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Toxic Gases in simulated aircraft interior fires using FTIR analysis

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In the Manchester Flight KT28M Boeing 737-236 fire in 1985, 54 people died but only six of these died from thermal effects of the fire, the rest died from breathing the toxic gases produced.

All surviving passengers reported pain and burning with the immediate onset of choking. They described the effect of the fire gases as burning acidic gases attacking their throats and they had immediate and severe breathing problems. With their first breath there was a feeling of tremendous pain in the lungs and the sensation that they had solidified.

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This and other aircraft fire incidents led to developments in the fire testing of materials used in aircraft cabins. Most of the FAA tests were Bunsen burner ignition tests and rates of flame propagation measurements of material samples, tested in the open in freely ventilated conditions. Vertical burning tests were used, as these produced the most rapid rate of fire propagation. These tests were developed into oil burner tests to better simulate hotter fire initiation conditions and later NBS smoke release tests were added. However, all of these regulatory tests are freely ventilated fires and no toxicity measurements are made other than for smoke.

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Cabin fires are characterized by limited air supply in a closed volume and fire and toxicity tests are required under realistic air supply conditions and the present work is a first step in this direction using a test facility that is relatively small, but larger than many of the regulatory tests.

Aircraft cabins are ventilated by air that is bled from the engine compressors and after passing through a cooler (air conditioning system) is fed into the cabin. The higher the airflow rate the greater the penalty in fuel consumption of the engines and hence the ventilation of the cabin is controlled as low as possible without compromising the comfort of passengers.

The aim is for a total cabin air change every 2-3 minutes or 20 – 30 air changes per hour. The fire ventilation rate in the present work was 22 air changes per hour.

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Although irritant and acidic gases are often quoted as being present in most fires as well as aircraft fires, from the reaction of those effected, there are very few measurements of these gases and the present work uses Fourier Transform Infra-Red spectroscopy (FTIR) specifically to investigate these gases.

Carbon monoxide is a colourless odourless gas and does not give the symptoms of irritant and acidic gases that are reported by surviving victims from fires, CO is a silent killer gas but it has to be in relatively high concentrations ~>3000 ppm to cause death.

Andrews et al. (2005) have shown that irritant and acidic gases have toxic effects at much lower concentration than CO and can, in air starved fires, be of more significance than CO.

In the present work a method of assessing the overall toxicity of fire product gases is used that is based on the EU COSHH [Control of Substances Hazardous to Health] occupational health exposure standards.

The COSHH 15 minute maximum exposure level is used, which is available for 200 toxic gases on a common method of assessment. This is a much wider data base than the 14 species that fire toxicity is known in terms of lethal concentrations (50% die).

Also the COSHH procedures detail how to deal with complex mixtures of gases. This is to ratio a measurement to its toxic limit and then add up these normalised toxicity values for all the gases present to produce an overall toxicity assessment. This is identical to the N gas procedure used in Fire toxicity.

EH40/2002 + Supplement 2003 Occupational Exposure Limits, HSE Books 2004.

Toxic Emissions from Air Starved Enclosed Fires

Prof. Gordon E. Andrews, ERRI, SPEME, U. Leeds, UK

Toxic Gas		15 Min Exposure Limit COSHH ppm	Threshold Limit Value TLV ppm	Short Term Exposure Limit STEL	Immediately Dangerous to Life And Health IDLH	5 Min Tenability Limit DD240 ppm	LC_{50} 30 min ppm
Carbon Monoxide	CO	200	20	100	1200	10,000	3,000
Nitric Oxide	NO	35	25		100		2,500
Nitrogen Dioxide	NO_2	5	0.2	5	20	80	500
Ammonia	NH_3	35					9,000
Hydrogen Cyanide	HCN	10		4.7	50	100	135
1,3 Butadiene	C_4H_6	10 *	2	1000	2000		
Benzene	C_6H_6	3**					
Toluene	C_7H_8	150					
Xylenes	C_8H_{10}	150			100 (EU)		
Trimethylbenzenes	C_9H_{12}	25					
Napthalenes	$C_{10}H_8$	15					

* 8Hr limit – no 15 min limit listed, but this is currently under review, this is a listed environmental toxic gas in the USA with benzene, toluene and the aldehydes.

** This is the 8 hour limit and this is reduced to 1 ppm from June 2003. COSHH recommends that the 15 min. limit is taken as 3x the 8 hour limit where no value is g and this has been used for Benzene based on the 1 ppm 2003 value.

Toxic Emissions from Air Starved Enclosed Fires

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Toxic Gas		15 Min Exposure Limit COSHH ppm	Threshold Limit Value TLV ppm	Short Term Exposure Limit STEL	Immediately Dangerous to Life And Health IDLH	5 Min Tenability Limit DD240 ppm	LC_{50} 30 min (23, 24) ppm
Methanol	CH_3OH	250					
Ethanol	C_2H_5OH	1000					
Acetaldehyde	C_2H_4O	50		25	200		20,000
Formaldehyde	CH_2O	2					250
Acrolein	C_3H_5O	0.3	0.1	0.3 0.05 (EU)	2	2	300
Acetic Acid	$C_2H_4O_2$	15	10	15	50		11,000
Formic Acid	CH_2O_2	5					
Carbonyl Sulfide	COS						2,000
SO2	SO_2	5				30	500 (5 min.)
HCl	HCl	5				200	3,700
HF	HF	3				120	2,000
HBr	HBr	3				200	3,000
Carbon Black	C		3.5 mg/m^3		1.75 g/m^3		

Relative Toxicity Compared with CO

Reference CO for COSHH = 200 and for LC50 = 3000 ppm

Toxic Gas	COSHH 15 min CO/Toxic	LC_{50} CO/Toxic
CO	1	1
NO_2	40	6
HCN	20	22
Acetaldehyde	4	0.15
Formaldehyde	100	12
Acrolein	667	10
SO2	40	6
HCl	40	0.81
HF	67	0.67
HBr	67	0.67
Acetic Acid	13	0.27

Although the relative toxicity for CO and HCN are similar for LC50 and occupational exposure data, comparison with the other gases show major disagreements in the irritant and acidic gases areas of acetaldehyde, formaldehyde, acrolein and acetic acid. The LC50 data requires much higher concentrations of these gases relative to CO whereas the occupational exposure data requires much lower levels relative to CO for the same exposure hazard. The differences are between one and two orders of magnitude depending on the gas.

The Leeds Ventilation Controlled Enclosed Fire Test Facility

U. Leeds enclosed fire restricted air ventilation test facility.
This is designed to simulate a fire in a room with passive fire protection with doors and windows closed and low air leakage.

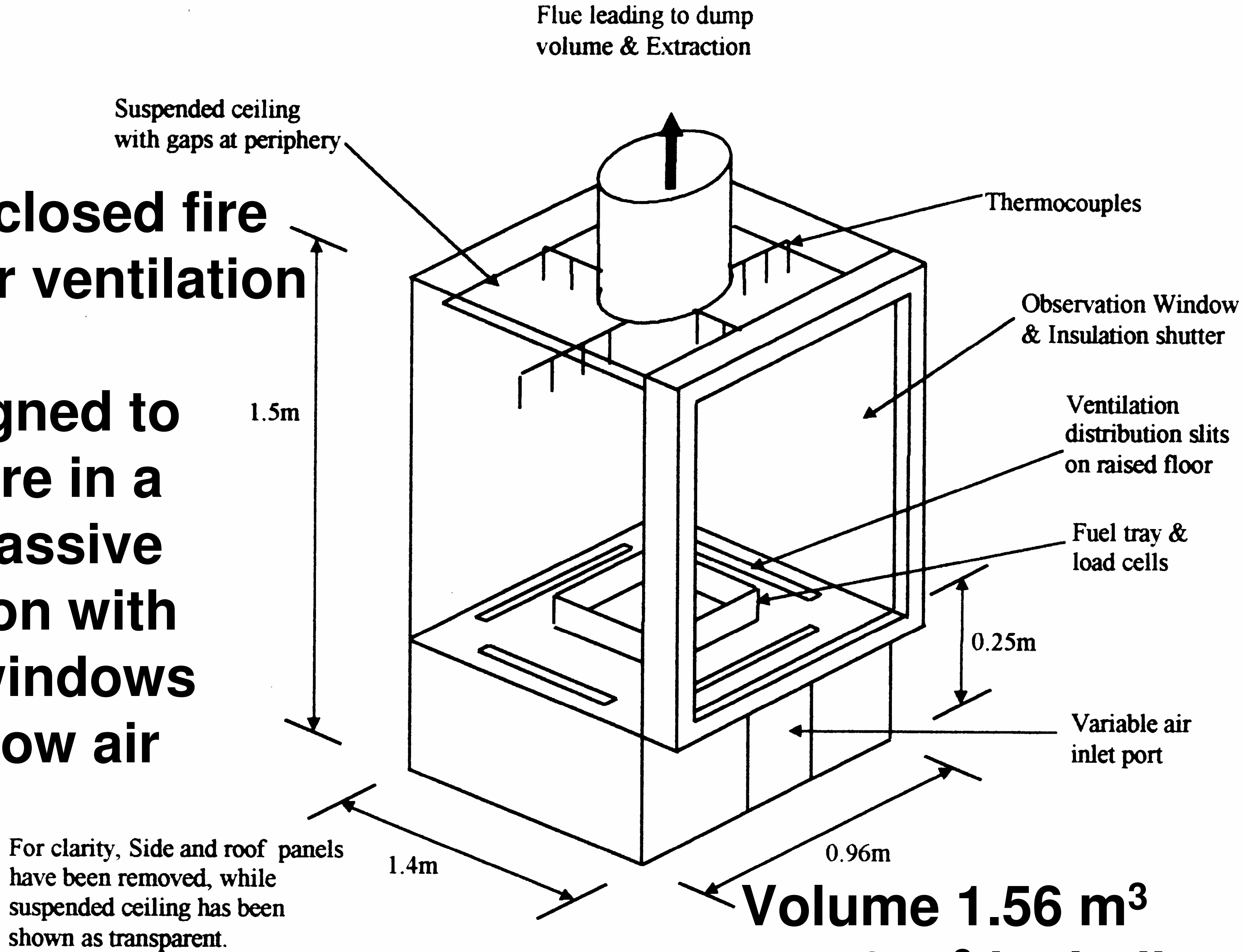
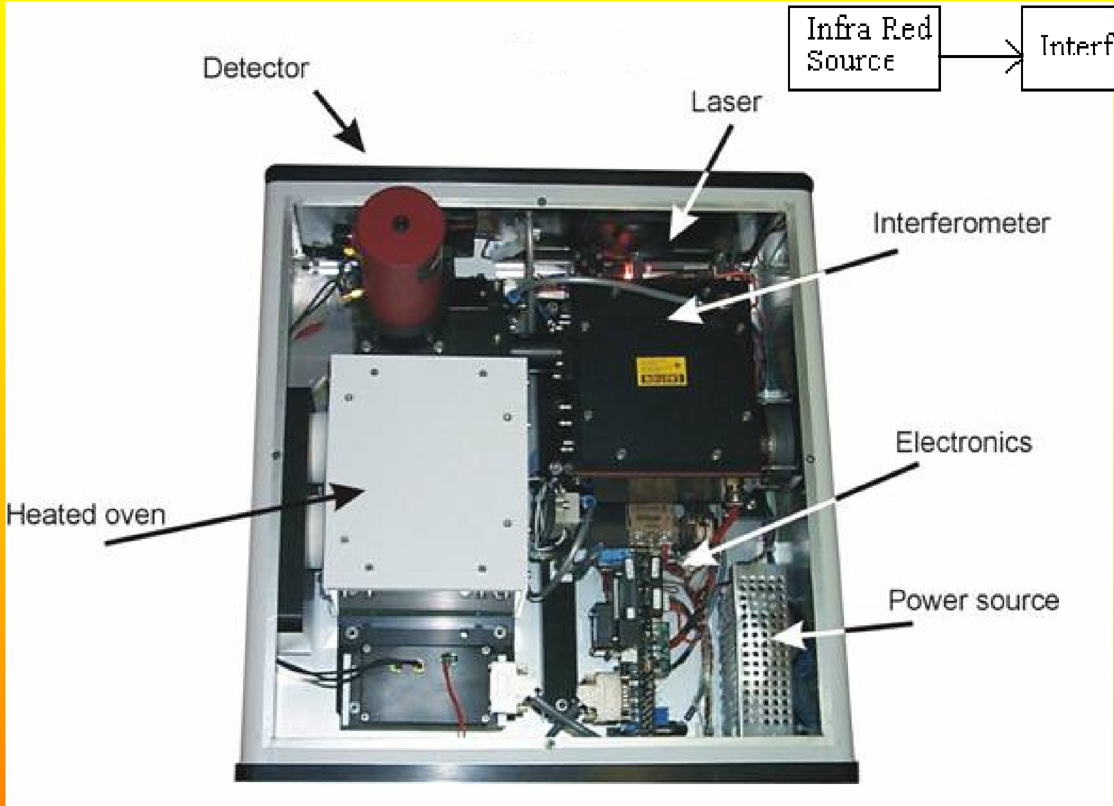
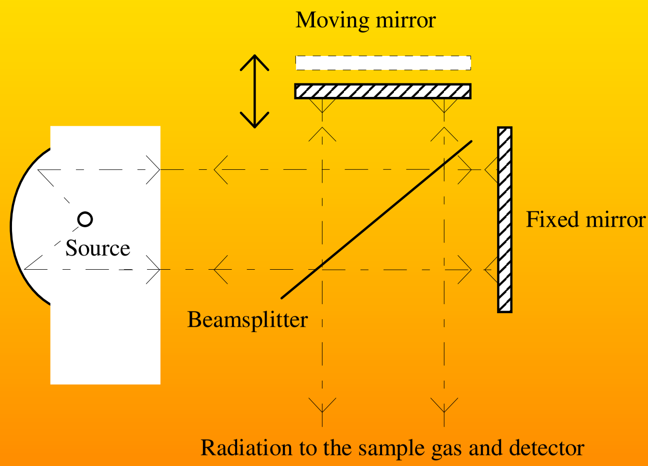


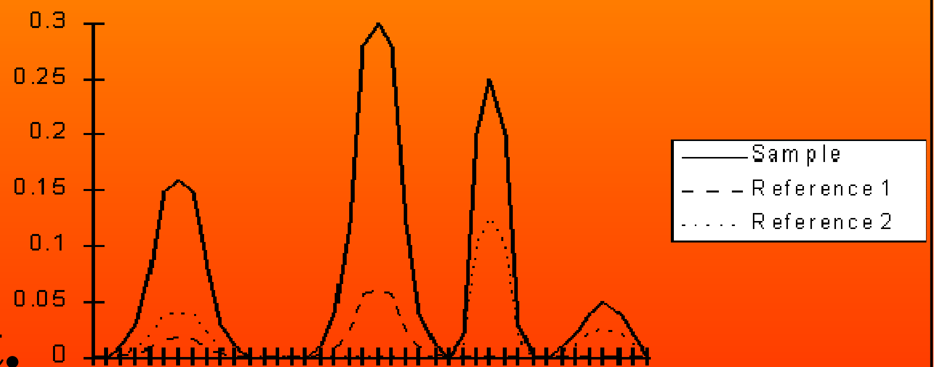
Fig. 1. Schematic diagram of experimental investigation rig.

Volume 1.56 m^3 or 1.9 m^3 including the plenum air feed.

Temet FTIR







Note that the sample is heated from the fire exit gas sample point to the heated detector and analysis is on a wet basis with water vapour present.

List of calibrated FTIR 51 component gases (30 Toxics)

Species	Calibrated range		Species	Calibrated range	
Water vapor	20	%	1,3-Butadiene	100	ppm
CO2	30.1	%	Benzene	500	ppm
CO	9960	ppm	Toluene	500	ppm
N2O	500	ppm	m-xylene	500	ppm
NO	2008	ppm	o-xylene	500	ppm
NO2	4885	ppm	p-xylene	500	ppm
SO2	1000	ppm	1,2,3-trimethylbenzene	500	ppm
COS	200	ppm	1,2,4-trimethylbenzene	500	ppm
NH3	503	ppm	1,3,5-trimethylbenzene	500	ppm
HCN	500	ppm	Ethylbenzene	*	ppm
HCl	489	ppm	Indene	*	ppm
HF	91	ppm	Methanol	500	ppm
Methane	995	ppm	Ethanol	500	ppm
Ethane C2H6	506	ppm	Propanol	500	ppm
Propane C3H8	500	ppm	Butanol	*	ppm
Butane C4H10	500	ppm	MTBE	500	ppm
Pentane C5H12	500	ppm	Dimethyl Ether	*	ppm
Iso-pentane C5H12	*	ppm	Formaldehyde	96	ppm
Hexane C6H14	500	ppm	Acetaldehyde	200	ppm
Heptane C7H16	500	ppm	Formic acid	500	ppm
Octane C8H18	*	ppm	Acetic acid	500	ppm
Iso-octane C8H18	500*	ppm	Acrolein	500	ppm
Cetane C16H34	*	ppm	Naphthalene	305	ppm
Acetylene C2H2	98.8	ppm	1-ethylnaphthalene	500	ppm
Ethylene C2H4	493	ppm	Sulfur hexafluoride	49.4	ppm
Propene C3H6	500	ppm			

*Generic libraries used for calibration

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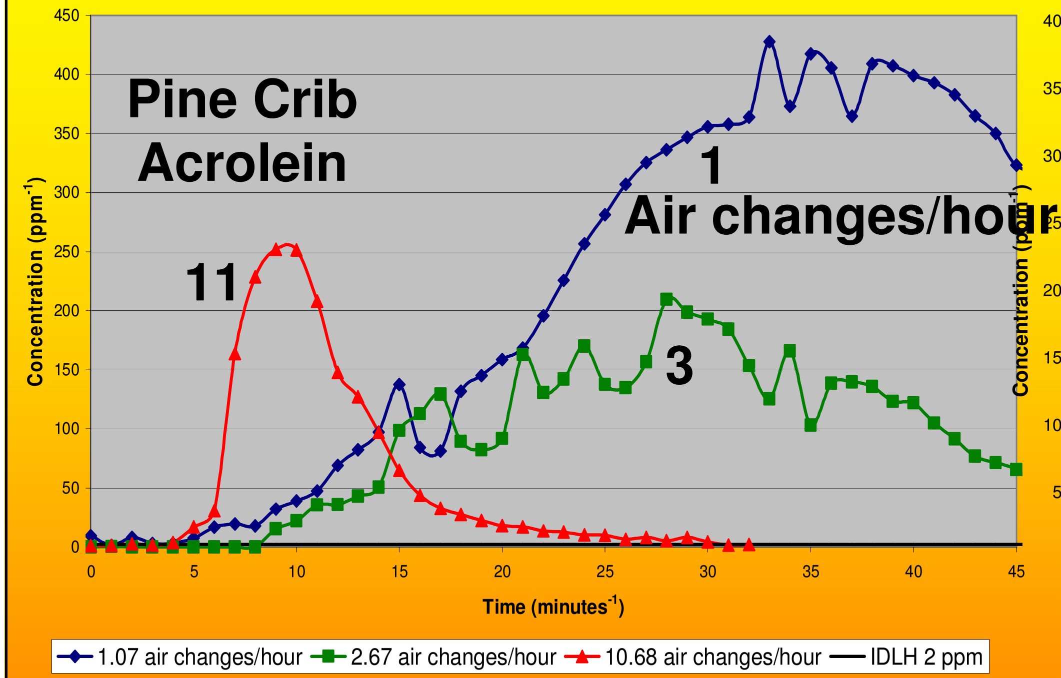
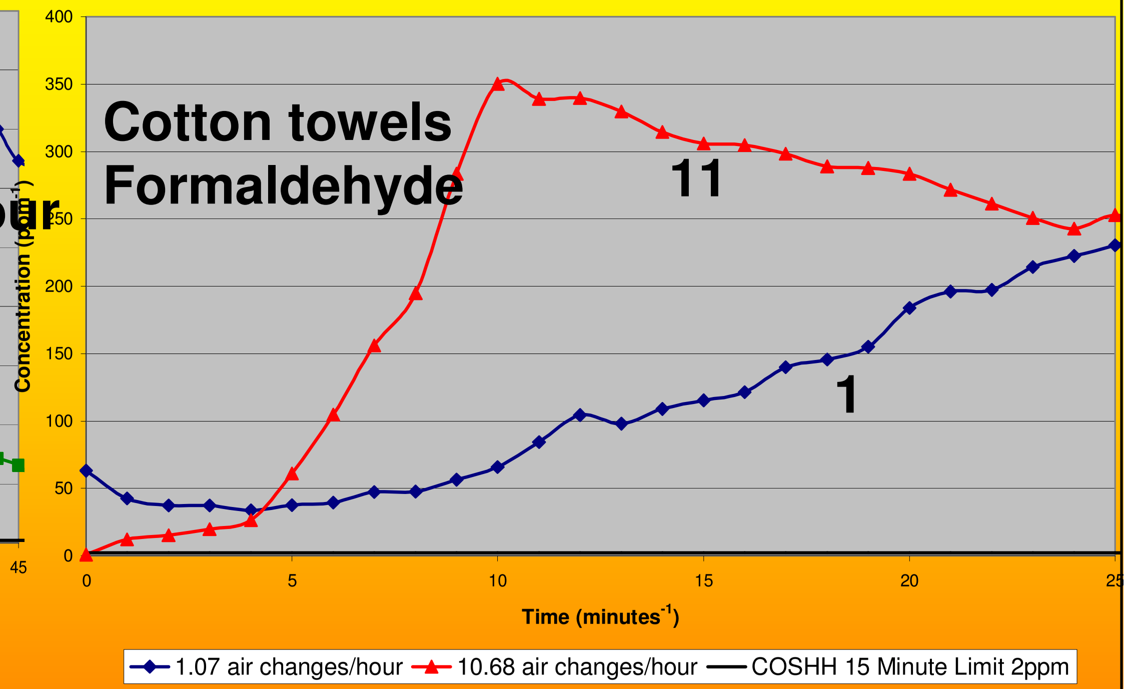
Pine Wood Acrolein (CH_2CHCHO)



Cotton Formaldehyde (H_2CO)



Previous work by the authors has investigated wood crib and cotton towel fires at a range of ventilation rates. Some typical results are shown here for acrolein in wood fires and formaldehyde in Cotton fires. These are two of the most important irritant gases.

European Combustion Meeting Chania Crete 2007

Toxic Gases in simulated aircraft interior fires using FTIR analysis

Ventilation controlled fires in the smouldering phase – 35 mins

Fire Load	Ventilation Air changes Per hour	SO_2 ppm	HCN ppm	B ppm	TMB ppm	AA ppm	FA ppm	FMA ppm	ACA ppm	A ppm	N COSHH 15 mins.	N LC_{50}
Crib	1.1	173	0	195	850	143	13	746	0	418	1946	9.26
Crib	2.7	21	7	5	72	132	18	297	24	134	680	5.86
Crib	10.7	2	0	6	12	6	2	79	0	2	67	1.43
Crib	40	0	0	1	1	0	NA	2	0	0	6	0.32
Cotton	1.1	54	6	0	116	16	22	242	22	141	613	2.74
Cotton	2.7	32	2	19	96	13	NA	149	32	14	150	3.13
Cotton	10.7	18	2	25	51	15	1	171	0	49	41	1.96
Cotton	40	1	0	1	1	0	NA	3	0	1	8	0.27
COSHH 15 min		5	10	3	25	15	5	2	50	0.3		
LC_{50}		500	135	NA	NA	1.1%	NA	250	2%	300		

B – Benzene; TMB – Trimethylbenzene; AA – Acetic Acid; FA – Formic Acid; FMA – Formaldehyde; ACA – acetaldehyde; A - acrolein

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Ventilation controlled fires at the maximum heat release

Fire Load	Ventilation Air changes Per hour	SO_2 ppm	HCN ppm	B ppm	TMB ppm	AA ppm	FA ppm	FMA ppm	ACA ppm	A ppm	N COSHH 15 mins.	N LC_{50}
Crib	**1.1**	**25**	**3**	**35**	**46**	**9**	**0**	**79**	**0**	**47**	**243**	**2.3**
Crib	**2.7**	**35**	**15**	**15**	**115**	**111**	**8**	**334**	**86**	**98**	**572**	**5.3**
Crib	**10.7**	**135**	**85**	**837**	**464**	**303**	**0**	**1402**	**75**	**252**	**1735**	**13.3**
Crib	**40**	**20**	**5**	**206**	**130**	**38**	**0**	**289**	**32**	**25**	**369**	**5.2**
Cotton	***1.1***	***52***	***5***	***0***	***110***	***13***	***22***	***258***	***21***	***129***	***585***	***1.8***
Cotton	***2.7***	***38***	***0***	***1***	***89***	***6***	***NA***	***191***	***30***	***25***	***145***	***1.0***
Cotton	***10.7***	***2***	***0***	***28***	***18***	***1***	***2***	***20***	***5***	***11***	***62.4***	***0.43***
Cotton	***40***	***8***	***0***	***15***	***28***	***5***	***NA***	***6***	***0***	***2***	***17.4***	***0.21***

B – Benzene; TMB – Trimethylbenzene; AA – Acetic Acid; FA – Formic Acid; FMA – Formaldehyde; ACA – acetaldehyde; A - acrolein

Pine Wood Crib:Relative COSHH Toxicity and major species

Time mins	Pine Wood Crib Fire – 5 kg/hour air – 2.7 air changes per hour				
	Total N	% CO	% benzene	% acrolein	% formaldehyde
2	3.4	11.8	17.6		74
5	28	14.2	18.3		71
10	179	9.9	2.8	41	41
15	572	9.4	0.9	57	29
20	596	9.1	0.8	52	34
25	738	8.5	0	62	25
30	915	7.9	0	70	18
35	684	9.1	0.3	65	22
40	621	8.5	0.5	66	33
45	405	13.8	0.6	54	47
50	232	12.5	2	39	41
60	129	11.6	0	29	55
70	84	8.3	5	20	61
80	59	5.1	4	17	68

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Normalised toxicity for wood crib and cotton towel fires expressed as a % of the total toxicity. COSHH 15 min. top and LC_{50} bottom (CO dominates).

Airflow per hour	Crib min. Oxygen				Crib 35 min.				Cotton Min. oxygen				Cotton 35 min.			
	A	FMA	CO	B	*A*	*FMA*	*CO*	*B*	A	FMA	CO	B	*A*	*FMA*	*CO*	*B*
1.1	65	16	11	5	*71*	*19*	*4*	*4*	74	22	1	0	*77*	*20*	*3*	*0*
2.7	57	29	9	1	*66*	*22*	*9*	*0*	32	51	2	6	*31*	*50*	*7*	*4*
10.7	48	40	5	2	*10*	*59*	*25*	*3*	59	16	7	15	*33*	*16*	*20*	*14*
40	22	40	16	19	*0*	*17*	*78*	*5*	39	17	9	17	*40*	*18*	*35*	*4*

Airflow Per hour	Crib min. oxygen				Crib 35 min.				Cotton min. oxygen				Cotton 35 min.			
	A	FMA	CO	B	*A*	*FMA*	*CO*	*B*	A	FMA	CO	B	*A*	*FMA*	*CO*	*B*
1.1	7	14	76	NA	*15*	*32*	*52*	*NA*	24	57	17	NA	*17*	*35*	*46*	*NA*
2.7	6	25	62		*8*	*20*	*71*		8	76	16		*2*	*19*	*79*	
10.7	6	42	45		*1*	*22*	*77*		9	19	67		*8*	*35*	*56*	
40	2	22	75		*0*	*3*	*97*		5	10	48		*0*	*4*	*70*	

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The three aircraft interior flammable materials fire loads

Fire	Kerosene Accelerant	Blankets Hanging	Pillows & Cover Fibre filled Synthetic cover	Lifejacket Coated Nylon	Other	Total Weight g
1	200g	2	1	0	None Pillow on the floor	1585g
2	100g	1	1	0	Lifejacket bag on the floor above the pillow Flight sock, - hanging. Flight Instruction Card	790g
3	100g	0	2	1	Eyemask Flight Magazine Headrest Cover	1161g

The blankets were flame retarded polyester fibre (poly ethyleneterephthalate),

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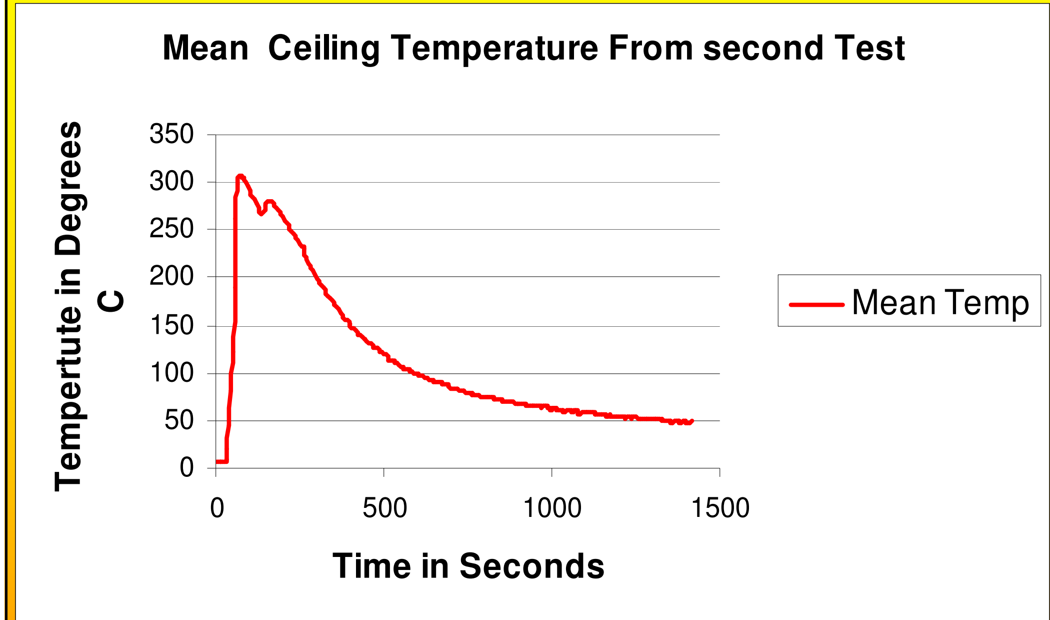

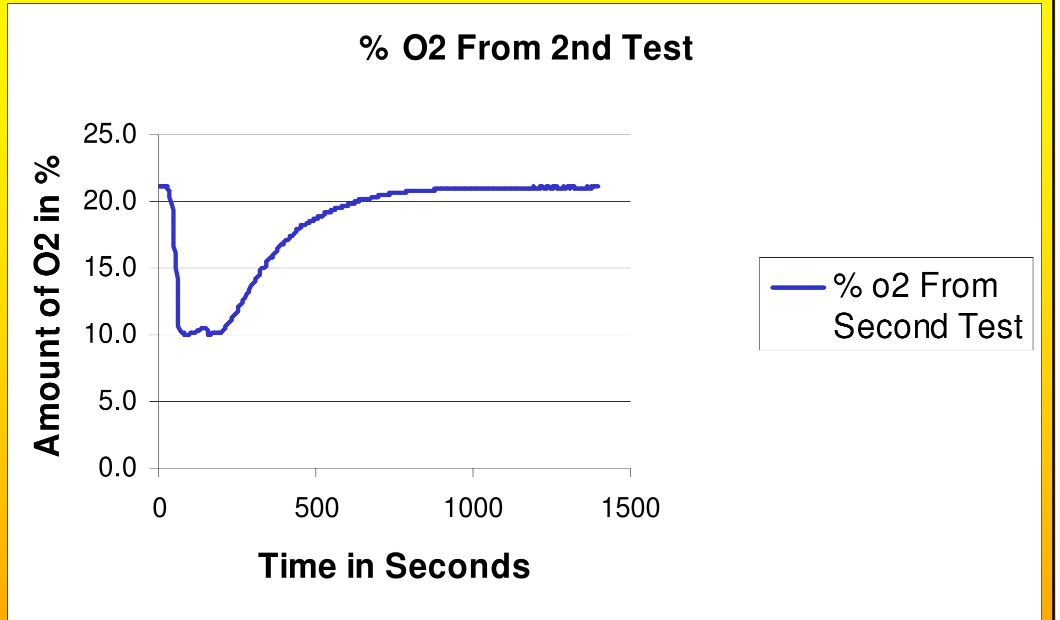

Fire	Total Fire Load Energy Content	Total weight loss in fire	% of fire Load burnt	MJ Heat Release	Fire load kg/m^2	Fire load Kg/m^3	Burnt Fire Load Kg/m^2
1	63 MJ	800g	50.5%	32	1.18	0.94	0.60
2	32 MJ	435g	55.1%	17.4	0.59	0.47	0.32
3	46 MJ	448g	38.6%	17.9	0.87	0.69	0.33

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Fire	Fire duration for 90% of the burnt mass	Ave. heat release rate. = 90% of heat release /fire duration	Peak Temp. °C	Time of peak T
1	330s	87 kW	295	135s
2	220s	71 kW	306	75s
3	515s	32 kW	267	175s

These fires are all relatively low temperature due to the limited ventilation rates. These temperatures are similar to those found for wood crib and pool fires at the same ventilation rates. The main fire duration occurred after the peak temperature, due mainly to the kerosene accelerant, at lower temperatures.

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Main toxic gases from Fire 2 – this includes a fire retarded blanket and a pillow.

Mass Burnt	A/F	NOx ppm	CO %	HC %	HCl %	HF pmm	HCN ppm	NH_3 ppm	SO_2 ppm	AA pmm	FOM ppm	OX ppm	B ppm
100g	84.4	89	0.09	0.13	0.54	20	1676	14	273	83	779	44	27
200g	23.9	268	0.91	0.97	1.16	74	4612	84	473	25	1196	20	159
300g	21.6	247	1.20	1.54	0.88	28	3819	66	411	39	1059	48	298
400g	24.0	175	1.14	1.18	0.35	18	1756	25	167	48	655	162	319
450g	50.4	71	0.42	0.41	0.16	10	570	8	75	32	373	103	146

AA – Acetic Acid; FOM – Formaldehyde; OX – o-xylene; B – Benzene

Note that acrolein was not significant.

Note the very high levels of HCl, HCN, NH_3 and SO_2 from fire retardants on the blanket.

HCl and HCN levels were out of calibration.

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Fire 2 Normalised toxicity to the COSHH 15 min. levels

Mass Burnt	CO	HCl	HF	HCN	NH_3	SO_2	AA	FOM	OX	B	Total Normalized toxicity - N
100g	4.3	1080	6.7	168	0.4	55	5.5	390	0.3	9	1719
200g	45.6	2320	25	461	2.4	95	1.7	598	0.1	53	3602
300g	60	1765	9.3	382	1.9	82	2.6	530	0.3	99	2932
400g	57	695	6	176	0.8	33	3.2	328	1.1	106	1406
450g	21	312	3.3	57	0.2	15	2.1	187	0.7	49	647

The most toxic gases are clearly HCl, HCN and formaldehyde on a COSHH 15 min. basis.

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Main toxic gases from Fire 3 – no blanket but life jacket

Mass Burnt	A/F	NOx ppm	CO %	HC %	HCl ppm	HF ppm	HCN ppm	NH3 ppm	SO2 ppm	AA ppm	FOM ppm	OX ppm	B ppm
100g	25	173	0.3	0.1	19	3	1	6	218	15	64	62	96
200g	22	242	0.5	0.1	60	4	221	8	414	38	139	106	138
300g	25	219	0.4	0.3	59	5	163	7	226	36	149	106	191
400g	33	187	0.2	0.1	39	2	28	2	55	27	49	46	16
450g	72	86	0.1	0.1	18	1	12	2	17	19	43	29	1

Note that there are much lower levels of HCl, HF, HCN when there is no fire retardants present.

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Normalised fire toxicity for Fire 3 on COSHH 15 min. basis

Mass Burnt	CO	HCl	HF	HCN	SO2	AA	FOM	OX	B	Total Normalized Toxicity - N
100g	16	4	1	14	44	1	32	0.4	5	117
200g	26	12	1.3	22	83	2.5	70	0.7	13	231
300g	23	12	1.7	16	45	2.4	75	0.7	12	188
400g	11	8	0.7	3	11	0.8	25	0.3	9	69
450g	5	4	0.3	1	3	0.5	22	0.2	6	42

Note that with no fire retarded blanket Fire 3 has a much lower importance for HCl and HCN and greater importance for formaldehyde and SO_2.

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Proportional Normalised % Toxicity at the Peak Toxicity

Fire Type	N	CO	HCl	HCN	SO_2	FOM	B	AC
Fire 1	1062	4	36	29	9	20	1	0
Fire 2	3602	1	64	13	3	17	2	0
Fire 3	231	11	5	10	36	30	6	0
Kerosene Pool (11)	145	11	0	0	0	29	27	27
Diesel Pool (11)	91	14	0	0	0	44	29	11
Pine Crib (11)	915	8	0	0	0	18	0	70

11 – Andrews et al. – 8th Fire Science Conference – Beijing.

AC – Acrolein; FOM – formaldehyde; B- Benzene

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Summary

1. An aircraft interior fire is a closed room fire scenario with a fixed ventilation rate of 20-30 air changes per hour. Experimental fires were undertaken in a closed room fire test facility for 22 air changes per hour.
2. Three fire loads were investigated: two blankets and cushion and a lifejacket and blanket, the same fire load but with one blanket and other items supplied to passengers and finally two pillows, one blanket and one lifejacket. A small kerosene accelerant was used to initiate the fires. This scenario represents the fire load that surrounds an individual in each seat and is the most readily ignited material. The blankets were fire retarded but they easily burnt with a kerosene spillage on them.
3. They were ignited in a vertical configuration representing the use of the blankets over a passengers knees and hanging down close to the lifejacket. The blankets burnt to leave a charred fabric that was very friable. The fire temperatures were of the order of 350°C at the peak temperature.

Toxic Gases in simulated aircraft interior fires using FTIR analysis

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Conclusions

- The FTIR toxic emissions for 30 species including HCl and HCN where extremely high and indicated pyrolysis of the fire protection material for the two fires with a fire retarded blanket. In all three fires levels of acrolein were low but there were high levels of aldehydes and acidic gases. In terms of the overall toxicity CO was not the main problem.
- These results indicate significant problems of toxic gases in the early stages of fires in aircraft from the most readily ignited material around passenger seating areas but excluding the seats.
- The main toxic species were quite different than for COH fires of wood and cotton and HC pool fires at the same ventilation rates.

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Thank you

Questions?

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