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Requirements and Sizing Investigation for Constellation Space Suit Portable Life Support System Trace Contaminant Control

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The Trace Contaminant Control System (TCCS), located within the ventilation loop of the Constellation Spacesuit Portable Life Support System (PLSS), removes hazardous trace contaminants from the spacesuit ventilation flow. This paper summarizes the results of a trade study that evaluated whether trace contaminant control could be achieved without a TCCS by relying on suit leakage, ullage loss from the carbon dioxide and humidity control system, and other factors. Trace contaminant generation rates were revisited to verify that values reflect latest designs for Constellation Spacesuit System pressure garment materials and PLSS hardware. TCCS sizing calculations were also performed, and a literature survey was conducted to review the latest developments in trace contaminant technologies.

Nomenclature

C_c = trace contaminant concentration

C_{ci} = initial trace contaminant concentration

C_{cs} = trace contaminant steady-state concentration

C_{SMAC} = 24-hr spaceflight maximum allowable concentration for ammonia

f = ratio of contaminant mass m_c to oxygen mass m_o

ζ = bed adsorption capacity

m_B = total bed mass

$m_{B,eff}$ = unused bed mass

m_c = total in-suit contaminant mass at the end of an EVA of duration t

m_{cads} = absorbed contaminant mass at the end of an EVA of duration t

$\dot{m}_{cgen}$ = contaminant mass generation rate

m_{ci} = initial trace contaminant mass

$\dot{m}_{CO_2}$ = mass flow rate of oxygen loss through carbon dioxide sensor

$\dot{m}_{Lj}$ = mass flow rate of oxygen exiting the ventilation system due to *j*th loss mechanism

m_o = oxygen mass

$\dot{m}_{PGSo}$ = mass flow rate of pressure garment system (PGS) oxygen leakage

$\dot{m}_{RCAo}$ = mass flow rate of RCA ullage loss

η_c = trace contaminant removal efficiency

ρ_B = GAC density

t = EVA duration

t_{Ro} = minimum residence time requirement

V = free volume in suit

$\dot{V}_o$ = volume flow rate of oxygen through ventilation system

I. Introduction

The Constellation Program (CxP) operational concepts documents[1,2] stipulate that crews must be able to perform suited extravehicular activities (EVAs) on the lunar surface for sorties, cargo unloading operations, extended-stay operations, and continuous-presence operations. Each EVA can last up to 8 hours. The only nominal EVA's using Constellation assets that are currently planned involve lunar surface operations. The second configuration of the Constellation Spacesuit System (CSSS), Configuration 2, is being developed to provide a self-contained, pressurized, portable environment to accommodate the lunar EVA requirements. A crucial component of the Configuration 2 suit system is the Portable Life Support System (PLSS), which provides oxygen (O_2) for breathing and pressurization, removes metabolically produced carbon dioxide (CO_2), water (H_20) and trace contaminants produced by both crew metabolism and equipment off-gassing, and regulates the thermal environment of the crewmember.

A trace contaminant is defined as a gaseous substance introduced into the spacesuit system via metabolic production, material, or hardware off-gassing. Depending on the substance, the trace contaminant can be hazardous to a crew member's health with side effects ranging from headaches to heart damage, as shown in Table 1, based on exposure level and duration. It is thus critical that spacesuit trace contaminant levels be controlled, whether by a Trace Contaminant Control System (TCCS) or by relying on other means to vent contaminants overboard using ventilation subsystem hardware and space suit leakage.

A trade study conducted in 2008[3] investigated the trace contaminant control (TCC) technologies used in NASA spacesuits and vehicles, as well as commercial and academic applications, to identify the best technology options for the PLSS. This 2008 trade study also looked at the feasibility of regeneration of TCC technologies, specifically to determine the viability of vacuum regeneration for on-back, real-time EVAs. Based on the knowledge gained in this study, activated charcoal was chosen as the Constellation PLSS baseline TCCS with further recommendations to impregnate the activated charcoal with zinc chloride for ammonia (NH_3) adsorption, and to include a chemically impregnated charcoal that specifically controls formaldehyde (CH_2O) levels. Furthermore, real-time regeneration of the TCCS during EVA was deemed unfeasible, so a replaceable activated charcoal bed that would support numerous EVAs was recommended. Follow-on work was proposed to identify proper sizing and implementation of the activated charcoal bed into the PLSS package.

Table 1. Summary of expected Constellation spacesuit PLSS ventilation loop trace contaminants, with generation rates,[4] spacecraft maximum allowable concentrations,[5] and adverse effects.[5]

		Generation Rate	24-hr SMAC Limit			
	Formula	*(mg/8-hr EVA)*	*(ppm)**	*(mg/m³)*	**Affected Organ**	**Effect**
Acetaldehyde[†]	CH_3CHO	0.027	6	10	Mucosa	Irritation
Acetone	CH_3COCH_3	0.045	200	500	Central Nervous System	Fatigue
Ammonia	NH_3	83	20	14	Eye	Irritation
n-Butanol	BuOH	0.17	25	80	Eye	Irritation
Carbon Monoxide[‡]	CO	11	100	114	Central Nervous System	Depression
					Cardiovascular	Arrhythmia
Ethyl Alcohol	C_2H_5OH	1.3	5000	10000	Eye	Irritation
					Mucosa	Irritation
					Skin	Flushing
Formaldehyde[†]	CH_2O	0.13	0.5	0.6	Mucosa	Irritation
Furan	C_4H_4O	0.1	0.36	1	Liver	Hepatotoxicity
Hydrogen	H_2CO	17	4100	340	-	Explosion
Methane	CH_4	0.47	5300	3500	-	Explosion
Methyl Alcohol	CH_3OH	200	70	90	Eye	Visual Disturbance
Toluene	C_7H_8	0.2	16	60	Central Nervous System	Dizziness

* Evaluated at 25°C and 1 atm.

† Carcinogen

‡ Carboxyhemoglobin target

This study was initiated to continue the efforts of the previous trade study. This paper presents the results of efforts to address the TCC functionality of the PLSS by revisiting and updating the removal requirements and generation rates of trace contaminant gasses, investigating the effects of anticipated O_2 leakage and ventilation rates on trace gas concentrations, and estimating the lifetime of a possible TCCS bed as a function of its size and mass to support ongoing TCCS design efforts.

II. Relevant Requirements and System Configuration

Results from the 2008 trade study[3] provided the basis for requirement CSSE3038 of CSSE EVA Requirements Document (ERD),[4] which specifies that the trace contaminant concentrations are not to exceed the 24-hr Spacecraft Maximum Allowable Concentrations (SMACs)[5] listed in Table 1. Implementing a strategy to satisfy this requirement necessitates knowledge of trace contaminant generation rates and the rates at which these contaminants are removed from the suit as entrainments in exhausted and/or leaked ventilation gases. These rates are dependent on hardware components and materials used in both the pressure garment and the PLSS.

The current design of the CSSS PLSS[6] is shown schematically in Figure 1. The ventilation loop is conditioned through use of a Rapid Cycle Amine (RCA) (GX-311a) system to remove CO_2 and humidity and a TCCS (GX-311d) to remove trace contaminants. Oxygen is nominally provided by the primary O_2 tank (TK-100), with a secondary O_2 tank (TK-200) as a backup. Thermal control and re-humidification of the ventilation loop are accomplished via heat and mass transfer with the cooling water loop by a humidifying heat exchanger (HX-526). The cooling water loop is cooled by a Suit Water Membrane Evaporator (SWME) (HX-501a).

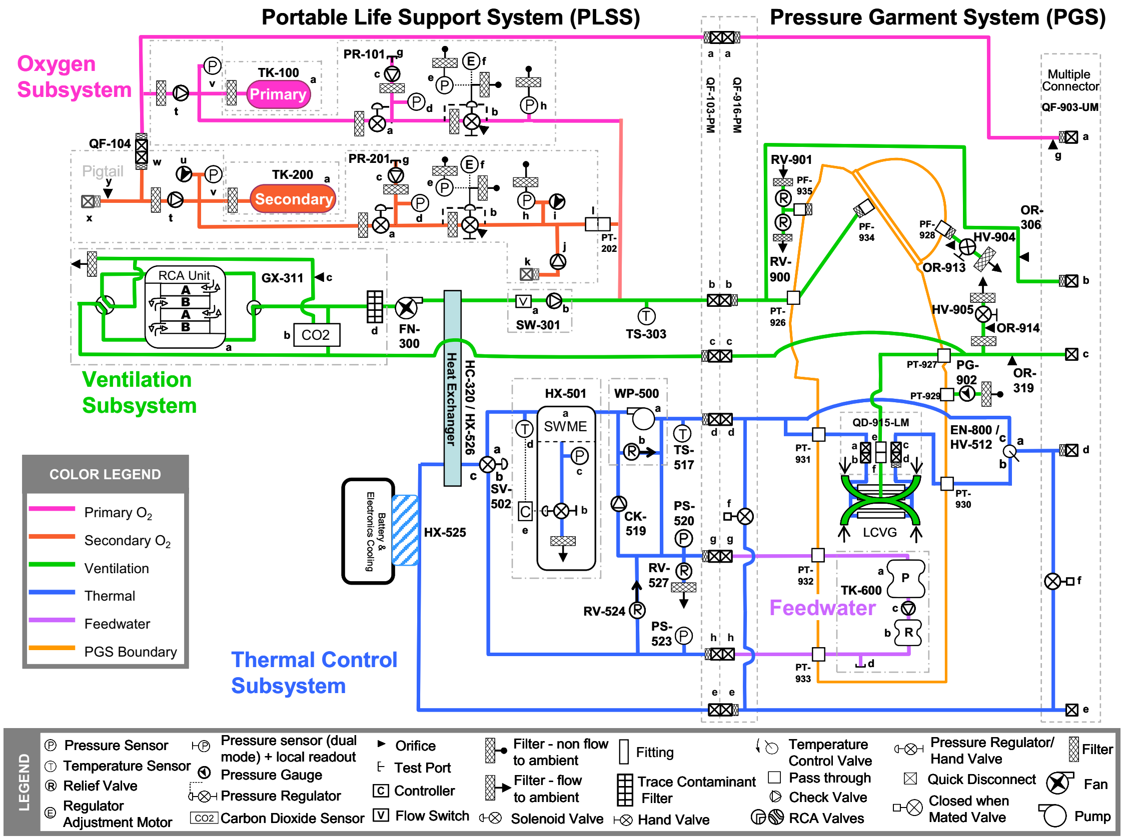

Figure 1. CSSE PLSS schematic.[6]

A. Trace Contaminant Generation

The trace contaminant generation rates, as estimated in the 2008 trade study,[3] are presented in Table 1. These rates were derived from data used during the development of the extravehicular mobility unit (EMU) and data from a NASA White Sands Test Facility amine bed off-gassing test.[7] As part of the current study, inquiries were made regarding any updated information that may affect the accuracy of the generation rate estimates. Representatives from the PLSS and pressure garment system (PGS) teams were contacted to generate the latest list of all components and materials planned for the spacesuit system, specifically those that would interact with the ventilation flow. At this point in development, we do not expect the O_2 subsystem to use any new materials that would potentially add contaminants to the ventilation loop. The thermal subsystem team is evaluating the use of ethylene vinyl acetate, which is currently used in the space shuttle EMU liquid cooling and ventilation garment (LCVG). The ventilation subsystem team has determined that 2% Pennzane 2001 solution and Braycote® 815Z, 25% to 35% volume fill will be used as fan assembly bearing lubricants. Both of these lubricants are certified and/or used in the EMU. The PGS team did not have any further input on new materials for the Constellation spacesuit, as the materials under consideration are similar to those currently used in the EMU. Based on this information, revised generation rate estimates remain unchanged from those of the 2008 trade study.[3]

B. Expulsion of Ventilation Gases

The trace contaminants generated within the spacesuit system are entrained within the ventilation loop gases. A portion of these contaminants are thus expelled from the suit at any point at which ventilation gases are lost to the vacuum environment; e.g., through RCA ullage, CO_2 sensor losses, and PGS leakage.

C. Rapid Cycling Amine System

The RCA system removes CO_2 and water vapor from the ventilation stream through adsorption within one of two solid amine sorbent beds. Once the active bed reaches capacity, the RCA system simultaneously redirects the ventilation stream through the second sorbent bed while regenerating the first bed via exposure to vacuum. The ventilation gases trapped within the first bed are vented to vacuum during the switchover, and the CO_2 is desorbed from the same bed. The duration of exposure of each bed to the ventilation gases is called the half-cycle time. As the crewmember's metabolic rate increases, CO_2 input rate into the RCA also increases. Figure 2[8] shows that shorter half-cycle times are required as CO_2 input rate increases if the partial pressure of CO_2 ($ppCO_2$) at the RCA outlet is to be kept below a targeted 6 mmHg, leading to increased ullage loss rates. According to Papale and Paul,[8] accommodating a peak metabolic rate of 600 W (EVA ERD requirement CSSE0008[4]) would require an RCA that treats a CO_2 input rate of 3 g/min, corresponding to a 1- to 2-minute half-cycle time and O_2 ullage losses ranging from 7 to 11 g/hr.

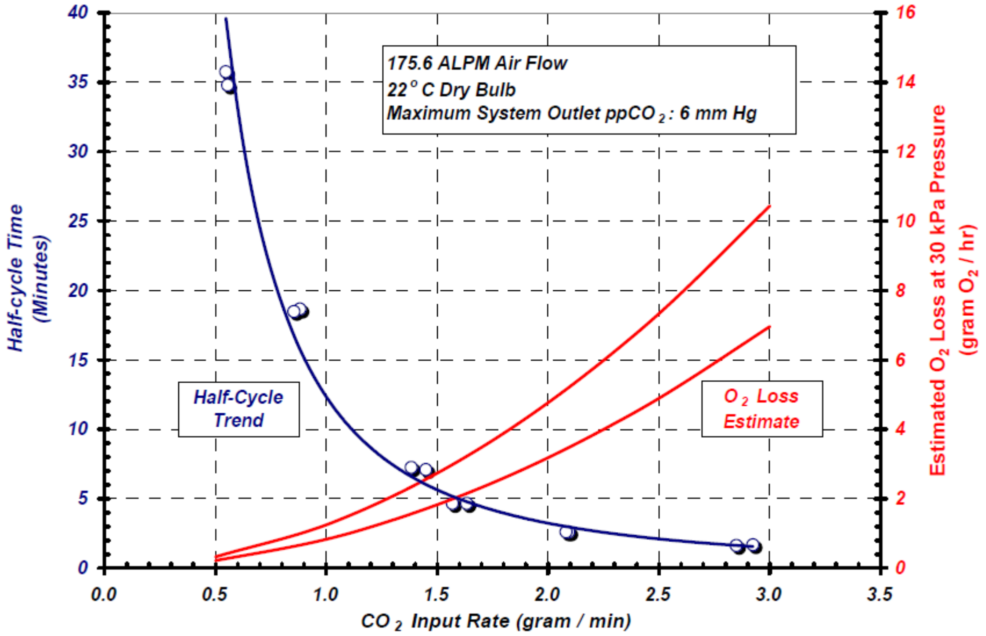

Figure 2. Required half-cycle time and corresponding ullage loss as a function of CO_2 input rate.[8]

D. Carbon Dioxide Sensor Losses

The CO_2 sensor (GS-311b) senses CO_2 levels entering the helmet and leaving the pressure garment via the LCVG to indicate RCA scrubbing performance and determine crew metabolic rate.[6] Two small streams of ventilation flow, extracted from the ventilation loop, flow through the CO_2 sensor and are then expelled to vacuum. Currently, the only estimate available for the O_2 losses through the CO_2 sensor is an order-of-magnitude approximation of 0.01 kg O_2 per 8-hr EVA.[13]

E. Suit Leakage

History shows that even the best spacesuit designs leak as they are pressurized systems operating in a vacuum environment. When researching suit leakage throughout the history of the spacesuit, it was found that requirements exist for *maximum* leakage for the spacesuit system but no requirements exist for its *minimum* leakage.

Table 2 shows data collected for suit leakage during lab testing of the Apollo spacesuits.[9] This information provided a baseline for the suit leakage calculations in this study, although the actual leak rates for the same suits would be lower.

The current maximum allowable leak rate for the CSSS when pressurized to 4.8 psid (33 kPa-d) during lunar surface EVA is established by the CSSE ERD (requirement CSSE1000)[4] as 300 sccm.

Table 2. Apollo preflight suit leakage.

Apollo PGA	Crewmember	Mission	Suit Pressure *(psia)*	Ambient Pressure *(psia)*	PreFlt Leakage *(sccm)*	Spec *(sccm)*
A7L-033	Collins	Apollo 11	18.47	14.72	60	180
A7L-077	Aldrin	Apollo 11	18.47	14.72	95	180
A7L-056	Armstrong	Apollo 11	18.47	14.72	50	180
A7L-066	Gordon	Apollo 12	18.47	14.72	55	180
A7L-067	Bean	Apollo 12	18.47	14.72	51	180
A7L-065	Conrad	Apollo 12	18.47	14.72	105	180
A7L-078	CDR	Apollo 13	18.47	14.72	80	180
A7L-061	LMP	Apollo 13	18.47	14.72	60	180
A7L-088	CMP	Apollo 13	18.47	14.72	130	180
A7L-090	CDR	Apollo 14	18.47	14.72	93	180
A7L-073	LMP	Apollo 14	18.47	14.72	90	180
A7L-085	CMP	Apollo 14	18.47	14.72	125	180

Mean Preflight leakage (sccm)	82.8333	
Max Preflight leakage (sccm)	130	
Min Preflight leakage (sccm)	50	
Mean-2sigma Leakage (sccm)	26.543	95% confidence
Mean-3sigma Leakage (sccm)	-1.60226	99% confidence

III. Feasibility of Satisfying Trace Contaminant Requirements without a TCCS

A primary objective of this trade study is to examine the feasibility of removing the TCCS and relying on the semi-open nature of the PLSS ventilation loop. The ventilation loop is considered “semi-open” due to the deliberate expulsion of a portion of ventilation gases from the system by the RCA and the CO_2 sensor. Suit leakage also contributes to the “opening” of the ventilation loop. The advantages of removing the TCCS from the PLSS include:

- Direct mass reduction – Approximately 0.24 kg (0.53 lbm) could be saved, assuming that the CxP PLSS TCCS bed mass is similar to the shuttle EMU charcoal bed mass and that the container mass scales similarly to the EMU LiOH Contaminant Control Cartridge[10] container.
- Secondary mass reduction – TCCS removal from the ventilation flow path eliminates a source of pressure drop, which leads to a reduction of ventilation fan power and, therefore, the required battery mass. Depending on the magnitude of the pressure drop reduction relative to the total ventilation system pressure drop, it may also be possible (although unlikely) to downsize the ventilation fan.
- Direct volume reduction – The TCCS is expected to occupy a currently unknown volume within the PLSS that is anticipated to be small relative to the other PLSS components.
- Secondary volume reduction – Battery and (possibly) fan volume reductions corresponding to the secondary mass reductions listed above will result from TCCS removal.
- Reduction in maintenance overhead – Removal of the TCCS eliminates the need to periodically replace the filter beds and maintain associated connectors and plumbing.
- Increase in system reliability – TCCS removal from the PLSS decreases the number of parts that can fail.
- Decrease in PLSS development and fabrication costs – The costs associated with designing, fabricating, and testing the TCCS would be eliminated if no TCCS is required.

For this investigation, an analysis was performed to determine trace contaminant concentrations within the suit environment at the end of an 8-hour EVA using the as-designed ventilation gas losses (i.e., RCA ullage and CO_2 sensor losses) with and without an estimated average suit leak rate. Since the suit leakage is not a design feature, selection criteria for whether or not to incorporate a TCCS should be based on a suit leak rate of 0 sccm, unless a specific exhaust port or orifice is added to the system to provide the required dilution (along with the added O_2 storage to accommodate the extra loss).

A. Assumptions

The trace contaminant post-EVA concentration analysis relies on the following assumptions:

- The RCA cycle time is held constant throughout the duration of the EVA.

- Oxygen loss via RCA venting is estimated to be 6 g/h. This is conservative compared to the 7 to 11 g/h range determined from Figure 2 for a 3 g/min CO_2 input rate. As the O_2 loss rate is very sensitive to half-cycle time, this conservative approach allows for the possibility that the half-cycle time is closer to 2 minutes.
- The rate of O_2 venting through the CO_2 sensor is approximately 0.01 kg O_2 per 8 hr EVA.
- The CSSS Configuration 2 leak rate is assumed equal to the average measured mean Apollo preflight value of 82.8 sccm.
- The suit environment contains no trace contaminants at the beginning of each EVA, so both the initial trace contaminant mass m_{ci} and the concentration C_{ci} are equal to zero.
- The free volume V within the suit is equal to 2 ft^3.
- The ratio f of contaminant mass m_c to O_2 mass m_o is identical at all O_2 venting locations (RCA, CO_2 sensor, and suit leak points).
- The mass generation (off-gassing) rate $\dot{m}_{cgen}$ of each trace contaminant is constant throughout the EVA duration.
- For cases in which a TCCS is present, the TCCS removal efficiency η_c of each contaminant species is a constant.

B. Analysis

According to mass conservation, the rate of change of each contaminant species mass m_c within the suit environment is equal to its generation rate $\dot{m}_{cgen}$ minus all losses. Thus,

$$\frac{dm_c}{dt} = \dot{m}_{cgen} - f\sum_i \dot{m}_{Li} , \tag{1}$$

where

$$f \equiv \frac{m_c}{m_o}$$

and $\dot{m}_{Li}$ is the mass flow rate of O_2 exiting the ventilation system due to the jth loss mechanism. Losses considered in this study include the RCA ullage $\dot{m}_{RCAo}$; O_2 loss through the CO_2 sensor $\dot{m}_{CO_2}$; PGS leakage $\dot{m}_{PGSo}$; and TCCS adsorption $\eta_c \dot{m}_o$, where η_c is the TCCS contaminant removal efficiency and $\dot{m}_o$ is the O_2 mass flow rate into the TCCS. For the case in which no TCCS is present, the contaminant removal efficiency η_c equals zero. The PGS leakage rate $\dot{m}_{PGSo}$ can also be set equal to zero whenever suit leakage effects are not to be considered. In the general case, the summation in Equation (1) expands to

$$\sum_i \dot{m}_{Li} = \dot{m}_{PGSo} + \dot{m}_{RCAo} + \dot{m}_{CO2} + \eta_c \dot{m}_o . \tag{2}$$

Integration of Equation (1) to find the total in-suit contaminant mass m_c at the end of an EVA of duration t yields

$$m_c = \dot{m}_{cgen}\tau - \left(\dot{m}_{cgen}\tau - m_{ci}\right)e^{-\frac{t}{\tau}} , \tag{3a}$$

where

$$\tau = \frac{m_o}{\sum_i \dot{m}_{Li}} . \tag{3b}$$

The contaminant concentration C_c, which is defined as the contaminant mass per unit volume V, is determined from the above result as follows:

$$C_c \equiv \frac{m_c}{V} = \frac{\dot{m}_{cgen}\tau}{V}\left(1 - e^{-\frac{t}{\tau}}\right) + \frac{m_{ci}}{V}e^{-\frac{t}{\tau}} \tag{4}$$

or

$$C_c = C_{cs}\left(1 - e^{-\frac{t}{\tau}}\right) + C_{ci} e^{-\frac{t}{\tau}}, \tag{5a}$$

where

$$C_{cs} \equiv \lim_{t\to\infty} C_c = \frac{\dot{m}_{cgen}\tau}{V}. \tag{5b}$$

The quantity C_{cs} is the steady-state concentration of the trace contaminant.

Calculation results for the trace contaminant concentrations at the end of an 8-hour EVA are shown in Table 3. The 24-hr SMAC limits are greatly exceeded by ammonia (NH_3) and slightly exceeded by formaldehyde (CH_2O). If an average suit leakage rate of 82.8 sccm is considered, the 8-hr formaldehyde CH_2O concentration will not exceed its SMAC limit. However, only values obtained with zero suit leakage should be used for design purposes since the PGS design goal is to minimize suit leakage as much as possible.

Table 3. Calculated 8-hr trace contaminant concentrations obtained with no TCCS in ventilation loop.

Chemical Name	Total Generation Rate *(mg/8-hr EVA)*	SMAC *(mg/m^3)*	8-hr Concentration* *(mg/m^3)* w/o Suit Leak	8-hr Concentration* *(mg/m^3)* w/ Suit Leak
Acetaldehyde	0.0267	10	0.181	0.104
Acetone	0.0445	500	0.301	0.173
Ammonia	83.3	14	564	324
n-Butanol	0.167	80	1.13	0.649
Carbon Monoxide	11.0	114	74.4	42.8
Ethyl alcohol	1.34	10,000	9.03	5.20
Formaldehyde	0.133	0.6	0.902	0.519
Furan	0.100	1	0.676	0.389
Hydrogen	16.7	340	113	64.9
Methyl alcohol	0.467	90	3.16	1.82
Methane	200	3,500	1,352	778
Toluene	0.201	60	1.36	0.781

* Highlighted values exceed SMAC concentrations.

Setting C_c equal to the SMAC NH_3 requirement and numerically solving Equations (2) through (5) for the PGS O_2 leakage rate $\dot{m}_{PGSo}$ reveals that 4,013 sccm of O_2 venting would be required, in addition to the RCA ullage and CO_2 sensor losses, to reduce the 8-hour NH_3 concentration to its 24-hr SMAC requirement. For an 8-hour EVA, this would require 2.22 kg (5.14 lbm) of O_2 storage beyond that which would otherwise be necessitated to accommodate metabolic consumption, maximum allowable suit leakage, RCA ullage, and CO_2 sensor losses. The mass associated with expanding the O_2 tank capacity would also add to this increase. Since the extra O_2 needed to satisfy NH_3 concentration requirements without a TCCS is significantly more massive than a 0.24 kg (0.53 lbm) TCCS, removal of the TCCS from the PLSS design is not recommended.

IV. TCCS Sizing Calculations

Given that the comparison between the shuttle EMU TCCS mass and the mass of extra O_2 needed to satisfy NH_3 concentration requirements greatly favors the use of a TCCS, an initial estimate was calculated for the bed mass of a TCCS designed for Constellation EVA conditions and requirements. As a TCCS bed material has not been selected yet for the CSSS PLSS and available data for most candidates are limited, a 10%-phosphoric-acid-impregnated Granular Activated Carbon (GAC) bed is assumed for initial sizing purposes. For this study, the TCCS bed is sized for the adsorption of NH_3, which exceeds requirements more than any other trace contaminant, as shown in Table 3.

As an early approximation, conditions within the suit are assumed similar enough to those within the International Space Station (ISS) to utilize the ISS TCCS adsorption capacity ζ of 4.4 mg NH_3/g carbon.[11] Additionally, sizing calculations performed for a Crew Exploration Vehicle (CEV) study[11] make use of a minimum residence time requirement t_{Ro} of 0.25 s, suggesting that residence time is the minimum required to obtain a high or near-optimal capture efficiency. The current study assumes that this same residence time requirement is valid when applied in the suit environment. With the full PLSS ventilation flow passing through the TCCS, the residence time requirement would be the main driver in sizing process, leading to a very large bed. To avoid an excessively large TCCS bed, the residence time requirement was relaxed, requiring the use of an assumed NH_3 capture efficiency η_c degradation strategy to account for the low residence time effects. For purposes of this investigation, the NH_3 capture efficiency η_c is assumed to equal 100% when this residence time t_R is greater than or equal to $t_{Ro} = 0.25$ s and to decrease linearly to 0% as the residence time decreases to 0 s. This efficiency degradation model is represented by the following relationship when t_R is less than t_{Ro} :

$$\eta_c = \frac{t_R}{t_{Ro}} \tag{6}$$

The residence time t_R is estimated from unused bed mass $m_{B,eff}$, GAC density ρ_B, and O_2 volume flow rate $\dot{V}_o$ as follows:

$$t_R = \frac{m_{B,eff}}{\rho_B \dot{V}_o} . \tag{7}$$

The unused bed mass is the total bed mass m_B minus the mass of bed material saturated with NH_3 (m_{cads}/ζ):

$$m_{B,eff} = m_B - \frac{m_{cads}}{\zeta} , \tag{8}$$

where m_{cads} is the total mass of contaminant (NH_3) adsorbed into the bed. Thus, the NH_3 capture efficiency η_c is expressed as

$$\eta_c = \frac{m_B - \dfrac{m_{cads}}{\zeta}}{\rho_B \dot{V}_o t_{Ro}} . \tag{9}$$

For times t much larger than the time constant τ, the contaminant concentration C_c is approximately equal to the steady-state contaminant concentration C_{cs} .

$$C_c \approx C_{cs} = \frac{\dot{m}_{cgen}\tau}{V} = \frac{\dot{m}_{cgen} m_o}{V\left(\sum_{i-1} \dot{m}_{Li} + \eta_c \dot{m}_o\right)} \tag{10}$$

The efficiency term is explicitly broken out of the summation term defined in Equation (2). Similarly, the adsorbed contaminant mass m_{cads} is approximated as

$$m_{cads} \approx \eta_c \dot{V}_o C_{cs} t . \tag{11}$$

The adsorbent bed mass m_B required to provide trace contaminant control such that in-suit NH_3 concentration C_c is less than or equal to the SMAC NH_3 concentration C_{SMAC} for duration t is found by combining Equations (9), (10), and (11), yielding

$$m_B \approx \frac{1}{\zeta}\left[\dot{m}_{cgen} - C_{SMAC} V\left(\frac{\sum_{i-1} \dot{m}_{Li}}{m_o}\right)\right]\left(t + \frac{\zeta \rho_B t_{Ro}}{C_{SMAC}}\right). \tag{12}$$

The linearity of the resulting approximation of bed mass m_B with duration t is consistent with previously published bed sizing analyses, such as the technique presented by Perry[12], when applied to axial-flow beds. The slope is the rate at which the bed becomes saturated. The intercept represents the mass of adsorbent in the mass transfer zone, which is the region of unsaturated bed material in which active adsorption (or chemisorption for the case of NH_3) of the contaminant occurs.

The resulting bed mass estimates are plotted, without safety margins, in Figure 3. The bed mass ranges from 43.6 g for a single 8-hr EVA to 117.6 g for five 8-hr EVAs.

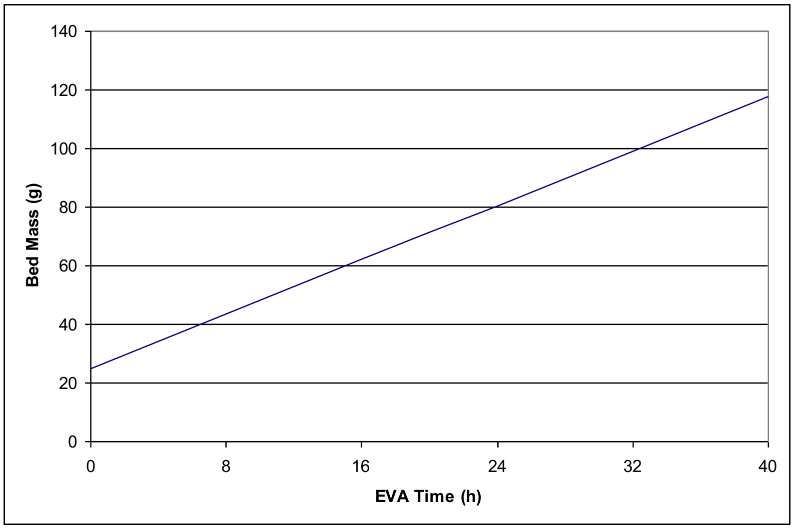

Figure 3. Estimated phosphoric acid (H_3PO_4)-impregnated GAC bed mass required for NH_3 treatment as a function of EVA time

V. Technology Development and Ongoing Research

Technology development for TCC technologies continues at several NASA centers as well as in industry and academia. NASA Marshall Space Flight Center (MSFC) is working on a TCC sorbent that uses microlith-based absorbers for the CEV. Testing was planned for the end of 2009 but, due to delays in acquiring process-monitoring instruments, the testing began late. Therefore, results were unavailable prior to completion of this study. The revised test completion date is May 2010. It is recommended that the PLSS ventilation subsystem team follow up with the engineers at MSFC to obtain the results.

The NASA Ames Research Center (ARC) continues to evaluate carbon technologies. The primary focus of this evaluation is to find a carbon or zeolite that can be used to remove NH_3. Research is specific for vehicle applications; however, results could influence decisions on spacesuit TCCS design, particularly since NH_3 is a contaminant anticipated to exceed allowable concentrations in the spacesuit system. According to November, 2009, correspondence from ARC engineer Bernadette Luna, tests have been conducting using dry and humid flows, as well as a higher (50 ppm) and a lower (25 ppm) NH_3 trace contaminant feed loads. The carbons were treated with either H_3PO_4, chloride, or nitrate. Overall the performance was highest for humid ventilation flows: the NH_3 levels were higher, and the carbon beds had larger mesh size. Preliminary results show that the phosphoric acid carbons work the best. Figure 4 presents the initial data from the ARC humid-flow NH_3 tests.

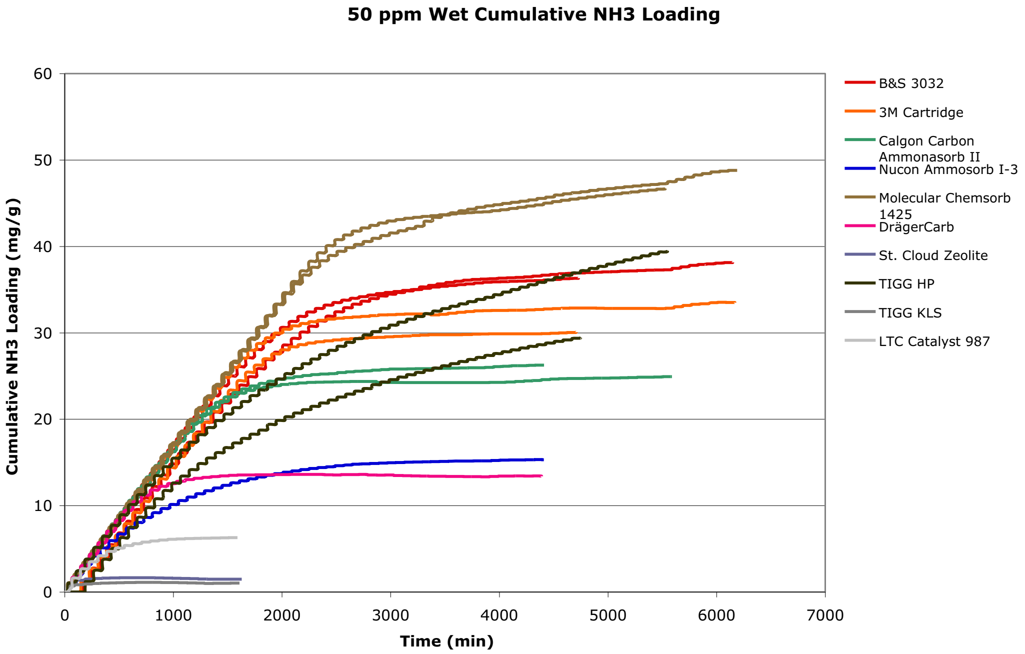

Figure 4. ARC NH_3 scrubbing results from humid flow tests.

VI. Conclusions and Recommendations

A review of the requirements and generation rates for trace contaminants in Configuration 2 of the CSSS has revealed no change from previously published data. However, the 0% scrubbing concentrations in section CSSE3038 of the CSSE ERD,[4] should be updated to the values in Table 3. As previously found, NH_3 is the most prevalent trace contaminant, relative to maximum concentration requirements, followed by CH_2O. Other contaminants generated in the suit system do not build up to toxic levels because of the ventilation effect of RCA ullage and CO_2 sensor losses.

An investigation of the effects of removing the TCCS from the PLSS schematic has shown that advantages do exist, but the extra O_2 mass required provides a significant enough mass penalty to recommend keeping the TCCS.

A preliminary sizing analysis based on NH_3 removal using H_3PO_4-impregnated granulated carbon shows that the required bed mass is a linear function of EVA time. Calculated bed mass results range from 43.6 g for a single 8-hr EVA to 117.6 g for five 8-hr EVAs. Once a specific adsorbent material is selected for the CxP PLSS, a more detailed sizing analysis should be performed.

Note that at the time of this research, the PLSS configuration incorporated a constant-cycle-time RCA. A recent design update has incorporated an adaptive cycle time capability into the RCA system, decreasing the ullage losses from those used within this document, particularly during low metabolic rate conditions. Future work should include revising this study to accommodate the lower RCA ullage losses produced by the design update.

Research continues for additional or alternative methods of trace contaminant removal within the Constellation spacesuit PLSS. The investigation at ARC for new TCCS materials seems promising, but further testing and evaluation are warranted before incorporating these materials into this TCCS.

It is recommended that all the research and continued technology development work be monitored for possible TCC use in future. A considerable amount of work remains in selecting the best adsorbent material and studying its properties and performance.

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Acronyms

ARC:	Ames Research Center
CEV:	crew exploration vehicle
CO_2:	carbon dioxide
CSSS:	Constellation Spacesuit System
CxP:	Constellation Program
EMU:	extravehicular mobility unit
ERD:	EVA Requirements Document
EVA:	extravehicular activity
GAC:	granular activated carbon
CH_2O:	formaldehyde
H_3PO_4:	phosphoric acid
ISS:	International Space Station
LCVG:	liquid cooling and ventilation garment
MSFC:	Marshall Space Flight Center
NH_3:	ammonia
O_2:	oxygen
PGS:	pressure garment subsystem
PLSS:	Portable Life Support System
$ppCO_2$:	partial pressure of carbon dioxide
RCA:	rapid cycle amine
SMAC:	spacecraft maximum allowable concentration
SWME:	suit water membrane evaporator
TCC:	trace contaminant control
TCCS:	Trace Contaminant Control System