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Abstract

The severity of a bed fire is a function of the fire performance of the components of the bed and the interactions among them. Accordingly, a series of tests was conducted to elucidate how varying the fire behavior of bed clothes might affect the fire performance and eventual flammability testing of the mattress and foundation. The tests were conducted on twin size mattress/foundation sets using bed clothes whose fiberfill content was either modified with regard to flammability or protected from direct flame impingement by a barrier layer. The mattress/foundation designs had varied heat release rate peaks and fire growth mechanisms. The ignition source was a match-size flame applied to the unmodified hanging sheets and blanket on the side of the bed. Significant reduction in heat release rate and increase in time to the peak were observed for mattress pads that provided protection of the side of the mattress, for those mattresses that did not already have such protection. Alteration to the comforter and pillow, in addition to the mattress pad, brought lesser decreases in heat release rate peak and the specific result depended significantly on the nature of the materials used. For a mattress design of greatly reduced peak heat release rate, the potential synergism with the bed clothes decreases. This is because (a) the early peak heat release rate from the bed assembly becomes controlled by the bed clothes flammability behavior, and (b) the bedclothes have burned away before any late heat release rate peak occurs.

Key words: fire, mattress, bed clothes, beds, fire growth, flammability, heat release rate

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Introduction

The risk posed by a severe bed fire is determined by the ease of ignition, the intensity with which the bed burns (as measured here by the peak rate of heat release) and the potential for the flames from the bed to ignite other combustibles within the room [1]. Decreases in fire risk can be achieved by interfering with any of these if the three steps are independent, e.g., if making the bed harder to ignite does not also create beds that burn more intensely. A synergistic interaction among these elements could, of course, be even more beneficial, e.g., if making the mattress less susceptible to ignition also reduced the rate of heat release.

In practice, manufacturers and regulators follow either or both of two approaches to fire risk reduction: (a) reduce the likelihood of sustained ignition and (b) mitigate the consequences of an ignition. In this program sponsored by the Sleep Products Safety Council, the research has focused on the latter approach.

A bed assembly consists of a complete set of bed clothes, a mattress, and a foundation. Bed clothes include the sheets, pillow, blanket, etc. Ignition most commonly occurs via the bed clothes, while the mattress and foundation contain an appreciable fraction of the fuel. In earlier work in this program [1, 2], it has been shown that incorporation of less flammable cushioning materials or the use of fire barrier materials to enclose conventional cushioning materials in the mattress and foundation can improve both the mattress burning intensity and the likelihood of ignition of other combustibles in the room.

This makes it important to resolve how the fire performance of the mattress and foundation depends on the extent and duration (timing) of their ignition source, the bed clothes[1]. If now or in the future, people were using bed clothes of lower flammability, there are potential ramifications for the techniques adopted by mattress manufacturers to improve their product and to the approach taken by regulators in promulgating a mattress flammability measurement method and the accompanying performance criteria.

It might seem self-evident that less flammable bedclothes would result in a smaller, and thus less consequential, fire. However, one should not presume that the overall rate of heat release is simply the sum of the contributions from the bedclothes and the mattress/foundation. For example:

- A change in the bedclothes could lead to protection of some aspect of mattress flammability that is already well improved.
- A flammable bedclothes component might nonetheless “blanket” the mattress, separating it from the air needed for its combustion.

[1] The bedclothes modifications utilized in this study were a very limited sampling of alternative materials having lesser flammability. The choice of materials was based entirely on flammability characteristics and not on other qualities which commercially acceptable alternative materials might require. No attempt was made to be comprehensive in choice of materials so this study was by no means an assessment of the state of the art in less flammable bed clothes.

- The components of the bed assembly might burn at differing rates and reach their peak burning at different times. Even if the burning of the components were concurrent, the complex interactions among them generally preclude simple additivity. Some of the mattress designs tested here actually yielded a mix of these behaviors since there were two significant heat release rate peaks.

The objective of the present research is to examine the nature of the effects bedclothes modifications can have on the overall fire behavior of the bed assembly: no effect, an additive effect, or a positive synergistic effect. Positive synergism would be indicated by a reduction, and possibly a delay, in the peak heat release rate beyond that expected from the heat release rate reductions in the bedclothes themselves. An outcome of the research would be the identification of implications of the bed clothes-mattress interaction for the design and testing of less flammable mattresses and foundations.

A bed assembly is a natural system in which to anticipate the existence of synergism. When bed clothes are ignited by a match-size flame, a prevalent real-world situation, they typically sustain a fire growth process that eventually engulfs the entire set (here a mattress pad, two sheets, a blanket, a comforter and a pillow) [1, 2]. This fire growth process is a very large magnifier of the original match flame and this greatly enlarged flame imposes a severe challenge to the mattress and foundation lying beneath the bed clothes. This challenge takes the form of randomly located "hot spots" which not only can locally ignite the outer cover of a mattress/foundation but also can burn through any protective layers that the mattress/foundation may incorporate, thereby spreading flames to its more vulnerable interior. Flames and flame radiation from any of the bed components can ignite nearby combustibles [1]. The fire physics thus suggests ample opportunity for synergism among the bed components in reducing the threat to life safety from a bed fire.

In the first part of the study, the focus is on the mattress pad. This component is in intimate contact with the mattress and is thus in the best place, potentially, to intervene in the imposition of "hot spots" on the mattress surfaces. Changes in the pad's fire behavior could involve a reduction in its heat release rate and/or a lessening of the heat transfer from the burning bedclothes to the mattress, making the mattress less likely to ignite or to burn more slowly if ignited. The two mattress pad modifications were:

- Replacement of the fiberfill (typically 100 % polyester) with a less flammable cushioning fiber.
- Surrounding the fiberfill by a protective shell inside the outer polyester/cotton fabric.

These should have different effects on the fire dynamics and provide a solid perspective on the interactions.

In the second part of the study, these same modes of improvement were also added to the other fiberfilled components, the comforter and the pillow, examining the effects of changes in all three components at once.

Within this limited approach, we make three observations:

- The pillow and comforter are in contact with only a portion of the mattress, and the comforter may not be present in some seasons of the year.
- With the exception of the overhang of the comforter, changes in these three components do not have a direct effect on the foundation. Unchecked foundation participation in the fire growth can provide a path around any of the modifications examined here and thus obscure the nature of the bed clothes-mattress interaction.
- While the fire characteristics of the bed clothes in this study have been carefully selected, the spread of flames across them depends on the properties of each of the layers and on their arrangement. The principles derived in this study should lead to improved fire performance for a large fraction of possible combinations of bed components, but not necessarily for all combinations.

Experimental Details

Bed Clothes. Table 1 lists the bed clothes, their weights and their nominal compositions. All were twin size. The same bed clothes components (mattress pad, fitted sheet, flat sheet, blanket, comforter, pillow in pillowcase) were used in all tests. Furthermore, the beds were always dressed in the same manner: a) in the component sequence just noted, b) using "hospital corners" on the foot end for the flat sheet and blanket, c) with the "top" edge of the pillow flush with the head end of the bed and centered laterally and d) with the covers (flat sheet, blanket and comforter) folded evenly back so as to just be in contact with the "bottom" edge of the pillow

The sheets, blankets and pillow cases were purchased from a department store. Table 1 shows that the fitted and flat sheets, the blanket and the pillowcase were always the same composition and were not specially treated for fire resistance. Furthermore, it was the combination of the flat sheet and the blanket to which the ignition source was applied so that the initial fire growth process was always the same, regardless of the alterations in other bed clothes components.

All of the modified and unmodified mattress pads, comforters and pillows were produced by a single commercial manufacturer. As indicated in the Introduction, the modifications used consisted of either replacing the normal polyester fiberfill with a fibrous material designed to have more fire resistance or leaving the normal polyester fiberfill in place but protecting it with a fire-resistant barrier material.

The mattress pad consists of a soft, absorbent material inside a covering shell and a skirt. The pad covers only the top of the mattress. The skirt covers the sides of the mattress and, since it has an elastic band on its bottom edge, it also covers 5 cm to 10 cm of the outer periphery of the bottom of the mattress. The majority of the mattress pads, both normal and modified, had a non-protective skirt material. A limited amount of a barrier fabric, different from that used in any other location, was available; it was substituted for the normal skirt on mattress pads A, C and D. Here again it completely covered the mattress sides and 5 cm to 10 cm of the outer periphery of the bottom of a mattress.

Mattresses/ Foundations. Three different mattress/foundation designs were used, designated M1, M3 and M5. Prior batches of the same designs were used in references 1 and 2 and had been shown to cover a wide range of fire performance as measured by peak heat release rate. Table 2, from reference 2, summarizes the materials in these designs. Figure 1 shows the locations of the components referred to in Table 2.

Design M1 is reasonably representative of currently available mattresses; designs M3 and M5 are experimental in nature and include potential features for improvements in fire behavior. Note that while the specific mattress and foundation sets that constitute the embodiments of these designs are nominally the same as those tested in references 1 and 2, material variability may have resulted in somewhat different behavior than was previously seen. In particular, design M3 in this study consistently exhibited a late fire originating in the foundation that was seen only occasionally with the M3 design in previous work.

Fire Test Protocol. The fire tests were all conducted in the NIST 6 meter heat release rate calorimeter. 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. The skirt also provides extra volume to assure plume capture if a fire should temporarily exceed the nominal 4 MW rating of the hood. In the present tests, which ranged in peak heat release rate from under 200 kW to about 2½ MW, there was no significant loss of the smoke plume at any time, nor was there any appreciable build-up of smoke in the hood volume.

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 ± 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, in the middle and after the tests 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 ± 0.5 % to the ± 5 % inherent uncertainty. Zero drift correction uncertainties are typically less than ± 2 % for fires of a few hundred kW or greater; the zero drift correction on one fire was as high as 10 %. System noise, coupled with 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 11½ cm high steel, twin-sized bed frame which, in turn, rested on a cement fiberboard (Durock[2]) surface that formed the bottom of a catch pan. The pan rested on a scale.

Each fire was initiated by a 30 s application of a small butane flame (1 cm to 2 cm tall) applied to the forward bottom edge of the folded back covers as they hung on the side of the bed. The flame was deliberately moved to follow any shrinkage of the heated materials so as to assure a

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[2] 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.

continuous contact during the application interval. As noted previously, the two bed clothes components which were contacted by the igniter flame were the flat sheet and the acrylic blanket.

The fires were terminated with a water spray when it was very clear that the peak heat release rate had been seen and the fire was dying out. 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 bed clothes subsequent to unpacking. The potential day-to-day variation in moisture content of the bed assemblies could conceivably affect fire performance[3]. To avoid any systematic distortion of the data by varying moisture contents, all of the tests were done in two randomized sequences. The mattress pad variations constituted the first test sequence and the further composition variations the second sequence. In this way, any effects of moisture content on fire performance contribute to the variability seen in the tests from one nominally identical bed assembly to the next but do not systematically bias the results.

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 additional issue was pursued in these tests. It was noted in recent tests at the California Bureau of Home Furnishings that for some mattress designs, flames could persist in the crevice between the mattress and the foundation for many minutes, eventually leading to a failure of the barrier material to protect the mattress contents. Crevice flames had been seen at NIST with both the M3 and M5 designs, though they did not appear to be related to barrier failures. Nevertheless, since they were comparable in size to those seen in the CBHF tests and appeared to involve comparable materials (the two layers comprising the top of the foundation), they were examined more closely here. In particular, the concern is that such flames constitute a significantly different exposure for barrier materials than the exposures imposed by the NIST gas burners described in reference 1; such a different exposure, if it can lead to barrier failure, is pertinent to the mattress screening protocol being developed by NIST for the Consumer Products Safety Commission. A hand-held, total heat flux gage (a Medtherm 6 mm dia. Schmidt-Boelter gage cooled with 77 °C water) was moved laterally back and forth through these flames to sample the heat flux levels that they impose on adjacent crevice surfaces. The flames themselves were constantly fluctuating in position and time; the resultant heat fluxes varied substantially in any given measurement (typically about one minute long; one measurement period in a given test). The results reported below give the range of heat fluxes seen in these measurement intervals.

[3] 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 several week test period, the humidity in the test bay varied from 20 % to 70 % but the majority of the time it was between 30 % and 60 %.

Results and Discussion

The test results are summarized in Table 3. The bed clothes descriptions there are to be understood as including all base case components except for the modification(s) noted. As shown in Table 3, the focus is first on a limited look at mattress design M3, which is already nominally well-protected. We then focus on the effects, for the two more flammable mattresses, M1 and M5, of varying only the mattress pad composition. Finally, we look at the additional effects of also modifying the comforter and pillow with these same two mattress designs. When all three components are modified, the bed clothes are referred to, in Table 3 and in the figures showing the results, as "Bed Set A", "Bed Set C", etc.

Limited Study of Design M3. Design M3 already has a protective barrier as the ticking on both the mattress and the sides of the foundation. One might well expect little improvement in adding further protection to the mattress other than some decrease in the bed clothes contribution to the fire. For this reason, only very limited testing of this mattress design was carried out.

This batch of M3 mattresses did not behave as well in this test series as did prior versions [1, 2], showing a consistent tendency here toward a significant foundation-forced fire, albeit slow to develop. While this behavior was seen in the past, it was the exception, not the rule. The reason for the increased flammability behavior here was not apparent in the tests themselves.

As has typically happened in the past, the bed clothes essentially burned off the bed with minimal involvement of the mattress or foundation. It is not unusual for flames to appear inside the barrier, especially of the foundation, when the bed clothes are burning even though there has been no break in the barrier ticking[4]. Usually this results only in small, localized flames that consume a portion of the 6 mm thick layer of polyurethane foam just inside the foundation sides. The heat release rate from these is estimated to be a few kilowatts. Here these flames inside the foundation sidewall barrier eventually spread onto the underside of the foundation top pad where they proceeded to spread laterally and grow, eventually igniting the wood in the base of the foundation. The foundation fire was then powerful enough to cook most or all of the combustibles out of the mattress above it. The net result was two peaks in heat release rate, as shown in Table 2. The first was easily dominated by the bed clothes, providing a reasonable measure of these, almost as if the mattress were inert. The second, higher peak, which occurred considerably later, was the result of the foundation-forced fire.

It appears that the two changes in the bed clothes had no significant effect on the overall bed flammability for these particular bed assemblies.

- Figure 2 shows the results of the first peak for the base case bed clothes and two variants. The peak heat release rates and their variability are comparable to those reported for the nominally same bed clothes composition (combination #4) in Ref. 2, as measured atop an inert fiberglass mattress. (Here the average was 177 kW with a standard deviation of 40 kW.) The two bed clothes variants did not yield significantly different results from the base case. In the first variant only the top composition of the mattress pad was altered; the polyester fiberfill was surrounded

[4] Evidently the fiberglass-based ticking can get hot enough with flames impinging on its exterior surface to ignite pyrolysis gases generated inside the barrier.

by charring barrier 2. The average peak heat release rate was similar (212 ± 25) kW to the base case. In the second variant, the mattress pad, comforter and pillow were replaced with "A" materials (the fiberfill in all three components was improved). The average peak heat release rate was also similar at (150 ± 8) kW. The implication here is that the modified bed clothes (at least the two sets examined here) may not be burning with any appreciably less intensity, despite the modifications. This does not necessarily mean that these types of modifications are always ineffective in the context of a burning bed assembly, however, as will be seen below. Furthermore, there was evidence, discussed below, that some bed clothes modifications did decrease that portion of the heat release rate curve most directly attributable to bed clothes burning.

- Figure 3 shows the second and larger heat release peaks seen in these three M3-based bed assemblies. These occurred only after times varying from 21 to 35 minutes. The results are not significantly different, given the large variability of the base case, (417 ± 167) kW. Here, the fire originates within the foundation, which has the least contact with the modified bed clothes, a fact which is in accord with the finding that the modifications did not make a substantial difference.

Mattress Pad Composition Variations with Designs M1 and M5. Consider next a mattress design, M1, which can yield a very high heat release rate peak and thus offers large potential room for improvement. Figure 4 shows the variation of peak heat release rate with mattress pad composition with an M1 mattress/foundation combination; Fig. 5 shows the variation in the time to reach that peak for the M1 case. As discussed in Ref. 1, heat release rate peaks of the order of 2 MW, as seen in Fig. 4, are highly likely to cause flashover in the room and spread life-threatening smoke to other spaces in the building.

At the left in each figure are the results of three replicate tests with the normal bed clothes set, which forms the base case reference for all other variants. The variability seen in these figures of the base case is small (± ca. 3 % based on one standard deviation). However, it is worth noting that this same nominal bed assembly gave two peak heat release rate values about 15 % higher, as reported in Ref. 1. Thus it is not entirely certain that the other results in Fig. 4, showing that all four mattress pad variations can <u>raise</u> the peak heat release rate, are real or just part of a natural variability of this system, though the frequency of this occurrence suggests that it might be real. The times to the peak here and in Ref. 1 are quite comparable and do not appear to be appreciably affected by mattress top pad variations.

The peak heat release rate of any fire is affected by the intensity of burning on various ignited surfaces at any given time. In particular, achieving the highest possible peak requires that all burning surfaces be at or near their peak burning rates at once. Strictly speaking, here this would require that all bed surfaces (exposed to air) be ignited at once. Since the fire is started on a highly localized region of the bed and grows in various directions, onto various surfaces, at varying rates, it is, in general, very unlikely that what is seen here is the maximum peak that such a system is capable of giving[5]. More to the point, the relative time of involvement of the underside surface of the foundation (as compared to the involvement of the top or interior of the mattress) was generally the most variable aspect of all of the fires seen in this study. The highest peaks seen here generally involved simultaneous intense burning of the foundation surfaces and the mattress surfaces, though generally some portion of the mattress surfaces, in particular,

[5] This highest peak is unlikely in any realistic fire.

was already burned out or otherwise destroyed by the time of the overall heat release rate peak. If the peak burning of these two basic components was somewhat shifted out of synchronization in time, then the peak heat release rate was reduced from the level achievable when they were in phase[6].

This synchronization issue between peak mattress and foundation burning was behind the very large variability in the two replicate tests with mattress pad C (i.e., the two cases to the left, having no protective sides on the mattress pad). The larger heat release peak (which was the highest for any of the M1 tests) was the result of very well synchronized burning of mattress and foundation plus relatively uniform involvement of both. In the other test, in which the heat release rate peak was nearly a factor of two less, the foundation fire was, for no evident reason, slow to propagate from one end of the bed to the other so that it was burning out on the foot end of the bed as it was igniting on the head end. A reduced foundation fire such as this brings a reduced mattress fire with it since the foundation fire heats the mattress intensely.

Figures 4 and 5 show another, more pronounced trend for the M1 mattress design. When the protective skirt is included as part of the modified mattress pad, the heat release rate peak is markedly reduced (by roughly a factor of two) and the time required to reach that peak is substantially longer (more than a factor of two). The amount of the reduction in the heat release rate peak for these best M1 cases frequently exceeded 1000 kW, which is much greater than the heat release rate peak attributable to the bed clothes themselves (roughly 200 kW)[7]. This points to the type of synergism sought in this study, where a change in bed clothes behavior causes a disproportionately large decrease in overall fire intensity.

In the absence of a protective skirt on the mattress pad, the M1 design responded in these tests by quickly allowing fire to burn into the sides of the mattress, exposing a space that is essentially lined with polyurethane foam. Thus the mattress fire tended to lead the overall fire development. When the mattress fire spread to the mattress bottom, it ignited the wood in the foundation and the heat release rate went quickly up to its peak. The protective pad on top of the mattress did not appear to alter this sequence appreciably. (Thus it was not apparent how or why the peak heat release rate went somewhat higher in the presence of a protective top pad.)

When the protective skirt was present, the mattress fire development was drastically slowed since easy access to the mattress interior was denied (much as with the M3 design). What happened next depended somewhat on the nature of the mattress top pad but, in essence, was the same in all cases. The fire persisted in some area of the mattress surface (usually in the pillow area but also elsewhere, in some cases), gradually overcoming the top barrier over a period of many minutes. The mattress fire would eventually grow larger on the top and/or the sides (through the intact skirt barrier), reach the mattress bottom, irradiate and ignite the wood in the foundation, thereby leading directly to the heat release rate

[6] There is an additional dependence on whether the mattress fire or the foundation fire is leading the fire growth process. When the foundation is leading, it tends to force the mattress into synchrony with it since it is below the mattress and heating it intensely. When the mattress fire is leading, as was the case with the M1 fires, its burning may have proceeded to varying degrees by the time the foundation fire grew to the point where it forced further heat out of the mattress. Thus there can be varying amounts of mattress heat left to be forced out by this process, resulting in a variable peak.

[7] While a factor of two reduction in peak heat release rate is impressive, the roughly 1 MW peaks still achieved can be life threatening [2].

peak. The nature of the top pad of the mattress pad could, in principal, play a role in determining the time to this eventual peak. The effects of top pad composition seen in Fig. 5 may be real but the limited data do not permit a definitive statement about this. The small differences here all look like they are within the test variance.

The fire behavior of the bed assembly incorporating mattress pad C with its protective skirt was exceptional (although the reproducibility of this result is unknown). The mattress fire essentially died out to the point of a few isolated small flames instead of gradually growing. Thus the peak reported in Fig. 4 is basically just that for the bed clothes and the short time to peak in Figure 5 is deceptive since it is the time to this rather small peak. The only thing that happened to the foundation was that the sides burned off as the bed clothes fire spread. The foundation sides contain little mass or potential heat. It is doubtful that this minimal fire (with no foundation burning) is a reproducible feature of this combination of materials.

Figures 6 and 7 show the measured heat release rate peaks and time to those peaks as a function of mattress pad composition in the case of an M5 mattress/foundation design. Note that this experimental design, which incorporates both flame retarded urethane foam and, inside this foam layer, boric acid treated cotton as a barrier, gives sharply reduced heat release rate peaks for the base case tests, as compared to the M1 design. Ref. 1 indicates that, nonetheless, there is still an appreciable life threat implicit in a peak heat release rate in the neighborhood of 600 kW.

The variability in the base case heat release rate is about ± 8 % here, based on one standard deviation. In spite of this and some greater variability in the other tests, Figs. 6 and 7 indicate that the presence of an improved mattress top pad (with no protective skirt) is probably yielding some small decrease in peak heat release rate and some delay in that peak, on average, though not in every individual case. The "D" material used as a mattress top pad appears, from this very limited sampling, to be more effective in this M5 context than the other materials. More data would be needed to make a definitive statement.

This mattress/foundation combination burns somewhat differently than the M1 design and this helps explain the effects seen here. Rather than the mattress leading the fire growth process to the peak, as it does in an M1 design, here the foundation leads[8]. Note, however, that the mattress pad provides no direct protection to the foundation. The bed clothes fire typically progressed over most of the bed, persisting longest in and around the pillow, before a foundation fire began to grow, most often from the foot end of the bed[9]. When the foundation fire began to peak, its plume forced flaming on the sides and then the top of the mattress, though this flaming was of much more limited intensity than that seen with an M1 design, thanks largely to the charring nature of the cotton in the mattress. This combined fire, forced by the foundation, yielded the peak heat release rate. Figure 7 indicates that reaching this peak required considerably more time than in the M1 cases with non-protective mattress pad skirts. Furthermore, the time to that peak tended to be increased (rather sporadically, roughly 10 % to 20 %, on average) by the presence of an improved top on the mattress pad.

[8] While the foundation fire clearly leads the way toward the heat release rate peak, the mattress may be partly complicit in the triggering of the foundation fire growth. Typically the sides of this mattress do open partially (in the absence of any added protection from the mattress pad skirt), allowing some limited fire penetration. This, in turn may help heat the top pad of the foundation through the bottom layers of the mattress, aiding the subsequent flame spread on the underside of the top pad of the foundation.

[9] The dominance of foundation fires originating at the foot end may have been the result of the comforter hanging over the corners of the bed, providing a more focused heating of foundation materials in the foot end corners.

In Fig. 6, the mattress pad with the "D" material appears, from limited data, to provide a greater benefit than the other materials. More generally, however, the data in Figs. 6 and 7 show that, as in the M1 cases, the improvements were greatest if the modified mattress pad also had the protective skirt material. In effect, this skirt helped limit the contribution of the mattress to the heat release rate peak from the overall assembly (mainly by lowering the burning rate on the sides of the mattress and limiting fire penetration into the sides) and it delayed that peak more consistently than did any of the modified top pads alone.

The data in Fig. 6 suggest that a peak heat release rate reduction approaching a factor of two is possible for an M5 design employing a mattress pad having an improved top pad and the protective skirt material on the sides. Reduction to the 300 kW level seen there is shown in Ref. 1 to provide the potential for significant life saving benefits, with the fire not only being confined to the room of origin but also likely being confined to the bed itself. The factor of two reduction amounts to an absolute heat release rate decrease of about 300 kW, again pointing to a synergistic effect of improved bed clothes in a bed assembly system based on an M5 mattress/foundation.

The preceding results indicate that the benefit provided by the improved mattress pads, particularly those with the protective skirt material, is dependent on the degree to which the mattress sides are vulnerable. The M1 design with its thin polyurethane foam layer on the sides is the most vulnerable and the protective mattress skirt yields its largest improvement in peak heat release rate here. The M5 design has a cotton batting barrier on the sides but that barrier is compromised and tends to open in a limited manner, after some delay, where it meets the mattress tape edge. The protective mattress pad skirt yields a more limited reduction to what is already a reduced rate of heat release. The least improvement comes with the M3 design which already has a very effective barrier on the sides of the mattress.

These inferences pertain to mattress designs based on the use of barriers to decrease their flammability. No mattress designs based exclusively on the use of flame retarded internal components (e.g., such as M2 in Ref. 2, which used FR polyurethane foam) have been examined here. One can speculate to a limited extent about how such a design might benefit from an improved mattress pad of the types used here. A mattress design based exclusively on melt-prone FR materials may offer no resistance to local flame penetration[10]. Local flames in the mattress interior then would spread at a speed depending on the degree of FR treatment. The presence of an improved pad with protective skirts would substantially delay this initial fire penetration, possibly until the fire in the unprotected foundation penetrated the bottom of the mattress. There thus appears to be a potential for a substantial delay in time to peak heat release rate in the use of an improved mattress pad (with protective skirts) on a mattress based on melting FR cushioning materials.

Effect of Additional Bed Clothes Changes with M1 and M5 Designs. Next consider the effect of inserting the same change[11] as that in the mattress pad into the two other fiberfilled components of each bed set. Again this was done for the M1 and M5 mattress/foundation designs. The "B" fiberfill was not used here since it was not suitable for filling a comforter or a pillow. In addition, only a limited

[10] There are FR PU foams available that char rather than melt; these may react to an improved mattress pad in much the same way the barrier-based designs did here.
[11] Set "A" had the same fiber blend in mattress pad and comforter but another fiberfill in the pillow, as Table 1 shows.

amount of the "D" material was available so that there were not sufficient complete bed sets to test it in this manner on the M1 mattress/foundation design.

Figures 8 and 9 show the effect on peak heat release rate from an M1 design of changing just the mattress pad or changing the pad plus the comforter and pillow. Each figure repeats the base case (unmodified bed clothes) and the mattress pad only results seen in the previous figures but now also includes the results from testing alterations in all three components.

Figure 8 is for material "A" (a fiberfill replacement) and an M1 mattress/foundation; note that the vertical ordinate range is large, reflecting the large heat release rate peaks this design can give. Figure 9 is for the "C" material (a protective barrier around the fiberfill); the vertical ordinate is the same as Figure 8. Viewing these two figures, one cannot escape the conclusion that, for the M1 design, the benefits of the bed clothes modifications tested here lie entirely in the effect of the protective side material used on the mattress pad. The protective sides appear to reduce the peak heat release rate by a factor of two. Reference to Table 3 indicates that the additional bed clothes changes might also further slow the time to the peak but the very limited data are ambiguous and the trend could simply be due to noise.

Figures 10, 11 and 12 show the effect on peak heat release rate from an M5 design of changing just the mattress pad or changing the pad plus the comforter and pillow. Here the effects of materials "A", "C" and "D" were examined. The general trend in all three of these figures is downward from left to right, implying that, for an M5 design, the additional bed clothes changes do tend to lower the peak heat release rate. The extra increment in improved performance appears to be less for the "D" materials; the performance with the complete D material set was quite comparable to the one result obtained with a mattress pad alone having a D top and protective skirt material. Generally speaking, the modified materials reduce the heat release rate peak by about a factor of two for the M5 design. Very limited data suggest that the complete C material set can do better than this. The time to peak data (Table 3) are more scattered and do not show any clear enhancement of the delay when the complete set of altered materials is used instead of just the altered mattress pad. The middle set of bars in Figures 10 and 11 (except for the side-protected pad) do not appear to be significantly different from the base case.

During the course of fire growth, the early effects of the additional improvements to the bed clothes were pronounced, especially for the two barrier materials "C" and "D" on the M5 design[12]. The "C" material reduced the early peak(s) in heat release rate, which were due mainly to the bed clothes, by a factor of two or more. The "D" material reduced these peaks by as much as a factor of four. In contrast, the "A" material, which is a substituted fiberfill, did not significantly reduce the bed clothes dominated heat release rate peaks. However, in these assemblies, the overall heat release rate peak came later and was substantially larger. The effects seen on the bed clothes peaks do not carry through proportionally to the later overall peaks because those overall peaks (reported in Figs. 10, 11 and 12) are due to a different mechanism, dominated by the burning of the foundation and the mattress above it. Only if the bed clothes

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[12] This increased effectiveness for barrier based materials is not surprising. The tops of the comforter and pillow are effectively a barrier for these cases, so that the majority of the top and sides of the bed are, in effect, covered by an inert material.

peaks were the dominant heat release rate peaks in the system would the full, direct effects of the improved material sets be more pronounced.

Crevice Heat Fluxes. The heat flux data obtained from the crevice flames are also shown in Table 3. More than two dozen measurements were made of the flux range these flames impose on a gage inserted laterally into the crevice flames. Averaging of the mean values from each measurement gives a value of (38 ± 6) kW/m^2 (one standard deviation). Flames were noted to persist in the crevice for more than 5 min in some tests with the M5 design. Crevice flames persisting for two to three times this have been noted in other tests with other designs performed at the California Bureau of Home Furnishings (CBHF). In those cases, the persistent crevice flames appeared to be associated with (and probably to cause) barrier failures (e.g., by initiating an extensive smoldering process inside the barrier or an eventual barrier penetration). The CBHF tests showed that the NIST burners [1] can induce this type of persistent crevice burning, similarly to burning bed clothes. Thus this potential failure mode is accounted for with those burners.

Conclusions

The effects of improved material components incorporated within bed clothes on the flammability of mattress/foundation/bed clothes assemblies have been examined in this limited study in two ways. In the first part of the study only the mattress pad was modified. In the second part, changes of the same type were included in the comforter and pillow also. The principal findings were the following (subject to the caveats of limited replicate testing and the limited sampling of improved materials in the bedclothes):

- Protecting the sides of the mattress from flame penetration is a major source of improvement in the flammability of the bed assembly. The improvements can take the form of decreased peak heat release rate and increased time to that peak. A mattress pad with side protection is synergistically effective if the mattress itself has no side barrier or if the mattress side barrier is of limited effectiveness. If the mattress already has side protection, there is no effect from mattress pad side protection.
- Other changes in the mattress pad, when it alone was the improved bedclothes component, had minimal effect on the bed assembly performance.
- The comforter, if modified, can also provide side and top protection though its loosely hanging character makes side protection less effective. Also, the comforter does not cover all of the top and sides of a mattress (and is not always used). This limited protection is valuable only when the mattress or mattress pad does not already provide the protection.
- There is the potential for a synergistic effect of comforter rate of heat release reduction on bed hazard. A comforter of current conventional composition typically burns intensely early in the type of fire scenario examined here (along with the other hanging bed clothes layers) and that peak can be decreased by comforter modification. For the mattress designs examined here, the largest heat release rate peak in the overall bed assembly fire occurs later and is dominated by the burning of the mattress and foundation. As mattress designs improve, this later peak will be reduced, leaving the peak dominated by the bed clothes unchanged and likely the largest heat release rate peak. It has previously been shown that, for some bed clothes combinations, this peak alone can pose a threat to life safety.
- There are additive effects of pillow flammability behavior on bed fire hazard. Pillows tend to burn for a long time on top of the mattress in an area where layers of potentially insulating char from bed clothes are absent. They thus pose two types of threat: (a) they can contribute a significant portion of the bed clothes heat release rate peak, especially if their numbers increase beyond the single unit tested here; (b) they can burn for a prolonged period atop a less protected portion of the top of the mattress, potentially compromising the mattress in this area (a potentially negative synergistic effect).
- For a mattress design of greatly reduced peak heat release rate, the potential synergism with the bed clothes decreases. This is because (a) the early peak heat release rate from the bed assembly becomes controlled by the bed clothes flammability behavior, and (b) the bedclothes have burned away before any late heat release rate peak occurs.

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1) Ohlemiller, T. and Gann, R., "Estimating Reduced Fire Risk Resulting From an Improved Mattress Flammability Standard," National Institute of Standards and Technology Technical Note 1446, August, 2002

2) Ohlemiller, T., Shields, J., McLane, R. and Gann, R., "Flammability Assessment Methodology for Mattresses," National Institute of Standards and Technology NISTIR 6497, June, 2000

Table 1. Bed Clothes Specifications

Component	Composition	Avg. Weight (kg) (± s.d.)[13]
Fitted and flat sheets	50 % cotton / 50 % polyester	1.18 ± 0.08[14]
Blanket	100 % acrylic	0.83 ± 0.05
Pillow Case	50 % cotton / 50 % polyester	0.14 ± 0.005
Normal Mattress Pad	100 % cotton top shell non-woven scrim as bottom shell 100% polyester fiberfill unidentified light weight skirt on sides, with elastic band	1.13 ± 0.05
Modified Mattress Pad A	same as normal except charring/non-charring fiberfill blend	1.11 ± 0.02
Modified Mattress Pad B	same as normal except charring fiberfill	1.18 ± 0.02
Modified Mattress Pad C	same as normal except top of fiberfill covered by charring barrier 1	1.70 ± 0.05
Modified Mattress Pad D	same as normal except top of fiberfill covered by charring barrier 2	1.47 ± 0.05
Modified Mattress Pads A', C', and D'	as indicated above for individual letter but also having a woven barrier material as a skirt	
Normal Comforter	100 % cotton shell over 100 % polyester fiberfill	1.83 ± 0.03
Modified Comforter A	normal cotton shell but same fiberfill blend as mattress pad A	1.82 ± 0.02
Modified Comforter C	normal polyester fiberfill but charring barrier 1 under normal cotton shell	3.8 ± 0.4
Modified Comforter D	normal polyester fiberfill but charring barrier 2 under normal cotton shell	4.1 ± 0.02

[13] Standard deviation based on 12 samples of unchanging items like sheets and blanket; based on all samples used for other items (3 to 11 samples).
[14] The two sheets were always weighed together.

Table 1 Cont'd. Bed Clothes Specifications

Component	Composition	Avg. Weight (kg) (± s.d.)
Normal Pillow	100 % cotton shell normal polyester fiberfill	0.69 ± 0.05
Modified Pillow A	normal cotton shell but modified (flame resistant) polyester fiberfill	0.66 ± 0.02
Modified Pillow C	normal cotton shell and polyester fiberfill but charring barrier 1 inside shell	0.90 ± 0.04
Modified Pillow D	normal cotton shell and polyester fiberfill but charring barrier 2 inside shell	0.82 ± 0.01

Table 2. Component Materials in Mattress Designs
(Refer to Figure 1 for Component Locations)

	MATTRESS 1		MATTRESS 3		MATTRESS 5
Ticking	Std. Damask		Combined fabric/barrier		MVSS 302 damask
Quilt	19 mm (3/4 in) std. PU foam (19.2 kg/m^3, 1.2 lb/ft^3) in quilt		Same as Mattress #1		19 mm (3/4 in) TB 117 PU foam in quilt
Topper Pad	25.4 mm (1 in) std. PU foam (19.2 kg/m^3, 1.2 lb/ft^3)		Same as Mattress #1		12.7 mm (0.5 in) TB 117 PU foam (19.2 kg/m^3, 1.2 lb/ft^3) over 1.1 kg/m^2 (3.5 oz/ft^2) boric acid treated cotton batt
Insulator	Thermo-plastic Mesh Pad		Thermo-plastic Mesh Pad		Thermo-plastic Mesh Pad
Spring Unit	Twin Innerspring		Twin Innerspring		Twin Innerspring
Mattress Border	6 mm (1/4 in) std. PU foam (19.2 kg/m^3, 1.2 lb/ft^3) under std. Damask		Same as Mattress #1		Boric acid treated cotton batt under MVSS 302 damask
Thread	Standard		Combustion modified		Standard
Foundation Border	Same as mattress		Same as mattress		Same as mattress
Foundation Top Pad	0.62 kg/m^2 (2 oz/ft^2) polyester fiber pad		0.62 kg/m^2 (2 oz/ft^2) polyester fiber pad		0.62 kg/m^2 (2 oz/ft^2) polyester fiber pad

Table 3. Peak Heat Release Rates and Time to Peak From Modified Bed Clothes Test Series

Test #	Materials	Peak Heat Release Rate (kW)	Time to HRR Peak (s)	Meas'd Heat Flux in Crevice (kW/m^2)	Comment
1	M3 with Normal Bed Clothes	155 / 270	415 / 2085		1st Peak is Bed Clothes
2	" "	145 / 650	180 / 1285	25 - 40	"
3	" "	230 / 330	565 / 1745		"
4	M3 with Mattress Pad D	245 / 410	1460	25 - 45	1st Peak is Bed Clothes
5	" "	185 / 280	1490		"
6	" "	205 / 360	1800	20 - 35	"
4'	M3 with Bed Set A	140 / 545	1275	25 - 40	1st Peak is Bed Clothes
5'	" "	160 / 525	1535	30 – 50	"
6'	" "	150 / 450	1655	30 - 40	"
7	M1 with Normal Bed Clothes	2030	390		
8	" "	1970	435		
9	" "	2135	395		
10	M1 with Mattress Pad A	2500	345		
11	" "	2230	405		
12	M1 with Mattress Pad A (+ Protective Skirt)	1150	825		

Table 3 Cont'd. Peak Heat Release Rates and Time to Peak From Modified Bed Clothes Test Series

Test #	Materials	Peak Heat Release Rate (kW)	Time to HRR Peak (s)	Comment
13	M1 with Mattress Pad B	2135	370	
14	" "	2410	415	
15	M1 with Mattress Pad B (+ Protective Skirt)	915	1165	
16	M1 with Mattress Pad C	1385	455	
17	" "	2670	400	
18	M1 with Mattress Pad C (+ Protective Skirt)	165	340	Foundation Fire Died Out Early
19	M1 with Mattress Pad D	2215	505	
20	" "	2440	370	
21	M1 with Mattress Pad D (+ Protective Skirt)	1260	1535	
1'	M1 with Bed Set A	2150	420	
2'	" "	2030	410	
3'	M1 with Bed Set A (Protec. Skirt on Matt. Pad)	1010	1260	
10'	M1 with Bed Set C	2065	445	
11'	" "	1950	500	
12'	M1 with Bed Set C (Protec. Skirt on Matt. Pad)	950	1305	

Table 3 Cont'd. Peak Heat Release Rates and Time to Peak From Modified Bed Clothes Test Series

Test #	Materials	Peak Heat Release Rate (kW)	Time to HRR Peak (s)	Meas'd Heat Flux in Crevice (kW/m^2)
22	M5 with Normal Bed Clothes	570	790	35 - 50
23	" "	680	730	30 – 40
24	" "	575	720	30 – 40
25	M5 with Mattress Pad A	630	1045	35 – 45
26	" "	500	810	30 – 50
27	M5 with Mattress Pad A (+ Protective Skirt)	455	1535	
28	M5 with Mattress Pad B	410	855	50 – 60
29	" "	670	905	40 - 50
30	M5 with Mattress Pad B (+ Protective Skirt)	280	1085	40 - 50
31	M5 with Mattress Pad C	565	1205	35 – 45
32	" "	540	805	
33	M5 with Mattress Pad C (+ Protective Skirt)	340	990	35 - 45
34	M5 with Mattress Pad D	420	1220	25 - 45
35	" "	440	890	30 - 40
36	M5 with Mattress Pad D (+ Protective Skirt)	310	1120	35 - 45

Table 3 Cont'd. Peak Heat Release Rates and Time to Peak From Modified Bed Clothes Test Series

Test #	Materials	Peak Heat Release Rate (kW)	Time to HRR Peak (s)	Meas'd Heat Flux in Crevice (kW/m^2)
7'	M5 with Bed Set A	530	980	30 - 40
8'	" "	440	1015	35 - 50
9'	M5 with Bed Set A (Protec. Skirt on Matt. Pad)	300	1495	35 - 50
13'	M5 with Bed Set C	450	925	
14'	" "	280	890	30 - 45
15'	M5 with Bed Set C (Protec. Skirt on Matt. Pad)	195	1065	20 - 30
16'	M5 with Bed Set D	340	1700	
17'	" "	290	725	
18'	M5 with Bed Set D (Protec. Skirt on Matt. Pad)	310	1085	

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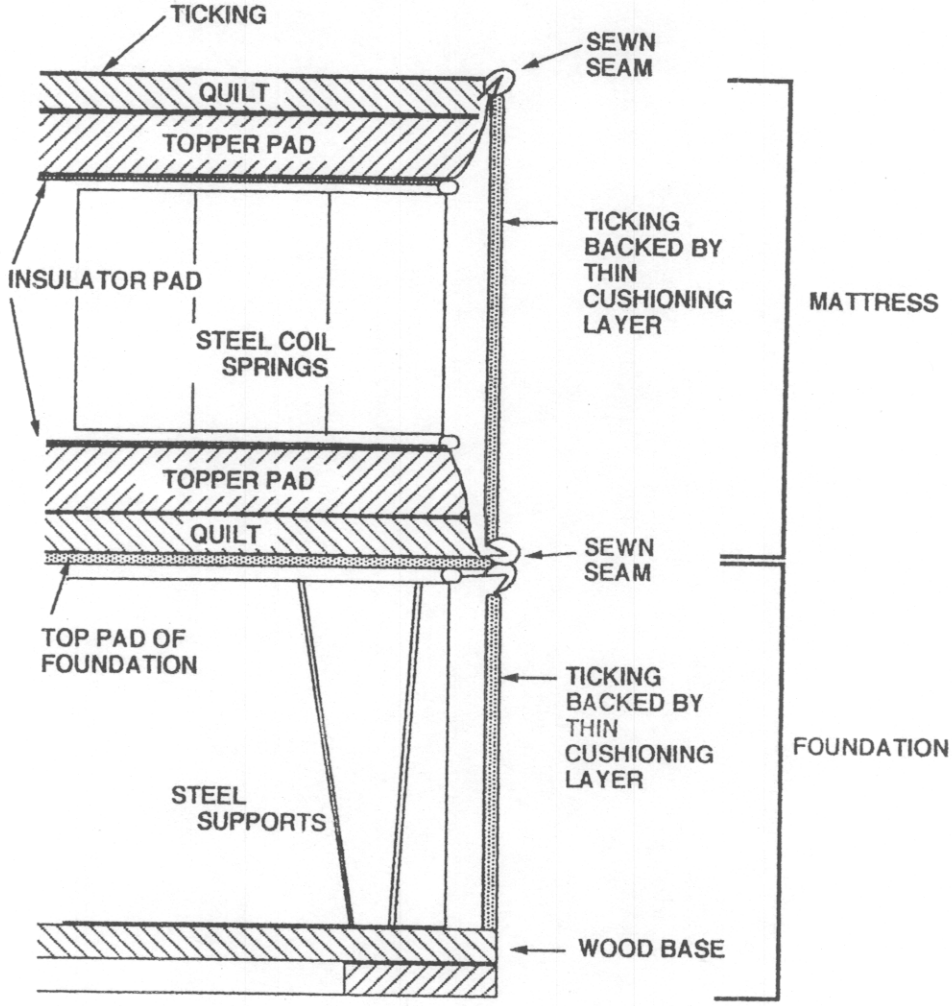

Figure 1. Cross-sectional view of mattress and foundation structure (not to fixed scale).

Figure 2
Effect of Two Bed Clothes Composition Variations on Bed Clothes Peak Heat Release Rate

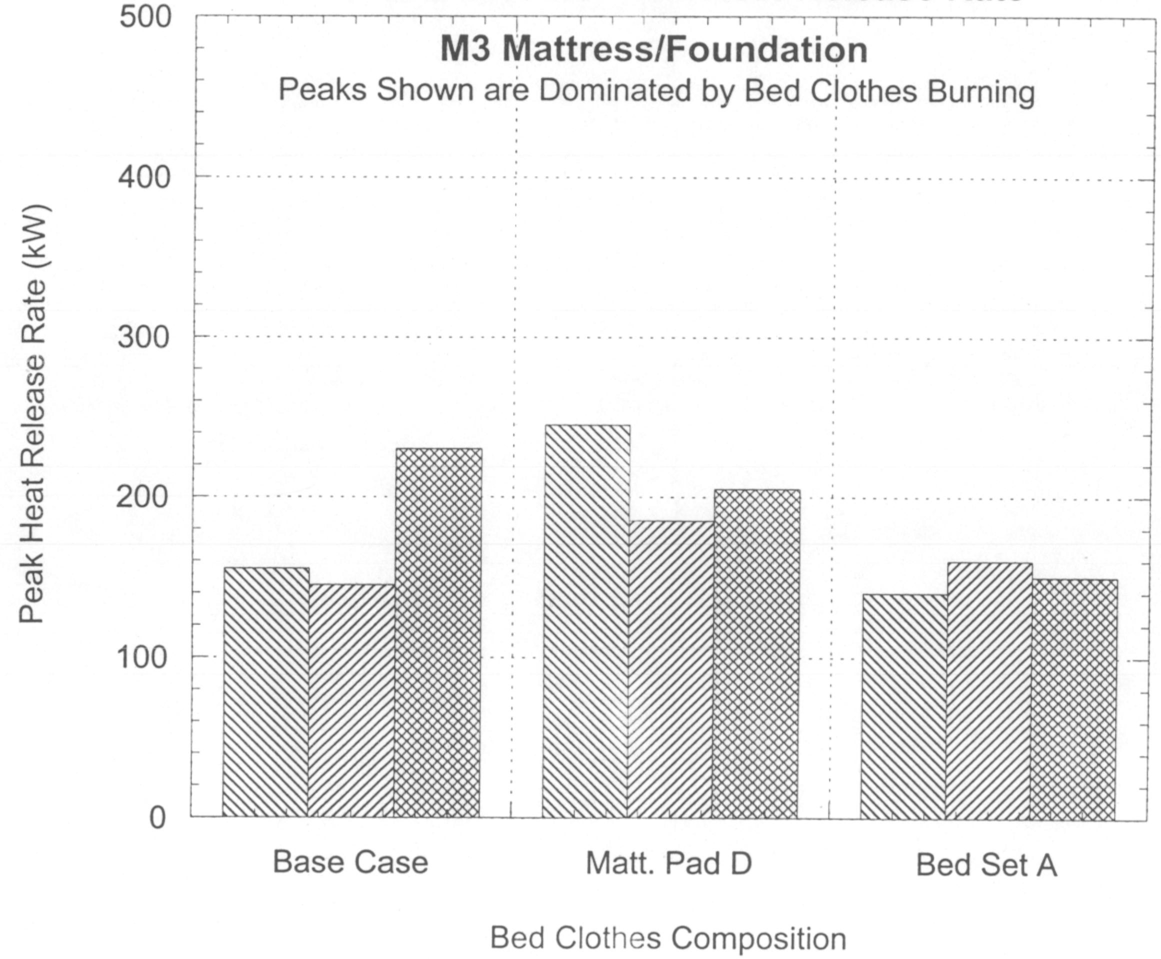

Figure 3
Effect of Bed Clothes Composition Variation Based on Two Differing Material Modifications (Peak Heat Release Rate)

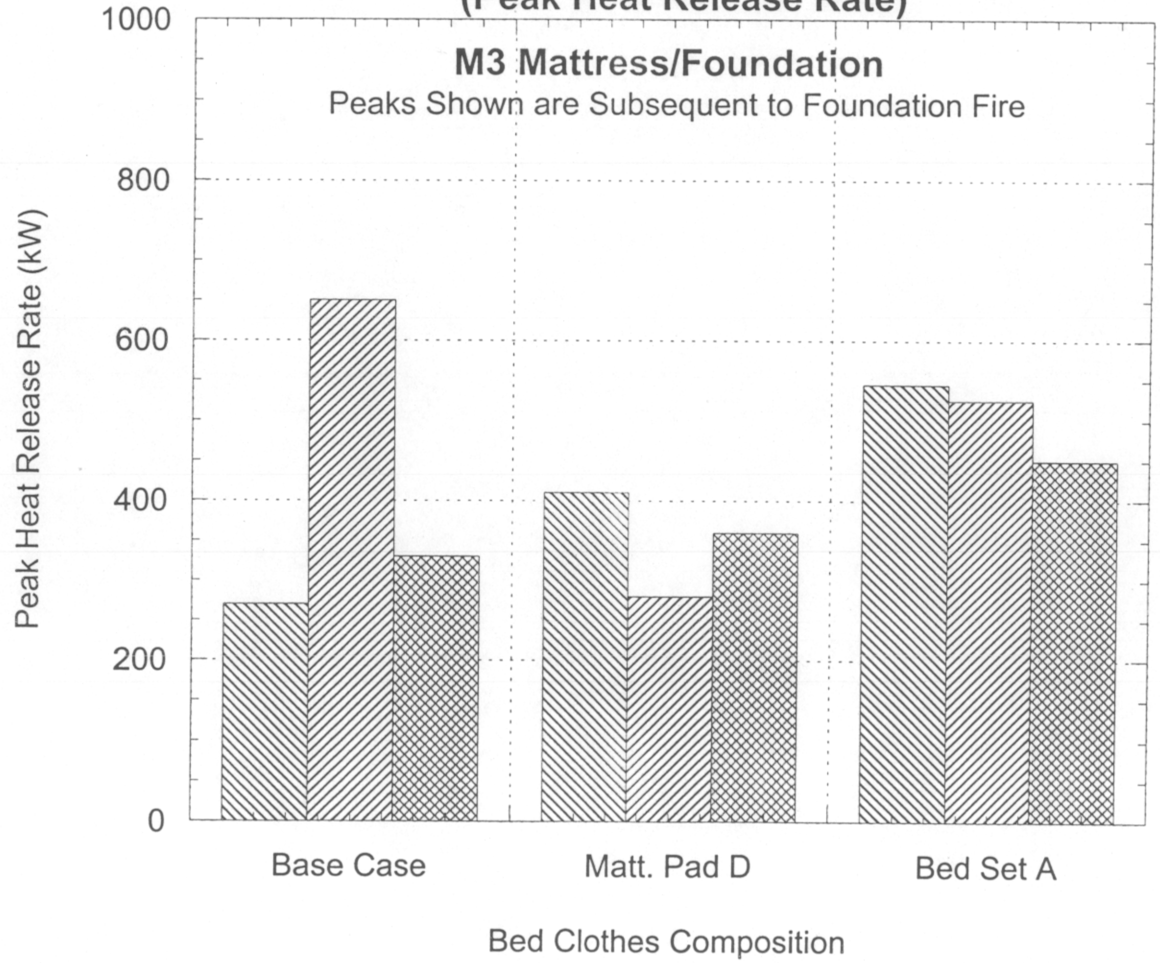

Figure 4
Effect of Mattress Pad Composition For M1 Mattress/Foundation (Peak Heat Release Rate)

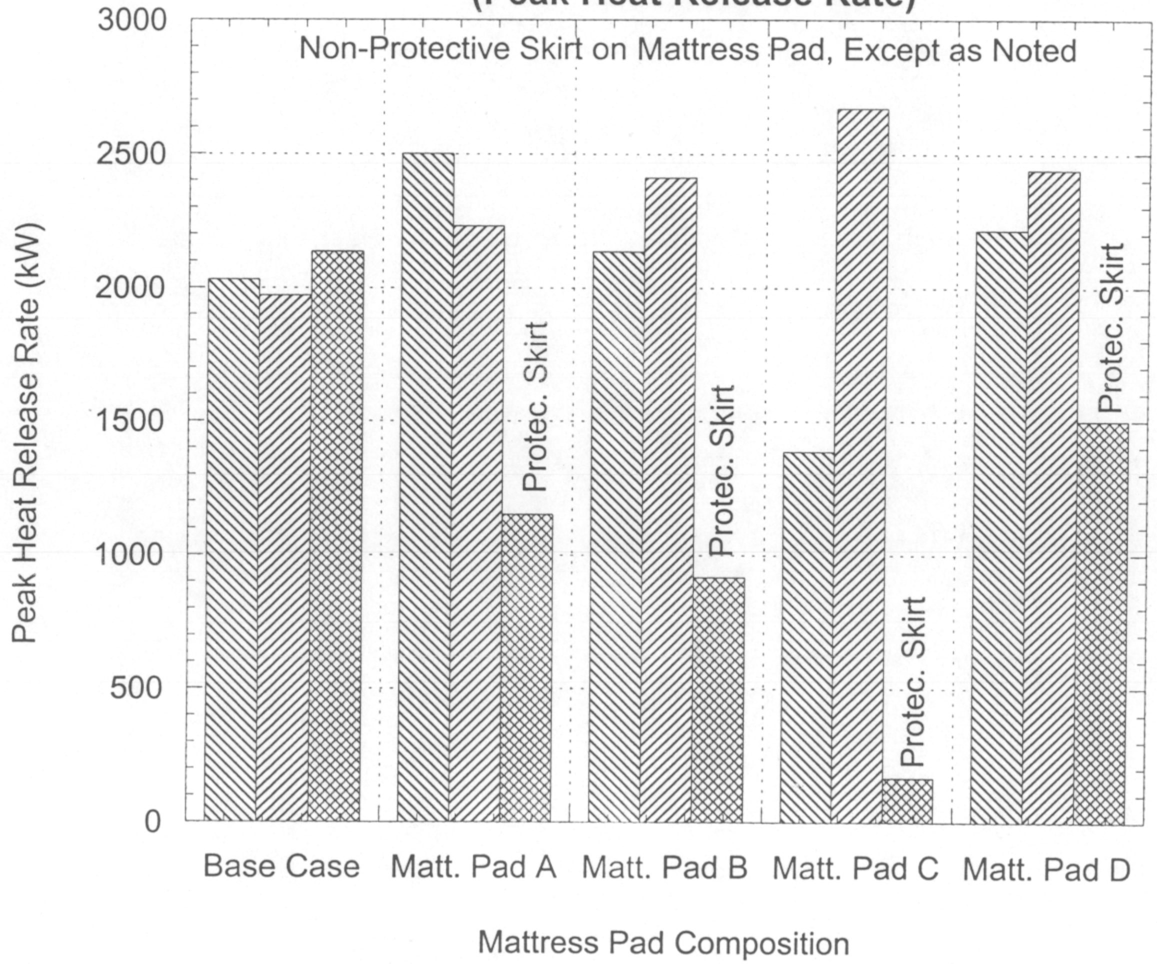

Figure 5
Effect of Mattress Pad Composition
For M1 Mattress/Foundation
(Time to Peak Heat Release Rate)

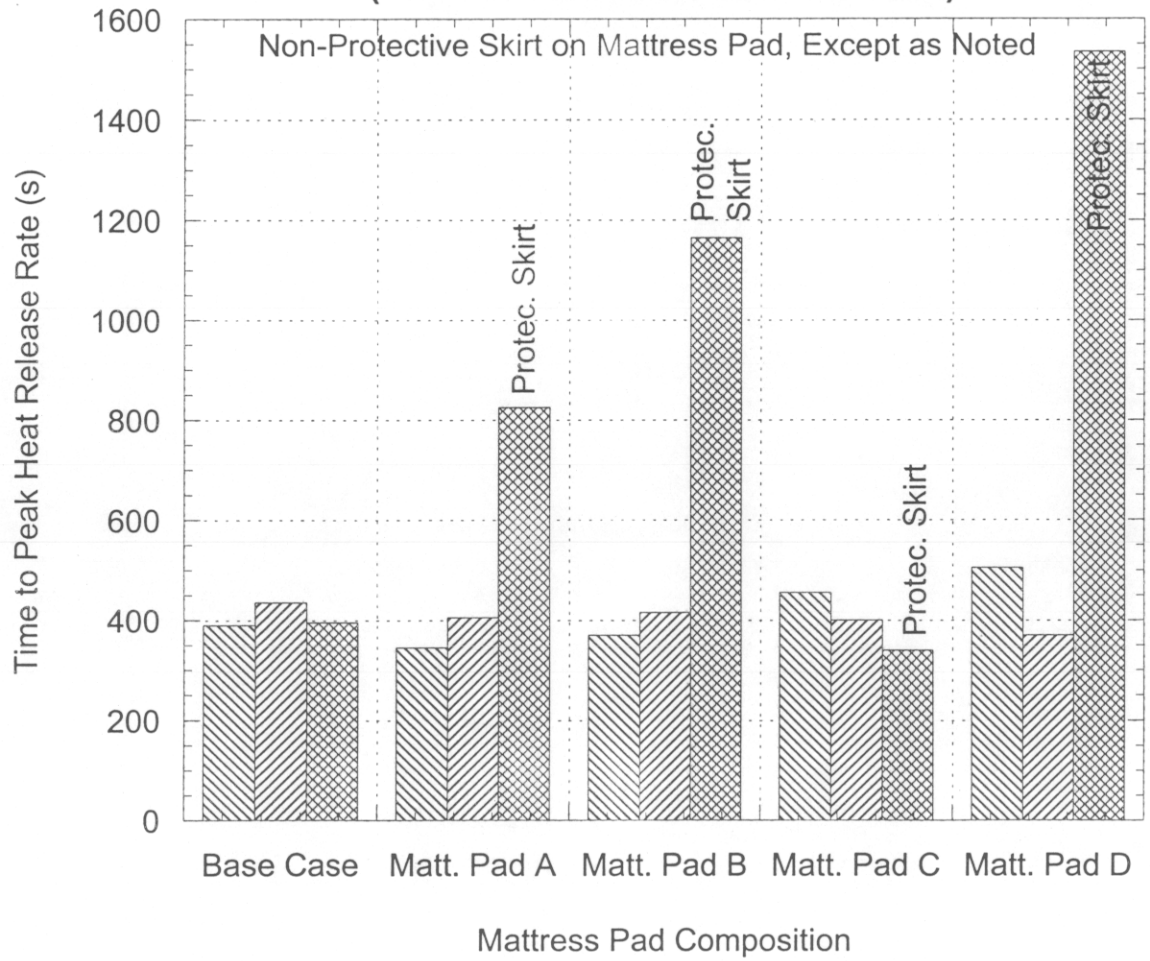

Figure 6
Effect of Mattress Pad Composition For M5 Mattress/Foundation (Peak Heat Release Rate)

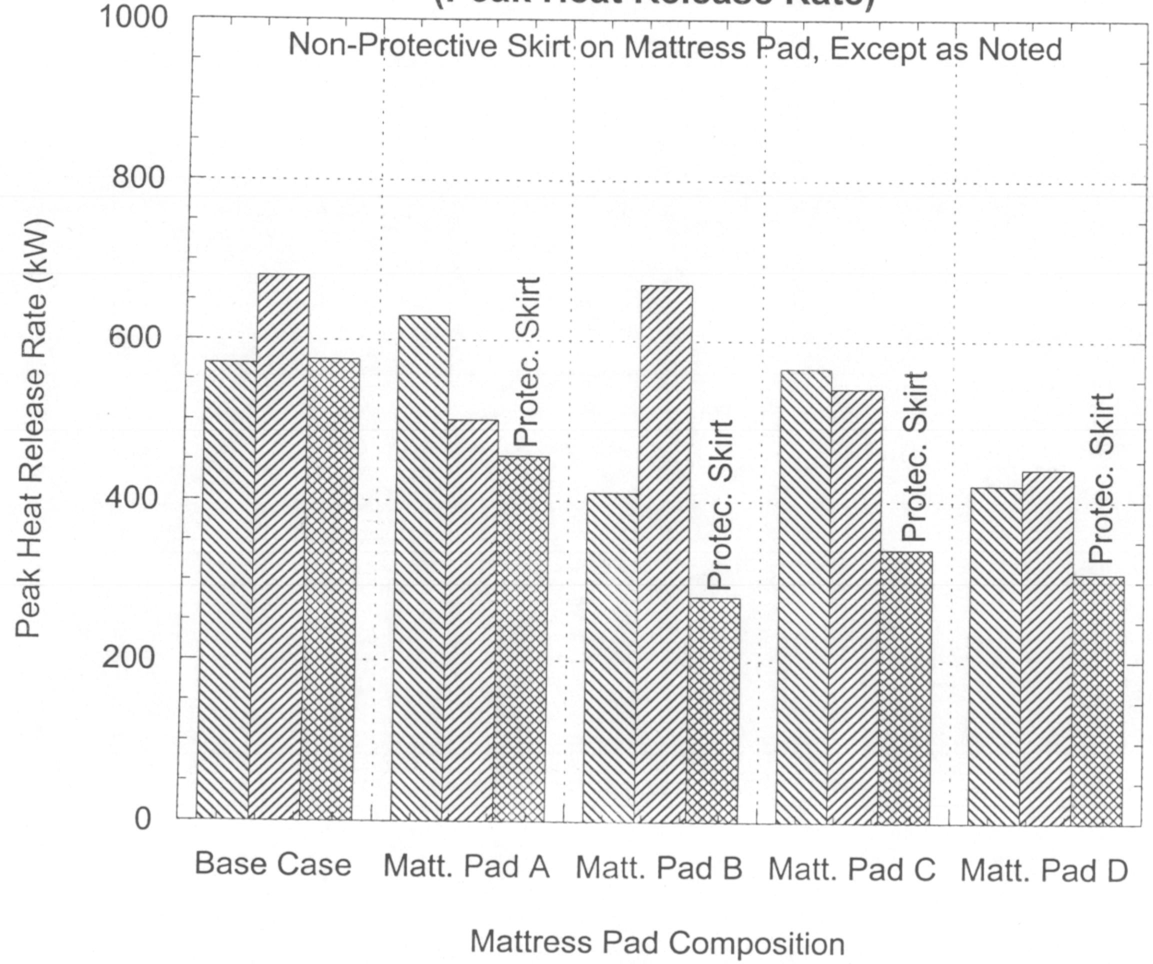

Figure 7
Effect of Mattress Pad Composition For M5 Mattress/Foundation (Time to Peak Heat Release Rate)

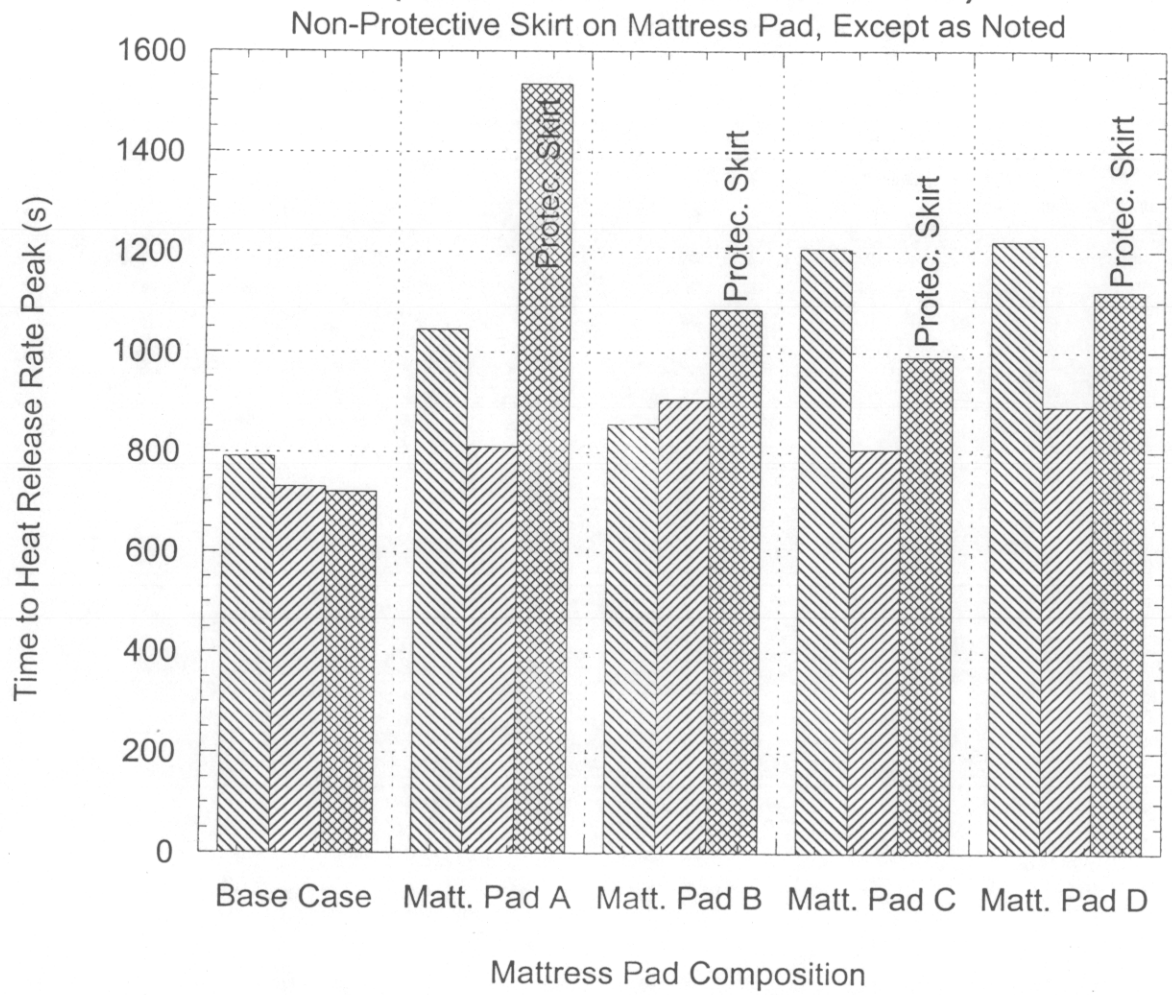

Figure 8
Effect of Bed Clothes Composition Variation
Based on "A" Materials
(Peak Heat Release Rate)

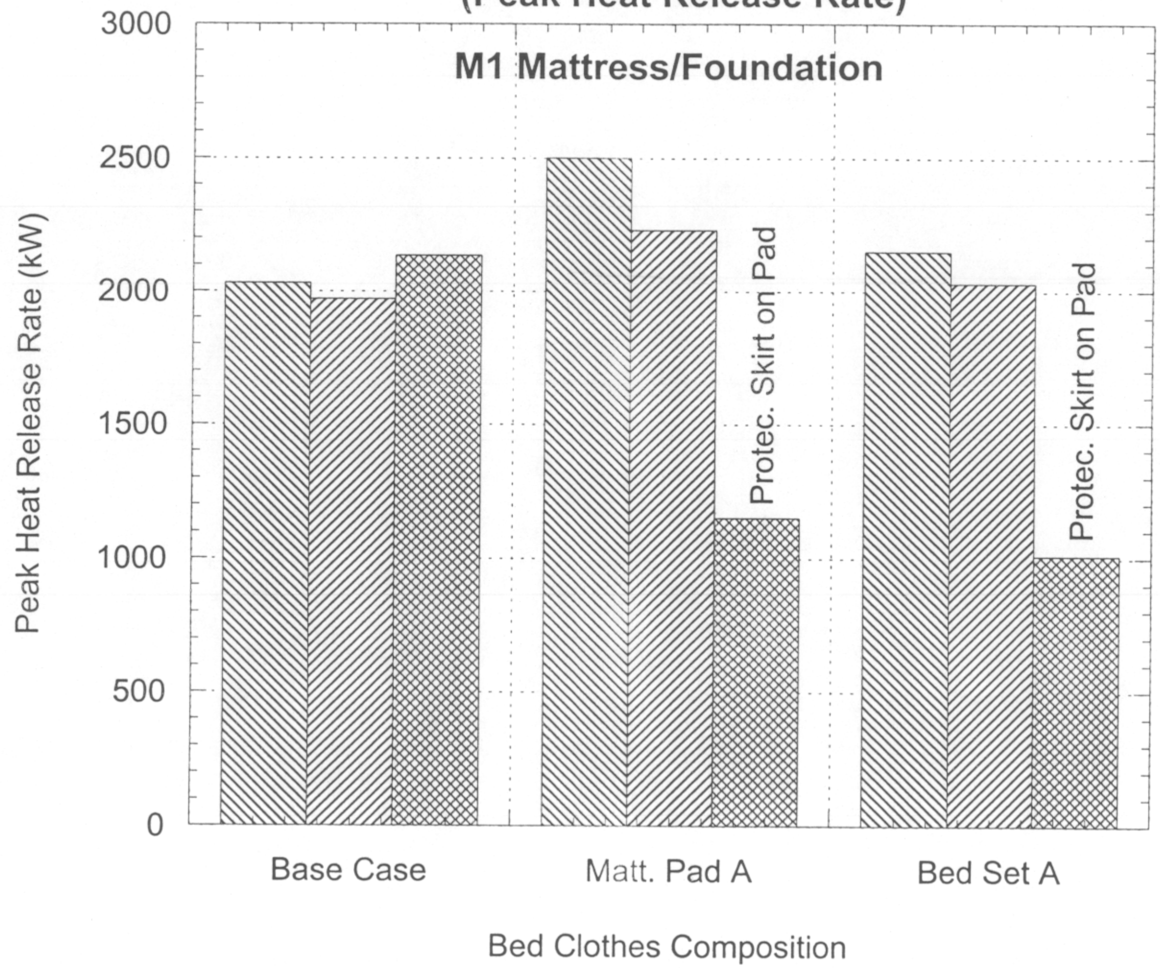

Figure 9
Effect of Bed Clothes Composition Variation
Based on "C" Materials
(Peak Heat Release Rate)

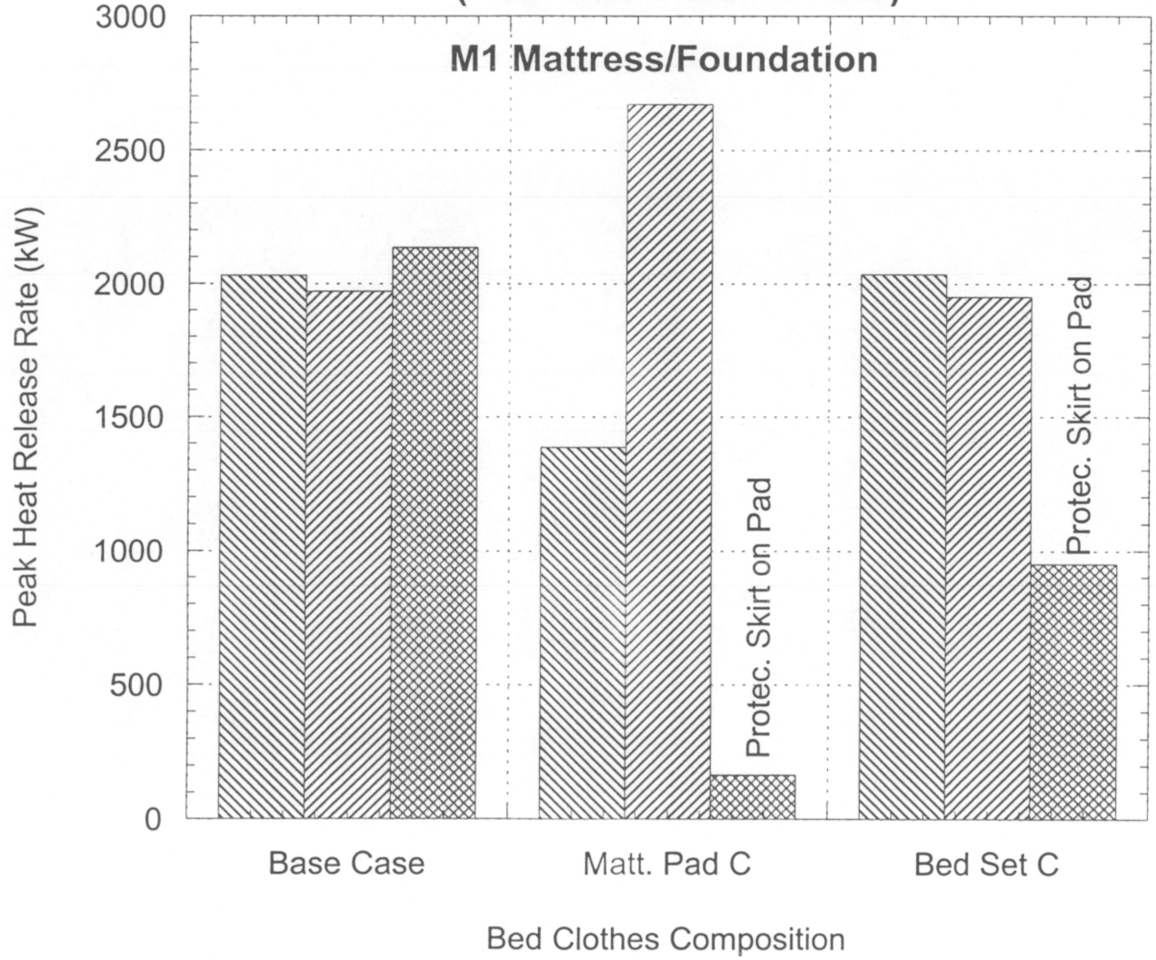

Figure 10
Effect of Bed Clothes Composition Variation
Based on "A" Materials
(Peak Heat Release Rate)

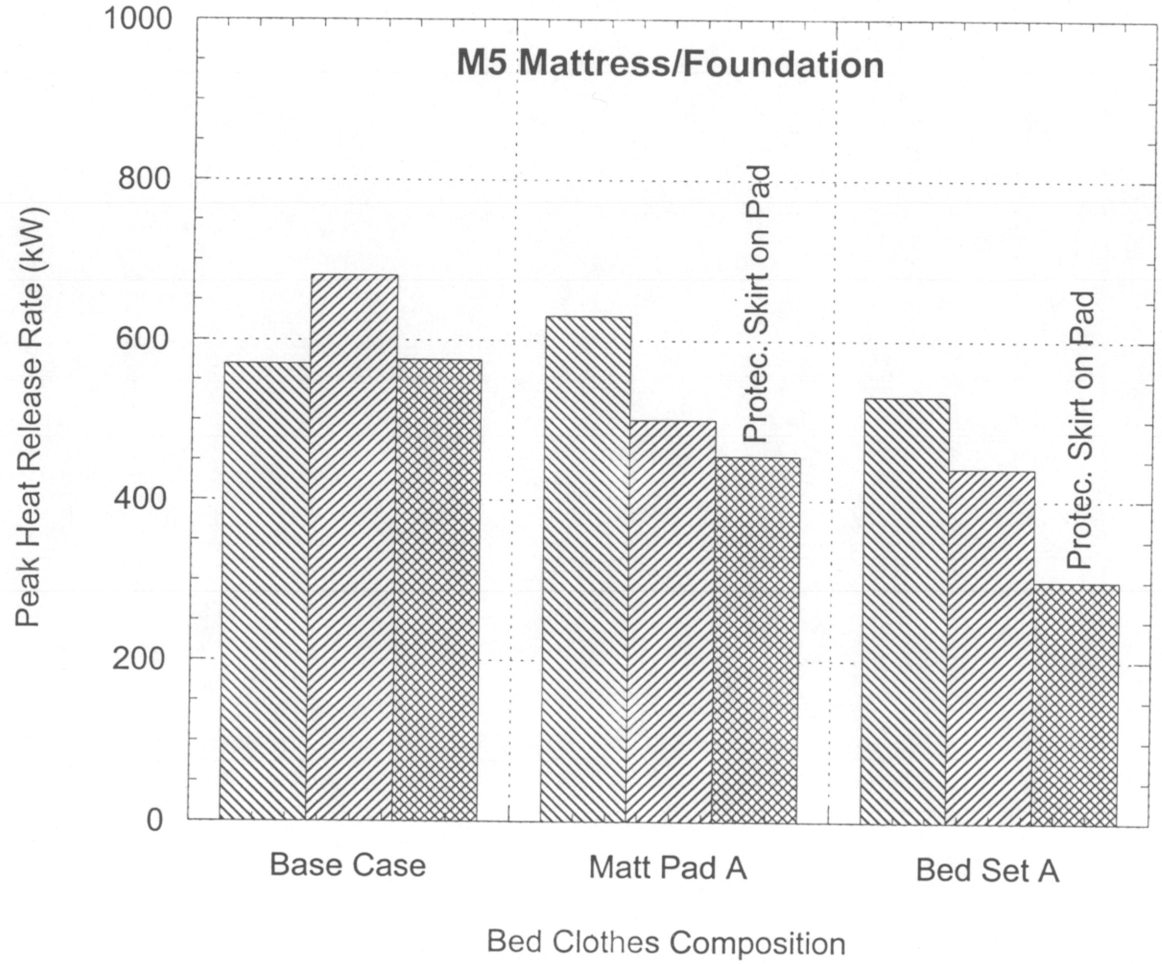

Figure 11
Effect of Bed Clothes Composition Variation
Based on "C" Materials
(Peak Heat Release Rate)

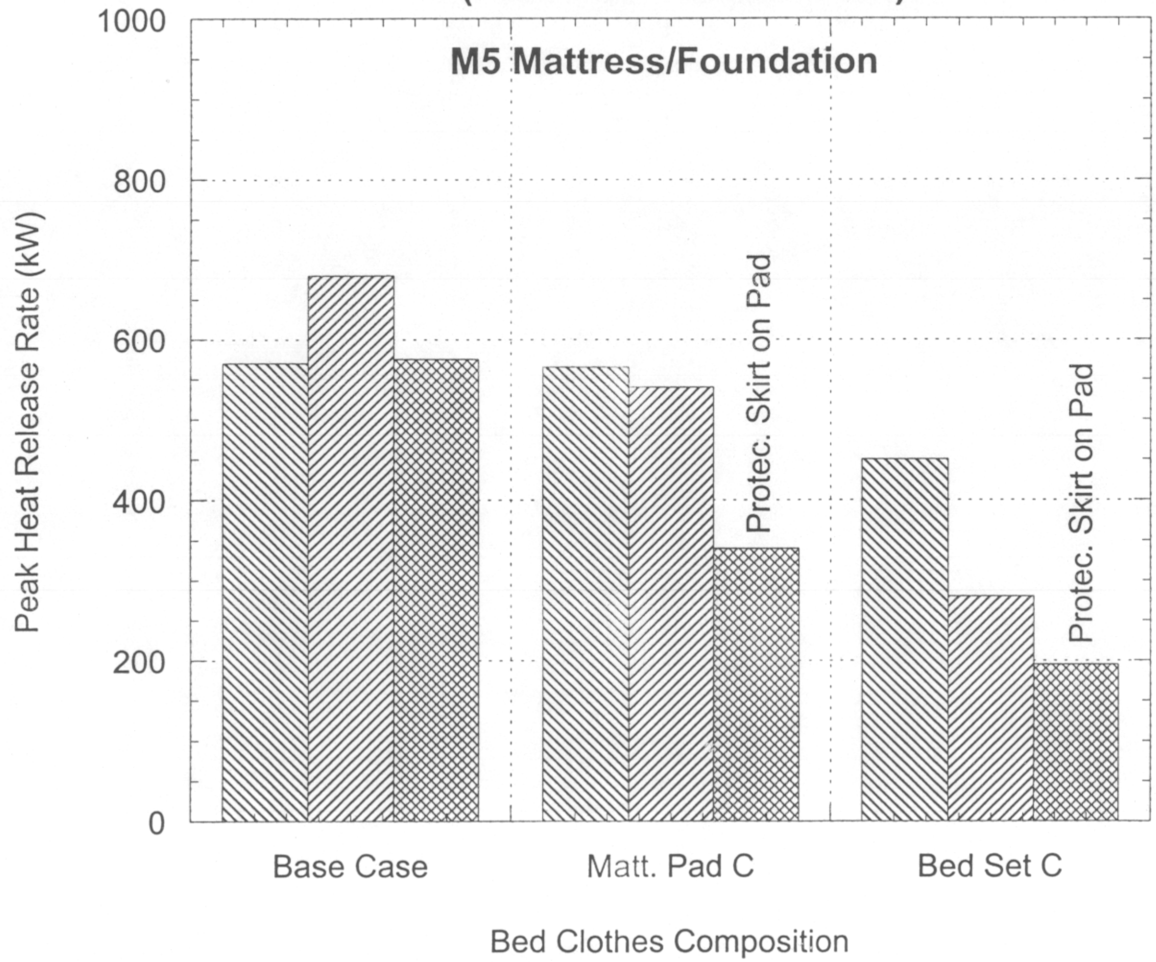

Figure 12
Effect of Bed Clothes Composition Variation
Based on "D" Materials
(Peak Heat Release Rate)