NASA/TM—2016–218223

Performance of International Space Station Alpha Trace Contaminant Control Systems

J.L. Perry
Marshall Space Flight Center, Huntsville, Alabama

May 2016

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Space Administration

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FOREWORD

The analysis presented herein was conducted during the early transitional period between the Space Station Freedom and the International Space Station programs as part of an effort to evaluate key design specifications and standards used by the United States and Russia. The analysis was originally documented under NASA cover letter ED62(36-94) dated August 16, 1994. The analysis was revised and rereleased under NASA cover letter ED62(51-94) dated November 14, 1994. These cover letters are provided here to guide programmatic context for the reader.

National Aeronautics and
Space Administration

George C. Marshall Space Flight Center
Marshall Space Flight Center, AL 35812

Reply to Attn of: ED62(36-94) August 16, 1994

TO: DA01/Mr. Mobley

FROM: ED62/Mr. Perry

SUBJECT: Analysis of the Capability of U.S. and Russian Trace Contaminant Control Systems to Meet Cabin Atmospheric Quality Standards

Reference is made to ED62(28-94), "Report on Air Quality Standard Negotiations for the International Space Station Alpha (ISSA) in Moscow, Russia" June 21, 1994.

Atmospheric quality negotiations for the International Space Station Alpha (ISSA) held in Moscow, Russia, produced a signed protocol but did not resolve whether to use the Russian or U.S. standards for the ISSA. As recommended in the referenced letter, we have conducted an analysis to assess the capabilities of both the U.S. and Russian trace contaminant control systems to meet atmospheric quality standards which have been set independently by both sides. The objectives of this analysis were to determine whether the lowest of the two standards could be met under normal ISSA operating conditions and to present recommendations for resolving the disconnect between the two sides with respect to cabin atmospheric quality standards. Results of this analysis are documented in the enclosed report.

During the course of the analysis, the full list of Russian standards were obtained from NPO Energia personnel for comparison to U.S. standards. As has been observed in the past, the Russian standards are significantly lower than the U.S.'s with the exception of benzene. Comparisons were made for 59 chemical compounds and are documented in the enclosed report. These compounds, in addition to another 12 which have had 180-day standards set by NASA, were used to assess the capabilities of both contamination control systems. Average contaminant generation rates derived from Spacelab offgassing tests were used as the analysis basis.

Conclusions drawn from the analysis are the following:

1. Both the U.S. and Russian trace contaminant control systems have the capability to control all chemical contaminants expected in the ISSA cabin atmosphere, with the exception of methanol and 2-butanone, to below both the U.S. and Russian standards. The generation rates for both these compounds were found to be conservative by factors of 110 and 1.2 when compared to spacecraft flight data; therefore, it is most likely that they would also be controlled below acceptable levels.

2. Comparison of Russian segment generation rates derived from flight data from Mir missions 10, 11, 12, and 13 to U.S. segment generation rates derived from Spacelab cabin atmosphere samples indicated that the Russian segment rates were lower than rates projected for the U.S. segment. Therefore, the Russian material selection and control process actually results in contaminant generation rates which are comparable to those expected in the U.S. segment.

Based upon these conclusions, the following recommendations are made for resolving the disconnect between the Russian and U.S. segment trace contaminant control design standards:

1. With the exception of benzene the Russian atmospheric quality standards should be adopted by the ISSA as the interface requirement for the U.S. and Russian segments.

2. The U.S. 180-day standard for benzene should be adopted as the interface requirement between the U.S. and Russian segments.

3. Neither the NASA Trace Contaminant Control subassembly (TCCS) nor the Russian Microimpurity Adsorption Device (MAD) designs should be changed. Both sides should continue to design their equipment using their current design standards.

4. On-orbit verification that cabin atmospheric quality meets the NASA and Russian standards should be conducted by each side using their respective toxicological assessment techniques with discrepancies in results resolved by a joint ISSA toxicology panel composed of both NASA and Russian toxicologists and TCCS engineers.

These recommendations reflect the fact that both systems can most likely meet the Russian standards and the reality that changing the design standards for the contamination control systems could result in cost impacts by requiring that tests and analyses be redone by both sides. By implementing the recommendations, the ISSA avoids cost impacts by maintaining the hardware design standards for both sides while addressing the segment interface issues.

Questions regarding this analysis and the conclusions reached should be addressed to the undersigned at 544-2730.

Jay L. Perry
Life Support Systems Branch

APPROVAL:

James C. Blair
Director
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Enclosure

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National Aeronautics and
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Reply to Attn of: ED62(51-94)

November 14, 1994

TO: DA01/Mr. Mobley

FROM: ED62/Mr. Perry

SUBJECT: Revised Recommendations on International Space Station Alpha (ISSA) Air Quality Standards

Reference is made to the "Analysis of the Capability of U.S. and Russian Trace Contaminant Control Systems to Meet Cabin Atmosphere Quality Standards," ED62(36-94), August 16, 1994.

As a result of the negotiations on air quality specifications during the Russian Technical Interchange Meeting (TIM) Number 12 held in Houston on August 15-26, 1994 modifications to the recommendations contained in the referenced letter have been made. In addition to the outcome of the Russian TIM, these changes reflect reviews by International Space Station Alpha (ISSA) program office and Boeing personnel in addition to the NASA Chief Scientist for Toxicology. These modifications have also been reflected in the cabin air quality section of the Specifications and Standards Task final report. Based upon all of this input, the recommendations are the following:

1. The ISSA trace contaminant control systems should be designed to control trace contaminants to their respective trace contaminant control design standards with the NASA system designed to NASA standards and the Russian system designed to Russian standards for the contaminant load for their respective segments.

2. Requirements wording should place the respective trace contaminant control design standards in the respective segment specification documents.

3. General wording with respect to controlling trace contaminants in the cabin atmosphere to ensure crew health should be placed in the ISSA system specification.

4. A joint standard for on-orbit assessment of the cabin atmosphere for purposes of maintaining crew health and assessing control system operations should be developed by the U.S. and Russian sides.

These recommendations replace those of the referenced document and its enclosure and are provided to maintain consistency within the ISSA program. The content of the enclosure to the referenced letter, however, is not affected and it still provides a comprehensive, accurate assessment of the ability of the ISSA contaminantion control systems to meet the air quality standards used by the two sides.

For further information contact the undersigned at 544-2730.

Jay L. Perry

Jay L. Perry

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LIST OF ACRONYMS AND SYMBOLS

ACM	atmospheric composition monitor
APM	Attached Pressurized Module
CO_2	carbon dioxide
ESA	European Space Agency
HX	heat exchanger
ISSA	International Space Station Alpha
JEM	Japanese Experiment Module
LiOH	lithium hydroxide monohydrate
MAC	maximum allowable concentration
MAD	microimpurity adsorption device
N_2	nitrogen
NASDA	National Space Development Agency
O_2	oxygen
RSA	Russian Space Agency
SMAC	spacecraft maximum allowable concentration
TCCS	trace contaminant control subassembly
THC	temperature and humidity control
TM	Technical Memorandum
U.S.	United States
ПDK	predelbno dopoostimi kontsehntratshens (Russian acronym for limiting permissible concentration)

TECHNICAL MEMORANDUM

PERFORMANCE OF INTERNATIONAL SPACE STATION ALPHA TRACE CONTAMINANT CONTROL SYSTEMS

1. INTRODUCTION

The combination of components from all the partners in the International Space Station Alpha (ISSA) project has resulted in uncertainty in some aspects of space station hardware integration. Among these uncertainties is the atmospheric trace contaminant load which will be present onboard the ISSA. Since the spacecraft is composed of elements and components developed in Europe, Japan, and Russia, some variations in material selection and control specifications and standards may exist. As a result, it is difficult to predict the actual trace contaminant generation rates from each contribution to the ISSA from the various international partners.

During previous designs of the ISSA, the offgassing contributions from hardware developed in Europe and Japan were easily predicted since both the European Space Agency (ESA) and the National Space Development Agency (NASDA) of Japan had adopted the NASA material selection and control specifications and standards. This is still the case for the ISSA. However, the ISSA has added a new partner, Russia, which is responsible for providing more than one-half the total ISSA hardware and habitable volume. This contribution is managed through the Russian Space Agency (RSA). As the dialogue between NASA and RSA officials continues, more understanding with respect to the specifications and standards for material selection and control by the two sides has been reached. In addition, important information exchange on the design performance of the U.S. Segment's trace contaminant control subassembly (TCCS) and the Russian Segment's microimpurity adsorption device (MAD) or Russian acronym БМП. Along with information on the TCCS and MAD performance, more information on Russian 'predelbno dopoostimi kontsehntratshens' (ПDKs) or permissible limiting concentrations, the equivalent of the NASA spacecraft maximum allowable concentrations (SMACs), has been obtained along with data on trace contaminant concentrations observed onboard Mir 1.

Although the information exchange has proved useful, it has shown that differences between the Russian and U.S. specifications and standards exist. In order to proceed with the development of the ISSA, these differences must be resolved directly or philosophically. Philosophical resolution is the most likely course of action since it does not dismantle the existing specification and standard structure within the two agencies. However, much work remains to be done to reach this resolution since both sides must fully understand and be comfortable with these specification and standard differences. Furthermore, both sides must understand the impacts to their respective hardware performance which may result from integrating the Russian and U.S. Segments into the ISSA.

The initial attempt by NASA to assess the performance of the Russian MAD is documented in NASA TM-108441.[1] This assessment did not have information concerning the design driving contaminants for the MAD and therefore concluded that it was not as effective as the NASA TCCS. Since that time, additional information on the MAD has become available and the updated analysis that follows has been conducted. This analysis is intended to supersede the analysis documented in NASA TM-108441. However, the descriptive summary of the MAD in NASA TM-108441 is still considered accurate.

Trace contaminant control standards are one of the issues that must be understood fully since both the Russian and U.S. Segments will produce and control trace contaminants. Meetings between RSA and NASA hardware designers and toxicology personnel in late April 1994 have added to the understanding of the respective contamination control standards for the two sides. A protocol, included as appendix A (on CD inside back cover), was prepared during these meetings which primarily addressed the on-orbit assessment of the ISSA cabin atmosphere. The protocol, however, did not fully resolve the issue of hardware design standards which must be included in the ISSA program specifications at the system and segment levels as well as guide the interfaces between the U.S.- and Russian-provided segments. In order to resolve this issue, the ability of the respective contamination control systems to meet the most stringent of the RSA and NASA standards must be understood along with any uncertainties associated with meeting them. Upon reaching these understandings, an appropriate recommendation can be made with respect to the maximum allowable concentrations that must be adopted for TCCS and MAD design purposes. Also, recommendations on the assessment of the cabin atmosphere during on-orbit ISSA operations can be made. The following analysis has been conducted to reach these understandings.

2. SPACE STATION LOAD MODEL

The RSA and NASA contamination control system designs are both based upon a particular load model. The NASA TCCS design is based primarily upon the load model documented by Leban and Wagner in 1989.[2] This model was based upon preliminary Spacelab trace contaminant offgassing and mass properties data and then updated with more recent data from Spacelab missions 1 and 3. The model was further supplemented by flight experience from the Apollo and Skylab programs. As more offgassing and mass properties data became available from the Spacelab program, this model was updated to reflect only Spacelab data. The current model, listed in appendix B (on CD inside back cover) consists of generation rates per unit mass of internal hardware for 214 chemical compounds. It is based upon offgassing test and mass properties data from internally mounted flight hardware for six Spacelab module missions. A reduction factor of 11.48 is included in determining the equipment offgassing rates to account for thermal and aging effects (J.L. Perry, "Continuation of the Prelaunch Spacelab Environmental Control System Trace Contaminant Removal Capability Assessment (Aggregate Assessment)," NASA Memo ED62 (20-93), NASA Marshall Space Flight Center, Huntsville, AL, June 22, 1993). Both the load model and adjustment factor are discussed in greater detail in NASA TM–108497. These data are considered to be the most representative of the U.S. Segment of the ISSA since the same material selection and control specifications and standards are used. Furthermore, both the Spacelab and ISSA U.S. Segment have the same concept of rack-mounted hardware. The contributions from the Apollo and Skylab programs have been removed from the model since they have been difficult to verify and do not represent a true analogue of the ISSA U.S. Segment.

The RSA MAD design is based on the ability to meet the maximum allowable concentrations for 109 chemical compounds documented in appendix C (on CD inside back cover). This listing represents the admixtures that are used for verification and qualification testing of the MAD (A. Riabkin, Personal Communication, NPO Energia, Moscow, Russia, June 1994). Generation rates used for testing are derived from the MAD flow rate and the maximum allowable concentrations. This, in turn, results in a maximum allowable generation rate for each contaminant. A listing of the test concentrations and MAD removal generation rates is presented in NASA TM-108441.[1] The Russian approach is to characterize the MAD by test, determine the maximum allowable contaminant generation rate, and limit the generation rate below the maximum allowable by material selection and control. Since the rates used to verify the MAD are not actual generation rates but a derived maximum allowable rate, the rates listed in appendix B are used as the basis to assess the performance of the Russian MAD to control contaminants for the Russian Segment and ISSA.

Overlap between the Russian and NASA trace contaminant load models is shown in table 1. In this table, the compounds that have either a NASA 180-day SMAC, a Russian 360-day ПDK, or both are listed. The mean generation rate derived from Spacelab module mission data is included along with the standard deviation and the metabolic generation rate. As can be seen by this comparison, most of the Russian ПDKs are significantly lower than the NASA SMACs.

Table 1. NASA and Russian trace contaminant load model overlap.

Chemical Name	Molecular Weight (g/mole)	NASA 180-Day SMAC (mg/m^3)	Russian 360-Day ΠDK (mg/m^3)	Mean Rate (mg/day*kg)	Standard Deviation (mg/day*kg)	Metabolic Rate (mg/man*day)
Methanol	32.04	9.00	0.20	8.55E–04	4.18E–04	1.50E+00
Ethanol	46.07	94.00	10.00	3.53E–03	4.32E–03	4.00E+00
2-propanol	60.09	150.00	1.50	2.51E–03	1.48E–03	–
n-propanol	60.09	98.30	0.60	1.11E–04	1.30E–04	–
1,2-ethanediol	62.07	13.00	10.00	2.03E–06	4.00E–06	–
n-butanol	74.12	–	0.80	2.27E–03	2.44E–03	1.33E+00
2-methyl-1-propanol	74.12	–	0.10	4.14E–04	4.33E–04	1.20E+00
Phenol	94.11	–	0.10	1.59E–04	3.24E–04	–
Cyclohexanol	100.16	–	0.20	2.67E–04	4.89E–04	–
2-hexanol	102.18	–	0.25	1.59E–06	8.90E–07	–
Methanal	30.03	0.05	0.05	1.74E–08	2.67E–08	–
Ethanal	44.05	4.00	1.00	6.86E–05	3.99E–05	9.00E–02
2-propenal	56.06	0.03	–	1.20E–06	2.26E–06	–
Benzene	78.11	0.30	2.00	1.51E–05	1.00E–05	–
Methylbenzene	98.13	60.00	8.00	1.53E–03	4.55E–04	–
Vinylbenzene	104.14	–	0.25	1.54E–05	1.59E–05	–
1,2-dimethylbenzene	106.16	220.00	5.00	3.07E–04	2.49E–04	–
1,3-dimethylbenzene	106.16	220.00	5.00	7.03E–04	1.32E–03	–
1,4-dimethylbenzene	106.16	220.00	5.00	6.68E–04	4.12E–04	–
Isopropylbenzene	120.20	–	0.50	1.00E–05	4.00E–06	–
Ethyl acetate	88.11	–	4.00	1.58E–04	1.38E–04	–
Methyl methacrylate	100.12	–	0.30	6.78E–05	6.19E–05	–
Isopropyl acetate	102.13	–	4.00	2.77E–06	3.05E–06	–
Butyl acetate	116.16	–	2.00	3.98E–04	3.48E–04	–
1,4-epoxybutane	72.11	–	3.00	3.38E–05	3.55E–05	–
Diethyl ether	74.12	–	10.00	3.88E–05	5.02E–05	–
1,4-dioxane	88.11	–	0.50	5.76E–05	5.60E–05	–
1,3,5-trioxane	90.08	–	0.10	1.48E–06	1.65E–06	–
2-ethoxyethanol	90.12	0.30	0.00	2.18E–04	3.83E–04	–
Epichlorohydrin	92.53	–	0.10	8.23E–07	1.84E–06	–
Chloromethane	50.49	–	0.50	3.52E–06	3.24E–06	–
Chloroethene	62.50	3.00	–	6.07E–07	8.49E–07	–
Dichloromethane	84.93	10.00	–	1.12E–03	1.03E–03	–
1,2-dichloroethane	98.97	1.00	0.50	4.24E–05	3.50E–05	–
Chlorobenzene	112.56	–	1.50	7.84E–04	7.60E–04	–
1,2-dichloropropane	112.99	–	42.20	3.01E–06	4.41E–06	–
Trichloroethylene	131.39	10.00	1.50	5.06E–05	3.56E–05	–
Tetrachloromethane	153.82	–	4.00	5.05E–06	4.55E–06	–
Chlorodifluoromethane	86.47	–	100.00	2.01E–05	3.74E–05	–
Dichlorodifluoromethane	120.91	–	150.00	6.25E–06	7.21E–06	–
1,1,2-triCl-1,2,2-triFlethane	187.40	400.00	–	8.64E–03	1.03E–02	–
Methane	16.04	3,800.00	3,342.00	5.43E–04	9.61E–05	1.60E+02
Ethene	28.05	–	20.00	7.00E–08	1.57E–07	–
1,3-butadiene	54.09	0.13	2.00	8.22E–07	1.84E–06	–
1-butene	56.10	–	15.00	5.66E–05	2.37E–05	–
Butane	58.12	–	10.00	2.43E–06	2.70E–06	–
2-methyl-1,3-butadiene	68.12	–	3.00	–	–	–

Table 1. NASA and Russian trace contaminant load model overlap (Continued).

Chemical Name	Molecular Weight (g/mole)	NASA 180-Day SMAC (mg/m^3)	Russian 360-Day ΠDK (mg/m^3)	Mean Rate (mg/day*kg)	Standard Deviation (mg/day*kg)	Metabolic Rate (mg/man*day)
Pentane	72.15	–	10.00	4.46E–05	5.08E–05	–
Cyclohexane	84.16	–	3.00	1.48E–04	2.31E–04	–
Hexane	86.18	–	5.00	3.55E–05	3.40E–05	–
Heptane	100.21	–	10.00	3.16E–05	2.44E–05	–
Octane	114.23	–	10.00	9.36E–06	6.75E–06	–
Decane	142.28	–	10.00	1.18E–05	1.60E–05	–
2-propanone	58.08	–	2.00	2.23E–03	1.39E–03	–
2-butanone	72.11	30.00	0.25	2.81E–03	3.20E–03	–
Cyclohexanone	98.14	–	1.30	4.34E–04	2.28E–04	–
Hydrogen sulfide	34.08	–	0.50	–	–	9.00E–02
Dimethyl sulfide	62.14	–	4.00	5.80E–08	1.30E–07	–
Carbon disulfide	76.14	–	1.00	1.58E–05	1.65E–05	–
Nitric oxide	30.01	–	0.40	–	–	–
Ethanoic acid	60.05	–	1.00	5.92E–07	8.31E–07	–
Hydrazine	32.05	0.005	–	–	–	–
Methylhydrazine	46.07	0.004	–	–	–	–
Nitromethane	61.04	13.00	–	1.40E–05	3.12E–05	–
N,N-dimethylformamide	73.10	–	1.00	9.27E–07	1.17E–06	–
2,3-benzopyrrole	117.15	0.25	–	–	–	6.25E+00
Hydrogen	2.02	340.00	–	2.41E–06	3.50E–06	2.60E+01
Ammonia	17.00	7.00	1.00	4.11E–05	4.35E–05	3.21E+02
Carbon monoxide	28.01	10.00	5.00	1.37E–03	6.58E–04	2.30E+01
Trimethylsilanol	90.21	40.00	–	7.89E–05	8.98E–05	–
Octamethyltrisiloxane	236.54	40.00	–	6.91E–05	1.42E–04	–

Generation rates for the Russian and U.S. Segments were derived for the analysis by multiplying the generation rates of table 1 by ISSA mass properties estimates. Internal hardware masses for the U.S. Lab, U.S. Hab, Node 1, Node 2, the Japanese Experiment Module (JEM), and the ESA Attached Pressurized Module (APM) have been estimated as 11,307, 14,937, 7,221, 7,359, 14,152, and 6,994 kg, respectively. This results in a total U.S. Segment internal hardware mass of 61,970 kg. Based on a mass-to-volume ratio of 150 kg/m^3 of habitable volume, the Russian Segment internal hardware mass is estimated to be 75,000 kg. The total station internal hardware mass estimate is 136,970 kg.

3. SPACE STATION CONFIGURATION

The ISSA configuration used for analysis was the completely assembled configuration as shown in figure 1. This configuration provides approximately 543 m^3 of volume for the U.S. Segment and 500 m^3 for the Russian Segment for a crew of six plus 1.25 human equivalents for research animals (N. Frazier, Personal Communication, The Boeing Company, Huntsville, AL, June 1994; A. Riabkin, Personal Communication, NPO Engergia, Moscow, Russia, June 1994). A NASA TCCS unit is mounted in the U.S. Lab and U.S. Hab; however, only one unit may operate at any one time. This TCCS unit is shown in figure 2. Flow rates for the TCCS are 15.29 m^3/hr through the charcoal bed and 4.59 m^3/hr through the high-temperature catalytic oxidizer. Condensing heat exchangers (HXs) in the U.S. Lab, U.S. Hab, Nodes, JEM, APM, airlock, and Russian Segment provide an average air flow of 410 m^3/hr each with the humidity condensate removal of 2.72 kg/person divided equally among the HXs.

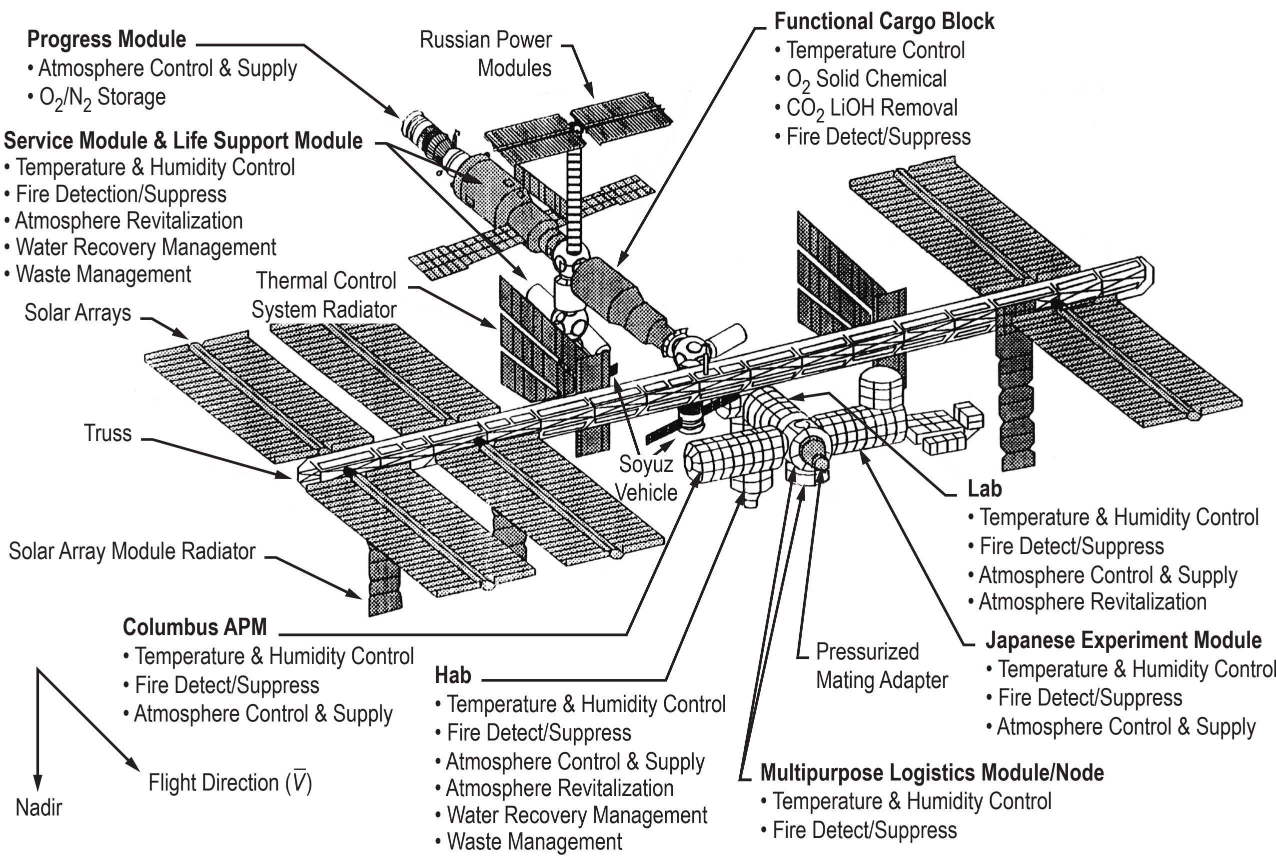

Figure 1. ISSA on-orbit configuration.

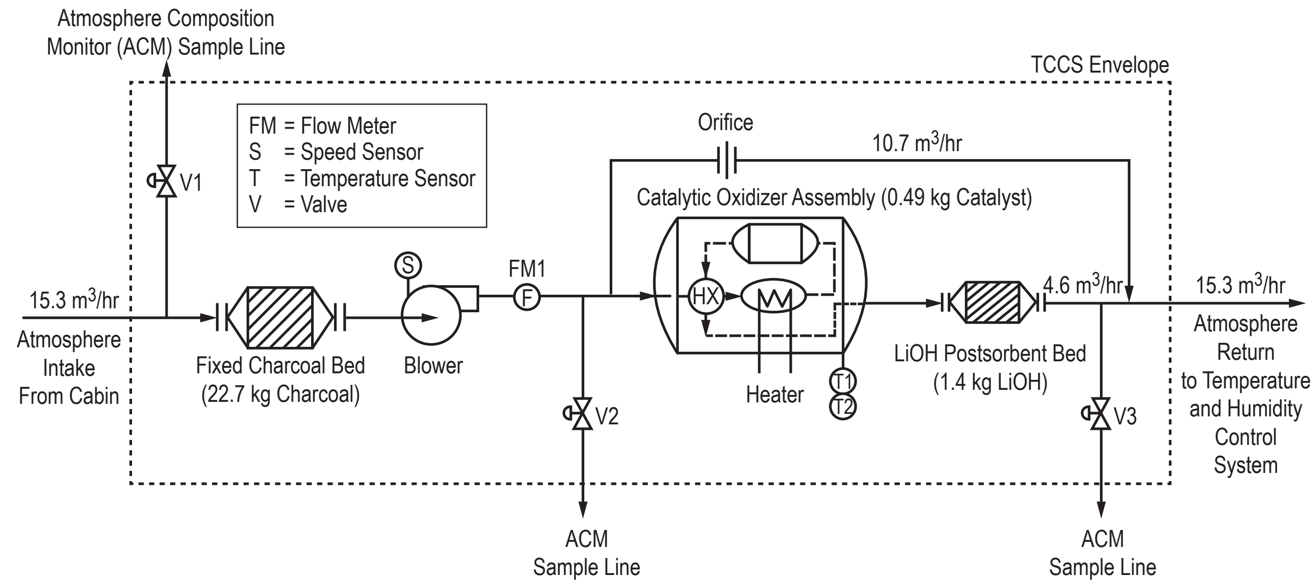

Figure 2. TCCS process flow diagram.

The Russian Segment MAD is shown in figure 3. It provides 20 m^3/hr of flow through expendable and regenerable activated charcoal beds in addition to an ambient temperature catalytic oxidation catalyst. More details on the actual design of the Russian MAD can be found in NASA TM-108441;[1] however, since this NASA document was published, more information on the performance of the activated charcoal performance for the MAD has been obtained. It has been found that the charcoal bed design driver is isopropylbenzene and that the equilibrium loading is 0.43 cm^3/gm of charcoal (A. Riabkin, Personal Communication at Houston, TX, NPO Energia, Moscow, Russia, March 1994). This loading is actually representative of the charcoal loading for NASA's TCCS as can be seen by plotting this data point on the TCCS charcoal characteristic curve in figure 4 (M.I. Leban, "Modification of Gaseous Contaminant Computer Program for Humidity Effect," Engineering Memo TCC-0070, Lockheed Missiles and Space Co., Inc., Sunnyvale, CA, May 18, 1993).

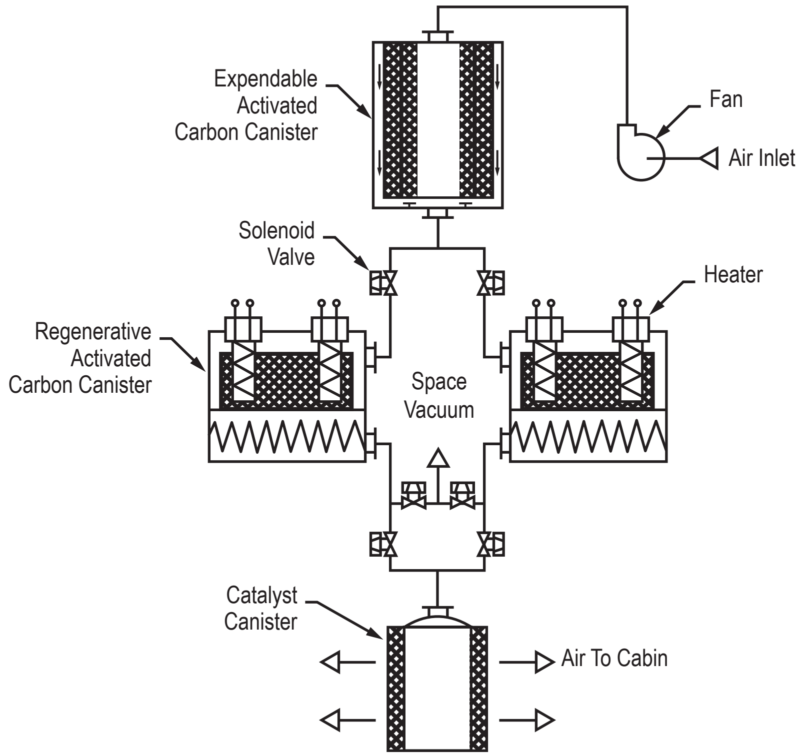

Figure 3. MAD process flow diagram.

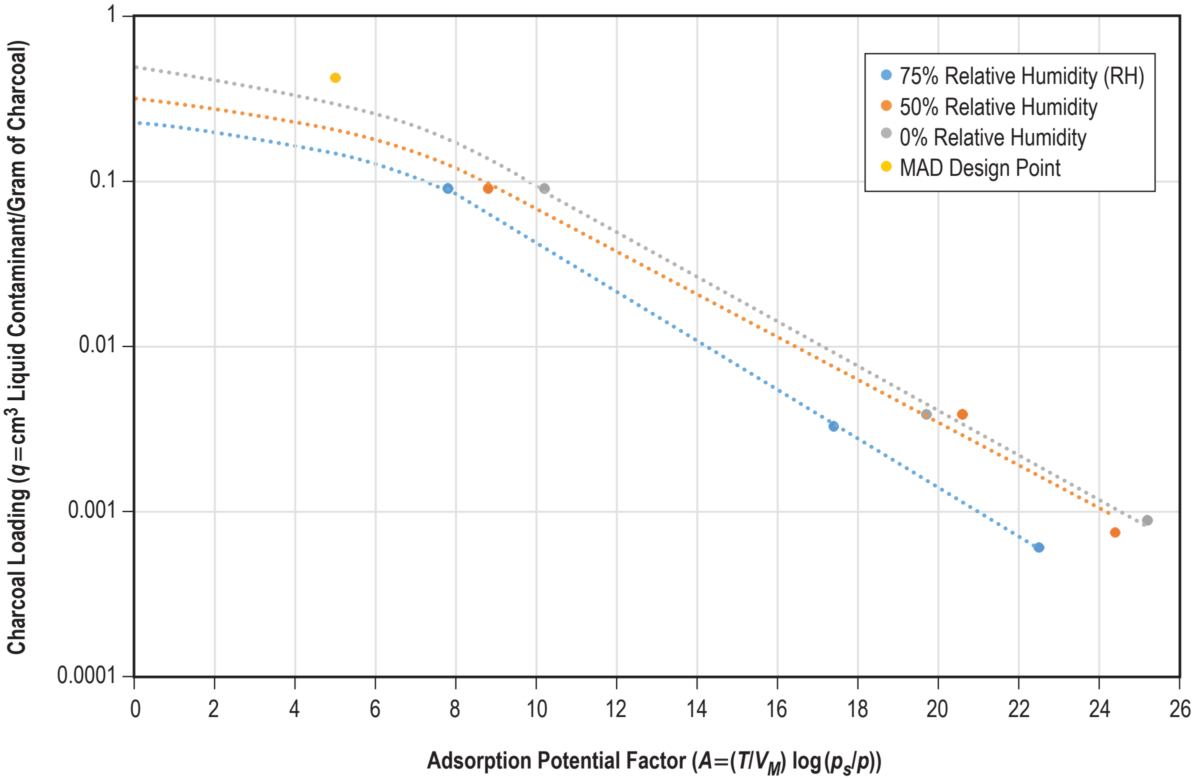

Figure 4. MAD charcoal performance with respect to TCCS charcoal characteristic curves.

4. ANALYTICAL CASE STUDIES

Two case studies were considered with five subcases each. Case I investigated the ability of the TCCS and MAD to control to below the Russian 360-day ПDKs and the NASA 180-day SMACs at the mean equipment offgassing rate plus crew generation. Case II investigated the performance for the mean plus one standard deviation offgassing rate plus crew generation. The five subcases studied for the two primary cases are as follows:

(1) The U.S. TCCS controlling only contamination generated from the U.S. Segment.
(2) The U.S. TCCS controlling contamination generated from the total ISSA.
(3) The Russian MAD controlling only contamination generated from the Russian Segment.
(4) The Russian MAD controlling contamination generated from the total ISSA.
(5) Both the U.S. TCCS and Russian MAD controlling contamination generated from the total ISSA.

Subcases (1) and (3) are actually similar to subcase (5); however, they were investigated to determine whether there would be any impact on TCCS and MAD capabilities if intersegment ventilation is minimal. Subcase (5) assumes that intersegment ventilation is sufficient to provide complete mixing between the segment volumes.

The mean and mean plus one standard deviation cases were selected based upon analysis of the Spacelab generation rate data and the impacts of including additional multiples of the standard deviation greater than the mean. The mean generation rate was investigated because previous design policy requested that the TCCS performance be assessed using generation rates based upon statistical averages of Spacelab generation rate data (NASA Memo DSS-2 (93-009), "Incorporation of New 180-day Spacecraft Maximum Allowable Concentrations (SMACs) of Contaminants," Deputy Manager, System Engineering and Integration Office, NASA Headquarters, Washington, DC, February 28, 1993). Unfortunately, using the mean generation rate does not provide a high level of confidence in the analytical results. Since the mean is equivalent to the 50% confidence limit, only a 50% confidence that the actual average generation rate will fall at that value or below can be maintained. As multiples of the standard deviation are added, the confidence in the average generation rate falling at or below that confidence limit rises. The mean plus one standard deviation represents the 96% confidence limit which provides analytical results that have a higher level of confidence that the average generation rate, and therefore the predicted cabin concentration for the ISSA, will fall at or below that rate and its accompanying projected concentration. Approximately one-and-one-half times the standard deviation above the mean provides the 99% confidence limit. As shown in table 1, the magnitude of the standard deviation in some cases is the same as the mean and the 96% confidence limit effectively doubles the mean. As shown in tables 2 and 3, using generation rates at two standard deviations above the mean to achieve a 99.6% confidence can exceed the flow rate capabilities of both the TCCS and MAD and would require a design change to both hardware systems to meet the Russian ПDKs. Therefore, it would not be cost effective to attempt to achieve an additional 3.6% confidence in the analytical results. The 96% confidence limit was accepted as the maximum case that most likely would not result in contamination control system design changes to meet maximum allowable concentrations.

Table 2. Contaminant generation rate threshold analysis for the TCCS.

Chemical Name	U.S. Mean Rate (mg/hr)	U.S. 0.5S Rate (mg/hr)	U.S. 1S Rate (mg/hr)	U.S. 1.5S Rate (mg/hr)	U.S. 2S Rate (mg/hr)	U.S. TCCS Max Rate (mg/hr)
Methanol	2.40	2.93	3.47	4.01	4.55	3.06
Ethanol	9.61	15.19	20.77	26.35	31.92	152.90
2-propanol	6.48	8.39	10.30	12.21	14.12	22.94
n-propanol	0.29	0.45	0.62	0.79	0.96	9.17
1,2-ethanediol	0.01	0.01	0.02	0.02	0.03	152.90
n-butanol	6.03	9.18	12.33	15.47	18.62	12.23
2-methyl-1-propanol	1.22	1.78	2.34	2.89	3.45	1.53
Phenol	0.41	0.83	1.25	1.67	2.08	1.53
Cyclohexanol	0.69	1.32	1.95	2.58	3.21	3.06
2-hexanol	–	0.01	0.01	0.01	0.01	3.82
Methanal	–	–	–	–	–	0.76
Ethanal	0.19	0.24	0.29	0.34	0.39	15.29
2-propenal	–	0.01	0.01	0.01	0.01	0.46
Benzene	0.04	0.05	0.06	0.08	0.09	4.59
Methylbenzene	3.95	4.54	5.13	5.71	6.30	122.32
Vinylbenzene	0.04	0.06	0.08	0.10	0.12	3.82
1,2-dimethylbenzene	0.79	1.11	1.44	1.76	2.08	76.45
1,3-dimethylbenzene	1.82	3.52	5.22	6.93	8.63	76.45
1,4-dimethylbenzene	1.72	2.26	2.79	3.32	3.85	76.45
Isopropylbenzene	0.03	0.03	0.04	0.04	0.05	7.65
Ethyl acetate	0.41	0.59	0.76	0.94	1.12	61.16
Methyl methacrylate	0.18	0.26	0.33	0.41	0.49	4.59
Isopropyl acetate	0.01	0.01	0.02	0.02	0.02	61.16
Butyl acetate	1.03	1.48	1.93	2.38	2.82	30.58
1,4-epoxybutane	0.09	0.13	0.18	0.22	0.27	45.87
Diethyl ether	0.10	0.17	0.23	0.29	0.36	152.90
1,4-dioxane	0.15	0.22	0.29	0.37	0.44	7.65
1,3,5-trioxane	–	0.01	0.01	0.01	0.01	1.53
2-ethoxyethanol	0.56	1.06	1.55	2.05	2.54	4.59
Epichlorohydrin	–	–	0.01	0.01	0.01	1.53
Chloromethane	0.01	0.01	0.02	0.02	0.03	7.65
Chloroethene	–	–	–	–	0.01	45.87
Dichloromethane	2.89	4.22	5.55	6.88	8.21	152.90
1,2-dichloroethane	0.11	0.15	0.20	0.25	0.29	7.65
Chlorobenzene	2.02	3.01	3.99	4.97	5.95	22.94
1,2-dichloropropane	0.01	0.01	0.02	0.02	0.03	645.24
Trichloroethylene	0.13	0.18	0.22	0.27	0.31	22.94
Tetrachloromethane	0.01	0.02	0.02	0.03	0.04	61.16
Chlorodifluoromethane	0.05	0.10	0.15	0.20	0.24	1,529.00
Dichlorodifluoromethane	0.02	0.03	0.03	0.04	0.05	2,293.50
1,1,2-triCl-1,2,2-triFlethane	22.31	35.61	48.90	62.20	75.50	6,116.00
Methane	21.40	21.53	21.65	21.77	21.90	51,099.18

Table 2. Contaminant generation rate threshold analysis for the TCCS (Continued).

Chemical Name	U.S. Mean Rate (mg/hr)	U.S. 0.5S Rate (mg/hr)	U.S. 1S Rate (mg/hr)	U.S. 1.5S Rate (mg/hr)	U.S. 2S Rate (mg/hr)	U.S. TCCS Max Rate (mg/hr)
Ethene	–	–	–	–	–	305.80
1,3-butadiene	–	–	0.01	0.01	0.01	1.99
1-butene	0.15	0.18	0.21	0.24	0.27	229.35
Butane	0.01	0.01	0.01	0.02	0.02	152.90
2-methyl-1,3-butadiene	–	–	–	–	–	45.87
Pentane	0.12	0.18	0.25	0.31	0.38	152.90
Cyclohexane	0.38	0.68	0.98	1.28	1.58	45.87
Hexane	0.09	0.14	0.18	0.22	0.27	76.45
Heptane	0.08	0.11	0.14	0.18	0.21	152.90
Octane	0.02	0.03	0.04	0.05	0.06	152.90
Decane	0.03	0.05	0.07	0.09	0.11	152.90
2-propanone	5.76	7.55	9.35	11.14	12.94	30.58
2-butanone	7.26	11.39	15.52	19.64	23.77	3.82
Cyclohexanone	1.12	1.42	1.71	2.01	2.30	19.88
Hydrogen sulfide	0.01	0.01	0.01	0.01	0.01	7.65
Dimethyl sulfide	–	–	–	–	–	61.16
Carbon disulfide	0.04	0.06	0.08	0.10	0.13	15.29
Nitric oxide	–	–	–	–	–	6.12
Ethanoic acid	–	–	–	–	0.01	15.29
Hydrazine	–	–	–	–	–	0.08
Methylhydrazine	–	–	–	–	–	0.06
Nitromethane	0.04	0.08	0.12	0.16	0.20	198.77
N,N-dimethylformamide	–	–	0.01	0.01	0.01	15.29
2,3-benzopyrrole	0.78	0.78	0.78	0.78	0.78	3.82
Hydrogen	3.26	3.26	3.27	3.27	3.27	5,198.60
Ammonia	40.17	40.22	40.28	40.34	40.39	15.29
Carbon monoxide	6.41	7.26	8.11	8.96	9.81	76.45
Trimethylsilanol	0.20	0.32	0.44	0.55	0.67	611.60
Octamethyltrisiloxane	0.18	0.36	0.55	0.73	0.91	611.60

Table 3. Contaminant generation rate threshold analysis for the MAD.

Chemical Name	Russian Mean Rate (mg/hr)	Russian 0.5S Rate (mg/hr)	Russian 1S Rate (mg/hr)	Russian 1.5S Rate (mg/hr)	Russian 2S Rate (mg/hr)	Russian TCCS Max Rate (mg/hr)
Methanol	2.86	3.51	4.17	4.82	5.47	4.00
Ethanol	11.53	18.28	25.03	31.78	38.53	200.00
2-propanol	7.84	10.16	12.47	14.78	17.09	30.00
n-propanol	0.35	0.55	0.75	0.96	1.16	12.00
1,2-ethanediol	0.01	0.01	0.02	0.03	0.03	200.00
n-butanol	7.27	11.07	14.88	18.69	22.50	16.00
2-methyl-1-propanol	1.44	2.12	2.79	3.47	4.15	2.00
Phenol	0.50	1.00	1.51	2.02	2.52	2.00
Cyclohexanol	0.83	1.60	2.36	3.13	3.89	4.00
2-hexanol	–	0.01	0.01	0.01	0.01	5.00
Methanal	–	–	–	–	–	1.00
Ethanal	0.23	0.29	0.35	0.41	0.48	20.00
2-propenal	–	0.01	0.01	0.01	0.02	0.60
Benzene	0.05	0.06	0.08	0.09	0.11	6.00
Methylbenzene	4.78	5.49	6.20	6.91	7.63	160.00
Vinylbenzene	0.05	0.07	0.10	0.12	0.15	5.00
1,2-dimethylbenzene	0.96	1.35	1.74	2.13	2.52	100.00
1,3-dimethylbenzene	2.20	4.26	6.32	8.38	10.45	100.00
1,4-dimethylbenzene	2.09	2.73	3.38	4.02	4.66	100.00
Isopropylbenzene	0.03	0.04	0.04	0.05	0.06	10.00
Ethyl acetate	0.49	0.71	0.93	1.14	1.36	80.00
Methyl methacrylate	0.21	0.31	0.41	0.50	0.60	6.00
Isopropyl acetate	0.01	0.01	0.02	0.02	0.03	80.00
Butyl acetate	1.24	1.79	2.33	2.88	3.42	40.00
1,4-epoxybutane	0.11	0.16	0.22	0.27	0.33	60.00
Diethyl ether	0.12	0.20	0.28	0.36	0.44	200.00
1,4-dioxane	0.18	0.27	0.36	0.44	0.53	10.00
1,3,5-trioxane	–	0.01	0.01	0.01	0.01	2.00
2-ethoxyethanol	0.68	1.28	1.88	2.48	3.08	6.00
Epichlorohydrin	–	0.01	0.01	0.01	0.01	2.00
Chloromethane	0.01	0.02	0.02	0.03	0.03	10.00
Chloroethene	–	–	–	0.01	0.01	60.00
Dichloromethane	3.50	5.11	6.72	8.33	9.94	200.00
1,2-dichloroethane	0.13	0.19	0.24	0.30	0.35	10.00
Chlorobenzene	2.45	3.64	4.82	6.01	7.20	30.00
1,2-dichloropropane	0.01	0.02	0.02	0.03	0.04	844.00
Trichloroethylene	0.16	0.21	0.27	0.33	0.38	30.00
Tetrachloromethane	0.02	0.02	0.03	0.04	0.04	80.00
Chlorodifluoromethane	0.06	0.12	0.18	0.24	0.30	2,000.00
Dichlorodifluoromethane	0.02	0.03	0.04	0.05	0.06	3,000.00
1,1,2-triCl-1,2,2-triFlethane	27.00	43.09	59.19	75.28	91.38	8,000.00
Methane	21.70	21.85	22.00	22.15	22.30	66,840.00
Ethene	–	–	–	–	–	400.00
1,3-butadiene	–	0.01	0.01	0.01	0.01	2.60

Table 3. Contaminant generation rate threshold analysis for the MAD (Continued).

Chemical Name	Russian Mean Rate (mg/hr)	Russian 0.5S Rate (mg/hr)	Russian 1S Rate (mg/hr)	Russian 1.5S Rate (mg/hr)	Russian 2S Rate (mg/hr)	Russian TCCS Max Rate (mg/hr)
1-butene	0.18	0.21	0.25	0.29	0.32	300.00
Butane	0.01	0.01	0.02	0.02	0.02	200.00
2-methyl-1,3-butadiene	–	–	–	–	–	60.00
Pentane	0.14	0.22	0.30	0.38	0.46	200.00
Cyclohexane	0.46	0.82	1.18	1.55	1.91	60.00
Hexane	0.11	0.16	0.22	0.27	0.32	100.00
Heptane	0.10	0.14	0.18	0.21	0.25	200.00
Octane	0.03	0.04	0.05	0.06	0.07	200.00
Decane	0.04	0.06	0.09	0.11	0.14	200.00
2-propanone	6.97	9.14	11.31	13.48	15.66	40.00
2-butanone	8.79	13.78	18.78	23.77	28.77	5.00
Cyclohexanone	1.36	1.71	2.07	2.43	2.78	26.00
Hydrogen sulfide	0.01	0.01	0.01	0.01	0.01	10.00
Dimethyl sulfide	–	–	–	–	–	80.00
Carbon disulfide	0.05	0.08	0.10	0.13	0.15	20.00
Nitric oxide	–	–	–	–	–	8.00
Ethanoic acid	–	–	–	0.01	0.01	20.00
Hydrazine	–	–	–	–	–	0.10
Methylhydrazine	–	–	–	–	–	0.08
Nitromethane	0.04	0.09	0.14	0.19	0.24	260.00
N,N-dimethylformamide	–	–	0.01	0.01	0.01	20.00
2,3-benzopyrrole	0.78	0.78	0.78	0.78	0.78	5.00
Hydrogen	3.26	3.26	3.27	3.27	3.28	6,800.00
Ammonia	40.19	40.26	40.33	40.39	40.46	20.00
Carbon monoxide	7.16	8.18	9.21	10.24	11.27	100.00
Trimethylsilanol	0.25	0.39	0.53	0.67	0.81	800.00
Octamethyltrisiloxane	0.22	0.44	0.66	0.88	1.10	800.00

5. CASE STUDY RESULTS

Results for cases I and II are summarized in tables 4 and 5. Both tables document the final cabin concentration for a simulated 90-day mission duration. Ninety days were used because most trace contaminant concentrations would have achieved a steady state concentration by that time. Also, 90 days has been a standard station resupply cycle and, therefore, has a basis in past space station design. Each case is documented in an individual column. The first column to the right of the column listing the chemical contaminant's molecular weight is the lowest maximum allowable concentration (MAC) for that particular compound. This column is a combination of NASA 180-day SMACs and Russian ΠDKs and lists the lowest of the two. To the right of the column documenting maximum allowable concentrations are columns documenting the five subcases. The U.S. TCCS performance for both the U.S. Segment alone and for the entire ISSA contaminant load are documented in the first two performance columns while the Russian MAD performance for the Russian Segment and entire ISSA contaminant loads are listed in the next two columns. The last column lists the final cabin concentration for the entire ISSA with both the U.S. TCCS and Russian MAD operating simultaneously. Only those contaminants with either a NASA 180-day or Russian 360-day ΠDK in addition to being in both the U.S. and Russian trace contaminant load models have been included in the analysis. Computer output for cases I and II can be found in appendices D and E, respectively (on CD inside back cover).

Table 4. Contamination control system performance using mean generation rates.

Chemical Name	Molecular Weight (g/mole)	Lowest MAC (mg/m^3)	U.S. TCCS Performance		Russian TCCS Performance		Combined Control Level (mg/m^3)
			U.S. Segment (mg/m^3)	Total Station (mg/m^3)	Russian Segment (mg/m^3)	Total Station (mg/m^3)	
Methanol	32.04	0.20	4.19E–01	7.20E–01	1.92E+00	1.73E+00	3.01E–01
Ethanol	46.07	10.00	1.12E+00	2.50E+00	5.81E–01	1.05E+00	5.98E–01
2-propanol	60.09	1.50	4.05E–01	8.42E–01	3.86E–01	6.72E–01	3.34E–01
n-propanol	60.09	0.60	1.79E–02	3.63E–02	1.69E–02	2.88E–02	1.40E–02
1,2-ethanediol	62.07	10.00	6.53E–04	6.53E–04	5.02E–04	5.02E–04	3.84E–04
n-butanol	74.12	0.80	3.86E–01	8.27E–01	3.60E–01	6.46E–01	3.42E–01
2-methyl-1-propanol	74.12	0.10	7.06E–02	1.33E–01	6.57E–02	1.08E–01	4.61E–02
Phenol	94.11	0.10	2.68E–02	5.94E–02	2.50E–02	4.55E–02	2.58E–02
Cyclohexanol	100.16	0.20	4.50E–02	9.90E–02	4.15E–02	7.58E–02	4.29E–02
2-hexanol	102.18	0.25	–	6.13E–04	–	4.76E–04	2.50E–04
Methanal	30.03	0.05	–	–	–	–	–
Ethanal	44.05	1.00	4.04E–02	8.49E–02	1.41E–01	2.48E–01	6.05E–02
2-propenal	56.06	0.03	–	6.52E–04	–	5.12E–04	2.87E–04
Benzene	78.11	0.30	2.61E–03	5.87E–03	2.51E–03	4.52E–03	2.56E–03
Methylbenzene	98.13	8.00	2.58E–01	5.70E–01	2.40E–01	4.41E–01	2.48E–01
Vinylbenzene	104.14	0.25	2.61E–03	5.87E–03	2.50E–03	4.50E–03	2.55E–03
1,2-dimethylbenzene	106.16	5.00	5.15E–02	1.14E–01	4.80E–02	8.74E–02	4.95E–02
1,3-dimethylbenzene	106.16	5.00	1.19E–01	2.62E–01	1.10E–01	2.01E–01	1.14E–01
1,4-dimethylbenzene	106.16	5.00	1.12E–01	2.49E–01	1.04E–01	1.90E–01	1.08E–01

Table 4. Contamination control system performance using mean generation rates (Continued).

Chemical Name	Molecular Weight (g/mole)	Lowest MAC (mg/m^3)	U.S. TCCS Performance		Russian TCCS Performance		Combined Control Level (mg/m^3)
			U.S. Segment (mg/m^3)	Total Station (mg/m^3)	Russian Segment (mg/m^3)	Total Station (mg/m^3)	
Isopropylbenzene	120.20	0.50	1.96E–03	3.91E–03	1.50E–03	3.00E–03	1.70E–03
Ethyl acetate	88.11	4.00	2.66E–02	5.81E–02	2.45E–02	4.49E–02	2.50E–02
Methyl methacrylate	100.12	0.30	1.17E–02	2.55E–02	1.05E–02	1.95E–02	1.11E–02
Isopropyl acetate	102.13	4.00	6.52E–04	1.30E–03	5.01E–04	1.00E–03	5.67E–04
Butyl acetate	116.16	2.00	6.71E–02	1.48E–01	6.19E–02	1.13E–01	6.39E–02
1,4-epoxybutane	72.11	3.00	5.87E–03	1.24E–02	5.55E–03	9.59E–03	5.39E–03
Diethyl ether	74.12	10.00	6.53E–03	1.44E–02	6.03E–03	1.11E–02	6.25E–03
1,4-dioxane	88.11	0.50	9.11E–03	1.83E–02	8.55E–03	1.46E–02	6.84E–03
1,3,5-trioxane	90.08	0.10	–	8.67E–05	–	8.34E–05	2.38E–05
2-ethoxyethanol	90.12	0.30	3.30E–02	6.42E–02	3.14E–02	5.17E–02	2.28E–02
Epichlorohydrin	92.53	0.10	–	–	–	–	–
Chloromethane	50.49	0.50	5.33E–03	1.04E–02	2.85E–02	3.36E–02	9.59E–03
Chloroethene	62.50	3.00	–	–	–	–	–
Dichloromethane	84.93	10.00	9.74E–01	2.32E+00	4.65E–01	1.15E+00	7.41E–01
1,2-dichloroethane	98.97	0.50	7.17E–03	1.56E–02	6.54E–03	1.21E–02	6.81E–03
Chlorobenzene	112.56	1.50	1.32E–01	2.92E–01	1.23E–01	2.24E–01	1.27E–01
1,2-dichloropropane	112.99	42.20	6.52E–04	1.30E–03	5.02E–04	1.00E–03	5.67E–04
Trichloroethylene	131.39	1.50	8.48E–03	1.89E–02	8.03E–03	1.46E–02	8.23E–03
Tetrachloromethane	153.82	4.00	6.53E–04	1.96E–03	1.00E–03	1.51E–03	8.52E–04
Chlorodifluoromethane	86.47	100.00	3.02E–02	6.26E–02	3.38E–02	6.99E–02	3.43E–02
Dichlorodifluoromethane	120.91	150.00	1.31E–03	2.61E–03	1.02E–03	2.04E–03	1.15E–03
1,1,2-triCl-1,2,2-triFlethane	187.40	400.00	1.46E+00	3.22E+00	1.38E+00	2.51E+00	1.41E+00
Methane	16.04	3,342.00	6.58E+00	1.86E+01	8.61E+01	8.56E+01	1.21E+01
Ethene	28.05	20.00	–	–	–	–	–
1,3-butadiene	54.09	0.13	–	–	–	–	–
1-butene	56.10	15.00	9.79E–03	1.09E–02	9.17E–03	1.63E–02	9.17E–03
Butane	58.12	10.00	6.53E–04	6.53E–04	5.04E–04	5.04E–04	2.84E–04
2-methyl-1,3-butadiene	68.12	3.00	–	–	–	–	–
Pentane	72.15	10.00	7.83E–03	1.63E–02	7.02E–02	1.26E–02	7.10E–03
Cyclohexane	84.16	3.00	2.48E–02	5.48E–02	2.31E–02	4.21E–02	2.38E–02
Hexane	86.18	5.00	5.87E–03	1.31E–02	5.50E–03	1.00E–02	5.67E–03
Heptane	100.21	10.00	5.22E–03	1.17E–02	5.00E–03	9.00E–03	5.10E–03
Octane	114.23	10.00	1.31E–03	3.26E–03	1.50E–03	2.50E–03	1.42E–03
Decane	142.28	10.00	1.96E–03	4.57E–03	2.00E–03	3.49E–03	1.98E–03
2-propanone	58.08	2.00	3.71E–01	8.13E–01	3.52E–01	6.35E–01	3.44E–01
2-butanone	72.11	0.25	4.03E–01	7.35E–01	3.94E–01	6.14E–01	2.44E–01
Cyclohexanone	98.14	1.30	7.16E–02	1.54E–01	6.69E–02	1.19E–01	6.36E–02
Hydrogen sulfide	34.08	0.50	2.12E–03	4.13E–03	3.32E–02	3.22E–02	3.54E–03
Dimethyl sulfide	62.14	4.00	–	–	–	–	–
Carbon disulfide	76.14	1.00	2.61E–03	5.94E–03	2.57E–03	4.62E–03	2.59E–03
Nitric oxide	30.01	0.40	–	–	–	–	–
Ethanoic acid	60.05	1.00	–	–	–	–	–
Hydrazine	32.05	0.005	–	–	–	–	–
Methylhydrazine	46.07	0.004	–	–	–	–	–
Nitromethane	61.04	13.00	5.31E–03	1.14E–02	2.40E–03	5.10E–03	3.55E–03
N,N-dimethylformamide	73.10	1.00	–	6.53E–04	–	5.02E–04	2.84E–04
2,3-benzopyrrole	117.15	0.25	2.13E–02	2.35E–02	1.92E–02	2.20E–02	6.16E–03

Table 4. Contamination control system performance using mean generation rates (Continued).

Chemical Name	Molecular Weight (g/mole)	Lowest MAC (mg/m^3)	U.S. TCCS Performance U.S. Segment (mg/m^3)	U.S. TCCS Performance Total Station (mg/m^3)	Russian TCCS Performance Russian Segment (mg/m^3)	Russian TCCS Performance Total Station (mg/m^3)	Combined Control Level (mg/m^3)
Hydrogen	2.02	340.00	7.05E–01	1.41E+00	1.82E–01	3.63E–01	2.89E–01
Ammonia	17.00	1.00	3.23E–01	2.63E–01	4.13E–01	3.90E–01	4.86E–02
Carbon monoxide	28.01	5.00	1.39E+00	2.93E+00	3.99E–01	7.57E–01	6.03E–01
Trimethylsilanol	90.21	40.00	1.31E–02	2.94E–02	1.25E–02	2.25E–02	1.28E–02
Octamethyltrisiloxane	236.54	40.00	1.17E–02	2.55E–01	1.10E–02	1.95E–02	1.10E–02

Table 5. Contamination control system performance using mean plus one standard deviation generation rates.

Chemical Name	Molecular Weight (g/mole)	Lowest MAC (mg/m^3)	U.S. TCCS Performance U.S. Segment (mg/m^3)	U.S. TCCS Performance Total Station (mg/m^3)	Russian TCCS Performance Russian Segment (mg/m^3)	Russian TCCS Performance Total Station (mg/m^3)	Combined Control Level (mg/m^3)
Methanol	32.04	0.20	6.06E–01	1.05E+00	2.82E+00	2.52E+00	4.39E–01
Ethanol	46.07	10.00	2.95E+00	5.99E+00	1.45E+00	2.94E+00	1.43E+00
2-propanol	60.09	1.50	6.43E–01	1.34E+00	6.14E–01	1.07E+00	5.30E–01
n-propanol	60.09	0.60	3.83E–02	7.89E–02	3.63E–02	6.29E–02	3.06E–02
1,2-ethanediol	62.07	10.00	1.31E–03	1.96E–03	1.00E–03	1.51E–03	8.52E–04
n-butanol	74.12	0.80	7.88E–01	1.69E+00	7.40E–01	1.33E+00	7.02E–01
2-methyl-1-propanol	74.12	0.10	1.35E–01	2.56E–01	1.28E–01	2.08E–01	8.90E–02
Phenol	94.11	0.10	8.16E–02	1.80E–01	7.54E–02	1.38E–01	7.82E–02
Cyclohexanol	100.16	0.20	1.27E–01	2.81E–01	1.18E–01	2.15E–01	1.22E–01
2-hexanol	102.18	0.25	6.35E–04	6.13E–04	4.90E–04	4.76E–04	2.50E–04
Methanal	30.03	0.05	–	–	–	–	–
Ethanal	44.05	1.00	6.16E–02	1.33E–01	2.47E–01	4.31E–01	9.73E–02
2-propenal	56.06	0.03	6.52E–04	1.30E–03	5.13E–04	1.03E–03	5.74E–04
Benzene	78.11	0.30	3.91E–03	9.13E–03	4.02E–03	7.03E–03	3.98E–03
Methylbenzene	98.13	8.00	3.35E–01	7.39E–01	3.12E–01	5.74E–01	3.22E–01
Vinylbenzene	104.14	0.25	5.22E–03	1.17E–02	5.00E–03	9.00E–03	5.10E–03
1,2-dimethylbenzene	106.16	5.00	9.39E–02	2.07E–01	8.70E–02	1.58E–01	8.98E–02
1,3-dimethylbenzene	106.16	5.00	3.41E–01	7.54E–01	3.16E–01	5.79E–01	3.27E–01
1,4-dimethylbenzene	106.16	5.00	1.82E–01	4.02E–01	1.69E–01	3.08E–01	1.75E–01
Isopropylbenzene	120.20	0.50	2.61E–03	5.22E–03	2.00E–03	4.00E–03	2.27E–03
Ethyl acetate	88.11	4.00	4.94E–02	1.09E–01	4.66E–02	8.46E–02	4.70E–02
Methyl methacrylate	100.12	0.30	2.15E–02	4.83E–02	2.05E–02	3.71E–02	2.10E–02
Isopropyl acetate	102.13	4.00	1.31E–03	1.96E–03	1.00E–03	1.50E–03	8.50E–04
Butyl acetate	116.16	2.00	1.26E–01	2.77E–01	1.16E–01	2.12E–01	1.20E–01
1,4-epoxybutane	72.11	3.00	1.17E–02	2.60E–02	1.11E–02	2.03E–02	1.14E–02
Diethyl ether	74.12	10.00	1.50E–02	3.33E–02	1.41E–02	2.58E–02	1.45E–02
1,4-dioxane	88.11	0.50	1.76E–02	3.60E–02	1.71E–02	2.87E–02	1.35E–02
1,3,5-trioxane	90.08	0.10	1.74E–04	1.73E–04	1.70E–04	1.67E–04	4.75E–05
2-ethoxyethanol	90.12	0.30	9.13E–02	1.78E–01	8.68E–02	1.43E–01	6.32E–02
Epichlorohydrin	92.53	0.10	6.53E–04	1.31E–03	5.02E–04	1.00E–03	5.68E–04
Chloromethane	50.49	0.50	1.07E–02	2.07E–02	5.94E–02	6.87E–02	1.94E–02
Chloroethene	62.50	3.00	–	2.66E–03	–	1.03E–03	7.20E–04

Table 5. Contamination control system performance using mean plus one standard deviation generation rates (Continued).

Chemical Name	Molecular Weight (g/mole)	Lowest MAC (mg/m^3)	U.S. TCCS Performance		Russian TCCS Performance		Combined Control Level (mg/m^3)
			U.S. Segment (mg/m^3)	Total Station (mg/m^3)	Russian Segment (mg/m^3)	Total Station (mg/m^3)	
Dichloromethane	84.93	10.00	2.19E+00	4.93E+00	1.27E+00	3.21E+00	1.88E+00
1,2-dichloroethane	98.97	0.50	1.30E–02	2.87E–02	1.20E–02	2.22E–02	1.25E–02
Chlorobenzene	112.56	1.50	2.60E–01	5.75E–01	2.42E–01	4.43E–01	2.40E–01
1,2-dichloropropane	112.99	42.20	1.30E–03	2.61E–03	1.00E–03	2.01E–03	1.13E–03
Trichloroethylene	131.39	1.50	1.44E–02	3.20E–02	1.36E–02	2.46E–02	1.39E–02
Tetrachloromethane	153.82	4.00	1.31E–03	3.26E–03	1.51E–03	2.51E–03	1.42E–03
Chlorodifluoromethane	86.47	100.00	9.75E–02	2.00E–01	1.67E–01	2.94E–01	1.29E–01
Dichlorodifluoromethane	120.91	150.00	1.96E–03	5.22E–03	2.04E–03	4.08E–03	2.29E–03
1,1,2-triCl-1,2,2-triFlethane	187.40	400.00	3.19E+00	7.05E+00	3.02E+00	5.51E+00	3.10E+00
Methane	16.04	3,342.00	1.05E+01	2.84E+01	8.73E+01	8.67E+01	1.77E+01
Ethene	28.05	20.00	–	–	–	–	–
1,3-butadiene	54.09	0.13	6.53E–04	1.31E–03	5.08E–04	1.02E–03	5.72E–04
1-butene	56.10	15.00	1.37E–02	3.00E–02	1.27E–02	2.35E–02	1.32E–02
Butane	58.12	10.00	6.53E–04	1.96E–03	1.01E–03	1.51E–03	8.54E–04
2-methyl-1,3-butadiene	68.12	3.00	–	–	–	–	–
Pentane	72.15	10.00	1.63E–02	3.52E–01	1.51E–02	2.72E–02	1.53E–02
Cyclohexane	84.16	3.00	6.39E–02	1.41E–01	5.93E–02	1.09E–01	6.14E–02
Hexane	86.18	5.00	1.17E–02	2.61E–02	1.10E–02	2.00E–02	1.13E–02
Heptane	100.21	10.00	9.14E–03	2.09E–02	9.00E–03	1.60E–02	9.07E–03
Octane	114.23	10.00	2.61E–03	5.87E–03	2.50E–03	4.50E–03	2.55E–03
Decane	142.28	10.00	4.57E–03	1.04E–02	4.49E–03	7.99E–03	4.53E–03
2-propanone	58.08	2.00	6.03E–01	1.71E+00	5.71E–01	1.03E+00	5.58E–01
2-butanone	72.11	0.25	8.61E–01	1.57E+00	8.42E–01	1.31E+00	5.23E–01
Cyclohexanone	98.14	1.30	1.09E–01	2.35E–01	1.02E–01	1.82E–01	9.70E–02
Hydrogen sulfide	34.08	0.50	2.12E–03	4.13E–03	3.32E–02	3.22E–02	3.54E–03
Dimethyl sulfide	62.14	4.00	–	–	–	–	–
Carbon disulfide	76.14	1.00	5.26E–01	1.49E–02	5.15E–03	9.29E–03	5.20E–03
Nitric oxide	30.01	0.40	–	–	–	–	–
Ethanoic acid	60.05	1.00	–	3.32E–04	–	2.91E–04	9.67E–05
Hydrazine	32.05	0.005	–	–	–	–	–
Methylhydrazine	46.07	0.004	–	–	–	–	–
Nitromethane	61.04	13.00	1.90E–02	4.31E–02	1.03E–02	2.13E–02	1.41E–02
N,N-dimethylformamide	73.10	1.00	6.53E–04	6.53E–04	5.02E–04	5.02E–04	2.84E–04
2,3-benzopyrrole	117.15	0.25	2.13E–02	2.35E–02	1.92E–02	2.20E–02	6.16E–03
Hydrogen	2.02	340.00	7.07E–01	1.41E+00	1.82E–01	3.64E–01	2.90E–01
Ammonia	17.00	1.00	3.25E–01	2.65E–01	4.16E–01	2.92E–01	4.87E–02
Carbon monoxide	28.01	5.00	1.75E+00	3.74E+00	5.14E–01	9.66E–01	7.69E–01
Trimethylsilanol	90.21	40.00	2.87E–02	6.26E–02	2.65E–02	4.81E–02	2.73E–02
Octamethyltrisiloxane	236.54	40.00	3.59E–02	7.83E–02	3.29E–02	5.99E–02	3.40E–02

6. DISCUSSION OF RESULTS

As can be seen in tables 4 and 5, all NASA 180-day SMACs can be met by either the U.S. TCCS or Russian MAD operating alone or in combination. Russian 360-day ПDKs can be met with only a few exceptions, which include methanol and 2-butanone for both the U.S. TCCS and Russian MAD controlling only their respective segment trace contaminant loads at the mean generation rate. These two compounds present a problem for meeting the Russian 360-day ПDKs for the combined operation of the contamination control systems for the entire ISSA at the 96% confidence limit generation rates. Only methanol is a problem for combined system operation at the mean rate. In addition to methanol and 2-butanone, one additional contaminant, 2-methyl-1-propanol, cannot be controlled below the Russian 360-day ПDK for the 96% confidence limit rate for the individual contamination control systems controlling their respective segment contamination loads. At the higher rate, both systems cannot control methanol, n-butanol, 2-methyl-1-propanol, phenol, cyclohexanol, and 2-butanone to below the Russian 360-day ПDKs. All cases, however, show that no NASA 180-day SMAC will be exceeded and that even though some Russian 360-day ПDKs are exceeded, the control level is much closer to the Russian ПDK than the NASA SMAC.

Additional analysis that considers the flight experience from both Spacelab and Mir 1 shows that the compounds that are difficult to control below the Russian 360-day ПDK still generally have conservative generation rates. Flight concentration data are listed in appendix F for Spacelab and appendix G for Mir 1 (on CD inside back cover). Contaminant generation rates have been derived from the mean plus one standard deviation concentration from the Spacelab data and extrapolated to the U.S. Segment internal hardware mass while Russian Segment rates have been derived by determining the average concentration for the Mir 10, 11, 12, and 13 missions by using the middle of each concentration range reported and dividing by the frequency of occurrence. Generation rates derived from these data show that the generation rates for methanol and 2-butanone would be 0.114 and 41.1 mg/hr, respectively. These rates are derived from the flight data using the assumption that methanol is removed by the TCCS at 1.1% and by the MAD at 100% while 2-butanone is removed at 100% by both systems. The generation rates used for design purposes are 7.64 mg/hr for methanol and 34.3 mg/hr for 2-butanone. Other generation rates derived from flight sample data are 7.95, 56.6, 0, and 0 mg/hr for n-butanol, 2-methyl-1-propanol, phenol, and cyclohexanol, respectively. The design rates for these compounds are 27.2, 5.1, 19.4, and 4.31 mg/hr, respectively. All of these compounds are assumed to be removed at 100% efficiency by both contamination control units. As can be seen by these comparisons with actual flight experience, in most cases, the design generation rates are overly conservative, particularly for methanol, n-butanol, phenol, and cyclohexanol. The 2-butanone rates compare favorably; however, 2-methyl-1-propanol is significantly underestimated.

A second interesting observation is that the Mir 1 generation rates derived from flight data are lower than the U.S. Segment rates derived from Spacelab flight data with the exception of 2-butanone. Rates for the U.S. Segment derived from the Spacelab flight sample results are 0.014, 2.9, 12.9, and 1.3 mg/hr for methanol, n-butanol, 2-methyl-1-propanol, and 2-butanone, respectively. In comparison, the Mir 1 rates derived from the flight data for these compounds are 0.055, 0.21, 0.24, and 27.1 mg/hr, respectively. As a direct comparison for these four compounds, the U.S. Segment rates are an average of 16.8 times greater than the Russian Segment rates. This would indicate that the material selection and control procedures used by the Russian spacecraft designers provide very good passive trace contaminant control.

7. CONCLUSIONS

Conclusions from the analysis to determine the projected performance of the NASA TCCS and the Russian MAD are as follows:

(1) The NASA TCCS, while operating alone, is capable of controlling trace contaminants generated at the 96% confidence limit to less than the NASA 180-day SMAC for the U.S. Segment and the total ISSA.

(2) The Russian MAD, while operating alone, is capable of controlling trace contaminants generated at the 96% confidence limit to less than the NASA 180-day SMAC for the Russian Segment and the total ISSA.

(3) Both the NASA TCCS and Russian MAD, when operating alone, have difficulty controlling methanol and 2-butanol when generated at the 96% confidence limit to less than the Russian 360-day ПДК for their respective ISSA Segments.

(4) Both the NASA TCCS and Russian MAD, when operating alone, have difficulty controlling methanol, n-butanol, 2-methyl-1-propanol, phenol, cyclohexanol, and 2-butanone when generated at the 96% confidence limit to less than the Russian 360-day ПДК for the entire ISSA.

(5) Both the NASA TCCS and Russian MAD, when operating simultaneously, have difficulty controlling methanol and 2-butanone when generated at the 96% confidence limit to less than the Russian 360-day ПДК for the entire ISSA.

(6) The design generation rates are usually conservative with respect to rates derived from Spacelab and Mir 1 flight experience.

(7) Russian material selection and control procedures limit contaminant generation rates to levels near or below those achieved by NASA procedures.

8. RECOMMENDATIONS

Based upon the analysis of the performance of the NASA TCCS and the Russian MAD to control trace contaminants below the NASA 180-day SMACs and the Russian 360-day ПDKs, the following recommendations are made:

(1) With the exception of benzene, adopt the Russian 360-day ПDKs as the ISSA design goal for the interface between the U.S. and Russian Segments.

(2) The NASA 180-day SMAC for benzene should be adopted as the design goal for the interface between the U.S. and Russian Segments.

(3) The NASA TCCS should be designed to control contaminants to NASA SMACs and the Russian MAD should be designed to control to Russian ПDKs at generation rates projected for their individual segments.

(4) The NASA TCCS should be designed to attempt to meet Russian ПDKs as a goal.

(5) On-orbit assessment of the cabin atmosphere for toxicological purposes should be conducted using the NASA and Russian techniques with case-by-case discrepancies on results resolved by a joint ISSA toxicology panel composed of both NASA and Russian toxicologists and trace contaminant control system engineers.

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14. ABSTRACT
During the International Space Station's (ISS's) early developmental stages, uncertainty existed concerning the trace contaminant control equipment design due to Russia being added to the program as a substantially contributing partner. This uncertainty was associated with differences in equipment offgassing testing procedures and maximum allowable concentrations for volatile organic compounds in the cabin atmosphere. Dialogue between NASA and Russian Space Agency personnel in 1994 established engineering analysis assumptions suitable for evaluating the active trace contaminant control capabilities that would reside in the future U.S. and Russian Segments of the ISS. The analysis presented was conducted in support of the efforts to integrate Russia into the ISS program via the early ISS Multilateral Medical Operations Panel's Air Quality Subgroup deliberations. This analysis, which superseded an analysis documented in NASA TM-108441, was instrumental in establishing framework for trace contaminant control system design and operations among the ISS program's international partners, particularly Russia, that has led to successfully managing the ISS common cabin environment.

15. SUBJECT TERMS
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