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The Impacts of Cabin Atmosphere Quality Standards and Control Loads on Atmosphere Revitalization Process Design

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Maintaining the cabin atmosphere's pressure, composition, and quality within specified parameters is a necessity for successful crewed space exploration missions. A properly maintained environment minimizes health impacts on the occupants and maximizes their comfort. The challenge is to accomplish this outcome economically. The insight gained during the International Space Station's (ISS) operational lifetime is driving toward more challenging cabin atmospheric quality standards for future exploration missions. At the same time, the metabolic loads are increasing to accommodate a broader crew body size range and more rigorous exercise protocols to mitigate health effects associated with long duration microgravity exposure. Compounding this situation is new process equipment for handling trash and waste that may vent contaminants into the cabin. The limits placed on the cabin atmospheric quality parameters combined with the contaminant load define the design space for the atmosphere revitalization (AR) subsystem technologies to be deployed aboard the spacecraft. The impacts of changes to cabin atmospheric quality standards and contamination loads are evaluated and implications to future AR subsystem equipment design for future crewed exploration missions are explored.

Nomenclature

AR	=	atmosphere revitalization
CDRA	=	Carbon Dioxide Removal Assembly
CFU	=	colony forming unit
ECLS	=	environmental control and life support
EVA	=	extravehicular activity
ISS	=	International Space Station
NASA	=	National Aeronautics and Space Administration
TCC	=	trace contaminant control
C	=	concentration/Celsius
d	=	day
ft	=	feet
g	=	gram
h	=	hour
K	=	Kelvin
m	=	mass/meter
M	=	molecular weight
mol	=	mole
mm	=	millimeter
p	=	pressure/partial pressure
Pa	=	pascal
t	=	time
T	=	temperature
T_H	=	toxic hazard index
r	=	generation rate
R	=	ideal gas constant
V	=	volume

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η	=	efficiency
ηm	=	micrometer
CO_2	=	carbon dioxide
Hg	=	mercury
LiOH	=	lithium hydroxide

I. Introduction

SUCCESSFULLY executing crewed space exploration missions requires a safe, breathable cabin atmosphere which is maintained within specified pressure, composition, and quality standards. The goal is to provide a living environment in which the occupants are healthy, comfortable, and productive during all mission phases. Such an environment minimizes health impacts on the occupants and maximizes their comfort. Accomplishing this goal economically is a substantial technical challenge for the environmental control and life support (ECLS) system. The ECLS system aboard crewed spacecraft consists of various subsystems to purify the atmosphere, control atmospheric pressure and composition, control cabin temperature and humidity levels, recover and manage water, manage waste, and respond to emergency situations.[1] Specific to minimizing crew health impacts, the atmosphere revitalization (AR) subsystem purifies the cabin atmosphere by removing carbon dioxide (CO_2), trace chemical contaminants, and particulate matter via various means.

Carbon dioxide removal is accomplished via consumable or regenerable means depending on the mission needs. Short duration missions, typically those lasting 20 days or less, have used consumable lithium hydroxide (LiOH)-based CO_2 removal approaches. Such an approach is economically and logistically impractical for longer duration missions which have used approaches based on regenerable sorbents.[2] According to a mission's logistics needs, the CO_2 removed from the cabin atmosphere may be disposed of or processed to recover oxygen.

Active trace contaminant control (TCC) is typically provided via a combination of adsorbent and catalytic oxidation processes. Granular activated carbon and precious metal catalysts are commonly employed in TCC process equipment.[3]

Removing suspended particulate matter, including the crew-generated bioburden and debris associated with crew activities, from the cabin atmosphere protects crew health, prevents equipment fouling, and aids in general housekeeping by maintaining a low total dust level in the cabin environment. Various screens and media filters are commonly deployed throughout the cabin ventilation system to collect particulate matter. The collected particulate matter is disposed of via filter element replacement coupled with routine housekeeping to remove debris that accumulates on ventilation screens.

All of the AR subsystem process equipment acts on a generation load to maintain the cabin atmosphere within a specified standards for CO_2 partial pressure, trace contaminant concentrations, and suspended particulate matter concentrations. The cabin material balance applied to the combination of generation load and cabin atmospheric standard provides the design guidance for establishing process equipment flow rates and single pass efficiencies. The following presents and discusses the influences that the generation load magnitude and cabin atmospheric standard have on AR subsystem process equipment design.

II. The Design Basis

For crewed space exploration missions the cabin atmospheric quality parameters are maintained within limits specified by the NASA Space Flight Human-System Standard (NASA-STD-3001) with further guidance provided by the NASA Human Integration Design Handbook (NASA/SP-2010-3407). In some instances, the specified limits and loads may be tailored for a particular mission by taking into account recently published research and crewed space flight experience. The limits placed on the cabin atmospheric quality parameters combined with the relevant contaminant load define the design space for the AR subsystem process equipment.

Selecting the specific process technologies to be deployed aboard the spacecraft for each AR subsystem function in order to best conform with mission objectives constitutes a trade space that is beyond the scope of this work. Examples presented by this work are not meant to endorse a specific process technology but are selected to illustrate influences that the combination of generation load magnitude and cabin atmospheric standards have on key equipment design parameters, particularly process air flow rate.

Using CO_2 removal as an example, the CO_2 partial pressure defined in NASA-STD-3001[4] and the crew metabolic load contained in NASA/SP-2010-3407[5] serve as inputs to a cabin-level CO_2 material balance that is used to determine the CO_2 removal equipment's effective process air flow rate. This material balance, defined by Eq. 1 for a mass basis, is similarly applied to TCC and particulate matter removal design and is instrumental for establishing the equipment's performance as well as understanding impacts resulting from varying the key cabin atmospheric quality parameters.

$$ {}^{dm}/_{dt} = r_i - \left({}^{\eta\dot{v}}/_{V} \right) \mathrm{m} \quad (1) $$

In Eq. 1, m is mass (g), t is time (h), r_i is contaminant generation rate (g/h), $\dot{v}$ is the removal device volumetric flow (m^3/h), η is the removal's single pass efficiency (dimensionless), and V is the cabin volume (m^3). Dividing Eq. 1 by the cabin volume yields Eq. 2 which is the material balance for a concentration basis where C is the contaminant concentration (g/m^3).

$$ {}^{dC}/_{dt} = {}^{r_i}/_{V} - \left({}^{\eta\dot{v}}/_{V} \right) C \quad (2) $$

For AR subsystem design, particularly for TCC and particulate matter removal, the steady state form of Eq. 2 is used in which the removal and generation terms balance. Equation 3 provides the steady state material balance for the concentration basis.

$$ C = {}^{r_i}/_{\eta\dot{v}} \quad (3) $$

In the case of CO_2 removal, a pressure basis is commonly used. Concentration can be converted to pressure via the ideal gas law according to Eq. 4 where M is molecular weight (g/mole), p is partial pressure (Pa), R is the ideal gas constant (8.314 m^3·Pa/mol·K), and T is absolute temperature (K).

$$ C = {}^{Mp}/_{RT} \quad (4) $$

Substituting Eq. 4 into Eq. 2 yields Eq. 5 which is the material balance for a pressure basis.

$$ {}^{dp}/_{dt} = \left({}^{RT}/_{MV} \right) r_i - \left({}^{\eta\dot{v}}/_{V} \right) p \quad (5) $$

At steady state, the rate of change is zero and the removal and generation terms balance. At this condition Eq. 5 simplifies to yield Eq. 6.

$$ p = \left({}^{RT}/_{M} \right) \left({}^{r_i}/_{\eta\dot{v}} \right) \quad (6) $$

Solving Eq. 6 for the removal flow rate, $\eta\dot{v}$, yields Eq. 7 which is the basic design equation for CO_2 removal

$$ \eta\dot{v} = \left({}^{RT}/_{M} \right) \left({}^{r_i}/_{p} \right) \quad (7) $$

equipment using a pressure basis. Similarly, solving Eq. 3 for the removal flow rate yields Eq. 8.

$$ \eta\dot{v} = {}^{r_i}/_{C} \quad (8) $$

Equations 7 and 8 illustrate the relationship that exists between the cabin air quality limit, the crew metabolic load, and the active removal hardware flow rate. As can be seen by examining Eqs. 7 and 8, the active AR subsystem removal device flow rate is directly proportional to the generation rate and inversely proportional to contaminant partial pressure or concentration. Thus, the required flow rate increases as the specified partial pressure or concentration decreases or as the generation rate increases. A combination of a high generation rate and a low partial pressure or allowable concentration specification requires high flow capacity to achieve the desired cabin condition. A high flow capacity results in attendant impacts on equipment mass, power, and volume.

The following considers the impacts associated with variations in the cabin air quality limits and generation rate specifications relating to AR subsystem equipment design. It is assumed that technologies used in the AR equipment is similar to those deployed aboard the International Space Station (ISS) for CO_2 removal, trace contaminant control, and airborne particulate filtration.

III. Carbon Dioxide Removal Design Impacts

As illustrated by Eq. 7, the key design parameters for CO_2 removal technologies are the crew metabolic load (r_i) and the cabin partial pressure limit (p) which are used to determine the necessary removal device flow rate ($\eta\dot{v}$). These parameters are applied to the exploration mission CO_2 removal system design constraints for mass, power, and volume.[6] In the case of CO_2, the crew metabolic load defined by NASA/SP-2010-3407 is 43.3 g/h for a single person. This equates to 173.3 g/h for a crew of four. This crew size is specified for cis-lunar and Mars transit habitable platforms[7] and is applied to the metabolic load defined by NASA/SP-2010-3407 as the basis for CO_2 removal technology development. [6]

Applying Eq. 7 to this 4-crewmember load for a range of cabin partial pressures yields the necessary volumetric flow. Varying the single pass efficiency, η, results in a family of curves illustrated by Fig. 1. This family of curves applies to the CO_2 removal function in general and is not specific to the process technology employed or the exploration vehicle or habitat platform on which the equipment is deployed. For reference, typical physical adsorption-based CO_2 removal process efficiencies range between 75% and 85% for a partial pressure control range between 213 Pa (1.6 mm Hg) and 533 Pa (4 mm Hg). Process efficiencies for other candidate process technologies may vary similarly.

The partial pressure range presented in Fig. 1 extends from 67 Pa (0.5 mm Hg) to 800 Pa (6 mm Hg) which covers a range of partial pressures of interest to designing and sizing spacecraft CO_2 removal equipment summarized in Table 1. Included in Table 1 are NASA spacecraft maximum allowable concentrations for continuous exposures ranging from 7 days to 1000 days[8, 9] and a recommended physiological limit[10] for long duration crewed exploration missions.

The typical operating range for the CO_2 partial pressure aboard the ISS that is maintained by the combined action of the CDRA in the U.S. Segment and the Vozdukh unit located in the Russian Segment on a 6-crewmember load is between 267 Pa (2 mm Hg) and 533 Pa. The Vozdukh provides up to 27 m^3/h actual flow[11] that when combined with the nominal ~35 m^3/h CDRA flow provides a total ~62 m^3/h CO_2 removal flow rate. This configuration nominally controls the CO_2 partial pressure to ~400 Pa (3 mm Hg) for a 6-crewmember load.[12]

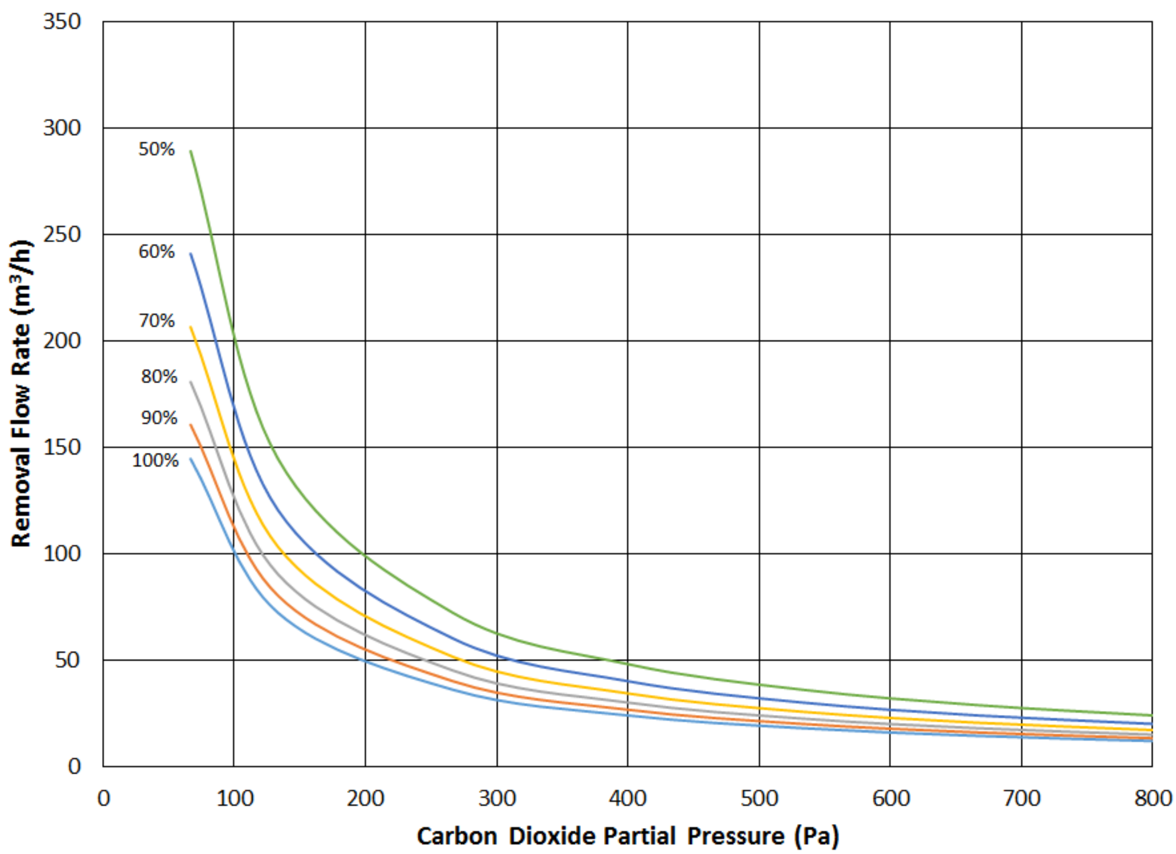

Figure 1. Flow rate for CO_2 control at different partial pressure targets.

Table 1. Carbon dioxide concentrations of interest for spacecraft ARS equipment design.

Concentration*					Notes
ppm	volume %	Pa	mm Hg	mg/m^3	
409	0.04	41	0.31	746	Earth atmospheric 2018 (https://www.co2.earth/daily-co2)
2150	0.22	218	1.6	3922	20% margin for proposed exploration mission
2632	0.26	267	2.0	4801	Proposed exploration mission
3947	0.39	400	3.0	7200	ISS CHIT (guideline); 20% margin for NASA 1000-d (2008)
5000	0.50	507	3.8	9121	Waligora nominal level 1979[10]; NASA 1000-d (2008)[8]
5263	0.53	533	4.0	9601	ISS Flight Rule B13-53
5578	0.56	565	4.2	10176	20% margin for NASA 180-d (1996; 2008)
7000	0.70	709	5.3	12770	NASA 7-/30-/180-d (1996; 2008)[8, 9]
10000	1.00	1013	7.6	18242	Waligora 1979 space flight limit[10]
12895	1.29	1307	9.8	23524	NASA 1-hour/24-hour (1996; 2008)[8, 9]
13158	1.32	1333	10.0	24003	NASA exposure >8 hours not permitted
19737	1.97	2000	15.0	36005	NASA off-nominal level, requires immediate action
26316	2.63	2666	20.0	48007	NASA emergency level

*At 101.3 kPa and 294 K.

A. Impacts from Design Point Specifications

As can be seen from Fig. 1, the volumetric flow rate required for the CO_2 removal process increases rapidly for cabin conditions below 300 Pa (2.5 mm Hg). Operating in the range below 267 Pa requires increasing the flow by 100% relative to operating at 533 Pa and by 50% relative to operating at 400 Pa (3 mm Hg). This holds for the entire family of curves in Fig. 1.

It should be noted that the family of curves depicted by Fig. 1 represent the flow rate necessary to maintain a steady state concentration condition. Actual flow rate capability must be higher to attenuate peak concentrations during the load levels experienced during crew exercise periods and also to account for crew distribution in a habitable volume. The former can become a significant challenge for exploration-class vehicles that will have a cabin volume that is ~80% smaller than the ISS cabin volume thus affording less concentration attenuation during peak metabolic load periods. The latter consideration can require applying up to a 20% margin to the target control point to account for concentration gradients.[13] Thus, if the target control point is 267 Pa, the CO_2 removal design point should use a 20% lower partial pressure or 213 Pa (1.6 mm Hg) as noted in Table 1. At this design point, the flow is 150% higher than controlling to 533 Pa and 88% higher than operating at 400 Pa. This margin magnitude is approximately two times the magnitude of the typical module-to-module partial pressure gradient of 37 Pa (0.28 mm Hg) compared to the control point of 400 Pa observed aboard the ISS; however, material balance studies under worst case conditions with the entire crew situated in a remote location from the removal equipment can approach a gradient magnitude of 80 Pa (0.6 mm Hg). Thus, the 20% margin is considered to be a reasonable magnitude.

A potential problem that may arise for CO_2 removal processes that include a process air drying stage is over-drying the cabin during low metabolic loading periods. The CO_2 removal equipment may have to provide an automated software control strategy and equipment capability to provide for variable flow and process variable adjustment capabilities. Adding such features may complicate the hardware control design. The need for such a capability requires additional study.

B. Impacts from Metabolic Load Specification

As is evident from Eq. 6, the CO_2 removal process flow rate is directly proportional to the metabolic load. If the daily exercise duration increases or the crewmember physical size increases, a higher metabolic load results. For example, modifying the exercise period to include 45 minutes of aerobic activity and 45 minutes of resistance activity combined with accounting for two 95th percentile male crewmembers at ~26% higher metabolic loading than the basic load specified by NASA/SP-2010-3407.[14] Incorporating the two 95th percentile crewmembers within the exploration mission 4-crew guideline increases the metabolic load by 17% to 202.5 g/h. Given that the CO_2 removal process flow rate is directly proportional to the metabolic load, an equivalent flow rate functional margin is necessary to accommodate variations in crewmember physical characteristics and their daily activity levels.

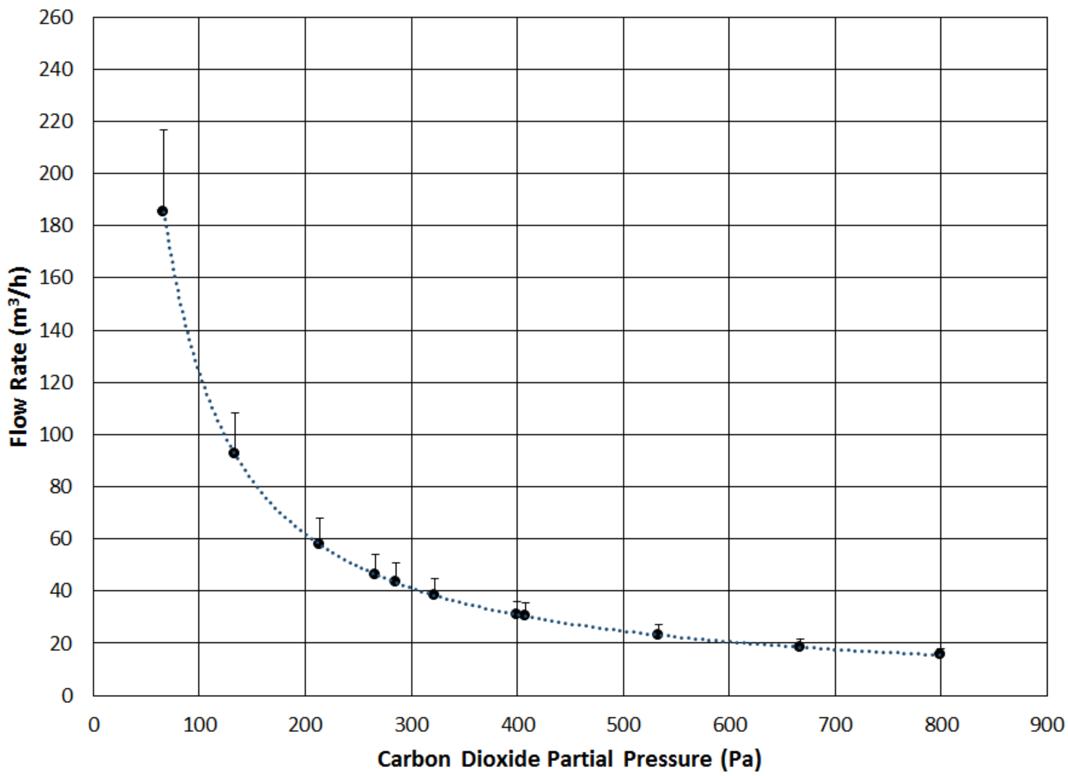

Figure 2. Functional margin applied to a CO_2 removal unit operating at 78% efficiency to accommodate metabolic load growth.

Figure 2 shows a 17% margin, depicted by the error bars, applied to the flow rate curve for a CO_2 removal unit operating at 78% efficiency. This functional margin is on top of the 20% design point margin. Thus, at a 213 Pa design point resulting from the 20% partial pressure design point margin the required flow to accommodate 17% increase in metabolic load is 67.7 m^3/h. This flow exceeds the combined flow of the ISS CDRA and Vozdukh units and is 119% and 191% higher than the unadjusted design points at 400 Pa and 533 Pa, respectively.

It is interesting to note that the technical evaluation reported by Ref. 12 indicates that the Vozdukh and two CDRA units must be operating to consistently maintain the CO_2 partial pressure below 267 Pa. The process flow capacity of operating the Vozdukh and two CDRA units provides ~96 m^3/h to maintain a CO_2 partial pressure condition <267 Pa for a 6-crewmember load. This normalizes to ~16 m^3/h-crewmember. Applying this specific flow rate to a 4-crewmember load yields ~64 m^3/h which is consistent with the 67.7 m^3/h flow rate necessary to accommodate both a lower partial pressure and crew metabolic load variation. This similarity in flow rate indicates that the CO_2 removal capability aboard the ISS is a good indicator of the resources necessary for CO_2 control aboard future exploration-class vehicles and habitats. As noted earlier, these flow rate increases apply to the CO_2 removal function in general and are not specific to the process technology employed or the exploration vehicle or habitat platform on which the equipment is deployed.

Further capability margin beyond 17% may be necessary to accommodate an exploration requirement for the Orion vehicle to provide a capability to support a crew size up to six.[15] The crew size for cis-lunar habitats and Mars transit vehicles is specified to be four;[7] however, these deep space habitats and vehicles may likely need to provide for at least the 17% capability margin.

C. Impacts from Interaction between the Design Point and Removal Efficiency

The removal efficiency is an important factor in Eq. 6. While Fig. 2 is based on 78% removal efficiency at the 267 Pa design point, as the design point is lowered a lower efficiency is likely. This is due to the mass transfer limitation associated with adsorption and absorption processes. Testing conducted in 2014 for an adsorption-based process operating at 42.5 m^3/h observed peak efficiency of ~83% at ~530 Pa.[16] At the 267 Pa design point, ~78% removal efficiency was observed. The flow rate magnitude required to control to the 267 Pa design point is consistent with the performance curve illustrated by by Fig. 2. Below the 267 Pa design point the efficiency was observed to decrease sharply toward 65% as the CO_2 partial pressure approached 133 Pa. At a 213 Pa design point, an efficiency of ~74% is expected based on these testing results. To accommodate reduced efficiency, a 5% flow rate increase is required. It should be noted that these results required adjusting the adsorbent bed regeneration cycle from 144 minutes to 90 minutes. The combination of a more rapid regeneration cadence required a minimum 200 W increase in heater power. Additional power is required to provide the higher flow rate.

D. Power Growth at Low Carbon Dioxide Partial Pressure Design Points

As the process flow rate rises, the means to provide flow through the system, managing pressure drop through the system, and provide process heating and cooling become more technically challenging. The higher flow rates necessary to achieve lower cabin CO_2 partial pressures lead to overall higher power requirements for the CO_2 removal functional element. As shown by Fig. 3,[17] the blower power and average heater power rise substantially for controlling the cabin CO_2 partial pressure below 400 Pa for state-of-the-art adsorbent-based process technology capable of supporting life support system mass closure. The ISS CDRA serves as a basis for the power growth estimate. The increase in heater power results because it is necessary to use shorter regeneration cycle times to accommodate the more rapid bed loading produced by the higher flow rate. The overall effect is that the total average power required for a CO_2 removal design point at 213 Pa is estimated to be >1.3 kW which is 62% higher than the 0.8 kW for the 400 Pa design point. This power magnitude is similar to what is indicated by Ref. 12 in which the systems aboard the ISS require ~350 W/crewmember to maintain a CO_2 partial pressure <267 Pa. The power may rise by a greater magnitude to provide the capability to attenuate peak cabin concentrations experienced during crew exercise periods. Peak power may increase by a similar magnitude.

It should be noted that the state-of-the-art CO_2 removal capabilities aboard the ISS cannot achieve partial pressures below 267 Pa without redesigning the blower to accommodate the higher flow rates needed. Therefore, a significant blower design effort is necessary along with developing other components such as selector valves that can withstand a greater number of actuation cycles per annum while still providing overall higher reliability. Some of these performance goals could prove to be mutually exclusive.

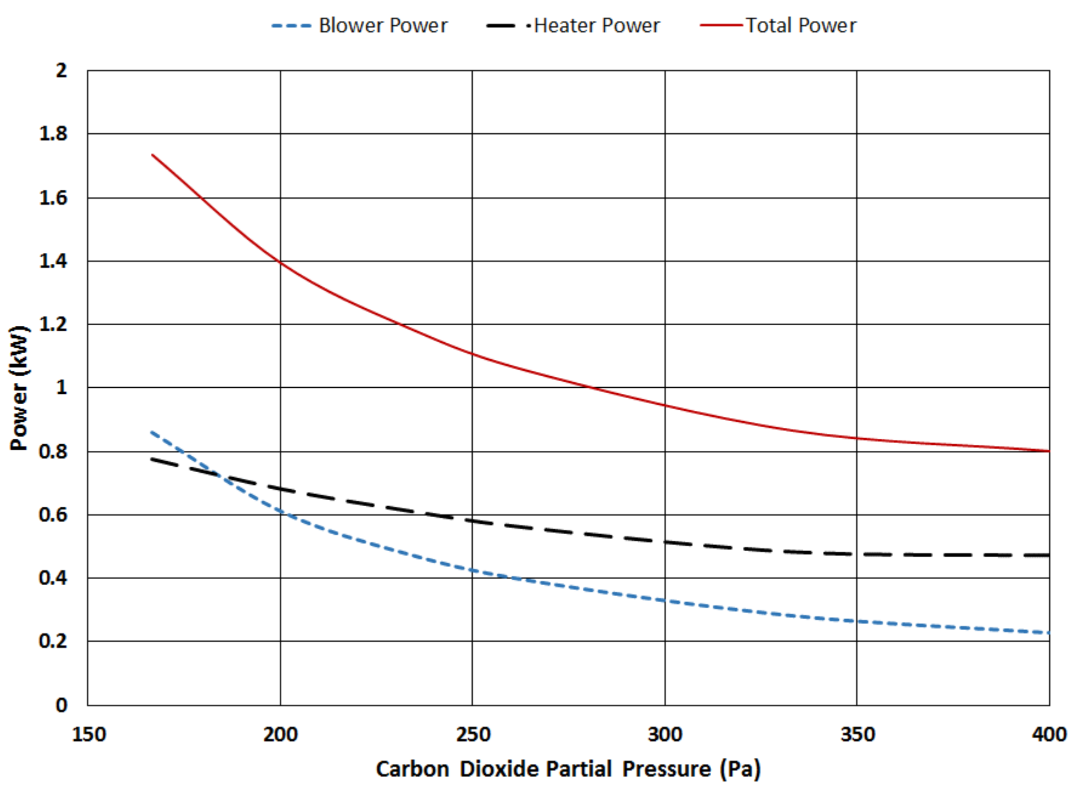

Figure 3. Average power for controlling CO_2 to various concentrations.[17]

E. Impacts on Recovering Oxygen from Carbon Dioxide

At lower cabin partial pressures, the working capacity of adsorption-based and absorption-based process technologies similar to the ISS CDRA and amine-based sorbents decreases because the mass transfer driving force, which is sensitive to concentration, decreases. This phenomenon is illustrated by Fig. 4 for a physical adsorption-based process using Grade 544 13X zeolite adsorbent media.[18] In this illustration, the adsorption isotherm at 10 °C is shown with the CO_2 partial pressure at 267 Pa compared to 133 Pa (1 mm Hg). At these conditions, there is a 19.8% reduction in working capacity which can be expected during the adsorption step (1). This is important in that as shown by Fig. 4, the reduced working capacity means a lesser quantity of CO_2 available at any time to deliver to a downstream CO_2 reduction process in step (2) and bed pressure reduction provided by a downstream compressor in step (3) which is illustrated by the red lines. The adsorption isotherm at 200 °C is shown which establishes the residual loading. To fully regenerate the adsorbent, exposure to space vacuum is necessary in step (4). The cycle then repeats. Compared to operating at partial pressures between 533 Pa and 400 Pa, operating at partial pressures of 267 Pa and lower can result in up to 33% reduction in working capacity for a system sized within the mass and volume constraints for state-of-the-art CO_2 removal technology. Such working capacity impacts are expected for any CO_2 removal technology that is mass transfer limited. Unless this effect is compensated for in some way, the ability to meet exploration goals for reclaiming oxygen from CO_2 will be compromised.

Compensating for the reduced working capacity may require process changes to use more rapid regeneration cycles than necessary merely to control the CO_2 load which have the effect of increasing the average power necessary to regenerate the beds beyond the levels discussed earlier. Improved single pass efficiency at higher process flow rates will also be necessary regardless of the process technology. This aspect needs to be evaluated in detail and fully understood to quantify the degree of the impact. These more rapid cycles also lead to more frequent valve cycling and higher duty cycles for other supporting components which lead to shorter service lives. In turn, shorter service lives leads to the need to plan for higher maintenance frequency and may require more spare parts to be maintained in the mission inventory leading to an overall increase in mission mass and volume. These effects can place the objective to provide a CO_2 removal function for exploration missions within a mass, power, and volume envelope that is smaller than the state-of-the-art equipment at significant risk. Substantial evaluation is necessary to fully quantify the extent of the impacts at both the functional and system levels.

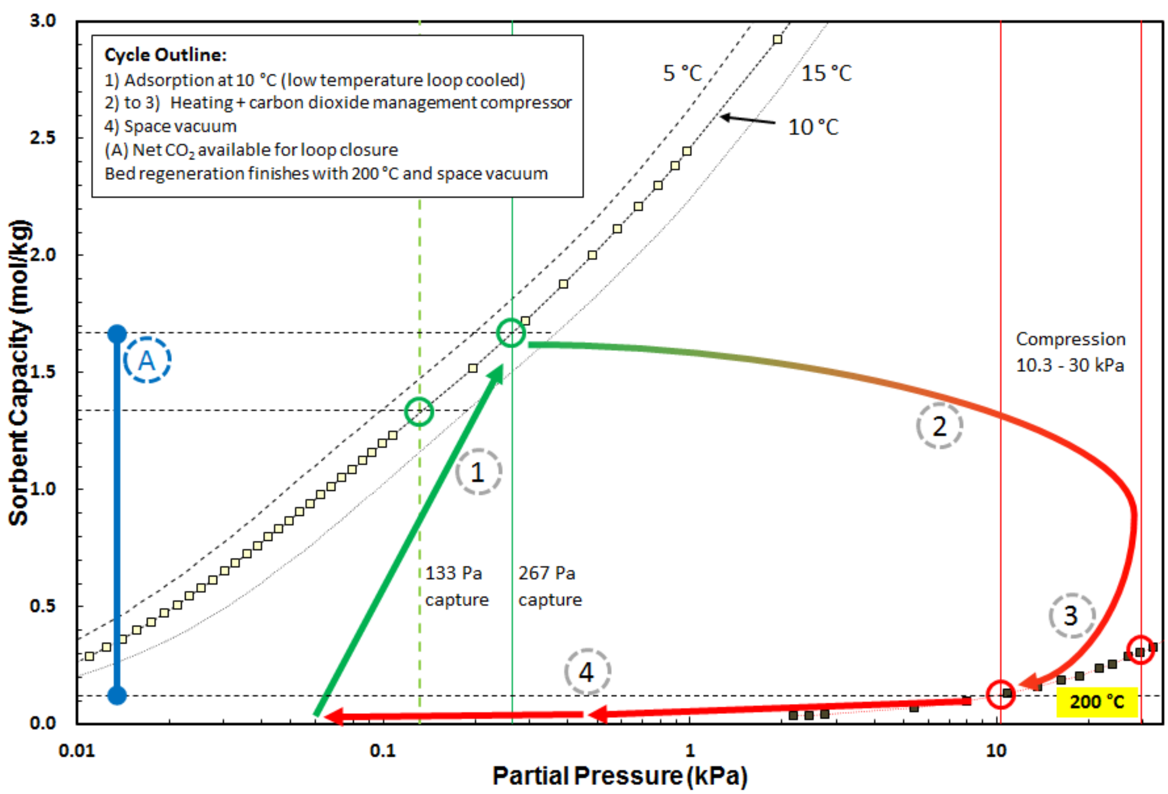

Figure 4. Cabin partial pressure effects on CO_2 available for delivery to reduction processes.[18]

IV. Trace Contaminant and Particulate Matter Removal Design Impacts

Equation 8 defines the effective flow rate for TCC and particulate matter removal equipment. As previously discussed, the process air flow rate is directly proportional to the load and inversely proportional to the maximum cabin concentration standard. Therefore, a higher process air flow rate is necessary to accommodate load growth combined with more stringent maximum cabin concentration standards.

A. Trace Contaminant Control

Design considerations for TCC are discussed in detail by Ref. 19 and a recommended design load is provided by Ref. 20 with additional guidance provided by Refs. 21 and 22. The total non-methane trace contaminant generation for an exploration class habitat with a crew of four is 37 mg/h. Ammonia, hydrogen, carbon monoxide, and methane generation are predominantly from human metabolic processes and four crewmembers add 8 mg/h, 17 mg/h, 3 mg/h, and 98 mg/h to the total load, respectively. The maximum cabin concentration standards are found in Ref. 9. The following narrative examines the impacts associated with trace contaminant load sources above the basic load consisting of crew metabolic products and equipment offgassing. As well, the impacts from more stringent maximum cabin concentration standards and how these standards are implemented for TCC equipment design are discussed.

1. Additional Trace Contaminant Load Source Impacts

In general, for small crewed vehicles and habitats trace contaminant generation from human metabolism is the dominant load source component. As the habitable cabin size approaches that of the ISS, the equipment offgassing component begins to become dominant. Yet, as the drive toward a higher degree of mission material balance closure is sought to achieve an Earth-independent logistics management goal, additional processing equipment for recovering water and managing trash is being introduced into the ECLS system that produce vent gases which contain a significant trace contaminant load. This additional equipment to recover water from urine distillation brine and a trash management unit that employs heated compaction.[23, 24] If these processes do not employ source contamination control as part of their design and vent their contaminants into the cabin, then the added contaminant load increases the overall load on the primary cabin TCC equipment. As indicated by Eq. 8, increased load is directly proportional to increased TCC equipment flow rate to maintain the allowable cabin concentration condition. While equipment operation can be scheduled to minimize the impact, it is prudent that the active TCC capability be sufficient to accommodate the total load.

Processing urine via vapor compression distillation has been observed to add 0.1 mg/h non-methane contamination to the basic TCC design load.[25] This additional contamination load is <1% of the basic TCC design load and is easily accommodated within the functional margin of the active TCC equipment. The additional processes to enhance the degree of mission mass closure, however, produce much higher contamination loads. Recovering water from urine distillation brine is projected to produce 38 mg/h of additional non-methane contamination load during a typical process run while the heated trash compaction process is projected to produce 118 mg/h additional non-methane contamination load during a typical 390 minute process run.[23, 26, 27] In practice, it is preferred to remove contamination from such processes at the source rather than venting it into the cabin environment. However, there may be utility in simplifying the urine brine and trash management equipment to vent directly into the cabin environment. Using Eq. 8 to evaluate the flow rate impact associated with TCC load growth from these sources shows flow rate increases at a minimum on the order of a factor of two and a factor of four for recovering water from urine distillation brine and heated trash compaction, respectively. If both processes are to be used, then the TCC equipment flow rate must be increased by more than a factor of five. Proportional increases in TCC equipment volume and power can also be anticipated. The acceptability of such mass, power, and volume increases for the cabin TCC equipment must be determined by trade analysis versus the mass, power, and volume impacts associated with providing contamination control at the generation source.

2. Maximum Cabin Concentration Updates and Implementation Impacts

The maximum cabin concentration standards are periodically updated as new knowledge from human toxicology research becomes available. As well, as future exploration mission durations approach 1000 days, some concentration standards have been revised to mitigate health effects associated with the cumulative chemical exposure associated with the longer mission durations. For example, the maximum cabin concentration standard for ammonia, a key contaminant used to define the TCC equipment flow rate, has decreased from 7 mg/m^3 in 1995 to 2 mg/m^3 in 2008. For a given load, evaluation using Eq. 8 indicates this decrease in maximum cabin concentration standard requires a 3.5 times increase in process air flow rate.

In 2009, the metabolic ammonia production was reassessed and the design load decreased from 351 mg/d-crewmember to 50 mg/d-crewmember.[20] Compared to the combination of load and control standard in 1995, the flow rate necessary to comply with the present load and control standard using common design practice to maintain the concentration below 50% of the maximum concentration standard is nearly two times lower. In this case the updated ammonia metabolic load offsets the lower maximum cabin concentration standard.

Beyond updates to the maximum cabin concentration standard and load, the concept of toxic hazard index, T_H, defined by Eq. 9 is being introduced as a TCC design criterion. In Eq. 9, C_i is the individual contaminant concentration

$$T_H = \sum {C_i}/{C_{max}} \tag{9}$$

and C_{max} is the maximum concentration standard for the individual contaminant. The toxic hazard index addresses additive health effects and is consistent with the guidelines for threshold limit values for mixtures issued by the American Conference on Governmental Industrial Hygienists. This concept is also used by spacecraft environmental health organizations to evaluate the combined effects of the mixture of trace contaminants found in a typical cabin atmosphere.

The relationship between toxic hazard index and the TCC effective flow rate is obtained by substituting for C_i in Eq. 9 with Eq. 8 solved for the contaminant concentration and rearranging to solve for the flow rate to yield Eq. 10.

$$\eta\dot{v} = \left({1}/{T_H}\right) \sum {r_i}/{C_{max}} \tag{10}$$

As can be seen from Eq. 10, flow rate and the toxic hazard index are inversely proportional. Also, the flow also increases as the number of contaminants used for design increases. Therefore, it is necessary to limit the number of contaminants used for design to avoid excessive flow rate growth when using the toxic hazard index as a design criterion.

A proposed goal is to maintain the metabolic load component below a toxic hazard index value of 0.5. Achieving this condition can require the control concentration target to be as low as 21% of the maximum concentration standard.[19] In total, accounting for maximum cabin concentration updates and load updates since 1995 and implementing the toxic hazard index as a design criterion results in a flow rate increase of 19% over the 1995 design point. Further analysis indicates that applying a toxic hazard index of 0.5 to the metabolic load component results in an increase in process air flow by a factor of 2.4 compared to the standard practice of designing to one-half the concentration standard. The latter flow increase magnitude can be reduced to a factor of 1.5 by maintaining an overall toxic hazard index value of 1.0 for the total contaminant instead of 0.5 applied to the metabolic load component.

As noted previously in the discussion of Fig. 3, as flow rate increases the power needed to provide the motive force and in cases of thermal catalytic oxidation to heat the process air increases proportionally. Other impacts associated with increasing flow rate include more rapid adsorbent bed capacity consumption which leads to increased recurring costs. Adsorbent bed and other component designs, therefore, must balance is pressure drop characteristics and size to yield the most economical solution relative to mass, volume, power, and logistics management.

B. Particulate Matter Removal

Design considerations for particulate matter removal are presented by Ref. 28. Media filters used aboard crewed spacecraft typically provide >99.97% removal efficiency for the particle size range of interest in NASA-STD-3001. Particulate matter sources with consideration to the bioburden component are summarized. The impacts of the bioburden component generation load component and surface dust intrusion on the particulate matter removal flow rate is evaluated and discussed.

1. Particulate Matter Control Standards and Generation Sources

Standards applied to particulate matter in the cabin atmosphere cover not only suspended particulate matter but also the biological component associated with human-generated particles. According to guidance provided by NASA-STD-3001, particulate matter concentrations in the cabin atmosphere must be maintained to <1 mg/m^3 for the size range between 0.5 µm and 10 µm and <3 mg/m^3 for the size range between 10 µm and 100 µm. This requirement is 80 times less challenging than that used by the ISS Program which specified <0.05 mg/m^3 for the size range between 0.5 µm and 100 µm. The microbial concentrations must be maintained to <1000 CFU bacteria/m^3 and <100 CFU fungus/m^3. Key to specifying the technical solution that provides these conditions is an understanding of the particle generation sources and total load along with the microbial content of that total load.

A literature survey indicates that people shed particles >0.5 µm in size at a rate of approximately 10^6 particles/hour or ~16670 particles/minute.[29] Further details from the literature survey indicate particle generation rates of 0.9 +/- 0.3 million particles/hour (10000 to 20000 particles/minute) for particles in the 2.5 µm to 10 µm range.[30] For particles >5 microns, Licina et al. reports 0.6 million/hour which is similar to findings of Bhangar et al. at 0.7 million/hour.[31] In general, the literature survey indicates that the fraction of particles below 1 µm can be generated at a rate of 57 million particles/hour (950000 particles/minute), the fraction >1 µm and <5 µm at a rate of 10 million particles/hour (166700 particles/minute), and the faction >5 µm and <10 µm at a rate of 1 million particles/hour (16670 particles/minute). An additional 20000 particles/minute can be generated for the size fraction >10 µm.[32] The 1.153 million particle/minute total generation rate for all size fractions is 51 times higher than the total load used as the design basis for the ISS cabin filtration design. On a mass basis, the generation is estimated to be ~1.33 mg/minute for a single crewmember. This is 4.3 times higher than the ISS cabin filtration design load. Of this mass generation load, 1.31 mg/minute is for the size fraction >10 µm. Controlling this load for a crew of four requires 0.8 m^3/minute (2.8 ft^3/minute) flow for the size fraction <10 µm and 1.7 m^3/minute (61.6 ft^3/minute) flow for the size fraction >10 µm. By comparison, meeting the ISS requirement using the ISS load for four crewmembers requires 24.8 m^3/minute (876 ft^3/minute). It is evident in this case that the less stringent cabin concentration standard results in a more manageable situation. However, another particulate matter removal component, the microbial generation load, which can dictate the total filtration system flow must be considered.

The total particulate matter load possesses a microbial component. The literature survey cited previously indicates that approximately one of every 10^3 of the particles >2 µm is fungal related while one of every 10^6 particles <1 µm and one of every 10^3 of particles >1 µm is bacterial related. The fungal particles typically are in the range of 2 µm to 50 µm and the bacterial particles are typically in the range of 0.1 µm to 6 µm.[33] Usually, <1% of the bioburden is viable. Applying the bacterial and fungal associations, the microbial generation is estimated to be 204 bacteria-related particles/minute and 53 fungal-related particles/minute. The total microbial load of 257 particles/minute is approximately six times lower than the design load used for the ISS cabin filtration design.

Coughing and sneezing can add significantly to this personal cloud. The number of particles produced by coughing varies from person to person and can produce between 1000 and 300000 particles for each instance.[34] Mean particle size is approximately 10 µm with a range from 0.6 µm to 16 µm for healthy adults.[35] Healthy adults cough infrequently according to one study at a rate of no more than twice each day.[36] However, a study of healthy children reported approximately 11 coughing episodes per day.[37] Similarly, sneezing can produce up to 100000 particles ranging in size between 1 µm and 2000 µm with most in the range between 2 µm and 100 µm. Reported geometric mean droplet size is approximately 74 µm.[35] Sneezing episodes are reported to be less than four per day. In total, coughing and sneezing can add 694 particles/minute to the total particle generation load. The microbial content, however, is projected to be low in comparison to the microbial generation discussed previously due to the infrequent nature of coughing and sneezing by healthy adults.

Based on a load consisting of 204 bacterial-related particles/minute and 53 fungal-related per crewemember, the filtration system flow to accommodate four crewmembers is 0.82 m^3/minute (29 ft^3/minute) and 2.12 m^3/minute (74.9 ft^3/minute). Controlling the fungal-related particle generation load is the greatest cabin filtration challenge and can serve as a surrogate for controlling the entire crew-generated particulate load. Incorporating 10% to 20% design margin should yield a highly capable cabin filtration design.

2. Surface Dust Intrusion

Surface dust intrusion overlays the basic particulate generation load and is a major challenge for the cabin filtration system design. Lunar surface dust that enters the cabin environment must be maintained below 0.3 mg/m^3 for the size range <10 µm according to guidance provided by NASA-STD-3001. Characterizing the surface dust intrusion load is instrumental to the filtration system design. Early attempts to characterize the load estimated that approximately 227 grams of surface dust in the size range <10 µm per crewmember could collect on the extravehicular activity (EVA) suit.[38] For a 2-person EVA, the time-averaged dust intrusion rate over 24 hours was estimated to be 22.1 mg/minute. This rate assumed that 7% of the dust becomes airborne while the remainder is controlled by other means before entering the surface habitat.[39] This is a dust intrusion barrier effectiveness of 93%. Controlling this time averaged load within the cabin concentration standard requires 73.7 m^3/minute (2600 ft^3/minute) flow through a filtration system rated at 99.97% efficiency. This flow is substantially higher than what is necessary to control the basic crew-generated particulate matter load. If more effective barrier and EVA suit cleaning techniques are used, then the basic cabin filtration capability may be sufficient. Barrier and cleaning capabilities that prevent 99.6% of the surface dust from entering the habitable environment reduce the filtration flow for controlling surface dust to within the flow range to control the basic crew-generated particulate matter load. Doubling cabin filtration system flow still requires 99.2% dust intrusion barrier effectiveness. From this assessment, it is evident that preventing surface dust intrusion into the habitable environment is a significant challenge to economical surface exploration missions that comply with cabin particulate matter control standards.

V. Summary

The cabin material balance shows the relationships between AR subsystem equipment flow rate, contaminant load, and allowable cabin partial pressure or concentration design point. These relationships were evaluated to quantify the impacts associated with changes in the generation loads and the partial pressure or concentration limits specified by the most current revisions of NASA-STD-3001, NASA/SP-2010-3407, and relevant supporting documentation. The primary impact is the need to increase the active AR subsystem equipment flow rate which to accommodate higher loads and lower design points leading to an accompanying power increase.

A. Carbon Dioxide Removal

In the example for a CO_2 load produced by a crew of four, it is necessary to increase the active CO_2 removal equipment flow rate by 87% from 31 m^3/h to 58 m^3/h in order to accommodate a lower partial pressure design point of 213 Pa relative to the 400 Pa control point imposed operationally aboard ISS and account for 20% functional margin. The lower partial pressure control point is expected to result in lower process efficiency which may require an additional 5% flow increase to 61 m^3/h which is comparable to the total flow capability provided by operating two CDRA units in combination with the Vozdukh unit. To accommodate a higher metabolic load to include larger crewmembers and longer exercise periods may require an additional 17% increase in flow rate to 71 m^3/h. In total, a 129% increase in flow rate is necessary to accommodate both a lower partial pressure and higher metabolic load.

Higher flow rates are accompanied by a need for a more capable and powerful blower and the need to cycle between adsorption and desorption cycles more rapidly. The estimated increase in average power for a system constrained within the mass and volume envelopes specified for exploration CO_2 removal equipment development is >1.3 kW which is 62% higher than state-of-the-art process equipment and comparable to the power associated with deploying the total CO_2 removal capability aboard the ISS. Peak power impacts may be expected to be similar in magnitude or higher.

The lower CO_2 partial pressure decreases the working capacity for the removal process. For a process based on physical adsorption, up to 33% reduction in working capacity may result from operating at a CO_2 partial pressure approaching 133 Pa compared to a range between 400 Pa and 533 Pa. It is anticipated that all processes that are based on mass transfer into a solid or liquid phase will experience similar limitations as the mass transfer driving force is reduced at lower partial pressures. The reduced working capacity may make it difficult to reclaim sufficient oxygen from CO_2 to meet exploration mission performance targets. This aspect requires further study to quantify the system-level and mission impacts.

Significant developmental work must be accomplished beyond core process technology selection to accommodate a lower partial pressure design point and greater metabolic load variation. Among this work is the need to provide high single pass efficiency as well as design and demonstrate the more capable and reliable hardware components that form the foundation of the exploration-class CO_2 removal unit. A more capable blower is needed along with more robust valves, instrumentation, and thermal management strategies. Process control that can respond to cabin conditions to avoid over-drying the cabin during metabolic load minima while accommodating peak loads requires consideration and investigation.

B. Trace Contaminant Control and Particulate Matter Removal

Trace contaminant load contributions by system venting into the cabin can result in significant cabin TCC equipment flow rate increases by a factor of two to four depending on the type of process and the quantity of contamination vented. While updates to the ammonia's maximum cabin concentration and generation load yield a flow rate reduction over the concentration and load design point in use in 1995, this reduction is offset by introducing the toxic hazard index as a design criterion. The equipment design impact can be minimized by specifying a toxic hazard index design criterion of 1.0 applied to the total load rather than 0.5 applied to the metabolic component of the load.

The most significant particulate matter removal challenges are airborne microbes and dust intrusion into the habitable cabin during surface exploration. Particulate matter associated with bacteria and fungi are the primary determinants for the flow rate needed to maintain a healthy cabin environment requiring approximately 22% higher flow than for the particle load associated with the human personal cloud. Therefore, designing for the microbial load component provides functional margin for controlling the remaining particulate matter load. A major exception, however, is the surface dust intrusion load. For the basic cabin filtration system to be feasible for a surface exploration habitat, the barriers and operational controls for dust intrusion must be >99% effective. To ensure that the best design basis is used for the filtration system, work must also be conducted to characterize the suspended particulate matter load in the cabin environment and make comparisons to the loads indicated by literature surveys.

VI. Conclusion

The estimated costs associated with a lower cabin atmospheric CO_2 partial pressure design point and higher metabolic load relative to NASA-STD-3001 and NASA/SP-2010-3407 specifications are 129% higher flow; >62% higher average power; nearly 33% loss in available working capacity to achieve exploration mission life support system resource mass closure; and the need for substantial design, development, test, and evaluation of core components to yield a robust hardware design for exploration missions.

The estimated costs for accommodating system venting in the cabin and using toxic hazard index as a design criterion are associated with a process flow increase by a factor of two to four. Attendant mass, power, and volume increases may be expected for TCC equipment capable of accommodating these contaminant load increase and air quality maximum concentration implementation. More detailed work must be accomplished to fully quantify the costs.

Controlling the microbial load is the primary cost driver for the cabin filtration system and offers 22% functional margin for controlling the particulate load associated with the human personal cloud. To increase confidence in the literature-based design load, work must be conducted to characterize the suspended particulate matter load in the cabin environment and compare the results to the load characteristics indicated by literature surveys. Economical surface exploration is highly dependent on highly effective barriers and operational controls for dust intrusion. These barriers and controls must be >99% effective for standard cabin filtration systems and techniques to be applicable.

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