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**Flammability Tests of Full-Scale
Mattresses: Gas Burners versus
Burning Bedclothes**

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Abstract

Six mattress and foundation designs were subjected to two modes of ignition: the NIST dual gas burner protocol and burning bedclothes. All of the designs represent substantial reductions in flammability compared to current residential designs but they nevertheless covered a wide range of performance, as measured by peak heat release rate and time to that peak. Variability of the fire behavior of some designs (in triplicate gas burner tests) made comparisons with the burning bedclothes results more difficult, however, a reasonable correlation was found between the two methods when worst case behavior was compared. Relatively late developing hazards of some otherwise well performing mattress designs would not be observed if the 1 h gas burner test duration were shortened, a degree-of-safety-improvement decision for regulatory authorities. Persistent crevice flames were a clear contributor to the failures seen in some of the tests (both with gas burners and bedclothes). Data are now available on crevice flame duration and heat flux so as to permit simulation of this exposure as part of the proposed CPSC bench-scale screening protocol.

INTRODUCTION

In previous work for the Sleep Products Safety Council, NIST examined the burning behavior of twelve different bedclothes combinations, characterized the heat flux patterns imposed on underlying surfaces from a sub-set of these and developed a pair of propane gas burners which emulated the worst case heat fluxes and durations [1]. The bedclothes flux pattern measurements pointed to differing thermal insults to the top of a mattress versus the sides of a mattress/foundation assembly. This was the result of the differing burning modes of bedclothes hanging over the side of a bed versus those laying on its top surface. Thus two gas burners were devised to mimic the two differing conditions of peak heat flux and duration; they are applied simultaneously to the top and side of a bed assembly.

The gas burners replace burning bedclothes as a tool in developing less flammable mattress designs and as a tool for regulating that flammability. They are not a perfect substitute but are inherently more reproducible than burning bedclothes. A comparison of the features of each is laid out in Table 1, discussed below.

The first point to note in Table 1 is that the burners produce a different type of exposure condition than that produced by burning bedclothes. They are applied to a single area of the bed assembly, subjecting it to the thermal conditions that the worst case bedclothes

from Ref. 1 could impose on this area.¹ The burners provide an indication as to whether the tested areas of the mattress/foundation, presumably representative of the entire assembly, can resist the burner attack without immediate penetration² of flames into the vulnerable cores of mattress or foundation. However, real bedclothes burn progressively over the entire exposed surface of a bed exposing that surface to a thermal insult which varies considerably from one area to the next, from worst case to less severe. Thus the two types of exposure (burner or burning bedclothes) differ insofar as the thermal insult that most of the area of the bed assembly sees. With the burners, the end of their flames may leave a much-diminished and slowly spreading fire that persists, for example, only in the crevice between the mattress and foundation. This leads to the second difference noted in Table 1. The post exposure burning on the mattress/foundation test specimen may take most of an hour to spread fully around the bed periphery. In contrast, the burning bedclothes expose the full bed area in a matter of ten minutes or so. Thus the probing for weaknesses occurs faster with the burning bedclothes and the burner provides an inherently slower test for many mattress designs.

The next three points in the bedclothes column of Table 1 indicate the most serious flaw of bedclothes as a heat source for mattress design development or regulation - they do not provide reproducible fire exposure conditions even in successive tests with nominally identical bedclothes. Also, there is no standard set of bedclothes obtainable on the market. In contrast, the gas burners have no problems in this area. If the standard protocol for burner usage is properly followed, the heat flux imposed and its duration will always be the same. It is worth noting, however, that localized gas burner exposure implicitly assumes that the area exposed is truly representative of the whole. If the materials or construction of the bed set have localized flaws, the gas burners may not find them whereas burning bedclothes more probably would.

Given the above comparisons, it was important to verify experimentally the degree to which the gas burners are a suitable substitute for burning bedclothes. This issue was examined in a limited way in an earlier study. In Ref. 1 results are reported for the testing of five mattress/foundation designs of widely differing flammability using both of these ignition sources. It was shown that the burner results correlated very well with the bedclothes test results for four of the five designs. The fifth design underwent an internal deflagration/over-pressurization that split its seams and led to a large fire in the presence of burning bedclothes. This behavior could not be produced with the gas burners with the result that only a small fire was seen. Thus at least one design exists for which the burners produce a prediction of real world behavior that is less hazardous than the actuality.

¹ Burning bedclothes impose more or less randomly placed "hot spots" on the surfaces beneath them that vary in intensity up to the levels chosen for the burners. In principle the worst case hot spot could occur anywhere on a surface. The burners must therefore impinge on areas that are representative of the entire accessible mattress/foundation surface. Note that "worst case" here was deduced from a limited set of bedclothes fires; the entire population of bedclothes currently in use across the country could well include sets capable of imposing more severe hot spots. The burners could potentially have been made to move progressively over the bed surface in imitation of a bedclothes fire; this was deemed too complex.

² Immediate here means during the burner exposure.

The goal of the present study is to expand the basis for the correlation between gas burner induced fire behavior and bedclothes induced behavior. Of particular interest again is comparability of the fire performance elicited by these differing ignition modes.

Six new designs, all of which constitute experimental attempts to greatly reduce the flammability of the bed assembly below that exhibited by current designs for the residential market, have been examined. In Ref. 2 it is shown that a design typical of the current market can produce a heat release rate peak in excess of 2 MW for a twin size bed. Ref. 2 also shows that only by reducing the heat release rate peak to well below 500 kW can one expect to eliminate a large fraction of the loss of life currently attributable to fires in which a bed is the first item ignited. It is highly probable that slowing the time to peak burning in a bed fire can also contribute substantially to decreasing the death toll from this fire source. However, as noted in Ref. 2, there is currently not enough information available to allow a quantitative estimate of the impact of slowing the time to peak heat release rate.

It is recognized that polyurethane foam, used extensively in current mattresses because of its inherent comfort qualities, is the most vulnerable element in a mattress with regard to flammability. Consequently the majority of these improved designs employ one or more fire barrier materials as protection for the foam and other flammable materials within a mattress and foundation. Other designs employ a more diffuse protection using polyurethane foam layered with flame-retarded cotton or other charring materials.

Each new design brings with it the possibility of new forms of fire behavior and the possibility that the inherent differences between burner exposure and burning bedclothes exposure, discussed above, will cause a divergence in the results. The study here sheds further light on this issue. However, there is the potential for future designs to show still different behavior that may or may not be replicated with gas burner testing.

The initially- proposed one hour duration of the gas burner tests has raised practical concerns with regard to the number of tests one can perform in a day. Thus another issue examined here is an appraisal of the using a shorter observation period subsequent to the gas burner exposure.

The Consumer Product Safety Commission is considering rule-making regarding residential mattress flammability. In the event of a regulation, the Commission would purchase specimens off the open market for testing. They have indicated a need for a bench-scale screening test protocol that could be performed on samples taken from a mattress or foundation to provide an indication of the flammability behavior to be expected from the full-scale mattress/foundation assembly. NIST is currently developing a protocol with this goal based on the gas burner exposure conditions. The data developed here serve also the purpose of being the full-scale results against which some of the bench-scale protocol results will be tested. The outcome of that comparison will be published separately.

There is an issue in the context of the bench-scale protocol for CPSC of whether to include an exposure that mimics the persisting crevice flames often seen in full-scale gas burner tests. In a previous study the heat flux levels that these flames impose were measured [3]. Here several measurements of the local duration (persistence time at a fixed location) of such flames were also made to help guide the conditions that could be used in bench-scale testing.

TEST MATERIALS

Table 2 summarizes the composition of the tested designs in generic terms. Any information missing was not available. The first two designs are essentially identical except for the nature of the charring barrier fabric under the ticking³. They incorporate much of the same components as current residential mattress/foundation designs but enclose those components within a fire barrier (whose seams are all closed with fire resistant thread). Design 3 is based on multiple layers of flame-retarded (FR) cotton interleaved with untreated polyurethane foam. FR cotton protects both the top and sides of the foundation. Design 4 incorporates an approach similar to Designs 1 and 2, i.e., a barrier layer just under the ticking that protects traditional, non-flame-retarded materials. In the mattress and foundation sides, the barrier layer is lighter in weight (1/3 lighter) than it is on the mattress upper/lower surfaces. Complete information was not available for Design 5. It is noteworthy for its use of a fiberfill layer outside the barrier. Such layers, when used with a complete bed assembly (i.e., including bedclothes), can be viewed as part of the bedclothes insofar as a fire is concerned. Design 6 uses both a charring fiberfill blend and FR cotton to protect a deeper layer of non-FR polyurethane foam. Here again the barrier on the mattress and foundation sides is less than on the mattress upper/lower surfaces. It consists of 25% less mass of the charring fiberfill blend and no cotton.

Bedclothes were used in one test with each mattress/foundation design; more test specimens for replicates were not available. Table 3 shows the component items and their weights. This set is intended to closely resemble Combination #4 used in Ref. 1, which was the basis for the gas burner heat flux and duration values. Compared to the bed set in Ref. 1, the mattress pad here is appreciably heavier (ca. 2X) but this is most likely due to the stretch side panels here; the top of the current pad was similar to that used in Ref. 1. The comforter weight here is more like that of the heavy weight comforter of Ref. 1 (which actually burned less intensely than the medium weight comforter in that study). As noted previously, bedclothes are not reproducible items and indications of this will be seen below. All of these items are current commercial products and contain no flame retardant features.

TEST PROCEDURES

The bulk of the tests utilized the commercial version of the pair of propane burners developed in Ref. 1 (the remainder used burning bedclothes). Thus triplicate tests of each

³ The two tickings also differed; that on Design 2 spread flames more persistently.

of the six mattress/foundation designs were performed with the burners as the ignition source. The 18 tests were performed in random order to minimize the effect on results for any given design from any systematic variations in environmental or other test conditions over the two week test period.

The test protocol was recently developed at NIST [4] and refined in conjunction with the current tests. It is also a draft response to California Assembly Bill AB 603 regarding the regulation of the flammability of residential mattresses. In brief, the protocol stipulates procedures for reproducibly setting up the pair of gas burners in a fixed relation to the top and side surfaces of a test specimen. (see Fig. 1). The test specimen consists of a mattress plus foundation⁴ sitting on top of a short (11.5 cm tall) bed stand which is, in turn, placed on top of a catch surface for any flaming melt/drip materials. The fixed burner separation distances and the specific propane flow values for each burner dictate the peak heat fluxes imposed on these surfaces. These heat fluxes and the duration of each burner exposure (70 s for the top burner; 50 s for the side burner) are the same as those inferred in Ref. 1. The burners are withdrawn from the proximity of the test specimen as soon as the longer flame exposure is over.

In accord with the burner protocol, the behavior of the test specimen was followed for one hour after the start of the ignition process. Recall the discussion above regarding the relative slowness of burner-induced flames to propagate around the mattress/foundation.

As noted above, one test was done on each mattress/foundation set using burning bedclothes as the ignition source. The bedclothes were arranged as in previous studies [1, 2, 3] with top sheet, blanket and comforter turned down evenly to form a doubled layer beginning immediately adjacent to the pillow. These bedclothes were ignited by a hand-held, match-size butane flame applied for 30 s at the bottom of the head end of the hanging, folded back covers.

All of the above tests were performed in the NIST Six Meter Hood Calorimeter facility. This facility is intended to measure the heat release rate of fires up to about 4 MW. The hood inlet is a 6 m (20 ft) square located 4.6 m (15 ft) above the floor. A fiberglass skirt draped downward from the hood lip effectively lowers its inlet to 3.05 m (10 ft) above the floor, assuring that the plume from relatively small fires is captured fully and properly measured.

Heat release rate is measured by oxygen consumption calorimetry (which requires full capture of the fire plume). This type of calorimetry has an inherent uncertainty of $\pm 5\%$ when applied to mixed organic materials like those here, due to this amount of variability in the heat evolved per unit mass of oxygen consumed. This system was calibrated before and after the present test series, using carefully measured flows of natural gas, with fires as large as 1.5 MW. The 95% confidence limits on the calibration data add only about $\pm 0.5\%$ to the $\pm 5\%$ inherent uncertainty. Zero drift correction uncertainties are typically less than $\pm 2\%$ for fires of a few hundred kW or greater but for fires below about 50 kW to 70 kW the zero drift uncertainties increase appreciably and are estimated to be $\pm 10\%$ to 15% . System noise, coupled with

⁴ The protocol also applies to cases in which no foundation is used.

inherent fire variability, limits the accuracy of reading sharp heat release rate peaks (as it does in any heat release rate system). Accuracy of reading a brief heat release rate peak is comparable to the level of system noise in the peak but a complete analysis of this is not yet available.

The mattress/foundation set was placed on top of an 11.5 cm high steel, twin-sized bed frame which, in turn, rested on a cement fiberboard (Durock⁵) surface that formed the bottom of a catch pan. The pan rested on a scale.⁶

The fires were terminated with a water spray if they were still burning after one hour. This facilitated a check on the heat release system baseline after the test and this, in turn, allowed correction for any baseline drift over the course of the test.

The NIST facility does not permit tight control of test bay humidity due to the large hood flow levels and the outside make-up air this entails. This is also the only available space large enough to permit conditioning of the mattresses and bedclothes subsequent to unpacking. The potential day-to-day variation in moisture content of the bed assemblies could conceivably affect fire performance⁷. To avoid any systematic distortion of the data by varying moisture contents (or other systematically varying unknowns), all of the tests were done in two randomized sequences, as noted above. The 18 gas burner tests comprised the first sequence; the 6 tests with bedclothes comprised the second sequence.

All tests were video-taped from two angles: from the ignited side and from the foot end. Verbal notes were made on the tapes regarding mechanistic physical phenomena affecting the fire growth process. An intense, hand-held white light was used to look for any holes in the blackened barrier layers on the mattresses and foundations.

RESULTS AND DISCUSSION

The observed behavior in the individual test modes (i.e., with the gas burners and with burning bedclothes) is examined first to give some insight into the behavior underlying the heat release rate results, then a comparison is made between the two types of test results. Finally, we discuss the issue of the appropriate duration for a gas burner test and comment on the duration of measured durations of crevice flames.

Gas Burner Tests. Table 4 summarizes the results of the 18 tests in which the fires were initiated with the gas burners. Inspection of this Table shows that the results varied widely over the six designs from rapid dying out of all burning soon after the burners

⁵ 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.

⁶ The use of a scale is to be omitted from future versions of the test protocol.

⁷ Only cotton and wood-based materials have an appreciable affinity for moisture. Moisture pick-up in cotton begins to be substantial only at humidity levels above about 70 % to 80 %. Wood picks up water only very slowly (over a period of weeks). During the two week test period, the humidity in the test bay varied from 5% to 20%; that in the conditioning area was comparable.

were removed to extensive smoldering fires to large flaming fires that developed late in the test period.

Consider the variation of the heat release rate results with mattress design. Three of the designs (1, 2 and 5) consistently looked good in this respect, yielding very low post-exposure heat release rates. Design 1 yielded rapid and total cessation of any form of burning after the burner exposure; the other two tended to keep going with limited flaming and/or smoldering. The source of the difference between Design 1 and Design 2 in this regard appeared to be largely a result of the differences in the ticking⁸. The ticking differed in color and texture between the two designs but no compositional data were available. The ticking on Design 2 tended to burn over the entire vertical height of the sides of the mattress and foundation, slowly and somewhat sporadically spreading around the periphery of the assembly.⁹ Persistent smoldering was initiated in every test in the Design 2 mattress top by the gas burner but it spread quite slowly. At the end of one hour the smolder zone was typically on the order of 30 cm in diameter and did not appear on the verge, at that point, of a transition to flaming.

With the belated exception noted for one test of Design 5 (due to a barrier defect described below), the burner exposures of the Designs 1, 2 and 5 did not yield any barrier penetrations that could be seen. With Design 5 one test (I assume this is one of the other two tests of Design 5) did appear to produce penetration of the foundation top, in the corners, inside the juncture of the continental edge and the mattress top pad where, apparently, the barrier did not extend¹⁰, though no significant flaming fire ensued. This test also showed extensive smoldering of the bottom of the mattress (detected only after the end of the test). The two observations may be related. Overall, however, it appeared that the barriers used in Designs 1, 2 and 5 were capable of preventing flaming (both that from the gas burners and that from persisting crevice flames) from reaching the flammable materials inside them. They were less successful in precluding smoldering combustion but the hazard it appeared to present in this one hour time frame was substantially less¹¹.

⁸ Alternatively, Design 1 could have had a flame-suppressing, volatile flame retardant in the barrier immediately below the ticking. No information on this possibility is available. If the ticking was the source of the difference in flame persistence, it is possible that a different ticking, with more persistent flames, could reveal more vulnerabilities in Design 1 (the bedclothes test, described below, is a more extreme version of this).

⁹ There were no crevice flames since the crevice was virtually closed by the meeting of the mattress tape edge with the top edge of the foundation on this exceptionally flat-surfaced design.

¹⁰ A continental edge design on a foundation provides an opportunity to extend the foundation sidewall barrier onto the foundation top, into the crevice area where it can protect against crevice flames. However, the crevice depth is dependent on the curvature of the mattress top/bottom surfaces and the crevice is deepest in the corners. Furthermore, some of the continental foundation designs used here had uneven extents of foldover onto the foundation top; the crevice on one side of the mattress might be protected but on the other side it would be vulnerable.

¹¹ Smoldering presents hazards due to both toxic gas production and to the threat of a transition to flaming. In Ref. 6, it is shown that the toxic gas threat tends to take one to three hours to develop. All current (and future) mattresses must resist smoldering initiation due to contact with a burning cigarette.

Design 4 also behaved consistently; in all three tests it yielded a fire in the foundation that went on to force flaming of the mattress as well, yielding the large HRR peaks noted in Table 4. The positive aspect is that this fire required a considerable time to reach this peak (though see below). Here again there was no indication of barrier or seam penetration by the burner flames. Crevice flames, persisting longest in the corners¹², were the ultimate source of the large fires. The absolute value of the time delay is not correctly measured in this test since, as noted above, fire development in the gas burner test is inherently slower than with burning bedclothes; we return to this issue below. The fact that eventually such a large fire can and will develop if not actively suppressed remains a significant deficit of this design.

Judging from the heat release rate data in Table 4, Designs 3 and 6 looked potentially as good as the Designs 1, 2 and 5 in two out of three of the burner tests. However, a third test of both of these designs gave a substantial, though late-developing fire.

A more detailed look at the behavior of Design 3 in the three tests is useful. For the test that gave the 455 kW peak, no problems (i.e., no holes in any barrier surface) were indicated during and immediately after the double burner exposure. By 20 min into the test persisting flames in the crevice between mattress and foundation began to open holes in the barrier materials exposed there until, at 30 min, an abrupt propagating flame occurred in the mattress (creating an excess interior pressure)¹³, probably due to ignition of pyrolysis gases inside of it by flames near one of the barrier holes. The fire grew from there, in both the mattress and foundation, to reach its peak, nearly one hour after the burner exposure began. A second test of this design was similar in that persistent crevice flames led to deterioration of the state of the barrier layers in this area. This time there was again an over-pressurizing flame propagation wave followed by repeated outbreaks of flaming in the foundation but not in the mattress. Ultimately, however, all of these flare-ups died back rather than growing. In the third test crevice flames failed to become established in the crevice¹⁴ and other flaming on the ticking eventually all died out. This variable behavior, generally happening well after the end of the burner exposure, suggests a design that is potentially very good (third test) but is somewhat close to the borderline and is vulnerable once crevice flames become established¹⁵. The variability in behavior may have been due to a variation in the flame retardant level in the outer barrier layer (cotton).

¹² The “local crevice flame duration” reported in Table 3 is that for crevice areas away from the corners of the mattress/foundation. There was a definite tendency for crevice flames to persist longer than these times in the corners for several designs.

¹³ This was similar to the “explosions” discussed in the Introduction but the prior existence of holes in the barrier precluded a sufficient pressure to split any seams.

¹⁴ Crevice flames were not an immediate consequence of the burner exposure in any of the tests with Design 3. Instead, when they occurred, they originated 4 min to 5 min later when flames from the ticking settled into the crevice area.

¹⁵ Precise measurements were not made during a test but the video tapes indicate that this design had crevice flames that could persist in a given location more than 15 min.

Design 6, which also produced one moderate-sized fire in three tests, also was prone to persistent crevice flames, especially in the corner areas. These flames tended to penetrate the mattress and foundation protective layers in the crevices though it is not clear that total penetration into the interior space of either mattress or foundation occurred¹⁶. The flames did tend to establish growing smolder zones in both of these components. In one case the flames may well have penetrated the foundation top barrier layer since it was the foundation which ignited on the interior and produced a spreading fire beneath the mattress, ultimately yielding the 490 kW HRR peak¹⁷. In one of the other tests the smoldering in the mattress was so extensive and intense that it transitioned spontaneously into flaming on the top of the mattress just after the end of the test (just before suppressive action was taken). While smoldering was frequently seen in the post burner exposure period for many of the designs, transition to flaming was rare, presumably because largely intact barriers inhibited the air supply that such a transition requires. With Design 6 there was an enhancement in air supply in the corner area that went into flaming. This was the only design to incorporate “handles” on the sides of the mattress (two per side). These consisted simply of reinforced strips of ticking sewn to the top and bottom tape edges of the mattress. For reasons that are not clear, every example of this design had a vertical seam behind two of these handles (both on the same end of the mattress). This seam was not closed with fire-resistant thread; when the “handle” was ignited by spreading crevice flames and burned up, the seam behind it opened over its full height. No permanent flame penetration resulted during the burner tests but the open holes enhanced the air supply in the mattress interior.

Smoldering is a form of self-sustained burning which both emits high concentrations of carbon monoxide and poses the threat of a spontaneous transition into flaming [5]. Since the conditions for this transition have not been quantified for the bed fire situation, it was decided that the gas burner test protocol should count it as a potentially threatening form of burning. Tests in which smoldering alone was persisting were not halted before the one hour time limit.

While the burner test protocol has yet to be assessed with regard to repeatability or reproducibility, the lateness of the two moderate-sized fires seen with both Design 3 and Design 6 plus their initiation well away from the burner exposure areas suggest that the variations in behavior are a result of test specimen variability, not burner exposure variability. They may also be indicative of designs that are too close to the edge of being

¹⁶ Note that this design had a charring fiberpad, not polyurethane foam, as the layer in contact with the mattress springs; this would be expected to make penetration to this point in the mattress interior less likely to yield a rapidly growing fire since the interior volume is thus lined with a charring material. On the other hand, this same type of pad was used on top of the foundation and this foundation did get heavily involved in flames in one test.

¹⁷ The barrier on the side of the foundation opened first in the area of burner impingement in all three Design 6 tests and continued to open further as time went on but the opening process trailed any flame fronts and was evidently not responsible for the flames in the foundation which consumed the sample in one test.

able to endure the overall effects of exposure to the burners (see bedclothes results below).

Design 5 also showed some variability though the consequences were less serious. In this case one test specimen had a local defect in its barrier in an area on top of the mattress that was more than 30 cm away from the gas burner exposure. Small flames (2 cm to 4 cm tall) spreading on the top surface after the burner was removed caused this defective region to open up and allow flames into the mattress interior. The hole grew slowly (ca. 15 cm by 70 cm by the end of the test) but it yielded only a very limited heat release rate. Were more than one such hole to appear in a barrier, the results could be a more severe fire since it could facilitate fire growth in the mattress interior. This design also showed a variable tendency to smolder subsequent to burner exposure but no transition to flaming occurred.

The variability in the peak heat release rate results with two of the designs complicates the effort to compare them with the results from the burning bedclothes tests. As will be seen below, the best way to make the comparison appears to be with the worst case behavior seen above.

The variability in the preceding results also complicates assessment of a design, pointing to a need for assurance of consistent materials and construction. It also suggests that one should not just look at the peak heat release rate in evaluating a design but also at the overall behavior that hints at weaknesses. Continuing crevice flames are a fairly consistent source of trouble. Openings in barriers, whether they occur immediately upon burner exposure or later, are signs of marginal performance. Smoldering may be a sign of trouble but this depends on its intensity (as judged by the area involved, its rate of growth, and the rate of smoke evolution). Any smoldering transition to flaming, even if temporary, is a sign of potential trouble. Even small flames that show up unexpectedly in semi-hidden locations such as on the foundation dust cover fabric, are also signs that a fire may be growing unseen. Unfortunately, none of these signs is a guarantee of subsequent behavior, only a hint that the design may be marginal. Since material and/or construction variability appears to be an issue in some cases, any indication of marginal behavior in a test with a given design is also an indication that another test sample of that same design might go over the edge and give a substantial fire. .

Tests with Burning Bedclothes. Table 5 shows the peaks of heat release rate and the times to those peaks for the same six mattress designs subjected to burning bedclothes. Now, however, there can be multiple peaks and these are all indicated in the Table, along with the items each peak chiefly involved (bedclothes or mattress/foundation). Unlike the case of an unimproved mattress/foundation design where the growing bedclothes fire turns rapidly into a composite fire of bedclothes plus mattress and foundation [1, 2], here there was a definite tendency for the bedclothes fire to dominate first, followed (if at all) by a mattress/foundation fire appreciably later. Figure 3 shows an example of the heat release rate behavior, in this case, for Design 6. Note that the peaks from the bedclothes are comparable to those from the mattress/foundation burning (and they occur much sooner).

In five of the six tests there were two bedclothes peaks that were distinct but overlapping. The first peak occurred at about the time that the spreading flames on the bedclothes reached the foot end corner on the ignited side of the bed. Flames then continued to spread both on the hanging covers and on those laying on top of the bed. These flame fronts would finally converge on the side opposite that where the ignition source had been applied. The second peak was due to a phenomenon not previously seen: the remaining bedclothes on the “far” side of the bed tended to fall to the catch pan surface, forming a loose pile that burned rapidly and intensely to produce the second heat release rate peak as a sharp, high shoulder on the main bedclothes peak. These flames were short-lived but sometimes quite intense. For example, they breached the barrier on the side of the foundation of Design 1. This was the only time this author has seen this type of barrier being breached and it suggests that at his stage, at least, this set of bedclothes was capable of producing a more intense thermal insult than any seen in Ref. 1 (on which the burner design was based). The exposure of the mattress/foundation caused by this phenomenon was dependent on where the pile of burning bedclothes fell and how they were distributed. This is one more example of the variability of bedclothes as an ignition source but also it is an example of the fact that they can present a more intense exposure than the gas burners.

As Table 5 shows, the first bedclothes peak was quite variable in height, from 160 kW to 360 kW. Part of this was due to varying contributions from the outer layers of the mattress/foundation as the bedclothes flame spread over these surfaces. However, Design 5, the only design that had a sacrificial layer of fiberfill on the mattress, outside of a barrier layer, did not yield a particularly high initial bedclothes peak.

Two of the six designs (Designs 1 and 5) yielded minimal burning in the mattress/foundation subsequent to the burning bedclothes peaks. Design 1 exhibited a weak smoldering process in one corner of the mattress and foundation that persisted for one hour but did not appear to threaten a transition to flaming. Design 5 had a failure of the vertical seam on the mattress side that allowed flames into the mattress interior but only in the immediate neighborhood of the open seam. This also caused some extensive smoldering in the mattress that was found only after the test was over.

The other four designs did yield significant heat release rate peaks from the mattress/foundation.

Comparison of Burner and Bedclothes Results. It is of interest to compare the mattress/foundation peaks (not the bedclothes peaks) from all of the designs with those seen with the gas burners as the ignition source. Figure 4 shows this comparison in a particular way: only the worst peak seen with the gas burners is used. This appears to be the best way to deal with the non-reproducibility of the gas burner results for Designs 3 and 6. In effect we look for a correlation between the worst behavior seen with the gas burners and the behavior seen with burning bedclothes. The fact that the bedclothes fire exposure tended to be worse than that with the burners means that it was eliciting worst case behavior and thus we compare that with the worst case behavior from the burners. There does indeed appear to be a correlation between the two but it is not as simple as

that seen in Ref. 1 with the designs tested for the Sleep Products Safety Council. Here, as in Ref. 1, there is a clear tendency for a larger fire with the gas burners to mean also a larger fire with burning bedclothes.

Figure 4 shows that the good behavior of Designs 1 and 5, seen with the gas burners, is carried over to the test with the burning bedclothes. The poor behavior of Design 4 is also seen both with the gas burners and with the bedclothes. The intermediate behavior of Designs 3 and 6 seen with the bedclothes is reflected in the worst case results for these designs with the gas burners.

However, Design 2 yielded distinctly worse behavior with the bedclothes than with the burners in that it did yield some burning subsequent to the bedclothes exposure but not subsequent to the gas burner exposure.

The burning bedclothes exposure of Design 2 did not appear to be exceptional in intensity or duration and yet it caused two “fractures” in the barrier on the side of the mattress and these ultimately led to the moderate mattress/foundation fire reported in Table 5. These are termed fractures because they appeared as narrow openings from the lower mattress tape edge to the top tape edge. This is not how a barrier burn through normally looks. The appearance suggests that the barrier failed in tension or shear as a result of shrinkage as it charred. This failure mode was not seen with the gas burners, perhaps because they shrank a lesser area of the mattress side than do the bedclothes flames. This is another example of a potential failure mode that is not necessarily picked up by gas burner exposure (recall the over-pressurization phenomenon mentioned above). The good news here is that this design is good enough that, in spite of the eventual development of a full foundation fire under the mattress, it yielded a peak less than 250 kW. Thus this is an example of an overly optimistic gas burner result that would, nevertheless, not be expected to lead to a severe fire in the real world.

Another feature of Fig. 4 is somewhat surprising: for Designs 3, 4 and 6 the peak heat release rate obtained with the gas burners was appreciably higher than that obtained subsequent to the burning bedclothes. In Ref. 1 the correlation was closer to 1:1. Actually, for Designs 3 and 6 the results are not that far from 1:1 and given the amount of scatter in this type of fire behavior (see Ref. 1, Fig. 5-2) more data might indicate a nearly 1:1 correlation. For Design 4, however, Fig. 4 shows that the two different ignition modes yielded results differing in peak heat release rate by a factor of two with the gas burner result being higher. Inspection of the videos shows that the two ignition modes did initially produce similar fire behaviors but the bedclothes initiated fire soon developed a complex, drawn-out history that had consumed much of the fuel before it reached its peak (thus reducing its value). Experience shows such complex histories are rarely reproducible so it is unclear whether the factor of two difference would hold up in repeated tests.¹⁸

¹⁸ Also note that the average of the three peaks for Design 4 with the gas burners was closer to 1 MW rather than the worst case value of 1.2 MW used in Fig. 3.

Overall the gas burner correlates reasonably well with the burning bedclothes results and there are no indications in the present study of a non-conservative gas burner result that could produce a severe real world fire. From the above discussion, it is apparent that burning bedclothes may reveal non-fatal weaknesses in a design that are not necessarily picked up in the gas burner tests. This suggests that tests with a bedclothes set like that used here may, in spite of their poor reproducibility, reveal useful information about real world behavior of a design developed with the aid of the gas burners.

Gas Burner Test Duration. There is a practical interest in shortening the burner test time from one hour to something less in order to facilitate a more rapid rate of testing. The feasibility of this depends on two issues:

- The time required for the gas burner exposure to reveal any flaws in the fire behavior of a test specimen.
- The correspondence between this time and the time for such a flaw to appear with burning bedclothes.

With regard to the first point, it was noted above that the burner exposure, being localized, inherently takes a long time for its consequences to play out, unless the only consequence is a rapid die-out of any locally-induced flaming and/or smoldering. More typically the consequences are slowly propagating flame fronts that move laterally outward from the exposed area on the mattress top, on the mattress/foundation sides and in the crevice between mattress and foundation. Since the last of these is the most adiabatic, it tends to be the most persistent. These consequences are not different from those induced by burning bedclothes, they are simply more slowly provoked at locations other than that impinged by the burners. Thus one must wait for the slow flame propagation, typically in the crevice, to proceed around the full periphery of the bed. This requires a time on the order of one hour. It might be possible to shorten the test duration by short-cutting this extended propagation process which is, after all, a result of ignition in one location only. Thus the test time might be cut sharply by applying the burners to two successive locations, on opposite sides of the bed. There are practical considerations that would have to be worked out for a double exposure and, furthermore, one would need to show that such an approach also correlates with burning bedclothes. (This approach would not be practical in a room enclosure.)

Comparison of the time to the mattress/foundation peaks for the gas burners versus the burning bedclothes shows that the bedclothes yielded their peak anywhere from 15 min to 30 min sooner. (This comparison can only be made for Designs 3, 4 and 6.) This is a clear indication that one cannot assume that the measured delay in peak heat release rate with a gas burner will carry directly over to the real world where burning bedclothes are the real threat in most bed fires.

Another possible approach to justifying a shorter test duration would be a demonstration that the ultimate result seen after a one hour test duration was clearly presaged by behavior exhibited appreciably earlier in the test. For the design that appeared least

flammable in these gas burner tests, Design #1, this was certainly true; all signs of burning or smoldering were gone in a time of the order of 10 min in all three tests. For Design #4, which consistently gave a large fire in all three tests, essentially nothing noteworthy happened in any of the three tests for the first 30 min other than a persistent (and unexceptional) crevice flame propagating around the mattress/foundation periphery. Starting at about 30 min there were small hints of vulnerability at the corners of the foundation, as small areas of flame propagation began there but typically died back again. Only quite late in the test did a major foundation fire get going with the typical consequences shown in Fig. 2: a rapid flare-up to a large fire that consumed both foundation and mattress.

If these two designs (Designs 1 and 4) were judged by their peak heat release rate relative to some pass/fail criterion (e.g., 150 kW) at some intermediate time up to 45 min or even more, they would both pass. If the test were ended at 45 min, one would conclude that Design 4 is quite benign. While this design does succeed in greatly delaying the occurrence of a large fire¹⁹ and thus does hold promise of probable life savings in some circumstances, it does not preclude a fire that could pose a very serious life threat in other circumstances. This is information that the test should reveal. Thus it does not appear that the test can be easily shortened on the basis of early precursor events that signal eventual failure. The early behavior for the other mattress/foundation designs also does not support the idea of a shorter test time since, as discussed above, the tests resulting in large fires with Designs 3 and 6 involved only ambiguous earlier behaviors.

Crevice Flame Duration. It was noted in the Introduction that the CPSC bench-scale screening protocol for mattresses needs an exposure that emulates that seen in the crevice flames mentioned frequently above. The heat flux that these small flames impose was sampled repeatedly in the study reported in Ref. 3; the mean value reported there was $(38 \pm 6) \text{ kW/m}^2$. Table 4 lists the crevice flame durations measured in this study. The average is $(9.0 \pm 2.3) \text{ min}$. Since corner crevice flames were noted to last longer than these values obtained away from any corner, a value 10 min or somewhat longer would be appropriate for use in a screening test for this mode of mattress design vulnerability.

SUMMARY

The six mattress designs examined here varied widely in performance in tests with the NIST gas burner protocol. Design 1 yielded rapid and complete cessation of burning after the gas burner exposure while Design 4 consistently gave large fires in the neighborhood of 1 MW. Even Design 4 represents a very substantial improvement in fire behavior over current residential designs with about a factor of two reduction in peak heat release rate and a large delay in that peak compared to current residential units. Most designs (4 of 6) yielded moderate heat release rate peaks in at least one test with the burners. In no case was there an immediate penetration of flames into the mattress interior due to the burner exposure. Instead many, if not most, of the subsequent fire development appeared to follow from the persistence of flames in the crevice between the

¹⁹ Though the real world delay is 30 min, as shown in Table 5, not the nearly 60 min seen in Table 4.

mattress and foundation. The failures were subtle in their inception and thus did not offer definite clues early in a test that a significant fire was going to develop (though they could be taken as clues that a design might need strengthening). Design 4, in particular, which consistently gave large, late fires, did not offer any real clues of this in the first 30 to 40 min of the test.

Comparison of the gas burner induced test results with those resulting from burning bedclothes was made more difficult by the variability of some of the burner results. When the worst case burner results were plotted against the bedclothes-induced peak heat release rate (from the mattress/foundation portion of the fire), a reasonable correlation was obtained. Even in the one case where the bedclothes produced a worse fire than the burners, that fire was moderate in size.

All of the gas burner tests that produced appreciable heat release rate peaks did so only after an extended time, sometimes approaching one hour. The burning bedclothes produced such peaks 15 min to 30 min sooner.

CONCLUSIONS

- The gas burner results provide a reasonable prediction of the behavior to be expected with burning bedclothes. The correlation for heat release rate peak is not perfect but it is adequate to assure that good performance with the gas burners will most likely (10 of 11 designs tested here and in Ref. 1) yield significantly improved behavior in the real world where burning bedclothes are the ignition source. The time to the heat release rate peak with the burners tends to be 15 min to 30 min slower than with burning bedclothes.
- It is necessary to be continually cautious in the testing of new mattress designs because new modes of behavior may emerge which might strain the relation between gas burner results and real world bed fires. Despite their poor reproducibility, burning bedclothes (i.e., a close analog to the set used here) may still prove useful as a final check for subtle weaknesses in a design developed with the aid of the gas burners.
- Shortening the 1 h gas burner test duration would miss significant, late developing hazards of some otherwise well performing mattress designs. It is the role of the regulator to determine the desired degree of safety improvement over current designs. A variation of the protocol, e.g., one involving successive burner exposures on two sides of the test sample, might permit a shorter total test period but this would require experimental verification.
- The behavior of some of the mattress/foundation designs was quite variable in the replicate tests with the gas burners. Since these variations showed up well after the burner exposure and involved differing modes of behavior, it is likely that they were due to variations in materials and/or construction of the samples. This

poses a challenge both to the manufacturers and to the Consumer Product Safety Commission (CPSC) with regard to assurance of product behavior in the real world.

- There is a need in the CPSC bench-scale screening protocol for an exposure condition which mimics the crevice flames so often seen in the full-scale mattress tests. Data are now available to indicate an appropriate flux level and duration for such an exposure condition.
- The results here reinforce a point made in Ref. 3. As mattress designs are improved, a bed fire tends to fall into two rather well-separated peaks, the first dominated by the bedclothes and the second dominated by the mattress/foundation. Good mattress designs bring the latter peak down to the point where the second peak is comparable to or less than that due to the bedclothes (and appreciably later). Further progress then implies a need to also bring down the heat release rate peak due to the bedclothes.

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Table 1. Features of Burning Bedclothes and Gas Burners as Ignition Sources

Burning Bedclothes	NIST Dual Gas Burners
Progressive burning (spread flames over bed surface)	Localized exposure to one area
Rapid exposure of all vulnerable surfaces	Slow spread to surfaces beyond that exposed
Highly variable heat flux to all bed surface locations	Worst case heat flux to <u>representative</u> locations only
Variable burning and heat flux from identical sets in successive tests	Reproducible heat flux exposure in successive tests
No provision for obtaining identical bedclothes sets over extended time periods	Uses a simple, reproducible fuel (high grade propane)
Real world exposure condition for mattress/foundation	Simplified exposure condition can miss or underestimate some failure modes

Table 2. Nominal Composition of Mattress/Foundation Designs²⁰

	Design 1	Design 2	Design 3	Design 4	Design 5	Design 6
Mattress Ticking	Class B damask 1	Class B damask 2	Class B	Class B PE/Cotton	65 % Cotton/35 % PE	PE, PP, cotton blend
Quilt Layer	<i>Charring barrier fabric A</i> over 19 mm (0.75 in) PU foam	<i>Charring barrier fabric B</i> over 19 mm (0.75 in) PU foam	<i>FR cotton</i> over 13 mm (0.5 in) PU foam	<i>Charring barrier fabric D</i> over 25 mm (1 in) soft PU foam	Fiberfill over <i>composite barrier layer</i> over 6 mm (0.25 in) PU foam	<i>Charring fiberfill blend</i> over 9.5 mm (0.38 in) PU foam
Layers on Springs	25 mm (1 in) PU foam over PP net	25 mm (1 in) PU foam over PP net	<i>FR cotton</i> over 25 mm (1 in) PU foam over needled <i>FR cotton</i> (6 mm)	19 mm (0.75 in) PU foam in two layers over shoddy pad	Two 25 mm layers of undescribed materials	<i>FR cotton</i> over 13 mm (0.5 in) PU foam over <i>blended fiber pad</i>
Mattress Border	Same as quilt layer but without PU foam	Same as quilt layer but without PU foam	Quilted <i>FR cotton</i>	Lighter weight <i>charring barrier fabric D</i> inside ticking	<i>Composite barrier layer</i> inside ticking; 6 mm PU foam behind barrier	Lighter weight <i>charring fiberfill blend</i> under ticking
Foundation Top	Std non-skid fabric over <i>charring barrier fabric C</i>	Std non-skid fabric over <i>charring barrier fabric C</i>	Cover fabric over two 6 mm layers of <i>FR cotton</i>	Cover fabric over “std 2 oz insulator” pad	<i>Composite barrier layer</i> under cover fabric	Cover fabric over <i>FR cotton</i> over <i>blended fiber pad</i>
Foundation Border	Same as mattress border; ca. 95 mm wide Cont'l	Same as mattress border; ca. 95 mm wide Cont'l	Same as mattress border; ca. 70 mm wide Cont'l	Same as mattress border; ca. 90 mm wide Cont'l	<i>Composite barrier layer</i> under ticking; ca. 65 mm Cont'l	Same as mattress border (but barrier is apparently lighter)
Seams	<i>All fire resistant thread</i>	<i>All fire resistant thread</i>	<i>All fire resistant thread</i>	<i>All fire resistant thread</i>	<i>All fire resistant thread</i>	<i>All fire resistant thread</i> (see text)

²⁰ Abbreviations: PU = polyurethane; PP = polypropylene; PE = polyester; FR = fire-retarded; Cont'l = continental border. All fire resistant features indicated in italics.

Table 3. Bedclothes Components²¹

Component & Composition	Weight (kg) ± Std. Dev.
Mattress pad (100 % cotton top shell; PE fiberfill; stretch side panels)	0.75 ± 0.025
Fitted sheet plus flat sheet (50/50 PE/cotton)	0.90 ± 0.005
Blanket (100 % acrylic)	1.05 ± 0.044
Comforter (50 % PE /50 %/cotton shell; PE fiberfill)	1.55 ± 0.078
Pillow (100 % cotton shell; PE fiberfill)	0.78 ± 0.024
Pillow case (50 % PE/50 % cotton)	0.11 ± 0.010

²¹ Abbreviation: PE = polyester

Table 4. Summary of Results from Gas Burner Tests of Mattresses^{22,23}

Mattress Design	Peak Heat Release Rate (kW)	Time to Peak HRR (s)	Comment
1	0	0	No barrier penetration; ticking flames died out in a few minutes
1	0	0	“
1	0	0	“
2	≤ 20	Not measurable	Ticking fire persisted on matt/fdn sides; smoldering on matt top
2	ca. 35		“
2	≤ 20	Not measurable	Ticking flames slowly died out; smoldering persisted
3	455	3525	Matt side opened after burner out; fire in matt ignited fdn to yield peak HRR
3	≤ 20	Not measurable	Ticking flames slowly died out; smoldering also died out
3	≤ 20	Not measurable	Fdn corners went from smoldering to flaming then back to smoldering
4	1245	3250	Fdn fire slowly grew then flared up to consume matt at HRR peak; local crevice flame duration = 10-12 min
4	995	3310	Behavior similar to above test; local crevice flame duration 12-14 min
4	870	3545	Flaming flare-ups in 3 fdn corners; fdn fire forced matt fire at HRR peak
5	ca. 50	900	Limited hole in matt top (not near burner) allowed localized burning followed by extensive smoldering in mattress
5	≤ 20	Not measurable	Extended crevice and top flames; meas'd local crevice flame duration = 7 min
5	≤ 20	“	Extended crevice flames yielded extensive smolder of matt bottom & fdn top; local crevice flame duration = 8 min
6	≤ 20	Not measurable	Crevice flames yielded holes in matt and fdn barriers and smoldering of matt (See text re “handle holes”)
6	490	2780	Slow fire initiated in fdn; involved matt at peak HRR; local crevice flame duration = 6 –7 min
6	≤ 20	Not measurable	Minimal flames but extensive matt smolder (transitioned to flaming at 62 min); local crevice flame duration = 8 min

²² A HRR value of zero means the fire quickly died out after burner exposure. A HRR value of ≤ 20 means a fire continued but the HRR was too small for the calorimeter to measure accurately.

²³ Abbreviations: matt = mattress; fdn = foundation; HRR = heat release rate

Table 5. Heat Release Rate Peaks with Burning Bedclothes²⁴

Mattress Design	Bedclothes HRR Peak (kW)	Time to Bedclothes HRR Peak (s)	Matt/Fdn HRR Peak (kW)	Time to Matt/Fdn HRR Peak (s)	Comment
1	160 / 230	310 / 530	None	-	Limited smoldering for 1 hour
2	245 / 265	240 / 485	225	2330	Fire spread from matt to fdn
3	210	320	370	1670	Fire spread from matt to fdn
4	360 / 325	290 / 455	595	1770	Fire spread from fdn to matt
5	230 / 365	290 / 500	ca. 20	1430	Open vertical seam on matt; smoldering in matt
6	285 / 350	270 / 485	330	1920	Fire spread from matt to fdn

²⁴ Abbreviations used: HRR = heat release rate; Matt = mattress; Fdn = foundation

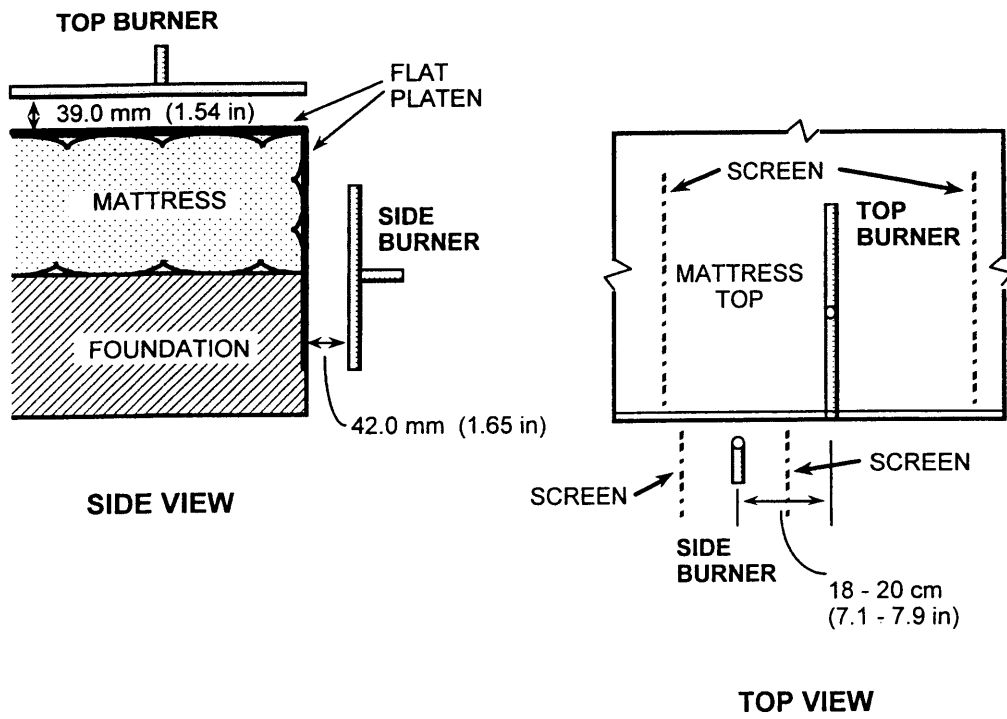
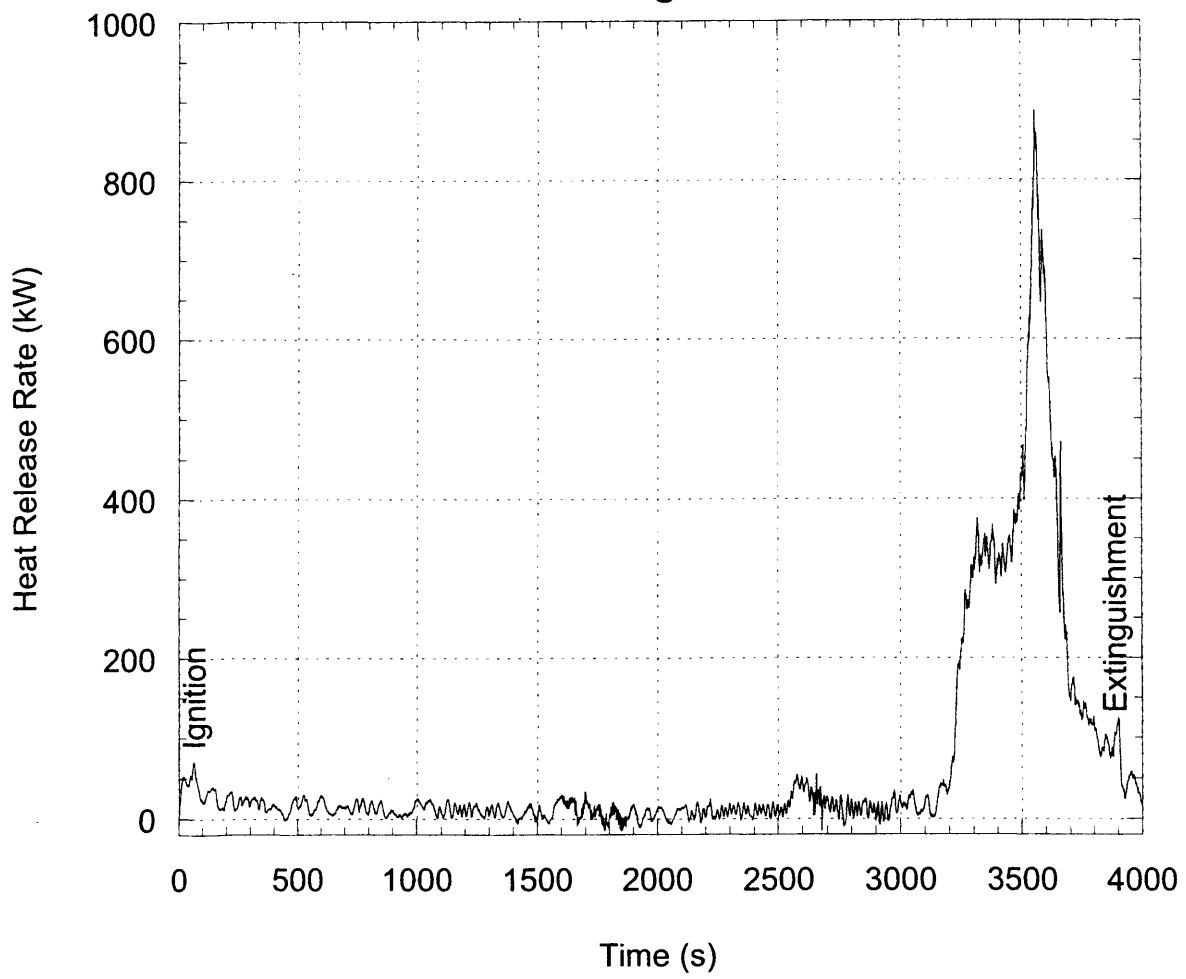
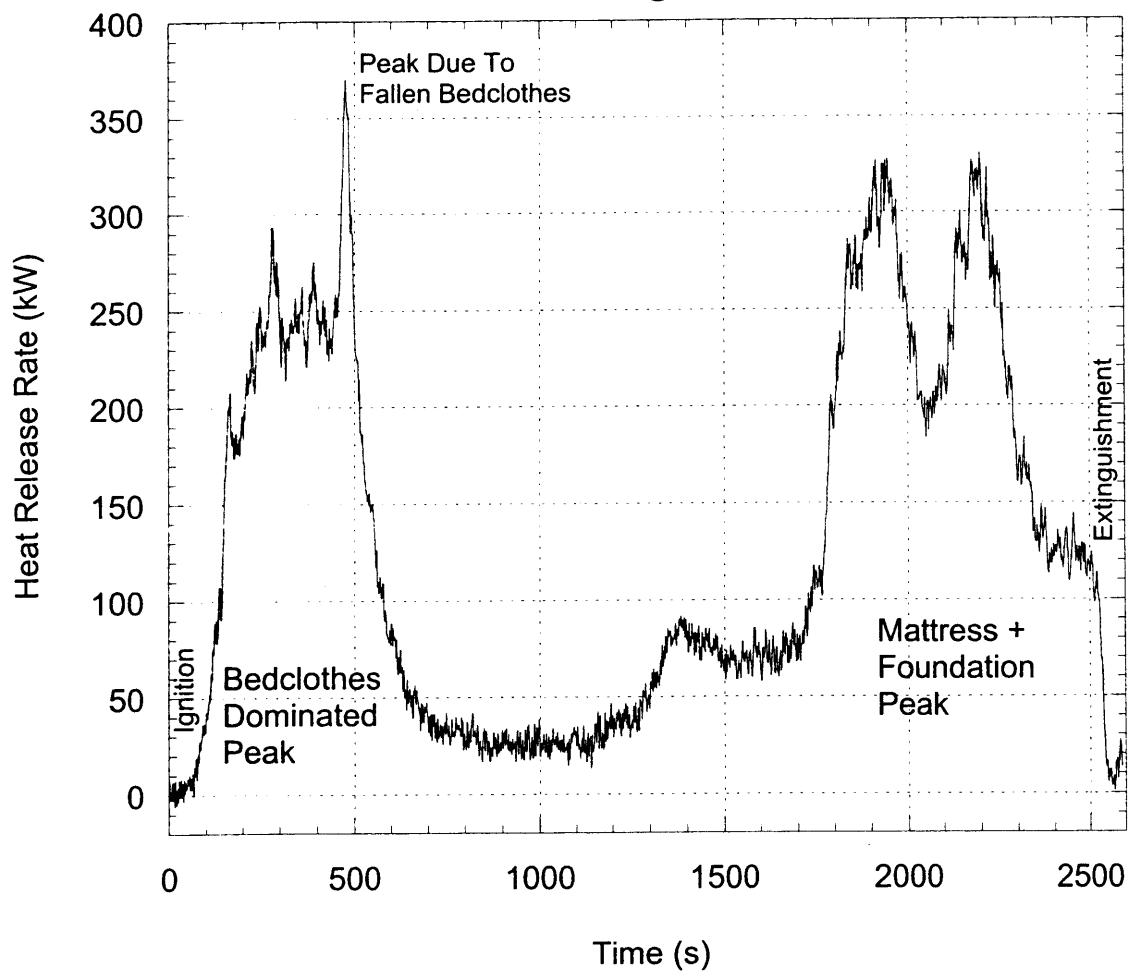


FIGURE 1. BURNER PLACEMENTS ON MATTRESS / FOUNDATION

**Figure 2. Heat Release Rate vs Time
Design 4**



**Figure 3. Heat Release Rate Behavior
With Burning Bedclothes
Design 6**



**Figure 4. Correlation of
Bed Clothes Peak Heat Release Rate
with Worst Case Peak Heat Release Rate Due to Burner**

