DEVELOPMENT OF AN FST/OSU PASSING RIGID POLYURETHANE FOAM FOR THE AEROSPACE INDUSTRY

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ABSTRACT

There is a growing need for structural materials that pass the stringent FAA Fire, Smoke, Toxicity (FST) and OSU Heat Release requirements. While materials exist that meet these specifications, many are not cost effective. Polymethacrylimide, polyether imide, and polyethersulfone materials pass the FST/OSU criteria, but are very expensive. Polyurethane and polycarbonate-based materials are cost effective, but none have been shown to pass the FST/OSU criteria. FR-3800 FST foam was developed as a cost effective polyurethane foam that passes the stringent FAA Fire, Smoke and Toxicity (FST) requirements and the OSU heat release requirements. Foams of various densities have passed vertical flame testing (extinguish time < 15 s, burn length < 15.2 cm), smoke density (< 200) and both peak and total heat release (< 65 kW/m^2 and < 65 kW min/m^2, respectively). These desirable properties have been achieved without the use of halogenated flame retardants. Physical properties such as compression at 21 ^oC, flexural strength, shear strength and tensile strength were also evaluated.

INTRODUCTION

There is a growing need for structural materials that pass the stringent FAA Fire, Smoke, Toxicity (FST) and OSU Heat Release requirements. Materials based on polymethacrylimide, polyether imide and polyethersulfone pass the FST/OSU criteria, but are relatively expensive. Materials such as polyurethane and polycarbonate are relatively inexpensive, but do not pass FST/OSU criteria. A comparison of some of the properties of these core materials is shown in Table 1. Because rigid polyurethane foam is currently used within aircraft cabin interiors as a cost effective alternative to other core materials, development of polyurethane foam that would pass the FST/OSU requirements, the standards of which are outlined below, was undertaken.

The Peak Heat Release (Heat Release Rate) refers to the rate at which heat energy is given off by a burning material. It is expressed in units of kW/m^2. Total Heat Release refers to the amount of energy given off by a burning material. It is expressed in units of kW min/m^2. Peak Heat Release and Total Heat Release can be measured using an OSU Heat Release Apparatus, shown in Figure 1. Details of this test and a description of the apparatus used can be found in Chapter 5 of the FAA Aircraft Fire Materials Handbook.[1] To pass this test, the Peak Heat Release must be less than 65 kW/m^2 and the Total Heat Release must be less than 65 kW min/m^2.

Smoke Density or Specific Optical Density (Ds) is the measure of the amount of smoke produced per unit area of a burning material. The value is optically measured and is dimensionless. The maximum value after burning for four minutes is reported as the Smoke Density of the material. To pass, this value must be less than 200. Smoke Density is measured using the apparatus shown in Figure 2. Details of this test and a description of the apparatus used can be found in Chapter 6 of the FAA Aircraft Fire Materials Handbook.[2]

Table 1. Physical Properties of Standard Core Materials

	Polyurethane	**Polyethersulfone**	**Polymethacrylimide**	**Polyetherimide**	**Polyethylene Terephthalate**
Density (kg/m^3)	80	90	75	80	75
Peak Heat Release kW/m^2)	> 65	<25	-	Pass	-
Total Heat Release (kW min /m^2)	>65	<20	-	Pass	-
Smoke Density	Pass	Pass	Pass	Pass	48
Vertical Flame	Pass	Pass	Pass	Pass	Pass
Maximum Processing Temp. (^oC)	127	220	130	179	149
Compressive Strength (kPa)	821	1200	1696	1103	821
Tensile Strength (kPa)	1020	2799	2220	2000	-

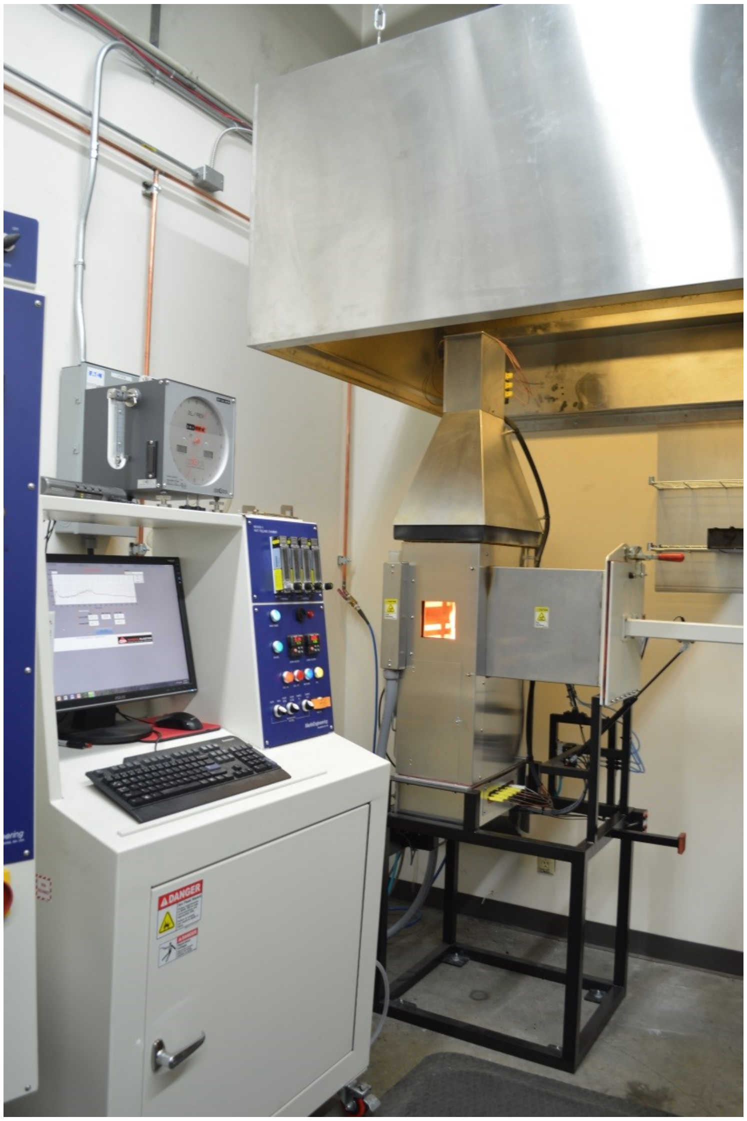

Figure 1. Heat Release Instrument

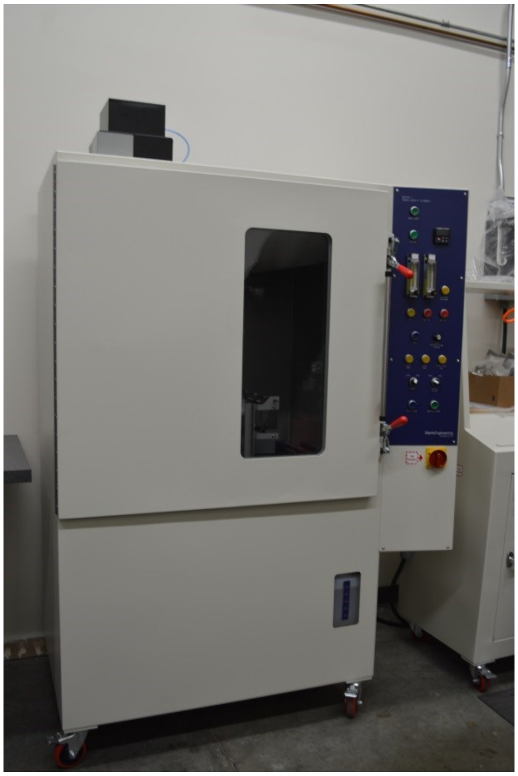

Figure 2. Smoke Density Instrument

Toxicity of the material refers to the amount of various toxic gases emitted from a burning material. These gases include carbon monoxide (CO), hydrocyanic acid (HCN), hydrofluoric acid (HF), hydrochloric acid HCl), sulfur dioxide (SO_2), hydrogen sulfide (H_2S), nitrous oxide (NO) and nitrogen dioxide (NO_2). The maximum amounts permissible of each gas are shown in Table 2. The amounts of these gases emitted by a sample material are obtained by analyzing the smoke emitted during burning. The procedure is given in ASTM Method 1678 - 15.[3]

Table 2. Maximum Allowable Amounts of Toxic Gases Emitted by Burning Materials

Toxin	**BSS 7239 Max Amt. (ppm)**	**AITM 3.0005 Max Amt. (ppm)**	**FR-3803 Toxicity Results (ppm)**
CO	3500	1000	100
HCN	150	150	25
HF	200	100	0
HCl	500	150	0
SO_2/H_2S	100	100	0
NO/NO_2	100	100	7

Flame testing refers to a vertical burn test.[4] In the 60 second vertical burn, a 30.4 cm x 7.6 cm x 1.3 cm sample is burned for 60 seconds. The flame is then removed from the sample, and the self-extinguish time is measured. The sample must not burn for more than 6 seconds and the burn length should not be more than 15.2 centimeters to pass. In the 12 second vertical burn, a sample of material 30.4 cm x 7.6 cm x 1.3 cm is burned for 12 seconds. The flame is then removed from the sample. The extinguish time should be less than 15 seconds and the burn length should be less than 20.3 centimeters to pass.

EXPERIMENTAL

FR-3803, FR-3804, FR-3808, FR-3818 and FR-3840 were made in both the laboratory and a large scale production setting. The aforementioned materials differ only in density. The last two digits of the product name refer to the density in pounds per cubic foot. These materials are made by reaction of a proprietary polyisocyanate with a proprietary polyol. Proprietary additives such as surfactants and flame retardants were used. No halogenated flame retardants were used in this foam. The amount of blowing agent used was adjusted to achieve the desired density.

Five production-made samples of each material were tested to determine the physical properties. Heat Release was tested according to the procedure outlined in Chapter 5 of the Aircraft Materials Fire Test Handbook.[1] Smoke Density was determined according to the procedure outlined in Chapter 6 of the Aircraft Materials Fire Test Handbook.[2] Toxicity testing was done according to the procedure outlined in ASTM 1678 - 15[3] Results are shown in Table 2.

Vertical flame testing was done according to the procedure outlined in FAR 25.853 Appendix F.[4] Both 12 second vertical and 60 second vertical flame tests were conducted on 30.4 cm x 7.6 cm x 1.3 cm specimens. Compression testing was done according to the procedure outlined in ASTM D 1621.[5] Flexure testing was done according the procedure outlined in ASTM D-790.[6] Shear testing was done according to the compression method outlined in ASTM C-273.[7] Tensile testing was done according to the procedure outlined in ASTM D-1623.[8] Results are shown in Table 3.

Heat Release samples (1.3 cm x 15.2 cm x 15.2 cm) and Smoke Density samples (1.3 cm x 7.6 cm x 7.6 cm) of FR-3804 were cut from the same sample of foam. Due to the potential variability of FST/OSU results, samples were sent to AIM Aerospace, Govmark, Herb Curry, Inc. and Krueger Testing and Consulting, all of whom maintain FAA approved testing facilities. A set of samples was also retained and tested by General Plastics. Results are shown in Table 4.

Heat Release samples (1.3 cm x 15.2 cm x 15.2 cm) and Smoke Density samples (1.3 cm x 7.6 cm x 7.6 cm) of FR-3818 were cut from the same sample of foam. Samples were sent to AIM Aerospace, Govmark, Herb Curry, Inc. and Krueger Testing and Consulting. A set of samples was also retained and tested by General Plastics. Results are shown in Table 5.

Table 3. Physical Properties of FR-3800 Foams

	FR-3803		FR-3804		FR-3808		FR-3818		FR-3840	
	Avg.	Std. Dev.	Avg.	Std. Dev.	Avg.	Std. Dev	Avg.	Std. Dev.	Avg.	Std. Dev.
Density (kg/m^3)	48		64		128		288		641	
Tg (^oC)	153	8.8	153	12	149	16	144	13	148	11
Heat Release Peak (kW/m^2)	37	2	37	2	47	2	51	5	44	3
Heat Release Total (kW min/m^2)	45	6	46	4	41	2	25	3	17	2
Smoke Density (Ds)	109	37	101	15	144	9	160	10	124	4
Compressive Strength (kPa)	319	17	529	21	1425	58	5142	360	23310	422
Compressive Modulus (kPa)	10274	1045	14688	780	44884	2000	178088	10041	747444	37604
Flexural Strength (kPa)	299	51.2	512	124	1470	156	4912	273	15415	4892
Flexural Modulus (kPa)	11228	113.8	16540	5166	49989	2953	200527	19895	751465	2324
Shear Strength (kPa)	231	16.5	363	18	668	40	1486	40	9663	208
Tensile Strength (kPa)	272	51	381	44	1002	73	3482	242	12757	563
60 sec Vertical Extinguish	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0

Time (sec)										
60 sec Vertical Burn Length (cm)	8.4	0.8	7.9	0.9	7.6	0.6	5.1	0.3	3.6	0.7
12 sec Vertical Extinguish Time (sec)	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0
12 sec Vertical Burn Length (cm)	6.8	1.0	7.1	1	6.1	0.9	2.5	0.4	2.0	0.4

Table 4. Round Robin Heat Release and Smoke Density Results for FR-3804 072315-19

FR-3804 072315-19	**Peak Heat Release (kW/m^2)**		**Total Heat Release ($kW\ min/m^2$)**		**Smoke Density**	
	Avg.	Std. Dev.	Avg.	Std. Dev.	Avg.	Std. Dev.
AIM	34.0	0.8	42.2	2.8	103	9
General Plastics	43.2	4.1	55.7	4.1	115	6
GovMark	39.8	3.2	57.3	3.6	120	10
Herb Curry	37.1	0.8	55.3	0.9	120	9
Krueger	40.0	2.7	50.1	2.4	126	9

Table 5. Round Robin Heat Release and Smoke Density Results for FR-3818 091715-13

FR-3818 091715-13	**Peak Heat Release (kW/m^2)**		**Total Heat Release ($kW\ min/m^2$)**		**Smoke Density**	
	Avg.	Std. Dev.	Avg.	Std. Dev.	Avg.	Std. Dev.
AIM	34.0	8.0	21.9	3.3	181	17
General	61.1	8.1	23.8	1.0	162	8

Plastics						
GovMark	41.2	4.2	43.1	6.2	184	9
Herb Curry	51.9	2.1	32.3	2.9	194	8
Krueger	36.4	6.5	29.8	3.0	194	3

DISCUSSION

Heat Release and Smoke Density are two tests that the FAA specifies. Several laboratories in the United States have been approved by them to test materials. In the course of development of an FST/OSU-passing polyurethane foam, it was noted that there is variation in the results among the test labs. Samples of the developed polyurethane foam were sent to AIM Aerospace, Krueger Test Laboratory, GovMark and Herb Curry, Inc. and were also tested at General Plastics.

All FR-3804 and FR-3818 samples used in outsourced testing were cut from the same two samples of foam to ensure consistency. A random distribution of these foam samples were sent to the testing facilities. The results of both Heat Release and Smoke Density testing are shown in Tables 4 and 5. Data for FR-3804 had little variation. Peak Heat Release and Total Heat Release results between the labs were similar. The greatest variation was noted in the Peak Heat Release of FR-3818 with a low of 34 kW/m^2 (AIM Aerospace) and a high of 61.1 kW/m^2 (General Plastics). Smoke Density data were similar among the labs.

The variation in heat release results of the higher density FR-3800 foams may be a result of their intumescent properties. As these samples burn, they intumesce – or form an expanding char layer. This char layer can expand to reach the flame nozzle in the instrument, although no extinguishing of the flame has been noted. The flame will generally penetrate the char layer and the material will begin to burn from the center of the sample. This results in a second heat release peak that in many instances is greater than the initial heat release peak. Variation occurs when the char layer is not penetrated by the flame and this second ignition does not occur. Regardless, this only causes variation in the results, but does not necessarily cause test failure.

A comparison of the physical properties of the FR-3800 foams to polyurethane foams of equivalent densities is shown in Table 6. FR-3700, FR-6700 and FR-3800 are all flame retardant polyurethane foams but each has a unique formulation. FR-6718 and FR-3740 foams do not pass Heat Release or Smoke Density. FR-3704 does not pass heat release. The FR-3804, FR-3818 and FR-3840 do pass Heat Release and Smoke Density. Passing criteria are a Peak Heat Release of less than 65 kW/m^2, a Total Heat Release of less than 65 kW min/m^2, and a Smoke Density of less than 200. All foams pass 60 sec and 12 sec Vertical Flame tests. Passing criteria for the 60 second vertical burn is an extinguish time less than 6 seconds and a burn length of less than 15.2 cm. Passing criteria for the 12 second vertical burn is an extinguish time less than 15 seconds and a burn length of less than 20.3 cm.

Compressive strength and modulus of the FR-3800 foams are similar to their non-FST counterparts at both 22 ^{o}C and 121 ^{o}C. Flexural strength, flexural modulus and tensile strength of the FR-3800 foams are weaker than their non-FST counterparts. Shear strength of the FR-3804 and FR-3840 foams are similar to their non-FST counterparts, while the FR-3818 foam is significantly weaker, as shown in Table 6. The unique components of these foams make it unlikely that the properties of the three foam families would be identical.

The FST properties of the FR-3800 foams give it a distinct advantage in applications where fire safety is of paramount importance. FR-3800 foams pass the FST/OSU criteria without the use of halogenated flame retardants, which are undesirable due to toxic combustion products.

Table 6. Comparison of Physical Properties of Polyurethane and FST/OSU Polyurethane Foams

	FR-3704	**FR-3804**	**FR-6718**	**FR-3818**	**FR-3740**	**FR-3840**
Density (kg/m^3)	64	64	288	288	641	641
Tg (^{o}C)	132	149	135	149	132	149
Heat Release Peak (kW/m^2)	113	37	134	51	112	44
Heat Release Total (kW min/m^2)	105	46	148	25	112	17
Smoke Density	124	101	284	160	469	124
Vertical Flame	Pass	Pass	Pass	Pass	Pass	Pass
Compressive Strength 22^{o}C (kPa)	503	524	7171	5059	31193	25001
Compressive Modulus 22^{o}C (kPa)	14280	14480	206622	176567	497888	499033
Compressive Strength 121^{o}C(kPa)	276	359	2917	2496	11377	10032
Compressive Modulus 121^{o}C (kPa)	8281	9977	99260	98550	381487	346708

Flexural Strength (kPa)	731	503	6826	4868	28663	16534
Flexural Modulus (kPa)	24746	6307	246386	198810	877554	805998
Shear Strength (kPa)	338	359	4150	1476	7750	10363
Tensile Strength (kPa)	655	379	4116	3558	19092	13680

CONCLUSION

FR-3800 foam was developed to pass the FAA FST/OSU Heat Release criteria. FR-3803, FR-3804, FR-3808, FR-3818 and FR-3840 have passed vertical flame testing (60 second burn extinguish time < 6 s, burn length < 15.2 cm), smoke density (< 200) and both peak and total heat release (< 65 KW/m^2 and < 65 kW min/m^2). These desirable properties have been achieved without the use of halogenated flame retardants. Physical properties such as compression at 21 ^oC, flexural strength, shear strength and tensile strength were also comparable to existing aerospace grade polyurethane materials.

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