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Development of A Fuel Package for Use in the Fire Performance of Houses Project

by

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Abstract

This paper presents results from medium- and room-scale experiments which were conducted in order to develop a fuel package to simulate a fire in a residential basement room as part of a project to investigate fires in basements in residential dwelling units. In order to achieve realistic fire growth, repeatability across tests and simplicity of the fuel package configuration, a fuel package consisting of a mock-up sofa constructed with exposed polyurethane foam (PUF) and wood cribs was developed. The polyurethane foam used for constructing the mock-up sofa was selected from PUF foams typically used to manufacture upholstered furniture based on the results of bench-scale and medium-scale tests conducted using a cone calorimeter and a 2 MW open calorimeter. Additional medium-scale tests were conducted in the open calorimeter with sections of used sofas, mock-up sofas and wood cribs of different sizes in order to provide information on heat release rates and products of combustion. The fire growth of the mock-up sofas generally lay between a fast- and ultra-fast t-squared fire curve and displayed a rapid fire decay following attainment of the peak heat release rate. Based on the results of a fire load survey and analysis of the results, the fuel package for simulating a residential basement fire was configured to include a full-size PUF mock-up sofa and 136.5 kg of wood cribs.

The fire development resulting from the fuel package was evaluated in a room-scale test conducted in a basement room of a full-scale house facility, which had been lined with non-combustible materials. As the first item ignited, the mock-up sofa quickly reached its peak heat release rate at about 180 s and the wood cribs sustained the fire after the sofa was consumed. The results of the test showed that the fuel package resulted in a fast-developing fire that caused complete fire involvement of the fuel package. This occurred under the ventilation conditions provided in the test setup, using one exterior window opening in the fire compartment and an interior doorway leading to the upper stories of the test facility. Temperatures at the ceiling level in the fire room exceeded 700°C for about 625 s during the fully-developed stage of the fire, indicating that this scenario would provide a reasonably severe basement fire scenario.

1 Background

This paper presents results from medium- and room-scale experiments that were conducted in order to develop a fuel package to simulate a fire in a residential basement room as part of a project (The Fire Performance of Houses) evaluating the impact of new and innovative construction products and systems on the fire safety of single-family residential dwellings. The initial phase of the project was concerned with the impact of a fire occurring in a basement room on an unprotected floor above it and tenability conditions in the dwelling. The scenario selected for this phase of the study had the fire initiated with an item of upholstered furniture. Repeatability across tests and simplicity of the material composition were two of the key requirements that the fuel package had to satisfy. To this end, a fuel package consisting of a mock-up sofa constructed with exposed polyurethane foam (PUF), the dominant combustible constituent of upholstered furniture, and wood cribs was selected. The mock-up sofa would be the first item ignited and the wood cribs would provide the remaining fire load to sustain the fully-developed fire for the desired period of time.

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The upholstery fabrics were omitted in the mock-up sofa since they largely affect the incipient stage of the fire by either delaying or hastening the involvement of the PUF in the fire. Given that the actual danger from an upholstered furniture fire begins when the PUF starts to burn, a sofa mock-up constructed with non-fire-retardant PUF, a non-combustible frame and no upholstery was deemed sufficient to simulate the inherent fire hazard.

Given that there are many different kinds of PUF available on the market, initial screening fire tests were conducted with representative samples of PUF ,which are used for upholstered furniture applications, using a cone calorimeter and a medium-scale open calorimeter in order to select two types of PUF that were used to construct the mock-up sofa test specimens for more extensive medium-scale testing, the results of which are presented here. The density of the PUF samples ranged from 14 kg/m^3 to 32.9 kg/m^3. PUF specimens for tests conducted in the cone calorimeter, were cut into blocks of 100 mm x 100 mm x 50 mm. For the tests in the open calorimeter, the nominal dimensions of the single PUF blocks, which were tested, were 610 mm long x 610 mm wide x 100 mm thick. A detailed description of this work is given by Bwalya et al.[1] Eventually, one type of PUF was selected for constructing the full-size mock-up sofa that was used in a room fire test.

Used sofas were tested before the mock-up sofas to provide reference data. The used sofas and mock-up sofas, which were tested, were all less than full size since the capacity of the medium-scale calorimeter to measure the heat release rate was limited to about 2 MW and peak heat release rates of sofas were known to exceed this value. Two fire tests were conducted with two wood cribs of different sizes to obtain their heat release rates.

2 Test Specimens

Used sofa specimens were cut into one-third and two-thirds sections to simulate an upholstered chair and a two-seat sofa, respectively, since full-size sofas could not be tested in the available open calorimeter. The density of three samples, "G", "H", and "I" taken from the used sofas were 30.2 kg/m^3, 32.9 kg/m^3 and 32.1 kg/m^3. Figures 1 and 2 show two of the used sofas which were tested.

Figure 1. One-third sofa specimen (nominal dimensions: 600 x 900 x 700 mm)

Figure 2. Two-thirds sofa specimen (nominal dimensions: 1280 mm x 800 mm x 650 mm)

The mock-up sofa specimens were comprised of a steel frame and PUF blocks (cushions) measuring 610 mm long x 610 mm wide and having two thicknesses: 100 mm and 150 mm. Two types of PUF, labeled as PUFs "D" and "E" having densities of 32.8 kg/m^3 and 32.3 kg/m^3, respectively, were used. These values compared well with the ones for the PUF used for making the seat cushions of the used sofas. The specimens for the medium-scale tests were of two sizes: one-third and two-thirds of full size. Figure 3 illustrates the one-third mock-up made with one set of cushions and gives the dimensions of the steel frame. A picture of the test specimen is shown in Figure 4. The two-thirds mock-up had a second set of cushions to represent a two-seat sofa, as shown in Figure 5.

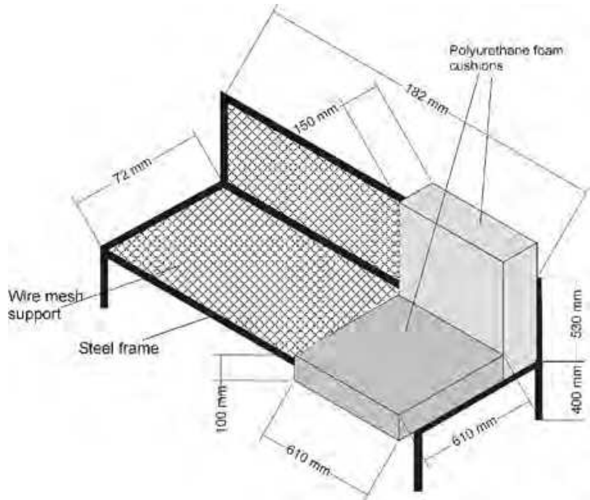

Figure 3. Dimensions of the one-third mock-up sofa

Figure 4. Typical one-third mock-up sofa specimen

Figure 5. Typical two-thirds mock-up sofa specimen

The wood cribs were made with kiln-dried (KD-HT), spruce-pine-fir (S-P-F) lumber pieces, each measuring 38 mm x 89 mm x 800 mm. The pieces were evenly spaced in rows of six and stacked (with upright 38 mm x 89 mm rectangular cross sections) in parallel pairs at right angles to the parallel pair immediately below to heights of 356 mm (4 rows high) and 712 mm (8 rows high) for a small crib (Figure 6) and large wood crib (Figure 7), respectively.

Figure 6. Small wood crib

Figure 7. Large wood crib

3 Test Facilities

3.1 Medium Scale Tests

The medium-scale fire experiments were conducted using an open calorimeter designed for measuring the heat release rate (HRR) and the production of light-obscuring smoke under well-ventilated conditions. The basic elements of the calorimeter are a 558-mm-diameter duct, an exhaust fan assembly, and a rectangular hood of 3900 mm x 3640 mm, which is 2350 mm above the ground. Measurements of the volumetric flow rate and temperature of the exhaust gases, and concentrations of oxygen, carbon dioxide and carbon monoxide were taken in the hood exhaust duct to facilitate calculation of the heat release rate by using the oxygen consumption method[2]. Additional measurements taken were: mass loss (using a weighing scale), and smoke optical density in the exhaust duct (using a pulsed white light smoke meter).

3.2 Room Scale Test

The room fire test was conducted in a test facility that was designed to represent a typical two-storey detached single-family house with a basement. Figure 8 shows a side view of the test facility. The fire room was setup in the basement of the test facility. A detailed description of the test facility is given by Taber et. al. [3]

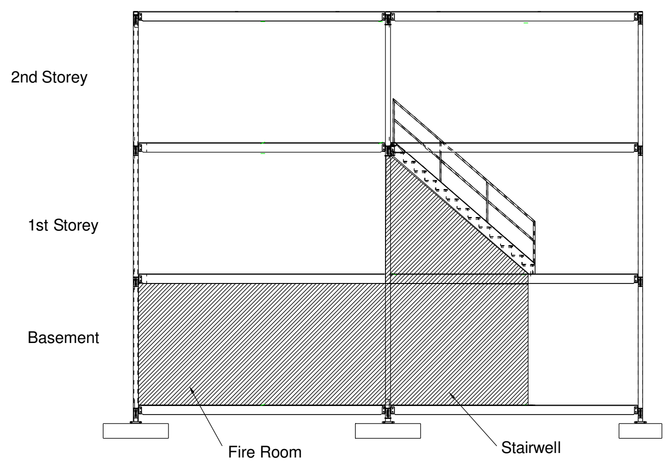

Figure 8. Elevation view of the test facility [3].

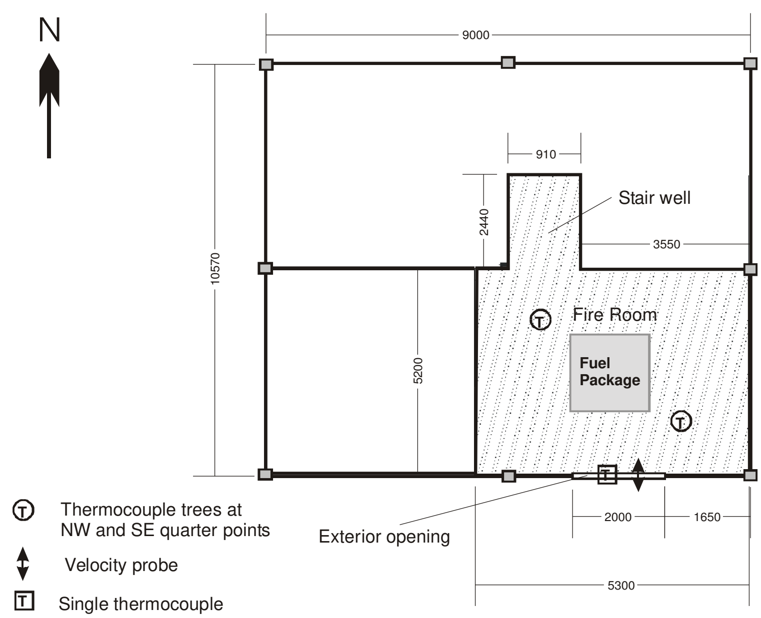

Figure 9. Fire room layout and instrumentation (not to scale; all dimensions in mm).

The basement level was partitioned and instrumented as shown in Figure 9. The fire room represented a 27.6 m^2 basement living area and was based on survey results [4]. The walls and ceiling of the fire room were lined with non-combustible cement boards. An empty stairwell enclosure (with no staircase) led from the fire room on the basement level to the first storey. The floor area above the fire room was covered with 2 layers of non-combustible cement board without any additional fire load. In future tests of structural floor assemblies, the floor assembly will be constructed on the 1st storey directly above the fire room.

A rectangular exterior opening measuring 2.0 m wide by 0.5 m high and located 1.8 m above the floor was provided in the south wall of the fire room. This size is equivalent to the area of two typical basement windows (1.0 x 0.5 m). A noncombustible panel was used to cover the opening. A 0.91 m wide by 2.05 m high door opening located on the north wall of the fire room led into the empty stairwell enclosure. At the top of this stairwell, a 0.81 m wide by 2.05 m high doorway led into the first storey. The test was conduced without the door in this doorway (open doorway).

The instrumentation in the fire room consisted of two vertical arrays of thermocouples (thermocouple trees) with thermocouples located at heights of 2.4 m, 1.9 m, 1.5 m and 0.4 m above the floor on each of the trees. A single thermocouple was installed at the top centre of the exterior opening to monitor the fixed temperature criterion used for uncovering the exterior opening to simulate fire-induced glass breakage and fallout.

The first storey had an open layout with no partitions. A 0.89 m wide by 2.07 m high doorway led to the exterior. A stairway led to the second storey which was partitioned to contain bedrooms, however there were no openings to the outside.

The test facility was not instrumented for rate of heat release measurements or mass loss measurements of the fuel package.

4 Medium-Scale Experiments and Results

In the open calorimeter tests, the sofa specimens were placed on a weighing scale directly under the hood and ignited with a 250 mm by 250 mm square burner with a propane flow rate of 13 L/min (HRR of about 19 kW) for 80 s, in accordance with the ASTM 1537 test protocol [5].

The wood cribs were ignited from underneath with 1000 mL of methanol (density 796 kg/m^3; heat of combustion 20 MJ/kg) [6] that was distributed equally among five shallow metal pans (200 mL per pan) having a mean diameter of 18.5 mm. The total heat output of this ignition source was at least 40 kW and the free-burning time was about 360 s. The clearance to facilitate the placement of the pans was achieved by resting the four bottom corners of a wood crib on concrete blocks 102 mm high.

Heat flux measurements were taken in two tests only: a test with a mock-up sofa and a test with a wood crib. The radiometers were set up at two positions behind the test specimens: 1) 1000 mm height above the base of the specimen, 200 mm away; and 2) 1100 mm height above the base of the specimen, 400 mm away.

4.1 Used Sofas

The test results for the used sofa specimens are summarized in Table 1 and the HRR vs. time is shown in Figure 10. Fire pictures of two of the tests are shown in Figures 11 and 12. The fire growth of specimen Test 2 (US2-H), which was observed to burn readily, aligns well with a fast t-squared fire [7]. This is a reasonable representation of the inherent fire hazard associated with upholstered furniture given that upholstered furniture is usually classified as having ultra-fast t-squared fire growth rates [7]. The differences in the heat release rate profiles of Tests 1, 2 and 3 are mostly due to the influence of the upholstery fabrics on the ignition of the PUF and surface flame spread. The fabrics in Tests 1 and 3 appeared to contribute to the delay of flame spread and consequently the time at which the peak heat release rate was attained. The upholstery fabric used in sofa Test 3 (US1-G) seemed to resist surface flame as can be seen in Figure 11. In the cases where there were two distinct peaks (Tests 1, 3 and 4), the first peak was caused by a backrest-predominant fire that resulted from the rapid upward flame spread. The second peak was due to burning confined to the seat section.

In test 4, the PUF components were quickly consumed by faster fire growth, which failed to ignite the wooden framing components and hence resulted in the lower total heat release value given in Table 1.

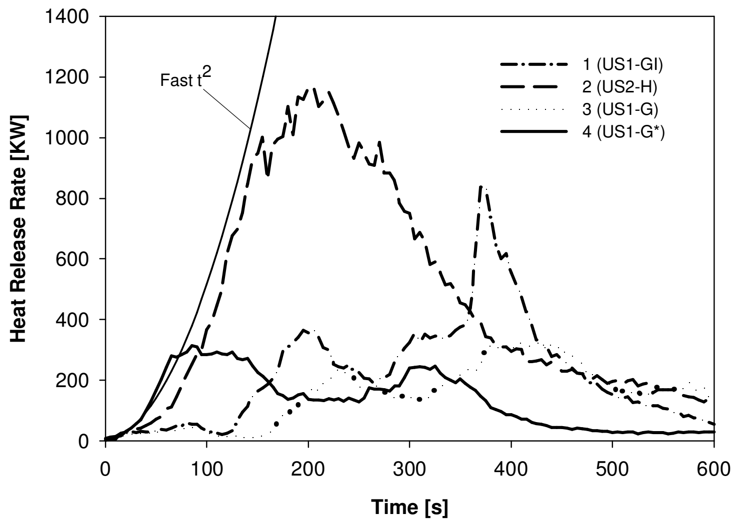

Figure 10. Heat release rate of used sofas

Figure 11. Fire picture: specimen US1-G

Figure 12. Fire picture: specimen US2-H

Table 1. Open calorimeter test results for used sofas for a 600 s duration of burning

Test	Specimen	Mass (kg)	Peak HRR (kW/m^2)	Time to peak (s)	HR (MJ)	Total smoke (m^2)	Mass loss (kg)
1	US1-GI	16.53	838	375	132.7	649	6.5
2	US2-H	24.54	1169	205	254.9	1847	18.2
3	US1-G	13.37	354	410	100.2	635	5.3
4	US1-G*	12.40	314	85	78.4	372	2.8

HRR – Heat Release Rate Total HR – Total Heat Release
Naming convention: size-PUF code
Size: US1: one-third section; US2: two-thirds section;
US1-GI: seat cushion made of PUF I
US1-G*: No upholstery fabric

4.2 Mock-up Sofas

Table 2 summarizes the results of the tests with mock-up sofas. Tests 5 to 9 investigated the effect of the seat and backrest thickness on the peak heat release. It was found that a thicker (150 mm versus 100 mm) backrest resulted in a higher peak heat release rate. Therefore, this configuration was selected for the test with the two-thirds mock-up sofa.

Table 2. Open calorimeter test results for mock-up sofas for a 600 s duration of burning.

Test	Specimen	Mass (kg)	Peak HRR (kW/m^2)	Time to peak (s)	HR (MJ)	Total smoke (m^2)	Mass loss (kg)
5	MS1-D-1	3.052	433	90	64.9	NA	2.3
6	MS1-D-1*	2.933	403	95	76.7	765	2.6
7	MS1-D-2	2.973	690	145	78.1	783	2.9
8	MS1-E-1	2.999	429	190	78.9	443	NA
9	MS1-E-2	3.005	780	135	90.6	446	2.7
10	MS2-D-2	5.840	1376	155	142.2	1019	5.5

HRR – Heat Release Rate; Total HR – Total Heat Release; NA – Data not available
* Placed on an aluminium foil pan to promote the formation of a pool fire
Naming convention: Specimen size-PUF code-PUF thicknesses
Specimen size: MS1: one-third mock-up; MS2: two-thirds mock-up
PUF thicknesses: 1: 150 mm seat thickness and 100 mm backrest thickness;
2: 100 mm seat thickness and 150 mm backrest thickness.

During the tests, it was observed that mock-up specimens constructed with PUF E melted readily and a pool fire formed beneath the sofa frame earlier than with PUF D specimens. This melting characteristic is undesirable as it promotes variability in burning behaviour. Figure 13 shows that the two-thirds mock-up MS2-D-2 achieved a rate of fire growth that lies between the ultra-fast and fast t-squared fire curves [7]. Typical fire pictures taken near the peak burning period are shown in Figures 14 and 15.

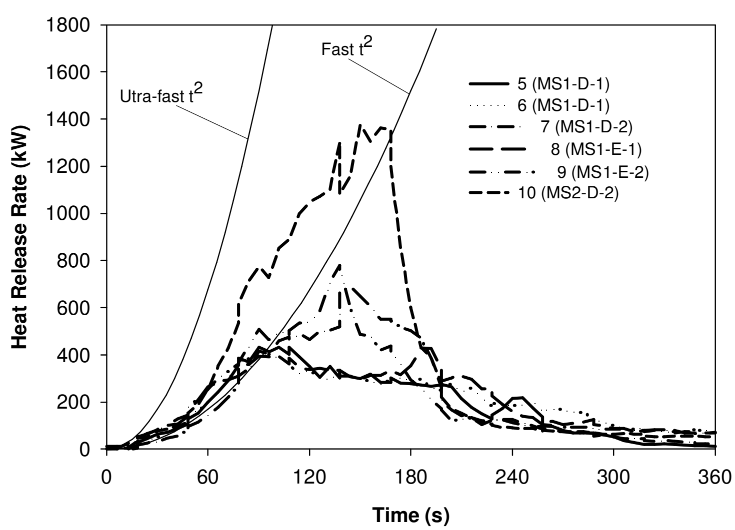

Figure 13. Heat release rate of mock-up sofas.

Figure 14. Typical fire stage with MS1 mock-up sofa specimens (MS1-E-1 shown)

Figure 15. Typical fire for MS2 mock-up sofa specimens (MS2-D-2 shown)

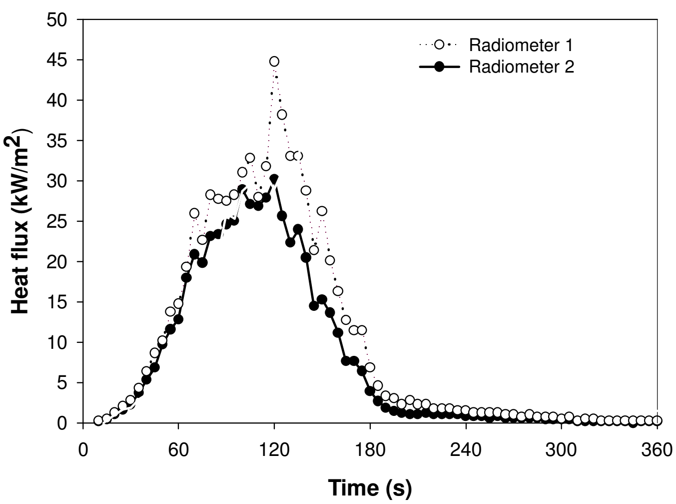

Figure 16. Heat flux measurements during Test 7 (Positions: Radiometer 1 – 1000 mm height, 200 mm behind sofa; Radiometer 2 – 1100 mm height, 400 mm behind sofa).

Figure 16 shows the results of heat flux measurements taken during Test 7 to investigate the likelihood of wood igniting at the two radiometer positions. For exposure to a constant heat flux, White and Dietenberger [8] found that ignition times for solid wood typically ranged from 3 s for a heat flux of 55 kW/m^2 to 930 s for a heat flux of 18 kW/m^2. A peak heat flux level of about 45 kW/m^2 was recorded at a point 200 mm behind the sofa. This is sufficient to ignite wood.

4.3 Wood Cribs

Table 3 summarizes the results of the tests with wood cribs. The heat release rates are shown in Figure 17 and fire pictures in Figures 18 and 19. Increasing the stack height from 356 mm (4 rows high) to 712 mm (8 rows high) had a significant effect on the peak HRR as it increased from 422 kW to 1383 kW as the burning rate is dependant on the stack height[9]. Both cribs portrayed similar burning behaviour with the HRR reaching a plateau after a rapid decline from its initial peak value.

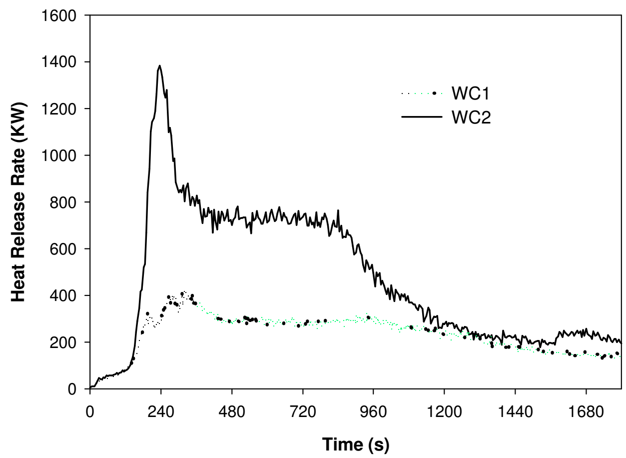

Figure 17. Heat release rate of wood cribs

Figure 18. Fire picture: WC1

Figure 19. Fire picture: WC2

Table 3. Open calorimeter test results for wood cribs for 1800 s duration of burning.

Test	Specimen	Density (kg/m³)	Mass (kg)	Peak HRR (kW/m²)	Time to peak (s)	HR (MJ)	Total smoke (m²)	Mass loss (kg)
12	WC1	378	25.9	422	318	408.1	1115	24.7
13	WC2	378	50.9	1383	235	829.7	NA	46.6

WC1: Small wood crib; WC2: Large wood crib
HRR – Heat Release Rate; Total HR – Total Heat Release; NA – Data not available.
The moisture content of the specimens used for measuring the density was 6%.
The tested wood cribs had a moisture content of 6%.

4.4 Fuel Package for the Room-Scale Fire Test

On account of its better melting characteristics, PUF D was selected for constructing the full size mock-up sofa for use in the room-scale fire test. Figure 20 summarizes the heat release rates of the MS2-D-2 two-thirds mock-up sofa and the two different-sized wood cribs during the open calorimeter tests. These results indicate that, as the first item to be ignited, a full-size mock-up sofa would be expected to quickly achieve a peak heat release rate greater than 2 MW since a proportional increase in the peak heat release rate would be expected with the increase in size from two-thirds to full-size.

Thereafter, the wood cribs would be expected to provide sufficient fuel to sustain the fire provided there is sufficient ventilation. Considering that the large wood cribs would have to be ignited by radiation in order to simulate a natural fire progression in the house test facility, and that their initial rate of fire growth would be slow, it was decided to integrate the mock-up sofa with two of the small wood cribs located underneath the sofa. In this scenario, the small wood cribs would be progressively ignited by the PUF pool fire as it forms beneath the sofa and they would have ignited completely by the time the sofa reaches its peak heat release rate. This would counteract the rapid decay of the sofa fire that would otherwise be expected to occur after attainment of the peak heat release rate and help to ignite the large wood cribs.

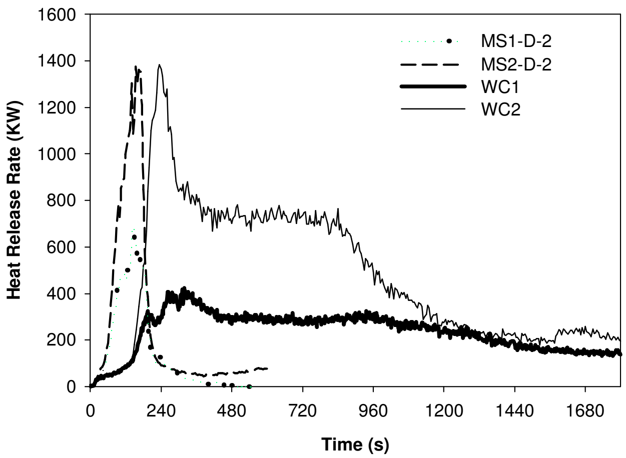

Figure 20. Summary of the heat release rates of the wood cribs and the selected mock-up sofa.

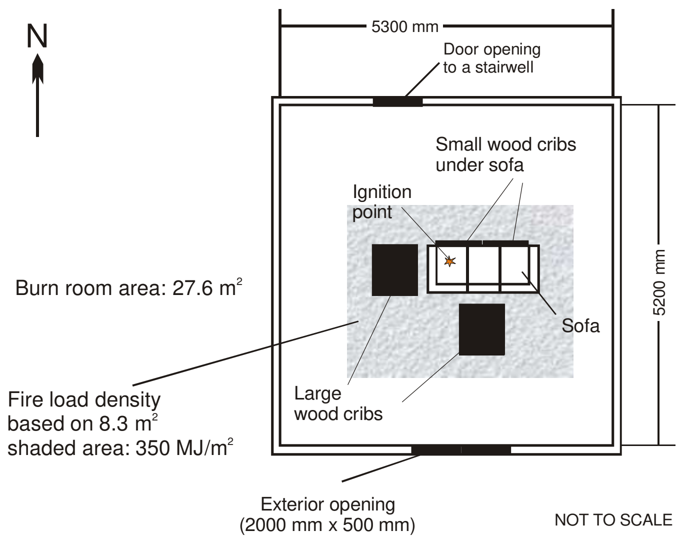

Figure 21. Arrangement of the fuel package in the fire room.

Based on survey results [4] for residential living areas, a fire load density of 350 MJ/m^2 and floor area of 27.6 m^2 was selected for the fire room. The dimensions of the room and location of openings are shown in Figure 21. The number of large wood cribs (in addition to the sofa and two small wood cribs) required to represent a fire load density of 350 MJ/m^2 in such a room is ten. However, given the expected limited ventilation opening to the outside of 1 m^2 provided by the single opening to the outside and a requirement to limit the potential duration of the fire to about 30 minutes, only two large cribs (representing a fire load density of about 350 MJ/m^2 in the shaded area shown in Figure 21) were included in the fuel package. Pictures of the fuel package arrangement in the fire room are shown in

Figures and 23. The mass of the elements of the fuel package and the ventilation conditions during the test are given in Tables 4 and 5.

Figure 22. Fuel package placed in the fire room

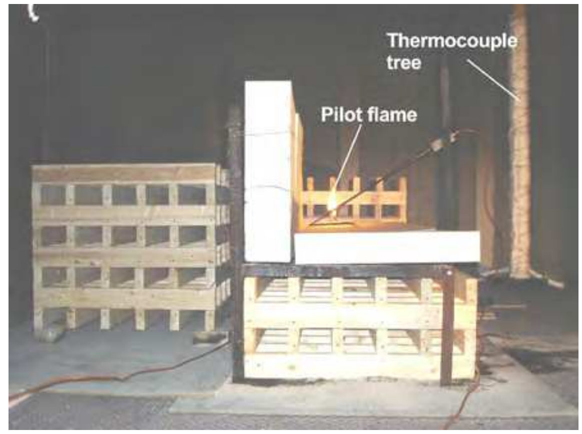

Figure 23. Side view of fuel package showing large wood crib behind the mock-up sofa

Table 4. Fire load and ventilation conditions

Sofa mass (kg)	Number of wood cribs		Total wood mass (kg)	Ventilation conditions	
	Small	Large		Fire room exterior opening [1]	Doorway at top of fire room stairs
8.90	2	2	136.5	Opened	Open

[1] The cover on the exterior opening was removed when a specified temperature of 300°C was reached at this location.

Table 5. Mass of wood cribs

Wood moisture content	Large cribs (kg)		Small cribs (under sofa) (kg)	
	Behind sofa	Beside sofa	# 1	# 2
-	46.0	46.0	23.0	23.0

5 Room-Scale Test and Results

5.1 Test Procedure

The sofa was ignited in accordance with the ASTM 1537 test protocol [5] and data was collected at 5 s intervals throughout the test. The non-combustible panel that covered the fire room's exterior opening during the initial stage of the test was manually removed when the temperature measured at the top-center of the opening (measured by a single thermocouple) reached 300°C. This simulated the fire-induced breakage and complete fall-out of a pane of glass that would occur in a single-pane window and thereby provided increased ventilation to the fire. To simulate occupants evacuating the house, the exterior door on the first storey was opened at 180 s after ignition and left open for the remaining duration of the test.

The test was terminated after a prolonged period of declining temperatures had been observed in the basement level fire room.

5.2 Results

Figures 24 and 25 show the temperature profiles recorded by the thermocouple trees in the NW and SE quadrants of the fire room. The fire developed rapidly following ignition until the first temperature peak was attained. The rate of temperature raise during fire growth period was more rapid than that of the ASTM E119 and ULC S101 standard time-temperature curve[10, 11] and the temperatures in both quadrants were significantly higher during the initial 240 s of the test. The first temperature peak signifies the maximum burning rate of the polyurethane foam fuel, which was the dominant burning fuel during this stage, and marks the transition to a wood crib-dominated room fire.

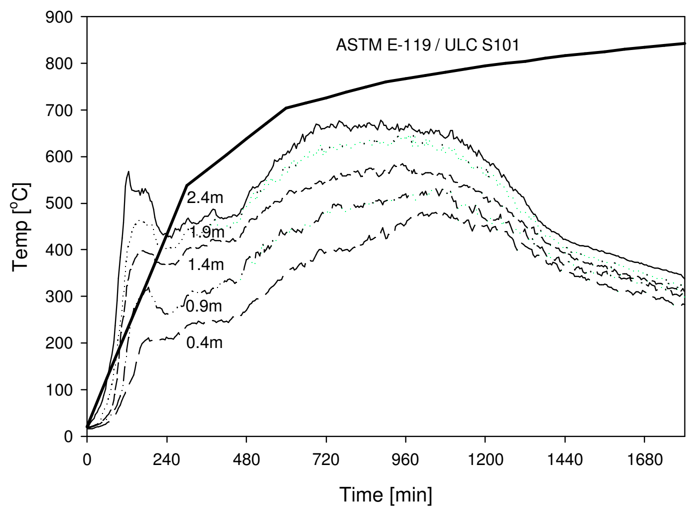

Figure 24. Fire room temperatures: NW thermocouple tree

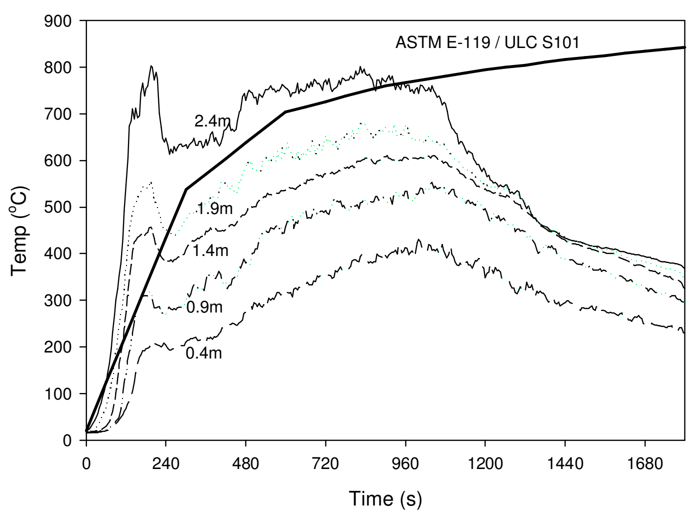

Figure 25. Fire room temperatures: SE thermocouple tree

The two small wood cribs beneath the sofa were ignited directly by the flaming droplets of polyurethane foam and the pool fire that formed on the floor beneath the sofa, whereas the large wood cribs were ignited by a combination of the radiant heat from the burning sofa and small wood cribs, and the descending layer of hot gases. The second temperature peak seen in Figures 24 and 25 corresponds to the time at which the peak burning rate of the wood cribs was reached. Figure 26 shows a picture of the fully-developed room fire (taken from outside the fire room) and Figure 27 shows that the full package was completely consumed at the end of the test.

The thermocouple tree in the SE quadrant recorded the highest temperatures and the temperature at the 2.4 m height consistently exceeded the standard time-temperature curve for much of the fully-developed burning period. A maximum temperature reading of 803^{o}C was obtained at 195 s from ignition at the 2.4 m height, coinciding with the peak burning rate of the mock-up sofa. The temperature of the hot layer exceeded the 600^{o}C and crumpled newspapers placed on the floor near the SE thermocouple tree were observed to ignite spontaneously, indicating that flashover occurred. Following this peak, there was a rapid drop in temperature as most of the PUF material was consumed and it dropped to about 600^{o}C before the wood cribs became fully ignited . Once the wood cribs were fully ignited, the temperature quickly rose and exceeded 700^{o}C for 625 s during the fully-developed period of the room fire. The temperature profiles in the NW quadrant were identical to those in the SE quadrant but temperatures were 100 to 200^{o}C lower. This is likely due to a combination of the dynamic movement of air and combustion gases and proximity of the thermocouple trees to the exterior opening, which supplied combustion air.

Figure 26. Fully-developed room fire viewed from outside the exterior opening

Figure 27. Debris at the end of the test

6 Conclusion

A fuel package to simulate a fire initiated by an item of upholstered furniture was designed using a series of calorimetric experiments and the fire development resulting from the fuel package was evaluated in a room-scale fire test. The results of the room-scale test showed that the fuel package resulted in a fast-developing fire that caused complete fire involvement of the fuel package under the ventilation conditions provided, in the test setup, using one exterior window opening in the fire compartment and an interior doorway leading to the upper stories of the test facility. As the first item ignited, the mock-up sofa quickly reached its peak heat release rate at about 180 s and the wood cribs sustained the fire after the sofa was consumed. Temperatures at the ceiling level in the south-east quadrant of the fire room exceeded 700^{o}C for about 600 s during the fully-developed stage of the fire, indicating that this scenario would provide a reasonably severe fire scenario for investigating the performance of building assemblies. The experimental results show that the initial fire growth from the package lies between the fast- and ultra-fast t-squared fire curves. The use of the fuel package in further full-scale fire scenario tests conducted in the Fire Performance of Houses test facility, including an analysis of tenability conditions, has been reported by Su et al. [12]

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