beds developed in-house by Vast address low molecular weight VOCs and carbon monoxide management. The packed bed testbed was developed with the capability to generate performance data via breakthrough curves and isotherms, to verify effects of potential poisons on the system, and to test the system within bounding environmental conditions for flight. The resulting testbed, shown in Fig. 2, includes the following capabilities:

- 1) Fluid flow control
- 2) Humidity control
- 3) Temperature control
- 4) Dual-component fluid injection
- 5) Sensing upstream and downstream of packed beds for contaminant challenge, humidity, temperature, and pressure

B. Assembly Level Testing

Assembly level testing was accomplished in partnership with NASA at Marshall Space Flight Center (MSFC) in Huntsville, Alabama. The collaboration between Vast and NASA MSFC for this testing allowed for knowledge transfer between commercial space exploration mission development concerns and NASA, the use of heritage test chambers used for ISS TCCS validation and exploration mission concept evaluation, and the use of advanced gas measurement devices. These features of the collaboration offer economies to the flight program developmental effort.

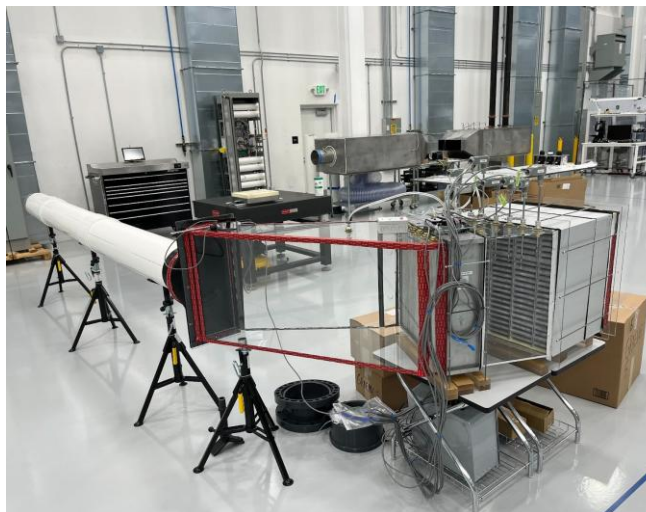


Figure 1. Original Pleated Filter Testbed Configuration.



Figure 2. Subscale Chemical Challenge Testbed.



Figure 3. Pleated Filter Testbed Configuration at MSFC with the TCC Tray attached. *Showing basic test article installation.*



Figure 4. Pleated Filter Testbed Configuration at MSFC. *Demonstrating simulated flight ingress operations.*

1. Overview

The TCC system test article consisted of both ground support equipment (GSE) and Tier 2 qualification hardware. The goal of the assembly level testing is to chemically qualify the TCC system in a representative environment, with the added benefit of gaining insight into the effects of the TCC system on the environment.

The TCC system test article, shown in Figs. 3 and 4, was mounted in the NASA Environmental-Chamber (E-Chamber), a 90 m³ enclosure with temperature and humidity control, with built-in passthroughs for contaminant injection and contaminant sampling. Contaminants were injected from the bottom of the chamber, with a passthrough over which a mixing fan blew to encourage volatilization of liquids and mixing/dispersion of gases. Contaminant sampling was set up at the inlet of the filtration system and at the outlet, with the ability to switch between the two on the instrumentation side for measurement. Sample ports are connected to a Syft Tracer i3 Selected Ion Flow Tube Mass Spectrometry (SIFT-MS) gas analyzer for primary concentration measurements and an Inficon micro-Gas Chromatography analyzer (micro-GC) for carbon monoxide concentration measurement.

The SIFT-MS was calibrated using a Kin-Tek gas standards generator with permeation tubes for all compounds except ammonia, which due to its complex behavior in the chamber environment was calibrated via injections into the chamber. Due to the effect of humidity on SIFT-MS readings a Sable Systems International DG-4 Dew Point Generator was added to the calibration setup so the relative humidity (RH) of the calibration standards matched the test RH of 50% at the test temperature. A five-point calibration was used, and calibration checks were performed

throughout testing to check for drift against acceptable total percent error. If error increased past acceptable limits, testing was paused and a five-point calibration was performed.

The Inficon micro-GC was calibrated separately from the chamber and Kin-Tek using a range of eight CO concentrations between 1 ppm and 100 ppm, concentrating more tightly on the lower end of the spectrum. Pure CO in a K-bottle was diluted with nitrogen using a mass flow controller (MFC). Ten replicates were performed for each concentration level, with an error ranging from 0.2% to 7% apart from the 5-ppm concentration level which yielded 31% error, the maximum error and correspondingly the percent error assigned to the instrument.

Acceptable maximum errors were calculated based on design margin and expected mission T-value calculations prior to calibrations. These were then compared to the instrument and total error for each compound prior to proceeding with testing. Final values are listed in Table 2. Calibration levels were determined based on theoretically estimated filter efficiencies and corresponding expected concentrations.

Table 2. Overview of percent error for each compound for the associated instrument.

Compound	Test Phase	Expected Range	Desired Maximum Error (%)	Instrument Employed	Instrument LOD (ppb)	Average Instrument Error (%)	Total Error (%)
Ammonia	CREWED	120–200 ppb	±30	SIFT-MS	100	20	20
n-butanol	CREWED	2.5–13 ppb	±20	SIFT-MS	4.8	9	11
Acetaldehyde	CREWED	2.5–13 ppb	±20	SIFT-MS	50	8	10
Dichloromethane	CREWED	0–729 ppb	±20	SIFT-MS	41.6	7	10
Ethanol	CREWED	5–14 ppb	±20	SIFT-MS	33.2	3	7
Ethanol	CREWED (first 24 hours)	23,000–26,000 ppb	±10	SIFT-MS	33.2	3	7
Carbon Monoxide	CREWED	0–12,000 ppm	±40	Micro-GC	1,000	31	31

Testing safety was established to allow for a planned human ingress into the chamber in between simulated uncrewed and extended crewed mission periods. This allowed for similar maintenance, repair, and replacement operations that mission crewmembers are expected to perform upon ingress on orbit. These operations are summarized in Table 3 and illustrated by Fig. 4, which is a photo taken during a planned ingress. Checks on the system were performed along with a planned filter installation. Data was acquired through both NASA and Vast assets on site and was monitored jointly by a NASA-Vast team, along with Syft who supported on-site and remotely from calibration through data analysis and processing.

Table 3. Overview of assembly level test cases representing different mission phases.

Test Case	Mission Phase	Test Duration	Description
1	Uncrewed Accelerated	3 days	Accelerated portion of testing to build up representative mass loading on the system of a 1-year equivalent uncrewed duration
2	Uncrewed	3 days	Representative uncrewed loading for 3 testing days, equivalent to 3 space days
3	Crewed	24 hours	Representative crewed loading for 24 hours representing crew presence immediately post-ingress, during which operations such as filter replacement are performed by crew that change the state of the contaminant scrubbing onboard Haven-1, while simultaneously the contaminant loading is changing due to human presence
Ingress			Representative of the actual filter replacement on-station, with a bounding scenario where filters are replaced at the end of the 24-hour allotted nominal time. In testing, an engineer ingressed and performed filter replacement.
4	Crewed	20 days	Representative crewed loading for 20 days post-crew ingress operations with filters in long-term crewed configuration

2. Multicomponent Chemical Challenge Testing

Multicomponent chemical challenge testing involved the simultaneous injection, detection, and quantification of the chemicals within the air. This multicomponent testing was performed using the SIFT-MS at NASA MSFC. The gases that are of interest to Vast and that were measured during the test are listed in Table 4 along with their generation rate ranges and SMAC values, with ratios of compounds changing depending on the mission state. Load rates were determined based on analysis of existing NASA literature^{1,2,13,14,15,16} and the Haven-1 design.

Components were introduced via both gaseous injection from gas cylinders and via liquid injection from liquid holding tanks. Pressurized ammonia and carbon monoxide injection into the chamber were regulated via a mass flow controller while mixtures of the remaining compounds corresponding to each mission phase (uncrewed and crewed) component ratio, were injected using a continuous pump system shown in Fig. 5.



Figure 5. Injection pump system for liquid contaminants.

Table 4. Multicomponent mixture compounds, their SMAC, target injection rates range.

Compound	Surrogate for the Following	30-day SMAC ² (ppm)	Target Test Injection Rate Range* (mg/day)
Acetaldehyde	Formaldehyde, acetaldehyde	2	0.7–9
Ammonia	Ammonia	3	0.5–1284
N-Butanol	N-butanol, benzene, methylbenzene, dimethylbenzene, trimethylsilanol, hexamethylcyclotrioxane	25	64–142
Dichloromethane	DCM, furan, methanol	7	18–23
Ethanol	Ethanol, 2-propanone (acetone)	1,000	52–222
Carbon monoxide	Carbon monoxide	15	12–196

*Varied depending on the mission phase simulated by each test phase.

3. Environmental Effect Evaluations

A byproduct of multicomponent chemical testing in a representative environment is the ability to determine how the system under test affects the habitable environment. This is most significant for humidity, temperature, pressure, and airflow. Airflow in the habitat was not a focus in this test and instead investigated in detail in a separate Vast testbed⁴. To remain within planned flight conditions, and to maintain consistency with gas measurement instrument calibration, target RH within the chamber was 50%. Target temperature was 20°C, which was maintained through temperature cycling the enclosure surrounding the E-Chamber, shown in Fig. 6. To maintain target humidity throughout testing, the chamber was humidity cycled due to the water absorption capacity of the TCC media. During this humidity cycling, water isotherms can be generated to correlate against expected humidity operations in preparation for launch and in space.

III. Interpretation of Results

C. Subscale Testing

1. Subscale Airflow Testing

Air flow testing was performed on pleated filters in line with a geometrically flight-representative section of ducting to assess assembly flow path effects on flow field uniformity. To conduct this test, a survey of the airflow velocity field was conducted along planes upstream and downstream of the pleated filter stack at total volumetric flow rates through the filters representative of bounding flight cases – uncrewed airflow of 100 standard cubic feet per minute (SCFM) and crewed airflow of 750 SCFM.

The results of this test indicate that the flow is turbulent based on variation in flow between samples at expected airflow rates and suggest that features associated with the filter pleating dominate the velocity field's nonuniformity as opposed to the turn made by the ducting downstream of the filters. Vast's pleated filter supplier agreed that the measured velocity fields indicated that there was a low risk that the adjacent ducting design would adversely affect filter performance. An example of these data is shown in Fig. 7. Color represents the velocity component normal to the filter face plane, ranging between 0 and 300 feet per minute. The construction of this testbed fed directly into the construction of the test assembly to be sent to NASA MSFC for multicomponent chemical qualification testing wherein the contribution of flight-like ducting effects on flow field were implicitly part of the test.

2. Subscale Chemical Testing

Subscale testing was aimed at the two in-house packed beds developed for Haven-1:

- 1) Ambient temperature catalytic oxidizer (ATCO)
- 2) Low molecular weight VOC activated carbon



Figure 6. Exterior of the E-Chamber.

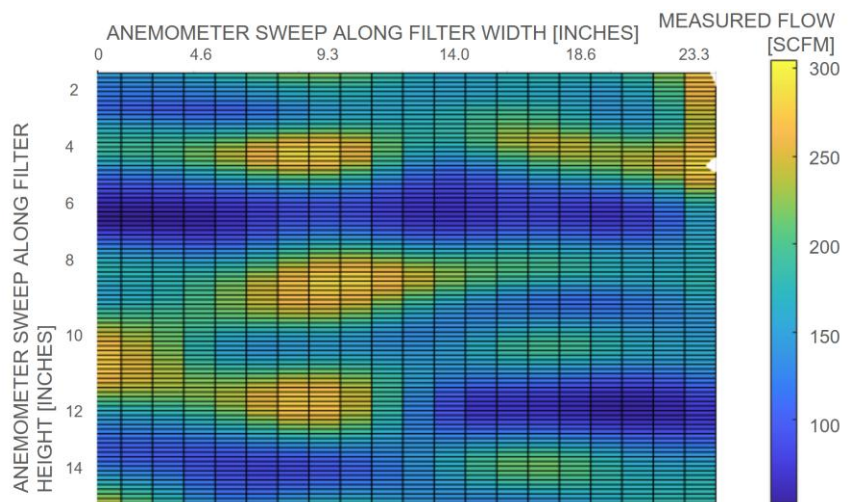


Figure 7. Example of flow distribution results from subscale testing downstream of the pleated filters. Flow in SCFM from 0 (blue) to 300 (yellow).

Testing for both packed beds quantified performance under nominal multicomponent conditions and up to worst-case expected dewpoint (maximum of 12° C dewpoint) temperature ranges, as well as performance under off-nominal environments from vendor specifications including both humidity and refrigerant as potential poisons. The ATCO testing validated the hypothesized 90+% efficiency for conversion of carbon monoxide to carbon dioxide under worst case temperature, humidity, and refrigerant conditions. Performance did not measurably decrease with increased humidity or refrigerant concentrations.

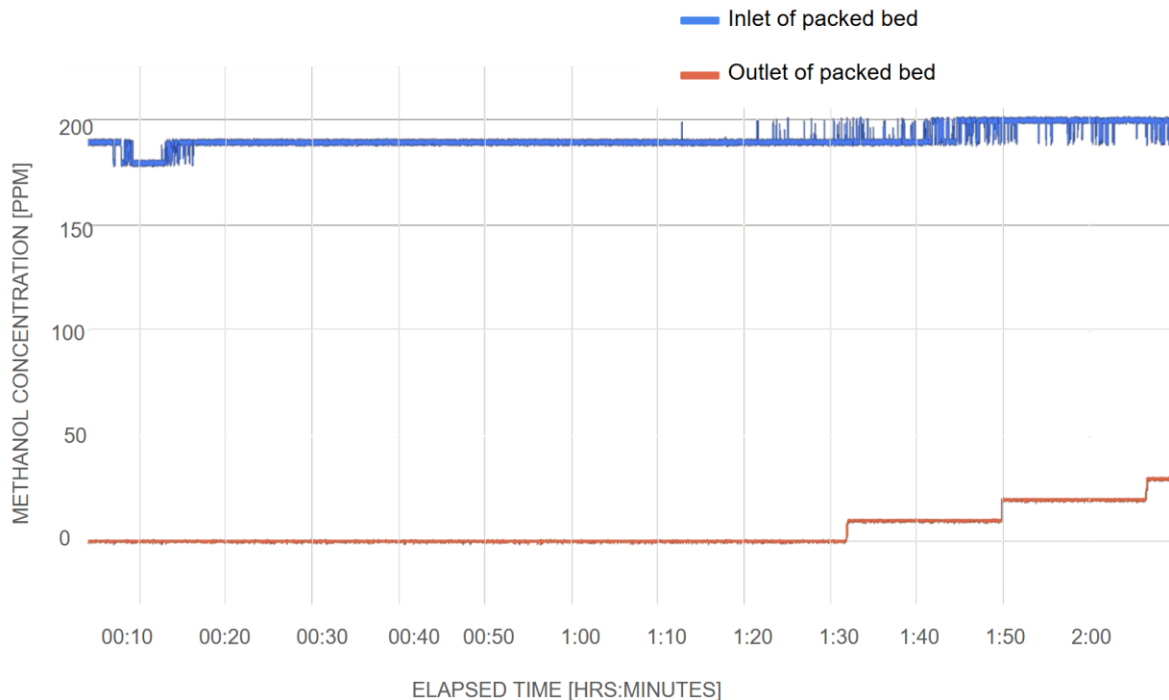


Figure 8. A representative breakthrough curve for packed bed targeting low molecular weight VOCs.
Breakthrough shown for methanol in a subscale packed bed.

The testing of the packed bed that targets low molecular weight VOCs generated a series of breakthrough curves for methanol as a representative compound, characterizing performance in representative environments with similar poisoning considerations as the catalyst. These breakthrough curves feed into an extrapolation of adsorption potential at varying inlet concentrations, which are incorporated into the data analysis for multicomponent assembly level testing. All breakthrough curves contained only one contaminant at the inlet, with the exception of humidity and poisoning additions, along with carrier gases that included air and nitrogen streams. An example breakthrough curve is shown in Fig. 8 where breakthrough was defined as the outlet concentration equating to 10% of the inlet concentration, which in this case was 200 ppm.

D. Multicomponent Chemical Testing

1. Filtration Efficiency and Mass Balance

Filtration efficiency is calculated in two ways. First by taking concentration measurements at the inlet and outlet of the TCC system and calculating the efficiency via Eq. 1.

$$\eta_{\text{filter}}(t) = \frac{(C_{\text{inlet}} - C_{\text{outlet}})}{C_{\text{inlet}}} \times 100 \quad (1)$$

Where C_{outlet} is the outlet concentration measurement, C_{inlet} is the last measurement from the inlet port before switching to the outlet port, and η is the efficiency of the filter.

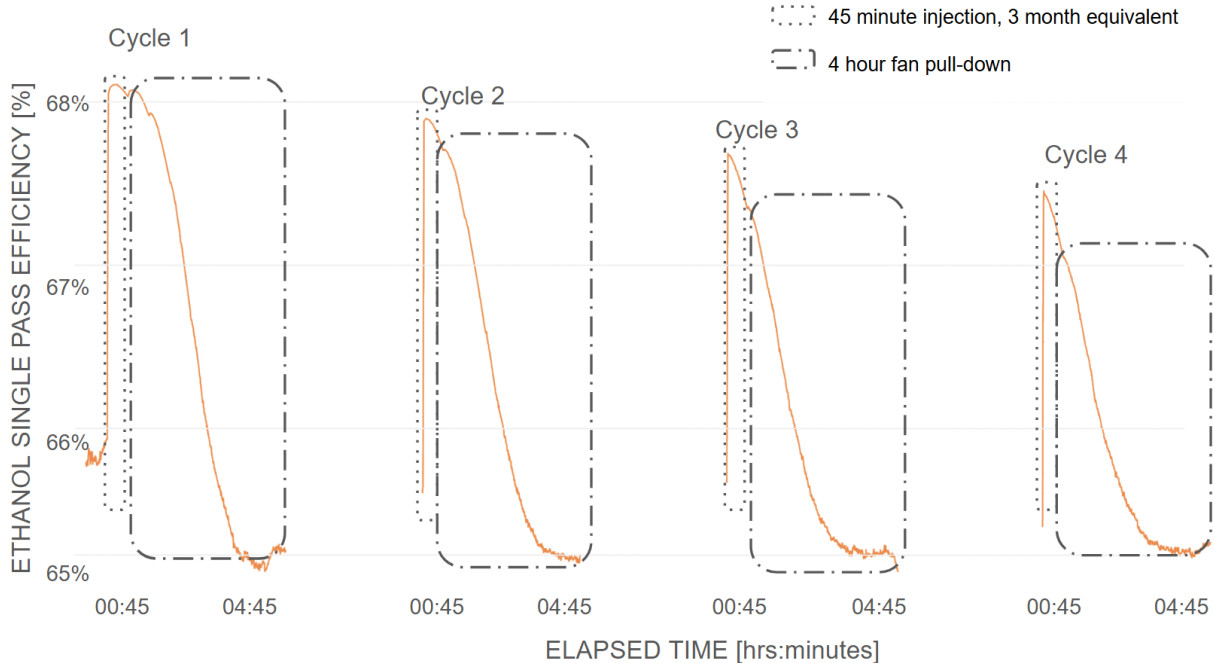


Figure 9. Efficiency for ethanol, based on concentration data pulled from the SIFT-MS using inlet vs outlet concentrations (Eq. 1). A year of uncrewed loads was broken up into four distinct cycles, at the beginning of which contaminants were injected in an accelerated manner for 45 minutes representing approximately 3 months equivalent loads. Fans were then turned on for 4 hours to circulate air through the filtration system and decrease concentrations in the chamber. As concentration in the chamber decreases, filter efficiency decreases, and as filter capacity decreases with each filter, efficiency also decreases.

2. Total T-Value Evaluation

Combined toxic hazard of the full set of pollutants represented in the test was calculated at any given point in the test by using the T-value methodology of Eq. 2 described in JSC-20584 where, T = toxic hazard index or

$$T = \sum C_i / C_{SMAC,i} \quad (2)$$

T-value, C_i = concentration of pollutant i , and $C_{SMAC,i}$ is the Spacecraft Maximum Allowable Concentration (SMAC) of component i per JSC-20584.

A T-value allowable upper limit of 1 was used as the pass/fail criteria for all test phases corresponding to crewed phases of flight. The SMAC of a given pollutant varies based on the expected exposure. T-value for the uncrewed phase was tracked based on the 24-hour SMAC because at the end of this uncrewed period there is a planned crewed ingress that includes filter replacement within the first 24 hours. Given that a mission may be as long as 20 days, the subsequent portion of the crewed test phase uses 30-day SMAC values for evaluating T-value.

As surrogates are used in the chemical qualification testing, T-values are calculated in a way that accounts for compounds that are not physically present within the system but that are tracked in flight (anything not included in Table 4). To do this, the T-value is calculated as if the concentration of a given surrogate instead consists of each of the pollutants that surrogate represents at concentrations that are proportional to the mass that they would be generated at in flight.

Using these assumptions, the total T-value is tracked throughout all phases of testing to validate the efficacy of the system in maintaining a safe habitat for Haven-1 astronauts, represented by a T-value of less than 1. Fig. 10 shows the T-value tracking for non-accelerated testing based on the 24-hour SMAC for the last 3 days of the uncrewed mission phase, and for the 24-hour ingress mission phase. Throughout both test phases, the T-value was maintained below 0.3, roughly one third of the maximum allowable concentration. Fig. 11 shows the T-value based on the 30-day SMAC. This SMAC was used to evaluate the 20-day crewed period, with the 24-hour ingress phase shown with the 30-day SMAC for comparison. The T-value for the crewed period was on average maintained below 0.4, roughly half of the maximum allowable value of 1.

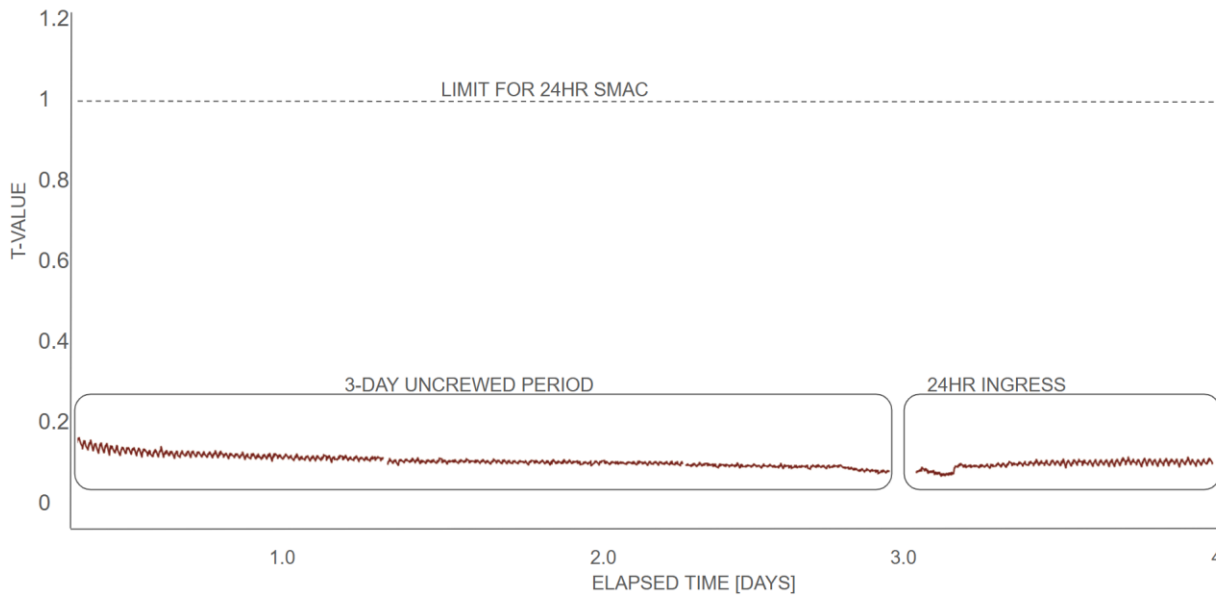


Figure 10. Data from SIFT-MS showing total T-value for uncrewed and ingress test phases. Toxic hazard was maintained at roughly one third of the maximum allowable value of 1.

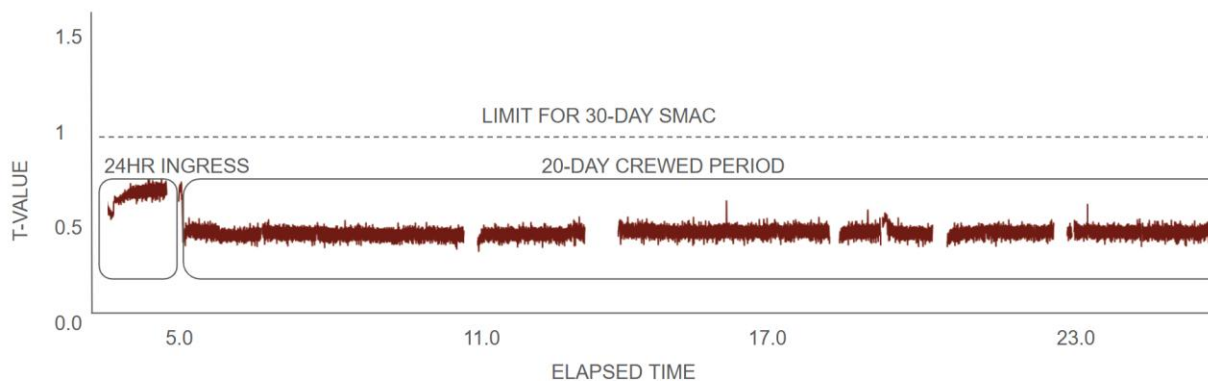


Figure 11. Data from SIFT-MS showing total T-value for the crewed phase which was maintained below half of the maximum allowable T value of 1. An additional filter is installed after the 24-hour ingress which explains the drop in overall T-value.

E. Additional Testing

1. Humidity Testing

Once chemical performance testing was completed, humidity isotherm data was collected in the chamber. Both pleated filters and packed bed filters are expected to add water vapor capacity to the cabin air. This phenomenon required compensation with humidity injection throughout contaminant testing to maintain close to 50% RH within the chamber to adequately measure concentration at the same humidity at which instruments were calibrated. An initial characterization was performed to better understand uncrewed and crewed humidity control modeling, and to inform any needed pre-conditioning of the filters prior to packing for flight. During this testing, filters were weighed and placed in the chamber, then humid air was injected until a new humidity equilibrium was reached.

2. Poisoning Testing

During chemical performance testing, refrigerant was not included as an input due to concerns that it could potentially contaminate the micro-GC utilized to detect carbon monoxide and jeopardize the ability to measure the efficiency of the ambient temperature catalytic oxidizer. The most sensitive portion of the trace contaminant control system is the ambient temperature catalytic oxidizer and the possibility of fouling the catalyst with refrigerant needed

to be explored. In post-chemical performance testing, the last set of testing planned to include refrigerant so that if the micro-GC was contaminated it would not affect any other testing. Two sets of tests were performed. The first injected carbon monoxide to the highest potential value on Haven-1 of 80 ppm given loads estimates and then turned on the ambient temperature catalytic oxidizer system to pull down the concentration. The half-life of the carbon monoxide concentration in the cabin was measured to be 4 hours. The second set of testing started by injecting the maximum nominally expected concentration of refrigerant on Haven-1. The carbon monoxide concentration was then increased and the ambient temperature catalytic oxidizer system was turned on to measure and compare the half-life. Both aligned at 4 hours, signifying that either the catalyst is resistant to poisoning, or that it is adequately protected against poisoning in the designed assembly.

IV. Conclusion

Vast has completed assembly-level chemical qualification testing for the Haven-1 vehicle based on assumed design loads for each subsystem. The filters met performance requirements by maintaining T-values below 1 with corresponding mission phase SMACs for the extent of their expected lifetime. Subscale testing is nearing completion which will provide more precise efficiency data of each individual filter. The integration of Vast's rapid in-house development with NASA's established testing infrastructure has facilitated a comprehensive test campaign that includes multicomponent system characterization.

Future work includes humidity testing soft goods in the integrated ECLSS module system test bed to quantify the humidity isotherms of the soft goods on Haven-1. Additionally, further testing is beginning shortly to characterize the offgassing of all Haven-1 soft goods with Vast's in-house SIFT-MS. Finally, prior to launching Haven-1, a closed-hatch offgassing test per NASA-STD-6001 Test 7 will be performed at NASA's Armstrong Test Facility during environmental testing.

The knowledge and data gained during this testing will inform Haven-1 validation and Haven-2 development, ensuring a safe and habitable environment for future crew.

Acknowledgments

Vast would like to thank NASA MSFC for the ongoing collaboration on assembly level chemical challenge qualification testing, and Tucker Kitchengs and Leslie Silva from Syft for their ongoing support of chemical quantitation during testing.

References

- ¹Perry, J. L., "Elements of Spacecraft Cabin Air Quality Control Design," NASA/TP-1998-207978, 1998.²Ryder, V., McCoy, J., and Hayes, J., "Spacecraft Maximum Allowable Concentrations for Airborne Contaminants," JSC 20584, 2020
- ³Silverman, J., Irby, A., and Agerton, T., "Development of the Crew Dragon ECLSS," *49th International Conference on Environmental Systems*, 2020.
- ⁴Ray, C. D., "Skylab Atmospheric Contamination Control", NASA TM X-64900, November 1974.
- ⁵Ray, C. D., Littles, J. W., Blair, J. L., and Jagow, R. B., "Design and Development of a Trace Contaminant Removal Canister for Spacelab". ASME 79-ENAs-16, *9th Intersociety Conference on Environmental Systems*, San Francisco, CA, 1979.
- ⁶Perry, J. L., "Space Station Freedom Environmental Control and Life Support System (ECLSS) Phase III Simplified Integrated Test Trace Contaminant Control Subsystem Performance", NASA TM 4202, 1990.
- ⁷Curtis, R. E., Perry, J. L., and Abramov, L. H., "Performance Testing of a Russian Mir Space Station Trace Contaminant Control Assembly", SAE 972267, *27th International Conference on Environmental Systems*, Lake Tahoe, NV, 1997.
- ⁸Perry, J. L., Curtis, R. E., Alexandre, K. L., Ruggiero, L. L., and Shtessel, N. "Performance Testing of a Trace Contaminant Control Subassembly for the International Space Station", SAE 981621, *28th International Conference on Environmental Systems*, Danvers, MA, 1998.
- ⁹Tatara J. D., Perry, J. L., and Franks, G. D., "Overview of the International Space Station System Level Trace Contaminant Injection Test", SAE 981665, *28th International Conference on Environmental Systems*, Danvers, MA, 1998.
- ¹⁰Perry, J. L., Abney, M. B., Frederick, K. R., Greenwood, Z. W., Kayatin, M. J., Newton, R. L., Parrish, K. J., Roman, M. C., Takada, K. C., Miller, L. A., Scott, J. P., and Stanley, C. M., "Functional Performance of an Enabling Atmosphere Revitalization Subsystem Architecture for Deep Space Exploration Missions", AIAA 2013-3421, *43rd International Conference on Environmental Systems*, Vail, CO, 2013.
- ¹¹Perry, J. L., Abney, M. B., Frederick, K. R., Greenwood, Z. W., Kayatin, M. J., Knox, J. C., Newton, R. L., Parrish, K. J., Takada, K. C., Miller, L. A., Scott, J. P., and Stanley, C. M., "Evaluation of an Atmosphere Revitalization Subsystem for Deep Space Exploration Missions", ICES-2015-107, *45th International Conference on Environmental Systems*, Bellevue, WA, 2015.
- ¹²Hansen, N., "ECLSS Module Integrated Air Revitalization Testing," *54th International Conference on Environmental Systems*, Prague, 2025.

- ¹³Bayt, Robert L., Lueders, Kathryn L., “ISS Crew Transportation and Services Requirements Document,” CCT-REQ-1130, 2016.
- ¹⁴Francisco, David, “NASA Spaceflight Human-System Standard,” NASA-STD-3001, 2023.
- ¹⁵Ewert, M., “Life Support Baseline Values and Assumptions Document,” NASA-TP-2015-218570, 2022.
- ¹⁶Kayatin, M., Perry, J. L., and Williams, J. G., “Design of an Adsorption Bed for Exploration Trace Contaminant Control,” ICES-2024-403, *53rd International Conference on Environmental Systems*, Louisville, Kentucky, 2024.