



Research Report and Preliminary Study

# Chemical Exposure & Flammability Study on Upholstered Furniture from the U.S. and U.K.

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## INTRODUCTION

Flame retardants have been traditionally added to upholstered furniture to meet flammability standards set in various locations (California Technical Bulletin 117 implemented in 1975, and The Furniture and Furnishings (Fire Safety) Regulations 1988 in the United Kingdom). While regulations like The Furniture and Furnishings (Fire Safety) Regulations 1988 may have led to decrease in casualties due to fire, CA TB 117 was modified and adopted in California (TB 117-2013) after it was brought to attention that humans may be exposed to flame retardants in furniture that may lead to health problems such as cancer, thyroid disruption, delayed mental and physical development, advanced puberty, and reduced fertility with extended exposure. This study was a first step in examining and comparing both chemical emissions and flammability of furniture from the US and the UK. A broad range of volatile organic compounds (VOCs) and aldehydes, including flame retardants, were measured using an emission test chamber, and flammability tests were conducted in a calorimeter room. This was a preliminary study with a limited sample set to evaluate analytical techniques and gain initial information on chemical levels. Product manufacture's names and product content details are unavailable.

## METHODS

### Product Description

With assistance from the UK fire service, a sofa and chair (Figure 1a and 3a) were sourced from a local furniture store in Surrey, UK. The UK furniture was labeled as complying with the Furniture and Furnishings (Fire Safety) Regulations 1988, which requires a furniture to be both cigarette and match resistant (Figure 1b).



Figure 1: a) U.K. chair in a chamber b) a tag attached to the chair

A similar chair and sofa set (Figure 2a and 3b) was chosen as a representative furniture set from the US. Purchased at a local store in Illinois, US, this set has the closest dimensions (Table 1) as

the UK furniture. The label (Figure 2b) on the US furniture does not designate any fire regulation.

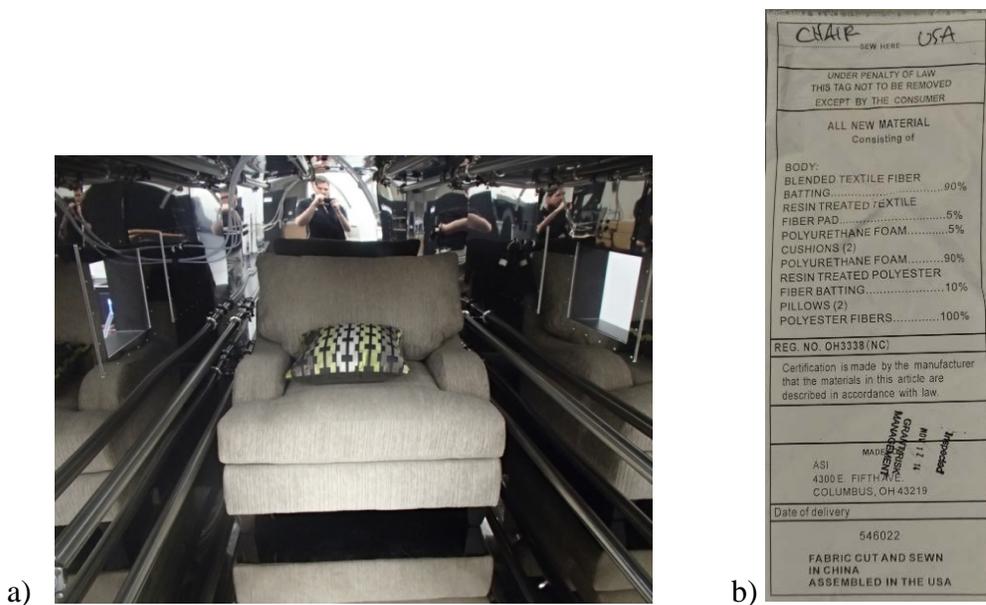


Figure 2: a) US chair in a chamber b) a tag attached to the chair

Table 1: Upholstered furniture specifications

	UK Sofa	US Sofa	UK Chair	US Chair
Weight (lb.)	94.0	98.0	56.2	74.2
Dimensions (l/w/h, in.)	71 / 31 / 38	68 / 40 / 39	32 / 37 / 36	40 / 41 / 39

## Chemical Exposure Test

### Environmental chamber

The single person lounge chairs were tested individually for chemical emissions. Each chair was tested in an environmental chamber 5.96 m<sup>3</sup> in volume, and chemical emissions were analytically measured. Environmental chamber operation and control measures used in this study followed the GREENGUARD Method and Laboratory Quality Requirements<sup>1</sup> and ASTM Standard D 6670<sup>2</sup> guidance. The chamber used is manufactured from stainless steel to minimize contaminant adsorption. Air flow through the chamber enters and exits through an aerodynamically designed

<sup>1</sup> UL 2821, “GREENGUARD Certification Program Method for Measuring and Evaluating Chemical Emissions From Building Materials, Finishes and Furnishings Using Dynamic Environmental Chambers” 2013.

<sup>2</sup> ASTM D 6670, “Standard Practice for Full-Scale Chamber Determination of Volatile Organic Emissions from Indoor Materials/Products.” ASTM, West Conshohocken, PA, 2007.



air distribution manifold also manufactured of stainless steel. Supply air to the chamber is stripped of formaldehyde, VOCs, and other contaminants, so that any contaminant backgrounds present in the empty chamber fall below strict levels ( $< 10 \mu\text{g}/\text{m}^3$  total VOC (TVOC),  $< 10 \mu\text{g}/\text{m}^3$  total particles,  $< 2 \mu\text{g}/\text{m}^3$  formaldehyde,  $< 2 \mu\text{g}/\text{m}^3$  for any individual VOC). Air supply to the chamber was maintained at a temperature of  $23^\circ\text{C} \pm 1^\circ\text{C}$  and relative humidity at  $50\% \pm 5\%$ . The air exchange rate was  $1 \pm 0.05$  air change/hour (ACH).

Air samples were collected for a one week period, where VOC and aldehyde samples were collected at time points at hour 0, 6, 24, 48, 72, 96, and 168 and duplicates taken at hour 72 and 168. Semi volatile organic compounds (SVOCs) were sampled at 72 and 168 hour time points. VOCs and SVOCs were sampled on Tenax absorbent tubes for 90 min at 0.2 L/min collection flow rate and aldehydes were collected in 2, 4 dinitrophenylhydrazine (DNPH) cartridges for 90 min at 0.5 L/min collection flow rate.

### *Analytical measurements*

Emissions of selected aldehydes including formaldehyde were measured following ASTM D 5197 and US EPA Method TO-11A<sup>3</sup>, measurement by high performance liquid chromatography (HPLC). Solid sorbent cartridges with DNPH were used to collect formaldehyde and other low-molecular weight carbonyl compounds in chamber air. The DNPH reagent in the cartridge reacted with collected carbonyl compounds to form the stable hydrazone derivatives retained by the cartridge. The hydrazone derivatives were eluted from a cartridge with HPLC-grade acetonitrile. An aliquot of the sample was analyzed for low-molecular weight aldehyde hydrazone derivatives using reverse-phase HPLC with UV detection. The absorbances of the derivatives were measured at 360 nm. The mass responses of the resulting peaks were determined using multi-point calibration curves prepared from standard solutions of the hydrazone derivatives. Measurements are reported to a quantifiable level of  $0.1 \mu\text{g}$  based on a standard air volume collection of 45 L.

VOC measurements were made using gas chromatography with mass spectrometric detection (GC/MS). Chamber air was collected onto a solid sorbent which was then thermally desorbed into the GC/MS. Instrumentation included a sample concentrator (Perkin Elmer Model TurboMatrix ATD or TurboMatrix 650), a Hewlett-Packard/Agilent 6890 or 7890 Series Gas Chromatograph and a Hewlett-Packard/Agilent 5973 or 5975 Mass Selective Detector. The sorbent collection technique, separation, and detection analysis methodology has been adapted from techniques presented by the USEPA and other researchers. The technique follows US EPA Compendium Method TO-17<sup>4</sup> and ASTM D 6196<sup>5</sup> and is generally applicable to  $\text{C}_6 - \text{C}_{16}$

<sup>3</sup> US EPA, 1999. Compendium method TO-11A, Determination of formaldehyde in ambient air using adsorbent cartridge followed by high performance liquid chromatography (HPLC) [active sampling methodology].

<sup>4</sup> USEPA (U.S. Environmental Protection Agency), 1999. Compendium Method TO-17 determination of volatile organic compounds in ambient air using active sampling onto sorbent tubes[S]. U.S. EPA Technical Assistance Document. EPA/625/R-96/010b.



organic chemicals with boiling points ranging from 35°C to 250°C. Measurements are reported to a quantifiable level of 0.04 µg based on a standard air volume collection of 18 L.

Individual VOCs were separated and detected by GC/MS. The TVOC measurements were made by adding all individual VOC responses obtained by the mass spectrometer and calibrating the total mass relative to toluene. Individual VOCs were identified using a specialized indoor air mass spectral database and quantitated using multipoint calibration standards, if available. Other compounds were identified with less certainty using a general mass spectral library available from the National Institute of Standards and Technology (NIST). Calibration is typically based on toluene equivalent unless an authentic standard is available. This library contains mass spectral characteristics of more than 75,000 compounds as made available from NIST, the USEPA and the National Institutes of Health (NIH).

#### *Air concentration determinations*

Predicted exposure concentrations were made with the following assumptions: air within open areas of the building is well-mixed at the breathing level zone of the occupied space; environmental conditions are maintained at 50% relative humidity and 23°C (73°F); there are no additional sources of these pollutants; and there are no sinks or potential re-emitting sources within the space for these pollutants.

The emission factors,  $EF_{m,t}$  in units of  $\mu\text{g}/(\text{m}^2\cdot\text{hr})$  or  $\mu\text{g}/(\text{unit}\cdot\text{hr})$ , are calculated from the measured chamber concentration as:

$$EF_{m,t} = C_c \left( \frac{N_c}{L} \right)$$

where,

- $EF_{m,t}$  = measured emission factor at time t ( $\mu\text{g}/\text{m}^2\cdot\text{hr}$ ) or ( $\mu\text{g}/\text{unit}\cdot\text{hr}$ )
- $C_c$  = chamber concentration ( $\mu\text{g}/\text{m}^3$ ) less any background concentration of chamber
- $N_c$  = chamber air change per hour (/hr) = 1.0/hr
- $L$  = product loading ( $\text{m}^2/\text{m}^3$  or  $\text{unit}/\text{m}^3$ ) = 1 chair/chamber volume

The predicted exposure concentrations ( $C_{P,t}$ ) ( $\mu\text{g}/\text{m}^3$ ) are calculated from the modeled emission factors as:

$$C_{P,t} = EF_{m,t} \left( \frac{A}{V} \right) \left( \frac{1}{N} \right)$$

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<sup>5</sup> ASTM D 6196 “Practice for the Selection of Sorbents and Pumped Sampling/ Thermal Desorption Analysis Procedures for Volatile Organic Compounds in Air.” ASTM, West Conshohocken, PA, 2009.



where,

$C_{P,t}$	=	predicted exposure concentration at time t ( $\mu\text{g}/\text{m}^3$ )
$EF_{m,t}$	=	modeled emission factor at time t ( $\mu\text{g}/\text{m}^2\cdot\text{hr}$ ) or ( $\mu\text{g}/\text{unit}\cdot\text{hr}$ )
A	=	product area exposed in room ( $\text{m}^2$ or unit) = 1 chair
V	=	personal breathing space ( $\text{m}^3$ ) = $1.0 \text{ m}^3$ for UK chair and $1.4 \text{ m}^3$ for US chair
N	=	room air change per hour (/hr) = 0.2/hr

Predicted concentrations were calculated using specifications listed in Table 1 and following assumptions. Personal breathing space was predicted based on width and length of a chair and the height between the ground and top of the head of an average person sitting down (1.33 m). To derive the height of a sitting person, average sitting height ratio of 52% of stature<sup>6</sup> and average height of 168.8 cm<sup>7</sup> with 45.7 cm lower leg length were used. The 0.2/hr is on the low end of air exchange rates mentioned in a toxicological report by National Academy of Sciences (2000) and EPA Exposure Factors Handbook<sup>7</sup> ventilation conditions for residential buildings. This low air exchange represents current energy efficient homes<sup>8</sup>.

## Flammability Test

### Setup

The flammability experiments were conducted using the oxygen consumption calorimeter at UL's Fire Research Center in Northbrook, Illinois. The experiments were performed in a 50 by 50 ft. test cell with a 25 ft. diameter hood to measure the heat release rate. In the test cell, four inlet ducts provide air to the room and are located 5 ft. above the floor to minimize induced drafts within the room. The two rooms placed under the hood were 12 ft. by 12 ft. with an 8 ft. ceiling and 7 ft. tall by 8 ft. wide opening on the front. Both rooms were furnished identically with the contents shown in Figure 3 through Figure 4 and detailed in Table 1 through 3. The only difference between the rooms was the sofa and chair.

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<sup>6</sup> Bogin, B., & Varela-Silva, M. I. (2010). Leg length, body proportion, and health: A review with a note on beauty. *Int. J. Environ. Res. Public Health*, 7 (3), 1047-1075.

<sup>7</sup> U.S. Environmental Protection Agency. (2011). *Exposure Factors Handbook: 2011 Edition*. Washington, D.C.: Office of Research and Development.

<sup>8</sup> Offerman, F. J., Robertson, J., Springer, D., Brennan, S., & Woo, T. (2007). Window usage, ventilation, and formaldehyde concentrations in new California homes: summer field sessions. *Healthy and Sustainable Buildings, ASHRAE*.



Figure 3: a) UK furnished room b) US furnished room

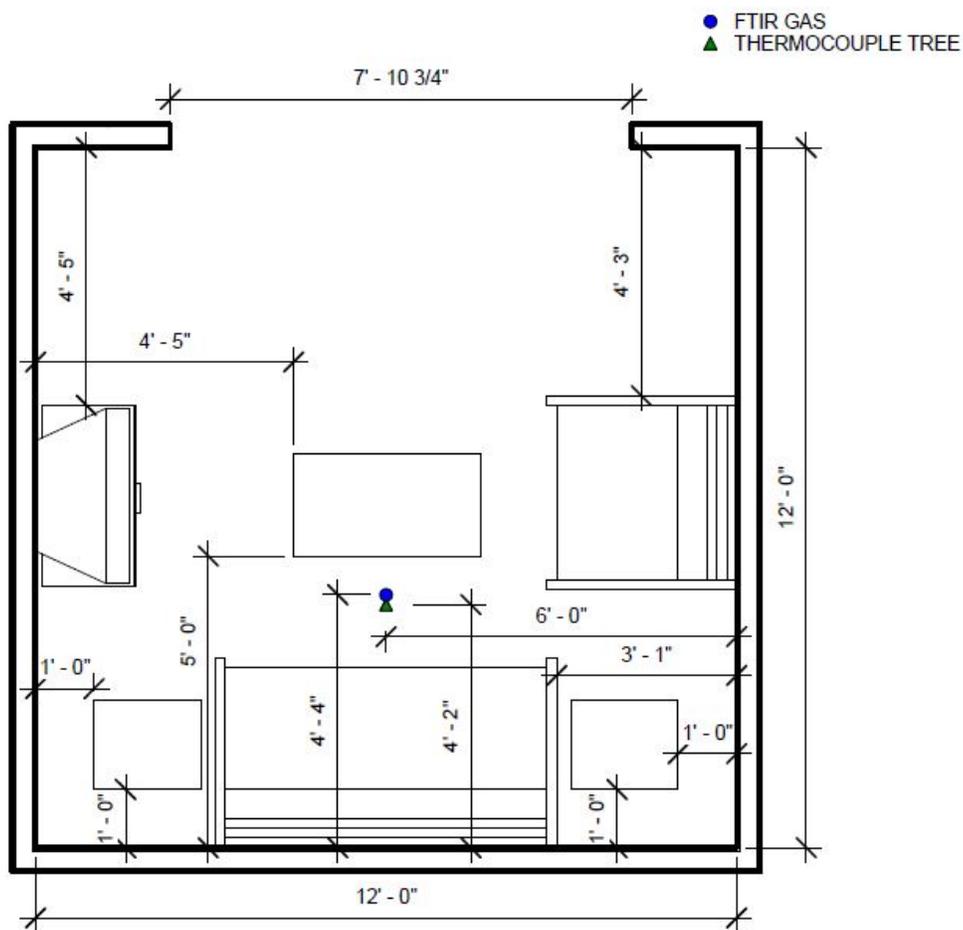


Figure 4: Experimental floor plan with instrument locations



Table 2: Room contents with weights

Item	Weight (lb.)
UK Sofa	94.0
US Sofa	98.0
UK Chair	56.2
US Chair	74.2
Coffee Table	46.0
TV Stand	61.5
End Table 1	34.1
End Table 2	34.1
Plastic Drawers	9.3
TV	162.3
Curtains	2.4
Carpet	47.9
Padding	44.0
Stuffed Animal 1	0.9
Stuffed Animal 2	0.4
Stuffed Animal 3	0.9
Small Wood Picture Frame	0.3
Medium Wood Picture Frame	1.3
Large Wood Picture Frame	6.4
Lamp Base	4.4
Lamp Shade	0.6
Plastic Flowers	0.3
Wicker Basket	0.3
Plastic Tub	2.3
Candle	1.2
Magazines	5.0
Books	2.2

Table 3: Experimental fuel loading

	UK	US
Total Weight (lb.)	618.3	640.3
Weight/area (lb./ft <sup>2</sup> )	4.29	4.45

### Ignition

Both rooms were ignited on the left side of the sofa where the seat, arm and back all come together. The ignition source was the gas flame ignition source, match-flame equivalent detailed



in British Standards Institution's EN 1021-2:2014 standard<sup>9</sup> which is the test performed for Furniture and Furnishings (Fire Safety) Regulations 1988. This source has been designed to give a calorific output approximating that of a burning match with a flame height of approximately 35 mm. The flame was applied for approximately 15 sec as outlined in the standard.

### *Measurements*

The heat release rate is measured through the use of oxygen consumption techniques. The oxygen consumption calorimeter is capable of accurately measuring the heat release rate up to 10 MW. Above 10 MW, larger inaccuracies are expected due to the combustion products overflowing the collection hood. Figure 5 shows the collection hood utilized for the calorimetry data.



**Figure 5: Calorimetry hood**

Temperatures were recorded using a bare-bead, Chromel-Alumel (type K) thermocouple with a 0.5 mm nominal diameter (Figure 5. 2). The uncertainty given by the manufacturer for the temperature measurements is  $\pm 2.2$  °C for temperatures below 293 °C and  $\pm 0.75$  % for higher temperatures<sup>10</sup>. The thermocouple readings will be lower than the air temperature when the thermocouple is in the flame region, due to radiative losses to the surrounding cooler environment. When the thermocouples are farther from the flame region, the impact of radiation will result in temperature readings higher than the air temperature. Due to the effect of radiative heat transfer to the thermocouples, the expanded uncertainty is approximately  $\pm 15$ %.

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<sup>9</sup> British Standards Institution EN 1021-2:2014 standard, "Furniture. Assessment of the ignitability of upholstered furniture. Ignition source match flame equivalent"

<sup>10</sup> The Temperature Handbook. Stamford, CT: Omega Engineering, 2005. Print.

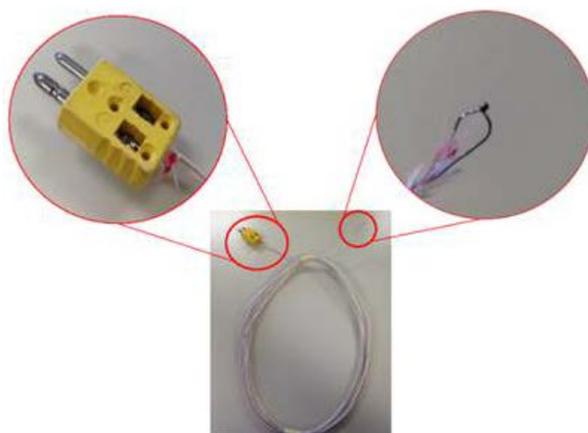


Figure 6: Chromel-Alumel (type K) thermocouple

Carbon monoxide, carbon dioxide, nitrogen monoxide, and hydrogen cyanide released during the burn were measured by Fourier transform infrared spectroscopy (FTIR) extractive gas spectrometer. MIDAC I1100 industrial gas analyzer simultaneously analyzes multiple gases in a combustion effluent stream from ppb to % levels with automatic temperature and pressure compensation. The gas analyzer has a 10 meter path length and a wave number range of 650/cm to 4,500/cm at a resolution of 0.5/cm. The instrument collects four data scans per minute and is recorded throughout the experiment. The FTIR gas analyzer is shown in Figure 7. Gas effluent data were sampled every 15 sec. AutoQuant Pro software was used to analyze the recorded spectra identifying gas compounds and quantifying the concentration.



Figure 7: Midac FT-IR gas analyzer



## RESULTS

### Chemical Exposure

#### *VOCs and aldehydes*

VOC (APPENDIX 1) and aldehyde (APPENDIX 2) emissions were measured from the chairs and are reported individually by decreasing emission levels. By the end of the testing period at hour 168, predicted TVOC concentrations for US and UK chairs decreased to  $168 \mu\text{g}/\text{m}^3$  and  $78 \mu\text{g}/\text{m}^3$  respectively (Figure 8a). The TVOC concentration for the US chair reached a high of  $1024 \mu\text{g}/\text{m}^3$  at hours following placement in the chamber. More VOC compounds were identified for the US chair (19 compounds) than for UK (3 compounds), which could have led to the higher TVOC concentration. Majority of TVOC was made up of various aldehydes and other compounds including tetramethylbutanedinitrile<sup>11</sup>, 1-methoxy 2- propanol<sup>8,12</sup>, acetic acid<sup>8</sup>, and 2-ethylhexanoic acid<sup>8</sup> from the US chair. The UK chair released 1-butanol 2-ethylhexanoic acid. Aldehydes were key emissions from both chairs with significant levels of formaldehyde, a known irritant and carcinogen under certain conditions<sup>8,9,10,13,14,15</sup> (Figure 8c). Levels at 168 hours were  $25.5 \mu\text{g}/\text{m}^3$  for the US chair and  $915.4 \mu\text{g}/\text{m}^3$  for the UK chair, which exceeds the recommended product levels within the US<sup>1,16</sup>. Predicted concentrations of top ten emitting compounds at 168 hour are listed in Table 4. Although they were purchased new, the age of the chairs was not known. Age and storage conditions of the chairs could affect the chemical emission levels.

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<sup>11</sup> American Conference of Governmental Industrial Hygienists Threshold Limit Values for Chemical Substances and Physical Agents

<sup>12</sup> California Office of Environmental Health's Hazard Assessment (OEHHA), Chronic Reference Exposure Levels

<sup>13</sup> California Health and Welfare Agency, Proposition 65 Chemicals

<sup>14</sup> National Toxicology Program

<sup>15</sup> International Agency on Research of Cancer

<sup>16</sup> ANSI/BIFMA X7.1-2011 Standard for Formaldehyde and TVOC Emissions of Low-emitting Office Furniture and Seating

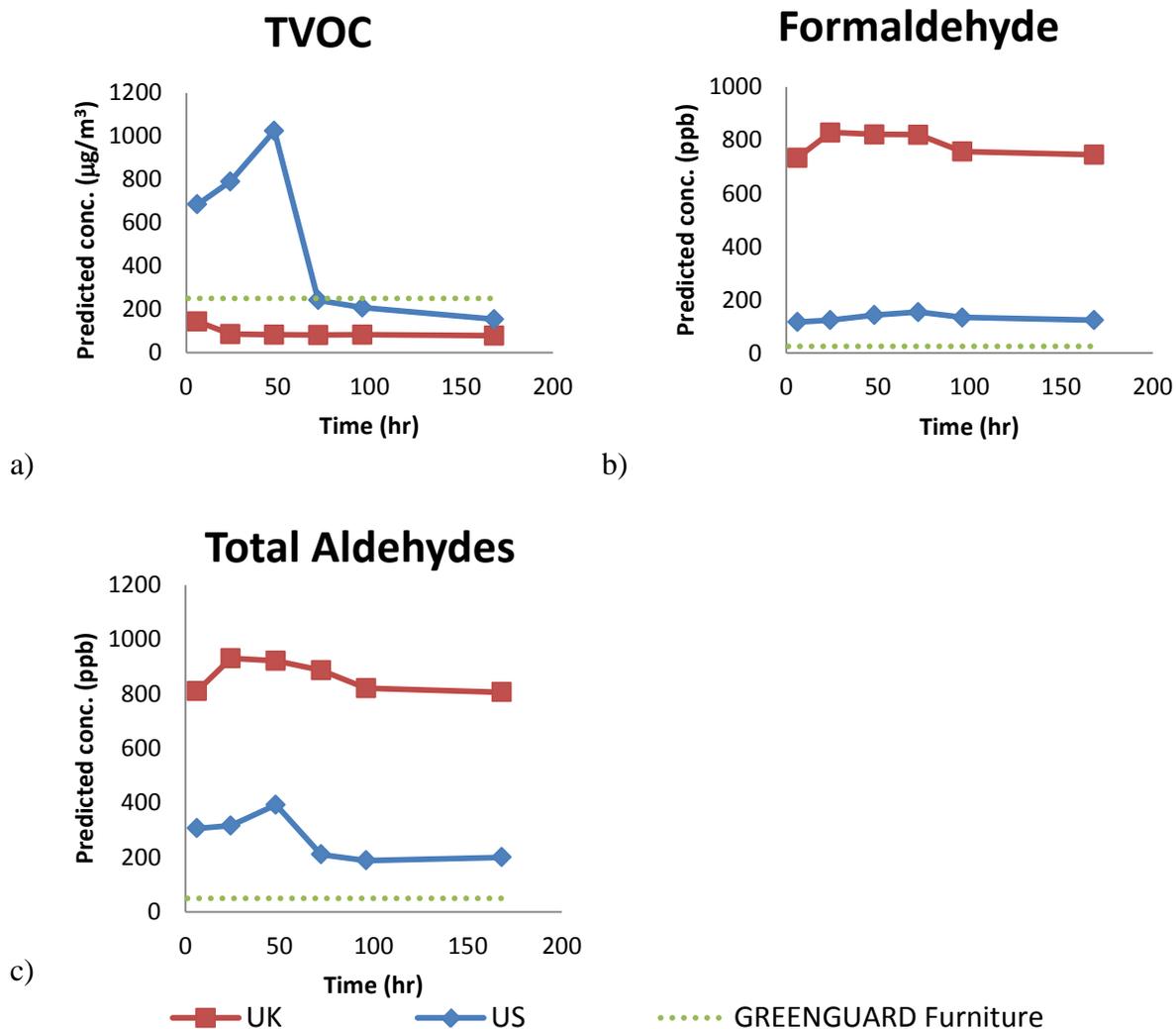


Figure 8: Predicted indoor air concentrations: a) total VOC b) formaldehyde, and c) total aldehydes for UK chair (red) and US chair (blue).

Table 4: Predicted concentrations of top ten emitting compounds at hour 168.

US		UK	
	(µg/m³)		(µg/m³)
Pentanal	182.6	Formaldehyde	915.4
Acetaldehyde	141.5	2-ethyl hexanoic acid	159.4
Hexanal	72.6	Acetaldehyde	96.5
Butanal	59.1	Hexanal	19.4
1-Pentanol (N-Pentyl alcohol)	54.9	Benzaldehyde	14.0
Benzaldehyde	52.8		
1-methoxy-2-Propanol	45.4		



Hexanal	35.1
Formaldehyde	25.5
Octanal	20.0

### Flame Retardant

Flame retardants were found emitting from the UK chair but not in the US chair. In addition, samples of foam and fabric materials from both chairs were analyzed by Duke Superfund Center Foam Project at Duke University. The UK chair materials were found to contain tris(chloroethyl) phosphate (TCEP) and Tris (1-chloro-2-propyl) phosphate (TCPP) as listed in Table 5. Both chemicals are listed as priority chemicals<sup>17,18</sup> for their carcinogenicity. There were no flame retardants detected in the US chair. Qualitative analysis by pyrolysis GC/MS also identified TCPP, brominated flame retardant, and melamine in the materials of the UK chair. TCPP was also detected from the environmental chamber test during the SVOC analysis. TCPP was continuously being released throughout the testing period (Figure 9b) at a predicted concentration level of 407  $\mu\text{g}/\text{m}^3$  (Figure 9a).

Table 5: Flame retardant concentrations in the UK chair materials.

	Foam	Fabric
TCEP (mg/g)	0.08	2.71 $\pm$ 0.15
TCPP (mg/g)	78.7 $\pm$ 2.33	0.89 $\pm$ 0.03

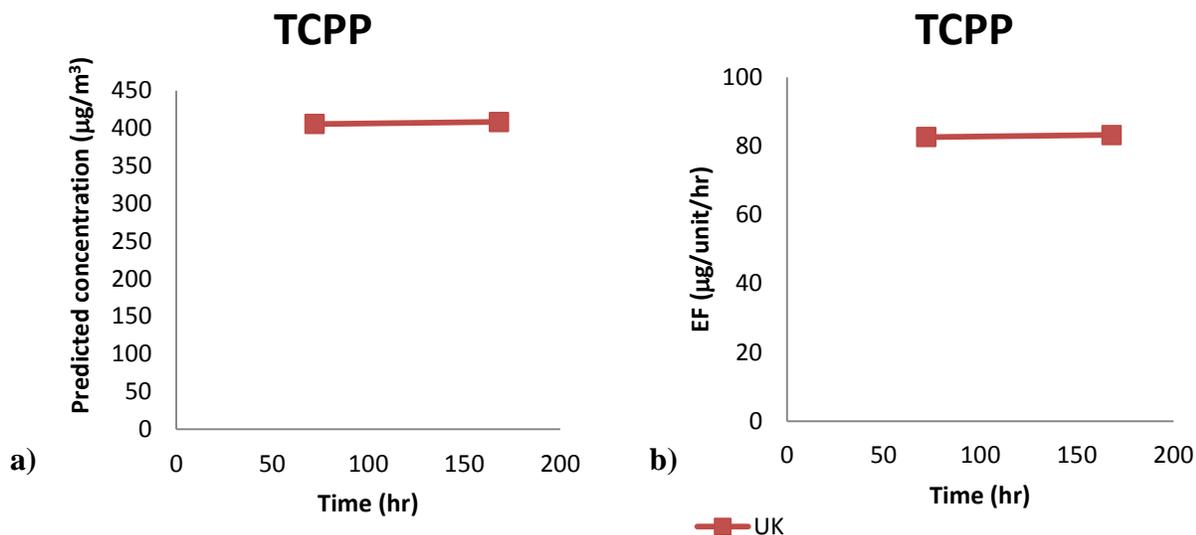


Figure 9: Predicted Tris(1-chloro-2-propyl)phosphate a) concentration and b) emission factor vs. time for the UK chair.

<sup>17</sup> State of California Environmental Protection Agency Department of Toxic Substances Control Safer Consumer Products Regulations- Informational list of Candidate Chemicals and Chemical Groups

<sup>18</sup> Priority Chemicals that are identified under the California Environmental Contaminant Biomonitoring Program



## Flammability

Both sets of furniture were ignited and allowed to burn until the contents were reduced to ashes. APPENDIX 3 shows still images taken every 30 sec during the fire experiment for both US and UK rooms. Both rooms transitioned to flashover, the US room in 2:45 min and the UK room in 6:35 min (Figure 10). Both rooms peaked between 7 MW and 8 MW indicating that the heat release rate was governed by the size of the ventilation opening on the front of the room. At the end of the 30 minute experiment, the US room released 3600 MJ of energy (12.4 MJ/kg of fuel) while the UK room released 3000 MJ (10.7 MJ/kg of fuel) (Figure 11).

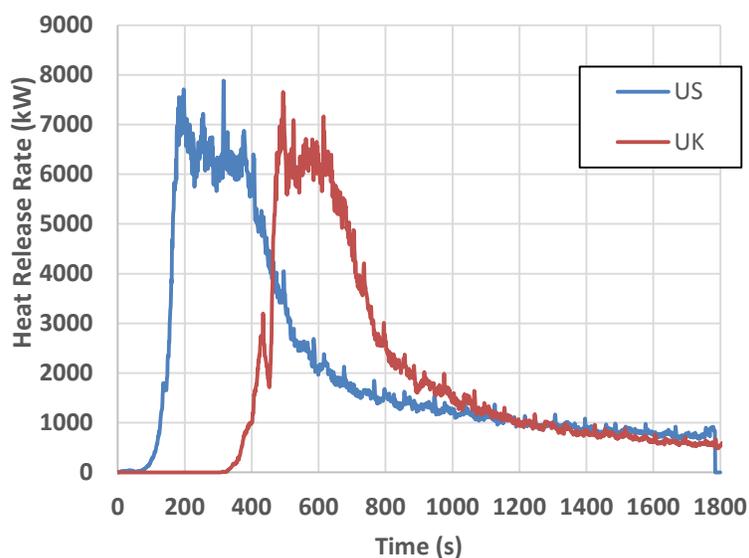


Figure 10: Heat release rate comparison

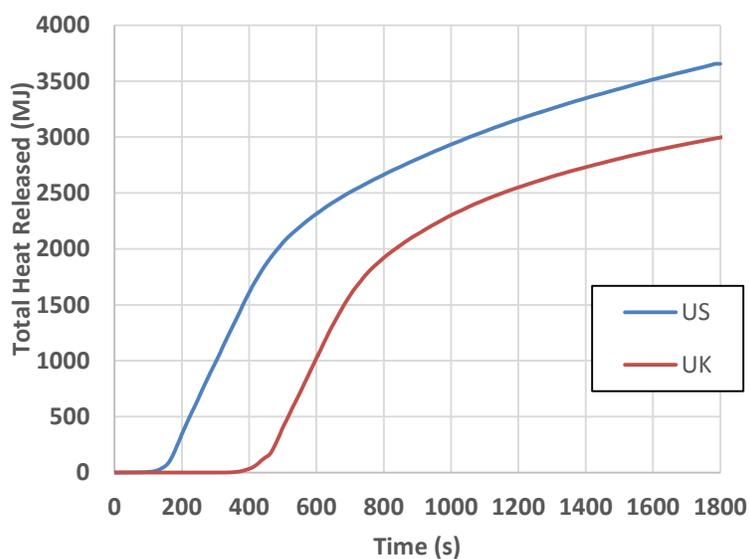


Figure 11: Total heat released comparison

Both rooms exceeded 2000 °F as they reach full room involvement in fire (Figure 12). The US room reached 300 °F at 5 ft above the floor in 2:04 min and the UK room reached 300 °F at 5 ft above the floor in 5:08 min. Research by Montgomery et. al. indicated that in humid air, rapid skin burns would occur at 100 °C (210 °F), and 150 °C (300 °F) was the exposure temperature at which escape was not likely<sup>19</sup>. Temperatures at all levels in both rooms escalated very quickly. Temperatures 1 ft above the floor increased from 300 °F to 1000 °F in both rooms in approximately 5 sec.

<sup>19</sup> Montgomery, R.R., C.F. Reinhardt, and J.B. Terrill. (1975). Comments on fire toxicity. *Combust. Toxicol.*, 2, 179-212.

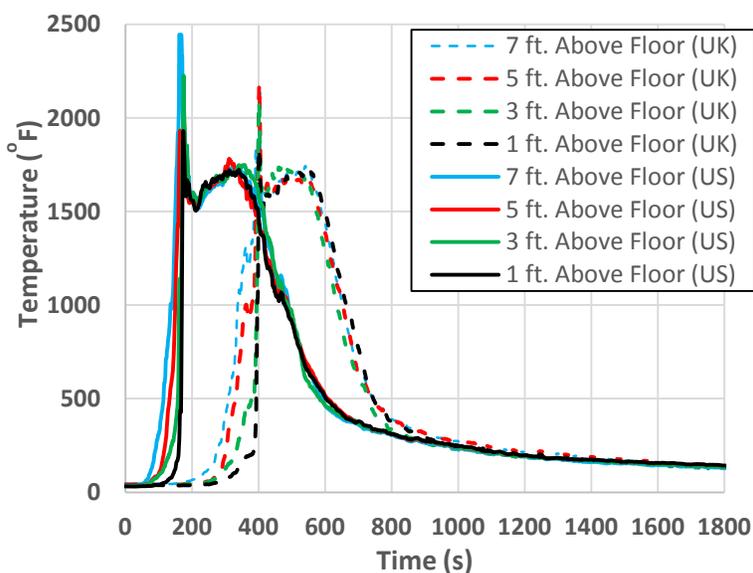


Figure 12: Room temperature comparison

Levels of carbon monoxide, carbon dioxide, hydrogen cyanide and nitric oxide are shown in Figure 13. Majority of the emissions during the burn was carbon dioxide for both rooms. There is very little HCN in the US furniture until flashover; in the UK furniture the HCN level is higher, and appears to increase significantly during the extinguishment phase.

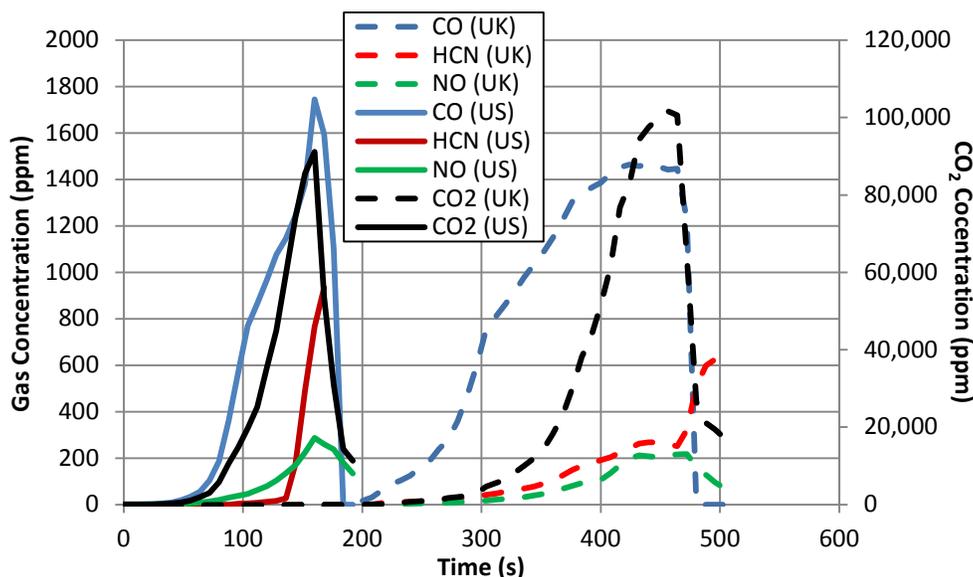


Figure 13: FTIR gas measurements for US (solid) and UK (dotted) rooms



## DISCUSSION

### Daily Exposure and Health Risk

Primary VOC emission from both chairs from UK and the US were aldehydes. Formaldehyde is often used in resins, and formaldehyde, pentanal, acetaldehyde, hexanal, butanal emissions are typically associated with pressed wood or composite boards<sup>20</sup>. Future studies will include emission studies of individual components to assist in identifying sources.

Flame retardant was released from the UK chair at a steady rate throughout the week long chamber test. The found flame retardant, TCPP, has been associated with various health effects depending on different sources. While some organizations expect TCPP to be carcinogenic, some animal tests identified the effects of TCPP to be minor (skin and eye irritant, weight loss, depression, tremor, etc.)<sup>21</sup>. TCPP's acute oral lethal dose (LD<sub>50</sub>) is 2000 mg/kg on average<sup>22</sup> and lethal concentration (LC<sub>50</sub>) is greater than 4.6 mg/L<sup>23</sup> in rat studies. Toxicity studies have been performed for various flame retardants, but there is a research gap between toxicity and human exposure. A future study will address how much humans are being exposed to semi-volatile flame retardants through inhalation, ingestion, and dermal exposure pathways.

### Flame Retardant and Flammability

Flame retardants suppress or delay combustion by endothermic degradation, thermal shielding, dilution of gas phase, and/or gas phase radical quenching. TCPP, included inside the UK furniture, uses gas phase radical quenching where chlorinated molecules react with radicals and minimize propagation of radical oxidation reactions during combustion. The effect of TCPP was shown by the delayed flashover for the UK furniture compared to the US furniture without flame retardant (Figure 10).

Volume, weight, and total heat release ratios of US over UK furniture are 1.35, 1.14, and 1.20 respectively. The ratios explain that the UK furniture have larger density, most likely to account for the mass amount of flame retardant included in the furniture. The total heat release ratio is similar to the weight ratio, which may imply that flame retardants simply delay the process of combustion. Mass of the room should be weighed before and after the fire experiment in order to correlate the amount of fuel consumed to emissions of CO and CO<sub>2</sub>, major compounds emitted from combustion process. Polyurethane contains nitrogen, therefore HCN and NO<sub>x</sub> emission may be related to the amount of polyurethane foam in the furniture. The strange behavior of HCN concentration for the UK room increasing during the extinguishment phase (Figure 13)

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<sup>20</sup> Baumann, M. G., Batterman, S. A., & Zhang, G. Z. (1999). Terpene emissions from particleboard and medium-density fiberboard products. *Forest Products Journal*, 49(1), 49-56.

<sup>21</sup> Tris(1-chloro-2-propyl)phosphate, UNEP OECD Screening Information Dataset (SIDS) for High Volume Chemicals (<http://www.inchem.org/documents/sids/sids/13674845.pdf>)

<sup>22</sup> Stauffer Report No. T-4030. Acute toxicity of Fyrol PCF; August 1972.

<sup>23</sup> Stauffer Report No. T-6556. Acute Inhalation Toxicity of Fyrol PCF in Albino Rats; January 1979.



may be related to the existence of flame retardants or other chemicals in the chair materials. Future experiment would need to be designed to answer these hypotheses.

### Flash Over and Response Time

In these room fire experiments it was clear that the sofa was the primary fuel contributing to the flashover time and time to potential occupant hazard. In each room, fire flames were seen exiting the top of the front of the room before the fire extended beyond the sofa. The radiation from the hot gases pyrolyzed the other furniture in the room and transitioned the room to flashover.

The room fire with the US sourced upholstered furniture transitioned to flashover in 2:45 min. This time is faster than previous experiments conducted at UL with similar furniture over the past 3 years. Three rooms with modern US furniture purchased from local retail stores produced flashover times of 3:20 min, 3:40 min and 4:45 min<sup>24</sup>. Each of these furnished rooms was compared to a room with “legacy” upholstered furniture that resulted in flashover times of 29:30 min, 34:15 min and one did not achieve flashover.

The room fire with the UK sourced upholstered furniture transitioned to flashover in 6:35 min. The materials used in the construction of this sofa clearly slowed down fire growth as compared to the US sofa. To comply with Furniture and Furnishings (Fire) (Safety) Regulations 1988, the flame is to be held in place for 15 sec (same as done in this experiment) and flaming or smoldering is supposed to self-extinguish within 120 sec. This was clearly not the case in this end product experiment.

These results pose the question, how long is an acceptable time to unescapable conditions? While the UK room took almost 4 min longer to reach flashover, 6:35 min may not be enough time to notice the fire or alarm and get out of the home safely.

An additional time to examine is the intervention time of the fire service. The intervention time of the fire service varies greatly across the US and Internationally. Fire department intervention time is based on several factors,  $t_1$ - $t_4$ . The time  $t_1$  depends upon a number of factors such as when the fire is detected after initiation and the time to call for fire service assistance. This time can vary greatly depending on the source of ignition, item ignited, presence of occupants, presence of fire protection devices and many other factors. The time  $t_2$  is the time for the 911 operator to call the appropriate fire station to respond. The US national standard NFPA 1221<sup>25</sup> define the maximum value for  $t_2$  as 60 sec. The time  $t_3$  is the time it takes for the firefighters to get onto the fire apparatus and respond. As per NFPA 1710 – Deployment of Career Fire

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<sup>24</sup> Kerber, S. “Analysis of Changing Residential Fire Dynamics and its Implications on Firefighter Operational Timeframes.” Fire Technology Journal. Volume 48, Number 4, 2012, p 865-891.

<sup>25</sup> NFPA 1221 (2010) Installation, maintenance, and use of emergency services communications systems



Departments<sup>26</sup> this equals 60 sec to begin the response. The time  $t_4$  is the time it takes for the firefighters to drive to the scene of the fire. Following NFPA 1710, the goal for fire emergency response is to arrive at the scene within 4 min after the 911 call is made. That is,  $t_2 + t_3 + t_4 = 6$  min.

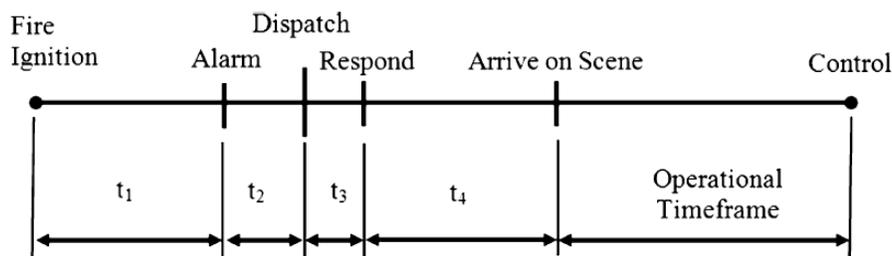


Figure 14: Fire service timeline

Following NFPA 1720 – Deployment of Volunteer Fire Departments<sup>27</sup>, the goal for fire emergency response is to arrive at the scene within 9 min in an urban area (~384 people/km<sup>2</sup>), 10 min in a suburban area (192 people/km<sup>2</sup> to 384 people/km<sup>2</sup>), 14 min in a rural area (~192 people/km<sup>2</sup>) and directly related to driving distance for remote areas greater than 8 miles from the closest fire station. Therefore  $t_2 + t_3 + t_4 = 11$  min to 16 min.

Analyzing the National Fire Incident Reporting System (NFIRS) database yields a very consistent average fire department response time to one and two family detached homes (Occupancy Code 419 in NFIRS) in the United States. Table 7 shows an average response time ( $t_2 + t_3 + t_4$ ) of approximately 6.4 min from 2006 to 2009.

Some international comparisons of fire department response times are available. In 2006, the average response time to dwelling fires in England was 6.5 min<sup>28</sup>. A report comparing residential fire safety in several countries states, “Response time goals in Sweden and Norway are more lenient than in the United States. The Scandinavian nations require the first responding unit to arrive in 10 min, versus a goal of 6 min in the typical United States city. Scandinavia generally gives more weight to prevention and early extinguishment by homeowners, less to rapid response”<sup>29</sup>. A report written by a German Fire Officer in 2004 examined response times

<sup>26</sup> NFPA 1710 (2010) Organization and deployment of fire suppression operations, emergency medical operations, and special operations to the public by career fire departments

<sup>27</sup> NFPA 1720 (2010) Organization and deployment of fire suppression operations, emergency medical operations, and special operations to the public by volunteer fire departments

<sup>28</sup> Review of fire and rescue service response times (2009) Fire Research Series. <http://www.communities.gov.uk>. Accessed 20 Jun 2011

<sup>29</sup> Schaenman P (2007) Global concepts in residential fire safety Part 1—best practices from England, Scotland, Sweden and Norway. System Planning Corporation, Arlington



in Europe by contacting country officials and asking them questions about their acceptable response times and conducting an internet search. Many countries such as Denmark, France, Greece, Ireland, Norway and Sweden had acceptable urban response times of 10 min and response times to suburban or rural areas of 15 min to 30 min<sup>30</sup>.

## CONCLUSIONS

A preliminary study of limited furniture from the US did not show the presence of flame retardants but similar furniture from the UK had significant levels of TCPP, Tris (1-chloro-2-propyl) phosphate. Flame retardants may be effective; however, there is concern that some of them may be harmful when consumers are exposed to them. Flame retardant emissions were found in the air surrounding the UK furniture, but it was also observed that burn flashover was delayed relative to the US furniture without flame retardants. This data indicates the need to further evaluate the relationship between flammability and flame retardant usage and to evaluate all parameters for harmonizing fire and chemical safety for users. Ongoing studies will evaluate a range of chemical emissions from furniture manufactured with different flame retardant technologies while also measuring the availability of different exposure routes. Investigated technologies will go through environmental chamber tests and flammability measures to further understand the relationship between flame retardant exposure and flammability.

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<sup>30</sup> Stiegel J (2004) Protection target definitions—a national and international comparison. Frankfurt Fire Department, Frankfurt



## APPENDIX 1: EMISSION FACTORS OF IDENTIFIED INDIVIDUAL VOLATILE ORGANIC COMPOUNDS

$\mu\text{g}/(\text{unit}\cdot\text{hr})$

### US CHAIR

CAS NUMBER	COMPOUND IDENTIFIED	ELAPSED EXPOSURE HOUR					
		6	24	48	72**	96	168**
66-25-1	Hexanal	47.7	52.4	59.6	72.4	57.2	59.0
124-13-0	Octanal <sup>†</sup>	31.6	36.3	39.3	48.9	36.3	33.7
142-62-1	Hexanoic acid	29.8	25.6	32.8	46.2	36.3	29.2
111-70-6	1-Heptanol	22.0	18.5	20.9	26.2	20.9	18.5
111-71-7	Heptanal (Heptaldehyde) <sup>†</sup>	19.7	23.8	26.2	32.8	25.0	25.0
109-52-4	Pentanoic acid (Valeric acid)	16.1	14.9	18.5	26.2	20.3	18.2
124-19-6	Nonyl aldehyde (Nonanal) <sup>†</sup>	15.5	17.9	20.3	32.2	24.4	18.2
141-63-9	Pentasiloxane, dodecamethyl	15.5	21.4	22.6	24.7	18.5	16.7
3333-52-6	Tetramethylbutanedinitrile <sup>†</sup>	14.9	20.3	20.9	24.1	17.9	16.7
110-62-3	Pentanal	14.3	15.5	19.1	23.2	19.1	20.3
111-87-5	1-Octanol				12.5		
71-41-0	1-Pentanol (N-Pentyl alcohol)			12.5	15.5	13.7	15.5
107-98-2	2-Propanol, 1-methoxy- <sup>†</sup>				13.1		12.8
64-19-7	Acetic acid		13.7	22.0	23.2	22.6	18.5
1632-73-1	Bicyclo[2.2.1]heptan-2-ol, 1,3,3-trimethyl*				11.9		
80-57-9	Bicyclo[3.1.1]hept-3-en-2-one, 4,6,6-trimethyl-*			11.9	17.6	14.3	



CAS NUMBER	COMPOUND IDENTIFIED	ELAPSED EXPOSURE HOUR					
		6	24	48	72**	96	168**
107-92-6	Butanoic acid			12.5	17.0	13.7	12.8
149-57-5	Hexanoic acid, 2-ethyl <sup>†</sup>			13.7	17.6	14.3	12.8
107-52-8	Hexasiloxane, tetradecamethyl*				11.9		

### UK CHAIR

CAS NUMBER	COMPOUND IDENTIFIED	ELAPSED EXPOSURE HOUR					
		6	24	48	72**	96	168**
149-57-5	Hexanoic acid, 2-ethyl <sup>†</sup>	33.4	35.7	34.6	33.7	34.0	32.5
541-02-6	Cyclopentasiloxane, decamethyl	13.1					
71-36-3	1-Butanol (N-Butyl alcohol) <sup>†</sup>	11.9	13.1				

\*Indicates NIST/EPA/NIH best library match only based on retention time and mass spectral characteristics.

\*\*Averages of duplicate measurements at 72 and 168 hours.

<sup>†</sup>Denotes quantified using multipoint authentic standard curve. Other VOCs quantified relative to toluene.

Quantifiable level is 0.04 µg based on a standard 18 L air collection volume.



## APPENDIX 2: EMISSION FACTORS OF TARGET LIST ALDEHYDES

$\mu\text{g}/(\text{unit}\cdot\text{hr})$

### US CHAIR

CAS NUMBER	COMPOUND IDENTIFIED	ELAPSED EXPOSURE HOUR					
		6	24	48	72**	96	168**
4170-30-3	2-Butenal	BQL	BQL	BQL	BQL	BQL	BQL
75-07-0	Acetaldehyde	19.1	22.6	30.4	37.8	35.2	39.9
100-52-7	Benzaldehyde	12.5	12.5	20.9	16.7	14.9	14.9
5779-94-2	Benzaldehyde, 2,5-dimethyl	BQL	BQL	BQL	BQL	BQL	BQL
529-20-4	Benzaldehyde, 2-methyl	BQL	BQL	BQL	BQL	BQL	BQL
620-23-5 /104-87-0	Benzaldehyde, 3- and/or 4-methyl	BQL	BQL	BQL	BQL	BQL	BQL
123-72-8	Butanal	BQL	BQL	11.9	14.9	13.7	16.7
590-86-3	Butanal, 3-methyl	BQL	BQL	BQL	BQL	BQL	BQL
50-00-0	Formaldehyde	40.5	43.5	49.5	53.3	46.5	42.9
66-25-1	Hexanal	117	116	131	151	120	122
110-62-3	Pentanal	41.1	39.3	46.5	57.2	47.1	51.5
123-38-6	Propanal	BQL	BQL	BQL	BQL	BQL	BQL



## UK CHAIR

CAS NUMBER	COMPOUND IDENTIFIED	ELAPSED EXPOSURE HOUR					
		6	24	48	72**	96	168**
4170-30-3	2-Butenal	BQL	BQL	BQL	BQL	BQL	BQL
75-07-0	Acetaldehyde	23.2	23.8	22.6	22.0	20.9	19.7
100-52-7	Benzaldehyde	11.9	13.7	13.7	14.9	13.7	17.0
5779-94-2	Benzaldehyde, 2,5-dimethyl	BQL	BQL	BQL	BQL	BQL	BQL
529-20-4	Benzaldehyde, 2-methyl	BQL	BQL	BQL	BQL	BQL	BQL
620-23-5 /104-87-0	Benzaldehyde, 3- and/or 4-methyl	BQL	BQL	BQL	BQL	BQL	BQL
123-72-8	Butanal	BQL	BQL	BQL	BQL	BQL	BQL
590-86-3	Butanal, 3-methyl	BQL	BQL	BQL	BQL	BQL	BQL
50-00-0	Formaldehyde	184	209	206	205	190	187
66-25-1	Hexanal	BQL	18.5	19.1	20.6	20.9	23.5
110-62-3	Pentanal	BQL	BQL	BQL	BQL	BQL	BQL
123-38-6	Propanal	BQL	BQL	BQL	BQL	BQL	BQL

BQL = Below quantifiable level of 0.1 µg based on a standard 45 L air collection volume.

\*\*Average of duplicate measurements at 72 and 168 hours.

### APPENDIX 3: FIRE EXPERIMENT PICTURES

#### a) Time lapse US room fire experiment pictures



Figure 15. Experiment Time 0:00 - Ignition



Figure 16. Experiment Time 0:30



Figure 17. Experiment Time 1:00



Figure 18. Experiment Time 1:30



Figure 19. Experiment Time 2:00



Figure 20. Experiment Time 2:30



Figure 21. Experiment Time 2:45 - Flashover



Figure 22. Experiment Time 3:00

b) Time lapse UK room fire experiment pictures



Figure 23. Experiment Time 0:00 - Ignition



Figure 24. Experiment Time 1:00



Figure 25. Experiment Time 2:00



Figure 26. Experiment Time 3:00



Figure 27. Experiment Time 4:00



Figure 28. Experiment Time 5:00



Figure 29. Experiment Time 6:00



Figure 30. Experiment Time 6:35 - Flashover



Figure 31. Experiment Time 7:00



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