Flexible Polyurethane Foams: A Comparative Measurement of Toxic Vapors and Other Toxic Emissions in Controlled Combustion Environments of Foams With and Without Fire Retardants

Matthew Blais and Karen Carpenter, Fire Technology Department, Southwest
Research Institute, 6220 Culebra Rd, San Antonio, TX 78238, USA*

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Abstract. A series of experiments were performed to measure the toxic vapor emissions of fires involving flexible polyurethane foams (FPUF) with and without flame retardants (FR). FPUF were covered with FR and non-FR fabrics to simulate cushion conditions. Testing was performed to both maximize detection of gases in small scale testing and measurement of exposure concentrations in realistic fire conditions in a room sized enclosures. A standard smoke box with load cell, open flame ignition source and Fourier transform infra-red spectrometer (FTIR) fit with a 2 m gas cell was used to monitor gas emission real time during testing with filter samples analyzed for acid gases and chloro-dioxins and furans. An NFPA 286 room was used to measure realistic smoke emissions from three seat furniture mock-ups with non-combustible frames. Oxygen consumption calorimetry, smoke opacity and smoke toxicity were measured during these tests. FTIR and grab sampling were performed during the room fires. Grab sampling using evacuated metal canisters were used to collect combustion gasses at various stages of the fire followed by analysis using EPA method TO-15 indoor air pollutants. In addition chloro-dioxins and furans were measured using a particulate filter collection system. The results of the study indicated that both FR and non-FR FPUF gave very similar results for smoke toxicity and both were less than what would be produced by an equivalent mass of wood. Use of fire barrier materials increased the toxicity of smoke produced from non-FR FPUF due to the creation of oxygen limited conditions. Use of fire barrier materials with FR FPUF would not sustain ignition and ended up producing less toxic smoke for up to 19 kW ignition source.

Keywords: Flexible polyurethane foam, Smoke box testing, Room corner testing, Smoke toxicity, Calorimetry

* Correspondence should be addressed to: Matthew Blais, E-mail: mblais@swri.org

1. Introduction

Numerous public advocacy groups claim that fire retardants in polyurethane foams (FPUF) do not increase the safety of these materials while increasing the toxicity of the smoke produced during a fire. A three cushion couch can contain millions of joules of energy and release them at a rate of up to 1.2 MW [1]. Numerous studies indicate that the test conditions and composition of the materials tested affect the toxic gas emission detected in FPUFs [2, 3]. In an effort to quantify the toxic gas evolution in fires involving flexible FPUF, a testing program was performed that measured the gases emitted by FPUFs with and without fire retardants and with fire retardant and non-fire retardant cover materials in fires caused by small ignition sources. These configurations covered the four possible combinations of the materials being studied. A direct comparison of multiple replicates of each configuration was performed to detect the nine standard toxic gases cited in ASTM E800 and smoke density as measured in general accordance with ISO 5659-2 in a standard smoke box. In addition, screening analysis was performed for dioxins and furans by the analysis of the particulate filters of the gas sampling system. The fire resistant cover materials used in this testing was confirmed to be NFPA 701 compliant. Existing furniture standards do not test against open flame for cover materials and the smolder only tests are insufficient ignition sources to cover the potential risks [4]. For this reason, small open flame ignition sources were used to initiate combustion for fabric covered FPUF cushions in both smoke box.

In addition, four materials configurations were tested in a NFPA 286 room with three seat couch mock-ups to look at realistic toxic gas concentrations created in a FPUF filled furnishing fire as an extension of the work performed by Janssens et al. [5]. The FPUF filled furnishings were exposed to four increasingly severe small open flame ignition conditions until sustained ignition was achieved and the gases evolved in the fire were monitored by Fourier transform infra-red (FTIR) spectroscopy and through the collection of grab samples that were analyzed for EPA TO-15 vapors and chloro dioxins and furan [6]. Sample collection was extended for 20 min after combustion ended to determine hazards that fire-fighters might encounter during salvage and overhaul operations [7]. Similar work has been executed at SP in Sweden on televisions by Blomqvist et al. [8]; this study uses many of the same smoke toxicity analytical techniques.

2. Experimental

2.1. Materials

2.1.1. FPUFs. CAL TB 117 compliant flexible polyurethane foam FR1354 was obtained from the San Antonio Upholstery Supply containing 8% tris-dichloro-propyl phosphate, (TDCPP) CAS # 40120-74-9, with a density of 23 kg/m³.

CAL TB 117 compliant FR1354n-FPUF was obtained from the San Antonio Upholstery Supply, containing 9% Fire Master 550™ (a flame retardant) with a

density of 21 kg/m³. 1030-FPUF was obtained from the San Antonio Upholstery Supply with a density of 17 kg/m³.

2.1.2. Fabrics. Non-FR-cotton, Eco Linen, Khaki colored was obtained from San Antonio Upholstery store with a fabric weight of 355 g/m².

FR-cotton, Supercoate Hvy Duvetyne #29776 Black #000 54" 100% Cotton FR was obtained from Dazian, N. Hollywood, CA with a fabric weight of 415 g/m². Analysis was unable to identify the specific FR used.

2.2. Smoke Box Test Equipment

A smoke box of interior dimensions of 914 mm × 914 mm × 610 mm with an integrated optical opacity and data acquisition systems was used during this series of tests. Small ignition sources were used for ignition of materials: Source #1 is a small gas burner described in BS5852 having a flow of 45 ml/min at 25°C providing a heat release rate of ca. 83 W and a flame height of 35 mm and source #2 is a small burner described in BS5852 having a flow of 160 ml/min at 25°C providing a heat release rate of ca. 295 W and a flame height of 145 mm. A load cell attached to the data acquisition system with a precision of ±0.01 g recorded mass data every second. A Thermo Fischer Nicolet 6700 FTIR equipped with a 2-m gas cell, potassium bromide windows and gold reflectors set to a flow of 1.5 slpm gave a concentration rise time of less than 30 s was used to measure nine gas concentration to between 1 PPM and 5 PPM detection limit. Ambient concentrations of H₂O and CO₂ are corrected by collecting a background sample prior to testing and subtracting from subsequent spectrum. The gas sampling system was equipped with a steal probe that is centroid in the smoke box, a heated Teflon™ coated fiber glass filter and a Teflon™ heated sample transfer line. The sample spectra are generated every 13.85 s composed of 12 individual scans with a 0.5 wave number resolution (cm⁻¹).

2.3. Room Corner Mock-Up Test is Shown in Figure 1

Dimensions are 2.44 m × 3.67 m × 2.44 m with a 0.78 m × 2.01 m door in center of 2.44 m wall. Walls and ceiling had two layers of 12.7 mm type X gypsum board and the floor had a single layer of calcium silicate board. Thermocouple tree was installed in the center of the doorway, radiometers in center of the floor and one wall, and load cell measured mass loss of the test specimen. A gas sampling probe with 9-1 mm holes placed one inch from the top and transitioned the entire doorway was attached to the FTIR system. Ignition burner source #2 and ASTM E 1537 were used. ASTM E 1537 ignition burner source was a 250 mm² × 250 mm² burner consisting of 13 mm outside diameter stainless steel tubing with holes pointing straight out, straight down and inward at a 45° angle at various locations. Propane gas was supplied at 13 l/min giving 19 kW flame. Smoke density was measured in the hood exhaust duct using light path optical opacity. Calorimetry was measured via oxygen consumption, CO and CO₂ generation with the values derived as the average by calculation of stoichiometry.

Figure 1. NFPA 286 room corner test with 3 cushion couch mock-up and flammable cover.

2.4. Procedures

2.4.1. Small Scale Tests. Small scale tests were performed in a standard smoke box configured to meet the requirements of ISO 5659-2 with the exception of the inclusion a load cell and the elimination of the radiant heat source. Samples, 10.2 cm × 10.2 cm × 5.1 cm were prepared from three different foam sources called FR1354, FR1354n and 1030. Each FPUF was enclosed in a fabric cover of either FR-cotton or non-FR-cotton. The fabric was stabled with overlap at the corners and covered the top of the foam and all four sides. The bottom was uncovered. Gas monitoring was performed via FTIR equipped with a particulate filter and a 2 m gas cell. Each materials was exposed to source #1 for 20 s, failure to ignite resulted in the material being rotated 90° and exposure to the source #2 for 40 s, if that did not ignite the sample was rotated 90° a vertical cut in the fabric of 3.65 cm and exposure to the source #2 for 40 s on the exposed foam. The smoke box door was secured and the gas evolution, smoke density and mass loss data were collected. The heated filter cartridge was analyzed by extraction for HCN, HCl, HBr, and HF and these values added to any detection from the FTIR. The cartridges were also analyzed for chloro-dioxins and furans. A total of ten tests were performed in this series to exam each material and FPUF configuration.

2.4.2. Room Corner Full Scale Mock-Up Test. Ignition source #2 was applied for 40 s to the center of the middle seat cushion. Failure to ignite resulted in exposure to ASTM 1357 burner for a total of 80 s. Figure 2 shows this large flame source burner applied to a three seat couch mock-up. If the Item failed to sustain ignition from the large burner, the cover was removed from the middle cushion, inverted and ignited without cover using either the source #2 for 40 s or the ASTM 1357 burner for 80 s. The test was monitored for the duration of the fire plus 20 min. A Summa™ canister captured the emissions during peak burning of the cushions, and another after the fire has been out for 20 min. The Summa™ canisters were analyzed via EPA method TO-15. The FTIR provided time phased concentration data for vapors. Background

Figure 2. Large burner ignition source.

was collected from the room corner prior to testing and was subtracted from all collected spectra. The heated filter cartridges were analyzed for chloro-dioxins, furans and the acid gases. Oxygen consumption, CO and CO₂ generation were measured in the calorimeter hood to provide data on heat release rate and total heat release. Optical opacity measured smoke opacity during the tests. A total of four tests were performed in this series looking at one-each of the possible configurations.

3. Results

3.1. Small Scale Testing

The data shown in Table 1 and Table 2 was obtained from the smoke box tests of various configurations of FPUF and cover materials. The following vapors were monitored in this test: carbon dioxide (CO₂), carbon monoxide (CO), hydrogen chloride (HCl), hydrogen bromide (HBr), hydrogen fluoride (HF), hydrogen cyanide (HCN), nitrogen dioxide (NO₂), nitrogen monoxide (NO), sulfur dioxide (SO₂), and acrolein. The concentration values given in Table 1 are peak concentrations which always occurred at the end of combustion, all of the values are corrected for background via subtraction using the Omnix software Version 8.3.103, 2011. The only vapors with confirmed detection in the combustion products via FTIR were CO, CO₂, HCN, HCl and H₂O. In a few cases, methane was detected which gave a false positive for HCl [9]. Figure 3 shows the spectrum collected during the peak vapor release for the 1030-FPUF with the FR-cotton cover. In this spectrum HCN, CO and CO₂ were positively detected, HCl was non-detect and methane was detected giving a false positive for HCl. Particulate filters were analyzed for acid gases and chloro-dioxins and furans that might attach to particles. These quantities were added to the FTIR concentration results in Table 1 to achieve total concentrations [10].

The following trends were noted for each category of tests in a comparative format. Examining the non-FR-cotton and each of the foam conditions, the non-FR-cotton fabric produces the rapid combustion of the foam cushion mock-ups

Table 1
FTIR and Filter Analysis for Highest Detected Concentration for Smoke Box Tests

Sample condition	CO (ppm)	CO ₂ (ppm)	HCN (ppm)	HCl (ppm)	Notes	Ignition source
Non-FR cotton/1030-FPUF	603	22,900	ND	ND	Ignition on material	Source #1
Non-FR cotton/1030-FPUF	475	22,900	ND	ND	Ignition on material	Source #1
Non-FR cotton/FR-1354-FPUF	742	22,100	ND	28.3	Ignition on material	Source #1
Non-FR cotton/FR-1354-FPUF	603	22,800	ND	16.5	Ignition on material	Source #1
FR cotton/1030-FPUF	3,040	19,900	220	ND*	Ignition on cut area exposing foam	Source #2
FR cotton/1030-FPUF	2,760	22,100	180	ND*	Ignition on cut area exposing foam	Source #2
FR cotton/FR-1354-FPUF	26.1	273	ND	0.75	No ignition on cut area exposing foam	Source #2
FR cotton/FR-1354-FPUF	51.1	374	ND	1.75	Ignition on cut area exposing foam	Source #2
FR cotton/FR-1354n-FPUF	1,370	3,200	124	ND*	Ignition on cut area exposing foam	Source #2
FR cotton/FR-1354n-FPUF	1,610	7,990	135	ND*	Ignition on cut area exposing foam	Source #2

* Methane detected

Table 2
Mass Loss and Smoke Density for Smoke Box Testing of Foam/Fabric Configurations

Sample condition	Initial mass (g)	Final mass (g)	Mass loss (g)	Max loss (s)	Optical density	Peak smoke (s)
Non-FR cotton/1030-FPUF	18.9	3.8	15.1	285	104	370
Non-FR cotton/1030-FPUF	18.8	3.3	15.5	275	87	340
Non-FR cotton/FR-1354-FPUF	23.7	0.4	23.3	175	262	260
Non-FR cotton/FR-1354-FPUF	21.9	9.4	12.5	290	187	275
FR cotton/1030-FPUF	20.4	5.4	15	610	530	375
FR cotton/1030-FPUF	19.7	3.8	15.9	305	476	190
FR cotton/FR-1354-FPUF	24.1	24	0.1	5	1.63	330
FR cotton/FR-1354-FPUF	24	23.8	0.2	5	11.5	130
FR cotton/FR-1354n-FPUF	23.3	17.1	6.2	260	547	180
FR cotton/FR-1354n-FPUF	23.5	16.7	6.8	235	560	220

Figure 3. Sample spectra showing analytical samples of H_2O , HCl , HCN , and CH_4 compared to a spectrum from the time of peak smoke production for 1030-FPUF and FR-cotton.

yielding roughly equal high levels of carbon dioxide, water vapor, and carbon monoxide for each foam case. HCl was detected during these runs when FR1354-FPUF was used. The non-FR-cotton resulted in average of 81% consumption of mass for the 1030-FPUF case and 78% for the FR1354-FPUF. These results are not statistically significantly different for mass loss but optical density is roughly twice as high for the FR1354-FPUF case.

Using a highly flame resistant FR-cotton in combination with the 1030-FPUF required the larger ignition source, source #2, applied directly to a cut in the fabric to initiate the burning condition. This resulted in very high levels of CO and the highest levels of HCN detected in this project. The CO_2 levels were equivalent to those obtained from the non-FR-cotton case. The 1030-PFUF condition lost

Table 3
Dioxin and Furan Detection Total for Smoke Box Samples, Screening Values Only

Sample condition	1,2,3,4,6,7,8, HpCDD 35822-46-9	OCDD 3268-87-9	Total in pg	TEQ in pg adjusted for toxicity	Adjusted for box volume emission in pg/m ³	Adjusted to mass loss in pg/kg of sample
CAS						
Non-FR-cotton/1030-FPUF	0	0.00624	0.00624	0.000000624	0.203	0.000135
Non-FR-cotton/1030-FPUF	0.0107	0	0.0107	0.000107	0.349	0.225
Non-FR-cotton/FR-1354-FPUF	0	0.00942	0.00942	0.000000942	0.307	0.000132
Non-FR-cotton/FR- 1354-FPUF	0	0	ND			
FR-cotton/1030-FPUF	0.0145	0.0065	0.021	0.000146	0.685	0.457
FR-cotton/1030-FPUF	0.011	0.00685	0.0179	0.000111	0.584	0.367
FR cotton/FR-1354-FPUF	0	0	ND			
FR cotton/FR-1354-FPUF	0	0.00557	ND	0.000000557		
FR cotton/FR-1354n-FPUF	0.00841	0.00488	0.0133	0.0000845	0.434	69.9
FR cotton/FR-1354n-FPUF	0	0.00865	0.00865	0.000000865	0.282	41.5

Table 4
Heat and Smoke Data from Room Corner Tests

Test ID	Sample mass loss	Ignition condition	pHHR (kW)	Time to pHHR	Total heat (°MJ)	Max OD	Time to max OD	Max RT	Time to max RT
Test 1-non-FR cotton/1030 foam	3.067 kg	Source #2 burner	255	00:13:37	51	0.31	00:12:12	301°C (574°F)	00:13:05
Test 2-FR cotton/1030 foam	0.723 kg	Source #2 burner on exposed foam	78	00:01:56	8	0.22	00:01:46	170°C (339°F)	00:01:41
Test 3-FR cotton/1354 foam	0.722 kg	TB 133 burner on exposed foam	122	00:01:21	10	1.1	00:01:10	226°C (439°F)	00:01:11
Test 4-non-FR cotton/1354 foam	3.487 kg	Source #2 burner	236	00:16:27	51	0.97	00:16:47	287°C (549°F)	00:16:03

an average of 77% of its mass and produced the optical density as high as that seen for the FR1354n/FR-cotton case.

The FR-cotton and FR1354-FPUF tests required the larger ignition source, source #2, applied to a cut in the fabric to achieve ignition. Upon removal of the ignition source the flame extinguished immediately in the first trial but burned for a few seconds in the second trial. Both continued to smolder for a couple of minutes. Mass loss and smoke density was negligible, and Very low levels of CO, CO₂, and HCl were detected during these tests.

The FR-cotton and FR1354n test also required the larger ignition source applied to a cut in the fabric to achieve ignition. The flaming continued for a short period then extinguished but still smoldered for approximately 200 s. Very dense smoke was generated achieving comparable results to the FR-cotton and 1030-FPUF case. Only 27% of the mass was consumed.

Of the 17 congeners of dioxins and furans analyzed, only the 1,2,3,4,6,7,8-HpCDD, and OCDD were detected and all detections were at trace levels below the calibration curve and are estimated masses. Adjusting sample volume to smoke box volume resulted in sub-picogram (pg) emission in smoke in all cases.

Table 5
EPA TO-15 Chemicals Detected During Room Corner Tests from Grab Samples

CAS#	Chemical	Non-FR cotton/ 1030 foam (ppm)		FR cotton/1030 foam (ppm)		FR cotton/ FR1354 foam (ppb)		Non-FR cotton/ FR1354 foam (ppb)	
		Test	Test	Test	Test	Test	Test	Test	Test
		1-1*	1-2	2-1	2-2	3-1	3-2	4-1	4-2
115-07-1	Propene	ND	1.4 (J)	9.60	0.12	11.8	ND	4.75	2.39
64-17-5	Ethanol	ND	ND	0.73 (J)***	0.03 (J)	0.71 (J)	ND	ND	ND
107-02-8	Acrolein	ND	ND	0.62 (J)	ND	1.34 (J)	ND	0.53 (J)	0.46 (J)
67-64-1	Acetone	ND	0.559 (J)	5.49	106	5.63	ND	1.89	1.39
67-63-0	Isopropanol	ND	ND	1.03 (J)	16.0 (J)	0.79 (J)	ND	ND	ND
78-93-3	2-Butanone	ND	ND	0.70 (J)	15.2 (J)	0.67 (J)	ND	ND	ND
142-82-5	Heptane**	ND	ND	0.26 (J)	ND	ND	ND	ND	ND
74-87-3	Chloromethane	ND	ND	ND	ND	1.03 (J)	ND	1.51	0.62 (J)
74-83-9	Bromomethane	ND	ND	ND	ND	0.62 (J)	ND	ND	ND
71-43-2	Benzene	ND	ND	ND	ND	2.85	ND	4.10	0.37 (J)
10061-01-5	Cis-1,3-dichloropropene	ND	ND	ND	ND	2.16	ND	0.44 (J)	0.92 (J)
10061-01-6	Trans-1,3-dichloropropene	ND	ND	ND	ND	1.94	ND	0.36 (J)	0.86 (J)
108-88-3	Toluene	ND	ND	ND	ND	ND	ND	0.27 (J)	ND
91-20-3	Naphthalene	ND	ND	ND	ND	ND	ND	0.29 (J)	ND

* Test sample 1-1 was collected at 15 in. above floor level, all others were collected at the center of the door frame and 1 in. from the top

** Heptane data is likely from laboratory contamination, Heptane was used as an accelerant in another test adjacent to the test being performed

*** (J)-signifies value is below calibration curve due to dilution of sample in method

The samples in Table 3 show detectable levels of emission in seven of ten tests with both FR and non-FR-FPUF equally represented.

3.2. Large Scale Testing

Table 4 summarizes the heat release and smoke data for the room corner tests. Table 5 contains the EPA TO-15 data, Table 6 contains the tentatively identified compounds (TIC) information obtained from the EPA TO-15 samples. The standard EPA TO-15 chemicals represent chemicals of concern for exposure for indoor air. The TIC compounds were identified by mass spectroscopy as a match to the 250,000 compound EPA Library of known compounds; the concentrations are estimates only as a specific calibration was not performed. Table 7 contains the data for the FTIR in all four tests. The FTIR data was lost for the first 20 min of test #1 due to early fault of the FTIR and a reset of the instrument.

In test #1 a three seat couch with a total of six cushions composed of non-FR-cotton and 1030-FPUF was exposed to the source #2 ignition for 40 s. It ignited and burned 91% (3.067 kg) of its mass in 15.25 min. A total of 0.136 $\mu\text{g}/\text{m}^3$ of dioxins and furans were detected during the burn. The FTIR faulted and only recorded the later part of the test collecting the last 3 min of burning and the 20 min following the end of the fire. Two Summa™ canisters were collected during the free-burning phase of the fire. The first canister was collected from the middle of the room at a height of 18 in. and failed to collect combustion gasses. The second canister was collected 1 in. down from the top center of the doorway at a few minutes past peak burning. TO-15 and TIC are found in Table 5 and Table 6 respectively.

In test #2 a three seat couch mock-up test with a total of six cushions composed of FR-cotton fabric and the 1030-FPUF required removal of the FR-cover from the center cushion with exposed foam to achieve ignition when exposed to ignition source #2

Table 6
TIC Data from EPA TO-15 Samples

CAS #	Compound	Non-FR cotton/ 1030 foam (ppb)		FR cotton/ 1030 foam (ppb)		FR cotton/ FR 1354 foam (ppb)		Non-FR cotton/FR 1354 foam (ppb)	
		Test 1-1	Test 1-2	Test 2-1	Test 2-2	Test 3-1	Test 3-2	Test 4-1	Test 4-2
460-19-5	Ethanedinitrile	ND	795	ND	ND	1,060	ND	7,960	ND
57-07-0	Acetaldehyde	ND	ND	1,310	23.1	774	ND	289	ND
534-22-5	2-methyl-furan	ND	ND	307	ND	ND	ND	ND	ND
1193-11-9	2,2,4-trimethyl- 1,3-dioxolane	ND	ND	371	ND	ND	ND	ND	ND
74-99-7	Propyne	ND	ND	ND	ND	372	ND	355	ND
75-05-8	Acetonitrile	ND	ND	ND	ND	523	ND	529	ND
107-13-1	2-propenenitrile	ND	ND	ND	ND	616	ND	775	247
96-18-4	1,2,3-trichloropropane	ND	ND	ND	ND	2,210	ND	1,240	777
100-47-0	Benzonitrile	ND	ND	ND	ND	1,410	ND	1,380	ND
1070-71-9	Propionitrile	ND	ND	ND	ND	ND	ND	529	ND

Table 7
FTIR Data for Room Corner Tests for Those Gases Detected and Confirmed

Sample condition	CO (ppm)	CO ₂ (ppm)	HCN (ppm)	HCl (ppm)	Notes	Ignition source
Room corner test #1	123*	3,930*	ND	ND	Ignition on material	Source #2
Room corner test #2	219	5,950	56	ND	Ignition on material	Source #2
Room corner test #3	247	1,190	ND	28	Ignition on material	ASTM 1357
Room corner test #4	1,110	6,420	ND	588	Ignition on material	Source #2

* Data incomplete due to FTIR faulting during data acquisition

Figure 4. HRR plots and total heat release for all of the tests in this series.

for 40 s. Only 14% of the initial mass was consumed corresponding to the one exposed foam cushion. FTIR data was collected during all three attempts to ignite the cushion and for the duration of the fire plus 20 min. Peak emissions occurred at 1.8 min after removal of the last ignition source. CO emissions return to baseline after 6.5 min and CO₂ after 26 min from point of ignition. The FTIR particulate filter was analyzed for dioxins and furans using a screening method and 1,2,3,4,6,7,8-HpCDD and OCDD were detected at a total concentration of 0.309 pg/m³. Two Summa canisters were collected during this test. The first canister was collected near the peak heat release rate (pHRR); the second was collected after the flames had been extinguished for 15 min. Data for TO-15 gases is located in Table 5. TIC compounds are found in Table 6. Figure 4 shows the time dependent HRR plots and total heat release for all of the tests in this series.

Figure 5. Confirmation of HCl for Test #4 and non-detect for HCN.

In test #3 a three seat mock-up using a total of six cushions composed of FR-cotton and the FR1354-FPUF required exposure to the ASTM1537 burner for 80 s to the center cushion with the cover removed exposing the FPUF to ignite. Only 17.6% of the couch was consumed corresponding to one uncovered cushion. FTIR data was collected for the duration of the fire plus 20 min. Peak emissions occurred at 1.5 min post ignition for CO. HCN and HCl gases were not detected by FTIR. CO emissions return to baseline after 5 min. The FTIR particulate filter was analyzed for dioxins and furans using a screening method; no dioxins or furans were detected. The first Summa canister was collected at pHRR and the second Summa canister was collected after the flames had been extinguished for 15 min.

In test #4 a three seat mock-up using six cushions composed of non-FR-cotton and FR1354-FPUF condition was exposed to source #2 ignition for 40 s. It ignited and burned 84% of its mass in 36 min. FTIR data was collected for the duration of the fire plus 20 min. Peak emissions occurred at 11 min post ignition for CO. HCl was also detected at 13 min post ignition and verified by manual examination of the spectra as shown in Figure 5. HCN also gave a reading at 13 min which was refuted upon examination of the spectra. CO emissions return to baseline after 24 min. HCl returns to baseline at 17 min after ignition. OCDD and 2,3,7,8-TCDF were both detected with a total of 8.97 $\mu\text{g}/\text{m}^3$. Two SummaTM canisters were collected during the test, the first canister was collected at pHRR, the second was collected after the flames had been extinguished for 15 min.

4. Conclusion

Use of a barrier material with a non-FR-FPUF resulted in the most toxic smoke. HCN concentration was roughly four times the IDLH [11] but below the LC₅₀ [12], also the CO levels exceeded the IDLH [11] by a factor of two in the smoke box tests for FR Cotton and FPUF 1030. Because the FR-cotton remains intact, it creates a ventilation limited oxygen starved environment in the combustion zone producing more HCN and CO which are both flammable [13] and would normally combust in an oxygen rich environment. This created extremely toxic smoke. The FR-cotton and FR1354-FPUF did not sustain significant ignition as seen in the mass loss data using the source #2 for 40 s. The use of the FR-FPUF in combination with a good barrier material like the FR cotton used here reduces the toxic gas emission by preventing ignition, while barriers with flammable foam increase toxic emission under small open flame ignition conditions.

Ignition source size does matter. The exposed FR1354-FPUF required ASTM 1537, 19 kW burner to achieve sustained ignition while the exposed 1030 FPUF ignited with the 295 W source #2.

The dioxin and furan data indicates that there is not an increase in emission for chlorine containing FR-FPUF. Forced combustion of the FR1354-FPUF gave as good or better data than the 1030 FPUF with the same non-FR Cotton fabric cover. The dioxin and furan emissions from the burning of wood in fire places and wood stoves of 0.82 ng/kg TEQ of all wood [14] indicates that foam fall well below that seen for wood fires. Another study gives even higher values 3.3 ng/kg TEQ for wood stoves and 28 ng/kg TEQ for fireplaces [15]. The highest value detected in this study is 0.006995 ng/kg TEQ. The amount of dioxins emitted by the combustion of wood in a fire place is 4,000 times that seen for all of the foams studied in this report and would be a negligible contribution to home fires. These conclusions are based on the screening method used but this has been shown to be representative [6].

In the room corner mock-up tests, the delay of and reduction to the pHHR for the FR-foam were noted with non-FR-cotton and FR1354FPUF versus 1030CPUF. These values are not identical to those obtained by Janssens et al. [5] because the test set-up was different, however the relationship was maintained as to which burned faster with higher pHHR. The total energy for the foams in these conditions was identical at 64 MJ.

The FR1354-FPUF generated more smoke than 1030-FPUF which was consistent with the data generated in the smoke box. There were also more products of incomplete combustion. All of the chemicals identified were at very low concentration and data collected 15 min after the end of combustion was even further reduced.

The composition of the smoke is more complex with FR-FPUF. It is important to note that most of the smoke components are not present after the combustion has ended or are at ppb levels for the EPA TO-15 and TIC chemicals. Acrolein was detected and is toxic [12] but is only present at approximately 1 ppm. Acrolein was detected in tests with both FR and non-FR-FPUF. Post combustion all TICs detected at less than ppm levels. This was significant because positive

pressure SCBA is worn during the active stage of fire but often not worn in the salvage and overhaul phase [7, 16]. The only chemicals detected at ppm levels post fire were acetone and propylene, neither of which are hazardous [11].

Polycyclic aromatic hydrocarbons (PAH) are a significant toxic hazard in smoke but were not studied here because they have been thoroughly studied by Blumqvist et al. [17]. They determined that FR FPUP produce lower molecular weight and less hazardous congeners of PAH than non-FR FPUF and that both of the FPUF are less hazardous by percent composition than the PAH produced by wood products.

In summary, FR FPUF does not increase the chronic and acute toxicity of the smoke in a fire compared to non-FR FPUF. The FPUF smoke toxicity is less than or equal to that created by wood on a mass/mass basis. Wood contributes a significantly greater mass percentage to residential fires and is therefore a much great contributor to residential fire smoke toxicity.

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