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HEAT RELEASE RATES OF MODERN RESIDENTIAL FURNISHINGS DURING COMBUSTION IN A ROOM CALORIMETER

Alex Bwalya, Eric Gibbs, Gary Lougheed and Ahmed Kashef

National Research Council Canada, Construction, Fire Safety

Ottawa, Ontario K1A 0R6, Canada

Abstract

Results are presented from a number of fire experiments that were conducted in a room environment to study the fire characteristics of typical residential furnishings and assist in the design of a subsequent phase of a project involving fully-furnished room fire experiments. The experiments were conducted in a 16 m² test room (with dimensions 3.8 m wide x 4.2 m long x 2.4 m high), which had a 1.5 m x 1.5 m window opening. The furnishings tested included mattresses, bed clothes, bed assemblies, upholstered seating furniture, clothing arrangements, books, plastic audio/video media and storage cases, toys, shoes and a computer workstation setup. The smoke from the room was collected using a hood system in order to measure the heat release rate (HRR) and optical density of the smoke. The test room was instrumented with load cells, heat flux gauges, thermocouples and velocity probes in order to take the following measurements: mass loss, total heat flux on gauges installed flush with the internal surfaces (floor, walls and ceiling), temperatures at numerous locations and gas velocities in the window opening.

Twin-size mattresses produced peak HRRs of approximately 3,800 kW and the maximum room temperature was approximately 980°C. The HRRs of bed assemblies of various sizes and configurations ranged from 1,800 kW for a twin-size bed, to 6,250 kW for a bunk bed. The maximum temperature and heat flux recorded in the experiments were 1,071°C and 221 kW/m², respectively. Upholstered chairs and sofas had HRRs ranging from 630 kW for an Ottoman, to 3,360 kW for a two-seat sofa. In tests with clothing, toys, shoes, books, computer workstation and CD/DVD media, the peak HRRs ranged from 440 kW for a bookcase to 2,045 kW for toys. Furnishings containing a large proportion of rigid thermoplastic plastics, such as shoes and media cases produced very dense smoke even at low HRRs. The effect of parameters such bed clothes, mattress type, foundation type, bed assembly and chair size, material composition and fuel package arrangement were evident in the results.

Since the room dimensions and wall lining materials remained constant, temperatures were linearly proportional to the peak HRR (and exposure time) until the ventilation-limit (approximately 4,100 kW) was reached.

1 INTRODUCTION

This paper presents and discusses the results of fire experiments that were conducted with various typical residential furnishings in a room environment in Phase 1 of a project titled “Characterization of Fires in Multi-Suite Residential Dwellings (CFMRD)”. The main purpose of the fire experiments was to develop the information that was required to design a series of full-scale fire experiments simulating various fully-furnished living areas in residential buildings in Phase 2 of the project. Thirty five (35) fire experiments were conducted with various residential furnishings in a well-instrumented 16 m² room (measuring 3.8 m wide x 4.2 m long x 2.4 m high, with a 1.5 m x 1.5 m square window opening) to capture the effect of radiation feedback and other room effects on fire behavior. The furnishings tested included mattresses, bed clothes, bed assemblies, upholstered seating furniture, clothing arrangements, books, plastic audio/video media and storage cases, toys and a computer workstation setup. The smoke from the room was collected using a hood system in order to measure the heat release rate (HRR). The underlying objective was to evaluate and determine combustion characteristics, such as HRR and calorific values, for single items of furniture or smaller groups of furnishings.

The main objective of this paper is to provide an insight into the combustion behavior of a range of modern combustible residential furnishings as well data from fire experiments conducted under realistic conditions in a room environment for such purposes as computer modelling or for evaluating the capabilities of existing correlations to predict flashover and room temperatures. Detailed information about the CFMRD test program and further characteristics for the furnishing have been published elsewhere [1].

For the purpose of the CFMRD project, and this paper, residential furnishings are divided into two broad groups: primary combustible furnishings (PCFs) and secondary combustible furnishings (SCFs). PCFs include items such as upholstered seating furniture and bed assemblies, which have long been recognized as the major combustibles that constitute the frequently-first-ignited items in many residential fires. SCFs consist of all other types of combustible contents, such as hard furniture, surface finishes (including flooring), clothing, paper and plastic articles that would be subsequently ignited at flashover and add fuel to a fire initiated by igniting a PCF. When PCFs are the first-ignited item, they are known to give rise to rapidly developing fires due to the flammability of the polyurethane foam (PUF) that is the dominant combustible constituent most often used in their manufacture. As a result, a considerable amount of research has been conducted over the last three decades to characterize their fire behavior, develop predictive methods and to reduce their flammability. However, PCFs are known to exhibit significant variations in their burning behavior, with peak HRRs ranging from less 500 kW to well over 3,000 kW having been reported in the literature [2 - 8]. Among the PCFs, bed assemblies have perhaps the greatest multiplicity of configurations since there are many components that can be assembled around a mattress. Available options for bed clothes include various types of mattress pads (including ones with substantial PUF content), blankets, bed sheets and comforters, sleep pillows and

decorator pillows, all of which have an influence on fire development. The test program reported in this paper reveals some of these issues. A glossary of terms used to describe upholstered furniture and components for bed assemblies, which will be used in this paper, is given in Table S1.

Indeed, much data pertaining to experiments conducted with PCFs can be found in the literature. However, some of the data has limitations such as: the experiments were conducted in open calorimeters, which may not be appropriate for use in computer modelling of room fires since it excludes room effects; the data is outdated in the face of new materials and construction styles ushered in by technological changes and fashion trends; or some pertinent details of the specimens, such as mass and material properties, are absent from the literature. In addition, there can be large variations in fire performance between different PCFs and different configurations of PCFs due factors such as the variation in the quantity of polyurethane foam used in a particular mattress style or brand, and whether or not barrier fabrics or fire retardants have been used, resulting in much-reduced peak HRRs of well below 1,000 kW.

In the CFMRD test program, there was more extensive fire testing of mattresses and bed assemblies due to their importance in fires origination in bedrooms. In addition, a residential survey [9] determined that bedrooms had the largest fire load energy content among all residential rooms that are associated with rapid fire growth due to the presence of PCFs containing substantial amounts of PUF.

2 TEST SPECIMENS

Test specimens were selected to cover a number of combustible household items identified in a residential survey [9]. The rationale behind the selection of items and testing methods were dictated by the long term objective of conducting post-flashover fire in fully-furnished (using realistic fire loads) rooms in the CFMRD project. Therefore, some of these details may not be important for the purpose of this paper, which is intended to document the combustion properties of the furnishings for general use. A multi-step testing process was adopted in which a number of the items of upholstered chairs and mattresses were tested during the initial evaluation step. After this step, one type of upholstered chair and mattress was selected for further testing to evaluate the effect of chair and bed assembly size and configuration on fire behavior.

To ensure consistency in later fully-furnished room tests, and to minimize variables, only PCFs and some SCFs, such as hard furniture items and plastic toys, were purchased in new condition from local furniture outlets. However, in the case of clothing, stuffed toys, shoes and books, used items were obtained from local sources, since these would be expected to burn during the post-flashover period of a fire and therefore would have a minimal effect on the growth phase of a room fire initiated by igniting a PCF (bed assembly or sofa).

The sequence of the tests was dictated by logistical factors relating to decision making time lines, for items requiring a selection process, and the need to limit any damage to the test facility. Therefore,

items that were expected to have high HRRs were not tested in succession so as to avoid prolonged exposure of the test facility to high intensity fires.

Photographs of the test specimens, fire progression and other additional information, such as dimensions and material composition, are given in a supplemental document in order not to make the paper voluminous. The test specimens are organized in groups of like combustible types, such as mattresses, bed assemblies, upholstered seats and secondary furnishings, and listed in the order of testing (i.e. by test number) within the groups. In most cases, the composition of the materials was taken from manufacturer's labels (where available) and no chemical analysis was conducted to verify the declared composition.

The following naming convention (Test ID) was adopted to identify tests and specimens: **XX-SI-YY**, where **XX** is the test number and **SI-YY** is the specimen identification (ID) code; for example, **5-SI-03** refers to Test 5 conducted with specimen SI-03.

2.1 Primary Combustible Furnishings (PCFs)

2.1.1 Mattresses

Table 1 lists six twin-size mattresses, which were selected to represent a broad range of solid core and innerspring types that were available in the Canadian marketplace. The nominal dimensions of the mattresses were 1.90 m long x 0.97 m wide, and thicknesses varied from 0.18 m to 0.33 m. As well, one mattresses (SI-05), which satisfied an open flame test standard for mattresses (16 CFR Part 1633 [10]), which was mandatory requirement in the U.S. (but not in Canada at the time of testing in the year 2008) was included in the test program. The 16 CFR Part 1633 test standard (to be referred to as "16CFR1633" hereafter) sets the following criteria to limit the growth of fire in a mattress or mattress set: a) the peak HRR must not exceed 200 kW within the 30 minutes of the test, and b) the total energy released must be less than 15 MJ for the first 10 minutes of the test.

The innerspring mattresses typically consisted of an outer ticking followed by a layer of polyester fibers and a varying number of layers of PUF thereafter. In the case of mattresses SI-02 and SI-03, which were made with independent coil units, there was a layer of recycled cotton batting on the top and bottom of the coil units. The internal cross-sections structure of mattresses SI-01, SI-02, SI-03, SI-04 and SI-05 are shown in Figures S4, S6, S2, S8 and S15, respectively.

Table 1. Experiments with twin-size mattresses.

Test ID ¹	Test Purpose ²	Picture Figure ³	Mattress Type	Total Mass (kg)	Thickness (m)	Combustible Mass (kg) ⁴
5-SI-03	S	S1	Innerspring	16.2	0.18	5.3 kg (33%)
6-SI-01	S	S3	solid core	12.5	0.22	12.5 kg (100%)
7-SI-02	S	S5	Innerspring	23.1	0.33	9.2 kg (40%)
8-SI-04	S	S7	Solid core	13.3	0.20	13.3 kg (100%)
14-SI-06	S	S15	Innerspring	17.8	0.31	10.5 kg (59%)
28-SI-05	I	S29	Innerspring	13.3	0.26	Not measured

¹ XX-SI-YY, where XX is the test number and SI-YY is the specimen identification (ID) code; ²

Objective of the test (S: Selection process; I: Information); ³ Figure number in supplemental

information; ⁴ Estimate only for innerspring mattresses

2.1.2 Bed clothes

Table 2 lists the tests conducted with various arrangements of bed clothes. Detailed information on the material composition of the bed clothes is given in Table S2. All the tests were conducted with an inert mattress. In Setup #1 (Figure S41), the comforter and top sheet were spread all the way to head of the bed and not folded back. The bed and decorator pillows were placed on top of the comforter. In Setup #2 (Figure S42), the comforter and top sheet were folded back at a distance of 0.470 m from the head-side edge of the bed. Setup #1 was found to be the most common arrangement from survey results [11], whereas Setup #2 was adopted from another study [5].

Table 2. Test arrangements for bed clothes (twin-size).

Test ID ¹	Picture Figure ²	Combinations of Bed clothes ³ (top to bottom arrangement)	Bed clothes Setup	Total Mass (kg)
11-SI-08	S11	Bed pillow, decorator pillow, comforter, sheet set, skirt, and mattress pad.	#2	6.7
12-SI-07	S2	Bed pillow, decorator pillow, comforter, blanket, sheet set, skirt, mattress pad, and foam mattress pad	#2	7.8
17-SI-75	S18	Bed pillow, comforter, sheet set, and skirt	#2	4.6
19-SI-83 30-SI-83	S20 S31	Bed pillow, decorator pillow, comforter, sheet set, and mattress pad.	#1	5.2

¹ XX-SI-YY, where XX is the test number and SI-YY is the specimen identification (ID) code; ² Figure number in supplemental information;

³ Note: A sheet set consisted of a fitted sheet and a flat sheet.

2.1.3 Bed Assemblies

Table 3 lists the tests that were conducted with bed assemblies. All the bed assemblies used a posture box foundation (Figure S40) except for Test 27, conducted with a mate's bed foundation, and Test 42, which used an open-flame-resistant box spring. Test 42 was conducted with a mattress and foundation set, which was compliant with the 16CFR1633 test standard. However, the bed clothes used in Test 42 did not meet any flammability requirements. Tests 34 and 44 were conducted to evaluate the effect of reducing the size of the window opening (from 1.5 x 1.5 m to 1.4 wide x 1.2 m high) on fire development.

The bunk bed (stacked bed; Figure S33) that was used in Test 32 was of the so called “twin-over-double” configuration, i.e. the lower section was a double bed assembly and the upper section was a twin bed assembly, without posture boxes.

Table 3. Tests with bed assemblies.

Test ID ¹	Picture Figure ²	Size	Mattress	Bed clothes	Foundation / configuration	Total mass (kg) ³	Window W x H (m)
21-SI-10	S22	Twin	SI-04	SI-83	PB	37.0	1.5 x 1.5
23-SI-76	S24	Twin	SI-06	SI-83	PB	40.4	1.5 x 1.5
27-SI-11	S28	Twin	SI-06	SI-83	Mate's	86.5	1.5 x 1.5
29-SI-12	S30	Double	SI-06	SI-77	PB	53.8	1.5 x 1.5
31-SI-13	S32	Queen	SI-06	SI-78	PB	66.2	1.5 x 1.5
32-SI-14	S33	Twin	SI-06	SI-77 / SI-83	Bunk	56.7	1.5 x 1.5
42-SI-85	S37	Twin	SI-05	SI-83	BS	42.5	1.5 x 1.5
44-SI-12	S39	Double	SI-06	SI-83	PB	53.9	1.4 x 1.2

¹ XX-SI-YY, where XX is the test number and SI-YY is the specimen identification (ID) code; ² Figure number in supplemental information;

³ Includes non-combustible mattress and foundation components, but excludes any supporting steel bed frame.

Abbreviations: PB: Posture box; BS: Box spring; Bunk: stacked beds fitted one on top of the other; Mate's: Wood foundation with drawers.

2.1.4 Upholstered Chairs

Table 4 lists the upholstered chairs that were tested. None of the chairs had any indication that the upholstery materials contained any fire retardants and only chair SI-27 had a tag from the Upholstered Furniture Action Council (UFAC) [12] stating its conformance to a smoldering ignition test standard. The seat cushions were made of PUF slabs with a layer of polyester fiber batting between the cover fabric and the PUF, whereas the cushioning material in the backrests and arm rests consisted of polyester fiber batting only. All the frames of the chairs were made of wood. The mass of the frames

was not determined. Tests 40 and 41 were conducted with two-seat and three-seat versions of the chair SI-26 to evaluate the effect of size.

Table 4. Tests with upholstered seating furniture.

Test ID ¹	Picture Figure ²	Size Description	Fabric	Total Mass (kg)
9-SI-25	S9	Chair	100% Polyester	30.8
10-SI-24	S10	Chair	100% Polyester microfibers	33.6
15-SI-27	S16	Chair	51% Acrylic, 49% Polyester	12.2
26-SI-26	S27	Chair	40% Acrylic; 60% Polyester	32.9
36-SI-29	S35	Ottoman	Unknown fabric	12.6
40-SI-31	None	Two-seat sofa	40% Acrylic; 60% Polyester	44.3
41-SI-32	S36	Three-seat sofa	40% Acrylic; 60% Polyester	55.6
43-SI-33	S38	Futon	Unknown fabric	17.0

¹ XX-SI-YY, where XX is the test number and SI-YY is the specimen identification (ID) code; ² Figure number in supplemental information;

³ Includes non-combustible components, such as fasteners and springs.

2.2 Secondary Combustible Furnishings (SCFs)

Table 5 lists eight experiments that were conducted with various SCFs.

Table 5. Tests with Secondary Combustible Furnishings.

Test ID ¹	Picture Figure ²	Description	Total Mass (kg)
13-SI-15	S13	Mixed clothes on steel rack	41.1
16-SI-16	S17	Particleboard wardrobe filled with clothes	92.0
18-SI-36	S19	27 inch CRT TV	32.0
20-SI-19	S21	Bookcase with audio/video media (CDs & DVDs & plastic cases)	48.3
22-SI-22	S23	Toys (stuffed and hard plastic types)	15.6
24-SI-18	S25	Shoes	29.0
25-SI-20	S26	Bookcase with books	66.2
33-SI-21	S24	Computer work station	68.6

¹ XX-SI-YY, where XX is the test number and SI-YY is the specimen identification (ID) code; ² Figure number in supplemental information;

3 EXPERIMENTAL SETUP

3.1 Test Facility

Figure 1 shows a photograph of the CFMRD test room and heat release rate calorimeter, which was located inside a large fire-testing hall. A detailed description of the design of the test facility is given in a separate publication [13]. The HRR calorimeter consisted of a 6 m x 6 m square sheet-metal hood with a vertical exhaust duct having a diameter of 1.32 m (Figure 2). The test room was built on a concrete slab using non-combustible materials except for the roof, which was constructed with plywood sheathing. Lightweight steel framing, using 152 mm steel studs spaced at 406 mm on center, was used for the wall and ceiling assemblies. The interior walls and floor were lined with a single layer of cement board having a thickness of 12.7 mm and the ceiling was formed with two layers of 15.9 mm thick Type-X gypsum board applied to steel furring strips, which were attached to the ceiling joists. The exterior walls were lined with a single layer of 12.7 mm cement board.

Figure 1. Test room and heat release rate calorimeter test facility.

Figure 2. Calorimeter hood and exhaust duct.

The interior dimensions of the test room (3.80 m wide x 4.20 m deep by 2.38 m high) were derived from residential survey results [11] to represent the average area of a primary (master) bedroom or a living room. The room was constructed so that the entire width of the window opening was directly under the hood, as shown in Figure 3, and the dimensions of the square window opening were chosen to be 1.5 m x 1.5 m after a series of preliminary fire simulations and experiments that were conducted with various window sizes [13, 14]. The theoretical ventilation-limited heat release rate for the selected window opening is approximately 4,200 kW (assuming 100% combustion efficiency) [15] and the HRR that has a potential to cause flashover is estimated using commonly used correlations [16, 17] to be in the range of 1,500 kW to 2,100 kW.

3.2 Instrumentation

Figure 3 shows a plan view of the instrumentation layout in the test facility. Various types of instrumentation were installed at numerous locations in the test room, but only those relating to the results discussed in this report are described. A detailed description of the design of the test room and other types and locations of instrumentation has been published separately [13].

The test room was instrumented with load cells, Gardon heat flux gauges, thermocouples (TCs) and velocity probes in order to take the following measurements: mass loss, total heat flux on gauges installed flush with the internal surfaces (walls and ceiling), temperatures at numerous locations and gas velocities in the window opening. Table 6 gives the coordinates of the heat flux gauges on various surfaces.

Various types of Type-K (Chromel-Alumel) prefabricated sheathed thermocouple configurations were used: TC “trees”, single TCs attached to wall surfaces and single TCs installed in the window opening. Four TC trees were installed at the center of each of the floor area’s quadrants and each TC tree consisted of five TCs suspended from the ceiling at the following heights above the floor: 0.40 m, 0.90 m, 1.40 m, 1.90 m and 2.38 m. The TC located at the 2.38 m height on the tree was attached to the ceiling.

Measurements of the mass flow rate, gas temperature and concentrations of oxygen, carbon dioxide and carbon monoxide were taken in the vertical section of the hood exhaust duct to facilitate calculation of the HRR by using the oxygen consumption method [18]. A pulsed white light smoke meter [19] was installed in the exhaust duct (Figure 2) for measuring smoke density in the diluted stream.

Table 6. Co-ordinates of heat flux gauge installations on the ceiling and walls of the test room.

	Ceiling	South wall	North wall	West wall	East wall
Location no. 1	(1.05, 2.85, 2.34) ¹	(0.00, 2.85, 1.8)	(4.20, 0.95, 1.8)	(3.15, 3.80, 1.8)	(1.05, 0.00, 1.8)
Location no. 2	(3.15, 0.95, 2.34)	-	-	-	-

¹ X, Y, Z co-ordinates in m (Directions: X – width; Y – length; Z – height; Origin: south-east corner)

Figure 3. Layout of instrumentation

3.2.1 Data Acquisition System

A 16-bit Solartron (Schlumberger) Instruments distributed data acquisition system with 3595 series isolated measurement pods (each having 20 channels) and a personal computer interface was used to record all measurements directly to a computer hard disk drive at specified time intervals. All temperature data were instantly processed by the data acquisition system and recorded as temperature values with an accuracy of better than 1°C. Outputs from heat flux gauges, load cells, pressure transducers, gas analyzers and the smoke meter were recorded as either direct current (DC) voltage or electric current values (mV or mA) and were converted by applying the appropriate calibration constants during the post-experiment data processing stage. The sensitivity of the data acquisition system for voltage and current measurements is 1 mV and 10 nA, respectively.

3.3 Ignition Sources

Various types of propane ignition sources were used for the ignition of the different types of furnishings that were tested. Table 6 lists the ignition sources used and their origins. In the case of mattresses and upholstered chairs, the indicated test standards were selected as the basis for initiating the fire experiment. In that case, the placement of the burners, strength and duration of applying the ignition source was in accordance with the test standard.

Table 7. Ignition sources used in the experiments.

Type of Test Specimen	Ignition source	Strength	Reference Standard
Mattresses	Dual T-burners	Horizontal: 18 kW (12.9 L/min) for 70s Vertical: 9 kW (50s)	16CFR1633 [10]
Bed assemblies and bed clothes	T-burner	9 kW (6.6 L/min) for 50s positioned 0.47 m from the head-side	Ad hoc – derived from 16CFR1633
Upholstered chairs and sofas	Square-burner	19 kW (13.0 L/min) for 80s	ASTM 1537 [20]
Secondary combustible furnishings	T-burner	19 kW for 80s or longer	Ad hoc

The dual burner ignition source used for testing mattresses was designed [5] to simulate the heat imposed on a mattress and foundation set by burning bed clothes. The arrangement of the ignition system, which consists of two T-shaped burners with different propane flow rates and duration of application, as indicated in Table 7. The ignition system was positioned within 0.30 m of the mid-point of the length of the test specimen (Figure S43). Flames from the vertical burner impinged on the side of the specimen for 50 s at a flow rate of 6.6 L/min (9 kW). Flames from the top (horizontal) burner impinged on the top of the specimen for 70 s at a flow rate of 12.9 L/min (18 kW). Figure S44 shows the flames from the two burners impinging on the specimen at the start of the test. For other items, a single T-burner was used, but the strength and duration of the ignition source was decided on an ad hoc basis depending on the ease of ignitability of the items being tested. For instance, in the case of bed clothes and bed assemblies, the dual T-burner ignition source was deemed to be unsuitable since it was intended to simulate the heat imposed by burning bed clothes on a mattress. Therefore, a smaller ignition source of 9 kW provided by a vertical T-burner, with flames impinging on the side of the mattress was used instead. The T-burner was positioned at a distance of 0.47 m from the head side end of the bed (Figure S45). The photograph in Figure S46 shows a test specimen being ignited with a square-burner.

3.4 Test Procedures

The data acquisition system (including video cameras) was started at least 60 s before ignition in order to collect pre-ignition data. A data acquisition rate of 2 s was used in all of the tests. All the test specimens were placed on a load platform at a distance of 1.50 m from the inside edge of the window opening. The specimens were centered along the width of the room and ignited using the ignition source listed in Table 7. Mattresses were placed on a 0.50-m-high steel bed frame (without a foundation). The foundation used for bed assemblies was a posture box (Figure S40) that was placed on a 0.23-m-high steel bed frame.

The tests were terminated, by extinguishing the flames or hot embers with water, after flaming had ceased or subsided considerably. The debris was collected and weighed after a few days had elapsed to allow the water to evaporate. This provided an estimate of the mass of material that was consumed during the fire, in addition to measurements from the load cells.

It is recognized that the ignition sources listed in Table 7 are severe in comparison to realistic igniters such as matches, cigarette lighters and candles, which are often mentioned in many fire statistics as the major causes of residential fires. However, it is common practice in the fire research community to use ignition sources similar to those listed in Table 7 for consistency. Weaker ignition sources may affect the time to ignition; however, it is believed that the post-ignition phase, during which the fire becomes self-sustaining, is the most important period in studying fires originating from PCFs and hence the reason for selecting stronger ignition sources that ensure ignition. A study on the influence of ignition sources on HRR in a furniture calorimeter [21] compared propane burners with ignition strengths ranging from 1.7 kW to 30 kW and found that the burning behavior of the burning items was similar regardless of the type of burner used. As well, the repeatability was better when a stronger ignition source was used. In that study they considered a HRR of 50 kW to be the fire size that can be detected by persons who are not fully alert or those who are further away from the burning item or a fire detector. Therefore, the period before sustained ignition occurs is considered to be relatively unimportant to the assessment of burning behavior and can be accounted for by appropriately modifying the time to ignition or attainment of the experimental HRR at ignition.

3.5 Data Processing

3.5.1 Heat Release Rate

The heat release rate (HRR) was calculated using the well-established method of oxygen-consumption calorimetry. The equations used were those derived by Janssens [18] and cited in numerous standard test methods from organizations such as the American Society for Testing and Materials (ASTM), National Fire Protection Association (NFPA) and the International Organization for Standardization (ISO). Measurements of O_2 , CO_2 and CO were used to calculate the HRR, and the effective heat of combustion was taken to be 13.1 MJ/kg of oxygen consumed. This approximation alone results in an uncertainty of 5% in the calculated HRR. Uncertainties in the measurement of other variables such as O_2 and mass flow are known to increase the uncertainty by as much as 5% [22]. During the calibration of the calorimeter [13], using a propane burner, it was found that the accuracy of HRR measurements was within 10% for HRRs greater than 1,000 kW.

For a calorimeter as large as the one used in this study, the system noise (and uncertainty) is expected to be greater during periods of low HRR (due to low O_2 depletion) as discussed by Brohez [23]; therefore, the HRR data presented in this report were not smoothed. The use of smoothing techniques, such as running time averages was considered, but was not pursued since there is a possibility of damping out some real features of the fires. The subject of smoothing has also been discussed by

Byrant and Ohlemiller [22] with respect to the design of a 3 MW HRR calorimeter. They reported that a “20 s smoothing reduced the apparent peak values by a couple of percent”.

3.5.2 Optical Density

The optical density per meter (OD/m) was processed using in-house calibration data. The total smoke released (TSR) was calculated using the procedure outlined in an ASTM test standard [20].

4 RESULTS AND DISCUSSION

The key results are presented in tabular form and multiple line graphs are provided to show the HRR and room temperature versus time profiles. Line graphs of HRR versus time for each test are given in Table S5 (Figures S81 to S121). A full table of results for all of the experiments is given in Table S4.

4.1 Primary Combustible Furnishings (PCFs)

4.1.1 Mattresses

The results of tests with mattress are given in Table 8. All five mattresses ignited readily and resulted in self-propagating fires by the time the ignition source was turned off. Figures 4 and 5 show the two typical types of fires that resulted based on the extent of flaming out of the window opening: a) limited or no flaming; or b) extensive flaming out of the window opening (indicative of post-flashover fires), respectively. Figures 6 and 7 show, respectively, the graphs of HRR versus time for five mattresses (excluding test 28-SI-05, shown in Figure S104, since the HRR profile was too low and noisy to show on the graph) and average temperature profiles measured at a height of 2.38 m on all four thermocouple trees in the room. All the mattresses had Gaussian-like HRR profiles, due to the accelerated rate of fire growth towards their peak HRRs followed by an equally rapid decrease in the HRR since there were no slow-burning components present, such as wood. Analysis of the results shows that the HRR began to decline after 45% to 70% of the mass of the specimen had been consumed.

Table 8. Summary of test results for the mattresses.

Test ID	HRR _{max}	THR	ODM _{max}	HC	$\bar{T}_{max}$	Q''_{mf}	$\bar{Q}''_{mwc}$	T_{∞}
	(kW)	(MJ)	(OD/m)	(MJ/kg)	(°C)	(kW/m ²)	(kW/m ²)	(°C)
5-SI-03	1,808 (174) ¹	144 (5.4) ²	0.4	26.7	594 (101) ³ [722 SE] ⁴	10	39 (20) ³ [67 SW CS] ⁴	18
6-SI-01	3,790 (234)	257 (12.5)	1.3	20.6	835 (54) [899 SE]	42	98 (32) [138 W wall]	18

7-SI-02	2,238 (258)	250 (9.3)	0.6	26.9	728 (135) [860 SE]	13	55 (27) [92 SW CS]	18
8-SI-04	3,757 (278)	328 (13.3)	1.7	24.6	924 (40) [978 NW]	87	111 (28) [160 W wall]	18
14-SI-06	3,796 (233)	282 (10.5)	2.4	26.9	905 (41) [956 SW]	46	100 (33) [129 N wall]	20
28-SI-05	< 200 (67)	N/A (3.0) ²	0.05	N/A	41 (4) ³ [47 SW] ⁴	N/A	0.8 (0.2) ³ [0.9 NE C] ⁴	18

$T_{\max}$ – Maximum temperature; $\bar{T}_{\max}$ – Maximum average room temperature (of four TC trees); Q_{mf}^* – Maximum heat flux at floor level; $\bar{Q}_{mwc}^*$ – Maximum average heat flux on the walls and ceiling; THR – Total heat released; SW C: SW ceiling location; W wall: West wall; N wall – North wall; NE C – NE ceiling location

¹ Time to reach the peak HRR (s); ² Mass loss (kg); ³ Standard deviation (SD); ⁴ $T_{\max}$ or Q_{mf}^* and its location.

Figure 4. Typical fire with mattresses SI-02 and SI-03 (limited flaming out of the window opening).

Figure 5. Typical fire with mattresses SI-01, SI-04 and SI-06 (extensive flaming out of the window opening with copious dense smoke).

Figure 6. HRR vs. time for mattresses.

Figure 7. Average maximum room temperature at ceiling height (2.38 m) vs. time graphs for mattresses.

Figures 8 and 9 show the stratification of temperatures (average of two TC trees) in the south and north sections, respectively, of the fire room for Test 14-SI-06. All other tests had similar temperature stratification profiles with magnitudes and peak positions being consistent with their HRR profiles. The temperatures (Figures 8 and 9) at the lowest point (0.4 m height) were typically higher in the north side of the test room compared to the south side, which experienced a cooling effect due to the inflow of fresh air from the window opening. Both temperature profiles are similar and the peak temperature values are identical since the test specimens were symmetrically positioned in the room. In some experiments, a faster rate of temperature decline was recorded in north side of the room likely due to reduced oxygen conditions, which results in a lowering of the HRR and hence temperatures.

Figure 8. South-side average temperature profiles at various heights for Test 14-SI-06.

Figure 9. North-side average temperature profiles at various heights for Test 14-SI-06.

All of the fires show an accelerated rate of fire growth beyond a HRR value of approximately 500 kW, which is likely due to room effects (radiation feedback from the hot layer). For all innerspring

mattresses, the ticking and padding material near the ignition zone burnt away quickly (Figure S47) exposing the inner cores of the mattresses and possibly contributing to the faster fire growth rates they exhibited compared to solid core PUF mattresses. The peak HRRs of mattresses SI-01, SI-04 and SI-06 (Tests 6, 8 and 14, respectively), the first two of which are solid core design, are all comparatively high values of around 3,700 kW. This was an interesting result for SI-06 given that other innerspring mattresses had lower peak HRRs. However, a look at the estimated combustible mass fraction in mattress SI-06 (given in Table 2) reveals that SI-06, which was constructed with the lighter independently wrapped (pocket) coils rather than the heavier-gauge open coil spring units, had a higher percentage of combustible material. Another reason is that the excessive melting behavior exhibited by the PUF in SI-06 (Figure S48) contributed to its higher peak HRR due to the additional burning area of the resulting pool fire, coupled with earlier ignition of the underside of the mattress by the pool fire. Other researchers [24] have observed that the type and style of design of a mattress and specific combination of components used could be major factors in fire performance. In experiments with mattresses constructed with fire-retarded PUF, it was found that some innerspring mattresses had poorer performance than solid core mattresses using the same type of PUF [24]. This seems to suggest that the presence of voids in a mattress core due to spring units or convoluted PUF structures (eg. Mattress SI-01; Figure S4) may accelerate fire growth. However, the experiments conducted in this work were insufficient to draw firm conclusions about the effect of the internal structure of a mattress on its burning behavior, given that this was not a focus of the study.

Test 28 involved an open-flame-resistant mattress design (SI-05), which had a certificate of conformance to the 16CFR1633 test standard. The experiment was conducted in accordance with the test standard and specimen SI-05 was found to be in conformance with the standard based on the peak HRR criteria - The HRR did not exceed 200 kW (HRR profile is shown in Figure S100) and the experiment was terminated after 30 min. However, it was impossible to determine whether the 15 MJ criterion was met due to the excessive noise in the HRR data. Figure S49 and S50 show pictures taken at the beginning and end of the test, respectively.

4.1.2 Bed clothes

Table 9 gives the results of experiments with various combinations of bed clothes (listed in Table 3). It was found that Setup #1, with the comforter not folded back, resulted in a faster rate of surface flame spread since the pillows were ignited earlier and the radiation from the resulting plume helped to accelerate the rate of flame spread.

Table 9. Summary of experimental results for the bed clothes.

Test ID	HRR _{max}	Time to peak	Total mass	$\bar{T}_{max}$ (°C)	Setup	t_{pillow}	t_{foot}
	(kW)	(s)	(kg)			(s)	(s)
11-SI-08	268	466	6.7	126	#2 (folded)	260	240
12-SI-07	388	582	7.8	204	#2	170	230
17-SI-75	210	756	4.6	143	#2	390	780
19-SI-83	N/A ¹	N/A	5.2	156	#1 (not folded)	60	98
30-SI-83	197	378	5.2	112	#1	N/A	120

t_{pillow} : Time for flames to reach the pillow; - t_{foot} : Time for flames to reach the foot of the bed.

¹ Instrumentation failure; ² Obscured view during video replay.

The measured peak HRRs were comparable with values published by other researchers: California Bureau of Home Furnishings (125 – 167 kW) [4] and NIST (up to 200 kW) [25].

4.1.3 Bed Assemblies

The results of tests with bed assemblies (complete with foundation and bed clothes) are given in Table 10. Figures 10 and 11 show the HRR and temperature vs. time graphs, respectively, for all the tests (except Test 44, which was conducted using a smaller window size and is discussed separately).

Table 10. Summary of test results for bed assemblies.

Test ID	HRR _{max}	THR	ODM _{max}	HC	$\bar{T}_{max}$	Q''_{mf}	$\bar{Q}''_{mwc}$	T_{∞}
	(kW)	(MJ)	(OD/m)	(MJ/kg)	(°C)	(kW/m ²)	(kW/m ²)	(°C)
21-SI-10 (Twin) ¹	2,978 (394) ²	773 (35.8) ³	0.9	21.5	826 (87) ⁴ [933 SE] ⁵	25	77 (28) ⁴ [99 W wall] ⁵	29
23-SI-76 (Twin)	3,358 (332)	595 (32.5)	1.3	18.3	891 (41) [942 SW]	39	95 (37) [140 W wall]	18
27-SI-11 (Mates')	2,052 (388)	1,309 (N/A)	0.2	N/A	621 (67) [708 SW]	16	59 (30) [102 S wall]	14.5
29-SI-12 (Double)	3,971 (247)	809 (40.7)	2.6	20.6	1,026 (21) [1,057 NE]	N/A	173 (32) [223 S Wall]	18
31-SI-13 (Queen)	3,762 (466)	835 (47.9)	2.7	18.2	1,052 (16) [1,071 NE]	128	177 (26) [221 S Wall]	20
32-SI-14 (Bunk)	6,258 (248)	957 (38.7)	2.4	21.4	1,003 (39) [1,061 NE]	89	167 (36) [221 E CS]	24

Test ID	HRR _{max}	THR	ODM _{max}	HC	$\bar{T}_{max}$	Q''_{mf}	$\bar{Q}''_{mwc}$	T_{∞}
	(kW)	(MJ)	(OD/m)	(MJ/kg)	(°C)	(kW/m ²)	(kW/m ²)	(°C)
43-SI-85 (Twin)	1,812 (564)	615 (22.1)	0.4	24.6	452 (45) [493 SW]	20	26 (8) [36 W wall]	-20.0
44-SI-12 (Double)	2,703 (442)	700 (40.1)	1.0	17.5	836 (236) [892 NE]	39	79 (22) [106 W wall]	2

¹ Size of bed assembly; ² Time to reach the peak HRR (s); ³ Mass loss (kg); ⁴ Standard deviation (SD); ⁵ T_{max} or Q''_{max} and its location.

Figure 10. HRR vs. time for various sizes of bed assemblies.

Figure 11. Average maximum room temperature vs. time graphs for bed assemblies.

4.1.3.1 Comparison of Two Mattress Designs

Tests 21 and 23 evaluated the fire behaviour of twin bed assemblies made up of two different mattresses (solid core SI-04 and innerspring SI-06, respectively). The results show that the HRRs and HC (heat of combustion) values for the twin-size bed assemblies (Test 21 and 23) were lower and occurred later than those obtained with the corresponding mattresses (SI-04 and SI-06) used the bed assemblies. The room temperatures and, consequently, the total heat flux recorded by the gauges were lower for the bed assembly tests, which is consistent with the lower HRRs.

There was a considerable reduction in the peak HRR in Test 21 (2,978 kW; bed assembly) compared with Test 8 (3,757 kW; mattress only). In both tests, the initial rate of fire growth was comparable until after about 180s into the tests. It is interesting to note that the peak optical density per meter (OD/m) was significantly lower in the bed assembly tests. The total heat released (MJ) for the bed assembly tests is considerably greater than for the mattress-only test due to the contribution from the posture box, as can be expected.

As previously noted, excessive melting and dripping of PUF was observed in the mattress-only tests. It is believed that this contributed to the higher peak HRRs obtained with a mattress alone due to the additional burning area of the resulting pool fire coupled with earlier ignition of the underside of the mattress by the pool fire. Figures S57 and S58 show the differences in the features of the fires during Test 8 (mattress only) and Test 21 (bed assembly), respectively. There was visibly less dripping during Tests 21 (and 23).

Bed clothes and the presence of a foundation likely contributed to the combustion behaviors observed in Tests 21 and 23. However, a fair comparison between the burning behavior of the bed assemblies and mattresses alone cannot be made due to the differences in the ignition methods: mattresses were ignited with a significantly stronger flame (9 kW side burner plus 19 kW top burner) positioned near the center of the front side (Figure 7), whereas the bed assemblies were ignited with a smaller 9 kW flame placed at 0.47 m from the head side (Figure 8). Despite these differences, it is evident that bed clothes have an effect on fire development. Indeed, other researchers have investigated this issue, albeit in the context of the effect of bed clothes on open-flame resistant mattresses [25], and found that bed clothes had an effect on the burning behavior of bed assemblies. It is likely that the slower rate of fire growth in Tests 21 and 23, compared to the fires with mattresses alone, is due to the combined effect of the protection that the bed clothes provided to the mattresses and the longer path the flames had to travel to cover the top surface since the ignition source was located near one end of the bed assembly. The fact that the bed assemblies had lower peak HRRs than their corresponding mattresses is possibly due to the slower rate of fire growth and differences in melt-pool formations – there is a discernible trend that for items with comparable combustible mass, a slower fire growth rate reduces the peak HRR.

4.1.3.2 Effect of Bed Assembly Size and Other Parameters (Tests 23, 29, 31 and 32)

The HRR and room temperature profiles are shown in Figures 12 and 13, respectively. The same mattress design (based on type SI-06) was used in all of the tests. There was a considerable increase in all the measured results with the increase of size from twin size bed assembly (Test 23) to double bed assembly (Test 29). As well, there was greater flame extension and luminosity of the flames issuing out of the window opening in Test 29 (Figure 14) compared with Test 23 (Figure 15). Comparing the peak HRRs, Test 23 was well below the theoretical ventilation limit of ~4,100 kW, whereas Test 29 approached the limit and hence the increase in flame extension and brightness. However, the most striking result is the extent by which the thermal radiation measured by the heat flux gauges increased. Whereas, the peak temperature rose by a modest 12%, the radiation intensity, being proportional to the fourth power of absolute temperature, increased by about 60% indicating a considerably greater increase in the potential thermal assault on the room boundaries in Test 29.

Figure 12. HRR vs. time for various sizes of bed assemblies.

Figure 13. Average maximum room temperature vs. time graphs for bed assemblies.

Figure 14. Test 29-SI-12 – Post-flashover fire with external flaming.

Figure 15. Test 23-SI-76 – Extent of flaming out of the window opening.

Comparing a double (Test 29) to a queen (Test 31) bed assembly, there was a slight decrease in peak HRR, but the temperature and heat flux results were comparable. Test 31 had a slightly higher peak temperature than Test 29 due to the great total heat released. The rate of fire growth in Test 31 was slower because a different set of bed clothes was used, i.e. the material composition of the components was similar but the comforters had different fabric prints. The slower rate of fire growth (and mass was consumed progressively) is one of the factors that likely contributed to the reduction of the peak HRR compared with Test 29. There was a greater proportion of the mass consumed by the time Test 31 approached the peak HRR point compared with Test 29 and hence the decay phase immediately follows the peak. This also explains why Test 29 had a wider plateau at around the peak HRR value – a greater amount of unburnt mass and the fire appears to undergo combustion controlled by the fuel

surface area given that fuel packages laden with PUF may not exhibit a ventilation-controlled plateau (excess pyrolysis gases can burn outside the fire compartment, increasing the measured HRR). However, the post-flashover features of the fire in Test 31 were similar to Test 29.

In Test 32, the surface area and amount of PUF was increased to investigate the burning behavior of a bunk bed, which is usually found in residential secondary bedrooms. This resulted in a considerable increase (~ 50%) in the peak HRR over Tests 29 and 31. This was clearly an under-ventilated fire with a considerable amount of burning occurring outside the fire compartment as can be seen from the photograph in Figure S60, which was taken shortly after all the flashover thresholds were exceeded. The measured HRR of 6,250 kW was significantly greater than the theoretical ventilation limit of approximately 4,100 kW since the pyrolysis of the PUF was unabated (a characteristic of melting plastic materials) and the unburnt fuel gases were simply transported outside the room where they underwent combustion resulting in considerably greater flame extension out of the window opening.

The room temperature values (and consequently heat flux) were less than those in Tests 29 and 31, which is likely due the adverse effects of severe oxygen deficiency (and fuel-rich conditions) on combustion efficiency. A comparison of temperature profiles measured by the TC Trees in the south-west quadrant for Tests 29 and 32 (Figures 16 and 17) shows that temperatures in Test 32 were not increasing during the period that the HRR exceeded 4,000 kW.

Figure 16. Test 29 – SW TC Tree temperature profiles.

Figure 17. Test 32 – SW TC Tree temperature profiles.

4.1.4 Effect of Foundation and Flame-Resistant Mattress Design (Tests 23, 27 and 42)

The HRR and average temperature versus time graphs are shown in Figures 18 and 19, respectively. The results show that the choice of foundation and use of open-flame-resistant bed components have a significant effect on fire behaviour. An identical set of bed clothes was used in all three experiments.

Figure 18. HRR vs. time for Tests 23, 27 and 42.

Figure 19. Temperature vs. time for Tests 23, 27 and 42.

With Test 23 as the baseline case:

1. **Mate's bed (Test 27):** Resulted in a much reduced and slightly delayed peak HRR (39% less than Test 23). Although the peak HRR reached 2,052 kW—bordering on the flashover threshold—with flames lightly emerging from the window opening shortly before the peak HRR was attained. The smoke density was considerably lower than in Test 23 due to the greater mass of wood and lower burning rate. The reduction in burning rate is due to the restriction of the burning area and air entrainment provided by the mate's bed foundation (Figure S28). Melting PUF dripped into a confined space with limited air supply, and, therefore, burning was restricted to the top exposed surface until the side of the mate's bed foundation burnt through. However, by this time much of the PUF in the mattress was consumed and the decay phase followed, albeit at a slow pace due to presence of wood-based (particleboard) components.

Figure 20. Test 21 – Bed assembly with posture box foundation.

Figure 21. Test 27 – Mate's bed (constrained surface area and air entrainment).

2. **16CFR1633-compliant bed assembly (Test 42):** Demonstrated the benefits of barrier fabric technology although the fire did propagate because the bed clothes used provided a strong ignition source. The peak HRR (value of 1,812 kW) occurred much later (at 564s) and its

magnitude was lower than any of the experiments with bed assemblies. The photographs in Figures S63 and S64 show the features of fire when the bed assembly was fully-involved and when the flames had subsided during the slow decay phase, respectively. Even though the total heat released was comparable to Test 23, it occurred over a considerably longer period of time, the decay immediately followed the peak HRR and hence lower temperatures resulted. Combustion appeared to be regulated by the rate of diffusion of flammable pyrolysis products through the barrier material and layers of charred bed clothes. Although the peak HRR was greater than the lowest flashover threshold of 1,573 kW, the temperatures were well below 600 °C, which suggests that flashover was unlikely to have occurred. However, the peak heat flux (Table 15) at floor level reached a value of 20 kW/m² at 556 s, indicating that flashover was imminent based on this criterion. The fire performance of such a mattress and foundation set could be enhanced by using bed clothes with reduced flammability, in which case peak HRRs of well under 1,000 kW can be achieved as demonstrated by the work conducted in the USA [25].

4.1.4.1 Effect of Window Size

The effect of ventilation was investigated in Test 44 by repeating Test 29 with a smaller window opening measuring 1.40 m wide by 1.20 m high. The theoretical ventilation-limited HRR for this window is estimated to be 2,703 kW. The flashover thresholds are 1,380 kW (Babrauskas' correlation) and 1,244 kW (Thomas' correlation). The HRR and temperature profiles are given in Figures 22 and 23, respectively.

Figure 22. HRR vs. time for Tests 29 and 44.

Figure 23. Average temperature profiles at 1.9 m height for Tests 29 and 44.

The total heat released in Test 44 was considerably lower than in Test 29, resulting in a lower value of the net heat of combustion of 17.5 MJ/kg compare to 20.5 MJ/kg for Test 29. As can be expected, the HRR in Test 44 was significantly reduced to a value of 2,703 kW, which is in good agreement with the

predicted ventilation limit. There was a slight increase in the duration of the fire, although there was no evidence of a ventilation-controlled plateau. This resulted in an appreciable decrease (~ 16%) in the peak room temperatures. After reviewing the test videos, the slower rate of fire growth in Test 44 is attributed to a change of bed clothes (since the set used in Test 29 was no longer available) rather than the reduction in ventilation.

4.2 Upholstered Chairs and Sofas

The results of the experiments with all of the upholstered seats are given in Table 11. The HRR and room temperature profiles are shown in Figures 24 and 25, respectively.

Table 11. Results of tests with upholstered furniture.

Test ID	HRR _{ma} x (kW)	THR (MJ)	ODM _{max} (OD/m)	HC (MJ/kg)	$\bar{T}_{max}$ (°C)	Q''_{mf} (kW/m ²)	$\bar{Q}''_{mwc}$ (kW/m ²)	T_{∞} (°C)
9-SI-25 (Chair)	1,843 (185) ¹	461 (27.3) ²	0.4	18.8	590 (91) ³ [713 SW] ⁴	12	35 (16) ³ [40 S wall] ⁴	15
10-SI-24 (Chair)	1,818 (206)	625 (30.1)	0.8	21.9	582 (25) [620 SE]	15	33 (10) [46 NE CS]	22
15-SI-27 (Chair)	906 (178)	152 (7.3)	0.4	20.8	308 (33) [346 NW]	6	14 (6) [25 SW CS]	16
26-SI-26 (Chair)	2,710 (142)	481 (27.8)	0.8	17.4	635 (44) [691 SW]	20	73 (27) [102 W wall]	25
36-SI-29 (Ottoman)	631 (509) ¹	73 (6.4) ²	0.3	11.4	149 (56) ³ [183 SW] ⁴	3	10 (4) [16 SW CS]	-24
43-SI-33 (Futon)	447 (1,008)	297 (16)	0.05	18.1	113 (62) [149 SE]	1	5 (1) [6 SW CS]	-13
40-SI-31 (Loveseat)	3,364 (189)	595 (37.1)	1.7	16.0	739 (190) [910 SW]	19	83 (52) [165 SW CS]	-4
41-SI-32 (Sofa)	3,170 (217)	886 (49.0)	>2.0 ⁵	18.1	800(191) [1006 SE]	23	94 (43) [144 SW CS]	-4

¹ Time to reach the peak HRR (s); ² Mass loss (kg); ³ Standard deviation (SD); ⁴ Maximum room temperature / heat flux (°C / kW/m²) and its location.

Figure 24. HRR vs. time for chairs.

Figure 25. Average maximum room temperature vs. time graphs for chairs.

4.2.1.1 Comparison of Different Chairs (Tests 9, 10, 15 and 26)

Test 26 (chair SI-26) was selected for subsequent tests to evaluate the effect of size since it had the highest peak HRR and the shortest time to reach its peak. All the flashover criteria were met in Test 26 and it was the only test (among the chairs), which produced a fire with some flames extending out of the window opening, from about 120 s (HRR $\sim$ 2,000 kW) from ignition, as shown in Figure 26. Figure 27 shows a photograph of the fire during Test 10-SI-24; there was dense smoke issuing from the window opening but minimal visible flames near the time that the peak HRR occurred.

Figure 26. Test 26-SI-26 – Flames emerged from the window opening when the HRR exceeded 2,000 kW.

Figure 27. Test 10-SI-24 – Dense smoke but hardly any flames emerged from the window opening.

4.2.1.2 Effect of Chair Size (Tests 26, 40 and 41)

The results of Tests 26, 40 and 41 (chair and two- and three-seat versions of the same chair) evaluated the effect of size on combustion behaviour. The peak HRRs of the chair, two-seat and 3-seat sofas were, 2710 kW, 3364 kW, and 3170 kW, respectively. The peak HRR of the two-seat sofa was greater than that of the chair and three-seat sofa by 24% and 6%, respectively. However, the chair had the quickest rate of fire growth, likely due to an increase in burning rate caused by radiation feedback from the arm rests, both of which ignited almost immediately given their proximity to the point of ignition.

The three-seat sofa had a lower peak HRR and slower growth rate than the two-seat sofa likely due to the arm rests being further apart in the three-seat sofa, in addition to the larger surface area the flames had to travel. However, the greater total heat energy released from the three-seat sofa (due to its larger mass) resulted in higher and prolonged room temperatures (Figure 25) than was the case with the two-seat sofa. Figures 27 and 28 show the pre- and post-flashover features, respectively, of the fire in Test 41, which were similar to Test 40. The smoke density generally increased with HRR as was observed in previous tests.

Figure 28. Pre-flashover period during Test 41-SI-32 (Three-seat sofa).

Figure 29. Post-flashover fire during Test 41-S-32 (Three-seat sofa).

4.2.1.3 Ottoman and Futon Mattress

The Ottoman (Test 36) and a Futon mattress (Test 43) had peak HRRs of 631 kW and 447 kW, respectively. The peak HRR of the Ottoman fire is consistent with its low mass and small horizontal surface orientation (i.e., for the same material, the rate of flame spread is faster on vertical surfaces than horizontal ones). Interestingly, the Futon mattress was not very flammable. Although the ticking ignited readily, the cushioning (filling) was resistant to combustion. The cushioning material

largely consisted of thick cotton batts with sparsely distributed shredded chunks of PUF embedded within.

The Futon mattress was ignited with the same 19 kW burner as the chair and sofas. Figure S69 shows a photograph of the Futon mattress immediately following ignition. The flames slowly spread across the surface leaving behind a protective layer of char from the cotton filling material and the fire almost self extinguished after 480 s (shown in Figure S70). The propane ignition source was then re-applied and left on for the entire duration of the test. After the ignition source was reapplied, there was sporadic flaming (left side of back rest in Figure S70) at areas where there was sufficient penetration of heat to pyrolyse the embedded PUF. Eventually, the entire surface was covered in flames, but the height of the flames was less than 0.50 m. While these results are likely representative of cotton-filled Futon mattresses, they cannot be generalized to all kinds of Futon mattresses since there are types that consist entirely of PUF and polyester fibers as the filling materials. Additional tests with Futon mattresses manufactured with different filling materials could not be accommodated in the test program.

4.3 Secondary Combustible Furnishings (SCFs)

The results of tests conducted with various SCFs are summarized in Table 12. There was a large variation in combustion behaviour, and values of HRRs ranged from about 100 kW to 2,000 kW. The HRR and room temperature profiles are shown in Figures 30 and 31, respectively.

Table 12. Summary of Experimental Results for Secondary Furnishings.

Test ID	HRR _{max}	THR	ODM _{max}	HC	$\bar{T}_{max}$ (°C)	Q''_{mf}	$\bar{Q}''_{mwc}$	T_{∞}
	(kW)	(MJ)	(OD/m)	(MJ/kg)		(kW/m ²)	(kW/m ²)	(°C)
13-SI-15 (Clothing)	1,855 (118) ¹	942 (32.1) ²	0.2	25.4	542 (60) ³ [598 SW] ⁴	12	34 (13) ³ [49 SW CS] ⁴	21
16-SI-16 (Wardrobe)	1,529 (622)	1,662 (89.8)	0.4	20.8	680 (34) [710 SE]	16	40 (24) [88 SW CS]	17
18-SI-36 (TV set)	93 (220)	N/A (0.5)	0.2	N/A	42 (1) [43 NW]	<1	<1	23
20-SI-19 (CD/DVDs)	1,294 (415)	1,229 (35.8)	1.3	28.9	442 (23) [473 NW]	7	21 (8) [33 W wall]	25
22-SI-22 (Toys)	2,048 (66)	408 (15.9)	1.4	25.7	603 (55) [667 SE]	14	41 (16) [65 SW CS]	20
24-SI-18 (Shoes)	1,229 (244)	529 (20.7)	1.0	25.6	375 (4) [379 NW]	8	26 (20) [69 SW CS]	23
25-SI-20 (Books)	443 (2,162)	881 (47.7)	0.1	18.5	183(9) [197 NE]	2	7 (5) [16 SW CS]	23
33-SI-21 (Workstation)	1,794 (433)	1,180 (54.0)	0.9	24.1	635 (72) [740 SW]	24	64 (28) [104 S wall]	24

¹ Time to reach the peak HRR (s); ² Mass loss (kg); ³ Standard deviation (SD); ⁴ Maximum room temperature / heat flux ($^{\circ}\text{C}$ / kW/m^2) and its location.

Figure 30. HRR vs. time for SCFs.

Figure 31. Temperature vs. time for Tests 13 and 16.

4.3.1 Clothing

Test 13 was conducted with clothes that were hung on two 1.0-m-long steel rails and there were no obstructions around the setup (Figure S13). In Test 16, the clothes were placed in a large open wardrobe (Figure S17). The HRR profiles in Figure 32 show that Test 13 had a very rapid rate of fire growth. The time to reach the peak HRR was the second shortest in the entire experimental program. In Test 16, the rate of fire growth was much slower since the exposed burning section was limited to the front section until the fire burnt through the rear cover of the wardrobe. In both experiments, the rate of upwards flame spread was very fast and the flames quickly impinged onto the ceiling as shown in Figures S69 and S70. Both tests had a very slow rate of decay since the test specimens collapsed into a large heap (due to melting of plastic clothes hangers and breakdown of particleboard), thereby limiting the exposed surface area. The onset of decay of the fire was possibly hastened by the collapse of the test specimens.

Figure 33 shows the temperature profiles in the room. Test 16 had higher temperatures due to the considerably-greater THR and time period during which the HRR exceeded 1,000 kW.

Figure 32. HRR vs. time for the Tests 13 and 16.

Figure 33. Temperature vs. time for Tests 13 and 16.

4.3.2 Television Set (Test 18)

Test 18 resulted in a non-propagating fire, which eventually self-extinguished after the TV casing material shrunk away from the propane burner as it burnt. The peak HRR did not exceed 100 kW, which is too low to be accurately measured by the large calorimeter. Despite the low HRR, it was observed that the smoke produced was very dense. The photographs of the casing during and after the fire test are shown in Figures S71 and S72.

5 CONCLUSIONS

The burning characteristics of a range of primary and secondary combustible furnishings were determined under one specific compartment configuration and several ignition scenarios. The experiments provide information on heat release rates, room temperatures (and heat flux), calorific values and various other aspects of combustion behaviour. The measured peak HRRs ranged from about 100 kW for a TV set to 6,200 kW for a bunk bed assembly. Measurements of the total heat release (THR), mass loss and effective heat of combustion have been reported for the specimens that were tested.

Some of the conclusions from this work are:

1. The results showed that four of the mattresses tested were capable of causing flashover in the 16 m² room and three of the mattresses produced significantly higher peak HRRs of approximately 3,800 kW, with peak room temperatures of approximately 980°C.
2. The fires grew in size and intensity with the increase in bed assembly size from twin to double. There was an 18% increase in peak HRR (3,358 kW to 3,971 kW) and the effect on other quantities was: 100% increase in smoke density; 12% increase in peak room temperature (942°C to 1,057°C); 59 % increase in peak total radiation measured by the heat flux gauges, a

significant increase given that thermal radiation is proportional to the fourth power of absolute temperature (on the Kelvin scale).

3. A number of tests demonstrated that bed clothes had a noticeable influence on fire growth. It was found the bed assemblies have lower peak HRRs than their corresponding mattresses. Tests 29 and 31 demonstrated that a change of bed clothes had a significant influence on the fire growth rate.
4. In a test with a bunk bed assembly, it was found that excessive amounts of PUF resulted in lower temperatures in the test room since the fire environment became severely under-ventilated.
5. A mate's bed was found to have a much lower peak HRR (39% lower than a bed assembly using a posture box foundation) since the wooden (particleboard) base restricted the burning area and air entrainment. Although the total amount of heat released was much greater than a bed assembly with a posture box, the latter poses a more critical fire hazard given that it caused flashover to occur earlier.
6. A bed assembly using a mattress and foundation that was compliant with the 16CFR1633 open flame test standard was found to significantly reduce and delay the peak HRR. Although a peak HRR of 1,573 kW was measured, the temperatures in the room were well below 600°C indicating that flashover did not occur. If this mattress and foundation were to be tested with bed clothes having improved combustion behavior, it is expected that the peak HRR of the bed assembly would be further reduced.
7. A reduction in the window size (from 1.5 m x 1.5 m to 1.4 m x 1.2 m) in a test with a double bed assembly resulted in a 16% reduction in the peak room temperatures.
8. In tests with chairs and sofas, it was found that the two-seat sofa had the highest peak HRR of 3,364 kW, which was attributed to the greater effect of radiation feedback from the armrests than in the case of a three-seat sofa (peak HRR of 3,170 kW) where the armrests are further apart. The chair had the shortest time (142 s) to reach the peak HRR, followed by the two-seat sofa (189 s), which seems to correlate with the distance between the arm rests.
9. In a test with a Futon mattress, it was found that the cotton filling material provided strong resistance to combustion due to the protective effect of the char and the measured peak HRR was less than 500 kW. This result may not reflect the combustion behavior of all Futon mattresses, since there are types that are manufactured entirely with PUF and polyester fibers as the filling materials. Such Futon mattresses would likely exhibit less resistance to combustion.
10. For the tests conducted with secondary combustible furnishings:
 - a. Clothing and stuffed toys resulted in extremely rapid fire growth, when there was unrestricted air flow around the test arrangement, due to the presence of low density and loosely packed (or stuffed) polyester materials.

- b. Furnishings containing a large proportion of rigid plastics, such as shoes, CD and DVD media packages and a computer workstation, produced very dense smoke, although the peak HRRs hardly exceeded 2,000 kW when the products were tested in smaller groups.
- c. The collapse of sample configurations (e.g. wardrobe, bookcases and clothing arrangements) was observed to be a factor that contributed to the earlier onset of the decay phase and increased its duration.
- d. A TV set with a cathode ray tube was found to resist ignition due to the fact that the housing materials met UL94 HB flammability test standards. Although the set contained an insignificant amount of combustible materials (~ 5.2 kg; ~ 15% of the total mass), the smoke produced at lower HRRs was very dense.

6 ACKNOWLEDGMENTS

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7 NOMENCLATURE

	Abbreviations	Units
CRT	Cathode ray tube	
CS	Ceiling surface	
HC	Effective heat of combustion (calorific value)	(<i>MJ / kg</i>)
HRR	Heat release rate	(<i>kW</i>)
N/A	Not available (data) or Not applicable	
OD	Optical density	
OD/m	Optical density per meter	(OD/m)
PCF	Primary combustible furnishing	
PUF	Polyurethane foam	
SCF	Secondary combustible furnishing	
SD	Standard deviation from the mean	
SI	Single item	-
TC	Thermocouple	
THR	Total heat released	(<i>MJ</i>)

TV Television

Compass Directions

W West

E East

S South

N North

NW North-West

SW South-West

Symbols

Q''	Radiant heat flux	$\left(\frac{kW}{m^2} \right)$
T	Temperature	(°C)
$\bar{T}$	Average temperature	(°C)
T_∞	Ambient temperature	(°C)
Q''_{mf}	Maximum heat flux at floor level	$\left(\frac{kW}{m^2} \right)$
$\bar{Q}''_{mwc}$	Mean heat flux measured at walls and ceiling surfaces	$\left(\frac{kW}{m^2} \right)$

Subscripts

Max Maximum

Min Minimum

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Supplemental Information: Photographs and Additional Details.

Table S1. Glossary

Bed Assembly (bed):	An assembly consisting of a mattress, foundation, bed clothes and bed frame, with or without a headboard and footboard.
Barrier fabric:	A layer of material (fabric, batting or pad) that is intended to reduce the flame spread of a bed clothing item, when secured to a combustible material or otherwise interposed between the material and the potential fire source, by delaying ignition and combustion of the material when the barrier is exposed to fire. Same as an interliner and fire barrier [32].
Bed clothing:	A unit of interior furnishing with a resilient filling material, covered in whole or in part with fabric or related material that is intended for use or may be expected to be used in homes, as an accessory on a mattress, mattress set or Futon. Also, known as a "top of the bed" product.
Bed Frame:	A frame that maintains the position of the foundation, headboard and footboard [33].
Box Spring:	A foundation made of cone-shaped wire coils.
Comforter:	A quilted item used as a thermal-insulating cover for a mattress set and consisting of a fabric cover and a resilient filling.
Foundation:	The bottom component of a sleep set that transfers and distributes the weight of the mattress.
Independent Coil:	An innerspring mattress construction that uses individually wrapped coils. Also called pocket-coil [33].
Innerspring Mattress:	A mattress with wire coils as its support system [33].
Mattress pad	A product designed to cover the top, sides or entire surface of a mattress or Futon to offer protection and additional resiliency and which contains quilted filling material covered by a fabric or ticking.
Open Coil or Bonnell Coil:	This is an hourglass-shaped wire coil, which is joined to adjacent coils by small wire spirals called helical coils. These are the oldest and most commonly used [33].
Pillow (bed):	Any item used on top of a bed as an accessory to a mattress, mattress set or Futon for the purpose of resting the head or any other portion of the body while sleeping.
Pillow (decorator):	Any item used on top of a bed as an accessory to a mattress, mattress set or Futon for the purpose of decoration only.
Pillow top:	The semi-attached layer at the top of a mattress that provides additional softness and support [33].
Posture Box:	A foundation that has no wire coil support system. It is made entirely of wood.
Sleep Set:	A general term to describe the combination of foundation, mattress, headboard, footboard and bed frame [33].
Ticking:	The fabric covering of a mattress or foundation [33].
Upholstered furniture:	Seating furniture such as upholstered chairs and sofas.
Upholstery Layers:	The foam, padding and fibers used between the support system and ticking of a mattress to provide cushioning and comfort [33].
Support System:	The basic supporting structure of the mattress. This structure could consist of various types of wire coils, foam, water or air [33].
Pillow top:	Refers to a type of mattress that is made with extra layers and cushioning to increase softness and comfort--as if the mattress were topped with a pillow.

Table S2. Test Specimens – Photographs and Additional Details

Test #	ID	Photograph of Specimen / Test Setup	Additional Information / Details
5	SI-03	<p>Figure S1. SI-03 twin-size mattress. (Dimensions: 1,900 x 965 x 180 mm)</p>	<p>Figure S2. SI-03 internal structure. Ticking: 72% polyester, 28% polypropylene.</p>
6	SI-01	<p>Figure S3. SI-01 twin-size mattress. (Dimensions: 1,865 x 980 x 220 mm)</p>	<p>Figure S4. SI-01 internal structure. Ticking: cotton/polyester blend. Inner core: 152 mm thick PUF slab with two contoured PUF layers of 25 mm thickness.</p>
7	SI-02	<p>Figure S5. SI-02 twin-size mattress. (Dimensions: 1,885 x 950 x 330 mm)</p>	<p>Figure S6. SI-02 internal structure. Ticking: 40% rayon, 37% polyamide, 16% polypropylene; 7% polyester. Features: Pillow top (~ 120 mm), with multiple layers of PUF and inter-liners.</p>
8	SI-04	<p>Figure S7. SI-04 twin-size mattress. (Dimensions: 1,895 x 970 x 200 mm)</p>	<p>Figure S8. SI-04 internal structure. Ticking: Cotton terry cloth. Mattress core: Top layer - Visco elastic foam (50 mm); Bottom layer - Regular PUF (150 mm).</p>

Test #	ID	Photograph of Specimen / Test Setup	Additional Information / Details		
9	SI-25	<p>Figure S9. SI-25 upholstered chair. (Dimensions: 950 x 940 x 910 mm)</p>	Decorator pillow	Polyester cover / polyester fibre fill	0.85 kg
			Fabric	100% polyester	-
			Backrest and armrests padding	Polyester fibers	-
			Remarks: PUF seat cushion wrapped with a layer of polyester fiber batting.		
10	SI-24	<p>Figure S10. SI-24 upholstered chair.</p>	Decorator pillow	Polyester cover / polyester fiber fill	0.85 kg
			Fabric	100% polyester micro-fiber	-
			Backrest and armrests padding	Polyester fibers	-
			Remarks: PUF seat cushion wrapped with a layer of polyester fiber batting. Dimensions (W x D x H): 1,040 x 980 x 1,020 mm.		
11	SI-07	<p>Figure S11. SI-07 bed clothes.</p>	Components(twin-size):		
			<ul style="list-style-type: none"> • Bed pillow • Decorator pillow • Comforter • Sheet set with skirt • Skirt: 100% Polyester • Mattress pad • Inert mattress 		
12	SI-08	<p>Figure S12. SI-08 bed clothes.</p>	Components(twin-size):		
			<ul style="list-style-type: none"> • Bed pillow • Decorator pillow • Comforter • Blanket • Sheet set with skirt • Mattress pad • PUF mattress pad (topper) 		

Test #	ID	Photograph of Specimen / Test Setup	Additional Information / Details		
13	SI-15		Clothing	Cotton (approximated)	22.2 kg
			Clothing	Synthetic fabrics (approximated)	13.0 kg
			Clothes hangers	Thermoplastic	5.9 kg
			Note: The type of synthetic fabrics was not recorded, but noted to be predominantly polyester fabrics.		
14	SI-06
			<p>Figure S15. SI-06 internal structure.</p> <p>Ticking: 36% polyamide, 47% polyester</p> <p>Support system: Independent coils (foam encased pocket coils).</p> <p>Upholstery: Multiple layers of PUF slabs.</p>		
15	SI-27		Decorator pillow	Polyester cover	0.85 kg
			Fabric	51% Acrylic / 49% Polyester	N/A
			<p>Conformance Labels: UFAC.</p> <p>Seat cushion: PUF</p> <p>Ticking: N/A</p> <p>Back and armrests: PUF</p> <p>Frame and legs: Wood.</p> <p>Dimensions (W x D x H): 740 x 600 x 1,025 mm.</p>		

Test #	ID	Photograph of Specimen / Test Setup
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Additional Information / Details		
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16 SI-16

Figure S17. Wardrobe with clothes.

Wardrobe	Particleboard	54.3 kg
Clothing	Cotton	19.9 kg
Clothing	Synthetic	16.0 kg
Hangers	Thermoplastic	0.8 kg

Note: Approximate composition. The type of synthetic fabrics was not recorded, but noted to be predominantly polyester fabrics.

Dimensions (W x D x H): 1,220 x 530 x 1,840 mm.

17 SI-75

Figure S18. SI-75 bed clothes.

- Mattress: Inert
- Bed pillow
- Comforter
- Sheet set
- Skirt and platform

18 SI-36

Figure S19. SI-36 television set.

Plastic housing	ABS UL 94 HB rated	5.2 kg
Circuit boards	Unknown materials	1.8 kg
Non-combustible parts	Cathode ray glass tube and metal parts	26.7 kg

Screen size : 686 mm (27 inches)

19 SI-83

Figure S20. SI-83 bed clothes.

- Bed pillow
- Decorator pillow
- Comforter
- Sheet set
- Mattress pad

Test #	ID	Photograph of Specimen / Test Setup	Additional Information / Details		
20	SI-19	<p>Figure S21. SI-19 media bookcase.</p>	Bookcase	Particleboard	19.7 kg
			Paper	Used for CD/DVD covers	3.3 kg
			CD / DVD cases	CD cases (14.1 kg); DVD cases (6.47 kg); CD/DVD media (4.5 kg)	25.1 kg
			Composition (excluding contents): 99.5% particleboard; 0.5% metal and plastic fittings. Dimensions W x D x H: 0.76 m x 0.30 m x 1.11 m.		
21	SI-10	<p>Figure S22. Twin-size bed assembly.</p>	Mattress: 15.1 kg Posture box: 16.7 kg Bed clothes: SI-83 – 5.2 kg Posture box dimensions: 1,890 x 960 x 150 mm.		
22	SI-22	<p>Figure S23. SI-22 toys.</p>	Stuffed toys	Fill: 100% polyester fibers	6.10 kg
			Hard plastic toys	Thermoplastic	7.85 kg
			Bin	Thermoplastic	1.65 kg
23	SI-76	<p>Figure S24. SI-76 twin-size bed assembly.</p>	Mattress	SI-06 (single)	18.8 kg
			Bed clothes	SI-83 with skirt	5.3 kg
			Posture box (foundation)	Wood / PUF / fabric	16.3 kg

Test # ID Photograph of Specimen / Test Setup

Additional Information / Details

24 SI-18

Figure S25. SI-18 shoes.

Shoe racks	Metal	9.00 kg
Shoes		20.00 kg

Note: Most shoes contained metal stiffening plates. Weight % was not determined, but reflected in unburnt mass.

25 SI-20

Figure S26. SI-20 bookcase with Books

Bookcase	Particleboard	19.80 kg
Books		46.30 kg
Plastic fittings		0.02 kg

Dimensions of shelf: 755 x 295 x 1,105 mm.

26 SI-26

Figure S27. SI-26 upholstered chair.

Decorator pillow	Polyester cover / polyester fiber fill	0.8 kg
Fabric	40% Acrylic; 60% Polyester	

Padding: PUF seat cushions with polyester fiber fill.

Back and arm rests: Polyester fiber fill.

Frame: wood

Dimensions (W x D x H): 1,000 x 1,000 x 935 mm.

27 SI-11

Figure S28. SI-11 twin-size mate s bed assembly.

Mattress	SI-06 (twin-size)	19.0 kg
Bed clothes	SI-83 (without skirt)	4.8 kg
Mates bed foundation	Particleboard with MDF mattress supports	62.7 kg

28 SI-05

Figure S29. SI-05 twin-size mattress.

Ticking: 36% polyamide, 47% polyester

Inner core: Foam encased independent coils, with multiple layers of PUF slabs.

Indicated weight of mattress includes innersprings.

Note: mattress compliant with 16CFR1633 open flame test standard.

Test # ID Photograph of Specimen / Test Setup

29 SI-12

Figure S30. SI-12 full-size bed assembly.

30 SI-83

Figure S31. SI-83 twin-size bed clothes.

31 SI-13

Figure S32. SI-13 queen-size bed assembly.

32 SI-14

Figure S33. SI-14 twin-over-double bunk bed assembly.

Additional Information / Details

Mattress SI-06 (full-size) 27.2 kg

Bed clothes Comforter, sheet set, mattress pad, two bed pillows, two decorator pillows 6.9 kg

Posture box Wood / PUF / fabric 19.7 kg

Total mass: 5.2 kg

Mattress SI-06 (queen) 31.6 kg

Bed clothes Not SI-83 (comforter, sheet set, mattress pad, four pillows, two decorative pillow) 9.6 kg

Posture box Wood / PUF / fabric 25.0 kg

Mattresses Lower: SI-06 (full) 44.5 kg
Upper: SI-06 (twin)

Bed clothes Single: SI-83 12.2 kg
Double: Same as test #29

Bed frame Steel frame (not weighed) -

Test #	ID	Photograph of Specimen / Test Setup	Additional Information / Details	
33	SI-21		Desk 99.5 % Particleboard 0.5% metal fittings. 28.8 kg Chair PUF padding, plastic cover, metal parts 14.9 kg CD / DVD cases 8.6 kg Keyboard, mouse: 1.4 kg; 19" LCD Monitor: 4.2 kg; CPU front plastic bezel: 0.35 kg; Printer: 9.8 kg; Paper: 2.5 kg Bookcase dimensions W x D x H: 760 x 300 x 1,110 mm	
36	SI-29		Attached label: "Body: 77% PUF; 23% Resin treated colored textile fiber pad. Seat cushion: 88% PUF; 12% Resin treated polyester fiber batting. Back cushion and Tossed pillow: 100% Polyester fiber" Remarks: Product label did not match the appearance, eg. Product had no back cushion and tossed pillow. Label may have been generic. Fabric appeared to be 100% polyester. Dimensions: 590 x 860 x 490 mm.	

Figure S34. SI-24 computer workstation.

Figure S35. Ottoman.

Test # ID Photograph of Specimen / Test Setup

Additional Information / Details

40 SI-32 No Photograph (two-seat sofa).

Total mass: 44.3 kg
Construction materials: Same as SI-26 (Test 26).

41 SI-33

Figure S36. SI-33 three-seat sofa (loveseat).

Total mass: 55.6 kg
Construction materials: Same as SI-26 (Test 26).

42 SI-85

Figure S37. Twin-size

Mattress	SI-05 (twin-size)	-
Bed clothes		-
Foundation	Posture box: Wood / PUF / Fabric	-

Note: mattress and foundation compliant with 16CFR1633 open flame test standard.

Test # ID Photograph of Specimen / Test Setup

Additional Details

43 SI-33

Figure S38. SI-33 futon.

Total mass: 17.0 kg
Internal structure: Cotton butts with sparsely distributed pieces of PUF. Exact composition (cotton vs. PUF) not determined, but observed to be predominantly cotton filling material.

44 SI-12

Figure S39. SI-12 full-size bed assembly.

Mattress	SI-06 (double)	27.2 kg
Bed clothes	Comforter, sheet set, mattress pad, two bed pillows, two decorator pillows.	6.9 kg
Posture box	Wood / PUF / fabric	19.8 kg

The total weight: 53.9 kg.

Test #	ID	Photograph of Specimen / Test Setup	Additional Information / Details
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None	None		
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Total mass: 16.20 kg

Figure S40. Twin-size posture box wood frame (with PUF and fabrics removed).

Breakdown:

- Wood frame: 14.3 kg
- PUF / plastic fittings: 0.24 kg
- Cardboard: 0.94 kg
- Ticking/fabrics: 0.82 kg
- Metal parts: 0.24 kg

Table S3. Test arrangements for bed clothes (twin-size).

Test no.	ID	Combinations of Bed clothes (top to bottom arrangement)	Bed clothes Setup	Total Mass (kg)
11	SI-08	Bed pillow (cover: 100% P; fill: 100% PF) Decorator pillow (cover: 100% P; fill: 100% PF) Comforter (cover: 60% P, 40% C; fill: 100% PF) Sheet set (100% C) Skirt: 100% P Mattress pad (cover: 60% P, 40% C; fill: 100% PF)	#2	6.7
12	SI-07	Bed pillow (cover: 70% P, 30% C, fill: 100% PF) Decorator pillow (cover: 100% P; fill: 100% PF) Comforter (cover: 60% P, 40% C; fill: 100% PF) Blanket (100% P) Sheet set (100% C) Skirt: 100% P Mattress pad (cover: 60% P; 40% C; fill: 100% PF) PUF mattress pad (topper): 100% PUF	#2	7.8
17	SI-75	Bed pillow (cover: 100% P; fill: 100% PF) Comforter (cover: 100% P; fill: 100% P) Sheet set (100% P) Skirt (100% P); Platform: 100% PP	#2	4.6
19, 30	SI-83	Bed pillow (cover: 100% P; fill: 100% PF) Decorator pillow (cover: 100% P; fill: 100% PF) Comforter (cover: 50% P / 50% C; fill: 100% PF) Sheet set (60% P / 40% C) Mattress pad (cover: 60% P, 40% C; fill: 100% PF)	#1	5.2

Abbreviations: C - Cotton; P - Polyester; PF – Polyester fibers; PP – Polypropylene; PUF – Polyurethane foam;

Note: A sheet set consisted of a fitted sheet and a flat sheet.

Figure S43. Mattress test arrangement showing the positioning of the dual T-burner system in Test 6.

Figure S44. Ignition of the test specimen using the dual T-burner system.

Figure S45. Ignition of a test specimen in Test 21 using a T-burner.

Figure S46. Ignition of a test specimen in Test 36 using a square-burner.

Figure S47. Typical fire development with innerspring mattress.

Figure S48. Dripping of melted PUF and formation of a pool fire during the test with mattress SI-06.

Figure S49. Beginning of Test 28-SI-05.

Figure S50. Condition of specimen SI-05 at the end of the experiment.

Figure S51. Fire progression at 210s in Test 8-SI-04.

Figure S52. Fire progression at 210s in Test 35-SI-04.

Figure S53. Flame spread in Test 11-SI-08.

Figure S54. Flame spread in Test 19-SI-83.

Figure S55. Test 14-SI-06 – Extent of flaming out of the window opening.

Figure S56. Test 23-SI-76 – Extent of flaming out of the window opening.

Figure S57

Figure 1. Test 8-SI-04 (mattress only)– Features of the fire during the period leading to flashover.

Figure S58

Figure 2. Test 21-SI-10 (bed assembly using mattress SI-04) – Features of the fire during the period leading to flashover.

Figure S59. Test 29-SI-12 – Post-flashover fire with external flaming.

Figure S60. Test 32-SI-14 – Post-flashover fire with extensive external flaming.

Figure S61
Figure 3. Test 27 – Mate's bed foundation.

Figure S62
Figure 4. Test 27 – Mate's bed (constrained surface area and air entrainment).

Figure S63

Figure 5. Test 42 – Fully-involved surface burning of bed assembly with open –flame-resistant mattress set.

Figure S64

Figure 6. Test 42 – Decay phase with flaming occurring only in places where pyrolysis gases were diffusing through the barrier fabric.

Figure S65

Figure 7. Test 26-SI-26 – Flames emerged from the window opening when the HRR exceeded 2,000 kW.

Figure S66

Figure 8. Test 10-SI-24 – Dense smoke but hardly any flames emerged from the window opening.

Figure S67

Figure 9. Test 33-SI-33 – Ignition with a 19 kW square burner applied for 80s.

Figure S68

Figure 10. Test 33-SI-33 – Fire almost self-extinguished after 480s.

Figure S69

Figure 11. Test 13 – Initial fire growth.

Figure S70

Figure 12. Test 16 – Initial fire growth.

Figure S71. Test 18 – Burning of the TV housing with a constantly applied ignition source.

Figure S72. Test 18 – Condition of the TV housing after the test (right side was unaffected by the fire).

Figure S73

Figure 131315. Test 20 – CD/DVD media.

Figure S74

Figure 141416. Test 22 – Toys.

Figure S75

Figure ~~1516~~17. Test 24 - Shoes.

Figure S76

Figure ~~1616~~18. Test 33 – Computer workstation.

Table S4. Results for all of the tests.

Test ID	HRR _{max}	THR	ODM _{max}	HC	$\bar{T}_{max}$	Q''_{mf}	$\bar{Q}''_{mwc}$	T_{∞}
	(kW)	(MJ)	(OD/m)	(MJ/kg)	(°C)	(kW/m ²)	(kW/m ²)	(°C)
05-SI-03 (Mattress)	1,808 (174) ¹	144 (5.4) ²	0.4	26.7	594 (101) ³ [722 SE] ⁴	10	39 (20) ³ [67 SW CS] ⁴	18
06-SI-01 (Mattress)	3,790 (234)	257 (12.5)	1.3	20.6	835 (54) 899 SE]	42	98 (32) [138 W wall]	18
07-SI-02 (Mattress)	2,238 (258)	250 (9.3)	0.6	26.9	728 (135) [860 SE]	13	55 (27) [92 SW CS]	18
08-SI-04 (Mattress)	3,757 (278)	328 (13.3)	1.7	24.6	924 (40) [978 NW]	87	111 (28) [160 W wall]	18
09-SI-25 (Chair)	1,843 (185)	461 (27.3)	0.4	18.8	590 (91) [713 SW]	12	35 (16) [40 S wall]	15
10-SI-24 (Chair)	1,818 (206)	625 (30.1)	0.8	21.9	582 (25) [620 SE]	15	33 (10) [46 NE CS]	22
11-SI-08 (Bed clothes)	268 (466)	123 (5.25)	0.1	23.4	119 (5) [126 SW]	0.6	2.5 (1) [3.8 SW CS]	15
12-SI-07 (Bed clothes)	388 (582)	102 (6.5)	N/A	15.7	195 (10) [204 SE]	1.6	5.4 (2) [7.9 SW CS]	15
13-SI-15 (Clothing)	1,855 (118)	942 (32.1)	0.2	25.4	542 (60) [598 SW]	12	34 (13) ³ [49 SW CS] ⁴	21
14-SI-06 (Mattress)	3,796 (233)	282 (10.5)	2.4	26.9	905 (41) [956 SW]	46	100 (33) [129 N wall]	20
15-SI-27 (Chair)	906 (178)	152 (7.3)	0.4	20.8	308 (33) [346 NW]	6	14 (6) [25 SW CS]	16
16-SI-16 (Wardrobe)	1,529 (622)	1,662 (89.8)	0.4	20.8	680 (34) [710 SE]	16	40 (24) [88 SW CS]	17
17-SI-75 (Bed clothes)	210 (756)	47 (3.7)	.2	12.9	116 (18) [143 NW]	.5	2.6 (1) [4.3 SW CS]	19
18-SI-36 (TV set)	93 (220)	N/A ⁵ (0.5)	0.2	N/A	42 (1) [43 NW]	<1	<1	23
19-SI-83 (Bed clothes)	N/A	N/A	.2	N/A	130 (5) [137 SW]	<1	3.1 (1) [4.6 W wall]	26
20-SI-19 (CD/DVDs)	1,294 (415)	1,229 (35.8)	1.3	28.9	442 (23) [473 NW]	7	21 (8) [33 W wall]	25
21-SI-10 (Bed assembly)	2,978 (394) ¹	773 (35.8) ²	0.9	21.5	826 (87) ³ [933 SE] ⁴	25	77 (28) ³ [99 W wall] ⁴	29
22-SI-22 (Toys)	2,048 (66)	408 (15.9)	1.4	25.7	603 (55) [667 SE]	14	41 (16) [65 SW CS]	20
23-SI-76 (Bed assembly)	3,358 (332) ¹	595 (32.5) ²	1.3	18.3	891 (41) ³ [942 SW] ⁴	20	95 (37) [140 W wall]	18
Test ID	HRR _{max}	THR	ODM _{max}	HC	$\bar{T}_{max}$	Q''_{mf}	$\bar{Q}''_{mwc}$	T_{∞}
	(kW)	(MJ)	(OD/m)	(MJ/kg)	(°C)	(kW/m ²)	(kW/m ²)	(°C)

24-SI-18 (shoes)	1,229 (244)	529 (20.7)	1.0	25.6	375 (4) [379 NW]	8	26 (20) [69 SW CS]	23
25-SI-20 (Books)	443 (2,162)	881 (47.7)	0.1	18.5	183 (9) [197 NE]	2	7 (5) [16 SW CS]	23
26-SI-26 (chair)	2,710 (142)	481 (27.8)	0.8	17.4	635 (44) [691 SW]	20	73 (27) [102 W wall]	25
27-SI-11 (Bed assembly)	2,052 (388)	1,309 (N/A)	0.2	N/A	621 (67) [708 SW]	16	59 (30) [102 S wall]	14.5
28-SI-05 (Mattress)	< 200 (67)	N/A (3.0)	0.05	N/A	41 (4) [47 SW]	N/A	0.8 (0.2) [0.9 NE C]	18
29-SI-12 (Bed assembly)	3,971 (247)	809 (40.7)	2.6	20.6	1,026 (21) [1,057 NE]	N/A	173 (32) [223 S Wall]	18
30-SI-83 (Bed clothes)	197 (378)	56 (3.3)	0.2	17.0	111 (4) [115 SE]	<1	3.9 (2) [4.9 S wall]	19
31-SI-13 (Bed assembly)	3,762 (466)	835 (47.9)	2.7	18.2	1,052 (16) [1,071 NE]	128	177 (26) [221 S Wall]	20
32-SI-14 (Bed assembly)	6,258 (248)	957 (38.7)	2.4	21.4	1,003 (39) [1,061 NE]	89	167 (36) [221 E CS]	24
33-SI-21 (workstation)	1,794 (433)	1,180 (54.0)	0.9	24.1	635 (72) [740 SW]	24	64 (28) [104 S wall]	24
34-SI-12 (Bed assembly)	1,912 (293)	853 (43.3)	0.8	20.4	583 (56) [629 SW]	18	35 (9) [51 SW CS]	17.7
35-SI-04 (Mattress)	3,351 (336)	265 (13.1)	1.9	20.2	749 (151) [921 SE]	29	66 (32) [129 SW CS]	-24
36-SI-29 (Ottoman)	631 (509)	73 (6.4)	0.3	11.4	149 (56) [183 SW]	3	10 (4) [16 SW CS]	-24
40-SI-31 (Loveseat)	3,364 (189)	595 (37.1)	1.7	16.0	739 (190) [910 SW]	19	83 (52) [165 SW CS]	-4
41-SI-32 (sofa)	3,170 (217)	886 (49.0)	>2.0	18.1	800(191) [1006 SE]	23	94 (43) [144 SW CS]	-4
42-SI-85 (Bed assembly)	1,812 (564)	615 (22.1)	0.4	24.6	452 (45) [493 SW]	20	26 (8) [36 W wall]	-20.0
43-SI-33 (Futon)	447 (1,008)	297 (16)	0.05	18.1	113 (62) [149 SE]	1	5 (1) [6 SW CS]	-13
44-SI-12 (Bed assembly)	2,703 (442)	700 (40.1)	1.0	17.5	836 (236) [892 NE]	39	79 (22) [106 W wall]	2

$T_{\max}$ – Maximum temperature; $\bar{T}_{\max}$ – Maximum average room temperature (of four TC trees); Q''_{mf} – Maximum heat flux at floor level; $\bar{Q}''_{mwc}$ – Maximum average heat flux on the walls and ceiling; THR – Total heat released; SW C: SW ceiling location; W wall: West wall; N wall – North wall; NE C – NE ceiling location.

¹ Time to reach the peak HRR (s); ² Mass loss (kg); ³ Standard deviation (SD); ⁴ $T_{\max}$ or $Q''_{\max}$ and its location. ⁵ N/A: Not available due to instrumentation malfunction or other omission.

Table S5. Heat Release Rate vs. Time Graphs.

Figure S77. Test 5-SI-03.

Figure S78. Test 6-SI-01.

Figure S79. Test 7-SI-02.

Figure S80. Test 8-SI-04.

Figure S81. Test 9-SI-25.

Figure S82. Test 10-SI-24.

Figure S83. Test 11-SI-08.

Figure S84. Test 12-SI-07.

Figure S85. Test 13-SI-15.

Figure S86. Test 14-SI-06.

Figure S87. Test 15-SI-27.

Figure S88. Test 16-SI-16.

Figure S89. Test 17-SI-75.

Figure S90. Test 18-SI-36.

Figure S91. Test 19-SI-83.

Figure S92. Test 20-SI-19.

Figure S93. Test 21-SI-10.

Figure S94. Test 22-SI-22.

Figure S95. Test 23-SI-76.

Figure S96. Test 24-SI-18.

Figure S97. Test 25-SI-20.

Figure S98. Test 26-SI-26.

Figure S99. Test 27-SI-11.

Figure S100. Test 28-SI-05.

Figure S101. Test 29-SI-12.

Figure S102. Test 30-SI-83.

Figure S103. Test 31-SI-13.

Figure S104. Test 32-SI-14.

Figure S105. Test 33-SI-21.

Figure S106. Test 36-SI-29.

Figure S107. Test 40-SI-31.

Figure S108. Test 41-SI-33.

Figure S109. Test 42-SI-85.

Figure S110. Test 43-SI-33.

Figure S111. Test 44-SI-12.