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ECHO Air
Design Testing for a Boeing 737-200

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ABBREVIATIONS

ACH	air change per hour
ACGIH	American Conference of Governmental Industrial Hygienists
AHU	air handling unit
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
A. fumigatus	*Aspergillus fumigatus* (toxigenic fungal species)
A. versicilor	*Aspergillus versicolor* (toxigenic fungal species)
BAP	benzo (a) pyrene
BETEX	benzene, toluene, ethyl benzene, xylene
BP	boiling point
^{o} C	degree s Celsius
cc	cubic centimeters
C_d	air leakage discharge coefficient
CFM	cubic feet per minute
CFU	colony forming units (fungi)
Clo	a unit to express insulation provided by clothing. Temperature target ranges are based on activity levels typical of light sedentary work, and clo values typical of seasonal clothing (i.e. heavy slacks, long sleeve shirt and sweater in winter; light slacks, short sleeve shirt in summer).
CO	carbon monoxide
CO_2	carbon dioxide
CPL	counts per liter (RSP)
C9	organic compound with 9 carbon atoms.
E_A	envelope area that may leak
ELA	equivalent leakage area
envelope	the perimeter section of a structure containing insulation, vapor and air barriers
ETS	environmental tobacco smoke
^{o} F	degrees Fahrenheit
FS	frame station (aircraft). A circumferential structural member. Alt refers to the section between two circumferential structural members
fpm	feet per minute
GC	gas chromatography (VOCs)
g	grams
h	hours
H_2O	water
HCHO	formaldehyde
HEPA	high efficiency particulate (filters)
HRV	heat recovery ventilator (air-to-air heat exchanger)
HVAC	heating, ventilation and air-conditioning
IAQ	indoor air quality
IAT	Indoor Air Technologies Inc.
l, L	litres
L_A	leakage area
LD	Legionnaires' disease
LPP	liquid process photocopiers (use liquid toner dispersant)
L/s	litres per second (1 L/s = 2 CFM approx.)
MBR	master bedroom
MC	moisture content
m^3	cubic meter (air)
min	minute
mm	millimeters
MS	mass spectroscopy
MVOCs	microbial volatile organic compounds
NO	nitric oxide
NO_2	nitrogen dioxide
O_3	ozone
p	person
P	pressure difference
P. brevi-compactum	*Penicillium brevicompactum* (toxigenic fungal species)
P. crustosum	*Penicillium crustosum*
P. variotti	*Paecilomyces variotti* (pathogenic fungal species)
Pa	Pascals (pressure)
PAH	polycyclic aromatic hydrocarbons
pCi/L	pico Curies per liter (radon)
P. viridicatum	*Penicillium auranteogrisium (P. cyclopium, P. polonicum, P. viridicatum)* (toxigenic fungal species)
ppb	parts per billion
ppm	parts per million

D	air density
Q	flow
RH	relative humidity
Rm	room
RSP	respirable suspended particulate matter
RT	GC compound retention time
S/A	supply air
SBS	Sick building syndrome. SBS symptoms include headaches, fatigue, eye and respiratory system irritation.
S. chartarum	*Stachybotrys chartarum or S. atra* (toxic fungal species)
SO_2	sulphur dioxide
stringer	longitudinal structural member (aircraft)
T	temperature
TLV	Threshold limit value
T. harzianum	*Trichoderma harzianum (viride)* (toxigenic fungal species)
TVOC	total volatile organic compound
TWA	time weighted average
UFFI	urea formaldehyde foam insulation
V	ventilation rate
VB	vapour barrier
VOC	volatile organic compound
:g/m^3	micrograms per cubic meter of air
20th %	20th percentile (only 20 percent of other buildings tested have a lower concentration)

EXECUTIVE SUMMARY

1. *The Objectives*

- The ECHO Air design objective is to control the transport of gases, vapors and particles between the envelope and cabin of an airplane by means of a small controllable pressure differential established between the two parts of the plane through a system of independent ventilation and exhaust flows. Isolating the envelope in this manner provides not only an effective barrier to the ingress of water vapor, but also provides a filter and a holding tank for pollutants that can be voided at appropriate times during the flight cycle.

- With this system, “rain in the plane” problems can be eliminated; undesirable gases (VOCs, ozone), particulate, smoke or noxious fire retardants can be isolated in the envelope and vented at will; and comfortable humidity levels can be maintained in the cabin without attendant condensation and “rain-in-the-plane” incidents or accelerated corrosion of the fuselage.

- Gaseous sorption and filtration in the envelope ensures that the ventilation air injected there is as clean or cleaner than its initial state before it enters the cabin, thereby improving cabin air quality and reducing the risk of lubricating-oil ingestion by crew or passengers.

2. *The System*

- The system components are: ventilation air injectors installed in the envelope and, optionally, envelope air flow blockers, envelope/cabin exhaust dampers and fuselage treatment.

- Sealing of openings in the cabin liner and installation of flow blockers that inhibit “stack” induced circumferential flows in the envelope, improve system performance.

- While the ideal is to maintain a positive envelope pressurization relative to the cabin throughout the flight, any injection of dry ventilation air into the envelope will reduce cabin condensation problems.

- The ECHO Air design can be applied to the complete cabin or to specific envelope areas of concern such as in the crown, the galley or the cockpit.

3. *Test measurements in a Boeing 737-200*

- This report describes the results of tests conducted in a Boeing 737 in June 1998 with the aim of developing ECHO Air design parameters for that aircraft model.

- Measurements were made both on the ground and in flight of envelope air-flow, pressure and VOCs in port, starboard and crown cabin envelope sections.

4. *Observations*

- Stack pressures between the cabin and the envelope were ~0.7 Pa at the crown and floor of the cabin with a temperature of 0 C behind the insulation and a cabin temperature of 22 C. The theoretical maximum for this temperature difference and the cabin geometry is 0.9 pa.

- Introduction of a mid-height flow blocker reduced stack pressures by a factor of ~ two.

- The in-flight envelope pressurization vs injection rate characteristics were ~ 27% lower than the on-the-ground pressurization vs injection rate measurements after accounting for stack effect pressures. This corresponds to the air pressure reduction within experimental error (1 atmosphere to 3/4 atmosphere) and indicates that ground testing is sufficiently accurate to establish ECHO Air injection rates.

- Envelope pressurization relative to the injection rate, normalized to wall area per passenger seat *p*, over 4 wall panel sections (floor to stowage bin) was ~ 0.73 Pa/CFM/p.

- Envelope longitudinal air flow was unrestricted over four frame stations.

- Envelope circumferential air flow was restricted at the stringers.

- On-the-ground envelope air had a high concentration of anti-corrosion oil coating VOCs.

- In-flight gasper air contained a high proportion of combustion contaminant VOCs. It is postulated that these VOCs were previously absorbed on oil deposits in the gasper ducts during ground exhaust ingestion incidents rather than being ingested from engine exhaust, for example, during the test flight.

- Envelope air had a higher proportion of microbial VOCs and gasper air a lower proportion than the norms for indoor environments.

5. *B737-2000 ECHO Air system design parameters*

- Design cabin envelope injection rates to offset an average stack pressure of 1.5 Pa above the neutral plane with no flow blocker and an average of 1 Pa above the two neutral planes with a mid-height flow blocker for a design cold soak temperature of -50 C.

- Seal obvious openings at cabin liner discontinuities (e.g. at the stowage bin).

- Supply an injection flow rate of 3 CFM/p for envelope sections to be pressurized with no flow blocker and 2 CFM/p for envelope sections to be pressurized with one mid-height flow blocker.

- Supply injection air in the top half of sections between flow blockers, or between a flow blocker and crown. Provide injectors in every second stringer space circumferentially and every 8^{th} frame station longitudinally and adjust flows to offset the projected stack pressure distributions.

6. *Discussion*

- The projected maximum stack pressure for a cold soak temperature of -50 C is 2.3 Pa with no flow blocker (i.e. an average of 1.2 Pa above the neutral plane with no flow blockers and 0.6 Pa above the two neutral planes with a mid-height flow blocker).

- Injection design rates are 50% above projected minimum requirements for the design cold soak temperature. This allowance is for factors such as sub-optimal air injection arrangements and non-linearity in envelope pressurization characteristics.

- These design envelope air injection rates that eliminate moisture problems associated with condensation and microbial growth are well within regulatory cabin ventilation requirements (i.e., 10 CFM/p to 15 CFM/p, depending upon jurisdiction). Higher injection rates provide improved cabin air quality and reduce ingestion incidence, but are unnecessary for moisture problem prevention.

- Injection at lower rates than design, or where there are obvious liner openings, will reduce moisture problems proportionately.

- Installation of envelope exhaust dampers which are opened during take-off will substantially reduce cabin air contamination by the envelope combustion and microbial VOCs identified in these tests.

- The system will reduce the entry into the cabin of the combustion VOCs identified in the gasper air and associated with desorption from oil residues in the envelope.

- Replacement of the anti-corrosion fuselage treatment used in this plane by appropriate absorbents will decrease cabin VOC concentrations both on the ground and in flight.

1.0 INTRODUCTION

The ECHO Air technology involves: (a) sealing of the cabin liner; (b) reduction of stack pressures through use of flow blockers in the cabin envelope; (c) distribution of a portion or all of the engine bleed/ cabin ventilation air into the envelope; (b) air exhaust from the envelope; (c) fuselage coating to enhance envelop sorption/desorption characteristics; (d) smoke detector arrays in the envelope; and (e) fire suppressant injection system. Some of the components are illustrated in Figure 1. Additional information is available in the patent descriptions and presentations on the web at **www.indoorair.ca**.

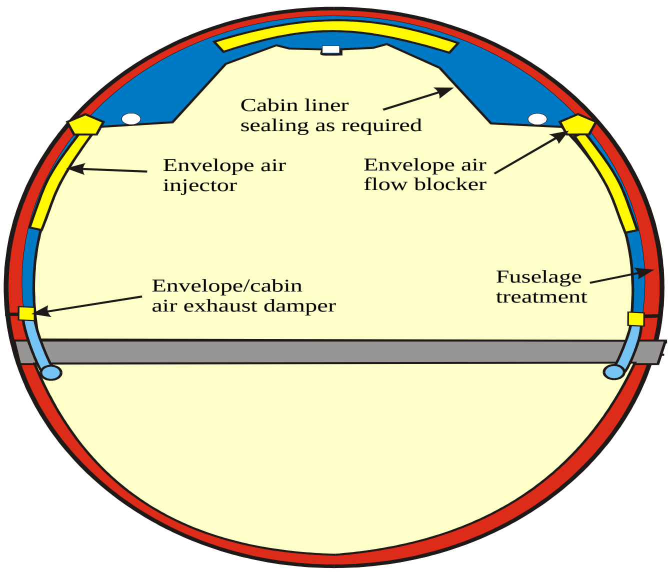


Figure 1 Illustration of some of the ECHO Air components

ECHO liner sealing allows for ready envelope pressurization. Envelope flow blockers reduce thermal stack pressures driving flows through liner openings (into the envelope from the cabin at the crown and vice versa at the floor). The ECHO Air aircraft cabin envelop ventilation system re-routes a portion or all of the aircraft ventilation (engine bleed) air through a portion or all of the cabin envelope during cruise. This ventilation flow, in conjunction with the liner sealing and envelope flow blockers, limits or prevents cabin moisture entering the envelope to minimize envelope moisture condensation problems by pressurizing the envelope. This eliminates cabin air flows into the envelope and limits molecular back diffusion against the leakage airflow through small openings. At the same time, this envelope ventilation air can be thermally conditioned to provide cabin radiant cooling and heating supplementing or eliminating the cabin air circulation heating and cooling load demand.

The ECHO Air design provides for exhausting of cabin air through the envelope which is placed at negative pressure at the beginning of each flight so as to purge the envelope of gases and moisture condensed and/or sorbed there during previous flights and/or on the ground . This feature also allows for the direct purging of smoke via and from the envelope in the event of a fire in the cabin or the envelope. It can also be used to allow injection of fire suppressant into an envelope fire without exposing passengers to any associated toxic gases in the envelope.

By this dynamic ventilation ‘sealing’ of the cabin air from the envelope air and vice versa , the ECHO Air can be used to:

- Eliminates ‘rain in the plane’ condensation drip in the crown of cabins and cockpits and reduce fuel costs by eliminating the weight of condensate accumulation.
- In conjunction with smoke detector arrays, reduce fire and smoke inhalation risks, both for envelop fires (e.g. (from electrical arcing), and for a cabin fire.
- Extends the life of the fuselage by reducing corrosion.
- Improve cabin air quality be exhausting envelope gases which are highest concentration when the plane is on the ground and during ascent when the envelope is warmest.
- Filters ventilation air prior to its entry into the cabin through ventilation air inertial deposition of particulate in injection flows directed at the fuselage, and through sorption of ventilation air contaminant gases on the cold fuselage during take off, cruise and initial descent (particularly the more dangerous SVOCs that might be generated by an oil release into the engine bleed), and desorption and exhaust of these gases on the ground and during take-off and initial descent.

The ECHO Air technology involves: (a) sealing of the cabin liner; (b) reduction of stack pressures through use of flow blockers in the cabin envelope; (c) distribution of a portion or all of the engine bleed/ cabin ventilation air into the envelope; (b) air exhaust from the envelope; (c) fuselage coating to enhance envelop sorption/desorption characteristics; (d) smoke detector arrays in the envelope; and (e) fire suppressant injection system. Additional information is available in the patent descriptions and presentations on the web at **www.indoorair.ca**.

The envelope ventilation air distribution system design depends upon envelop flow characteristics and cabin-envelope in-flight ‘stack effect’ pressure distribution. It can be focused in particular areas, for example to solve ‘rain in the plane or corrosion problems. While any flow of ventilation air into the envelope will reduce moisture problems, the tighter the cabin liner, the greater the reduction for any given flow

Envelope air flow characteristics and cabin liner tightness have been investigated in a B737-200. The findings follow.

2.0 B737-200 ECHO Air TESTS

A B737-200 envelope pressurization was investigated in June 1998 during a flight check of the aircraft following a C check. The plane tested had just undergone a C check in which the seats, liner and insulation had been removed, the fuselage coated with an anti-corrosion treatment oil, and the jet engines maintained. The seats were not in place for the flight check .

Test sections were chosen towards the rear of the cabin on both sides. The location of the test sections are shown in Figure 2, along with the pressure, flow, and gaseous contaminants measured.

Air injection was behind the insulation on the Port sections and in front in the Starboard test sections. A number of pressure versus flow tests were conducted on the ground on three different days. Envelope air volatile organic compounds (VOCs) were measured while on the runway just before take off from the Quebec City airport. The weather was sunny and warm. Gasper bleed air VOCs were measured during cruise. The flight test lasted 40 minutes at 28,000 feet.

Instrumentation is described in Appendix A. Photographs are provided in Appendix B.

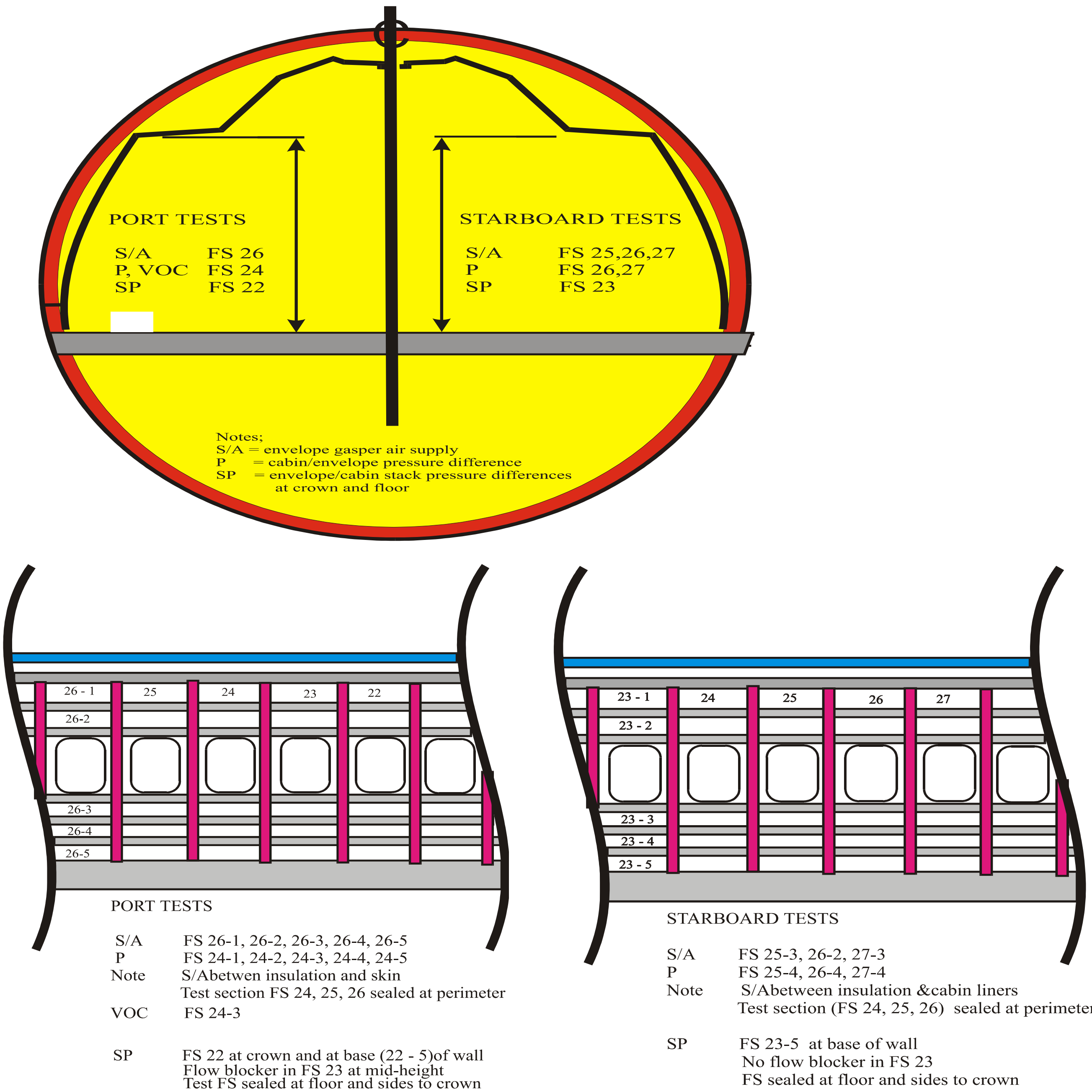


Figure 2 ECHO Air test arrangements

3.0 B737-200 ECHO Air TEST RESULTS

Pressures and flows

The Port Side 19 June 10:51 h test did not identify any longitudinal flow restrictions behind the insulation over three frame stations (Table 1). The Port Side 19 June 14:35h test identified some circumferential flow blockage by the stringers (Table 2).

Table 1 Longitudinal pressure variation with air injected at one end of the port side test section

TEST 19 June'98		*GROUND*	*PORT SIDE*		*10:51 h*		
		Temp in cabin = 28 C, behind insulation = 27 C at 16:30 h					
PRESSURES (envelope-cabin)			ENVELOPE S/A				
Section	Location	Pressure	Location	Section	Tube dia.		Injection rate
		Pa			inches	fpm	cfm
24	2	6.1	1 to 5	24	0.75	0	0.0
24	4	7.0	1 to 5	25	0.75	0	0.0
25	2	5.7	1 to 5	26	0.75	6920	21.2
25	4	7.2					
26	2	5.8					
26	4	6.1					
				Total			21.2
Average		6.3					
Median		6.1					
Standard deviation		0.6					

Table 2 Circumferential pressure variation with air injected at the bottom of the port side test section

TEST 19 June'98		*GROUND*	*PORT SIDE*		*14:35 h*		
		Temp in cabin = 28 C, behind insulation = 27 C at 16:30 h					
PRESSURES (envelope-cabin)			ENVELOPE S/A				
Section	Location	Pressure	Location	Section	Tube dia.		Injection rate
		Pa			inches	fpm	cfm
24	1	0.3	5	24	0.75	1420	4.4
24	2	0.4	5	25	0.75	1850	5.7
24	3	1.6	5	26	0.75	1070	3.3
24	4	1.8					
24	5	4.0					
				Total			13.3
Average		1.6					
Median		1.6					
Standard deviation		1.5					

On the ground, envelope minus cabin pressure was approximately 1

Pa/CFM/passenger seat (Figure 3).

In flight (altitude of 28,000 ft), envelope minus cabin pressure was approximately 0.73 Pa/per CFM/passenger seat (Figure 4).

The detailed ground and in flight pressure vs flow data are provided in Appendix C.

Stack effect pressures were -0.6 Pa at the crown (envelope depressurized relative to cabin; 4.6 C between the insulation and the skin); + 0.7 Pa at the floor on the starboard side where there was no flow blocker (envelope pressurized relative to cabin; -1 C between the insulation and the skin) and +0.2.5 Pa at the floor on the port side where there was a mid-height flow blocker (4.6 C between the insulation and the skin). The cabin temperature was ~ 22 C at the time of these measurements.

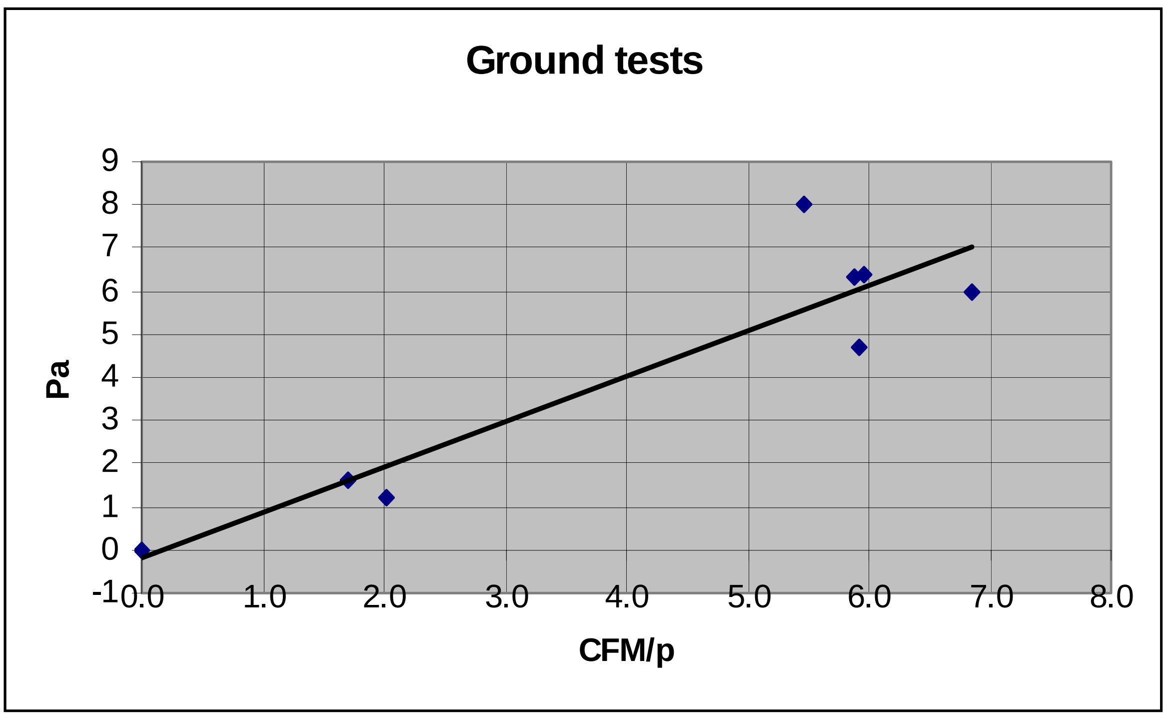
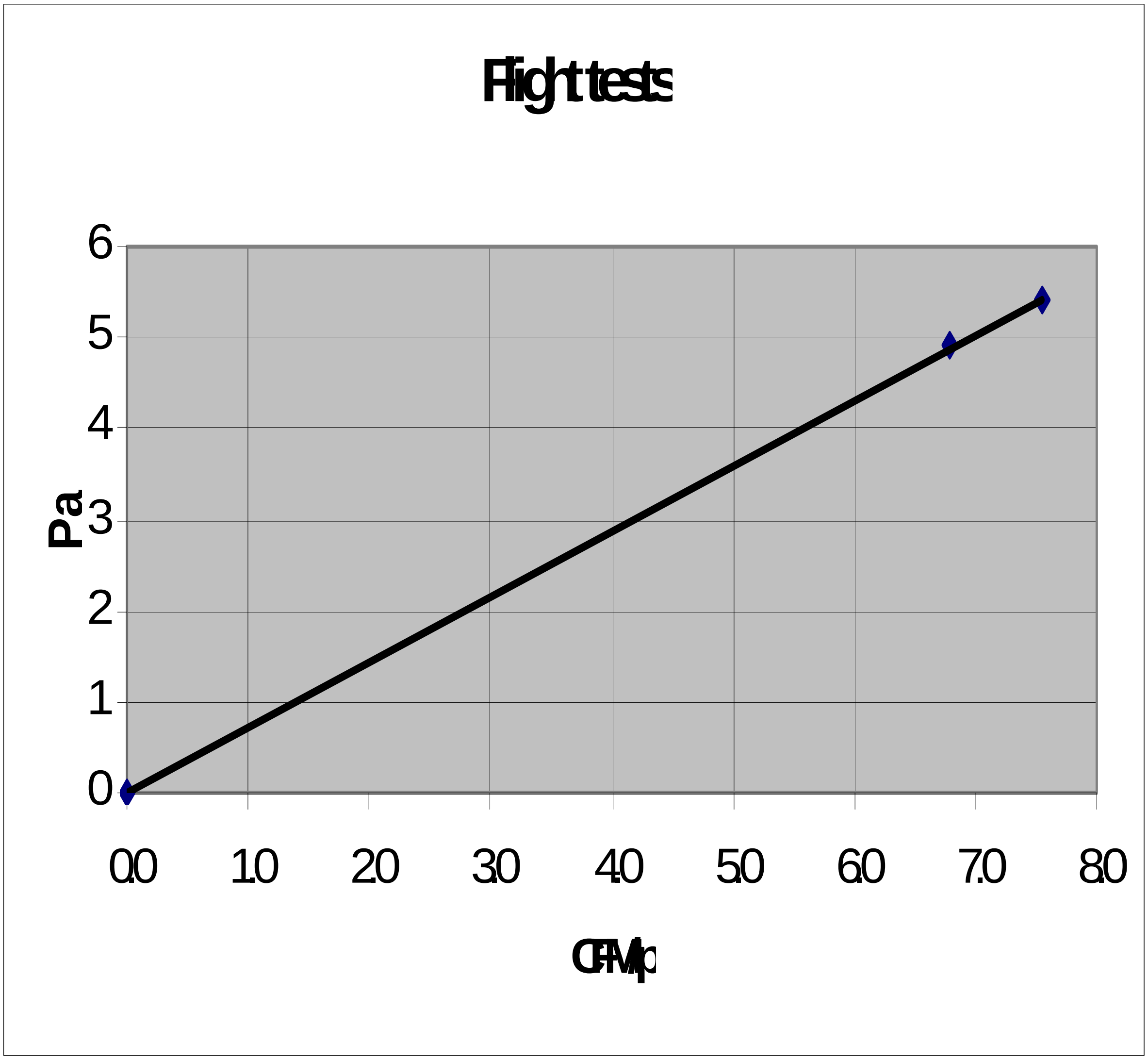


Figure 3 On-the-ground envelope pressurization vs injection rate per passenger seat


Flight tests
Pa
0
1
2
3
4
5
6
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0

Volatile organic compounds
Gasper ventilation air (/bleed air)

A volatile organic compound chromatogram from a 5 litre sample of gasper air (bleed air only, no recirculation) taken during flight is provided in Figure 7.

The TVOC concentration was about four time that measured in typical air in downtown urban environments. Gasper air branched alkane, n-alkane, BTEX and aromatic compound concentrations were proportionately higher than in the envelope sample, and higher than found in a downtown air sample. Ketones and aliphatics were lower than in the downtown sample (Figure 8).

Figure 8a

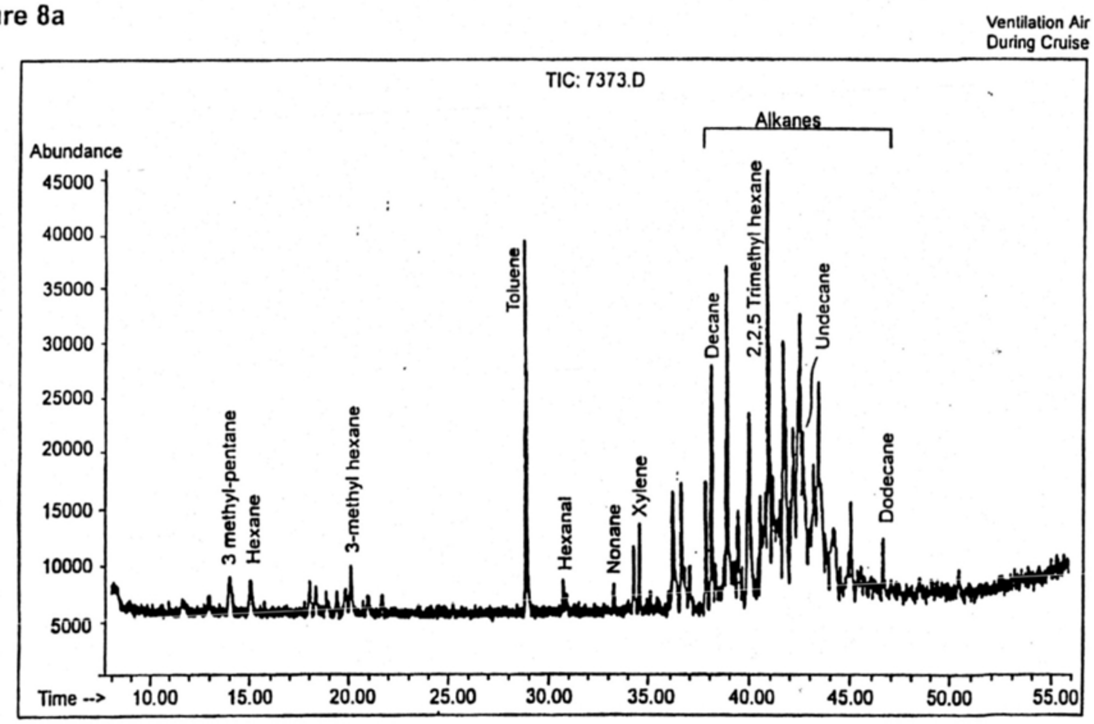


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Figure 8 Gasper air chromatogram. TVOC = 270 :g/m^3 (200 :g/m^3 in 3/4 atmosphere cabin air).

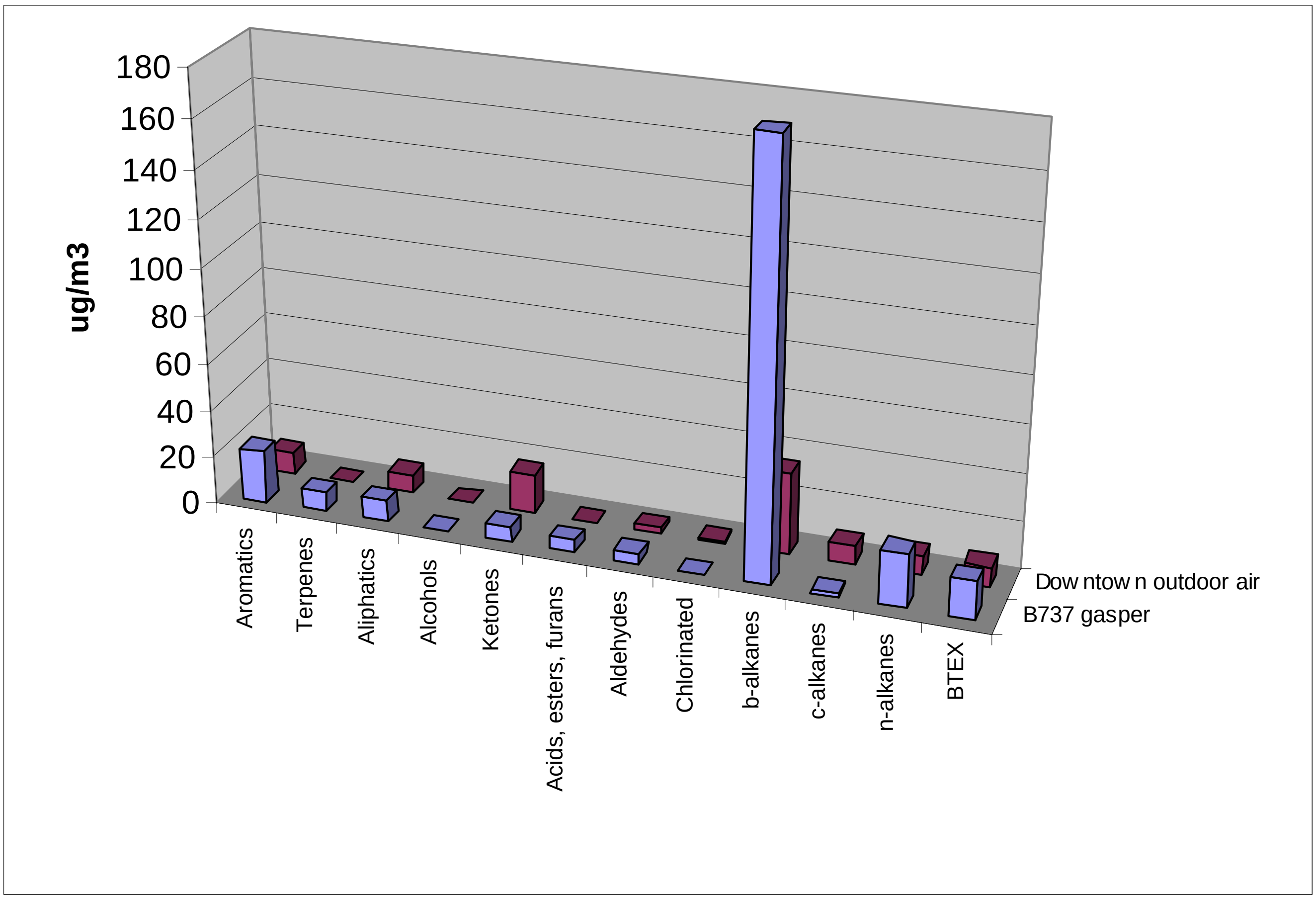

Figure 8 Comparison of B737-200 Test gasper air (bleed air) VOCs with outdoor air in downtown Ottawa

Envelope VOCs

Envelope VOCs were measured behind the liner while the aircraft was on the runway. Branched alkane concentrations were much higher in the envelope sample than in the gasper air or in typical building findings. The chromatogram for the envelope air sample with some other VOC findings is shown in Figure 9. A comparison of the gasper and envelope air samples is provided in Figure 10.

The individual VOC compounds identified and their concentrations are provided in Appendix

Figure 8b

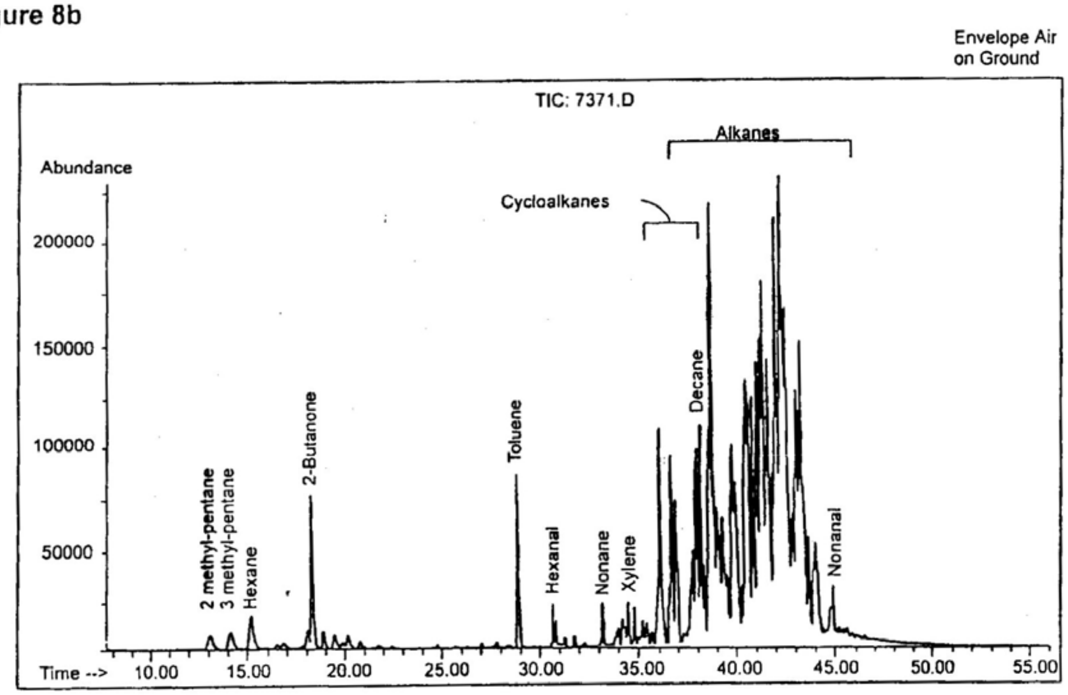

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Figure 9 B737-200 envelope air on the ground with plane exposed to a strong sun, just prior to take off. TVOC = 22,100 :g/m^3. Envelope temperature = 35C

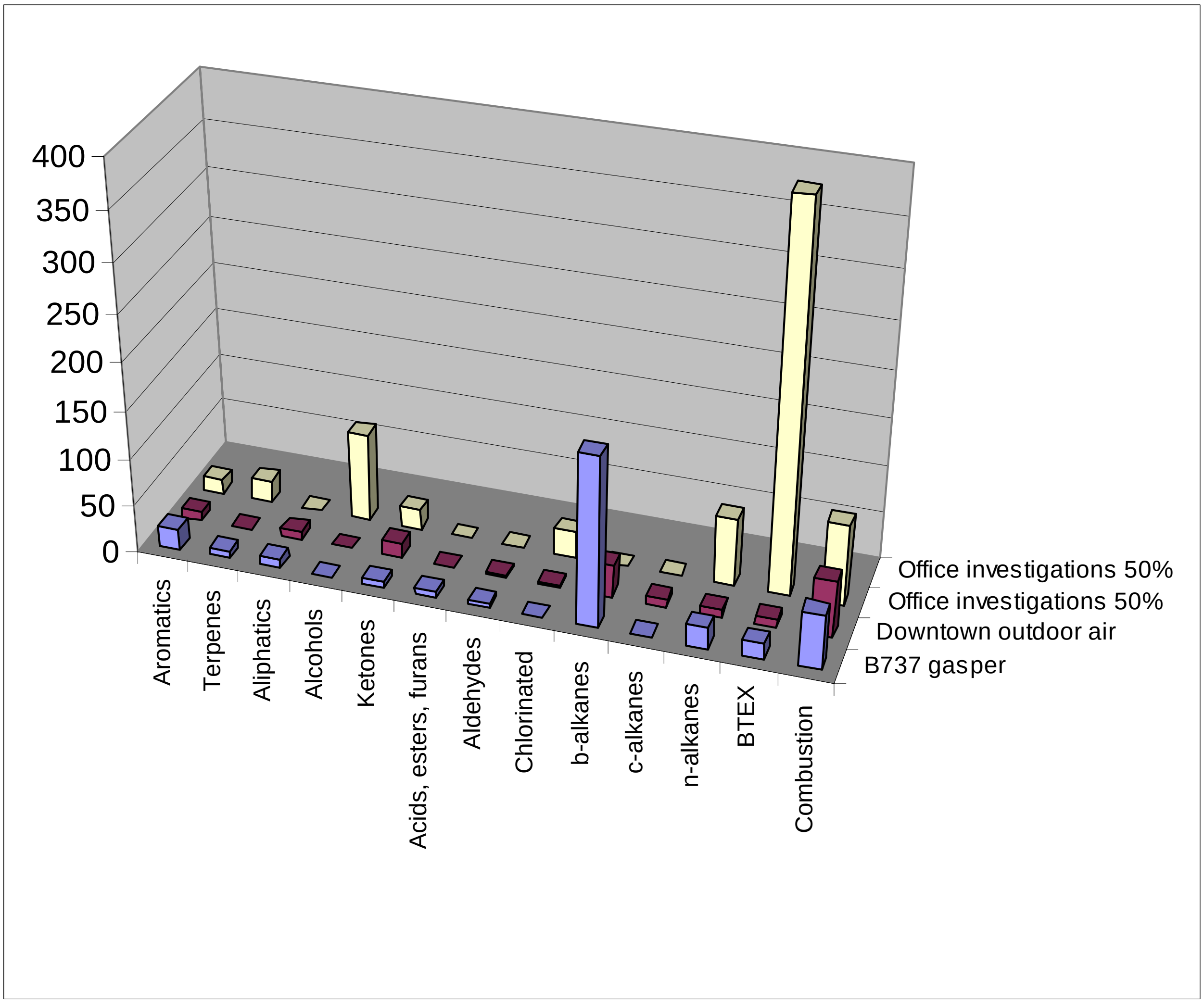

Figure 10 Comparison of B737 test envelope and gasper VOC subgroups with VOCs in building investigations, a new office building and a downtown outdoor air sample

4.0 DISCUSSION

4.1. Pressures and flows

The variation of ground test findings on pressure vs injection rate suggests some changes in test section leakage characteristics between test dates. Temperature could have been a factor in this, with some ground tests conducted outdoors and some in the hangar. The injection rate/pressure relationship, while apparently linear at the pressure range tested, needs further investigation at the design injection flows.

The 27 % reduction in envelope pressurization after accounting for stack effect pressurization of the test section vs on the ground corresponds to the air pressure reduction (1 atmosphere to 3/4 atmosphere). This finding confirms that ground testing can be used to establish design ECHO Air injection rates.

The stack pressure of 0.7 Pa at the crown and floor of the cabin with a temperature of 0 C behind the insulation and a cabin temperature of 22 C is 77% of the theoretical maximum for this temperature difference and the cabin geometry (i.e. 0.9 pa). On this basis, stack induced envelope depressurization at the crown and pressurization at the floor would be ~ 2.3 Pa at the extreme envelope 'cold soak' temperature (-50 C) vs 3.1 Pa theoretical maximum.

Introduction of a mid-height flow blocker on the starboard side reduced stack pressure by a bout one-half (i.e. to 37% of the theoretical maximum).

- B737-2000 system design parameters:
    - Design injection rates to offset an average stack pressure of 1.5 Pa above the neutral plane with no flow blocker (average stack pressure is projected to be 1.2 Pa = 2.3 Pa/2 drawing air into the envelope. The extra 25% pressure allowance is for less than optimum injection flow created pressures above the neutral plane) and 1 Pa above the two neutral planes with a mid-height flow blocker.
    - Seal obvious openings at cabin liner discontinuities (e.g. at the stowage bin).
    - Supply an injection flow rate of 3 CFM/p for envelope sections to be pressurized with no flow blocker and 2 CFM/p for envelope sections to be pressurized with one mid-height flow blocker.
    - Supply injection air in the top half of sections between flow blockers, or between a flow blocker and crown. Provide injectors in every second stringer space circumferentially and every 8^{th} frame station longitudinally.

- Discussion

    - The design envelope air injection rates to avoid moisture problems are well within regulatory cabin ventilation requirements (i.e., 10 CFM/p to 15 CFM/p, depending upon jurisdiction). Higher injection rates provide improved cabin air quality and ingestion incidence avoidance but are unnecessary for moisture problem prevention.

    - Injection at lower rates than design, or where there are obvious liner openings, will still reduce moisture problems.

    - Installation of envelope exhaust dampers which are opened during take-off will substantially reduce cabin air contamination by the envelope VOCs identified in these tests.

    - The system will reduce the entry into the cabin of the combustion VOCs identified in the gasper air in these tests through envelope VOC sorption.

    - Replacement of the anti-corrosion fuselage treatment used in this plane by an system designed treatment will decrease cabin VOC concentrations both on the ground and in flight.

    - To allow for variations in profiles between aircraft of a given model, 3 CFM/p injected into the upper half of the cabin envelope should prevent cabin air inflow on transcontinental flights while a 1 CFM/p injection should be sufficient on regional flights. Injection at lower rates will reduce cabin air inflow rates and associated moisture problems proportionately. These injection rates are well within regulatory cabin ventilation requirements (i.e., 7.5 CFM/p).

    - Based on the flow restriction findings, ECHO Air injection locations behind the insulation should perhaps be at every 8th frame station between every stringer in the crown area and between every other stringer approaching the stowage bin level.

4.2 Volatile Organic Compounds (VOCs

Gasper Air

The dominant branched alkanes are typically associated with fuels and solvents (see for example the jet fuel chromatogram in Figure 11 (Figure 9b in USA patent)). Their origin could have been the oil coating the ducts acting as a sorbent of, for

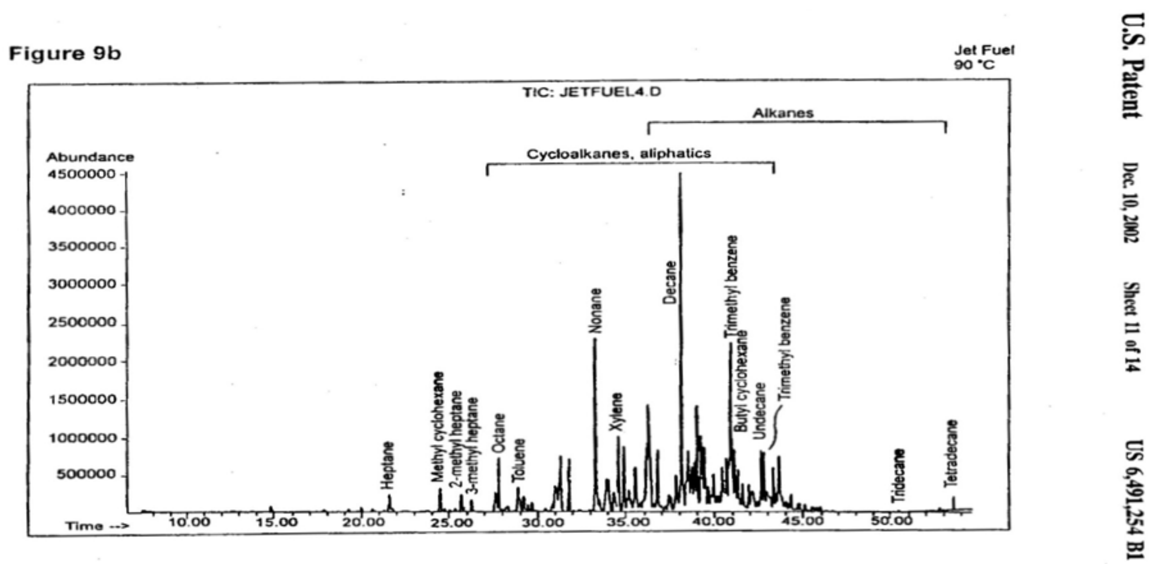

Figure 11 Jet fuel head space GC/MS chromatogram

example, earlier ingested engine exhaust fumes.

The gasper air TVOC concentration of benzene, toluene, ethyl benzene and xylene (BTEX) compounds constituted 6% of the gasper air VOCs, while all compounds known to possibly originate with combustion comprised 22% of gasper air VOCs. These findings point to a combustion source(s) as the main contributor to the gasper air VOCs. Such combustion aerosols will typically contain semi-volatile organic compounds, some of which will be carcinogens, as well as volatile organic compounds. Pyrolysis of lubricating oils typically will contain organo-phosphate additive SVOCs which are toxigenic.

Since the gasper air sample was taken during flight, the possibility of engine exhaust ingestion seems remote. A more likely possibility is the desorption of combustion gases previously ingested at airports and sorbed by the oil coating the ducts. Such in-flight desorption is more likely the older and therefore the oilier the ducts. Oil coatings can result from the ingestion of oil aerosols from lubricating oil leaks which has been reported by others. ECHO air re-routing of some or all of the ventilation air through the envelope will reduce such offgasing during flight. Through envelope fuselage cold surface coating sorption.

Envelope VOCs

The primary origin of the envelope VOCs appeared to be the freshly applied anti-corrosion treatment (Ultra-lite lube), the head space GC/MS chromatogram for which

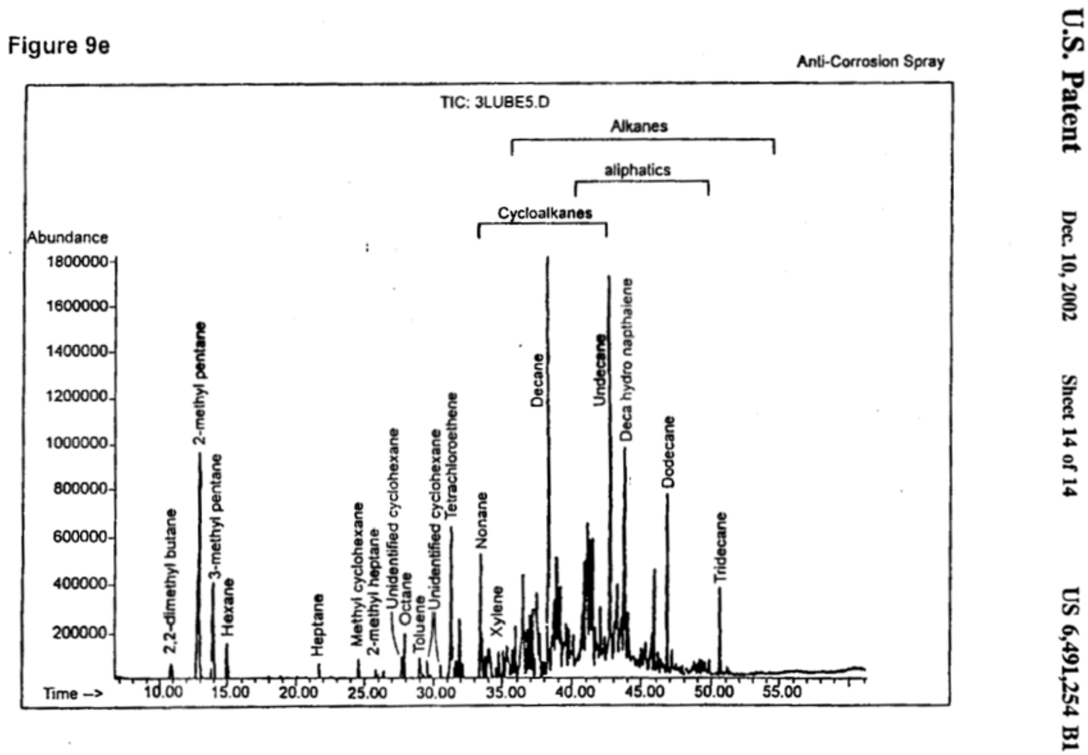

Figure 12 Anti-corrosion spray (Ultra-lite lube) head space GC/MS chromatogram

is provided in Figure 12.

Ingestion of these envelope VOCs into the cabin will be highest on the ground and during take-off when the cabin is being depressurized and the envelope is at ground level temperatures. It will be worse in cabins where air is recirculated. Such ingestion will be eliminated during take off and ascent by the operation of the ECHO Air envelope exhaust system at that time. Ingestion of envelope VOCs could continue during cruising flight, particularly if there is recirculation of cabin air, depending upon the oil coating characteristics with and without envelope pressurization. If so, this In-flight coating off-gassing can be eliminated with the proposed ECHO Air fuselage coating.

BTEX compounds constituted 2.3% of the envelope air VOCs, while all compounds known to possibly originate with combustion comprised 9.5 % of envelope VOCs. These findings indicate that combustion pollutants were also a source. As no combustion sources were present at the time of the test, combustion VOCs were likely desorbing from the anti-corrosion oil coating the fuselage, having being absorbed in this coating during previous on the ground engine exhaust ingestion incidents.

Envelope air also had a high quantity of microbial VOCs. Likely these originated in the insulation bags which were well worn and presumably as old as the aircraft itself.

Other VOC sources

Head space GC/MS chromatograms are provided in Figures 13, 14 and 15 for a number of other potential volatile and semi-volatile fluids used in the test aircraft.

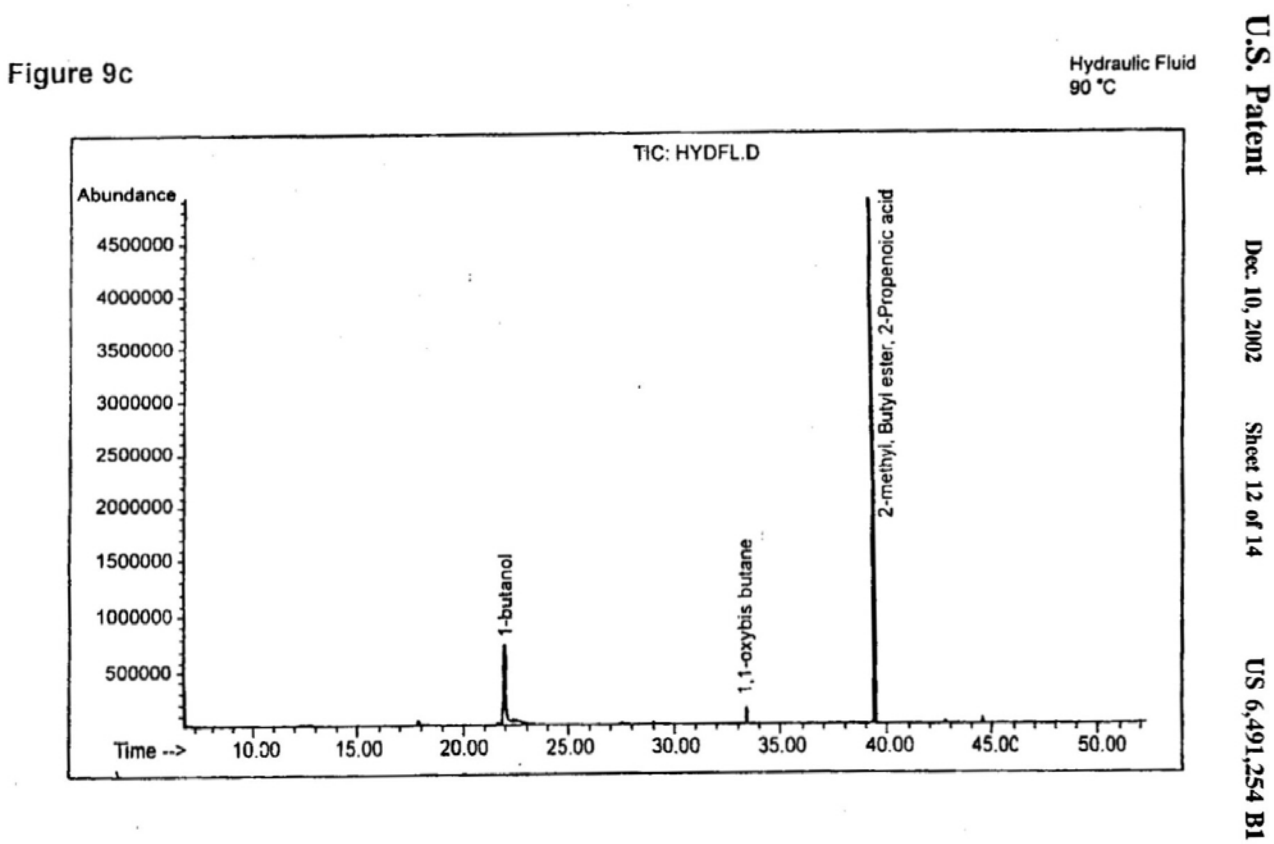

Figure 13 Head space GC/MS chromatogram of the test aircraft hydraulic fluid

Figure 9a

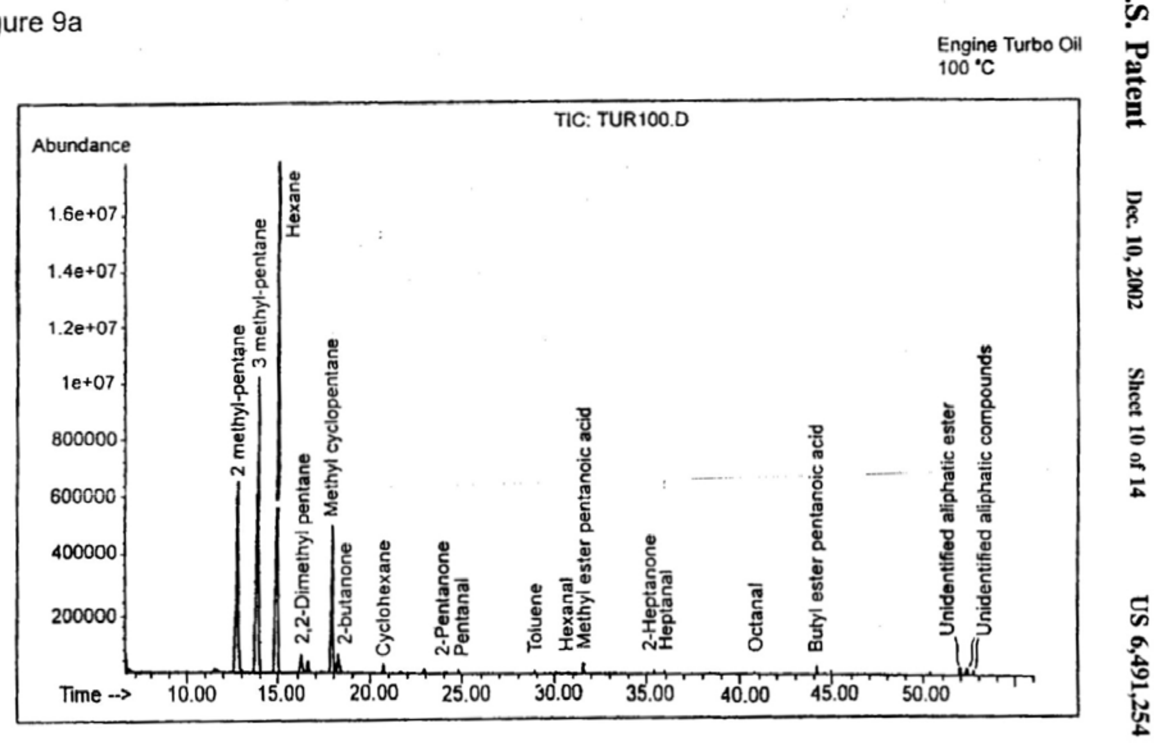

Figure 14 Head space GC/MS chromatogram of the test plane engine turbine lubrication oil

Figure 9d

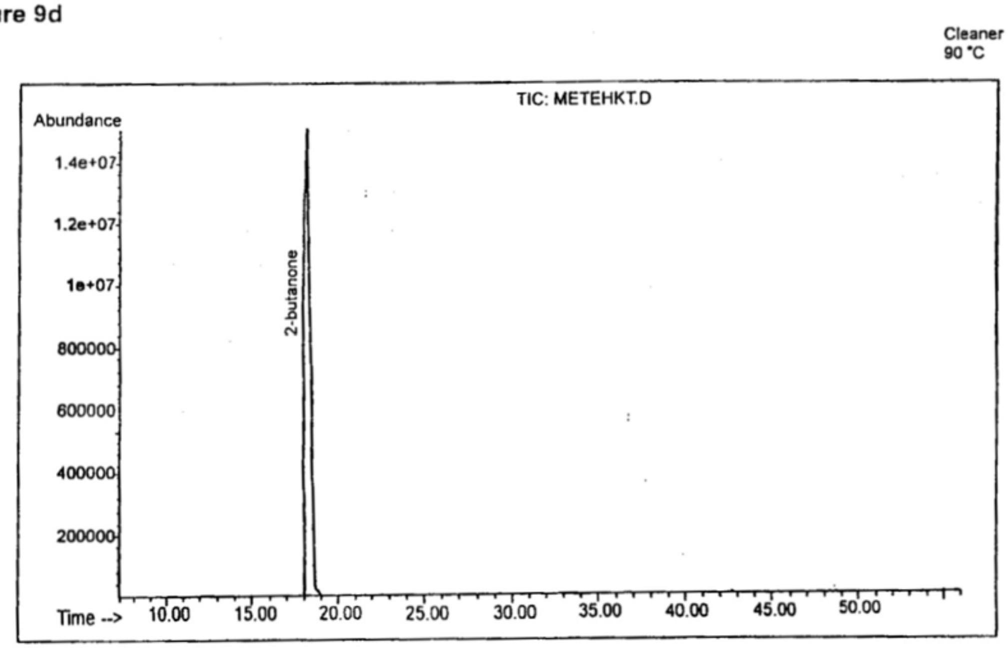

Figure 15 Head space GC/MS chromatogram of a general purpose cleaner used in test aircraft the cabin.

5.0 CONCLUSIONS

1. ECHO Air ventilation air injection parameters (positions in the envelope and injection rates at these points) can be optimized for particular aircraft using ground air flow/pressure measurements and in flight stack pressure/temperature measurements.

2. Seal obvious openings at cabin liner discontinuities (e.g. at the stowage bin) and design injection rates to offset stack pressure of 1.5 Pa with no flow blocker and 1 Pa with a mid-height flow blocker.

3. ECHO Air envelope pressurization sufficient to fully prevent cabin air ingestion due to stack pressures during flight can be achieved in this aircraft type for flows of 3 CFM/p when injected between the crown and the stowage bin, and 2 CFM/p with a mid height flow blocker and injection areas from the crown to half-way to the stowage bin, and halfway above the floor to the stowage bin.

4. These injection rates are well within proposed and current regulatory cabin ventilation (outdoor air) requirements (i.e., 7.5 CFM/p to 10 CFM/p at 8000 ft (3/4 atmosphere) cabin pressure).

5. Injection at lower rates will reduce cabin air inflow rates and associated moisture problems proportionately.

6. Injection between the insulation and the skin encounters little longitudinal flow restriction. However, circumferential flow is restricted by stringers. Hence, where there is no flow blocker, injection points between the insulation and the skin should be at perhaps every 8^{th} frame station, and between every stringer in the crown area and every other stringer approaching the the stowage bin.

7. In general, supply injection air in the top half of sections between flow blockers, or between a flow blocker and crown. Provide injectors in every second stringer space circumferentially and every 8^{th} frame station longitudinally.

8. ECHO Air envelope exhausting on the runway and during take-off and ascent when the envelope is potentially the warmest, will reduce cabin air pollution from anti-corrosion treatment VOCs and other VOCs they tend to sorb.

9. ECHO Air bleed air circulation through the envelope could reduce SVOCs that may be in the bleed air as well as some of the VOC contaminants measured in the bleed air, which is used to ventilate the cabin.

10. Replacement of the anti-corrosion fuselage treatment used in this plane by appropriate absorbents will decrease cabin VOC concentrations both on the ground and in flight.

APPENDIX A

DATA COLLECTION

A.1 Data collection

Pressure differences and air velocities were measured with a micro manometer and Pitot tubes.[1]

Volatile organic compounds (VOCs) were collected on three part sorbent tubes at 250 cc/m. The compounds on the sorbents were thermally desorbed, identified and their concentrations estimated using gas chromatography/mass spectroscopy (GC/MS).[2]

[1] Air Neotronics MPTS20S digital micro manometer, serial no. 9097. Accuracy better than 1% of reading. Reading from 0 Pa in 0.1 Pa increments.

[2] Air was sampled at 250 cc/min (normally for 20 min) through an 18 cm long thermal desorption tube packed with Carbotrap C, Carbotrap B and Carboseive S-III.

VOC's collected by the sorbents were released thermally under a flow of helium using a Tekmar 3000 Desorber Accessory kit attached to an HP purge and trap concentrator, and injected into a Supelco Vocol bonded phase capillary column (60 m long, 0.25 mm ID) for analysis using an HP G1800A GCD GC/MS.

The mass spectrum of each detected VOC was searched using the Wiley 138K mass spectral library and the total ion chromatogram plotted. Total VOC concentration is calculated using the area of the total ion chromatogram calibrated against cyclohexane. The cyclohexane standard is prepared as follows: the same desorption tube used for sampling is reconditioned. The sampling inlet end of the tube is then attached to a glass tube packed with a small amount of glass wool onto which 10 :l of a 1 mg/ml cyclohexane in methanol standard was deposited (total of 10 :g cyclohexane). The sampling outlet end of the tube is connected to a pump with a flow rate of 250 cc/min. for the same time as the sampling time. Thus the 10 :g cyclohexane is drawn through the desorption tube under the same conditions used for sampling.

Individual VOC concentrations are estimated from their areas in the total ion chromatogram as a percent of the TVOC concentration.

APPENDIX B

PHOTOGRAPHS

Figure B.1 View of the B737 cabin interior showing port and starboard cabin envelope sensor tubing

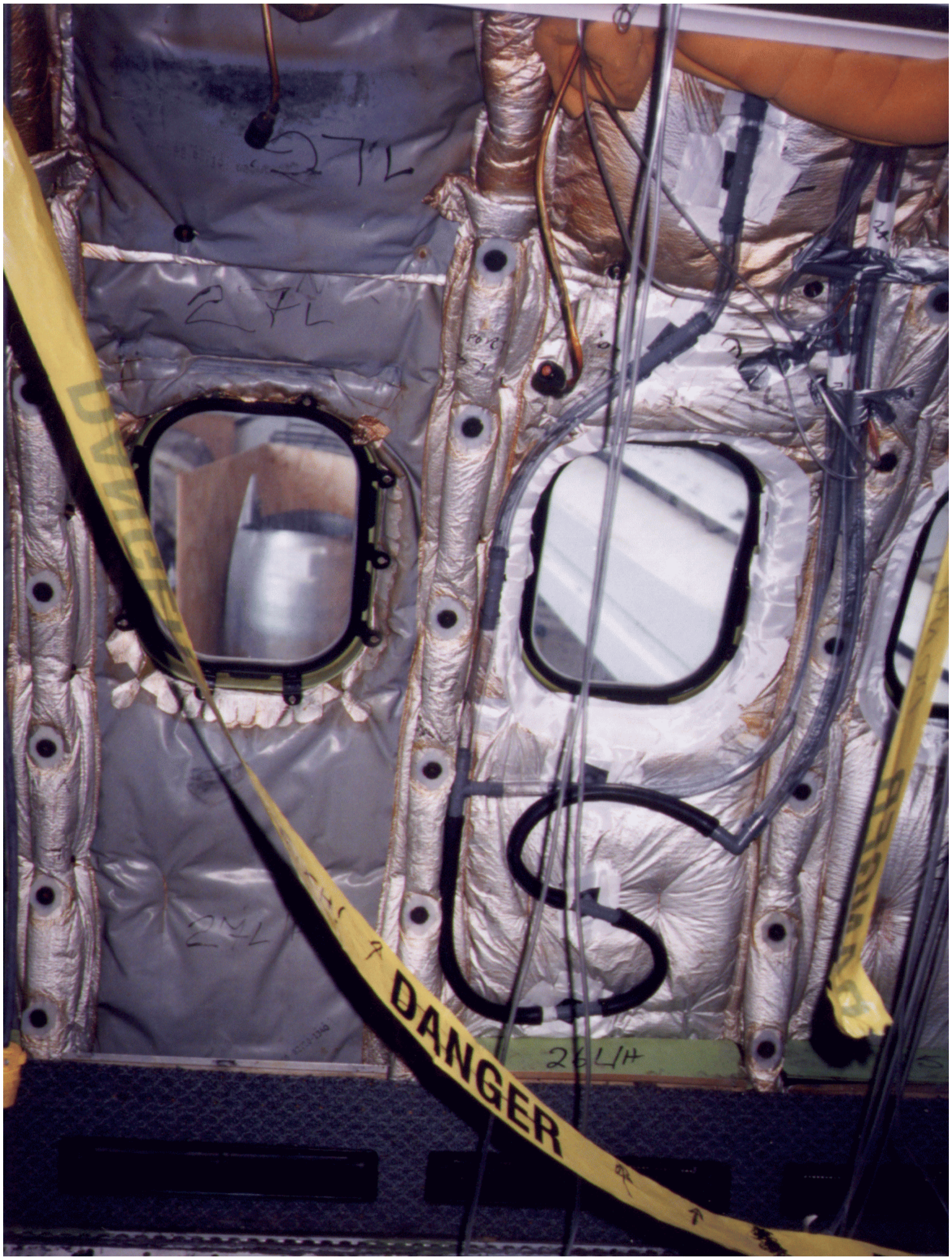

Figure B.2 View of 3/4"ID PVC injection tubing behind the B737 cabin insulation

Figure B.3 View of 3/4"ID PVC injection air tubes, 1/4" and 3/16" ID PVC pressure and VOC sampling tubes between the B737 cabin insulation and liner

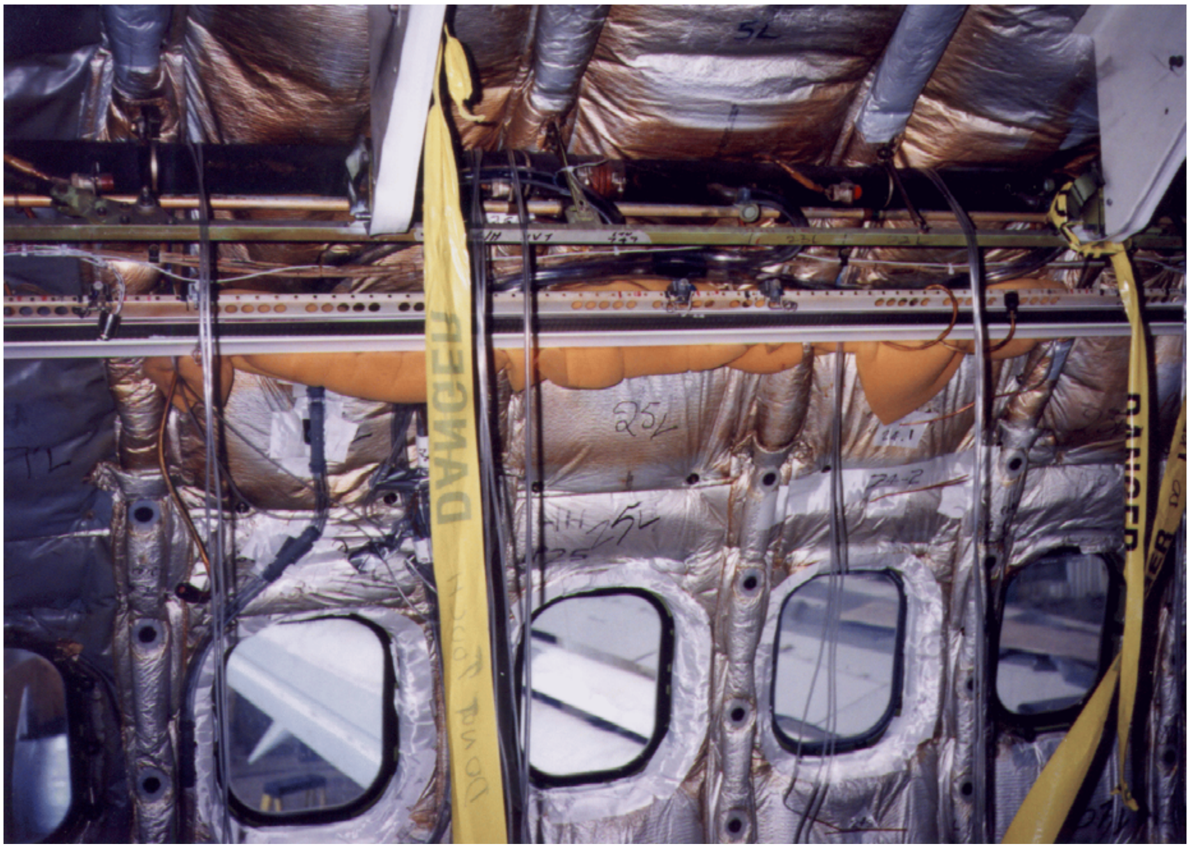

Figure B.4 View of the B737 Sections 24, 25 and 26 (port side) injection air tubes, pressure and VOC sampling tubes, and Section 22 pressure sampling tubes with the cabin liner and stowage bins removed

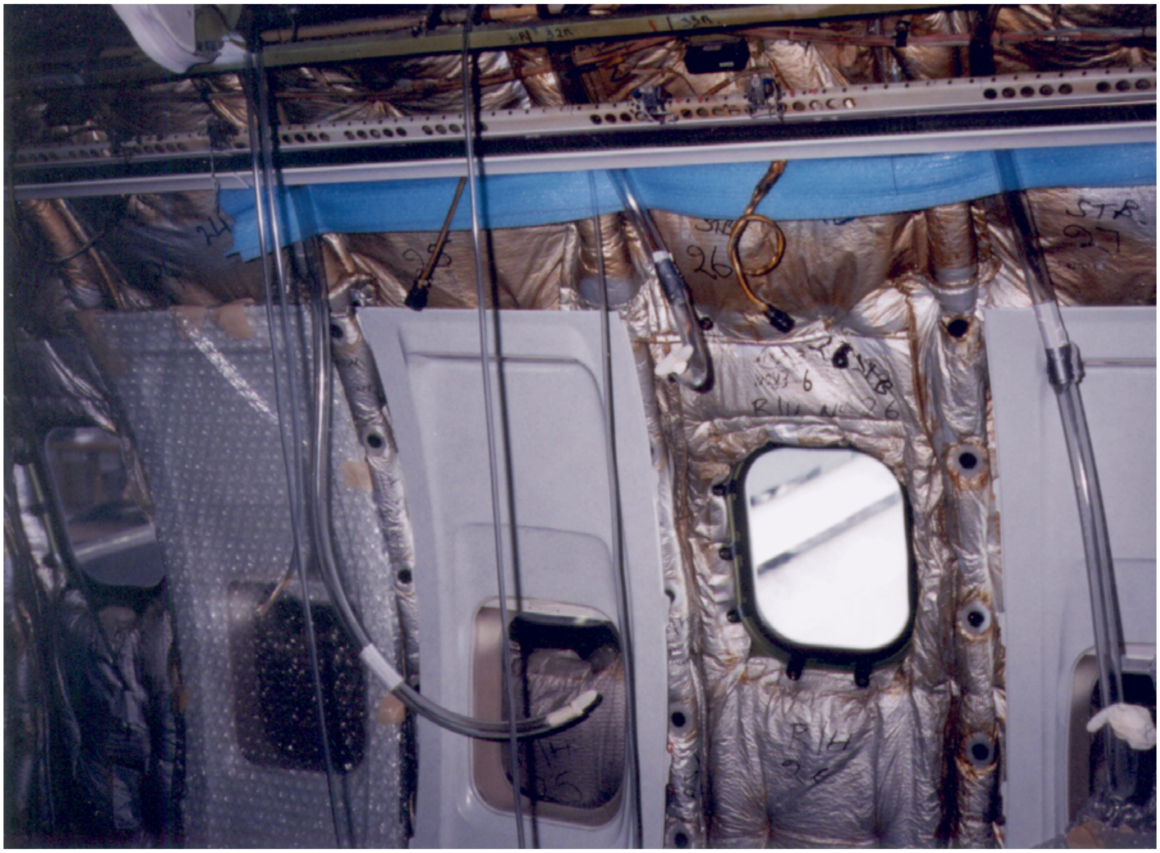

Figure B.5 View of the B737 Sections 24, 25 and 26 (port side) injection air tubes, pressure and VOC sampling tubes, and Section 22 pressure sampling tubes with the cabin stowage bins removed

APPENDIX C

PRESSURE VS INJECTION RATE DATA

Table C.1 Port side ground test, 11 June 1998

TEST 11 June'98		*GROUND*	*PORT SIDE*				
PRESSURES (envelope-cabin)			ENVELOPE S/A				
Section	Location	pressure (Pa)	Location	Section		Tube dia.	Injection rate
					inches	fpm	cfm
24	1	6.8	1 to 5	24	0.75	4300	13.2
24	2	8.9	1 to 5	25	0.75	5450	16.7
24	3	8.3	1 to 5	26	0.75	6300	19.3
24	4	8.1					
24	5	8.1					
				Total			49.2
Average		8.0					
Median		8.1					
Standard deviation		0.8					

Table C.2 Port side ground test, 10:40 h, 19 June 1998

TEST 19 June'98		*GROUND*	*PORT SIDE*	*10:40 h*			
		Temp in cabin = 28 C, behind insulation = 27 C at 16:30 h					
PRESSURES (envelope-cabin)			ENVELOPE S/A				
Section	Location	Pressure	Location	Section	Tube dia.		Injection rate
		Pa			inches	fpm	cfm
24	1	5.0	1 to 5	24	0.75	4340	13.3
24	1	6.2	1 to 5	25	0.75	6200	19.0
24	1	6.8	1 to 5	26	0.75	6920	21.2
24	1	7.0					
24	1	7.2					
				Total			53.6
Average		6.4					
Median		6.8					
Standard deviation		0.9					

Table C.3 Port side ground test, 10:51 h, 19 June 1998

TEST 19 June'98		***GROUND***	***PORT SIDE***	***10:51 h***			
		Temp in cabin = 28 C, behind insulation = 27 C at 16:30 h					
PRESSURES (envelope-cabin)			**ENVELOPE S/A**				
Section	**Location**	**Pressure**	**Location**	**Section**	**Tube dia.**		**Injection rate**
		Pa			inches	fpm	**cfm**
24	**2**	**6.1**	**1 to 5**	**24**	0.75	0	**0.0**
24	**4**	**7.0**	**1 to 5**	**25**	0.75	0	**0.0**
25	**2**	**5.7**	**1 to 5**	**26**	0.75	6920	**21.2**
25	**4**	**7.2**					
26	**2**	**5.8**					
26	**4**	**6.1**					
				Total			**21.2**
Average		**6.3**					
Median		**6.1**					
Standard deviation		**0.6**					

Table C.4 Port side ground test, 14:35 h, 19 June 1998

TEST 19 June'98		***GROUND***	***PORT SIDE***	***14:35 h***			
		Temp in cabin = 28 C, behind insulation = 27 C at 16:30 h					
PRESSURES (envelope-cabin)			**ENVELOPE S/A**				
Section	**Location**	**Pressure**	**Location**	**Section**	**Tube dia.**		**Injection rate**
		Pa			inches	fpm	**cfm**
24	**1**	**0.3**	**5**	**24**	0.75	1420	**4.4**
24	**2**	**0.4**	**5**	**25**	0.75	1850	**5.7**
24	**3**	**1.6**	**5**	**26**	0.75	1070	**3.3**
24	**4**	**1.8**					
24	**5**	**4.0**					
				Total			**13.3**
Average		**1.6**					
Median		**1.6**					
Standard deviation		**1.5**					

Table C.5 Port side ground test, 15:05 h, 19 June 1998

TEST 19 June'98		*GROUND*	*PORT SIDE*		*15:05 h*			
		Temp in cabin = 28 C, behind insulation = 27 C at 16:30 h						
PRESSURES (envelope-cabin)				**ENVELOPE S/A**				
Section	**Location**	**Pressure**		**Location**	**Section**	**Tube dia.**		**Injection rate**
		Pa				inches	fpm	**cfm**
24	**1**	**4.8**		**1 to 5**	**24**	0.75	5120	**15.7**
24	**2**	**5.8**		**1 to 5**	**25**	0.75	4530	**13.9**
24	**3**	**6.8**		**1 to 5**	**26**	0.75	7630	**23.4**
24	**4**	**6.9**						
24	**5**	**7.0**						
					Total			**53.0**
Average		**6.3**						
Median		**6.8**						
Standard deviation		**0.9**						

Table C.6 Starboard side ground test, 15:20 h, 19 June 1998

TEST 19 June'98		*GROUND*	*STARBOARD SIDE*		*15:20 h*			
		Temp in cabin = 28 C, behind insulation = 27 C at 16:30 h						
PRESSURES (envelope-cabin)				**ENVELOPE S/A**				
Section	**Location**	**Pressure**		**Location**	**Section**	**Tube dia.**		**Injection rate**
		Pa				inches	fpm	**cfm**
25				**3**	**25**	0.75	6710	**20.6**
26	**3**	**4.9**		**2**	**26**	0.75	6260	**19.2**
27	**3**	**7.1**		**3**	**27**	0.75	7150	**21.9**
					Total			**61.7**
Average		**6.0**						
Median		**6.0**						
Standard deviation		**1.6**						

Table C.7 Port side ground test, 13:30 h, 20 June 1998

TEST 20 June'98		*GROUND*	*PORT SIDE*		*13:30 h*			
		Temp in cabin = 21.8 C, behind insulation = 32.3 C at 13:30 h						
PRESSURES (envelope-cabin)				**ENVELOPE S/A**				
Section	**Location**	**Pressure**		**Location**	**Section**	**Tube dia.**		**Injection rate**
		Pa				inches	fpm	**cfm**
24	**1**	**4.1**		**1 to 5**	**24**	0.75	4510	**13.8**
24	**2**	**4.6**		**1 to 5**	**25**	0.75	5070	**15.6**
24	**3**	**4.6**		**1 to 5**	**26**	0.75	7750	**23.8**
24	**4**	**5.2**						
24	**5**	**5.1**						
					Total			**53.2**
Average		**4.7**						
Median		**4.6**						
Standard deviation		**0.4**						

Table C.8 Starboard side ground test, 13:40 h, 20 June 1998

TEST 20 June'98		*GROUND*	*STARBOARD SIDE*		*13:40 h*			
		Temp in cabin = 21.8 C, behind insulation = 32.3 C at 13:30 h						
PRESSURES (envelope-cabin)				**ENVELOPE S/A**				
Section	**Location**	**Pressure**		**Location**	**Section**	**Tube dia.**		**Injection rate**
		Pa				inches	fpm	**cfm**
25				**3**	**25**	0.75	6570	**20.2**
26	**3**	**4.0**		**2**	**26**	0.75	6050	**18.6**
27	**3**	**6.1**		**3**	**27**	0.75	6960	**21.4**
					Total			**60.1**
Average		**5.1**						
Median		**5.1**						
Standard deviation		**1.5**						

Table C.9 Port side ground test, 14:10 h, 20 June 1998

TEST 20 June'98		*GROUND*	*PORT SIDE*		*14:10 h*			
Temp in cabin = 21.8 C, behind insulation = 32.3 C								
PRESSURES (envelope-cabin)				ENVELOPE S/A				
Section	Location	Pressure		Location	Section	Tube dia.		Injection rate
		Pa				inches	fpm	cfm
24	1	1.1		1 to 5	24	0.75	1320	4.0
24	2	1.4		1 to 5	25	0.75	1530	4.7
24	3	2.5		1 to 5	26	0.75	2160	6.6
24	4	1.6						
24	5	1.6						
					Total			15.4
Average		1.6						
Median		1.6						
Standard deviation		0.5						

Table C.10 Starboard side ground test, 14:20 h, 20 June 1998

TEST 20 June'98		*GROUND*	*STARBOARD SIDE*		*14:20 h*			
		Temp in cabin = 21.8 C, behind insulation = 32.3 C at 13:30 h						
PRESSURES (envelope-cabin)				ENVELOPE S/A				
Section	Location	Pressure		Location	Section	Tube dia.		Injection rate
		Pa				inches	fpm	cfm
25				3	25	0.75	2000	6.1
26	3	0.8		2	26	0.75	1810	5.6
27	3	1.6		3	27	0.75	2080	6.4
					Total			18.1
Average		1.2						
Median		1.2						
Standard deviation		0.6						

Table C.11 Starboard side flight test, 16:33 h, 20 June 1998

TEST 20 June'98		*FLIGHT*	*STARBOARD SIDE*	*16:33 h*			*Ambient air at 28,000 ft -34 C*
		Stack pressure = 0.5 to 0.7 Pa at the floor, T = -1 to + 6 C behind the insulation and 22-26 C in the cabin					
PRESSURES (envelope-cabin)			ENVELOPE S/A				*2 packs + gasper fan*
Section	Location	Pressure	Location	Section	Tube dia.		Injection rate
		Pa			inches	fpm	cfm
25			3	25	0.75	7400	22.7
26	3	7.0	2	26	0.75	6860	21.0
27	3	4.1	3	27	0.75	7930	24.3
				Total			68.1
Average		5.6					
Median		5.6					
Standard deviation		2.1					
Average - stack		5.0					

Table C.12 Port side flight test, 16:38 h, 20 June 1998

TEST 20 June'98		*FLGHT*	*PORT SIDE*	*16:38 h*			*Ambient air at 28,000 ft -34 C*
		Stack pressure = 0.5 to 0.7 Pa at the floor, T = -1 to + 6 C behind the insulation and 22-26 C n the cabin					
PRESSURES (envelope-cabin)			ENVELOPE S/A				*2 packs + gasper fan*
Section	Location	Pressure	Location	Section	Tube dia.		Injection rate
		Pa			inches	fpm	cfm
24	1	4.5	1 to 5	24	0.75	5920	18.2
24	2	5.0	1 to 5	25	0.75	8890	27.3
24	3	4.3	1 to 5	26	0.75	5190	15.9
24	4	5.5					
24	5	5.4					
				Total			61.4
Average		4.9					
Median		5.0					
Standard deviation		0.5					
Average - stack		4.3					

APPENDIX D

INDIVIDUAL VOLATILE ORGANIC COMPOUNDS

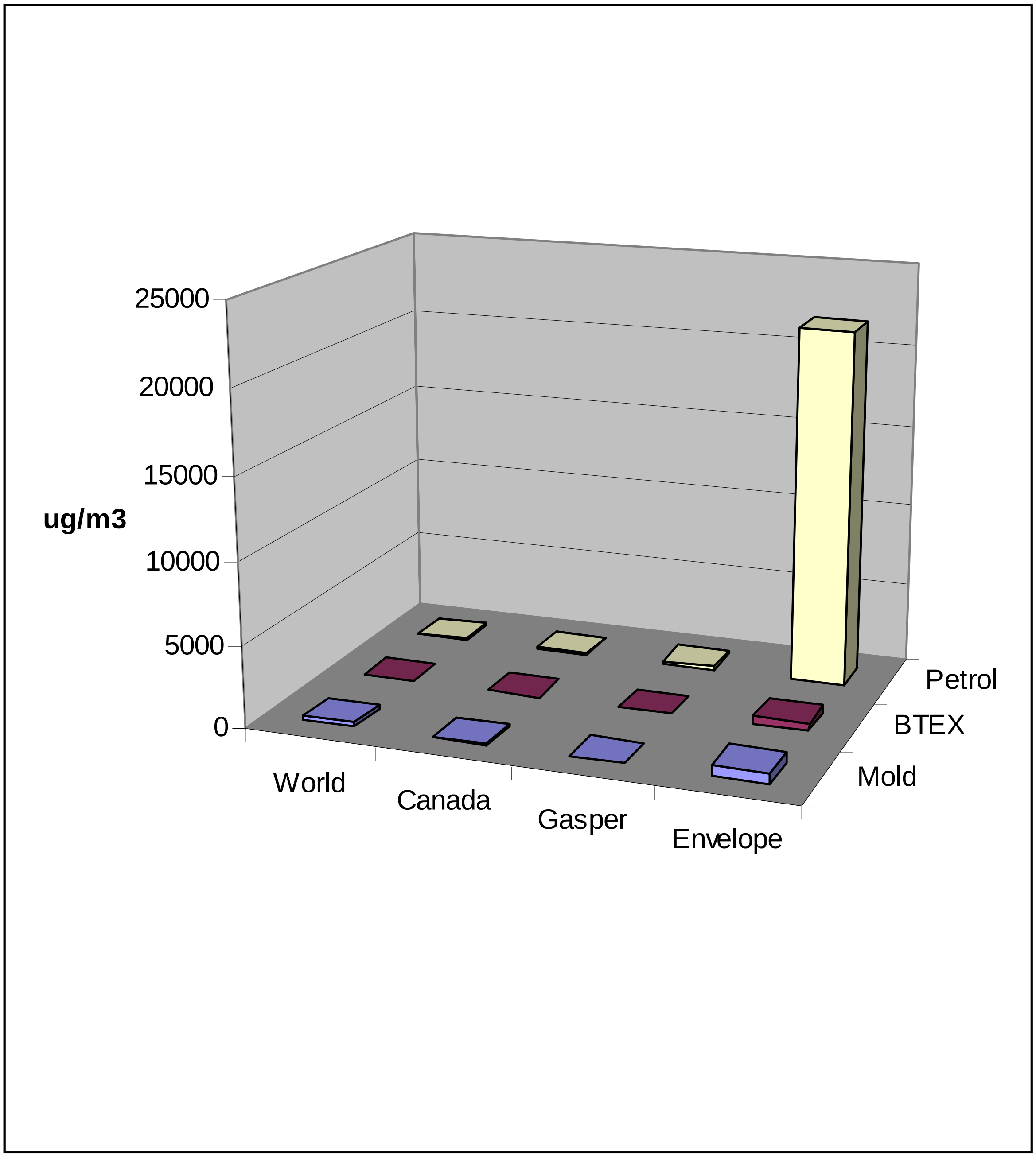

Figure D.1 Sums of Volatile Organic Compounds in Gasper and Envelope possibly originating with mold, BTEX (benzene, toluene, ethyl benzene and xylene), or petroleum/combustion sources vs indoor air norms

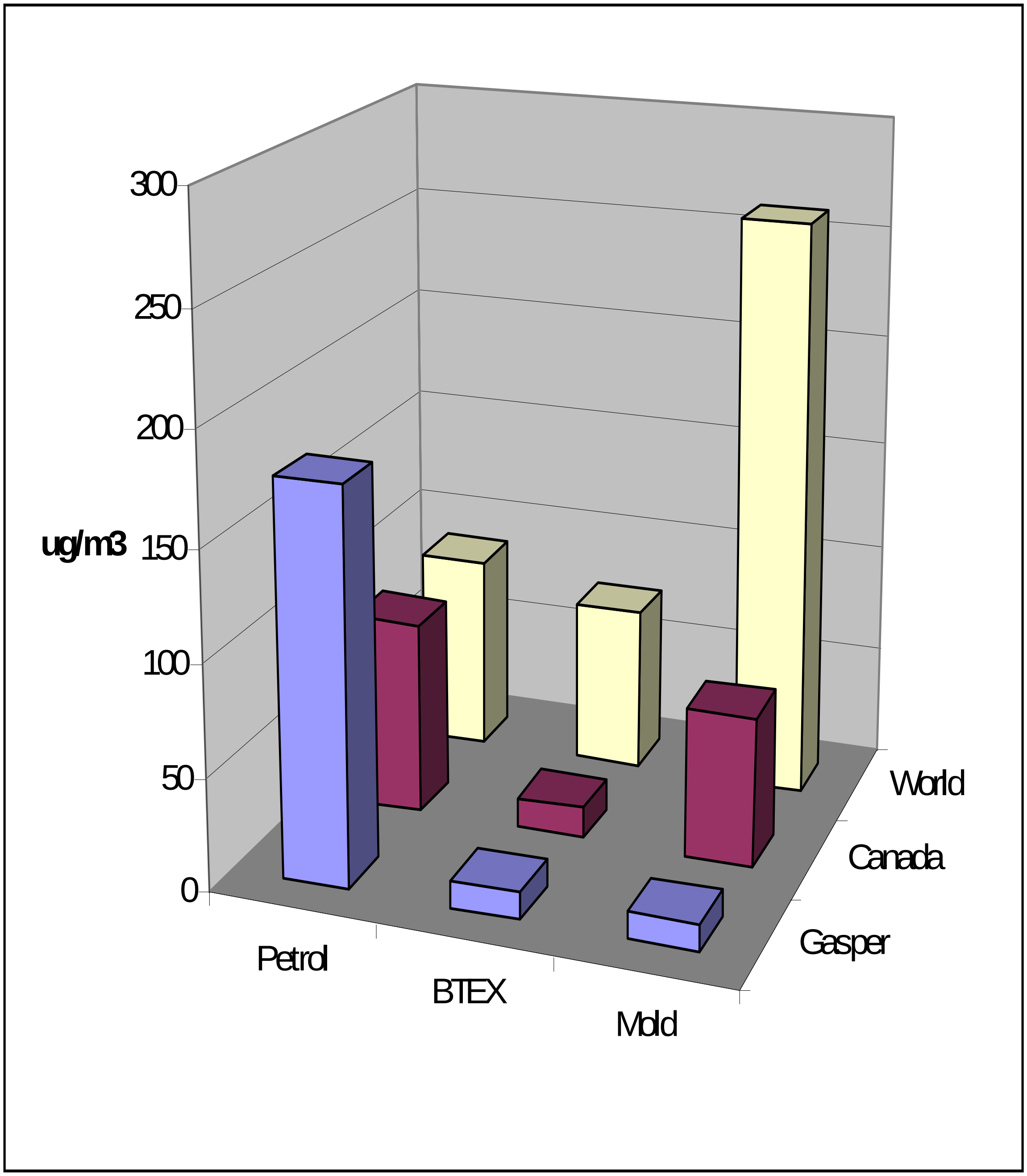

Figure D.2 Sums of Volatile Organic Compounds in Gasper possibly originating with mold, BTEX (benzene, toluene, ethyl benzene and xylene), or petroleum/combustion sources vs indoor air norms

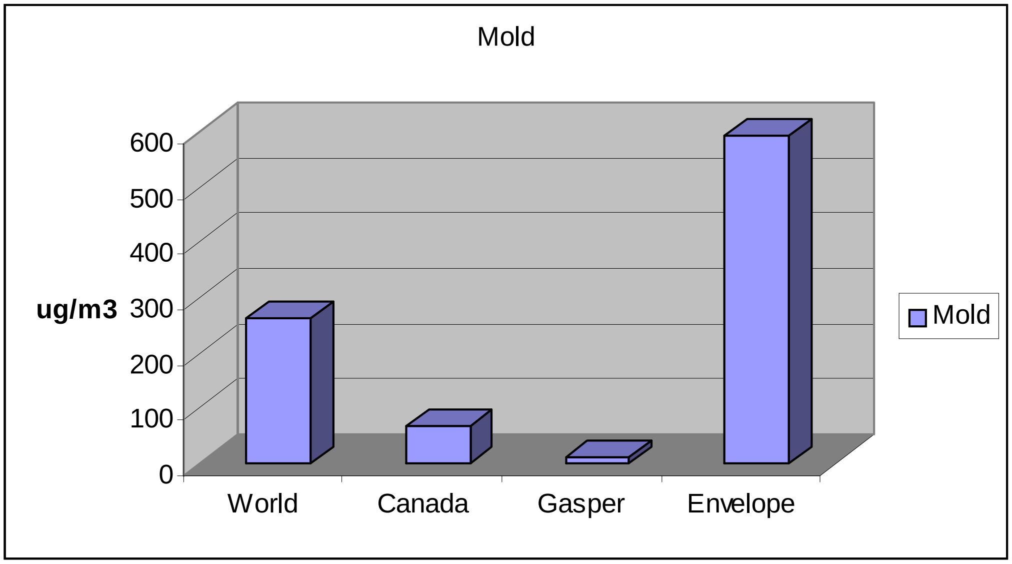

Figure D.3 Sums of Volatile Organic Compounds in Gasper and Envelope possibly originating with mold vs indoor air norms

Table D.1 Comparison of cabin gasper VOCs during cruise (uncorrected for cabin air density of 3/4 atmosphere) and envelope VOCs on the ground with the plane exposed to a strong sun, with some norms, standards and sources

COMPOUND	VOC CONCENTRATIONS (:g/m^3)					
Alternate names ACGIH TLV/10 (:g/m^3) Some origins and sources	**Gasper air during flight** (uncorrected for cabin pressure)	**Cabin envelope on the ground**	**Jet Fuel**	**Ultra-light lube**	**World 1994 [1]** **GM estab. offices**	**Canada 1992 [2]** **50th% office investig.**
TVOC (:g/m^3)	**200**	**22100**			**1,130**	**400**
AROMATIC HYDROCARBONS						
Sub totals	16.4	506.4	0	0	74	15
benzene C6H6 *160*		4.4			8	3.5
Derived from petroleum,. Toxic vapour. Adhesives, solvents, paints, ETS. Mold. Found in outdoor air.						
toluene C7H8 18,800	10.4	373			37	3.5
Derived from naphthenes. Used in autos (high octane gasoline), jet fuel, solvent-based paints, lacquers, ETS, carpet, under carpet, linoleum, vinyl flooring, photocopier, silicone concrete sealer. Found in outdoor air.						
m,o,p-xylenes C8H10 *43,400*	2	109			24	6.8
Derived from naphthenes or coal tar. Used in solvents (solvent-based paints), photo-copiers, ETS lacquers, adhesives, automotive sources (gasoline), jet fuel, silicone concrete sealer. Mold. Outdoor air.						
ethyl benzene CH2CH3 *43,400*		20			5	

COMPOUND	**VOC CONCENTRATIONS (:g/m^3)**					
Alternate names **ACGIH TLV/10 (:g/m^3)** **Some origins and sources**	**Gasper air during flight** **(uncorrected for cabin pressure)**	**Cabin envelope on the ground**	**Jet Fuel**	**Ultra-light lube**	**World 1994** [1] **GM estab. offices**	**Canada 1992** [2] **50th% office investig.**
TVOC (:g/m^3)	**200**	**22100**			**1,130**	**400**
Carpet, under-carpet, ETS, photocopier, jet fuel, gasoline, lacquered furniture finish, silicone concrete sealer. Found in outdoor air.						
butyl benzene						
propylbenzene Jet fuel, gasoline, ETS, silicone concrete sealer						
1-ethyl,(1+2+3+4)-methyl-benzene Jet fuel, gasoline, ETS, silicone concrete sealer. Found in outdoor air.	1.2					
1-methyl-ethyl-benzene Jet fuel, gasoline, silicone concrete sealer						
styrene (*vinyl benzene*) C8H8 8,500 Strong irritant. Sources include carpets, under carpets, photo-copiers, building materials (e.g., polystyrene insulation), combustion byproducts (e.g., ETS)						0.9
4-phenyl cyclohexene (4-PC) Some carpeting						
cumene(isopropylbenzene) C9H12 24,600 Formed by reaction of benzene and propene. Carpeting, caulking						
1-methylethenyl benzene ETS						
1-methylethyl benzene silicone concrete sealer						

COMPOUND	**VOC CONCENTRATIONS (:g/m^3)**					
Alternate names ACGIH TLV/10 (:g/m^3) Some origins and sources	**Gasper air during flight (uncorrected for cabin pressure)**	**Cabin envelope on the ground**	**Jet Fuel**	**Ultra-light lube**	**World 1994** [1] **GM estab. offices**	**Canada 1992** [2] **50th% office investig.**
TVOC (:g/m^3)	**200**	**22100**			**1,130**	**400**
1-hexene Jet fuel, gasoline.						
indane (2,3 dihydo-1-indene) C9H10 ETS, jet fuel, gasoline.						
1,2,3 trimethyl benzene 12,300 Jet fuel, gasoline, some carpet/glue, ETS, silicone concrete sealer.						
1,2,4-trimethyl benzene 12,300 Jet fuel, gasoline, carpet, under-carpet (carpet/glue), building materials, automotive sources, ETS, silicone concrete sealer. Traces in rooftop outdoor air						
1,3,5-trimethyl benzene 12,300 Jet fuel, gasoline, some carpet/glue, ETS, silicone concrete sealer.						
naphthalene C10H8 Gives addition and substitution reactions more readily than benzene. Found in plasticizers, alkyd resins, dyestuffs, ETS, silicone concrete sealer.						
decahydronaphthalene Jet fuel, gasoline, silicone concrete sealer						
methyldecahydronaphthalene silicone concrete sealer						
1,2,3,4 tetrahydronaphthalene silicone concrete sealer						
Unidentified aromatic compounds	2.8					

COMPOUND	VOC CONCENTRATIONS (:g/m^3)					
Alternate names ACGIH TLV/10 (:g/m^3) Some origins and sources	**Gasper air during flight (uncorrected for cabin pressure)**	**Cabin envelope on the ground**	**Jet Fuel**	**Ultra-light lube**	**World 1994 [1]** GM estab. offices	**Canada 1992 [2]** 50th% office investig.
TVOC (:g/m^3)	**200**	**22100**			**1,130**	**400**
Compounds containing a benzene skeleton. ETS. Silicone concrete sealer. Microbial growth (e.g., butylated hydroxytoluene).						
TERPENES (aromatic hydrocarbons)						
Sub totals	6.2	51	0	0	35	23
("+$)-pinene C10H16						4.7
Mold growth. In oils derived from coniferae. Forms terpentine. With sulphuric acid, forms limonene, camphene...						
" terpinene (p-menthadiene) C10H16						
Found in cardamom, majoram, coriander oils. Produced by pinene + sulphuric acid. Lemon smell						
Camphene					14	
Found in citronella, valerian oils, turpentine, ginger, rosemary, and spike oils. Sources include mold.						
Myrcene						
Mold.						
limonene(C10H10) (citrene, carvene)	6.2				21	18
Characteristic lemon odour.Widely use as a masking odour, in cleaners, ETS, deodorant, for example. Other sources include under-carpet and mold (e.g., *A. Versicolor*). Traces in rooftop outdoor air.						
1,3-octadiene, octadiene isomer, octatriene isomer						
Mold (e.g., *A. Versicolor*)						
isoprene						

COMPOUND	**VOC CONCENTRATIONS (:g/m^3)**					
Alternate names **ACGIH TLV/10 (:g/m^3)** **Some origins and sources**	**Gasper air during flight** (uncorrected for cabin pressure)	**Cabin envelope on the ground**	**Jet Fuel**	**Ultra-light lube**	**World 1994** [1] **GM estab. offices**	**Canada 1992** [2] **50th% office investig.**
TVOC (:g/m^3)	**200**	**22100**			**1,130**	**400**
Isoprene polymers used as an elastomer and rubber replacement. Carpet, linoleum, mold (e.g., *A. Versicolor*)						
terpenes unidentified *(e.g., C10H16; C15H22;7C15, a-terpinolene, B-phellandrene, muurolene, ocimene, a-amorphene, aromadendrene, a-copaene, a-farnesene,trans b-farnesene, megastigma-4,6 (E&Z),8(E&Z)-triene...)* -		51				
Unsaturated, very reactive compounds. Characteristic and usually pleasant odours. Usually derived from vegetable products. Pharmaceutical use - eg., eucalyptus oils, camphor, menthol, Perfumes, lemon scents, fire log, mold.						
ALIPHATICS						
Sub totals	6.7	130	0	0	0	0
unidentified aliphatic hydrocarbons	6.7	130				
Fats and fatty acids (carbon atoms arranged in chains, not rings). Found in ETS, jet fuel, gasoline, silicone concrete sealer, outdoor air						
ALCOHOLS						
Sub totals	0	0	0	0	158	93
ethanol (ethyl alcohol) *CH3CH2OH* 188,000					120	14

COMPOUND	**VOC CONCENTRATIONS (:g/m^3)**					
Alternate names ACGIH TLV/10 (:g/m^3) Some origins and sources	**Gasper air during flight (uncorrected for cabin pressure)**	**Cabin envelope on the ground**	**Jet Fuel**	**Ultra-light lube**	**World 1994 [1] GM estab. offices**	**Canada 1992 [2] 50th% office investig.**
TVOC (:g/m^3)	**200**	**22100**			**1,130**	**400**
Pleasant odour. Central depressant. Produced by human metabolism, fungi, fermentation. Solvent. Caulking, latex paints.						
methanol *26,200* adhesives(flooring, fire proofing), lacquer, human, mold					29	
(n+i)-butanol (butyl alcohol) *C4H10O* *30,300* Used as a solvent for resins and lacquers. Pressed wood products. Artificial flavours, perfumes. Iso and n butanol produced by mold, eg. on filters. 2 -butanol used in the manufacture of 2 butanone (Methyl Ethyl Ketone)						
2-pentonal mold						
hexanol pressed wood products						
1-octen-3-ol mold						
3-methyl 1-butanol mold						
2-propoxyethanol silicone acrylic concrete sealer						
2-*ethoxy-acetate-ethanol*						
1-*methoxy-2-propanol* ETS						
2-*methoxy-1-propanol*						
1-propoxy-2-propanol silicone acrylic concrete sealer						

COMPOUND	VOC CONCENTRATIONS (:g/m^3)					
Alternate names ACGIH TLV/10 (:g/m^3) Some origins and sources	**Gasper air during flight** (uncorrected for cabin pressure)	**Cabin envelope on the ground**	**Jet Fuel**	**Ultra-light lube**	**World 1994 [1]** **GM estab. offices**	**Canada 1992 [2]** **50th% office investig.**
TVOC (:g/m^3)	**200**	**22100**			**1,130**	**400**
2-butoxyethanol 12,100 Suspected endocrine disruptor. Furniture lacquer (water based, acrylic), carpet, mold, soap and other detergents						
2-(2-butoxythoxy)- ethanol carpet						
dimethylaminoethanol found in 1 building						
i-amylalcohol C5H12O Distillation of fusel oil (fusel oil is a high boiling fraction during distillation of fermentation alcohol). Unpleasant odour. Inhalation causes violent coughing.						
2-ethyl-1-hexanol (*2-ethylhexyl alcohol, octyl alcohol* C8H18O Irritant. Pleasant odour. Formed by hydrolysis of phthalic ester plasticizers. Sources include water-damaged floor construction. Mold. Carpeting. Solvent for cellulose acetate lacquers, dyes, resins.						
2-propanol (isopropyl alcohol) solvent for resins, aerosols, antifreeze , caulking, latex paint						79
2-*methyl 1-propanol* mold						
2-*methyl 2-proponal* ETS, mold						
2-*methyl 1-butanol* mold						
3-*methyl 1-butanol* mold						
3-octanol						

COMPOUND	**VOC CONCENTRATIONS (:g/m^3)**					
Alternate names **ACGIH TLV/10 (:g/m^3)** **Some origins and sources**	**Gasper air during flight** (uncorrected for cabin pressure)	**Cabin envelope on the ground**	**Jet Fuel**	**Ultra-light lube**	**World 1994** [1] **GM estab. offices**	**Canada 1992** [2] **50th% office investig.**
TVOC (:g/m^3)	**200**	**22100**			**1,130**	**400**
mold						
phenol					9	
ETS, human, mold						
2-methyl-phenol						
ETS						
benzyl alcohol C6H5CH2OH						
some carpeting						
1-octen 3-ol						
mold						
2-octen 1-ol						
mold						
3 methyl acetate 1 butanol						
1,8 cineole (eucalyptol)						
a colourless, viscous oil with camphor-like smell present in eucalyptus, cajaput and wormseed oils						
1*,10-dimethyl-trans-9-decalol (geosmin)*						
mold, (eg., Penicillium crustosum, toxigeneic) found in an HVAC unit						
2-methyl-iso-borneol						
Microbial growth						
chrysophanol						
fungal growth - e..g., *trichodermna viride*.						
unidentified alcohols						
microbiol growth (musty odour: 1-octen 3-ol, 1-pentanol, 3-octenol, 3-octanone 2 methyl 1 propanol, , 3-methyl 1-butanol; 2 -mthyl isoborneol), disinfectants, carpets						

COMPOUND	**VOC CONCENTRATIONS (:g/m^3)**					
Alternate names **ACGIH TLV/10 (:g/m^3)** **Some origins and sources**	**Gasper air during flight** **(uncorrected for cabin pressure)**	**Cabin envelope on the ground**	**Jet Fuel**	**Ultra-light lube**	**World 1994 [1]** **GM estab. offices**	**Canada 1992 [2]** **50th% office investig.**
TVOC (:g/m^3)	**200**	**22100**			**1,130**	**400**
KETONES (Carbonyls C=O)						
Sub totals	5.1	395.2	0	0	42	21
acetone (propanone, dimethyl ketone) *C3H6O 118,800* Pleasant, ethereal odor. Product of the destructive distillation of wood, humans, mold, of benzene + propene. Jet fuel, gasoline, solvent, ETS, glued wood products, linoleum, carpet, humans, outdoor air.	1	4.4			32	21
2-butanone (*methyl ethyl ketone, M.E.K.*) C4H8O. 59,000 Product of the destructive distillation of wood. Pleasant odour. A solvent. Used in solvent based paints, spray paints. Used in vinyl and acrylic resins, de-waxing of lubricating oils, silicone acrylic concrete sealer. Found in caulking, from mold, ETS, outdoor air.	0.8	382			4	
3-butan-2-one ETS						
3-buten-2-one ETS						
3-methyl 2 butanone						
2-pentanone ETS, mold						
2-hexanone mold						
3-hexanone mold						
4-methyl-3-hexanone						

COMPOUND	VOC CONCENTRATIONS (:g/m^3)					
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TVOC (:g/m^3)	**200**	**22100**			**1,130**	**400**
mold						
2-heptanone						
ETS, mold						
5-ethyl-4-methyl-3-heptanone						
mold (e.g., *A. versicolor*)						
3-octanone						
mold						
3-methyl-2-pentanone						
mold *(e.g. A. versicolor*)						
4-methyl-2-pentanone (methyl isobutyl ketone, MIBK, hexone) CH3COCH2CHMe2		8.8				
Ketone used in solvent extraction and as a solvent for polymers (e.g. acrylic esters), alkyds, polyvinylacetate). From solvent-based paints						
1-(2-methyl-2-cyclopenten-1-yl)-ethanone						
ETS						
2-methyl-2-cyclopenten-1-one						
ETS						
4-hydroxy-4-methyl-2-pentanone						
Silicone acrylic concrete sealer						
diethylketone					6	
cyclohexanone	3.3					
cyclononanone						
1-methyl-2-pyrrolidone						
6-pentyl-"-pyrone						
fungal growth - e..g., *trichodermna viride.*						
unidentified ketones (e.g., acetophenone)						

COMPOUND	**VOC CONCENTRATIONS (:g/m^3)**					
Alternate names **ACGIH TLV/10 (:g/m^3)** **Some origins and sources**	**Gasper air during flight** **(uncorrected for cabin pressure)**	**Cabin envelope on the ground**	**Jet Fuel**	**Ultra-light lube**	**World 1994** [1] **GM estab. offices**	**Canada 1992** [2] **50th% office investig.**
TVOC (:g/m^3)	**200**	**22100**			**1,130**	**400**
mold growth						
ACIDS (carbonyls C=O), ESTERS, ALKALOIDS, FURANS, SULPHIDES						
Sub totals	4	92.6	0	0	0	0
Formic acid *HCOOH*						
Carpeting, caulking, latex paint						
Ethanoic (acetic) acid *CH3COOH*						
Carpeting, caulking, latex paint, vinyl flooring, mold						
Ethyl acetate (ethyl ethanoates, ethyl ester acetic acid)		46				
Fruity smell. Made from ethanol, ethanoic acid and sulphuric acid. Solvent for cellulose lacquers. Adhesive. Cosmetics, artificial essence. ETS. Mold growth.						
(n+i) butyl acetate (butyl ethanoates, butyl ester acetic acid)	0.4	40				
Fruity smell. Solvent. Solvent based paints. Solvent for cellulose lacquers. Spray paints. Adhesives. ETS. Iso butyl acetate from mold growth.						
n,n dimethyl acetamide (ethanamide)	3.6					
2-(2-butoxyethoxy)-ethylacetate		6.6				
vinyl flooring						
Ethenyl ester acetic acid						
ETS						
Methyl ester acetic acid						
3 *ethoxy-ethyl ester propanoic acid*						
ETS						

COMPOUND	VOC CONCENTRATIONS (:g/m^3)					
Alternate names **ACGIH TLV/10 (:g/m^3)** **Some origins and sources**	**Gasper air during flight** (uncorrected for cabin pressure)	**Cabin envelope on the ground**	**Jet Fuel**	**Ultra-light lube**	**World 1994** [1] **GM estab. offices**	**Canada 1992** [2] **50th% office investig.**
TVOC (:g/m^3)	**200**	**22100**			**1,130**	**400**
2 *methyl, methyl ester, 2-propanoic acid*						
propyl ester acetic acid						
ETS						
2 methylpropyl ester acetic acid						
1 methoxy-2-propyl ester acetic acid						
butyl ester butanoic acid						
benzo*furan*						
ETS						
2-*ethyl-furan*						
ETS						
2-*methyl-furan*						
ETS						
3 methyl-furan						
mold (e.g., A. versicolor)						
tetrahydrofuran						
2,5 dimethyl furan						
ETS						
2 pentylfuran						
mold						
dimethyl disulphide						
mold						
unidentified acids, esters, alkyloids, furans, sulphides,						

COMPOUND	**VOC CONCENTRATIONS (:g/m³)**					
Alternate names ACGIH TLV/10 (:g/m³) Some origins and sources	**Gasper air during flight (uncorrected for cabin pressure)**	**Cabin envelope on the ground**	**Jet Fuel**	**Ultra-light lube**	**World 1994 [1]** **GM estab. offices**	**Canada 1992 [2]** **50th% office investig.**
TVOC (:g/m³)	**200**	**22100**			**1,130**	**400**
Acids combine with alcohols to produce esters with characteristic fruity smell. Alkaloids are found in plants. Formed from amino acids combining with methanoate or methionine, terpenes. Many are derivatives of pyridine, quinoline, isoquiniline, pyrimidine. Include several important drugs: morphine, caffeine, nicotine, atropine. Some esters, acids, alkyloids, furans, sulphides are associated with mold growth. Some esters with caulking (silicone). Some acids with carpeting, caulking, latex paints.						
ALDEHYDES (Carbonyls C=O)						
Sub totals	2.8	145.6	0	0	0	0
formaldehyde, H2C=O *0.1 ppm* **Not detected by GC/MS and thus not included in totals** adhesives (glued wood), UFFI, ETS, mold.						0.04 ppm
acetaldehyde (ethanal) CH3.CHO human, adhesives (glued wood), ETS, mold.						
benzaldehyde C7H6O glued wood (particle board), ETS, mold						
2-furancarboxaldehyde ETS						
2-butenal ETS						
butanal (butaldehyde, butyraldyde) pungent odour. Rubber. Outdoor air						

COMPOUND	VOC CONCENTRATIONS (:g/m^3)					
Alternate names **ACGIH TLV/10 (:g/m^3)** **Some origins and sources**	**Gasper air during flight** (uncorrected for cabin pressure)	**Cabin envelope on the ground**	**Jet Fuel**	**Ultra-light lube**	**World 1994** [1] **GM estab. offices**	**Canada 1992** [2] **50th% office investig.**
TVOC (:g/m^3)	**200**	**22100**			**1,130**	**400**
pentanal ETS, outdoor air		6.6				
hexanal Glued wood (particle board), linoleum, mold. ETS. Found in outdoor air.	0.7	64				
heptanal						
octanal Mold. Found in outdoor air.						
nonanal linoleum, vinyl flooring	2.1	75				
propanal linoleum						
2-methyl propanal						
3-methyl propanal						
unidentified aldehydes mold growth						
HALOGENATED (chlorinated) COMPOUNDS						
Sub totals	0	2.2	0	0	39	27
Chloroethane C2H5Cl Ethereal odour. Local anaesthesia.						
Methylene chloride (dichloromethane) CH2Cl2 17,400 Chloroform-like odour. Somewhat toxic. Manufactured by chlorination of methane. Surfactants, finishing agents. Lubricating oils and greases. Used as a solvent for paint removal, dissolving cellulose acetate, degreasing						6.6

COMPOUND	**VOC CONCENTRATIONS (:g/m^3)**					
Alternate names ACGIH TLV/10 (:g/m^3) Some origins and sources	**Gasper air during flight** **(uncorrected for cabin pressure)**	**Cabin envelope on the ground**	**Jet Fuel**	**Ultra-light lube**	**World 1994 [1]** **GM estab. offices**	**Canada 1992 [2]** **50th% office investig.**
TVOC (:g/m^3)	**200**	**22100**			**1,130**	**400**
chloroform (trichloromethane) CHCl3 4,900 Little used anaesthetic because of potential hepatotoxicity. Used in manufacture of CFC refrigerants.						1.9
p(1,4) dichlorobenzene 6,000 o=1,2 and p=1,4 isomers manufactured by chlorination of benzene. P-isomer used an air freshener, deodorant, moth repellant. O-isomer used as in dyes, insecticides, solvents. Trace in rooftop air.					8	3.1
Perchlorethylene (1,1,2,2 tetrachloroethene, tetrachloroethylene) Cl2C=CCl2 17,000 Dry cleaning solvent, metal degreaser. Lubricating oils and greases.		2.2			7	3.6
carbon tetrachloride (tetrachloromethane) CCl4 3,100 Used in dry cleaning fluid, as a solvent for oils, lacquers, varnishes and natural resins, in fire extinguishers, as a fumigant						
1,1,2 trichloroethene (trichloroethylene) CHCl=CCl2 Chloroform-like odor. Toxic to liver. Used for metal degreasing. .						2.6
1,1,1 trichloroethane (methylchloroform)					24	6.2

COMPOUND	VOC CONCENTRATIONS (:g/m^3)					
Alternate names ACGIH TLV/10 (:g/m^3) Some origins and sources	**Gasper air during flight** (uncorrected for cabin pressure)	**Cabin envelope on the ground**	**Jet Fuel**	**Ultra-light lube**	**World 1994** [1] **GM estab. offices**	**Canada 1992** [2] **50th% office investig.**
TVOC (:g/m^3)	**200**	**22100**			**1,130**	**400**
Used for metal degreasing. Cleaning plastic molds, solvent for waxes and natural resins. ETS						
1,1,1 trichloro 2,2,2 trifluoroethane						
Used for metal degreasing. In dry cleaning fluid.						
1,1,2 trichloro 2,2,2 trifluoroethane						
dichlorodifloromethane CCl2F2						
Freon 12. Much less toxic than carbon tetrachloride. Used as refrigerant and aerosol propellant						
trichlorofloromethane CCl3F						3.3
Prepared by fluorination of carbon tetrachloride . Used as a refrigerant in air conditioners & refrigerators, or as an aerosol propellant.						
BRANCHED ALKANES						
Sub totals	133.7	19689.6	0.0	0.0	0	0
2-methyl butane		2.2				
Occurs in natural gas and petroleum gas. Found in gaseous fuels, jet fuel, gasoline, aerosols, ETS. Outdoor air.						
1,1,'-*oxybis-butane*						
2,2,3 trimethylbutane		2.2				
2,2,6 trimethyloctane						
1,3,5 trioxane						
Formaldehyde derivative. Found in outdoor air.						

COMPOUND	VOC CONCENTRATIONS (:g/m^3)					
Alternate names ACGIH TLV/10 (:g/m^3) Some origins and sources	**Gasper air during flight (uncorrected for cabin pressure)**	**Cabin envelope on the ground**	**Jet Fuel**	**Ultra-light lube**	**World 1994 [1] GM estab. offices**	**Canada 1992 [2] 50th% office investig.**
TVOC (:g/m^3)	**200**	**22100**			**1,130**	**400**
2-methyl pentane	0.8	75				
Derived from petroleum. Jet fuel, gasoline. Used in solvents, adhesives, paints. ETS. Found in outdoor air.						
3-methyl pentane	2	80				
Derived from petroleum. Jet fuel, gasoline. Used in solvents, adhesives, paints. Found in outdoor air.						
3-ethyl pentane	0.7	2.2				
2,2 dimethyl pentane		13				
Component of jet engine lubricating oil						
2,3 dimethyl pentane	1.1	15				
Jet fuel, gasoline.						
2,4 dimethyl pentane		22				
Jet fuel, gasoline.						
2-methyl hexane	0.6	46				
Jet fuel, gasoline.						
3-methyl hexane	1.5	26				
Jet fuel, gasoline.						
2,3,5,8 tetramethyldecane						
2,5 dimethyldodecane						
2,2,3,4 tetramethylpentane						
(2+3+4) methylheptane						
Jet fuel, gasoline.						
hexamethyldisiloxane						
molecular compounds containing silicon, the second most abundant material in the earth's crust. Used in building materials, glass, transistors						

COMPOUND	VOC CONCENTRATIONS (:g/m³)					
Alternate names ACGIH TLV/10 (:g/m³) Some origins and sources	**Gasper air during flight (uncorrected for cabin pressure)**	**Cabin envelope on the ground**	**Jet Fuel**	**Ultra-light lube**	**World 1994 [1] GM estab. offices**	**Canada 1992 [2] 50th% office investig.**
TVOC (:g/m³)	**200**	**22100**			**1,130**	**400**
unidentified branched alkanes	127	19406				
petroleum products (e.g., jet fuel, gasoline, silicone acrylic concrete sealer)						
CYCLOALKANES						
Sub totals	1.1	89	0	0	0	0
cyclohexane C6H12		18				
Recovered from natural gases. Jet fuel, gasoline. Solvent for oils, fats, waxes. Paint remover.						
1-methylcyclohexane C7H14	1.1	53				
Jet fuel, gasoline, solvent, carpet, linoleum, ETS, silicone acrylic concrete sealer						
ethyl*cyclohexane*						
Jet fuel, gasoline , silicone acrylic concrete sealer						
methylethylcyclohexane						
Jet fuel, gasoline, silicone acrylic concrete sealer						
butylcyclohexane						
Jet fuel, gasoline, silicone acrylic concrete sealer						
propyl cyclopentane						
Jet fuel, gasoline.						
ethylcyclopentane						
1-methylcyclopentane						
Jet fuel, gasoline, carpet rubber underpad, outdoor air						
hexamethyl-cyclotrisiloxane						
carpet treatment, furniture lacquer outdoor air (silica derivative)						
adamantane C10H16						

COMPOUND	**VOC CONCENTRATIONS (:g/m^3)**					
Alternate names **ACGIH TLV/10 (:g/m^3)** **Some origins and sources**	**Gasper air during flight** **(uncorrected for cabin pressure)**	**Cabin envelope on the ground**	**Jet Fuel**	**Ultra-light lube**	**World 1994** [1] **GM estab. offices**	**Canada 1992** [2] **50th% office investig.**
TVOC (:g/m^3)	**200**	**22100**			**1,130**	**400**
3 fused chain cyclohexane rings. Occurs in petroleum fractions. Derivatives used as lubricants and resins; treatment for viral infections; Parkinson's disease.						
unidentified cycloalkanes		18				
silicone acrylic concrete sealer, jet fuel, gasoline. Found in outdoor air						
UNIDENTIFIED C5H6...C7H14 HYDROCARBONS						
Subtotals	0	0	0	0	0	0
C5H6						
combustion products, ETS						
C5H8						
combustion products, ETS						
C5H10						
combustion products, ETS						
C6H8						
combustion products, ETS						
C6H10						
combustion products, ETS						
C6H12						
combustion products, ETS						
C7H10						
combustion products, ETS						
C7H12						
combustion products, ETS						
C7H14						
combustion products, ETS						
C8H16						
combustion products, ETS						
MISCELLANEOUS						
Subtotals	0	0	0	0	0	0
2-methyl propanenitrile						

COMPOUND	VOC CONCENTRATIONS (:g/m^3)					
Alternate names **ACGIH TLV/10 (:g/m^3)** **Some origins and sources**	**Gasper air during flight** (uncorrected for cabin pressure)	**Cabin envelope on the ground**	**Jet Fuel**	**Ultra-light lube**	**World 1994** [1] **GM estab. offices**	**Canada 1992** [2] **50th% office investig.**
TVOC (:g/m^3)	**200**	**22100**			**1,130**	**400**
combustion products, ETS						
4-methyl pentanenitrile ETS						
pyrrole C4H5N pyrrole occurs naturally in tobacco leaves. It is aromatic in character.. ETS						
1-methyl-1H-pyrrole ETS						
n-ALKANES (Paraffins)						
Sub totals	17	823.8	0	0	10	72
n-pentane C5H12 177,000 Constituent of petroleum., jet fuel, gasoline. Solvents, paints, adhesives. Found in outdoor air.		2.2				
n-hexane C6H14 *17,600* Constituent of petroleum. Jet fuel, gasoline. Adhesives, solvents, paint, ETS. Lubricating oils and greases. Found in outdoor air.	1.6	152			5	
n-heptane C7H16 *164,000* Constituent of petroleum. Liquid fuels. Jet fuel, gasoline. ETS. Outdoor air.	0.7	8.8				
n-octane C8H18 *140,000* Constituent of petroleum. Liquid fuels. Jet fuel, gasoline. ETS. Silicone acrylic concrete sealer		8.8				
n-nonane C9H20 105,000	0.6	62				4

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TVOC (:g/m³)	**200**	**22100**			**1,130**	**400**
Constituent of petroleum. Liquid fuels, jet fuel, gasoline, LPP, carpet (glue), ETS, silicone acrylic concrete sealer.						
n-decane C10H22 Constituent of petroleum. Liquid fuels, jet fuel, gasoline, LPP, carpet (glue), ETS, silicone acrylic concrete sealer.	6	590			5	21
n-undecane C11H24 Constituent of petroleum.. Jet fuel, gasoline. Carpet, under-carpet (glue), LPP, building materials, cleaners, adhesives, silicone acrylic concrete sealer.	6.7					32
n-dodecane C12H26 Constituent of petroleum. LPP	1.4					5.1
n-tridecane C13H28 Constituent of petroleum.. Jet fuel, gasoline.						2.8
n-tetradecane C14H30 Constituent of petroleum.. Jet fuel, gasoline.						2.3
n-pentadecane C15H32 Constituent of petroleum.						3.4
n-hexadecane (cetane) C16H34 Constituent of petroleum.						1.3
unidentified n-alkanes (paraffins) CnH2n+2 Chief constituents of petroleum						
SUMS OF ALL COMPOUNDS						
BTEX *benzene, toluene, m,o,p-xylenes, ethylbenzene*	12	506	0	0	74	14
	6%	2%	0%	0%	21%	5%
Total identified VOCs which could have a petroleum (combustion) or ETS source	152	20,735	0	0	10	72
	24	1,018	0	0	78	15

COMPOUND	**VOC CONCENTRATIONS (:g/m³)**					
Alternate names **ACGIH TLV/10 (:g/m³)** **Some origins and sources**	**Gasper air during flight** **(uncorrected for cabin pressure)**	**Cabin envelope on the ground**	**Jet Fuel**	**Ultra-light lube**	**World 1994** [1] **GM estab. offices**	**Canada 1992** [2] **50th% office investig.**
TVOC (:g/m³)	**200**	**22100**			**1,130**	**400**
	91%	99%	0%	0%	25%	34%
Total identified VOCs which could have a known microbial source	12	592	0	0	261	67
	6%	3%	0%	0%	73%	27%
Totals VOCs identified	193	21,925	0	0	358	251
	96%	99%	0%	0%	32%	63%

1 Brown et al, Concentrations of volatile organic compounds in indoor air - a review, Indoor Air, Munksgaard, V4, N2, 1994, 123-134.2
Note: 1- Unidentified compounds (e.g. alkanes, aliphatics) were not available to be included in table.

2 Tsuchiya et al, Volatile organic compounds in Canadian indoor air, 5th International Jacques Cartier Conference, Montreal, 1992 (National Research Council Canada, Ottawa).
Notes: 1-TVOCs are interpolated from paper as average of values for buildings with no LPP, and with LPP but copier LPP VOCs removed.
2- Unidentified compounds (e.g. alkanes, aliphatics) were not available to be included in table.

LPP Liquid process photocopier
ETS Environmental tobacco smoke