Memoranda on Full-Scale Upholstered Furniture Testing, 2014-2015

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This analysis was prepared by the CPSC staff and it has not been reviewed or approved by, and may not necessarily reflect the views of, the Commission.

The U.S. Consumer Product Safety Commission (CPSC) is involved in rulemaking to consider a mandatory flammability standard for upholstered furniture. In 2012, CPSC staff conducted a study that assessed chair designs built with textile components having enhanced flammability performance or "barriers." The chairs with barrier components were assessed in full- and bench-scale tests. The data suggested that fire barriers used in upholstered chair designs may be a way to improve the chair's flammability performance by significantly reducing fire growth and energy output. In 2013, staff held an Upholstered Furniture Fire Safety Technology Meeting with industry and other stakeholders to discuss the feasibility of barriers in upholstered furniture for improving upholstered furniture flammability performance.

After the meeting, CPSC staff developed a limited test program to evaluate both smoldering and open-flame performance of upholstered furniture when constructed with a selection of barriers. Five different fire barriers were selected and used as components in upholstered chair designs for testing. 24 of the 96 chairs were tested for smoldering performance using the NIST standard reference material (SRM), 1196 cigarettes, as the ignition source, while 72 of the 96 chairs used in the test program were ignited by a small open flame.

To support the study further, a selection of the chairs was mechanically stressed to evaluate the durability of the barriers. Staff conducted a statistical analysis of the test results and reports those results here. CPSC staff also conducted a chemical screening of the five selected fire barrier materials used to construct the test chairs. In addition, NIST staff, through an interagency agreement, conducted a series of thermal and physical tests on each of the fire barriers.

The attached memoranda detail the findings of the test study, chemical assessment, statistical analysis, and thermal physical properties. This package includes four reports, A through D, each of which is listed in the Table of Contents below.

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UNITED STATES
CONSUMER PRODUCT SAFETY COMMISSION
BETHESDA, MD 20814

Memorandum

Date: January 28, 2016

TO : Andrew Lock, Ph.D., Fire Protection Engineer, Laboratory Sciences, Upholstered Furniture Project Manager

THROUGH : Andrew G. Stadnik, P.E., Associate Executive Director, Directorate for Laboratory Sciences
Allyson Tenney, Division Director, Division of Engineering

FROM : Linda Fansler, Division of Engineering
Andrew Lock, PhD, Division of Engineering

SUBJECT : Summary Report of Open Flame and Smoldering Tests on Chairs

Introduction

As part of the Upholstered Furniture Project, U.S. Consumer Product Safety Commission (CPSC) staff conducted bench-scale and full-scale furniture testing, reviewed fire data, and assessed strategic approaches to manage fire risk from fires involving upholstered furniture. In 2012, CPSC staff conducted a full-scale upholstered chair test program that included using a fire barrier in some chairs[1]. The analysis of the data from this study indicated that fire barrier use is a way to improve flammability performance. In 2013, CPSC staff held an Upholstered Furniture Fire Safety Technology Meeting to promote a discussion of fire barrier technologies and the potential benefits barriers could provide toward improving or reducing furniture flammability.

As a result of that meeting, CPSC staff developed a limited test program to assess fire barrier effectiveness in reducing the fire hazards posed by upholstered furniture. Five commercially available fire barrier materials were included in this study. The fire barriers sourced from four manufacturers included different types that are typically used in mattress constructions. Chairs constructed with these barriers were subjected to small open-flame and smoldering ignition sources. In addition, some chairs were also evaluated in a mechanically stressed condition to assess the effect of wear on flammability performance. This memorandum provides the details of this test program and presents the results for these five fire barriers in full-scale tests.

Test Program

The test program was designed to evaluate five fire barriers for their flammability performance. The test program did not specify a performance threshold, but, rather, it was intended to obtain additional information on the general performance of these five fire barriers when included in a specific chair construction. CPSC staff had 96 full scale upholstered chairs built using specific materials and construction techniques to evaluate the fire barriers and their effectiveness at reducing the potential hazard from fires involving upholstered furniture. The chairs were constructed with combinations of three different upholstery fabrics, five different fire barriers and no fire barrier, and one type of foam. Not every combination was tested in open flame and smoldering testing; the specific combinations used in each are outlined in the *Test Materials* section of this report. Fire barrier performance was also studied in some chairs that were mechanically stressed. Seventy-two chairs were evaluated with the open flame ignition source, and an additional 24 chairs were evaluated for smoldering ignition. The test order of the chairs followed a randomization scheme provided by the CPSC Directorate for Epidemiology[2]. The complete test protocol is provided in Appendix A.

The chairs used in this evaluation were made-to-order based on CPSC staff specifications for fabrics, fire barriers, and a non-fire retardant polyurethane foam (PU), which were installed on a basic wooden frame that was identical to previous tests[5]. Figure 1 illustrates the dimensional construction of the chairs.

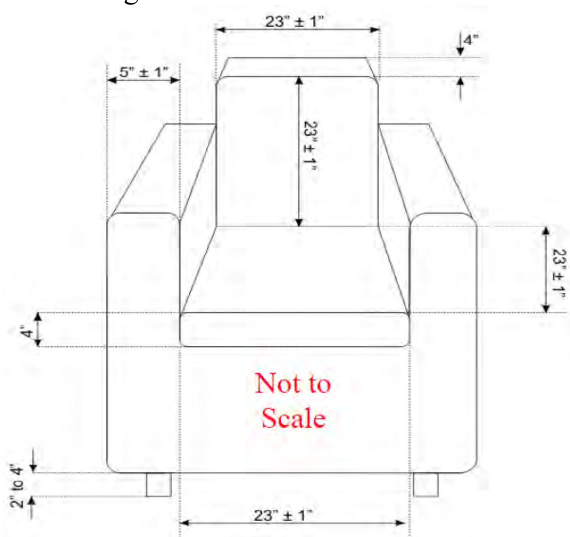

Figure 1. Schematic representation of the dimensions of the test chairs used in this series.

Mechanical Stress

The strategy of incorporating fire barrier materials in residential upholstered furniture is a recent approach that CPSC staff is evaluating to manage fire risk. Fire barrier materials are not commonly found in residential upholstered furniture. CPSC staff included a mechanical stress variable to study the potential impact of general wear on flammability performance.

CPSC staff developed a constant force pounding procedure based on a prior study[3], which looked at the effect of wear on upholstery fabric flammability. A force of 750 ± 20 N (169 ± 4.5 lbf) was applied vertically downward at the center of the seat cushion. The force was applied through a 250 ± 1 mm diameter plate with a 25 ± 1 mm radius at the edges, at 70 ± 5 cycles per minute. Two hundred thousand cycles were applied to the cushions to simulate wear.

Flammability
The upholstered chairs were evaluated following the protocol outlined in Test Protocol – Full Scale Chair Evaluations (Appendix A). Each chair was conditioned for a minimum of 48 hours at a temperature of 20 $\pm$ 3 °C (70 $\pm$ 5 °F) and a relative humidity of 50 $\pm$ 5 % prior to testing[i]. Tests were conducted in the open calorimetry laboratory at the CPSC National Product Testing and Evaluation Center. One chair was tested at a time to capture the heat release rate (HRR) measurement of each tested chair. In addition to the physical measurement data, each test was video recorded and photographs were taken before and after the test.

Open Flame
The open-flame source was chosen to be consistent with previous test work and is intended to simulate a small, open-flame source. [ii] A 240 mm butane flame was applied to the center of the crevice of the seat and back cushions of the tested chair for 70 $\pm$ 1 seconds[4]. During the test, the HRR data were monitored; the test was allowed to continue until the peak heat release rate (PHRR) was observed. Visual observations, such as progression of the flame spread, time to flame out, and time to flaming through the back of chair, were also annotated while tests were being conducted.

Smoldering
Two standard ignition source cigarettes were placed in four locations in each chair's seating area: (1) left side crevice, (2) right side crevice, (3) back crevice, and (4) seating surface. Figure 2 shows the placement of the eight cigarettes. Each cigarette was covered with a cotton sheeting square to minimize air currents and reduce variability. The test was allowed to continue until, either all cigarettes self-extinguished, or the PHRR was observed. Visual observations, such as the progression of char, time to flaming, and the presence and amount of smoke, were also annotated while the tests were being conducted. At the end of the test, char measurements were made on those chairs where the cigarettes self-extinguished.

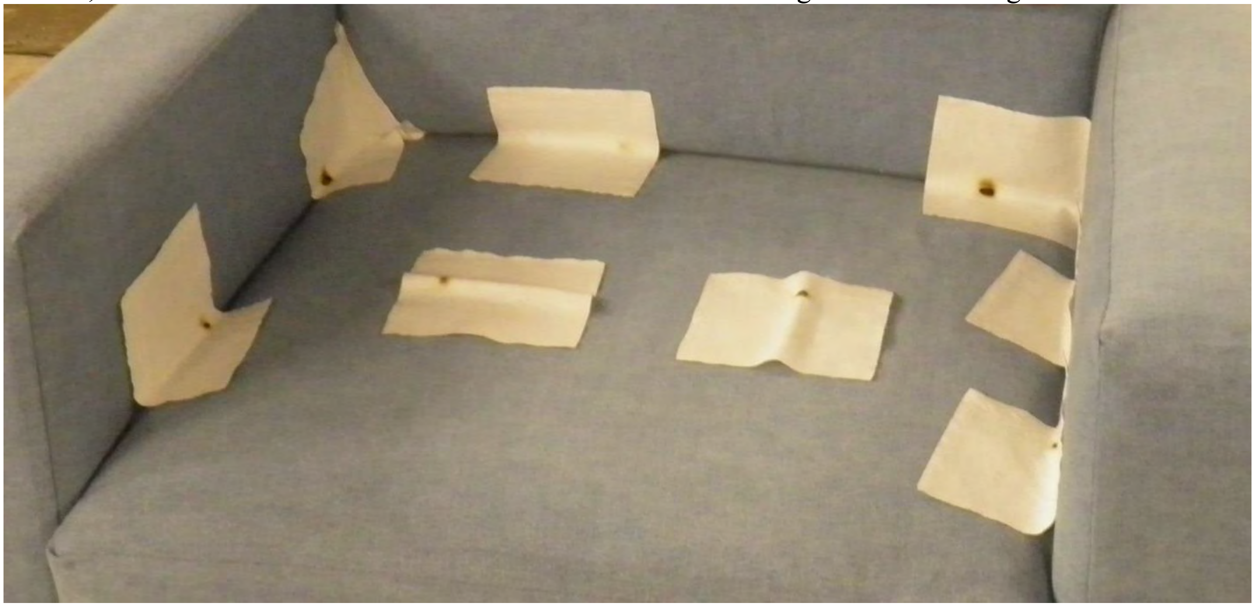

Figure 2. Placement of cigarettes for the smoldering ignition chairs.

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[i] These conditioning requirements were chosen to be consistent with other large-scale flammability test methods, *e.g*., 16 CFR part 1633, "Standard for the Flammability (Open Flame) of Mattress Sets."

[ii] This ignition source is specified in the British Standard, BS 5852, as Source 3. The flame size and duration are needed to evaluate the interior fire-barrier's ability to prevent the spread of fire to underlying materials. Because interior fire barriers would be located between flammable cover fabrics and filling materials, it is critical that interior fire-barriers be capable of withstanding the heat exposure presented by an ignited cover fabric.

Test Materials

The materials, including materials with improved flammability performance, specifically fire barriers, were all commercially available and purchased by the furniture manufacturer. The justification for material selection is discussed later in this report. The chairs evaluated with the open-flame ignition source used 12 combinations of materials (1 foam, 5 fire barriers plus no fire barrier, and 2 cover fabrics). There were 12 combinations evaluated with the smoldering ignition source. The materials used are listed in Table 1 for open-flame testing and Table 2 for smoldering testing.

Table 1. Chair Material Combinations for Full-Scale, Open-Flame Testing

Combination	**Foam**	**Polyester Batting**	**Fire Barrier**	**Cover Fabric***	**Number of Chairs****	
					Mechanically Stressed	**Non-Stressed**
2	PU	YES	FB6***	F2	3	3
3	PU	YES	FB6***	F3	3	3
5	PU	NO	FB1	F2	3	2
6	PU	NO	FB1	F3	3	3
8	PU	NO	FB2	F2	3	3
9	PU	NO	FB2	F3	3	2
11	PU	NO	FB3	F2	3	3
12	PU	NO	FB3	F3	3	2
14	PU	NO	FB4	F2	3	5
15	PU	NO	FB4	F3	4	2
17	PU	NO	FB5	F2	3	3
18	PU	NO	FB5	F3	2	5

* Cover Fabric F1 was only used in smoldering chair tests.
** The randomization scheme originally identified three chairs, each for mechanically stressed and non-stressed conditions. However chairs were not always constructed to the specifications.
*** FB6 = no fire barrier. FB6 is a polyester batting that is found in current construction furniture to aid in preventing smoldering ignitions and for comfort.

Table 2. Chair Material Combinations for Full-Scale, Smoldering Testing

Combination	**Foam**	**Polyester Batting**	**Fire Barrier**	**Cover Fabric***	**Number of Chairs**	
					Mechanically Stressed	**Non-Stressed**
1	PU	YES	FB6**	F1	1	1
2	PU	YES	FB6**	F2	1	1
4	PU	NO	FB1	F1	1	1
5	PU	NO	FB1	F2	1	1
7	PU	NO	FB2	F1	1	1
8	PU	NO	FB2	F2	1	1
10	PU	NO	FB3	F1	1	1
11	PU	NO	FB3	F2	1	1
13	PU	NO	FB4	F1	1	1
14	PU	NO	FB4	F2	1	1
16	PU	NO	FB5	F1	1	1
17	PU	NO	FB5	F2	1	1

* Cover Fabric F3 was only used in open flame chair tests.
** FB6 = no fire barrier. FB6 is a polyester batting that is found in current construction furniture to aid in preventing smoldering ignitions and for comfort.

Upholstery Fabrics

Three upholstery fabrics were included in this study. They are described in Table 3. Fabrics F1 and F2 are smolder-prone fabrics, while fabric F3 is a non-smolder-promoting fabric and was excluded from smolder testing. Fabric F1 and F3 were used in prior testing, and a fabric very similar to F2 has been used in prior testing by CPSC staff.[5]

Table 3. Upholstery Fabrics for Full-Scale Tests

Fabric Code	**Fiber Content**	**Weight (oz/yd^2)**	**Fabric Construction**
F1	100% cotton	8	Twill
F2	100% cotton	13	Twill (denim)
F3	56% rayon/34% polyester/10% cotton	10	Jacquard

Foam

The chairs were constructed with the same commercially available foam.

Non-Flame-Retardant Polyurethane Foam:

- Density: 1.8 $\pm$ 0.1 lb/ft^3;
- Indentation Load Deflection (ILD): 25% to 30%;
- Air Permeability: Greater than 4.0 ft^3/min; and
- No flame-retardant (FR) chemical treatment

Analysis[6] by CPSC staff determined that the foam contained 7 $\pm$ 2% melamine. No brominated or phosphorous/chlorinated FR chemicals were detected.

Fire Barrier

Five fire barriers were evaluated in this study. They are described in

Table 4. The commercially available fire barriers were originally developed for use in mattress designs that meet the performance requirements specified in 16 C.F.R. part 1633--*The Standard for the Flammability (Open Flame) of Mattress Sets*. Staff was interested in evaluating the flammability performance of upholstered chairs constructed with barriers in this limited study. Because a performance threshold has not yet been established for upholstered chairs, the barriers were selected based on conversations with fire barrier manufacturers regarding each barrier's potential performance. The manufacturers identified products they thought would likely have enhanced flammability performance in upholstered chair constructions. In addition, staff attempted to obtain fire barriers with various fabric constructions and fiber contents from several different fire barrier manufacturers. The fiber content and construction for each of the fire barriers were provided by each manufacturer. The five fire barriers were produced by four different barrier manufacturers.

Table 4. Fire Barriers for Full-Scale Tests

Fire Barrier Code	Fiber Content	Construction*	Chemical Analysis[6]	Comments
FB1	Cellulose based	Nonwoven	0.6% Phosphorous 0.2% Chlorine	Indicates possible FR chemical additive
FB2	Fibrous glass/modacrylic/polyester	Needle punched	2.6% Antimony	Indicates possible FR chemical additive
FB3	Modacrylic/silica	Knit/sock	0.8% Antimony 0.3% Phosphorous 11.0% Chlorine	Indicates possible FR chemical additives
FB4	Rayon/polyester	High loft	1.0% Phosphorous 0.3% Chlorine	Indicates possible FR chemical additive
FB5	Rayon/polyester	Densified	1.2% Phosphorous 0.2% Chlorine	Indicates possible FR chemical additive

*Construction description from manufacturer.

The fire barriers were placed in the following locations on the chair:

- Six-sided wrap on seat cushion;
- Six-sided wrap on back cushion;
- Inside arms facing seating area;
- Across the top of the arms, down the outside of the chair; and
- Inside the back (behind back cushion), from below the crevice, up to the top of the chair frame.

The furniture manufacturer labeled each chair to identify the fire barrier used in the construction of the chair. The chairs were tested following a randomized test scheme.[2] CPSC staff did not conduct an initial verification of the components used in the test chairs before testing. As testing progressed, staff noted a difference in performance between two chair replicates that were labeled as using the same barrier. Upon further inspection, staff noted some other discrepancies in the chair labels, compared to the actual materials used in the construction of some of the chairs. Because of this, rigorous verification of the fire barriers used in the construction of each chair was not done by CPSC staff until open-flame ("OF") test number 10. There may be discrepancies in the barrier reported for the first nine tests. These discrepancies were identified and excluded where appropriate as to not confuse the results.

Polyester Batting

The 100 percent polyester batting was nominally 8 oz/yd^2, 0.75 inch thick, nonwoven. Polyester batting is typically included in upholstered furniture as a smoldering barrier and to improve the comfort of the furniture. The polyester batting was included in the seat and back cushion constructions in one of the following configurations:

- Used by itself as in test combinations 1, 2, and 3 in Table 1 and Table 2, or;
- Placed under the fire barrier in all other test combinations (Table 1 and Table 2).

Testing Order

The combinations were tested in a predetermined randomized order. The chairs were labeled as OF# for open flame testing and S# for smoldering testing (where # is the number in the test series). The testing order is listed in Table 5 and Table 6.

Table 5. Open Flame test order.

Test Name/#	Combo	Fabric	Barrier	Stressed
OF01	6	F3	FB1	Y
OF02	8	F2	FB2	N
OF03	14	F2	FB4	N
OF04	5	F2	FB1	Y
OF05	9	F3	FB2	N
OF06	2	F2	FB6*	N
OF07	9	F3	FB2	Y
OF08	18	F3	FB5	N
OF09	2	F2	FB6*	Y
OF10	2	F2	FB6*	Y
OF11	18	F3	FB5	N
OF12	15	F3	FB4	N
OF13	11	F2	FB3	Y
OF14	11	F2	FB3	N
OF15	17	F2	FB5	Y
OF16	18	F3	FB5	Y
OF17	8	F2	FB2	Y
OF18	8	F2	FB2	N
OF19	15	F3	FB4	Y
OF20	8	F2	FB2	N
OF21	11	F2	FB3	N
OF22	11	F2	FB3	Y
OF23	18	F3	FB5	Y
OF24	3	F3	FB6*	N
OF25	12	F3	FB3	Y
OF26	5	F2	FB1	N
OF27	3	F3	FB6*	Y
OF28	6	F3	FB1	N
OF29	17	F2	FB5	N
OF30	2	F2	FB6*	Y
OF31	8	F2	FB2	Y
OF32	15	F3	FB4	Y
OF33	3	F3	FB6*	Y
OF34	5	F2	FB1	N
OF35	8	F2	FB2	Y
OF36	11	F2	FB3	Y

Test Name/#	Combo	Fabric	Barrier	Stressed
OF37	15	F3	FB4	N
OF38	12	F3	FB3	N
OF39	18	F3	FB5	N
OF40	3	F3	FB6*	N
OF41	12	F3	FB3	N
OF42	14	F2	FB4	N
OF43	6	F3	FB1	N
OF44	14	F2	FB4	Y
OF45	14	F2	FB4	N
OF46	12	F3	FB3	Y
OF47	14	F2	FB4	Y
OF48	6	F3	FB1	N
OF49	2	F2	FB6*	N
OF50	18	F3	FB5	N
OF51	17	F2	FB5	N
OF52	17	F2	FB5	Y
OF53	14	F2	FB4	Y
OF54	5	F2	FB1	Y
OF55	9	F3	FB2	N
OF56	14	F2	FB4	N
OF57	14	F2	FB4	N
OF58	9	F3	FB2	Y
OF59	12	F3	FB3	Y
OF60	3	F3	FB6*	N
OF61	18	F3	FB5	N
OF62	5	F2	FB1	Y
OF63	9	F3	FB2	Y
OF64	17	F2	FB5	N
OF65	2	F2	FB6*	N
OF66	9	F3	FB2	Y
OF67	11	F2	FB3	N
OF68	15	F3	FB4	Y
OF69	17	F2	FB5	Y
OF70	3	F3	FB6*	Y
OF71	6	F3	FB1	Y
OF72	15	F3	FB4	Y

*FB6 = no barrier. FB6 is a polyester batting found in current construction furniture to aid in preventing smoldering ignition and provide comfort.

Table 6. Smoldering test order.

Test Name/#	Combo	Fabric	Barrier	Stressed
S01	13	F1	FB4	Y
S02	7	F1	FB2	N
S03	11	F2	FB3	N
S04	8	F2	FB2	N
S05	5	F2	FB1	Y
S06	14	F2	FB4	Y
S07	10	F1	FB3	N
S08	7	F1	FB2	Y
S09	16	F1	FB5	Y
S10	4	F1	FB1	N
S11	5	F2	FB1	N
S12	14	F2	FB4	N
S13	2	F2	FB6*	N
S14	16	F1	FB5	N
S15	13	F1	FB4	N
S16	1	F1	FB6*	Y
S17	2	F2	FB6*	Y
S18	11	F2	FB3	Y
S19	17	F2	FB5	Y
S20	1	F1	FB6*	N
S21	8	F2	FB2	Y
S22	4	F1	FB1	Y
S23	10	F1	FB3	Y
S24	17	F2	FB5	N

*FB6 = no barrier. FB6 is a polyester batting found in current construction furniture to aid in preventing smoldering ignition and provide comfort.

Data and Observations

During the tests, staff observed and noted relevant events in each test. Heat flux was measured in three places around the chair, and CO, CO_2, and O_2 levels were recorded from the effluent gases in the exhaust hood. Flame spread across the cushions, melt dripping, and full involvement of the chair were also observed. The HRR was also measured via oxygen consumption calorimetry in the hood. Char measurements were taken for chairs evaluated with the smoldering ignition source.

Heat Release Rate Data

The HRR is a measure of the rate at which energy is released by the fire. The HRR can be determined as a function of the gas flow rate, O_2, CO, and CO_2 quantities in the effluent coming off of a burning hydrocarbon fuel source, in this case, upholstered furniture. This quantitative measure provides an understanding of how severe the fire is, how the fire is likely to be affecting tenability in the environment, and the likelihood of the fire spreading to nearby items.

The PHRR is the maximum instantaneous HRR measured during a test. The PHRR is important because it provides a measure of the potential maximum severity of a fire. The time to PHRR is also recorded because of implications for escape and response time. The shorter the time before the PHRR, the less time occupants and emergency responders have to react to the fire.

Plots of all the HRR data from all 96 chairs are detailed in Appendix B for open-flame tests and Appendix C for smoldering tests. A summary of each test is provided in Table 7 for open-flame tests and Table 8 for smoldering tests. Both tables include information on the test number, the combo number, fabric ID, fire barrier ID, and whether each specimen was mechanically stressed or not. The five data columns relate to the HRR measurements taken during each test. The *Peak at 15 min* indicates the highest HRR observed within the first 15 minutes of the test from when the ignition burner was removed from the specimen. The *Peak HRR* indicates the maximum HRR observed throughout the entire test. The *TTPeak HRR* refers to the amount of time from when the ignition burner was removed until the maximum overall HRR peak (previous column) was observed. The *TT 200 kW* refers to the amount of time after the ignition burner was removed until the fire reached 200 kW. Staff chose 200 kW as a benchmark for the tests because of its significance in the mattress open-flame regulation 16 C.F.R. part 1633. The *THR @ 10 min*, measured in Joules, indicates the total amount of heat produced in the first 10 minutes of the fire. Again, this is a benchmark related to the total heat release requirement in 16 C.F.R. part 1633. In each of the data columns, a value of zero indicates that a value below the measurement threshold was observed.

The highest PHRR observed in this testing was 2,171 kW from a non-barriered chair. The lowest non-zero PHRR observed was 469 kW. Essentially all chairs that burned produced a PHRR of approximately 500 kW or higher. In general the barriers reduced the intensity of the fire.

Figure 3 and Figure 4 show examples of fires with all five fire barriers and without all five barriers for fabrics F3 and F2, respectively. In each case, the chairs with fire barriers tended to reduce the PHRR (by about 40% to 60%) and delay the onset of the fire (by about 8 to 20 minutes). In both figures, the chair without the fire barrier had a much higher PHRR and burned much more rapidly.

Figure 5 and Figure 6 indicate the relative performance of the fire barriers over all open-flame tests for cover fabrics F3 and F2, respectively. As observed in Figure 3 and Figure 4, the fire barriers used in this test series generally reduce the severity of the fire by reducing the PHRR.

Figure 7 and Figure 8 show the time to Peak HRR for all the various fire barriers for cover fabrics F3 and F2, respectively. In general the fire barriers slowed down the fire, substantially increasing the TTPeak in most cases.

It is important to note that, of the five fire barriers included in this study, only two of the barriers, FB2 and FB3, succeeded in preventing a fire altogether in open-flame testing. Of those two, only FB2 prevented a fire more than once. However, this study is only a preliminary look at the performance of these five fire barriers currently on the market. Not much can be said about the relative performance among the fire barriers, because the design of the experiment was to compare each barrier with “no barrier,” rather than relative to one another. Additional factors not included in this study, such as chair design and location of the barrier, may also impact the flammability performance of a fire barrier.

Table 7. Summary of Open-Flame test data.

Test Name	Combo	Fabric	Barrier	Stressed	Peak at 15 min	Peak HRR (kW)	TTPeak HRR (min)	TT 200 kW (min)	THR @ 10 min	Exception
OF01	6	F3	FB1	Y	1616	1616	3.33	1.45	189.97	* Likely wrong Barrier
OF02	8	F2	FB2	N	0	0	0.00	0.00	0.00	Barrier not Verified
OF03	14	F2	FB4	N	55	785	24.88	17.52	3.61	Barrier not Verified
OF04	5	F2	FB1	Y	10	675	43.47	35.33	0.41	Barrier not Verified
OF05	9	F3	FB2	N	0	0	0.00	0.00	0.00	Barrier not Verified
OF06	2	F2	FB6*	N	1266	1266	8.68	4.20	189.74	Barrier not Verified
OF07	9	F3	FB2	Y	374	892	19.47	12.65	6.46	Barrier not Verified
OF08	18	F3	FB5	N	382	903	19.50	12.18	5.26	Barrier not Verified
OF09	2	F2	FB6*	Y	1186	1186	7.98	3.93	206.94	Barrier not Verified
OF10	2	F2	FB6*	Y	1411	1411	10.08	5.38	137.73	
OF11	18	F3	FB5	N	4	1007	37.72	31.32	0.00	
OF12	15	F3	FB4	N	235	702	19.98	14.10	5.20	
OF13	11	F2	FB3	Y	9	665	30.63	24.53	3.05	
OF14	11	F2	FB3	N	12	876	28.75	22.85	2.41	
OF15	17	F2	FB5	Y	44	741	21.25	17.32	4.60	
OF16	18	F3	FB5	Y	394	744	19.08	13.08	5.33	
OF17	8	F2	FB2	Y	0	0	0.00	0.00	0.00	
OF18	8	F2	FB2	N	0	0	0.00	0.00	0.00	
OF19	15	F3	FB4	Y	678	979	15.98	10.92	22.91	
OF20	8	F2	FB2	N	5	498	32.95	22.22	0.67	
OF21	11	F2	FB3	N	10	870	28.22	23.87	2.00	
OF22	11	F2	FB3	Y	11	727	30.63	27.15	1.72	
OF23	18	F3	FB5	Y	325	956	17.83	14.72	15.46	
OF24	3	F3	FB6*	N	2171	2171	3.72	1.47	253.73	
OF25	12	F3	FB3	Y	1264	1264	9.70	6.52	130.87	
OF26	5	F2	FB1	N	12	595	30.30	25.72	2.82	
OF27	3	F3	FB6*	Y	1974	1974	3.93	1.65	252.35	
OF28	6	F3	FB1	N	287	779	20.43	13.92	5.07	
OF29	17	F2	FB5	N	9	1184	32.55	29.72	1.86	
OF30	2	F2	FB6*	Y	1346	1346	9.10	4.82	183.62	
OF31	8	F2	FB2	Y	0	0	0.00	0.00	0.00	
OF32	15	F3	FB4	Y	183	866	21.55	15.02	4.28	
OF33	3	F3	FB6*	Y	2003	2003	4.10	2.10	243.60	
OF34	5	F2	FB1	N	12	469	31.18	25.42	3.27	
OF35	8	F2	FB2	Y	0	0	0.00	0.00	0.00	
OF36	11	F2	FB3	Y	0	0	0.00	0.00	0.00	
OF37	15	F3	FB4	N	90	836	21.77	15.50	3.25	
OF38	12	F3	FB3	N	1115	1115	12.98	8.42	37.55	

*FB6 = no barrier. FB6 is a polyester batting found in current construction furniture to aid in preventing smoldering ignition and provide comfort.

Test Name	Combo	Fabric	Barrier	Stressed	Peak at 15 min	Peak HRR (kW)	TTPeak HRR (min)	TT 200 kW (min)	THR @ 10 min	Exception
OF39	18	F3	FB5	N	24	861	24.63	18.63	4.08	
OF40	3	F3	FB6*	N	1329	1329	4.92	2.75	232.92	
OF41	12	F3	FB3	N	363	774	18.68	13.50	5.02	
OF42	14	F2	FB4	N	13	660	29.45	23.12	2.98	
OF43	6	F3	FB1	N	465	698	19.42	11.80	8.79	
OF44	14	F2	FB4	Y	12	672	29.93	24.67	3.41	
OF45	14	F2	FB4	N	12	686	30.38	22.90	2.46	
OF46	12	F3	FB3	Y	381	900	18.25	14.25	4.77	
OF47	14	F2	FB4	Y	31	648	26.22	19.47	4.35	
OF48	6	F3	FB1	N	267	762	20.88	13.08	6.14	
OF49	2	F2	FB6*	N	1417	1417	7.93	4.45	205.70	
OF50	18	F3	FB5	N	431	686	17.98	12.53	17.24	
OF51	17	F2	FB5	N	15	571	31.05	22.52	4.52	
OF52	17	F2	FB5	Y	32	757	24.62	21.20	3.45	
OF53	14	F2	FB4	Y	38	743	24.48	19.50	2.87	
OF54	5	F2	FB1	Y	26	568	28.90	22.97	3.44	
OF55	9	F3	FB2	N	291	717	20.78	14.40	1.22	
OF56	14	F2	FB4	N	30	761	27.53	21.75	3.58	
OF57	14	F2	FB4	N	52	617	24.07	16.43	3.47	
OF58	9	F3	FB2	Y	197	735	20.43	15.92	0.45	
OF59	12	F3	FB3	Y	1343	1343	14.70	11.02	9.06	
OF60	3	F3	FB6*	N	1945	1945	3.72	1.28	252.64	
OF61	18	F3	FB5	N	242	824	21.55	14.70	6.43	
OF62	5	F2	FB1	Y	36	666	29.38	20.88	2.62	
OF63	9	F3	FB2	Y	0	0	0.00	0.00	0.00	
OF64	17	F2	FB5	N	12	750	30.93	23.97	2.90	
OF65	2	F2	FB6*	N	1340	1340	8.30	3.98	215.92	
OF66	9	F3	FB2	Y	0	0	0.00	0.00	0.00	
OF67	11	F2	FB3	N	10	770	28.40	24.18	2.09	
OF68	15	F3	FB4	Y	381	872	21.95	14.02	7.23	
OF69	17	F2	FB5	Y	24	621	24.81	19.15	3.93	
OF70	3	F3	FB6*	Y	1648	1648	4.37	1.65	260.02	
OF71	6	F3	FB1	Y	351	648	18.52	12.38	5.17	
OF72	15	F3	FB4	Y	778	778	14.50	9.38	31.19	

*FB6 = no barrier. FB6 is a polyester batting found in current construction furniture to aid in preventing smoldering ignition and provide comfort.

Table 8. Summary of Smoldering test data.

Test Name/#	Combo	Fabric	Barrier	Stressed	Peak at 15 min	Peak HRR (kW)	TTPeak HRR	TT 200 kW	THR @ 10 min
S01	13	F1	FB4	Y	0	0	0	0	0.00
S02	7	F1	FB2	N	0	560.302	196.5	193.25	0.00
S03	11	F2	FB3	N	0	743.575	122.9333	119.0667	0.00
S04	8	F2	FB2	N	0	674.372	99.41667	91.66667	0.00
S05	5	F2	FB1	Y	0	640.069	148.8333	139.8667	0.00
S06	14	F2	FB4	Y	0	723.936	124.4833	118.75	0
S07	10	F1	FB3	N	0	0	0	0	0
S08	7	F1	FB2	Y	0	739.54	201.3833	197	0
S09	16	F1	FB5	Y	0	0	0	0	0
S10	4	F1	FB1	N	0	0	0	0	0
S11	5	F2	FB1	N	0	706.85	123.8	118.2667	0
S12	14	F2	FB4	N	0	780.55	104.35	101.7333	0
S13	2	F2	FB6*	N	0	1027.84	287.1333	285.3	0
S14	16	F1	FB5	N	0	0	0	0	0
S15	13	F1	FB4	N	0	0	0	0	0
S16	1	F1	FB6*	Y	0	0	0	0	0
S17	2	F2	FB6*	Y	0	1268.6	207.0667	205.1333	0
S18	11	F2	FB3	Y	0	998.777	145.1333	143.3167	0
S19	17	F2	FB5	Y	0	539.001	125.0667	119.1667	0
S20	1	F1	FB6*	N	0	0	0	0	0
S21	8	F2	FB2	Y	0	809.218	169.6167	165.15	0
S22	4	F1	FB1	Y	0	0	0	0	0
S23	10	F1	FB3	Y	0	997.912	145.45	142.2	0
S24	17	F2	FB5	N	0	649.076	187.4833	183.1667	0

*FB6 = no barrier. FB6 is a polyester batting found in current construction furniture to aid in preventing smoldering ignition and provide comfort.

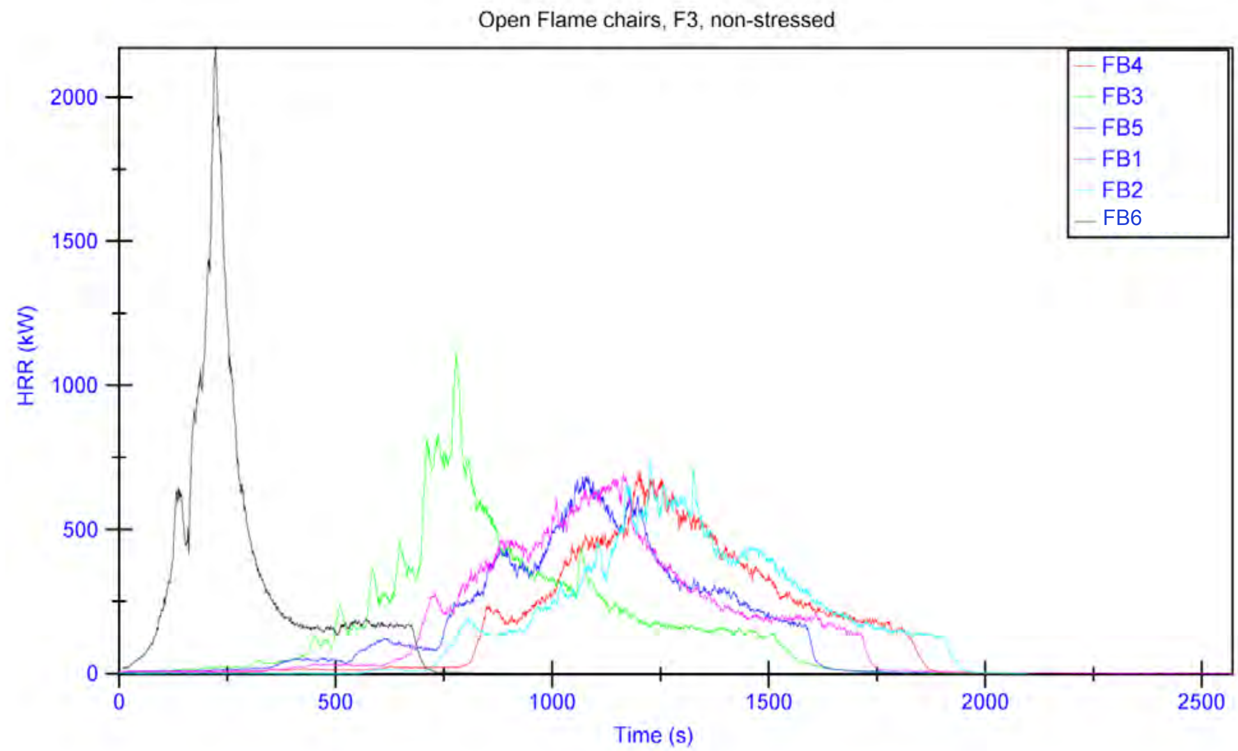

Figure 3. Example comparison of different fire barriers on open-flame chairs with cover fabric F3, non-stressed.

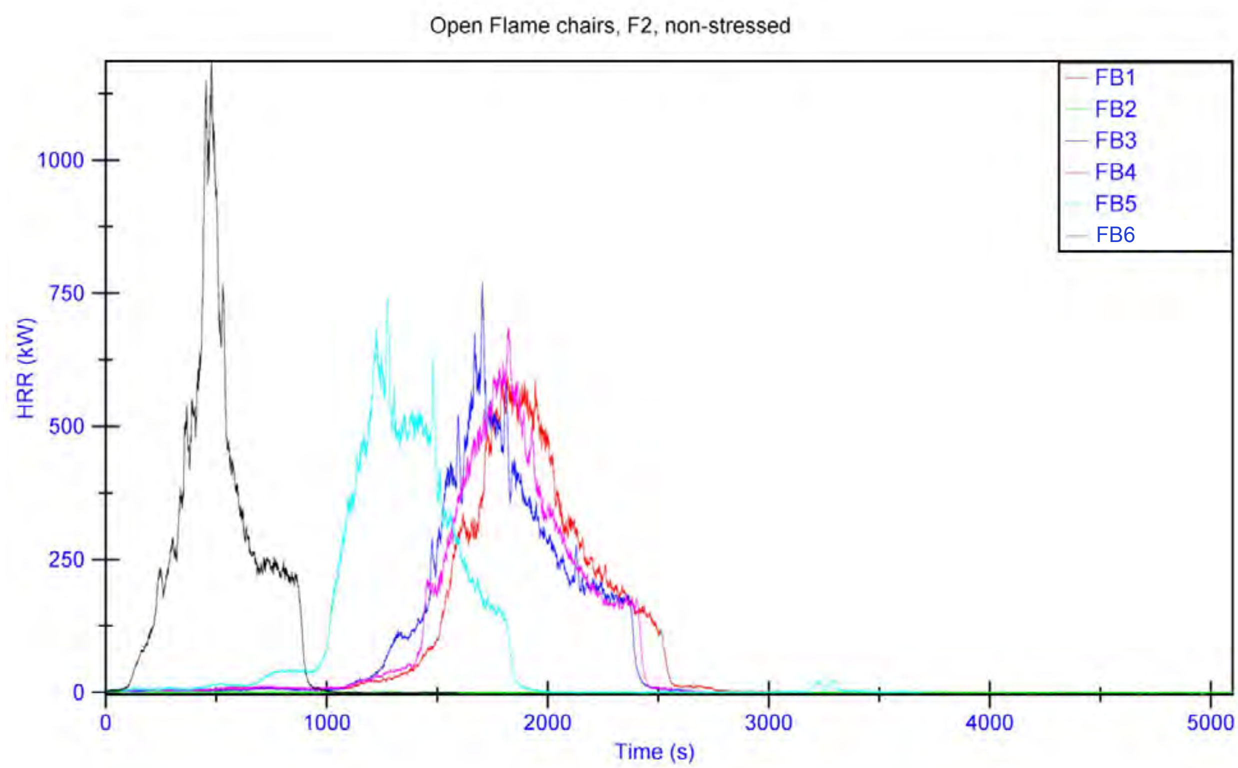

Figure 4. Example comparison of different fire barriers on open flame chairs with cover fabric F2, non-stressed. Notice that FB2 is zero for the entire test.

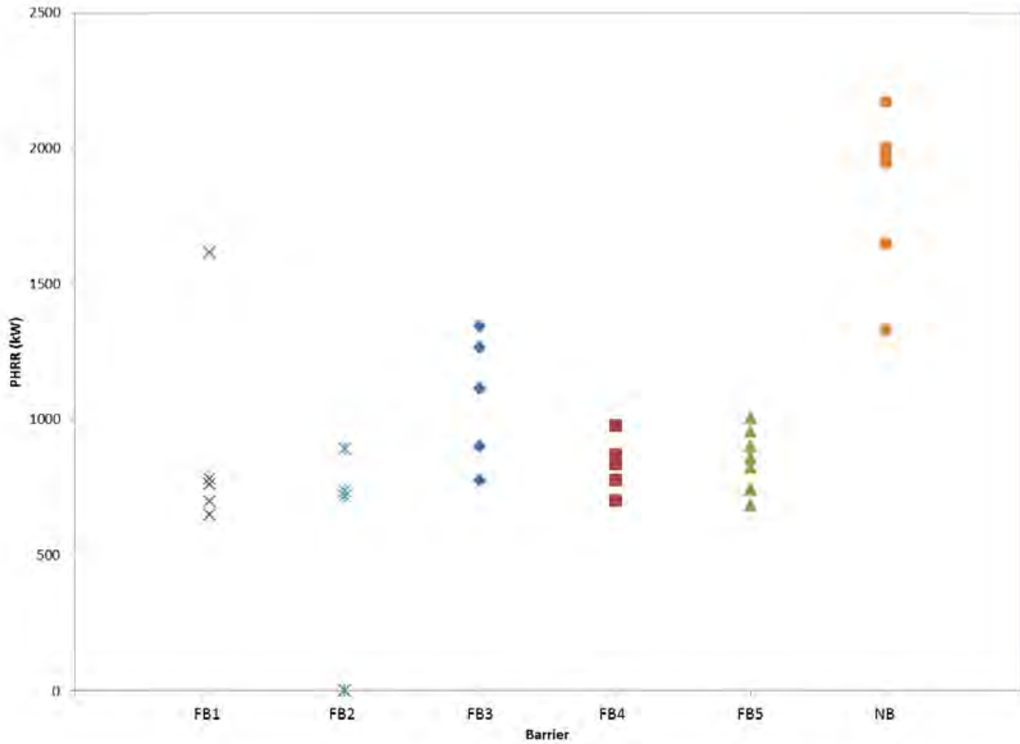

Figure 5. Relative performance of barriers in open-flame testing of chair with cover fabric F3, both stressed and non-stressed.

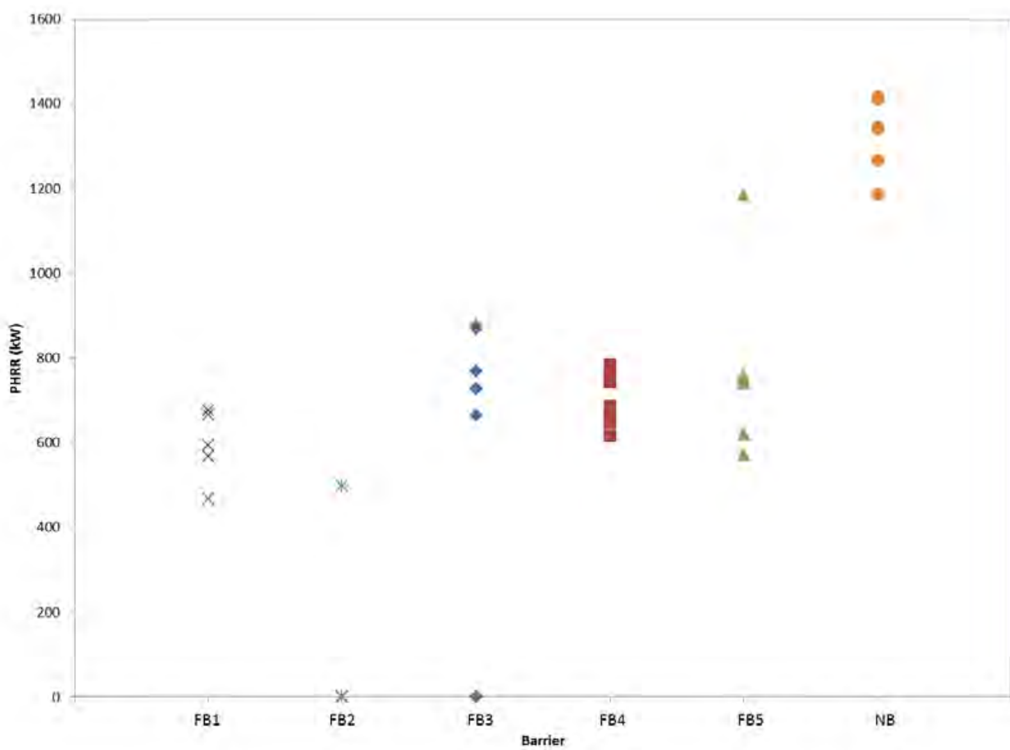

Figure 6. Relative performance of barriers in open-flame testing of chair with cover fabric F2, both stressed and non-stressed.

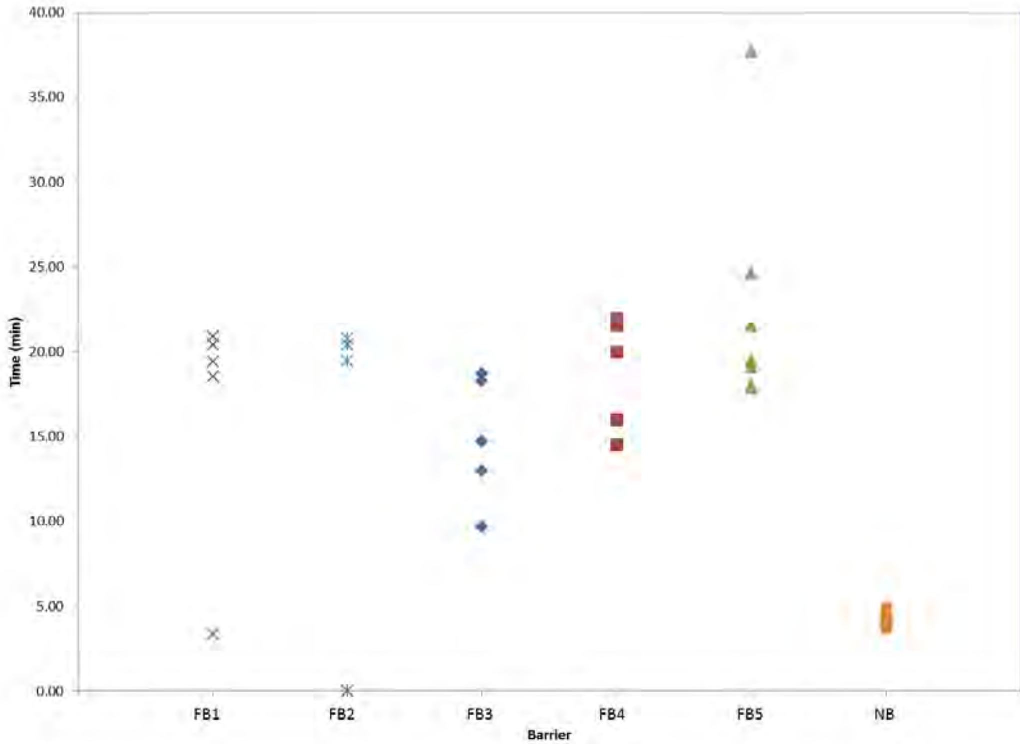

Figure 7. Time to Peak HRR ("TTPeak") for all open-flame tests on chairs with cover fabric F3. Note that a zero value indicates that no PHRR was observed.

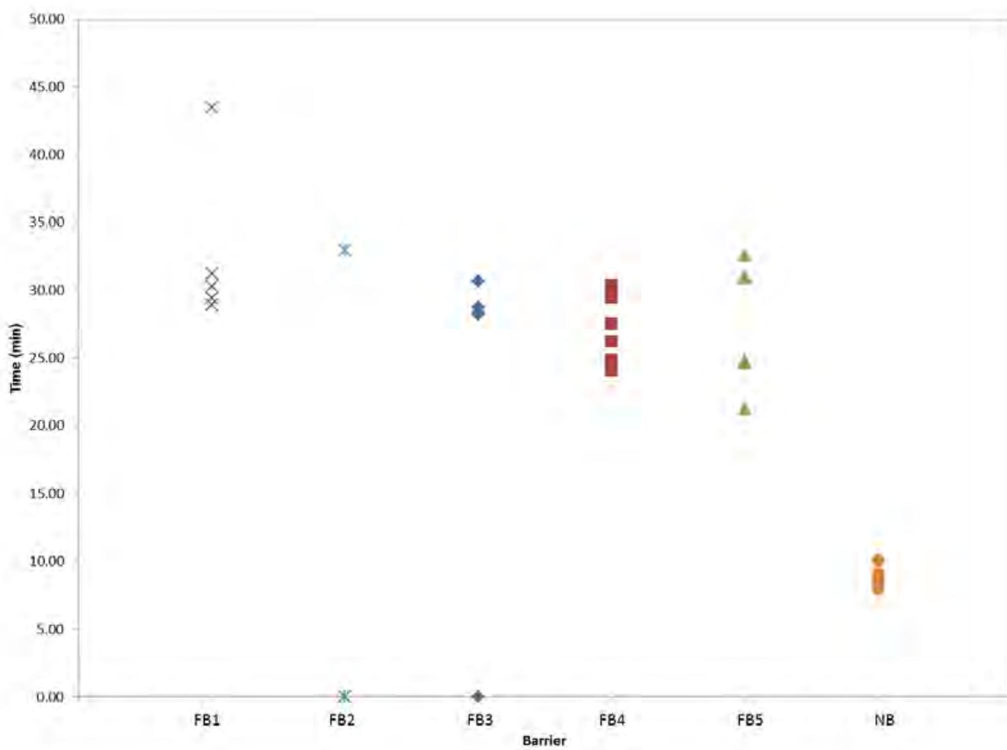

Figure 8. Time to Peak HRR ("TTPHRR") for all open-flame tests on chairs with cover fabric F2. Note that a zero value indicates that no PHRR was observed.

Additional Measurements

A few additional measurements were made in these tests to assist in future modeling. These measurements included Heat Flux, Mass Loss, and soot measurements. These measurements were collected to be used in modeling at the National Institute of Standards and Technology (NIST) so that they can assist in our understanding of fire severity and risk assessment.

Observations

In addition to recording the HRR of the burning chairs, visual observations during testing identified qualitative differences in the burning behaviors of the chair samples.

Open Flame

For chairs where the fire barrier offered effective protection to the filling, the flames were typically smaller, less intense, and self-extinguished in a matter of minutes. For chairs with no fire barrier (FB6), or with less-protective fire barriers, the flame spread on all the chairs ignited by open flame was similar, but this progression generally took significantly longer time for chairs with fire barriers than without. Aside from those that self-extinguished, the general pattern for flame spread was as follows: When the ignition flame was removed, there were flames on the seat and back cushions. Initially, the flame spread was up the back cushion and toward the corners of the seating area. Next, flames either reached the top of the back cushion, or went around the side of the back cushion between the back cushion and the back of the chair. The flame front on the seat cushion moved outward as well. The flames increased in intensity and size and continued to burn as the back cushion and back of the chair became more involved in the combustion process. The back cushion burnt through first, followed by the back of the chair, which led to rapid progression, with the entire chair soon engulfed in flames. As the seating area became more involved, melt dripping occurred below the chair.

Smoldering

Smoldering ignition of upholstered furniture can occur when a lit cigarette transfers heat to the upholstery fabric. Fabrics F1 and F2 were chosen for their smolder-promoting properties. These properties include transferring the smolder easily from the cigarette to these 100 percent cellulosic fabrics and then to the materials below the upholstery fabrics. Char is formed on these fabrics during the smoldering process, and as the heat builds up, the charred surface surrounding the lit cigarette continues to grow. Smoke is observed during this thermal decomposition of the fabric and filling materials. Smoldering ignition often transfers to flaming over time.

For this study, cigarettes were lit and allowed to burn no more than 4 mm (0.16 inch) before being placed on the chair. The cigarettes were observed during the test to determine if the cigarette self-extinguished or burned its full length. The test continued until all eight cigarettes and the seating materials stopped smoldering or PHHR had occurred, whichever came first.

The start time for each test occurred as soon as the last cigarette was placed on the chair. Observations were recorded for each cigarette test location at 45 minutes and then at 15-minute intervals throughout the test. Subjective notations of temperature (hot, warm, or cool) and the presence of smoke were recorded at these time intervals. Cigarettes were determined to have self-extinguished when the test operator recorded a “cool” notation.

Fifteen of the 24 chairs evaluated with a smoldering ignition source transitioned from smoldering to flaming. The shortest amount of time for this transition was 1 hour 26 min, and the longest time was 4 hours 43 minutes. All 12 chairs constructed with fabric F2, and three chairs constructed with fabric F1 went to flaming. Table 9 provides a summary of the chairs that transitioned from smoldering to flaming.

Table 9. Chairs That Transitioned From Smoldering to Flaming

Combo No.	Fabric Code	Fire Barrier Code	Mechanically Stressed	Time to Flames	Cig Location
2	F2	FB6*	No	4 hours 43 min	4
2	F2	FB6*	Yes	3 hours 23 min	4
5	F2	FB1	No	1 hour 52 min	4
5	F2	FB1	Yes	2 hours 17 min	4
7	F1	FB2	No	3 hours 12 min	2
7	F1	FB2	Yes	3 hours 15 min	2
8	F2	FB2	No	1 hour 26 min	4
8	F2	FB2	Yes	2 hour 41 min	2
10	F1	FB3	Yes	2 hour 19 min	1
11	F2	FB3	No	1 hour 57 min	4
11	F2	FB3	Yes	2 hour 17 min	2
14	F2	FB4	No	1 hour 29 min	4
14	F2	FB4	Yes	1 hour 56 min	4
17	F2	FB5	No	3 hour 2 min	2 & 4
17	F2	FB5	Yes	1 hour 57 min	4 & 5

*FB6 = no barrier. FB6 is a polyester batting found in current construction furniture to aid in preventing smoldering ignition and provide comfort.

The results support previous studies that suggest that the upholstery fabric plays a bigger role in determining if these chairs transition to flames than if a fire barrier was present, what fire barrier was used, or if the seat cushion was mechanically stressed. The two chairs covered with fabric F2 that did not have fire barriers were slower to transition from smoldering to flames than any of the F2 chairs with fire barriers, although there was at least a 1 ½ hour delay in transition time for the F2 chairs with fire barriers. It is important to note, however, that for the smoldering chair tests where the chairs progressed to flaming, the peak HRR was lower for the chairs with fire barriers than with no barrier.

For cigarette test locations that transitioned to flames, the inside corners had a greater chance of the transition happening. With one exception, the two corner locations were involved in those ignitions.

Nine of the 24 chairs did not transition to flaming. Instead, the test cigarettes self-extinguished and only slightly charred the surface of the upholstery fabric. All of these chairs contained F1 upholstery fabric; some had fire barriers, and others did not. Table 10 contains the summary of those results.

Table 10. Chairs with Smoldering Locations that Self-Extinguished

Combo No.	Fabric	Fire Barrier	Mechanically Stressed	End of Test	Max Char
1	F1	FB6*	No	1 hour 15 min	¾ inch
1	F1	FB6*	Yes	1 hour 15 min	½ inch
4	F1	FB1	No	2 hours	1 inch
4	F1	FB1	Yes	2 hours	¾ inch
10	F1	FB3	No	1 hour 30 min	½ inch
13	F1	FB4	No	1 hour 30 min	1 inch
13	F1	FB4	Yes	1 hour 30 min	½ inch
16	F1	FB5	No	1 hour 45 min	½ inch
16	F1	FB5	Yes	2 hours	1 inch

*FB6 = no barrier. FB6 is a polyester batting found in current construction furniture to aid in preventing smoldering ignition an d provide comfort.

The overall maximum char length on all chairs, where measurements were taken, was 1 inch. The presence of the fire barrier and whether the seat cushion was mechanically stressed did not appear to influence the measured char lengths at the end of the test. The time to end of test ranged from 1 hour 15 minutes to 2 hours.

Effect of Mechanical Stress

As mentioned above, half of the sample chairs were subjected to mechanical stresses simulating use and wear. This section describes some of the observations of the effects of that.

Open Flame

The mechanically stressed chairs' HRR curve was compared to the non-stressed chairs. The mechanically stressed chairs had similar PHRR to the non-stressed chairs. However, in general, the fires seem to peak earlier for the stressed chairs than for the non-stressed chairs. Specifically, of the 12 combinations tested, on average, seven of the stressed combinations reached the PHRR earlier than the non-stressed combinations. In the remaining five combinations, the non-stressed chairs reached the PHRR earlier than the stressed chairs. HRR plots for Combo 15 and Combo 17 are presented below in Figure 9 and Figure 10, respectively. These two combinations have both different cover fabrics and different fire barrier materials. In both cases, the mechanically stressed chairs generally peak earlier than the non-stressed chairs; however, there is some overlap.

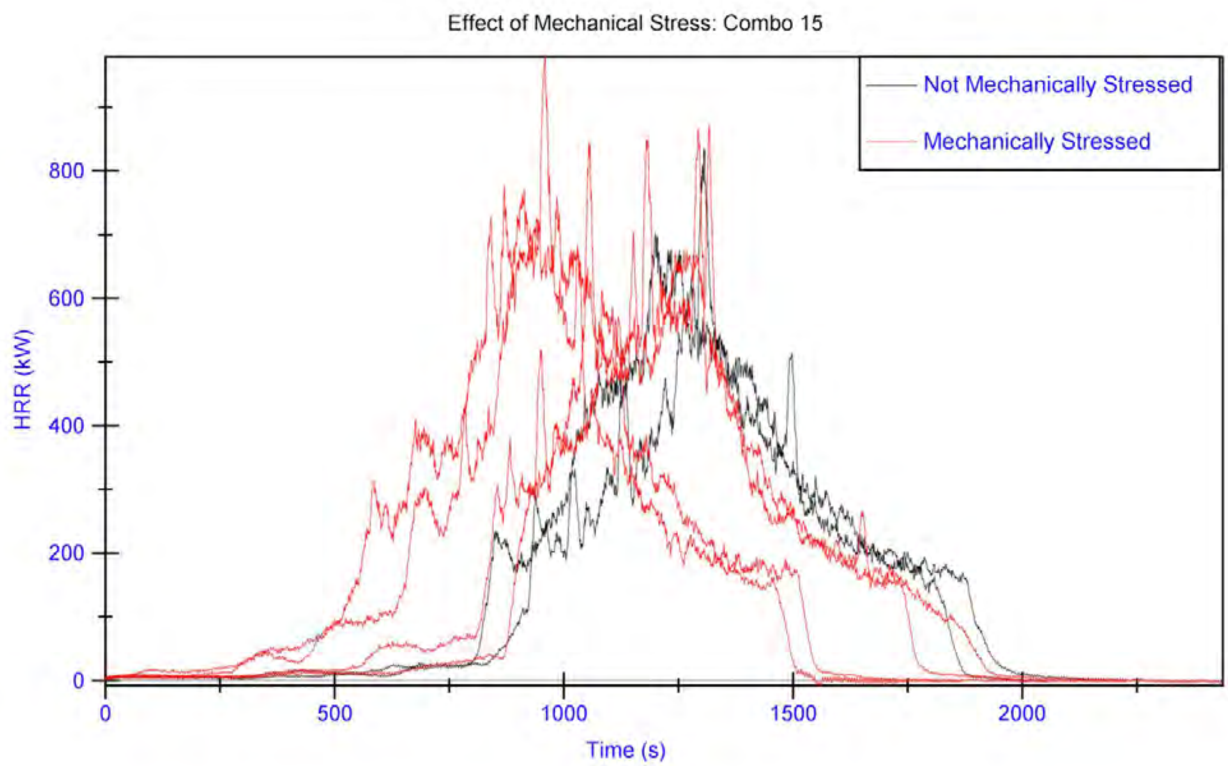

Figure 9. Comparison of the HRR of mechanically stressed and non-stressed chairs of identical construction, Combo 15.

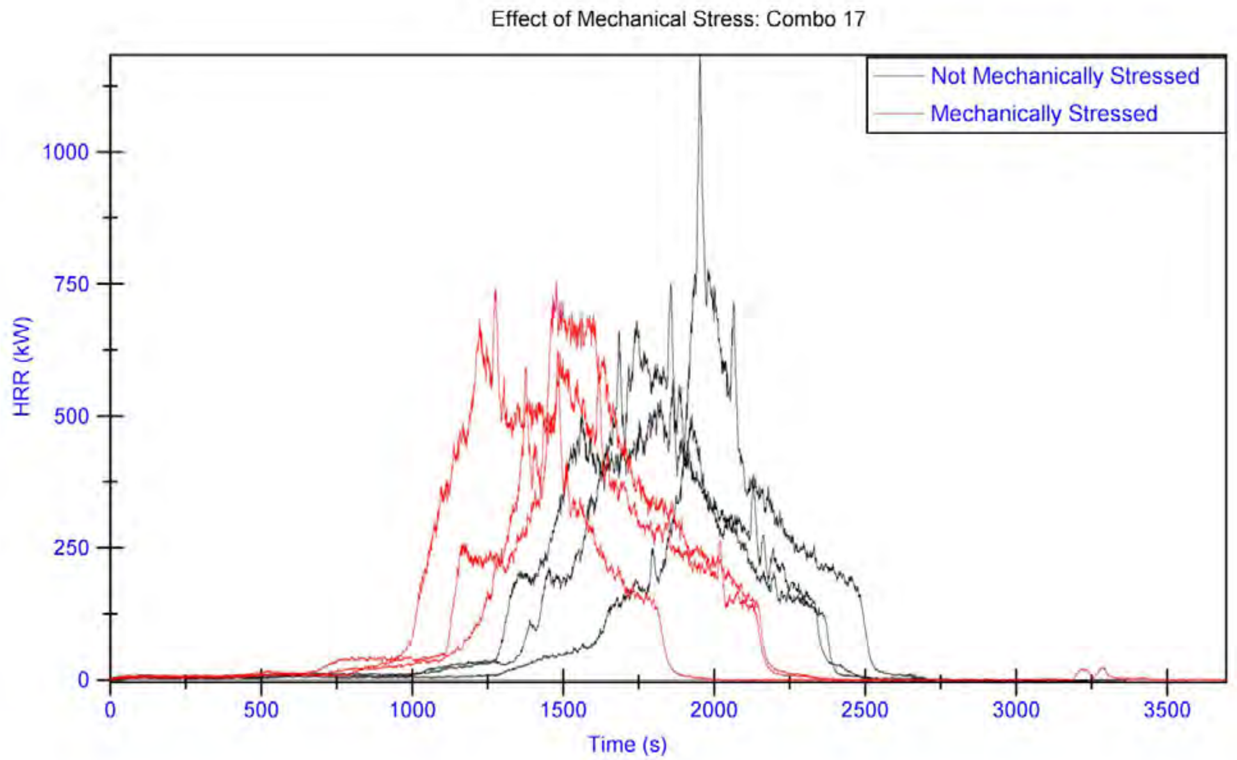

Figure 10. Comparison of the HRR of mechanically stressed and non-stressed chairs of identical construction, Combo 17.

Smoldering
The mechanically stressed chairs' HRR curve was compared to the non-stressed chairs' HRR curve. The mechanically stressed chairs had similar PHRR to the non-stressed chairs. However, in general, the fires seem to peak later for the stressed chairs than for the non-stressed chairs. Specifically, of the 12 combinations tested, six of the combinations with non-stressed chairs reached the PHRR earlier than the stressed chairs. Two of the combinations with non-stressed chairs reached the PHRR later than the stressed chairs, and the remaining four combinations were the same (no ignition) for both stressed and non-stressed chairs. HRR plots for Combo 5 and Combo 7 are presented below in Figure 4 and Figure 5, respectively. These two combinations have both different cover fabrics and different fire barrier materials. In both cases the mechanically stressed chairs generally peak earlier than the non-stressed; however, there is some overlap.

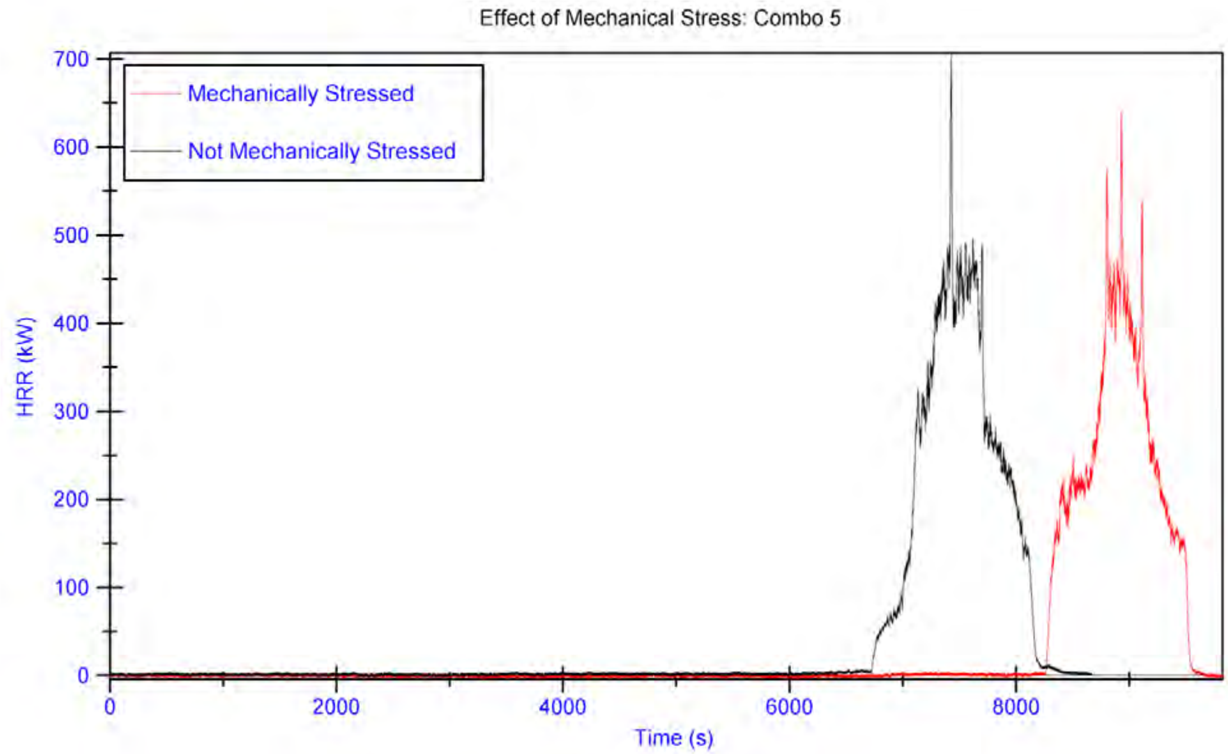

Figure 11. Heat Release Rate plot of mechanically stressed and non-stressed chair combo 5 in smoldering ignition testing.

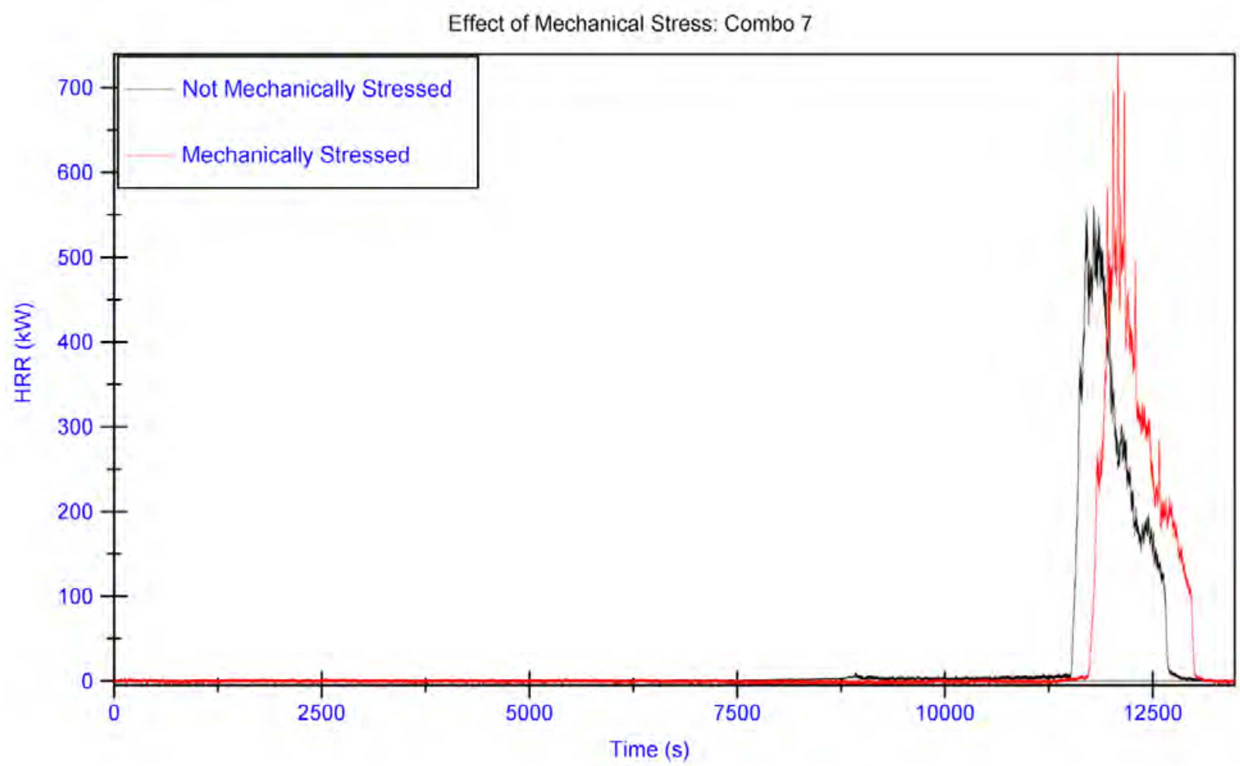

Figure 12. Heat Release Rate plot of mechanically stressed and non-stressed chair combo 7 in smoldering ignition testing.

Conclusion

Staff conducted a series of open-flame and smoldering-ignition tests on full-scale upholstered chairs at the CPSC flammability laboratory to evaluate the flammability performance when components with enhanced flammability properties, such as fire barriers, are used. The test series expanded on a previous test series where one fire barrier was used in the construction of some upholstered chairs. The chairs were constructed to be identical structurally to chairs tested previously by CPSC,[3,5] including a solid wood frame and PU that was requested to not be treated with FR chemicals[i]. The seat and back cushion were both wrapped in polyester batting. The chairs with fire barriers were wrapped between the polyester batting and the cover fabric on all six sides of the cushions, on the inside and outside of the arms, and behind the back cushion of the chair. Staff selected the five fire barriers based on barrier construction and input from the industry; the study was designed to evaluate a range of fire barrier construction types that are currently used in mattress constructions. Additional fire barrier types are available, but the study could not include every possible combination due to resource constraints. The general results of the open-flame and smoldering tests are detailed below.

Open Flame

A series of open-flame tests were conducted on a set of chairs with a combination of two cover fabrics, five fire barriers or no barrier, and with and without mechanical stressing. Each combination was repeated three times, except in cases where manufacturing errors resulted in more or less available specimens of certain combinations. In general, staff observed that the fire barriers used in this study reduced the severity of the fires and delayed the most intense burning, although to different degrees, depending on the specific barrier type. The mechanical stressing affected the flammability of the chairs in this study, generally causing open-flame chairs to burn slightly faster. Not much can be said about the relative performance among the fire barriers because the design of the experiment was to compare each fire barrier with "no barrier," rather than compare each fire barrier relative to one another. However, it is important to note that two of the fire barriers (FB2 and FB3) successfully prevented fires in at least one specimen beyond the initial ignition flame. FB3 only prevented a fire of one specimen, and FB2 prevented a fire in several specimens, but not in all tested specimens.

Smoldering

Staff conducted a series of smoldering ignition source flammability tests on a set of chairs that included a combination of two cover fabrics, five fire barriers or no barrier, and with and without mechanical stressing. Staff repeated each combination three times. Overall, it appears that the upholstery fabric contributed more to whether a chair transitioned to flaming than whether one of these fire barriers was present; however, these fire barriers tended to result in worse performance regarding the time to transition to flaming. All of the chairs covered with the heavier twill F2 fabric transitioned to flames. The mechanical stressing affected the smoldering flammability of the seat cushion. In general, the fires seemed to peak later for the stressed chairs than the non-stressed chairs.

Future Work

The scope of this work was fairly limited because staff looked at only one chair design with a convenience sample of five barriers that were not designed for upholstered furniture, but rather, were for use in mattresses subject to a mandatory standard with specific performance criteria. The upholstered furniture market is large, with differences in design, decorative features, components, constructions, and sizes, which together present a further complication in assessing the performance needed from a fire barrier used with upholstered furniture to address the hazard.

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[i] Seven percent melamine was measured in the foam used in this study.

This preliminary study, looking at several fire barriers in chair constructions, showed promise for open-flame ignition. Additional fire barriers should be investigated to determine how representative the five barriers included in this study are of the universe of barriers. Significant variations in chair construction, such as blown-in, loose-filled back cushions, and fire barriers placed in other locations in the of the chair (*i.e.,* outer back or dust cover locations), different chair geometries, different upholstery fabrics, etc., should be evaluated to see how the fire barriers perform in those configurations. Including a fire barrier designed to reduce smoldering ignitions should also be considered for any future work since it is historically difficult to create a barrier that works well for smoldering and open flame ignitions. Continued close coordination with the fire barrier industry is also needed so that the best performing fire barriers for these applications are included in future studies. Further work evaluating small scale tests for fire barriers is also needed to find cost effective ways to evaluate the performance of fire barriers.

Related Memoranda

Memorandum to Andrew Lock, from M. Dreyfus, Ph.D., Laboratory Sciences, "Chemical Analysis of Flame Retardant Barriers," January 2015.

Memorandum to Andrew Lock, from D. Miller, Ph.D., Epidemiology, "Analysis of Chair Open-Flame and Smoldering Data," January 2015.

[1] Memorandum to Dale R. Ray, Project Manager, Upholstered Furniture Project, from S. Mehta, Engineering Sciences, “Upholstered Furniture Full Scale Chair Tests-Open Flame Ignition Results and Analysis”, May 2012.
[2] Email from David Miller, CPSC, Directorate for Epidemiology, “Full-Scale Testing Plan,” June, 2013.
[3] Memorandum to Dale Ray, Project Manager, Upholstered Furniture Project, from W.Tao, G. Sushinsky, B. Bhooshan, and David Cobb, Laboratory Sciences, “Cleaning and Wear Effects on Upholstery Fabric Flammability,” May 2000.
[4] BS-5852, Methods of Test for Assessment of the Ignitability of Upholstered Seating by Smoldering and Flaming Ignition Sources. 1990.
[5] Memorandum to Dale Ray, Project Manager, Upholstered Furniture Project, from L. Fansler, Laboratory Sciences, “Summary of Data Collected During Smoldering Chair Tests,” July 2012.
[6] Email from Matthew Dreyfus, CPSC Directorate for Laboratory Sciences, “Barrier Materials”, September 2014.

Memorandum

Appendix A

Test Protocol – Full-Scale Chair Evaluations

Test Facilities and Instrumentation Setup

This section contains the necessary information to construct the testing environment; *i.e*., type and location of instrumentation and room design. During testing, the PIs can change the test setup conditions; however, it is the initial assumption that the information contained in this section will not be a variable in this testing study.

- Tests are to be conducted in the open calorimetry lab located in room 123A at the CPSC National Product Testing and Evaluation Center (NPTEC), instrumented as detailed in this section. The burn room conditions will be maintained between 15 and 27 °C, with a relative humidity less than 75 percent. To achieve these conditions in the burn room, there may be a delay in starting the next test while the room recovers after it has been exhausted of smoke and heat from the prior test.
- The hood flow rate will initially be set at a minimum of 1,500 CFM and adjusted as necessary to accommodate smoke and fire development.
- Heat flux gauges will be placed near the chair. Exact placement will be determined on the first day of testing.
- Heat Release Rate (HRR) will be measured by oxygen consumption calorimetry.
- Two video cameras will be used to record each test. The cameras will be placed so the front of the chair is captured by one, and the right side of the chair is captured by the other.
- One thermal imaging camera will be used to record the thermal changes of the surface of the chair. The camera will be directed toward the front of the chair.
- The ignition source and fuel are to be provided by the CPSC.
- The chair will be placed in the center of the 10 ft. x 10 ft. canopy hood.

Sample Preparation

The upholstered chair specimens, sheeting squares, and cigarettes are required to be conditioned at a temperature of 20 ± 3 °C (70° + 5° F) and a relative humidity of 50 % ± 5 % for 48 hours. The test will start within 10 minutes of removing the specimens from the conditioning area.
The upholstered chair samples will be removed from any packaging before conditioning.

Test Procedure

The details of the testing protocol are in Appendix D1 of this document and include the following factors:

- Ignition sequence (smoldering and open-flame ignition)
- Testing sequence
- Duration and termination parameters
- Data collection specifics, such as beginning and ending measurements and sampling frequency.

Data Collection

The data collected will include:

- Heat release rate vs. time. Within this measurement is data collection for CO, CO_2, and O_2 in the fire effluent
- Heat flux meter data
- Peak heat release rate
- Time to peak heat release
- Total energy release, as needed.

Test Setup

Smoldering and open-flame ignition testing of upholstered furniture will be conducted under the open calorimetry hood in room 123A, instrumented as follows:

- Heat flux facing the chair back, front and sides;
- Heat release rate;
- At least two video cameras;
- At least one thermal imaging camera.

Test Protocol

Note: Have a means for extinguishing the sample. The exact chemical content of the FR foams is not known, so prepare appropriately.

1. Pretest–
    - Record the initial total mass of the sample.
    - Place sample chair in the center under the 10 ft. x 10 ft. canopy hood.
    - Ensure Test ID is visible on placard and within the viewing frame of the video cameras.
    - Ensure LED timer is visible and within the viewing frame of the video cameras.
    - Record temperature and RH% inside 123A.
    - Clear all personnel from under the hood.
    - Turn on data acquisition system (including all sensors). Ensure appropriate readings. Begin background measurements.
    - The data should be taken in 1-second intervals.
    - Start all video and IR cameras. Ensure that chair and LED timer are clearly visible and not cropped in any camera.
    - Photograph the sample in place.
2. Ignition: Choose either open-flame or smoldering ignition source according to test plan.
    - Open-Flame Ignition: Lighting the igniter flame–
        i. Away from the chair, open the butane tank slowly, and light the end of the burner tube. Adjust the gas flow to the appropriate rate to achieve a 240 mm flame. Allow the flame to stabilize for at least 2 minutes.
        ii. Apply the flame for 70 ± 1 second at the center of seat/back crevice of the sample, using the bent burner tube; then immediately remove ignition source from the sample.
        iii. This is the test "Start Time." For open-flame ignition, note in data acquisition system, and start large LED timer upon removal of the ignition flame.
    - Smoldering Ignition: Placing cigarettes:
        i. Light cigarettes so that no more than 4 mm (0.16 inch) is burned away.
        ii. Place one cigarette in each test location.

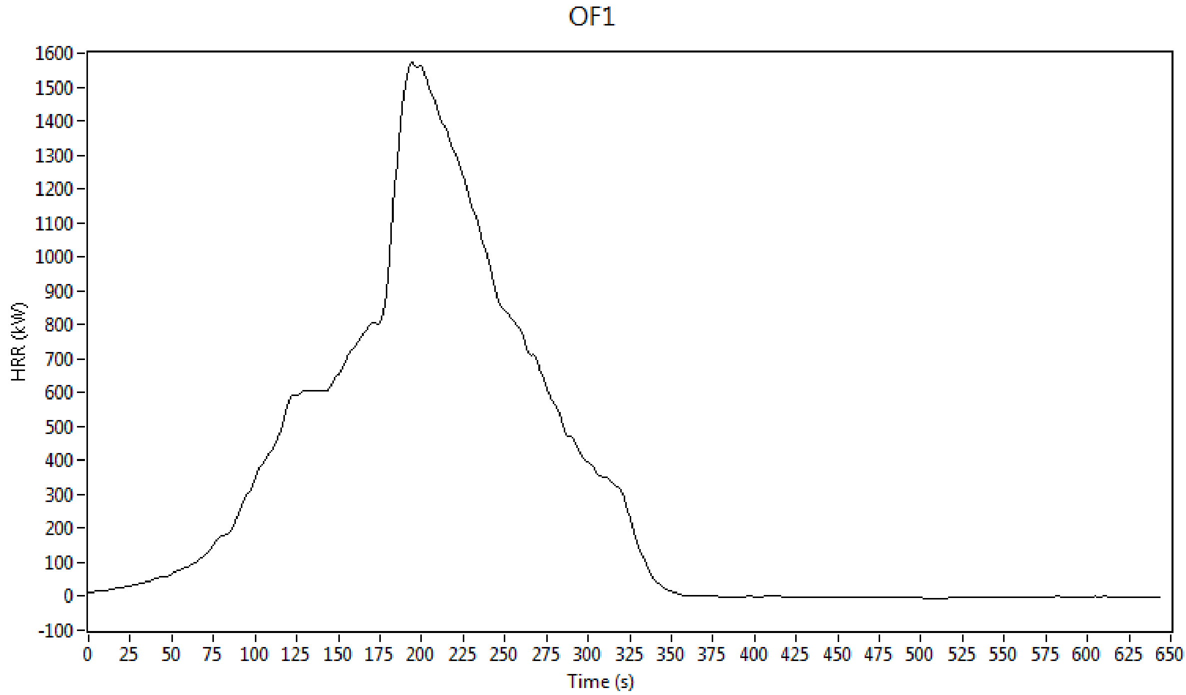
iii. Immediately after placement of the lit cigarette, cover cigarettes with a cotton sheeting square, and run one finger over the sheet along the length of the covered cigarette to ensure good contact between the sheeting square and the burning cigarette.

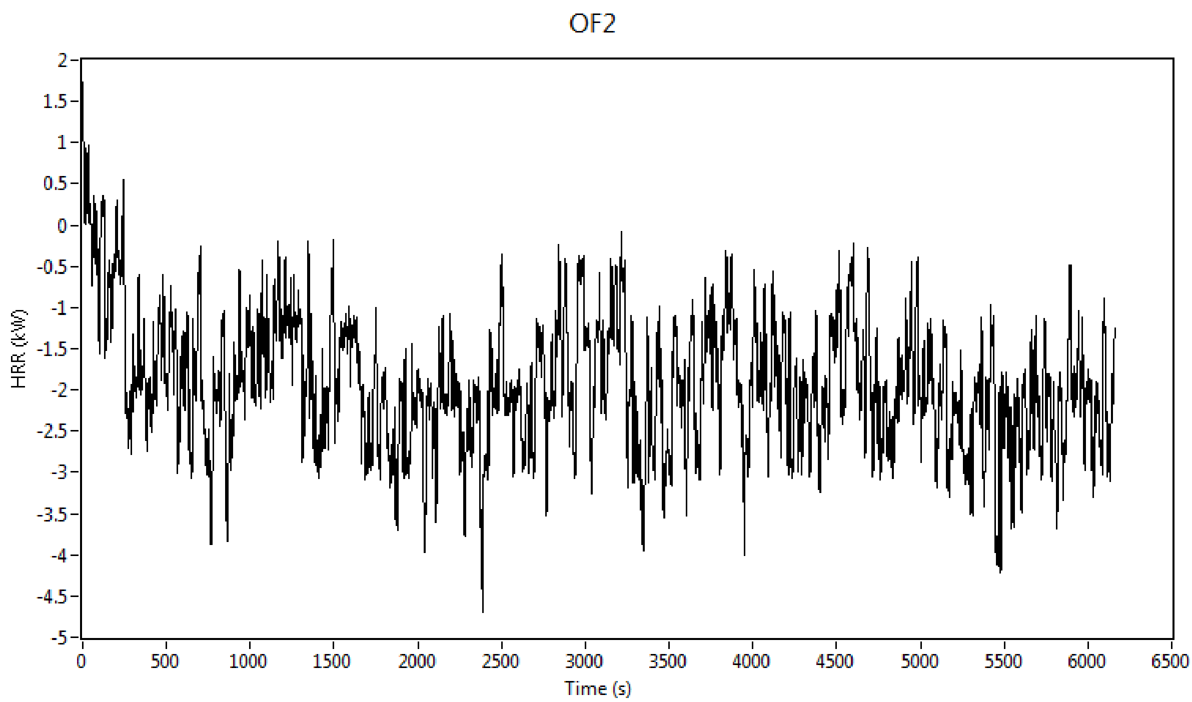
iv. “Start Time”: For smoldering ignition, begins as soon as the last cigarette has been placed. Note in data acquisition system, and start large LED timer.

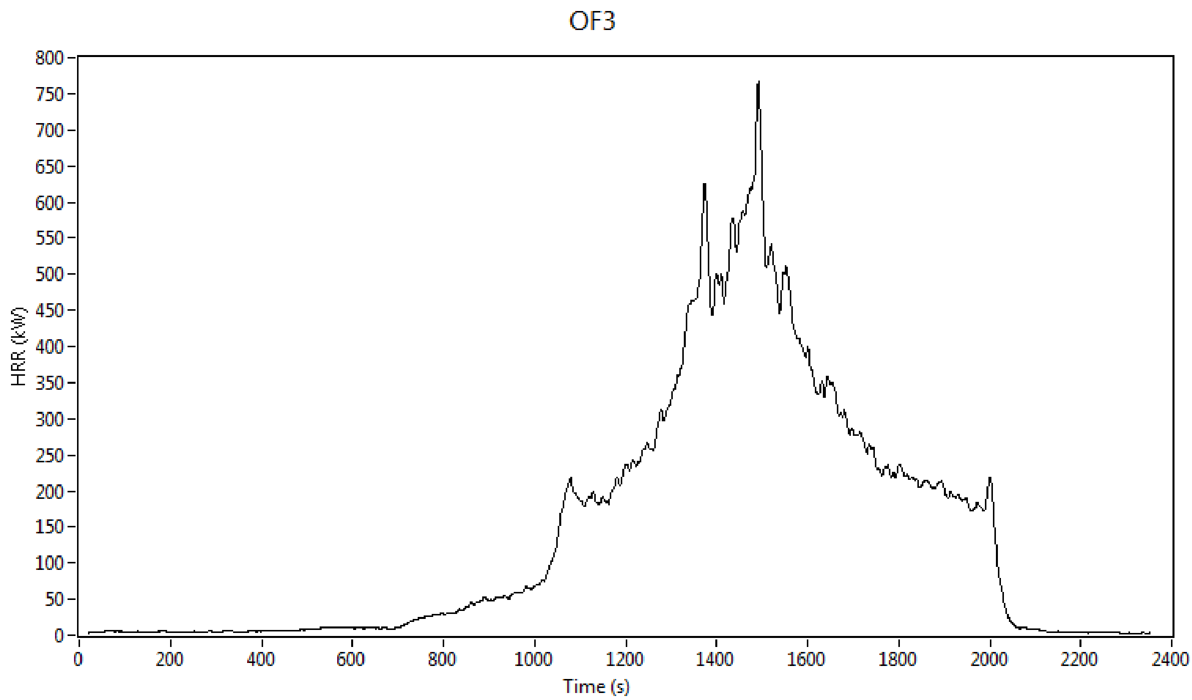
3. Performing the test–
   - Make observations and notes throughout the test.
   - Periodically check on measurement readings.
   - Once peak HRR has been observed, the operator will decide how much longer to continue test. Additionally, there may be multiple peaks in HRR; the PI will determine the length of test (Note: If the instantaneous HRR of a sample under test is high and the fire is observed to be growing, the test may be terminated for safety reasons.)
   - Observe the sample combustion behavior for X minutes after a Peak HRR has been reached. (Note: If the instantaneous HRR of a sample under test is X, and the fire is observed to be growing, the test may be terminated for safety reasons. To be determined by the PIs and safety officer.)

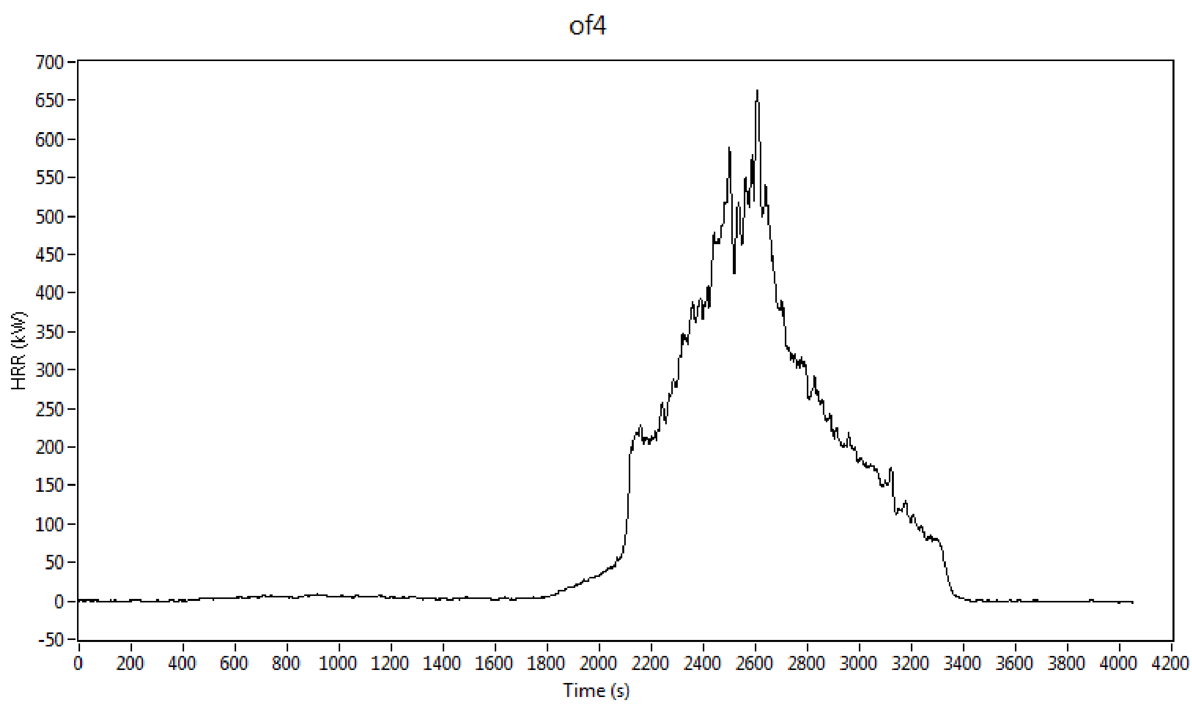
1. Post-Test–
   - Stop all measurements and video cameras.
   - Collect “drift measurements.”

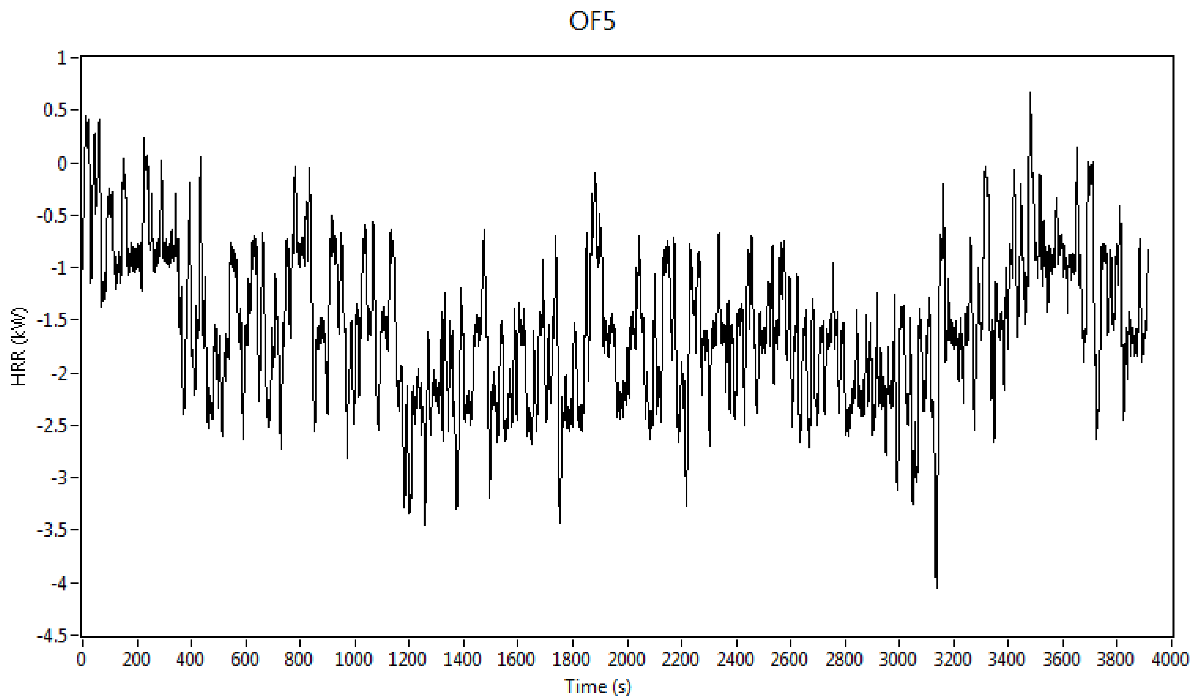
Appendix B
HRR Plots for Open-Flame Tests

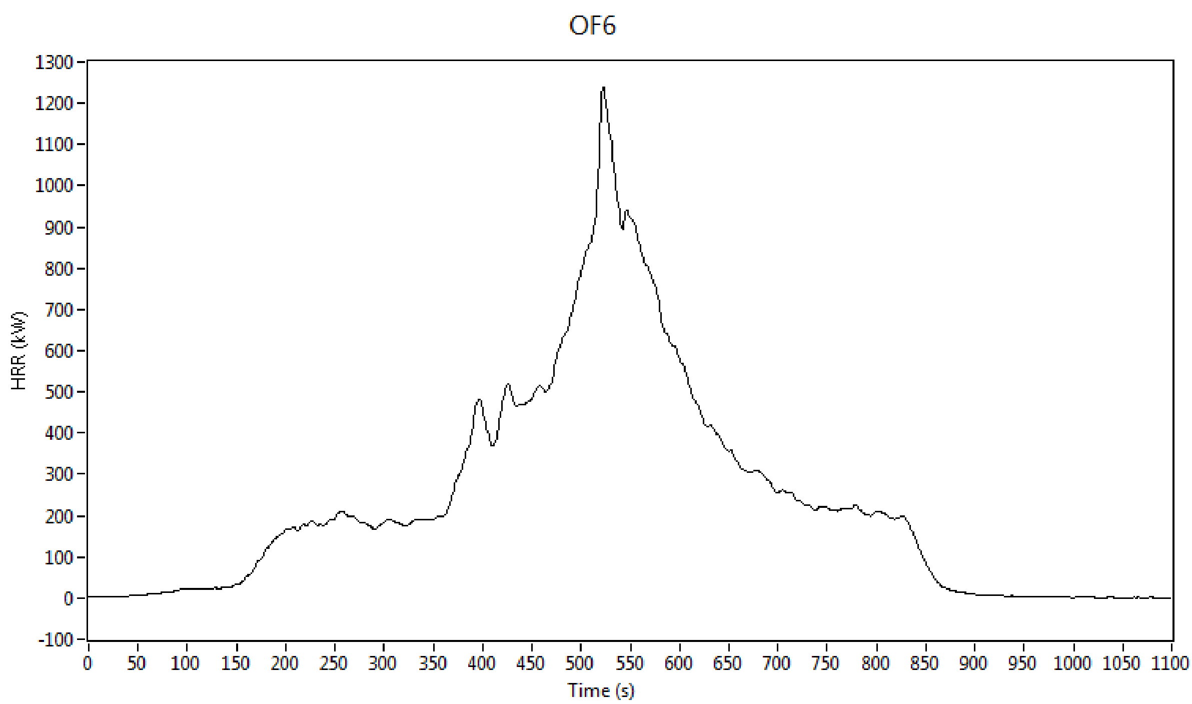


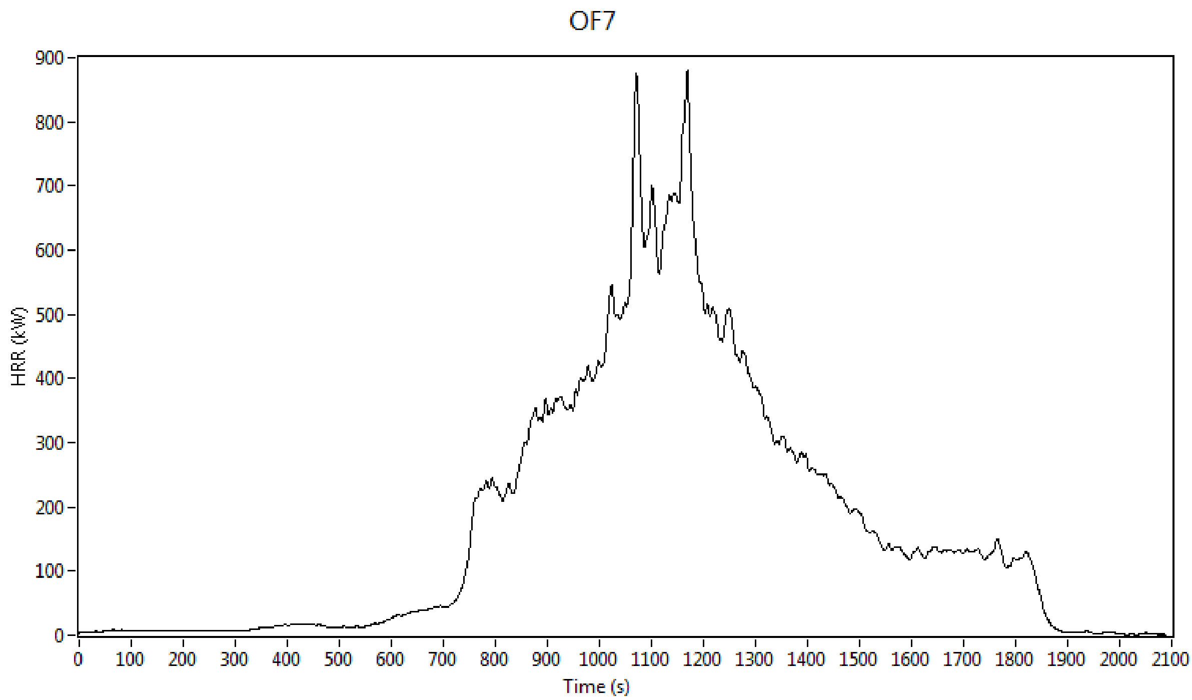


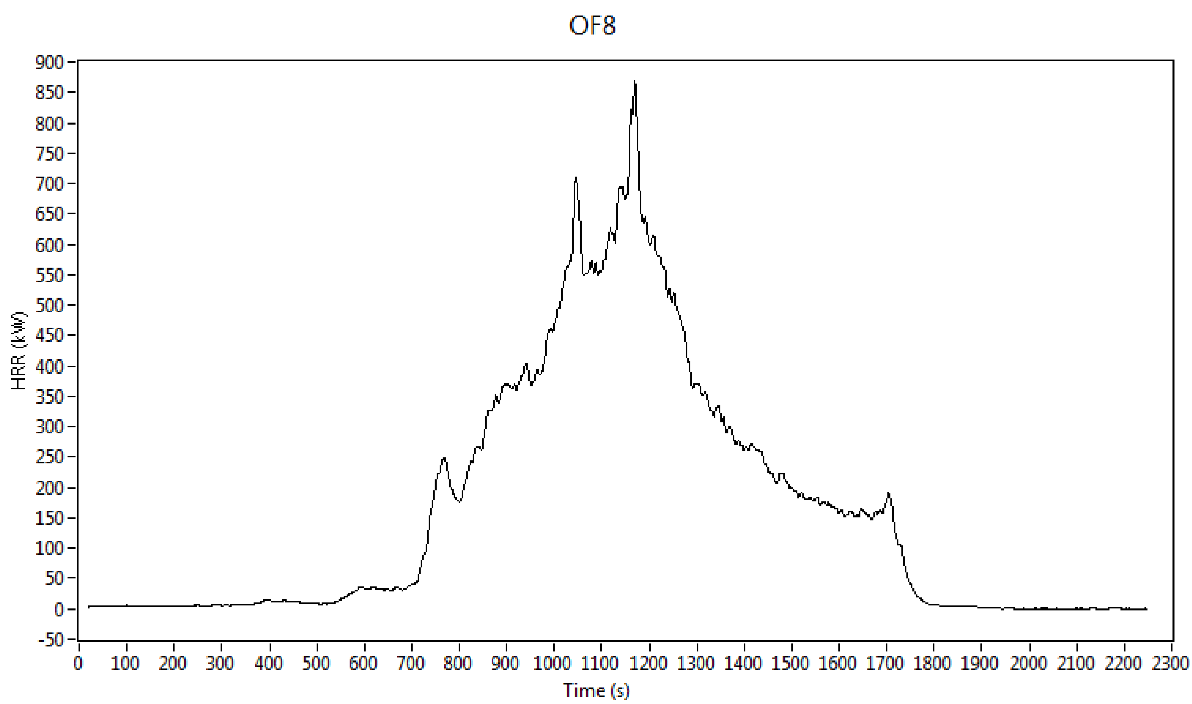

OF3
HRR (kW)
Time (s)
800
750
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400

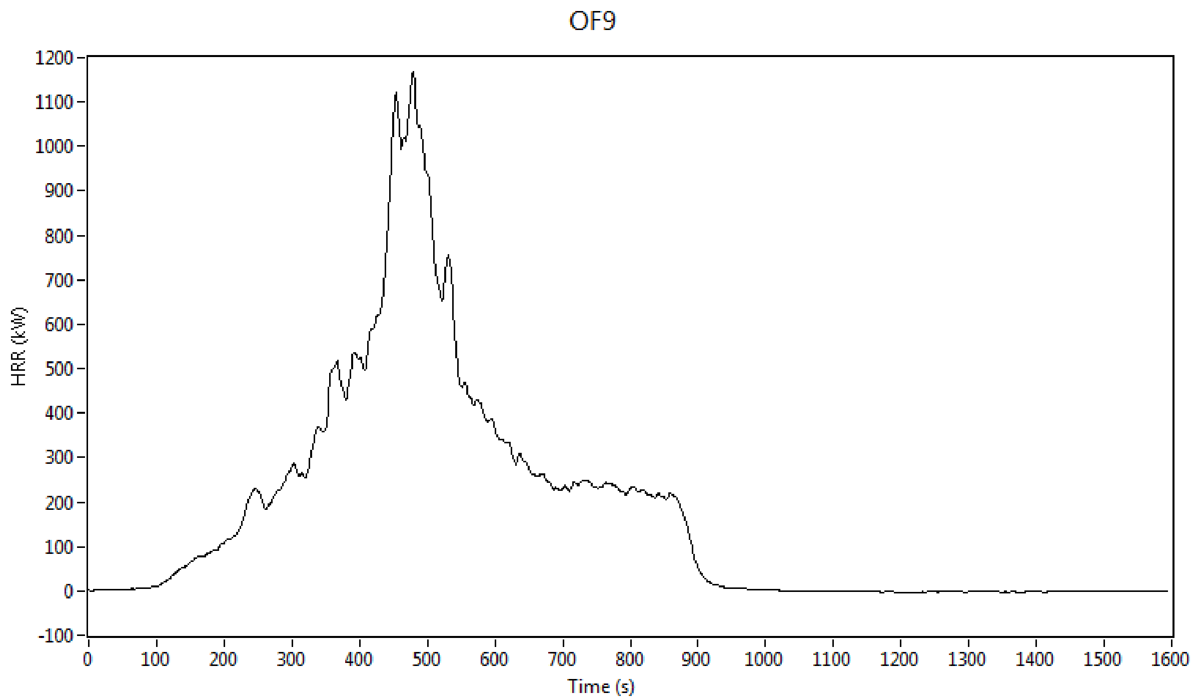

of4
HRR (kW)
Time (s)
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
-50
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
3200
3400
3600
3800
4000
4200

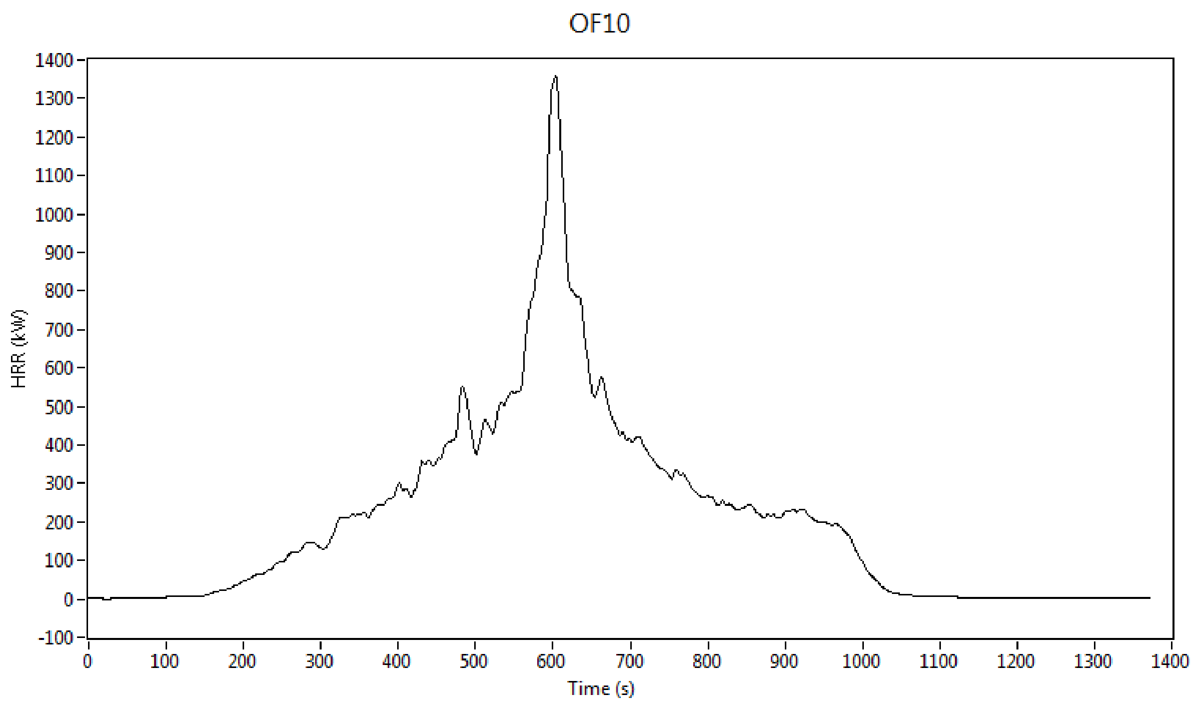

OF5
HRR (kW)
Time (s)
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
3200
3400
3600
3800
4000

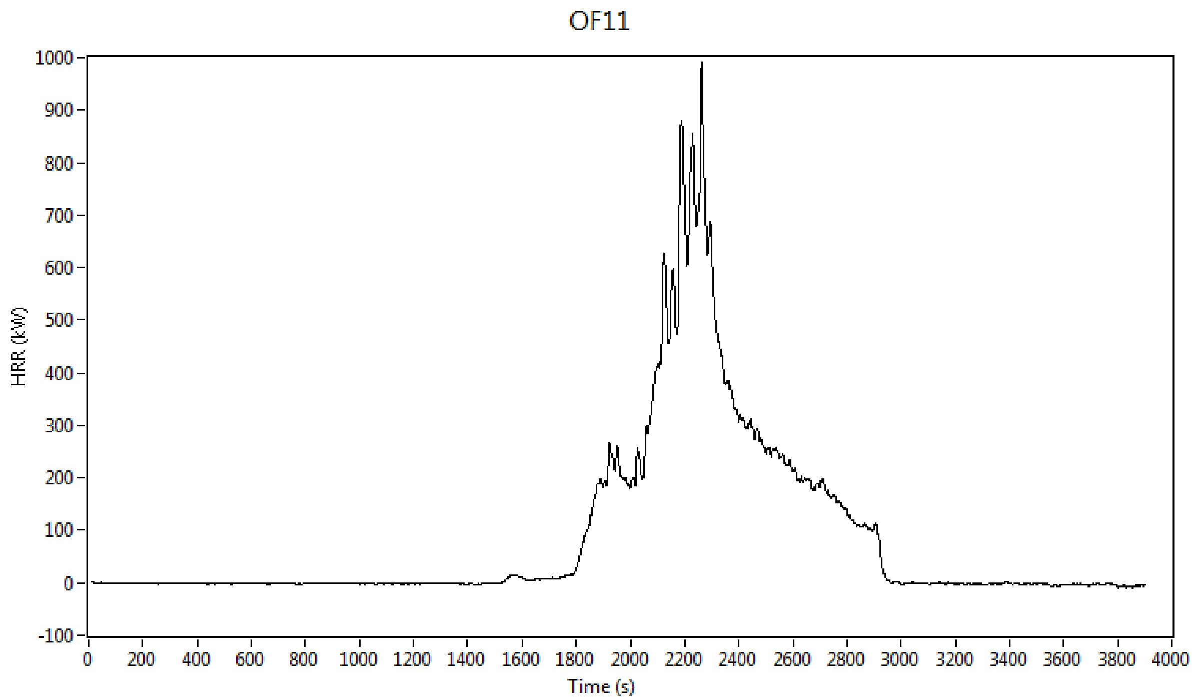

OF6
HRR (kW)
Time (s)
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
-100
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
800
850
900
950
1000
1050
1100

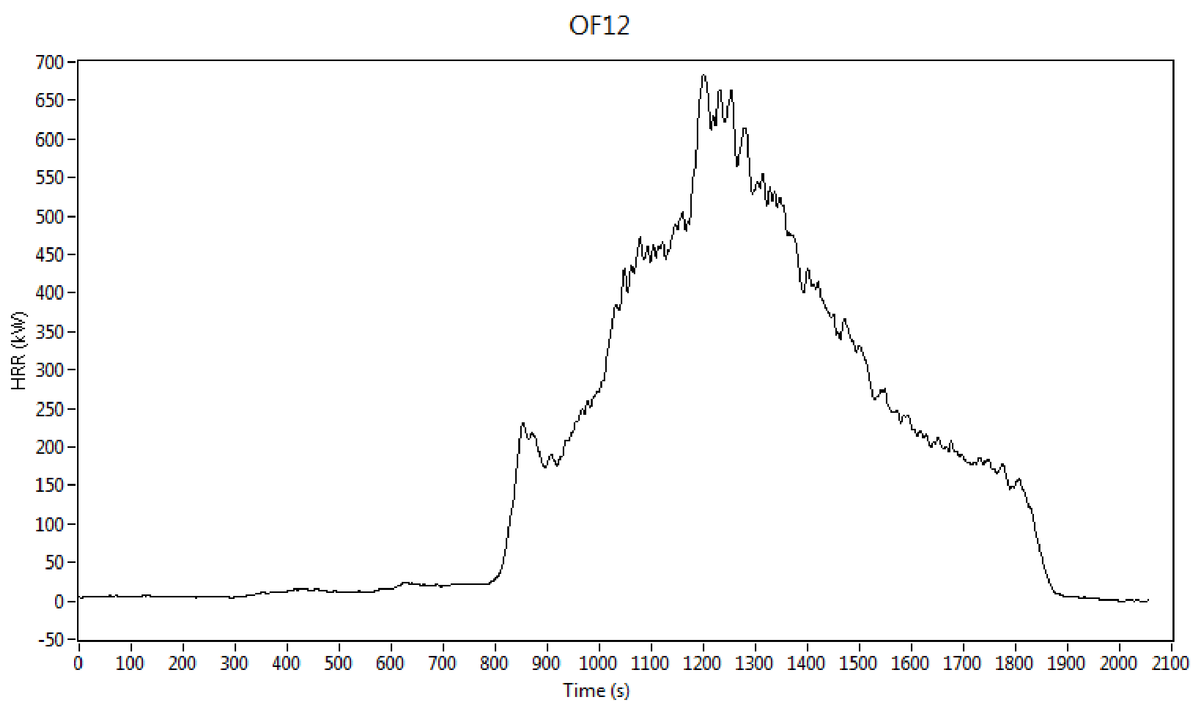

OF7
HRR (kW)
900
800
700
600
500
400
300
200
100
0
0 100 200 300 400 500 600 700 800 900 1000 1100 1200 1300 1400 1500 1600 1700 1800 1900 2000 2100
Time (s)

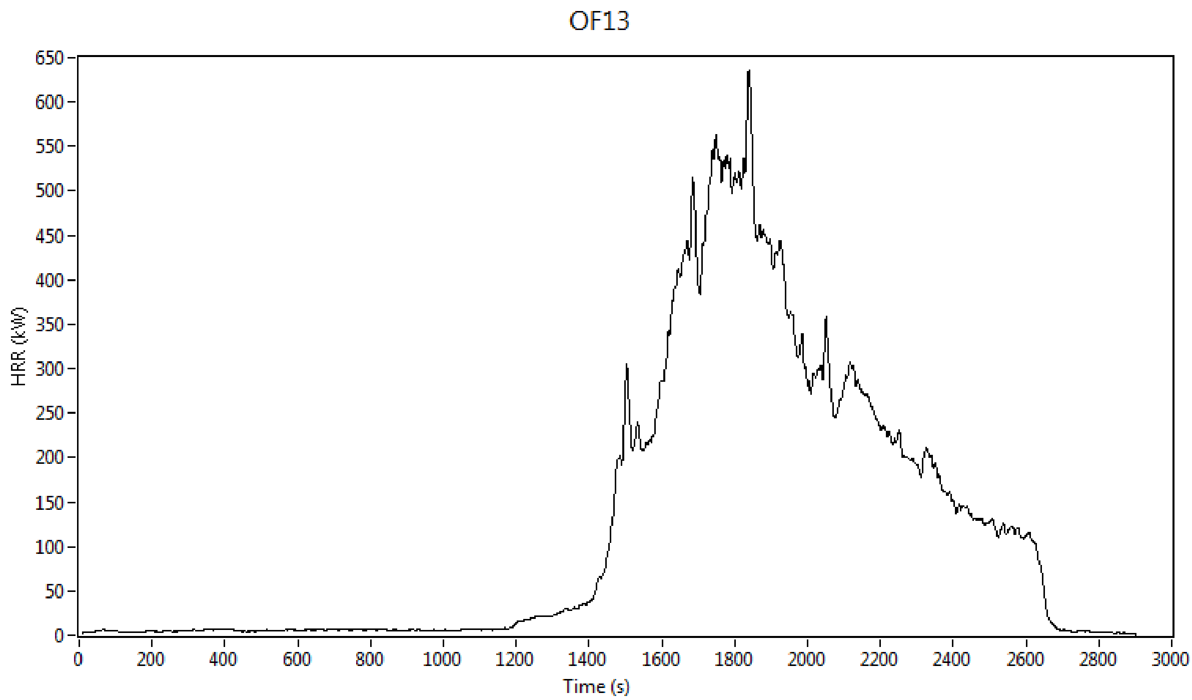

OF8
HRR (kW)
900
850
800
750
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
-50
0 100 200 300 400 500 600 700 800 900 1000 1100 1200 1300 1400 1500 1600 1700 1800 1900 2000 2100 2200 2300
Time (s)

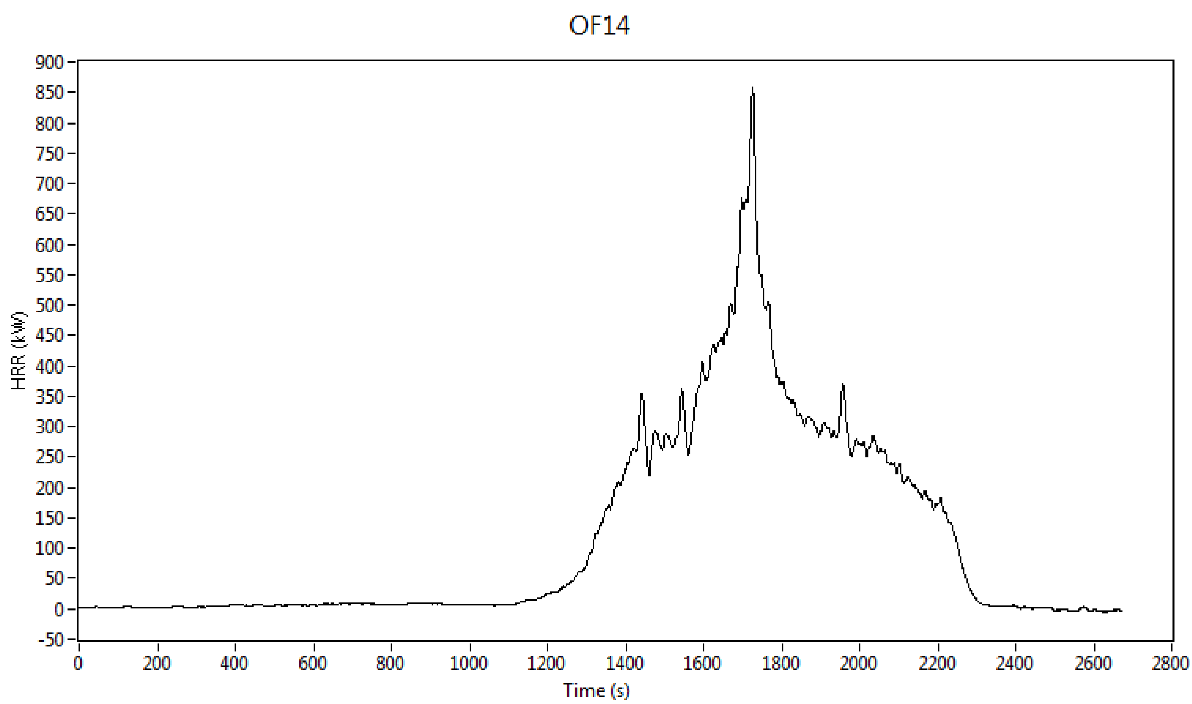

OF9
HRR (kW)
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
-100
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
Time (s)

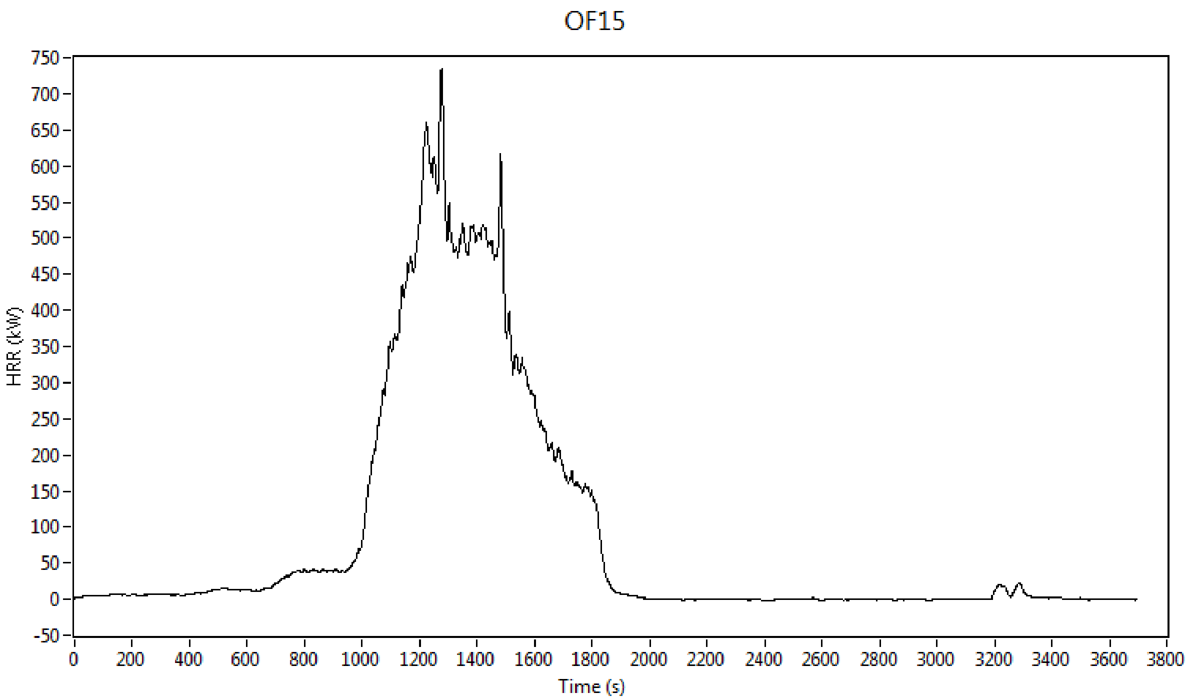

OF10
HRR (kW)
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
-100
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
Time (s)

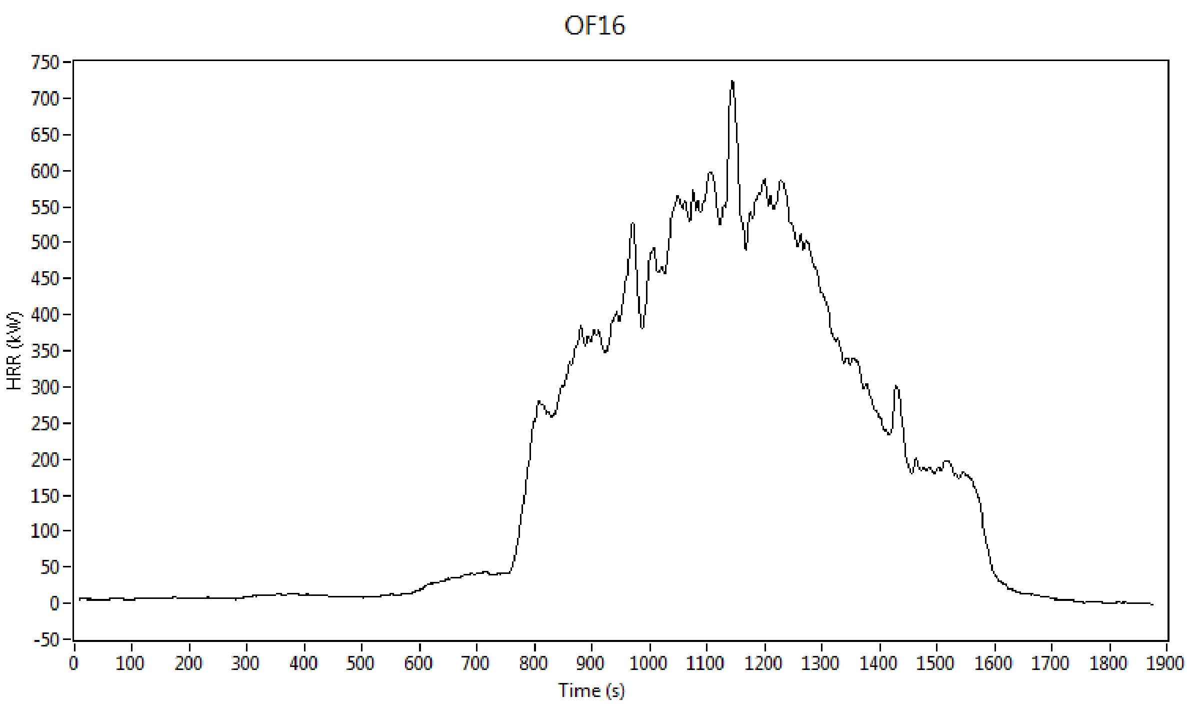

OF11
HRR (kW)
1000
900
800
700
600
500
400
300
200
100
0
-100
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
3200
3400
3600
3800
4000
Time (s)

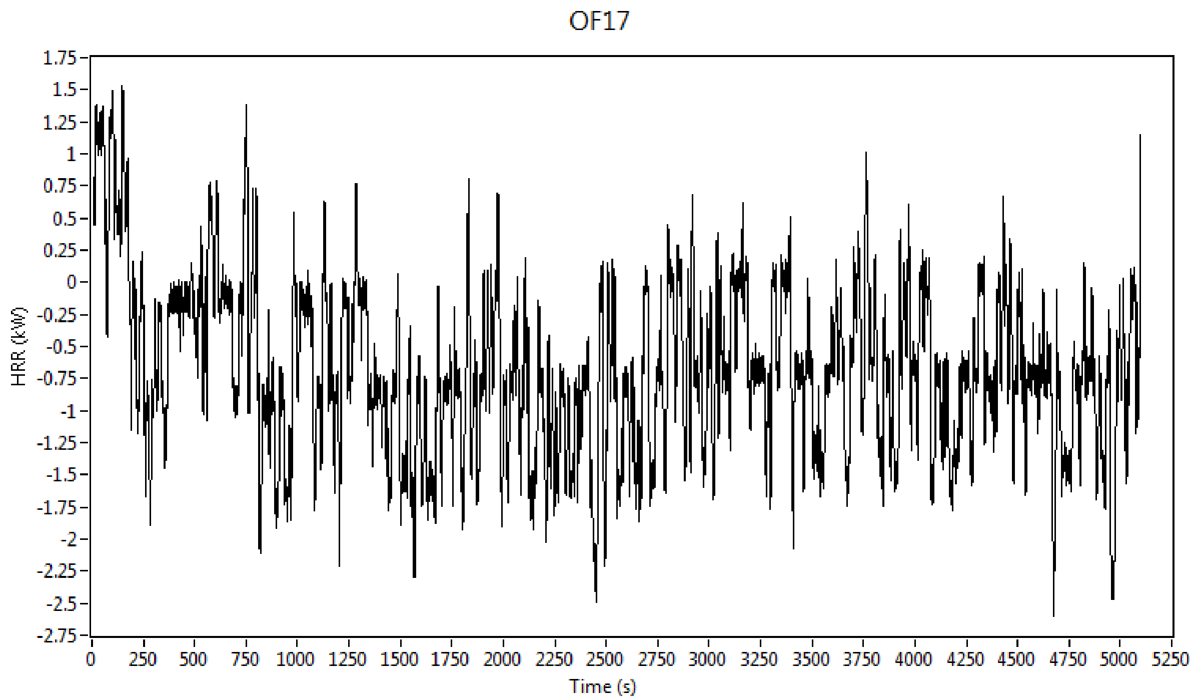

OF12
HRR (kW)
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
-50
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
2100
Time (s)

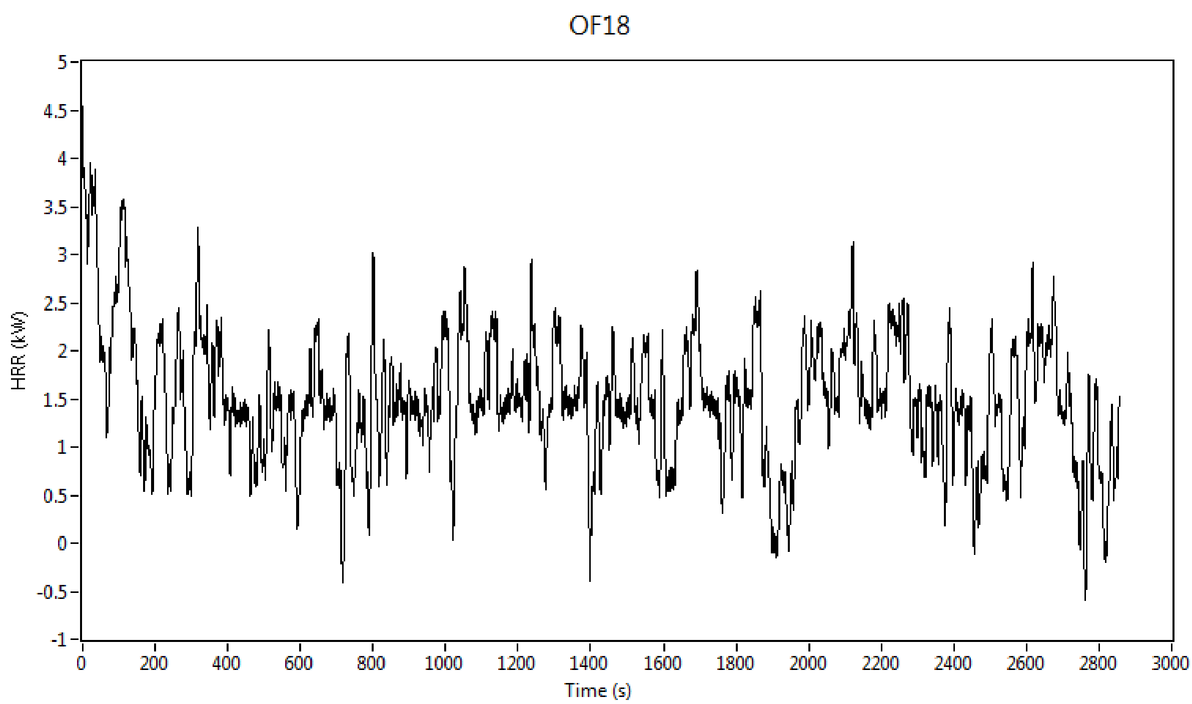

OF13
HRR (kW)
650
600
550
500
450
400
350
300
250
200
150
100
50
0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
Time (s)


OF14
HRR (kW)
900
850
800
750
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
-50
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
Time (s)

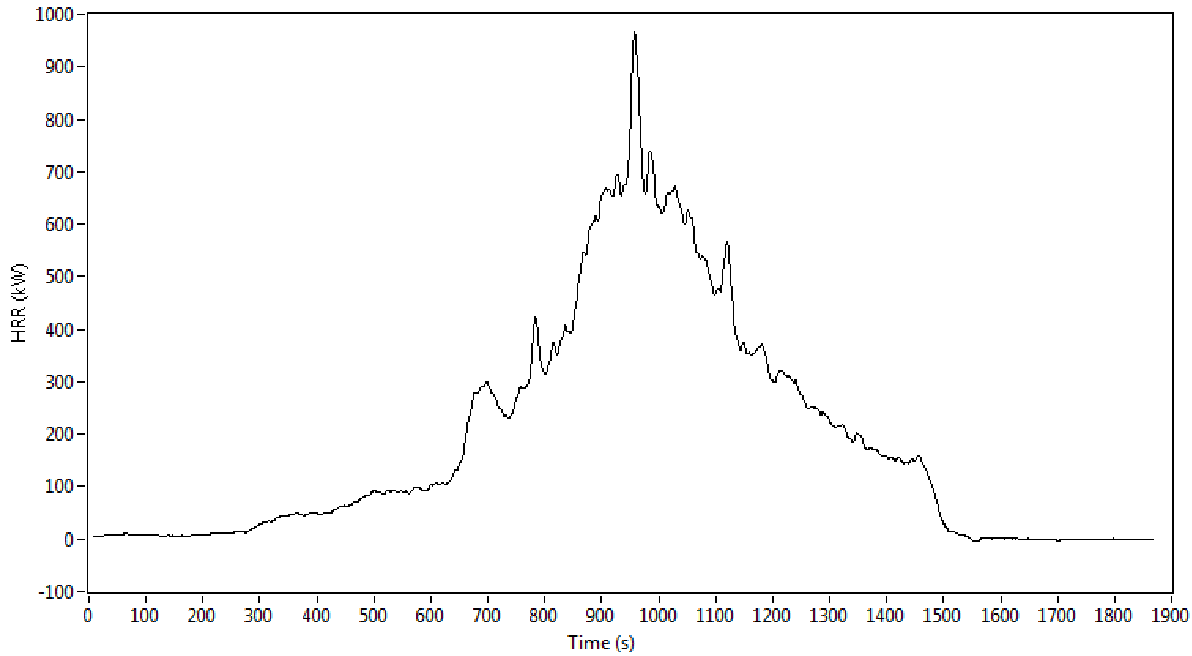

OF15
HRR (kW)
750
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
-50
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
3200
3400
3600
3800
Time (s)


OF16
HRR (kW)
750
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
-50
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
Time (s)


OF17
HRR (kW)
1.75
1.5
1.25
1
0.75
0.5
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
-1.75
-2
-2.25
-2.5
-2.75
0
250
500
750
1000
1250
1500
1750
2000
2250
2500
2750
3000
3250
3500
3750
4000
4250
4500
4750
5000
5250
Time (s)

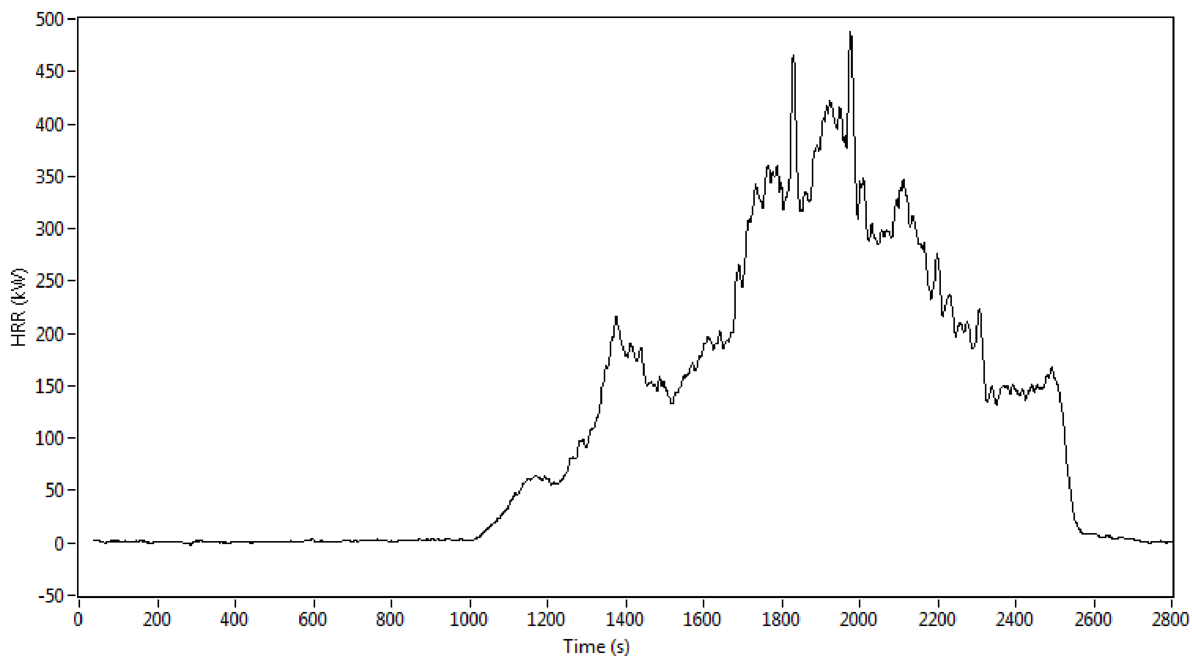

OF18
HRR (kW)
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-1
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
Time (s)

OF19



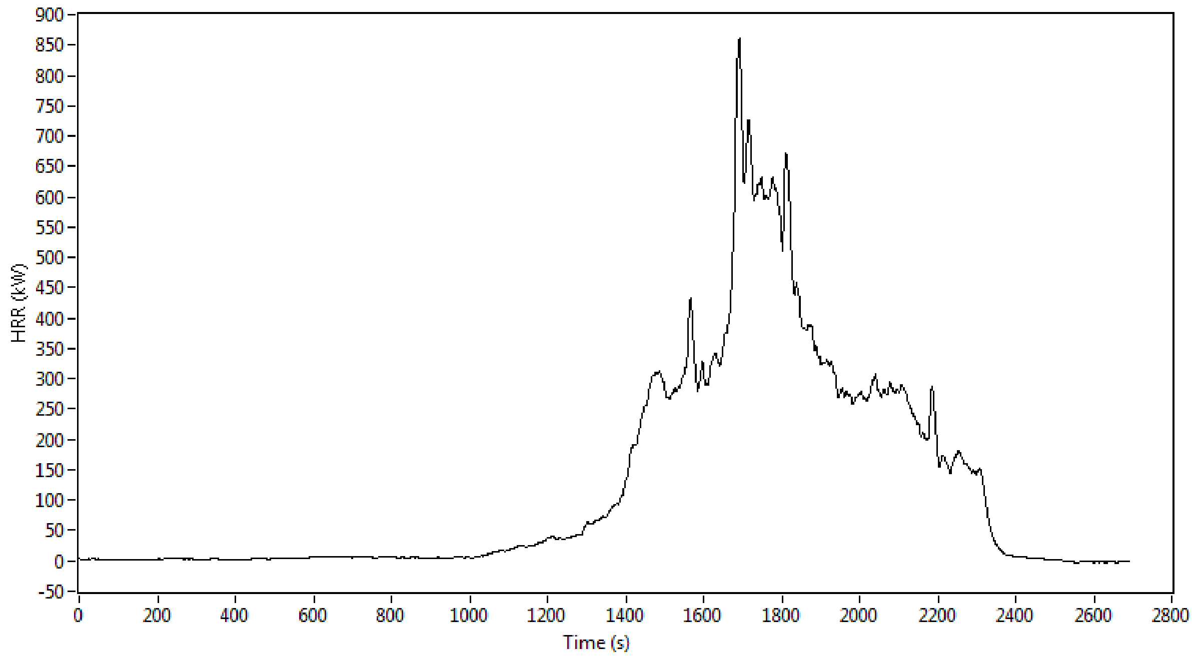
HRR (kW)
1000
900
800
700
600
500
400
300
200
100
0
-100
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
Time (s)

OF20

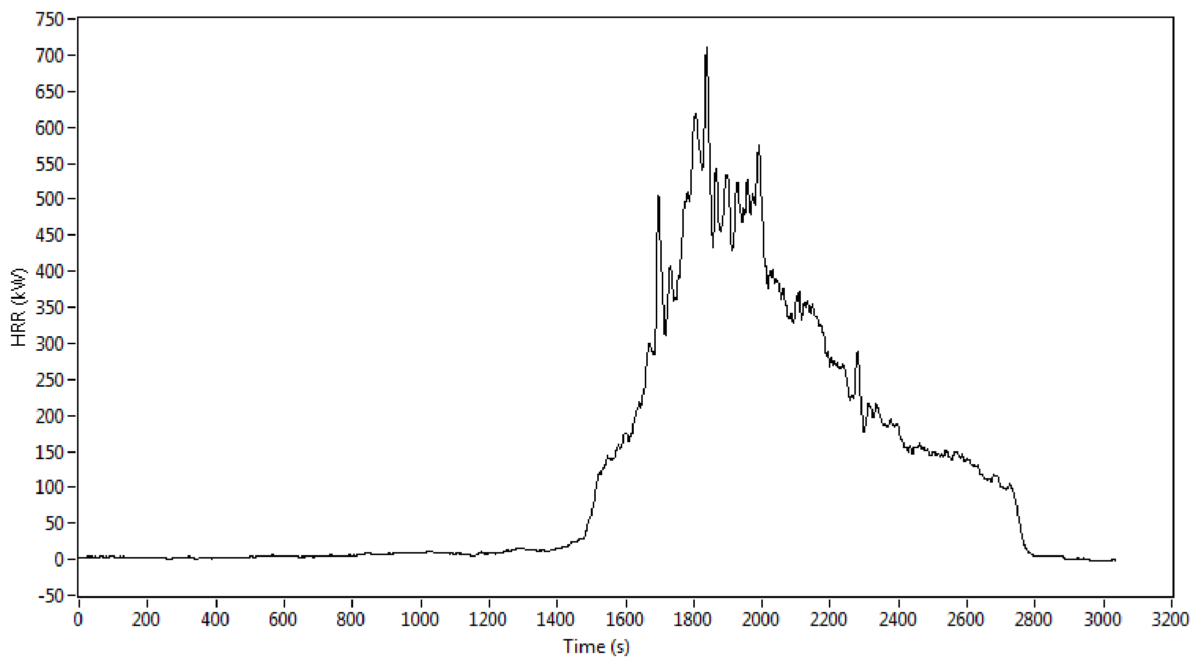


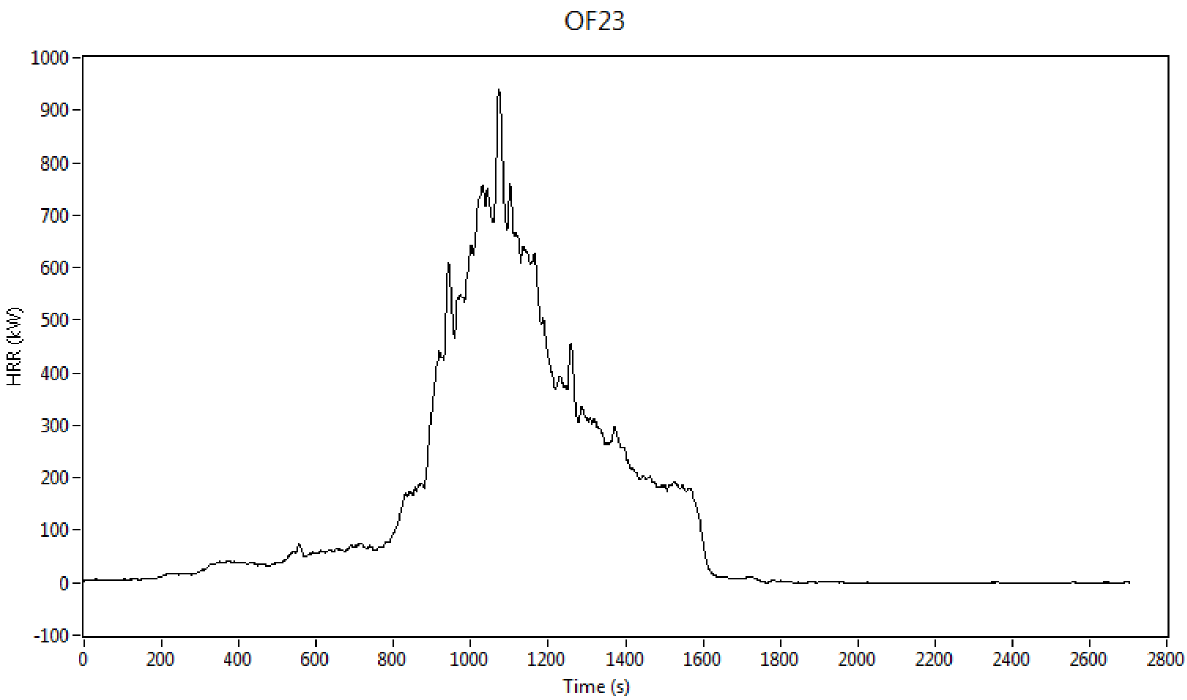
HRR (kW)
500
450
400
350
300
250
200
150
100
50
0
-50
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
Time (s)

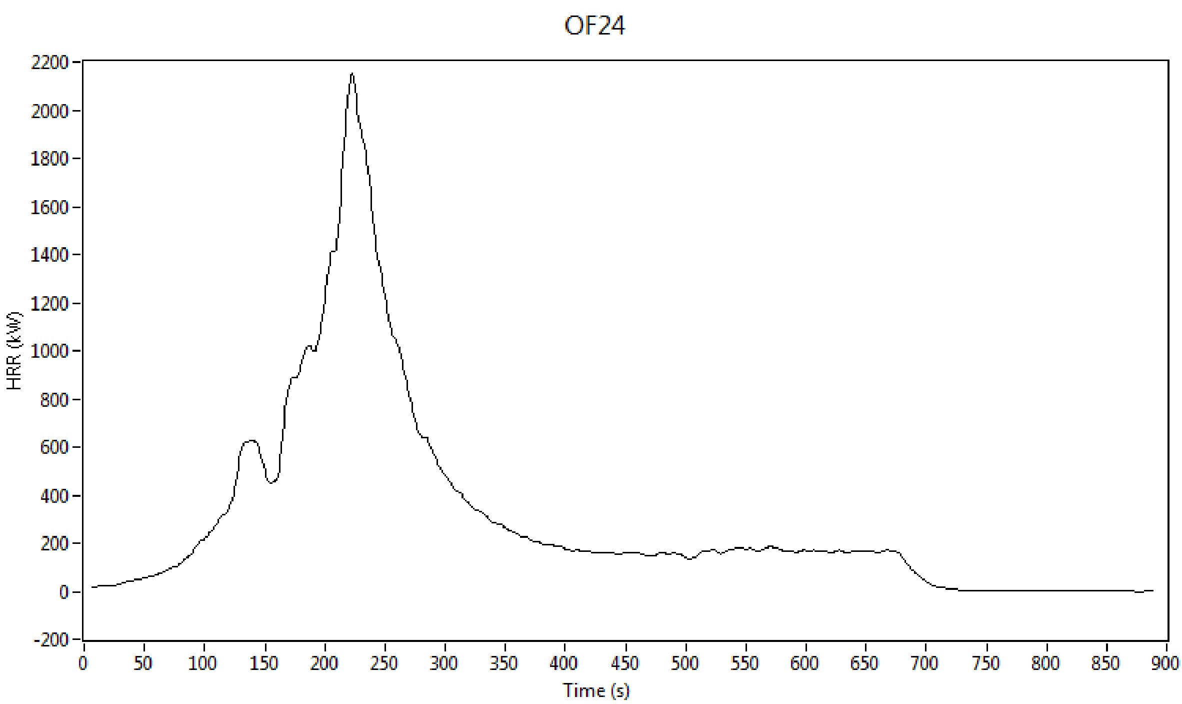
OF21

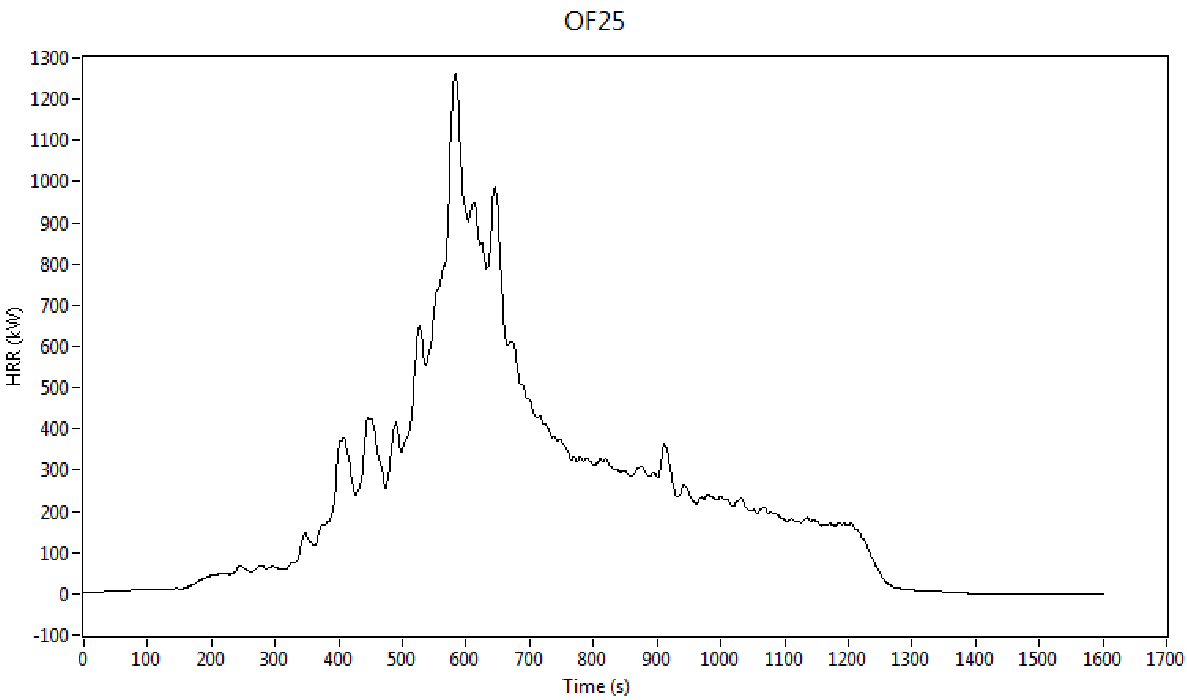

HRR (kW)
900
850
800
750
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
-50
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
Time (s)

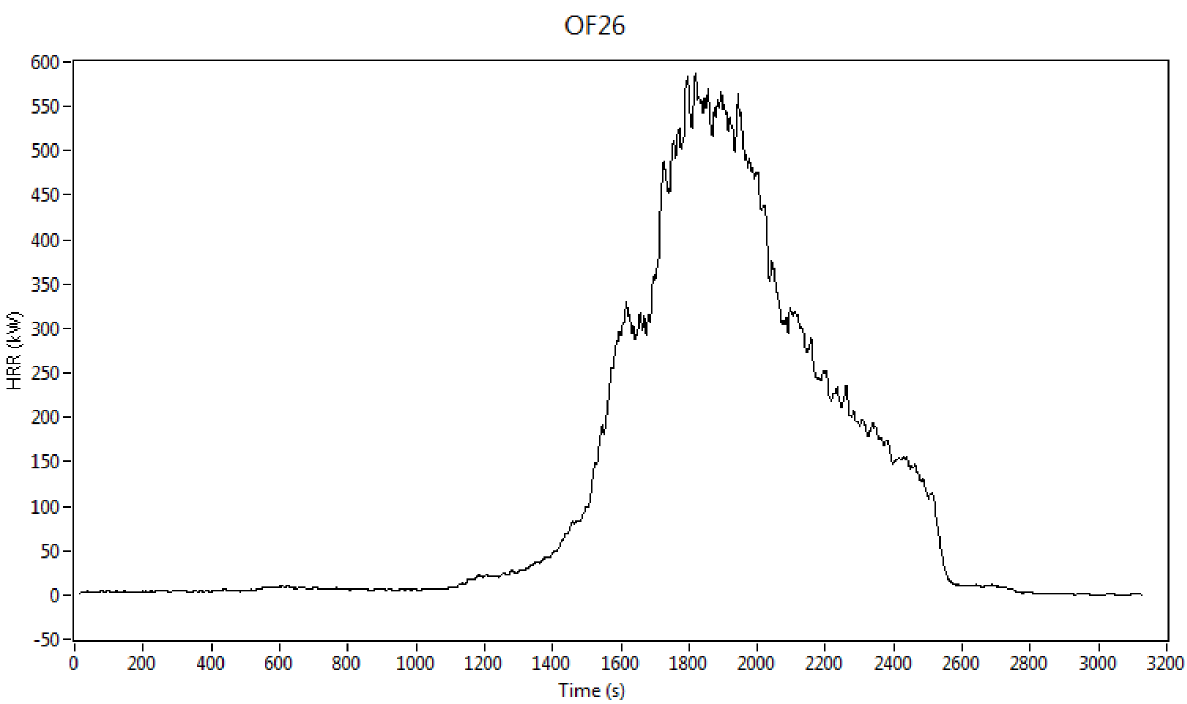
OF22

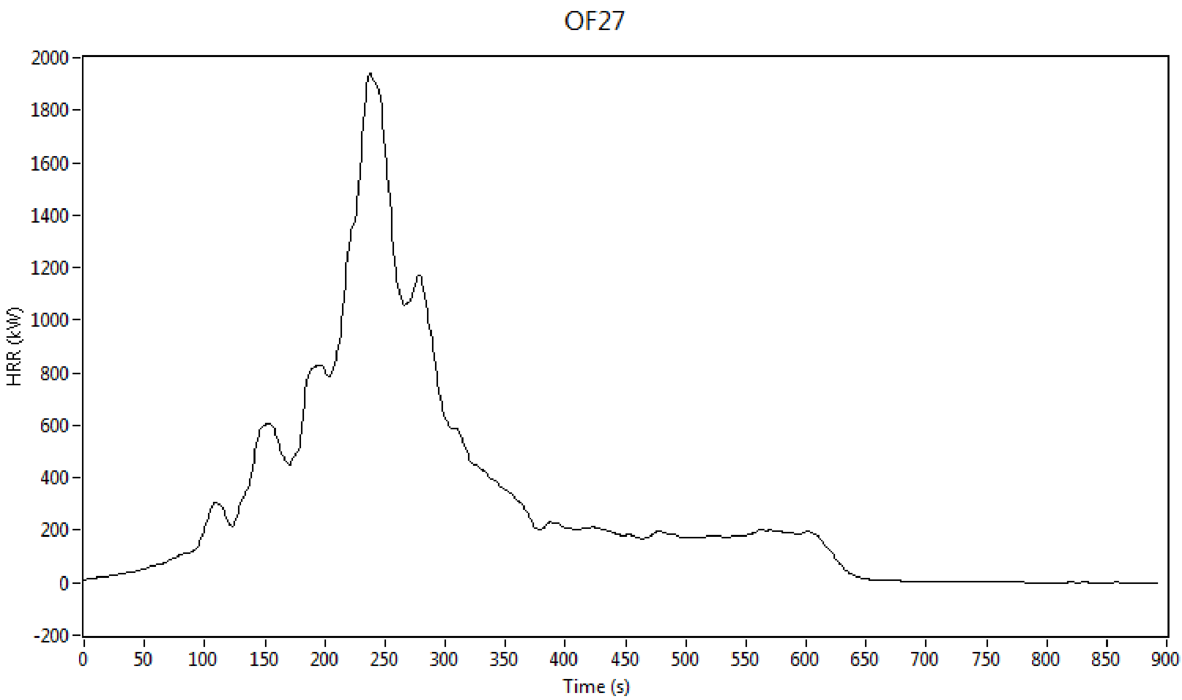

HRR (kW)
750
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
-50
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
3200
Time (s)

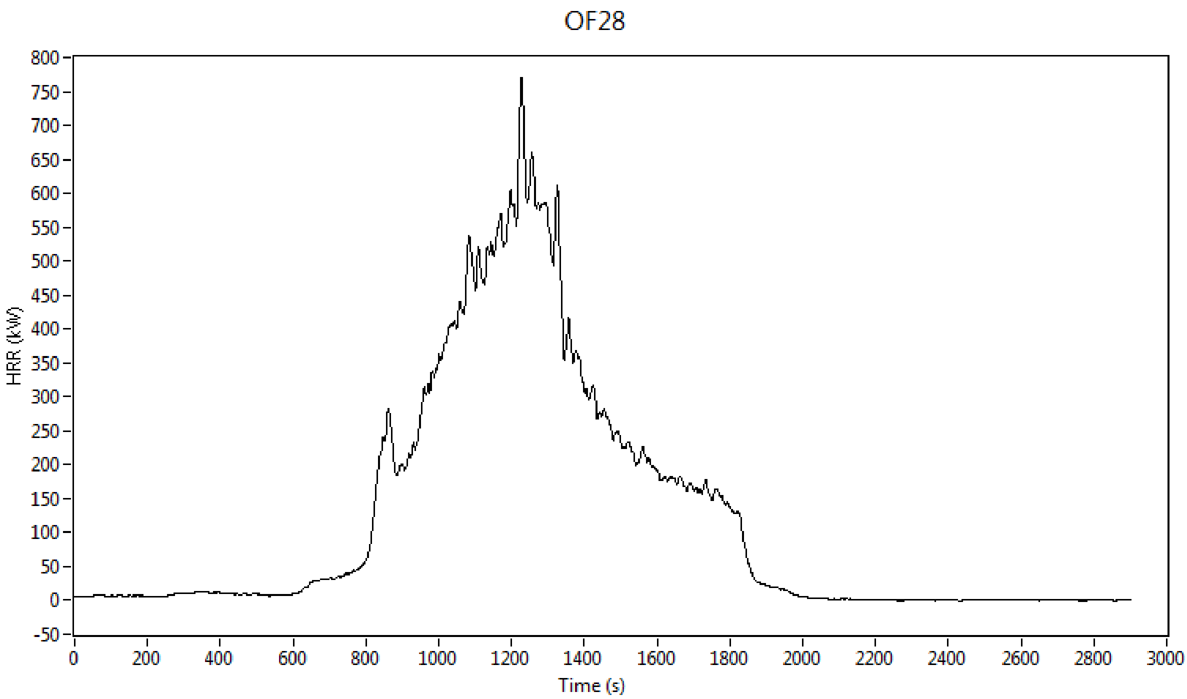

OF23
HRR (kW)
Time (s)

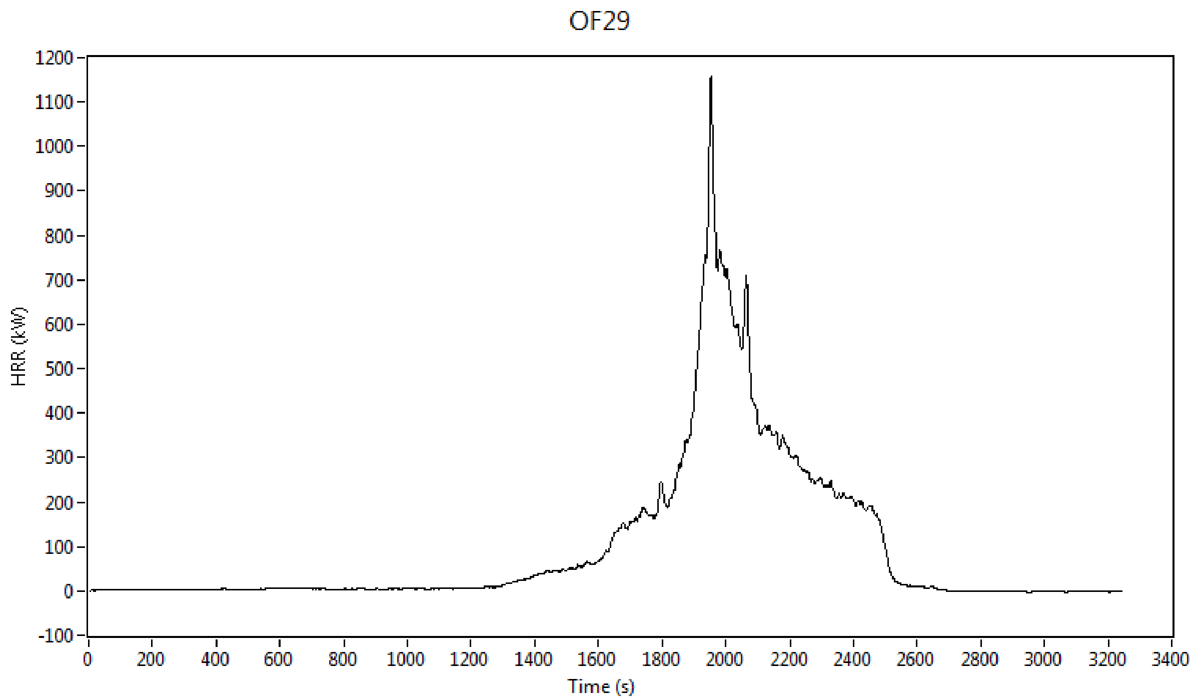

OF24
HRR (kW)
Time (s)

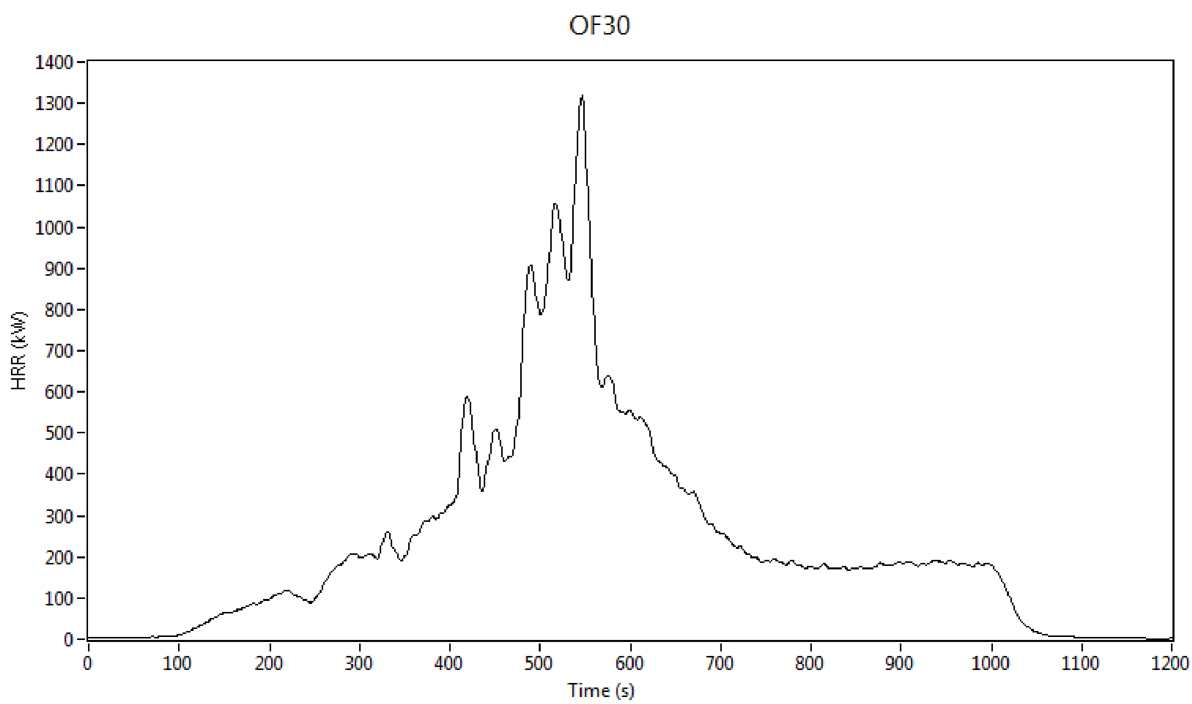

OF25
HRR (kW)
Time (s)
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
-100
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700

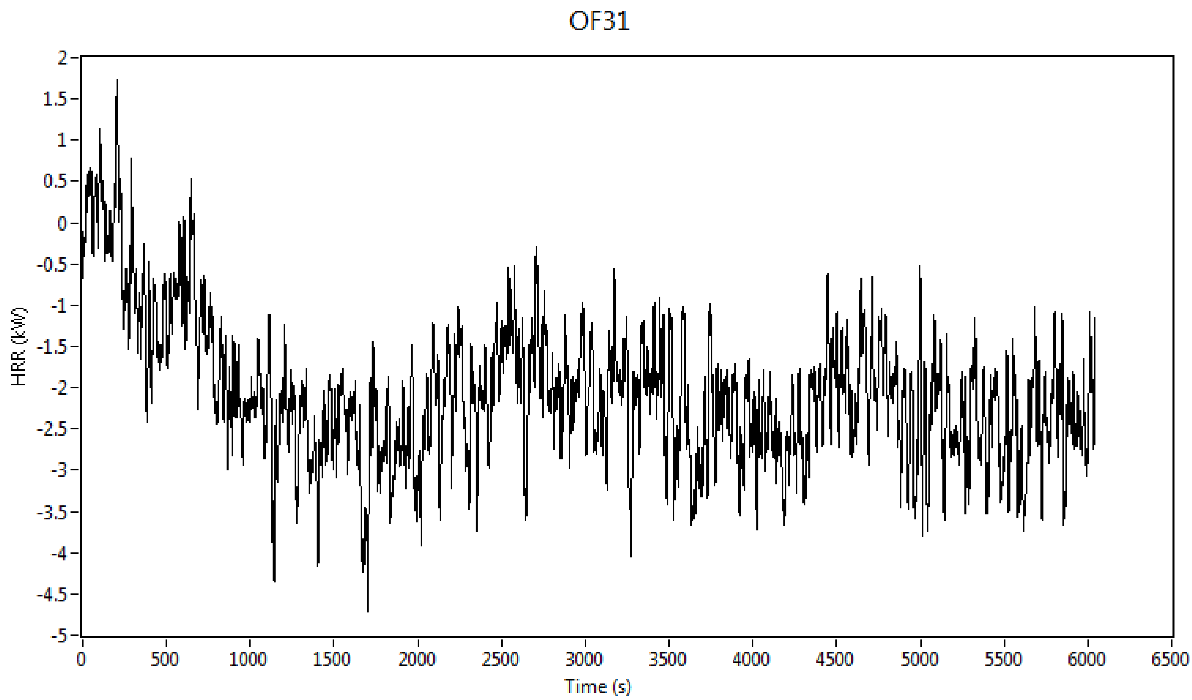

OF26
HRR (kW)
Time (s)
600
550
500
450
400
350
300
250
200
150
100
50
0
-50
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
3200

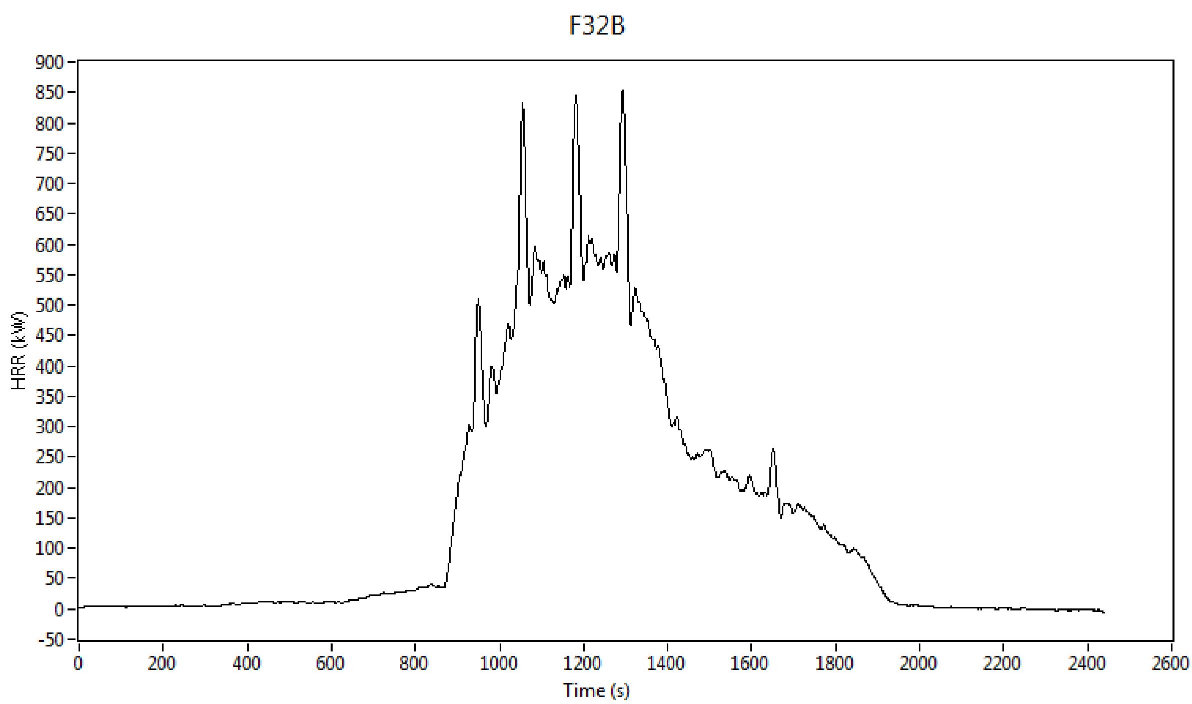

OF27
HRR (kW)
Time (s)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
-200
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
800
850
900

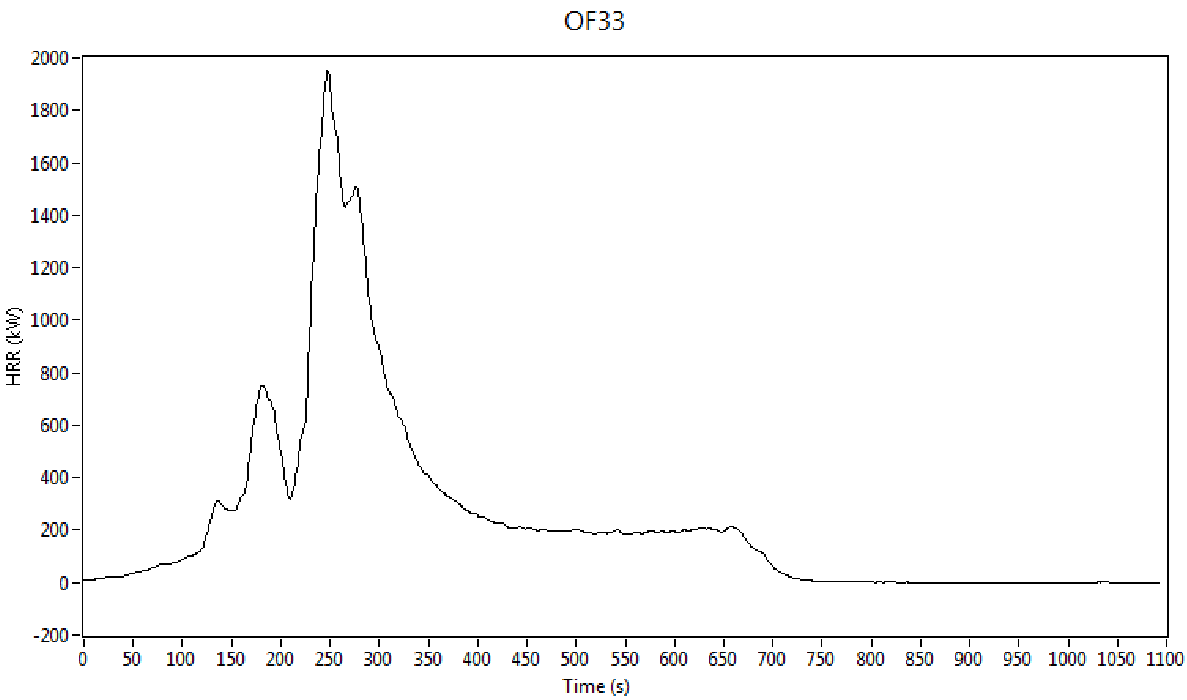

OF28
HRR (kW)
Time (s)
800
750
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
-50
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000

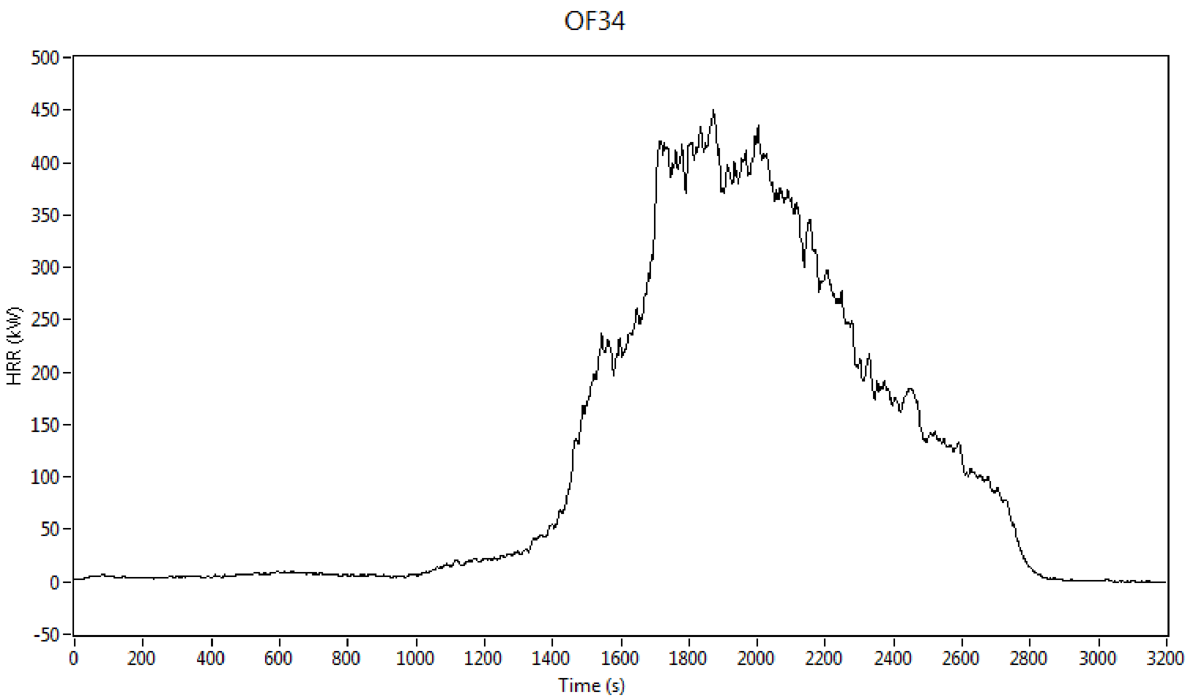

OF29
HRR (kW)
Time (s)
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
-100
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
3200
3400

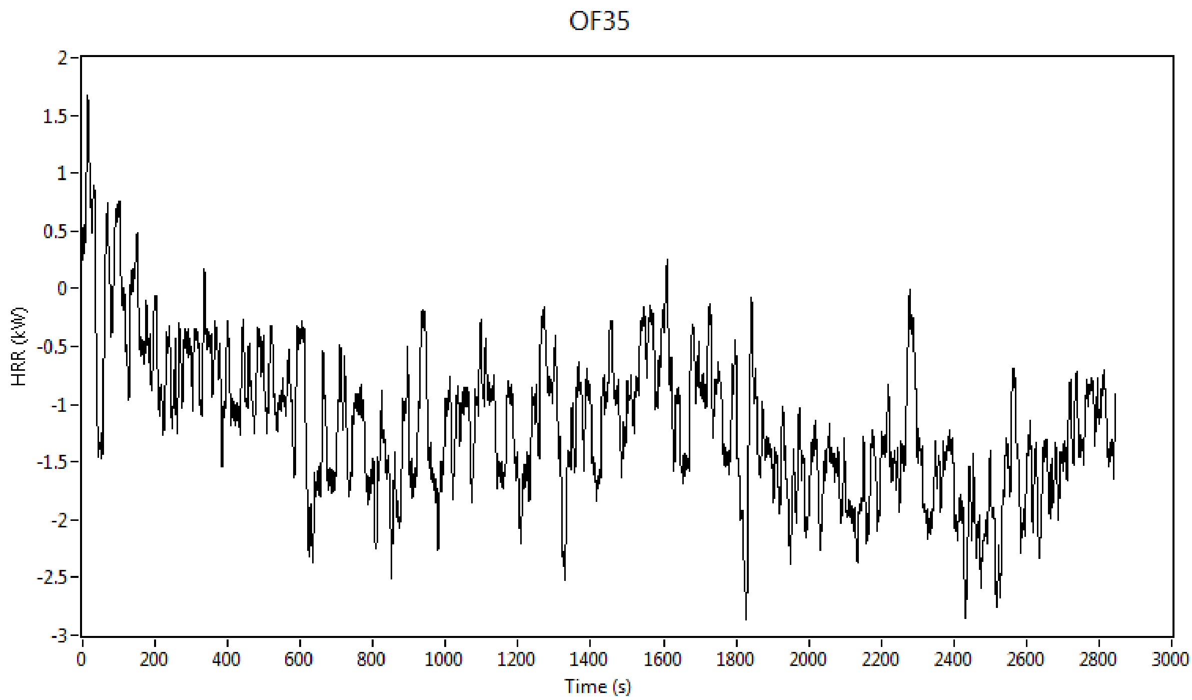

OF30
HRR (kW)
Time (s)
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
0
100
200
300
400
500
600
700
800
900
1000
1100
1200

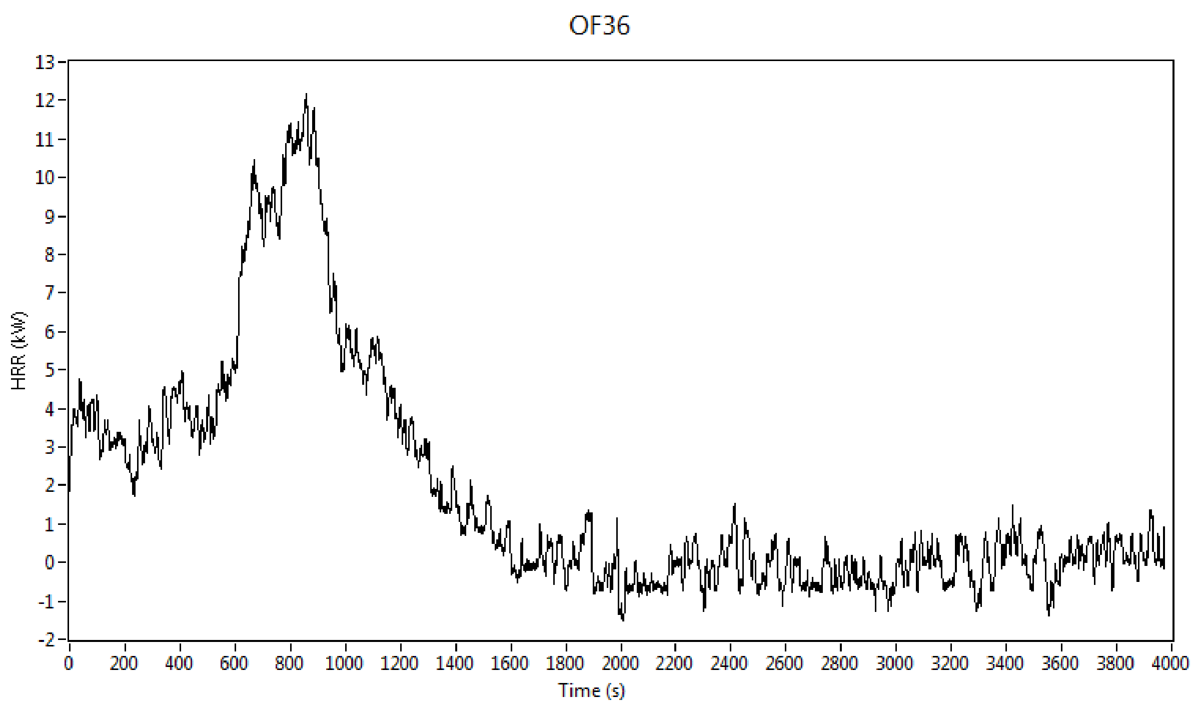

OF31
HRR (kW)
Time (s)
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
-5
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
6500


F32B
HRR (kW)
Time (s)
900
850
800
750
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
-50
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600

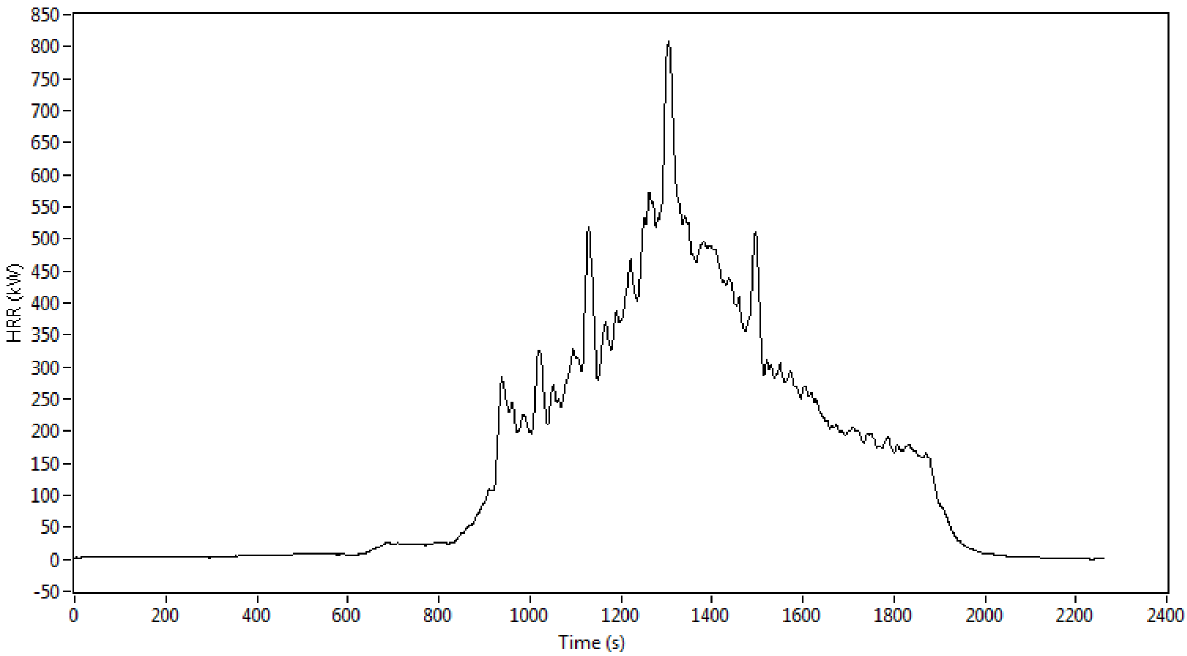

OF33
HRR (kW)
Time (s)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
-200
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
800
850
900
950
1000
1050
1100


OF34
HRR (kW)
Time (s)
500
450
400
350
300
250
200
150
100
50
0
-50
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
3200


OF35
HRR (kW)
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
Time (s)

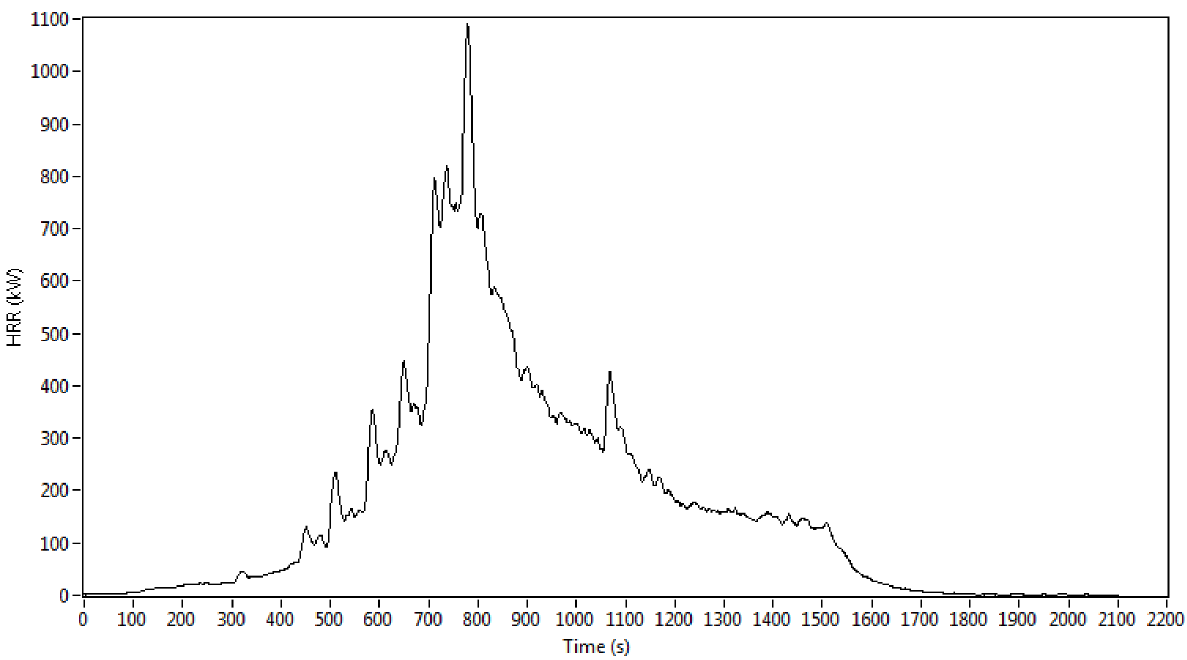

OF36
HRR (kW)
13
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
3200
3400
3600
3800
4000
Time (s)

OF37

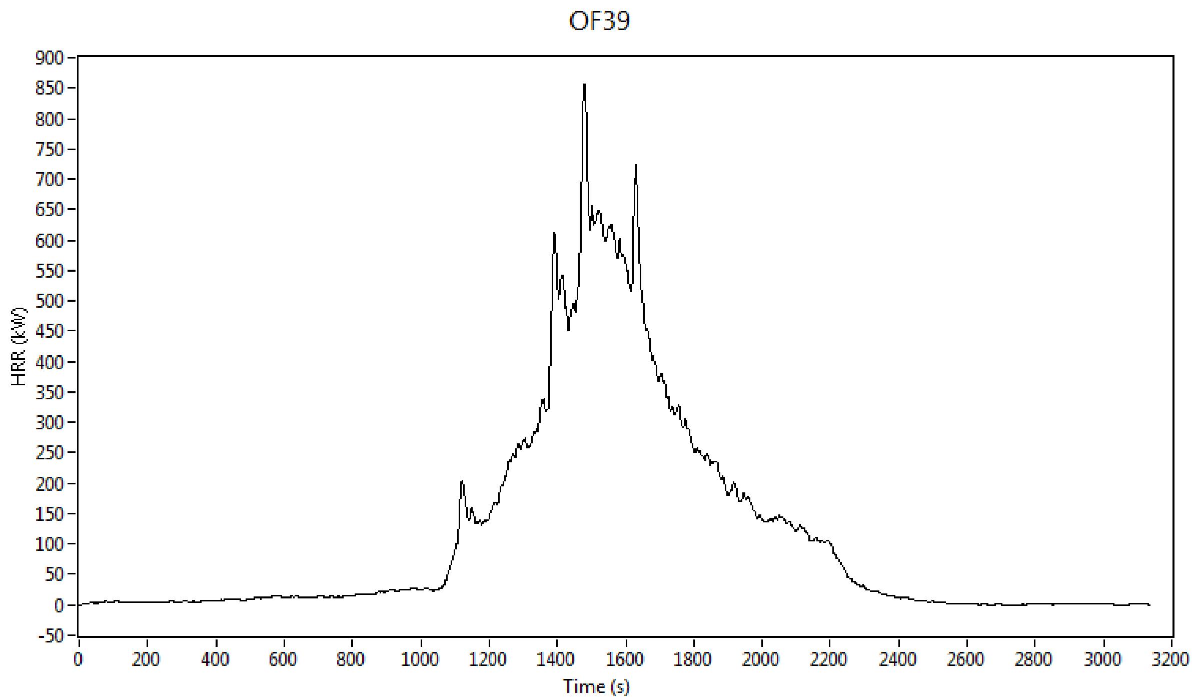


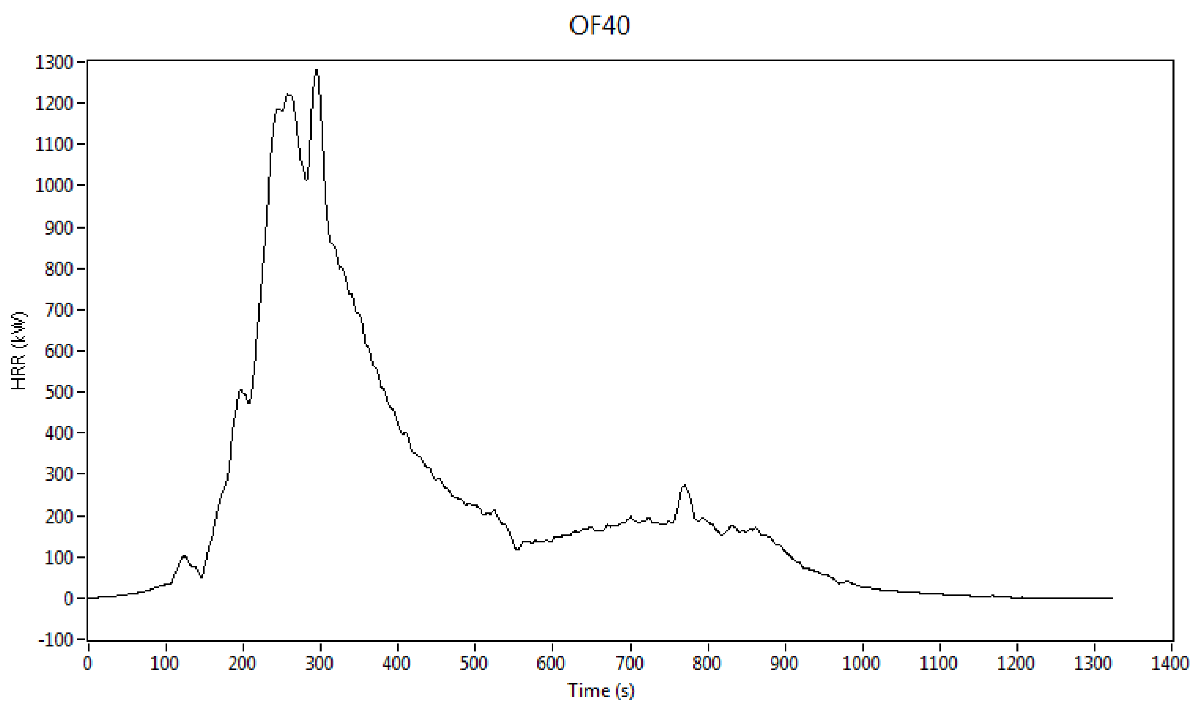
850
800
750
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
-50
HRR (kW)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
Time (s)

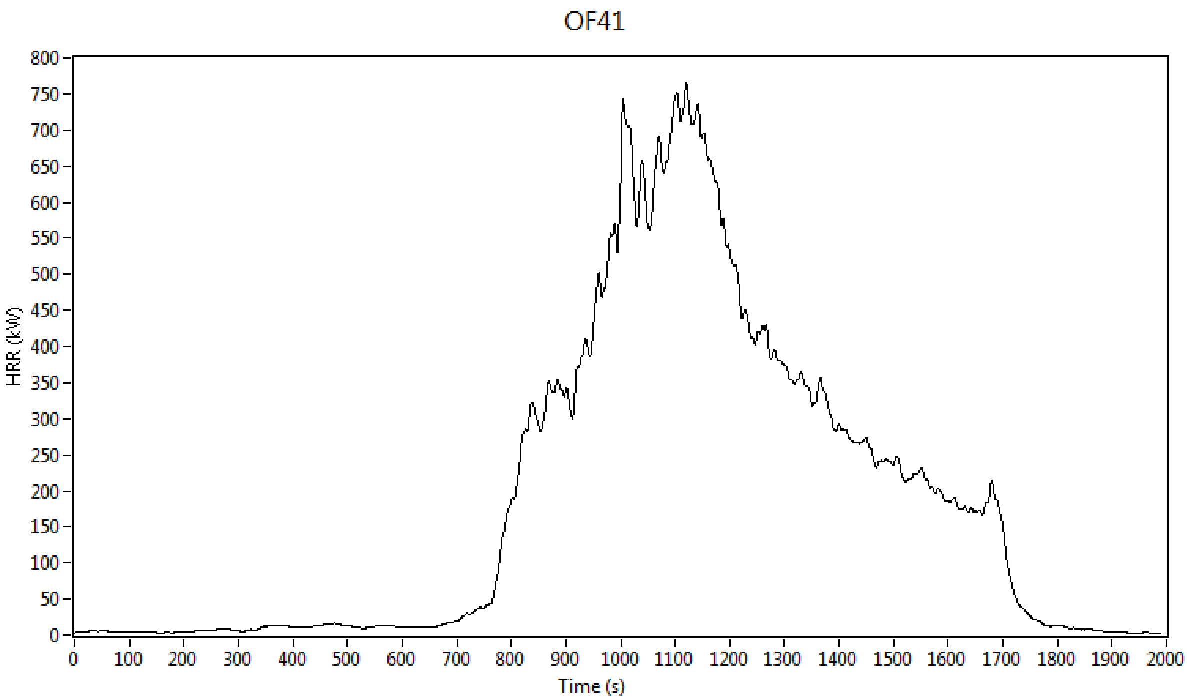
OF38

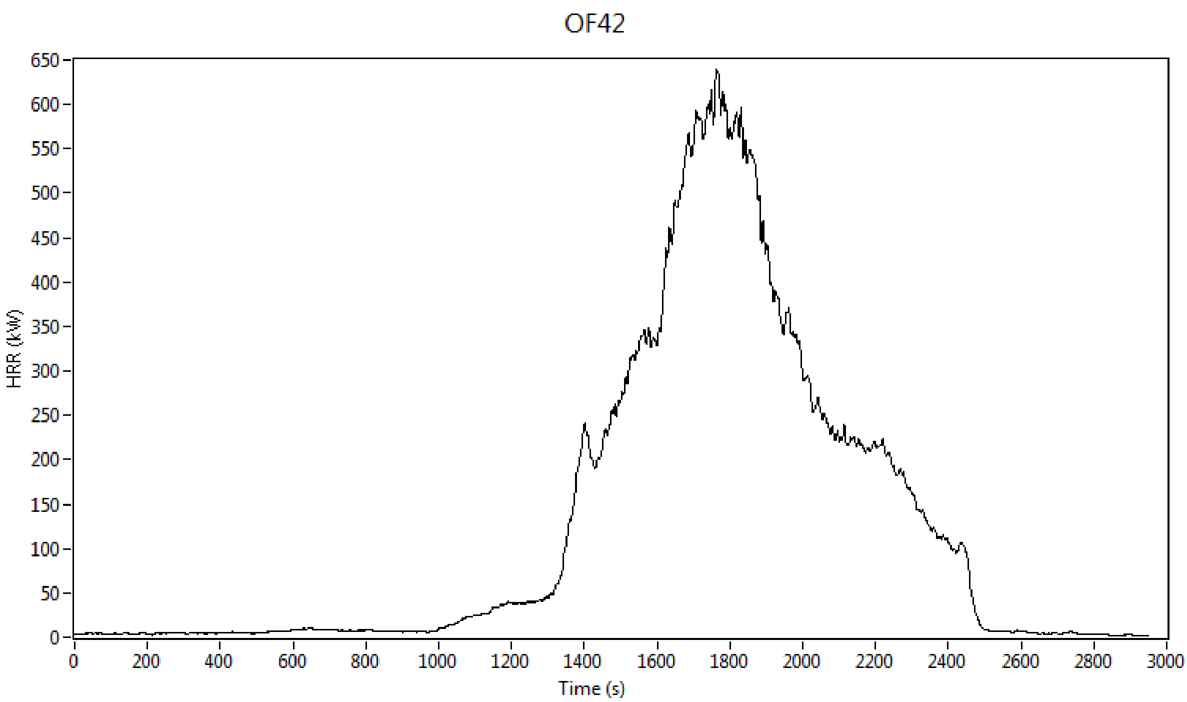


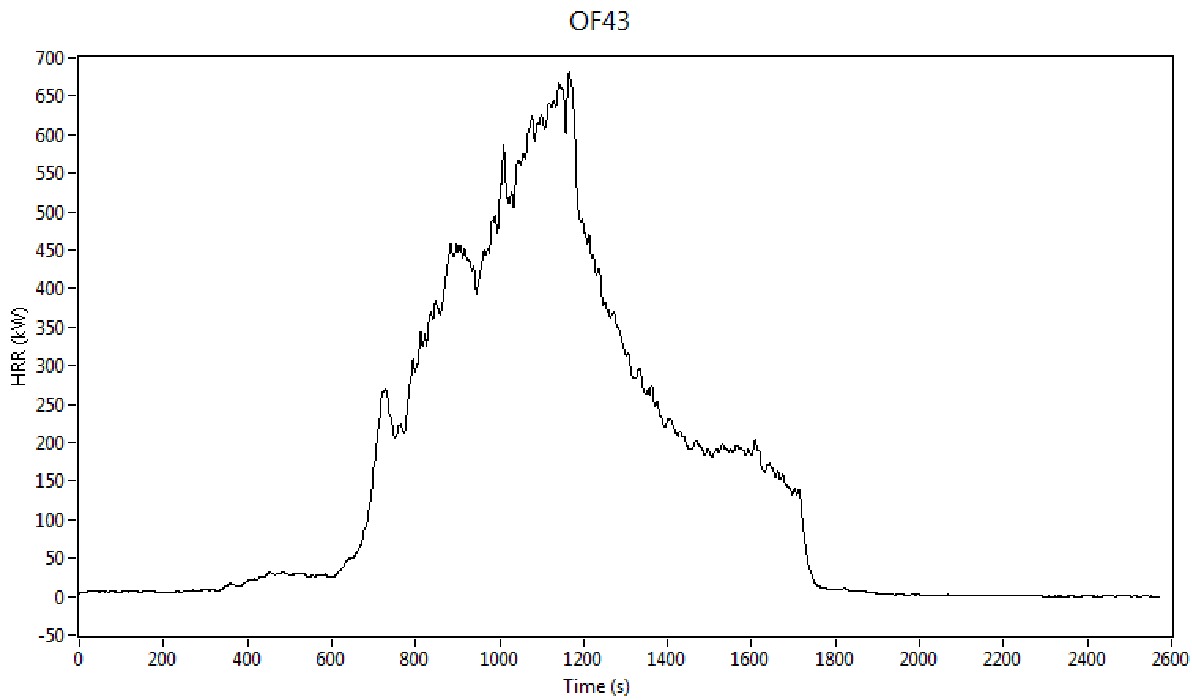
1100
1000
900
800
700
600
500
400
300
200
100
0
HRR (kW)
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
2100
2200
Time (s)

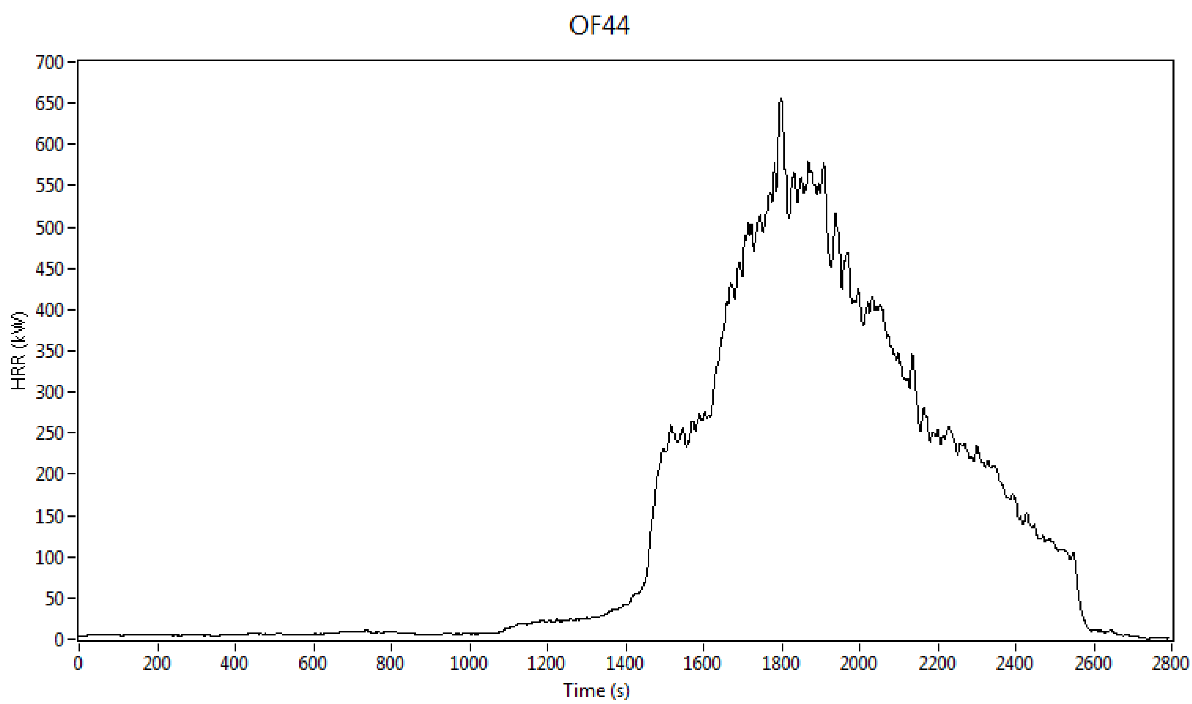

OF39
HRR (kW)
Time (s)
900
850
800
750
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
-50
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
3200


OF40
HRR (kW)
Time (s)
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
-100
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400

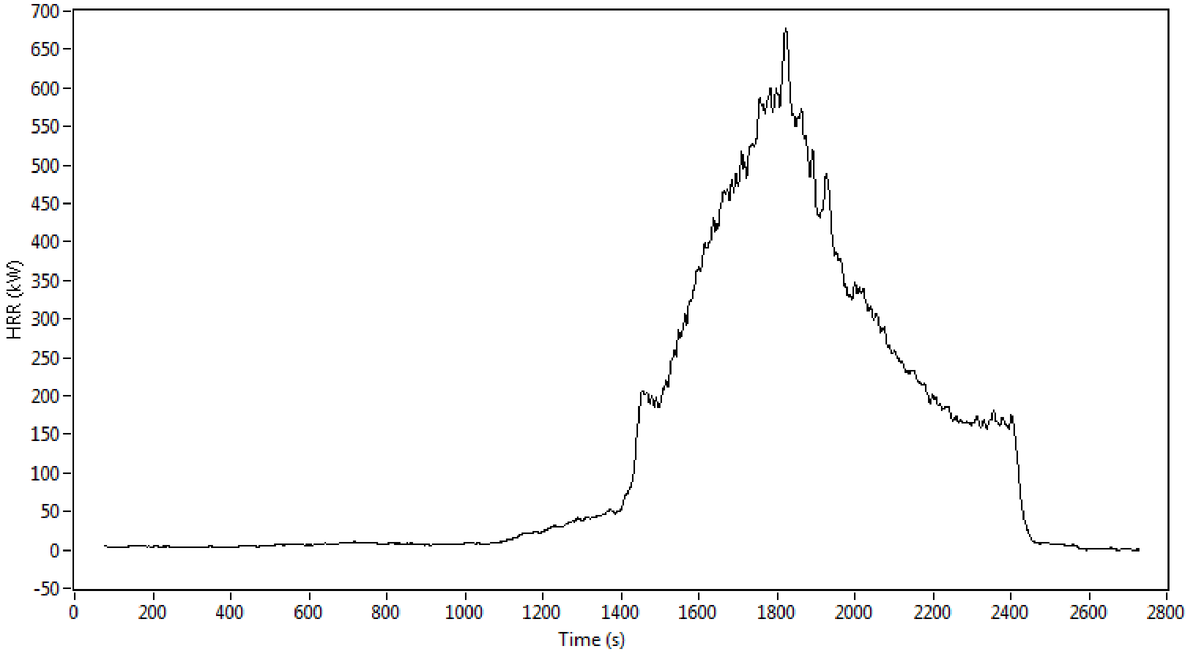

OF41
HRR (kW)
Time (s)
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
800
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000


OF42
HRR (kW)
Time (s)
0
50
100
150
200
250
300
350
400
450
500
550
600
650
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000

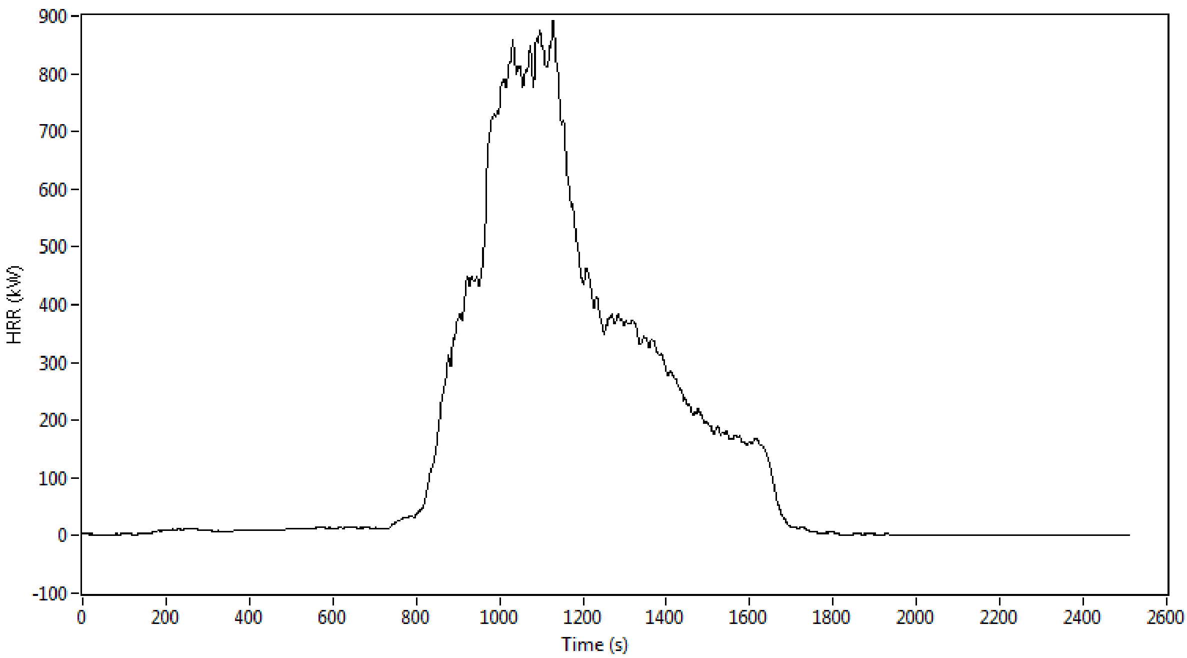

OF43
HRR (kW)
Time (s)
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
-50
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600

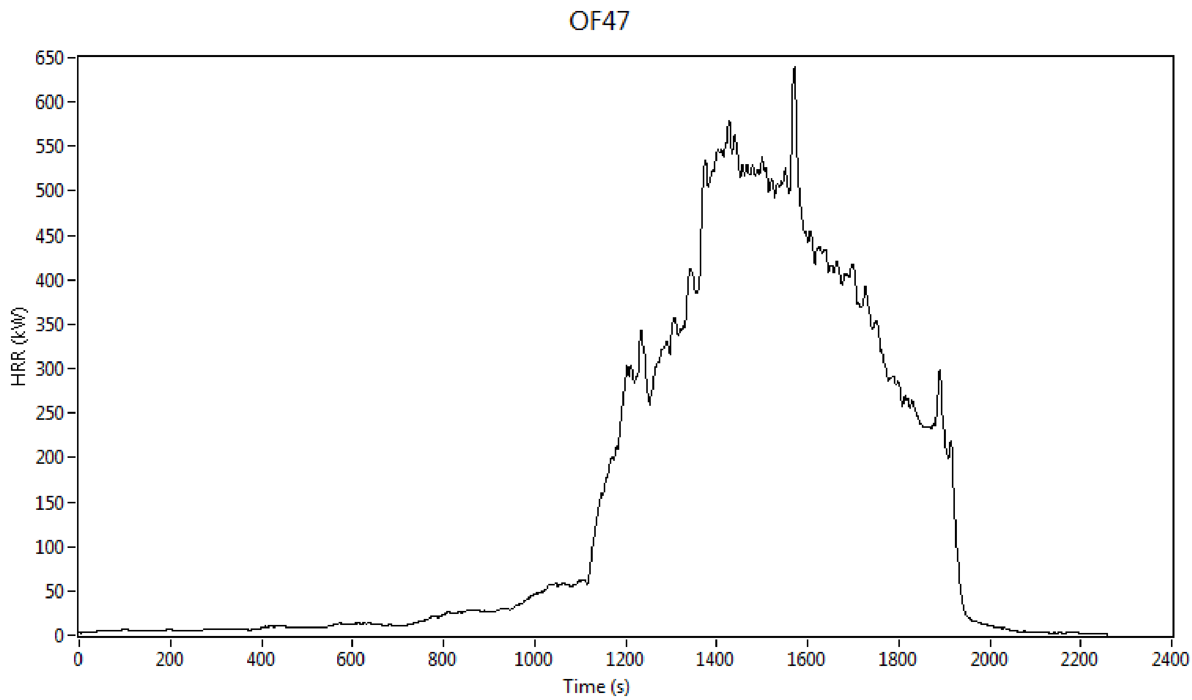

OF44
HRR (kW)
Time (s)
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800

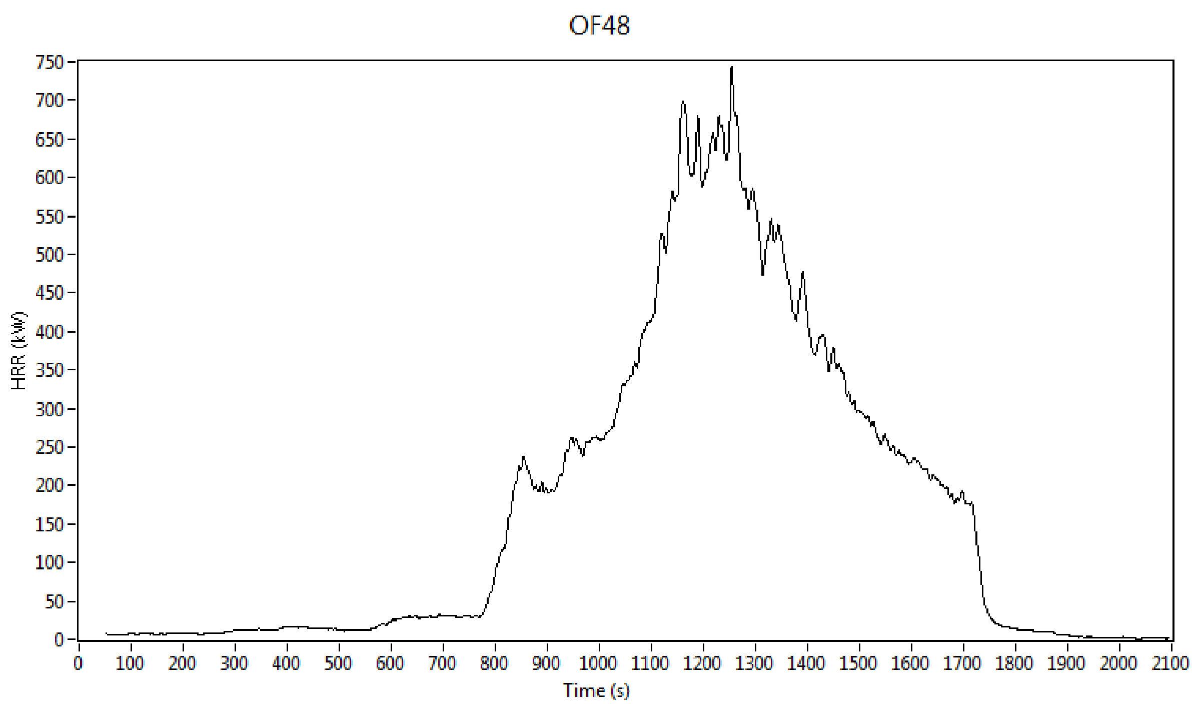
OF45



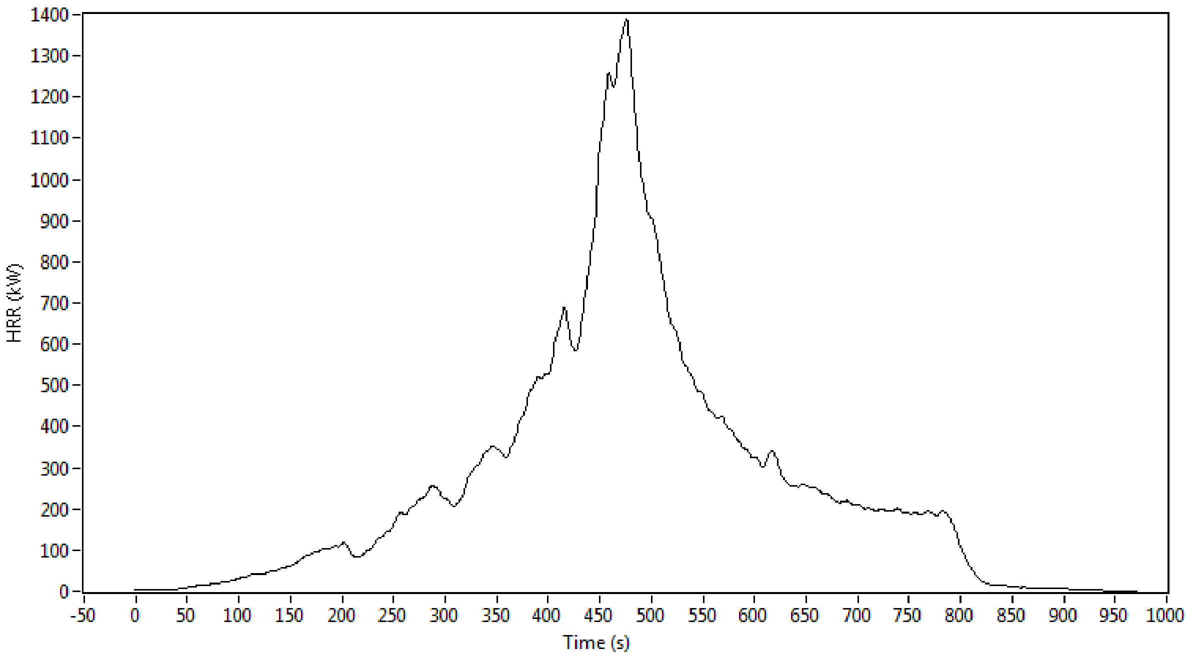
OF46




OF47
HRR (kW)
650
600
550
500
450
400
350
300
250
200
150
100
50
0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
Time (s)

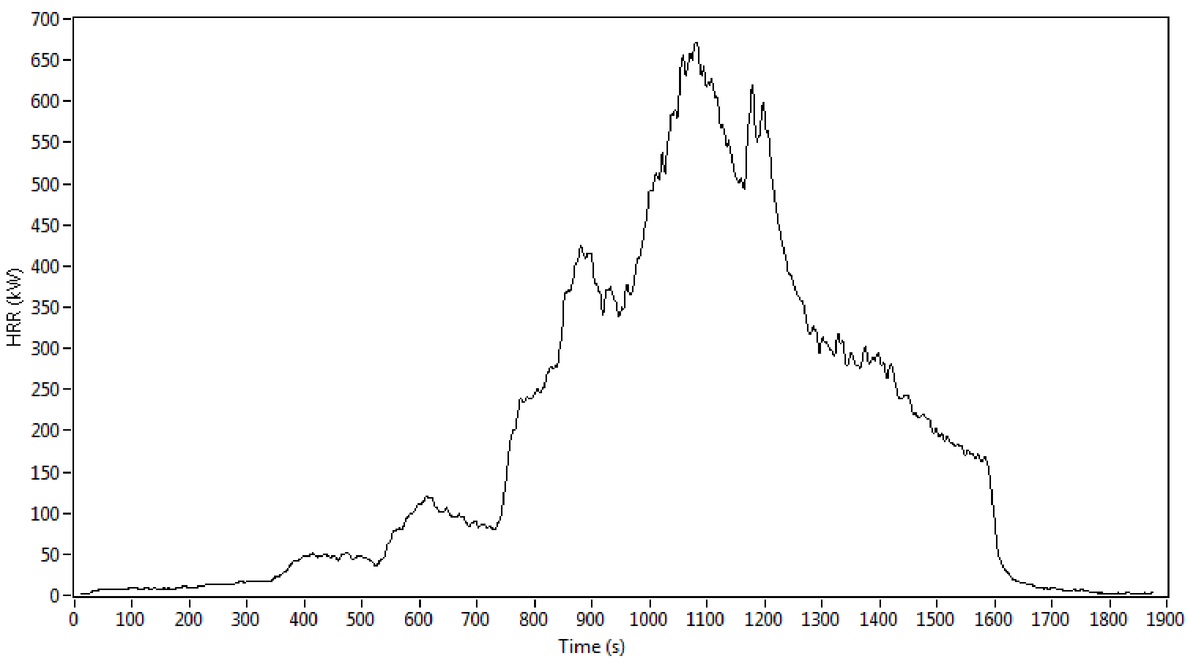

OF48
HRR (kW)
750
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
2100
Time (s)

OF49

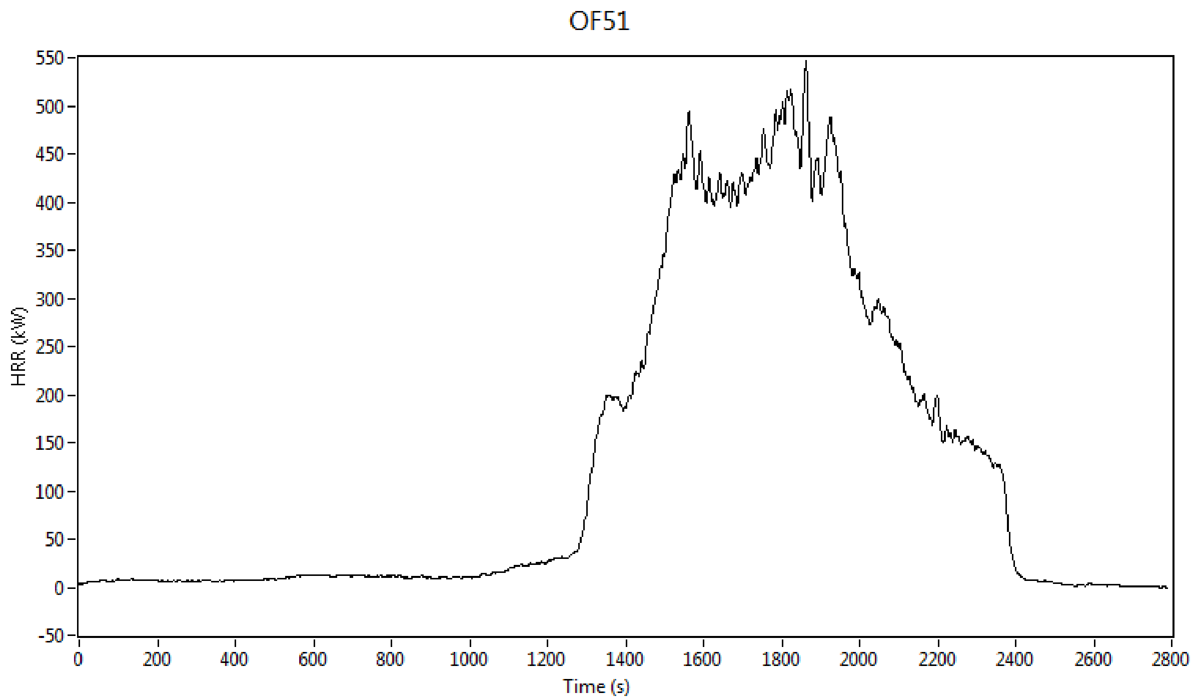


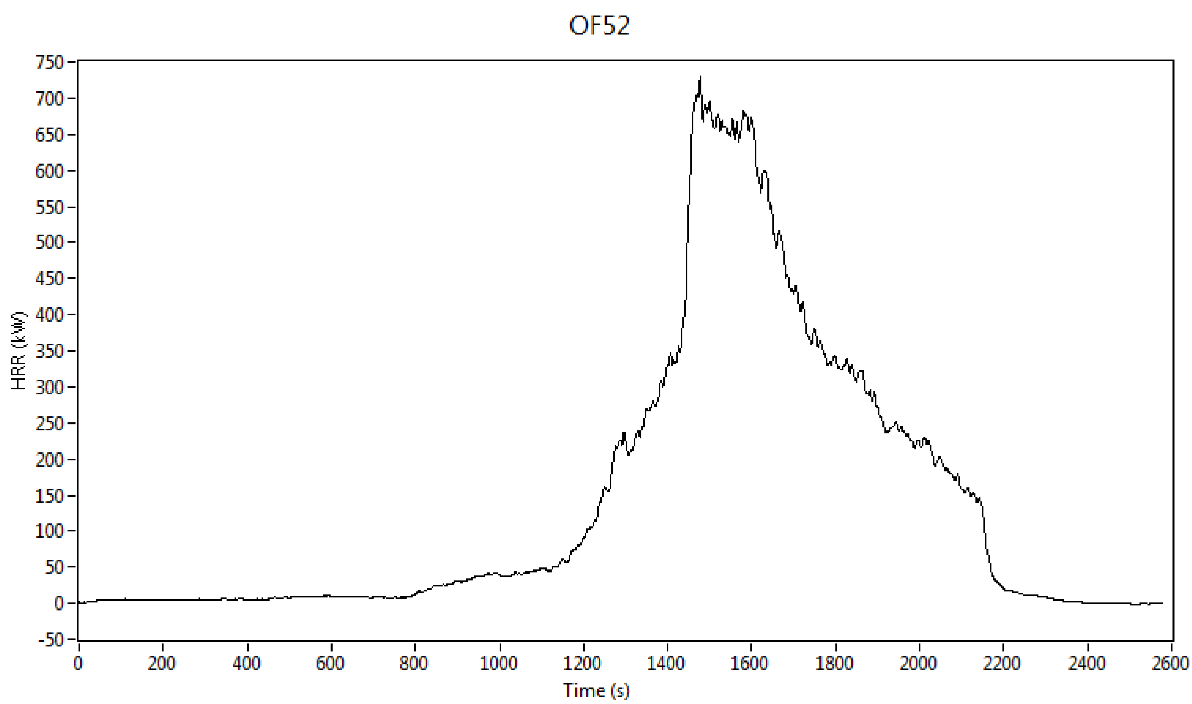
HRR (kW)
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
-50
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
800
850
900
950
1000
Time (s)

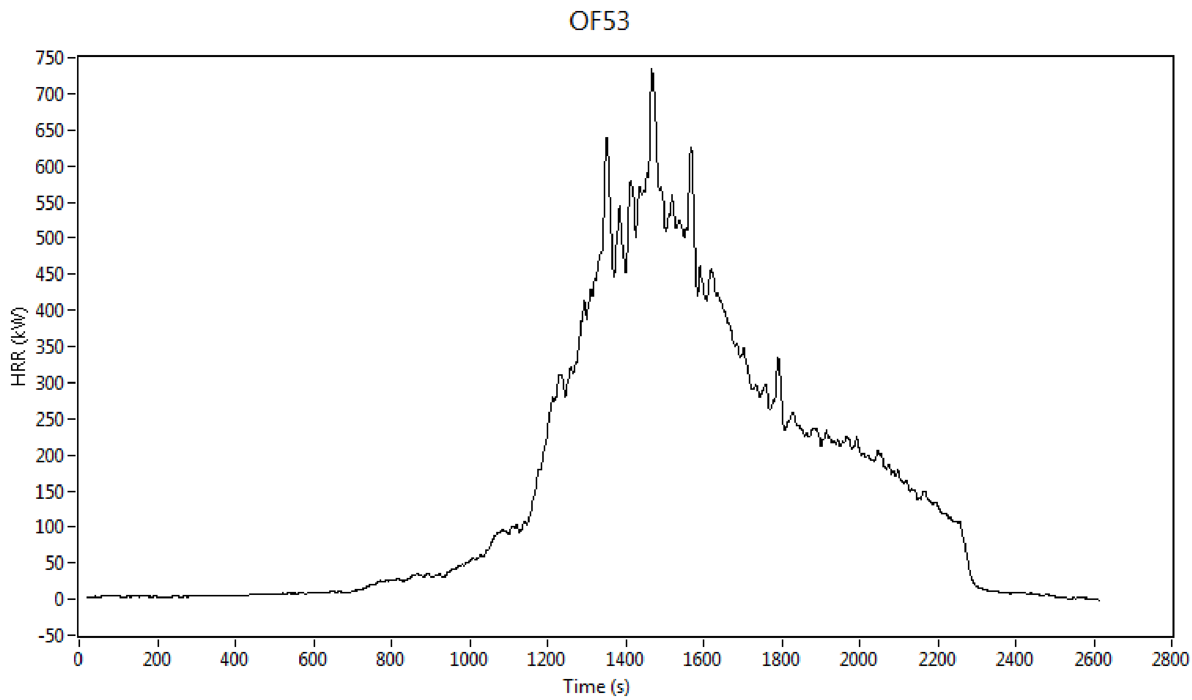
OF50

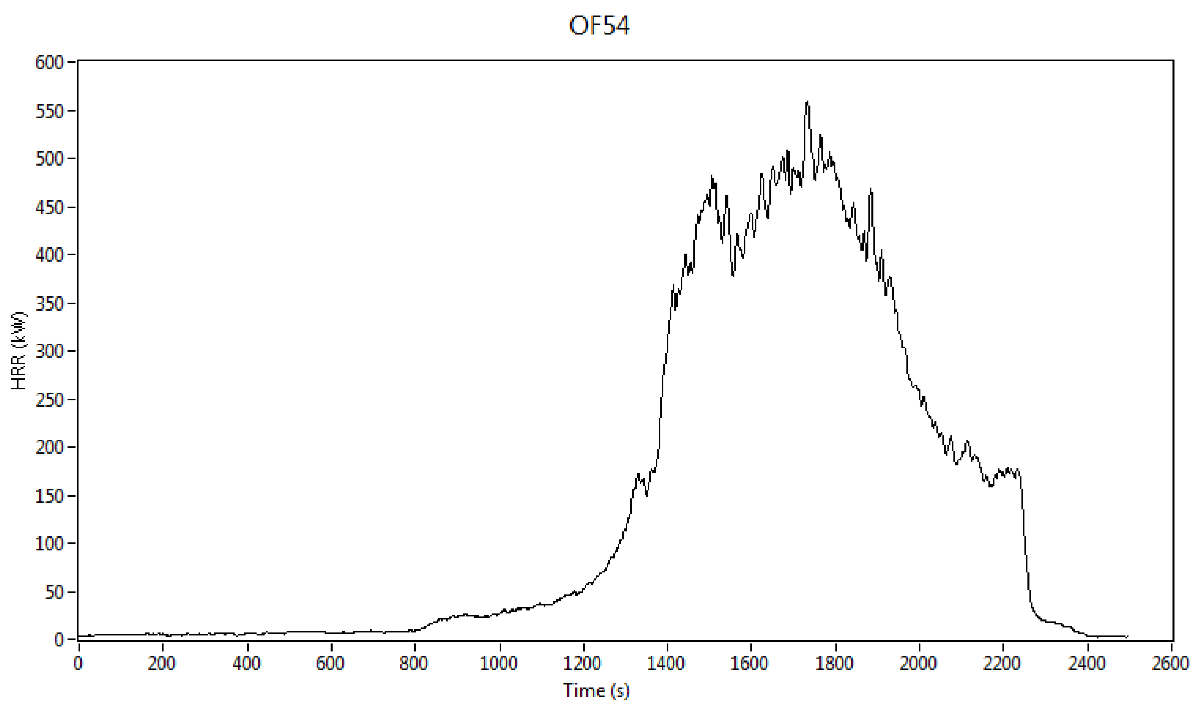


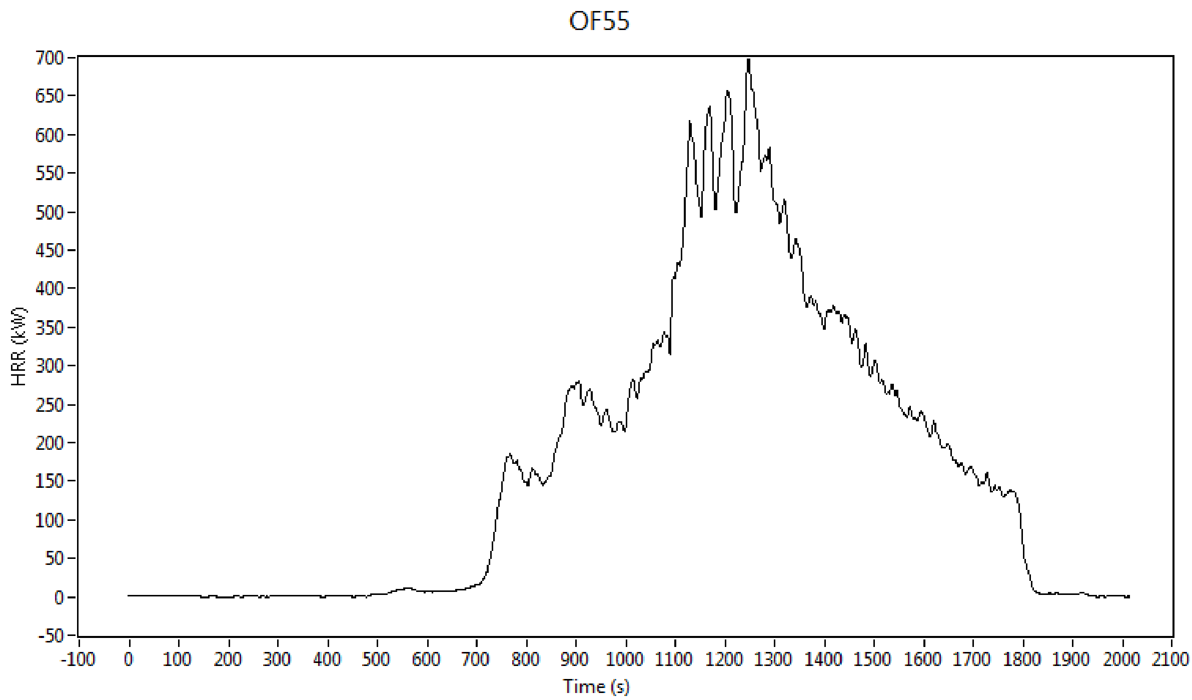
HRR (kW)
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
Time (s)

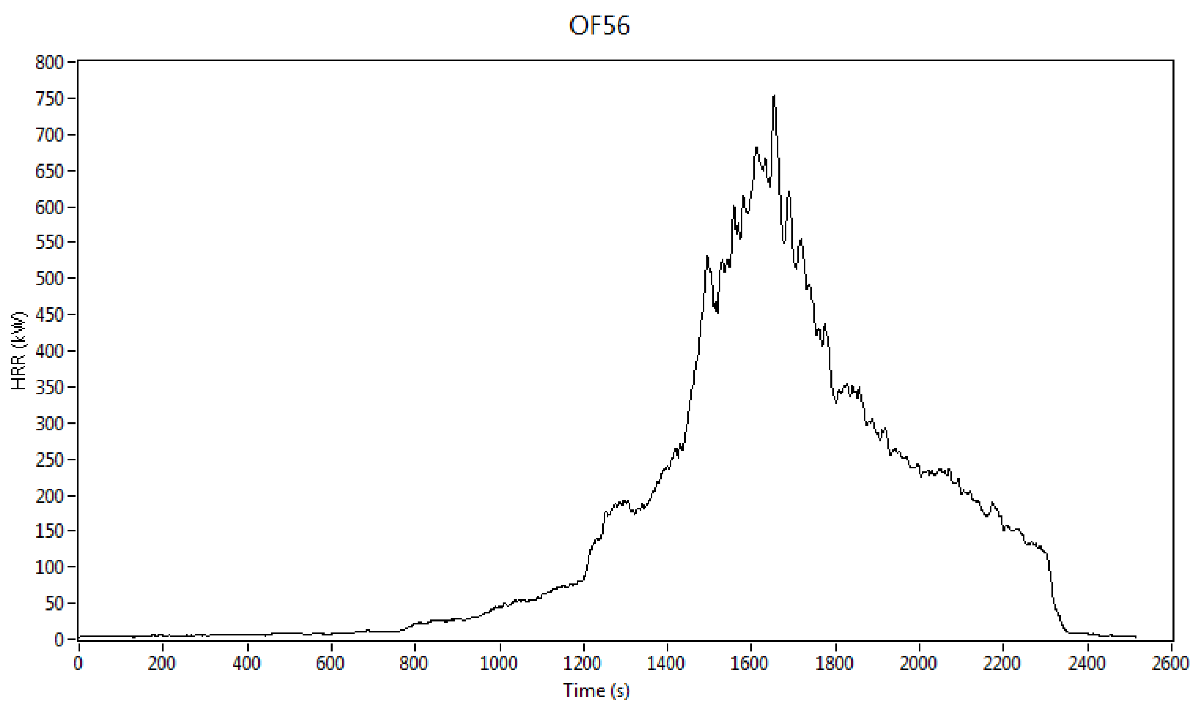

OF51
HRR (kW)
Time (s)


OF52
HRR (kW)
Time (s)

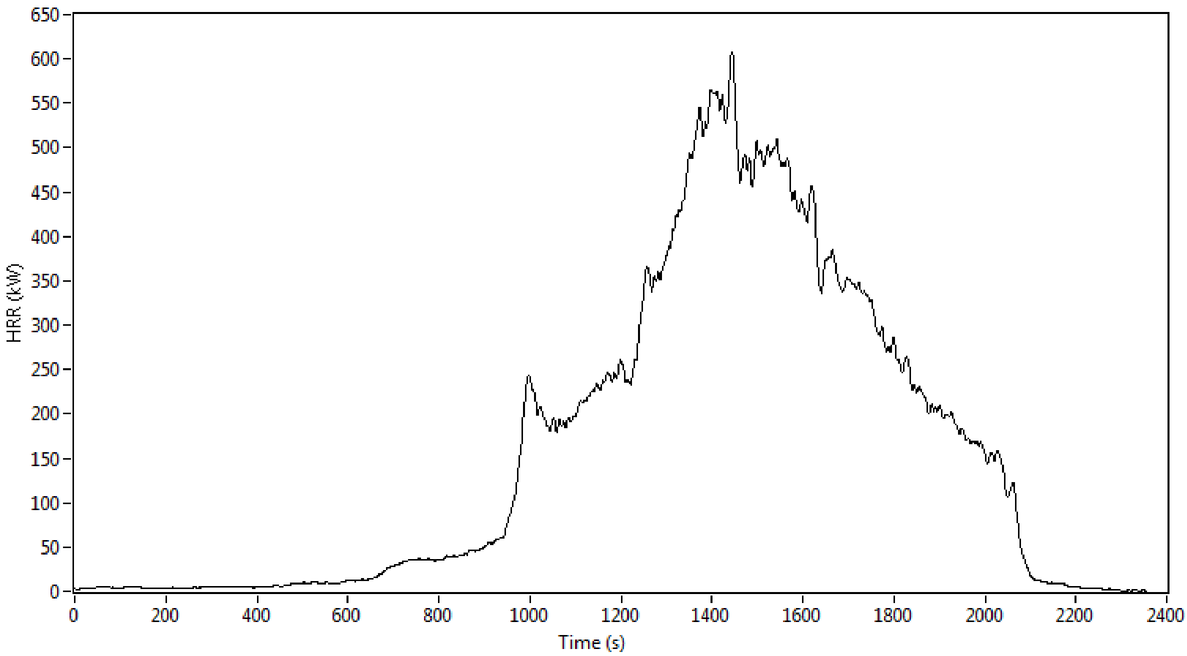

OF53
HRR (kW)
Time (s)
750
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
-50
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800


OF54
HRR (kW)
Time (s)
600
550
500
450
400
350
300
250
200
150
100
50
0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600


OF55
HRR (kW)
Time (s)

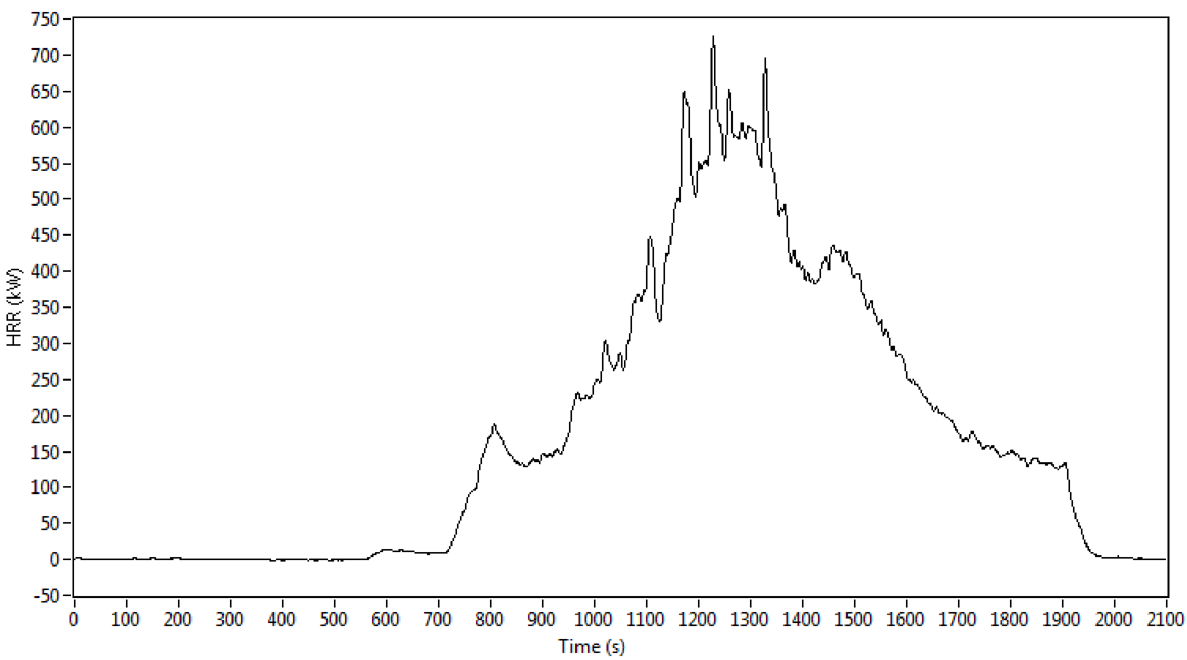

OF56
HRR (kW)
Time (s)

OF57

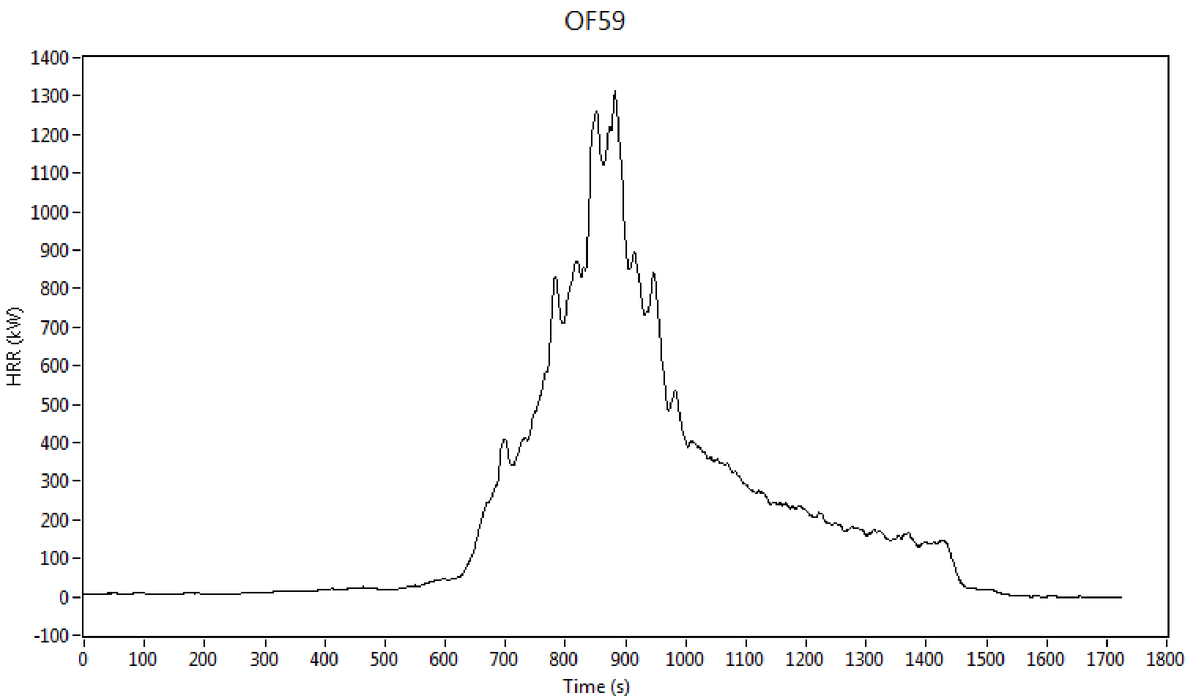


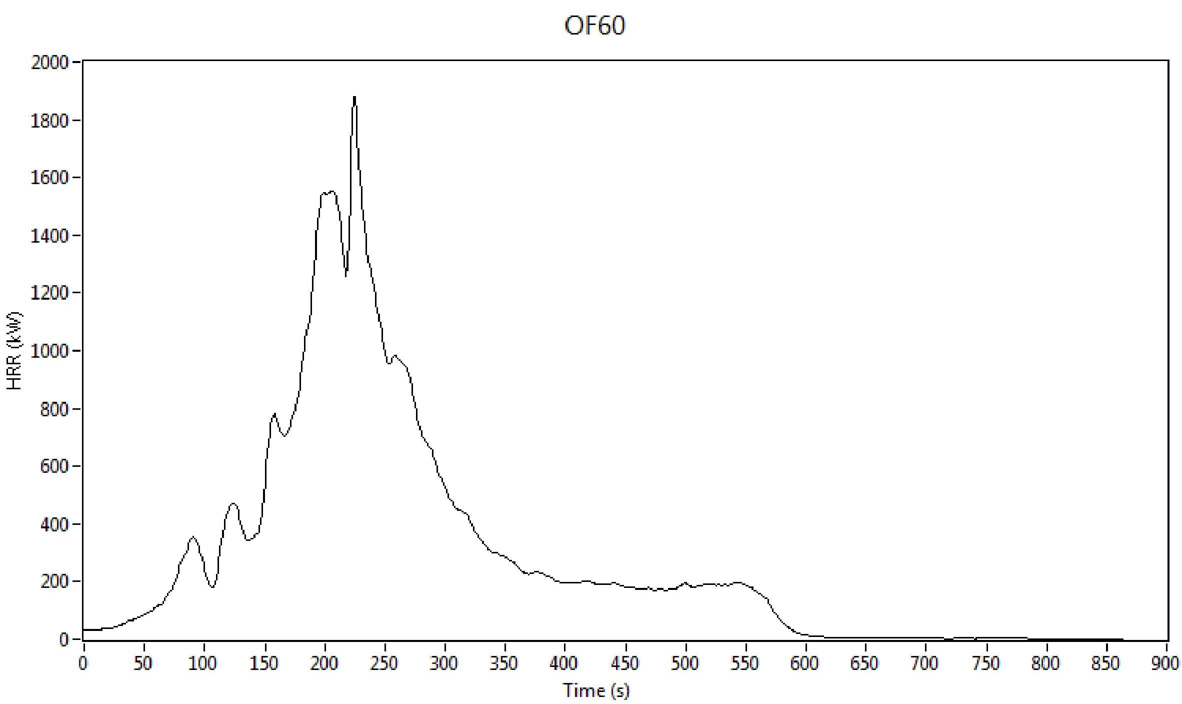
HRR (kW)
650
600
550
500
450
400
350
300
250
200
150
100
50
0
0 200 400 600 800 1000 1200 1400 1600 1800 2000 2200 2400
Time (s)

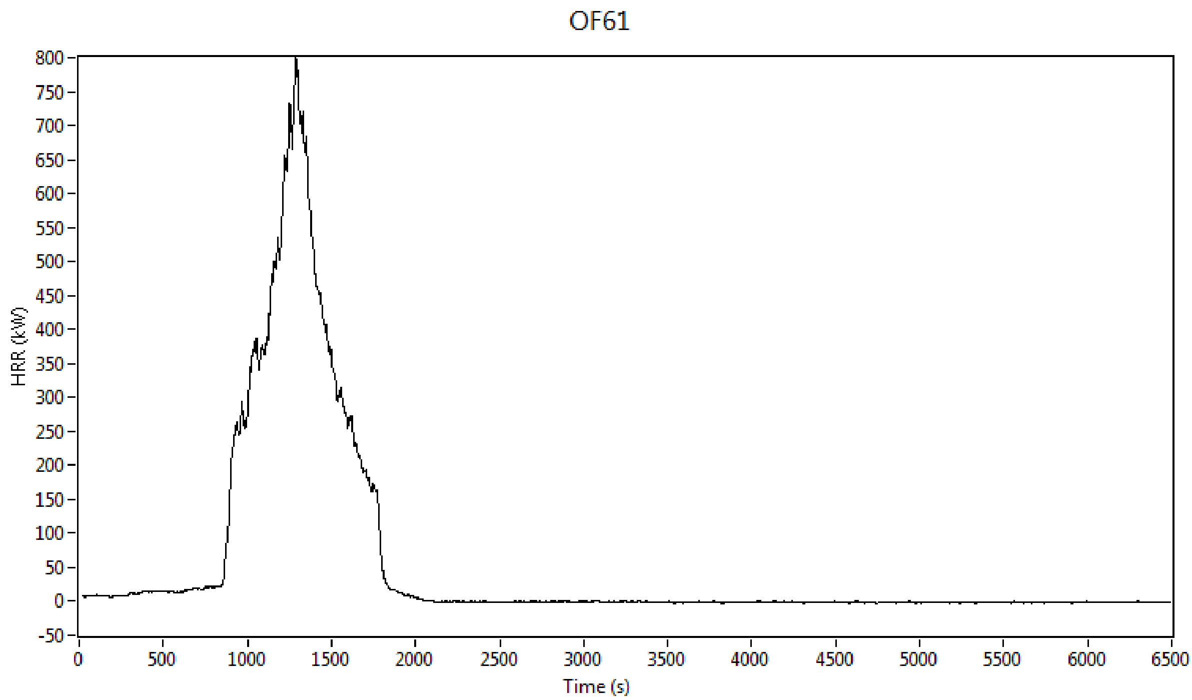
OF58



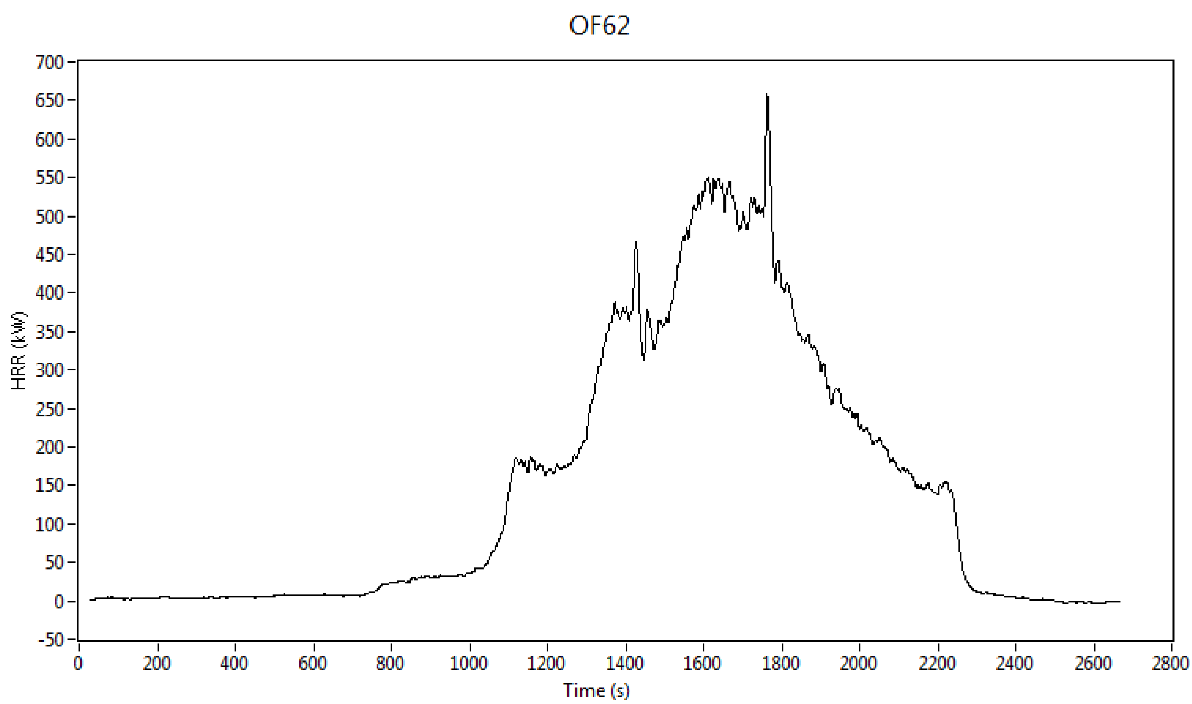
HRR (kW)
750
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
-50
0 100 200 300 400 500 600 700 800 900 1000 1100 1200 1300 1400 1500 1600 1700 1800 1900 2000 2100
Time (s)


OF59
HRR (kW)
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
-100
0 100 200 300 400 500 600 700 800 900 1000 1100 1200 1300 1400 1500 1600 1700 1800
Time (s)

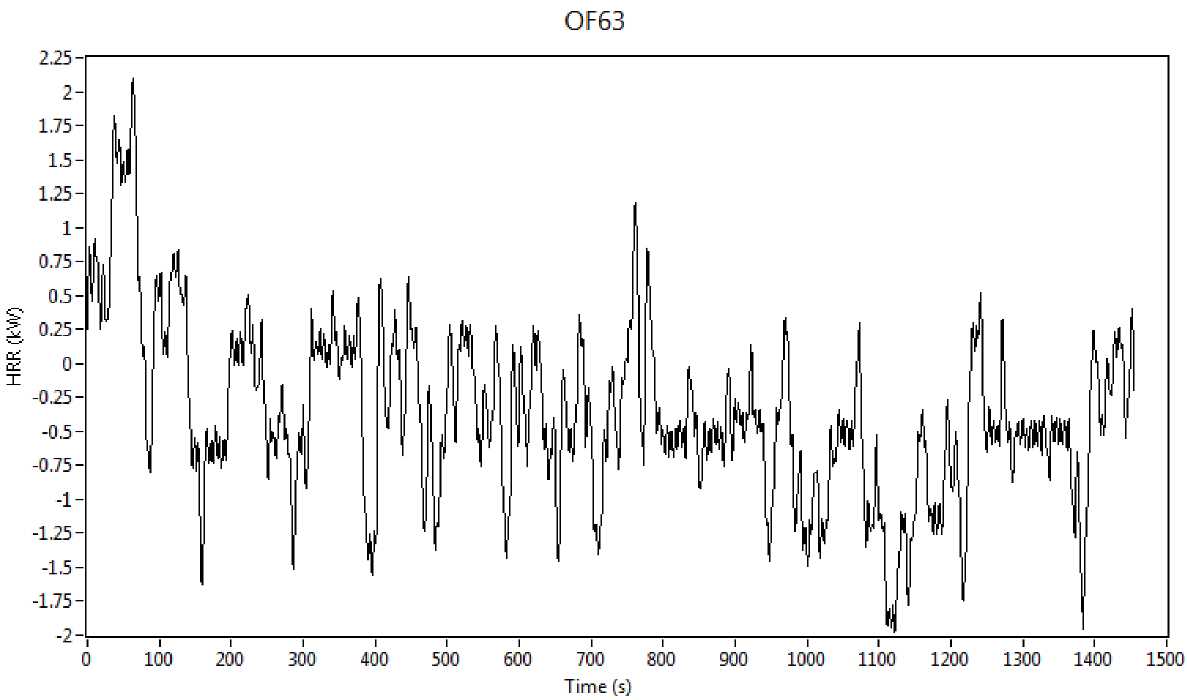

OF60
HRR (kW)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
0 50 100 150 200 250 300 350 400 450 500 550 600 650 700 750 800 850 900
Time (s)

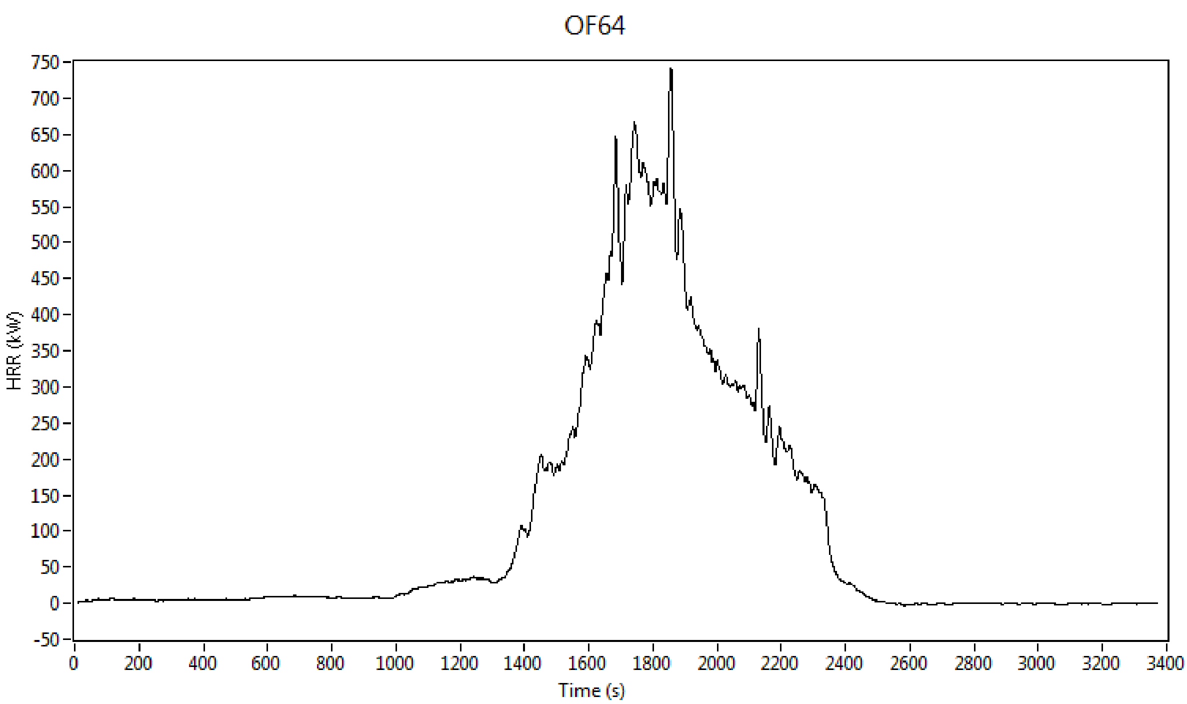


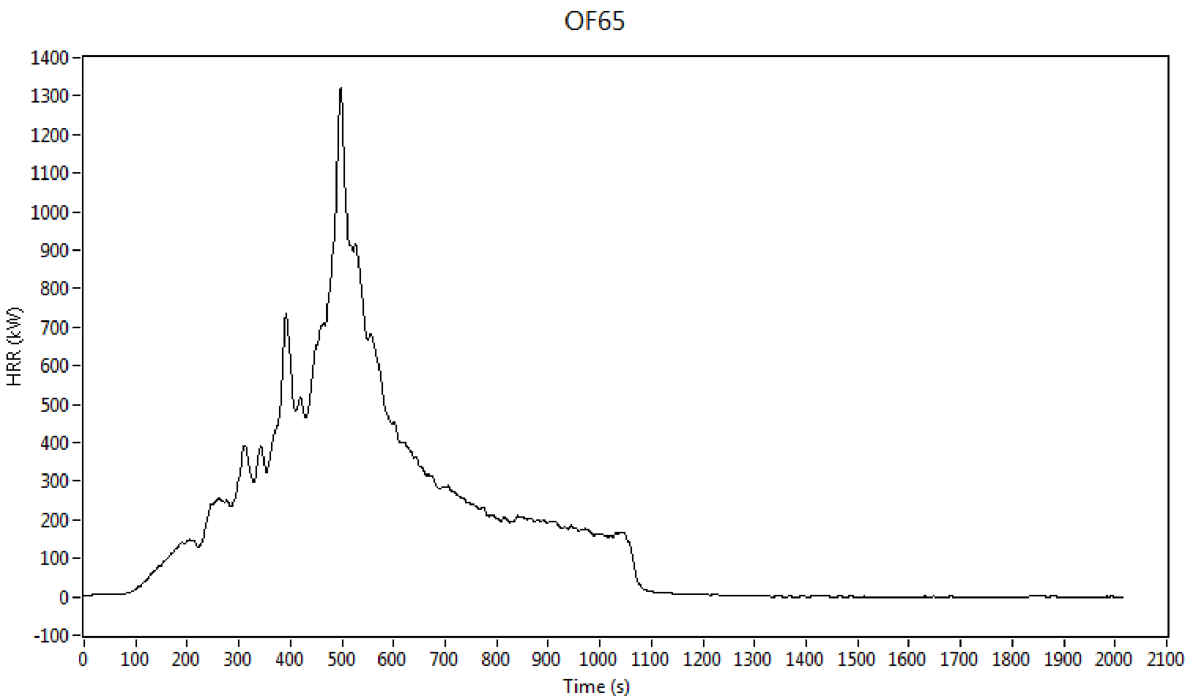
OF61
HRR (kW)
Time (s)
800
750
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
-50
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
6500

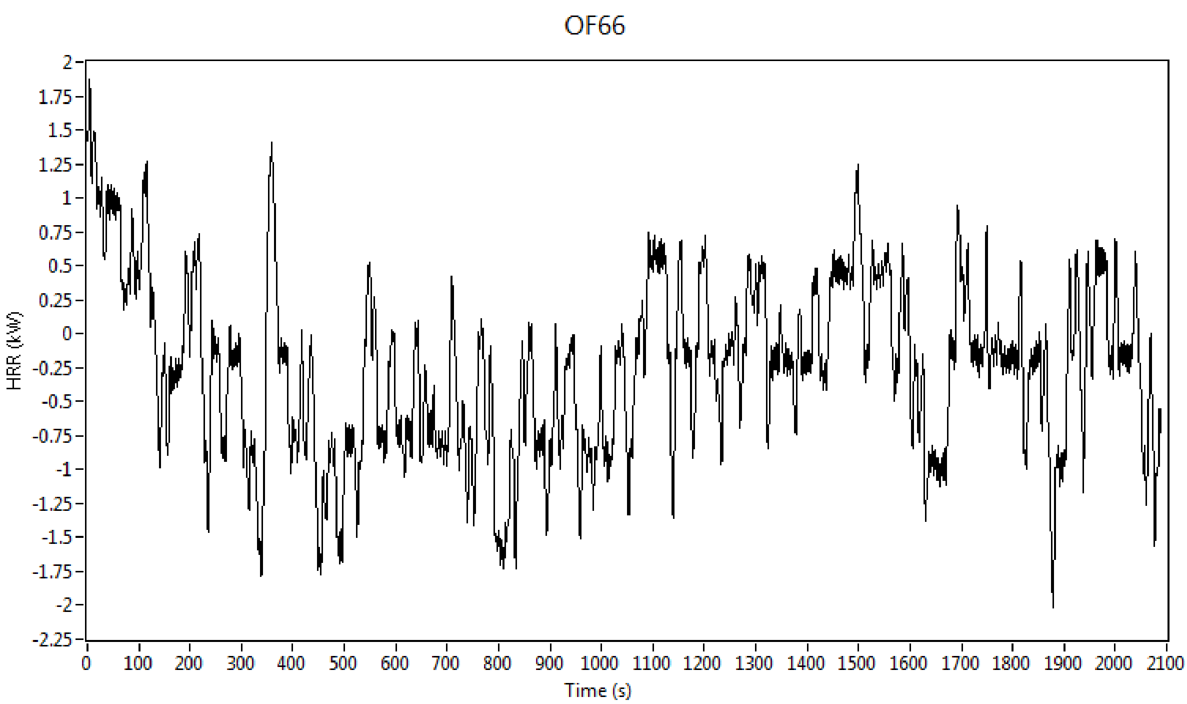


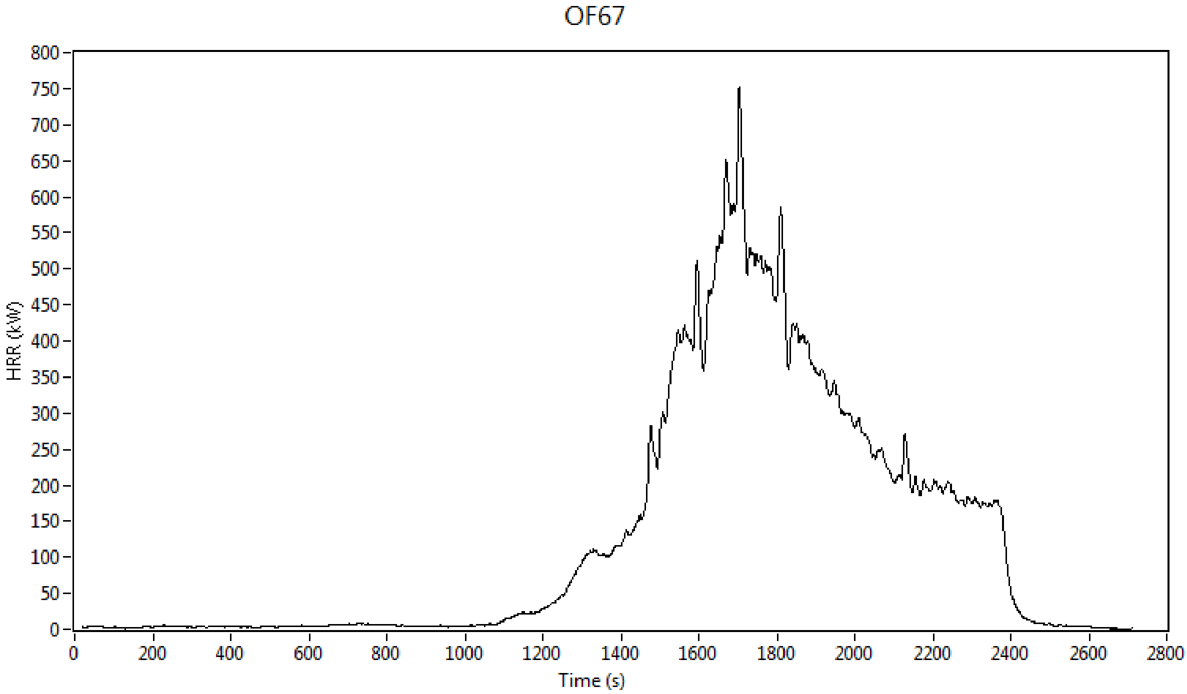
OF62
HRR (kW)
Time (s)
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
-50
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800

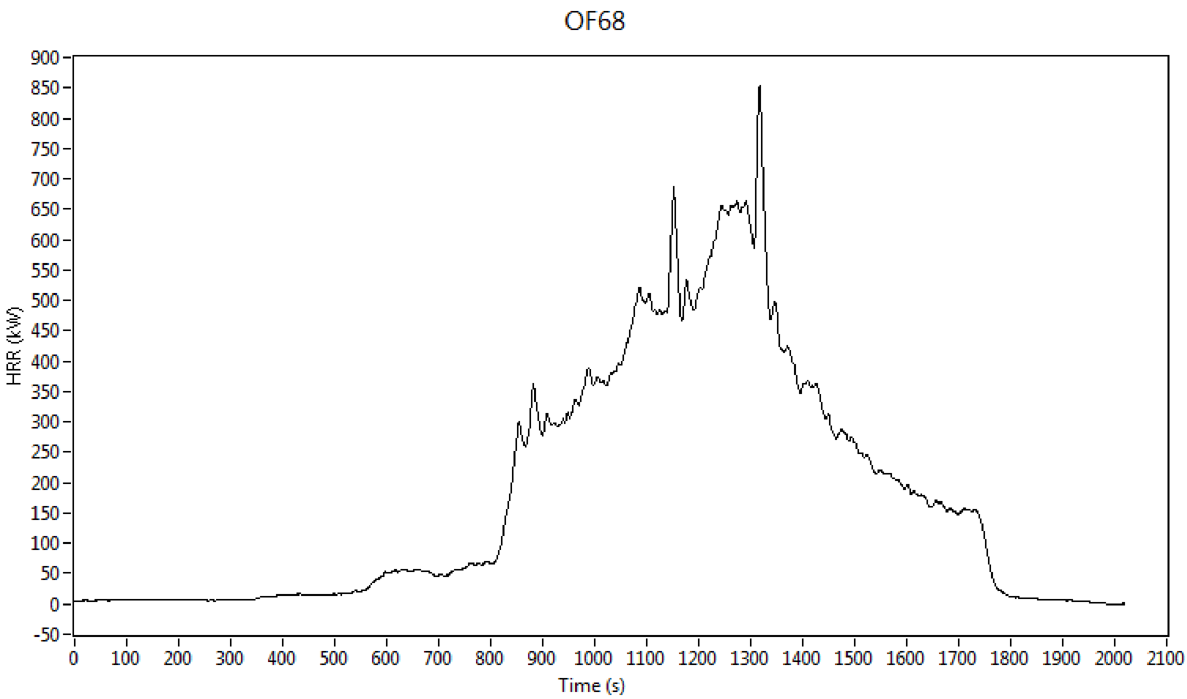

OF63
HRR (kW)
2.25
2
1.75
1.5
1.25
1
0.75
0.5
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
-1.75
-2
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
Time (s)


OF64
HRR (kW)
750
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
-50
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
3200
3400
Time (s)

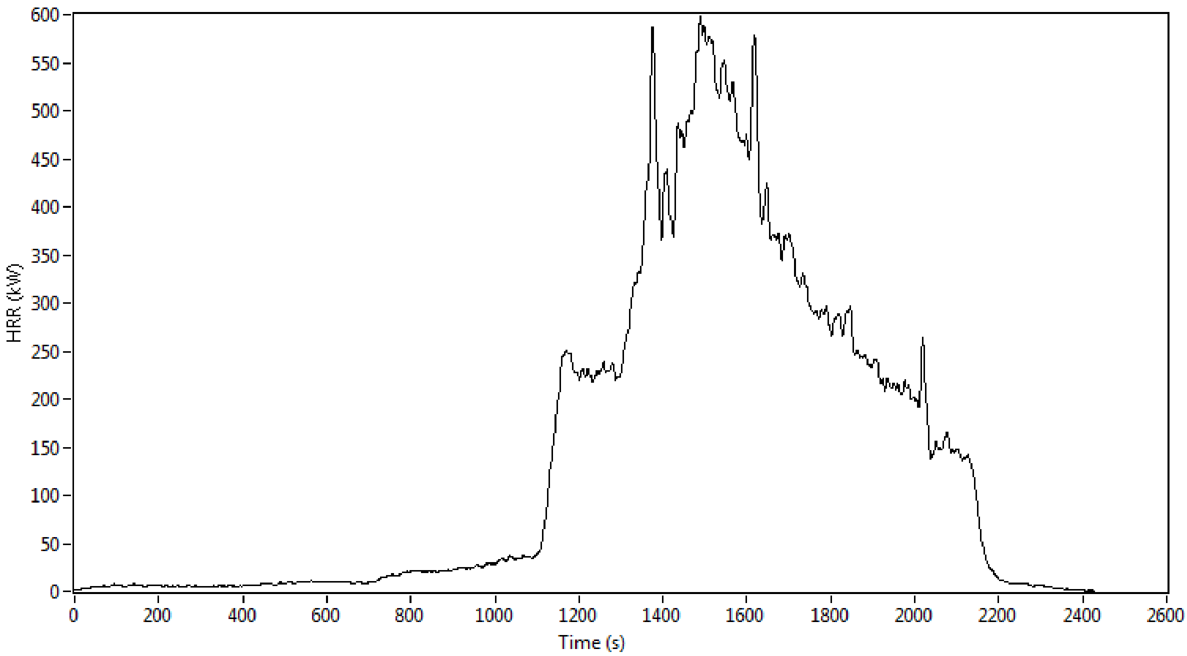

OF65
HRR (kW)
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
-100
0 100 200 300 400 500 600 700 800 900 1000 1100 1200 1300 1400 1500 1600 1700 1800 1900 2000 2100
Time (s)


OF66
HRR (kW)
2
1.75
1.5
1.25
1
0.75
0.5
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
-1.75
-2
-2.25
0 100 200 300 400 500 600 700 800 900 1000 1100 1200 1300 1400 1500 1600 1700 1800 1900 2000 2100
Time (s)


OF67
HRR (kW)
Time (s)

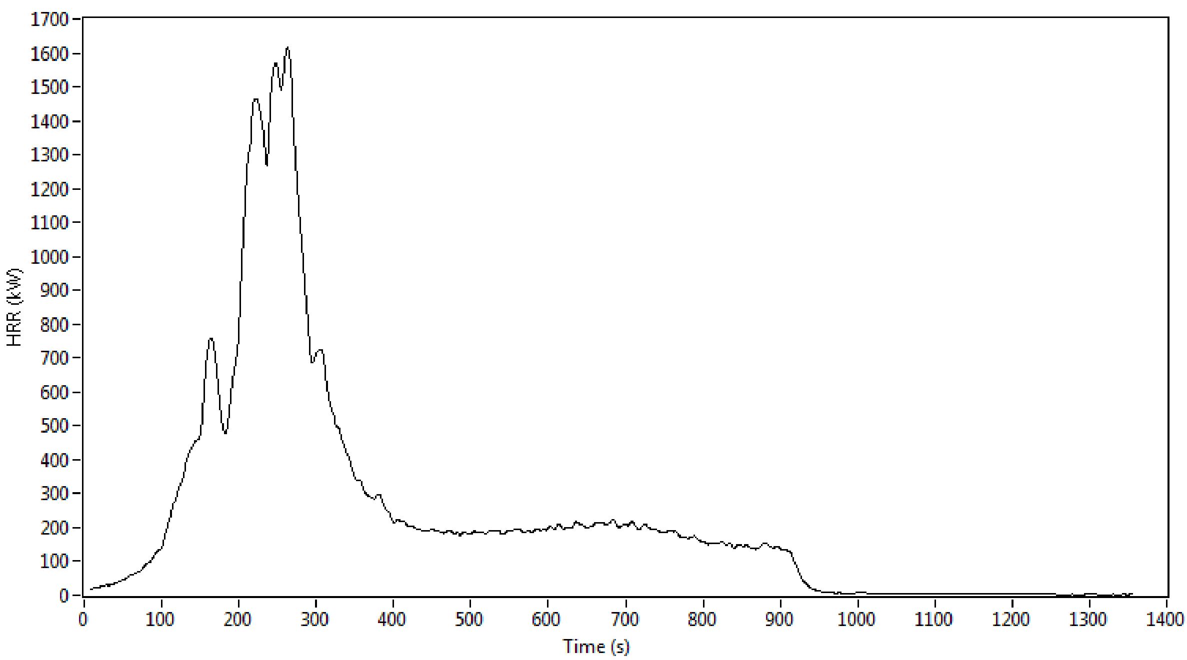

OF68
HRR (kW)
Time (s)

OF69

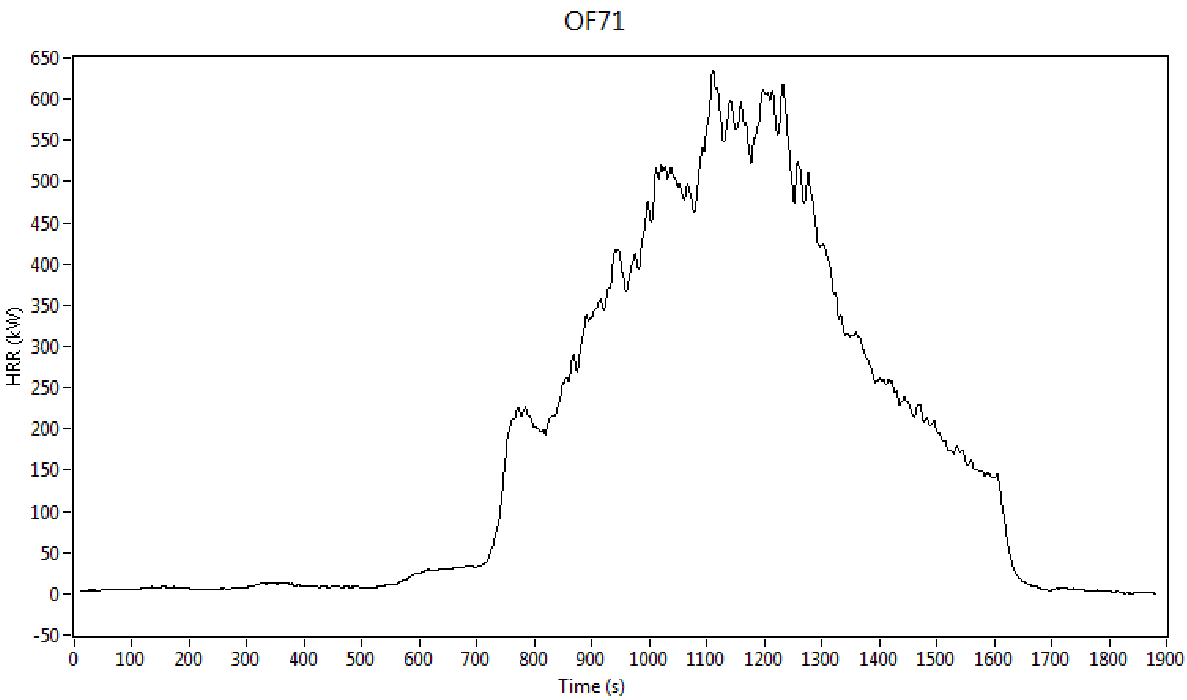


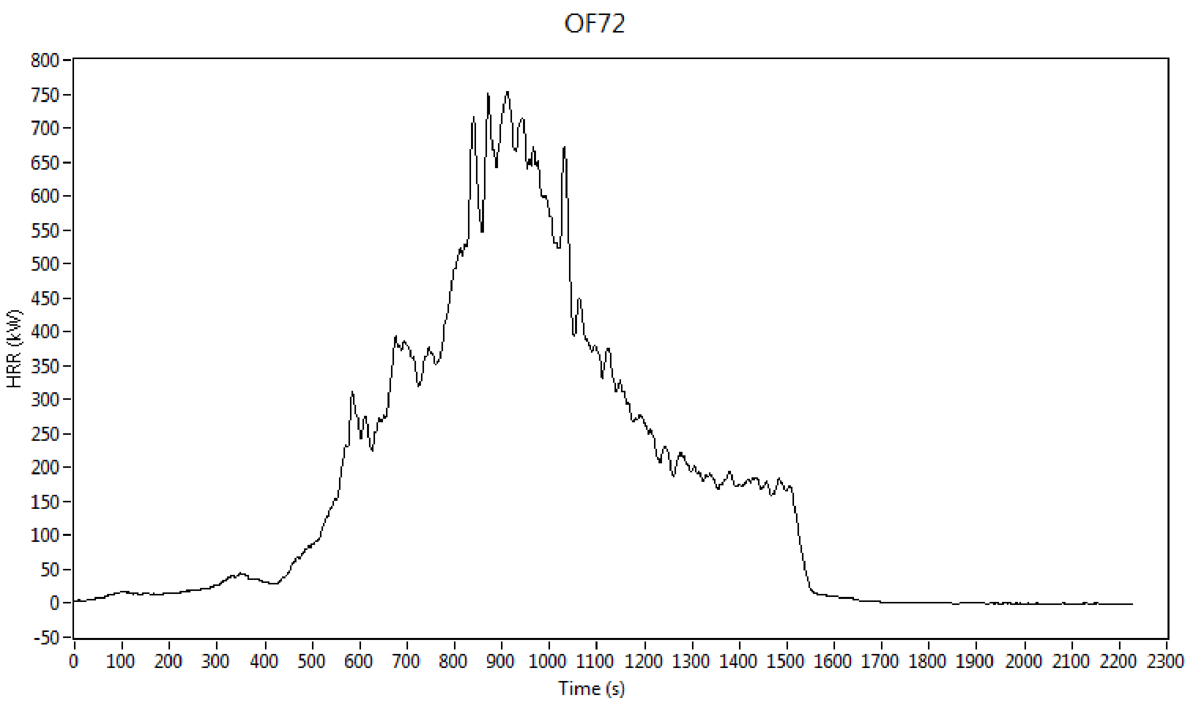
HRR (kW)
600
550
500
450
400
350
300
250
200
150
100
50
0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
Time (s)

OF70



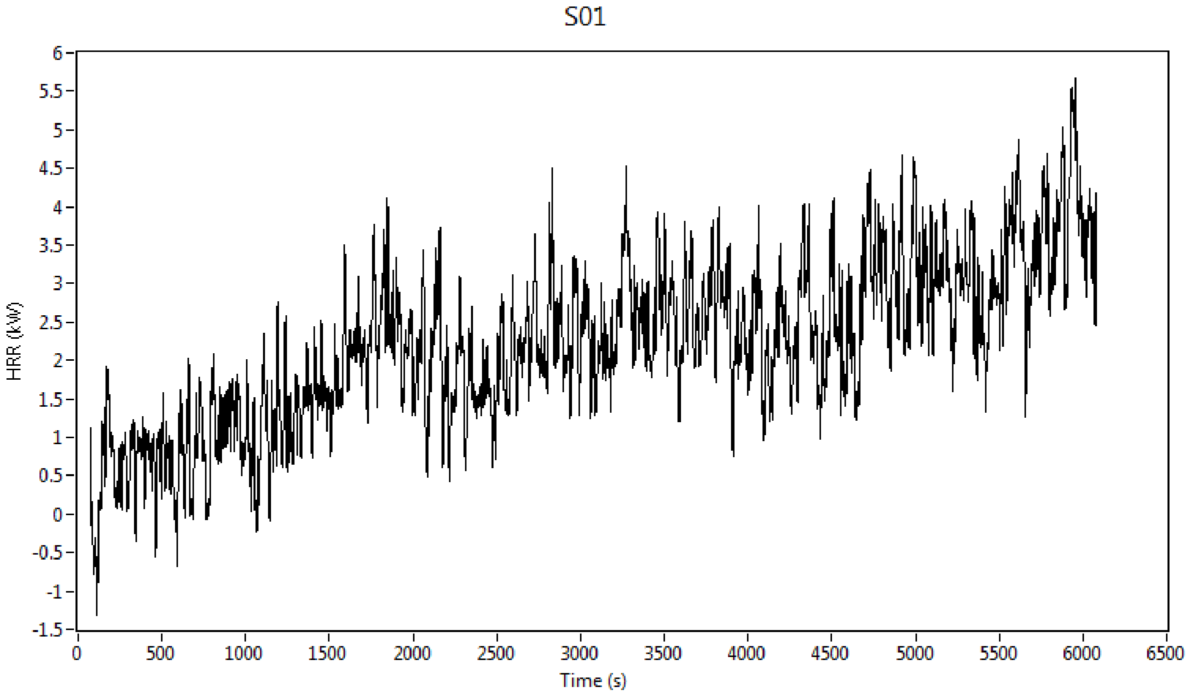
HRR (kW)
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
Time (s)

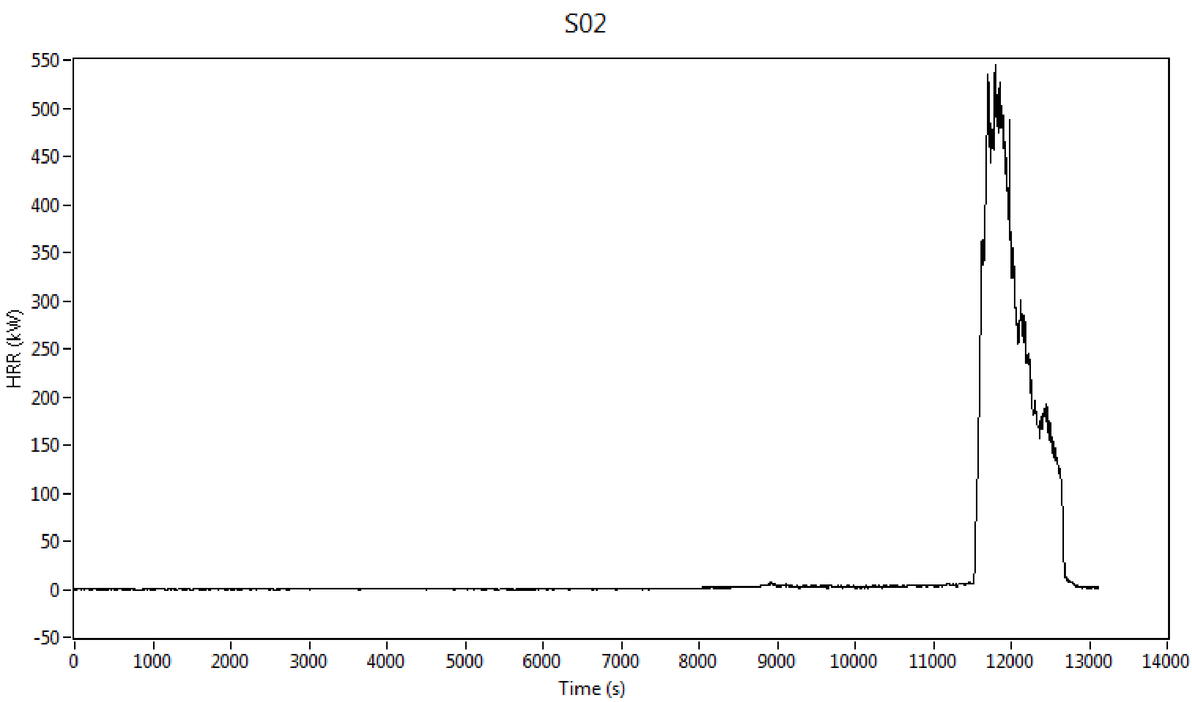

OF71
HRR (kW)
Time (s)

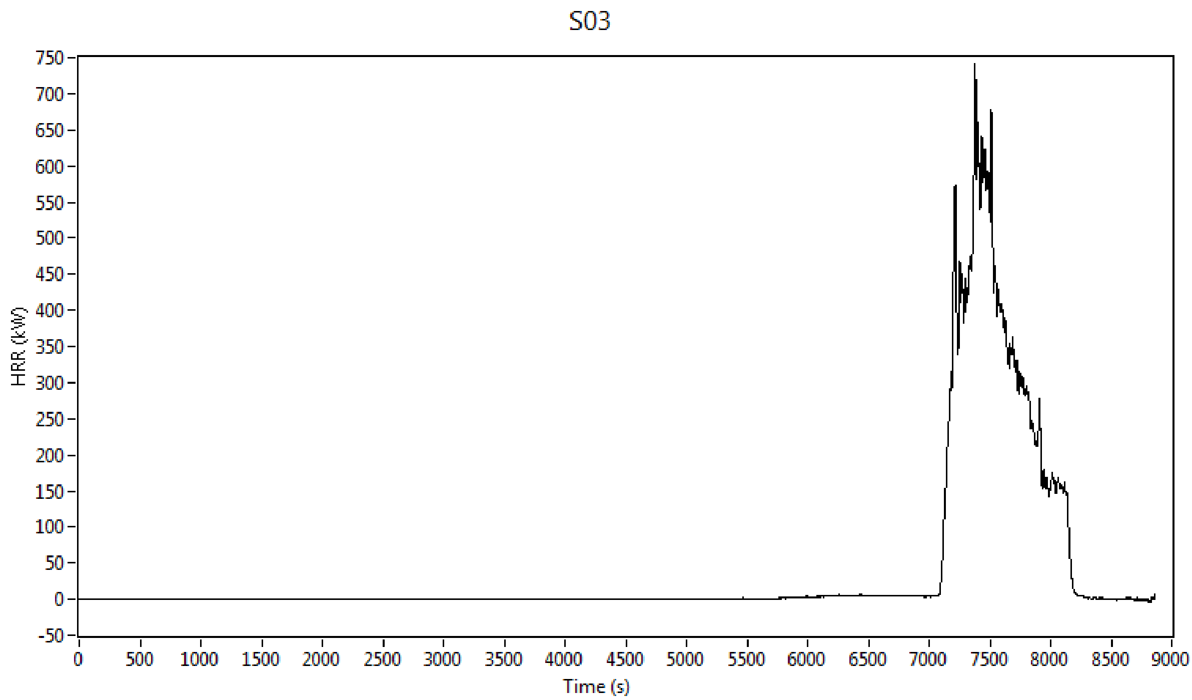

OF72
HRR (kW)
Time (s)

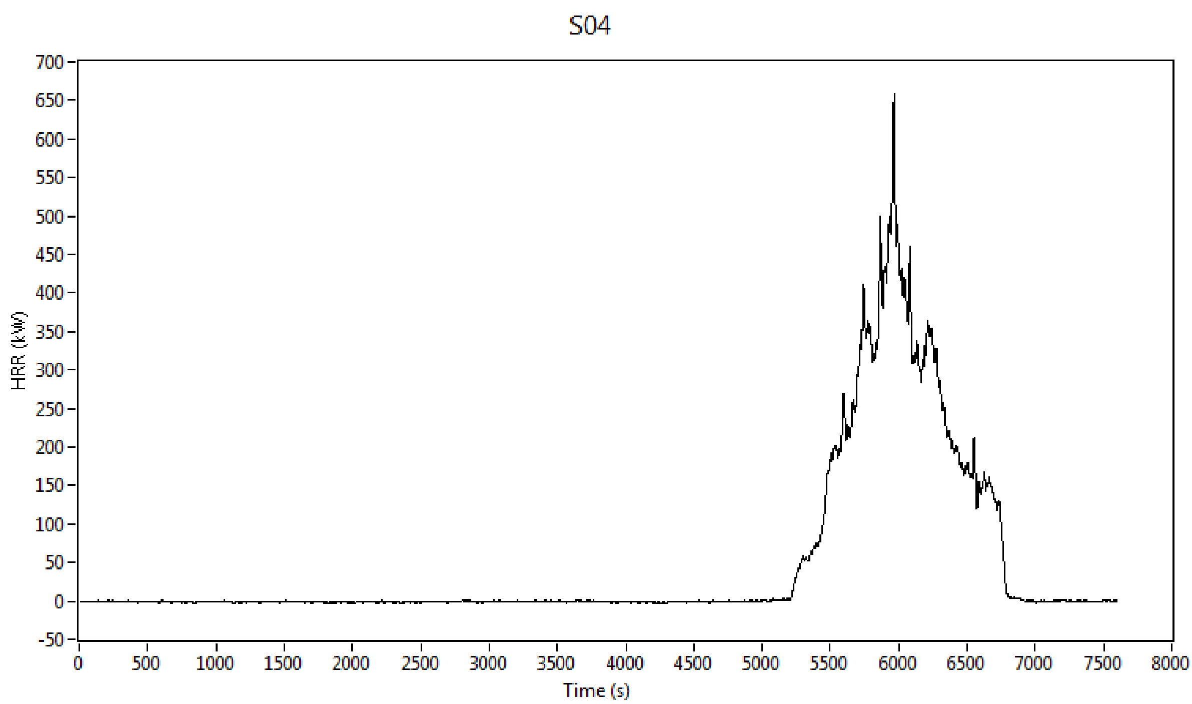
Appendix C

HRR Plots for smoldering chairs.

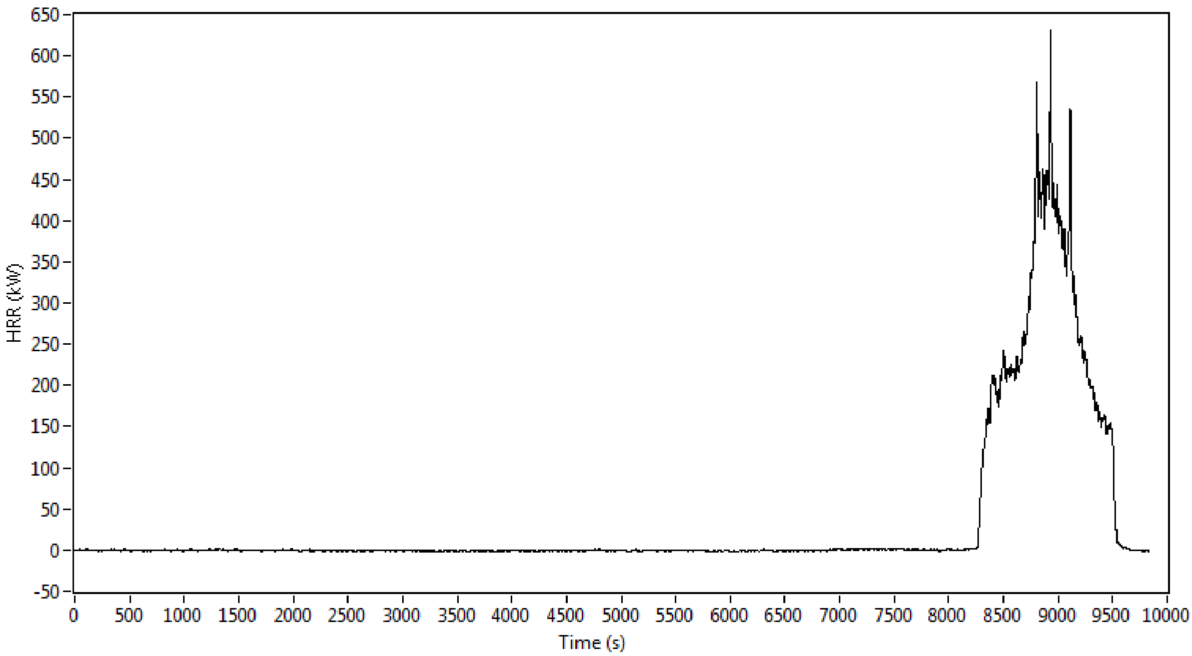




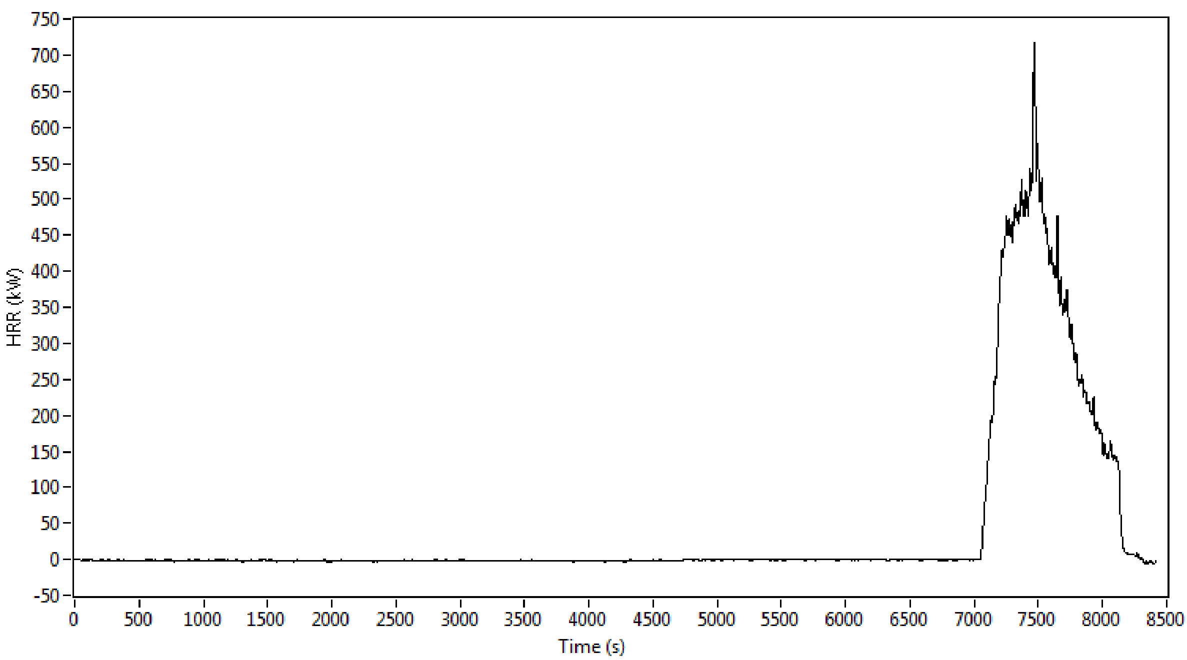

S03
HRR (kW)
Time (s)
750
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
-50
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
6500
7000
7500
8000
8500
9000

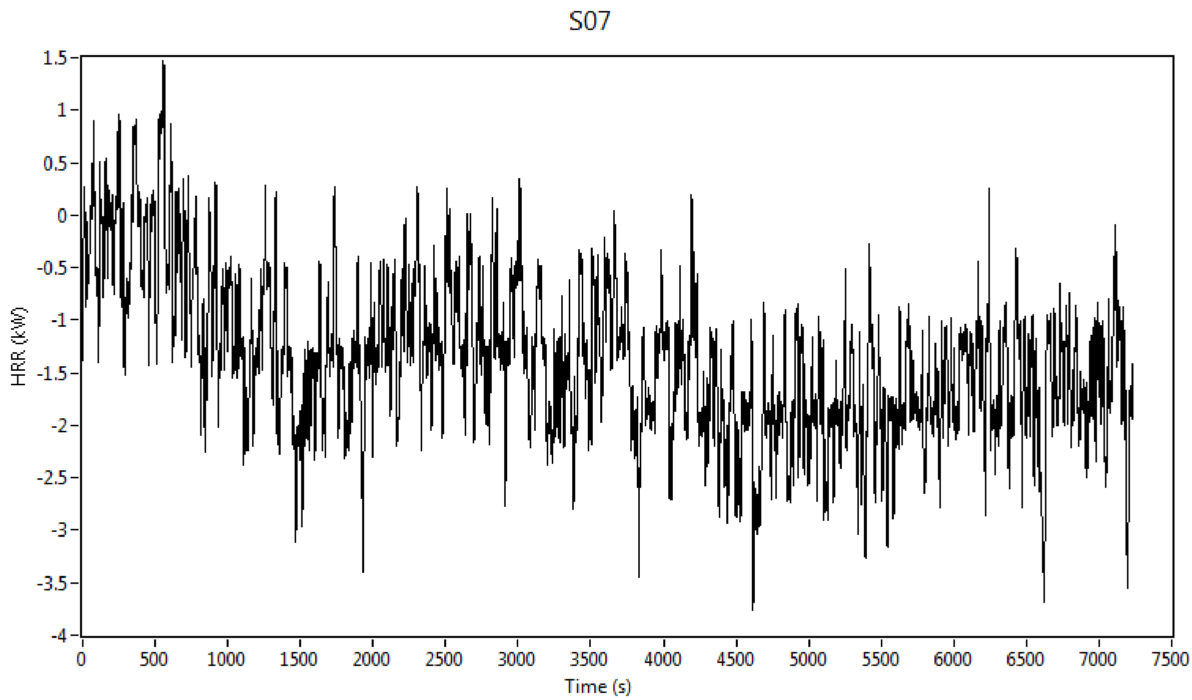

S04
HRR (kW)
Time (s)
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
-50
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
6500
7000
7500
8000

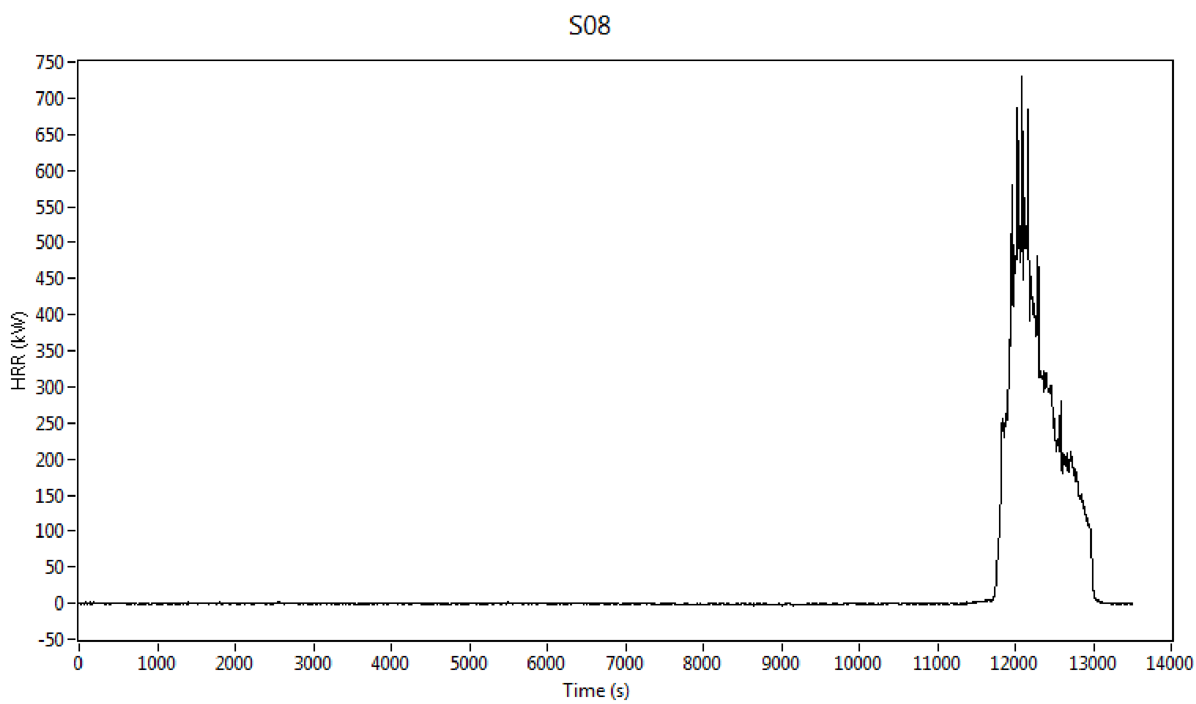
S05

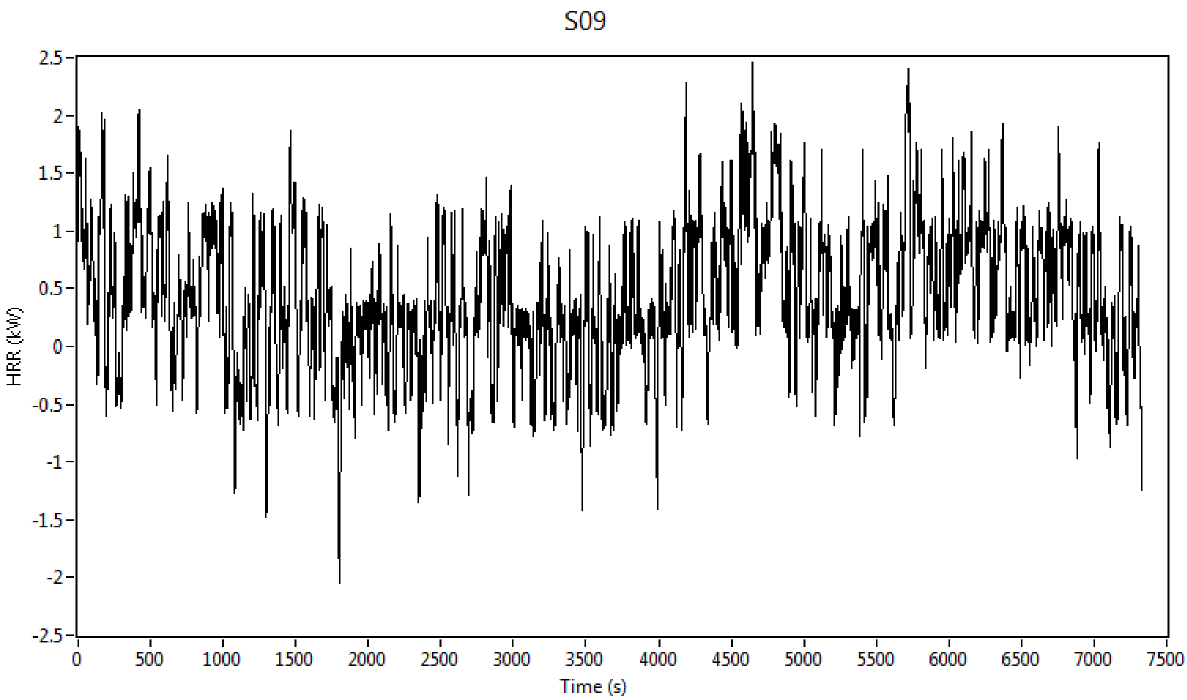

HRR (kW)
650
600
550
500
450
400
350
300
250
200
150
100
50
0
-50
0 500 1000 1500 2000 2500 3000 3500 4000 4500 5000 5500 6000 6500 7000 7500 8000 8500 9000 9500 10000
Time (s)

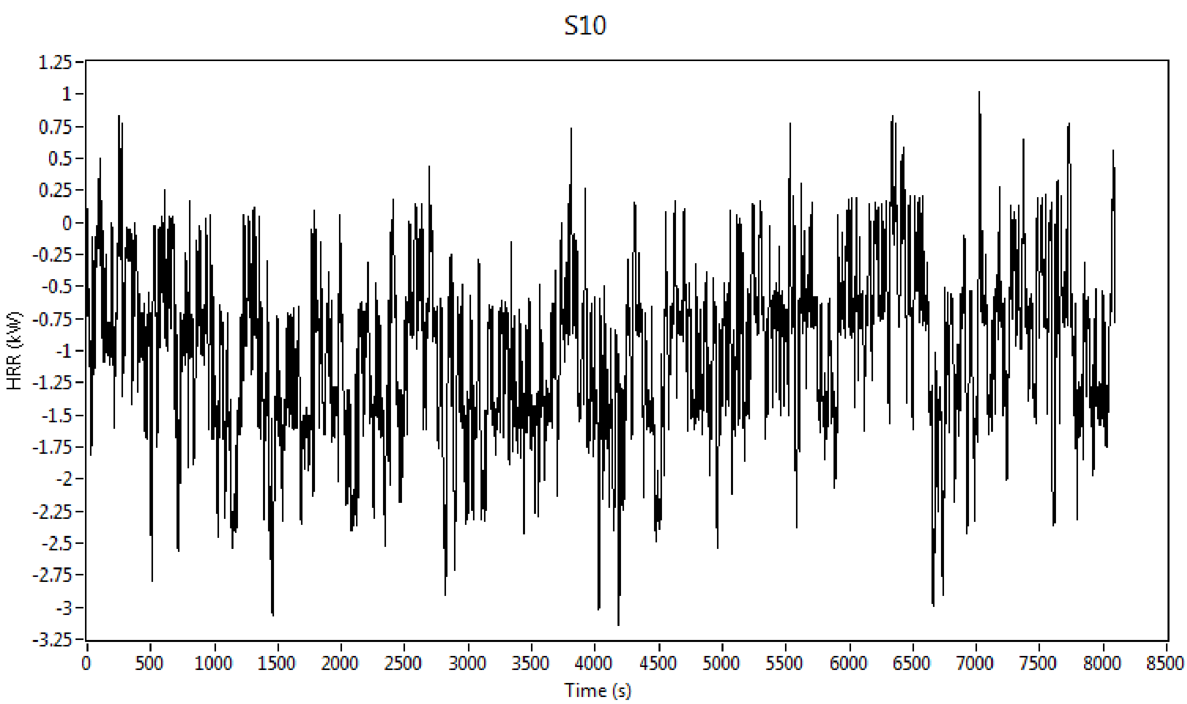
S06


HRR (kW)
750
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
-50
0 500 1000 1500 2000 2500 3000 3500 4000 4500 5000 5500 6000 6500 7000 7500 8000 8500
Time (s)


S07
HRR (kW)
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
6500
7000
7500
Time (s)


S08
HRR (kW)
750
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
-50
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
13000
14000
Time (s)


S09
HRR (kW)
Time (s)
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
6500
7000
7500


S10
HRR (kW)
Time (s)
1.25
1
0.75
0.5
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
-1.75
-2
-2.25
-2.5
-2.75
-3
-3.25
0
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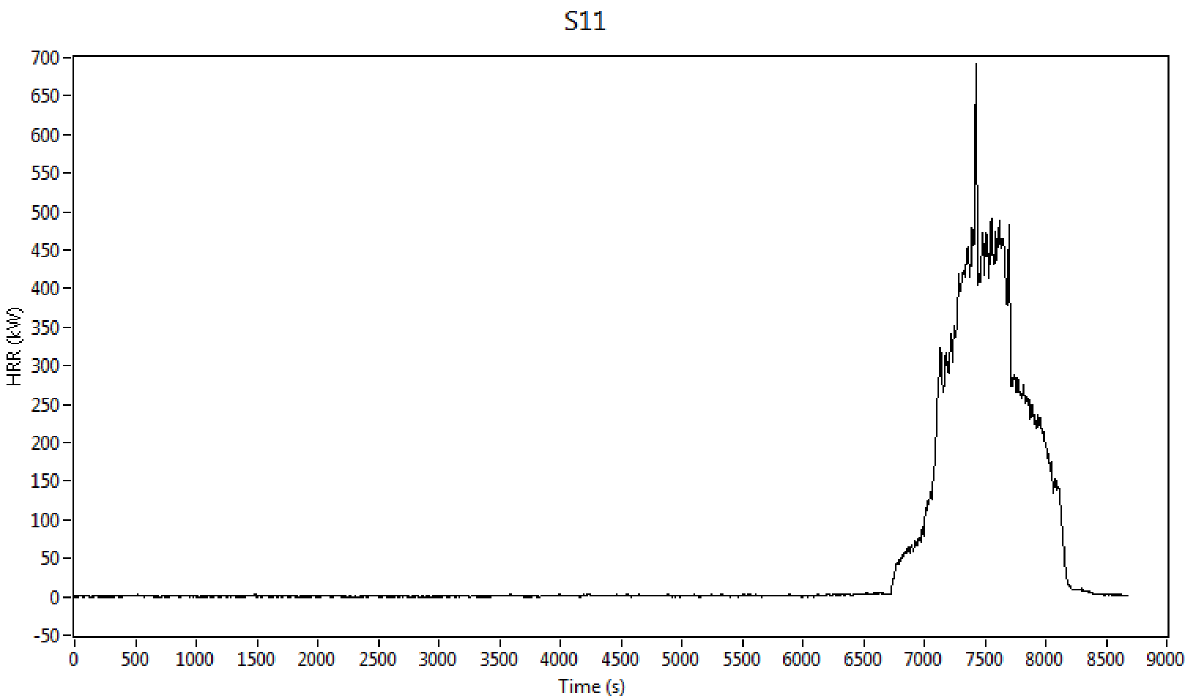
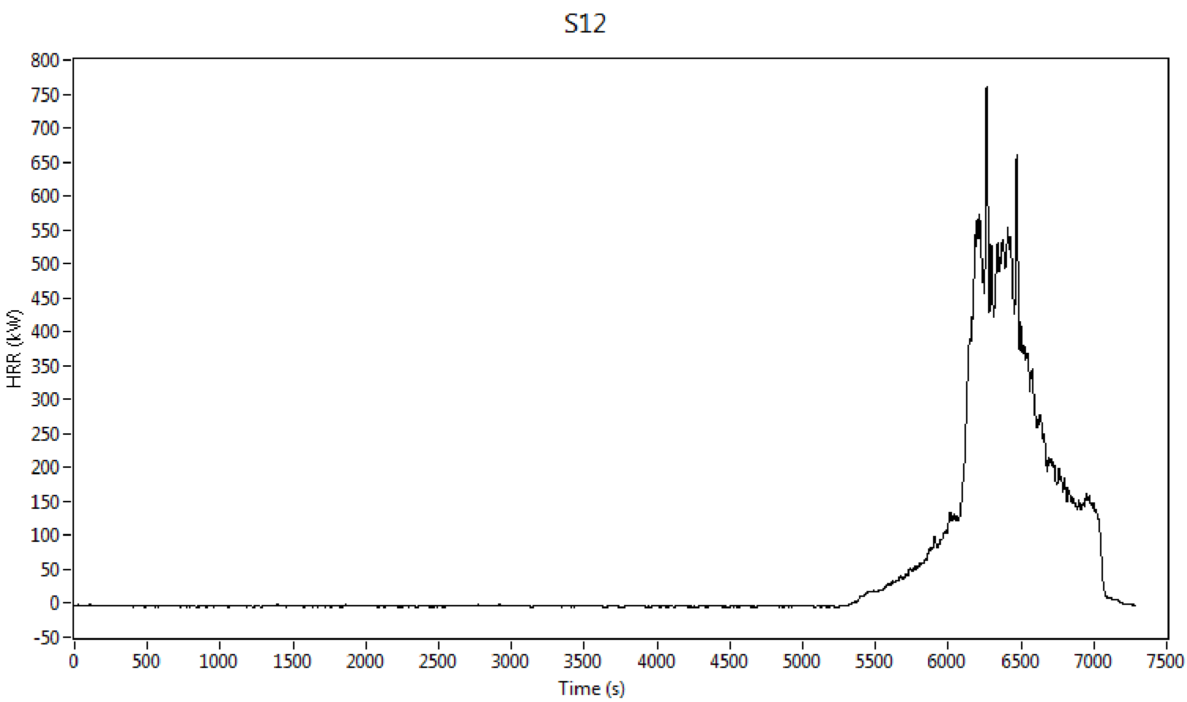
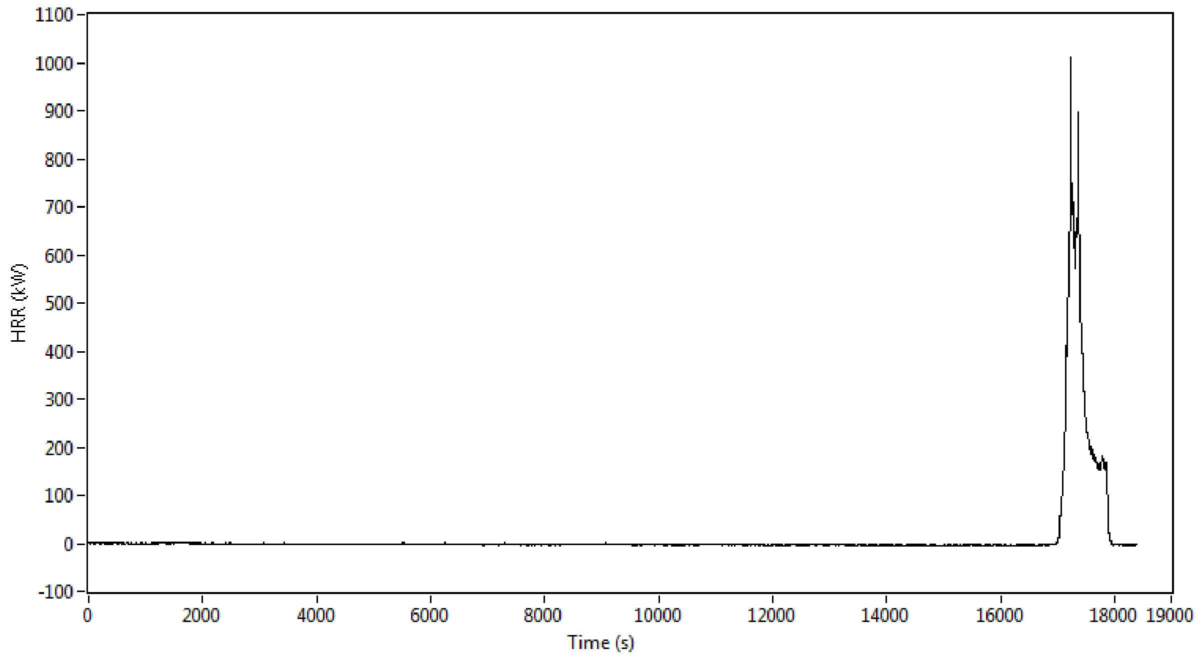
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
6500
7000
7500
8000
8500

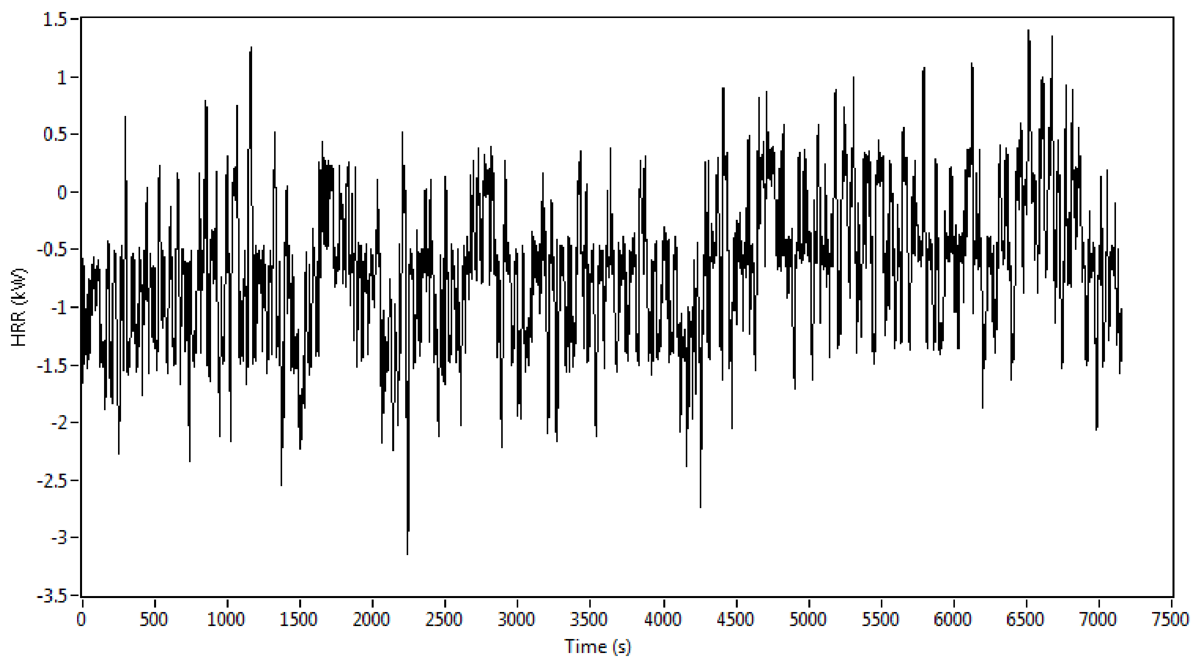

S11
HRR (kW)
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
-50
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
6500
7000
7500
8000
8500
9000
Time (s)


S12
HRR (kW)
800
750
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
-50
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
6500
7000
7500
Time (s)

S13


HRR (kW)
1100
1000
900
800
700
600
500
400
300
200
100
0
-100
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
19000
Time (s)

S14


HRR (kW)
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
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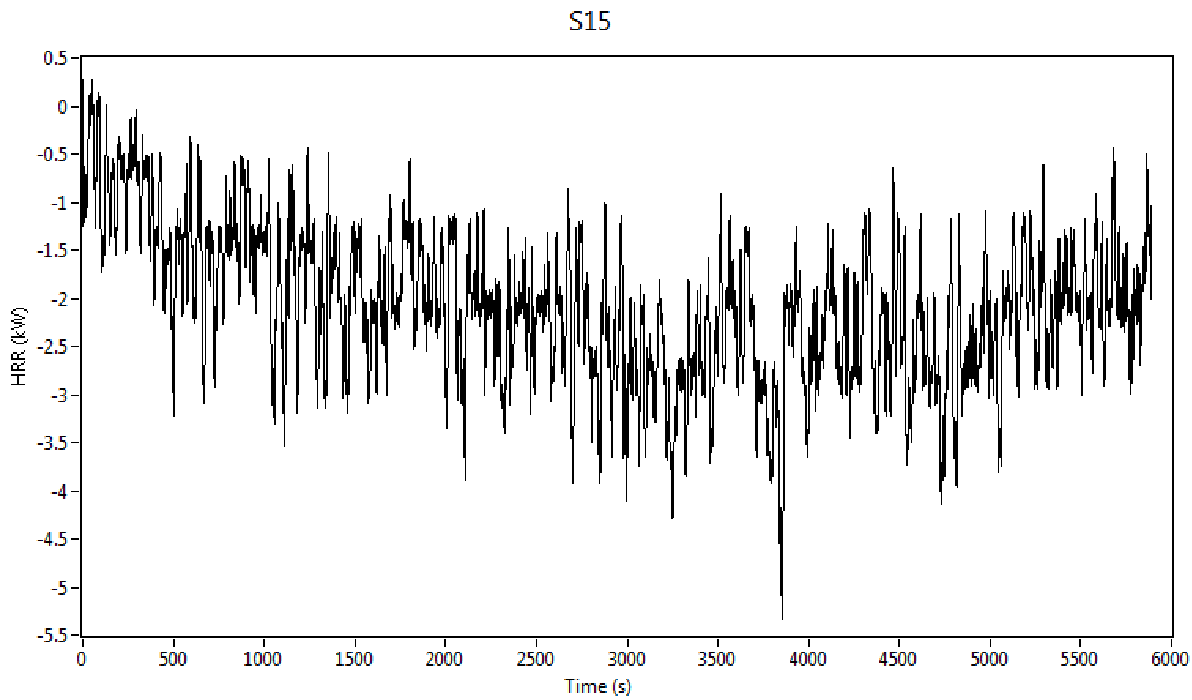
7000
7500
Time (s)


S15
HRR (kW)
Time (s)
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-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
-5
-5.5
0
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3000
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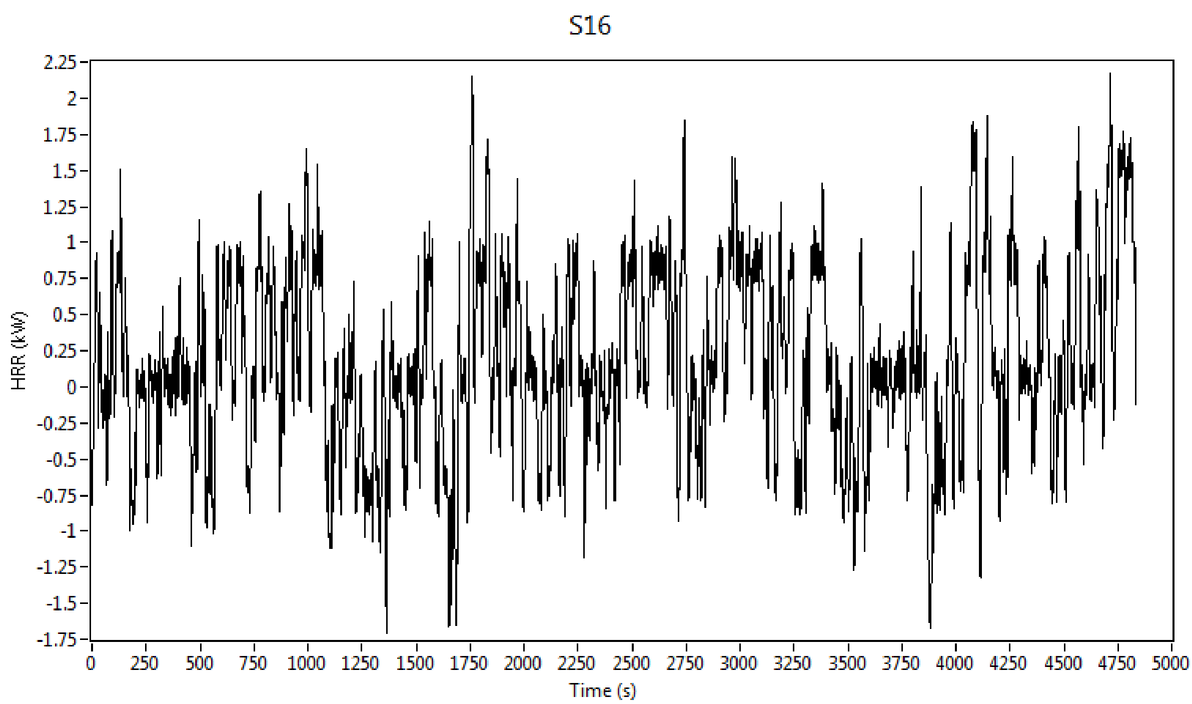
4000
4500
5000
5500
6000


S16
HRR (kW)
Time (s)
2.25
2
1.75
1.5
1.25
1
0.75
0.5
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
-1.75
0
250
500
750
1000
1250
1500
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2000
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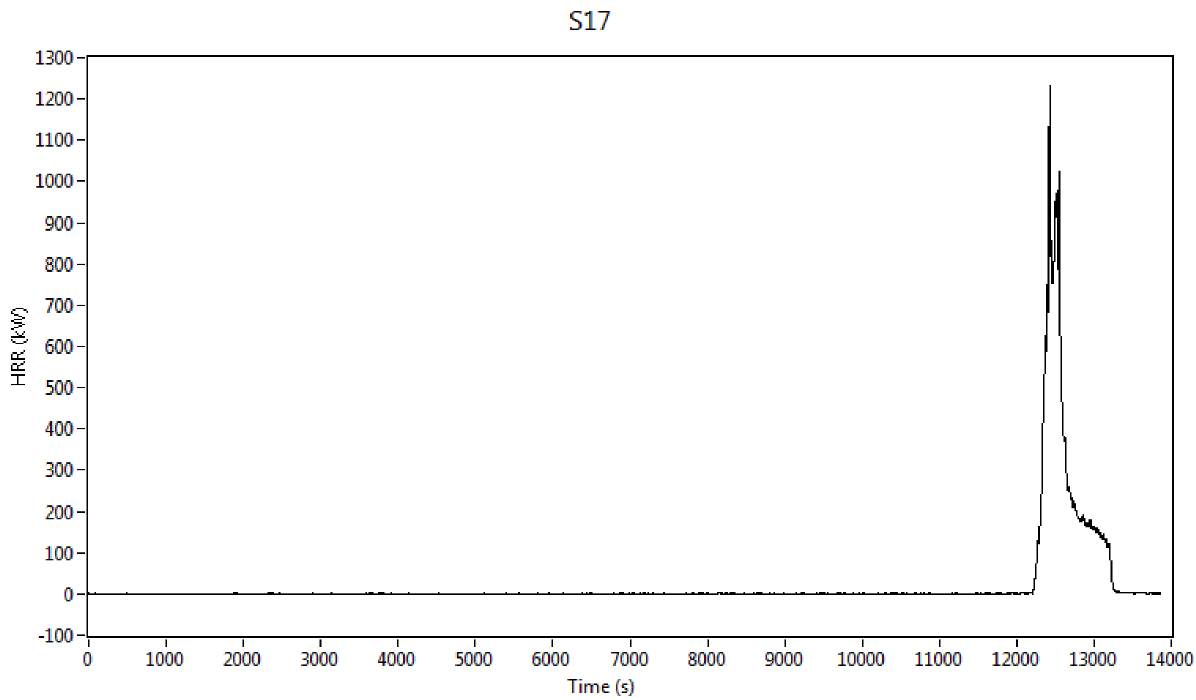
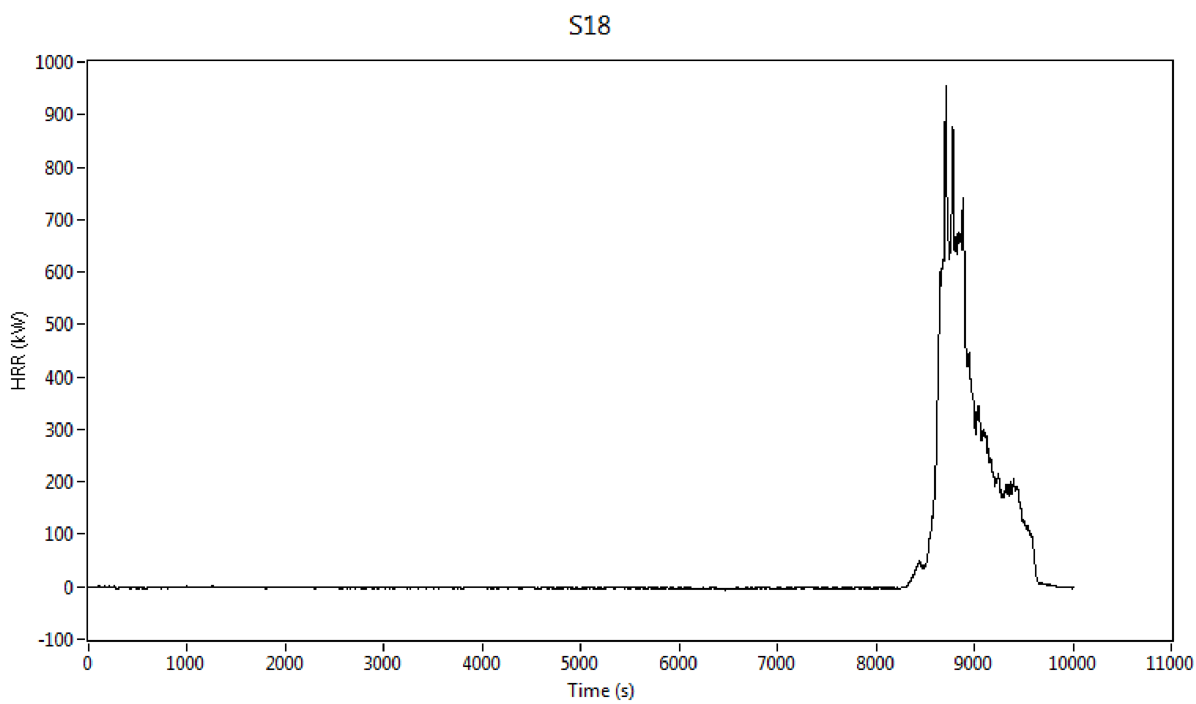
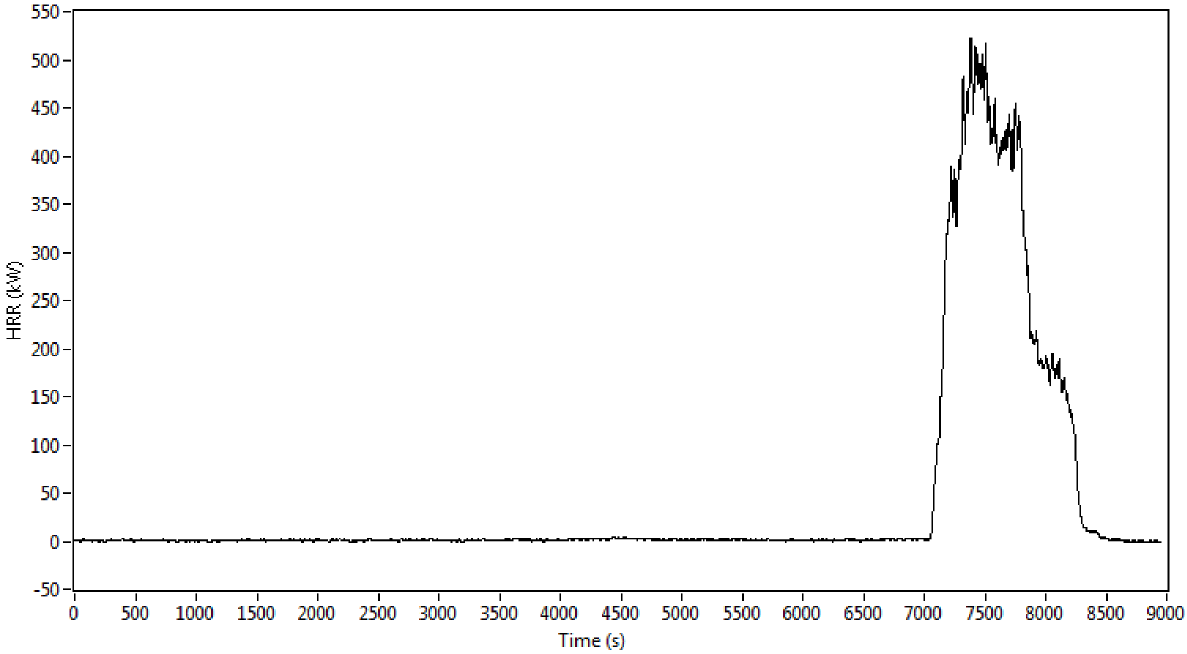
4250
4500
4750
5000


S17
HRR (kW)
Time (s)

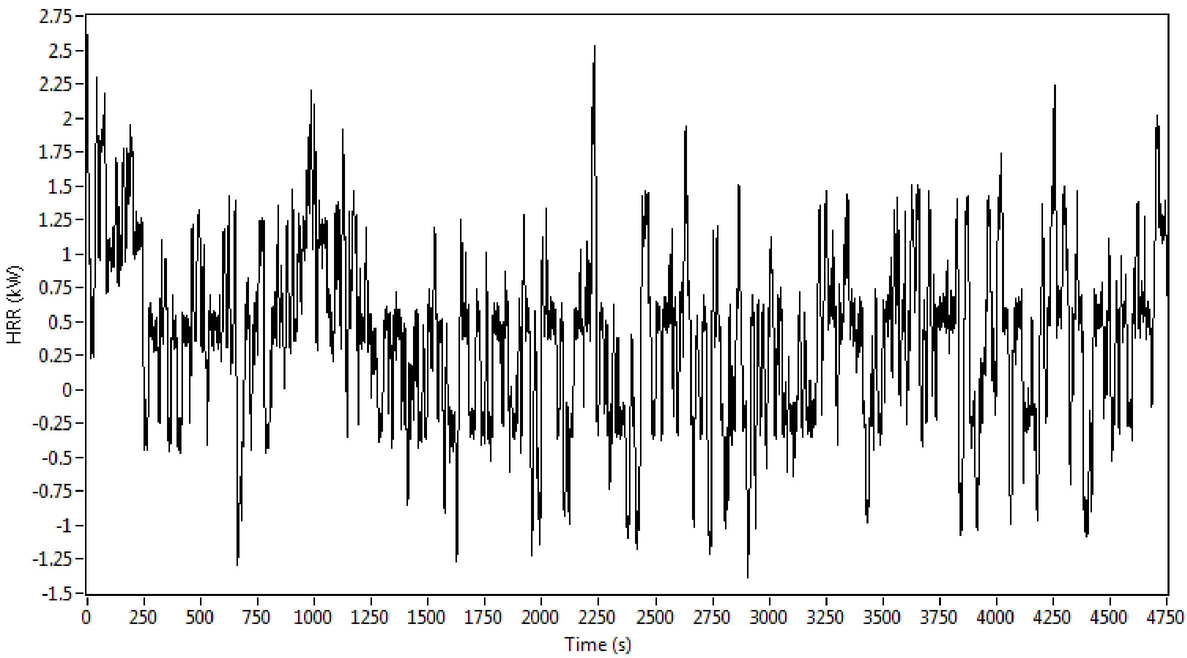

S18
HRR (kW)
Time (s)

S19

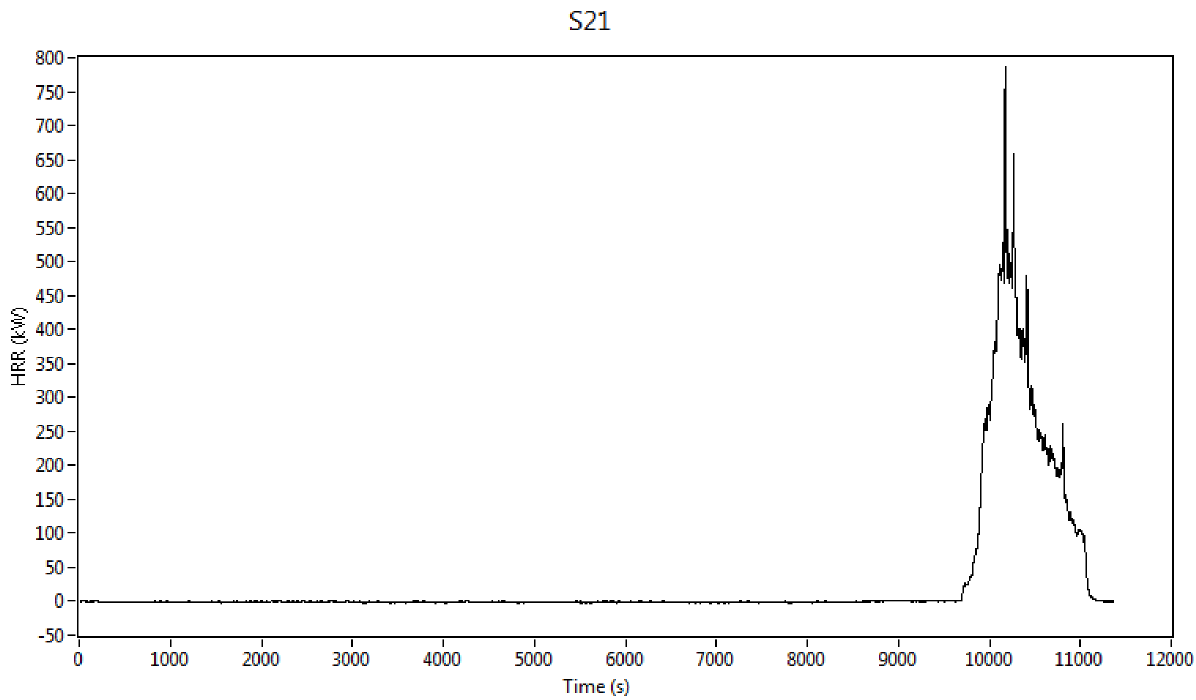


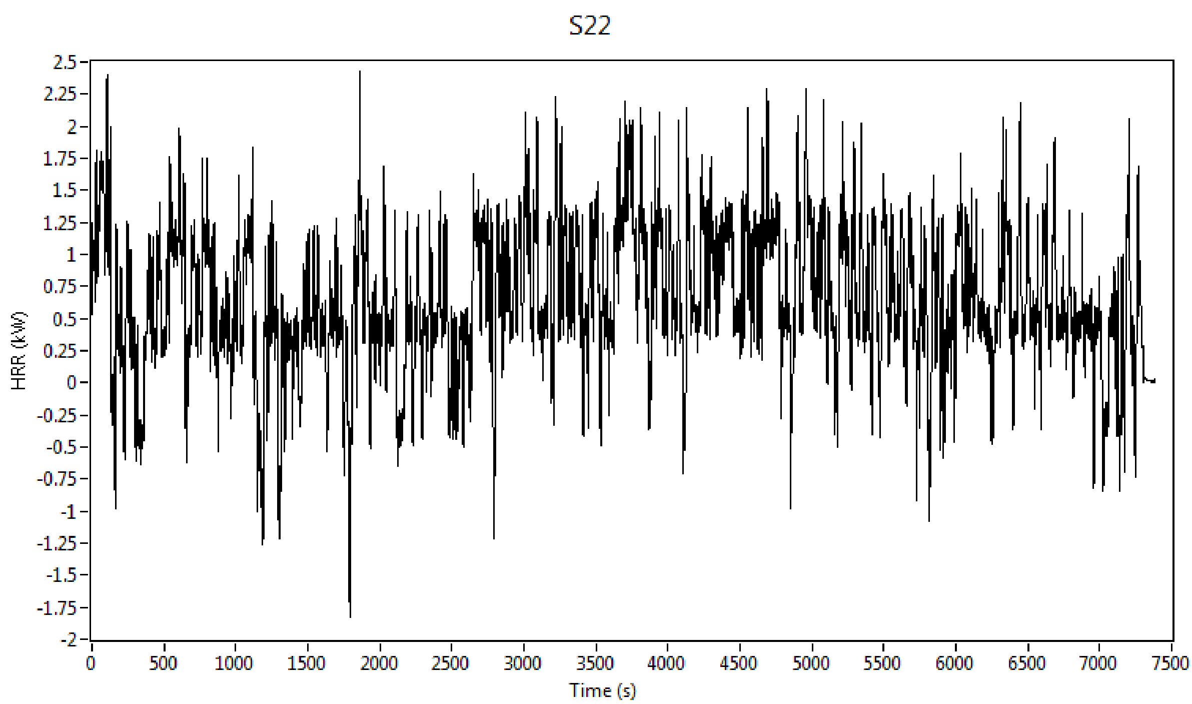
HRR (kW)
550
500
450
400
350
300
250
200
150
100
50
0
-50
0 500 1000 1500 2000 2500 3000 3500 4000 4500 5000 5500 6000 6500 7000 7500 8000 8500 9000
Time (s)

S20



HRR (kW)
2.75
2.5
2.25
2
1.75
1.5
1.25
1
0.75
0.5
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
0 250 500 750 1000 1250 1500 1750 2000 2250 2500 2750 3000 3250 3500 3750 4000 4250 4500 4750
Time (s)


S21
HRR (kW)
Time (s)
800
750
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
-50
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000


S22
HRR (kW)
Time (s)
2.5
2.25
2
1.75
1.5
1.25
1
0.75
0.5
0.25
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
-1.75
-2
0
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1000
1500
2000
2500
3000
3500
4000
4500
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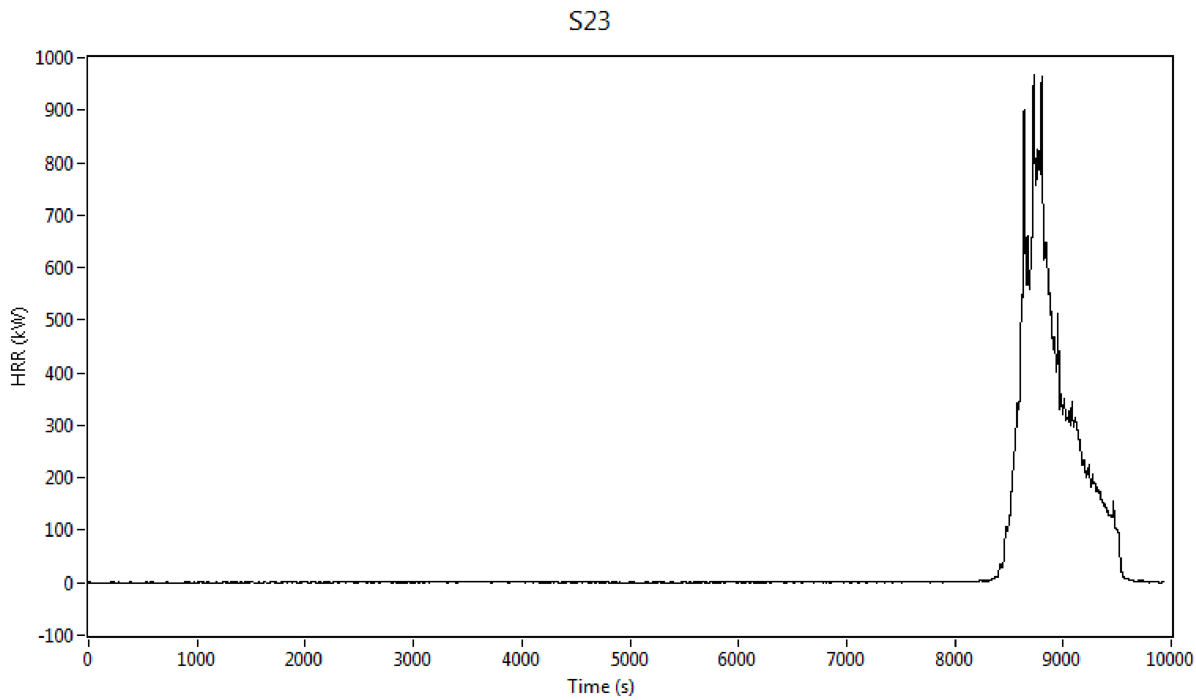
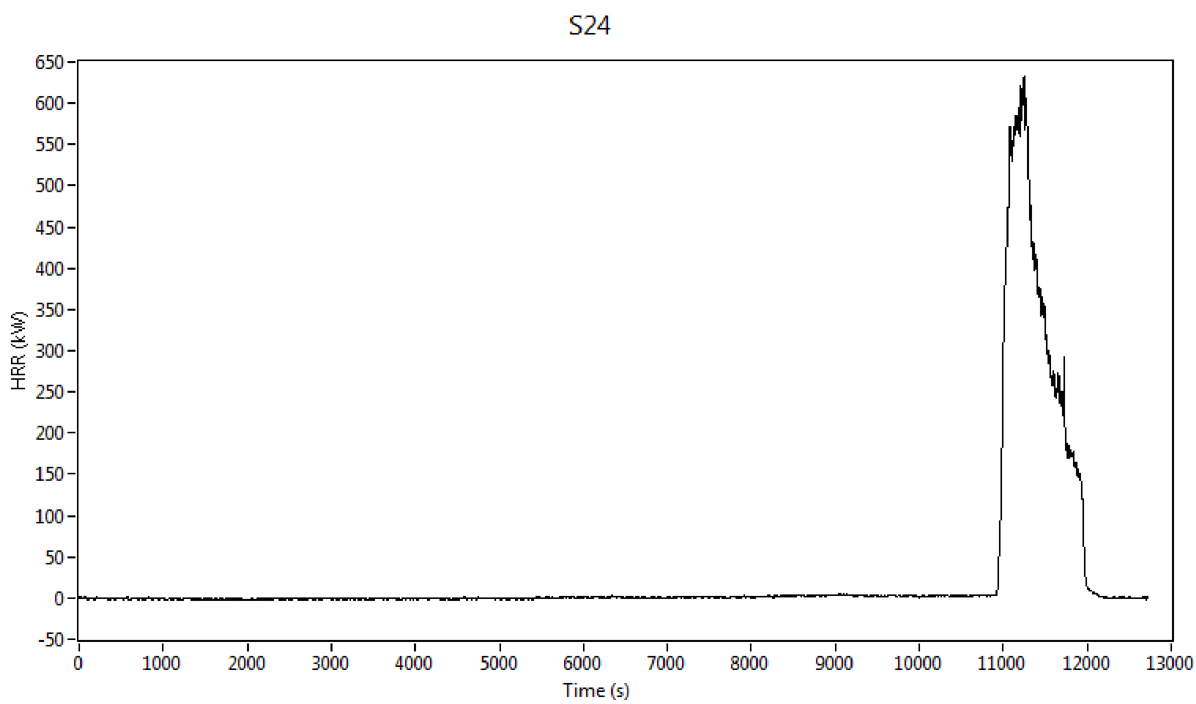
6000
6500
7000
7500


S23
HRR (kW)
1000
900
800
700
600
500
400
300
200
100
0
-100
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
Time (s)


S24
HRR (kW)
650
600
550
500
450
400
350
300
250
200
150
100
50
0
-50
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
13000
Time (s)

UNITED STATES
CONSUMER PRODUCT SAFETY COMMISSION
4330 EAST WEST HIGHWAY
BETHESDA, MD 20814

Memorandum

Date: January 22, 2016

TO: Andrew Lock Directorate for Laboratory Sciences
Upholstered Furniture Project Manager

THROUGH : Kathleen Stralka
Associate Executive Director
Directorate for Epidemiology

Stephen J. Hanway
Division Director
Division of Hazard Analysis

FROM: David Miller
Division of Hazard Analysis

SUBJECT: Analysis of Chair Open-Flame and Smoldering Data

Background:

In March 2008, the U.S. Consumer Product Safety Commission ("CPSC") issued a notice of proposed rulemaking ("NPR") for a standard for the Flammability of Residential Upholstered Furniture. As part of an effort to develop such a standard, CPSC staff has conducted bench-scale and full-scale testing, reviewed data, and considered different approaches to reducing the upholstered furniture fire risk to consumers. Staff conducted a recent test program to evaluate the potential effectiveness of fire barriers at CPSC's National Product Testing and Evaluation Center involving full-scale chairs[1] and open-flame, as well as cigarette-ignition sources.

Purpose:

The main purpose of this testing is to assess the effectiveness of a convenience sample of fire barriers in reducing the intensity and slowing the progress of full-scale chair fires. The testing was also designed to assess the effect of different chair fabrics and the age of the chair (age was simulated by using mechanical stressing). The testing evaluated these factors separately for open-flame and smoldering (cigarette) ignition sources.

[1] Full-scale chairs means actual, full-size chairs, as opposed to miniature, mockup chairs for testing.

Test Program

Staff conducted two different sets of tests. One was open-flame testing, where a 240-millimeter butane flame was applied to a chair for 70 $\pm$ 1 seconds[2]. During these tests, the heat release rate was monitored throughout. The other set of tests are smoldering tests, where two lit cigarettes are placed on each of four locations (left side crevice, right side crevice, back crevice, and seating surface) on a chair and allowed to continue burning until all cigarettes self-extinguished or the chair reached a peak heat release rate (PHRR). During these tests, the heat release rate was monitored, and at the end of the tests, char measurements were taken for each cigarette. The barriers and fabrics that were selected for testing were not randomly selected from a larger pool of barriers and fabrics. Therefore, the conclusions are limited to the barriers and fabrics that were tested.

Preview of Findings:

Open-Flame Testing: The tests showed that each of the five tested barriers were effective at reducing the intensity of open-flame chair fires. The barriers also proved effective at slowing the progress of open flame chair fires. The cover fabric also made a difference in the size and rate of progress of open-flame chair fires.

Smoldering Testing: Although the smoldering testing did not produce statistically significant differences, a higher proportion of the chairs with barriers transitioned to flaming, as opposed to the chairs without barriers. Additionally, of the smoldering chairs that transitioned to flaming, the ones with barriers did so more quickly than the chairs without barriers. The possibility of barriers expediting a transition to flaming will be an issue to explore in future testing. There was a large difference in the proportion of chairs of one fabric that transitioned to flaming, as opposed to the chairs with the other fabric.

Results and Analysis:

A. Open-Flame Testing:

Independent Variables:

- Fire barriers: there were five different fire barriers (FB1, FB2, FB3, FB4, FB5) being evaluated, and some chairs had no fire barrier[3]. Consequently, there were six different possibilities for a chair's fire barrier.

- Cover fabric: there were two different cover fabrics (F2, F3) used in the chairs for the open-flame tests.

- Age: aging is simulated by the mechanical stressing of chairs. There are two possibilities for this variable ('YES' - chairs that were mechanically stressed; 'NO' – chairs that were not stressed). Stressed chairs will also be referred to as "old," whereas, chairs that were not stressed are referred to as "new."

[2] BS-5852, Methods of Test for Assessment of the Ignitability of Upholstered Seating by Smoldering and Flaming Ignition Sources. 1990.
[3] No fire barrier or no barrier is referred to as FB6 in the technical memo

Dependent Variables:

- Peak Heat Release Rate (PHRR)

- Time to Peak Heat Release Rate (Time to Peak)

<u>Test Plan:</u>

The design of experiments (DOE) called for three replicates of each combination of barrier, fabric, and age (mechanically stressed or not). There are 6*2*2 = 24 combinations. Three replicates of each of 24 combinations means 72 chairs were tested. The DOE was conceived to produce an analysis of variance (ANOVA) for both PHRR and Time to Peak and to be able to compare the effect of each fire barrier to the "no barrier" chairs for both PHRR and Time to Peak. The test was not set up to compare fire barriers to each other.

Table 1. Plan for Open-Flame Chair Testing

		Number of Chairs	
Fire Barrier	**Cover Fabric**	**Mechanically Stressed**	**Non-Stressed**
None	F2	3	3
None	F3	3	3
FB1	F2	3	3
FB1	F3	3	3
FB2	F2	3	3
FB2	F3	3	3
FB3	F2	3	3
FB3	F3	3	3
FB4	F2	3	3
FB4	F3	3	3
FB5	F2	3	3
FB5	F3	3	3

When testing began, staff learned that some chairs were not built with the specifications they were labeled. Additionally, for nine of the chairs that were tested, staff was unable to confirm which barriers were used in the chair. Due to the uncertainty about the barriers, staff excluded these nine chairs from the analysis.

Table 2. Characteristics of Chairs Included in Analysis for Open-Flame Tests

Fire Barrier	Cover Fabric	Number of Chairs	
		Mechanically Stressed	Non-Stressed
None	F2	2	2
None	F3	3	3
FB1	F2	2	2
FB1	F3	1	3
FB2	F2	3	2
FB2	F3	3	1
FB3	F2	3	3
FB3	F3	3	2
FB4	F2	3	4
FB4	F3	4	2
FB5	F2	3	3
FB5	F3	2	4

Although the specifications of the chairs tested did not match the DOE exactly, the analysis proceeded with the 63 chairs for which the barrier (or 'no barrier') was known.

Peak Heat Release Rate (PHRR):

Staff performed an analysis of variance (ANOVA) with PHRR as the dependent variable and barrier, fabric, and age as the independent variables. Model selection began with the full model. In the full model, there are three main effects (barrier, fabric, and age) and four interactions: one three-way interaction and three two-way interactions (barrier*fabric, barrier*age, and fabric*age). Interaction terms were eliminated if their p-values were greater than 0.25. This led to a model with the three main effects and two interactions: barrier*fabric and fabric*age.

Chairs that did not Ignite:

Of the 63 chairs tested with an open flame for which the correct barrier (or "no barrier") was identified, 56 ignited. Seven did not ignite. The chairs that did not ignite had a Peak Heat Release Rate (PHRR) between 3 kilowatts and 14 kilowatts. The 56 chairs that did ignite had a PHRR between 469 kilowatts and 2,003 kilowatts. Of the seven chairs that did not ignite, six were chairs that had Fire Barrier 2 (FB2). The other chair that did not ignite had FB3. Although the chairs that did not ignite had much lower PHRRs than those that did, they were included in the data for the PHRR analysis. One of the ways that a fire barrier can be effective is to prevent ignition. It appears that FB2 was effective in this way. It makes sense for the chairs that did not ignite to have lower PHRR numbers and for FB2 to get "credit" for this. This may seem obvious, but it merits mentioning, nevertheless, because of the different way chairs that did not ignite were treated in the smoldering testing analysis.

Assessing normality:
In an ANOVA, the residuals[4] are assumed to be distributed normally. Three goodness-of-fit tests[5] for normality were run on this model. All three tests had p-values above 0.05, which suggests an approximately normal distribution.

[4] A *residual* is the difference between an observation and the mean for the variable grouping for that observation.

Table 3. PHRR Residual Goodness-of-Fit Tests for the Normal Distribution

Goodness-of-Fit Test	P-value
Kolmogrov-Smirnov	>0.150
Cramer-von Mises	0.073
Anderson-Darling	0.053

Interactions:

In an ANOVA, before evaluating the main effects, one looks at the interactions. Staff decided to leave interactions in the model, if their p-value was below 0.25. The three-way interaction was removed from the model because its p-value was 0.387; and barrier*stress was removed because its p-value was 0.497.

Table 4. Peak Heat Release Rate Model Interactions

Interaction	F-value	df	P-value
Barrier*Fabric	1.44	5	0.2264
Fabric*Age	1.41	1	0.2416

Neither of these interactions (barrier*fabric and fabric*age) that were left in the model are significant at the .05 level.

Main effects:

The main effects are the effects that each individual variable has on PHRR (aside from the interactions). The main effects in this model are fire barrier, fabric, and age. The fire barrier and fabric effects are statistically significant, but the age effect is not.

Table 5. Peak Heat Release Rate[6] Main Effects

Effect	Estimate	95% Confidence Interval	Standard Error	P-value
Fire Barrier	FB1 = -1,120.3	FB1 = (-1,399.8, -840.9)	139.1	< 0.0001
	FB2 = -1,483.2	FB2 = (-1,762.6, -1,203.7)	139.1	< 0.0001
	FB3 = -767.0	FB3 = (-1,026.8, -507.1)	129.3	< 0.0001
	FB4 = -1,008.1	FB4 = (-1,256.9, -759.4)	123.8	< 0.0001
	FB5 = -996.7	FB5 = (-1,245.5, -748.0)	123.8	< 0.0001
Fabric	F2 = -532.4	F2 = (-830.5,-234.2)	148.4	0.0008
Age	Not stressed = -11.7	Not stressed = (-175.1, 151.7)	81.3	0.89

The ANOVA model demonstrates strongly significant fire barrier and fabric effects. The estimates for fire barriers are relative to "No Barrier" Another way of saying this is that "No Barrier" is the baseline for the barrier variable. For example, the estimate of -1,120.3 for FB1 says that having a chair with the fire barrier FB1 means an estimated 1,120.3 kW lower PHRR for that chair than if it had no barrier. The corresponding 95 percent confidence interval for FB1 shows a range of 840.9 kW to 1,399.8 kW for this

[5] A *goodness-of-fit test* is a statistical hypothesis test used to assess how well data fit a probability distribution. In this case, the data are being evaluated to see how well they fit the normal distribution because ANOVA assumes normally distributed residuals.

[6] In kilowatts (kW)

effect. The estimate for fabric is relative to F3. Fabric 3 is the baseline level for the fabric variable. Chairs with the F2 cover fabric have an estimated effect of a 532.4 kW lower PHRR than chairs with the F3 cover fabric.

The p-value for age is 0.88 and not statistically significant. The estimate of -11.7 is relative to the stressed chairs. "Stressed" is the baseline level for the age variable. The 95 percent confidence interval for age shows numbers on either side of zero.

PHRR Model Estimates:

The PHRR model is an Analysis of Variance model with the three main effects (barrier, fabric, and age) and two interactions (barrier*fabric and fabric*age). Neither interaction is statistically significant, but each remains in the model because each has p-values below 0.25. The ANOVA model is below:

Estimated PHRR = Intercept + Barrier Effect + Fabric Effect + Age Effect + Fabric*Age + Barrier*Fabric

The intercept is the estimated peak heat release rate (PHRR) of a chair at all the baseline levels for the variables. The baseline levels are chairs with "No Barrier," cover fabric F2, and mechanically stressed. Our ANOVA provides estimates for the intercept and subsequent main effects and interactions. The R-squared value for the model is 0.843.

Table 6. Peak Heat Release Rate Model Parameter Estimates

Parameter	Estimate	Confidence Interval
Intercept	1,850.9	(1,657.9, 2,043.8)
Fire Barrier 1	-1,120.3	(-1,399.8, -840.9)
Fire Barrier 2	-1,483.2	(-1,762.6, -1,203.7)
Fire Barrier 3	-767.0	(-1,026.8, -507.1)
Fire Barrier 4	-1,008.1	(-1,256.9, -759.4)
Fire Barrier 5	-996.7	(-1,245.5, -748.0)
Cover Fabric 2	-532.4	(-830.5, -234.2)
New (Not Stressed)	-11.7	(-175.1, 151.7)
Fabric 2 * Not Stressed	131.7	(-91.6, 355.1)
Fire Barrier 1*Fabric 2	316.3	(-95.7, 728.4)
Fire Barrier 2*Fabric 2	219.5	(-181.6, 620.5)
Fire Barrier 3*Fabric 2	42.1	(-337.2, 421.5)
Fire Barrier 4*Fabric 2	304.9	(-61.2, 671.0)
Fire Barrier 5*Fabric 2	388.9	(17.0, 760.8)

So, for example, for a chair with fire barrier 4, cover fabric 2, that has been mechanically stressed, the model estimates a Peak Heat Release Rate of 1,850.9 + (-1,008.1) + (-532.4) + (304.9) = 615.3 kW.

To give perspective, a small camp fire has a heat release rate of about 100 kW and a 1,000 kW fire is often looked at as a critical fire size where the room will likely reach flashover. A flashover is a catastrophic fire where the entire room is on fire.

Barrier Effectiveness:

The main purpose of the study is to assess the effectiveness of the barriers in reducing the intensity and slowing the progress of full-scale chair fires. Looking at the effect of fire barriers on Peak Heat Release

Rate (PHRR) addresses the “reducing-the-intensity” part. Staff decided before the testing began that barriers would be compared using statistical inference to the “no barrier” chairs, but not to each other. Figure 1 shows the average PHRR by barrier and includes 95 percent confidence intervals. Figure 1 illustrates the much higher average PHRR for the chairs without barriers.

Figure 1. Average Peak Heat Release Rate by Barrier

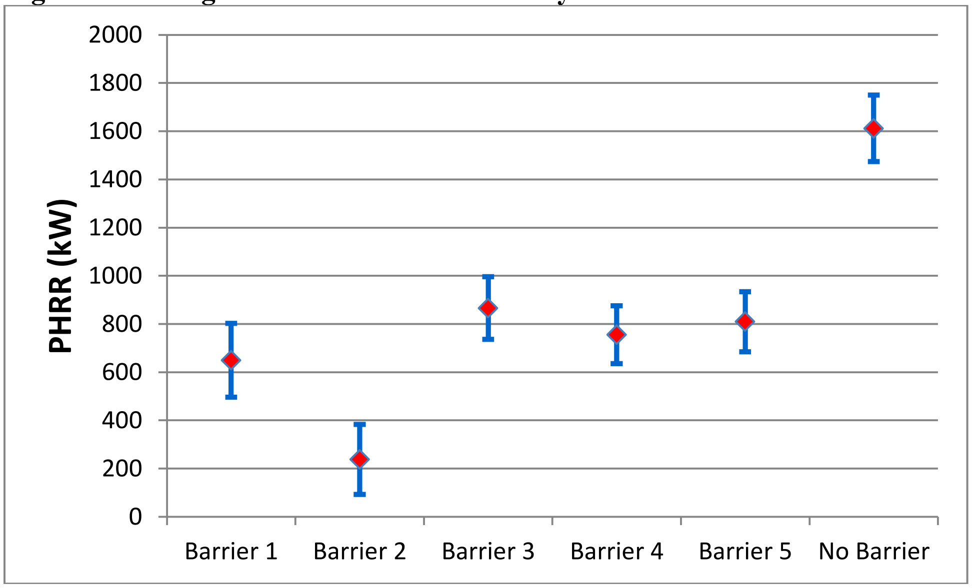
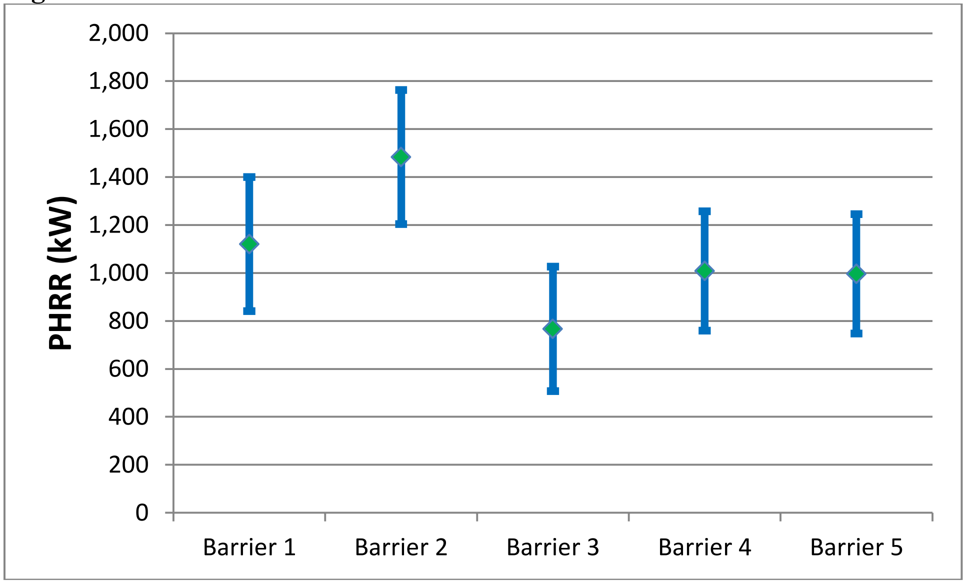


Figure 2 shows the estimated barrier effects and their 95 percent confidence intervals, as listed in Tables 5 and 6. These are the statistical *barrier* comparisons: Barrier X vs. “No Barrier” for PHRR. This is the model’s depiction of the ability of the individual barrier’s effect in reducing the intensity of open-flame fires in full-scale chairs. The effects are negative when compared with the baseline level of “no barrier” (the PHRRs for chairs with barriers are lower than for chairs without barriers);, but for simplicity, they will be depicted as positive numbers. Although these are the statistically signficant barrier effects, remember that there is also a statistically significant fabric effect.

Figure 2. Estimated Barrier Effects – Reduction in Peak Heat Release Rate



Even the smallest estimated barrier effect (the one for FB3) is more than 760 kW. The lowest lower confidence limit is more than 500 kW.

Time to Peak Heat Release Rate:

As with PHRR, staff performed an analysis of variance (ANOVA) with Time to Peak Heat Release Rate (Time to Peak) as the dependent variable and barrier, fabric, and age as independent variables. Staff performed model selection similarly to the model for PHRR. However, unlike with PHRR, the chairs that did not ignite were removed from the data. Time to Peak helps assess the effectiveness of the barriers at slowing the progress of the fire. The Time to Peak, for the chairs that did not ignite, like their PHRR, was very low. For PHRR, lower is better. However, for Time to Peak, higher numbers are better because it is better for consumers if the fire progresses slowly. For the chairs that ignited, the chairs with higher PHRR tend to have lower Time to Peak. However, the chairs that did not ignite reached their low peaks almost immediately. Although a lower time to peak is worse in chairs that ignite, including results for chairs that have very low times to peak, but did not ignite, would be quite misleading. Accordingly, these were removed from the data before model selection.

Of the 63 chairs whose barriers (or lack thereof) were confirmed, seven did not ignite. Results for these seven chairs were removed before proceeding with the analysis. Thus, the Time to Peak model has only 56 chairs and with FB2, only 4 chairs. The model selection process led to a model with three main effects: barrier, fabric, and age; and the barrier*fabric and barrier*stressed interactions.

Table 7. Characteristics of Chairs Included in Open-Flame Time to Peak Analysis

Fire Barrier	Cover Fabric	Number of Chairs	
		Mechanically Stressed	Non-Stressed
None	F2	2	2
None	F3	3	3
FB1	F2	2	2
FB1	F3	1	3
FB2	F2	0	1
FB2	F3	1	1
FB3	F2	2	3
FB3	F3	3	2
FB4	F2	3	4
FB4	F3	4	2
FB5	F2	3	3
FB5	F3	2	4

Assessing Normality:

As with PHRR, the ANOVA involves an assumption that the residuals are normally distributed[7]. Again, three goodness-of-fit tests for normality were conducted. All three tests have p-values below 0.05, which suggests that the residuals in our model are not normally distributed.

Table 7. Time to Peak Residual Goodness-of-Fit Tests for the Normal Distribution

Goodness-of-Fit Test	P-value
Kolmogrov-Smirnov	**<0.010**
Cramer-von Mises	**<0.005**
Anderson-Darling	**<0.005**

The probability plot did not appear consistent with normality. There are more data in both tails and near the median and less data between the tails and the middle than would be expected in a normally distributed dataset. The log model[8] also was not normally distributed. The Box Cox transformation[9] was applied, with a lambda of 0.07[10] selected, but this did not lead to p-values above 0.05 for the goodness-of-fit tests. The probability plot for the residuals did not appear normal. Because ANOVA assumes the residuals to be normally distributed, and neither the untransformed, nor the transformed model appears to satisfy this requirement, bootstrapping (explained below) was performed for the Time to Peak model.

The Statistical Bootstrap:

[7] The normal distribution is a continuous probability distribution that is also sometimes called the bell curve. One of the assumptions in ANOVA is that the data residuals are a fit to a bell curve.
[8] This is the model using the natural log of Time to Peak as the dependent variable.
[9] The Box Cox transformation involves raising the dependent variable to an exponent (lambda) to try to find a function of the dependent variable that fits the normal distribution.
[10] This leads to a model with Time to Peak Heat Release raised to the 0.07 power as the dependent variable.

Bootstrapping is a statistical technique used when the underlying distribution of a parameter is unknown. Our ANOVA model is able to estimate the main effects and interactions; but statistical inference, such as confidence intervals and p-values for these parameters, are dependent upon knowing the underlying distribution. In the case of ANOVA, this statistical inference is dependent upon having the residuals following the normal distribution.

Our ANOVA model and its parameter estimates come from one set of tests of 56 chairs. The bootstrap simulates many more such tests. It does so by sampling randomly from the residuals from our actual test. In this way, using computer simulation, thousands of such tests of 56 chairs are produced. So, where our model provides, for example, an estimate of the effect of FB2 on Time to Peak, the bootstrap can provide thousands of these estimates. The variance of these estimates can then be computed, which enables statistical inference, *e.g.*, p-values and confidence intervals. In the end, the parameter estimates from our ANOVA model are used in conjunction with the variance estimates from the bootstrap to assess the effects of our fire barriers, cover fabrics, and age (mechanical stressing) on Time to Peak.

SAS™ was used to perform a statistical bootstrap for the Time to Peak model using the actual residuals from the original Time to Peak ANOVA. The bootstrap used 10,000 simulations (10,000 samples of 56 chairs), and the parameter estimates converged to those of the model. The standard errors (measure of variability) from the bootstrap were consistently 17 percent to 19 percent lower than those from the ANOVA model.

Interactions:

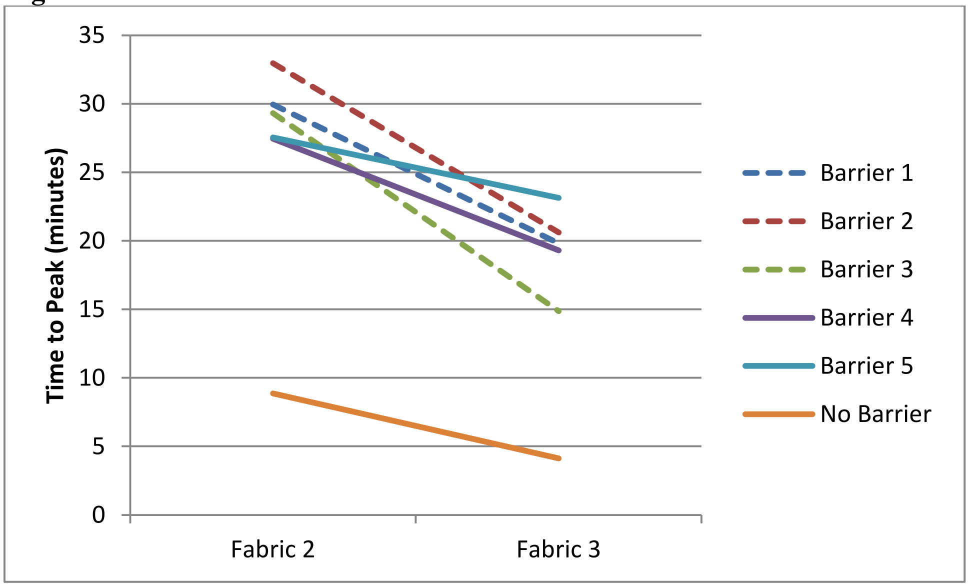
Two interactions remained in the Time to Peak ANOVA model. These are the barrier*fabric interaction and the barrier*age interaction. According to the ANOVA F-tests, the barrier*fabric interaction is statistically significant (p-value below 0.05), and the barrier*age interaction is not statistically significant.

Table 8. Time to Peak Model Interactions

Interaction	**F-value**	**df**	**P-value**
Barrier*Fabric	**3.17**	**5**	**0.0172**
Barrier*Age	2.32	5	0.0624

These F-values and p-values involve the assumption of normal residuals, which we do not have. The standard errors from the bootstrap will help us to evaluate these interactions. Figure 3 and Figure 4 give us pictures of these interactions.

Figure 3. Barrier*Fabric Interaction for Time to Peak

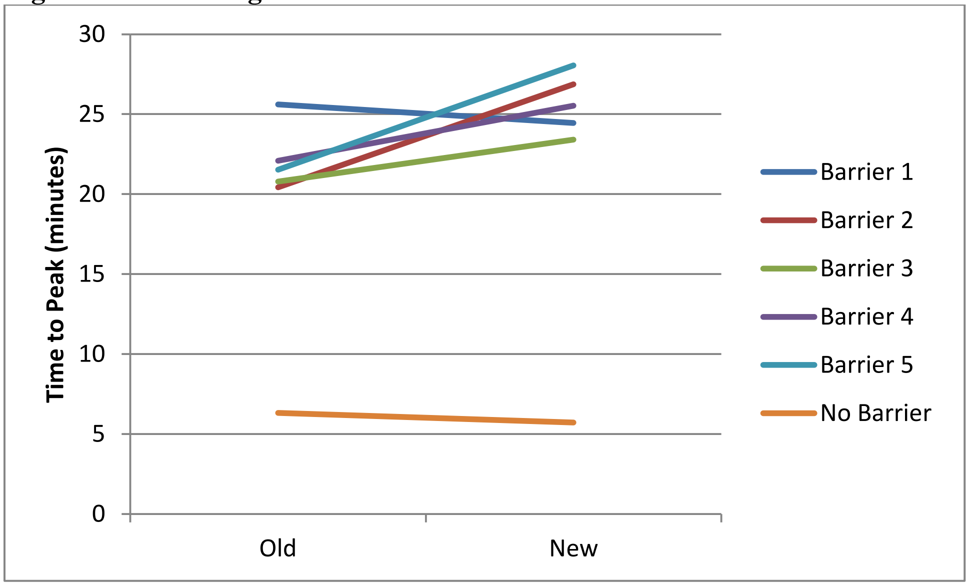


Each of the lines has a downward slope because the average Time to Peak was lower for Fabric 3 chairs than Fabric 2 chairs for all barriers (and 'No Barrier'). If there were no interaction, all of the lines would be parallel to each other, or close to parallel. The fabric effect appears to be greater for Barriers 1, 2, and 3 (dashed lines) than for Barriers 4, 5, and "No Barrier" (solid lines). For example, Barrier 3 has an average Time to Peak that is more than 14 minutes lower for Fabric 3 chairs than Fabric 2 chairs; whereas, the difference is less than 5 minutes for Fire Barrier 5.

The p-value from the ANOVA for the overall barrier*fabric interaction is 0.0172. This involves an assumption of normally distributed residuals. The p-values using the bootstrap standard errors and with "No Barrier" as the baseline reference level, were statistically significant for Barrier 1 (p-value = 0.02185) and Barrier 3 (p-value = 0.00003)[11]. This implies that the fabric effect is different for chairs with FB1 and FB3 than it is for chairs without barriers.

[11] The ability to find a statistically significant result for the interaction with FB2 and fabric may have been hampered by having so many FB2 chairs removed from the data because they did not ignite. Although nine of the 63 chairs with known barriers tested had FB2, only three of the 56 that ignited had FB2. Six of the seven chairs that did not ignite were FB2 chairs.

Figure 4 Barrier*Age Interaction for Time to Peak



If there were no barrier*age interaction we would expect all of the lines to be parallel to each other or close to parallel. Notice that the "No Barrier" and FB1 lines are slightly downward sloping. For "No Barrier" and FB1 chairs, the mechanically stressed chairs actually had a higher average Time to Peak than the non-stressed chairs. Chairs with FB2, FB3, FB4, or FB5 had a higher average Time to Peak for the non-stressed chairs. The difference was largest for FB2 and FB5 chairs. FB2 chairs that were not stressed had a Time to Peak an average of 6.4 minutes higher than the stressed chairs. For FB5 chairs, the difference was 6.5 minutes. The only barrier for which the barrier*age interaction was statistically significant was FB5. The p-value is 0.00032. As with the barrier*fabric interaction, the lack of FB2 chairs (there were only three FB2 chairs that ignited) may have prevented the model from demonstrating a statistically significant barrier*age interaction for FB2.

<u>Main effects:</u>

The main effects, as in the PHRR model, are fire barrier, fabric, and age. The effects for fire barrier and fabric are statistically significant. The effect for age is not statistically significant. The estimates of the effects come from the model. The standard errors that are used to compute the confidence intervals and p-values, are derived from the bootstrap.

Table 9. Time to Peak Main Effects

Effect	Estimate	95% Confidence Interval	Standard Error (Bootstrap)	P-value
Fire Barrier	FB1 = 14.1	FB1 = (9.4, 18.9)	2.4	< 0.0001
	FB2 = 16.0	FB2 = (10.2, 21.8)	3.0	< 0.0001
	FB3 = 10.5	FB3 = (6.8, 14.3)	1.9	< 0.0001
	FB4 = 14.3	FB4 = (10.8, 17.8)	1.8	< 0.0001
	FB5 = 13.7	FB5 = (9.8, 17.6)	2.0	< 0.0001
Fabric	F2 = 4.7	F2 = (1.4, 8.0)	1.7	0.0050
Age	Not stressed = -0.6	Not stressed (-3.9, 2.7)	1.7	0.7189

The baseline level for fire barrier is "No Barrier." Table 9 shows that the estimated effect of having a chair with FB1 is taking 14.1 minutes longer to reach peak heat release rate than a chair with no fire barrier. Likewise, Fabric 3 is the baseline level for fabric; and the estimated effect of having a chair with fabric F2, is 4.7 minutes longer to peak than F3 chairs. The baseline level for age is "Stressed" chairs. The effect of having a chair that is new (not stressed), is reaching the peak an estimated 0.6 minutes more quickly than stressed chairs; but it is far from statistically significant (p-value = 0.7189). On the other hand, the p-values for barrier and fabric are very statistically significant.

Time to Peak Model Estimates:

The Time to Peak model is an Analysis of Variance model with the three main effects (barrier, fabric, and age) and two interactions (barrier*fabric and barrier*age). The barrier*fabric interaction is statistically significant overall in the ANOVA model and specifically for FB1 and FB3. The ANOVA model is below:

Estimated Time to Peak = Intercept + Barrier Effect + Fabric Effect + Age Effect + Barrier*Fabric + Barrier*Age

The intercept is the estimated time to peak heat release rate of a chair at all the baseline levels for the variables. The baseline levels are chairs with "No Barrier," cover fabric F2, and that were mechanically stressed. Our ANOVA provides estimates for the intercept and subsequent main effects and interactions.

Table 10. Time to Peak Model Parameter Estimates

Parameter	Estimate	Confidence Interval
Intercept	4.4	(1.8, 7.1)
Fire Barrier 1	14.1	(9.4, 18.9)
Fire Barrier 2	16.0	(10.2, 21.8)
Fire Barrier 3	10.5	(6.8, 14.3)
Fire Barrier 4	14.3	(10.8, 17.8)
Fire Barrier 5	13.7	(9.8, 17.6)
Cover Fabric 2	4.7	(1.4, 8.0)
New (Not Stressed)	-0.6	(-3.9, 2.7)
Fire Barrier 1*Fabric 2	5.8	(0.8, 10.8)
Fire Barrier 2*Fabric 2	7.4	(-0.5, 15.4)
Fire Barrier 3*Fabric 2	9.8	(5.2, 14.4)
Fire Barrier 4*Fabric 2	3.0	(-1.4, 7.5)
Fire Barrier 5*Fabric 2	0.9	(-3.6, 5.4)
Fire Barrier 1*New	2.3	(-2.8, 7.3)
Fire Barrier 2*New	0.9	(-7.0, 8.9)
Fire Barrier 3*New	0.3	(-4.4, 5.0)
Fire Barrier 4* New	2.2	(-2.2, 6.6)
Fire Barrier 5*New	8.1	(3.7, 12.5)

For example, the model estimates that a chair with fire barrier 5, cover fabric 2, that was mechanically stressed will take 4.4 + 13.7 + 4.7 + 0.9 = 23.8 minutes to reach its peak heat release rate. It is worth reiterating that, in addition to providing an estimated 13.7 minutes to the Time to Peak, FB2 demonstrated a propensity to prevent ignition. Six of the nine FB2 chairs did not ignite.

Barrier Effectiveness:

The effect of fire barriers on Time to Peak demonstrates the ability of the fire barriers to slow the progress of fires. The barriers are compared to the "no barrier" chairs, but not to each other. Figure 5 shows the average Time to Peak by barrier and includes 95 percent confidence intervals. The "No Barrier" chairs clearly reach their peak much sooner than the chairs with barriers.

Figure 5. Average Time to Peak by Barrier

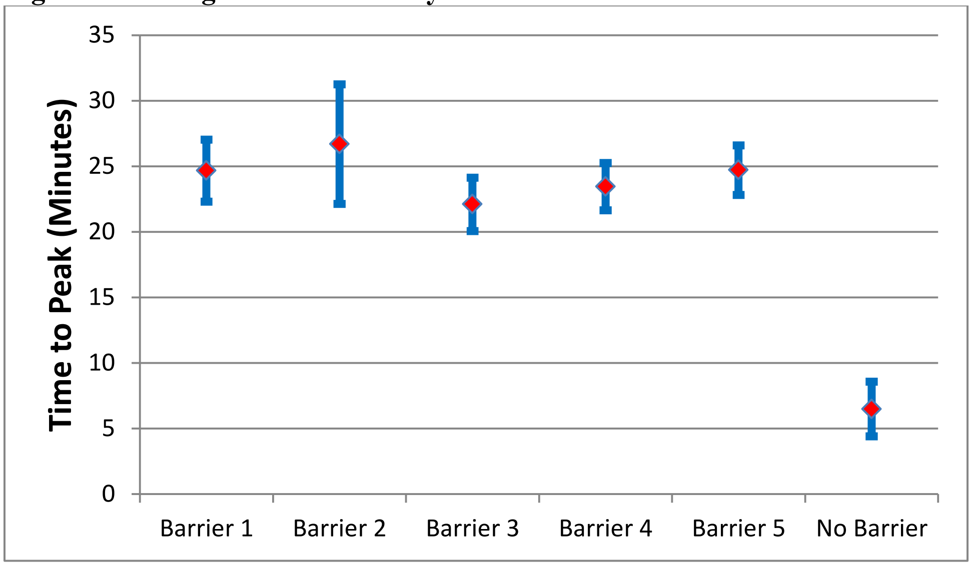
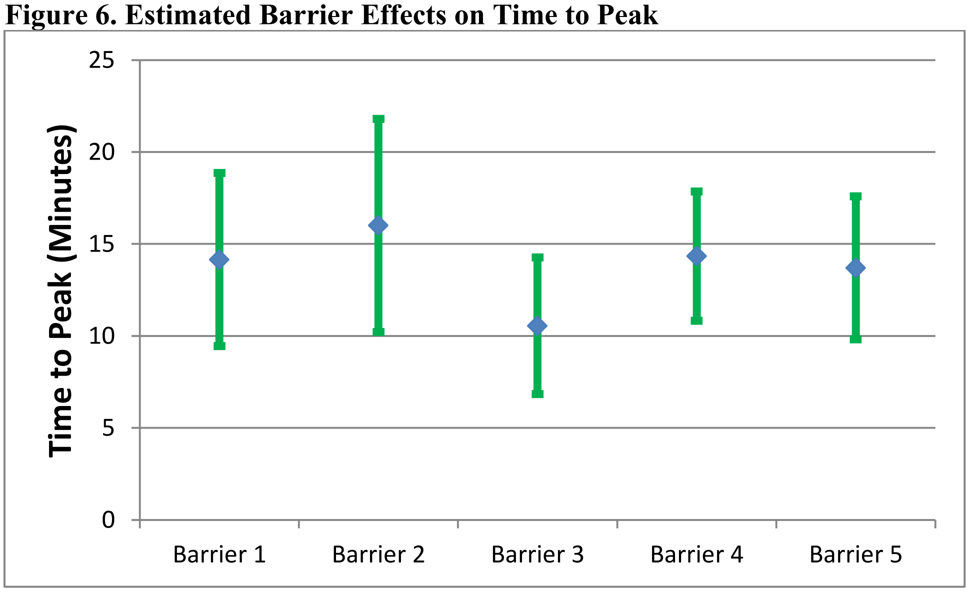


Figure 6 shows the estimated barrier effects and the 95 percent confidence intervals, as listed in Table 10. These are the statistical barrier comparisons: Barrier X vs. "No Barrier" for Time to Peak. This is the model's depiction of the barriers' effect in slowing the progress of open-flame fires in full-scale chairs. All of the effects are positive, which indicates an increase in the Time to Peak. Although these are the barrier effects, there is also a statistically significant fabric effect and statistically significant interactions between barrier and fabric.

Figure 6. Estimated Barrier Effects on Time to Peak



Each of the estimated barrier effects is larger than 10 minutes. The lower 95 percent confidence bounds are above 6 minutes for each of the barriers.

B. Smoldering Testing

In addition to the open-flame testing, there were separate tests of chairs done with cigarettes. There were eight cigarettes placed on each of 24 chairs, and the cigarettes were allowed to burn until they self-extinguished or the chair ignited and reached a PHRR.

Independent Variables:

- Fire barriers: there are five different fire barriers (FB1, FB2, FB3, FB4, FB5) being evaluated, and some chairs will have no fire barrier. So there are six different possibilities for a chair's fire barrier.

- Cover fabric: there are two different cover fabrics (F1, F2) used in the chairs for the open-flame tests. F2 was also used in the open-flame analysis. F1 was only used for smoldering chairs. F3 was only used for open-flame chairs.

- Age: aging is simulated by the mechanical stressing of chairs. There are two possibilities for this variable ("YES" - chairs that were mechanically stressed; "NO" – chairs that were not stressed). Stressed chairs will also be referred to as "old"; whereas, chairs that were not stressed are referred to as "new."

Dependent Variables:

- Peak Heat Release Rate (PHRR) of the chair

- Time to Peak Heat Release Rate (Time to Peak) of the chair

- Char – maximum length of char for a cigarette on the chair. This was measured on chairs that did not ignite.

- Transition to Flaming – whether any of the cigarettes on the chair transitioned to flaming and ignited the chair.

Unlike the open-flame testing, there were no replicates for the chairs tested. The smoldering testing was not set up to do statistical inference and find statistically significant differences. The smoldering testing was done to get a preliminary view of smoldering behavior with different barriers, fabrics, and mechanical stressing. There was one chair tested for each of the 24 combinations of barrier, fabric, and age. Table 11 shows the 24 combinations of barrier, fabric, and age, each of which had exactly one chair tested.

Table 11. Characteristics of Chairs Included in Smoldering Tests

Fire Barrier	Cover Fabric	Number of Chairs	
		Mechanically Stressed	Non-Stressed
None	F1	1	1
None	F2	1	1
FB1	F1	1	1
FB1	F2	1	1
FB2	F1	1	1
FB2	F2	1	1
FB3	F1	1	1
FB3	F2	1	1
FB4	F1	1	1
FB4	F2	1	1
FB5	F1	1	1
FB5	F2	1	1

Table 12 and Figures 7 and 8 depict the proportion of chairs that transitioned to flaming and ignited by barrier. Note that the four chairs for each barrier that were tested were not identically constructed. The four chairs for each barrier included a Fabric 1 chair that was stressed, a Fabric 2 chair that was stressed, a Fabric 1 chair that was not stressed, and a Fabric 2 chair that was not stressed.

Table 12. Chairs by Fire Barrier in Smoldering Tests

Fire Barrier	Number of Chairs Tested	Number of Chairs Ignited[12]
No Barrier	4	2
FB1	4	2
FB2	4	4
FB3	4	3
FB4	4	2
FB5	4	2

[12] These are chairs in which at least one of the cigarettes transitioned to flaming and ignited the chair.

Figure 7. Proportion of Smoldering Chairs that Ignited by Barrier

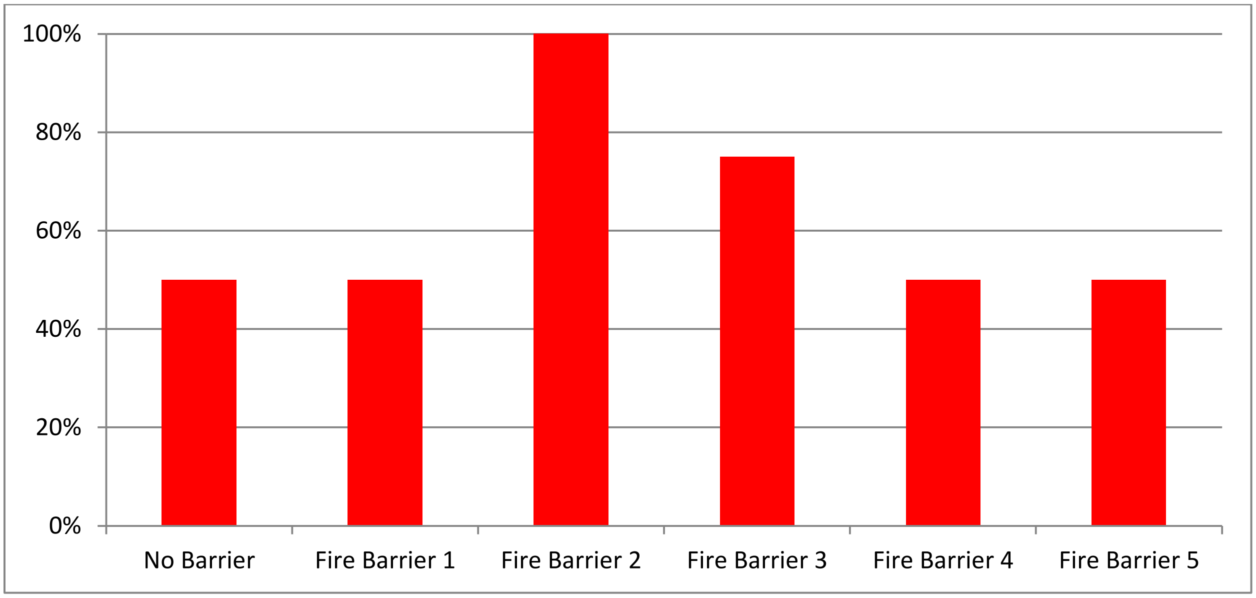
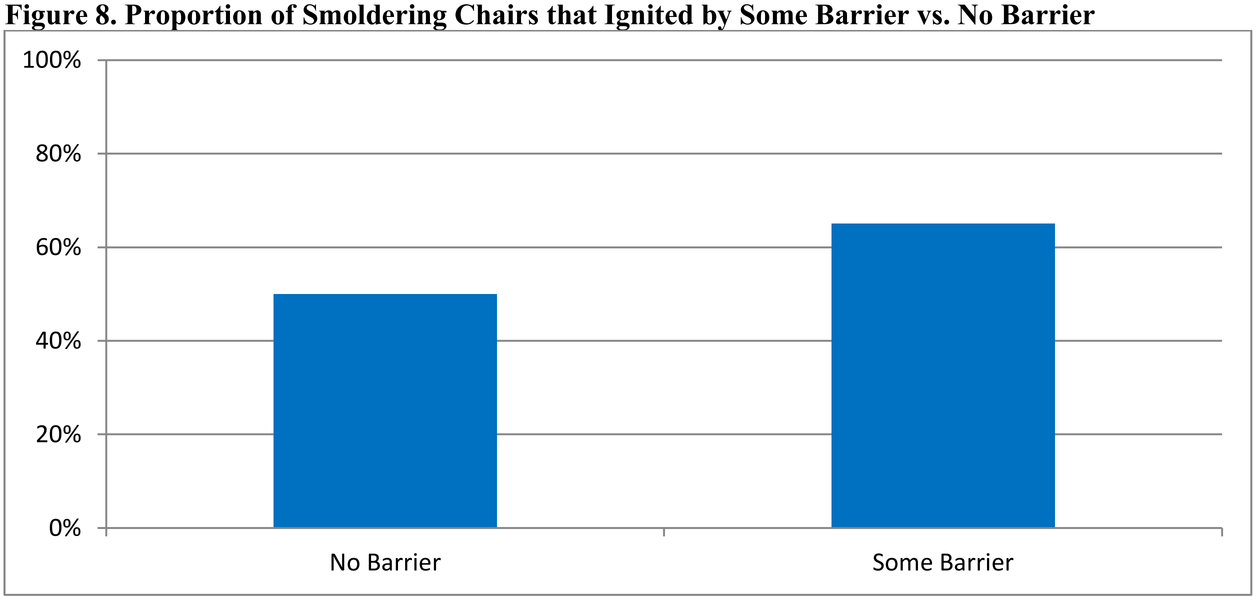


Figure 8. Proportion of Smoldering Chairs that Ignited by Some Barrier vs. No Barrier



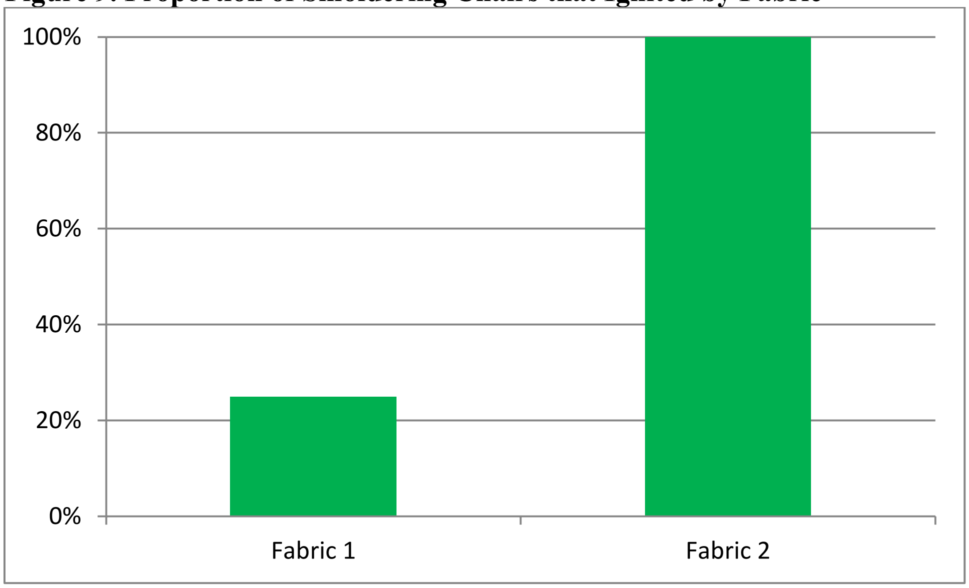
Two of the four chairs that had no fire barrier, ignited. There were 20 chairs tested that had some fire barrier (FB1, FB2, FB3, FB4, or FB5). Thirteen (65%) of these ignited. All four of the FB2 chairs that were tested, ignited. There is not enough information to determine statistical significance in likelihood to ignite by barrier.

Table 13 and Figure 9 show the proportion of chairs that ignited by fabric. The 12 chairs tested for each fabric (F1 and F2) are across the six levels of barrier and two levels for age.

Table 13. Chairs by Cover Fabric in Smoldering Tests

Fire Barrier	Number of Chairs Tested	Number of Chairs Ignited[13]
Fabric 1	12	3
Fabric 2	12	12

Figure 9. Proportion of Smoldering Chairs that Ignited by Fabric



Although the tests were not designed for statistical inference, the fact that all 12 of the F2 chairs ignited and only three of the 12 F1 chairs ignited, suggests there might be a relationship between the fabrics and ignition propensity. If a binomial comparison test was done between the Fabric 1 and Fabric 2 chairs for ignition propensity, the difference would be statistically significant; however, this is dependent on the chairs within each group being identical. They are not identical; they vary in barrier and age.

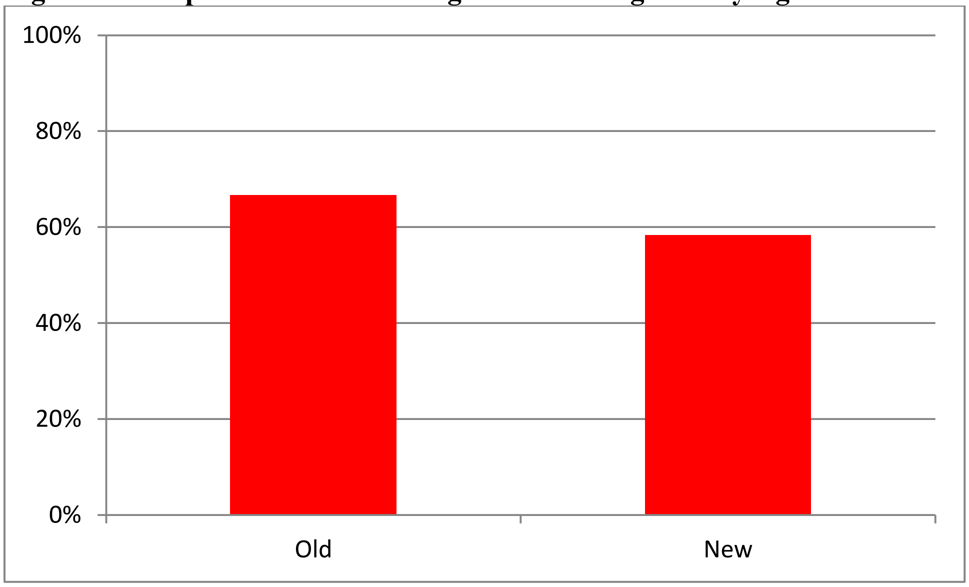
Table 14 and Figure 10 show the proportion of chairs that ignited by age (whether or not they were mechanically stressed).

Table 14. Chairs by Age in Smoldering Tests

Fire Barrier	Number of Chairs Tested	Number of Chairs Ignited[14]
Old	12	8
New	12	7

[13] These are chairs in which at least one of the cigarettes transitioned to flaming and ignited the chair.
[14] These are chairs in which at least one of the cigarettes transitioned to flaming and ignited the chair.

Figure 10. Proportion of Smoldering Chairs that Ignited by Age



Eight of the 12 mechanically stressed chairs ignited. Seven of the 12 chairs, that were not stressed, ignited. It is not clear that the stressing of the chairs has any effect on its ignition propensity.

For chairs that did not ignite, the maximum char of the cigarettes was measured. Fifteen of the 24 chairs ignited. The maximum char was ½ inch to 1 inch for each of the nine chairs that did not ignite.

The PHRR and Time to Peak were measured for the chairs that ignited. Figures 11 and 12 show the average PHRR and the average Time to Peak by barrier for the chairs that ignited.

Figure 11. Peak Heat Release Rate by Barrier for Smoldering Chairs that Ignited

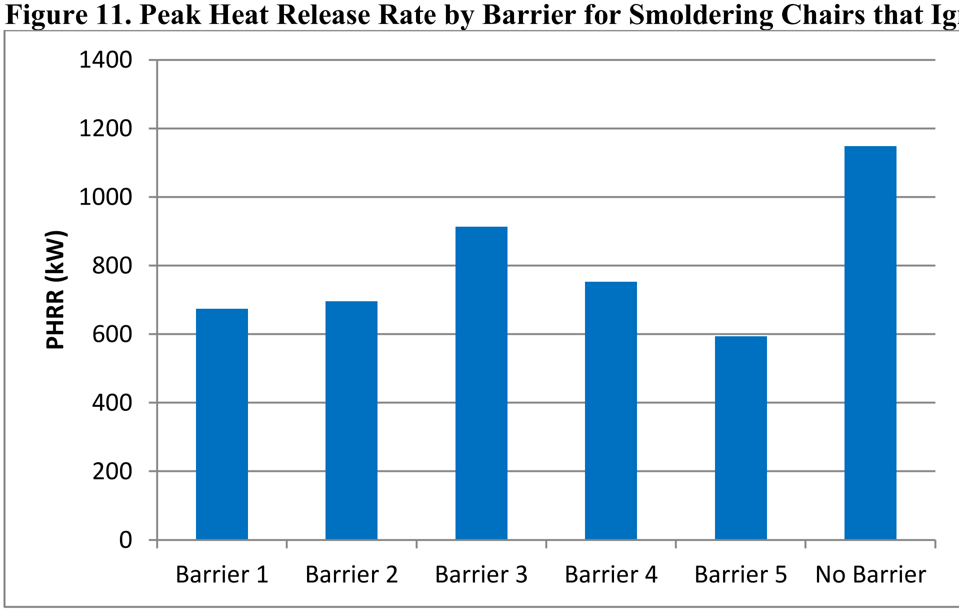
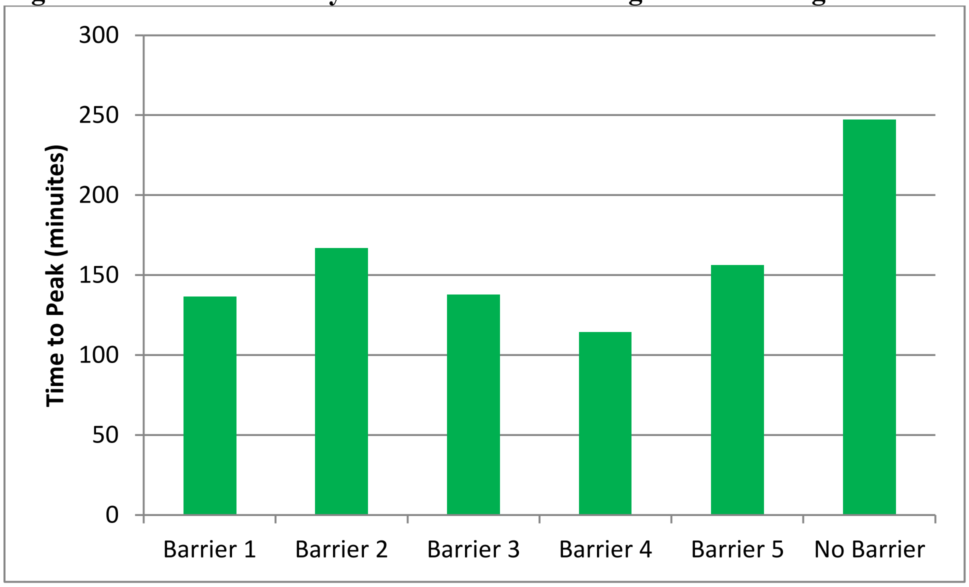


Figure 12. Time to Peak by Barrier for Smoldering Chairs that Ignited



The average PHRR was higher for the "No Barrier" chairs than for the chairs with fire barriers. Interestingly, the Time to Peak was also higher for the "No Barrier" chairs than for the barriered chairs. The time it took for the chair to reach peak after it transitioned to flaming was actually shorter for the "No Barrier" chairs, but when factoring in the time it took before the chair ignited, the "No Barrier" chairs had a higher Time to Peak. The chairs without barriers took longer to transition to flaming.

Conclusions:

The open-flame testing revealed that each of the tested fire barriers are effective in reducing the peak heat release rate of full-scale chairs and delaying the time to peak heat release rate. The barriers' effect in reducing PHRR was estimated to be 767 kW for the lowest (Fire Barrier 3) and 1,483 kW for the highest (Fire Barrier 2). The barriers increase the time to peak by an estimated 10.5 minutes for the lowest (Fire Barrier 3) and 16.0 minutes for the highest (Fire Barrier 2). Fire Barrier 2 also appears to be effective at preventing ignition. Six of the nine chairs tested that had Fire Barrier 2, did not ignite. There was only one other chair that did not ignite, and it was a chair with Fire Barrier 3.

The cover fabric also had a statistically significant effect on PHRR and Time to peak. The effect of Fabric 2 chairs, as opposed to Fabric 3 chairs, was an estimated 532 kW lower PHRR and a 4.7 minutes longer Time to Peak. The mechanical stressing of chairs did not affect the PHRR or Time to Peak of chairs statistically significantly.

The results of the smoldering testing suggest that chairs with Fabric 2 may be more likely to transition to flaming than chairs with Fabric 1. All 12 of the Fabric 2 chairs ignited, but only three of the Fabric 1 chairs ignited.

Two of the four chairs with no fire barrier ignited. Thirteen of the 20 chairs with a fire barrier ignited. Although Fire Barrier 2 was the most effective at reducing peak heat release and delaying the time to peak in open-flame testing, all four of the Fire Barrier 2 chairs ignited in the smoldering testing. It is not clear if chairs with fire barriers are more likely to ignite from cigarettes than those without fire barriers. It would require additional testing to assess the effect of fire barriers in promoting a transition to flaming in smoldering chairs.

The barriers and fabrics tested were selected as part of a convenience sample and not selected randomly from probability samples. Therefore, the conclusions are limited to the barriers and fabrics tested and not to barriers and fabrics generally.

UNITED STATES
CONSUMER PRODUCT SAFETY COMMISSION
5 RESEARCH PLACE
ROCKVILLE, MD 20850

Memorandum

Date: February 2, 2016

TO : Andrew Lock, Ph.D., Fire Protection Engineer, Laboratory Sciences, Upholstered Furniture Project Manager

THROUGH : Andrew G. Stadnik, P.E., Associate Executive Director, Directorate for Laboratory Sciences
Aaron Orland, Ph.D., Division Director, Division of Chemistry

FROM : Matthew Dreyfus, Ph.D., Chemist, Division of Chemistry, Laboratory Sciences

SUBJECT : Chemical Analysis of Fire Barriers

BACKGROUND

The U.S. Consumer Product Safety Commission ("CPSC") staff conducted a series of full-scale chair tests to support rulemaking to develop a mandatory flammability standard for upholstered furniture. The tested chairs were designed and manufactured to include fire barriers, components with improved flammability characteristics. The selected fire barriers are used in other products to reduce flammability. A series of tests were conducted to assess the effectiveness of the selected fire barriers when used in upholstered furniture by reducing the hazard of fires involving upholstered furniture.

Here, staff chose five commercially available fire barriers to represent different types of barrier products from various manufacturers. Although some fire barriers are made with inherently fire-resistant fibers, others become fire-resistant through the addition of flame-retardant ("FR") chemicals added at various stages of production. All of the fire barriers used in this study were tested for the presence of FR chemicals by the Division of Chemistry, Directorate for Laboratory Sciences ("LSC") staff to support the upholstered furniture flammability rulemaking project. This work focused on confirming the chemical identity of the bulk material and screening for additives where the chemical's primary function is to impart flame resistance to the bulk material. Of particular interest were halogenated FR chemicals, but other elements of concern (such as antimony) were also prioritized.

The results reported here are not indicative of a consumer's potential exposure to these chemicals; rather, they are meant to provide preliminary information to aid in future toxicological studies.

ANALTYICAL METHODS

Each fire barrier material was subject to an array of chemical analyses:

- X-ray Fluorescence ("XRF") is an elemental analysis technique. Elements common in certain FR chemicals, such as bromine, chlorine, and phosphorous, were targeted. Low-mass elements (such as boron and carbon) cannot be measured by this technique. Although matrix-dependent, the detection limits for this technique range from 0.0001 to 0.0010%).

- Inductively coupled plasma-optical emission spectroscopy (“ICP”) is an elemental analysis technique. ICP was specifically used to detect the presence of boron and antimony in this work. Detection limits are in the parts per billion (ppb) range.
- Scanning electron microscopy (“SEM”) is a microscopy technique. This analysis can differentiate between different fiber types and provide basic elemental data. For example, this technique could identify and differentiate between glass and polyester fibers.
- Direct Analysis in Real Time Mass Spectrometry (“DART-MS”) is a chemical analysis technique that identifies compounds as opposed to the individual elements. DART-MS was used to determine the presence of halogenated FR chemicals, such as tris(1,3-dichloro-2-propyl) phosphate. Detection limits are expected to be in the nanogram to high picogram range.
- One sample was also analyzed by gas chromatography/mass spectrometry (“GC-MS”), a chemical analysis technique that both separates complicated mixtures and identifies chemicals.

The resulting data were tabulated and compared to the information provided by the sample’s Safety Data Sheet (“SDS”).

Fire Barrier 1 (FB1)

SEM identified two distinct fibers; one containing silicon and oxygen, the second mainly carbon. The SDS only lists cellulose as a component, which does not explain the silicon/oxygen fiber. The XRF confirmed the presence of silicon at a significant amount (18%). Other elements found in trace amounts include phosphorous, chlorine, sulfur, calcium and titanium. A summary of these results are displayed in Table 1.

No halogenated FR chemicals of concern were observed by DART-MS.

Table 1. XRF and ICP results for FB 1. Only cellulose (a hydrocarbon polymer) is listed in the SDS.

Element (Symbol)	XRF Result (%)	ICP Result (%)	SDS
Bromine (Br)	ND	NT	NA
Antimony (Sb)	ND	ND	NA
Phosphorous (P)	0.6	NT	NA
Chlorine (Cl)	0.2	NT	NA
Silicon (Si)	18.0	NT	NA
Sulfur (S)	0.2	NT	NA
Calcium (Ca)	0.2	NT	NA
Aluminum (Al)	ND	NT	NA
Titanium (Ti)	0.1	NT	NA
Boron (B)	NA	ND	NA
Balance (Mainly carbon and oxygen)	80.6	NA	Cellulose

ND = Not Detected (below detection limits)
NT = Not Tested
NA = Not Applicable

Fire Barrier 2 (FB2)

SEM identified three distinct fibers. First, is a fibrous glass that contains silicon, aluminum, and calcium. Second is a modacrylic (modified acrylic) fiber that contains chlorine. Based on the SDS, this fiber likely contains the acrylonitrile/vinylidene chloride copolymer and antimony oxide. The third fiber is a type of polyester, as described by the SDS.

The pertinent elemental analysis results are shown below in Table 2. The values confirm the elements observed by SEM. Antimony was found at 2.6 percent by XRF and 3.9 percent by ICP. Boron was found at a negligible level (31 ppm).

DART-MS did not detect any halogenated FR chemicals of concern. Acyrlonitrile and vinlyidene chloride monomers were not detected above ppm levels, despite being listed as components of a copolymer. To confirm that no acyrlonitrile or vinlyidene chloride monomers were available, the sample was extracted in dichloromethane and sonicated for 1 hour. The solvent was then analyzed by GC-MS. No acrylonitrile or vinlyidene chloride were detected, confirming the results from the DART-MS. Therefore, these compounds are not available as monomers, unless an outside force broke down the copolymer.

Table 2. XRF and ICP results for FB 2. Elements observed are compared to those listed in the SDS.

Element (Symbol)	**XRF Result (%)**	**ICP Result (%)**	**SDS**
Bromine (Br)	ND	NT	NA
Antimony (Sb)	2.6	3.9	4-6 % Sb_2O_3
Phosphorous (P)	0.3	NT	NA
Chlorine (Cl)	14.0	NT	36%-41% Acrylonitrile/vinylidene chloride copolymer
Silicon (Si)	9.9	NT	45%-55% Fibrous Glass
Sulfur (S)	0.2	NT	NA
Calcium (Ca)	15.3	NT	NA
Aluminum (Al)	1.6	NT	NA
Titanium (Ti)	0.3	NT	NA
Boron (B)	NA	0.0031	NA
Balance (Mainly carbon and oxygen)	55.4	NA	NA

ND = Not Detected (below detection limits)
NT = Not Tested
NA = Not Applicable

Fire Barrier 3 (FB3)

SEM identified two distinct fibers. The first contains carbon and oxygen and, based on the SDS, is likely a modacrylic. The second fiber contains silicon, calcium and chloride and is likely the silica fiber blend listed in the SDS.

The elemental analysis results confirmed the SDS; mainly silicon, carbon, and oxygen, with some antimony, although the reported value is well below the upper limit defined by the SDS. Calcium is also present, confirming the SEM results.

No halogenated FR chemicals of concern were observed by DART-MS.

Table 3. XRF and ICP results for FB 3. Elements observed are compared to those listed in the SDS.

Element (Symbol)	XRF Result (%)	ICP Result (%)	SDS
Bromine (Br)	ND	NT	NA
Antimony (Sb)	0.8	1.2	<10% Sb_2O_3
Phosphorous (P)	0.3	NT	NA
Chlorine (Cl)	11.0	NT	NA
Silicon (Si)	1.2	NT	Crystalline Silica Fiber
Sulfur (S)	0.2	NT	NA
Calcium (Ca)	3.3	NT	NA
Aluminum (Al)	ND	NT	NA
Titanium (Ti)	0.1	NT	NA
Boron (B)	NA	0.0051	NA
Balance (Mainly carbon and oxygen)	82.7	NA	Modacrylic/Silica Fiber blend

ND = Not Detected (below detection limits)
NT = Not Tested
NA = Not Applicable

Fire Barrier 4 (FB4)

SEM identified two distinct fibers. Based on the SDS, one fiber is rayon cellulose, and the second is low-melt polyester.

The XRF results confirm the chemical listing reported in the SDS: mainly silicon, carbon, and oxygen. Other elements (chlorine, phosphorous, sulfur, calcium, titanium) appear in low amounts and are likely impurities in the production process. ICP found a negligible amount of boron (153 ppm).

No halogenated FR chemicals were observed by DART-MS.

Table 4. XRF and ICP results for FB 4. Elements observed are compared to those listed in the SDS.

Element (Symbol)	XRF Result (%)	ICP Result (%)	SDS
Bromine (Br)	ND	NT	NA
Antimony (Sb)	<0.01	ND	NA
Phosphorous (P)	1.0	NT	NA
Chlorine (Cl)	0.3	NT	NA
Silicon (Si)	25.0	NT	NA
Sulfur (S)	0.3	NT	NA
Calcium (Ca)	0.2	NT	NA
Aluminum (Al)	ND	NT	NA
Titanium (Ti)	0.1	NT	NA
Boron (B)	NA	0.0153	NA
Balance (Mainly carbon and oxygen)	73.0	NA	Rayon Cellulose Fibers and Polyester Low-Melt Fiber

ND = Not Detected (below detection limits)
NT = Not Tested
NA = Not Applicable

Fire Barrier 5 (FB5)

SEM identified two distinct fibers. Based on the SDS, one fiber is rayon cellulose and the second is low-melt polyester.

The XRF results confirm the chemical listing reported in the SDS: mainly silicon, carbon and oxygen. Other elements (chlorine, phosphorous, sulfur, calcium, titanium) appear in trace amounts and are likely impurities in the production process. ICP found a negligible amount of boron (164 ppm).

No halogenated FR chemicals were observed by DART-MS.

Table 5. XRF and ICP results for FB 5. Elements observed are compared to those listed in the SDS.

Element (Symbol)	XRF Result (%)	ICP Result (%)	SDS
Bromine (Br)	ND	NT	NA
Antimony (Sb)	<0.01	ND	NA
Phosphorous (P)	1.2	NT	NA
Chlorine (Cl)	0.2	NT	NA
Silicon (Si)	29.7	NT	NA
Sulfur (S)	0.3	NT	NA
Calcium (Ca)	0.3	NT	NA
Aluminum (Al)	ND	NT	NA
Titanium (Ti)	0.2	NT	NA
Boron (B)	NA	0.0164	NA
Balance (Mainly carbon and oxygen)	68.0	NA	Rayon Cellulose Fibers and Polyester Low Melt Fiber

ND = Not Detected (below detection limits)
NT = Not Tested
NA = Not Applicable

SUMMARY

CPSC staff performed a series of analytical tests on several brands of fire barriers to determine the chemical composition of the barriers and the presence of any additive FR chemicals. The different brands use different types of polymers or silicon-based fibers to construct the base material. These fibers are inherently flame resistant, which may explain the general absence of additional FR chemicals. FB 2 had detectable levels of the element antimony, most likely in the form of antimony trioxide. Further tests would be required to determine the form of the antimony, and potential consumer exposure, which would be necessary for any risk-assessment analysis.

UNITED STATES
CONSUMER PRODUCT SAFETY COMMISSION
4330 EAST WEST HIGHWAY
BETHESDA, MD 20814

Technical Report

SUBJECT: **NIST Internal Report 8082 -- "*Assessing the Thermal Protective Performance of Fire Blocking Barrier Fabrics for Residential Upholstered Furniture*"** [18]

The attached report is NIST **Internal Report 8082 -- "*Assessing the Thermal Protective Performance of Fire Blocking Barrier Fabrics for Residential Upholstered Furniture*.**" The work was conducted under Inter-Agency Agreement CPSC-I-13-0022, and is the final deliverable of Task A. NIST was contracted by the Consumer Product Safety Commission (CPSC) to assess thermal and fire-resistance performance of five selected textile barriers. The same barriers were used in a study of upholstered furniture flammability conducted by CPSC staff.

CPSC staff is involved in rulemaking to reduce the fire hazards associated with upholstered furniture. In 2013, CPSC staff held an Upholstered Furniture Fire Safety Technology Meeting to promote a discussion of fire barrier technologies and the potential benefits barriers could provide toward improving or reducing furniture flammability. After that meeting, staff conducted a test program at CPSC's National Product Testing and Evaluation Center involving full-scale chairs exposed to open-flame and cigarette-ignition sources to evaluate the potential effectiveness of five selected fire barriers. The results of the full-scale testing, chemistry analysis and a toxicity analysis of the barrier materials are the subjects of separate reports by CPSC staff.

The objectives of the study conducted by NIST were to test and report on the physical, thermal, and fire performance of the selected barrier materials used in the CPSC's full-scale chair flammability study. The NIST report includes a summary of physical characteristics of each barrier, including structure, density, thickness, and other relevant properties. NIST evaluated a variety of thermal and fire properties, as well, including heat transfer, heat release rates, total heat released, time to ignition, and other relevant properties, such as physical characteristics. The results show how different barriers had varying performance, depending on the test. None of the barriers' performance was superior in all of the testing that was performed.

[18] This statement was prepared by the CPSC staff, and the attached report was produced by NIST for CPSC staff. The statement and report have not been reviewed or approved by, and do not necessarily represent the views of, the Commission.

NIST Internal Report 8082

Assessing the Thermal Protective Performance of Fire Blocking Barrier Fabrics for Residential Upholstered Furniture: Report to Consumer Product Safety Commission for Interagency Agreement CPSC-I-13-0022

Shonali Nazare, John Shields, Szabolcs Matko, and Rick D. Davis

Flammability Reduction Group
Fire Research Division
Engineering Laboratory

September 2015

NIST National Institute of Standards and Technology • U.S. Department of Commerce

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U.S. Department of Commerce
Rebecca Blank, Acting Secretary

National Institute of Standards and Technology
Patrick D. Gallagher, Under Secretary of Commerce for Standards and Technology and Director
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National Institute of Standards and Technology Technical Note
Natl. Inst. Stand. Techn. Internal report, 28 pages (September 2015)
CODEN: NTNUE2

Abstract

Properties of barrier fabrics (BF) that influence their effectiveness as fire barriers for residential upholstered furniture have been measured for five barrier fabrics supplied by the Consumer Product Safety Commission. In addition, two composite tests have been included for testing barrier effectiveness in protecting the flexible polyurethane foam.

The quantitative component test methods assess permeability, strength, ignitability, heat release rate, char yield, and heat transfer properties of barrier fabrics. All of these properties are believed to be important for barrier fabric effectiveness in protecting the soft cushioning of upholstered furniture. The qualitative composite test methods (the modified Mydrin test and, the recently proposed California open-flame test) have 'pass/fail' criteria and thus do not allow a relative ranking the BFs effectiveness. However, they have been suggested as approaches for identifying poorly performing barrier fabrics. They have been included here in order to allow comparison of their results with those of the quantitative component test methods.

The results of the quantitative tests for each of the five barriers are provided along with the pass/fail results for the two composite tests.

Keywords
Upholstered furniture; flammability; barrier fabrics; open-flame; test methods

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List of Acronyms

ASTM	ASTM International
BF	Barrier Fabric
CAL TB	California Test Bulletin
CBEARHFTI	California Bureau of Electronic Appliances and Repair Home Furnishings and Thermal Insulation
CFR	Code of Federal Regulations
CPSC	U.S. Consumer Product Safety Commission
FIGRA	Fire Growth Rate Index
FO	Flame Out
FR	Flame Retarded
HRR	Heat Release Rate
HTF	Heat Transfer Factor
ISO	International Organization for Standardization
NIST	National Institute of Standards and Technology
PHRR	Peak Heat Release Rate
FPUF	Flexible Polyurethane Foam
THR	Total Heat Released
THT	Total Heat Transferred
TPI	Thermal Protective Index
TPP	Thermal Protective Performance
RUF	Residential Upholstered Furniture

1. Introduction

In residential upholstered furniture (RUF), the flexible polyurethane foam (FPUF) is one of the most flammable components. Barrier fabrics (BFs) have been routinely used in contract furniture to protect FPUF from heat and flames. For this purpose, the barrier fabrics are placed between the outer layer (cover fabric) and the polyurethane foam. A wide range of barrier fabrics, including a variety of fiber blends, flame retarding technologies, and textile structures, are commercially available. However, the test methods for evaluating barrier fabrics have been limited to quality control (pass/fail) tools. None of these tests provides an effective tool for screening (quantitatively) BFs. The United States Consumer Safety Commission (CPSC) is investigating technologies, such as barrier fabrics, that could reduce the flammability of RUF. The National Institute of Standards and Technology (NIST) is providing the technical basis for a test method(s) to evaluate the flammability performance of barrier fabrics (BFs) for residential upholstered furniture.

This study is focused on the flammability performance of BFs as a component as well as the fire behavior of composites incorporating BF component. Effects of fiber content, BF structures, and other physical properties resulting from the structure of the BFs are also investigated. The technical basis for this study is derived from [7] and [8]. This report provides descriptions of the test methods used to assess permeability, strength, ignitability, heat release rate, and heat transfer properties of BFs. The results of the quantitative tests for each of the five barriers are provided along with the pass/fail results for the two composite tests. The qualitative composite test methods (the modified Mydrin test and, the California Bureau of Electronic Appliances and Repair Home Furnishings and Thermal Insulation (CBEARHFTI) proposed open-flame test) been included here in order to allow comparison of their results with those for the quantitative component test methods.

2. Experimental[‡‡‡‡‡]

Uncertainties are reported as one standard deviation (σ) based on repeat measurements [9,10].

2.1 Barrier Fabrics

Five commercially available BFs were provided by the CPSC. The sample description and physical properties of barrier fabrics are given in Table 1. Digital images of the barrier fabrics are shown in Figure 1.

2.2 Physical Properties of Barrier Fabrics

The area density of BFs was determined by dividing the weight of the specimen by the area (100 mm × 100 mm) of the specimen. Average area densities of 10 specimens are reported in Table 1. The thickness of BFs was determined using a Check-line Digital Thickness Gauge (model 500-JD-A). This device measures changes in capacitance with changes in the thickness of the BF. The change in voltage due to change in capacitance is converted to a distance. The thickness of BFs was determined at a low measuring force of 0.6 N ± 0.3 N per unit area.

[‡‡‡‡‡] Certain commercial equipment, instruments or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for this purpose.

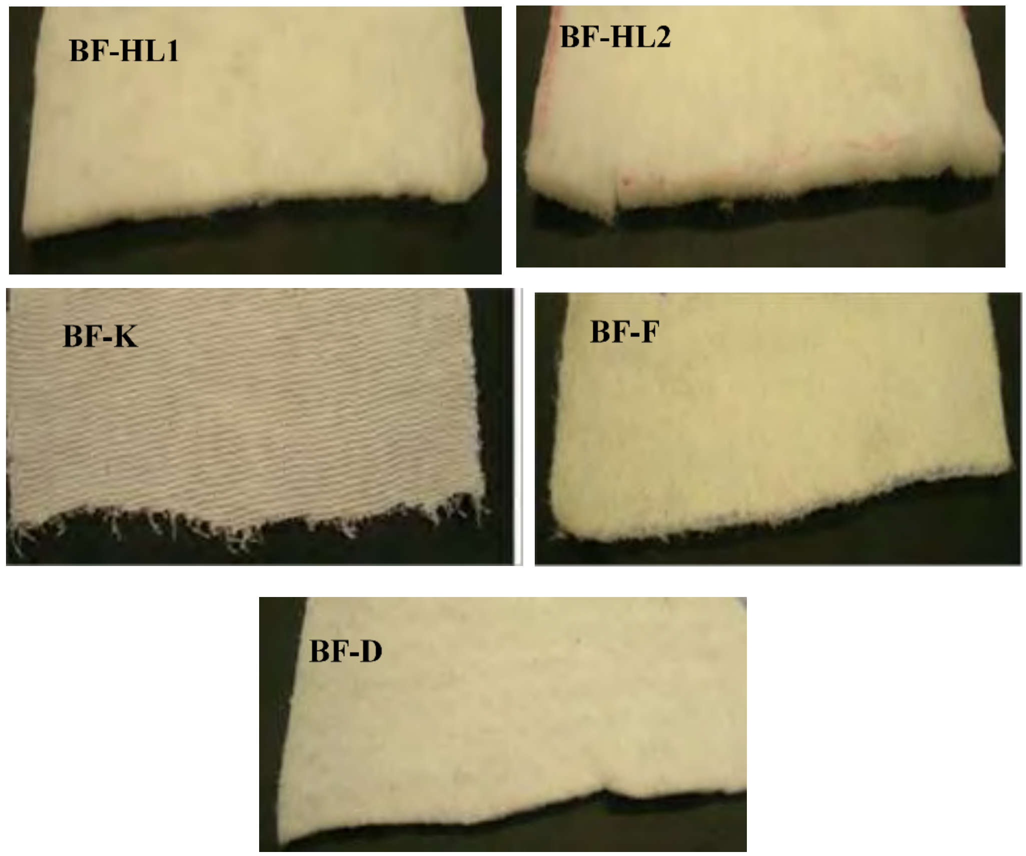

Figure 13. Digital images of the five BFs investigated in this study.

Air permeability is described as the rate of air flow passing perpendicularly through a known area under a prescribed air pressure differential between the two surfaces of the material. Air permeabilities for the BFs were measured using an electronic high differential pressure air permeability-measuring instrument (FAP 5352 F2, Frazier Precision Instrument Co. Inc., Hagerstown, MD). The air pressure differential between the two surfaces of the material was set to 125 Pa (13 mm of water). Fabrics were clamped in a circular specimen holder, exposing 6.45 cm^2 to the perpendicular air flow. Nozzles with orifice diameters of 2.0 mm, 3.0 mm, and 6.0 mm were used in order to reach the target pressure drop (125 Pa). The value of permeability (ϕ) in terms of volumetric air flow was read in cubic feet of air per square foot per minute (CFM) and was converted to cubic meters per square meter of sample per second or simply meters per second) at a room temperature of 22 °C ± 3 °C and atmospheric pressure of 100 kPa. Six readings were taken for each of the BFs and calculated averages with uncertainties are reported in Table 1.

The strength of a BF is expressed in terms of burst strength. Tensile strength tests are generally employed for woven fabrics, where there are definite warp and weft directions. However, most BFs in this study are not fabrics that have definite warp and weft directions. Knitted, non-woven or high loft fabrics do not have a principle direction where the strength reaches a maximum. Such fabrics cannot be easily prepared for tensile testing or have poor reproducibility when tested in tensile mode. Bursting strength in which the material is stressed in all directions at the same time is an alternative method for measuring the strength of such fabrics.

The bursting strength was measured using an universal testing machine (model 5582, Instron Corp., Northwood, MA) equipped with a 10 kN load cell and custom clamping device for fabrics. The bursting strength of BFs was determined in conformity with ASTM D 6797 (*Standard Test Method for Bursting Strength of Fabrics Constant-Rate-of-Extension (CRE) Ball Burst Test*). The attachment for the CRE machine comprises two parts: a lower fixed clamping device of fixed aperture diameter and an upper moving ball that impacts on the fabric surface. The clamping device has upper and lower plates with concentric grooves and crowns that intermesh with the test piece to provide grip. Test specimens were cut into square shapes of sufficient size to protrude outside the perimeter of the lower plate. The face of the test specimen was arranged perpendicular to the direction of the application of the force. The fabric specimen is clamped in place around the device that applies force by four C clamps. The material is stressed in all directions by the same amount regardless of the fabric construction. The force is normally applied using a stainless steel ball.

A 25.4 mm polished steel ball was advanced at a constant rate (305 mm/min) through the test material. The center portion pushes against a polished steel ball at a constant rate until it ruptures. The ball-burst strength is defined as the force that is required to burst the material when applied perpendicular to the plane of the material. Three specimens were tested for each BF. The bursting strength of all the BFs tested is given in Table 1.

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[7] S. Nazaré, W. Pitts, S. Flynn, J. Shields, and R.D. Davis, Towards a New Approach for Evaluating Fire Blocking Barrier Fabrics, NIST TN 1798, National Institute of Standards and Technology, Gaithersburg MD, April 2013.

[8] S. Nazaré, W. Pitts, S. Flynn, J. Shields, and R. D. Davis, Evaluating Fire Blocking Performance of Barrier Fabrics, Fire and Materials. **38**(7), 695-716 (2014).

[9] B.N. Taylor and C.E. Kuyatt, Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results, NIST Technical Note 1297, 1994 Edition (Supersedes 1993 Edition), Gaithersburg, MD, 20878.

[10] Evaluation of measurement data — Guide to the expression of uncertainty in measurement. JCGM 100:2008. http://www.bipm.org/utils/common/documents/jcgm/JCGM_100_2008_E.pdf

Table 11. Physical properties and description of BFs.

ID	Structure	Avg. area density (g/m^2)	Avg. thickness (mm)	Bulk density (g/cm^3)	Air permeability*		Bursting strength* (N)	Type of BF
					(ft^3/min)	m/s		
BF-HL1	Nonwoven Highloft	270 ± 37	4.5 ± 0.4	0.0595	475 ± 26	2.2 ± 0.1	110 ±12	Passive
BF-HL2	Nonwoven Highloft	350 ± 22	4.8 ± 0.3	0.0727	380 ± 9	1.8 ± 0.04	125 ± 10	Passive
BF-D	Nonwoven Densified	235 ± 12	3.5 ± 0.1	0.0671	360 ± 16	1.7 ± 0.07	130 ± 13	Passive
BF-K	Knitted	325 ± 9	1.6 ± 0.1	0.2025	530 ± 22	2.5 ± 0.1	340 ± 37	Active
BF-F	Nonwoven Flat	210 ± 5	2.7 ± 0.1	0.0770	430 ± 26	2.0 ± 0.1	180 ± 18	Active

*Uncertainties are reported one standard deviations.

2.3 Fire Performance of Barrier Fabrics

2.3.1 Thermal Protective Performance: A thermal protective performance (TPP) instrument developed by Measurement Technology Northwest was used to quantify the heat transfer characteristics of the BFs. A modified NFPA 1971 [1] test method has been employed to quantify the thermal protection provided by a BF. A BF specimen is exposed to a specified heat flux for a given amount of time. The results of the test are reported in terms of the heat flux passing through the material measured using a slug calorimeter. Low heat flux values imply good insulation properties, which help prevent heat being transferred to the underlying cushioning.

A schematic of the test apparatus is shown in Figure 2. It consists of two propane fueled Meker burners and a bank of 9 quartz radiant heating elements calibrated to provide 50 % convective and 50 % radiative heat flux. The Meker burners are tilted at angles of 45º from the horizontal (Figure 2) so that the flames converge at a point immediately under the test specimen. Burner flames were visually monitored to avoid any turbulence. The specimens were exposed to a total heat flux of 65 kW/m² ± 5 kW/m² for 70 s. This exposure condition represents the maximum heat flux that a mattress top experiences during a full-scale open flame test [2,3] as described in 16 CFR part 1633 [4]. The total heat flux was calibrated every day prior to experimentation.

The sample carriage consists of a frame for securing the BF specimen and a heat sensor placed in direct contact with the back of the BF. The heat sensor is a slug calorimeter embedded in an insulating board which is placed face down on the fabric assembly. The heat flux sensor with calibrated slug calorimeter is connected to a data acquisition system. Thermocouples secured in the copper slug calorimeter, which is in direct contact with the back surface of the specimen, measure the rise in temperature. The rates of temperature rise or the slope of the temperature versus time trace are used in conjunction with the calorimeter constants provided by the manufacturer to compute the heat flux received. The water-cooled shutter is pneumatically actuated and automated for precise control of exposure timing. It covers the heating elements to allow time for the sample carriage to move into position above the heat source. At the start of the test, the heat sensors are approximately at room temperature. The rise in temperature during and after exposure is calculated by subtracting the starting temperature from the recorded temperature.

Cover fabric and BF materials were placed on the sample holder in the same configuration used in upholstered furniture with the cover fabric exposed to the heating elements and the BF in contact with the sensor. The cover fabric was a stitchbond fabric containing a 69 % rayon/31 % FR polyester blend, which was used for all composite specimens. This cover fabric was chosen to prevent any melt-dripping of the cover fabric and/or BFs from damaging the quartz tubes.

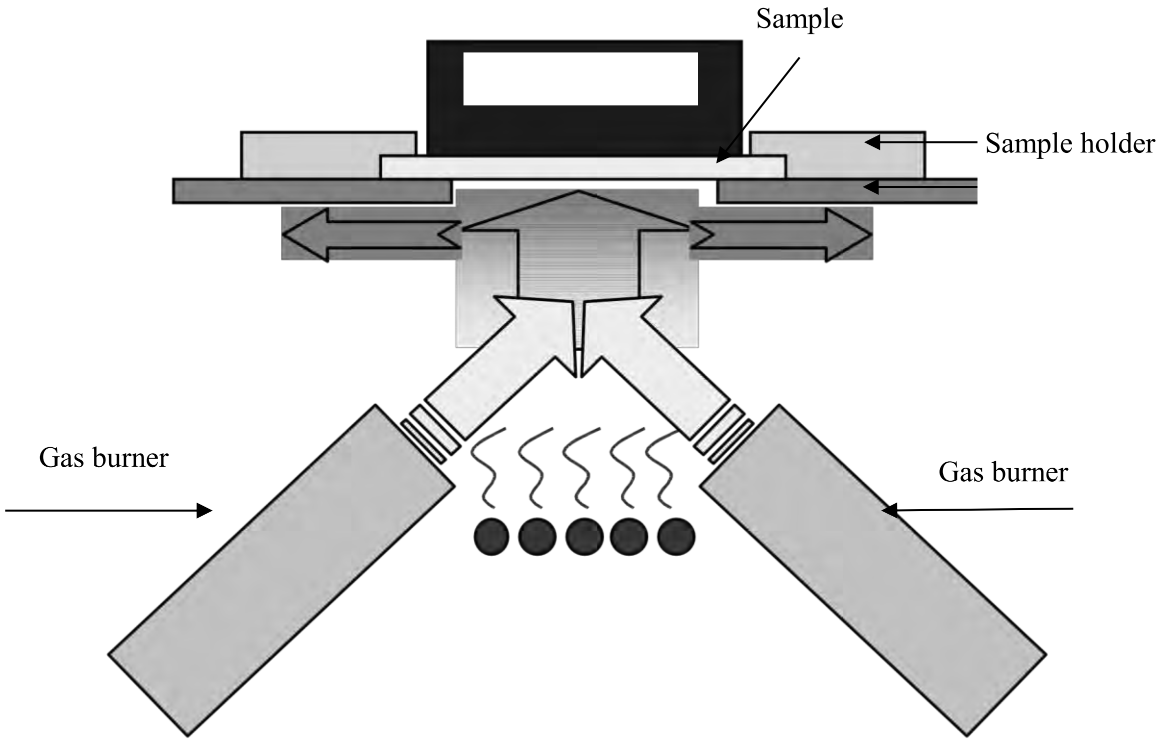


Figure 14. Schematic of TPP testing device for measuring heat transfer properties of BFs.

2.3.2 Cone Calorimeter: Important information with regards to evaluating BFs can be obtained from cone calorimetry data. Cone calorimeter parameters likely to distinguish between BFs include ignition time, peak heat release rate (PHRR), total heat released (THR), and char yield. The time to ignition (TTI) relates to how quickly a BF can ignite if the ticking or cover fabric catches fire. The PHRR is related to the maximum heat released by the burning BF that maintains the fire due to a positive feedback mechanism involved in the burning process while the THR reflects the total amount of flammable content of the specimen. The peak fire growth rate (FIGRA) index is calculated by dividing the peak heat release by the time to peak heat release (TPP) which can be used to estimate the fire spread rate [6]. The higher the FIGRA index value (=PHRR/TPP), the higher the fire hazard. The char yield, both qualitative and quantitative, is related to the thermal protective property of the BF after it has been degraded (both thermally and structurally) in the fire.

The cone calorimeter was operated according to the procedures provided in ISO 5660-1 [5]. The sample was located 2.5 cm below the base of the cone. In order to limit configuration changes in flexible textile materials and improve measurement reproducibility, the specimen assembly [6] shown in Figure 3 was used. Pieces of ceramic blanket of various thicknesses were utilized to ensure that barriers were located at the proper height below the cone calorimeter.

An incident heat flux of 50 kW/m² was selected because (1) it represents a developing fire more than a fully developed fire (at about 65 kW/m²) [7], (2) this flux represents the immediate reaction- to-fire when the BF is exposed to the burners in a full-scale mattress flammability test described in 16 CFR 1633 [4], and (3) since the BFs are expected to be fire resistant and /or flame resistant materials, ensuring ignition of such materials at incident heat fluxes below 50 kW/m² was problematic.

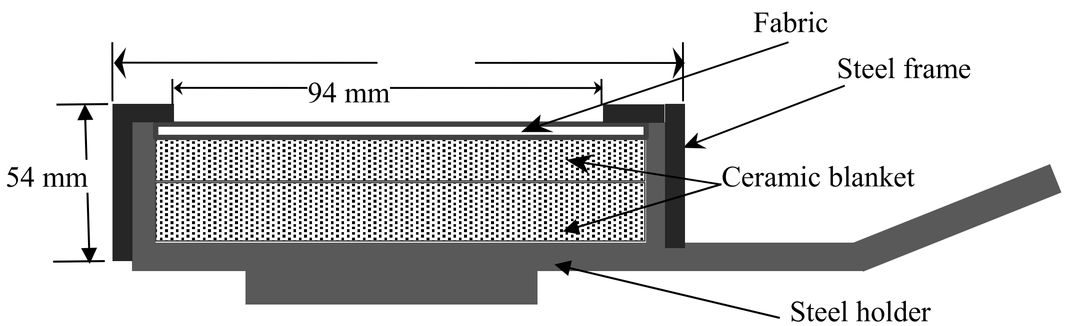


Figure 15. Specimen assembly for cone calorimetry experiments.

2.3.3 Composite Test: The purpose of this test is to assess flammability of composite samples incorporating a BF component. A modified Mydrin test [8] was chosen as the bench-scale composite test for the BFs. The Mydrin test was originally developed [9] as a simplified version of BS5852: 1979 [10]. Only the vertical component of the original mock-up is included in the Mydrin test. A small butane flame as specified in the BS 5438:1989 [11] was used as the ignition source. The test set-up is shown in Figure 4.

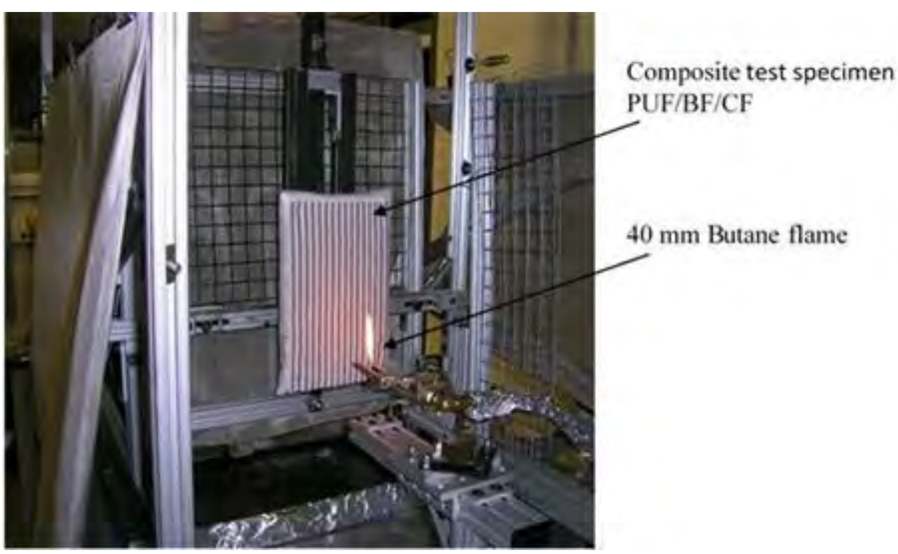


Figure 16. Vertical flammability test set-up for the Mydrin test.

The modified Mydrin test includes a specimen configuration consisting of a piece of FPUF (conforming to Cal TB 117-2013 standard foam [12]) with dimensions 220 mm × 150 mm × 25 mm as the flammable filling part of the composite to be tested. Standard non-flame retarded FPUF pieces of known dimensions were procured from Innocor Foam Technologies, Coldwater, MS. The BFs were cut into pieces, 264 mm × 194 mm and pinned onto the foam to form an upholstered composite. The back side of the foam was not covered with BF. A 40 mm butane flame was applied to the face of the composite specimen for 20 s. The burning behavior of the composite specimen was characterized in terms of duration of the flaming, thermal damage to the foam, and self-extinguishing behavior. The fire blocking performance of the BFs was also assessed in the presence of the cover fabric. The cover fabric selected for this composite test was the Type 1 cover fabric specified in Cal TB 117-2013 [12]. The BF was placed between the cover fabric and the FPUF. A 10 s flame application time was sufficient to ignite the cover fabric. In addition to assessing the burning behavior of FPUF/BF/CF composites, the percentage mass loss for these samples was also recorded.

2.3.4 CBEARHFTI proposed open-flame test: Recently, the CBEARHFTI proposed an open-flame ignition test [13] for barrier materials, herein referred to as the open-flame ignition test, to be used in testing barrier materials for residential upholstered seating furniture applications. The proposed open-flame ignition test is similar to the ASTM D7140 Standard Test Method to Measure Heat Transfer through Textile Thermal Barrier Materials [14]. ASTM D7140 measures the heat penetration through a BF when exposed to an open flame and determines whether the heat transfer is sufficient to ignite underlying materials. The standard, however, does not define a heat transfer threshold for textile materials that can be used as a criterion for fire barrier materials. The CBEARHFTI proposed open-flame ignition test, on the other hand, assesses thermal penetration by monitoring the ignition of a FPUF layer placed in contact with the unexposed side of the barrier fabric. Thus, while ASTM D7140 is a quantitative test, the CBEARHFTI proposed open-flame ignition test is largely qualitative.

The schematic of the CBEARHFTI proposed open-flame ignition apparatus is shown in Figure 5. A BF specimen (approximately 250 mm × 250 mm dimensions) is sandwiched between two rigid fire-rated insulating boards supported by a metal rack. A piece (127 mm × 127 mm × 12.7 mm) of "standard" non-fire retardant polyurethane foam [15] is placed directly over the BF test specimen, fitting snugly in the upper mounting plate rectangular opening, so that the foam contacts the barrier material at all points.

A Meker-Fisher burner (Humbolt Manufacturing Co. Part number H-5600) with a diameter top of 32 mm and orifice size of 1.2 mm is used. A pre-mixed butane flame (with a flow rate of 500 ± 10 mL/min) obtained by keeping the venturi throat in a fully open position [16] is used. The flame is applied to the test specimen from underneath. The Meker-Fisher burner is manually placed in the center of the bottom plate of the test rig such that the top of the burner is positioned 102 mm below the center of the bottom surface of the test specimen (Figure 5). The flame is applied for a period of 60 s. A test specimen fails to meet the requirements of this test procedure if the standard FPUF ignites. A barrier material passes the test if three specimens pass the test.

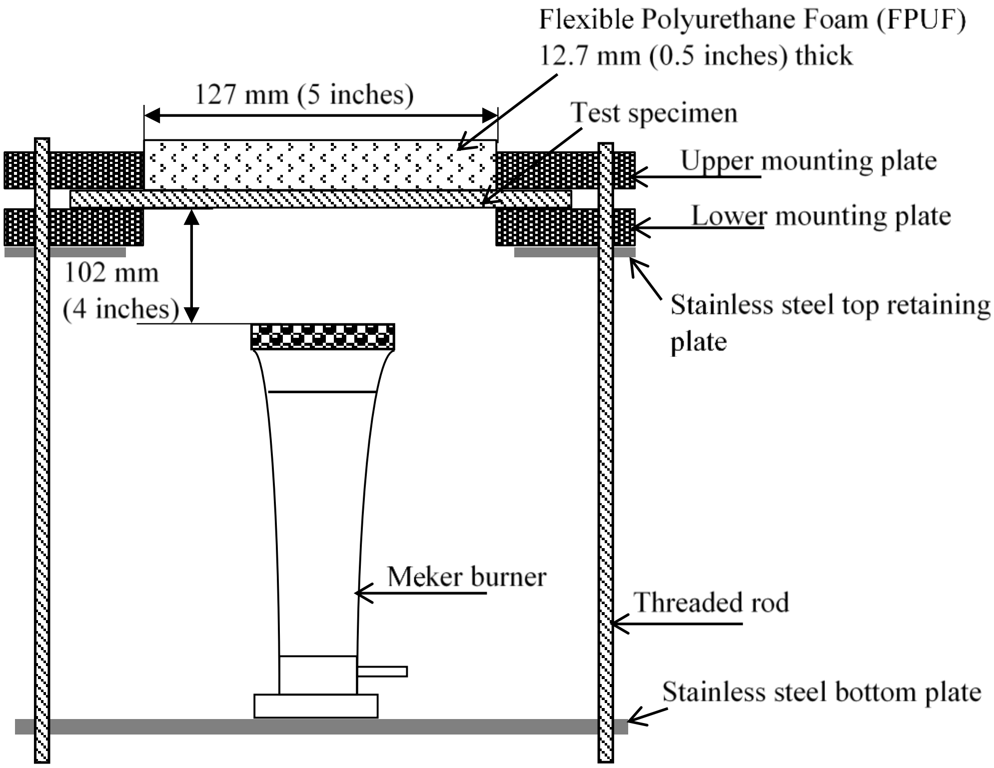


Figure 17. CBEARHFTI proposed open flame ignition test apparatus [14]

3. Results

3.1 Physical Properties of Barrier Fabrics

The physical properties of the BFs are largely determined by their structure and the manufacturing technology employed. The BFs considered in this study can be broadly classified as nonwoven and knitted BFs. BF-HL1 and BF-HL2 are non-woven highlofts. Highloft barriers have low density with a greater volume of air than fiber. In principle, highlofts are defined as low density fibrous structures characterized by a high ratio of thickness to area density [[17]]. BF-HL1 (area density 268 g/m^2) and BF-HL2 (area density 349 g/m^2) are highloft barriers with almost identical thicknesses (4.5 mm ± 0.3 mm). The lower bulk density (0.0595 g/cm^3), lower bursting strength (110 N ± 12 N) and higher air permeability (2.2 m/s ± 0.1 m/s) of BF-HL1 can be attributed to its lower area density when compared to BF-HL2.

BF-D is a densified nonwoven whereby highloft intermingled fibers are compressed or densified by the process of needle-punching, stitch-bonding or thermal-bonding. This results in lowering the thickness and increasing the bulk density and bursting strength of the barrier material (see Table 1). The air permeability of the densified BF is also lower as compared to the highloft barriers.

BF-F is also a nonwoven material with a woven glass fabric substrate. Functional fibers are bonded to the substrate by the process of needle punching and/or thermal bonding. The bursting strength of such barrier materials is largely controlled by the woven glass fabric substrate. The bursting strength of BF-F is the highest of the non-woven barriers considered in this study.

BF-K is a knitted barrier made from core spun yarn. Core spun yarn (also known as core-sheath yarn) is generally made with an inherently fire resistant fiber core (*e.g.,* glass). This core is then coated with functional fibers, usually charring fiber blends in the case of fire barriers. Knitted BFs are physically thin and hence thermally thin materials. The lower thicknesses of these materials yield higher bulk densities. The open knit structure results in higher air permeability. Despite its lower area density, BF-K has a high bursting strength (340 N ± 37 N), which can be attributed to the significant elongation that the knitted fabric undergoes during the ball bursting test. Moreover, the tensile strength of the core spun yarn is significantly higher than the fibers used in nonwoven BFs.

3.2 Heat Transfer of Barrier Fabrics

The average rise in temperature, the total amount of heat energy transferred (THT) through the BF, and the maximum heat flux measured in the TPP testing device at the unexposed side of a BF during a 70 s exposure time are given in Table 2. The increases in temperature of the unexposed surface as a function of time for all the BFs tested are shown in Figure 6. Changes in the slopes of the temperature-time curves vary because the heat exposure produces fundamental changes in fabric thermal and spatial properties through mechanisms of pyrolysis, char formation, and shrinkage.

For most of the BFs, rises in temperature at the unexposed surface are not seen until 3 s to 4 s of exposure to the heat flux. Generally, the nonwoven highloft BF-HL2 shows a slower rise in temperature and hence lower heat transfer as compared to BF- HL1. The nonwoven highloft BFs (BF-HL1 and BF-HL2) have similar highloft construction. The difference in heat transfer properties of BF-HL1 and BF-HL2 is primarily due to the difference in their area densities. Thicker barrier materials with temperature gradients behaved as thermally thick barriers (*e.g.,* BF-HL2) and resulted in lower heat transfer rates (84 °C/min ± 1 °C/min), whereas thermally thin barriers (*e.g.,* BF-K) with almost constant temperatures throughout the depth of the material resulted in higher heat transfer rates (170 °C/min ± 5 °C/min). Thus, for better barrier effectiveness, the material should have a larger thermal thickness.

The process of heat transfer through the fabric is also affected by thermal heat capacity, thermal conductivity, fiber-to-air ratio and air void distribution. It is more meaningful to rank BFs using some type of protective index. Reported in Table 2 are the BF mass normalized THT values, called the heat transfer factor (HTF) with units of J/g. HTF is the ratio of the THT value to the fabric unit mass in g/m². We refer to the inverse of the HTF as the thermal protective index (TPI) for a BF. The ranking of BFs using TPI is shown in Figure 7. Depending on the thermal thickness and fiber content, different BF types yield different TPI values. The higher the TPI value, the better the thermal protective performance of a BF. The highest TPI value (10.7) was recorded for BF- HL2, whereas the lowest TPI value was recorded for BF-F (2.9).

Table 12. Heat transfer characteristics of BFs used in soft furnishings. Uncertainties are reported as one standard deviation.

ID	**Average heating rate of heat sensors (°C/min)**	**Maximum heat flux at unexposed side of barrier at 70 s (kW/m²)**	**Total amount of heat transferred (MJ/m²)**	**HTF (kJ/g)**	**Description of char**
BF-HL1	132	12.0 ± 0.2	54.2 ± 0.6	201	Thin, flexible char
BF-HL2	84	8.0 ± 0.2	32.7 ± 0.4	93	Thick flexible char with no cracks or holes
BF-D	120	10.7 ± 0.5	46.2 ± 1.9	197	Flexible char with no cracks or holes
BF-K	170	15.1 ± 0.5	70.3 ± 2.2	216	Thin, flexible, permeable char
BF-F	164	14.7 ± 0.5	71.8 ± 2.4	342	Thin, flexible, permeable char

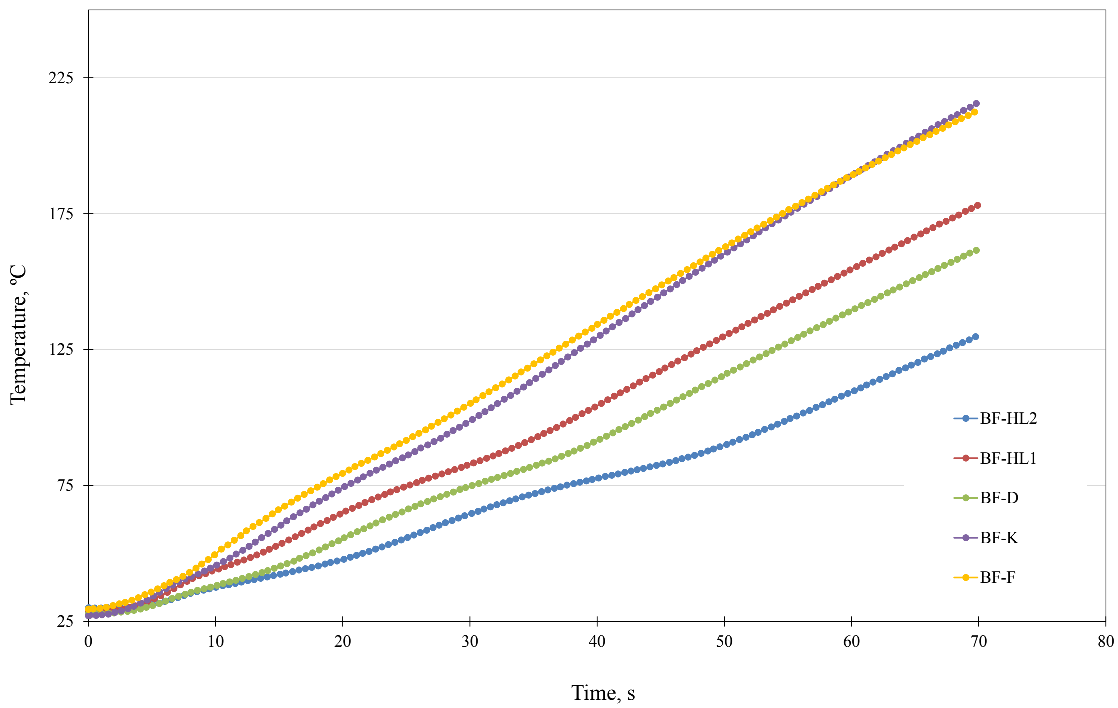


Figure 18. Temperature of the slug calorimeter on the unexposed side of the BFs.

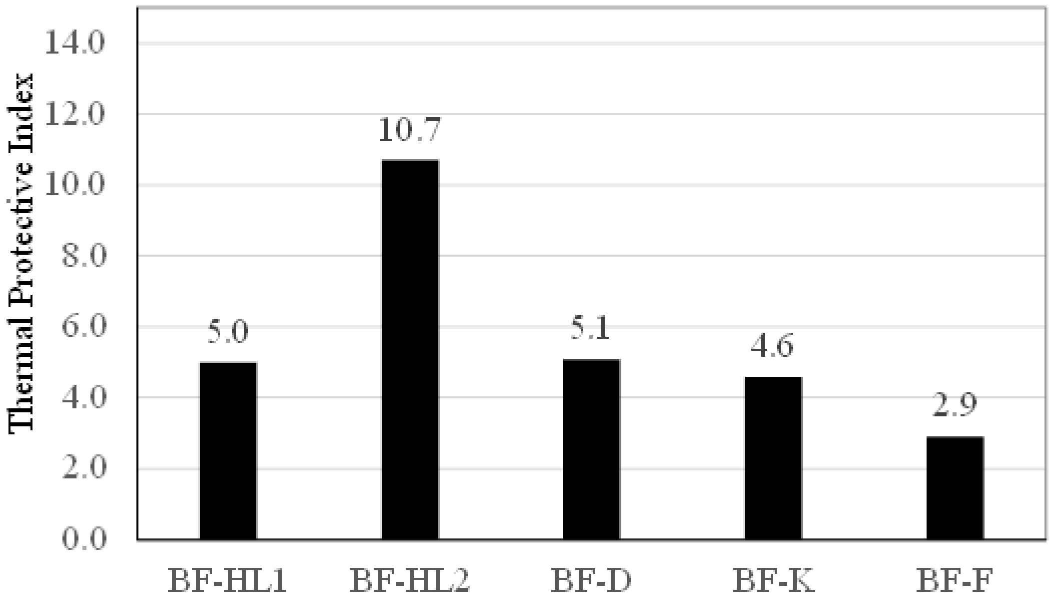


Figure 19. Thermal protective index (TPI) for BF. The higher TPI values indicate better thermal insulation.

3.3 Flammability Barrier Fabrics

3.3.1 Cone Calorimeter: Cone calorimeter measurements on materials such as those considered in the current study can provide significant experimental challenges associated with the materials' low mass, thickness, and burning behavior [7]. Various approaches for improving the reliability and reproducibility of the measurements have been discussed by a number of researchers. These same sample properties often lead to periods of heat release in typical cone calorimeter experiments that last on the order of seconds or tens of seconds. Such heat release times are comparable to the response times of most cone calorimeters, with a value of close to 6 s being typical. Recorded HRRs are known to be distorted from the actual time behavior when rapid changes take place over periods comparable to the response time. For the sharp peaks characteristic of these experiments, measured values of maximum HRR would be expected to underestimate the actual value, while the time required to reach the maximum value would be overestimated [[18]]. The following results are based on the experimental data as recorded, without correcting the time response effects. As a result, the findings represent relative characterizations of BFs and should not be considered as absolute values.

Various parameters derived from the cone calorimeter data including ignition times, peak heat release rate, time to peak heat released (TTP), total heat released, FIGRA indices, and % mass loss at 50 kW/m^2 are given in Table 3 for various BFs. All the BFs had very short TTI (< 10 s), but self-extinguished quickly (flame out (FO) time < 60 s). Generally, experimental times for such materials are relatively short where burning takes place at a high rate before the sample self-extinguishes. The residual mass after combustion was measured, and all the BFs had at least 24 % of their original mass retained.

The TTI data suggests that the physical thickness does not influence the time to ignition of BFs under a given set of conditions. Time to ignition is slightly higher for BFs containing inorganic fibers (*e.g.,* BF-K and BF-F). These barriers also have small flaming periods, low THRs (< 22 kJ), and lower mass loss due to the presence of inherently fire resistant fibers. BFs containing organic fibers (BF-HL1, BF-HL2, and BF-D) ignite almost instantaneously as the sample is exposed to the incident heat flux and continue to burn for longer durations. Generally, the BFs burned with a PHRR in the range of 100 kW/m^2 to 160 kW/m^2. Thermally thin barriers, *e.g.,* BF-D, BF-K, and BF-F have slightly higher PHRR values compared to thermally thick BFs (*e.g.,* BF-HL1 and BF-HL2) and this is most likely due to the fact that the whole sample is pyrolyzed at the same time, giving a sharp peak and higher PHRR value. However, since the PHRR values obtained from cone calorimetry experiments are strongly dependent on the external heat flux applied [7], a simplified index (FIGRA) is deduced from the PHRR. As can be noted from Table 3, the FIGRA values clearly differentiate the performance of the various BFs.

Table 13. Flammability properties of BFs under fully-ventilated conditions in the cone calorimeter at 50 kW/m^2. Uncertainties are reported as one standard deviation.

Sample	TTI (s)	FO (s)	PHRR (kW/m^2)	TTP (s)	FIGRA (kW/s)	Residual mass (%)	THR (kJ)
BF-HL1	4	43 ± 6	100 ± 5	8	12.5	24 ±2	27
BF-HL2	5	57 ± 9	105 ± 4	6	15.0	41 ± 6	37
BF-D	6	36 ± 1	145 ± 3	10	14.5	24 ± 1	24
BF-K	10	19 ± 2	130 ± 6	12	10.8	40 ± 1	22
BF-F*	6	17	157	12	13.4	47	11

* Data for only one specimen was collected

3.3.2 Modified Mydrin: Digital images of FPUF/BF composite assemblies tested without cover fabric are shown in Table 4. All the composite assemblies in Table 4 exhibited self-extinguishing behavior *i.e.,* samples self-extinguished as soon as the ignition source was removed from the sample. The thermal damage on the highloft barriers (BF-HL1 and BF-HL2) was minimal. Thermally thick highloft barriers protected the FPUF from the flame heat of the ignition source. Thermal damage on respective foams was negligible. The flame spread on composite samples with thermally thin BFs and the thermal damage on the respective FPUF was slightly higher. As noted earlier, the thermally thin BFs have relatively high heat transfer rates when exposed to combined radiant and convective heat fluxes in the TPP test (see Table 2).

Digital images of composite samples (FPUF/BF/CF) exposed to a 40 mm butane flame for 10 s are shown in Table 5. In most cases the cover fabric ignited immediately and burned completely. The thermal damage to the FPUF (after removing the BF layer) is also shown in Table 5. The thermal degradation of the foam, however, was not sufficient to support combustion. The duration of flaming for these composite assembles was generally between 2 min and 4 min. The flaming period for the composite sample with BF-K was highest (4.3 min). This is mainly due to the fact that BF-K is an active barrier. Active barriers not only help prevent the ignition of interior foam but can also prevent the cover fabric from burning. Note that the cover fabric in the case of the composite sample with BF-K was not completely consumed by the fire. Passive barriers, on the other hand, prevent or delay the ignition of the interior foam; however, they did not prevent burning of the cover fabric. The cover fabric, in cases of composites with passive barriers burned out quickly giving a smaller duration of flaming.
Ignoring edge effects, most of these BFs burned with the cover fabric and formed a char in place. The extent of damage to the underlying foam primarily depend on the type and structure of the charred barrier material, which in turn depends on fiber content, structural attributes, and thickness of the BF.

In addition to qualitative analysis of burning behavior of composite samples in the modified Mydrin test, some quantitative information was also recorded. The flaming time and percent mass values for various test samples are given in Table 5. Percentage mass losses for the test specimens can provide insight into how well the BF is protecting the FPUF. It may be assumed that the higher the mass loss, the higher is the thermal degradation of the FPUF [[19]]. The percentage mass loss for all samples was between 11 % and 15 %. The higher mass loss was seen in the case of BF-D, whereas BF-HL2 showed a minimum mass loss value, suggesting that the thermally thick barrier better protected the FPUF from thermal degradation. The extent of damage to the foam was much greater in the case of thermally thin barrier materials with no active flame retardants (*e.g.,* BF-D). Thus it can be suggested that if the BF is not an active fire barrier, then the amount of heat transfer through a barrier is critical, *i.e.*, the material should be thermally thick to protect the underlying foam.

Table 14. Digital images of composite samples (FPUF/BF) exposed to 40 mm butane flame for 20 s.

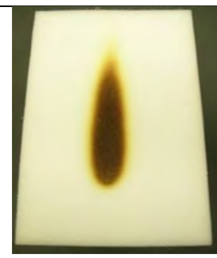
ID	**BF-HL1**	**BF-HL2**	**BF-D**	**BF-K**
FPUF/BF				
FPUF				

Table 15. Digital images of composite samples (FPUF/BF/CF) exposed to 40 mm butane flame for 10 s.

ID	FPUF/BF	FPUF	Flaming time (min)	% Mass loss
BF-HL1			4.00	13
BF-HL2			3.40	11
BF-D			3.40	15
BF-K			4.30	13
BF-F			2.50	14

3.3.3 CBEARHFTI proposed open-flame test: Four (BF-HL1, BF-HL2, BF-D, and BF-F) of the five barriers passed the open-flame ignition test proposed by the CBHEARFTI. BF-K consistently failed the test, in that the FPUF ignited in less than 30 s. Digital images of FPUF and BFs exposed to the CBEARHFTI proposed open-flame test are shown in Figure 20.

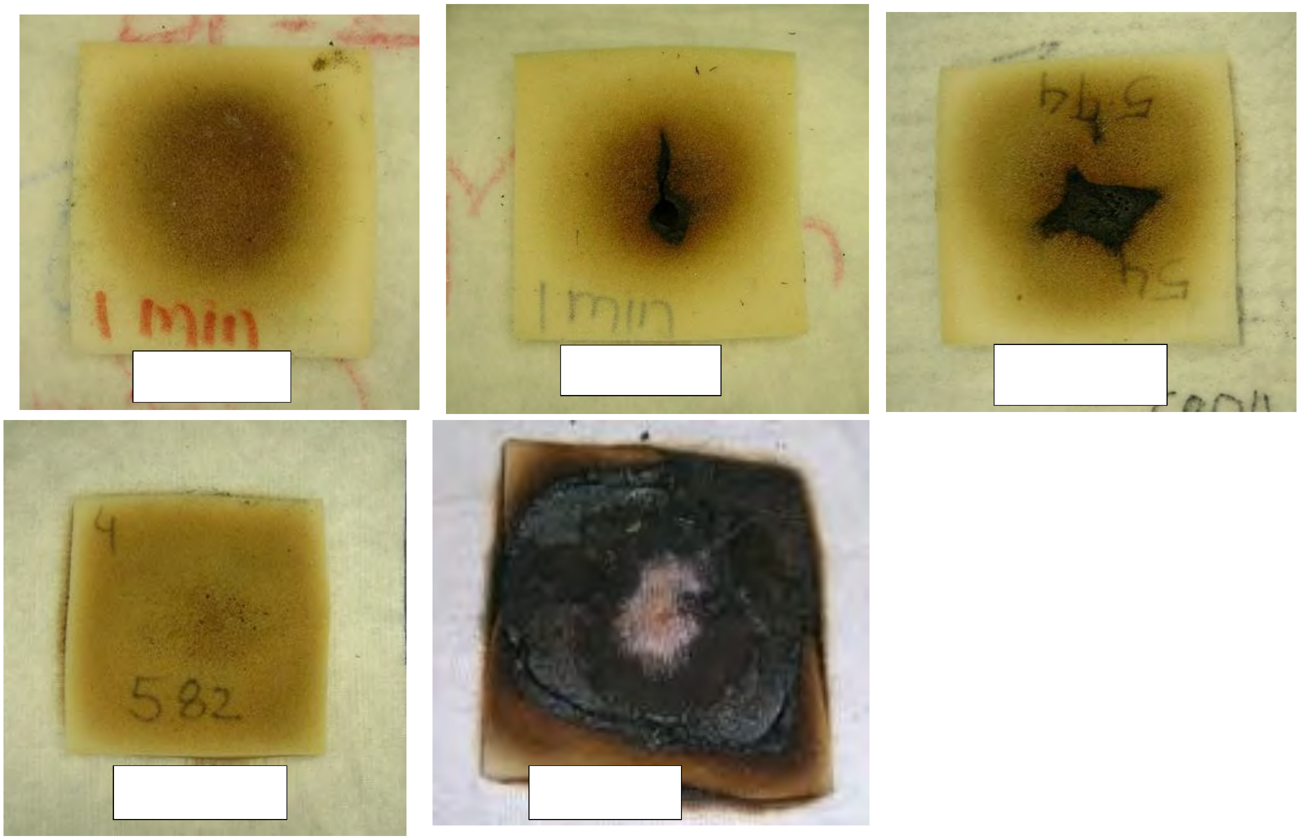


Figure 20. Digital images of FPUF and BFs exposed to CBEARHFTI proposed open-flame test.

As mentioned earlier in the experimental section, the open flame impinges on the BF at the center. Depending on whether the BF is flammable or flame resistant, the flame spreads radially away from the tip of the applied flame. As a BF continues to be heated by the flaming ignition source, the FPUF shrinks away from the heat source and forms a dome shape with the peak directly over the position of the applied flame. This may have a significant effect on the ignition process and the test results. For BF-HL1, the dome structure is more uniform as opposed to BF- HL2, where the dome structure collapses forming voids in the FPUF (see Figure 8).

For the BF-HL1, the FPUF does not undergo significant thermal degradation. This highloft barrier provided significant thermal insulation, thus protecting the FUPF. In the case of BF-HL2 and BF- D, the volatile degradation products escaped into the exhaust or the volatiles did not reach a critical concentration flux and/or the necessary autoignition temperature. For thermally thin BF-F, the FPUF melted and accumulated on the BF. This melt drip burned in the presence of a flaming ignition source. There was no hole formation in the FPUF (see sample BF-F in Figure 8). Thus, the pyrolysis gases do not ignite or burn on the top, but the melt drip burns on the BF-F, thereby passing the test criterion. BF-K that failed the test had a hole in the BF char and the flame from the ignition source came into direct contact with volatiles leading to flash ignition of the FPUF.

4. Conclusions

Fundamental properties of barrier fabrics (BF) that influence the heat transfer properties, as they relate to thermal protection of cushioning components in upholstered products have been tested. Five barrier fabrics have been evaluated both as an individual component and as a part of a composite sample, using different test methods. The physical properties such as the permeability and strength of the BFs were measured to largely depend on the structure of the barrier materials.

The quantitative component test methods used in this study (Cone Calorimeter and the TPP test), in principle, assessed ignitability, heat release rate, and heat transfer properties of barrier fabrics. Cone calorimeter measurements distinguish between barrier materials with respect to ignition times, peak heat release rate (PHRR), total heat released (THR), and char yield. The time to ignition (TTI) relates to how quickly a BF can ignite if the cover fabric ignites. The PHRR is related to the maximum heat released by the burning BF that maintains the fire due to a positive feedback mechanism involved in the burning process, whereas the THR reflects the total amount of flammable content of the BF specimen. The char yield, both qualitative and quantitative, reflects the thermal protective property of the BF after it has been exposed to external heat flux. Thus, important information with regards to evaluating BFs can be obtained from cone calorimetry data. Such measurements are suitable for screening new materials and the data may be used to model the barrier effectiveness in end-use applications.

The TPP test quantified heat transfer properties of BFs that could be used for relative ranking of BFs under given heat exposure conditions. The derived heat transfer factor (HTF) and the thermal protective index (TPI) can be used to rank relative performance of barrier materials. However, these component tests cannot fully characterize the fire hazard posed by full-scale upholstered composites.

The modified Mydrin test and the CBHEARFTI proposed open-flame ignition tests are composite tests. These qualitative composite test methods have 'pass/fail' criteria but they do not quantify relative performance of the BFs. NIST is currently evaluating the effectiveness of these composite tests as potential approaches for assessing fire blocking performance of barrier fabrics by combining results from the various tests discussed here.

In addition to the above mentioned properties, it is important to note that the fire blocking performance of barrier fabrics in upholstered furniture strongly depends on physical properties such as porosity, thermal shrinkage, bursting strength, *etc.* For example, the size of the pores defines the rate of gas permeability, which in turn impacts the pyrolysis rate of materials within the barrier. The permeability should be low enough to prevent flaming combustion inside the BF, especially when pyrolysis gases accumulate underneath the barrier. Permeability of a BF before and after heat exposure should provide insight into changes in porosity and whether or not the material will act as an effective barrier to gas exchanges. Since many factors can contribute to the capability of a given material to perform effectively as a BF, general principles for selecting BFs and engineering their fire safety need to be established. It is important to identify correlations between the physical properties and the thermal protective performance of the BFs. Most importantly, it is critical to correlate the BF performance in bench-scale mock-ups with large-scale, if not full-scale, product testing. Large-scale mock-up testing with selected barrier fabrics is underway at NIST and should provide an improved understanding of the relation between bench-scale and large-scale performance.

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