NIST Technical Note 1601

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ABSTRACT

The Sleep Products Safety Council is sponsoring a study at NIST of the viability of a bench-scale version of CFR 1632 (cigarette ignition of mattresses). In the context of this study, NIST was also asked by the Consumer Product Safety Commission to look into the criteria used to decide the outcome (smoldering/non-smoldering) of such tests. Three markers were examined in 241 bench-scale tests conducted to date: existence of continued smoke emissions, extent of "charred" area progression away from the cigarette and the peak temperature of this charred area as seen by an infrared thermometer. All three of these markers were found to be useful in reaching an early decision as to the outcome of a test but certain precautions are necessary. Recommendations for a viable procedure using these markers are made.

Introduction

Federal Regulation 16 CFR 1632 – Standard for the Flammability of Mattresses and Mattress Pads, which examines the susceptibility to smoldering ignition by cigarettes, has been in effect since 1973. In this standard, a complete mattress of commercial size is exposed to a standardized smoldering cigarette in locations of varied geometry which also may incorporate varied materials composition. The locations include smooth surfaces on the mattress top, indented areas created by tufting or quilt seams and the peripheral tape edge. Separate examples of all such areas are tested three times, both without and with a layer of bed sheeting above and below the cigarette. In all, eighteen cigarette tests are performed on each mattress design and this is replicated on three mattress specimens of a design. The test is thus thorough but labor intensive to perform.

With the recent enactment of 16 CFR 1633 – Standard for the Flammability (Open Flame) of Mattress Sets, mattress manufacturers have begun incorporating a flame barrier layer under the outer fabric layer (ticking) of the mattress. Mattress manufacturers petitioned the Consumer Product Safety Commission (CPSC) for a lessening of their testing burden, presumably on the assumption that the flame barrier layer would also provide smoldering protection. Given the differences between the heat exposure parameters of the flaming and smoldering exposures, as well as the differences between the combustion chemistry involved in smoldering and flaming, this is not a safe assumption[1]. The Sleep Products Safety Council (SPSC), with partial support from CPSC, has initiated a study at NIST to see if the cigarette test could at least be reduced to a bench scale test that might bracket the composition and geometry limits that permit smoldering initiation. If feasible, this could limit the testing burden for future mattress designs.

The CPSC support for the NIST work in this area is focused specifically on the issue of the criteria to be used to decide, in the course of a cigarette test, whether the test specimen has ignited to a self-sustaining smolder condition or has successfully resisted this. While the SPSC study is yet to be completed, due to a variety of factors, NIST has been exploring the smoldering ignition criterion. This report summarizes those results and provides some recommendations with respect to that subject.

Experimental Details

The bench scale test utilizes the same open-top, wooden box enclosure as is used in CFR 1632 for classifying tickings; see Fig. 1. The external dimensions of the box are 30 ½ cm by 30 ½ cm by 15.2 cm deep (12 in by 12 in by 6 in) and it is made from 1.3 cm thick plywood. There is one 1.3 cm diameter hole through the center of two opposite vertical sides. In all of the tests reported here, the box was filled with a 15 cm thick layer of a particular polyurethane foam (24.0 kg/m^3, 1.5 lb/ft^3; 147 N, 33 lb IFD (Indentation Force Deflection); non-flame retarded). In separate tests using a temperature-controlled, brass-encased rod heater[2] embedded in the foam, this substrate foam was found to be unexceptional (as compared to 7 other normal polyurethane foams also tested) in the minimum heater temperature required to initiate smoldering. Test specimens (square sections of mattress quilt layers) were placed on top of this foam layer and held in firm contact with it by the weight of a peripheral, steel frame (33 cm by 33 cm, made of 3 mm thick, 3.7 cm angle with added flat stock to reduce the interior frame opening to 21.7 cm by 21.7 cm; see Figs. 1 and 2).

A test specimen consisted of a quilt layer having a ticking over a fire barrier layer over a foam (or cotton) filler and, finally, a non-woven scrim as a backer layer. The compositions of the fire barrier and the foam filler (and, to a lesser extent, the filler thickness) were the main variables in the tests reported here. Table 1 shows the limited information available on these materials (along with cigarette test results from one segment of the study). The initial size of each layer in the quilt was 30 ½ cm by 30 ½ cm; by the time they were edged and quilted, the test specimens were 26 cm by 26 cm or less. The J barriers were based on cotton batting; note that both FR treated and non-FR versions were used. The other barriers were commercial, non-woven fiber blends for which further information is not available. All of the quilt components were from the spectrum of materials used in commercial mattresses.

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[1] The May 15, 2007 progress report from NIST on our CFR 1632 study, in fact, reported that three different commercial flame barriers allowed a substantial percentage of smoldering initiations in a particular polyurethane foam immediately beneath those barriers. See the Appendix here.

[2] The apparatus and procedure for assessing the smolder tendency of filling materials (in terms of the minimum temperature required to initiate smoldering) are described in the Appendix.

All test specimens were quilted (by a mattress manufacturer, using polyester/cotton thread) in the same pattern: all four edges were double sewn with an overcast edger and the main body of the sample was compressed by two seams in an X-shape, running diagonally from corner to corner; see Fig. 3. This particular straight seam design follows from the rationale of the SPSC study. It is assumed that the worst case geometry for encouraging smolder initiation in a susceptible material is one which increases the cigarette-substrate contact and thus maximizes the total heat transferred from the cigarette to the test specimen. This enlarges the heated zone in the tested material, enhancing the net heat generated versus heat lost to the surroundings, which favors the development of sustained smolder. This implies that, for a given test specimen, a configuration in which the cigarette is partially engulfed by the specimen is more smolder-prone than one in which the cigarette simply sits atop a flat surface. Here that partial engulfment is provided by either of the straight seams forming the X pattern[3]; the straightness of the seam allows the cigarette to sit more deeply than would a curved seam. The cigarette thus sits as low as possible in a V-shaped valley formed by the seam. The depth of that valley is increased as the thickness of the filler layer in the test specimen is increased since the seam thread (in the bottom of the valley) is pulled tight enough by the sewing machine to tightly crush the foam (or cotton) and barrier layers along the seam line. The SPSC study is intended to provide a bench-scale method for determining the minimum[4] and maximum quilt layer thicknesses that may be conducive to smoldering in a given material combination. A related goal of the SPSC study is to demonstrate that the bench-scale test can predict the full-scale smolder susceptibility of an actual mattress composed of the same materials.

The SPSC study will look (for both size scales) at the effect of engulfing the cigarette in one layer of bed sheeting (on top) or two layers (on top and bottom) or not at all, as it sits in the groove provided by the X seam[5]. In many previous studies, it has been assumed that the two sheet case is the worst case. The top sheet reduces the air supply rate to the smoldering cigarette coal, slowing its burning rate and allowing more time for the heat from the cigarette to penetrate further into the substrate. This may encourage smolder initiation though the cigarette coal temperature is simultaneously reduced so the net effect is not guaranteed. In any event, for the present purposes, we note that the presence of a sheet over the cigarette tends to somewhat obscure the area of the test specimen that is affected by the cigarette.

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[3] Two seams (rather than a single straight line) provide a more extensive compressed area where they cross and a choice of the straighter of the two lines (which are not always perfect).

[4] A minimum quilt layer thickness becomes an issue if the material <u>below</u> the mattress quilt is prone to smoldering.

[5] Here the cigarette was placed into one leg of the X-shaped quilt seam with one end near the intersection of the two crossing seams. In about 2/3 of the tests the end placed toward that seam intersection was the lit end; in the other 1/3 of the tests the lit end was placed away from the intersection so the cigarette coal moved toward it. No difference in results was noted as a consequence of changing the cigarette smolder direction, but, in keeping with the spirit of CFR 1632 (cigarette smolder progression toward the more compacted zone), future tests will use configuration with the lit end away from the intersection.

As written, the present CFR 1632 test method has no time limit. The test (for one cigarette) is ended when either a char zone has spread at least 5.1 cm away from the cigarette periphery in any direction (as seen from above) or the cigarette is out and nothing more is happening, as determined by the operator placing his hand above the test area to sense a lack of heat emission.

Markers of Specimen Ignition Status. CPSC asked whether it was possible to provide more definite criteria for establishing the end of a test and its outcome (smolder initiation or non-initiation). For this purpose, NIST examined three markers of specimen behavior. All of the results reported here are for the bench-scale test. The first marker was smoke emission. Definitive observation of smoke emission requires careful control of the lighting situation. For control of airflow in the neighborhood of the test specimen, the entire box assembly was placed inside of a clear plastic box (see Fig. 4). Then to enhance smoke visibility, the back vertical interior surface of the box was covered with flat black paper. Soft lighting from above was usually sufficient to make smoke visible against this background, but, if in doubt, the operator used a hand-held, white LED light held against one side of the box. One precaution was that the operators clothing, if too light in color, could, by reflecting from the front surface of the plastic enclosure, obscure the smoke. This was avoided either with dark clothing or with a piece of black cardboard held between the operator and the front of the enclosure. By these means, it was possible to ascertain if smoke emission had ceased.

The second marker was the use of a simple wire mesh grid placed on top of the test specimen, centered on the cigarette (placed there at the start of the cigarette exposure)[6]. This allowed continuous monitoring of the extent of the "char" zone, as seen from the top of the specimen. Figure 5 shows a picture of the final form of this grid. The material is zinc-coated steel with four wires per inch in both directions; the wires are 0.064 cm diameter. The other dimensions are noted in the figure caption. The grid allows monitoring of the "char" zone front position anywhere around the cigarette to better than 3 mm (1/8 inch). Note that the grid includes eight wire prongs protruding inward toward the cigarette. The two protruding in from the long direction allow aligning the grid on the cigarette axis. The six protruding in from the sides (three per side) are bent downward at roughly 30º to act as stand-offs that hold the inner portion of the grid out of contact with the specimen so as not to heat sink a developing smolder zone. As noted above, when there is a bed sheet on top of the cigarette, the "char" zone, as seen from above, is less sharply defined. The sheet turns brownish gray, not black, and the color transition is spread over several millimeters in distance. Here we have, in cases like this, arbitrarily called the outer edge of the discolored zone the edge of the char zone.

When a top sheet is not present, the char zone edges are sharply defined. In 25 tests with no sheets present and which did not result in sample ignition, the char zone width was distinctly less than with a top sheet present.

The third marker followed here was the peak temperature reading from an infrared thermometer. Two commercial thermometers were used, an Omega Engineering Model

[6] The grid went on top of the bedsheet covering the cigarette, when present.

OS534E and a Fluke Model 572.[7] Both have automatic saving and display of the maximum reading seen during a period of continual reading. Such units read a 300 ºC blackbody to an accuracy of about ± 5 ºC, typically. Both of these devices emit red laser patterns intended to indicate the area whose temperature is being read. Only in the Fluke device was the laser coaxial with the field of view of the infrared sensor at all distances so that the indicated area and the area being read actually coincided even at short distances (here less than about 25 cm)[8]. For the Omega device at such a distance, the area actually being read could be 2 cm to 3 cm above the laser-marked area. Although both devices could be used for the present purpose, the alignment issue with the Omega unit could easily be misleading if not constantly borne in mind. Both devices read an area larger than the width of a cigarette coal (for the Omega unit, a circle about 8 mm in diameter; for the Fluke unit a circle about 10 mm in diameter, both at about 25 cm from the target). The temperature reading is an average over the indicated laser circle diameter so it will always be low when pointing at a small source such as a cigarette coal. Another characteristic that has to be kept in mind is that the time response of the sensor is a bit slow (half second or less); thus it is necessary to scan the area of possible combustion somewhat slowly (typically about 12 s to 14 s). These characteristics, if understood, do not preclude the use of such devices for determining when a cigarette test has ended. One has to use the reading conservatively and also look at the trend in two successive readings to decide if all combustion has ceased or is progressing[9].

In the tests reported here, all of these markers were noted repeatedly at time intervals in keeping with the fact that four cigarette tests were conducted simultaneously in four apparatuses set up side-by-side in a single overhead fume hood (Fig. 6). A test was started in the first apparatus; two minutes later a test was started in the second apparatus, etc. This simultaneous testing is an inevitable result of the fact that the go/no-go nature of a smolder ignition test requires a large number of replicates for reasonable confidence limits on the fraction of ignitions and the comparison of this fraction on the two test scales (an SPSC objective). At 18 minutes after ignition in each apparatus, typically, the state of the three markers was first recorded. This cycle of recording the markers for the four test apparatuses was subsequently repeated continuously (at intervals that were typically 3 min but could reduce to 1 ½ min when only one set-up was still in play) as the fate of the four test assemblies became evident (ignition or non-ignition).

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[7] Certain trade names and company products are mentioned in the text or identified in an illustration in order to specify adequately the experimental procedure and equipment used. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products are necessarily the best available for the purpose.

[8] The top central section of the plastic box (which had slots for smoke escape) was slid forward about 2/3 of its length to give the thermometer a clear field of view of the cigarette area. This gave some weak disturbance of the smoke plume from the cigarette. There was no noticeable effect of this plume disturbance on the ignition behavior but, if it is a concern, it should be possible to re-design the box top to eliminate the need to slide it open.

[9] It is useful to have a ca. 300 ºC blackbody available or some other elevated temperature object (preferably painted black) of known temperature to check the accuracy of an IR thermometer periodically.

In all cases the materials used were conditioned for at least 24 hours at a relative humidity between 40% and 50%, which was the same humidity condition for the tests themselves. The cigarette was a commercial, 85 mm long, non-filter packing long used for the ignition testing of mattresses in accord with CFR 1632.

Results and Discussion

The experiments reported here were run in the context of different sub-sections of the SPSC study, including a survey of potential quilt materials and an assessment of materials submitted for use in a study of the effect of covering (or not) the cigarette. In all, about 240 tests were run in the above manner. For the present purposes, the results of those experiments, i.e., the number of ignitions versus the type of material, are not of interest, though we summarize some of this information below. We are interested mainly in the consistency of the above markers as indicators of the initiation or non-initiation of smoldering in the test specimen and whether they indicate definitive cut off points for a test.

As noted above, three markers were followed in each experiment: existence of smoke emissions, dimensions (length and width) of the "charred" area as seen from above and the peak temperature recorded by sweeping an infrared thermometer over the charred area. In every test in which ignition occurred[10], the unique marker of ignition was the width of the charred area. All of the ignitions (and the majority of the tests) involved the use of two cotton sheets, one below and one above the cigarette. As noted above, this made the discolored area (of the top sheet) more diffuse at the edges so that precise measurement was not possible (nor really necessary). Nevertheless, in the non-ignition cases, this area never exceeded 3.8 cm (1 ½ in) in total width and widths of this magnitude occurred in only two of the non-ignition tests. For the vast majority of non-ignitions the char area width was approximately 2.5 cm (1 in) or less. The earliest clear signal of ignition thus became a char area width exceeding 5.1 cm (2 in). This could occur as early as about 15 min to 16 min after the start of a test but was sometimes as late as 30 min. Note that this is the total width of the discolored area on the top sheet with the centerline of the cigarette being near the center of this area, since it was always fairly symmetrical about the cigarette centerline. Extension of the length of the charred area beyond about 9 cm (3 ½ in, slightly longer than the cigarette) rarely occurred since the smolder zone in the quilt was stopped by the cross quilt seam (the other leg of the X). The reason for this was presumably a lack of air supply in the crushed foam fill layer at the seam.[11]

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[10] In the 241 tests conducted, about 30 resulted in smoldering ignition of the quilt layer.

[11] One cannot assume that quilt seams are a reliable means of limiting the extent of smoldering in a mattress. Here the smoldering did not get into the foam layer below the quilt (Foam "h" in Table A-1 in all tests), probably because of the limited area allowed to smolder (before the test was ended) and the limitations imposed by the frame holding down the quilt layer (heat loss and air supply limitation). In general, if the smoldering got into this layer on a real mattress, it could spread right under any quilt seams. Use of a material more smolder-prone than Foam "h" could also encourage this.

No case here in which the char zone width exceeded 5 cm (2 in) failed to continue to go onward to a wider and wider char zone[12], indicating self-sustaining smolder in the quilt layer. Thus, on the basis of these results, a 5 cm (2 in) wide smolder zone (or, more conservatively, a char zone reaching 2 ½ cm (1 in) in any direction) away from the cigarette centerline could be regarded as a test failure.

Non-ignition was by far the more frequent occurrence in these tests. The cigarettes always burned their full length but the time required for this varied substantially (ca. 22 min to 30 min for the predominant, sheet covered configuration). In the present bench-scale set-up, cessation of smoke emission was the most readily observed signal of the end of a test but this can be subtle; at times, late in a test, the weak smoke emission was difficult to spot. Furthermore, for a full-scale mattress being tested in a large, open space, spotting weak smoke emission could be nearly impossible.

The infrared thermometer is more definitive, if used conservatively. The maximum temperature readings obtained while smoke emission was visible varied considerably, from a little under 200 ºC to well over 400 ºC. As noted above, none of these numbers is likely to accurately reflect the true peak temperature of a cigarette coal which, on its surface, tends to peak above 500 ºC in a free burning state (open air, natural convection, with no cover sheet). The surface temperature of smoldering polyurethane could be substantially less though the smolder zone temperatures tend to peak around 350 ºC in a weak air supply situation. In any event one has to take into account the tendency of the IR thermometer to read low due to averaging over the area it images. Thus we noted that two successive peak readings, at least two minutes apart, that were less than 100 ºC, and with the second reading being lower than the first, always corresponded to extinguishment and thus the end of a test. Apparent cessation of smoke emission is thus best taken as a signal to begin taking IR thermometer readings.

Recommendations

There is no need to carry out the tedious, continual monitoring/recording of all three markers during a test. At the same time, all three of these markers serve a useful role in deciding, as soon as possible, when a test specimen has reached a self-sustained smoldering state or an extinguished state.

In the context of a bench-scale smoldering test (assuming that the SPSC project proves the feasibility of such a test), realistically speaking, when the operator is carrying out four tests in parallel, he will not be able to achieve the optimal shortest possible test time for all specimens. It does not matter if one or more of a set of four simultaneous tests goes on a couple of minutes longer than this optimal time. Extinguishment presents no threat at all; a longer smoldering time (by a few minutes) will typically not appreciably increase the potential hazard of the smoldering test assembly. Thus we recommend the following in the bench-scale context.

[12] Tests were typically stopped when the char zone was 7 ½ cm to 10 cm (3 in to 4 in) wide.

- Use the mesh shown in Figure 5 as a means of keeping visual track of the width of the "char" zone on the top of the mock-up. Its 6.4 cm (2 ½ in) wide central open area is a bit more lenient than the 5 cm wide criterion for self-sustained smoldering found above but it is also more conservative than the current criterion in CFR 1632[13]. Stop the test and record a failure if any part of the char zone reaches either of the long edges of the inner hole in the mesh shown in Fig.5. (Though no cases were seen here, and the general physical conditions of the test layout here make it unlikely, one should also declare a failure if the char zone reaches either of the outer ends of the mesh in Fig. 5)

- Closely watch for the continuing existence of smoke emissions after the cigarette smolder zone has reached its full length (assuming no ignition by the criterion above). When smoke emissions appear to have ceased (using side lighting against the black paper background described above), begin taking IR thermometer readings by sweeping slowly (at least 12 s to 14 s) over the entire "charred" area. Record the time and peak temperature value on a note attached to each test box. Stop the test and record a pass when two successive readings are below 100 ºC and the second reading (at least 2 min after the first reading on this specimen) is at least 5 ºC lower than the preceding reading).

For the full-scale mattress test, the mesh is still useful but here there is the possibility of smolder spreading in the cigarette axis direction, as well as laterally. The mesh in Fig. 5 can still be used since 5 cm spread in the longitudinal direction would put the char front at the end (in either direction) of the mesh[14]. In the large open space where full scale testing would be done, monitoring of the smoke is inexact, but still would be suggestive of the time to begin IR temperature scans, in the same manner as above. Thus as soon as smoke appears to have ceased (and the cigarette has burned full length), one should begin to track the peak IR temperature reading and follow the same rules as above. Because the potential threat from an out-of-control smoldering process from one cigarette is now appreciably greater, the number of tests to be done in parallel has to be carefully considered and could vary with the safety record of the particular specimen design under test.

None of the tests done here involved a tape edge configuration but there is no evident reason why the use of the mesh plus the IR thermometer and the above pass/fail criteria could not be adapted to this situation. Given the minimal material typically in the side of a mattress, there is little reason to expect smolder there[15]. Thus one could, in effect, cut

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[13] It was noted previously in the text that tests that did not use a cover sheet on the cigarette tended to give a narrower, more sharply-defined char area for non-ignition (probably because hot gases trapped between the cover sheet and the test specimen surface tended to weakly pyrolyze the cover sheet out beyond any active smolder zone). Then imposing this same 6.4 cm criterion on cover-free tests implies that they will have progressed further in their smoldering away from the cigarette than is the case for tests with a cover sheet. Such a difference will have existed in all prior tests with CFR 1632, as well, despite the larger smolder "reach" criterion used there.

[14] Note that the basic mesh can be adapted to the current CFR 1632 criterion by a simple size change.

[15] A solid foam mattress might be the exception here. A re-shaping of the mesh to handle this situation should be possible.

the mesh in half and use it according to the above rules. Similarly, no tests involved the flat surface of a mattress, between quilt seams, but again, the same approach should work. In the tests here, the mesh is normally bent into a shallow V-shape along the longitudinal axis so that it sits slightly into the seam above the cigarette. For a flat surface, the mesh is easily bent to a flat shape. Some further, peripheral, downward-bent prongs may be desirable to minimize the contact between the mesh and the sample surface.

Table 1. Summary of Materials Combinations Tested in Quilt Survey[16] And Cigarette Ignition Test Results

DESIGN	BARRIER[17]	FILL[18]	No. of Non-Ignitions	No. of Ignitions
Q1	M light	Foam a	6	0
Q2	M high loft	Foam b (18.4 kg/m^3, 1.15 lb/ft^3; 36 N, 8 lb IFD)	1	6
Q3	M light	Foam c (18.4 kg/m^3, 1.15 lb/ft^3; 71 N, 16 lb IFD)	6	0
Q4	M high loft	Foam d (19.2 kg/m^3, 1.2 lb/ft^3; 125 N, 28 lb IFD)	6	0
Q5	J light **untreated**	Foam b	2	5
Q5’	J heavy **untreated**	Foam c	2	3
Q6	J light	Foam a	6	0
Q7	J heavy	Foam b	6	0
Q8	J light	Foam c	6	0
Q9	J heavy	Foam d	6	0
Q10	W light	Foam a	6	0
Q11	W high loft	Foam b	6	0
Q12	W light	Foam c	5	0
Q13	W high loft	Foam d	6	0
Q14	C	Foam a	6	0
Q15	C	Foam b	3	5
Q16	C	Foam c	6	0
Q17	C	Foam d	6	0
Q18	B light	Foam a	6	0
Q19	B high loft	Foam b	3	5
Q20	B light	Foam c	6	0
Q21	B high loft	Foam d	7	0

[16] All samples had the same 100 % polyester ticking and 100 % polypropylene backer scrim.
[17] Two grades of barrier were requested from each supplier, if available: a lighter weight (mass per unit area) and a heavier weight. The heavier weight generally had a greater thickness or loft. Barriers with the same capital letter designation came from the same supplier.
[18] All polyurethane foam fill slabs were 5 cm (2 inches) thick and nominally non-flame retarded. The cotton fills were somewhat thinner but less determinate in thickness.

Table 2. Summary of Materials Combinations Tested in Assessment of Specimens for Cigarette Cover Effect[19]

Designation	Barrier	Fill
QQ1	M heavy	Foam b
QQ3	M heavy	Foam c
QQ7	C	Foam b
QQ10	B heavy	Foam b (half thickness)

[19] All had the same 100% polyester ticking (different from Table 1) and nominally the same backer scrim as in Table 1.

Figure 1. Overview of the bench-scale box test assembly showing the cigarette placement. The 30 ½ cm by 30 ½ cm

(12 in by 12 in) laundered, cotton bedsheet sections, used in most of the tests reported here (over and under the cigarette), are not shown.

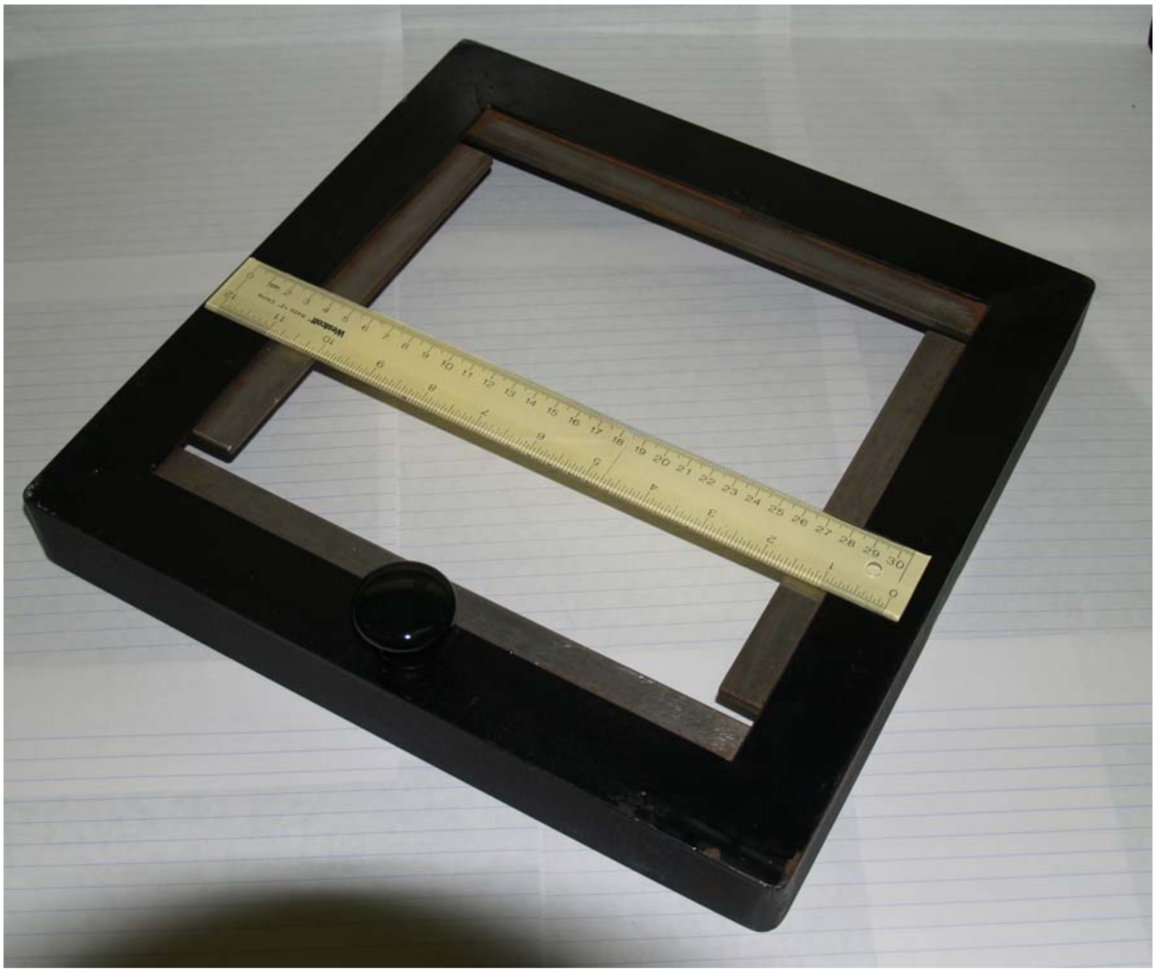

Figure 2. Steel frame used to hold a quilt sample firmly on top of the foam fill in the bench-scale box test. The knob facilitates placement of the frame on top of the test box when it is inside the plastic enclosure shown in Fig. 4.

Figure 3. Example of a quilt layer sample showing the edge seams and the central X seams. The cigarette is placed into one leg of the X.

Figure 4. Bench-scale cigarette test assembly contained inside clear plastic box for draft control. Note slotted section of top of plastic box that is slid forward to permit IR thermometer readings.

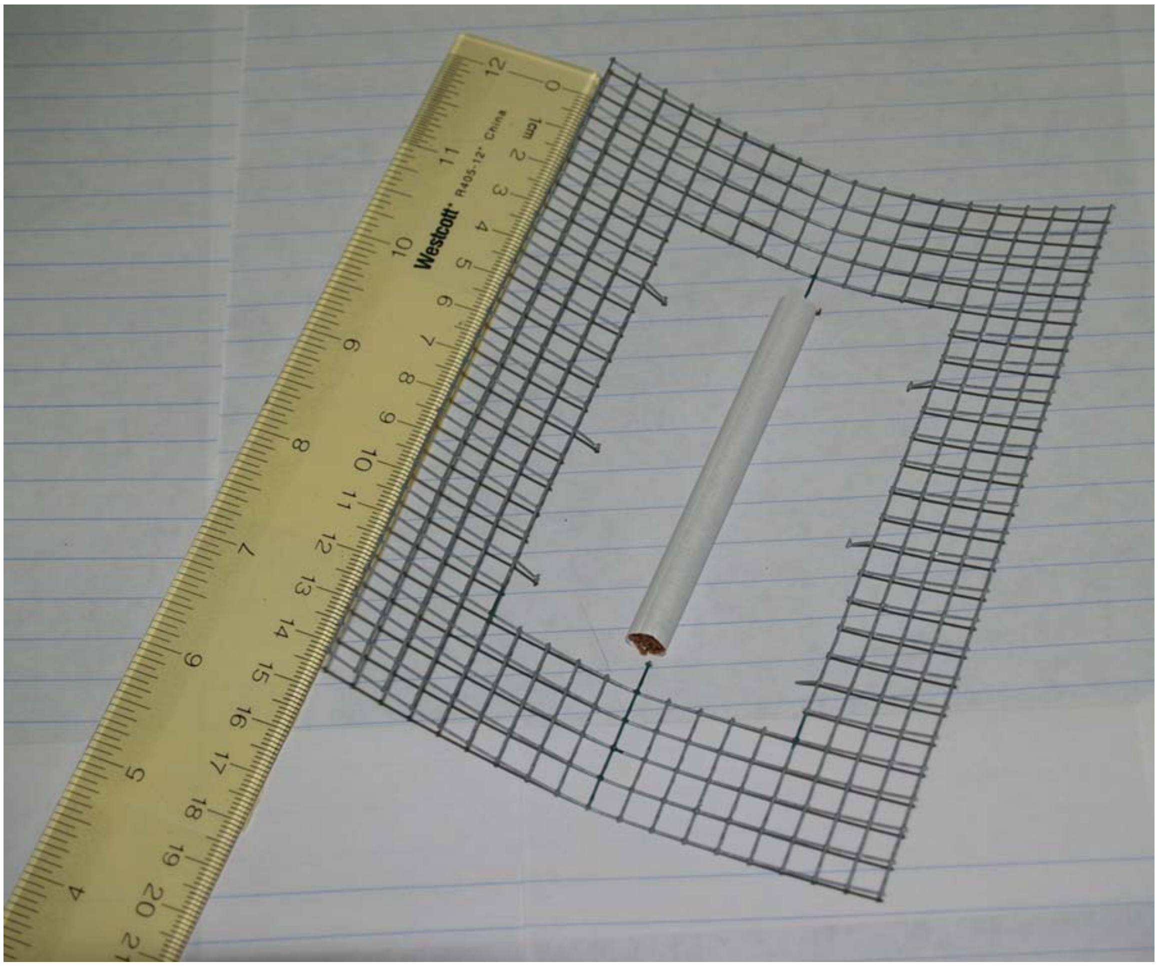

Figure 5. Wire mesh (4 mesh/inch) for visual monitoring of size of "char" area on top of test specimen assembly. The outside dimensions of the mesh are 11.4 cm by 15.2 cm (4 in by 6 in). The cut-out section in the middle of the mesh is 10.2 cm by 6.4 cm (4 in by 2.5 in). Note the slight Vee-bend of the mesh along the cigarette axis (ca. 2.5 cm depth over full width of wire mesh).

Figure 6. Apparatus for four simultaneous bench-scale cigarette ignition tests conducted in one overhead fume hood.

Appendix

Determination of the Minimum Temperature For Self-Sustained Smoldering of a Filling Material

Smoldering combustion of the resilient filling materials used in upholstered furniture has long been recognized as a problem [A-1]. Cotton batting, polyurethane foam and latex foam all have some tendency to undergo smoldering combustion since they present a large, porous surface area to oxygen attack when heated. Of these three types of material, polyurethane foam is, in one sense, the most marginal in smolder tendency; when heated the foam can collapse to a liquid, losing the large surface area that facilitates exothermic oxygen attack. Rapid heating tends to produce this result, which makes smoldering (but not flaming) impossible. However, if the foam is heated slowly enough, competing, oxygen-dependent, degradation pathways come into play which yield a solid char and thereby sustain the extended surface area, enabling smoldering combustion. As it happens, the rate of heating provided by a dropped cigarette or by the smoldering of a cellulosic upholstery cover fabric can provide the conditions needed for a polyurethane foam to sustain smoldering. Given the fact that polyurethanes are an entire class of materials and not a uniquely defined polymer, it is not surprising that some formulations should be more smolder prone than others.

If polyurethane foams have varying smolder tendencies, this immediately raises the question, in the present context, of what foam to use, since it may affect the results. In particular, for the purposes of the SPSC study, which seeks to compare smoldering ignition tendency on two scales (bench-scale and full-scale mattress), it is vital to have at least some material formulations which have an intermediate tendency to smolder. In that way, some fraction of tests will yield smoldering on the two scales and those fractions can be compared.[20] The first goal of the SPSC study thus became one of measuring the smoldering tendency of potential resilient fill materials (to go into the quilt layer and the layer below the quilt).

This, in turn, raises the question of how to make a meaningful measure of this smoldering tendency. The test method must be simple, reproducible and not dependent on "standard" materials. This last requirement eliminates smoldering cotton upholstery fabrics as a possible heat source and leads us to an electric heater. The need to limit and control the rate of heating, so as to allow char formation, means that this heater must be powered through a programmable temperature controller. In a further refinement, since electric heaters are not very uniform in their surface temperature, we insert the heater (6.4 mm dia) into a brass jacket (19 mm OD) to help smooth out temperature variations. Figure A-1 shows a photo of the heater/jacket/holder assembly used here. Figure A-2 shows it inserted into the foam contained within the test box.

[20] If the fraction rises to 1.0 or falls to 0.0 for all materials used, the ability of the study results to meaningfully compare the two test scales is largely lost.

The material to be tested is contained within the CFR 1632 plywood box, (over) filling it to a depth of 15.2 cm. The jacket (9.4 cm long) is inserted vertically from above into a hole in the center of the test material. For foams (polyurethane or latex) the hole is made in the specimen with a #10 cork borer (17 1/2 mm dia) leaving a hole which is somewhat smaller than the 19 mm dia heater jacket, assuring a snug fit. For cotton batt, a more irregular hole is made with a screwdriver. The four splayed, flat "arms" that constitute the holder on top of the heater jacket assure that the heater will not sink downward should the test specimen tend to melt. The outer portions of the arms rest either on the top of the foam specimen or on the top edges of the plywood box. One arm has a holder for a thermocouple that inserts into the test specimen vertically at a distance of 31 mm from the central axis of the heater. It monitors the local temperature of the specimen at about the mid-depth of the heater assembly.

There are two possible ways in which to use this apparatus to monitor the response of a specimen. The heater can be programmed upward continually (at a constant rate) until the behavior of the sample is clear or it can be programmed upward to some pre-determined temperature which is then maintained steady until the response of the sample is clear. Both approaches were tried. The rate of heating for the first test mode (continual heating) was about 6 ºC/min; for the second mode it was about 14 ºC/min. Either rate is slower than the rate one can estimate as the result of a smoldering cigarette coal spreading over the top of a mattress quilt (in the neighborhood of 20 ºC/min). Thus charring of polyurethane foam is encouraged, if it can occur in the given formulation[21].

The first heating mode has the potential advantage of characterizing foam response in one test. In practice the evolution of smoldering in the foam is slow and out of sight below the sample surface so that one cannot reliably tell when it is beginning to develop. The temperature reading of the monitoring thermocouple rises steadily but exhibits no definitive changes in rate of rise to signal the onset of smoldering. The results from these tests were therefore mainly used to guide the temperature plateau levels to be examined with the second mode of heating. This second mode gives substantially more definitive results, but at the cost of repeated tests. The test lasts for a total of about one hour. At a given plateau temperature, it may become clear in viewing the top of the sample that there is a radially outward spreading smolder zone or, conversely, the monitoring thermocouple has peaked and is in decline with no indication in the top view of a spreading smolder zone. The most definitive indication of the test outcome, however, comes after the test is over and one cuts open the sample to see the diameter of the char zone in the sample (at about mid-depth)[22]. A non-smolder-sustaining heater temperature may result in a char zone diameter of about 5 cm; a smolder sustaining heater temperature can result in a char zone diameter three to four times this. This is thus a go-no-go test which was sensitive to a 10 ºC change in the plateau temperature of the heater.

[21] A second requirement for the formation of char from the polyurethane is the presence of oxygen in the heated zone [A-2]. Here the oxygen diffuses in from above (vertically and radially) through the open cells of the foam. If the porosity of the foam is sufficiently low, there will be insufficient oxygen for char formation and the foam will not smolder. This is true also for cigarette ignition though the two situations are not necessarily completely equivalent.

[22] Very resistant formulations may give nothing more than a hole in the foam due to a lack of char formation and a bias toward foam collapse to a liquid.

Such a test requires a large number of replicates for good statistical certainty on the minimum heater temperature required to assure self-sustained smoldering in a foam formulation. In practice, in surveying the series of material compositions of Table A-1, it was too time-consuming and unrealistic to do more than replicate tests above and below the minimum temperature, typically 10 ºC apart.[23]

The results of applying this test method to several polyurethane foams, as well as to a latex foam and to cotton batting, are shown in Table A-1.

Table A-1. Approximate Minimum Temperatures for Smoldering Combustion

Foam Designation	Minimum Smolder Temperature (ºC)
Polyurethane Foam "a"	≥ 360
" " "b"	315 to 320
" " "c"	330 to 340
" " "d"	ca. 330 (from scan test)
" " "e" (24.8 kg/m^3,1.55 lb/ft^3; 245 N, 55 lb IFD)	340 to 350
Polyurethane Foam "f" (23.2 kg/m^3, 1.45 lb/ft^3; 178 N, 40 lb IFD)	335 to 345
Polyurethane Foam "g" (24.0 kg/m^3, 1.50 lb/ft^3; 267 N, 60 lb IFD)	380 to 390
Polyurethane Foam "h" (24.0 kg/m^3,1.50 lb/ft^3; 147 N, 33 lb IFD)	330 to 340
Viscoelastic PU Foam 1 (46 kg/m^3, 2.87 lb/ft^3)	No Char
Viscoelastic PU Foam 2 (71.3 kg/m^3, 5.2 lb/ft^3 ; 44.5 N, 10 IFD)	No Char
Latex Foam (60 kg/m^3, 3.75 lb/ft^3; 53 N, 12 lb IFD)	260 to 270
Unretarded Cotton Batting	330 to 340

[23] Note that the differences in foam smolder tendency may make it desirable for mattress manufacturers (or their suppliers) to use a test like this to impose a smolder "resistance" requirement on foams they use in quilt layers or just below the quilt. The test need only confirm that the minimum smolder temperature is above some limit of acceptability and the number of tests is thereby reduced. That limit of acceptability will depend on the thermal resistance provided by the flaming barrier layer. In fact, the flaming barrier layer can become a smoldering barrier layer as well, if it is shown to always keep the temperature of the filler layers well below their minimum smolder ignition temperatures.

The first point that jumps out from Table A-1 is that the latex foam[24] was by far the material most readily ignited to smolder. Its minimum ignition temperature is about 50 ºC less than the next most ignitable material, polyurethane foam "b".[25] This latex material was not chosen for the remainder of the study because it posed a severe and persistent noxious fume problem (and it may be so smolder prone as to give 100 % ignitions).

Another point that emerges from Table A-1 is the wide degree of variability in the minimum smolder temperatures of various polyurethane foam formulations (these foams differed in both density and mechanical properties; air flow data were not available). The two viscoelastic foams produced no char (only melt) despite the slow heating rate and thus gave no smoldering. A retarded cotton batting gave no smoldering at the highest temperature tested (400 ºC). Note that the minimum ignition temperature of the worst foam ("b") was somewhat lower than that of unretarded cotton batting. Foam "b" is used extensively in the quilt compositions that are the focus of the SPSC study since it does provide an intermediate number of smoldering ignitions (see Table 1 of the main text).

It is important to note that the absolute value of the minimum smolder ignition temperature obtained in the above manner is context-dependent. Smoldering ignition, being typically the result of a weak heat generation process, is sensitive to the rate of heat loss from the heated zone and the absolute dimensions of that zone. The minimum smoldering ignition temperature of a fixed material can vary considerably with these factors [ca. 150 ºC in the case of cellulosic insulation material; see Ref. A-3]. One can speculate that, since ignition by a cigarette involves a much smaller heat source than that used in the above tests, the minimum ignition temperature that the cigarette must impose on the smolderable material is higher than the values in Table A-1. If so, the values in Table A-1 could serve as a guideline for how effective an insulator a mattress fire barrier layer must be in order to preclude smoldering ignition of the material below that layer. This would have to be checked experimentally since it assumes that the fire barrier layer is inert in these circumstances (not a source of heat itself); this may not be the case for all fire barrier materials.

[24] It should be noted that this material came only in 2.5 cm thick layers (stacked 6 deep in the testing) and had a pattern of 2 mm to 3 mm dia holes through the depth of the foam to provide enhanced compressibility.

[25] A second batch of foam "b", made about a year later, was found to be more smolder resistant. The reasons for the difference are under investigation but tests have shown that differences in air flow do not explain the difference in smolder tendency.

References for Appendix

A-1) Ohlemiller, T., "Smoldering Combustion," Chapter 2-9 of the SFPE Handbook of Fire Protection Engineering, Third Edition, published by the National Fire Protection Association, Quincy, Mass. (2002)

A-2) Rogers, F. and Ohlemiller, T., "Minimizing Smolder Tendency in Flexible Polyurethane Foams," *Journal of Consumer Product Flammability*,***5*** (1978) p. 59

A-3) Ohlemiller, T., "Cellulosic Insulation Material. III. Effects of Heat Flow Geometry on Smolder Initiation," *Combustion Science and Technology*, ***26*** (1981) pp. 89-105

Figure A-1. Smolder test device showing cylindrical jacket containing heater and arms that support the unit on top of the foam.

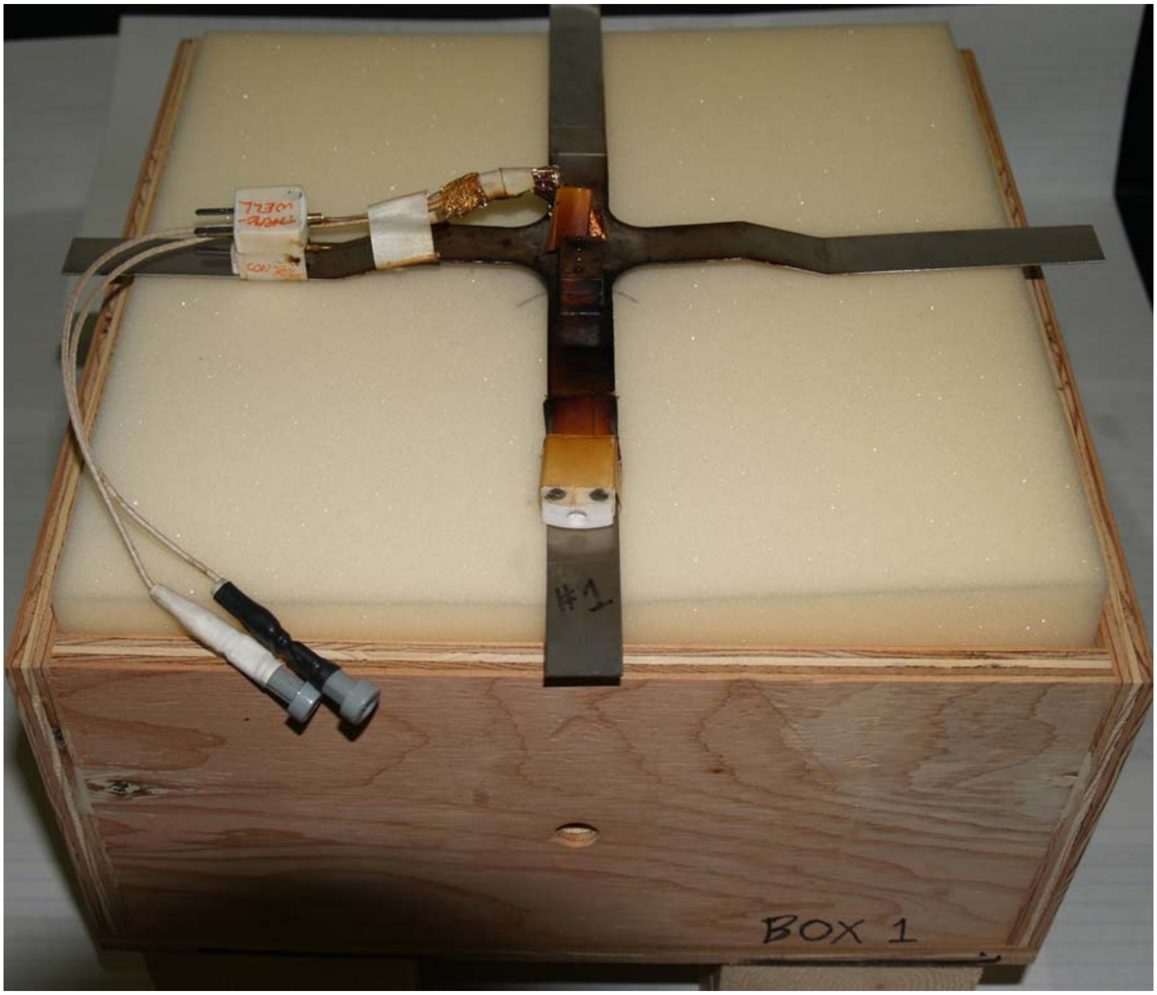

Figure A-2. Smolder test device inserted into foam.