NIST Technical Note 1465

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Thomas Ohlemiller

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Thomas Ohlemiller

Building Fire Research Laboratory
Gaithersburg, MD 20899

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A Study of Size Effects in the Fire Performance of Beds

T. J. Ohlemiller

Abstract

Three mattress/foundation designs of varied fire resistance were tested with the California Technical Bulletin 603 protocol (TB 603, using a pair of gas burners as the ignition source) and also with a set of heavy bedclothes ignited by a match-size flame. All designs were tested in both twin and king size; one design was tested also in queen size. A major goal was to assess the possible existence of a mattress size dependence in the response to the TB 603 protocol. All testing was done inside a room (3.66 m wide by 4.27 m long by 2.44 m high) with a single door opening half the width of a fully opened door. The design yielding the lowest peak heat release rate (HRR) showed no mattress size dependence. The two other designs were more ambiguous but showed no size dependence in their response judged against the TB 603 pass/fail criteria. The bedclothes fires atop the lowest HRR mattress showed a large size dependence in their HRR peak. The queen and especially the king size bedclothes peaks were large enough to pose serious secondary ignition threats in a realistic bedroom context. When tested atop the other two, less resistant, mattress designs, the bedclothes fires yielded controlled fires for the twin size but runaway fires for the king size.

Introduction.

The Consumer Product Safety Commission is considering a regulation of the flammability behavior of mattresses and their associated foundations. The probable test method at the heart of this regulation is expected to be closely analogous to that described in California Technical Bulletin 603. In that protocol, a twin size sample of the mattress and foundation is subjected to a pair of gas burners designed to mimic the local heat flux conditions imposed by burning bedclothes. The heat release rate (HRR) that ensues from this exposure is measured over a 30 min period. In TB 603, the peak HRR must not exceed 200 kW in this period for a mattress/foundation design to be acceptable.

The TB 603 protocol accepts testing in either an open hood environment or in a burn room. A substantial fraction of the available fire testing facilities in this country can use only a burn room environment. A room can impact the intensity of burning of an object in ways described below. Previous data [1] indicated that TB 603 results would not be expected to depend on the ambient surroundings (room vs. open hood) as along as the pass/fail limit was as low as 200 kW. The same study showed that some effect of the room environment on the fire could be seen for higher peak HRRs [1].

Roughly two-thirds of the beds now being sold in this country are larger than twin size. On the other hand, the fire test facilities that use burn rooms cannot accommodate any size larger than twin. When burned under an open hood, unimproved beds (i.e., those having no fire protection) larger than twin size give higher peak HRR values than those seen with twin beds. This raises the issue as to whether tests of twin beds of less flammable design might underestimate the heat release rate behavior to be seen in larger beds. Since real world bed fires occur in rooms, this issue must be considered in light of the possibility that room effects may influence the magnitude of any bed size effect that is seen. Bed size effect on peak HRR, in the context of a room, is, therefore, the subject of the present study.

A room environment can impact a burning process within it by at least two mechanisms. The first mechanism (and the principal concern here) involves thermal feedback to the burning surfaces on the bed. When any object is burning in a room, the buoyant, hot smoke rising from the fire is captured beneath the ceiling, forming a layer at least as deep as the distance between the ceiling and the top of any opening (a door or window)[1]. Because of its soot content, such a layer is typically a good radiator of heat, especially as its temperature rises due to continuing heat input from the fire. Downward radiation from the smoke layer can impact the rate of spread and HRR of the fire feeding this smoke layer, especially for exposed burning surfaces that face upward. (In contrast, a fire with little unobstructed view of the hot upper layer, such as an internal foundation fire, would show little or no response.) Surfaces that are affected then contribute more heat to the upper layer, further enhancing the feedback to themselves. The potential thus exists for a strong enhancement of overall HRR from upward facing surfaces. Exposed vertical surfaces may show a weaker response due to their lesser view of the radiation from the smoke layer.

The other mechanism by which a room environment affects a fire is oxygen limitation. With an open window or door, this only comes into effect as the room approaches flashover and so much material is burning that the opening cannot supply the needed air (while still allowing hot smoke to escape). Since this limitation comes into play at a HRR of about 1 MW for existing test rooms, it is not a concern here.

The susceptibility of a mattress to room effects in a TB 603 test is design dependent. In particular, the amount and location of continued flaming after the gas burner exposure varies with design. As noted above, burning zones on top of the mattress are most likely to experience direct feedback from the smoke layer. For this reason, three different designs (all having greatly reduced flammability relative to current commercial practice) were used in this test, though there was no way to select *a priori* designs prone to top surface burning. An attempt was made to find designs likely to give differing HRR levels.

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[1] A closed room will behave in a more extreme manner since smoke cannot escape. The smoke layer will fill the room, encompassing the fire, and when the available oxygen drops (to the neighborhood of 10 % to 15 %), the fire will go out. It may take little burning to reach this condition (ca. 1 kg for a small bedroom) and room conditions will be hazardous before this point is reached [2]. This situation is not addressed here.

The TB 603 protocol mimics (by means of the pair of gas burners) the local heat flux that burning bedclothes bring to bear on a mattress or foundation. It does not mimic the complete fire behavior of burning bedclothes. Local ignition of a full set of bedclothes by a match size flame leads to a spreading fire on the bedclothes assembly that typically grows (in an open hood environment) to a maximum burning area in the region of 1 m^2 to1.5 m^2. The burning area does not grow larger than this because the spreading flame front is followed by a burn-out front which represents the point at which all of the layers have been consumed. The burning zone (between the ignition front and the burn-out front) spreads over a bed in a time of the order of 10 min. Twin size bedclothes themselves may give a HRR peak of 200 kW or more. They too are thus potentially subject to room heat feedback effects. In examining bed size effects in this study, some tests of each design were therefore carried out with burning bedclothes rather than the TB 603 gas burners.

Experimental Details.

All of the mattress designs were based on box springs in their interiors. Other available details were as follows:

- Design AA was a two-sided tight top mattress that utilized flame-retarded cotton as both a barrier and as part of its cushioning. The material in the mattress side panels was not identified. The foundation was based on conventional linear wire springs attached to a wood base; it had a continental edge.
- Design BB was a high-end mattress with a velour ticking and extra thick top/bottom padding. It also was a tight top design. It utilized a high loft barrier under the ticking. Its foundation contained coil springs attached to a wood base; it had a continental edge.
- Design CC was a two-sided pillow top mattress that used an unidentified barrier layer under the ticking. Its foundation was unusual in having a full three-dimensional wood frame; it also had a continental edge.

Two of the mattress designs, AA and CC, were tested in twin and king size; design BB was tested in queen size as well. Twin and queen size mattresses both have one piece foundations. King size mattresses are supported by a pair of foundations, each approximately the size of a twin foundation.

The test room layout is shown in Figure 1. The interior was 3.66 m wide by 4.27 m long by 2.44 m high (12 ft by 14 ft by 8 ft). This room size represents a compromise between two opposing factors: (1) a desire to maximize room effects by keeping the room small and (2) a need to have a room sufficiently large for a king size bed plus the gas burner assembly. The wood frame construction was lined with 1.3 cm thick calcium silicate board above the mid-height; this lining was full-height over the 2.3 m wide wall section where the head of a bed was nearby. The remainder of the room was lined with 1.3 cm thick gypsum board. However, the area under the bed was covered with 1.3 cm fiber-cement board. These lining materials precluded any significant heat release contributions from the paper lining of the gypsum board; the other lining materials are inert. The thermal properties of the calcium silicate board lining the walls and ceiling are comparable to gypsum board except in the temperature range from about 120 ºC to 210 ºC where gypsum dehydrates and effectively behaves as if it has a much larger heat capacity. In the present tests this means that the walls and ceiling will tend to heat more rapidly than gypsum board in this temperature interval. Since wall heat-up is a relatively slow process[2] compared to other critical processes in these tests, this difference in thermal properties is not believed to have any significant effect here.

The fiber-cement board under the bed is likely also to be different in its properties from materials such as wood flooring that might be found in real bedrooms. This could mean that the development of a melt-drip fire on the floor differs here from such an event in the real world. None of the mattress designs examined exhibited any marked tendency to yield a melt/drip fire on the floor. In the absence of bedclothes, the only flaming melt material that reached the floor was from the dust cover on the bottom of the foundation; this created minimal fires of no real concern. Flaming bedclothes frequently drop burning material to the floor; the resulting layers are typically thick enough for their burning to be uninfluenced by the floor material. Carpeting under a bed may make some of these floor fire issues more serious but that issue was not examined here.

The bed foundations were placed atop steel bed frames 10 cm to 11 cm high (essentially the same as those specified in TB 603). Precautions were taken to preclude an issue noted previously with the 2.5 cm wide steel angle used in the twin frame specified in TB 603. It had previously been found that when a foundation, with its typically rounded corners, was placed atop the square-cornered bed frame, a small gap (up to several mm) appeared between the frame and the foundation corner (at all four corners). This gap appears to offer a potential path for small flames on the ticking of the foundation to reach the underside of the foundation. Such behavior was never actually witnessed in several closely-watched tests but the potential for it was deemed an unrealistic artifact of the narrow support frame (real bed frames tend to be wider than 1 inch). Here each corner of the bed frame was covered diagonally with a double-layer swath of heavy duty aluminum foil to close off this gap.

The room had two openings. That shown at the top in Fig. 1 was an access door which was open during the burner exposure. It was closed immediately after the burner was removed through it. Its periphery was sealed with ceramic wool. The other opening, that in the left wall in Fig. 1, represented a partially open bedroom door and it remained fixed except when the test sample was being moved in or out of the room. By not being fully open, this doorway yielded a somewhat restricted air flow to the fire. The intent was to force the smoke layer temperature upward somewhat to enhance the room feed back effect in the same manner it would be if a bedroom door were partially closed. This also forces the smoke layer to be thicker (lower). For these tests it was not considered desirable to have the smoke layer so low that it obscured the fire on the top of the bed. CFAST[3] predictions were used to select the half-normal doorway width used throughout

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[2] The time for a temperature wave to penetrate a 1.3 cm calcium silicate board is of the order of 20 min. The wall or ceiling will thus require a time of this order to fully respond to the hot smoke layer with which it is in contact.

[3] CFAST is the NIST Consolidated Fire and Smoke Transport model.

these tests. Those predictions indicated that the smoke layer temperature would be increased by roughly 60 ºC (relative to the fully open door case) if the fire peaked at around 400 kW. The corresponding change in maximum radiative feedback from the smoke layer (taken as a black body with a view factor of unity for the top of the bed) was from 4.6 kW/m^2 to 7.0 kW/m^2. These calculations treat the fire as having a single, concentrated plume. In reality the fires tended to be strung out linearly and spatially patchy. This could be expected to enhance room air entrainment, lower the smoke layer temperature and thus decrease the actual radiative feedback below these estimates.

For differing bed sizes, the burner-exposed side was always in the position shown in Fig. 1. (The position of the opposite side of the bed relative to the wall at the bottom in Fig. 1 thus varied with bed size.) Thus any effect of the airflow into the room on the early part of the bed fire should have been independent of bed width. In practice, the air flow did not appear to have any noticeable effect on the bed fire. The head of the bed was always placed approximately 13 cm from the wall. This allowed burning to progress along this side of the mattress and foundation.

As Fig. 1 indicates, the half open door was located beneath the hood of the NIST 3 MW calorimeter to permit HRR measurement. The details of this device are discussed fully in Ref. 3. The expanded relative uncertainty for the larger fires recorded here (several hundred kW) is ± 11 %; for the smallest fires (below 50 kW) the expanded uncertainty rises to ± 27 %.

Two of the windows were used for video cameras, that in the upper wall and that in the lower wall, as seen in Fig. 1. The fields of view of both cameras were less than the length of the bed so the cameras had to be panned to follow fire spread. An observer could also use the half open door. In general, viewing of the fire behavior was much less satisfactory than that which is possible in an open hood.

The tests were conducted in a randomized order but all tests of a given size bed were grouped together. This was a concession to the awkwardness of moving the heavy king size bed frame in and out of the room.

High ambient humidity during much of this test series led to a potential source of baseline drift in the calorimeter readings. It was noted that by about 30 min into a test, there were signs that water vapor was just beginning to penetrate the water trap system and reach the oxygen meter where it caused some signal drift. Since the TB 603 cut-off time is 30 min, the data were logged up to that time. Immediately, after this, while the test continued, the calorimeter system was switched off line for 5 min while the water traps were replaced. Each test then continued for a full test period of 60 min (unless the fire was extinguished, as discussed below). In only one test did this gap in the data lead to a significant loss of pertinent results. That case was for an AA design with bedclothes. The second peak was missed; its size was estimated visually from the flame volume and previous experience.

To preclude fire damage to the room lining, some of the tests were stopped before they reached their full intensity. In the early tests the stopping point was as low as 400 kW. As experience with the behavior of these systems was gained, the stopping point was raised to 800 kW. This left some ambiguities in the interpretation of certain results, discussed below, that had to be resolved through other sources of information. When a fire is referred to below as a "runaway fire", it was, in the author's judgment, on its way to flashover at the time it was extinguished.

Results and Discussion

Table 1 summarizes the data obtained in this study on peak HRR and time to that peak. Tests in which the fire was extinguished before it reached its full intensity are denoted by a bold **E**. Gas burner tests with twin size samples of design BB all gave very low heat release rates. The timing of the very weak, post-burner peaks was difficult to quantify; this is indicated in the Table.

Gas Burner Tests. Figure 2a summarizes the peak HRR for the gas burner tests as seen over the full 60 min test period. The time to the peak or the time of extinguishment is also shown on each bar (which represents one test). The results nearly all fall at the extremes of HRR behavior, giving either very small or very large fires. Thus all tests of design BB gave essentially only ticking fires[4]. These fires were most persistent in the peripheral crevice between the mattress and foundation (a behavior seen often in other studies [4, 5]) and these crevice flames became most intense in the corner areas. A break in the barrier (on the mattress side, near a corner, in the last 15 min of the test) was seen only once in these BB tests and it appeared to have no adverse consequences by the end of the test.

Clearly, there was no significant size effect with the TB 603 burners when they were applied to design BB. Here the fire had no scale dependence. It amounted to a rather patchy and variable burn zone(s) propagating in the mattress/foundation crevice. (The fire on the mattress top went out soon after the burners were turned off.) The burning zones were variable in length and time reaching 1 m or more in width in some cases. The HRR from such a fire has no dependence on the total length of the crevice that it is in since it never occupies that full length at any one time. In fact the crevice fires never even made it all the way around the full periphery of the twin size beds in the 60 min tests. At the same time, the small HRR of the crevice fires means that they have no chance of building up a smoke layer in the room hot enough to yield any noticeable feedback to the burning process. Thus there is no mechanism for a mattress size effect in a case like this.

The king size BB, as well as the other mattress designs, had, as noted above, a two part foundation. The crevice between the two foundations, which lay under the longitudinal centerline of the mattress, appeared to form an area of potential vulnerability. The

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[4] Such a fire appears to involve only the ticking itself. In actuality, especially when it persists in the crevice area, it is likely that it is also consuming pyrolysis vapors from the barrier (a charring organic material) below the ticking and possibly even from material layers below the barrier.

horizontal mattress/foundation crevice fire, when it reached this vertical crevice between foundation sections, would intensify and “bore in”. That is, the fire moved inward into the vertical crevice over the full foundation height, seeming to form a chimney as the foundation side materials charred and shrank, leaving space for an improved air supply. Any flames in this chimney impinged on the bottom of the mattress. As threatening as this appeared in the tests performed here, it did not noticeably change the results with any of them. The BB design could withstand this; the other designs were in trouble for other reasons by the time this effect came in to play. However, since this is a feature unique to king size beds and is thus not tested in TB 603, it is worth bearing in mind when barrier materials are chosen.

When tested with the gas burners, the king size versions of designs AA and CC all gave runaway fires that were extinguished as they passed 800 kW. Note that this occurred sooner with design AA than with design CC; design CC easily passed the TB 603 criteria whereas design AA did not. Aside from this, the HRR results in Fig 2a do not allow a distinction between the two designs since all of the tests were halted. Visually it was apparent early-on that the flames on the sides of the AA design were substantially more intense; the laterally spreading fires (moving in opposite directions from the ignited region) covered the entire height of the mattress and foundation side rather than being essentially confined to the mattress/foundation crevice as with design BB and CC. Similarly, design AA showed a continuing, radially spreading flame zone on top of the mattress whereas designs BB and CC did not.

Figure 2a seems to show a much lesser fire intensity from both AA and CC twin size beds, as compared to the king size versions of the same designs. In fact, any size effect was not nearly so pronounced, as will be seen.

Consider the AA case first. All of these fires, for both bed sizes, looked essentially alike in terms of fire growth patterns and HRR for roughly the first 20 min. They looked like the king size design AA fire described above. The mechanisms behind their increased HRR after about 20 min were the same – foundation fire growth coupled with some evidence of interaction with the wall on the head end of the bed. The HRR up to this time (less than 80 kW) and the location of a significant fraction of it within the foundation precludes a sufficiently hot upper smoke layer and a sufficient fire area in its radiative field to initiate room feedback effects. Even the one design AA test which did not run away, the first twin test, started to run away due to a foundation fire; for reasons which were not apparent, in this one case, the foundation fire did not yield an increased mattress fire before everything died back. In any event, prior to runaway, the fires were all too small to interact with the room and the runaway was by a mechanism which did not depend on mattress size. Thus the second and third design AA twin tests were very likely on their way to fire sizes as large as were seen in the king size tests (before the king beds were extinguished) but these twin bed fires were stopped earlier in this fire growth process. This is not to say that the king size mattress would not ultimately give a larger fire than the twin size mattress but both would likely have pushed a room toward flashover on essentially the same time line. Thus, from the viewpoint of flashover prevention or from the viewpoint of TB 603 pass/fail, the two mattress sizes were equal.

The increased threat represented by the king size AA mattress design is probably to spaces beyond the room of fire origin.

The CC mattress designs are somewhat more ambiguous as to mattress size effect on overall fire behavior. The first twin bed test involved a defective sample – the barrier was missing from one quarter of the mattress periphery – and so that result must be discarded. The fires in the other samples of both sizes started and grew in very much the same manner, primarily along the mattress/foundation crevice initially. Eventually this fire would reach the vertical mattress seam at the foot end. This seam appeared to lack combustion resistance and would open rather readily, allowing flames into the mattress interior. The fires would thus grow from the foot end on and into the mattress. Sometimes this was abetted by growth from the head end, on the mattress top, as well. Partial foundation involvement, generally late, was seen only with the twin mattresses, for no evident reason. Late in the tests, the larger top area of the king mattresses began to make a difference in that it yielded a sufficient HRR to generate room feedback. This caused the king size mattress fires to run away, with minimal evident contribution from the foundations. The twin mattresses developed the same mattress top/interior fires on approximately the same time scales but did not run away before 60 min had elapsed. Both of the twin size fires appeared capable of running away, given a little more time, and one was in fact rapidly increasing in HRR at 60 min when it was suppressed. The net result is that the king size mattresses did run away late in all three of their tests while the twin size mattresses appeared to be approaching this point when the tests ended. Here, at the very least, the effect of bed size was to shorten the time to a runaway condition by several minutes. Since the tests were ended at 60 min, we cannot be certain that the CC twin bed fires would have run away or merely become larger and more threatening as their foundations began to burn more extensively along with the mattresses. Again there was no size effect on TB 603 pass/fail (both sizes passed).

Figure 2b shows the peak HRR results that were seen within the first 30 min of the test. These thus indicate directly which specimens passed the 200 kW limit (anytime in the first 30 min) set in TB 603. As noted above, design AA had only one pass, a twin mattress. Design CC had only one fail, a twin mattress but, as noted above, this specimen was defective, lacking a portion of its mattress side barrier. All of the design BB specimens passed the TB 603 HRR criterion. The general lack of a mattress size effect on TB 603 passage or failure can be seen in Fig. 2b.

Overall the effect of bed size was minimal, having a definite effect only in the case of the CC mattress design. It was this design which showed the greatest vulnerability to room feedback by virtue of burning extensively on the mattress top surface. Even here the effect was exhibited only late in the tests and may have amounted only to a shortening of the time to a fire size which threatened flashover. A definite contributor to the CC mattress burning behavior was the poor heat resistance of the thread in the vertical side seam placed here on the end away from the wall. This allowed a relatively early passage of flames into the mattress interior. Had a more resistant thread been used, it is possible that the runaway behavior seen here would have been pushed beyond the 60 min point.

On the other hand, burning bedclothes would find any such vulnerability much sooner, so lateness in a test does not necessarily mean an event is non-threatening in the real world.

Appendix A discusses barrier materials in general terms and some issues related to how and when they might show vulnerabilities in a TB 603 test and also in a real world fire involving burning bedclothes.

Bedclothes Tests. As noted in the Introduction, real world bed fires usually involve burning bedclothes initiated locally by some small flame source. Current commercial bedclothes, when ignited locally, will allow progressive flame spread over their entire outward facing surface in a time of the order of 10 min. Since this fire is on surfaces facing upward and sideways in a room environment, it is again in the right position to be influenced by radiation from hot gases accumulating in the upper part of the room.

It was noted earlier that the burning area on bedclothes (under an open hood) reaches a roughly steady value that is much less than the total outer area of the bedclothes. Thus, if the HRR per unit area of bedclothes is small enough, there will not be enough total HRR from the bedclothes to push the upper smoke layer into a domain where radiant feedback is significant. In other words, despite the fact that the situation is, in one sense, primed for significant feedback and therefore a strong size effect, it does not necessarily occur.

There are two other parameters of this problem, as well. First is the sensitivity of the burning rate of the bedclothes assembly to added external radiation. This type of sensitivity is readily measured in a device such as the Cone Calorimeter where the behavior of a sample subjected to various fixed levels of radiant heat flux is measured. The other parameter is the ignitability of the topmost layer of the bedclothes; here this is the cover fabric on the comforter. If this layer readily ignites[5] in the combined heat from flames spreading on top of the bedclothes plus radiation from the hot smoke layer, the spreading flame front it represents will run further and further ahead of the burn-out front on the bedclothes. The net result is that the area of burning bedclothes increases beyond that steady-state value seen in an open hood and the net total HRR goes up, increasing the smoke layer temperature, which, in turn, increases the smoke layer radiation back to the bedclothes, etc. The stage is set for the HRR to run upward. Since the total bedclothes area is bigger for a larger bed, the HRR from the larger bed can run further upward.

Putting together all of the above parameters to determine their net effect and thereby predict the overall behavior of burning bedclothes in a room enclosure requires a sophisticated model such as the NIST Fire Dynamics Simulator (FDS, Ref. 6). That remains for a future study. Here we confine our observations to the experimental results obtained for one set of bedclothes.

Figure 3 shows the results of this type of scenario on top of design BB beds of three sizes. As noted in the Introduction, the fires were started by applying a match-size flame to the bottom forward (head end) edge of the folded back region of the hanging

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[5] Ease of ignition for a fabric like this depends both on its chemical stability and also on its weight per unit area. Thinner (lighter weight) fabrics will be more rapidly ignited.

bedclothes. The early HRR peaks, in the first 1000 s, are dominated by the bedclothes[6]. There is quite clearly a major bed size effect on the burning of the bedclothes in this room context; the peak HRR goes from about 260 kW for the twin size bed to about 800 kW for the king size bed. Note that the HRR curves begin to depart from one another in the neighborhood of 200 kW, roughly 4 min to 4.5 min after ignition. The differences in burning area that prompt this early divergence are too subtle to be seen in the restricted-access videos taken of these tests. Later one can clearly see the effect of radiative pre-heating well ahead of the spreading flame front on the comforter in the king size case; the heat causes the cover fabric on the comforter to wrinkle, possibly because the polyester fibers in it are melting. Note that the king size bedclothes, with their roughly doubled area and mass relative to the twin size bedclothes, burned up in a time that was essentially the same as that for the twin size bedclothes.

The size of the bedclothes HRR peak in the king size bed case is truly remarkable and it poses a substantial flashover threat by itself (i.e., via ignition of secondary objects placed nearly anywhere within the same room) using the criteria developed in Ref. 1. Even the queen size peak is threatening in the presence of other significant flammable objects in the bedroom.

Figure 4 shows how the bedclothes HRR peak size on design BB beds relates to the top area of the bed. Note that the least squares fit line is second order in bed area. This greater than linear dependence follows from the increasing heat feedback which a larger bed receives from the hot smoke layer in the room environment.

The impact of this intense bedclothes fire on the bed beneath it is clear in Fig. 3, in the HRR behavior after the bedclothes peak. Recall that, after the gas burner exposure for design BB, there was persisting flaming but minimal HRR peaks, regardless of mattress size. Here, after the bedclothes fire died back, there was an extended lull and one saw again the types of localized flaming that the gas burners exposure induced – mainly persisting crevice flames. For the twin bed, while the gas burners produced long-lived crevice flames (ca. 20 min to 25 min), especially at the corners, for this design, the bedclothes produced corner flames that lasted even longer[7]. This appeared to be the source of the second, later flare-up for the twin size bed in Fig. 3. Persisting corner flames eventually got a fire going in the mattress interior; there was no evident foundation involvement.

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[6] The HRR here is predominantly but not exclusively due to the bedclothes. The top and sides of the mattress are contributing some heat but there is no way to distinguish that portion. Design BB was chosen for this because, on the basis of the gas burner tests, it was believed that it would contribute the least to the bedclothes HRR peaks.

[7] A substantial difference between the gas burner exposure and the burning bedclothes exposure is the total amount of heat deposited in the mattress/foundation. The greater heat content in the case of the bedclothes fire apparently favored a continued fuel supply to the crevice flames, sustaining them long enough to burn through the mattress barrier.

The king size bedclothes fire, on the other hand, constituted an exposure to the mattress that was far more intense than those[8] measured in Ref. 7 and which were the basis for the design of the gas burners. Indications of this increased intensity were evident on the video tapes. A horizontal flame front was driven down the sides of the foundation by the hot smoke layer radiation. Two strong puffs occurred in the mattress as the bedclothes peak was receding. Two and possibly more holes appeared in the mattress side barrier; these were conceivably caused by the over-pressurization during the puffs but they were not visible until several minutes afterward. It was these holes which allowed flames into the mattress interior and eventually yielded the second, large HRR peak (which was extinguished).

The overall behavior of the queen size BB mattress with bedclothes was comparable. There was a weaker puff in the mattress followed later by multiple holes in the mattress side barrier which led to an interior mattress fire that provided the second HRR peak.

The gas burner exposure cannot be expected to be a good predictor of response to the queen and king size bedclothes fires in a room context since these fires are more intense than that which the burners mimic. On the other hand, these bedclothes fires constitute a substantial threat in themselves and, furthermore, they are not delayed like the mattress/foundation fires.

The preceding results do indicate that if the queen and king bedclothes fire size was limited to the 200 kW size specified in TB 603 for mattresses, it is likely that the later mattress fires seen in Fig. 3 would also be brought under control.

Bedclothes tests were also conducted with designs AA and CC in twin and king size (one test each); the results are summarized in Fig. 5. Mattress design clearly has a major effect on the peak HRR during the bedclothes fire; see Fig. 6 for the twin size beds. The AA design more than doubled the peak HRR seen with the BB design. For design AA even the twin size bedclothes fire peak is a substantial secondary ignition threat by the criteria given in Ref. 1. Designs BB and CC are much less threatening in this regard. Figure 6 is a clear illustration of the extent to which the mattress and foundation can, in some cases, contribute heat to the bedclothes peak. In the case of the AA design this appeared to take the form of prolonged burning of the upper layers of the mattress during and after the bedclothes fire passage. Eventually this led to multiple holes in the mattress and finally a combined mattress/foundation fire to yield the second, later HRR peak. The behavior of the CC twin design was similar, though less intense and slower to yield a mattress/foundation HRR peak. Again there were indications that the bedclothes fire was partially compromising the protective barrier on the mattress and thereby extracting more heat from the system.

When the same type of bedclothes were burned atop king size versions of designs AA and CC, the room-enhanced bedclothes fire proved to be too much for the mattress barriers and the bedclothes fires had to be extinguished as they passed 800 kW; see Fig.

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[8] Various sets of twin-size bedclothes were burned in an open hood atop a special inert mattress. The bedclothes set most comparable to that used here gave less than 200 kW as its peak HRR.

5. In the case of design AA, all outer surfaces (mattress top and sides plus foundation sides) were caught up in the strong room feedback and forced to burn with enhanced intensity. There did not appear to be time for the interior of the mattress or foundation to make much contribution by the time the fire was suppressed.

Conclusions.

The significant conclusions from this study are as follows:

- When tested with the TB 603 gas burners and in a room context, a mattress/foundation design yielding only a very low HRR (design BB) exhibited no signs of a size dependence in its burning response.
- The results for designs yielding greater HRR were somewhat obscured by differing test termination conditions. However, close inspection of the available evidence indicates that design AA would yield runaway fires at essentially the same time regardless of mattress size. Both fires would thus have failed the TB 603 HRR criteria in the same time frame though the fire from the larger bed would probably ultimately be larger. Design CC, with HRR results falling between those of BB and AA, appeared prone to yield somewhat more rapid fire development with the larger mattress and the fire size was possibly prone to be larger as well. Both sizes of Design CC would easily pass TB 603 criteria since all fire growth was in the last 15 or less minutes of the 60 min test period.
- Bedclothes fires were found to be strongly dependent on bed size when burned in a room context. This appeared to be the result of a combination of physical parameters which favored maximal response to the heat feedback from the hot smoke layer to the burning bedclothes.
- The peak HRR from queen size and, especially, king size bedclothes was found to constitute a strong secondary ignition threat and thus would be likely to produce flashover in many real world fires. The threat is enhanced by the fact that this peak occurs within 5 min to 6 min of ignition by a match-size flame.
- The room-enhanced bedclothes fires for king size beds overwhelmed the protective barrier of two of the designs (AA and CC) leading to runaway fires during the bedclothes peak. Even the most resistant design (BB) was compromised by these enhanced bedclothes fires (queen and king size) and eventually yielded runaway fires.

Acknowledgments

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Table 1. Summary of Peak HRR Data from CPSC Bed Size Study

Design / Size / Ign. Condition	**Replicate Values of Peak HRR (kW) @ Time (s)[9]**		
AA / Twin / Gas Burners	140 @ 1648	408 @ 1460 / **E**	550 @ 1249 / **E**
AA / King / Gas Burners	>800 @ 1574 /**E**	>800 @ 1625 /**E**	>800 @ 1534 / **E**
AA / Twin / Bedclothes/ Pk 1[10]	552 @ 603		
AA / Twin / Bedclothes/ Pk 2	ca. 500 @ ca. 2000		
AA / King / Bedclothes/ Pk 1	>800 @ 488 / **E**		
AA / King / Bedclothes/ Pk 2	-		
BB / Twin / Gas Burners	ca. 25 @ ca. 2000	ca. 15 @ ca. 3600	ca. 15 @ ca. 3600
BB / Queen / Gas Burners	ca. 25 @ ca. 1800	ca. 20 @ ca. 1800	
BB / King / Gas Burners	ca. 25 @ ca. 3200	ca. 25 @ ca. 3400	ca. 25 @ ca. 3600
BB / Twin / Bedclothes/ Pk 1	265 @ 470		
BB / Twin / Bedclothes/ Pk 2	175 @ 3358		
BB / Queen / Bedclothes/ Pk 1	508 @ 524	525 @ 421	
BB / Queen / Bedclothes/ Pk 2	>800 @ 2558 / **E**	>800 @ 3197 / **E**	
BB / King / Bedclothes/ Pk 1	794 @ 404 / **E**	800 @ 409	
BB / King / Bedclothes/ Pk 2	-	>800 @ 2402 / **E**	
CC / Twin / Gas Burners	>378 @ 1693 / **E**[11]	140↑ @ 3600	50 @ 3243
CC / King / Gas Burners	>800 @ 3492 / **E**	>800 @ 2734 / **E**	>800 @ 3235 / **E**
CC / Twin / Bedclothes/Pk 1	338 @ 508		
CC / Twin / Bedclothes/Pk 2	314 @ 2444		
CC / King / Bedclothes/ Pk 1	>800 @ 456 / **E**		
CC / King / Bedclothes/ Pk 2	-		

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[9] HRR peak corrected for baseline drift and calorimeter calibration; averaged over 10 seconds around absolute peak; **/E** means fire was extinguished starting at time shown

[10] Pk 1 is first peak and is dominated by bedclothes burning; Pk 2 is second peak and is dominated by mattress and foundation burning

[11] High HRR due to missing section of barrier material. ↑ for second test result indicates climbing HRR.

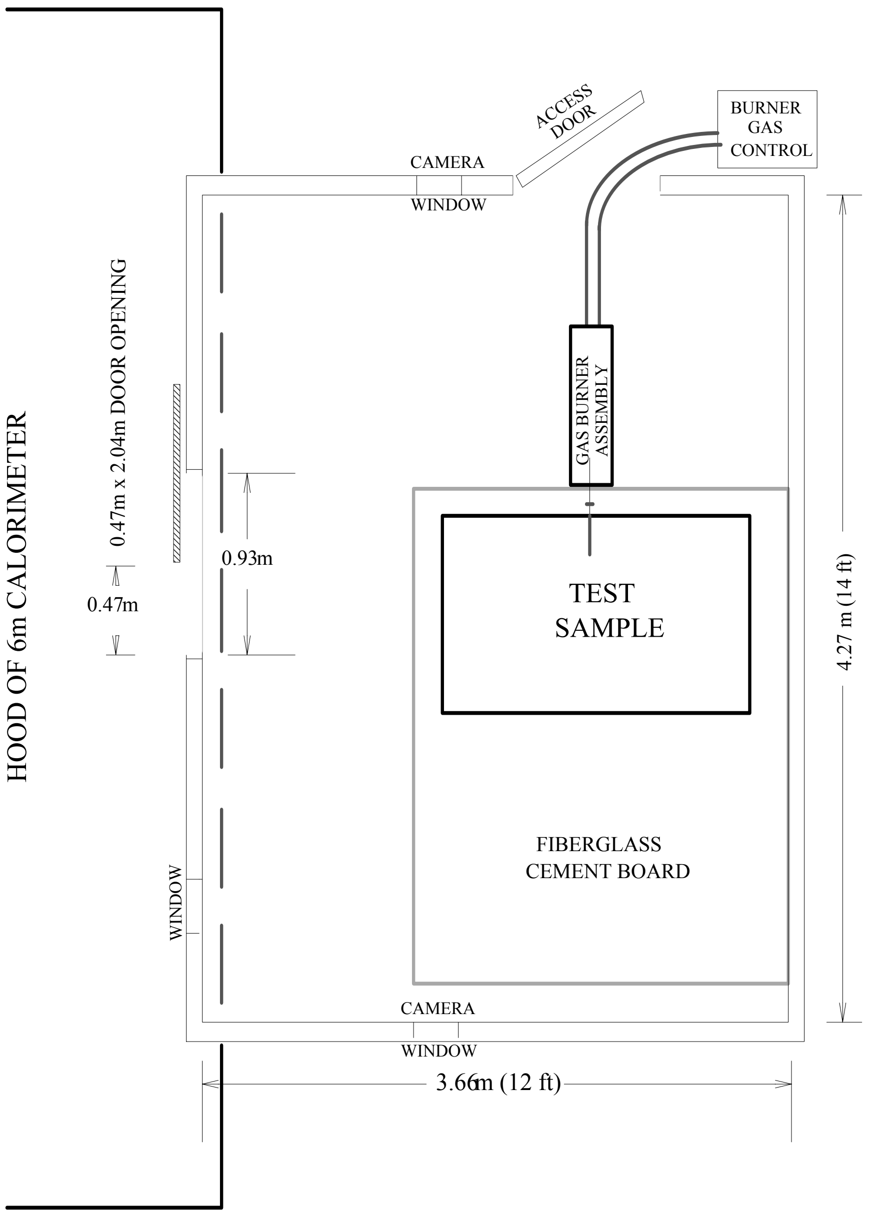


FIGURE 1. Layout of burn room.

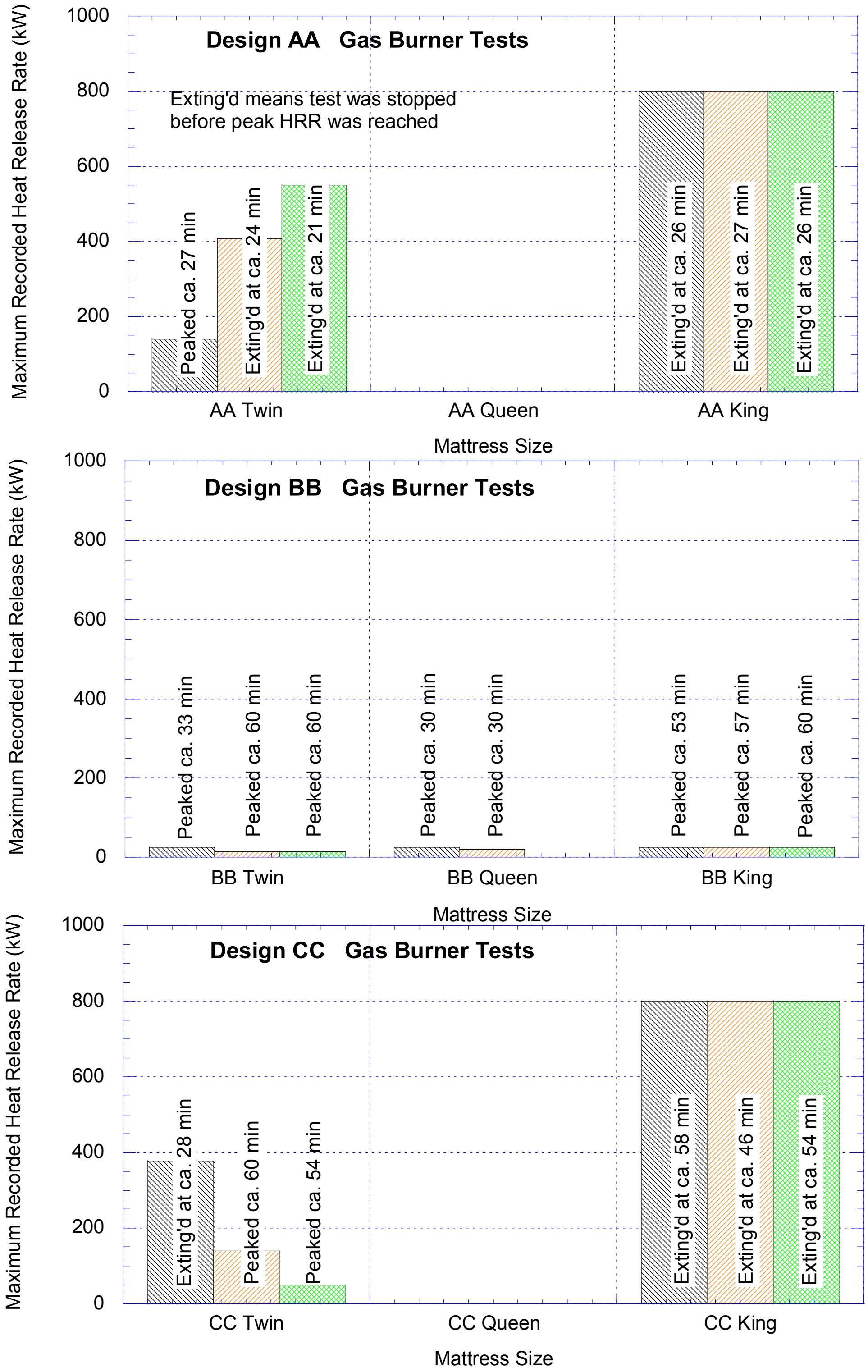


Figure 2a. Summary of Peak HRR Results (With Annotated Times) for All Mattress Sizes and Designs

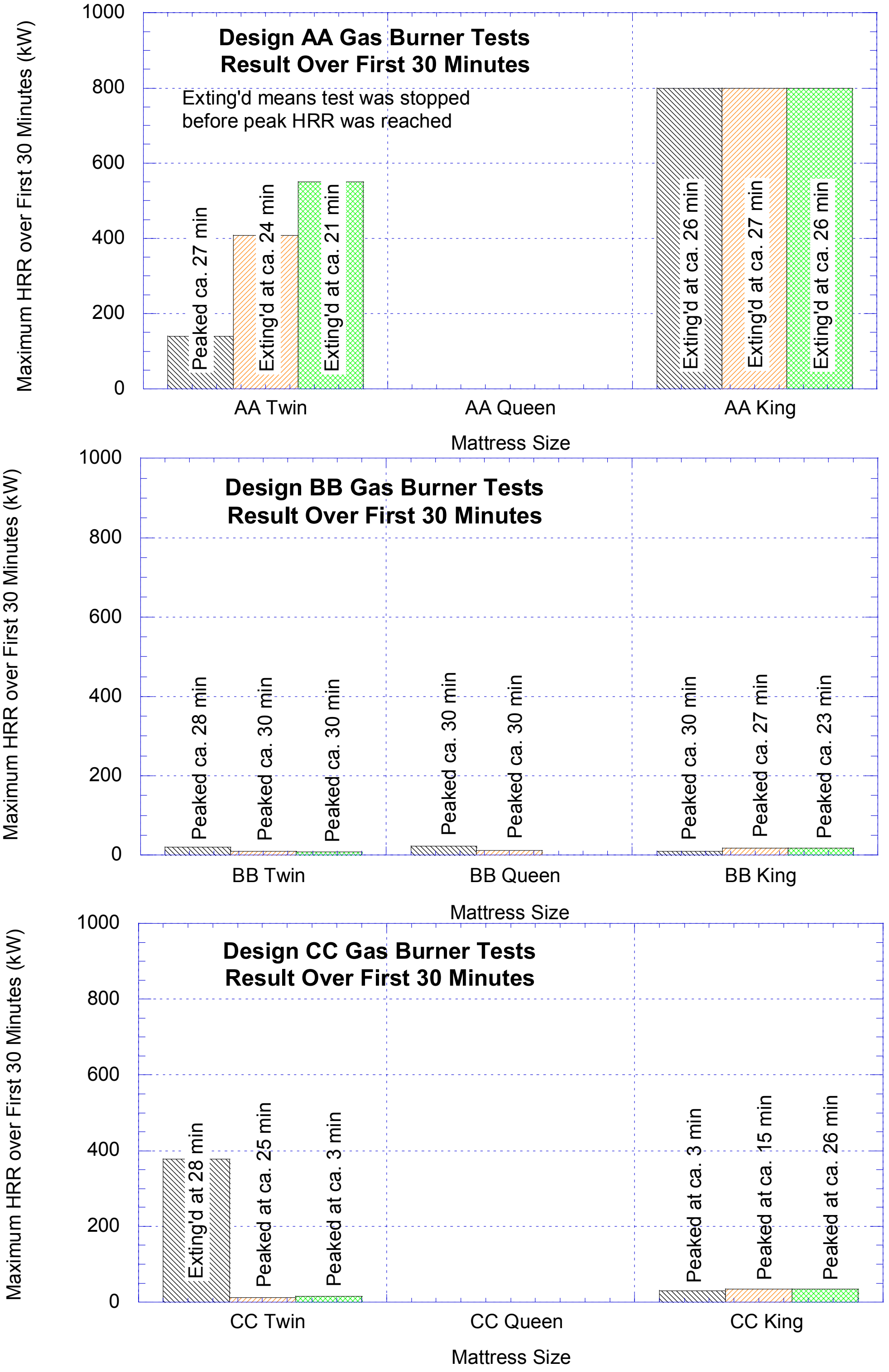


Figure 2b. Summary of Peak HRR Results (With Annotated Times) for All Mattress Sizes and Designs Over First 30 Minutes of 60 Minute Test Period

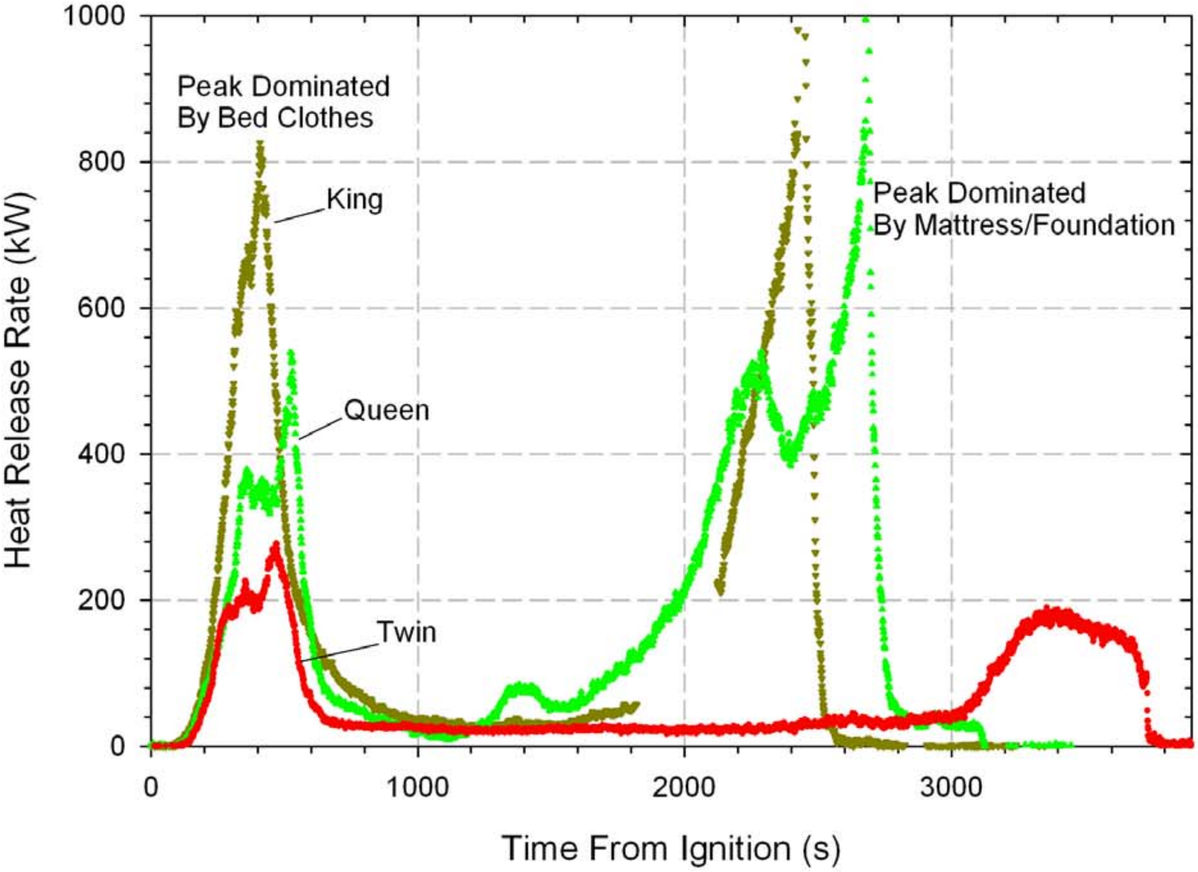
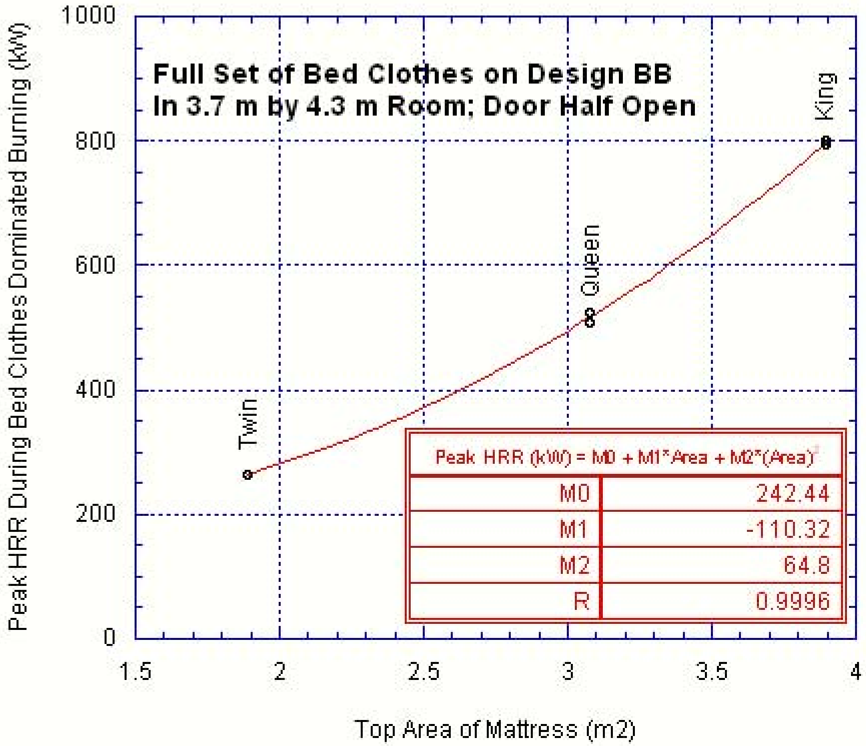


Figure 3. HRR Behavior of Design BB with Bed Clothes



Peak HRR (kW) = M0 + M1*Area + M2*$(Area)^2$	
M0	242.44
M1	-110.32
M2	64.8
R	0.9996

Figure 4. Peak HRR From Bedclothes Atop Design BB as a Function of Top Area of mattress

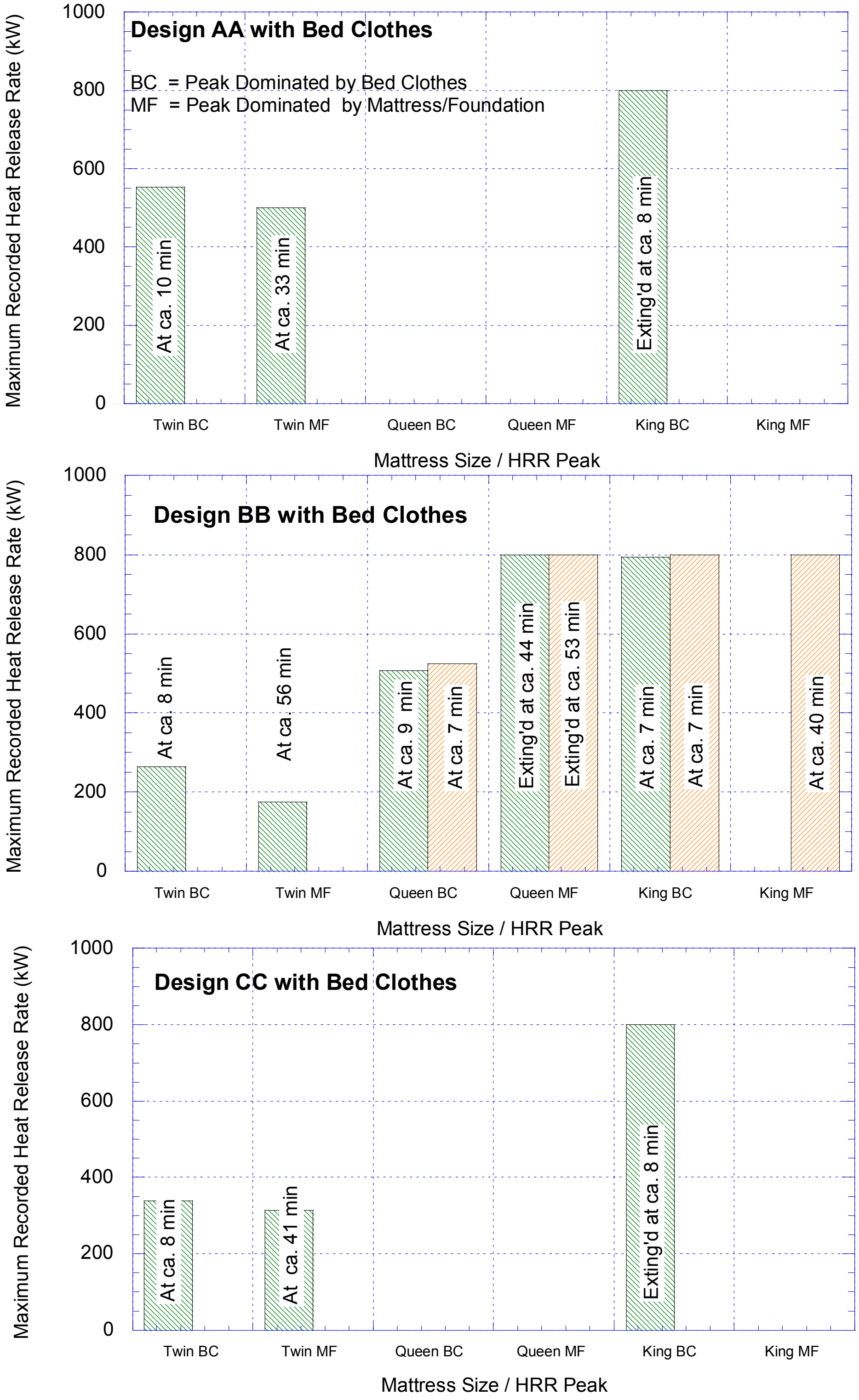


Figure 5. Summary of Peak HRR Results (With Annotated Times) for All Mattress Sizes and Designs, with Bed Clothes

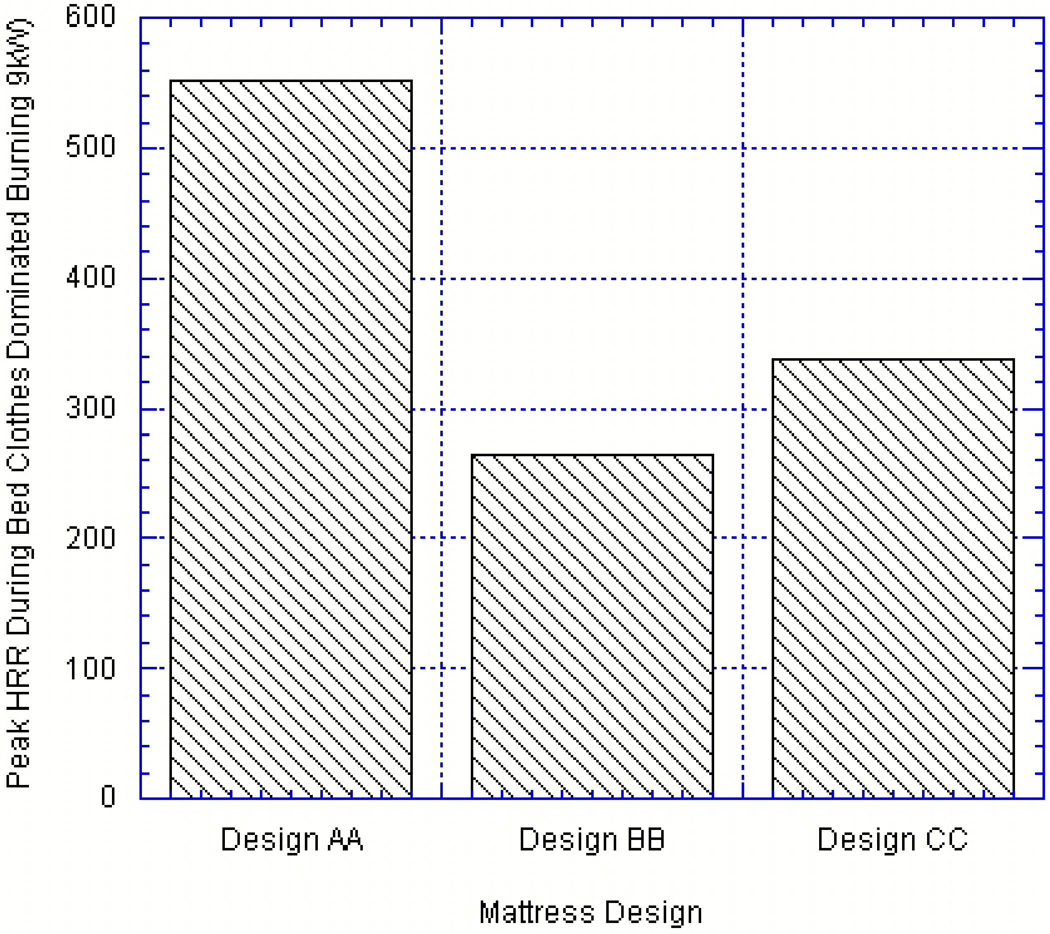


Figure 6. Effect of Mattress Design on Peak HRR During Bed Clothes Burning. Results are for Twin Beds.

Appendix A
Expected Effects of Various Barrier Imperfections on Heat Release Rate Performance in TB 603

Introduction. It is of interest to explore how various barrier imperfections could be expected to be reflected in the HRR curves obtained from a localized gas burner test such as TB 603 and from an actual bedroom fire. Ultimately, it is essential that inferences made from TB 603 behavior carry over (though not necessarily in a one-to-one manner) to real bed assemblies in which the bedclothes are the first items ignited. All results to date indicate that this will be so for twin mattresses. However, the results in the main body of this report indicate that the bedclothes fire can be magnified to the point of dominance on larger beds (queen, king) in a room context. In such cases, mattress/foundation barrier performance (as measured in TB 603) is still relevant to the size of the total fire but it does not control the timing of that fire nor fully dictate its peak intensity.

This discussion is predicated on the assumption that the burning bedclothes fire is itself reasonably controlled so that the dominant fire load in the bed assembly is the mattress/foundation. This dominant fire load controls the magnitude and timing of the highest HRR peak though both elements may make significant HRR contributions.

Background Discussion of Fire Barriers. The barrier on a mattress and foundation design covers a large fuel load within its boundaries. Given sufficient air and flame access to some part of that fuel load, a growing fire will occur, though there will almost always be some limitation on the speed of growth and peak HRR of that fire as a result of the presence of even an imperfect barrier.

The use of barriers in this way tends to raise the possibility of “binary” behavior, i.e., the outcome of an ignition exposure can either be a minimal fire if the barrier on the particular sample exposed is fully effective or a substantial fire if the barrier at some point allows flame penetration to the large fuel load within its bounds. This type of behavior poses difficult statistical issues in its assessment. Achieving a high confidence level that a barrier design is effective can require a large number of test replicates. On the other hand, attention to detail in designs that use barriers coupled with attention to uniformity of fire resistance in barrier materials can go a long way toward preventing the occurrence of localized weak spots that might allow a significant fire.

A barrier works by limiting heat and air access to the flammable material within it. The ideal barrier would, at any point on its surface, never let enough heat through to the material inside to cause that material to gasify at all, despite an intense fire on the barrier exterior. If that was the case, the only heat that would be released would be from material exterior to the barrier (and possibly from the barrier material itself). Cost will generally preclude such a heat impermeable barrier. Real barriers do permit degradation and partial gasification of polyurethane foam within them (in particular, the foam immediately adjacent to a barrier surface that is exposed to flames). This is a transient effect with more heat penetration and attendant foam degradation occurring as the duration of flaming exposure is extended.

Because the barrier must allow normal functioning of the structure it covers, it must be somewhat permeable to air (to avoid a "balloon" effect). That permeability should be kept low enough so as to preclude flaming combustion inside the barrier even when pyrolysis gases accumulate there. However, the requisite air supply rate to sustain flaming may be a complex inverse function of the size of the heated area and the heating duration so this condition may not be met indefinitely in a real fire. That is, at some point in the growth of a bed fire, it may be possible to sustain a weak fire in the interior of a mattress even though the barrier is essentially intact.

A barrier material is porous but its pores must be small enough to preclude direct flame propagation through them. Generally this means pores smaller than a millimeter or less. Barriers meeting this criterion can still, during severe fire exposure, allow flames to appear within the protected volume. This has been observed with some woven fiberglass barriers. It is probably a result of the barrier itself becoming hot enough to serve as an ignition source for a flammable gas mixture inside the barrier. If the entire barrier remains intact in such a circumstance, the burning rate of the materials within the barrier, limited by air supply rate, will remain low so this form of "failure" may not be particularly threatening.

Real products such as mattresses, made with barriers, must have seams where edges of the barrier material are joined together. These seams must serve the same functions as the rest of the barrier and so must be closed with thread that can withstand fire exposure without allowing the seam to open. Actual practice is somewhat forgiving in this regard, as indicated below.

Many of the barrier materials currently available are based on organic fibers which char when heated. Thus it is often a char which serves as the actual barrier between flames and the vulnerable contents of a mattress (so the insulative properties of the char are important as is its lack of fissuring). Such chars are prone to oxidation during flame exposure which effectively erodes them, giving the barrier a finite period of protection. This protection period depends on the nature of the organic fiber, minor contaminants in the fiber (some metal ions catalyze char oxidation; borates and phosphates can suppress char oxidation and also, for a fiber like cotton, increase the fraction of the fiber converted to char), the char mass per unit area and the temperature at which the char is held. This last condition depends on the heat flux which the charred fiber receives; the higher the flux, the higher the char temperature and, therefore, the shorter the protection period. The TB 603 gas burners (like some portions of burning bedclothes) provide high fluxes which have, however, a relatively short duration, mimicking that of local bedclothes flames. Most current barriers are designed to withstand this exposure. Crevice flames provide about half the heat flux but can last much longer (up to 20 min or more). Thus it is frequently crevice flames, often at mattress corners where they are most intense and persistent, which ultimately cause barrier failure.

Experience indicates that the most threatening type of barrier failure situation is one in which flames from the exterior reach all the way into some portion of the open cavity occupied by the springs in either a mattress or a foundation[12]. Flames on the interior surfaces of this volume of a mattress are well-insulated and prone to spread, probably at a rate limited mainly by the air supply rate. Transient heat accumulation within the mattress interior will also cause the burning rate (and HRR) to grow.

A foundation, subject to the same fire breakthrough into its interior cavity, presents a somewhat different situation. First, its internal fire growth is not limited by air supply; the bottom of a foundation is virtually open. Fire growth appears to be frequently limited by the very thin nature of some of the materials (on the sides and the dust cover) which support only small flames. These flames may spread sporadically and not get an appreciable fire going on the real fuel sources – the wood base and the top pad. When these latter materials do burn together, the resulting fire is serious and poses a severe threat to the mattress as well, since it is directly under it.

In many mattress and foundation designs, it is along the sides that this interior volume is nearest to exterior bedclothes flames. This is why a good side barrier and protected side seams are necessary. The tape edge seams, on the other hand, are somewhat removed from the spring cavity, typically by compressed layers of foam or other cushioning material. Experience shows that the tape edge seam does frequently have a tendency to open slightly as the materials it captures shrink or partly melt away. This does amount to providing a hole (actually more of a slit, ca. 2 mm wide, of varying length) in the barrier. This does not appear to lead rapidly to a growing fire because any flames which enter encounter foam, perhaps 2 cm to 3 cm or more thick, blocking access to the spring cavity. Crevice flames, typically quite limited in size, can eventually melt through such a blockage if they persist at one location for many minutes. The overall negative consequences of such edge seam openings seem to be quite sporadic from one test to the next, from negligible to serious (a type of binary behavior described above). Among other things, this could be one path that yields an internal "puff" in the mattress that often leads to a growing fire over the next several minutes.

The above discussion implies that barrier materials must qualify by having both short term resistance to the high heat flux from the TB 603 gas burners as well as long-term, low flux resistance to crevice flames. A test for the latter is in development in the context of mattress material assemblies. In addition, since barrier materials are, at least in some locations, under tension, they need to have some degree of tensile strength. This is particularly an issue as the barrier is heated and chars since that process can both weaken the fibers and cause the barrier material to shrink, thereby increasing the tensile stress; the result can be a split. At present, the author is not aware of any available tests for barrier shrinkage.

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[12] This does not mean that a solid foam core mattress is inherently safer. Such a mattress may be subject to other problems such as a melt pool fire on the floor.

Qualitative HRR Consequences of Various Barrier Failures. With the above discussion in mind, we consider how various possible deficiencies in a barrier could be reflected in the HRR seen during a TB 603 test. The ultimate concern is to infer if they imply an early and serious fire in a real bed assembly. Generally speaking, it is not possible to predict the ultimate consequences of barrier deficiencies in any quantitative manner (i.e., how big the HRR peak will be or exactly when). There are too many variables affecting these measures. Instead we attempt to estimate qualitatively when and how the mattress/foundation fire will begin to grow in response to a barrier deficiency. Experience has shown that there are a number of barriers available that can give quite good performance in TB 603 and with bedclothes fires; some, however, appear to be marginally effective. This same experience also suggests that potentially good barriers are compromised by quality variations leading to either large areas (comparable to the mattress dimensions) or small areas (several square centimeters) of lessened fire resistance. These two scales of defects have differing implications in TB 603, as discussed below. Similarly, the mattress construction may be at fault, with, for example, missing sections of barrier material or improper thread in the seams, resulting in localized or global vulnerabilities. Alternatively, the barrier material used may inherently be marginally adequate in fire resistance, particularly when used in combination with other mattress design parameters. We want to pursue the probable consequences of these various shortcomings as seen in the resulting HRR curves.

Case 1: A good barrier with large scale deficiencies in the sample tested. By assumption, this case involves a barrier (in the particular sample being tested) which is less than adequate to pass the TB 603 criteria over most of either the mattress or foundation (or both) surfaces. Then the chances are high that the burners will be applied to the deficient area. That makes this case qualitatively the same as one in which the barrier is not defective but, even when perfect, is marginally adequate for the given mattress design. The barrier deficiency (or inadequacy) can take several forms including excessive heat transmission (due to insufficient thickness, an improper blend of fibers or, in the case of cotton, insufficient char-promoting flame retardant), decreased fire duration resistance (leading to early burn-through, most likely either where the burner flames strike or in a corner crevice) or increased shrinkage when heated. More than one of these may apply at the same time.

- Excessive heat transmission means that material immediately inside the barrier will be degraded, gasified and burned more extensively than normal resulting in an increased HRR from the start with contributions from all fire-affected surfaces. Crevice flames will be larger and more persistent, especially if the deficient barrier is in both the mattress and foundation. The implications for a real bedroom fire driven by burning bedclothes are worrisome since, in general, the larger burning area there will mean a larger heat release rate contribution from the mattress/foundation. Larger and/or more persistent crevice flames in a TB 603 tests also tend to provoke the problem in the next bullet below, i.e., barrier burn-through.

- Decreased fire duration resistance means an increased probability of barrier burn-through, usually (but not exclusively) either in the burner application area or at crevice corners. This latter failure location cannot begin to be tested until the crevice flames reach the corners, often more than 10 to 15 min into a test. A failure at either location in a TB 603 test will usually let fire into the mattress interior with the result being a growing fire. A bedclothes fire will, of course, exploit this type of vulnerability relatively quickly since it will bring flames to the corners quickly (less than 10 min).

- Increased shrinkage means there is an enhanced probability that the charred barrier will break open, probably starting at the burner application area, likely leading to a growing fire centered there soon after burner application, especially if the affected item is the mattress. Char breakage due to shrinkage is problematic since it may be dependent on the size of the area being heated. That implies it could be worse (i.e., more likely though no sooner) with a bedclothes fire than with the burners since they heat a larger area. An implication is that a barrier which shows such behavior in a burner test is probably not acceptable.

If the large scale defect is the use of a non-fire resistant thread throughout the tape edge seams, the consequences will be a growing fire from the burner exposure onward, despite a good barrier material, since the fire will get increasingly into the mattress as the crevice flames begin to spread and open the seams. A bedclothes fire would produce similar early mattress fire growth. If the only defect were the use of non-fire resistant thread in vertical seams, the consequences are similar to Case 2 below.

Case 2: <u>A good barrier with small scale deficiencies in the sample tested.</u> Another variant of this is local deficiencies in the seams. Here the chances are high that the burners will not hit the small defective area since it will occur at a random location[13]. The good barrier material (or good seam length) will yield a low HRR for a varying amount of time, depending on how long it takes for the ticking and/or crevice fires to reach the defect zone[14]. Since the defect may see only the ticking fire, it may not be completely compromised; burning bedclothes would be more likely to fully compromise such a local defect since they can bring a more intense fire to bear than a ticking fire. Furthermore, on average, burning bedclothes will “find” this defect area sooner than the ticking/crevice flames (essentially, within 10 min).

Regardless of the type of local deficiency (as laid out above) in a good barrier, the worst immediate consequence of a local defect is a local hole all the way into the mattress or foundation internal cavity. For a mattress, the good barrier elsewhere will limit the air

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[13] A defect on the bottom of the mattress or the top of the foundation would not be found by the post-burner ticking fire or by a bedclothes fire. Similarly, there is an equal chance it would have no consequences in a real world fire.

[14] Some combinations of material outside the barrier layer do not sustain flame propagation over the entire exposed mattress/foundation surface. Therefore there is a finite chance the defect will not be revealed in a TB 603 test. A real bed fire is more likely to find most defects on these exposed surfaces.

supply to the fire and therefore its size. Such fires, when they occur on top of a mattress, tend to stay localized with the burning chiefly exterior to the mattress. A hole in the mattress side can dump more heat into the interior causing some relatively slow fire growth. Such a hole in the foundation can have no effect or a serious longer term effect depending on whether the hole location includes sufficient fuel to induce top pad and wood involvement. The consequences with bedclothes are similar but will occur sooner.

Case 3: <u>A marginal barrier with small scale deficiencies in the sample tested.</u> A marginal barrier is one which just passes the TB 603 criteria. Presumably its marginality is due to performance in one or more of the three categories laid out under Case 1 above. Its localized deficiencies may involve areas where its performance is distinctly inadequate (not just marginal) in these categories or could involve local physical damage like a cut. Since the deficiency is randomly located, it will again be unlikely to be hit by the burners and must wait for the slow subsequent flame propagation to reveal it. As in Case 2 above, the worst immediate consequence of the defect (when it finally is overtaken by ticking or crevice flames) is a hole into the mattress or foundation interior. Given the marginal character of the rest of the barrier, however, its ability to resist the intensified flaming around this hole is doubtful. The fire will tend to grow from the hole outward, possibly getting serious only as it begins to grow synergistically in the mattress and foundation. The problem will again show up sooner with bedclothes and, given the impact of the overall added heat and potential additional damage from the bedclothes fire, the resultant will probably grow faster than in TB 603.

The preceding discussion is necessarily qualitative in nature because there is a continuum of possible barrier performance levels and deficiencies. We do not have quantitative measures of the relation between barrier characteristics and TB 603 HRR performance. The common thread in the above discussion is that localized barrier defects and/or overall barrier marginality usually mean that the observed HRR from a TB 603 test is greater than that seen from a good, defect-free barrier. While it is impractical to spot barrier deficiencies directly in tests performed in a room enclosure due to poor visual access, the above discussion suggests that such deficiencies will usually be reflected in the HRR behavior being recorded. The increased HRR resulting from global deficiencies occurs immediately both on TB 603 and in complete bed assemblies. Localized barrier deficiencies show up later in TB 603 than in complete bed assemblies.