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Trace Contaminant Control for the International Space Station's Node 1—Analysis, Design, and Verification

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April 2017

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AC/GAC	acid-treated granular activated charcoal
ATCO	ambient temperature catalytic oxidizer
CACEA	cabin air catalyst element assembly
FGB	functional cargo block
GAC	granular activated charcoal
GFE	government-furnished equipment
IMV	intermodule ventilation
ISS	International Space Station
ISSA	International Space Station Alpha
IVA	intravehicular activities
JSC	Johnson Space Center
KSC	Kennedy Space Center
LPC	limiting permissible concentration
MSFC	Marshall Space Flight Center
PIDS	Prime Item Development Specification
PMA	pressurized mating adapter
Pt	platinum
SMAC	spacecraft maximum allowable concentration
TCCS-CP	Trace Contaminant Control Simulation-Computer Program
T-value	toxic hazard index
U.S.	United States

TECHNICAL PUBLICATION

TRACE CONTAMINANT CONTROL FOR THE INTERNATIONAL SPACE STATION'S NODE 1—ANALYSIS, DESIGN, AND VERIFICATION

1. INTRODUCTION

Trace chemical contaminant generation inside crewed spacecraft cabins is a technical and medical problem that must be continuously evaluated. Although passive control through materials selection and active control by adsorption and catalytic oxidation devices is employed during normal operations of a spacecraft, contaminant buildup can still become a problem. Buildup is particularly troublesome during the stages between the final closure of a spacecraft during ground processing and the time that a crewmember enters for the first time during the mission. Typically, the elapsed time between preflight closure and first entry on orbit for spacecraft such as Spacelab modules was 30 days. During that time, the active contamination control systems are not activated and contaminants can potentially build up to levels which exceed the spacecraft maximum allowable concentrations (SMACs) specified by NASA toxicology experts. To prevent excessively high contamination levels at crew entry, the Spacelab active contamination control system was operated for 53 hours just before launch.

Analysis of the atmosphere at initial crew entry during Spacelab missions found that contaminant concentrations are relatively low, indicating that the contaminant generation combined with the prelaunch decontamination was sufficiently conservative to provide the crew with an acceptable cabin atmosphere.[1] As a result, it was found that operating the contamination control system before launch was not necessary for Spacelab missions. The Space Station, however, presented a new challenge to contamination control engineering because the various modules may spend long periods on the ground before launch, leading to a greater potential for significant contaminant buildup by the time the crew enters a module for the first time. For example, during the Space Station Freedom program, preliminary analysis of contaminant buildup in Node 2 over a 50-day period—before initial crew entry—indicated that some type of active contamination control system was necessary to maintain acceptable contamination levels in the atmosphere.[2]

The following narrative presents the technical progression between November 1994 and January 1998 for the trace contaminant control technical approach for the International Space Station's (ISS's) Node 1 module. This approach benefited from experience gained during the Spacelab program. These materials, presented in three parts, consist of preliminary analysis, detailed performance analysis, and verification analysis.

2. PRELIMINARY ANALYSIS OF TRACE CONTAMINANT CONTROL DURING INITIAL ENTRY OF THE INTERNATIONAL SPACE STATION ALPHA NODE 1

The analysis was originally conducted in October 1994 and released under NASA Memorandum ED62(62-94) dated January 10, 1995.

2.1 Background

The redesign of the Space Station as part of the transition from the Space Station Freedom program to the International Space Station Alpha (ISSA) program as well as the introduction of Russian hardware has further complicated the situation for trace contaminant control by not only introducing unknown contamination sources but also increasing the amount of time between Node 1 closure on the ground and crew entry during on-orbit Station assembly. The amount of time which could elapse between Node 1 closure and crew entry was up to 455 days according to the vehicle assembly schedules. This long period, combined with the lack of active contamination control hardware within Node 1, raised concern with respect to the safety of the atmosphere within the Node upon crew entry.

According to the ISSA assembly sequence, the crew from the Shuttle would enter Node 1 during flight 5A on flight day 5. The ISSA configuration during this flight which consists of the U.S. Laboratory, Node 1, the Russian functional cargo block (FGB), and the Russian service module is shown in figure 1. Upon entering, 81.55 m^3/hr (48 cfm) atmosphere exchange between Node 1 and the Shuttle would be established. Dilution of the built-up contamination in Node 1 by the cleaner Shuttle atmosphere occurs as the dominant contamination control mechanism. After 139 minutes, the crew would open the hatch to the Russian FGB. More dilution could occur at this time; however, up to an additional 210 minutes would elapse before the 237.86 m^3/hr (140 cfm) intermodule ventilation would be established. After this ventilation link was established, the Russian microimpurity adsorption device would provide active contamination control. For the first few hours, however, dilution via intermodule ventilation would dominate.

To understand the effects of chemical contaminant dilution during the course of flight 5A, a rigorous analysis was conducted. This analysis investigated the mass balance between the Shuttle and Node 1 volumes followed by a mass balance between the Shuttle/Node 1 and Russian segment volumes. The intent was to determine the projected trace chemical contaminant concentration that the crew will be exposed to during the course of Node 1 activation and establish a technique for assessing similar situations during the assembly of the ISSA.

Figure 1. ISSA configuration for flight 5A.

2.2 Analysis Approach

The ISSA flight 5A configuration was analyzed by setting up a material balance on trace chemical contaminants in Node 1 and the Shuttle volumes. The material balance equations for two well-mixed cabin volumes A and B are provided by equations (1) and (2), respectively:

$$\frac{dm_A}{dt} = \frac{\dot{v}_B}{V_B} m_B - \frac{\dot{v}_A}{V_A} m_A - \frac{\sum \eta v}{V_A} m_A + r_A \tag{1}$$

and

$$\frac{dm_B}{dt} = \frac{\dot{v}_A}{V_A} m_A - \frac{\dot{v}_B}{V_B} m_B - \frac{\sum \eta v}{V_B} m_B + r_B \,, \tag{2}$$

where

m_A = total mass of contaminant in cabin volume A
m_B = total mass of the contaminant in cabin volume B
V_A = cabin A free volume
V_B = cabin B free volume
$\dot{v}_A$ = intermodule ventilation flow from cabin volume A to cabin volume B
$\dot{v}_B$ = intermodule ventilation flow from cabin volume B to cabin volume A
$\sum \eta v$ = removal capacity in the respective cabin volume
r_A = generation rate in cabin volume A
r_B = generation rate in cabin volume B.

Simultaneous solution of equations (1) and (2) provide an equation for each cabin volume in the form of equation (3):

$$m = \alpha + \beta e^{x_2 t} + \gamma e^{x_3 t}, \tag{3}$$

where

m = total mass of contaminant in the reference cabin volume
α, β, and γ = constants calculated from the cabin free volume, ventilation flow, removal capacity, and contaminant generation rate
x_2 and x_3 = integration constants calculated from the cabin free volume, ventilation flow, and removal capacity parameters.

Concentration is calculated by simply dividing the contaminant mass determined from equation (3) by the cabin free volume.

Node 1 contamination was allowed to build up over a period of 455 days to accommodate ground processing and the time elapsed on-orbit before crew entry. Crew entry from the Shuttle was scheduled to occur on flight day 5 of assembly mission 5A. It was assumed that this activity begins at time equals zero on flight day 5 and that intermodule ventilation is initiated at this time. Up to 349 minutes then elapse before the crew would open the hatch between the Shuttle/Node 1 configuration and the Russian segment. A second pair of differential equations in the form of equation (3) applies to the Shuttle/Node 1 and Russian segment volumes. Concentrations for 12 contaminants that were determined to be greater than the NASA SMACs documented in appendix A were calculated for the Shuttle/Node 1 and Shuttle/Node 1/Russian segment configurations as a function of time. A period up to 24 hours was investigated to determine whether the contaminant concentrations could be reduced to less than the 180-day SMACs within that time since it is most likely that reduction to these concentrations within 24 hours would be acceptable both from a toxicological and safety viewpoint.

Trace chemical contaminant concentrations in Node 1 at the beginning of the flight 5A, flight day 5 timeline were calculated using the trace contaminant load model generation rates documented in appendix B. These final concentrations are listed in appendix C. Initial concentrations for the Shuttle cabin atmosphere were obtained from postflight Shuttle atmospheric sample analysis results while initial Russian segment concentrations were based upon steady state concentrations derived from the load model in appendix B combined with expected contamination control system performance.

An additional case considering Node 1 entry from the Russian segment during flight 3A after 250 days of contaminant buildup was also considered. This case used mass balance equations based on equation (3) with initial Node 1 concentrations documented in appendix C. As with the assembly mission 5A case, initial Russian segment concentrations were based upon steady state estimates.

2.3 Analysis Results

Calculation of the initial trace chemical contaminant concentrations showed that 12 compounds would most likely exceed their maximum allowable concentrations. Although this comparison is based upon the NASA 180-day SMACs, most of these compounds would likely be at concentrations higher than the 24-hour SMACs. Table 1 shows a comparison between NASA SMACs, Russian limiting permissible concentrations (LPCs), and the projected initial concentrations for the 12 compounds in Node 1, the Shuttle cabin, and the Russian segment cabin.

Table 1. Initial cabin concentrations upon Node 1 entry during ISSA flight 5A.

Chemical Compound	NASA SMAC (mg/m^3)	Russian LPC (mg/m^3)	Initial Concentrations (mg/m^3)		
			Node 1	Shuttle	Russian Segment
Methanol	9	0.2	34.5	0.02	0.8
n-butanol	40	0.8	127	0.07	0.3
Phenol	7.7	0.1	13.1	–	0.03
2-propenal	0.03	–	0.094	–	0.0002
Benzene	0.2	2	0.68	0.003	0.002
2-ethoxyethanol	0.3	–	16.3	0.003	0.04
Dichloromethane	10	–	58.1	0.3	0.14
1,2-dichloroethane	1	0.5	2.1	0.002	0.005
Freon 113	400	–	513	1.5	1.2
Propanone	52	2	98	0.8	0.23
2-butanone	30	0.25	163	0.07	0.38
Carbon monoxide	10	5	55	0.6	0.13

After the Node 1 hatch is opened to the Shuttle and ventilation between the two volumes is initiated, the chemical contaminant concentrations approach a uniform level in approximately 2 hours. Since the active contamination control capabilities onboard the Shuttle are limited, this concentration level is maintained until the Shuttle/Node 1 configuration is opened to the Russian segment which contains a more capable contamination control system. From the time that Node 1 is opened to the Shuttle cabin, approximately 5.8 hours elapses before ventilation is established with the Russian segment. At this time, the cabin concentrations in Node 1 and the Shuttle are similar as can be seen in table 2.

Using the final concentrations of table 2 as the new initial contaminant level for the Shuttle/Node 1 configuration and the Russian segment initial concentrations listed in table 1, a new overall concentration level for the Shuttle/Node 1/Russian segment configuration is approached within another 2 hours. After another 16 hours, all of the problem contaminants are well below their NASA 180-day and 7-day SMACs with the exception of 2-ethoxyethanol which is below its 30-day SMAC. Table 3 shows the final concentrations for the entire Shuttle/Node 1/Russian segment configuration 23.8 hours after the Node 1 entry activities began. Figures 2 through 5 illustrate typical cabin concentration profiles for 2-propenal, dichloromethane, 2-butanone, and carbon monoxide for the flight 5A timeline. Time zero for these profiles is at initial Node 1 entry.

Table 2. Shuttle and Node 1 cabin concentrations 5.8 hours after entering Node 1 during flight 5A.

Chemical Compound	NASA SMAC (mg/m^3)	Russian LPC (mg/m^3)	Final Concentrations (mg/m^3)	
			Node 1	Shuttle
Methanol	9	0.2	12.1	12
n-butanol	40	0.8	44.7	44.4
Phenol	7.7	0.1	4.6	4.6
2-propenal	0.03	–	0.03	0.03
Benzene	0.2	2	0.24	0.24
2-ethoxyethanol	0.3	–	5.7	5.7
Dichloromethane	10	–	20.6	20.4
1,2-dichloroethane	1	0.5	0.74	0.73
Freon 113	400	–	181.2	180
Propanone	52	2	34.9	34.7
2-butanone	30	0.25	57.3	57
Carbon monoxide	10	5	19.7	19.5

Table 3. Final cabin concentrations in the Shuttle/Node 1 and Russian segment cabins 23.8 hours after entering Node 1 during flight 5A.

Chemical Compound	NASA SMAC (mg/m^3)	Russian LPC (mg/m^3)	Final Concentrations (mg/m^3)	
			Shuttle/Node 1	Russian Segment
Methanol	9	0.2	1.31	1.28
n-butanol	40	0.8	5.03	4.89
Phenol	7.7	0.1	0.52	0.50
2-propenal	0.03	–	0.0037	0.0036
Benzene	0.2	2	0.027	0.026
2-ethoxyethanol	0.3	–	0.64	0.63**
Dichloromethane	10	–	2.32	2.25
1,2-dichloroethane	1	0.5	0.083	0.081
Freon 113	400	–	20.4	19.8
Propanone	52	2	3.93	3.82
2-butanone	30	0.25	6.46	6.27
Carbon monoxide	10	5	2.22	2.15

** Less than the 30-day SMAC of 2.

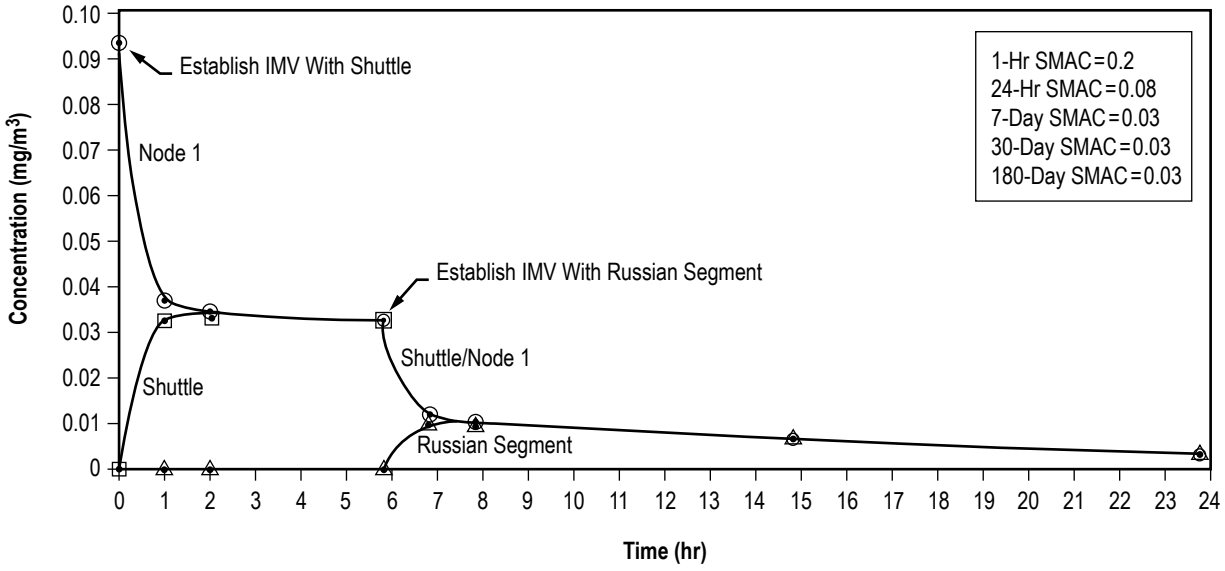


Figure 2. Cabin concentration profile for 2-propenal during assembly mission 5A.

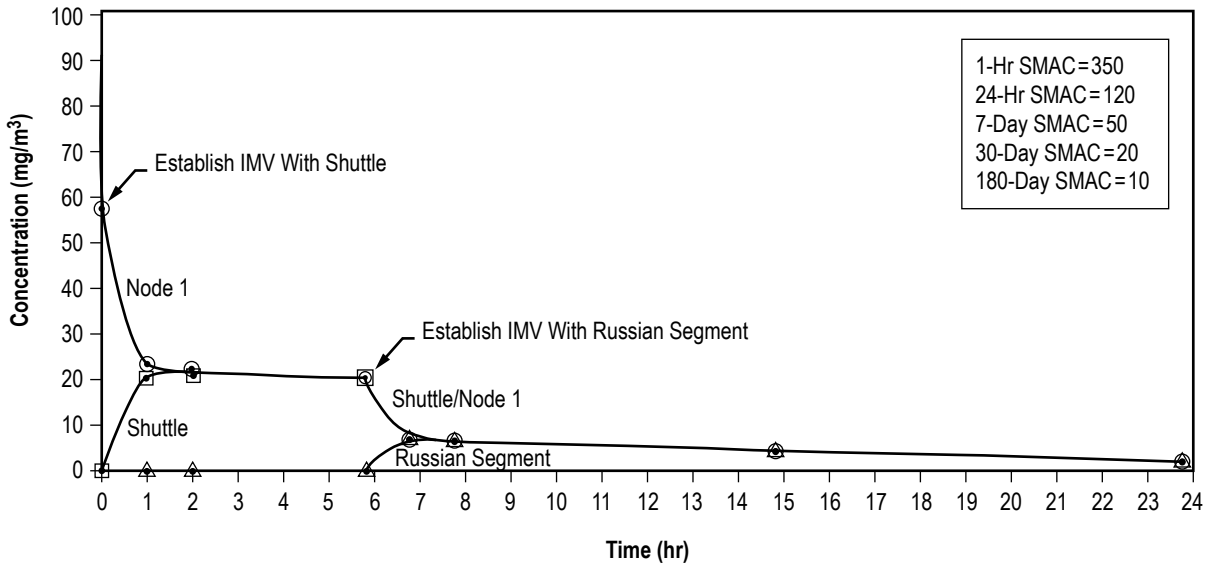


Figure 3. Cabin concentration profile for dichloromethane during assembly mission 5A.

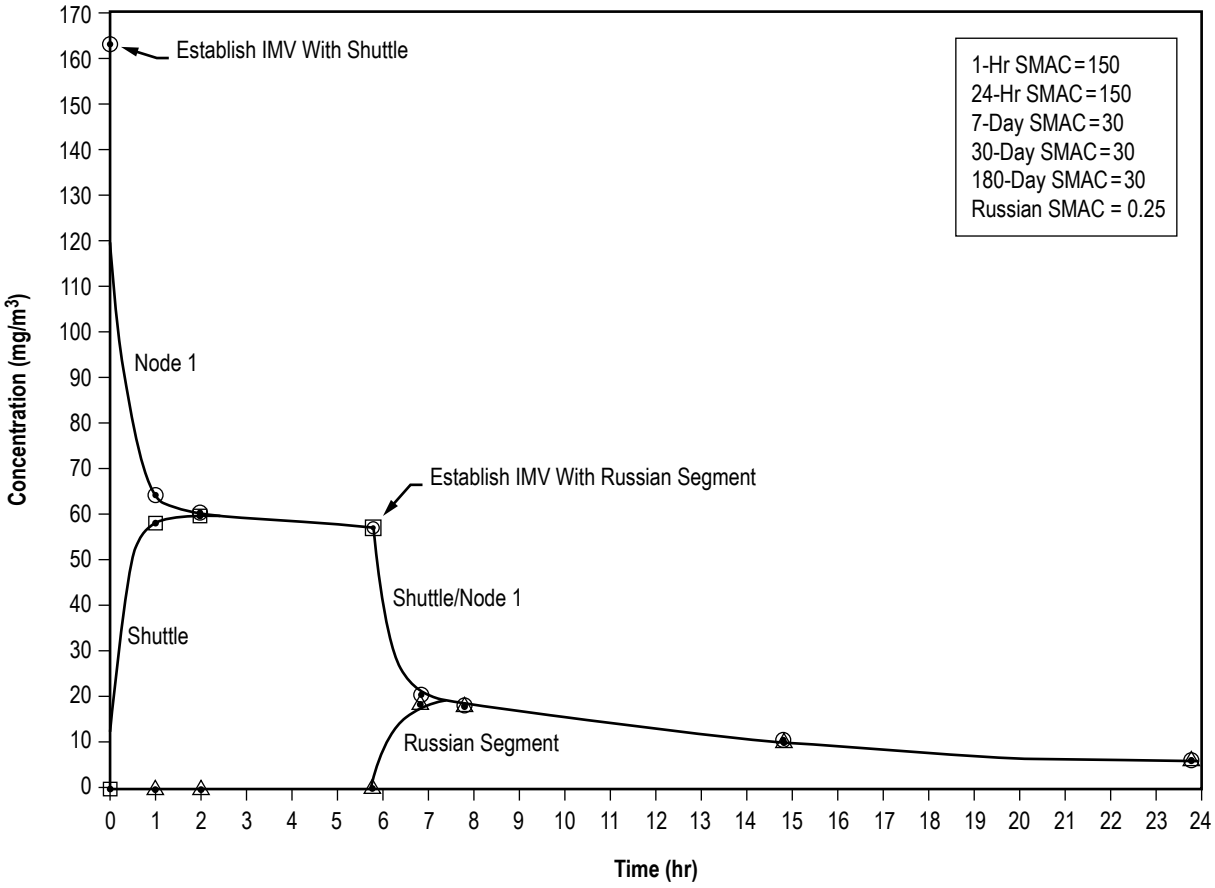


Figure 4. Cabin concentration profile for 2-butanone during assembly mission 5A.

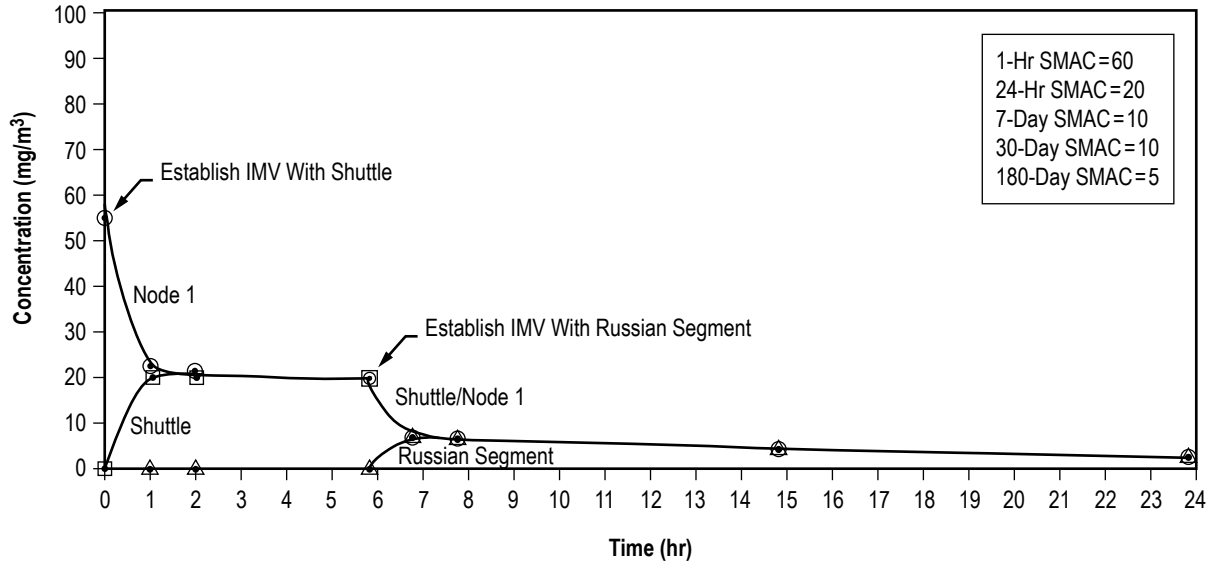


Figure 5. Cabin concentration profile for carbon monoxide during assembly mission 5A.

For the case where Node 1 is entered from the Russian segment during flight 3A after 250 days on orbit, the cabin concentrations for the 12 problem compounds are reduced to the common intermediate level in 1 to 2 hours and all are well below their NASA 180-day SMACs within 24 hours. Table 4 summarizes the final concentrations experienced for this case. Initial Node 1 concentrations are listed in appendix C and initial Russian segment concentrations are listed in table 1.

Table 4. Final cabin concentrations in the Node 1 and Russian segment cabins 24 hours after entering Node 1 during flight 3A.

Chemical Compound	NASA SMAC (mg/m^3)	Russian LPC (mg/m^3)	Final Concentrations (mg/m^3)	
			Node 1	Russian Segment
Methanol	9	0.2	0.53	0.52
n-butanol	40	0.8	1.65	1.63
Phenol	7.7	0.1	0.17	0.17
2-propenal	0.03	–	0.00014	0.00014
Benzene	0.2	2	0.0088	0.0087
2-ethoxyethanol	0.3	–	0.21	0.21
Dichloromethane	10	–	0.75	0.74
1,2-dichloroethane	1	0.5	0.027	0.027
Freon 113	400	–	6.63	6.54
Propanone	52	2	1.27	1.25
2-butanone	30	0.25	2.1	2.07
Carbon monoxide	10	5	0.71	0.7

2.4 Discussion

Analysis results indicate that contaminant concentrations between two connected volumes reach an intermediate level within approximately 2 hours after initiating intermodular ventilation. This appears to be consistent for any volume that is launched and integrated with the Space Station volumes already on orbit. Any additional volumes, such as laboratory modules and logistics modules, should be within relatively safe trace chemical contaminant concentrations within this period. Of course, the initial concentration for the new volume plays an important part. The longer the module is closed, the higher the initial trace contaminant concentration levels and the higher the initial relative hazard to crew health. This hazard, however, is transient and, for the most part, short lived. Calculation of the toxic hazard index (T-value) which is the summation of the ratios of each contaminant's cabin concentration to its SMAC, $\sum C_i / C_{i\mathrm{SMAC}}$, allows the relative hazard to which the crewmembers may be subjected during ISSA assembly to be determined. A T-value below 1 is the desired relative hazard for mixtures of trace chemical contaminants in the cabin atmosphere during normal spacecraft operations.

Of the 12 compounds that are projected to be greater than their SMAC within the Node 1 volume upon crew entry, 8 contribute substantially to the toxic hazard index. They are methanol, n-butanol, benzene, dichloromethane, freon 113, 2-propanone, 2-butanone, and carbon monoxide. These contaminants are also included in the list to be monitored by the ISSA program. For the case where Node 1 is entered and activated during flight 5A after 455 days on orbit, the toxic hazard index

begins at a magnitude of approximately 28. After 5.8 hours, the index decreases to approximately 10. A toxic hazard index of approximately 1 is achieved about 24 hours after Node 1 is entered for the first time. By comparison, the toxic hazard index for Node 1 upon entry during flight 3A begins at approximately 15.5 and is reduced to roughly 4 within 1 hour. After 1.6 hours, the index is 1.6 and is reduced to 0.4 after 24 hours.

As can be seen by these estimates for the toxic hazard index, the crew hazard at the initial entry of Node 1 during flight 5A is roughly 28 times that desired for normal cabin conditions; however, this relative hazard is reduced to the desired level within 24 hours. Likewise, the hazard for Node 1 entry during flight 3A begins at a level 15 times higher than desired for normal cabin conditions. Similarly, the relative hazard is reduced to 1 or below within 24 hours.

The toxic hazard index is sensitive not only to the contaminant generation rates but also the number of chemical compounds actually detected and quantified upon initial crew entry. As has been observed in the past, some generation rates used for analysis have been conservative which leads to high estimates for cabin concentration and, therefore, a high estimate of the *T*-value. Efforts to quantify this conservatism have been made and the rates used for this analysis build upon this experience by reducing raw offgassing test data by a factor of 11.48.[1] This factor accounts not only for temperature-induced conservatism but also for generation rate reduction resulting from material aging. Since these factors affecting generation rate have been accounted for, the estimates for concentration and *T*-value are considered to be with the same order of magnitude for the actual flight hardware and can be used to make decisions with respect to crew entry during flights 5A and 3A.

2.5 Conclusions

Conclusions based upon the analysis conducted for the initial entry of Node 1 during ISSA flights 5A and 3A are the following:

(1) Trace chemical contaminant concentrations in the Node 1 volume may exceed long- and short-duration SMACs for 12 contaminants in the U.S. segment trace contaminant control design standard upon initial crew entry during flight 5A.

(2) Mixing between element volumes rapidly provides significant contamination level reduction.

(3) Trace chemical contaminant concentrations can be reduced to below all 24-hour SMACs within 5.8 hours after initiating intermodular ventilation between Node 1 and the Shuttle cabin during flight 5A.

(4) All contaminant concentrations are reduced to below their 7-day SMACs within 7 hours after entering Node 1.

(5) Trace chemical contaminant concentrations can be reduced to below U.S. long-duration SMACs within 23.8 hours after entering Node 1 for the first time by initiating intermodular ventilation between Node 1 and the Russian segment at approximately 5.8 hours after Node 1 is entered for the first time from the Shuttle.

(6) Trace chemical contaminant concentrations can be reduced to below U.S. long-duration SMACs within 1 hour after entering Node 1 from the Russian segment during flight 3A.

(7) Toxic hazard index estimates indicate that for contaminants to be monitored by the ISSA program, the index will be at 1 or less within 24 hours after entering Node 1 during flights 5A and 3A.

2.6 Recommendations

Analysis of the trace chemical contamination levels which may be experienced during ISSA flights 5A and 3A and the conclusions drawn from the analysis indicate that the cabin atmosphere may present some potential risk to the crew during the first 24 hours after entering Node 1. Based upon this potential risk, the following recommendations are made:

(1) The NASA toxicology subject matter experts should be consulted by the ISSA program concerning the results of this analysis to obtain final guidance with respect to entering Node 1 during either flights 5A or 3A.

(2) Offgassing test data from Node 1 and the Russian segment should be collected to determine actual ISSA hardware offgassing rates to support a final analysis of trace chemical contaminant concentrations in the spacecraft cabin during flights 5A or 3A.

3. DETAILED PERFORMANCE ANALYSIS OF TRACE CONTAMINANT CONTROL DURING EARLY INGRESS OF THE INTERNATIONAL SPACE STATION NODE 1

The analysis was originally conducted between March and December 1996 and released under NASA Memorandum ED62(09-97) dated January 22, 1997.

3.1 Background

Trace chemical contaminant generation from materials offgassing is a pervasive technical problem during the ISS on-orbit assembly. Although the materials selection and control program provides a passive means for minimizing generation rates, zero generation cannot be fully achieved. During ISS assembly, buildup of trace contaminants in the habitable atmosphere, in particular Node 1, has been a problem for various reasons. In some instances, such as Node 1, a long period of time elapses between ground closeout and the first ingress on orbit. During this time, no power is available to operate an onboard active contamination control system. Also, constraints in volume and ventilation system configuration have led to limitations in the Node 1 contamination control system design. In order to adequately design a contamination control system for Node 1, the challenges that the situation present, past flight experience, past analyses, the ISS assembly timeline, and active contamination control design options must be thoroughly reviewed and understood.

3.1.1 Node 1 Contamination Control Challenges

Assembly of the ISS presents significant challenges to maintaining an acceptably clean cabin atmosphere during all phases. Offgassing products from the equipment in Node 1 will accumulate in its atmosphere for a significant length of time before the initial ingress. In some instances, contaminant levels may exceed SMACs. To complicate the assembly timeline, many of the Station elements either do not have active onboard contamination control systems or have active control systems that cannot be immediately operated. The requirement for early ingress of Node 1 during flights 2A, 3A, and 4A present both challenges.

Node 1 is outfitted with four activated charcoal beds that are direct retrofits of the cabin air particulate filters. However, during flight 2A, electrical power to operate the Node 1 cabin fan is not available to provide needed atmospheric scrubbing. As a result, alternative means for providing an acceptably clean atmosphere for the crew during flight 2A must be explored. These means include purging Node 1 or running the cabin fan while on the ground, taking advantage of the dilution of contaminants that will occur when the Node 1 and Shuttle atmospheres mix, and operating selected Shuttle contamination control systems to remove contamination from the combined atmospheres. Combinations of these means must also be considered and their timely application in the Node 1 ground and on-orbit processing timeline must be determined. Subsequent ingress and intravehicular activities (IVA) of Node 1 during flights 3A and 4A can benefit from operating the cabin fan to provide air flow through the charcoal beds. The actual duration of fan operation and the life of the

charcoal beds must be assessed to optimize the IVA timeline without compromising crew performance and near-term health.

3.1.2 Previous Experience

The challenge presented by Node 1 is not new. The Spacelab program has employed either a ground purge or activated the cabin fan to draw air through its activated charcoal scrubber to reduce contamination levels during the time between closeout and on-orbit ingress. As more data were collected, however, the need to continue large-scale contamination control analyses and ground operations was significantly reduced. Although preflight performance analyses were eliminated, reduction of ground operations for Spacelab module missions was recommended to be evaluated on a case-by-case basis. This approach was determined to be acceptable for Spacelab primarily because of the wealth of data obtained from previous missions. New spacecraft, however, still require a significant amount of preflight analysis and ground processing in addition to onboard contamination control means to ensure an acceptably clean atmosphere.

3.1.3 Previous Analyses

During the Space Station Freedom program, analysis of the contamination buildup in the Node 2 atmosphere over a 50-day period before initial ingress indicated that some type of active contamination control capability was necessary.[2] Activated charcoal beds were designed as retrofits to the particulate filter element assemblies in Node 2 to provide the needed atmospheric scrubbing capability. Subsequent program restructuring, redesign, and the transition to the ISS with the addition of Russian hardware has further complicated the situation. Node 1 also became the first U.S. element to be launch rather than Node 2. Another complicating factor was that the Node charcoal beds were deleted from the program as a cost savings. Recent analysis of the Node 1 atmospheric contamination situation has resulted in the revival of the charcoal bed retrofit approach to providing active contamination control.

Analysis of the Node 1 contamination control situation was first conducted in November 1994 and is summarized in section 2. This analysis considered the effects of dilution of Node 1 contaminant concentrations with the Shuttle atmosphere and the dynamics of this process. In the analysis, Node 1 was sealed for 455 days before the first ingress that was then planned for flight 4A. Assessment of the expected contaminant load for Node 1 identified 12 key contaminants that contribute the most to the overall contaminant load. These 12 contaminants were considered in the detailed analysis. At the end of the 455 days, contaminant concentrations in Node 1 were predicted to rise well above SMACs. Within 2 hours after initiating intermodule ventilation (IMV) flow, a fully mixed intermediate concentration is established in the combined Shuttle/Node 1 volume. At that time, contaminant concentrations were reduced to levels very close to their 7-day SMACs. Four hours later, the hatch between Node 1 and the Russian segment was opened. After another 2 hours, a new intermediate concentration for the Shuttle/Node 1/Russian segment volume is reached. This second plateau effectively reduced contaminant concentrations below their 7-day SMACs. Further processing by the Russian segment contamination control system reduced the contaminant concentrations to below 180-day SMACs.

Although an effective approach, relying completely on dilution for contamination control raised some concerns. First, the initial contaminant concentrations in Node 1 were much higher than the 7-day SMACs. This presented an unusually high risk to crew health during a time when they would be conducting a lot of operations. The probability for eye, throat, and nose irritation in addition to headache was considered to be high. Also, previous agreements with the Russian side documented by the meeting minutes for the April 1994 meeting of the Group on Toxicological and Hygienic Evaluation of the ISS Atmosphere to meet Russian maximum allowable concentrations during the early phases of Station assembly could not be readily met before opening the hatch between Node 1 and the Russian segment. The only way to reliably provide the crew with an acceptably clean atmosphere and comply with agreements between the U.S. and Russian sides was to provide active contamination control in Node 1. The Node charcoal beds were brought back into the ISS program to meet these requirements.

3.1.4 Timeline Through Flight 4A

The current timeline from Node 1 processing on the ground through crew first entry during flight 4A is provided in appendix D. This timeline was the most detailed understanding available on how Node 1 was processed before launch and the approximate timing for ingress during flights 2A, 3A, and 4A. Previous versions of the timeline served as the basis for the trace contaminant control analyses which follow. These analyses actually helped to refine the timeline to its current status.

After Node 1 was delivered to NASA Kennedy Space Center (KSC), it was subjected to various acceptance tests. The last powered activity before Node 1 was sealed for launch was a dehumidification purge through the IMV circuit. This purge was planned to be conducted between 40 and 50 days before launch.

The planning for the time between Node 1 closeout in Huntsville, Alabama, and the purge 40 to 50 days before launch included collecting several grab samples from the sealed cabin atmosphere. The planning for the sampling called for the first sample to be taken while Node 1 was in Huntsville just before shipment to KSC. A second sample was collected upon Node 1's arrival at KSC approximately 10 to 14 days after its closeout in Huntsville. Two to three days later, a third sample was collected just before Node 1 was opened for acceptance testing. These samples were to be used to confirm the actual magnitude of contaminant generation rates. Data provided by the samples would assist in determining precisely what actions are required on-orbit during Node 1 ingress to minimize the effects that offgassed products may have on crew health and performance.

Ingress during flight 2A was to occur on approximately flight day 8. A 9-month quiescent period would occur between flights 2A and 3A. Two ingress opportunities were identified for flight 3A on flight days 4 and 8. Another 3-month quiescent period occurred between flights 3A and 4A. The final ingress occurred on approximately flight day 7 of flight 4A. After that time, Node 1 was to remain open to the Russian segment.

3.1.5 Charcoal Bed Design

The Node 1 charcoal beds were designed to temporarily take the place of the cabin air particulate filters. Four filter locations are available with each accommodating up to 127 m^3/hr (75 cfm). Nominal flow through each filter (charcoal bed) during Node 1 ingress was to be at least 85 m^3/hr (50 cfm). Allowable pressure drop for each charcoal bed was 498 Pa (2 inches of water).

The procedure for designing activated charcoal beds is well developed and must consider the primary contaminants to be removed, their affinity for charcoal, and the total amount to be removed.[1,3] This procedure is iterative to account for multicontaminant adsorption. Example calculations on charcoal bed sizing are provided in reference 1.

3.1.5.1 Hardware Source Options. As the need for active contamination control means in Node 1 became apparent, the ISS program began to explore options for their design and fabrication. Initially, an option to provide the charcoal beds as government-furnished equipment (GFE) was explored. NASA Marshall Space Flight Center (MSFC) was requested to develop a design and project plan with a cost estimate in March 1996. At the same time, Hamilton Standard (Windsor Locks, Connecticut) was requested to study a design. Evaluation of these concepts by the ISS Program Office was conducted to select a design that met contamination control requirements and presented the least risk to the overall hardware development schedule. At the conclusion of this review, the Hamilton Standard concept was selected for detailed design and ultimate deployment onboard Node 1.

In September 1996, another GFE atmospheric scrubbing concept was suggested by NASA Johnson Space Center (JSC). This concept involved the use of existing Shuttle avionics air fans and odor control filter charcoal beds. Subsequent analysis on the performance of this concept concluded that it was inadequate to perform the Node 1 atmospheric scrubbing job with respect to logistics requirements and atmospheric scrubbing time. The Hamilton Standard design was retained as the Node 1 contamination control hardware baseline. All three concepts are described and their basic relative performance summarized for completeness.

3.1.5.2 Government-Furnished Equipment Charcoal Bed Design Description and Performance. Design options developed as GFE included a retrofit to the Node 1 particulate filters and an external scrubbing kit that used excess Shuttle hardware. These options are described and the results of design performance analyses discussed.

3.1.5.2.1 Marshall Space Flight Center Option. The MSFC charcoal bed design used the well documented methodology described in reference 1. The key design-driving contaminant is methanol which is poorly adsorbed by charcoal. Another 11 compounds projected to be present in large amounts were also considered in the design. To provide adequate conservatism, initial calculations were based upon an inlet concentration of one-half the SMAC for each contaminant. Original estimates for the internal Node 1 hardware mass were approximately 2,400 kg (5,290 lb). The minimum amount of charcoal for the saturation zone was determined to be 3.9 kg (8.6 lb), however, analysis of the adsorption zone length indicated that more charcoal would be necessary to provide a reasonable bed life. At the flow conditions, breakthrough will occur rapidly, although the large cross-sectional area helped to reduce linear flow velocity and thus the mass transfer zone velocity through the bed.

As the design progressed, an allowable pressure drop of 498 Pa (2 inches of water) was established by the ISS program. Also, the air flow rate through each bed was reduced from 127 m^3/hr to 85 m^3/hr. At the same time, the Node 1 internal hardware mass basis was increased to 3,900 kg (8,598 lb) which was considered to be the equivalent of two racks with a support structure. It was also decided that the design should not take into account any atmospheric leakage and its accompanying contaminant removal assist.

Using the Ergun equation, analysis of the amount of charcoal that would produce a 498 Pa pressure drop indicated that the filter element volume could theoretically be filled completely with charcoal. Therefore, a maximum allowable depth of 7.1 cm (2.8 in) was determined based upon the sizing for the charcoal containment structure. Additional analysis of the amount of charcoal needed showed that a total of 7.9 kg (17.4 lb) was necessary to do the job. The maximum packing depth was determined to be 5.8 cm (2.3 in). To accommodate this much charcoal, three of the filter housings would need to be filled with activated charcoal alone. Pressure drop for this design at the new flow rate was calculated at 274 Pa (1.1 inches of water) which includes 62 Pa (0.25 inch of water) for the containment structure.

The final design approach was to fill three beds with the 7.9 kg of activated charcoal. The fourth bed was to be filled with 2% Pt on charcoal. A sufficient depth of 2% Pt on charcoal is necessary to allow for a sufficient contact time to yield a reasonable single-pass removal efficiency. Typically, a contact time of no less than 0.2 s yields 100% single-pass removal efficiency.[4] Based upon past performance testing and pressure drop considerations, a depth of 7.1 cm was selected for the 2% Pt on charcoal. This bed would provide a single-pass efficiency for carbon monoxide oxidation of 98% at ambient temperature and 40% relative humidity. Data on carbon monoxide oxidation performance in dry air versus 40% relative humidity air for a similar material indicated little impact on performance. These data as well as the effect of temperature on performance are provided in appendix E.

Although the bed containing 2% Pt on charcoal would have a pressure drop of only 219 Pa (0.88 inch of water) compared to the activated charcoal pressure drop of 274 Pa, no appreciable effects on design performance would result. Natural flow balancing would cause a slight increase in flow through the 2% Pt on a charcoal bed of no greater than 8.5 m^3/hr (5 cfm), thus reducing the single-pass carbon monoxide oxidation efficiency to a minimum of 87%. Likewise, a slightly reduced flow through the charcoal beds would enhance single-pass efficiency and slightly extend bed life.

3.1.5.2.2 Johnson Space Center External Kit Option. The concept suggested by JSC used a Shuttle orbiter avionics air fan combined with flexible ducting, odor control filters (part number SVHS783970) containing 2.3 kg (5 lb) of activated charcoal, and hydrazine absorber cartridges (part number SVHS791197) containing 2.3 kg of 2% Pt on charcoal to remove offgassed products from the Node 1 atmosphere. The flexible ducts connected to the Node 1 IMV ports. The Shuttle avionics air fan provided up to 170 m^3/hr (100 cfm) at a pressure rise of approximately 1.05 kPa (4.25 inches of water). Analysis of the expected bed pressure drop and contaminant removal capacity was conducted. Pressure drop for the radial flow odor control and hydrazine absorber cartridges calculated using the Ergun equation ranged between 274 and 324 Pa (1.3 inches of water); however, contaminant removal performance was found to be poor. This was due to the short bed depth

combined with the high air velocity. As a result, scrubbing time was unreasonably long. The best performance was obtained by scrubbing for 12 hours using a total of 12 beds.

Another alternative was to assess the potential for using a specially-designed axial flow bed or the Spacelab transfer tunnel scrubber cartridge. The Spacelab cartridge contains phosphoric acid-treated activated charcoal, untreated activated charcoal, and 2% Pt on charcoal in an axial flow configuration. The specially-designed axial cartridge would contain only activated charcoal and 2% Pt on charcoal. This option was found to achieve acceptable contaminant removal performance using three beds over a period of 6 hours using a flow rate of 42 m^3/hr (25 cfm) regardless of whether the specially-designed or Spacelab cartridge was used. Unfortunately, excess hardware was not available from the Spacelab program. Also, the calculated packing pressure drop for an axial flow bed was found to be 747 Pa (3 inches of water). Additional pressure drop for the housing and charcoal containment structure, ducting, and IMV ports would most likely exceed the 1.05 kPa pressure rise provided by the Shuttle avionics air fan. Previous testing of the Spacelab tunnel scrubber pressure drop indicated a total pressure drop in excess of 996 Pa (4 inches of water) at 4.2 m^3/hr (2.5 cfm). Additional pressure drop versus flow testing would need to be conducted for this option; however, it was considered unlikely that the pressure drop would be compatible with the external kit concept.

Based upon the performance analyses conducted on the external scrubbing kit option, it was not selected for use in decontaminating the Node 1 atmosphere.

3.1.5.3 Hamilton Standard Charcoal Bed Design Description and Performance. The Hamilton Standard design was slightly different from the MSFC design in that each bed contains both activated charcoal and 2% Pt on charcoal. In all, the beds contained a total of 4.3 kg (8.7 lb) of charcoal and 3.4 kg (7.5 lb) of 2% Pt on charcoal. The charcoal packing depth was approximately 3.2 cm (1.25 in) while the 2% Pt on charcoal packing depth was 2.5 cm (1 in). The 2% Pt on charcoal provided approximately 36% single-pass oxidation efficiency for carbon monoxide. The estimated pressure drop ranged between 130 Pa (0.52 inch of water) and 249 Pa (1 inch of water) for the packing with another estimated 62 Pa (0.25 inch of water) for the containment structure.

Initial analysis of the performance of this design option centered upon using the same design and performance assessment criteria used for the MSFC design. These criteria indicated that an additional 0.43 kg (0.94 lb) of charcoal would be necessary to achieve a similar performance to the MSFC design. This would require increasing the charcoal packing depth by 1.3 cm (0.5 in).

In order to determine whether the Hamilton Standard-provided charcoal beds could do the job with no modification, detailed assessments of performance must be conducted. These assessments must emphasize the various system-level assists to contamination control provided by dilution with the Shuttle atmosphere, Shuttle-provided contamination control equipment, and ground processing operations. This analysis and its results follow.

3.2 Node 1 Charcoal Bed Performance Analyses

Performance analyses were conducted for the baseline Node 1 charcoal beds to be provided by Hamilton Standard to ensure that the design contamination load can be controlled. All system level and timeline analyses were conducted by building the appropriate input files and then using the Trace Contaminant Control Simulation-Computer Program (TCCS-CP), Version 8.1, to project bed performance and the resulting cabin concentrations. The TCCS-CP is well documented and has been subjected to a validation and general uncertainty analysis.[5–7] According to the general uncertainty analysis, results from the TCCS-CP are considered to be within ±16% for projected contaminant concentrations. This is well within the observed analytical uncertainty of most contamination control system tests and analytical results from grab samples.

3.2.1 Basic Analysis Assumptions

Basic assumptions established for all phases of the analyses are the following:

- Cyclic Node 1 atmospheric conditions for temperature and relative humidity have negligible effects on the total mass of offgassed products.
- The Node 1 leakage rate is zero.
- Pressurized free volumes are 6.1 m^3 (215.4 ft^3) for the pressurized mating adapter (PMA), 51.3 m^3 (1,811.6 ft^3) for Node 1, and 65.8 m^3 (2,323.7 ft^3) for the Shuttle.
- The total Node 1 internal hardware mass contributing to offgassing is 3,536 kg (7,795.5 lb).
- The total scrubbing flow rate is 340 m^3/hr (200 cfm) with the flow split evenly between the four charcoal beds.
- Each charcoal bed contains 1.07 kg (2.36 lb) of activated charcoal packed to a depth of 3.2 cm (1.25 in) and 0.85 kg (1.87 lb) of 2% Pt on charcoal packed to a depth of 2.5 cm (1 in).
- Seven-day SMACs apply.
- The load model documented by the U.S. Lab Prime Item Development Specification (document number S683-29523, table VII-A) applies.
- Contaminant generation rates are considered to be constant with little decay over time which is considered to be a worst case.

These assumptions were used for parametric and timeline analyses to validate the charcoal bed performance and, therefore, the feasibility of the proposed Node 1 ingress timeline from element closeout through flight 4A. In addition, the life limitations of the charcoal beds were assessed to determine how long the Node 1 cabin fan may be activated during this timeframe.

It should be noted that recent studies of offgassing have shown that using 72-hour offgassing test data as the rate basis and assuming a constant rate over time provides accurate predictions up to 70% of the time.[8] Furthermore, offgassing regimes exhibited are the following:

- Offgassing that decreases with time.
- Continuous offgassing.
- Continuous offgassing after an induction period.

Of the materials studied, 30% exhibit offgassing type 1, 39% exhibit type 2, and 31% exhibit type 3.[8] In total, 69% exhibit some type of continuous offgassing characteristics. Given this high percentage for continuous offgassing, the assumption that rates are constant over time is considered to be appropriate and to provide adequate conservatism to any contamination control performance analysis.

3.2.2 Full Factorial Performance Analysis

The first issue that needed clarification was the timing of the initial ingress during flight 2A relative to any ground-based purge or scrub of the Node 1 atmosphere. The duration of the scrub time also had to be determined. Not only would this scrub time apply to flight 2A but also to flights 3A and 4A. A full factorial analysis was conducted using a reduced list of contaminants for simplicity. Primary conclusions from this analysis are the following:

- Scrubbing effectiveness is highest during the first few hours. An optimum scrubbing time of 2 hours was recommended for all flights.

- Contamination levels at ingress are most sensitive to internal hardware mass.

- The ground scrub or purge needed to occur within 17 days of Node 1 launch to ensure an acceptably clean atmosphere as initially defined by the JSC Toxicology Group to be a *T*-value ≤1.

3.2.3 Toxicological Guidelines

The first two conclusions from the full factorial analysis present no problems to the Node 1 ingress scenarios. The short-duration scrub and assessment of the charcoal bed performance using a high internal mass provide for adequate margin in capabilities. The third conclusion, however, presents a particular challenge to ground-processing activities for Node 1. In addition, by using the full contaminant load model, the criteria for meeting the acceptable *T*-value of 1 was virtually impossible since the purge or scrub would have to be conducted very close to launch. A better definition for an acceptably clean atmosphere for initial ingress was needed to resolve this situation.

Discussions with NASA toxicology experts led to establishing ground rules for defining an acceptably clean atmosphere for crew entry. Table 5 summarizes these ground rules. The initial *T*-value is the relative contamination level at the time on-orbit decontamination operations begin. The allowable scrub time is the amount of time that the crew may be exposed to a continuously decreasing relative contamination based upon the initial value. In addition, the number of days that may pass until the respective *T*-value is reached is provided. In addition, it was established that if

a *T*-value of 3 or less was present in Node 1 at ingress, the crew could enter without any special precautions. At the same time, personnel at KSC indicated that an acceptable window for conducting a ground purge or scrub was at approximately launch minus 43 days.

As can be seen in table 5 and figure 6, it is most likely that a *T*-value of 6 or lower at mission 2A ingress would be expected based upon the ISS design load model with 3,536 kg of internal Node 1 hardware contributing to the contamination generation rate and a ground decontamination within 68 days of ingress. However, to achieve a *T*-value of 3 or less, the ground decontamination would have to occur closer to launch than the allowable 43 days. Therefore, some additional on-orbit processing would have to occur.

Table 5. Ingress contamination control ground rules.

Initial Node *T*-Value	Allowable Scrub Time (hr)	Days to *T*-Value
10	1	109
7	2	78
6	8	68
5	24	57
4	36	47

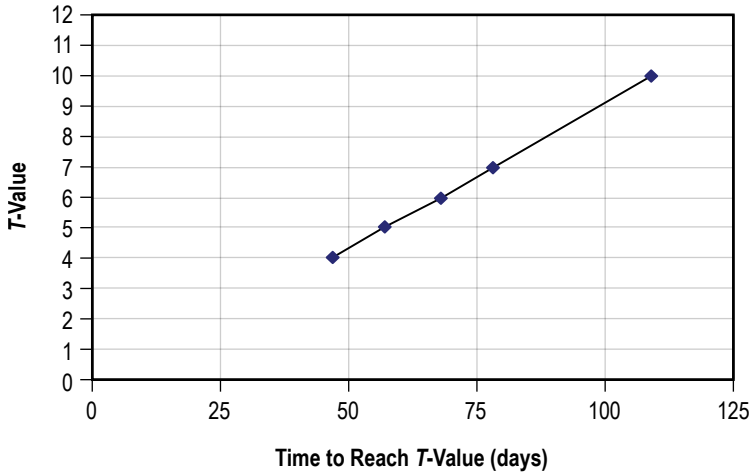


Figure 6. Node 1 relative contamination buildup.

3.2.4 Flight 2A Analysis

In order to determine whether the available contamination control means could effectively reduce the predicted relative contamination in Node 1 to a *T*-value <1, an analysis was conducted for each initial *T*-value case in table 5.

Since power was not available to Node 1 during flight 2A, a means other than operating the Node 1 cabin fan must be employed to reduce the relative contamination levels to within a *T*-value of 1 within the specified amount of time. Scrubbing means available included the Shuttle condensing heat exchanger, the ambient temperature catalytic oxidizer (ATCO), dilution provided by combining the Shuttle and Node 1 cabin volumes, and expendable activated charcoal beds (part number SVHS783970) in place of one Shuttle lithium hydroxide bed. Under normal circumstances, it is assumed that the Shuttle relative contamination will be approximately a *T*-value of 0.5.

In the simulation timeline, once the Node 1 hatch is opened, the crew establishes ventilation between the Shuttle and Node 1 at a minimum of 85 m^3/hr (50 cfm). Air flow through the condensing heat exchanger is 655 kg/hr (1,445 lb/hr). The flow rate through the ATCO and expendable charcoal bed is 1.7 m^3/hr (1 cfm) and 42.5 m^3/hr (25 cfm), respectively. Humidity condensate is removed at the equivalent of a seven-person production rate of 0.69 kg/hr (1.5 lb/hr) to account for soluble compound removal via absorption in humidity condensate. Two hours pass before the combined Shuttle/Node 1 volume would reach full dilution according to the analysis in part I. The dilution is simulated by increasing the simulation reference volume from 57 m^3 (2,012.9 ft^3) to 133 m^3 (4,696.8 ft^3) within the 2 hours. Once the Node 1 hatch is opened, 6 hours of scrubbing by the available Shuttle systems is conducted in parallel with the dilution.

The results from the analysis are provided in table 6. Representative plots of relative contamination over time for each run are provided in figures 7 through 11. As can be seen from table 6 and figures 7 through 11, the available Shuttle contamination control systems can accommodate a Node 1 starting *T*-value of 6. This result applies not only to flight 2A but also flights 3A and 4A. Based upon an extrapolation of the analysis data, 7.3 hours and 11.3 hours are required to reduce the Node 1 *T*-value magnitude from 7 and 10 to 1, respectively. Logistics requirements are provided in table 7.

Table 6. Time to reduce Node 1 contamination to acceptable limits.

Initial Node *T*-Value	Allowed Time to *T* = 1 (hr)	Predicted Time to *T* = 1 (hr)
10	1	11.3
7	2	7.3
6	8	6
5	24	4.8
4	36	3.3

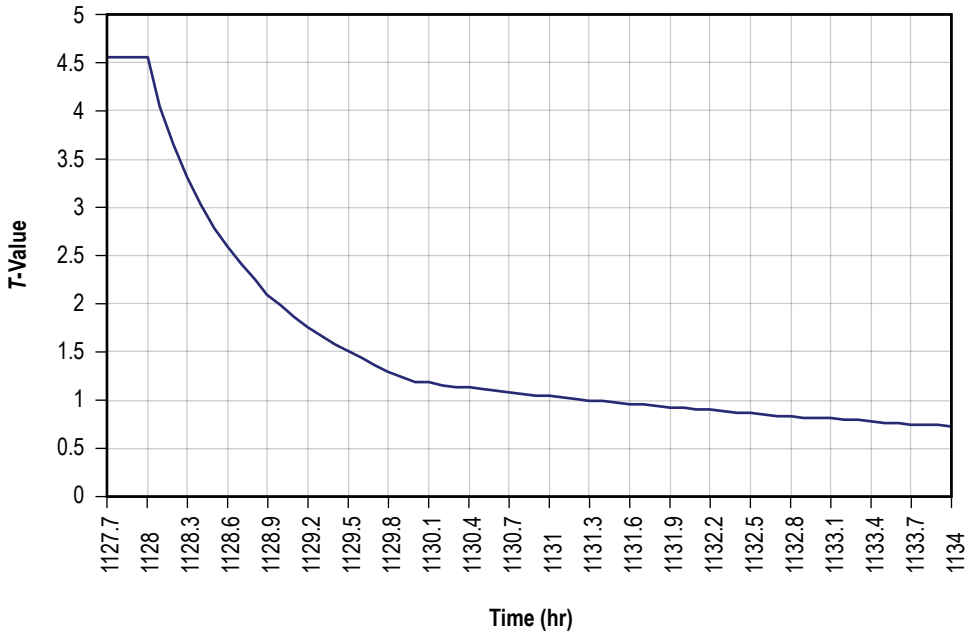


Figure 7. Node 1 decontamination on-orbit 47 days after ground purge.

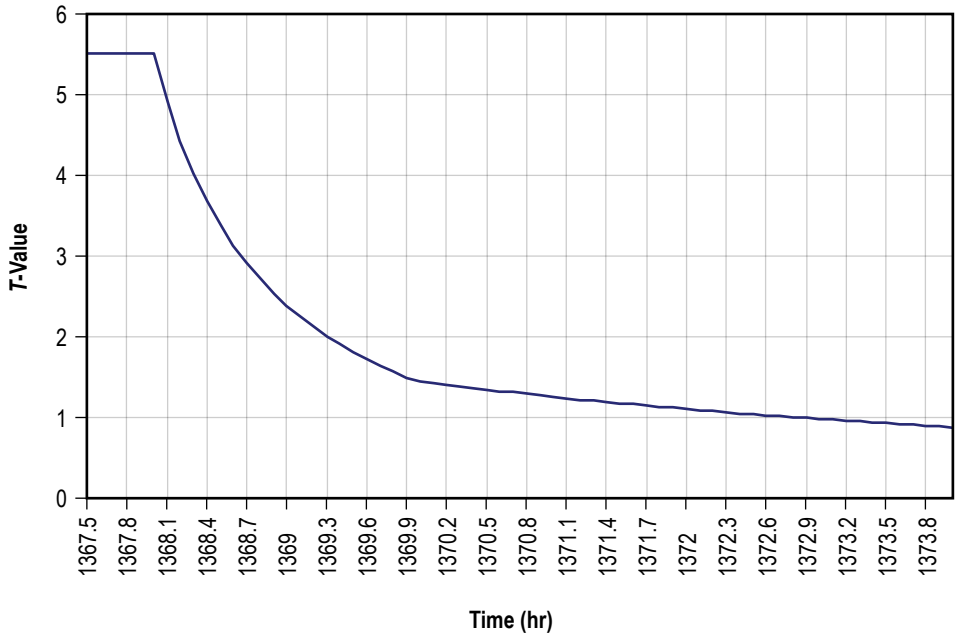


Figure 8. Node 1 decontamination on-orbit 57 days after ground purge.

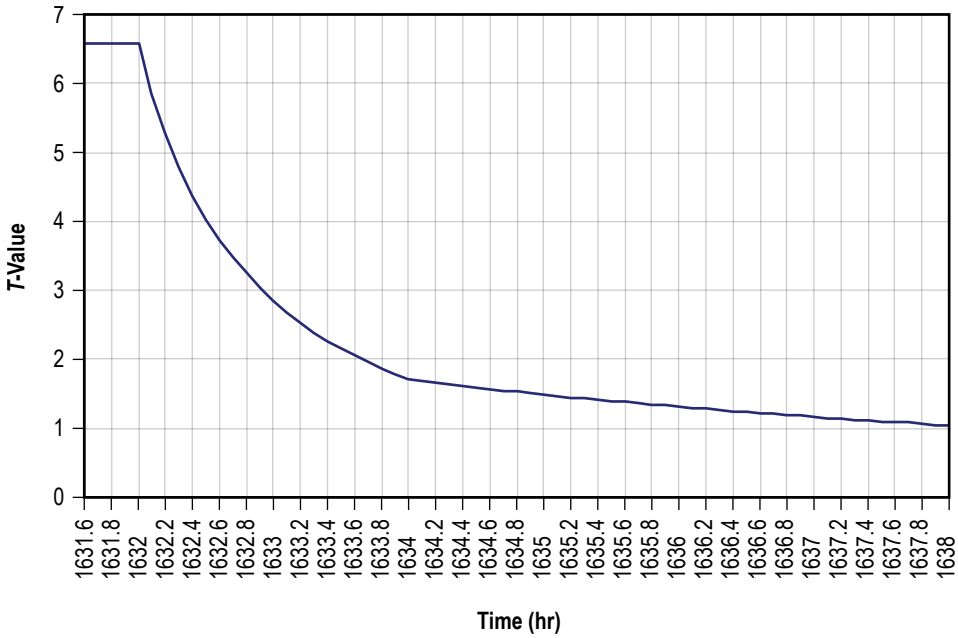


Figure 9. Node 1 decontamination on-orbit 68 days after ground purge.

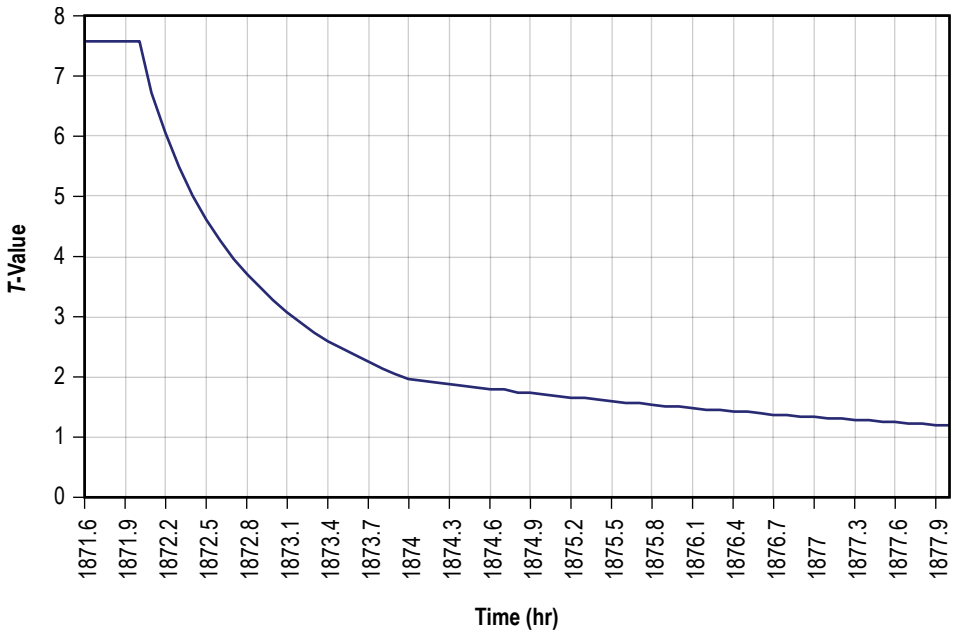


Figure 10. Node 1 decontamination on-orbit 78 days after ground purge.

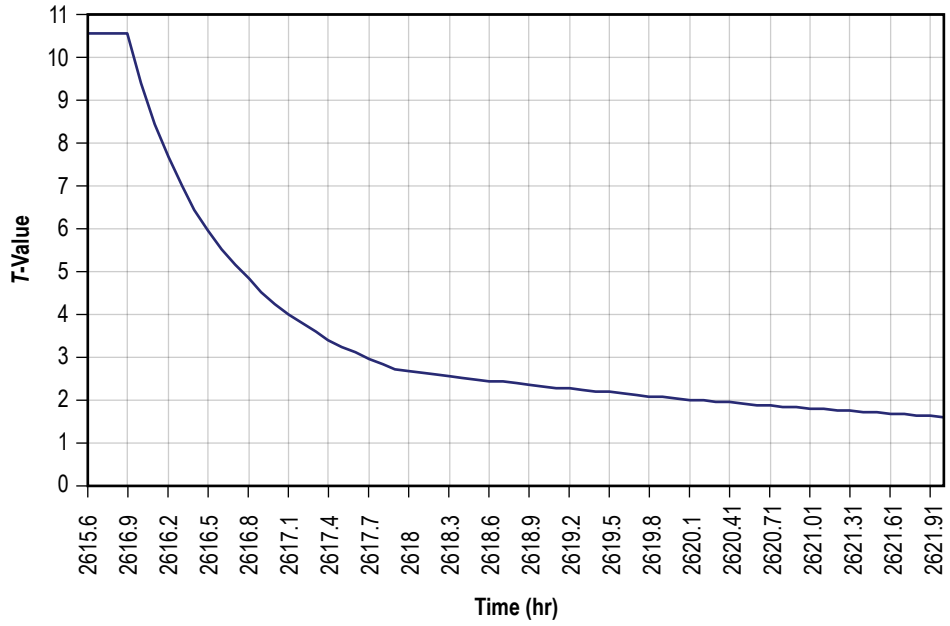


Figure 11. Node 1 decontamination on-orbit 109 days after ground purge.

Table 7. Logistics requirements.

Initial Node *T*-Value	Number of Charcoal Beds
10	12
7	8
6	6
5	5
4	4

Based upon these analysis results, it was concluded that the Node 1 ground decontamination must be conducted within 68 days of ingress (60 days before launch). Also, additional resources must be provided onboard the Shuttle to provide an acceptably clean atmosphere in the combined Shuttle/Node 1 volume within an acceptable time period. The assistance provided by the Shuttle hardware should be capable of reducing the Node 1 contamination to within acceptable levels within 6 hours. The crew should be able to enter Node 1 for IVA 1 hour after initiating the atmospheric exchange and, at the same time, operating the Shuttle contamination control systems. A launch slip that would place the last ground decontamination more than 68 days before ingress would require a second ground decontamination to ensure that toxicological requirements are met. It should be noted that the atmospheric samples taken from Node 1 will further assist in refining the results of this analysis.

3.2.5 Flights 3A and 4A Analysis

A complete analysis of the timeline described earlier and documented in appendix F was conducted to obtain a complete estimate of the Node 1 charcoal bed capacity as well as the estimated relative contamination during the later ingress operations. This analysis used the basic analysis assumptions listed previously; however, instead of utilizing a dry gas purge for ground decontamination, the Node 1 cabin fan was turned on. This approach represents a worst case load for the charcoal beds during the Node 1 ingress timeline through flight 4A. The chief design-driving compound for determining Node 1 charcoal bed life is methanol. Therefore, the ability to reduce methanol concentrations effectively in addition to the *T*-value levels were considered.

As previously noted, concern existed with respect to the Node 1 charcoal bed capacity over the required useful life. In this case, up to 436 days elapse between when Node 1 is sealed on the ground and the ingress operations during flight 4A. If no leakage or dilution effects are considered, theoretically, the charcoal beds are undersized. However, when dilution by the Shuttle atmosphere is considered, the Node 1 charcoal bed design is capable of meeting the total requirements for relative contamination as well as for meeting SMACs. Figure 12 shows the relative contamination profile for the entire Node 1 ground and flight processing timeline. Peaks in relative contamination occur after ground closeout just before the ground decontamination and at flights 2A, 3A, and 4A just before on-orbit decontamination operations. It is expected that *T*-values in Node 1 of up to 2.5, 1.4, and 2 will be experienced just before ingress. Individual assessment of each flight follows.

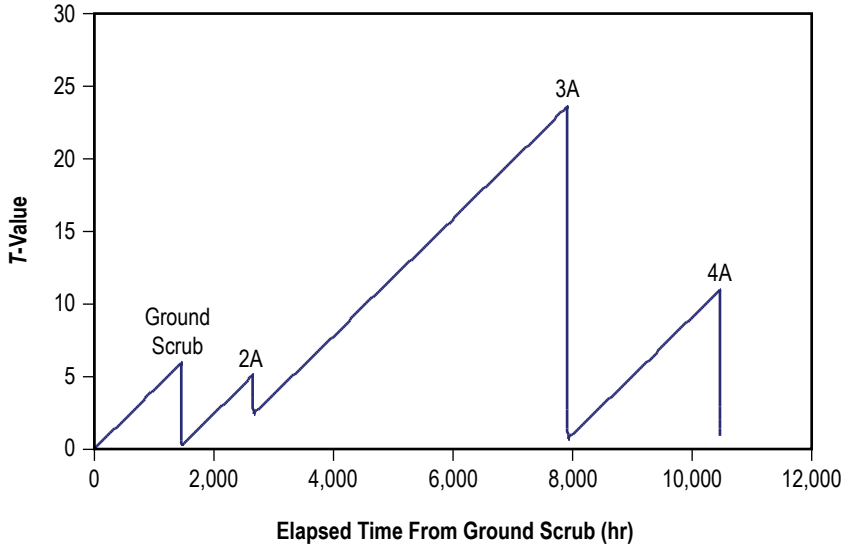


Figure 12. Relative contamination of PMA/Node 1 during missions 2A, 3A, and 4A (launch minus 45-day scrub and full specification load).

Detailed analysis of flight 2A was presented earlier. Figure 8 best represents the situation during flight 2A ingress. The relative contamination in Node 1 will rise to a *T*-value of approximately 5. In this case, the crew will open the Node 1 and PMA hatches, initiate IMV flow, and return to the Shuttle for at least 1 hour while the atmospheric mixing combined with the contamination removal provided by Shuttle systems reduces the relative contamination level. According to table 3, at least five charcoal canisters will be needed in the Shuttle manifest for flight 2A. During this operation, the *T*-value is reduced to less than 1 in 5 hours.

Between flights 2A and 3A, up to 9 months elapse. Figure 13 illustrates the situation during flight 3A. Relative contamination in Node 1 will rise to a *T*-value of up to 23.6. At this time, the Node 1 cabin fan will be started and run for at least 2 hours before the Node 1 hatch is opened and IMV flow is established. This scrub will reduce the *T*-value to 1.45. At that time, the Node 1 hatch will be opened, and IMV flow established. Mixing of the Node 1 and Shuttle atmospheres over the next 2 hours results in a final *T*-value of 0.7. In this case, no special contamination control equipment is necessary in the Shuttle manifest to meet the toxicological requirements for an acceptably clean atmosphere.

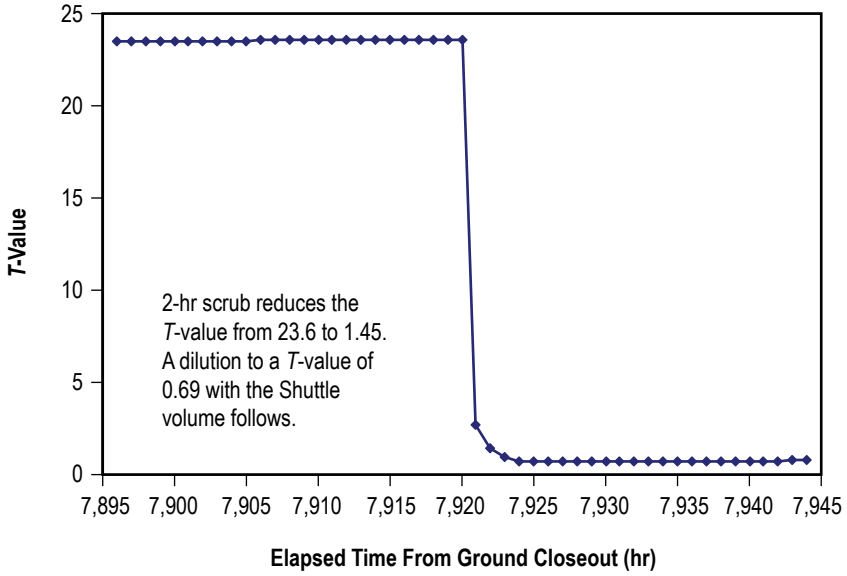


Figure 13. Relative contamination of PMA/Node 1 during mission 3A (launch minus 45-day scrub and full specification load).

Up to 3 months elapse between flights 3A and 4A. Figure 14 shows the flight 4A situation in detail. During this time, the relative contamination rises to a *T*-value of approximately 10.9. Two hours before ingress, the Node 1 cabin fan is started and run for at least 2 hours. The *T*-value is reduced to 2 during this time. At the end of 2 hours, the Node 1 hatch is opened and IMV flow established. Over the next 2 hours, the *T*-value is further reduced to 0.9 by the mixing of the Node 1 and Shuttle atmospheres. As with flight 3A, no special contamination control equipment is necessary in the Shuttle manifest.

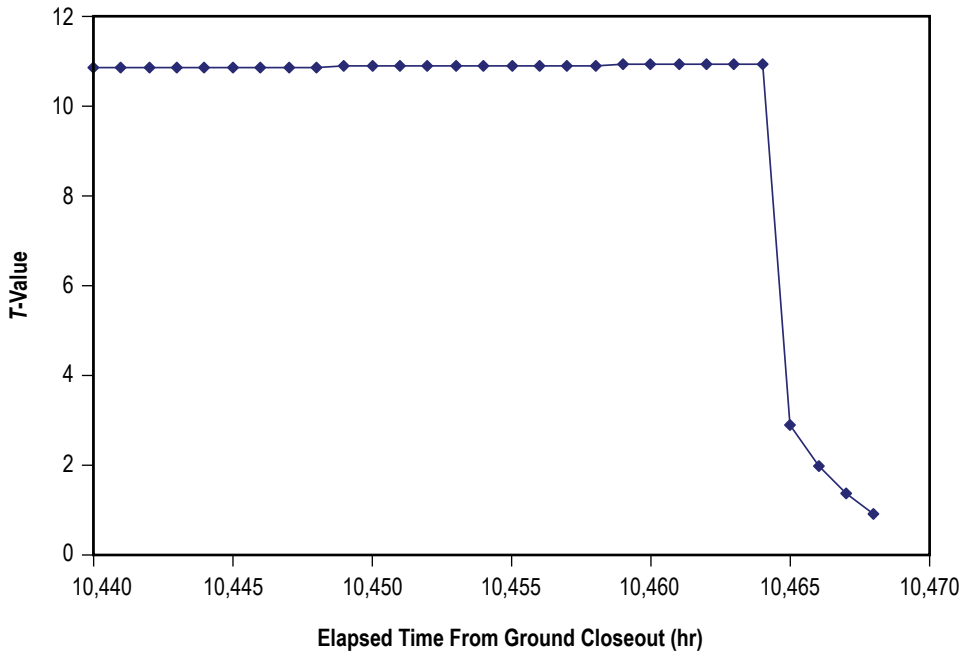


Figure 14. Relative contamination of PMA/Node 1 during mission 4A (launch minus 45-day scrub and full specification load).

3.3 Other Considerations

Other factors can have effects on the performance of the Node 1 charcoal beds and the need for additional Shuttle-provided contamination control hardware. The effects of ground purge air cleanliness and purge methodology may prematurely load the Node 1 charcoal beds. At the same time, programmatic agreements to meet selected Russian maximum allowable concentrations during the early ISS assembly timeline may require additional Shuttle-provided contamination control hardware. Simplified analyses have been conducted to address these concerns.

3.3.1 Effects of Contamination of Ground Purge Air on Charcoal Bed Capacity

In the event that the method of conducting a ground purge of the Node 1 atmosphere requires both purge air and Node 1 atmosphere to flow through the Node 1 charcoal beds via the cabin air circuit, a potential for reduced charcoal bed life may exist. A preliminary analysis was conducted to assess the effects of such a purge on charcoal bed useful life. The purge air contamination specification is not yet available; therefore, the capacity for the bed design driver, methanol, has been assessed for purposes of the preliminary analysis.

Considering that up to 4.5 mg/day of methanol can be produced from the Node 1 hardware, a total of up to 1,958 mg may be produced during the total 436 days between ground closeout and 4A ingress. The original charcoal bed design is for 455 days of offgassing or 2,043 mg of methanol. Therefore, a margin of 19 days or 85 mg of methanol offgassing exists.

If the ground purge is conducted via the cabin air circuit at approximately 40 days before launch, then up to 135 mg of methanol will have been produced. Assuming that the purge air contains no detectable methanol (only light hydrocarbons such as methane) and that the purge provides at least a 50% dilution of the Node 1 atmosphere flowing through the charcoal beds, then approximately 67 mg of methanol would load onto the charcoal beds. At this level, an 18-mg methanol (4-day) margin exists. The margin for methanol control goes to zero if the purge is conducted 37 days after Node 1 closeout. Therefore, any ground purge via the cabin air circuit may have to be conducted within 37 days after Node 1 closeout. Overall, a purge through the IMV circuit with no flow through the charcoal beds would be the preferred option to eliminate these concerns.

Caution should be exercised regarding this preliminary analysis. Since the purge air contamination specification is not yet available, a final recommendation cannot yet be made. Additional analysis will be required if a purge through the cabin air circuit is selected.

3.3.2 Capability to Meet Selected Russian Maximum Allowable Concentrations

The 1994 protocol between U.S. and Russian experts on contamination control and analysis established 12 contaminants for which Russian maximum allowable concentrations must be met during early ISS assembly operations. For a 12th compound, benzene, the Russian side adopted the U.S. SMAC of 0.2 mg/m^3. Table 8 summarizes this agreement.

Table 8. Contaminant limits from April 1994 U.S.-Russian protocol.

Compound	Concentration Limit (mg/m^3)
n-butanol	0.8
Methanol	0.2
Ethanol	10
Formaldehyde	0.05
Acetaldehyde	1
Benzene	0.2
Toluene	8
Isopropylbenzene	0.25
Ethyl acetate	4
Acetone	1
Carbon monoxide	5

By considering the previous analysis conducted for flights 2A, 3A, and 4A, it is possible to estimate the contaminant concentrations that may be present for these compounds at the time the U.S. and Russian segments are opened to each other. These concentrations are summarized in table 9 and assume that the Russian segment is composed of the FGB, Service module, and Universal Docking module. As can be seen, n-butanol, methanol, and acetone present the greatest challenge relative to the table 8 maximum allowable concentrations. According to the analysis presented in part I, dilution between the Shuttle/Node 1 and Russian segment would be expected to take approximately 2 hours. After dilution is complete, a midpoint concentration would be achieved. A summary of

concentrations for the three problem compounds after dilution with the Russian segment is provided in table 10. Of these compounds, only methanol cannot be reduced to below its maximum allowable concentration listed in table 8.

Table 9. Contaminant concentrations in Shuttle/Node 1 before opening FGB hatch.

Compound	Concentration Limit (mg/m^3)	Flight 2A (mg/m^3)	Flight 3A (mg/m^3)	Flight 4A (mg/m^3)
n-butanol	0.8	1.4	0.04	0.08
Methanol	0.2	0.9	4.1	5.8
Ethanol	10	3.5	1.7	2.9
Formaldehyde	0.05	0*	0*	0*
Acetaldehyde	1	0.08	0.2	0.3
Benzene	0.2	0.01	0.002	0.002
Toluene	8	0.7	0.02	0.05
Isopropylbenzene	0.25	0.004	0.0001	0.0003
Ethyl acetate	4	0.1	0.009	0.02
Acetone	1	1.8	0.4	0.7
Carbon monoxide	5	2.8	0.2	0.1

* Insufficient data to estimate a generation rate or concentration.

Table 10. ISS contaminant concentrations after dilution with the Russian segment.

Compound	Maximum Concentration Limit (mg/m^3)	Average Russian Concentration (mg/m^3)	Diluted Concentrations		
			Flight 2A (mg/m^3)	Flight 3A (mg/m^3)	Flight 4A (mg/m^3)
n-butanol	0.8	0.17	0.6	0.12	0.14
Methanol	0.2	0.27	0.5	1.7	2.3
Acetone	1	0.66	0.6	0.56	0.67

In order to address the methanol problem, additional means for removing methanol have been considered. These include additional Shuttle-provided charcoal beds and replacement Node 1 charcoal beds to be used before opening the FGB hatch. Concentration decay calculations based upon a 50% removal capacity estimate 19.5 hours, and 2.4 hours would be necessary to further reduce the Shuttle/Node 1 methanol concentration to the table 8 maximum allowable using Shuttle-provided charcoal beds and fresh Node 1 charcoal beds, respectively. From a logistics and timeline viewpoint, replacing the Node 1 charcoal beds is the better approach.

If the standard Russian trace contaminant control equipment is available onboard the Service module, the methanol concentration estimated for flight 4A would be reduced to the table 8 maximum allowable within 51 hours. This assumes that the regeneration cycle is accelerated to maintain at least a 50% methanol removal efficiency. This approach would be capable of reducing the Russian segment methanol concentration to the maximum allowable within 45 hours at flight 3A and 20 hours at flight 2A.

Formaldehyde is a concern mainly because it is difficult to monitor and little flight data are available. Recent analyses for formaldehyde onboard both the Shuttle and Mir, however, indicate that concentrations may be expected to be very close to the maximum allowable. Average concentrations reported from samples collected onboard Mir have been reported to be approximately 0.058 mg/m^3 according to measurements made during the Mir 18 expedition. Similarly, samples collected onboard the Shuttle during STS-67 have reported average concentrations of 0.056 mg/m^3. It would be reasonable, therefore, to assume that the situation during flights 2A, 3A, and 4A would be very similar. There would appear to be no impact to either the Shuttle/Node 1 or Russian segment atmosphere with respect to formaldehyde.

From this analysis, it is likely that some means of active contamination control would have to be used to reduce the combined Shuttle/Node 1 contamination to within the table 8 limits before opening the Node 1 and FGB hatches unless a joint agreement can be reached regarding methanol. Methanol is well below the NASA SMAC of 9 mg/m^3 during all early Node 1 ingress scenarios as shown in tables 9 and 10; however, the joint agreement summarized in table 8 is not met. Given that the methanol concentration is not presenting an immediate threat to the crew life or health according to U.S. SMAC documentation, additional discussion between the U.S. and Russian sides is necessary to resolve this matter.

3.4 Conclusions

Based upon the basic understanding of contamination buildup in the Node 1 atmosphere over time and the information gained by the performance analysis of the available Node 1 and Shuttle contamination control systems, conclusions that can be reached are the following:

- Ground decontamination is necessary to meet toxicological guidelines for an acceptably clean atmosphere in Node 1 during ingress operations during flight 2A.

- A ground decontamination at approximately launch minus 43 days (51 days before ingress) provides a margin of up to 17 days to accommodate a launch slip.

- The Node 1 charcoal bed capacity is sufficient to provide an acceptably clean atmosphere in Node 1 during all on-orbit ingress operations when dilution with the Shuttle atmosphere is considered.

- If a dry air purge through the cabin air circuit of Node 1 is selected as the ground decontamination and/or dehumidification means, it must occur within 37 days of Node 1 closeout to prevent excessive charcoal bed loading.

- Further decontamination by Shuttle contamination control systems is necessary to provide an acceptably clean atmosphere for flight 2A.

- Each Shuttle charcoal canister (SVHS783970) has approximately a 1-hour useful life.

- At least 2 hours of Node 1 cabin fan operation is necessary to reduce the relative contamination to an acceptable level for flights 3A and 4A.

- Charcoal bed capacity should not be significantly affected by low levels of contamination in the ground purge air if the contamination is limited to highly volatile hydrocarbons such as methane; however, these effects should be reassessed in the event that a purge via the cabin air circuit is selected.

- Additional contamination control means may be necessary to meet selected Russian maximum allowable concentrations for early Node 1 ingress during flights 2A, 3A, and 4A.

3.5 Recommendations

Based upon the detailed analysis of contamination control in Node 1 during ingress operations, recommendations are the following:

- Conduct Node 1 ground decontamination within 68 days of flight 2A ingress.

- Conduct the dry air purge via the IMV circuit within 68 days before on-orbit ingress as the primary ground decontamination means.

- Operate the Node 1 cabin fan as the backup ground decontamination means if significant launch delays occur and another purge is not feasible.

- Manifest at least six charcoal canisters (SVHS783970) onboard the Shuttle for flight 2A to provide contamination control capabilities.

- Replace each Shuttle charcoal canister after no more than 1 hour.

- Operate Shuttle contamination control systems for up to 6 hours total.

- Operate the Node 1 cabin fan for at least 2 hours before ingress during flights 3A and 4A to reduce the Node 1 relative contamination to an acceptable level.

- Reassess the effects of low level purge air contamination Node 1 charcoal bed life once its specification becomes better defined.

- Negotiate an agreement between the U.S. and Russian sides regarding methanol concentrations during early Node 1 ingress.

Since the analysis conducted is based upon contaminant generation rates obtained from statistical assessment of flight offgassing data, good engineering practice dictates that data obtained from the Node 1 flight configuration be used as a final check to validate these analytical results. Therefore, it is further recommended that the conclusions and recommendations be revisited once grab samples of the Node 1 atmosphere have been collected and analyzed. Final conclusions and recommendations should be based upon the actual Node 1 offgassing data. However, the current conclusions and recommendations are considered to be valid and to possess appropriate conservatism for planning purposes.

4. VERIFICATION ANALYSIS OF THE TRACE CONTAMINANT CONTROL CAPABILITY FOR INTERNATIONAL SPACE STATION NODE 1

The analysis was originally conducted in December 1997 and released under NASA Memorandum ED62(104-97) dated January 8, 1998.

4.1 Background

Trace contaminant control of the cabin atmosphere is a challenge that spans the design, manufacturing, on-orbit deployment, and operations of a spacecraft. While efforts are made during the design and manufacturing phases to limit the sources of trace chemical contamination, they cannot be eliminated altogether. For this reason, active contamination control means must be considered for use aboard spacecraft.

4.1.1 Node 1 Contamination Control

Node 1 represents a specific challenge to the ISS because of the relatively long quiescent periods that will occur from the time that it is sealed for launch until it is finally part of a habitable Space Station at the conclusion of assembly flight 4A. During these periods, Node 1 is in an inactive state and trace chemical contaminants may build up to unacceptable levels as described by previous analyses in sections 2 and 3. This presents a problem because of plans to enter Node 1 several times during assembly flights 2A, 2A.1, 3A, and 4A. Although the Russian-built FGB has active contamination control capabilities, they cannot be used because the Node will not have permanent electrical power to allow for proper thermal control. Therefore, the hatch between Node 1 and the FGB will remain closed until assembly flight 4A. As a result, Node 1 is considered to be a stand-alone element that must provide its own contamination control capability during the period from its closeout before launch and its permanent activation during assembly flight 4A.

4.1.2 Cabin Air Catalyst Element Assembly Description

In order to address this problem, Node 1 has been outfitted with four cabin air catalyst element assemblies (CACEAs) containing Barnebey & Sutcliffe type 3032, 4×6 mesh phosphoric acid-treated granular activated charcoal (AC/GAC) and Engelhard Corporation 2% Pt on charcoal (2% Pt/GAC). The design of the CACEA has been incremental. They were first introduced during the Space Station Freedom program when it became apparent that an additional means for actively controlling trace chemical contamination buildup in a Node during the early phases of Space Station assembly. Several possible designs were considered as discussed in section 3.

The final design selected was provided to the ISS program by United Technologies Corp. Hamilton Standard Space Systems International, Inc. of Windsor Locks, Connecticut. This design, shown in cross section in figure 15, calls for the retrofit of four cabin air bacteria filter elements with

AC/GAC and 2% Pt/GAC. Minimum packing depths of the AC/GAC and 2% Pt/GAC are 3.3 cm (1.3 in) and 1.27 cm (0.5 in), respectively. Verification of these packing depths was reported by Hamilton Standard in analysis inspection records that were completed on June 2, 1997, and provided herein as appendix G. Flow dimensions of the CACEA are approximately 72.3 cm (28.48 in) long and 9.2 cm (3.6 in) wide providing an area of 662.4 cm^2 (102.7 in^2) according to an inspection of a cabin air bacteria filter element (CACEA) part number SVSK119898 manufactured on November 22, 1993, for NASA Contract NAS8-50000.

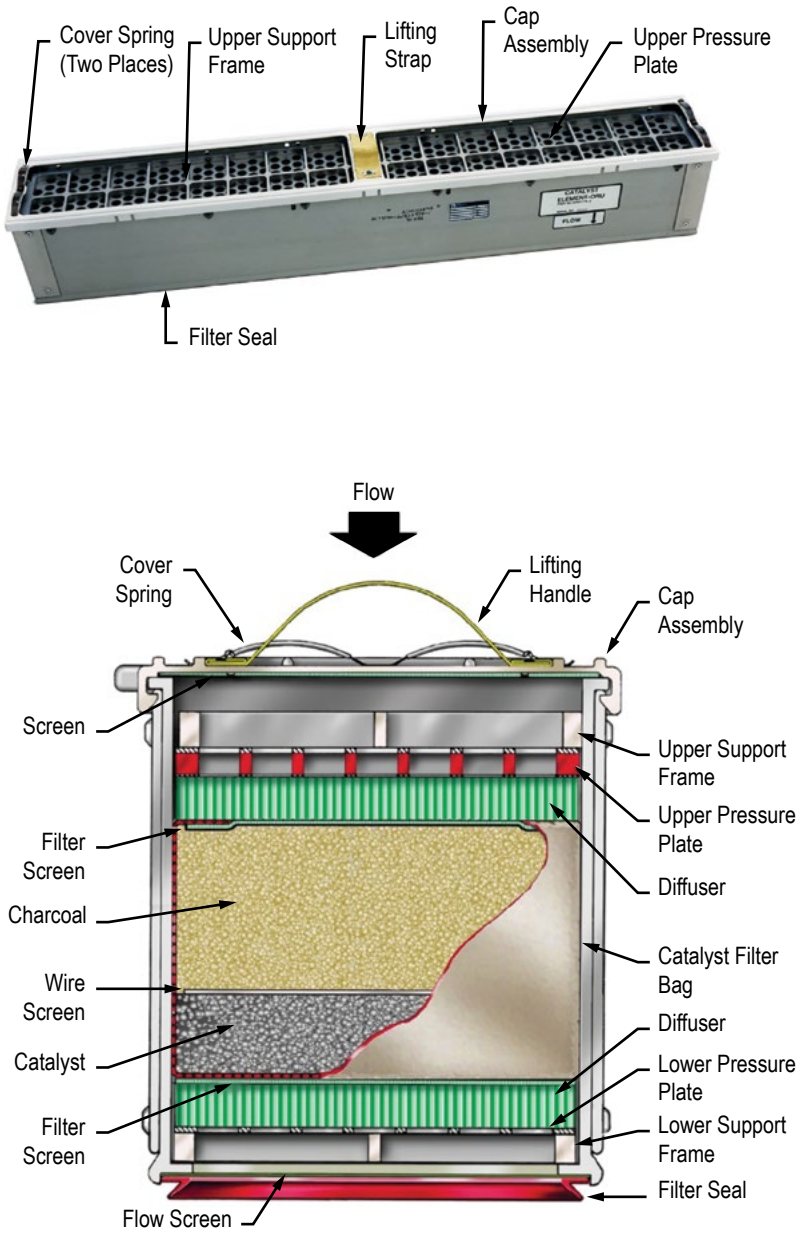


Figure 15. CACEA features and cross section.

4.2 Requirements

Specific requirements regarding Node 1 contamination control are contained in the Node 1 Prime Item Development Specification (PIDS). Paragraphs 3.2.1.63 and 4.3.2.1.63 provide details on the Node 1 contamination control capability and verification requirements. A summary of these requirements is provided by the following:

- Control individual contaminant concentrations to less than or equal to the appropriate SMAC listed in Node 1 PIDS (tables XI and XII).
- The trace contaminant load model basis is defined by Node 1 PIDS (table XII).
- The internal hardware mass contributing to trace contaminant generation is 2,359 kg (5,200 lb).
- No metabolic contaminant generation.
- Verification is by analysis and inspection.
- Catalytic filter qualification test data will be used for the verification analysis.

Further, a trace chemical contaminant removal verification analysis report is required that includes the qualification data used in the analysis.

In addition to the Node 1 PIDS requirements, toxicological guidelines for ingress operations have been issued by JSC's Medical Sciences Division. These guidelines center upon the T-value which is defined by $T=\sum C_i/C_{\mathrm{SMAC}}$, where C_i is the individual contaminant concentration and C_{SMAC} is the respective SMAC. The T-value guidelines are provided in table 5. The Node 1 verification analysis also addresses these guidelines even though they are not a Node 1 PIDS requirement. According to the guidelines, if the predicted T-value is ≤ 3, then ingress without first scrubbing Node 1 can be considered acceptable. All other cases require some form of active contamination removal before ingress.

4.3 Purpose

The purpose of the analysis summarized by the following discussion is to verify that the Node 1 trace contaminant control capability, at a minimum, meets the requirements for trace contaminant control summarized by Node 1 PIDS (paragraphs 3.2.1.63 and 4.3.2.1.63).

4.4 Objectives

Verification of the Node 1 trace contaminant removal capability was conducted by analysis. Specific objectives of the analysis which allow for appropriate verification of this capability are the following:

- Determine the trace contaminant concentrations during early Node 1 ingress operations during assembly flights 2A, 2A.1, 3A, and 4A.

- Determine the adequacy of the Node 1 CACEAs for meeting the relevant Node 1 PIDS requirements.

4.5 Assumptions

To conduct the Node 1 trace contamination control capability verification analysis, assumptions must be made concerning the offgassing rates flight, cabin atmospheric conditions, hardware configuration, CACEA configuration, and mission timeline.

4.5.1 Offgassing and Cabin Conditions

Basic assumptions pertaining to offgassing rates and cabin atmospheric conditions for all phases of the verification analysis are the following:

- Node 1 internal hardware mass contributing to offgassing is 2,359 kg according to Node 1 PIDS 3.2.1.63 for analysis case 1.

- Node 1 internal hardware mass contributing to offgassing is most likely to be 1,361 kg (3,000 lb) according to ISS program Product Group 1 mass properties analyses for analysis case 2.

- Node 1 leakage is zero.

- Node 1 atmospheric conditions are on average 10 ºC (50 ºF), 30% relative humidity (20 ºF dewpoint), and 1 atm.

- Offgassing rates are defined by the Node 1 PIDS (table XII). These rates are constant with time and effects of temperature and pressure fluctuations are negligible.

- Seven-day SMACs apply for the analysis. 180-day SMACs are included for comparison to satisfy Node 1 PIDS (paragraph 3.2.1.63).

4.5.2 Node 1 Configuration

On orbit, Node 1 is attached to a PMA which is in turn attached to the Shuttle during each assembly flight. Node 1 is provided with a contamination control capability consisting of a cabin fan and four CACEAs located in the cabin air return duct in place of the cabin air bacteria filter elements. The configuration provides at least 340 m^3/hr (200 ft^3/min) total air flow rate through the CACEAs. Assumptions pertaining to the Node 1 configuration and its contamination control capability are the following:

- Pressurized free volumes of Node 1, the PMA, and Shuttle are 51.3 m^3 (1,811.6 ft^3), 6.1 m^3 (215.4 ft^3), and 65.8 m^3 (2,323.6 ft^3), respectively.

- The total Node 1 scrubbing rate is 340 m^3/hr with the flow split evenly between four individual CACEAs.

- Each CACEA has a minimum AC/GAC packing depth of 3.3 cm (1.3 in) and a 2% Pt/GAC packing depth of 1.27 cm (0.5 in).

4.5.3 Mission Timeline

Node 1 is launched during assembly flight 2A. Approximately 45 days before launch, a final purge is conducted to provide a dry atmosphere. This purge has the added benefit of removing trace contaminants. During mission 2A, Node 1 ingress activities are conducted on flight day 8. The ingress operation begins with a 2-hr scrub of the Node 1 atmosphere using the Node 1 cabin fan and four CACEAs. Following the scrub, the hatch is opened and IMV between Node 1 and the Shuttle cabin is initiated. The IMV forces an additional dilution of the remaining trace contaminants in Node 1's atmosphere. Ingress operations continued for approximately 8 hours. At the completion of flight 2A, a period of untended operations of approximately 150 days begins. After that time, the next planned ingress activities occur during assembly of flight 2A.1. Multiple ingress events occur during flight 2A.1. A similar ingress approach employing a 2-hr scrub followed by hatch opening and IMV activation. At the conclusion of flight 2A.1, the expended CACEAs are replace with fresh ones. There are approximately 30 days between flights 2A.1 and 3A. Ingress operations during flight 3A are the same as those for previous flights. After flight 3A, approximately 90 days elapse before flight 4A. Again, the same ingress approach is used. After flight 4A, Node 1 is operationally supported for trace contaminant control by the Russian segment. Details on the timeline are provided in appendix F.

4.6 Approach

The following discussion summarizes the trace contaminant load model, the analytical tool, and cases considered for the analysis.

4.6.1 Load Model

The trace contaminant load model is defined by Node 1 PIDS (table XII) and provided herein in appendix B. This model was derived from Spacelab program mission offgassing data and represents the 95% confidence interval upper bound for expected offgassing rates from spacecraft hardware.[9] The 2,359 and 1,361 kg Node 1 hardware mass cases were applied to the load model to derive the generation rates used for the verification analysis. The resulting rates are provided in appendix H.

4.6.2 Trace Contaminant Control Simulation Computer Program

The TCCS-CP, version 8.1, was used to conduct the analysis.[6] This analytical tool calculates the cabin concentration of individual trace chemical contaminants when generated at a specified rate and controlled by any combination of removal devices. It contains subroutines for simulating the performance of AC/GAC and 2% Pt/GAC. The TCCS-CP, version 8.1, has previously been assessed for its applicability for use in spacecraft trace contaminant control verification analyses and was found to be acceptable.[7]

The subroutine for the 2% Pt/GAC uses a carbon monoxide oxidation performance basis previously reported by Lockheed-Martin in Sunnyvale, California, in 1977.[4] This basis has been checked against qualification data supplied by Hamilton Standard and was found to predict carbon monoxide removal efficiency consistent with low temperature operations for the CACEA geometry. The TCCS-CP predicts a 17.8% removal efficiency for a 0.0355-s residence time at 24 °C. By comparison, the 2% Pt/GAC qualification data provided in appendix I shows a similar performance: 17.7%

removal efficiency for a 0.033-s residence time at 10 ºC. Therefore, using the TCCS-CP 2% Pt/GAC subroutine for the documented CACEA geometry results in a conservative performance assessment.

4.6.3 Analysis Cases Considered

Two analytical cases were considered. The first uses the Node 1 PIDS load model applied to 2,359 kg of internal hardware. The second uses a hardware mass basis of 1,361 kg. In both cases, the cabin temperature is 10 ºC to most accurately simulate 2% Pt/GAC performance. Data from each case were obtained at the completion of the preingress scrub to demonstrate compliance with the Node 1 PIDS requirements.

4.7 Results

Tables 11 and 12 summarize the results of the Node 1 contamination control verification analysis. The results using an offgassing basis of 2,359 kg of internal hardware are provided in table 11 and the offgassing basis of 1,361 kg are provided in table 12. As can be seen by these results, no single contaminant exceeds either its 7- or 180-day SMAC at the conclusion of the preingress scrub for assembly flights 2A, 2A.1, 3A, and 4A. Figures 16 and 17 show the relative contamination as defined by the *T*-value during the entire mission timeline. The *T*-value was calculated using the 7-day SMAC only because the mission duration for each flight is closer to 7 days and crew exposure to the Node 1 contamination load after each preingress scrub is much less than 7 days. In all cases, the ingress toxicological guidelines summarized in table 5 are met.

Table 11. Trace contaminant concentrations for Node 1 for the 2,359-kg hardware basis.

Compound Name	Concentration (mg/m^3)				SMAC (mg/m^3)	
	2A	2A.1	3A	4A	7-Day	180-Day
Methanol	8.38E-01	2.47E+00	6.05E-01	1.55E+00	9.00	9.00
Ethanol	2.49E-01	1.03E+00	1.77E-01	6.18E-01	2,000.00	2,000.00
2-propen-1-ol	1.10E-04	2.71E-04	7.93E-05	1.89E-04	1.00	1.00
2-propanol	4.25E-02	1.03E-01	3.21E-02	7.25E-02	150.00	150.00
n-propanol	3.86E-03	8.63E-03	2.90E-03	6.24E-03	98.00	98.00
1,2-ethanediol	1.22E-04	2.65E-04	9.17E-05	1.94E-04	13.00	13.00
2-methyl-1-propanol	4.11E-03	8.29E-03	3.23E-03	6.23E-03	120.00	120.00
2-methyl-2-propanol	8.70E-04	1.96E-03	6.52E-04	1.41E-03	120.00	120.00
n-butanol	1.23E-02	2.29E-02	1.01E-02	1.78E-02	80.00	40.00
n-pentanol	4.48E-04	8.59E-04	3.60E-04	6.56E-04	130.00	130.00
Phenol	1.11E-03	1.93E-03	9.21E-04	1.54E-03	7.70	7.70
Cyclohexanol	1.45E-03	2.56E-03	1.21E-03	2.02E-03	120.00	120.00
2-hexanol	1.02E-05	2.24E-05	7.79E-06	1.62E-05	170.00	170.00
Methanal	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.05	0.05
Ethanal	2.02E-02	9.18E-02	1.38E-02	5.51E-02	4.00	4.00
2-propenal	3.18E-04	8.38E-04	2.25E-04	5.68E-04	0.03	0.03
Propanal	1.22E-02	3.29E-02	8.79E-03	2.22E-02	95.00	95.00
Butanal	4.62E-03	9.90E-03	3.55E-03	7.25E-03	120.00	120.00
Pentanal	5.58E-04	1.22E-03	4.23E-04	8.88E-04	110.00	110.00

Table 11. Trace contaminant concentrations for Node 1 for the 2,359-kg hardware basis (Continued).

Compound Name	Concentration (mg/m^3)				SMAC (mg/m^3)	
	2A	2A.1	3A	4A	7-Day	180-Day
Benzaldehyde	9.26E-05	1.92E-04	7.19E-05	1.42E-04	173.00	173.00
Benzene	5.26E-04	1.25E-03	3.86E-04	8.80E-04	1.50	0.20
Methylbenzene	6.67E-03	1.34E-02	5.29E-03	1.01E-02	60.00	60.00
Ethenylbenzene	1.32E-04	2.75E-04	1.02E-04	2.03E-04	43.00	43.00
1,2-dimethylbenzene	1.18E-03	2.21E-03	9.58E-04	1.70E-03	220.00	220.00
1,3-dimethylbenzene	2.93E-03	5.10E-03	2.47E-03	4.03E-03	220.00	220.00
1,4-dimethylbenzene	1.89E-03	3.43E-03	1.56E-03	2.67E-03	220.00	220.00
Ethylbenzene	4.21E-04	8.35E-04	3.35E-04	6.29E-04	130.00	130.00
Alpha-methylstyrene	0.00E+00	0.00E+00	0.00E+00	0.00E+00	140.00	140.00
1,2,4-trimethylbenzene	7.24E-05	1.34E-04	5.96E-05	1.03E-04	15.00	15.00
1,3,5-trimethylbenzene	8.78E-06	1.81E-05	6.90E-06	1.34E-05	15.00	15.00
1-ethyl-2-methylbenzene	1.38E-05	2.82E-05	1.09E-05	2.10E-05	25.00	25.00
Isopropylbenzene	3.53E-05	7.11E-05	2.81E-05	5.31E-05	74.00	74.00
Propylbenzene	2.93E-04	5.16E-04	2.46E-04	4.05E-04	49.00	49.00
1-isopropyl-4-methylbenzene	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.10	0.10
Methanoic acid methyl ester	3.92E-04	1.07E-03	2.77E-04	7.19E-04	0.10	0.10
Methanoic acid ethyl ester	2.52E-04	6.31E-04	1.81E-04	4.35E-04	91.00	91.00
Ethanoic acid methyl ester	3.88E-03	9.37E-03	2.84E-03	6.57E-03	120.00	120.00
Ethanoic acid ethyl ester	2.94E-03	6.60E-03	2.21E-03	4.76E-03	180.00	180.00
Methyl 2-methyl propenoate	8.92E-04	1.95E-03	6.78E-04	1.42E-03	100.00	100.00
Ethanoic acid isopropyl ester	5.59E-05	1.31E-04	4.14E-05	9.25E-05	210.00	210.00
Ethanoic acid propyl ester	1.36E-03	2.81E-03	1.06E-03	2.08E-03	170.00	170.00
Ethanoic acid butyl ester	1.23E-03	2.24E-03	1.02E-03	1.74E-03	190.00	190.00
Ethanoic acid isobutyl ester	3.80E-04	7.54E-04	3.03E-04	5.67E-04	190.00	190.00
Lactic acid ethyl ester	1.71E-05	3.70E-05	1.30E-05	2.70E-05	190.00	190.00
Ethanoic acid amyl ester	7.52E-05	1.40E-04	6.20E-05	1.07E-04	160.00	160.00
2-ethoxyethyl ethanoate	8.09E-04	1.33E-03	6.99E-04	1.07E-03	160.00	160.00
1,4-epoxy-1,3-butadiene	2.32E-04	6.17E-04	1.64E-04	4.17E-04	0.11	0.11
1,4-epoxybutane	1.81E-03	4.34E-03	1.33E-03	3.05E-03	120.00	120.00
Diethyl ether	1.50E-03	3.56E-03	1.10E-03	2.51E-03	240.00	240.00
2-methylfuran	1.38E-04	3.44E-04	9.91E-05	2.38E-04	0.13	0.13
2-ethoxyethanol	1.80E-03	3.42E-03	1.45E-03	2.62E-03	3.00	0.30
Chloromethane	6.12E-03	2.33E-02	4.23E-03	1.41E-02	41.00	41.00
Chloroethene	3.40E-04	1.01E-03	2.41E-04	6.60E-04	3.00	3.00
Chloroethane	0.00E+00	0.00E+00	0.00E+00	0.00E+00	260.00	260.00
Dichloromethane	1.47E-01	6.46E-01	1.02E-01	3.82E-01	50.00	10.00
1,1-dichloroethene	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.90	7.90
1,2-dichloroethane	1.77E-03	4.17E-03	1.30E-03	2.95E-03	2.00	1.00
Chlorobenzene	5.13E-03	1.01E-02	4.09E-03	7.64E-03	46.00	46.00
1,2-dichloropropane	1.29E-04	3.06E-04	9.49E-05	2.16E-04	42.00	42.00
Trichloromethane	7.24E-04	1.79E-03	5.22E-04	1.24E-03	4.90	4.90
Trichloroethene	1.47E-03	3.41E-03	1.09E-03	2.43E-03	50.00	10.00
1,1,1-trichloroethane	6.31E-03	1.42E-02	4.75E-03	1.02E-02	160.00	160.00
1,1,2-trichloroethane	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.50	5.50
1,2-dichlorobenzene	3.37E-05	7.13E-05	2.60E-05	5.25E-05	30.00	30.00
Tetrachoromethane	2.15E-04	5.18E-04	1.56E-04	3.63E-04	13.00	13.00
Tetrachloroethene	3.54E-03	7.33E-03	2.75E-03	5.45E-03	34.00	34.00
Chlorodifluoromethane	1.28E-02	6.03E-02	8.70E-03	3.55E-02	350.00	350.00
Dichlorofluoromethane	0.00E+00	0.00E+00	0.00E+00	0.00E+00	21.00	21.00
1-chloro-1,2,2-trifluorethane	3.36E-04	8.67E-04	2.39E-04	5.92E-04	480.00	480.00

Table 11. Trace contaminant concentrations for Node 1 for the 2,359-kg hardware basis (Continued).

Compound Name	Concentration (mg/m^3)				SMAC (mg/m^3)	
	2A	2A.1	3A	4A	7-Day	180-Day
Dichlorodifluoromethane	1.11E-03	2.93E-03	7.82E-04	1.98E-03	490.00	490.00
1,2-dichloro-1,2-difluoroethene	1.20E-04	3.08E-04	8.55E-05	2.10E-04	140.00	140.00
Trichlorofluoromethane	3.39E-02	9.06E-02	2.46E-02	6.12E-02	560.00	560.00
Bromotrifluoromethane	4.45E-02	2.26E-01	3.00E-02	1.29E-01	11,000.00	11,000.00
Dichlorotetrafluoroethane	7.24E-04	1.79E-03	5.23E-04	1.24E-03	700.00	700.00
Trichlorotrifluoroethane	8.17E-02	1.99E-01	6.28E-02	1.38E-01	400.00	400.00
Tetrachlorodifluoroethane	2.45E-04	5.51E-04	1.85E-04	3.96E-04	830.00	830.00
Methane	1.39E+00	4.79E+00	1.07E+00	3.17E+00	3,800.00	3,800.00
Ethene	0.00E+00	0.00E+00	0.00E+00	0.00E+00	340.00	340.00
Ethane	1.08E-03	5.45E-03	7.40E-04	3.28E-03	1,200.00	1200.00
Propene	3.16E-04	9.44E-04	2.23E-04	6.16E-04	860.00	860.00
Propane	2.26E-04	6.16E-04	1.59E-04	4.13E-04	900.00	900.00
1,3-butadiene	2.21E-04	5.75E-04	1.57E-04	3.92E-04	0.70	0.13
1-butene	2.93E-03	7.53E-03	2.11E-03	5.16E-03	460.00	460.00
2-methylpropane	4.19E-04	1.06E-03	3.00E-04	7.28E-04	240.00	240.00
Butane	2.16E-04	5.44E-04	1.55E-04	3.75E-04	240.00	240.00
1-pentene	0.00E+00	0.00E+00	0.00E+00	0.00E+00	190.00	190.00
2-methylbutane	4.76E-05	1.17E-04	3.44E-05	8.14E-05	300.00	300.00
Pentane	1.12E-03	2.61E-03	8.31E-04	1.85E-03	590.00	590.00
Cyclohexane	2.54E-03	5.54E-03	1.93E-03	4.03E-03	210.00	210.00
Methylcyclopentane	3.05E-04	7.01E-04	2.27E-04	5.00E-04	52.00	52.00
2,2-dimethylbutane	2.49E-05	5.95E-05	1.83E-05	4.18E-05	88.00	88.00
3-methylpentane	4.68E-05	1.09E-04	3.47E-05	7.73E-05	1,800.00	1,800.00
Hexane	3.88E-04	8.54E-04	2.95E-04	6.18E-04	180.00	180.00
1-heptene	0.00E+00	0.00E+00	0.00E+00	0.00E+00	200.00	200.00
Methylcyclohexane	2.60E-04	5.55E-04	2.01E-04	4.07E-04	60.00	60.00
Heptane	1.59E-04	3.28E-04	1.25E-04	2.43E-04	200.00	200.00
1,1-dimethylcyclohexane	1.36E-04	2.75E-04	1.08E-04	2.05E-04	120.00	120.00
Trans-1,2-dimethylcyclohexane	1.27E-04	2.55E-04	1.01E-04	1.91E-04	120.00	120.00
Octane	3.07E-05	6.05E-05	2.48E-05	4.55E-05	350.00	350.00
Nonane	9.45E-06	1.75E-05	7.85E-06	1.34E-05	320.00	320.00
Isopropenylmethylcyclohexene	4.70E-06	9.03E-06	3.84E-06	6.84E-06	557.00	557.00
Decane	2.11E-05	3.27E-05	1.87E-05	2.68E-05	230.00	230.00
Undecane	1.39E-05	1.95E-05	1.28E-05	1.67E-05	320.00	320.00
Dodecane	0.00E+00	0.00E+00	0.00E+00	0.00E+00	280.00	280.00
2-propanone	7.72E-02	2.37E-01	5.60E-02	1.53E-01	50.00	50.00
2-butanone	4.03E-02	9.49E-02	3.08E-02	6.72E-02	30.00	30.00
2-pentanone	4.12E-05	9.65E-05	3.04E-05	6.83E-05	70.00	70.00
3-methyl-2-butanone	2.96E-04	6.67E-04	2.22E-04	4.79E-04	70.00	70.00
4-methyl-3-penten-2-one	6.82E-04	1.38E-03	5.36E-04	1.03E-03	40.00	40.00
Cyclohexanone	1.16E-03	2.00E-03	9.72E-04	1.59E-03	60.00	60.00
4-methyl-2-pentanone	2.79E-03	5.22E-03	2.28E-03	4.01E-03	140.00	140.00
Acetophenone	0.00E+00	0.00E+00	0.00E+00	0.00E+00	250.00	250.00
2-octanone	0.00E+00	0.00E+00	0.00E+00	0.00E+00	100.00	100.00
2,6-dimethyl-4-heptanone	3.61E-06	6.48E-06	3.04E-06	5.03E-06	58.00	58.00
Hydrogen sulfide	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.80	2.80
Carbonyl sulfide	6.03E-03	2.68E-02	4.31E-03	1.72E-02	12.00	12.00
Dimethyl sulfide	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.50	2.50
Carbon disulfide	2.59E-03	6.99E-03	1.84E-03	4.72E-03	16.00	16.00
Ethanoic acid	2.12E-04	5.40E-04	1.51E-04	3.71E-04	7.40	7.40

Table 11. Trace contaminant concentrations for Node 1 for the 2,359-kg hardware basis (Continued).

Compound Name	Concentration (mg/m^3)				SMAC (mg/m^3)	
	2A	2A.1	3A	4A	7-Day	180-Day
Methyl cyanide	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.70	6.70
2,3-benzopyrrole	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.25	0.25
Hydrogen	1.36E-03	4.03E-03	9.17E-04	2.60E-03	340.00	340.00
Ammonia	2.58E-05	2.84E-05	2.53E-05	2.70E-05	7.00	7.00
Carbon monoxide	5.42E-01	1.61E+00	3.66E-01	1.04E+00	10.00	10.00
Trimethylsilanol	1.11E-03	2.43E-03	8.46E-04	1.77E-03	40.00	40.00

Table 12. Trace contaminant concentrations for Node 1 for the 1,361-kg hardware basis.

Compound Name	Concentration (mg/m^3)				SMAC (mg/m^3)	
	2A	2A.1	3A	4A	7-Day	180-Day
Methanol	4.91E-01	1.30E+00	3.54E-01	1.23E+00	9.00	9.00
Ethanol	1.47E-01	5.32E-01	1.06E-01	3.33E-01	2,000.00	2,000.00
2-propen-1-ol	6.10E-05	1.52E-04	4.38E-05	1.05E-04	1.00	1.00
2-propanol	2.77E-02	6.52E-02	2.09E-02	4.63E-02	150.00	150.00
n-propanol	2.52E-03	5.69E-03	1.88E-03	4.10E-03	98.00	98.00
1,2-ethanediol	8.28E-05	1.83E-04	6.19E-05	1.33E-04	13.00	13.00
2-methyl-1-propanol	2.73E-03	5.60E-03	2.13E-03	4.18E-03	120.00	120.00
2-methyl-2-propanol	5.61E-04	1.28E-03	4.18E-04	9.14E-04	120.00	120.00
n-butanol	8.28E-03	1.56E-02	6.70E-03	1.20E-02	80.00	40.00
n-pentanol	2.96E-04	5.80E-04	2.35E-04	4.39E-04	130.00	130.00
Phenol	7.50E-04	1.35E-03	6.15E-04	1.06E-03	7.70	7.70
Cyclohexanol	9.64E-04	1.75E-03	7.92E-04	1.37E-03	120.00	120.00
2-hexanol	5.81E-06	1.29E-05	4.40E-06	9.32E-06	170.00	170.00
Methanal	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.05	0.05
Ethanal	1.13E-02	4.74E-02	7.77E-03	2.89E-02	4.00	4.00
2-propenal	2.22E-04	5.84E-04	1.57E-04	3.96E-04	0.03	0.03
Propanal	7.59E-03	2.00E-02	5.48E-03	1.36E-02	95.00	95.00
Butanal	3.00E-03	6.50E-03	2.30E-03	4.75E-03	120.00	120.00
Pentanal	3.62E-04	8.02E-04	2.73E-04	5.80E-04	110.00	110.00
Benzaldehyde	6.07E-05	1.28E-04	4.68E-05	9.44E-05	173.00	173.00
Benzene	3.38E-04	8.06E-04	2.47E-04	5.67E-04	1.50	0.20
Methylbenzene	4.38E-03	8.91E-03	3.45E-03	6.66E-03	60.00	60.00
Ethenylbenzene	8.58E-05	1.82E-04	6.62E-05	1.34E-04	43.00	43.00
1,2-dimethylbenzene	7.67E-04	1.48E-03	6.18E-04	1.12E-03	220.00	220.00
1,3-dimethylbenzene	1.91E-03	3.40E-03	1.59E-03	2.66E-03	220.00	220.00
1,4-dimethylbenzene	1.23E-03	2.29E-03	1.01E-03	1.77E-03	220.00	220.00
Ethylbenzene	2.74E-04	5.54E-04	2.16E-04	4.14E-04	130.00	130.00
Alpha-methylstyrene	0.00E+00	0.00E+00	0.00E+00	0.00E+00	140.00	140.00
1,2,4-trimethylbenzene	4.68E-05	8.88E-05	3.82E-05	6.78E-05	15.00	15.00
1,3,5-trimethylbenzene	6.32E-06	1.32E-05	4.94E-06	9.73E-06	15.00	15.00
1-ethyl-2-methylbenzene	9.15E-06	1.90E-05	7.17E-06	1.40E-05	25.00	25.00
Isopropylbenzene	2.25E-05	4.61E-05	1.77E-05	3.42E-05	74.00	74.00
Propylbenzene	1.88E-04	3.41E-04	1.56E-04	2.65E-04	49.00	49.00
1-isopropyl-4-methylbenzene	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.10	0.10

Table 12. Trace contaminant concentrations for Node 1 for the 1,361-kg hardware basis (Continued).

Compound Name	Concentration (mg/m^3)				SMAC (mg/m^3)	
	2A	2A.1	3A	4A	7-Day	180-Day
Methanoic acid methyl ester	2.71E-04	7.40E-04	1.91E-04	4.96E-04	0.10	0.10
Methanoic acid ethyl ester	1.62E-04	4.08E-04	1.16E-04	2.81E-04	91.00	91.00
Ethanoic acid methyl ester	2.46E-03	5.96E-03	1.79E-03	4.17E-03	120.00	120.00
Ethanoic acid ethyl ester	1.90E-03	4.31E-03	1.43E-03	3.10E-03	180.00	180.00
Methyl 2-methyl propenoate	5.78E-04	1.28E-03	4.37E-04	9.25E-04	100.00	100.00
Ethanoic acid isopropyl ester	3.66E-05	8.62E-05	2.70E-05	6.09E-05	210.00	210.00
Ethanoic acid propyl ester	8.83E-04	1.86E-03	6.83E-04	1.37E-03	170.00	170.00
Ethanoic acid butyl ester	7.96E-04	1.49E-03	6.52E-04	1.14E-03	190.00	190.00
Ethanoic acid isobutyl ester	2.45E-04	4.96E-04	1.94E-04	3.70E-04	190.00	190.00
Lactic acid ethyl ester	1.23E-05	2.71E-05	9.38E-06	1.96E-05	190.00	190.00
Ethanoic acid amyl ester	4.79E-05	9.10E-05	3.91E-05	6.94E-05	160.00	160.00
2-ethoxyethyl ethanoate	5.19E-04	8.77E-04	4.43E-04	7.00E-04	160.00	160.00
1,4-epoxy-1,3-butadiene	1.24E-04	3.31E-04	8.77E-05	2.24E-04	0.11	0.11
1,4-epoxybutane	1.14E-03	2.76E-03	8.35E-04	1.94E-03	120.00	120.00
Diethyl ether	9.49E-04	2.27E-03	6.96E-04	1.60E-03	240.00	240.00
2-methylfuran	9.74E-05	2.44E-04	6.98E-05	1.69E-04	0.13	0.13
2-ethoxyethanol	1.19E-03	2.32E-03	9.52E-04	1.77E-03	3.00	0.30
Chloromethane	3.20E-03	1.16E-02	2.21E-03	9.28E-03	41.00	41.00
Chloroethene	1.78E-04	5.14E-04	1.26E-04	3.39E-04	3.00	3.00
Chloroethane	0.00E+00	0.00E+00	0.00E+00	0.00E+00	260.00	260.00
Dichloromethane	8.40E-02	3.27E-01	5.91E-02	2.00E-01	50.00	10.00
1,1-dichloroethene	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.90	7.90
1,2-dichloroethane	1.13E-03	2.69E-03	8.30E-04	1.90E-03	2.00	1.00
Chlorobenzene	3.39E-03	6.78E-03	2.68E-03	5.10E-03	46.00	46.00
1,2-dichloropropane	8.13E-05	1.94E-04	5.94E-05	1.37E-04	42.00	42.00
Trichloromethane	4.61E-04	1.15E-03	3.32E-04	7.94E-04	4.90	4.90
Trichloroethene	9.39E-04	2.20E-03	6.92E-04	1.56E-03	50.00	10.00
1,1,1-trichloroethane	4.07E-03	9.24E-03	3.05E-03	6.63E-03	160.00	160.00
1,1,2-trichloroethane	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.50	5.50
1,2-dichlorobenzene	2.17E-05	4.66E-05	1.66E-05	3.41E-05	30.00	30.00
Tetrachoromethane	1.31E-04	3.19E-04	9.51E-05	2.23E-04	13.00	13.00
Tetrachloroethene	2.32E-03	4.88E-03	1.79E-03	3.60E-03	34.00	34.00
Chlorodifluoromethane	7.02E-03	3.04E-02	4.82E-03	1.82E-02	350.00	350.00
Dichlorofluoromethane	0.00E+00	0.00E+00	0.00E+00	0.00E+00	21.00	21.00
1-chloro-1,2,2-trifluoroethane	2.14E-04	5.54E-04	1.52E-04	3.78E-04	480.00	480.00
Dichlorodifluoromethane	6.71E-04	1.78E-03	4.75E-04	1.20E-03	490.00	490.00
1,2-dichloro-1,2-difluoroethene	6.53E-05	1.68E-04	4.63E-05	1.15E-04	140.00	140.00
Trichlorofluoromethane	2.12E-02	5.50E-02	1.54E-02	3.76E-02	560.00	560.00
Bromotrifluoromethane	2.40E-02	1.09E-01	1.64E-02	6.37E-02	11,000.00	11,000.00
Dichlorotetrafluoroethane	4.52E-04	1.12E-03	3.26E-04	7.78E-04	700.00	700.00
Trichlorotrifluoroethane	5.23E-02	1.22E-01	4.01E-02	8.61E-02	400.00	400.00
Tetrachlorodifluoroethane	1.57E-04	3.56E-04	1.17E-04	2.55E-04	830.00	830.00
Methane	8.03E-01	2.77E+00	6.19E-01	1.83E+00	3,800.00	3,800.00
Ethene	0.00E+00	0.00E+00	0.00E+00	0.00E+00	340.00	340.00
Ethane	4.84E-04	2.33E-03	3.32E-04	1.40E-03	1,200.00	1,200.00
Propene	1.65E-04	4.79E-04	1.16E-04	3.15E-04	860.00	860.00
Propane	1.21E-04	3.26E-04	8.45E-05	2.19E-04	900.00	900.00
1,3-butadiene	1.55E-04	4.02E-04	1.10E-04	2.74E-04	0.70	0.13
1-butene	1.82E-03	4.65E-03	1.31E-03	3.19E-03	460.00	460.00
2-methylpropane	2.69E-04	6.82E-04	1.92E-04	4.69E-04	240.00	240.00

Table 12. Trace contaminant concentrations for Node 1 for the 1,361-kg hardware basis (Continued).

Compound Name	Concentration (mg/m^3)				SMAC (mg/m^3)	
	2A	2A.1	3A	4A	7-Day	180-Day
Butane	1.38E-04	3.51E-04	9.90E-05	2.41E-04	240.00	240.00
1-pentene	0.00E+00	0.00E+00	0.00E+00	0.00E+00	190.00	190.00
2-methylbutane	2.63E-05	6.52E-05	1.89E-05	4.51E-05	300.00	300.00
Pentane	7.11E-04	1.67E-03	5.25E-04	1.18E-03	590.00	590.00
Cyclohexane	1.64E-03	3.63E-03	1.24E-03	2.63E-03	210.00	210.00
Methylcyclopentane	1.97E-04	4.57E-04	1.46E-04	3.25E-04	52.00	52.00
2,2-dimethylbutane	1.39E-05	3.34E-05	1.01E-05	2.34E-05	88.00	88.00
3-methylpentane	3.06E-05	7.19E-05	2.26E-05	5.08E-05	1,800.00	1,800.00
Hexane	2.47E-04	5.51E-04	1.87E-04	3.97E-04	180.00	180.00
1-heptene	0.00E+00	0.00E+00	0.00E+00	0.00E+00	200.00	200.00
Methylcyclohexane	1.67E-04	3.61E-04	1.28E-04	2.63E-04	60.00	60.00
Heptane	1.03E-04	2.15E-04	8.00E-05	1.58E-04	200.00	200.00
1,1-dimethylcyclohexane	8.69E-05	1.79E-04	6.83E-05	1.33E-04	120.00	120.00
Trans-1,2-dimethylcyclohexane	8.15E-05	1.67E-04	6.43E-05	1.24E-04	120.00	120.00
Octane	1.91E-05	3.83E-05	1.53E-05	2.86E-05	350.00	350.00
Nonane	5.89E-06	1.12E-05	4.85E-06	8.49E-06	320.00	320.00
Isopropenylmethylcyclohexene	3.34E-06	6.51E-06	2.71E-06	4.90E-06	557.00	557.00
Decane	1.29E-05	2.05E-05	1.14E-05	1.67E-05	230.00	230.00
Undecane	8.53E-06	1.22E-05	7.80E-06	1.04E-05	320.00	320.00
Dodecane	0.00E+00	0.00E+00	0.00E+00	0.00E+00	280.00	280.00
2-propanone	4.79E-02	1.36E-01	3.49E-02	9.03E-02	50.00	50.00
2-butanone	2.62E-02	6.01E-02	2.00E-02	4.30E-02	30.00	30.00
2-pentanone	2.95E-05	6.95E-05	2.17E-05	4.91E-05	70.00	70.00
3-methyl-2-butanone	1.91E-04	4.35E-04	1.42E-04	3.11E-04	70.00	70.00
4-methyl-3-penten-2-one	4.45E-04	9.20E-04	3.47E-04	6.83E-04	40.00	40.00
Cyclohexanone	7.69E-04	1.37E-03	6.37E-04	1.08E-03	60.00	60.00
4-methyl-2-pentanone	1.82E-03	3.47E-03	1.47E-03	2.65E-03	140.00	140.00
Acetophenone	0.00E+00	0.00E+00	0.00E+00	0.00E+00	250.00	250.00
2-octanone	0.00E+00	0.00E+00	0.00E+00	0.00E+00	100.00	100.00
2,6-dimethyl-4-heptanone	2.56E-06	4.68E-06	2.14E-06	3.61E-06	58.00	58.00
Hydrogen sulfide	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.80	2.80
Carbonyl sulfide	3.34E-03	1.54E-02	2.37E-03	9.84E-03	12.00	12.00
Dimethyl sulfide	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.50	2.50
Carbon disulfide	1.60E-03	4.28E-03	1.14E-03	2.90E-03	16.00	16.00
Ethanoic acid	1.16E-04	2.98E-04	8.27E-05	2.04E-04	7.40	7.40
Methyl cyanide	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.70	6.70
2,3-benzopyrrole	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.25	0.25
Hydrogen	8.15E-04	2.42E-03	5.50E-04	1.56E-03	340.00	340.00
Ammonia	1.49E-05	1.64E-05	1.46E-05	1.56E-05	7.00	7.00
Carbon monoxide	3.13E-01	9.27E-01	2.11E-01	5.97E-01	10.00	10.00
Trimethylsilanol	7.20E-04	1.59E-03	5.45E-04	1.15E-03	40.00	40.00

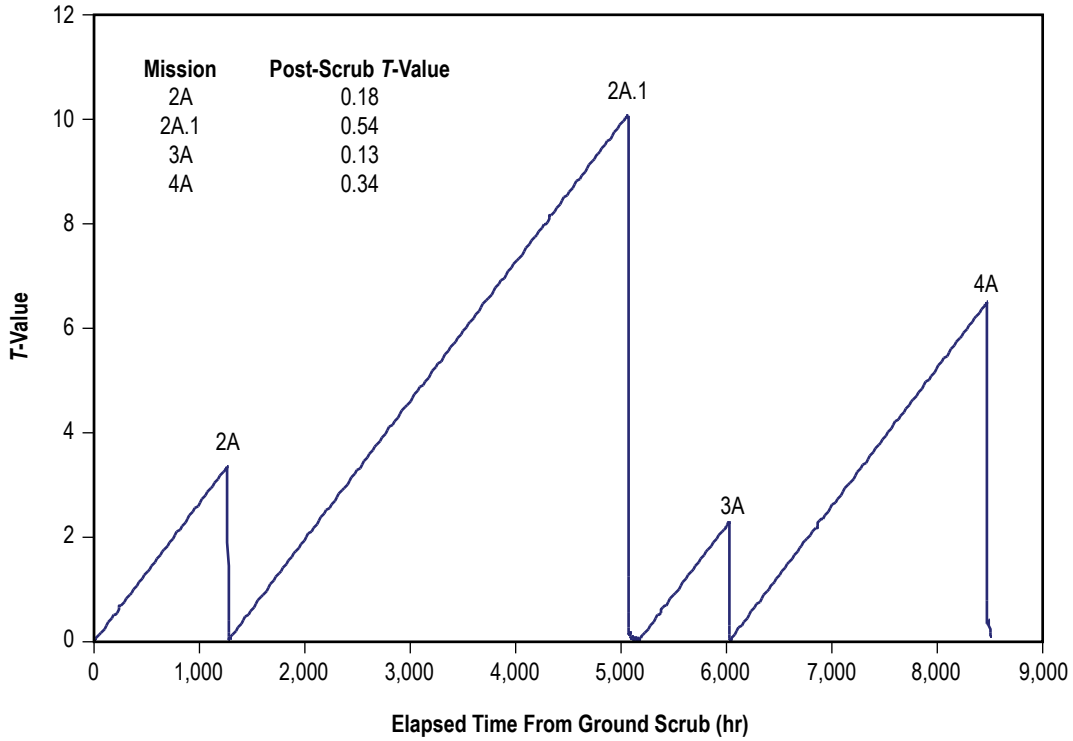


Figure 16. Relative contamination of Node 1 for a 2,359-kg hardware basis.

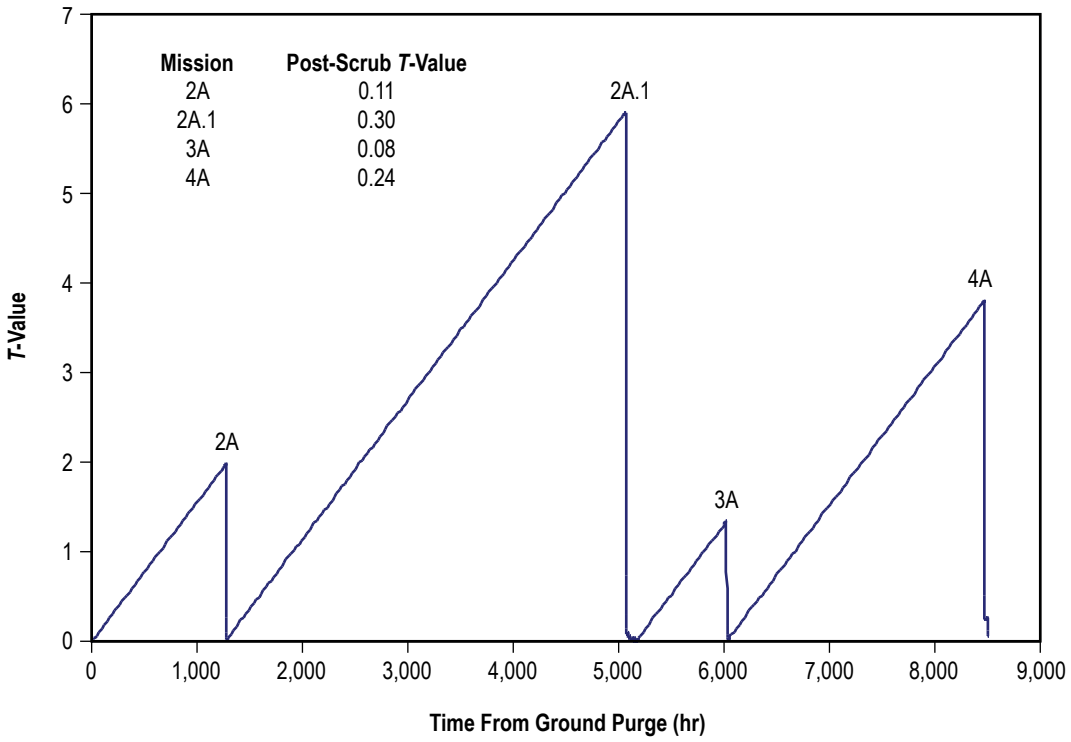


Figure 17. Relative contamination of Node 1 for a 1,361-kg hardware basis.

4.8 Conclusion

Based upon the analysis results, it is concluded that the Node 1 contamination removal capability provided by the CACEAs exceeds that required by the Node 1 PIDS.

5. SYNOPSIS

The technical challenges associated with trace contaminant control engineering during the ISS's early assembly stages have been presented and discussed. Contaminant buildup during quiescent periods between habitable module launch and on-orbit activation as well as the periods between crew visits before permanent habitation was identified as the major challenge.

Early assessment presented in section 2 identified the challenge and developed the cabin material balance equations and techniques. The material balance equations and analysis approach became the primary method for assessing dynamic contamination control during the ISS's assembly and operation. This initial effort also found that two adjacent habitable volumes approach a well-mixed condition within 2 hours after ventilation is initiated between them. At prevailing intermodule ventilation flow rates, this time period for approaching a well-mixed condition has been repeatable. The early assessment recommended that each habitable element be subjected to an offgassing test to obtain data that allows for the actual trace contaminant load to be determined and compared to the load used for design. Determining the actual trace contaminant load verifies the effectiveness of passive trace contaminant control methods as well as aids in quantifying the active contamination control operational margins.

The assessment presented in section 3 evaluated a more detailed assembly mission timeline and the effectiveness of three active trace contaminant control options. The final active contamination control approach was evaluated in detail. This approach included scrubbing the Node 1 cabin for 2 hours before first entry and supplementing the Node 1 active contamination control resources with Shuttle-provided resources. This assessment also recommended that in-flight cabin atmospheric grab samples be collected as an aid to verify the approach. The practice of collecting in-flight cabin atmospheric grab samples during habitable module first entry ultimately becomes the accepted practice throughout the ISS's assembly and operations.

Active trace contaminant control performance validation analysis presented in section 4 found that the capability provided in Node 1 exceeded specified requirements. Not only were the engineering requirements exceeded but also the cabin atmospheric quality guidelines established by NASA toxicology personnel were met. The cabin atmospheric quality guidelines presented in sections 3 and 4 became the basis for flight rules governing ISS habitable module first entry operations.

The engineering analysis techniques and tools developed throughout this period of ISS development became the standard by which each new habitable module was assessed in support of its activation on orbit. These techniques and tools are directly applicable to future crewed space exploration missions and programs.

APPENDIX A—NASA AND RUSSIAN MAXIMUM ALLOWABLE CONCENTRATIONS

Spacecraft Maximum Allowable Concentrations

Chemical Compound	NASA Spacecraft Maximum Allowable Concentration (mg/m^3)					
	Current 7-Day	1-Hr	24-Hr	7-Day	30-Day	180-Day
Methanol	52.4	40.0	13.0	9.0	9.0	9.0
Ethanol	94.0	4,000.0	4,000.0	2,000.0	2,000.0	2,000.0
2-propanol	98.3	1,000.0	240.0	150.0	150.0	150.0
n-butanol	121.0	150.0	80.0	80.0	80.0	40.0
2-methyl-2-propanol	121.0	150.0	150.0	150.0	150.0	100.0
1,2-ethanediol	127.0	35.0	10.0	1.6	0.3	0.2
1,5-pentanedial	0.1	0.49	0.08	0.024	0.012	0.002
2-propenal	0.11	0.2	0.08	0.03	0.03	0.03
Methanal	0.12	0.5	0.12	0.05	0.05	0.05
Ethanal	54.0	20.0	10.0	4.0	4.0	4.0
Benzene	0.32	35.0	10.0	1.6	0.3	0.2
Ethylbenzene	86.8	780.0	260.0	130.0	130.0	50.0
Methylbenzene	75.3	60.0	60.0	60.0	60.0	60.0
Dimethylbenzene (o-, m-, p-)	86.8	430	430	220	220	220
Ethyl acetate	180.0	1,440.0	1,440.0	–	–	–
2-butoxyethanol	24.2	20.0	4.0	0.7	0.7	0.7
2-ethoxyethanol	73.7	40.0	40.0	3.0	2.0	0.3
1,2-dichloroethane	98.97	2.0	2.0	2.0	2.0	1.0
Chloroethene	0.26	330.0	75.0	3.0	3.0	3.0
Dichloroethyne	0.1	2.4	0.16	0.12	0.1	0.06
Dichloromethane	86.8	350.0	120.0	50.0	20.0	10.0
Trichloroethene	0.54	270.0	60.0	50.0	20.0	10.0
Trichloromethane	4.9	–	–	–	–	–
1,1,2-trichloro-1,2,2-trifluoroethane	383.0	400.0	400.0	400.0	400.0	400.0
Bromotrifluoromethane	608.8	21,350.0	21,350.0	11,000.0	11,000.0	11,000.0
1,3-butadiene	221.2	4.0	4.0	0.7	0.3	0.13
n-hexane	176.0	–	–	–	7.0	7.0
Methane	1,771.0	3,800.0	3,800.0	3,800.0	3,800.0	3,800.0
2-butanone	59.0	150.0	150.0	30.0	30.0	30.0
4-methyl-2-pentanone	23.5	140.0	140.0	140.0	140.0	140.0
Propanone	712.5	210.0	84.0	52.0	52.0	52.0
Ethanoic acid	7.4	–	–	–	–	–
Nitromethane	0.1	65.0	40.0	18.0	18.0	13.0
Methyl hydrazine	0.08	0.004	0.004	0.004	0.004	0.004
Hydrazine	0.05	5.0	0.4	0.05	0.03	0.005
2,3-benzopyrrole	0.48	5.0	1.5	0.25	0.25	0.25
Ammonia	17.4	20.0	14.0	7.0	7.0	7.0
Hydrogen	247.3	340.0	340.0	340.0	340.0	340.0
Carbon monoxide	28.6	60.0	20.0	10.0	10.0	10.0
Carbon dioxide	7,102.5	27,000.0	27,000.0	18,000.0	18,000.0	18,000.0
Octamethyltrisiloxane	114.0	4,000.0	2,000.0	1,000.0	200.0	40.0
Trimethylsilanol	1.8	600.0	70.0	40.0	40.0	40.0
Hydrogen chloride	1.5	7.0	3.0	1.5	1.5	1.5
Hydrogen cyanide	1.1	0.7	0.7	0.7	0.1	0.1
Hydrogen fluoride	0.082	2.0	1.0	0.1	0.08	0.04
Mercury	0.006	0.1	0.02	0.01	0.01	0.01

SMACs set by the NASA Chief Scientist for Toxicology as of November 1994.
All other compounds must reference JSC 20584 or MAPTIS.

Limiting Permissible Concentration

Common Name	IUPAC Name	Molecular Weight (g/mol)	Design Standard (mg/m^3)
Alcohols			
Methyl alcohol	Methanol	32.04	0.20
Ethyl alcohol	Ethanol	46.07	10.00
Propyl alcohol	N-propanol	60.09	0.60
Isopropyl alcohol	2-propanol	60.09	1.50
Ethylene glycol	1,2-ethanediol	62.07	10.00
Butyl alcohol	N-butanol	74.12	0.80
Isobutyl alcohol	2-methyl-1-propanol	74.12	0.10
Phenol	Phenol	94.11	0.10
Hexahydrophenol	Cyclohexanol	100.16	0.20
Methylpentanol	2-hexanol	102.18	0.25
Heptyl alcohol	Heptanol	116.20	1.30
Octyl alcohol	Octanol	130.22	1.30
Bisphenol A	2,2-bis(4-hydroxyphenol)	228.29	0.80
Aldehydes			
Formaldehyde	Methanal	30.03	0.05
Acetaldehyde	Ethanal	44.05	1.00
Furaldehyde	Furfural	96.09	0.20
Aromatic Hydrocarbons			
Benzene	Benzene	78.11	0.20
Toluene	Methylbenzene	92.15	8.00
Styrene	Ethenylbenzene	104.14	0.25
Alpha-methylstyrene	2-phenylpropene	118.18	0.25
Cumene	Isopropylbenzene	120.20	0.50
Propylbenzene	Diethylbenzene	134.22	0.50
Esters			
Vinyl acetate	Ethenyl acetate	86.09	0.70
Ethyl acetate	Ethyl acetate	88.11	4.00
Methyl methacrylate	Methyl methacrylate	100.12	0.30
Isopropyl acetate	Isopropyl acetate	102.13	4.00
Butyl acetate	Butyl acetate	116.16	2.00
Methyl phenyl formate	4-methylphenyl formate	120.15	0.80
Butyl acrylate	2-propenoic acid, butyl ester	128.17	1.00
Butyl phthalate	Dibutyl benzene-1,2-dicarboxylate	278.35	0.15
Ethers			
Oxirane (ethylene oxide)	Epoxyethane	44.05	0.15
Furan	1,4-epoxy-1,3-butadiene	68.07	0.11
Tetrahydrofuran	1,4-epoxybutane	72.11	3.00
Ether	Diethyl ether	74.12	10.00
P-dioxane	1,4-dioxane	88.11	0.50
Halocarbons			
Methyl chloride	Chloromethane	50.49	0.50
Freon 22	Chlorodifluoromethane	86.47	100.00
Chloroprene	2-chloro-1,3-butadiene	88.54	0.03
Chloropropylene oxide	Epichlorohydrin	92.52	0.10
Chlorobenzene	Chlorobenzene	112.56	1.50
Freon 12	Dichlorodifluoromethane	120.91	150.00
Tri	Trichloroethylene	131.39	1.50
Carbon tetrachloride	Tetrachloromethane	153.82	4.00
Freon 218	Octafluoropropane	188.02	150.00
Freon 114 B-2	1,2-dibromo-1,1,2,2-tetrafluoroethane	259.85	100.00

Common Name	IUPAC Name	Molecular Weight (g/mol)	Design Standard (mg/m^3)
Hyrocarbons			
Methane	Methane	16.04	3,342.00
Ethylene	Ethene	28.05	20.00
Ethane	Ethane	30.07	1,230.00
Propylene	Propene	42.08	860.30
Propane	Propane	44.09	901.40
Vinylethylene	1,3-butadiene	54.09	2.00
Ethylethylene	1-butene	56.10	15.00
Butane	Butane	58.12	10.00
Isoprene	2-methyl-1,3-butadiene	68.11	3.00
Pentane	Pentane	72.15	10.00
Hexamethylene	Cyclohexane	84.16	3.00
n-hexane	Hexane	86.18	5.00
Heptane	Heptane	100.21	10.00
Isooctane	2,2,4-trimethylpentane	114.00	8.00
n-octane	Octane	114.23	10.00
Ketones			
Acetone	2-propanone	58.08	2.00
Methyl ethyl ketone	2-butanone	72.11	0.25
Maleic anhydride	2,5-furandione	98.06	0.10
Cyclohexanone (pimelic ketone)	Cyclohexanone	98.14	1.30
Mercaptans and Sulfides			
Hydrogen sulfide	Hydrogen sulfide	34.08	0.50
Methyl sulfide	Dimethyl sulfide	62.14	4.00
Sulfur dioxide	Sulfur dioxide	64.06	2.00
Carbon disulfide	Carbon disulfide	76.14	1.00
Organic Acids			
Acetic acid	Ethanoic acid	60.05	7.40
Butyric acid	Butanoic acid	88.10	4.00
Propionic acid	Propanoic acid	–	5.60
Valeric acid	Pentanoic acid	102.10	2.90
Phthalic anhydride	Phthalic anhydride	148.11	0.20
Dimethylbenzeneacetic acid	2-methyl-2-phenylpropanoic acid	164.20	0.20
Capric acid	Decanoic acid	172.26	2.90
Organic Nitrogens			
Amylase	Amylase	–	4.00
Ethoxyethylenediamine	ethoxy-1,2-diaminoethane	–	0.50
Petroleum ligroin	Benzine	–	5.00
Polyethyleneimine	Polyethyleneimine	–	0.25
Acetonitrile	Methyl cyanide	41.05	6.70
Aziridine	Ethyleneimine	43.07	0.01
Dimethylamine	Dimethylamine	45.09	1.00
Acrylonitrile	Propenenitrile	53.06	0.07
Dimethylformamide	–	73.10	1.00
Aniline	Aminobenzene	93.10	0.06
Triethylamine	Triethylamine	101.19	1.00
Caprolactam	–	113.16	0.30
Hexamethylenediamine	1,6-diaminohexane	116.21	0.10
Dimethylanaline	Dimethylaminobenzene	121.18	0.02
Dimethylbenzylamine	–	135.21	0.80
Toluene diisocyanate	Toluene diisocyanate	174.15	0.03
Tetranitromethane	Tetranitromethane	196.04	0.05

Common Name	IUPAC Name	Molecular Weight (g/mol)	Design Standard (mg/m^3)
Miscellaneous			
Polyorganosilicon	Polyorganooxosilane	–	0.20
Hydrogen	Hydrogen	2.02	340.00
Ammonia	Ammonia	17.03	1.00
Hydrogen fluoride	Hydrogen fluoride	20.01	0.01
Hydrogen cyanide	Hydrogen cyanide	27.03	0.005
Carbon monoxide	Carbon monoxide	28.01	5.00
Nitric oxide	Nitric oxide	30.01	0.40
Hydrogen peroxide	Hydrogen peroxide	34.01	1.00
Hydrogen chloride	Hydrogen chloride	36.46	0.05
Ozone	Ozone	48.00	0.03
Chlorine	Chlorine	70.91	0.20
Arsine	Arsenic anhydride	77.94	0.005
Sulfuric acid	Sulfuric acid	98.08	2.00
Siloxane	Oxosilane	104.17	5.00
Phosphorous pentoxide	Phosphorous pentoxide	141.94	0.10

APPENDIX B—TRACE CHEMICAL CONTAMINANT DESIGN LOAD MODEL

Common Name	IUPAC Name	Molecular Weight (g/mol)	SMAC (mg/m^3)	Equipment Rate (mg/day*kg)	Metabolic Rate (mg/man*day)	Total Rate (%)	Equipment Rate (%)	Required Flow	
								m^3/hr	ft^3/min
Alcohols									
Methyl alcohol	Methanol	32.04	9.00	1.27E-03	1.50E+00	0.01	0.02	0.53	0.31
Ethyl alcohol	Ethanol	46.07	2000.00	7.85E-03	4.00E+00	0.07	0.11	0.01	0.01
Allyl alcohol	2-propen-1-ol	58.08	1.00	2.35E-06	0.00E+00	–	–	0.01	–
Isopropyl alcohol	2-propanol	60.09	150.00	3.99E-03	0.00E+00	0.04	0.05	0.09	0.05
Propyl alcohol	n-propanol	60.09	98.30	2.41E-04	0.00E+00	–	–	0.01	0.01
Ethylene glycol	1,2-ethanediol	62.07	0.20	6.03E-06	0.00E+00	–	–	0.10	0.06
2-butanol	2-butanol	74.12	121.00	9.63E-06	0.00E+00	–	–	–	–
Isobutyl alcohol	2-methyl-1-propanol	74.12	121.00	8.46E-04	1.20E+00	0.01	0.01	0.03	0.02
Tert-butyl alcohol	2-methyl-2-propanol	74.12	100.00	7.38E-05	0.00E+00	–	–	–	–
Butyl alcohol	n-butanol	74.12	40.00	4.71E-03	1.33E+00	0.04	0.06	0.42	0.25
n-amyl alcohol	n-pentanol	88.15	126.00	1.62E-04	0.00E+00	–	–	–	–
Phenol	Phenol	94.11	7.70	4.83E-04	0.00E+00	–	0.01	0.22	0.13
Hexahydrophenol	Cyclohexanol	100.16	123.00	7.56E-04	0.00E+00	0.01	0.01	0.02	0.01
2-hexanol	2-hexanol	102.18	167.00	2.48E-06	0.00E+00	–	–	–	–
Aldehydes									
Formaldehyde	Methanal	30.03	0.05	4.40E-08	0.00E+00	–	–	–	–
Acetaldehyde	Ethanal	44.05	4.00	1.09E-04	9.00E-02	–	–	0.10	0.06
Acrolein	2-propenal	56.06	0.03	3.46E-06	0.00E+00	–	–	0.40	0.24
Propionaldehyde	Propanal	58.08	95.00	3.19E-04	0.00E+00	–	–	0.01	0.01
n-butylaldehyde	Butanal	72.10	118.00	8.59E-04	0.00E+00	0.01	0.01	0.03	0.01
Valeraldehyde	Pentanal	86.13	106.00	7.84E-05	8.30E-01	–	–	–	–
Benzenecarbonal	Benzaldehyde	106.12	173.00	1.99E-05	0.00E+00	–	–	–	–
Aromatic Hydrocarbons									
Benzene	Benzene	78.11	0.32	2.51E-05	0.00E+00	–	–	0.27	0.16
Toluene	Methylbenzene	92.15	60.00	1.98E-03	0.00E+00	0.02	0.03	0.11	0.07
Styrene	Vinylbenzene	104.14	42.60	3.13E-05	0.00E+00	–	–	–	–
O-xylene	1,2-dimethylbenzene	106.16	220.00	5.56E-04	0.00E+00	–	0.01	0.01	0.01
M-xylene	1,3-dimethylbenzene	106.16	220.00	2.03E-03	0.00E+00	0.02	0.03	0.03	0.02
P-xylene	1,4-dimethylbenzene	106.16	220.00	1.08E-03	0.00E+00	0.01	0.01	0.02	0.01
Ethylbenzene	Ethylbenzene	106.16	86.80	1.50E-04	0.00E+00	–	–	0.01	–
Alpha-methylstyrene	alpha-methylstyrene	118.18	145.00	1.67E-07	0.00E+00	–	–	–	–

Common Name	IUPAC Name	Molecular Weight (g/mol)	SMAC (mg/m^3)	Equipment Rate (mg/day*kg)	Metabolic Rate (mg/man*day)	Total Rate (%)	Equipment Rate (%)	Required Flow	
								m^3/hr	ft^3/min
Pseudocumene	1,2,4-trimethylbenzene	120.20	15.00	4.49E-05	0.00E+00	–	–	0.01	0.01
Mesitylene	1,3,5-trimethylbenzene	120.20	15.00	3.63E-06	0.00E+00	–	–	–	–
1-ethyl-2-methylbenzene	1-ethyl-2-methylbenzene	120.20	25.00	4.88E-06	0.00E+00	–	–	–	–
Cumene	Isopropylbenzene	120.20	73.70	1.40E-05	0.00E+00	–	–	–	–
Propylbenzene	Propylbenzene	120.20	49.10	2.15E-04	0.00E+00	–	–	0.02	0.01
Esters									
Ethyl formate	Ethyl formate	74.08	90.90	4.51E-06	0.00E+00	–	–	–	–
Methyl acetate	Methyl acetate	74.08	121.00	1.41E-04	0.00E+00	–	–	–	–
Ethyl acetate	Ethyl acetate	88.11	180.00	2.97E-04	0.00E+00	–	–	0.01	–
Methyl methacrylate	Methyl methacrylate	100.12	102.00	1.30E-04	0.00E+00	–	–	–	–
Isopropyl acetate	Isopropyl acetate	102.13	209.00	5.81E-06	0.00E+00	–	–	–	–
Propyl acetate	Propyl acetate	102.13	167.00	3.38E-04	0.00E+00	–	–	0.01	–
Butyl acetate	Butyl acetate	116.16	190.00	7.46E-04	0.00E+00	0.01	0.01	0.01	0.01
Isobutyl acetate	Isobutyl acetate	116.16	190.00	1.52E-04	0.00E+00	–	–	–	–
Ethyl lactate	Ethyl lactate	118.13	193.00	3.64E-06	0.00E+00	–	–	–	–
n-amyl acetate	n-amyl acetate	130.18	160.00	4.78E-05	0.00E+00	–	–	–	–
Cellosolve acetate	2-ethoxyethyl acetate	132.16	162.00	7.46E-04	0.00E+00	0.01	0.01	0.02	0.01
Ethers									
Furan	1,4-epoxy-1,3-butadiene	68.07	0.11	1.84E-06	0.00E+00	–	–	0.06	0.03
Tetrahydrofuran	1,4-epoxybutane	72.11	118.00	6.93E-05	0.00E+00	–	–	–	–
Ether	Diethyl ether	74.12	242.00	8.90E-05	0.00E+00	–	–	–	–
Sylvan	2-methylfuran	82.10	0.13	3.46E-06	0.00E+00	–	–	0.09	0.05
Ethyl cellosolve	2-ethoxyethanol	90.12	0.30	6.01E-04	0.00E+00	0.01	0.01	6.96	4.10
Chlorocarbons									
Methyl chloride	Chloromethane	50.49	41.30	6.76E-06	0.00E+00	–	–	–	–
Vinyl chloride	Chloroethene	62.50	3.00	1.46E-06	0.00E+00	–	–	–	–
Ethyl chloride	Chloroethane	64.52	263.70	8.99E-08	0.00E+00	–	–	–	–
Methylene chloride	Dichloromethane	84.93	10.00	2.15E-03	0.00E+00	0.02	0.03	0.75	0.44
Dichloroethene	1,1-dichloroethene	96.95	7.90	5.64E-07	0.00E+00	–	–	–	–
Ethylene dichloride	1,2-dichloroethane	98.97	1.00	7.74E-05	0.00E+00	–	–	0.27	0.16
Chlorobenzene	Chlorobenzene	112.56	46.00	1.54E-03	0.00E+00	0.01	0.02	0.12	0.07
Propylene chloride	1,2-dichloropropane	112.99	42.20	7.42E-06	0.00E+00	–	–	–	–

Common Name	IUPAC Name	Molecular Weight (g/mol)	SMAC (mg/m^3)	Equipment Rate (mg/day*kg)	Metabolic Rate (mg/man*day)	Total Rate (%)	Equipment Rate (%)	Required Flow	
								m^3/hr	ft^3/min
Chloroform	Trichloromethane	119.38	4.90	1.76E-05	0.00E+00	–	–	0.01	0.01
Tri	Trichloroethylene	131.39	10.00	8.62E-05	0.00E+00	–	–	0.03	0.02
Methyl chloroform	1,1,1-trichloroethane	133.41	164.00	6.72E-04	0.00E+00	0.01	0.01	0.01	0.01
Vinyl trichloride	1,1,2-trichloroethane	133.41	5.50	8.24E-08	0.00E+00	–	–	–	–
Dichorobenzene	1,2-dichlorobenzene	147.01	30.00	6.33E-06	0.00E+00	–	–	–	–
Carbon tetrachloride	Tetrachloromethane	153.82	13.00	9.60E-06	0.00E+00	–	–	–	–
Tetrachloroethylene	Tetrachloroethene	165.83	34.00	7.28E-04	0.00E+00	0.01	0.01	0.07	0.04
Chlorofluorocarbons									
Freon 22	Chlorodifluoromethane	86.47	353.60	5.75E-05	0.00E+00	–	–	–	–
Freon 21	Dichlorofluoromethane	102.90	21.00	6.36E-07	0.00E+00	–	–	–	–
Chlorotrifluoroethane	1-chloro-1,2,2-trifluoroethane	118.50	484.50	4.88E-06	0.00E+00	–	–	–	–
Freon 12	Dichlorodifluoromethane	120.91	494.40	1.35E-05	0.00E+00	–	–	–	–
Dichorodifluoroethene	1,2-dichloro-1,2-difluoroethene	132.93	136.00	1.89E-06	0.00E+00	–	–	–	–
Freon 11	Trichlorofluoromethane	137.40	561.80	1.41E-03	0.00E+00	0.01	0.02	0.01	0.01
Halon 1301	Bromotrifluoromethane	148.90	11000.00	2.61E-04	0.00E+00	–	–	–	–
Freon 114	1,1-dichloro-1,2,2,2-tetrafluoroethane	170.92	702.90	2.62E-05	0.00E+00	–	–	–	–
Freon 113	1,1,2-trichloro-1,2,2-trifluoroethane	187.40	400.00	1.89E-02	0.00E+00	0.17	0.26	0.16	0.10
Freon 112	1,1,2,2-tetrachloro-1,2-difluoroethane	204.00	834.20	3.33E-05	0.00E+00	–	–	–	–
Hyrocarbons									
Methane	Methane	16.04	3800.00	6.39E-04	1.60E+02	0.11	0.01	0.01	0.01
Ethylene	Ethene	28.05	344.10	2.27E-07	0.00E+00	–	–	–	–
Ethane	Ethane	30.07	1230.00	1.17E-06	0.00E+00	–	–	–	–
Propylene	Propene	42.08	860.30	2.56E-06	0.00E+00	–	–	–	–
Propane	Propane	44.09	901.40	9.21E-07	0.00E+00	–	–	–	–
Vinylethylene	1,3-butadiene	54.09	0.13	2.66E-06	0.00E+00	–	–	0.07	0.04
Ethylethylene	1-butene	56.10	458.00	8.03E-05	0.00E+00	–	–	–	–
Isobutane	2-methylpropane	58.12	237.60	1.10E-05	0.00E+00	–	–	–	–
Butane	Butane	58.12	237.60	5.13E-06	0.00E+00	–	–	–	–
Propylethylene	1-pentene	70.13	186.00	2.20E-08	0.00E+00	–	–	–	–
Isopentane	2-methylbutane	72.15	295.00	1.80E-06	0.00E+00	–	–	–	–
Pentane	Pentane	72.15	590.00	9.54E-05	0.00E+00	–	–	–	–
Hexamethylene	Cyclohexane	84.16	206.00	3.79E-04	0.00E+00	–	0.01	0.01	–

Common Name	IUPAC Name	Molecular Weight (g/mol)	SMAC (mg/m^3)	Equipment Rate (mg/day*kg)	Metabolic Rate (mg/man*day)	Total Rate (%)	Equipment Rate (%)	Required Flow	
								m^3/hr	ft^3/min
Methylpentamethylene	Methylcyclopentane	84.16	51.60	2.97E-05	0.00E+00	–	–	–	–
Neohexane	2,2-dimethylbutane	86.17	88.10	1.67E-06	0.00E+00	–	–	–	–
Diethylmethylmethane	3-methylpentane	86.18	1762.00	5.97E-06	0.00E+00	–	–	–	–
Hexane	Hexane	86.18	7.00	6.95E-05	0.00E+00	–	–	0.03	0.02
1-heptylene	1-heptene	98.18	201.00	1.10E-08	0.00E+00	–	–	–	–
Hexahydrotoluene	Methylcyclohexane	98.18	60.20	6.09E-05	0.00E+00	–	–	–	–
Heptane	Heptane	100.21	205.00	5.59E-05	0.00E+00	–	–	–	–
Dimethylcyclohexane	1,1-dimethylcyclohexane	112.22	115.00	2.61E-05	0.00E+00	–	–	–	–
Trans-1,2-dimethylhexamethylene	trans-1,2-dimethylcyclohexane	112.22	115.00	5.23E-05	0.00E+00	–	–	–	–
Octane	Octane	114.23	350.00	1.61E-05	0.00E+00	–	–	–	–
Nonane	Nonane	128.26	315.00	7.35E-06	0.00E+00	–	–	–	–
Citrene (limonene)	4-isopropenyl-1-Mecyclohexene	136.23	557.00	3.58E-06	0.00E+00	–	–	–	–
Decane	Decane	142.28	223.00	2.78E-05	0.00E+00	–	–	–	–
Hendecane	Undecane	156.31	319.00	2.51E-05	0.00E+00	–	–	–	–
Dodecane	Dodecane	170.34	278.00	6.91E-07	0.00E+00	–	–	–	–
Ketones									
Acetone	2-propanone	58.08	52.00	3.62E-03	2.00E-01	0.03	0.05	0.24	0.14
Methyl ethyl ketone	2-butanone	72.11	30.00	6.01E-03	0.00E+00	0.05	0.08	0.70	0.41
Methyl propyl ketone	2-pentanone	86.13	70.40	4.03E-06	0.00E+00	–	–	–	–
Methyl isopropyl ketone	3-methyl-2-butanone	86.13	70.40	3.11E-05	0.00E+00	–	–	–	–
Mesityl oxide (methyl isobutenyl ketone)	4-methyl-3-penten-2-one	98.14	40.10	1.91E-04	0.00E+00	–	–	0.02	0.01
Cyclohexanone (pimelic ketone)	Cyclohexanone	98.14	60.20	6.62E-04	0.00E+00	0.01	0.01	0.04	0.02
Methyl isobutyl ketone	4-methyl-2-pentanone	100.16	140.00	1.41E-03	0.00E+00	0.01	0.02	0.03	0.02
Phenyl methyl ketone	acetophenone	120.14	245.00	5.66E-07	0.00E+00	–	–	–	–
Methyl hexyl ketone	2-octanone	128.21	105.00	1.65E-07	0.00E+00	–	–	–	–
Diisobutyl ketone	2,6-dimethyl-4-heptanone	142.20	58.10	3.34E-06	0.00E+00	–	–	–	–
Mercaptans and Sulfides									
Hydrogen sulfide	Hydrogen sulfide	34.08	2.80	0.00E+00	9.00E-02	–	–	0.01	–
Carbon oxisulfide	Carbonyl sulfide	60.07	12.00	6.05E-06	0.00E+00	–	–	–	–
Methyl sulfide	Dimethyl sulfide	62.14	2.50	1.88E-07	0.00E+00	–	–	–	–
Carbon disulfide	Carbon disulfide	76.14	16.00	3.23E-05	0.00E+00	–	–	0.01	–

Common Name	IUPAC Name	Molecular Weight (g/mol)	SMAC (mg/m^3)	Equipment Rate (mg/day*kg)	Metabolic Rate (mg/man*day)	Total Rate (%)	Equipment Rate (%)	Required Flow	
								m^3/hr	ft^3/min
Organic Acids									
Acetic acid	Ethanoic acid	60.05	7.40	1.42E-06	0.00E+00	–	–	–	–
Organic Nitrogens									
Acetonitrile	Methyl cyanide	41.05	6.70	1.70E-08	0.00E+00	–	–	–	–
Indole	2,3-benzopyrrole	117.15	0.25	0.00E+00	6.25E+00	–	–	6.08	3.58
Miscellaneous									
Hydrogen	Hydrogen	2.02	340.00	5.91E-06	2.60E+01	0.02	–	0.02	0.01
Ammonia	Ammonia	17.00	7.00	8.46E-05	3.21E+02	0.20	–	11.17	6.57
Carbon monoxide	Carbon monoxide	28.01	10.00	2.03E-03	2.30E+01	0.03	0.03	1.26	0.74
Trimethylsilanol	Trimethylsilanol	90.21	40.00	1.69E-04	0.00E+00	–	–	0.01	0.01
Hexamethylcyclotrioxosilane	Hexamethylcyclotrisiloxane	222.40	227.00	1.62E-04	0.00E+00	–	–	–	–
Octamethyltrioxosilane	Octamethyltrisiloxane	236.54	40.00	2.11E-04	0.00E+00	–	–	0.02	0.01

APPENDIX C—PREDICTED CONCENTRATIONS FOR NODE 1 UPON CREW ENTRY

Common Name	IUPAC Name	Molar Mass (g/mol)	SMAC (mg/m^3)	Equipment Gen Rate (mg/day*kg)	Time to Reach SMAC (days)	Node 1 at 250 Days (mg/m^3)	Node 1 at 455 Days (mg/m^3)	Node 1 at 730 Days (mg/m^3)
Alcohols								
Methyl alcohol	Methanol	32.04	9.00	1.27E-03	118.82	1.89E+01	3.45E+01	5.53E+01
Ethyl alcohol	Ethanol	46.07	2,000.00	7.85E-03	4282.12	1.17E+02	2.13E+02	3.41E+02
Allyl alcohol	2-propen-1-ol	58.08	1.00	2.35E-06	7160.45	3.49E-02	6.35E-02	1.02E-01
Isopropyl alcohol	2-propanol	60.09	150.00	3.99E-03	632.44	5.93E+01	1.08E+02	1.73E+02
Propyl alcohol	n-propanol	60.09	98.30	2.41E-04	6861.74	3.58E+00	6.52E+00	1.05E+01
Ethylene glycol	1,2-ethanediol	62.07	13.00	6.03E-06	36236.49	8.97E-02	1.63E-01	2.62E-01
2-butanol	2-butanol	74.12	121.00	9.63E-06	211230.19	1.43E-01	2.61E-01	4.18E-01
Isobutyl alcohol	2-methyl-1-propanol	74.12	121.00	8.46E-04	2403.08	1.26E+01	2.29E+01	3.68E+01
Tert-butyl alcohol	2-methyl-2-propanol	74.12	121.00	7.38E-05	27536.33	1.10E+00	2.00E+00	3.21E+00
Butyl alcohol	n-butanol	74.12	121.00	4.71E-03	431.81	7.01E+01	1.27E+02	2.05E+02
n-amyl alcohol	n-pentanol	88.15	126.00	1.62E-04	13076.58	2.41E+00	4.38E+00	7.03E+00
Phenol	Phenol	94.11	7.70	4.83E-04	267.97	7.18E+00	1.31E+01	2.10E+01
Hexahydrophenol	Cyclohexanol	100.16	123.00	7.56E-04	2735.00	1.12E+01	2.05E+01	3.28E+01
2-hexanol	2-hexanol	102.18	167.00	2.48E-06	1131299.61	3.69E-02	6.72E-02	1.08E-01
Aldehydes								
Formaldehyde	Methanal	30.03	0.05	4.40E-08	19080.23	6.55E-04	1.19E-03	1.91E-03
Acetaldehyde	Ethanal	44.05	4.00	1.09E-04	619.35	1.61E+00	2.94E+00	4.71E+00
Acrolein	2-propenal	56.06	0.03	3.46E-06	145.76	5.15E-02	9.36E-02	1.50E-01
Propionaldehyde	Propanal	58.08	95.00	3.19E-04	5000.95	4.75E+00	8.64E+00	1.39E+01
n-butylaldehyde	Butanal	72.10	118.00	8.59E-04	2307.92	1.28E+01	2.33E+01	3.73E+01
Valeraldehyde	Pentanal	86.13	106.00	7.84E-05	22719.76	1.17E+00	2.12E+00	3.41E+00
Benzenecarbonal	Benzaldehyde	106.12	173.00	1.99E-05	146080.47	2.96E-01	5.39E-01	8.65E-01
Aromatic Hydrocarbons								
Benzene	Benzene	78.11	0.20	2.51E-05	133.83	3.74E-01	6.80E-01	1.09E+00
Toluene	Methylbenzene	98.13	60.00	1.98E-03	508.57	2.95E+01	5.37E+01	8.61E+01
Styrene	Vinylbenzene	104.14	42.60	3.13E-05	22902.29	4.65E-01	8.46E-01	1.36E+00
O-xylene	1,2-dimethylbenzene	106.16	220.00	5.56E-04	6651.90	8.27E+00	1.50E+01	2.41E+01
M-xylene	1,3-dimethylbenzene	106.16	220.00	2.03E-03	1824.88	3.01E+01	5.49E+01	8.80E+01
P-xylene	1,4-dimethylbenzene	106.16	220.00	1.08E-03	3424.12	1.61E+01	2.92E+01	4.69E+01
Ethylbenzene	Ethylbenzene	106.16	86.80	1.50E-04	9737.63	2.23E+00	4.06E+00	6.51E+00
Alpha-methylstyrene	Alpha-methylstyrene	118.18	145.00	1.67E-07	14570063.00	2.49E-03	4.53E-03	7.26E-03

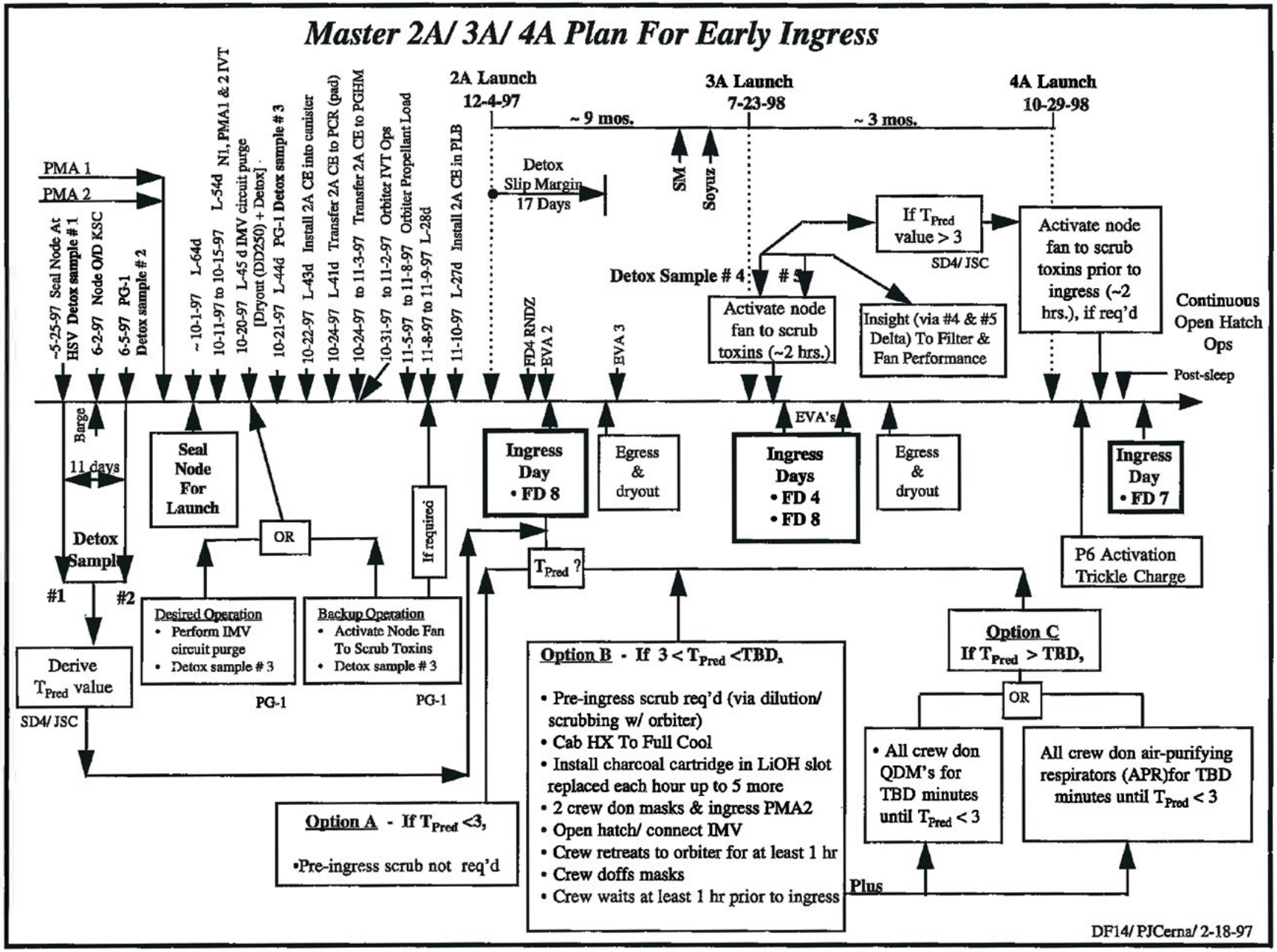
Common Name	IUPAC Name	Molar Mass (g/mol)	SMAC (mg/m^3)	Equipment Gen Rate (mg/day*kg)	Time to Reach SMAC (days)	Node 1 at 250 Days (mg/m^3)	Node 1 at 455 Days (mg/m^3)	Node 1 at 730 Days (mg/m^3)
Pseudocumene	1,2,4-trimethylbenzene	120.20	15.00	4.49E-05	5616.87	6.68E-01	1.22E+00	1.95E+00
Mesitylene	1,3,5-trimethylbenzene	120.20	15.00	3.63E-06	69412.77	5.40E-02	9.83E-02	1.58E-01
1-ethyl-2-methylbenzene	1-ethyl-2-methylbenzene	120.20	25.00	4.88E-06	86112.30	7.26E-02	1.32E-01	2.12E-01
Cumene	Isopropylbenzene	120.20	73.70	1.40E-05	88434.68	2.08E-01	3.79E-01	6.08E-01
Propylbenzene	Propylbenzene	120.20	49.10	2.15E-04	3829.16	3.21E+00	5.83E+00	9.36E+00
Esters								
Ethyl formate	Ethyl formate	74.08	90.90	4.51E-06	338784.88	6.71E-02	1.22E-01	1.96E-01
Methyl acetate	Methyl acetate	74.08	121.00	1.41E-04	14431.54	2.10E+00	3.81E+00	6.12E+00
Ethyl acetate	Ethyl acetate	88.11	180.00	2.97E-04	10200.22	4.41E+00	8.03E+00	1.29E+01
Methyl methacrylate	Methyl methacrylate	100.12	102.00	1.30E-04	13217.19	1.93E+00	3.51E+00	5.63E+00
Isopropyl acetate	Isopropyl acetate	102.13	209.00	5.81E-06	604133.51	8.65E-02	1.57E-01	2.53E-01
Propyl acetate	Propyl acetate	102.13	167.00	3.38E-04	8300.26	5.03E+00	9.15E+00	1.47E+01
Butyl acetate	Butyl acetate	116.16	190.00	7.46E-04	4279.85	1.11E+01	2.02E+01	3.24E+01
Isobutyl acetate	Isobutyl acetate	116.16	190.00	1.52E-04	21050.16	2.26E+00	4.11E+00	6.59E+00
Ethyl lactate	Ethyl lactate	118.13	193.00	3.64E-06	891289.50	5.41E-02	9.85E-02	1.58E-01
n-amyl acetate	n-amyl acetate	130.18	160.00	4.78E-05	56266.69	7.11E-01	1.29E+00	2.08E+00
Cellosolve acetate	2-ethoxyethyl acetate	132.16	162.00	7.46E-04	3648.84	1.11E+01	2.02E+01	3.24E+01
Ethers								
Furan	1,4-epoxy-1,3-butadiene	68.07	0.11	1.84E-06	1013.50	2.74E-02	4.98E-02	8.00E-02
Tetrahydrofuran	1,4-epoxybutane	72.11	118.00	6.93E-05	28608.31	1.03E+00	1.88E+00	3.01E+00
Ether	Diethyl ether	74.12	242.00	8.90E-05	45679.45	1.32E+00	2.41E+00	3.87E+00
Sylvan	2-methylfuran	82.10	0.13	3.46E-06	632.07	5.14E-02	9.36E-02	1.50E-01
Ethyl cellosolve	2-ethoxyethanol	90.12	0.30	6.01E-04	8.39	8.94E+00	1.63E+01	2.61E+01
Chlorocarbons								
Methyl chloride	Chloromethane	50.49	41.30	6.76E-06	102681.22	1.01E-01	1.83E-01	2.94E-01
Vinyl chloride	Chloroethene	62.50	3.00	1.46E-06	34642.10	2.16E-02	3.94E-02	6.32E-02
Ethyl chloride	Chloroethane	64.52	263.70	8.99E-08	49310702.89	1.34E-03	2.43E-03	3.90E-03
Methylene chloride	Dichloromethane	84.93	10.00	2.15E-03	78.33	3.19E+01	5.81E+01	9.32E+01
Dichloroethene	1,1-dichloroethene	96.95	7.90	5.64E-07	235224.55	8.40E-03	1.53E-02	2.45E-02
Ethylene dichloride	1,2-dichloroethane	98.97	1.00	7.74E-05	217.20	1.15E+00	2.09E+00	3.36E+00
Chlorobenzene	Chlorobenzene	112.56	46.00	1.54E-03	500.76	2.30E+01	4.18E+01	6.71E+01
Propylene chloride	1,2-dichloropropane	112.99	42.20	7.42E-06	95579.48	1.10E-01	2.01E-01	3.22E-01

Common Name	IUPAC Name	Molar Mass (g/mol)	SMAC (mg/m^3)	Equipment Gen Rate (mg/day*kg)	Time to Reach SMAC (days)	Node 1 at 250 Days (mg/m^3)	Node 1 at 455 Days (mg/m^3)	Node 1 at 730 Days (mg/m^3)
Chloroform	Trichloromethane	119.38	4.90	1.76E-05	4675.79	2.62E-01	4.77E-01	7.65E-01
Tri	Trichloroethylene	131.39	10.00	8.62E-05	1949.30	1.28E+00	2.33E+00	3.74E+00
Methyl chloroform	1,1,1-trichloroethane	133.41	164.00	6.72E-04	4102.03	1.00E+01	1.82E+01	2.92E+01
Vinyl trichloride	1,1,2-trichloroethane	133.41	5.50	8.24E-08	1121597.53	1.23E-03	2.23E-03	3.58E-03
Dichorobenzene	1,2-dichlorobenzene	147.01	30.00	6.33E-06	79695.95	9.41E-02	1.71E-01	2.75E-01
Carbon tetrachloride	Tetrachloromethane	153.82	13.00	9.60E-06	22762.19	1.43E-01	2.60E-01	4.17E-01
Tetrachloroethylene	Tetrachloroethene	165.83	34.00	7.28E-04	784.62	1.08E+01	1.97E+01	3.16E+01
Chlorofluorocarbons								
Freon 22	Chlorodifluoromethane	86.47	353.60	5.75E-05	103426.72	8.55E-01	1.56E+00	2.50E+00
Freon 21	Dichlorofluoromethane	102.90	21.00	6.36E-07	555147.38	9.46E-03	1.72E-02	2.76E-02
Chlorotrifluoroethane	1-chloro-1,2,2-trifluoroethane	118.50	484.50	4.88E-06	1669298.23	7.26E-02	1.32E-01	2.12E-01
Freon 12	Dichlorodifluoromethane	120.91	494.40	1.35E-05	617446.13	2.00E-01	3.64E-01	5.85E-01
Dichorodifluoroethene	1,2-dichloro-1,2-difluoroethene	132.93	136.00	1.89E-06	1210333.28	2.81E-02	5.11E-02	8.20E-02
Freon 11	Trichlorofluoromethane	137.40	561.80	1.41E-03	6704.76	2.09E+01	3.81E+01	6.12E+01
Halon 1301	Bromotrifluoromethane	148.90	11,000.00	2.61E-04	709175.90	3.88E+00	7.06E+00	1.13E+01
Freon 114	1,1-dichloro-1,2,2,2-tetrafluoroethane	170.92	702.90	2.62E-05	450945.73	3.90E-01	7.09E-01	1.14E+00
Freon 113	1,1,2-trichloro-1,2,2-trifluoroethane	187.40	400.00	1.89E-02	354.85	2.82E+02	5.13E+02	8.23E+02
Freon 112	1,1,2,2-tetrachloro-1,2-difluoroethane	204.00	834.20	3.33E-05	420968.69	4.95E-01	9.02E-01	1.45E+00
Hyrocarbons								
Methane	Methane	16.04	3,800.00	6.39E-04	99999.14	9.50E+00	1.73E+01	2.77E+01
Ethylene	Ethene	28.05	344.10	2.27E-07	25524245.16	3.37E-03	6.13E-03	9.84E-03
Ethane	Ethane	30.07	1,230.00	1.17E-06	17720686.71	1.74E-02	3.16E-02	5.07E-02
Propylene	Propene	42.08	860.30	2.56E-06	5650432.67	3.81E-02	6.93E-02	1.11E-01
Propane	Propane	44.09	901.40	9.21E-07	16453020.09	1.37E-02	2.49E-02	4.00E-02
Vinylethylene	1,3-butadiene	54.09	0.13	2.66E-06	820.94	3.96E-02	7.21E-02	1.16E-01
Ethylethylene	1-butene	56.10	458.00	8.03E-05	95909.51	1.19E+00	2.17E+00	3.49E+00
Isobutane	2-methylpropane	58.12	237.60	1.10E-05	362546.47	1.64E-01	2.98E-01	4.78E-01
Butane	Butane	58.12	237.60	5.13E-06	777802.97	7.64E-02	1.39E-01	2.23E-01
Propylethylene	1-pentene	70.13	186.00	2.20E-08	142190550.08	3.27E-04	5.95E-04	9.55E-04
Isopentane	2-methylbutane	72.15	295.00	1.80E-06	2753189.85	2.68E-02	4.88E-02	7.82E-02
Pentane	Pentane	72.15	590.00	9.54E-05	103985.29	1.42E+00	2.58E+00	4.14E+00
Hexamethylene	Cyclohexane	84.16	206.00	3.79E-04	9123.02	5.65E+00	1.03E+01	1.65E+01

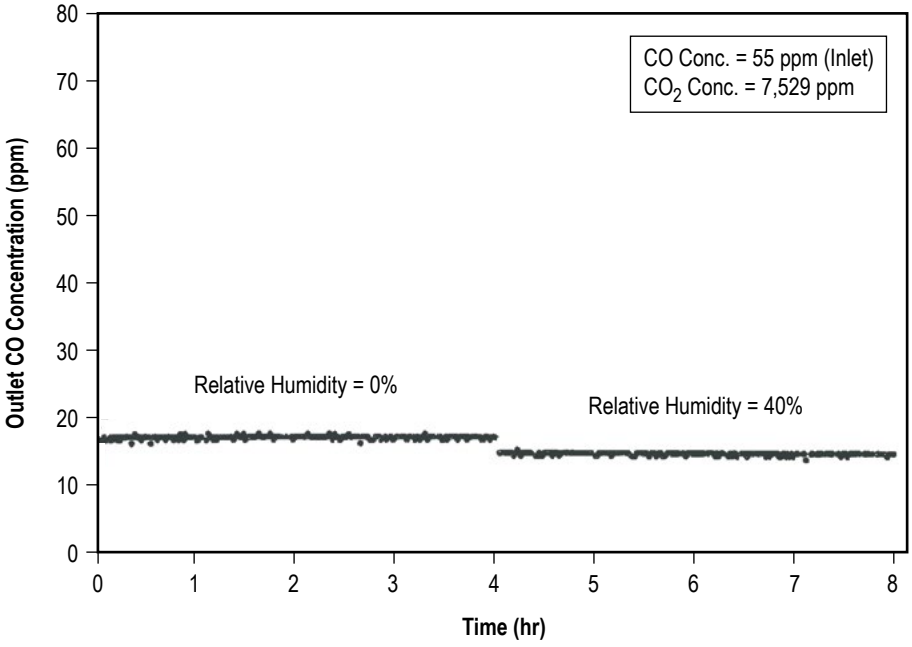
Common Name	IUPAC Name	Molar Mass (g/mol)	SMAC (mg/m^3)	Equipment Gen Rate (mg/day*kg)	Time to Reach SMAC (days)	Node 1 at 250 Days (mg/m^3)	Node 1 at 455 Days (mg/m^3)	Node 1 at 730 Days (mg/m^3)
Methylpentamethylene	Methylcyclopentane	84.16	51.60	2.97E-05	29211.04	4.42E-01	8.04E-01	1.29E+00
Neohexane	2,2-dimethylbutane	86.17	88.10	1.67E-06	885556.88	2.49E-02	4.53E-02	7.26E-02
Diethylmethylmethane	3-methylpentane	86.18	1762.00	5.97E-06	4962404.36	8.88E-02	1.62E-01	2.59E-01
Hexane	Hexane	86.18	7.00	6.95E-05	1693.75	1.03E+00	1.88E+00	3.02E+00
1-heptylene	1-heptene	98.18	201.00	1.10E-08	307205142.72	1.64E-04	2.98E-04	4.78E-04
Hexahydrotoluene	Methylcyclohexane	98.18	60.20	6.09E-05	16614.64	9.06E-01	1.65E+00	2.65E+00
Heptane	Heptane	100.21	205.00	5.59E-05	61613.82	8.32E-01	1.51E+00	2.43E+00
Dimethylcyclohexane	1,1-dimethylcyclohexane	112.22	115.00	2.61E-05	74149.85	3.88E-01	7.06E-01	1.13E+00
Trans-1,2-dimethylhexamethylene	Trans-1,2-dimethylcyclohexane	112.22	115.00	5.23E-05	36920.43	7.79E-01	1.42E+00	2.27E+00
Octane	Octane	114.23	350.00	1.61E-05	365254.67	2.40E-01	4.36E-01	7.00E-01
Nonane	Nonane	128.26	315.00	7.35E-06	720404.73	1.09E-01	1.99E-01	3.19E-01
Citrene (limonene)	4-isopropenyl-1-Mecyclohexene	136.23	557.00	3.58E-06	2613567.09	5.33E-02	9.70E-02	1.56E-01
Decane	Decane	142.28	223.00	2.78E-05	134706.49	4.14E-01	7.53E-01	1.21E+00
Hendecane	Undecane	156.31	319.00	2.51E-05	213830.06	3.73E-01	6.79E-01	1.09E+00
Dodecane	Dodecane	170.34	278.00	6.91E-07	6756900.92	1.03E-02	1.87E-02	3.00E-02
Ketones								
Acetone	2-propanone	58.08	52.00	3.62E-03	241.31	5.39E+01	9.80E+01	1.57E+02
Methyl ethyl ketone	2-butanone	72.11	30.00	6.01E-03	83.90	8.94E+01	1.63E+02	2.61E+02
Methyl propyl ketone	2-pentanone	86.13	70.40	4.03E-06	293560.80	6.00E-02	1.09E-01	1.75E-01
Methyl isopropyl ketone	3-methyl-2-butanone	86.13	70.40	3.11E-05	37994.07	4.63E-01	8.43E-01	1.35E+00
Mesityl oxide (methyl isobutenyl ketone)	4-methyl-3-penten-2-one	98.14	40.10	1.91E-04	3534.72	2.84E+00	5.16E+00	8.28E+00
Cyclohexanone (pimelic ketone)	Cyclohexanone	98.14	60.20	6.62E-04	1527.27	9.85E+00	1.79E+01	2.88E+01
Methyl isobutyl ketone	4-methyl-2-pentanone	100.16	143.00	1.41E-03	1704.44	2.10E+01	3.82E+01	6.12E+01
Phenyl methyl ketone	Acetophenone	120.14	245.00	5.66E-07	7271020.37	8.42E-03	1.53E-02	2.46E-02
Methyl hexyl ketone	2-octanone	128.21	105.00	1.65E-07	10715827.26	2.45E-03	4.46E-03	7.15E-03
Diisobutyl ketone	2,6-dimethyl-4-heptanone	142.20	58.10	3.34E-06	291944.33	4.98E-02	9.05E-02	1.45E-01
Mercaptans and Sulfides								
Hydrogen sulfide	Hydrogen sulfide	34.08	2.80	0.00E+00	INFINITE	0.00E+00	0.00E+00	0.00E+00
Carbon oxisulfide	Carbonyl sulfide	60.07	12.00	6.05E-06	33336.64	9.00E-02	1.64E-01	2.63E-01
Methyl sulfide	Dimethyl sulfide	62.14	2.50	1.88E-07	223837.00	2.79E-03	5.08E-03	8.15E-03
Carbon disulfide	Carbon disulfide	76.14	16.00	3.23E-05	8317.02	4.81E-01	8.75E-01	1.40E+00

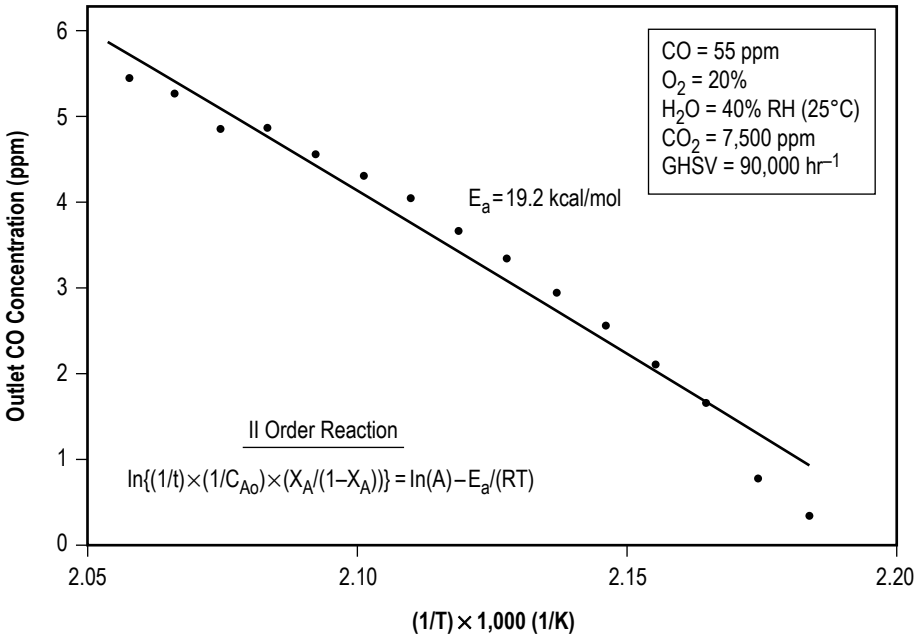
Common Name	IUPAC Name	Molar Mass (g/mol)	SMAC (mg/m^3)	Equipment Gen Rate (mg/day*kg)	Time to Reach SMAC (days)	Node 1 at 250 Days (mg/m^3)	Node 1 at 455 Days (mg/m^3)	Node 1 at 730 Days (mg/m^3)
Organic Acids								
Acetic acid	Ethanoic acid	60.05	7.40	1.42E-06	87387.56	2.12E-02	3.85E-02	6.18E-02
Organic Nitrogens								
Acetonitrile	Methyl cyanide	41.05	6.70	1.70E-08	6616228.70	2.53E-04	4.61E-04	7.39E-04
Indole	2,3-benzopyrrole	117.15	0.25	0.00E+00	INFINITE	0.00E+00	0.00E+00	0.00E+00
Miscellaneous								
Hydrogen	Hydrogen	2.02	340.00	5.91E-06	967600.27	8.78E-02	1.60E-01	2.57E-01
Ammonia	Ammonia	17.00	7.00	8.46E-05	1390.85	1.26E+00	2.29E+00	3.67E+00
Carbon monoxide	Carbon monoxide	28.01	10.00	2.03E-03	82.79	3.02E+01	5.50E+01	8.82E+01
Trimethylsilanol	Trimethylsilanol	90.21	40.00	1.69E-04	3985.00	2.51E+00	4.57E+00	7.33E+00
Hexamethylcyclotrioxosilane	Hexamethylcyclotrisiloxane	222.40	227.00	1.62E-04	23612.67	2.40E+00	4.37E+00	7.02E+00
Octamethyltrioxosilane	Octamethyltrisiloxane	236.54	40.00	2.11E-04	3185.19	3.14E+00	5.71E+00	9.17E+00

APPENDIX D—FLIGHT 2A, 3A, AND 4A TIMELINE


Master 2A/ 3A/ 4A Plan For Early Ingress
2A Launch 12-4-97
3A Launch 7-23-98
4A Launch 10-29-98
~ 9 mos.
~ 3 mos.
Detox Slip Margin 17 Days
SM
Soyuz
PMA 1
PMA 2
~5-25-97 Seal Node At HSV
Detox sample # 1
6-2-97 Node O/D KSC
6-5-97 PG-1 Detox sample # 2
~ 10-1-97 L-64d
10-11-97 to 10-15-97 L-54d N1, PMA1 & 2 IVT
10-20-97 L-45 d IMV circuit purge [Dryout (DD250) + Detox]
10-21-97 L-44d PG-1 Detox sample # 3
10-22-97 L-43d Install 2A CE into canister
10-24-97 L-41d Transfer 2A CE to PCR (pad)
10-24-97 to 11-3-97 Transfer 2A CE to PGHM
10-31-97 to 11-2-97 Orbiter IVT Ops
11-5-97 to 11-8-97 Orbiter Propellant Load
11-8-97 to 11-9-97 L-28d
11-10-97 L-27d Install 2A CE in PLB
FD4 RNDZ
EVA 2
EVA 3
Detox Sample # 4
5
If T_{Pred} value > 3
SD4/ JSC
Activate node fan to scrub toxins prior to ingress (~2 hrs.), if req'd
Activate node fan to scrub toxins (~2 hrs.)
Insight (via #4 & #5 Delta) To Filter & Fan Performance
Continuous Open Hatch Ops
Post-sleep
EVA's
Barge
11 days
Seal Node For Launch
Ingress Day • FD 8
Egress & dryout
Ingress Days • FD 4 • FD 8
Egress & dryout
Ingress Day • FD 7
P6 Activation Trickle Charge
Detox Sample
#1
#2
OR
If required
T_{Pred} ?
Derive T_{Pred} value
SD4/ JSC
Desired Operation
• Perform IMV circuit purge
• Detox sample # 3
PG-1
Backup Operation
• Activate Node Fan To Scrub Toxins
• Detox sample # 3
PG-1
Option A - If T_{Pred} <3,
•Pre-ingress scrub not req'd
Option B - If 3 < T_{Pred} <TBD,
• Pre-ingress scrub req'd (via dilution/ scrubbing w/ orbiter)
• Cab HX To Full Cool
• Install charcoal cartridge in LiOH slot replaced each hour up to 5 more
• 2 crew don masks & ingress PMA2
• Open hatch/ connect IMV
• Crew retreats to orbiter for at least 1 hr
• Crew doffs masks
• Crew waits at least 1 hr prior to ingress
Option C If T_{Pred} > TBD,
OR
• All crew don QDM's for TBD minutes until T_{Pred} < 3
All crew don air-purifying respirators (APR)for TBD minutes until T_{Pred} < 3
Plus
DF14/ PJCerna/ 2-18-97

APPENDIX E—3% Pt ON ACTIVATED CHARCOAL PERFORMANCE IN DRY AIR





APPENDIX F—NODE 1 ENTRY VERIFICATION ANALYSIS MISSION TIMELINE

Event	Time (hr)
• Node 1 purge at L-45 days completed	0
• Ingress during mission 2A flight day 8	1272
➢ 2-hour scrub	1272-1274
➢ Dilution with shuttle free volume	1274-1276
➢ 8-hour ingress event with fan operating	1274-1282
• Flight 2A complete	1368
• 150 days elapse between missions 2A and 2A.1	4968
• Ingress no. 1 on mission 2A.1 flight day 4	5064
➢ 2-hour scrub	5064-5066
➢ Dilution with shuttle free volume	5066-5068
➢ 8-hour ingress event with fan operating	5066-5074
• Ingress no. 2 on mission 2A.1 flight day 5 with no preliminary scrub	5088
➢ 8-hour ingress event with fan operating including dilution with shuttle free volume	5088-5096
• Ingress no. 3 on mission 2A.1 flight day 6 with no preliminary scrub	5112
➢ 8-hour ingress event with fan operating including dilution with shuttle free volume	5112-5120
• Ingress no. 4 on mission 2A.1 flight day 7 with no preliminary scrub	5136
➢ 8-hour ingress event with fan operating including dilution with shuttle free volume	5136-5144
• Ingress no. 5 on mission 2A.1 flight day 8 with no preliminary scrub	5160
➢ 8-hour ingress event with fan operating including dilution with shuttle free volume	5160-5168
➢ CACEAs replaced with fresh units	5184
• Flight 2A.1 complete	5208
• 30 days elapse between missions 2A.1 and 3A	5928
• Ingress during mission 3A flight day 4	6024
➢ 2-hour scrub followed by dilution with shuttle free volume	6024-6026
➢ 8-hour ingress event with fan operating	6026-6034
• Flight 3A complete	6168
• 90 days elapse between missions 3A and 4A	8328
• Ingress during mission 4A flight day 6	8472
➢ 2-hour scrub	8472-8474
➢ Dilution with shuttle free volume	8474-8476
➢ 8-hour ingress event with fan operating on flight day 7	8496-8506

Timeline reference: A DeVera white paper on TCC plan for flights 2A to 7A.

Flight 2A Through 4A Ingress Time Table

Flight	Ingress Flight Day	Task	Duration of task	Launch date	Mission duration	Approximate Elapsed Time between each mission
2A				**07/09/98**	**11+2**	
	FD8	Activate Cabin fan for scrub	2 hours			
	FD8	Perform IVA tasks with cabin fan operating continuously	8 hours			
2A.1				**12/15/98**	**10+1+2**	**150 days**
	FD4	Activate Cabin fan for scrub	2 hours			
	FD5	Perform IVA tasks with cabin fan operating continuously	8 hours			
	FD6	Reactivate Cabin fan for IVA ventilation	8 hours			
	FD7	Reactivate Cabin fan for IVA ventilation	8 hours			
	FD8	Reactivate Cabin fan for IVA ventilation	8 hours			
3A				**01/15/99**	**9+2+2**	**30 days**
	FD4	Activate Cabin fan for scrub	2 hours			
	FD4	Perform IVA tasks with cabin fan operating continuously	8 hours			
4A				**04/15/99**	**8+2+2**	**90 days**
	FD6	Activate Cabin fan for scrub	2 hours			
	FD7	Perform IVA tasks with cabin fan operating continuously	8 hours			

REF. A.L. DEVERA, 12-15-97.

APPENDIX G—CABIN AIR CATALYST ELEMENT ASSEMBLY PACKING DEPTH VERIFICATION

International Space Station
Temperature and Humidity Control Subsystem
Analysis/Inspection Record

Analysis/Inspection Record No.: QIR-9640-159**

CEI Part No.: SV821776-1** **CEI Nomencalature:** CABIN AIR CATALYST ELEMENT ASSEMBLY**

Design Specification No.: SVHS14382** **Design Specification Paragraph No.:** 3.2.2.3**

Design Requirement [SHALL #]: 159

Design Requirement Text: CHARCOAL DEPTH. THE CACEA CHARCOAL DEPTH SHALL [159] BE 1.3 INCHES MINIMUM.**

Analysis/Inspection Method: INSPECTION OF CACEA DESIGN TO VERIFY CHARCOAL DEPTH OF 1.3 INCHES MINIMUM.**

Analysis/Inspection Results: INSPECTION OF THE ASSEMBLY OPERATION SHEETS AND TOOLING FOR P/N SV821776-1 REVEALS THAT CHARCOAL DEPTH IS 1.3 INCHES MINIMUM.

559

Analysis/Inspection Date: 3/12/97**

Originating Group: DESIGN **Author:** R. REXER

Approvals:

Quality Assurance: R. C. Woodruff **Date:** 6/2/97

Project Engineer: C. Tomki **Date:** 6/2/97

Hamilton Standard
A United Technologies Company

OPERATION SHEET

Standard Operation Sheet

Description of Operation	Type of Machine	Dept. No	Part Number	Sht Rev No	Op. No.	Sheet No.
CHARGE ELEMENT ASSEMBLY	BRANFORD VIBRATOR OR EQUIV	195	SV821776-1		60	10 OF 24

CAUTION: REFER TO MSDS PRIOR TO ANY CHEMICAL OR TEST MEDIA USAGE. ASSY | INSP

D.) SLOWLY POUR (REDUCE DUST PARTICULATE) APPROXIMATELY A .100 TO .300 THICK LAYER OF CHARCOAL. USE LEVELING SPATULA, **SV821776CT001 (3–4)** TO LEVEL THE LAYER OF CHARCOAL.

LDO 6/12/97 ASSY

E.) INSTALL LOAD PLATE, **SV821776CT002 (3–5)** ON TOP OF THE LEVELED CHARCOAL AND VIBRATE FOR ***45 ± 15 SECONDS AT A SETTING OF 20***. REMOVE THE LOAD PLATE AND EXAMINE THE CHARCOAL FOR VOID REGIONS. ELIMINATE ANY VOID REGIONS BY TAMPING WITH TAMPER, **SV821776CT001 (4–4)**.

LDO 6/12/97 ASSY

560

F.) MEASURE THE CHARCOAL DEPTH USING DEPTH GAGE **SV821776CT501** AS DESCRIBED PER **FIGURE 4** NEXT SHEET. THIS WILL VERIFY THAT THE **1.290 ± .060** DIMENSION (B/P LOC. D3-2) IS MET.

LDO 6/12/97 ASSY

G.) IF DIMENSION **IS MET** N/A THIS STEP AND CONTINUE TO NEXT STEP. IF DIMENSION **IS NOT MET**, ADD OR REMOVE CHARCOAL AND PROCESS PER STEPS 12D, E AND F AGAIN. REPEAT THIS PROCESS UNTIL DIMENSION IS MET.

LDO 6/12/97 ASSY

H.) AFTER CHARGING, THE UNUSED PORTION OF THE CHARCOAL, IF ANY, SHALL BE PLACED IN (2) HEAT-SEALED POLYETHYLENE BAGS AND STORED IN THE CONTAINER IT WAS RECEIVED IN FOR POSSIBLE USE LATER.

LDO 6/12/97 ASSY

SVHSER18181 Rev. -

14

13. INSPECT THE CHARCOAL DEPTH, **1.290 ± .060** (B/P LOC. D3-2) USING DEPTH GAGE **SV821776CT501** AS DESCRIBED PER **FIGURE 4** NEXT SHEET. REF. 21 (B/P LOC. D2-2)

MIP 6/12/97

71

International Space Station
Temperature and Humidity Control Subsystem
Analysis/Inspection Record

Analysis/Inspection Record No.: QIR-9640-160**

CEI Part No.: SV821776-1**

CEI Nomencalature: CABIN AIR CATALYST ELEMENT ASSEMBLY**

Design Specification No.: SVHS14382**

Design Specification Paragraph No.: 3.2.2.4**

Design Requirement [SHALL #]: 160

Design Requirement Text: CATALYST DEPTH. THE CACEA CATALYST DEPTH SHALL [160] BE 0.5 INCHES MINIMUM.**

Analysis/Inspection Method: INSPECTION OF CACEA DESIGN TO VERIFY CATALYST DEPTH OF 0.5 INCHES MINIMUM.**

Analysis/Inspection Results: INSPECTION OF THE ASSEMBLY OPERATION SHEETS AND TOOLING FOR P/N SV821776-1 REVEALS THAT CATALYST DEPTH IS 0.5 INCHES MINIMUM.

Analysis/Inspection Date: 3/12/97**

Originating Group: DESIGN

Author: R. REXER

Approvals:

Quality Assurance: R.C. Woodruff **Date:** 6/6/97

Project Engineer: C Fowler **Date:** 6/2/97

Hamilton Standard
A United Technologies Company

OPERATION SHEET

Standard Operation Sheet

Description of Operation	Type of Machine	Dept. No	Part Number	Sht Rev No	Op. No.	Sheet No.
CHARGE ELEMENT ASSEMBLY	BRANFORD VIBRATOR OR EQUIV	195	SV821776-1		60	7 OF 24

CAUTION: REFER TO MSDS PRIOR TO ANY CHEMICAL OR TEST MEDIA USAGE. | ASSY | INSP

D.) INSTALL LOAD PLATE, **SV821776CT002 (3–5)** ON TOP OF THE LEVELED CATALYST AND VIBRATE FOR ***45 ± 15 SECONDS AT A SETTING OF 20.*** REMOVE THE LOAD PLATE AND EXAMINE THE CATALYST FOR VOID REGIONS. ELIMINATE ANY VOID REGIONS BY TAMPING WITH TAMPER, **SV821776CT001 (4–4)**. — LDO 6-12-97 ASSY

E.) MEASURE THE CATALYST DEPTH USING DEPTH GAGE **SV821776CT501** AS DESCRIBED PER **FIGURE 3** NEXT SHEET. THIS WILL VERIFY THAT THE 2.765 ± .060 DIMENSION (B/P LOC. D4–2) IS MET. — LDO 6/12/97 ASSY

F.) IF DIMENSION **IS MET** N/A THIS STEP AND CONTINUE TO NEXT STEP. IF DIMENSION **IS NOT MET**, ADD OR REMOVE CATALYST AND PROCESS PER STEPS 9C, D AND E AGAIN. REPEAT THIS PROCESS UNTIL DIMENSION IS MET. — N/A 6-12-97 ASSY

564

G.) AFTER CHARGING, THE UNUSED PORTION OF THE CATALYST, IF ANY, SHALL BE PLACED IN (2) HEAT–SEALED POLYETHYLENE BAGS AND STORED IN THE CONTAINER IT WAS RECEIVED IN FOR POSSIBLE USE LATER. — LDO 6-12-97 ASSY

10. INSPECT THE CATALYST DEPTH, **2.765 ± .060** (B/P LOC. D4–2) USING DEPTH GAGE **SV821776CT501** AS DESCRIBED PER **FIGURE 3** NEXT SHEET. REF. 10 (B/P LOC. D4–2) — SE MIP 6/12/97

11. INSTALL WIRE SCREEN, (7) AS SHOWN PER B/P **SECTION B–B** (B/P LOC. C4–2) — LDO 6-12-97 ASSY

SVHSER18181 Rev. -

APPENDIX H—TRACE CONTAMINANT GENERATION RATES

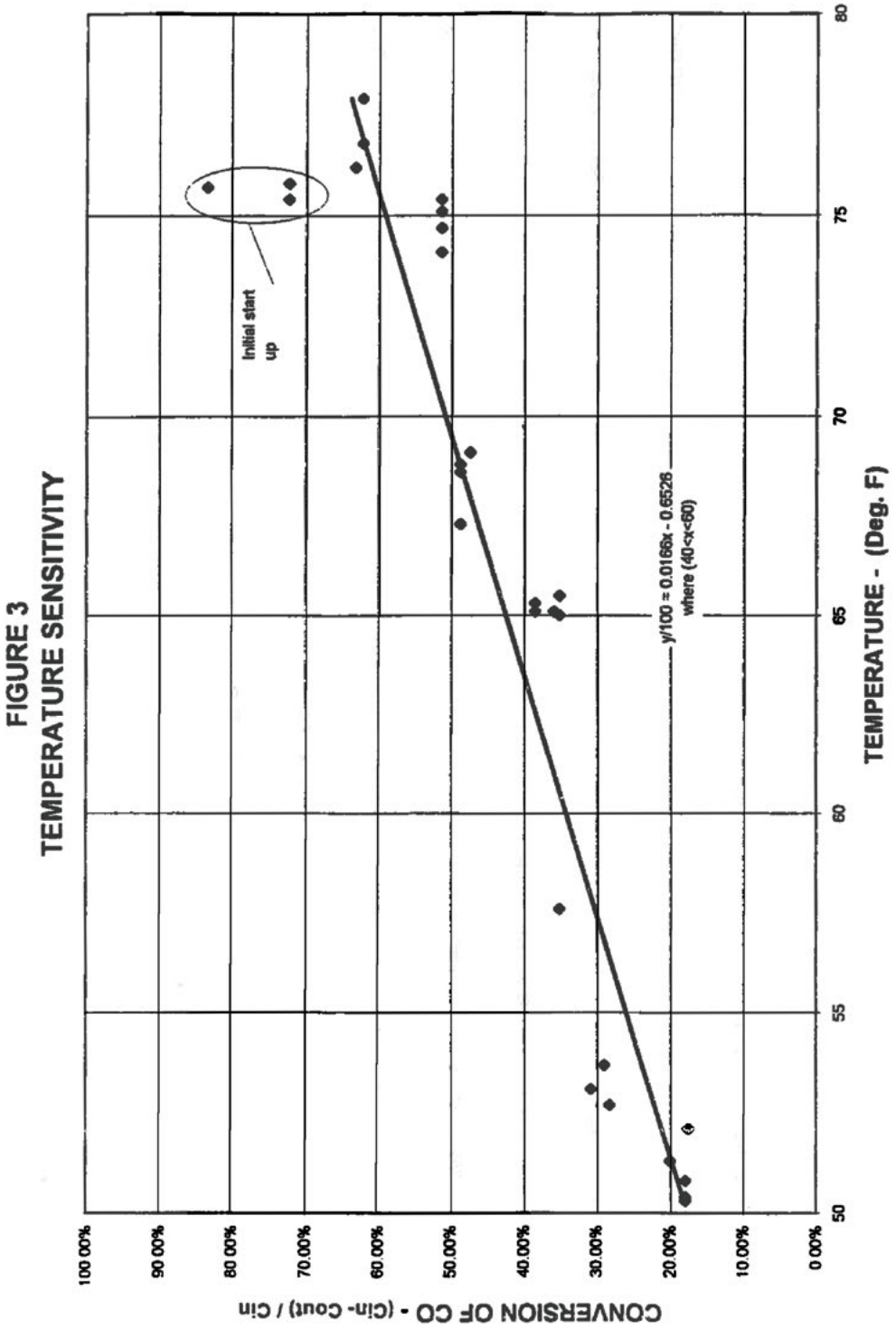
IUPAC Name	Generation Rate (mg/hr) 2,359 kg Basis	Generation Rate (mg/hr) 1,361 kg Basis
Alcohols		
Methanol	0.1251	0.0722
Ethanol	0.7715	0.4451
2-propen-1-ol	0.0002	0.0001
2-propanol	0.3918	0.2260
n-propanol	0.0237	0.0137
1,2-ethanediol	0.0006	0.0003
2-butanol	0.0009	0.0005
2-methyl-1-propanol	0.0832	0.0480
2-methyl-2-propanol	0.0073	0.0042
n-butanol	0.4629	0.2671
n-pentanol	0.0159	0.0092
Phenol	0.0475	0.0274
Cyclohexanol	0.0743	0.0429
2-hexanol	0.0002	0.0001
Aldehydes		
Methanal	0.0000	0.0000
Ethanal	0.0107	0.0062
2-propenal	0.0003	0.0002
Propanal	0.0314	0.0181
Butanal	0.0845	0.0487
Pentanal	0.0077	0.0044
Benzaldehyde	0.0020	0.0011
Aromatic Hydrocarbons		
Benzene	0.0025	0.0014
Methylbenzene	0.1949	0.1124
Vinylbenzene	0.0031	0.0018
1,2-dimethylbenzene	0.0546	0.0315
1,3-dimethylbenzene	0.1991	0.1149
1,4-dimethylbenzene	0.1061	0.0612
Ethylbenzene	0.0147	0.0085
Alpha-methylstyrene	0.0000	0.0000
1,2,4-trimethylbenzene	0.0044	0.0025
1,3,5-trimethylbenzene	0.0004	0.0002
1-ethyl-2-methylbenzene	0.0005	0.0003
Isopropylbenzene	0.0014	0.0008
Propylbenzene	0.0212	0.0122

IUPAC Name	Generation Rate (mg/hr) 2,359 kg Basis	Generation Rate (mg/hr) 1,361 kg Basis
Esters		
Ethyl formate	0.0004	0.0003
Methyl acetate	0.0139	0.0080
Ethyl acetate	0.0292	0.0168
Methyl methacrylate	0.0127	0.0074
Isopropyl acetate	0.0006	0.0003
Propyl acetate	0.0332	0.0192
Butyl acetate	0.0733	0.0423
Isobutyl acetate	0.0149	0.0086
Ethyl lactate	0.0004	0.0002
n+-amyl acetate	0.0047	0.0027
2-ethoxyethyl acetate	0.0733	0.0423
Ethers		
1,4-epoxy-1,3-butadiene	0.0002	0.0001
1,4-epoxybutane	0.0068	0.0039
Diethyl ether	0.0088	0.0050
2-methylfuran	0.0003	0.0002
2-ethoxyethanol	0.0591	0.0341
Chlorocarbons		
Chloromethane	0.0007	0.0004
Chloroethene	0.0001	0.0001
Chloroethane	0.0000	0.0000
Dichloromethane	0.2109	0.1217
1,1-dichloroethene	0.0001	0.0000
1,2-dichloroethane	0.0076	0.0044
Chlorobenzene	0.1517	0.0875
1,2-dichloropropane	0.0007	0.0004
Trichloromethane	0.0017	0.0010
Trichloroethylene	0.0085	0.0049
1,1,1-trichloroethane	0.0660	0.0381
1,1,2-trichloroethane	0.0000	0.0000
1,2-dichlorobenzene	0.0006	0.0004
Tetrachloromethane	0.0009	0.0005
Tetrachloroethene	0.0716	0.0413
Chlorofluorocarbons		
Chlorodifluoromethane	0.0056	0.0033
Dichlorofluoromethane	0.0001	0.0000
1-chloro-1,2,2-trifluoroethane	0.0005	0.0003
Dichlorodifluoromethane	0.0013	0.0008
1,2-dichloro-1,2-difluoroethene	0.0002	0.0001
Trichlorofluoromethane	0.1384	0.0799
Bromotrifluoromethane	0.0256	0.0148
1,1-dichloro-1,2,2,2-tetrafluoroethane	0.0026	0.0015
1,1,2-trichloro-1,2,2-trifluoroethane	1.8621	1.0743
1,1,2,2-tetrachloro-1,2-difluoroethane	0.0033	0.0019

IUPAC Name	Generation Rate (mg/hr)	
	2,359 kg Basis	1,361 kg Basis
Hydrocarbons		
Methane	0.0628	0.0362
Ethene	0.0000	0.0000
Ethane	0.0001	0.0001
Propene	0.0003	0.0001
Propane	0.0001	0.0001
1,3-butadiene	0.0003	0.0002
1-butene	0.0079	0.0046
2-methylpropane	0.0011	0.0006
Butane	0.0005	0.0003
1-pentene	0.0000	0.0000
2-methylbutane	0.0002	0.0001
Pentane	0.0094	0.0054
Cyclohexane	0.0373	0.0215
Methylcyclopentane	0.0029	0.0017
2,2-dimethylbutane	0.0002	0.0001
3-methylpentane	0.0006	0.0003
Hexane	0.0068	0.0039
1-heptene	0.0000	0.0000
Methylcyclohexane	0.0060	0.0035
Heptane	0.0055	0.0032
1,1-dimethylcyclohexane	0.0026	0.0015
Trans-1,2-dimethylcyclohexane	0.0051	0.0030
Octane	0.0016	0.0009
Nonane	0.0007	0.0004
4-isopropenyl-1-Mecyclohexene	0.0004	0.0002
Decane	0.0027	0.0016
Undecane	0.0025	0.0014
Dodecane	0.0001	0.0000
Ketones		
2-propanone	0.3560	0.2054
2-butanone	0.5906	0.3408
2-pentanone	0.0004	0.0002
3-methyl-2-butanone	0.0031	0.0018
4-methyl-3-penten-2-one	0.0187	0.0108
Cyclohexanone	0.0651	0.0376
4-methyl-2-pentanone	0.1386	0.0800
Acetophenone	0.0001	0.0000
2-octanone	0.0000	0.0000
2,6-dimethyl-4-heptanone	0.0003	0.0002
Mercaptans and Sulfides		
Hydrogen sulfide	0.0000	0.0000
Carbonyl sulfide	0.0006	0.0003
Dimethyl sulfide	0.0000	0.0000
Carbon disulfide	0.0032	0.0018

IUPAC Name	Generation Rate (mg/hr)	
	2,359 kg Basis	1,361 kg Basis
Organic Acids		
Ethanoic acid	0.0001	0.0001
Organic Nitrogens		
Methyl cyanide	0.0000	0.0000
2,3-benzopyrrole	0.0000	0.0000
Miscellaneous		
Hydrogen	0.0006	0.0003
Ammonia	0.0083	0.0048
Carbon monoxide	0.1995	0.1151
Trimethylsilanol	0.0166	0.0096
Hexamethylcyclotrisiloxane	0.0159	0.0092
Octamethyltrisiloxane	0.0207	0.0120

APPENDIX I—2% Pt ON CHARCOAL QUALIFICATION TEST PERFORMANCE



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14. ABSTRACT

Trace chemical contaminant generation inside crewed spacecraft cabins is a technical and medical problem that must be continuously evaluated to ensure mission health and safety. Although passive control via materials selection and active control devices is employed during normal operations of a spacecraft, contaminant buildup can still become a problem. Such contaminant buildup is particularly troublesome during the quiescent period between the final closure of a spacecraft during ground processing and the time that a crewmember enters. The International Space Station (ISS) presented a new challenge to contamination control engineering because the various modules may spend long periods on the ground before launch, leading to a greater potential for significant contaminant buildup by the time the crew enters a module for the first time. As well, long quiescent periods between crew visits during early assembly on orbit are a challenge for maintaining cabin atmospheric quality. The progression between November 1994 and January 1998 is presented for the trace contaminant control technical approach developed for the ISS's Node 1 module. This approach was refined as the Space Station's assembly progressed. The materials presented address preliminary engineering, performance, and verification analysis.

15. SUBJECT TERMS

space station, contaminant control, air quality, activated carbon, catalyst, ingress, maximum allowable concentration, material balance, design verification

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