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Methane and Carbon Monoxide Concentration Dynamics of the International Space Station Cabin Atmosphere

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Methane and carbon monoxide are gaseous contaminants commonly found in a crewed spacecraft's cabin environment that are of interest to trace contaminant control equipment design. Generation sources include crew metabolism and equipment offgassing. Sources and generation rates of methane and carbon monoxide aboard the International Space Station (ISS) are examined. Cabin atmosphere concentration dynamics covering 19 years of ISS crewed operations are presented and correlation with octafluoropropane (Freon 218) concentration levels is analyzed.

Nomenclature

BMP = Russian acronym, micropurification block
COA = Catalytic Oxidizer Assembly
GSC = grab sample canister
ISS = International Space Station
PKF = Russian acronym, ambient temperature catalytic filter
PKF-T = Russian acronym, thermal catalytic filter
TCC = trace contaminant control
TCCS = Trace Contaminant Control Subsystem
C = Celsius
d = day
g = gram
h = hour
kg = kilogram
L = liter
m = meter
mg = milligram
mL = milliliter
ppm = parts per million
μmol = micromole

I. Introduction

METHANE and carbon monoxide are common trace contaminants observed in a crewed spacecraft's cabin environment. Human metabolic processes are significant sources for both contaminants; therefore, active control must be provided aboard crewed spacecraft. The following narrative provides an overview of the primary generation sources, considerations for active control design, and observations relating to active control performance aboard the International Space Station (ISS) over a period of 19 years of crewed operations.

II. Methane and Carbon Monoxide Generation Sources

Methane and carbon monoxide generation consists of two components—human metabolic processes and equipment offgassing. The following presents literature survey results for the human metabolic generation component and considers the significance of the equipment offgassing generation component for trace contaminant control (TCC) equipment design.

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A. Methane Sources

The primary methane sources in a crewed spacecraft cabin environment arise from human breath and flatus. Between 30% and 60% of the human population produces methane as a metabolic product.[1-3] It is estimated that approximately 80% of methane is excreted via flatus and approximately 20% via breath and that production can vary between males and females as well as across ethnicities and races.[2] Given the incidence of methane production in the general human population, it is necessary to understand the generation rate magnitude and account for its variability for spacecraft cabin air quality control equipment design.

Table 1. Methane generation from breath.

COMPOSITION	RATE* (mg/h)	SOURCE
1.29 µmol/L	9.517	McKay et al. (1985)[1]
14.8 ppm	4.526	Bond et al. (1971)[5]
25.5 ppm	7.797	Kinoyama et al. (2009)[6]
11.4 ppm	3.487	Szabo et al. (2015)[7]
1.4 µmol/L	10.332	Tadesse et al. (1980)[8]
-	4.140	Christl et al. (1992)[9]
1.24 mg/m^3	0.571	Nefyodov et al. (1973)[10]
-	0.808	Dimitriyev et al. (1987)[11]
7 ppm	2.141	Marthinsen and Fleming (1981)[12]

Table 2. Methane generation from flatus.

COMPOSITION	RATE* (mg/h)	SOURCE
16.3%	15.34	Bond et al. (1971)[5]
7.2%	11.27	Kirk (1949)[13]
17.78%	16.73	Suarez et al. (1997)[14]
22.3%	20.98	Kustov and Tiunov (1971)[15]
18%	16.94	Murphy (1964)[16]

Table 3. Daily flatus production.

RATE* (mL/d)	SOURCE
2131.2	Kirk (1949)[13]
1490.4	Tomlin et al. (1991)[17]
3775.2	Suarez et al. (1997)[14]
1014	Marthinsen and Fleming (1981)[12]
1200	Murphy (1964)[16]

A literature survey, summarized by Table 1, indicates 4.81 mg/h average from breath with 3.62 mg/h standard deviation. The 95% confidence interval upper bound is 7.06 mg/h. From flatus the literature survey, summarized by Table 2, indicates average methane generation of 14.34 mg/h with a standard deviation of 3.07 mg/h. The 95% confidence interval upper bound is 17.26 mg/h. The generation magnitude from flatus is based on the literature sources in Table 3 which indicates an average 1922.2 mL/d production rate with a standard deviation of 1119.2 mL/d which yields a 95% confidence interval upper bound value of 2988.2 mL/d. Emissions from the skin contribute another 0.22 mg/h.[11] The total methane production from all sources for the 95% confidence interval is 24.5 mg/h or 588 mg/d. This magnitude is nearly two times higher than indicated by the previous literature survey in 1995. Equipment offgassing is a very minor methane source according to Ref. 4 with offgassing from nearly 10500 kg of equipment producing 1% of the metabolic load from a single crewmember; therefore, methane production from equipment offgassing can usually be neglected for TCC equipment design purposes.

B. Carbon Monoxide Sources

The primary carbon monoxide sources in a crewed spacecraft cabin environment are from human metabolic processes and equipment offgassing. The metabolic generation pathway is reported to be associated with the hemoglobin chemical oxidation step in the heme catabolism process.[17] A literature survey, summarized by Table 4, indicates an average 0.641 mg/h production rate per crewmember with a standard deviation of 0.2 mg/h. The 95% confidence interval upper bound for the six literature sources is 0.745 mg/h or 17.9 mg/d. This rate is comparable in magnitude but slightly higher than the 17.5 mg/d rate indicated by a literature survey conducted in 1995.[4] Offgassing from approximately 8980 kg of equipment is equivalent to the generation from a single crewmember's metabolic processes. Therefore, the equipment offgassing component cannot be neglected for TCC equipment design purposes. Aboard the ISS, the equipment offgassing component is estimated to contribute approximately 31 mg/h.

Table 4. Endogenous carbon monoxide.

RATE* (mg/h)	SOURCE
0.6127	Coburn (2012)[18]
0.5877	Coburn et al. (1963)[19]
0.9378	Sjostrand (1965)[20]
0.4589	Coburn (1970)[21]
0.6252	Coburn (1964)[22]
0.6750	Conkle (1970)[23]
0.4520	Conkle (1967)[24]
0.9790	Mochalski et al. (2015)[25]
0.9080	Shimoda et al. (1998)[26]
0.5740	Dimitriyev et al. (1987)[11]
0.3840	Nefedov et al. (1973)[10]

III. Active Control Methods for Methane and Carbon Monoxide

Active control for both methane and carbon monoxide is provided aboard crewed spacecraft via catalytic oxidation-based processes. Platinum group metal catalysts supported on a variety of substrates such as alumina and activated carbon are commonly employed.[27] Methane catalytic oxidation requires operating temperatures in the range of 400 °C to be effective while carbon monoxide oxidation can occur at ambient temperature.

Catalytic oxidation-based processes can be inhibited or poisoned when certain contaminants enter the reactor. The effects of contaminants such as ammonia, nitrogen oxides, halocarbons, and sulfur-containing compounds on catalysts used in spacecraft TCC equipment have been studied.[28-32] Typically ambient temperature catalytic reactions are more susceptible to poisoning than high temperature reactions. Therefore, protective adsorbent beds are located upstream of catalytic oxidation-based TCC components. The following summarizes the observed inhibition and poisoning effects on catalyst activity for methane and carbon monoxide oxidation.

A. Observations on Methane Catalytic Oxidation Poisoning

The effects of various contaminants on platinum group metal-based methane oxidation catalyst activity has been reported by Refs. 29 through 32. Observations show hydrogen sulfide (H_2S) irreversibly poisons the methane oxidation reaction[4,5] while sulfur hexafluoride (SF_6) exhibits a reversible poisoning effect.[30] The effects of halocarbons on methane oxidation catalyst activity, specifically dichloromethane, bromotrifluoromethane (Halon 1301), and 1,1,2-trichloro-1,2,2-trifluoroethane (Freon 113), were found to be reversible over multiple cycles.[29, 30] The degree of methane oxidation inhibition by halocarbons was also found to be influenced by the concentration entering the oxidation reactor with higher concentrations producing a greater poisoning effect. After an octafluoropropane (Freon 218) leak aboard the ISS in 2001, testing was conducted to evaluate the potential for producing hazardous oxidation products in the Trace Contaminant Control Subassembly's (TCCS) Catalytic Oxidizer Assembly (COA). This testing indicated that Freon 218 oxidation was negligible and likely in the range <<1%.[31] Extending this earlier work, the effects of octafluoropropane (Freon 218) on methane oxidation were investigated and found to have no measurable effect on methane oxidation catalyst activity.[32] This is attributed to the observation that the oxidation efficiency for octafluoropropane is <0.06% compared to >80% and >30% for dichloromethane and Freon 113, respectively. The observed reversible poisoning that results from catalyst exposure to halocarbons is consistent with other results reported in the literature.[33] In general, the primary poisons of interest are present in a spacecraft cabin environment at concentrations that produce <10% reversible poisoning.

B. Observations on Carbon Monoxide Catalytic Oxidation Poisoning

Platinum group metal-based catalysts used for ambient temperature carbon monoxide oxidation aboard crewed spacecraft have been investigated for their susceptibility to poisoning.[28, 29] Poisons investigated include ammonia (NH_3), methanethiol, sulfur dioxide (SO_2), H_2S, nitrogen oxides (NO and N_2O), trichlorofluoromethane (Freon 11), and dichlorodifluoromethane (Freon 12) by Ref. 28 and NH_3, ethyne (C_2H_2), H_2S, and Halon 1301 by Ref. 29. The experiments documented by Ref. 28 observed 30% carbon monoxide oxidation efficiency reduction by Freon 11 and Freon 12 for low palladium-loaded catalyst but no effects for higher catalyst loadings or for platinum-based catalysts. In the study documented by Ref. 29, no catalyst poisoning was observed from Halon 1301 exposure. Both studies observed significant poisoning by NH_3 and sulfur-containing compounds. Nitrogen oxides and ethyne were also observed to poison the ambient temperature carbon monoxide oxidation reaction.

IV. Methane and Carbon Monoxide Cabin Concentration Dynamics

The active trace contaminant control equipment aboard the ISS consists of the Trace Contaminant Control Subassembly (TCCS) located in the U.S. Segment and the Micropurification Block (BMP) located in the Russian Segment.[34, 35] The TCCS and BMP operate in tandem to control the trace contaminant load in the ISS's common cabin environment. The TCCS includes a Catalytic Oxidizer Assembly (COA) that treats 4.6 m^3/h of process air flow at a 400 °C operating temperature. At this condition, the COA provides >95% single pass methane oxidation efficiency and 100% carbon monoxide oxidation efficiency. The BMP includes an ambient temperature carbon monoxide oxidation catalyst bed, the PKF, that treats 25 m^3/h of process air flow and >95% single pass carbon monoxide oxidation efficiency. A thermal catalytic oxidizer component, the PKF-T, was retrofit to the BMP in 2003. This unit operates at 250 °C to 280 °C and provides between 0.4 m^3/h and 0.6 m^3/h process air flow. At this condition the unit is projected to provide 100% carbon monoxide oxidation efficiency and up to 50% methane oxidation efficiency.

A. Methane Concentration Dynamics

The methane concentration in the ISS cabin atmosphere is controlled primarily by the TCCS COA. The low flow rate PKF-T thermal catalytic oxidation unit that was retrofit to the BMP during the fifth year of ISS operations accounts for approximately six percent of the total methane load control capability aboard the ISS. As shown by Fig. 1, the methane concentration has been maintained well below the 3800 mg/m^3 maximum allowable concentration during the ISS's operational lifetime. Typically, the concentration has been maintained <20 mg/m^3 with a few exceptions. Even during those exceptional periods before the TCCS unit was deployed in the U.S. Segment and periods when the TCCS was not operating, the concentration has been well controlled. The average concentration from 516 whole air grab samples is 14.3 mg/m^3 with a standard deviation of 28.4 mg/m^3. Since the TCCS was deployed in the second year of ISS operations the concentration has averaged 11.5 mg/m^3 with a standard deviation of 19.5 mg/m^3.

Variability in the cabin concentration has been observed to be consistent with methane generation variability within the general human population. Assessment of average methane concentration across 43 crew increments, summarized in the Appendix, indicates 31% of the crew to be methane producers on average. The range is 2% to 100% methane producers. The 99% confidence interval for the 43 crew increments is 44% methane producers. The general TCC design practice is to assume that the crew consists of 100% methane producers. This approach yields a conservative design that provides substantial operational margin as indicated by the ability to control to <1% of the maximum allowable concentration for over 19 years of crewed operations aboard the ISS.

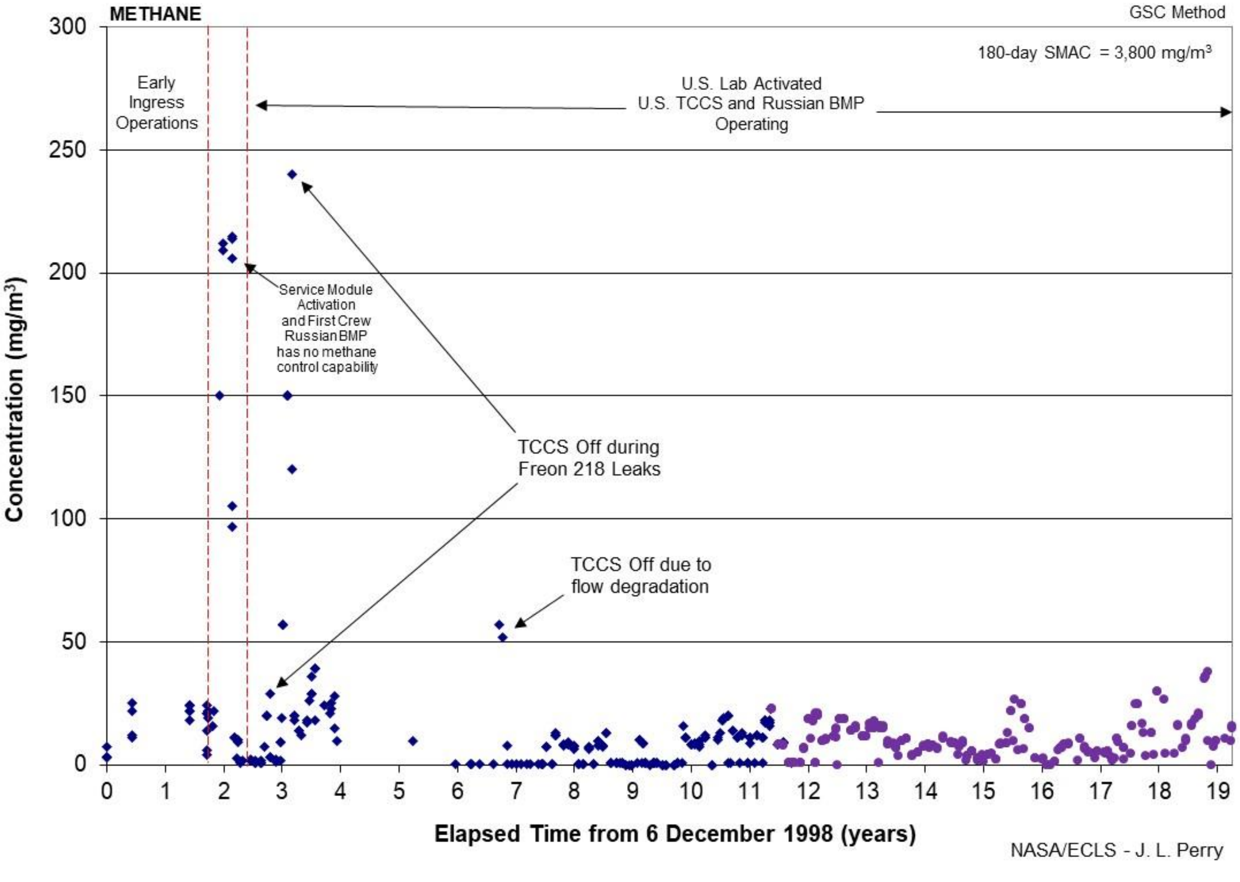

Figure 1. Methane concentration in the ISS cabin atmosphere.

B. Carbon Monoxide Concentration Dynamics

As shown by Fig. 2, the carbon monoxide concentration in the cabin atmosphere has been maintained below the 17 mg/m^3 maximum allowable concentration. The cabin concentration is typically <2 mg/m^3. The average concentration is 1 mg/m^3 with a standard deviation of 1.25 mg/m^3. The expected concentration accounting for the crew metabolic load and equipment offgassing ranges between 1.3 mg/m^3 and 1.9 mg/m^3. Concentrations above 2 mg/m^3 are typically associated with samples collected from cargo vehicles and early crew-tended operations when contaminants accumulate in sealed volumes that lack active TCC equipment. Exceptions are associated with isolated events that may include overheating equipment or potential active TCC equipment performance degradation due to catalyst poisoning. Notably, the high cabin concentrations spanning the tenth through the twelfth year of ISS operations coincide with a large leak of octafuoropropane (Freon 218) followed by its slow removal from the cabin atmosphere. In general, the active TCC design consisting of the TCCS and BMP operating in tandem has shown the capability to control the combined crew metabolic and equipment offgassing loads to <12% of the maximum allowable concentration on average.

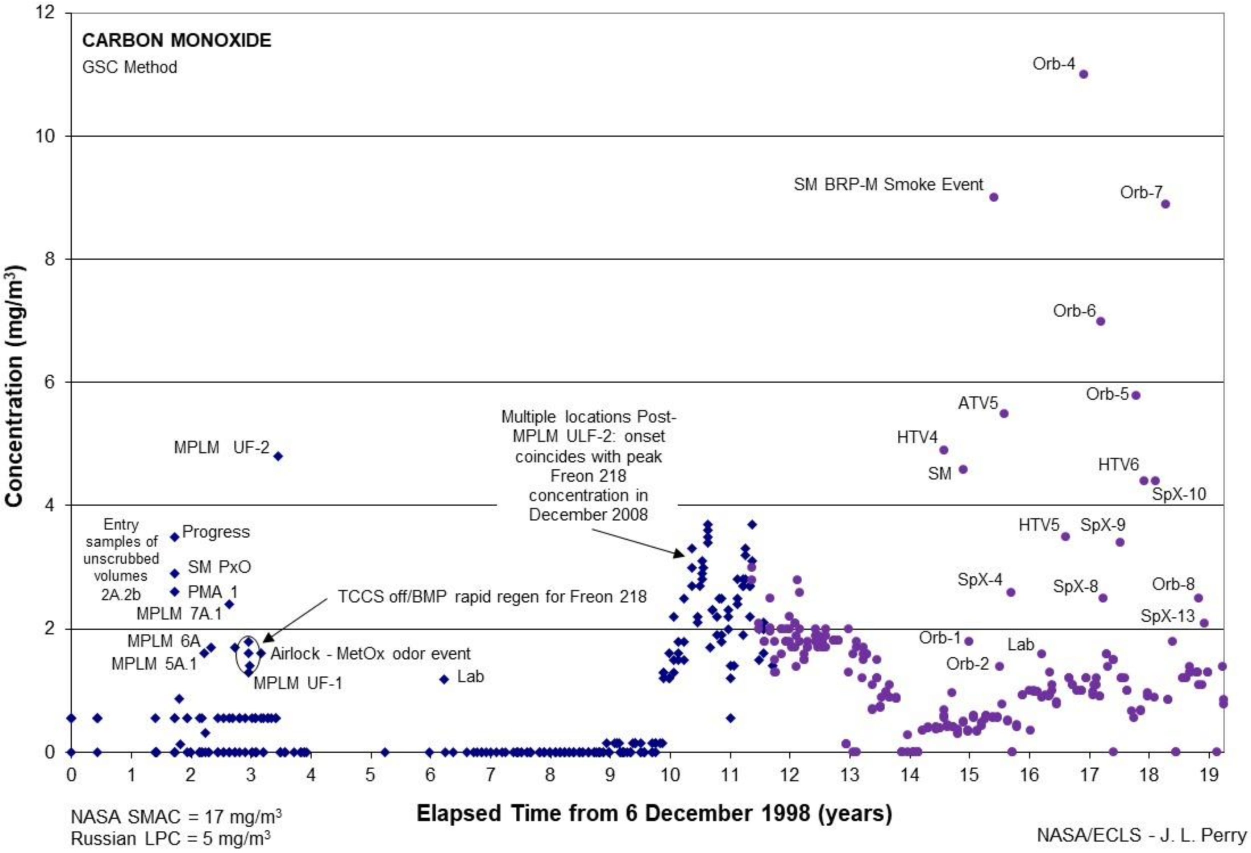

Figure 2. Carbon monoxide concentration in the cabin atmosphere.

C. Methane and Carbon Monoxide Concentration Dynamics in the Presence of Octafluoropropane

The air conditioning units in the Russian Segment contain 750 g of octafluoropropane (Freon 218) coolant each. Small fugitive leaks occur over time leading to a persistent background concentration. The air conditioning units are serviced periodically and larger releases into the cabin can occur during servicing. As seen by Fig. 3, there have been at least four significant Freon 218 releases into the ISS cabin and at least one minor release. The first release of approximately 730 g occurred in 2001 which was during the third year of ISS flight operations. This release consisted of 200 g leaked at a rate of 4 g/d over a period of approximately four months. The leakage rate increased to approximately 20 g/d over the next eight weeks releasing another 400 g into the cabin. An additional 130 grams was released during air conditioning unit servicing. In total, nearly all of the coolant from a single air conditioning unit leaked into the cabin environment.[32] Since the leak occurred over a period of several months the active TCC capability

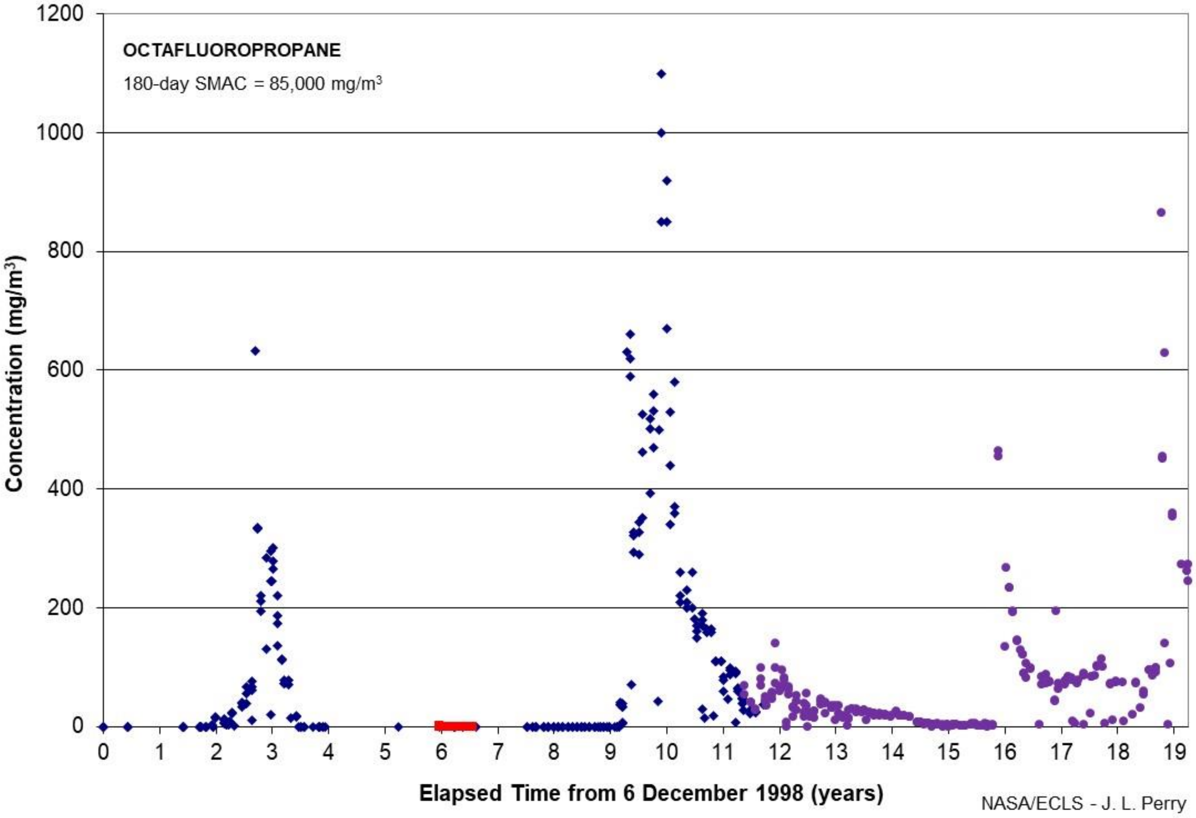

Figure 3. Octafluoropropane concentration in the ISS cabin atmosphere.

was able to limit the peak concentration. Freon 218 leakage was negligible until 2008, the tenth year of ISS operations, when bulk release of nearly 900 g of Freon 218 occurred. A smaller leak occurred in the twelfth year (2010). At the beginning of the seventeenth year (2014), another bulk leak occurred. Sustained leakage continued thereafter followed by another bulk leak in the twentieth year (2018).

As a result of these bulk and sustained leak events, the physical adsorption-based components of the active TCC capability that remove the Freon 218 from the cabin atmosphere becomes saturated leading to a persistent Freon 218 concentration which has existed since 2008. This TCC capacity saturation allows Freon 218 to reach the catalytic oxidation components in both the TCCS and BMP which increases the potential for catalyst poisoning. Observations from correlation analysis of whole air grab sample analysis and comparing Figs. 1 and 2 with Fig. 3 indicate that TCC catalyst poisoning may be occurring during periods of high Freon 218 concentration. The following presents and discusses these observations.

Although the methane concentration increased during the first Freon 218 leak event, that increase was due to shutting down the TCCS for precautionary reasons until data on the potential for producing hydrogen fluoride (HF) was available from ground-based tests. Testing the TCCS COA performance in the presence of Freon 218 had not been completed at the time of the first Freon 218 leakage event. Therefore, the TCCS was shut down as a precaution until the testing was completed. Because the testing indicated unmeasurable HF production when Freon 218 enters the TCCS COA, the TCCS has remained operational during subsequent Freon 218 leakage events.

Visually comparing Fig. 1 with Fig. 3 during the second and third Freon 218 leakage events indicates the appearance of greater methane concentration variability coincidental with the second Freon 218 leak event. This variation was determined to warrant further evaluation. Likewise, visually comparing Fig. 2 and Fig. 3 indicates periods of high carbon monoxide concentration coinciding with periods of high Freon 218 concentration. The carbon monoxide concentration variation during three Freon 218 leakage events was determined to warrant further evaluation.

Examining the methane and carbon monoxide concentration data reported from whole air grab sample analyses during three Freon 218 leakage events indicates that the methane and carbon monoxide concentrations become more variable during high Freon 218 concentration periods. When the Freon 218 concentration is low, the methane and carbon monoxide concentration variation moderates. Correlation analysis using Pearson and Spearman's Rho techniques was conducted for the periods of greatest variation.

A. Methane Concentration Correlation with Octafluoropropane Concentration

The Pearson correlation between methane concentration and Freon 218 concentration was found to be weak, with correlation coefficients in the range of 0.3 to 0.4. Examination via Spearman's Rho analysis, however, indicates that the correlation is not statistically significant. These results are not unexpected given the <<1% Freon 218 oxidation efficiency by the TCCS COA and the variation in methane concentration that results from human metabolic load variations that most likely mask small variations caused by reversible catalyst poisoning. The effects of Freon 218 on the TCCS COA's methane oxidation performance are very small and the primary root cause for methane concentration variation in the ISS cabin is attributed to a fluctuating human metabolic source.

B. Carbon Monoxide Concentration Correlation with Octafluoropropane Concentration

The Pearson correlation between carbon monoxide concentration and Freon 218 concentration was also found to be very week with correlation coefficients in the range of 0.04 to 0.2. Interestingly, the Spearman's Rho evaluation found no statistical significance for the first and third leakage events but did indicate weak correlation with a 0.4 coefficient with statistical significance for the second leakage event. The Spearman's Rho correlation coefficients were similar to the Pearson correlations. In general, these results are consistent with the low potential for carbon monoxide catalyst poisoning by halocarbons discussed in Section III. The weak correlation and the statistical significance associated with the second Freon 218 leakage event may be indicative of the effects of other contaminants, such as impurities in a batch of Freon 218, which could have a more pronounced effect on catalyst activity. Further examination of the whole air grab sample analysis results, however, do not indicate any other catalyst poisons at unusually high concentrations.

Considering a cabin material balance with an assumed constant carbon monoxide generation source, the cabin concentration changes can be indicative of a 41% reduction in removal capability. However, it cannot be readily assumed that the carbon monoxide generation source remains constant. An increase in generation rate is possible and must be considered. Examining Fig. 2 shows cargo vehicle first entry samples with very high carbon monoxide concentrations during the period covering the third Freon 218 leakage event. Therefore, it is possible that offgassing sources increased concurrently with Freon 218 leakage events.

In summary, while a 30% reduction in carbon monoxide oxidation catalyst activity has been indicated in one instance discussed in Section III, when considered along with other confounding factors such as the presence of other halocarbons and additional carbon monoxide generation sources, catalyst poisoning by exposure to Freon 218 cannot be established as a primary root cause. Testing ambient temperature carbon monoxide oxidation catalyst performance in the presence of Freon 218 can provide useful insight.

V. Summary

Methane and carbon monoxide are trace contaminants commonly observed in a crewed spacecraft cabin atmosphere and are among the key contaminants that the active TCC equipment design must address. The generation sources, active TCC control methods, concentration dynamics in the ISS cabin atmosphere, and the potential effects of persistent Freon 218 concentrations in the cabin atmosphere were presented and discussed.

Generation sources were examined with emphasis on the human metabolic source. Human metabolism typically accounts for 99% of the methane generation source and 13% of the carbon monoxide generation source aboard crewed spacecraft comparable in size to the ISS. A literature review provided new source documentation for the metabolic generation source basis. This literature review indicates metabolic generation from a single crewmember of 588 mg methane/day and 17.9 mg carbon monoxide/day. The methane rate is nearly two times higher than previously established via literature review in 1995. The carbon monoxide rate is four percent higher than the rate established in 1995.

Both methane and carbon monoxide concentrations are controlled in the cabin environment via catalytic oxidation processes. Thermal catalytic oxidation is required for methane while ambient temperature catalytic oxidation can be accomplished for carbon monoxide. Both catalytic oxidation processes are sensitive to poisoning by halocarbons and sulfur-containing compounds. Ambient temperature catalysts are also sensitive to poisoning by NH_3.

Cabin concentrations for a period covering over 19 years of ISS flight operations were presented. The methane concentration has averaged 11.9 mg/m^3 over the ISS's operational lifetime after the U.S. Segment TCCS was activated. Concentration variability was found to be consistent with the 30% to 60% incidence of methane production within the general human population reported in literature. The methane concentration dynamics over 43 crew increments indicates a 31% average incidence of methane generation within the crew population and 44% incidence at the 99% confidence interval upper bound. The carbon monoxide concentration has typically been maintained <2 mg/m^3 which is consistent with an expected upper concentration of 1.9 mg/m^3 indicated by the combined projected equipment offgassing load and the crew metabolic load. Isolated cabin volumes, particularly cargo vehicles at first entry, usually reported higher concentrations. Increases in carbon monoxide concentration were observed to coincide with high Freon 218 concentrations.

The effects of high Freon 218 concentrations in the ISS cabin on methane and carbon monoxide concentrations were evaluated. Whole air grab sample data indicate four significant and one minor Freon 218 leak events over the ISS's operational lifetime to date. Methane and carbon monoxide concentration measurements show greater variability during the periods when the Freon 218 concentration is high. Pearson correlation of Freon 218 concentrations with methane and carbon monoxide concentrations was found to be weak. Spearman's Rho analysis showed no statistical significance for correlation with the exception of the carbon monoxide concentration during the second and largest Freon 218 leak event in 2008. Up to 41% active removal capability reduction is possible for carbon monoxide based on documented catalyst poisoning test results. However, attributing the higher carbon monoxide concentration during the second Freon 218 leakage event solely to oxidation catalyst poisoning is confounded by the potential that cargo delivered to the ISS contributed to an increase in the equipment offgassing generation load. Specific catalyst performance testing is necessary to fully understand Freon 218's effects on carbon monoxide catalytic oxidation at ambient temperature.

VI. Conclusion

Generation sources of methane and carbon monoxide have been reviewed and updates to the human metabolic load component have been developed. The recommended methane metabolic load is 588 mg/d and the carbon monoxide metabolic load is 17.9 mg/d for a single crewmember. These recommended metabolic loads are nearly two times and four percent higher than the methane and carbon monoxide metabolic loads, respectively, indicated by a literature review conducted in 1995. Both methane and carbon monoxide have been well controlled aboard the ISS by catalytic oxidation-based processes. Methane concentration variability is consistent with a crew population composed of 31% methane producers on average. This methane production incidence is within the range of the general human population. Both methane and carbon monoxide concentration variability indicated weak correlation with periods of high Freon 218 concentration. Past testing also indicates that methane oxidation catalyst poisoning by Freon 218 is a very minor factor in the observed cabin methane concentration variability. Examining cabin methane concentration variability indicates a source magnitude that fluctuates with the crew increments. Therefore, human metabolic generation source variations are concluded to be the dominant reason for methane concentration variability in the ISS cabin atmosphere. Tying carbon monoxide concentration variability solely to oxidation catalyst poisoning is indicated by the statistical significance found by Spearman's Rho analysis of the second Freon 218 leakage event. However, determining that actual magnitude of the effects produced by high Freon 218 concentrations in contact with the carbon monoxide oxidation catalyst are confounded by the equipment offgassing generation source variability induced by cargo shipments to the ISS. Specific testing designed to characterize the effect that Freon 218 has on carbon monoxide catalytic oxidation at ambient temperature must be accomplished to better understand the effects on of catalyst activity.

Appendix

Methane concentration and generation rate for 43 crew increments aboard the ISS.

Average Concentration (mg/m^3)	Incremental Change* (mg/m^3)	Total Rate (mg/h)	Individual Rate (mg/h)	Percent Generator (decimal)
2.53	-	11.61	92.90	0.16
2.35	0.18	10.79	86.29	0.15
16.63	14.28	76.31	610.47	1.04
28.08	11.46	128.90	1031.22	1.75
6.68	21.40	30.67	245.36	0.42
5.96	0.72	27.35	218.81	0.37
2.30	3.66	10.54	84.31	0.14
0.40	1.90	1.84	14.69	0.02
7.54	7.14	34.59	276.70	0.47
11.33	3.80	52.02	416.16	0.71
13.00	1.67	59.67	238.68	0.41
11.80	1.20	54.16	216.65	0.37
8.55	3.25	39.24	156.98	0.27
17.57	9.02	80.65	322.61	0.55
6.22	11.35	28.56	114.26	0.19
0.80	5.42	3.67	14.69	0.02
16.24	15.44	74.55	298.20	0.51
10.25	5.99	47.05	188.19	0.32
15.85	5.60	72.75	291.01	0.49
14.67	1.18	67.32	269.28	0.46
14.73	0.07	67.63	270.50	0.46
8.83	5.90	40.55	162.18	0.28
9.40	0.57	43.15	172.58	0.29
4.53	4.87	20.79	83.14	0.14
8.09	3.56	37.13	148.51	0.25
9.18	1.09	42.11	168.45	0.29
8.78	0.39	40.32	161.26	0.27
4.82	3.97	22.11	88.43	0.15
3.89	0.93	17.86	71.44	0.12
5.48	1.58	25.13	100.52	0.17
19.04	13.56	87.38	349.53	0.59
17.00	2.04	78.03	312.12	0.53
1.03	15.97	4.74	18.97	0.03
6.65	5.61	30.50	122.01	0.21
7.05	0.40	32.36	129.44	0.22
5.40	1.65	24.79	99.14	0.17
7.44	2.04	34.16	136.65	0.23
19.57	12.13	89.83	359.33	0.61
22.60	3.03	103.73	414.94	0.71
13.43	9.18	61.62	246.48	0.42
17.33	3.91	79.56	318.24	0.54
29.43	12.10	135.08	540.31	0.92
10.30	19.13	47.28	189.11	0.32

*Absolute value.

Acknowledgments

Data from the cabin air quality assessments compiled by the Toxicology and Environmental Chemistry Group at NASA's Johnson Space Center that report the results of whole air grab sample analysis are the basis for Figs. 1 through 3. The continuing efforts to plan for, collect, and analyze whole air grab samples of the ISS cabin atmosphere over the ISS operational lifetime are appreciated for the vital information products that provide insight into TCC equipment performance and inform future TCC equipment design for future deep space exploration missions.

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