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The Role of System Compatibility and Cabin Environmental Impact Assessment in Environmental Control and Life Support System Design and Flight Operations

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Contamination of a crewed spacecraft's cabin environment leading to ECLS system functional capability and operational margin degradation or loss can have an adverse effect on NASA's space exploration mission figures of merit—safety, mission success, effectiveness, and affordability. Experience gained during the International Space Station program has shown the vital role that evaluating ECLS system compatibility and cabin environmental impact serves as a passive trace contaminant control tool which can provide guidance to crewed spacecraft system and payload developers relative to designing for minimum risk. As well, such evaluations can aid in guiding containment design, developing flight rules and procedures suitable for protecting the ECLS system and cabin environment, and defining contamination event remediation approaches. The approach to evaluating ECLS system compatibility and cabin environmental impact developed during the ISS program is presented and its role in future exploration spacecraft design is discussed.

Nomenclature

DMSD = dimethylsilanediol
ECLS = environmental control and life support
FMECA = failure mode effects and criticality analysis
OSHA = Occupational Health and Safety Administration
SMAC = spacecraft maximum allowable concentration
TCC = trace contaminant control
VOC = volatile organic compound
A = adsorption potential
C = concentration
$k_H(T)$ = Henry's Law constant at the process temperature, T
kPa = kilopascal
m = meter
$\dot{m}_L$ = humidity condensate mass collection rate
mg = milligram
mL = milliliter
P = cabin pressure
q = adsorbent saturation capacity
T = temperature
$\dot{\upsilon}$ = volumetric flow rate
V_m = molar volume
η = efficiency

I. Introduction

FIGURES of merit for crewed space exploration missions include safety, mission success, effectiveness, and affordability[5] and maintaining the highest standard for crew health and safety during all mission phases is a vital component of realizing these mission attributes. Contamination of the crewed spacecraft cabin environment can

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originate in a variety of ways and in some instances can adversely impact environmental control and life support (ECLS) system capability or function in ways that may jeopardize crew health, safety, and ultimately mission success. Therefore, understanding the impacts chemicals and materials may have on ECLS system and the cabin environment early in the vehicle's design can prevent or mitigate hazards, avoid costly redesigns, and better assure a successful mission.

A number of technical areas must be considered relative to how they may influence approaches to active and passive trace contaminant control (TCC) methods toward ensuring crew health and safety. Passive TCC plays a key role during the design process by minimizing the equipment offgassing load which aids in sizing the active TCC equipment and reducing risk for releasing pollutants into the cabin environment during the mission.[1] Technical considerations associated with passive TCC include materials selection and control, containment methods, manufacturing processes, chemical process design, process conditions, and system operational approaches as well as others.[2] Still, even with careful consideration and attention to these details, a complex spacecraft transporting people to exotic destinations is bound to have contamination sources aboard or conditions may develop which may cause contamination that presents challenges to mission success. Yet, by giving consideration to active TCC design practice, types of contaminant emissions, and their impacts along with careful consideration during the spacecraft design, the risk and magnitude of contamination events can be minimized such that the ECLS system, and in particular the active TCC equipment sizing, functional capability, capacity margins, and operational approach, can be designed to achieve minimum risk.

A. Active Trace Contaminant Control Design Considerations

Since specifying, designing, and sizing the active trace contaminant control equipment for a spacecraft precedes detailed knowledge of the actual load, the standard design practice conservatively assumes the active TCC equipment performs its function unassisted by any other systems or processes in the cabin such as overboard leakage and other air purification equipment.[2] As well, the active TCC is not used as a hazard control for other onboard systems or payloads. In this context, contaminant releases into the cabin overlay the active TCC design capacity with its functional margin. The impact on that design capacity and functional margin is considered. Ideally any planned or unplanned contaminant releases into the cabin environment would not exceed the TCC equipment's functional margin.

In the event that a vehicle system or process is changed during a vehicle's lifetime, a complete assessment for ECLS system compatibility and cabin environmental impact is necessary to ensure any potential impacts to the cabin environment, as well as the ECLS system equipment, are within acceptable operational margins.

B. Types of Pollutant Emissions

Contamination may enter the cabin environment via two means—bulk quantity and fugitive emissions. Bulk quantity emissions involve releasing a large amount of material released into the cabin environment over a short time period while fugitive emissions release a small quantity of material over a long time period. Since bulk quantity emissions are a difficult remediation challenge and may cause acute safety hazards, design practices to implement hazard controls are applied to yield minimum risk for the hazard to occur. Fugitive emissions, however, due to the small quantity of material involved can present a greater challenge because their location and magnitude may vary. Fugitive emissions by their very nature can be pervasive and diverse. Among the types of fugitive emissions are valve and flange leakage, periodic system venting, cleaning solvent evaporation during housekeeping operations, reagent leakage during payload operations, and solvent evaporation from personal care products. Some of these emissions may actually be within their allowable daily release quantities, yet over time may result in a cumulative impact to the cabin environment and the ECLS system. System and payload venting is among the larger fugitive emissions that may require special treatment to minimize impacts to the cabin environment. Usually, fugitive emissions are adequately controlled by specifying maximum allowable equipment leakage rates and following material usage procedures. Although most fugitive emissions are small and are well within the operational margins of the active TCC equipment, the potential for increases in the number, size, and distribution of emission sources aboard a spacecraft over time can reach a point that may overwhelm the active TCC equipment. For this reason, all emissions must be identified and evaluated relative to ECLS system compatibility and cabin environmental impact.

C. Impacts from Pollutant Emissions

Pollutants that are released into a spacecraft's habitable volume can impact the cabin environment, the ECLS system performance, or both. Three examples of chemical classes that are associated with cabin environmental and ECLS system impacts are polar volatile organic compounds (VOC), perfluorocarbon compounds, and volatile methyl siloxanes.

Polar VOCs such as low molecular weight alcohols, ketones, and glycols are commonly used in experiment payload reagents and some cleaning fluids used for in-flight housekeeping and prelaunch hardware processing. These compound classes can readily partition into humidity condensate which increases the contaminant load delivered to the water processing subsystem.[1,3,4] In order to minimize the impact to the water processing system the cabin concentrations for these compound classes must be maintained far below each individual compound's spacecraft maximum allowable concentration (SMAC). Therefore, the active TCC capability must be supplemented via additional operational approaches to minimize these impacts.

Although perfluorocarbon compounds have very high SMACs, the active TCC equipment typically has removal capacities leading to their long-term persistence in the cabin atmosphere. These compounds and impurities that may be found in them may decompose to form toxic compounds on contact with hot surfaces.[5, 6]

Volatile methyl siloxanes are pervasive contaminants originating from many sources aboard a crewed spacecraft. These compounds can decompose via interaction with ECLS system equipment and the cabin environment to yield dimethylsilanediol (DMSD) which readily partitions into humidity condensate. The DMSD load in the humidity condensate presents a functional challenge to the water processing subsystem which is discussed elsewhere.[7-9]

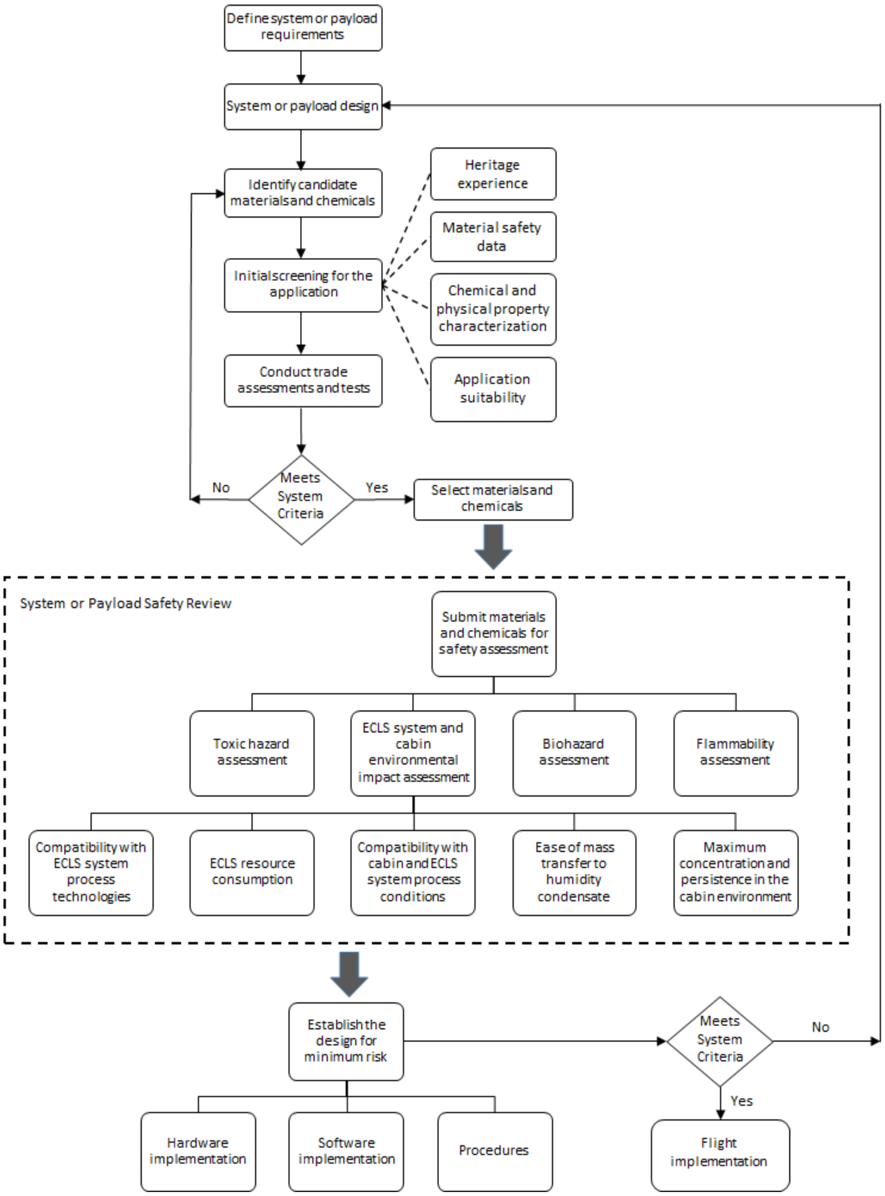

Figure 1. ECLS and cabin environmental impact evaluation.[10]

As these examples illustrate, understanding the interactions that materials and chemicals used aboard the vehicle have with the ECLS system and their fate in the cabin environment is a vital component of ensuring mission safety and success. To reach this understanding, a methodical process, such as illustrated by Fig. 1[10], must be followed.

II. A Process for Evaluating ECLS System and Cabin Environmental Impact

The process illustrated by Fig. 1 addresses experiment payload materials and chemicals as well as materials used in vehicle systems and processes. Contamination associated with payload and system hardware may originate from hardware and material manufacturing residues, prelaunch hardware cleaning, in-flight housekeeping, and other sources. The process begins by identifying material candidates and conducting an initial screening based on heritage flight experience, safety data, chemical properties, and physical properties. Candidates that pass initial screening and pass system selection gates are assessed for ECLS system compatibility and persistence in the cabin environment in addition to their thermal and chemical stability, toxicity, flammability, and biohazard. The results from ECLS system compatibility and cabin environmental impact assessment are useful to vehicle system and experiment payload developers as guidance for achieving a design that provides for minimum risk through ensuring adequate containment and developing safe operational protocols supported by flight rules and procedures to ensure ECLS system protection and to minimize the potential for contamination of the cabin environment. The process results in ratings for ECLS system compatibility and cabin environmental impact. The following describes these ratings and their relation to hazard rating categories and severity.

A. ECLS System and Cabin Environmental Impact Rating Definitions

The definitions for the ECLS system compatibility and cabin environmental impact are based on the Occupational Safety and Health Administration's (OSHA) guidance for hazard classification[11] and the globally harmonized system for classifying and labelling chemicals developed by the United Nations[12] which use environmental hazard categories based on aquatic system impacts. Considering a spacecraft cabin and its ECLS system to be an analog to Earth-based environmental compartments allows these hazard classification to be adapted for application to space-based environmental impact evaluation. Table 1 provides the ECLS system compatibility rating categories which are

Table 1. ECLS system compatibility rating definitions.

Compatibility Level	Criteria
Category E0	Functional capacity consumption is <2%. 100% of the functional margin is retained. No ECLS functional performance degradation. No change in scheduled maintenance.
Category E1	Functional capacity consumption is >2% and <10%. >10% of the functional margin is consumed. No ECLS functional performance degradation. No change in scheduled maintenance.
Category E2	Functional capacity consumption >10% and <25%. >25% of the functional margin is consumed. ECLS functional performance is degraded by <10%. Early replacement of consumable components may be necessary within nine months.
Category E3	Functional capacity consumption >25% and <50%. >50% of the functional margin is consumed. ECLS functional performance is degraded by >10% and <25%. Early replacement of consumable components may be necessary within six months.
Category E4	Functional capacity consumption >50% and <75%. >75% of the functional margin is consumed. ECLS functional performance is degraded by >25% and <50%. Early replacement of consumable components may be necessary within one month.
Category E5	Functional capacity consumption >75% and <90%. 100% of the functional margin is consumed. ECLS functional performance is degraded by >50% and <75%. System maintenance is required to restore functional performance within one week.
Category E6	Functional capacity consumption >90%. 100% of the functional margin is consumed. ECLS functional performance is degraded by >75%. System maintenance is required to restore functional performance within one day.

based on functional resource consumption and impact on the equipment maintenance cycle. The cabin environmental impact assesses the time to recover after a contamination event. The time to recover considers only the unassisted "natural" removal provided by the ECLS system's operation to reduce the initial contamination level by 95%. The cabin environmental impact categories, provided by Table 2, are indicators of a contaminant's persistence in the cabin environment.

Table 2. Cabin environmental impact rating definitions.

Impact Level	Criteria
Category A	Time to recover < 2 hours.
Category B	Time to recover is >2 hours and <24 hours.
Category C	Time to recover is >24 hours and <72 hours.
Category D	Time to recover is >72 hours and <168 hours.
Category E	Time to recover is >168 hours or the ECLS system is unable to remove the material and it persists in the cabin environment.

B. Compatibility Ratings versus Hazard Severity Categories

The ECLS compatibility and cabin environmental impact ratings do not define a hazard as it is normally understood but addresses the potential for life cycle cost impact and worst case functional capacity and/or capability degradation or loss. The ECLS compatibility and cabin environmental impact ratings alone are not intended to dictate levels of containment. The ECLS compatibility category indicates the degree of functional degradation or loss which may occur in the worst case scenario which may dictate early repair and replacement for an ECLS component leading to increased life cycle costs. The cabin rating provides insight for toxicology regarding the potential persistence in the cabin environment that can be good information for evaluating the toxic hazard associated with the dose the crew may experience.

The ECLS compatibility and environmental impact ratings are complementary to assessments of toxic hazard, biohazard, and flammability that are vital to conducting the safety review and can serve as a component in failure mode effects and criticality analysis (FMECA). When considering the failure severity categories listed by Table 3,[13-15] the ECLS compatibility and cabin environmental impact ratings typically exist in failure severity categories 3 and 4. On rare occasions, a failure such as a bulk leak of anhydrous ammonia into the cabin environment that overwhelms the ECLS capability leading to evacuating the vehicle, may rise to failure severity categories 1 and 2. The probability for material emissions typically occur in the "remote" to occasional probability range as defined by Ref. 15 and summarized by Table 4.

Table 3. Failure severity categories.

Category	Description
1	Catastrophic—Loss of Mission: Failure modes that may cause death or permanent disabling injury or the destruction of a major system or the vehicle during the mission.
2	Critical—Degraded Mission: Failure modes that may result in loss of one or more mission objectives.
3	Marginal—Loss of Redundancy: Failure modes that may result in degradation of mission objectives
4	Negligible—Failure modes that may result in insignificant or no loss to mission objectives.

Table 4. Failure probability levels.

Level	Description
A	Frequent—Likely to occur often during the mission.
B	Probable—Likely to occur several times during the mission.
C	Occasional—Likely to occur sometime during the mission.
D	Remote—Unlikely, but possible to occur during the mission.
E	Improbable—So unlikely it can be assumed the event may not occur during the mission.
F	Eliminated—Incapable of occurring during the mission. Applied to failure modes that have been identified and later eliminated.

III. Assessment Approach

The ECLS system hardware and process compatibility and cabin environmental impact assessment approach determines the functional and logistical impacts associated with bulk quantity and fugitive emissions into a spacecraft cabin atmosphere. The impact assessment may consider cabin air quality interface requirements, flight rule guidelines, emergency response guidelines, guidelines pertaining to hatch opening and cabin atmosphere exchange between a primary crewed space vehicle and a visiting vehicle, and other guidelines as appropriate for the specific crewed spacecraft configuration. Information that is needed to conduct an assessment includes the following:

1) Quantity and purity of the material
2) Material chemical and physical properties
3) Material thermal stability and decomposition products
4) Material reactivity and incompatibilities
5) Vehicle and ECLS configuration including cabin volume, cabin ventilation flow rates, ECLS system characteristics

Information on the material are necessary to evaluate its volatility, ease of removal via ECLS system processes, and its potential for interacting with components of the cabin atmosphere such as humidity or oxygen.

Once the information on the material to be evaluated, the vehicle, and the ECLS system configuration are obtained, detailed calculations involving the contaminant emission rate, cabin material balance, and ECLS system removal routes and impacts are determined using the calculation methods described in Ref. 10. These calculations compare adsorbent loading capacity and humidity condensate loading levels to the available resource to determine the ECLS system compatibility rating. As well, compounds are assessed for their chemical stability when exposed to the cabin environment and ECLS system process conditions. The evaluation also determines whether the materials can foul or poison ECLS system components such as catalytic reactors. The result of the ECLS resource consumption, fouling, or poisoning form the basis for the ECLS system compatibility rating according to Table 1. The material balance allows a concentration decay rate to be determined. The rating that is assigned from Table 2 is based on the time required to remove 95% of the released material from the cabin environment.

IV. Evaluation Results for Selected Compounds

Contaminants released into the cabin environment aboard the International Space Station (ISS) are removed via the active TCC equipment and, for contaminants which are soluble in water, incidental absorption in humidity condensate. Many contaminants may be removed via both routes; however, two extremes exist. The first extreme consists of contaminants that in insoluble in water. These contaminants are removed by the active TCC equipment only which employ adsorbent media and catalytic oxidation. The adsorbent media is primarily a consumable resource aboard the ISS and the capacity for removing water insoluble contaminants is limited by the adsorbent media saturation capacity. Fluorinated thermal working fluids are examples of this extreme. The second extreme consists of contaminants that are soluble in water. Although these contaminants are removed by the active TCC equipment, their solubility in water promotes incidental removal via absorption by humidity condensate. Absorption by humidity condensate can be the dominant removal mechanism for contaminants that are miscible in water. The fraction that enters the humidity condensate must be handled by the water processing system. An excessive humidity condensate loading that may occur from a bulk or fugitive emission of a water soluble contaminant can impact the water processing system's performance, particularly with respect to life cycle economics. It is informative to examine representative contaminants at these two extremes.

A. Fluorinated Thermal Working Fluids

Fluorinated compounds used aboard ISS in thermal control systems and payload equipment such as tetradecafluorohexane (FC-72), octafluoropropane (Freon 218), 1-methoxyheptafluoroproane (HFE-7000), and 1,1,1,2-tetrafluoroethane (Freon 134a) are insoluble in water, and have high vapor pressures. The fully saturated compounds with straight carbon chains have high SMACs on the order of 85000 mg/m^3. The hydrofluoroether and hydrofluorcarbons require additional study by toxicology experts to establish SMACs.

1. Fluorinated Compound Removal via Physical Adsorption

Upon release into the cabin environment these compounds are in the vapor phase and are removed by the active TCC equipment with no assist via incidental removal routes. Therefore, the adsorbent media saturation capacity becomes the limiting parameter for their ECLS system impact. Determining the saturation capacity of the activated carbon used in the active TCC equipment is based upon the Polanyi adsorption potential theory.[2, 16] The adsorption potential, as defined by Eq. 1, is used to calculate the activated carbon saturation capacity. In Eq. 1, *T* is temperature

Table 5. Fluorinated compound ISS ECLS system compatibility levels.

Compound	Trade Name	Bulk Release Quantity for ECLS Impact Category (mL)						
		E0	E1	E2	E3	E4	E5	E6
Tetradecafluorohexane	FC-72	<77	>77 - 386	>386 - 964	>964 - 1929	>1929 - 2893	>2893 - 3858	>3858
Methoxyheptafluoropropane	HFE-7000	<27	>27 - 135	>135 - 338	>338 - 676	>676 - 1015	>1015 - 1353	>1353
Octafluoropropane	Freon 218	<5	>5 - 26	>26 - 66	>66 - 132	>132 - 198	>198 - 263	>263
Tetrafluoroethane	Freon 134a	<1	>1 - 6	>6 - 16	>16 - 33	>33 - 49	>49 - 65	>65

in Kelvin, V_m is the liquid molar volume at the normal boiling point in cm^3/mole, C_s is vapor pressure expressed in concentration units, mg/m^3, and C is the cabin concentration in mg/m^3.

$$A = (T/V_m)\log_{10}(C_s/C) \tag{1}$$

The adsorption potential is used in a Freundlich-type isotherm equation as shown in its general form by Eq. 2 where

$$q = \alpha e^{-\beta A} \tag{2}$$

the activated carbon loading, q, is in mL liquid contaminant/g charcoal, and the pre-exponential factor, α, is 2.1 for soluble compounds and 1.41 for insoluble compounds at 50% relative humidity. The exponential factor, β, is 0.31.

2. *Fluorinated Compound Bulk Release Quantities*

Table 5 summarizes the bulk release quantities of each compound that result in varying levels of ISS ECLS system impact for a hypothetical 100 mg/m^3 cabin concentration. In this case the Category E6 quantity represents the condition where the adsorbent's saturation capacity is exceeded. The range is significant with as little as 65 mL of tetrafluoroethane exceeding the active TCC adsorbent bed capacity compared to over 3.8 liters of tetradecafluorohexane. To prevent a significant impact to the active TCC capacity, the system's lifetime leakage would need to be less than the Category E0 quantity. This quantity can serve as a basis for establishing allowable leakage specifications for a system.

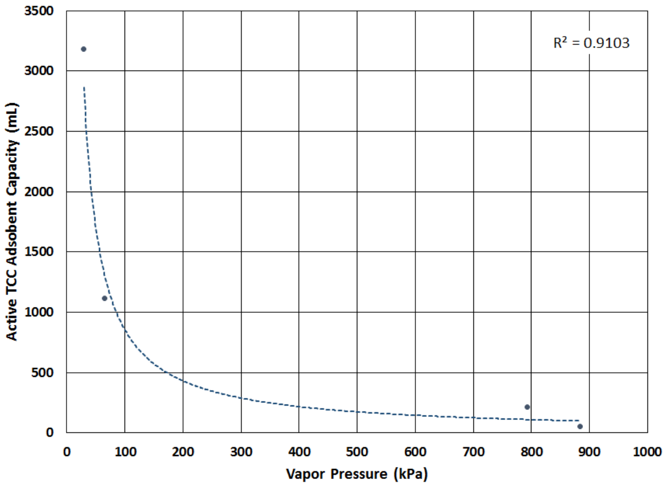

Figure 2. Vapor pressure influence on adsorbent capacity.

3. *Physical and Chemical Properties*

Physical and chemical property screening can provide early indication of the potential for ECLS system impact. As shown by Figs. 2 and 3, the active TCC adsorbent capacity is high for compounds that possess a combination of low vapor pressure and large molar volume. Therefore, when considering system fluids to use aboard a crewed spacecraft, the vapor pressure and molar volume can be helpful initial screening criteria toward developing a design for minimum risk relative to ECLS impacts.

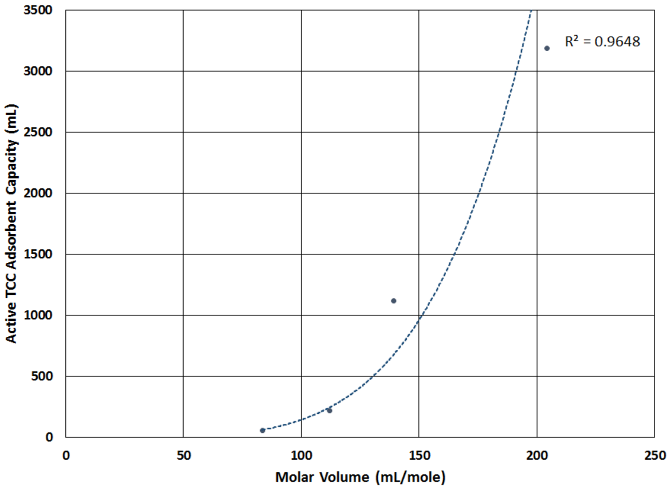

Figure 3. Molar volume influence on adsorbent capacity.

4. *Fluorinated Compound Thermal Stability*

Fluorocarbon compounds typically exhibit good thermal stability, particularly the straight carbon chain, fully halogen-saturated compounds such as tetradecafluorohexane and octafluoropropane. These compounds become concerns for thermal decomposition at temperatures >500 °C. The hydroflouroether and hydrofluorocarbon compounds, however, begin to decompose at temperatures <290 °C. Therefore, released quantities that exceed the active

TCC adsorbent's capacity are of greater concern because under active TCC thermal catalytic oxidizer operating conditions (400 °C), these compounds may decompose to form carbonyl fluoride (COF_2), trifluoroeacetyl fluoride (CF_3COF), hexafluoropropene (C_3F_6), and small quantities of hydrogen fluoride (HF). Thermal decomposition for these compounds usually requires long duration exposure to the high temperature condition on the order of hours to days. Comparatively the exposure duration is <1 second for most ECLS system high temperature processes. Yet, even considering a 1% oxidation efficiency, the risk for decomposition product production can reduce the quantity of leaked material that results in a concern substantially. In some cases the leaked material quantity based on thermal decomposition can be >98% lower than the quantity that results in active TCC adsorption capacity saturation. Therefore, care should be taken to select materials that are stable at temperatures exceeding 450 °C to provide margin.

5. Fluorinated Compound Removal Dynamics

Fluorinated compounds that are removed primarily by the active TCC aboard the ISS require approximately 60 hours to remove 95% of a given released quantity as long as the adsorbent capacity has not been exhausted. Under such conditions the environmental impact Category C applies. However, for quantities that exceed the active TCC capacity, the time to return the cabin to the initial condition that existed before the contaminant was released can exceed the 168 hours of Category E.

B. Polar Volatile Organic Compounds

Polar VOCs are another extreme as their incidental removal via absorption by humidity condensate can lead to impacts on water processing systems. While this compound class is removed by the active TCC equipment, extent of solubility in water can cause the incidental removal by humidity condensate to become the dominant removal route.

1. Polar VOC Removal via Absorption in Humidity Condensate

The single pass decimal removal efficiency, η, is calculated from Eq. 3 and used to determine the net increase in humidity condensate loading.[17] In Eq. 3, $\dot{m}_L$ is the humidity condensate collection rate in kg/h, T is the condensing

$$\eta = (0.004558889\dot{m}_L T)/[0.0045559\dot{m}_L TP + k_H(T)\dot{v}] \qquad (3)$$

heat exchanger operating temperature in Kelvin, P is the cabin total pressure of 1 atm, $k_H(T)$ is the Henry's Law constant in atm adjusted for the condensing heat exchanger's operating temperature, and $\dot{v}$ is the process air flow rate through the condensing heat exchanger core in m^3/h.

2. Polar VOC Bulk Release Quantities

For the ISS ECLS system Category E6 level, Table 6 shows that daily release quantities are typically below 1 mL. The very small daily quantity that contributes to a significant increase in humidity condensate loading highlights the need to use polar VOCs sparingly aboard crewed spacecraft. Suitable alternatives should be considered to reduce the risk for ECLS system impacts.

3. Polar VOC Removal Dynamics

As noted previously, the polar VOCs are removed by the active TCC with an assist from incidental removal via absorption in humidity condensate. The fraction of the load in the cabin environment can approach 20% for ethanol and >90% for triethylene glycol.[17] Aboard the ISS, the combined removal processes can provide 95% removal of this compound class within 5 hours for the most soluble compounds and 32 hours for the less soluble compounds. Therefore their cabin environmental impact aboard the ISS is typically in the range of Category B to Category C.

Table 6. Polar VOC ISS ECLS system compatibility levels.

Compound	Daily Release Quantity for ECLS Impact Category (mL)						
	E0	**E1**	**E2**	**E3**	**E4**	**E5**	**E6**
Ethanol	<0.05	>0.05 - 0.25	>0.25 - 0.64	>0.64 - 1.27	>1.27 - 1.9	>1.9 - 2.5	>2.5
Methanol	<0.004	>0.004 - 0.02	>0.02 - 0.05	>0.05 - 0.1	>0.1 - 0.16	>0.16 - 0.2	>0.2
Glycerol	<0.0003	>0.0003 - 0.0014	>0.0014 - 0.0034	>0.0034 - 0.0069	>0.0069-0.01	>0.01-0.014	>0.014
Isopropanol	<0.006	>0.006 - 0.03	>0.03 - 0.07	>0.07 - 0.14	>0.14 - 0.2	>0.2 - 0.3	>0.3
Ethylene glycol	<0.0005	>0.0005 - 0.002	>0.002 - 0.006	>0.006 - 0.012	>0.012 - 0.017	>0.017 - 0.023	>0.023
Propylene glycol	<0.0032	>0.0032 - 0.016	>0.016 - 0.04	>0.04 - 0.08	>0.08 - 0.12	>0.12 - 0.16	>0.16
Triethylene glycol	<0.0015	>0.0015 - 0.0017	>0.0017 - 0.0019	>0.0019 - 0.0022	>0.0022 - 0.0027	>0.0027 - 0.0031	>0.0031
Dimethylsulfoxide	<0.009	>0.009 - 0.01	>0.01 - 0.012	>0.012 - 0.014	>0.014 - 0.016	>0.016 - 0.02	>0.02
Acetone	<0.012	>0.012 - 0.06	>0.06 - 0.16	>0.16 - 0.32	>0.32 - 0.47	>0.47 - 0.63	>0.63

V. Conclusion

Contamination of a crewed spacecraft's cabin environment leading to ECLS system functional capability and operational margin degradation or loss can adversely affect space exploration mission safety, mission success, effectiveness, and affordability. Therefore, care in evaluating and selecting materials and chemicals used in vehicle and crew systems as well as experiment hardware plays an important role toward preserving the ECLS system's capabilities and functional margins in the event that a material is released into the cabin environment. A component of the overall process involves assessing ECLS system compatibility and cabin environmental impact as an integral part of TCC engineering. Including such assessments as a component of TCC design practice to effectively minimize the total trace contaminant load delivered into the cabin environment. The general approach to conducting ECLS system and cabin environmental impact assessments was presented and the rating definitions were introduced. Evaluation results for fluorinated thermal working fluids and polar VOCs show greater ECLS sensitivity for compounds that partition easily into humidity condensate. The ECLS system compatibility and cabin environmental impact assessment provides important information to crewed spacecraft system and payload developers relative to ensuring adequate physical and operational containment toward realizing a design for minimum risk.

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