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Offgassing Characterization of the Columbus Laboratory Module

Riccardo Rampini, Cesare Lobascio
Alenia Spazio S.p.A.

Jay L. Perry
NASA Marshall Space Flight Center

Stephan Hinderer
EADS Space Transportation GmbH

ABSTRACT

Trace gaseous contamination in the cabin environment is a major concern for manned spacecraft, especially those designed for long duration missions, such as the *International Space Station* (*ISS*).

During the design phase, predicting the European-built *Columbus* laboratory module's contribution to the *ISS's* overall trace contaminant load relied on "trace gas budgeting" based on material level and assembled article tests data. In support of the Qualification Review, a final offgassing test has been performed on the complete *Columbus* module to gain cumulative system offgassing data.

Comparison between the results of the predicted offgassing load based on the budgeted material/assembled article-level offgassing rates and the module-level offgassing test is presented. The *Columbus* module offgassing test results are also compared to results from similar tests conducted for Node 1, U.S. Laboratory, and Airlock modules.

INTRODUCTION

Trace gaseous contamination in the cabin environment is a major concern for manned spacecraft, especially those designed for long duration missions, such as the *ISS*. Potential health risks to the crew can arise if the concentrations of trace atmospheric components are not properly controlled. A contaminated environment can also adversely affect sensitive payloads and equipment accommodated in the spacecraft.

For these reasons, design requirements for *ISS* modules place limits on internal airborne contamination by defining spacecraft maximum allowable concentrations (SMACs) for trace atmospheric components. Controls rely on a combination of passive and active methods. Passive methods include carefully selecting materials of construction and manufacturing processes as well as regulating in-flight operations performed by the crew. Active methods include maintaining adequate ventilation rates and deploying air quality control equipment to continually remove contaminants from the cabin atmosphere. Monitoring systems ensure that the passive and active control methods are working. The European-built *Columbus* laboratory module (Figure 1) employs primarily passive controls and relies upon ventilation with and active air quality control equipment located in interfacing modules elements to continually remove contaminants produced by equipment offgassing.

During the design phase, predicting the *Columbus* module's contribution to the *ISS's* overall trace contaminant load relied on "trace gas budgeting" based on material level and assembled article tests data. Cases for both on-orbit and isolated conditions were analyzed. In support of the Qualification Review, a final offgassing test has been performed on the complete *Columbus* module to gain cumulative system offgassing data. Test results have been utilized for a final offgassing evaluation, where predictions for the same cases, on-orbit and isolated, have been formulated. The test has been conducted in active mode, representative of the on-orbit module condition, and the offgassing rate results have been conservatively extended also to the passive mode, representative of isolated module conditions.

Comparison between the results of the predicted offgassing load based on the budgeted material/assembled article-level offgassing rates and the module-level offgassing test is presented. The *Columbus* module offgassing test results are also compared to results from similar tests conducted for Node 1, U.S. Laboratory, and Airlock modules.

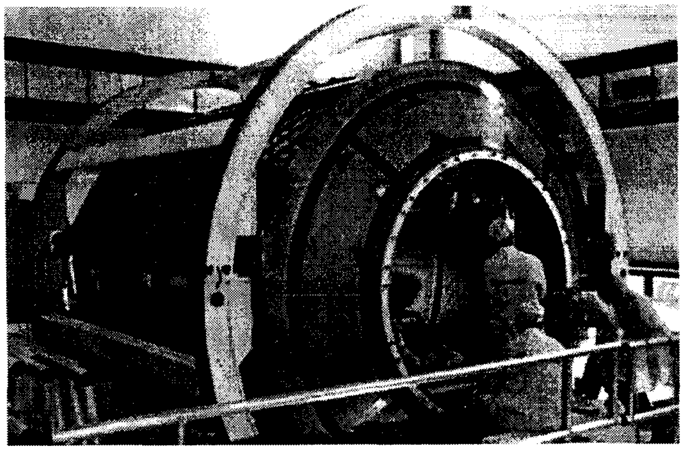


Figure 1 - The European-built *Columbus* laboratory module

APPLICABLE SMACS

For the *Columbus* module, as for the other *ISS* modules, a set of contractually applicable SMACs has been established. The Columbus SMACs list, coming from the Columbus System Requirements Document (CSRD) [1], reports the SMACs for 24 airborne contaminants, for 5 different potential exposure periods, as showed in Table 1.

		Potential Exposure Period				
		1h	24h	7d	30d	180d
Acetaldehyde	mg/m^3	20	10	4	4	4
Acrolein	mg/m^3	0.2	0.08	0.03	0.03	0.03
Ammonia	mg/m^3	20	14	7	7	7
Carbon dioxide	mmHg	10	10	5.3	5.3	5.3
Carbon monoxide	mg/m^3	60	20	10	10	10
1,2-Dichloroethane	mg/m^3	2	2	2	2	1
2-Ethoxyethanol	mg/m^3	40	40	3	2	0.3
Formaldehyde	mg/m^3	0.5	0.12	0.05	0.05	0.05
Freon 113	mg/m^3	400	400	400	400	400
Hydrazine	mg/m^3	5	0.4	0.05	0.03	0.005
Hydrogen	mg/m^3	340	340	340	340	340
Indole	mg/m^3	5	1.5	0.25	0.25	0.25
Mercury	mg/m^3	0.1	0.02	0.01	0.01	0.01
Methane	mg/m^3	3800	3800	3800	3800	3800
Methanol	mg/m^3	40	13	9	9	9
Methyl ethyl ketone	mg/m^3	150	150	30	30	30
Methyl hydrazine	mg/m^3	0.004	0.004	0.004	0.004	0.004
Dichloromethane	mg/m^3	350	120	50	20	10
Octamethyltrisiloxane	mg/m^3	4000	2000	1000	200	40
2-Propanol	mg/m^3	1000	240	150	150	150
Toluene	mg/m^3	60	60	60	60	60
Trichloroethylene	mg/m^3	270	60	50	20	10
Trimethylsilanol	mg/m^3	600	70	40	40	40
Xylene	mg/m^3	430	430	220	220	220

Table 1 – Columbus SMACs

DESIGN PHASE PREDICTIONS

During the design phase, predicting the *Columbus* module's contribution to the *ISS's* overall trace contaminant load relied on "trace gas budgeting" based on material level, assembled article tests data and metabolic generation. For the purpose, dedicated spreadsheets and databases using Microsoft Excel© and Access© have been developed.

MATERIAL GENERATION RATES - Evaluation of trace gas concentrations has been performed by "budgeting" all the Columbus materials, their masses and off-gassing rates.

Off-gassing information have been collected from all *Columbus* system, subsystem and equipment level responsible parties, exception made for *ISS* common items. The reason for this is that *ISS* does not use offgassing summations at equipment level anymore, thus materials lists are available only for a limited number of common items. Their contribution, in terms of offgassing generation rates, has been obtained by multiplying the historical offgassing generation rates from previous manned missions by their non-structural hardware mass.

For researching Columbus materials, checking provided data and supplementing insufficient information, extensive research has been performed on:

- NASA MAPTIS on-line database
- ESA RD: 02, Toxicity and Flammability Data for Spacecraft Materials
- Columbus Declared Materials, Mechanical Parts and Processes Lists

Off-gassing rates have been conservatively assumed constant over time, since decay laws are generally not available for specific materials.

CREW GENERATION RATES - Crew metabolic generation rates, necessary for the analysis of *Columbus* nominal conditions, have been derived from research on literature references such as the draft version of ESA-PSS-03-401, [2], SAE paper 891513 [3], both tracing back to H-EV-1-12-CNES, Physiological Environment Human Factors Limitations [4]. For CO_2 metabolic rates, International Space Station Alpha System Specification [5], Table XXIX data have been used.

ANALYSIS CASES - The trace gas analysis considered that two different *Columbus* conditions are foreseen:

- isolated, with *Columbus* working without Inter Module Ventilation (IMV) air exchange
- nominal, the *Columbus* working with IMV air exchange

SMAC VALUES - Since material test data are not limited to the 24 gases contained into the *Columbus* SMAC list, analytical predictions compared resulting concentrations to a more extended gas set. The contractually applicable CSRD SMACs in Table 1 have been considered for requirement verification. More precisely, we considered the 180 days SMACs for the nominal analysis and the 1 hour SMACs for the isolated analysis.

For additional comparisons, we considered:

- For other detected trace gases, SMACs from the MAPTIS database, typically 7 days SMACs.
- Where only a Total Organics (TO) value was available from test data, a SMAC of 0.1 mg/m^3, conservative as a mean SMAC of a hypothetical

organic gas mixture (see also MAPTIS default value).

- For unidentified traces of every kind, a SMAC of 0.1 mg/m^3, as used inside MAPTIS.

DESIGN DATA - Design data of interest for the analysis were:

- IMV air flow rate - 229 m^3/h
- *Columbus* volume - 64 m^3
- *Columbus* isolation time - elapsing between hatch close-out on-ground (Astrium-Bremen clean room) and hatch reopening on-station, currently estimated as 180 days

RESULTS - Results were directly obtained from the generated database, in terms of concentrations. Trace gas contamination levels in the IMV supply air (*ISS* to *Columbus*) or, as equivalent, the removal rates at the *Columbus* IMV interface are unknown. Therefore we evaluated the "*Columbus* contribution" to *Columbus* concentration levels: actual *Columbus* levels will be the sum of the *Columbus* contribution plus the IMV contribution. To assess performances of the *ISS* trace gas removal system, the *ISS* performs an overall analysis.

Here below the main results relevant to the two analyzed cases are reported and compared to the applicable SMACs.

For easier interpretation of results, the concentration to SMAC ratios are also reported as well as the Time to SMAC for the isolated conditions.

Trace gas	Generation rate [mg/h]	APM contribution to concentration [mg/m^3]	SMACs (180 d) [mg/m^3]	Concentration to SMAC (180 d) ratio [-]
Indole	3.1	1.36E-02	0.25	5.46E-02
Carbon dioxide	127000.0	5.56E+02	13000	4.27E-02
Ammonia	59.4	2.59E-01	7	3.70E-02
Formaldehyde	0.3	1.30E-03	0.05	2.60E-02
2-Propanol	227.0	9.90E-01	150	6.60E-03
Carbon monoxide	10.2	4.46E-02	10	4.46E-03
Methanol	3.0	1.32E-02	9	1.47E-03
Trimethylsilanol	5.9	2.59E-02	40	6.47E-04
Acrolein	0.0	1.17E-05	0.03	3.89E-04
Acetaldehyde	0.3	1.42E-03	4	3.55E-04
Toluene	4.3	1.89E-02	60	3.16E-04
Trichloroethylene	0.5	2.19E-03	10	2.19E-04
Methyl ethyl ketone	1.3	5.59E-03	30	1.86E-04
2-Ethoxyethanol	0.0	4.66E-05	0.3	1.55E-04
Dichloromethane	0.2	1.02E-03	10	1.02E-04
Methane	76.4	3.34E-01	3800	8.78E-05
Hydrogen	6.3	2.73E-02	340	8.03E-05
Freon 113	2.7	1.17E-02	400	2.93E-05
Xylene (sum)	0.4	1.59E-03	220	7.23E-06
1,2-Dichloroethane	0.0	6.00E-06	1	6.00E-06
Octamethyltrisiloxane	0.0	1.82E-05	40	4.56E-07
Hydrazine	0.0	0.00E+00	0.005	0.00E+00
Mercury	0.0	0.00E+00	0.01	0.00E+00
Methylhydrazine	0.0	0.00E+00	0.004	0.00E+00

Table 2 – On station nominal conditions, main analysis results

For the on station nominal conditions the calculated concentrations have been compared with relevant 180 days CSRD SMACs, i.e. the ones to be considered for long term exposure. On the other hand, for isolated conditions, the calculated concentrations have been compared with relevant 1 hour CSRD SMACs, i.e. the ones to be considered for short term exposure. We supposed that the crew could be exposed to such levels for less than one hour, i.e. the 'relatively high concentrations' reached during the isolation phase will quickly decrease in the first hours due to air revitalization via IMV/hatch.

Trace gas	Generation rate [mg/h]	APM concentr. after 180 days [mg/m^3]	SMACs (1 h) [mg/m^3]	Concentr. to SMAC (1 h) ratio after 180 days [-]	Time to SMAC (1 h) [d]
Formaldehyde	0.3	2.01E+01	0.5	4.02E+01	4.5
2-Propanol	227.0	1.53E+04	1000	1.53E+01	11.8
Carbon monoxide	6.1	4.09E+02	60	6.81E+00	26.4
Toluene	4.3	2.93E+02	60	4.88E+00	36.9
Methanol	2.8	1.92E+02	40	4.79E+00	37.5
Acetaldehyde	0.3	2.12E+01	20	1.06E+00	170
Acrolein	0.0	1.80E-01	0.2	9.02E-01	199
Trimethylsilanol	5.9	4.00E+02	600	6.67E-01	270
Methyl ethyl ketone	1.3	8.63E+01	150	5.76E-01	313
Freon 113	2.7	1.81E+02	400	4.53E-01	397
Trichloroethylene	0.5	3.38E+01	270	1.25E-01	1438
Xylene (sum)	0.4	2.46E+01	430	5.72E-02	3147
1,2-Dichloroethane	0.0	9.27E-02	2	4.64E-02	3882
Dichloromethane	0.2	1.58E+01	350	4.51E-02	3995
Ammonia	0.0	7.70E-01	20	3.85E-02	4676
Methane	1.4	9.60E+01	3800	2.53E-02	7123
2-Ethoxyethanol	0.0	7.20E-01	40	1.80E-02	9999
Carbon dioxide	0.1	8.54E+00	23000	3.71E-04	484675
Octamethyltrisiloxane	0.0	2.82E-01	4000	7.05E-05	2553378
Hydrogen	0.0	7.08E-03	340	2.08E-05	8642946
Hydrazine	0.0	0.00E+00	5	0.00E+00	inf.
Indole	0.0	0.00E+00	5	0.00E+00	inf.
Mercury	0.0	0.00E+00	0.1	0.00E+00	inf.
Methylhydrazine	0.0	0.00E+00	0.004	0.00E+00	inf.

Table 3 – Isolated conditions, main analysis results

FINAL OFFGASSING TEST

In support of the *Columbus* Qualification Review, a final offgassing test has been performed on the complete *Columbus* module to gain cumulative system offgassing data. Test results have been utilized for a final offgassing evaluation, where predictions for on-orbit and isolated cases have been formulated. The test has been conducted in active mode, representative of the on-orbit module condition, and the offgassing rate results have been conservatively extended also to the passive mode, representative of isolated module conditions.

TEST ARTICLE CONFIGURATION - During the test the Columbus module has been operated in nominal active mode simulating realistic on-orbits processes besides payload operation, i.e. with Columbus internal equipment configured as much as possible in "flight conditions" but without any payload rack. This means in particular all subsystems activated: Electrical Power Distribution System (EPDS), Data Management System (DMS), Active Thermal Control System (ATCS), Environmental Control and Life Support System (ECLSS), Video and Illumination.

An offgassing test with *Columbus* in passive mode, representative of the isolated phase, will be performed, under ESA/NASA responsibility, with the module outfitted with the initial payload complement, to characterize the Columbus isolated atmosphere.

Columbus internal layout was as close as possible to the flight configuration. Devices not foreseen for flight, and not strictly necessary for test execution were not present. Only the Ground Operation Floor (Aluminum structure) was left inside *Columbus* for allowing access to the module interior. The impact of this discrepancy with respect to the test objectives is not significant because of the metallic material nature.

Every subsystem, in particular ECLSS, ATCS and Avionics, was fully integrated. In order to verify offgassing properties of all materials involved in the cabin hardware, every non-metallic internal equipment has been placed into the cabin if not already integrated. Concerning the DMS, the *Columbus* test configuration was not final. In particular additional Personal Computer Memory Card International Association (PCMCIA) cards were not present into the module during the test. Their contribution to offgassing has been considered by analysis on the basis of card level offgassing data.

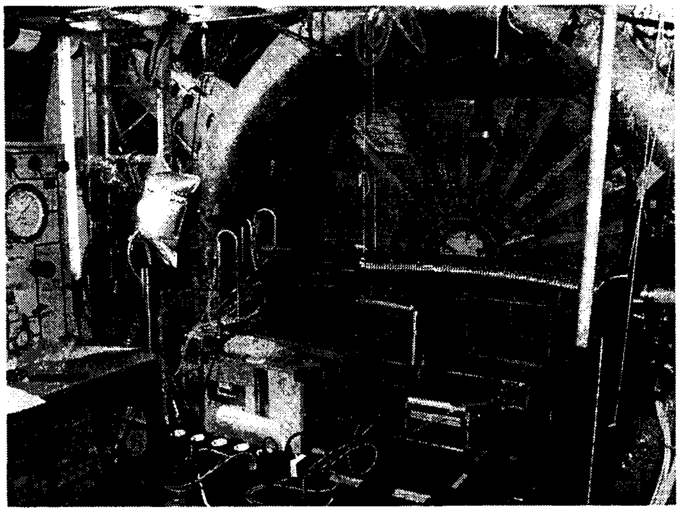


Figure 2 – *Columbus* module during the offgassing test

In order to prevent air exchange with the cleanroom, the Module has been isolated from the external atmosphere, i.e. the Hatch has been closed, and the Starboard Cone Aft Panel (SAC) installed. The IMV loop was short-circuited outside the module by means of a metallic jumper. The IMV jumper provided several sampling ports for the air sample acquisition.

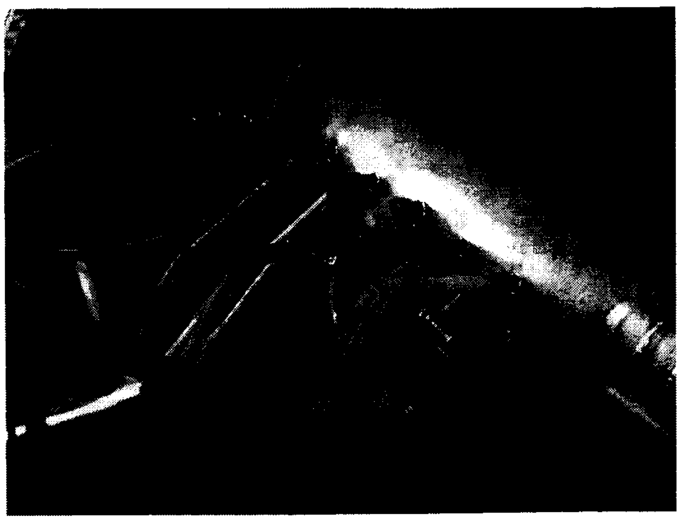


Figure 3 – IMV jumper with the sampling ports

STANDARD TEST AND LABORATORY EQUIPMENT - The air samples has been collected by means of adsorption traps, Dinitrophenylhydrazine (DNPH) cartridges and gas sampling bags adapted to the contaminant analysis process. Depending on the gas to be detected, samples have then been analyzed by means of Gas Chromatography - Mass Spectrometry (GC-MS), High Performance Liquid Chromatography - Diode Array Detection (HPLC-DAD) or Gas Chromatography - Flame Ionization Detector (GC-FID) techniques.

TEST SEQUENCE - The *Columbus* Offgassing Test has been executed into the integration and test hall, B41 at EADS ST premises in Bremen, during the Mission Simulation Test (MST), from the 2nd to the 5th of April 2004.

Internal cleaning with volatile solvents has been stopped four weeks before closure of the module, in order to avoid the entrapment of unwanted gaseous trace contaminants and to assure that the maximum evaporation of solvents has occurred. Moreover, during the first days of the Mission Simulation Test, the Columbus module was already operated in nominal mode with the hatch open and air exchange with the cleanroom. This period was considered as a purging of the module from those possible unwanted gaseous trace contaminants. The actual Offgassing Test started as the module was isolated from the cleanroom, i.e. with the hatch closure and the IMV short-circuiting.

The module has been kept isolated and powered for a total of approximately 74 hours. After two initial background sample set, representative of both clean room and Columbus trace contaminants levels, 6 additional sample sets were taken, totaling in all 8 sample sets. The background sampling has been performed:

- approximately 4 days before the test, inside the module, with the hatch open, and
- at the very beginning of the test, just after closure of the hatch

The first background sampling of the clean room environment, taken approximately 4 days before the beginning of the Offgassing Test, was intended not only to measure the background contamination but also to optimize the needed sampling volumes. The volume of each sample was tailored to the needed accuracy.

The detailed sampling sequence is reported in Table 4.

The *Columbus* module has been operated with a slight overpressure in order to avoid incoming air from the cleanroom. Therefore, after each sampling activity the module has been repressurized to recover the pressure decay due to the sampling itself. The module pressurization has been performed with a Nitrogen Pressure Supply Unit, utilizing class 4 nitrogen. The overpressure has been checked at least every 12 hours.

For closure of the *Columbus* offgassing requirements, just the gases defined in the CSRD SMAC table have been evaluated. Only for the first and the last acquisition, OGAS 010 and OGAS 080 samplings, a comprehensive analysis has been performed in order to detect all potential gases according to a "common" offgassing test. These two additional sets of results were for information only and they were not subject of evaluation for the closure of the Columbus offgassing requirements.

Procedure Module	Date	Sampling Time	Sampled volume [l]
OGAS 010	29.03.04	Start: 11.20 End: 14.15	- (Hatch open)
OGAS 020	02.04.04	Start: 19.55 End: 22.07	301.4
OGAS 030	03.04.04	Start: 00.00 End: 01.49	299.2
OGAS 040	03.04.04	Start: 08.05 End: 09.56	254.2
OGAS 050	03.04.04	Start: 18.06 End: 20.58	719.2
OGAS 060	04.04.04	Start: 18.04 End: 20.38	742.2
OGAS 070	05.04.04	Start: 08.03 End: 10.37	744.2
OGAS 080	05.04.04	Start: 19.34 End: 21.55	754.5

Table 4 – Sampling sequence

TEST RESULTS AND FINAL OFFGASSING EVALUATION - For each gas defined in the CSRD SMAC table, chemical analysis results and the calculated concentrations, suitably scaled due to N_2 introduction during repressurization phases of the *Columbus* module, were presented and their trends were plotted in a dedicated "Gas data sheet", similar to the one represented in Figure 4.

On the same data sheet, calculation dedicated to the final offgassing evaluation were reported.

Final evaluation cases - As for the design phase predictions two cases have been analyzed:

- Nominal case: Columbus on-station in ACTIVE mode and IMV operating - representative of the on-orbit module condition
- Isolated case: Columbus isolated in PASSIVE mode and IMV not operating - representative of the storage module condition. Remark: The test has been conducted in active mode and the H/W generation results have been conservatively extended also to the passive mode. This analytical evaluation shall be considered only as an indication of the offgassing concentrations behavior inside the module in case of isolation

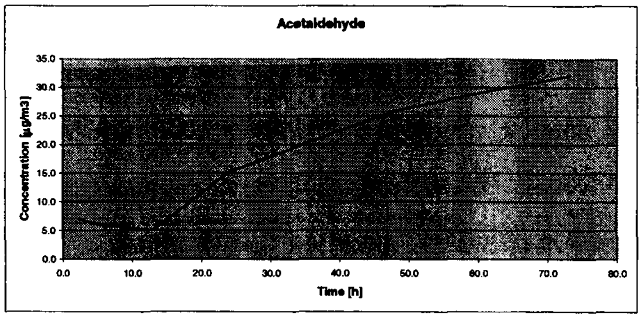
Design data - Design data of interest for the final offgassing evaluation are the same as for the design phase predictions, exception made for the *Columbus* free volume that have been re-evaluated to be close to 72 m^3.

Trends - Depending on the recorded trend during the test of each gas, different data treatment have been implemented. Four main "trend groups" have been found:

- Measured concentrations leveling off, asymptotic level not reached - the production rates have been conservatively calculated from the concentration values of the last period of the test, i.e. between ~60 (OGAS 070) and ~72 hours (OGAS 080). Gases part of this group are: Acetaldehyde (see Figure 4), Methyl ethyl ketone and Toluene.
- Measured concentrations leveling off, asymptotic level reached - the production rates is considered to be zero at the end of the test. Gases part of this group are: 2-Propanol, Trichloroethylene, Trimethylsilanol and Xylenes (see Figure 5).
- Measured concentrations fluctuating - a linear interpolation, by using the least squares method, has been adopted for the calculation of the production rates. Gases part of this group are: Formaldehyde, Carbon dioxide, 1,2-Dichloroethane, 2-Ethoxyethanol (see figure 6), Freon 113, Octamethyltrisiloxane and Methane.
- Non detectable concentrations - the production rates have been conservatively calculated assuming the concentration at the end of the test equal to the detection limit for the specific gas. Gases part of this group are: Acrolein (see Figure 7), Carbon monoxide, Ammonia, Methanol and Dichloromethane. As a remark, we do not consider Hydrogen, Mercury, Indole, Hydrazine and Methyl hydrazine as part of this group since their production is avoided by design and by the absence of metabolic generation during the test.

Acetaldehyde

	Time		Detection Limit	Measured Concentration	"Corrected" Concentration	Calculated Generation rate
	[d]	[h]	[µg/m³]	[µg/m³]	[µg/m³]	[µg/h]
OGAS 010	-3.48	-103.3	0.5	n.d.		
OGAS 020	0.92	2.3	5	7	7.0	
OGAS 030	1.04	5.2	5	6	6.0	-24.4
OGAS 040	1.37	13.2	5	5	5.0	-8.9
OGAS 050	1.82	24.0	0.5	15	15.3	68.0
OGAS 060	2.81	47.7	0.5	25	25.7	31.9
OGAS 070	3.38	61.4	0.5	28	29.3	18.5
OGAS 080	3.86	73.1	0.5	30	32.0	16.7



Columbus offgassing test

Trend:	Levelling off, asymptotic level NOT reached	
Prod. Rate, S	16.7	µg/h

PCMCIA offgassing test

Prod. Rate, S	0	µg/h

Final Offgassing evaluation - Nominal conditions

S_{st}	16.7	µg/h
On-orbit Conc.	7.28E-05	mg/m³
SMAC (180d)	4	mg/m³

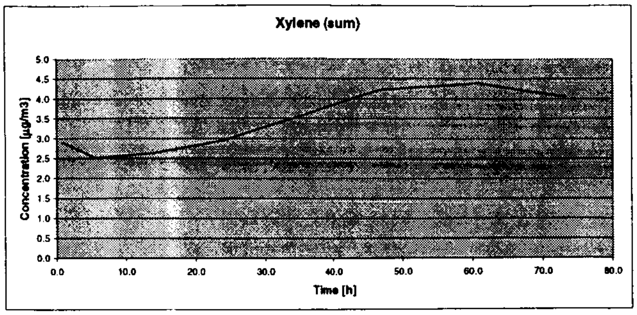
Final Offgassing evaluation - Isolated conditions

S_{isol}	16.7	µg/h
Isolated Conc.	1.02E+00	mg/m³
SMAC (1h)	20	mg/m³
Time to SMAC	3596.7	d

Figure 4 – Acetaldehyde data sheet

Xylene (sum)

	Time		Detection Limit	Measured Concentration	"Corrected" Concentration	Calculated Generation rate
	[d]	[h]	[µg/m³]	[µg/m³]	[µg/m³]	[µg/h]
OGAS 010	-3.48	-103.3	0.2	2.3		
OGAS 020	0.85	0.8	0.2	2.9	2.9	
OGAS 030	1.05	5.6	0.2	2.5	2.5	-5.8
OGAS 040	1.39	13.7	0.2	2.6	2.6	1.0
OGAS 050	1.82	23.9	0.2	2.9	2.9	2.3
OGAS 060	2.77	46.8	0.2	4.1	4.2	4.0
OGAS 070	3.36	60.9	0.2	4.2	4.4	0.9
OGAS 080	3.87	73.1	0.2	3.8	4.1	-2.0



Columbus offgassing test

Trend:	Levelling off, asymptotic level reached	
Prod. Rate, S	0	µg/h

<———— assumed to be zero at the end of the test

PCMCIA offgassing test

Prod. Rate, S	2.72E-02	µg/h

Final Offgassing evaluation - Nominal conditions

S_{st}	0.0	µg/h
On-orbit Conc.	1.19E-07	mg/m³
SMAC (180d)	220	mg/m³

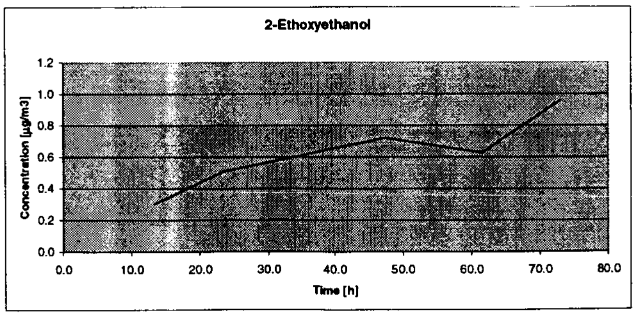
Final Offgassing evaluation - Isolated conditions

S_{isol}	0.0	µg/h
Isolated Conc.	6.03E-03	mg/m³
SMAC (1h)	430	mg/m³
Time to SMAC	47387271.1	d

Figure 5 – Xylenes data sheet

2-Ethoxyethanol

	Time		Detection Limit	Measured Concentration	"Corrected" Concentration	Calculated Generation rate
	[d]	[h]	[µg/m³]	[µg/m³]	[µg/m³]	[µg/h]
OGAS 010	-3.47	-102.9	0.1	n.d.		
OGAS 020	0.86	1.0	0.1	n.d.	n.d.	
OGAS 030	1.04	5.2	0.1	n.d.	n.d.	-
OGAS 040	1.37	13.3	0.1	0.3	0.3	-
OGAS 050	1.80	23.5	0.1	0.5	0.5	1.5
OGAS 060	2.79	47.3	0.1	0.7	0.7	0.6
OGAS 070	3.38	61.5	0.1	0.6	0.6	-0.5
OGAS 080	3.86	73.0	0.1	0.9	1.0	2.1



Columbus offgassing test

Trend:	Fluctuating, mainly increasing.	
Prod. Rate, S	0.6	µg/h

<———— linear interpolation

PCMCIA offgassing test

Prod. Rate, S	0	µg/h

Final Offgassing evaluation - Nominal conditions

S_{st}	0.6	µg/h
On-orbit Conc.	2.79E-06	mg/m³
SMAC (180d)	0.3	mg/m³

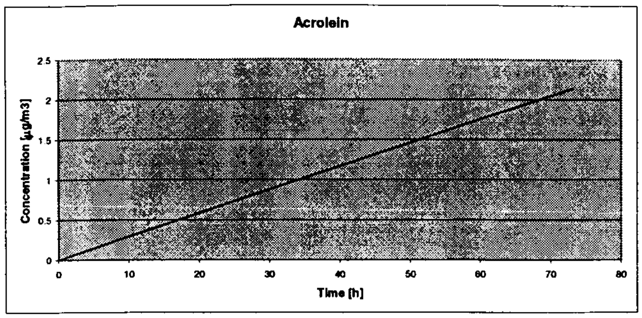
Final Offgassing evaluation - Isolated conditions

S_{isol}	0.6	µg/h
Isolated Conc.	3.85E-02	mg/m³
SMAC (1h)	40	mg/m³
Time to SMAC	188019.1	d

Figure 6 – 2-Ethoxyethanol data sheet

Acrolein

	Time		Detection Limit	Measured Concentration	"Corrected" Concentration	Calculated Generation rate
	[d]	[h]	[µg/m³]	[µg/m³]	[µg/m³]	[µg/h]
OGAS 010	-3.48	-103.3	2	n.d.		
OGAS 020	0.92	2.3	20	n.d.	n.d.	
OGAS 030	1.04	5.2	20	n.d.	n.d.	-
OGAS 040	1.37	13.2	20	n.d.	n.d.	-
OGAS 050	1.82	24.0	2	n.d.	n.d.	-
OGAS 060	2.81	47.7	2	n.d.	n.d.	-
OGAS 070	3.38	61.4	2	n.d.	n.d.	-
OGAS 080	3.86	73.1	2	n.d.	2.1	2.1



Columbus offgassing test

Trend:	Linear, assuming the concentration at the end of the test equal to the detection limit	
Prod. Rate, S	2.1	µg/h

PCMCIA offgassing test

Prod. Rate, S	0	µg/h

Final Offgassing evaluation - Nominal conditions

S_{st}	2.1	µg/h
On-orbit Conc.	9.17E-06	mg/m³
SMAC (180d)	0.03	mg/m³

Final Offgassing evaluation - Isolated conditions

S_{isol}	2.1	µg/h
Isolated Conc.	1.26E-01	mg/m³
SMAC (1h)	0.2	mg/m³
Time to SMAC	285.7	d

Figure 7 – Acrolein data sheet

Results summary – Results from the final offgassing test are summarized, in terms of concentrations, in Table 5 and 6, respectively for the On station and the Isolated conditions. Also in this case, we calculated the "*Columbus* contribution" to *Columbus* concentration levels.

For easier interpretation of results, the concentration to SMAC ratios are also presented as well as the Time to SMAC for the isolated conditions.

Trace gas	Generation rate [mg/h]	APM contribution to concentration [mg/m³]	SMACs (180 d) [mg/m³]	Concentration to SMAC (180 d) ratio [-]
Acrolein	0.0021	9.17E-06	0.03	3.06E-04
Carbon monoxide	0.27	1.18E-03	10	1.18E-04
Ammonia	0.10	4.38E-04	7	6.26E-05
1,2-Dichloroethane	0.011	4.80E-05	1	4.80E-05
Methanol	0.050	2.19E-04	9	2.44E-05
Acetaldehyde	0.017	7.28E-05	4	1.82E-05
2-Ethoxyethanol	0.00064	2.79E-06	0.3	9.29E-06
Methyl ethyl ketone	0.019	8.40E-05	30	2.80E-06
Toluene	0.017	7.63E-05	60	1.27E-06
Dichloromethane	0.0011	4.60E-06	10	4.60E-07
Methane	0.16	6.96E-04	3800	1.83E-07
Octamethyltrisiloxane	0.00046	2.01E-06	40	5.02E-08
2-Propanol	0.00038	1.68E-06	150	1.12E-08
Xylene (sum)	0.000027	1.19E-07	220	5.40E-10
Formaldehyde	0	0.00E+00	0.05	0.00E+00
Carbon dioxide	0	0.00E+00	13000	0.00E+00
Hydrogen	0	0.00E+00	340	0.00E+00
Mercury	0	0.00E+00	0.01	0.00E+00
Freon 113	0	0.00E+00	400	0.00E+00
Indole	0	0.00E+00	0.25	0.00E+00
Trichloroethylene	0	0.00E+00	10	0.00E+00
Trimethylsilanol	0	0.00E+00	40	0.00E+00
Hydrazine	0	0.00E+00	0.005	0.00E+00
Methylhydrazine	0	0.00E+00	0.004	0.00E+00

Table 5 - On station nominal conditions, from test results

Trace gas	Generation rate [mg/h]	APM concentr. after 180 days [mg/m^3]	SMACs (1 h) [mg/m^3]	Concentr. to SMAC (1 h) ratio after 180 days [-]	Time to SMAC (1 h) [d]
Acrolein	0.0021	1.26E-01	0.2	6.30E-01	285.7
1,2-Dichloroethane	0.011	6.62E-01	2	3.31E-01	545.1
Ammonia	0.10	6.02E+00	20	3.01E-01	598.0
Carbon monoxide	0.27	1.62E+01	60	2.70E-01	667.5
Methanol	0.050	3.01E+00	40	7.53E-02	2389.4
Acetaldehyde	0.017	1.02E+00	20	5.08E-02	3596.7
Toluene	0.017	1.08E+00	60	1.80E-02	10299.4
Methyl ethyl ketone	0.019	1.20E+00	150	8.00E-03	23390.8
Methane	0.16	1.10E+01	3800	2.90E-03	71482.3
2-Ethoxyethanol	0.00064	3.85E-02	40	9.63E-04	188019.1
Dichloromethane	0.0011	6.32E-02	350	1.81E-04	997058.6
2-Propanol	0.00038	1.15E-01	1000	1.15E-04	7814044.9
Octamethyltrisiloxane	0.00046	2.77E-02	4000	6.92E-06	26110683.5
Xylene (sum)	0.000027	6.03E-03	430	1.40E-05	47387271.1
Carbon dioxide	0	7.68E+02	23000	3.34E-02	inf.
Formaldehyde	0	6.40E-03	0.5	1.28E-02	inf.
Trimethylsilanol	0	9.06E-02	600	1.51E-04	inf.
Trichloroethylene	0	3.66E-03	270	1.36E-05	inf.
Freon 113	0	4.26E-04	400	1.07E-06	inf.
Hydrogen	0	0.00E+00	340	0.00E+00	inf.
Mercury	0	0.00E+00	0.1	0.00E+00	inf.
Indole	0	0.00E+00	5	0.00E+00	inf.
Hydrazine	0	0.00E+00	5	0.00E+00	inf.
Methylhydrazine	0	0.00E+00	0.004	0.00E+00	inf.

Table 6 - Isolated conditions, from test results

COMPARISON BETWEEN ANALYTICAL PREDICTIONS AND TEST RESULTS

An interesting exercise is to compare the analytical predictions by "trace gas budgeting" with the module level test results.

For this purpose the results of the design phase predictions have been treated to be congruent with the ones coming from the offgassing test:

- For the On station case - the load due to metabolic production, to the Portable Fire Extinguisher (PFEX), and to the Portable Breathing Apparatus (PBA), not present during the test, but taken into account in the design analysis, has been subtracted
- For the Isolated case – results coming from the design phase analysis have been suitably scaled in order to consider the new Columbus free volume of 72 m^3 instead of 64 m^3

This comparison is presented in Table 7, for the On station conditions and Table 8, for the Isolated conditions.

From table 7 the following can be remarked:

- Five gases that have been predicted to be present have not been detected during the test
- Two gases, 1,2-dichloroethane and 2-ethoxyethanol, have been detected without being predicted
- All the detected concentrations are lower than predicted, exception made for ammonia (factor of 10)

From table 8 the following can be remarked:

- Times to SMAC derived from test results are always greater than predicted, except for 1,2-dichloroethane and ammonia
- For 2-propanol the prediction was 13 days, that did not comply with the projected duration of isolated phase; Test results show a time to SMAC five orders of magnitude greater. Also for Xylenes test results show a Time to SMAC four orders of magnitude greater than predicted
- According to test results, time to SMAC for all gases is always greater than the projected duration of 180 days, while according to predictions, five gases did not comply with the projected duration

Trace gas	Concentration to SMAC (180 d) ratio [-] Final Offgassing Evaluation (A)	Design Phase Predictions (B)	Ratio A/B
Acrolein	3.06E-04	3.80E-04	0.80
Carbon monoxide	1.18E-04	2.63E-03	0.04
Ammonia	6.26E-05	6.18E-06	10.13
1,2-Dichloroethane	4.80E-05	0.00E+00	inf.
Methanol	2.44E-05	1.37E-03	0.02
Acetaldehyde	1.82E-05	3.41E-04	0.05
2-Ethoxyethanol	9.29E-06	0.00E+00	inf.
Methyl ethyl ketone	2.80E-06	1.71E-04	0.02
Toluene	1.27E-06	3.13E-04	0.00
Dichloromethane	4.60E-07	8.53E-05	0.01
Methane	1.83E-07	1.62E-06	0.11
Octamethyltrisiloxane	5.02E-08	4.72E-08	1.06
2-Propanol	1.12E-08	6.60E-03	0.00
Xylene (sum)	5.40E-10	5.94E-06	0.00
Formaldehyde	0.00E+00	2.60E-02	0.00
Carbon dioxide	0.00E+00	4.25E-08	0.00
Hydrogen	0.00E+00	0.00E+00	-
Mercury	0.00E+00	0.00E+00	-
Freon 113	0.00E+00	2.56E-05	0.00
Indole	0.00E+00	0.00E+00	-
Trichloroethylene	0.00E+00	2.18E-04	0.00
Trimethylsilanol	0.00E+00	6.47E-04	0.00
Hydrazine	0.00E+00	0.00E+00	-
Methylhydrazine	0.00E+00	0.00E+00	-

Table 7 – On station nominal conditions, comparison between predictions and test results

Trace gas	Time to SMAC (1 h) [d] Final Offgassing Evaluation (A)	Design Phase Predictions (B)	Ratio A/B
Acrolein	285.7	223.9	1.28
1,2-Dichloroethane	545.1	4367.3	0.12
Ammonia	598.0	5260.5	0.11
Carbon monoxide	667.5	29.7	22.47
Methanol	2389.4	42.2	56.64
Acetaldehyde	3596.7	191.3	18.81
Toluene	10299.4	41.5	248.10
Methyl ethyl ketone	23390.8	352.1	66.43
Methane	71482.3	8013.4	8.92
2-Ethoxyethanol	188019.1	11248.9	16.71
Dichloromethane	997058.6	4494.4	221.85
2-Propanol	7814044.9	13.3	588628.61
Octamethyltrisiloxane	26110683.5	2872550.3	9.09
Xylene (sum)	47387271.1	3540.4	13384.82
Carbon dioxide	inf.	545259.4	inf.
Formaldehyde	inf.	5.1	inf.
Trimethylsilanol	inf.	303.8	inf.
Trichloroethylene	inf.	1617.8	inf.
Freon 113	inf.	446.6	inf.
Hydrogen	inf.	9723314.3	inf.
Mercury	inf.	inf.	-
Indole	inf.	inf.	-
Hydrazine	inf.	inf.	-
Methylhydrazine	inf.	inf.	-

Table 8 – Isolated conditions, comparison between predictions and test results

COMPARISON TO OTHER ISS ELEMENT TESTS

Offgassing tests conducted for the U.S. Segment elements have been in the passive mode. That is, the module systems were not powered during the testing. Testing duration ranged from 120 hours for Node 1 to 444 hours for the U.S. Lab module. The typical goal is for the minimum passive testing duration to be approximately one-fifth the planned elapsed time between final hatch closure on the ground and first crew entry on orbit. This allows for the passive offgassing test results to prove more precise prediction of cabin air quality at the time the crew enters the module for the first time. In the next planned *Columbus* offgassing test, the module will be passive and with payloads integrated. The test duration will be set according to the above mentioned guideline to ensure consistency. Table 9 provides a summary of the major U.S. Segment passive element-level offgassing test results.[6, 7, 8]

TRACE GAS	GENERATION RATE (mg/h)		
	U.S. LAB	NODE 1	AIRLOCK
Methanol	1.07	0.0396	0.0757
Ethanol	1.06	0.8873	0.266
2-propanol	1.08	0.8276	0.237
n-propanol	0.15	0.1377	0.0669
2-methyl-2-propanol	0	0.0211	0
n-butanol	0.097	0.1099	0.0298
Ethanal	0.04	0.0366	0.00298
2-propenal	0	0.0001	0
Propanal	0	0.0278	0.0122
2-methyl-2-propenal	0	0.0211	0
Butanal	0	0.2095	0
Pentanal	0	0.0079	0
Hexanal	0	0.0079	0
Heptanal	0	0.0079	0
Methylbenzene	0.076	0.0612	0.0238
1,2- & 1,3-dimethylbenzenes	0	0.0553	0
1,4-dimethylbenzene	0	0.0211	0
Ethylbenzene	0	0.0211	0
Butyl acetate	0	0.0079	0
Dichloromethane	0.035	0.1163	0
Tetrachloroethene	0.038	0	0
Trichlorofluoromethane	0	0.0211	0
Trichlorotrifluoroethane	0.5	0.0702	0.0147
2-propanone	0.42	0.2178	0.0499
2-butanone	0.14	0.1101	0.016
Cyclohexanone	0.03	0.0367	0.0189
Hexamethylcyclotrisiloxane	0.69	0.0211	0.208
Octamethylcyclotetrasiloxane	0.22	0.15	0.0258
Decamethylcyclopentasiloxane	0.07	0	0
Trimethylsilanol	0.93	0	0.149
Carbon Monoxide	0	0	0
1,2-dichloroethane	0.01	0	0

Table 9 – Results from ISS U.S. Segment Passive Offgassing Tests

In comparison, results from the *Columbus* module active testing indicates offgassing rates that are comparable to those observed during passive testing of other U.S. Segment modules. Overall, the *Columbus* module testing results most closely resembles those obtained during testing of Node 1.

These are very encouraging results because temperature and equipment age can significantly affect offgassing rate. The active testing condition can induce elevated temperature that can contribute up to 10 times greater offgassing rates compared to equipment at 20 ºC.[9] Equipment age can also result in significant offgassing rate reduction. The offgassing rate for equipment aged 50 days has been reported to decrease by >90%.[10] Taking these effects into account, the *Columbus* module equipment offgassing load can be expected to be lower when launched and activated on orbit. A more direct comparison will be possible once the final passive offgassing test is conducted on the *Columbus* module.

CONCLUSION

Conclusions from the *Columbus* module active offgassing test are the following:

1. The offgassing load from the *Columbus* module is expected to be well within the capabilities of the ISS's active cabin air quality control equipment.
2. *Columbus* module active offgassing test results are comparable to those observed from passive tests of other U.S. Segment modules, particularly Node 1.
3. Conducting the final passive offgassing test as close to the *Columbus* module's launch is necessary to most accurately predict the trace gas concentrations at the time the crew enters for the first time.

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CONTACT

For more information, please contact

Riccardo Rampini, Functional Architecture and Environment
Alenia Spazio S.p.A.
Strada Antica di Collegno 253 - 10146 Torino
phone: +39 011 7180758
email: riccardo.rampini@aleniaspazio.it

DEFINITIONS, ACRONYMS, ABBREVIATIONS

ATCS: Active Thermal Control System
CCN: Contract Change Notice
CSRD: Columbus System Requirements Document
DAD: Diode Array Detection
DMS: Data Management System
DNPH: Dinitrophenylhydrazine
ECLSS: Environmental Control and Life Support System
EDPS: Electrical Power Distribution System
ESA: European Space Agency
FID: Flame Ionization Detector
GC: Gas Chromatography
HPLC: High Performance Liquid Chromatography
IMV: Inter Module Ventilation
ISS: International Space Station
MS: Mass Spectrometry
MST: Mission Simulation Test
NASA: National Aeronautics and Space Administration
PBA: Portable Breathing Apparatus
PFEX: Portable Fire Extinguisher
PCMCIA: Personal Computer Memory Card International Association
SAC: Starboard Cone Aft Panel
SMAC: Spacecraft Maximum Allowable Concentration
TO: Total Organics