NISTIR 6497

Flammability Assessment Methodology for Mattresses

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Technology Administration, U.S. Department of Commerce

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June 2000

U. S. Department of Commerce
William M. Daley, Secretary
Technology Administration
Dr. Cheryl L. Shavers, Under Secretary of Commerce for Technology
National Institute of Standards and Technology
Raymond G. Kammer, Director

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Abstract

This study addresses the fire behavior of bed assemblies, including a mattress, foundation and bedclothes. The focus is on development and application of a reproducible means of simulating the thermal impact which burning bedclothes materials impose on a mattress. Twelve different sets of bedclothes were burned on top of an inert mattress to obtain data on heat release rate, flame spread rates and, to a lesser degree, heat flux to nearby objects. Six of these sets were selected for characterization of the heat flux patterns they impose on an inert mattress surface. A unique, infrared imaging technique was developed for this purpose. The results, in terms of peak heat flux, duration and area, were used to develop a pair of propane burners which impose on the side and top of a mattress heat flux patterns which mimic those imposed at a typical, fixed location by burning bedclothes. These burners were applied to a set of five mattress designs, including one typical of current residential mattresses; the four other designs included potentially less flammable design elements to permit a wide range of fire behaviors. This facilitated a broad assessment of the ability of the gas burners to predict the fire behavior of mattresses. The duration of the burner application was varied. Also, as a check on the burner-induced behavior, the same mattress designs were tested with one bedclothes combination. All of the altered designs offered some modification in fire behavior but they differed strongly in overall effect. The effects ranged from a delay in the time to reach an undiminished heat release rate peak to greatly reduced mattress involvement in the fire. The burners successfully predicted the behavior of four of the mattress designs. They failed to predict the fire behavior (with burning bedclothes) of one design since the bedclothes produced a phenomenon (internal overpressurization and seam rupture) which the burners did not produce.

Keywords: beds, bedclothes, bedding, fire spread, heat flux, heat release rate, mattresses, sleep sets

Executive Summary

Beds pose a unique fire hazard problem. Products from several manufacturers are placed together to form one functioning unit, with no one manufacturer being responsible for the potential fire hazard of this assembly. To date, there is no methodology for relating tests of the individual components to the likely fire performance of the assembly. This study is focused on sorting out the role which the mattress, plus its foundation, (termed a sleep set) plays in such fires.

The first element of the problem to be examined was the bedclothes, since they are most likely to be ignited first and they serve as a magnifier of the match-size flame from a careless smoker or child playing with matches. Twelve combinations of bedclothes were selected for fire behavior characterization; the materials are believed to be reasonably representative of the current market though no statistical data were available. They ranged from light (two sheets and a pillow) to heavy (mattress pad, two sheets, blanket, heavy comforter and pillow). Five different blanket materials were examined as well as two comforter weights and two pillow compositions. Heat release rate and fire spread rates were measured for each bedclothes combination when placed onto a fiberglass mattress. The peak heat release rates ranged up to about 200 kW which is much less than the rate required to cause flashover in a small bedroom (ca. 1 MW).

Six of these bedclothes combinations were selected for characterization of the heat impact they impose on the surface of a mattress. This impact was measured in terms of the peak heat flux, its duration and the area affected. These measurements were made by placing the bedclothes on top of a different type of inert mattress, consisting of a twin-bed-size frame over which was placed a thin metal foil. The foil served as a transducer to convert the heat flux from the burning bedclothes into a brightness signal as seen by an infrared imaging camera viewing the back (under) side of the thin metal foil. The heat impact data were highly variable with time as the bedclothes burned over the inert mattress surface. The emphasis was placed on a determination of the maximum values seen over the entire burn period for all six bedclothes combinations. These provide measures of the maximum thermal insult which a mattress must endure. The data indicated a distinct difference between the thermal impact on the side of a mattress versus that on the top surface, with the latter being more severe.

A pair of gas burners was designed to mimic the measured thermal impacts. One burner impinges on the top of a mattress surface while the second impinges nearby on the mattress side. The burners each impose a fixed heat flux for a period determined by a time delay relay. The burner heat flux level and duration were derived from the measurements on the bedclothes.

These burners were applied to a set of five mattresses. These comprised one design typical of current residential technology and four designs incorporating potentially fire resisting features. For comparison, these same designs were subjected to heat from

burning bedclothes (one of the most severe bedclothes combinations from the earlier phase of this study). The goal was to assess the ability of the burners to produce a result that correlated with the bedclothes fires for a wide range of mattress behavior.

The burner tests of the five mattress deigns did show a wide range of fire growth and heat release rate behaviors. The changes ranged from a slowed but undiminished heat release rate peak to minimal involvement of the mattress.

The heat release rate results from the above tests showed that the fire behavior produced by the gas burners correlated with that from the bedclothes-induced fires in four out of the five cases. The exception involved a new phenomenon not seen with the gas burners, an internal over-pressurization in the mattress which ruptured its seams and allowed fire penetration into its interior. Apparently the bedclothes are able to induce this phenomenon because they heat a larger area of the mattress than the gas burners do and thus they is able to yield a flammable gas mixture within the mattress volume.

Chapter 1. Introduction

Despite substantial decreases over the past two decades, fires and fire deaths in which a bed was listed as the first item ignited persist as major contributors to the fire toll in this country [1]. Most of these fires still result from cigarette ignitions. However, the fraction ignited by small flames, such as matches or lighters, is substantial and increasing as the cigarette-initiated fraction decreases.

The ultimate fire that may result from either type of ignition can produce heat and toxic gas release levels that pose a serious threat to occupants of the room and beyond. In the aftermath of such fires, the contributions of all the consumed products are examined. While the investigation may note that the first item ignited was "the bed," in fact most beds in residences comprise a mattress and a foundation (i.e., a sleep set) surrounded by sheets, blankets, pillows, etc. Indeed, the bed clothes are most often in direct contact with the small flame or cigarette and serve as potential magnifiers of what shows up in the fire statistics as the primary source of ignition. Thus, beds pose a unique fire hazard problem. Products from several manufacturers are placed together to form one functioning unit, with no one manufacturer being responsible for the potential fire hazard of this assembly. To date, there is no methodology for relating tests of the individual components to the likely fire performance of the assembly.

This report describes the first part of an effort by the Sleep Products Safety Council (SPSC) to conduct scientific research that will help industry, relevant government agencies and fire safety professionals understand the dynamics of fires involving mattresses and bedclothes assemblies and evaluate the effectiveness of alternative product designs and component materials that can reduce the risk of death, injury and property damage associated with such fires. The report focuses on the means for establishing a reasonable, reproducible and accurate test method that can simulate the impact of fires involving mattress/foundation /bedclothes assemblies using a mattress/foundation configuration alone.

Nearly 60 percent of the fire deaths in the U.S. occur in rooms other than the ones in which the fires started [2]. The fatal fires have proceeded beyond flashover, the point at which the entire room is in flames. The high heat release rate and the resulting buoyancy push smoke from the room and into other parts of the dwelling. The people most often die from inhalation of this smoke. Prior to flashover, a fire forces relatively little smoke from the room, and that smoke is fairly dilute. Thus, preventing flashover would be a major step in reducing fatalities from smoke inhalation.

Typically flaming ignition of a bed begins with ignition of the bedclothes by children playing with matches or a cigarette lighter. The flames spread over the sheets, blanket, comforter, etc., and, at some point, ignite the mattress. There may be sufficient fuel from the combination of conventional bedclothes, mattress and foundation to drive a bedroom to flashover.

The approach of this project is to characterize both the heat release rate from a mattress that has been ignited by burning bedclothes and the heat release rate contribution of the burning bedclothes. This will enable an approximation of the "window" for non-flashover performance of the mattress: the difference between the total that leads to flashover and the rate of heat release from the bed clothes. Mattress manufacturers can then develop or select product designs with heat release rate values below flashover-causing levels.

Of course, should the bedclothes alone generate sufficient heat, then improving the mattress is not likely to reduce fire losses. Using established formulae [3], it is possible to calculate the value of heat release rate that would lead to flashover for a given room volume and ventilation opening. For example, the value for a 2.4 m x 2.4 m x 2.4 m (8 ft x 8 ft x 8 ft) room with an open door is 1.1 MW.

The next step is to determine the burning behavior of bedclothes. This not only provides key input to the flashover calculation, but also indicates how fast such fires grow. Since people use a wide variety of bedclothes, there may also be a wide variation in the rate and extent of their combustion. The initial task in this study was thus to examine the fire behavior of several combinations of bedclothes placed on an inert mattress. The number of layers and their composition was varied. In the next task, a subset of these bedclothes combinations was characterized with respect to the heat flux patterns they imposed on an inert mattress surface. In the third task, this heat flux information was used to design a pair of gas-powered burners which simulate the local thermal load imposed by bedclothes. The two burners simulate the heat effect imposed locally on parts of both the top and side surfaces of a mattress by burning bedclothes. In the fourth and final task of this study, these burners were applied to a typical current mattress design as well as to a set of four potentially improved designs derived from earlier flammability test results in the literature. This testing provides an indication of the ability of the burners to correctly predict the degree of involvement of the mattress regardless of mattress design or extent of its fire growth.

In the report below, the four tasks described above are the subject of the next four chapters. The final chapter also includes a discussion of the overall implications of this study.

Chapter 2. Fire Behavior of Bedclothes on an Inert Mattress

2.1 Introduction

As a first step in assessing the interaction between bedclothes and the underlying mattress during a bed fire, a series of twelve bedclothes combinations was burned atop an inert mattress. The goal was to determine the range of behavior exhibited by combinations that ranged from very light (two sheets) to heavy (two sheets, a blanket and a heavy comforter). The composition of the various elements was varied, as well.

The fire behavioral aspects which were examined include the heat release rate as a function of time, the time and level of the peak heat release rate, the rate of spread of flames over the covers in various directions and the heat flux to locations near the bed (not to the mattress). These are pertinent to determining the manner in which the bedclothes serve as a magnifier of the original ignition source (here the size of a large match) and whether the bedclothes fire alone constitutes a substantial hazard in an enclosure. As a result of this study, six of the combinations were chosen for further examination in studies (described in Chapter 3) of the heat flux which burning bedclothes impose on an underlying mattress.

2.2 Experimental Details

The twin-size inert mattress was composed of rigid fiberglass batts (Owens Corning[1] Type 704/AF545, 67 kg/m^3, 4.2 lb/ft^3). Because this material is only available in small batts
(60 cm by 120 cm by 5 cm thick; 2 ft by 4 ft by 2 in thick), the mattress was built up from these units around a central sheet metal stiffening plate; the plate incorporated metal spikes to keep the blocks firmly in place. (All of the metal components were well immersed within the fiberglass and did not appear to influence the fire behavior.) This assembly was wrapped with two layers of woven roving E-glass cloth (0.61 kg/m^2; 18 oz/yd^2); the inner wrap was transverse and the outer wrap was longitudinal, thus covering all of the exterior fiberglass batt surfaces. This assembly was used throughout the testing after being prepped by the burning of two successive bedclothes combinations purchased locally for this purpose; this preparation minimized any contribution to the measured heat release from binder resins in the fiberglass batts. Those preliminary tests also made it clear that the polyester fiberfill pillows, in particular, would be

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[1] 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.

problematical, causing residue accumulation in the otherwise inert mattress. Thus an additional layer of the same fiberglass cloth was added to the top of the mattress (covering also the head and foot end) as a disposable covering. Beneath this top layer, in the pillow area only, a layer of non-asbestos paper backed by aluminum foil was added to prevent molten polyester from soaking into the mattress. In other areas of the mattress, when localized spots of melted-in residue were found after a test, they were burned off with a torch to prevent their contributing heat to the subsequent tests.

The mattress was placed on top of a simple angle iron frame with the same horizontal dimensions as the twin-size mattress (190 cm by 99 cm; 75 in by 39 in). Two sides of the frame (the ignited side and the foot end) had a single layer of inert fibrous material (ceramic paper or fiberglass cloth) extending down below the bottom edge of the mattress for 20 cm (8 in) to simulate the blockage that would exist if a foundation were below the mattress. The other two sides were open below the bottom edge of the mattress allowing an observer to see how much the flames tended to play on the bottom surface of the mattress.

The bedclothes combinations tested are listed in Table 2-1a ; Table 2-1b shows the weight variation in each component. All of the bedclothes combinations were selected by NIST in consultation with Gordon Damant [4]. All materials were provided by the American Textile Manufacturers Institute. They were conditioned at 55 % relative humidity for more than 24 hours at room temperature. The relative humidity in the test laboratory was not controlled but it was recorded; it varied from 39 % to 54 % over the course of the tests. The conditioned materials were kept in plastic bags until about 20 min before ignition so that exposure to the lesser humidity levels was minimized (though the range seen here is unlikely to have any large effect on the results).

Each bedclothes combination to be tested was placed onto the inert mattress by two persons following a fixed set of rules to minimize variability. Each layer above the fitted sheet was marked at the head end to define its mid-width point. This was centered on a mark on the middle of the head of the bed and the top surface was smoothed down to assure good contact between layers. The overhang length on the igniter side of the bed was adjusted on the foot end to equal that on the head end. Top sheets and blankets (with the exception of the wool blankets) were tucked successively using "hospital" corners at the foot end. The comforter layer, if present, was not tucked at the foot end. Each layer was then folded straight back successively at the head end by 47 cm (18.5 in) with care to assure good contact between successive layers along the fold line. A pillow, carefully fitted into a pillow case, was placed with one long edge immediately adjacent to the head end of the folded-over region of the covers. The open end of the pillow case faced toward the igniter side of the bed; it was laid flat on the sheet in the same manner each time.

The igniter was based on the British Standard 5852 "match" flame with some significant differences. A 7.9 mm OD by 6.2 mm ID (5/16 in by ¼ in.) stainless steel tube was used in a vertical orientation. A spacer wire was secured to the side of the tube and extended up 30 mm (1.2 in) above its top. The igniter was fed propane at a rate of 96 cm^3/min (room temperature and pressure; larger than the BS 5852 flow rate of 45 cm^3/min). This produced a flame that extended 30 mm (1.2 in) above the top of the spacer wire. The lower half of this flame was surrounded by a cylindrical, doubled layer of screening approximately 40 mm (1.6 in) in diameter to help suppress lateral movements due to random air currents. (This was supplemented by a separate screen around the ignited area of the bed, which was removed after one minute of igniter exposure.) The igniter was mounted in a holder such that it could be pre-positioned in relation to the covers, swung out, pre-heated for at least two minutes, then swung back into position to ignite the covers at the start of a test.

The ignition point on all of the bed cover combinations was at the head end base of the hanging folded covers on one side of the bed; see Fig. 2-1. The igniter was positioned so that the top of its spacer wire just touched the lowest point of these hanging covers. The material first contacted by the flame could be either the top sheet, the blanket or the comforter, depending on the particular combination. Contact was typically lost in a matter of 20 s or less, as the material ignited and shrank away. The igniter was then removed after 30 s. In a few cases (typically involving a wool blanket) the igniter was left in place for one minute.

The tests were conducted in the NIST Furniture Calorimeter[2] using skirts to lower the effective hood height. The increased inflow velocity had some tendency to disturb the burning on the horizontal surface of the mattress, especially late in a test; this is not believed to be a significant influence on the results. The calorimeter was calibrated each morning before each daily series of tests using natural gas at measured flow rates. The uncertainty due to the heat release per gram of oxygen for the materials tested here combined with scatter in the calibration data give a total heat release rate uncertainty estimate of ± 7 % to 8 %.[3]

The tests were recorded with two video cameras, one having a fixed view of the ignited side, and the other starting with a view of the foot end and then moving to include a view of the side away from the igniter.

Two Schmidt-Boelter total heat flux gages were used to measure the flux to two specific external regions near the burning bed covers (see Fig. 2-1). The gages were calibrated against a secondary standard and have an estimated uncertainty of about ± 3 %.[4] These provided an indication as to the combined convective and radiative heat flux the burning bed covers might impose on immediately adjacent objects. Note that these are not

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[2] This oxygen consumption-based calorimeter is generally similar to the system described in ASTM 1590.

[3] This is a type B estimate of uncertainty based mainly on the authors calibration experience with the system. A more detailed uncertainty assessment of heat release rate measurements in the NIST Furniture Calorimeter is the subject of a current project.

[4] This is a type B estimate of uncertainty in heat flux measurements based mainly on the scatter in heat flux calibrations. A more detailed assessment of the uncertainties in heat flux measurements is the subject of a current project at NIST.

measures of the heat flux to the mattress. Both were at the height of the top surface of the covers. One faced the middle of the head end of the bed from a distance of about 1 cm. The other faced the mid-length of the foldover region of the covers from the side of the bed opposite that being ignited. Here the covers extended outward, at a steep slope, a distance which depended on the number of bedclothes layers. The spacing varied somewhat relative to the covers at the top of the bed but generally was no more than 2 cm away.

2.3 Results and Discussion

Bedclothes Heat Release Rate Behavior. The heat release rate from a burning object is a primary measure of the hazard it presents [5]. To put this measure in perspective, it is useful to remember that a small bedroom (2.44 m cube; 8 ft cube) requires a heat release rate of about 1.1 MW to cause flashover [3]. After flashover, the bedroom is untenable and the thermal and toxic threat spreads to other rooms.[5] Before flashover (or with sub-flashover fires) the hazard is contained within the bedroom and depends on the occupant's proximity to the fire [6]. The time it takes for the fire to grow is also relevant to both the likelihood of escape and the probability of containment by a responding fire department.

Figure 2-2 shows the peak heat release rate measured in replicate tests for the twelve bedclothes combinations listed in Table 2-1a. The results are arranged in accord with the average of the peaks measured for the two replicates. (For combination 3 the replicate test was voided by the use of an incorrect blanket.) Note the variability of the heat release peaks in the replicate tests despite the care, described above, in assembling the bedclothes. In general this may be due to the unpredictable manner in which the various layers tend to curl under the influence of approaching flames. One case is discussed in more detail below.

There are few data in the literature with which to compare the results in Fig. 2-2 but Damant *et al.* [7] did report a case similar to the combination 3 used here atop a fiberglass mattress, using match ignition ; that result (102 kW) compares closely to that seen here (96 kW). This degree of agreement is probably somewhat fortuitous in view of the variability seen in the replicate tests. Damant reported substantially higher peak heat release rates from some bedclothes combinations similar to ours only when his inert mattress was wrapped with screen wire, a situation which is difficult to relate to real applications.

Figure 2-3 gives an example of the heat release versus time curves; these were obtained for bedclothes combination #4, which yielded one of the highest peak averages. This is the combination used in the tests of improved mattress technologies (Chapter 5). Note that the replicate tests start out very similarly for the first three minutes, then diverge

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[5] It should be noted that this typical scenario assumes that the room has an open door. It has been pointed out that if the room is closed, the toxic hazard could become substantial in a much smaller fire [15].

sharply (at about 300 seconds in Fig. 2-3). Inspection of the video tapes shows that the divergence is largely due to the behavior of the fire on the covers, not the pillow. For Test #SPSC14 the spread of flames on the overhanging covers was substantially more rapid, especially on the foot end (see discussion of fire spread below). This led to more material being involved earlier. All of that material could be seen to burn intensely. For Test #SPSC16 the spread of flames was slower and the intensity of burning (as judged by flame height), especially of single thickness materials on the horizontal surface of the bed, was reduced. The reasons for the differences in burning intensity were not immediately apparent from the video tapes. (The weights of all of the components in the replicate bedclothes sets were quite comparable.)

It is clear that even the highest heat release rate peak seen in this study is well below the level necessary to cause flashover by itself in a small bedroom. Thus the thermal and toxicity threat from the bedclothes, burning by themselves, is essentially confined to the bedroom.[6] For a room where a heat release rate of 1.1 MW is needed to reach flashover, the additional contribution from the mattress would need to be about 900 kW (assuming no contributions from other objects in the room). Note that near flashover-level fires involving a single item are dangerous because they are more likely to ignite other items with the net result that flashover is reached. Thus the mattress contribution should be kept substantially lower than 900 kW, if possible, to stay well away from the possibility of flashover and to minimize the hazard in the room of origin.

Note that even the lowest heat release combination represents a very large magnifier for the original ignition source (ca. 130 W). In this sense, all of the bedclothes combinations represent a major challenge to a mattress.

A few observations regarding the effect of the bedclothes composition on peak heat release rate are notable. First, the heaviest combination (#5) did not give the highest heat release rate; rather, the top two heat release rate combinations involved the medium weight comforter (#10 and #4). Since these two types of comforter had nominally the same composition, one would expect the heavier (thicker) item to yield a wider burn zone and thus a higher heat release rate. The reversal of this expectation may involve some differences in the treatment of the polyester fiberfill or other details of the quilting of the comforters. Next note that substitution of 100 % cotton for the polyester/cotton components in combinations 4 or 10, along with the substitution of a cotton blanket (for acrylic or polyester), resulted in a factor of 2 or more reduction in peak heat release rate (see combination #6). The charring nature of the cotton was most likely responsible for this; the char tended to form an insulating barrier.[7] Substitution of a wool blanket, again a char former, had a similar effect (see combination #11). A cotton blanket alone (i.e., as

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[6] Of course the burning bedding could ignite other nearby materials, starting a chain of events which leads to flashover. The point here is that an isolated 100-200 kW fire, in even a small room, presents a localized hazard both from burns and toxic gases. The extent of the toxicity hazard depends, among other things, on whether the door is open or closed; it could be substantial with a closed door [15].

[7] Cotton can be a mixed blessing since cigarettes are more frequently the ignition source than matches and pure cotton may smolder more readily than a PE/cotton blend.

the top layer, see combination #9) was not effective at lowering the peak heat release rate, relative to other blanket types; compare combinations #7 and #8 with #9. This particular cotton blanket had a very open weave. Finally note that the bedclothes combination with the latex pillow (#12) gave a substantially higher heat release rate peak than did the combination with the polyester fiberfill pillow (#1).

Figure 2-4 shows the time to reach the peak heat release rate; the results are arranged in the same order as in Fig. 2-2. In cases where there were multiple heat release rate peaks of nearly the same magnitude occurring in a cluster, the time used in Fig. 2-4 is that of the first peak even though the highest peak (reported in Fig. 2-2) may have been somewhat later. Comparison of Fig. 2-2 with Fig. 2-4 does not indicate any appreciable correlation between the peak heat release rate and the time to reach that peak. Note that many of these peaks are reached after more than 7 min to10 min of burning. In an actual bed fire with current residential materials the heat release from the mattress would be expected to have begun to dominate well before this (see Chapter 5).

Bedclothes Fire Growth Behavior. The way in which the bedclothes fires grew underlies their heat release rate behavior. The initial ignition zone typically grew rapidly upward from the base to the top of the overhanging covers. (Combination 11 with the wool blanket was the slowest.) Flame fronts then progressed along several paths as indicated by the arrows in Fig. 2-1. Thus flames proceeded simultaneously along the overhanging covers on the igniter side and upward onto the horizontal surface of the bed, moving fastest there along the juncture of the pillow and the folded-back covers.[8] The direction of propagation of a flame front on the overhanging covers on the side away from the igniter depended on which flame front from the igniter reached this part of the covers first. Rapid progress along a given path meant a relatively high heat release rate from that path but a high overall heat release rate required simultaneous rapid progress along multiple fronts. If there were more layers to burn along a given path, this also increased the heat release contribution from that path.

Figures 2-5, 2-6, 2-7 and 2-8 are bar graphs showing the rate of fire spread along the paths indicated in Fig. 2-1. The rate shown is the overall average for the front to reach the extreme ends of the path on the top surface of the bed. These average rates have an uncertainty of about ± 5 % due to the vagueness of somewhat non-flat flame fronts reaching corners which were themselves not sharp. The instantaneous spread rate varied substantially during portions of the path, especially for the overhanging covers on the sides of the bed. The local spread rate was up to four times faster than the average, in some cases. Fast localized spread was frequently associated with the continuous formation of a flaming rope-like segment hanging from the bottom edge of one of the layers of covers. This could come from the top sheet, the blanket or the comforter. This

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[8] Elsewhere on the horizontal surface of the bed, the movement of flames tended to lag, partly because they started later. The flame front on the single thickness region atop the bed varied from a well-developed line for cases where a comforter or acrylic blanket formed the top layer to an erratic and irregular front in cases where a sheet formed the top layer.

was not necessarily a reproducible feature and is one of the sources of variability in the spread rate and heat release rate data.

The rate of spread along the bedclothes layers hanging over the sides of the bed is enhanced by the fact that gravity does not act very effectively to hold the various layers together. Thus flames can interpenetrate between the layers to the extent that air is available there to sustain them. Distortion of a given layer due to curling or crinkling under the influence of heat from the nearby flames serves to open the layers further (but in a highly variable manner). In contrast, the bedclothes layers on top of the mattress are held together more effectively by gravity, precluding multiple burn zones through the depth of the bedclothes and forcing a slower top-to-bottom burn through process that sustains a slower rate of flame spread.

Another source of variability in the overall fire behavior was a fifth path, not quantified in the figures. This was fire spread along the vertical surface of the fitted sheet toward and across the head of the bed. It involved very little heat release rate because of the minimal material involved but it was a variable path for ignition of the pillow case. The pillow case was always first ignited by flames moving up onto the horizontal surface from the hanging cover area above the igniter. In some cases, however, the pillow case was subsequently ignited along its head end edge when the fitted sheet popped loose (due to burn through of the elastic on the corner) and contacted the pillow case there; this was unpredictable. It had the effect of accelerating the time of occurrence of the significant heat release peak due to full involvement of the pillow.

Comparison of Figs. 2-5 through 2-8 shows that fire spread along the juncture of the pillow and the folded covers generally tended to be the slowest of the recorded paths (because of the gravity effect noted above). Flames spread laterally from this region to encompass first the doubled region of covers on the horizontal upper surface of the bed and then the single cover set region (toward the foot end of the bed). Flame spread over this latter region of the bed was not recorded because of its generally erratic nature but it tended to be the slowest on any part of the bed covers. The erratic nature of this spread was contributed to by the uneven way in which flames emerged up onto the horizontal surface from the hanging covers on the ignited side. This erratic spread also interrupted the monotonic spread along the hanging covers on the foot end; this is the reason for the several missing data points in Fig. 2-7. (Similar erratic behavior eliminated some points from the other graphs.) It is also apparent from Fig. 2-7 that fire spread on the foot end was the most widely varying with bedclothes combination. In general, it spread quickly when there was a loose, overhanging layer there (a comforter) and slowly when this was not the case; note, however, that the heavy weight comforter responded to the composition of the blanket beneath it by allowing faster spread for the acrylic blanket vs. the wool blanket (combination #5 vs. combination #11).

Comparison of Figs. 2-5 and 2-6 indicates that the average spread rate of flames on the side opposite the igniter was sometimes slower than on the igniter side. This would seem to be anomalous since the two sides involved the same configurations of the same layers of materials. The only fixed difference was the existence of the blocking layer on the igniter side (to simulate the presence of a foundation). The greater contributing factor to the differences seen was most likely the difference in the way the two sides became involved in flaming, coupled with the way in which the fire spread process was measured. The ignited side became involved via the match-like igniter and the spread process was measured from the time at which flames reached the top surface of the overhanging material. Thus the covers were in flames from bottom to top when the horizontal spread process along the overhanging covers was taken to begin. On the side of the bed opposite that subjected to the igniter, the spread process could originate at either end, depending on how the fire first reached that side. It could arrive first at the head end or the foot end of the overhang. This depended on the relative speed of the earlier pathways away from the ignition source. When the fire started from the head end, it ignited first the top edge of the overhanging covers and spread slowly downward before spreading more rapidly in a horizontal manner. This slow step lowered the average velocities recorded for that side, since ignition of the top was always taken as the start of the measured flame interval.

Threat to a Mattress from Burning Bedclothes. The ignition scenario used here was chosen to mimic one possible situation that might be posed by a child playing with matches, though the parameters of this have deliberately been chosen to push toward a worst case. The ignition source was larger than a match (though plausible for a cigarette lighter) and it was applied long enough to assure a strong, localized ignition process for all of the bedclothes material variants. The specific location of flame application was also chosen to yield a rapidly growing fire. A flame applied at the bottom of the forward end of the overlapped covers grows rapidly upward and still has adequate fuel to sustain the resulting enlarged flame zone. This soon leads to flame spread onto the top surface of the bed very near another major source of fuel, the pillow. Thus the chosen ignition location favors rapid development of a relatively large fire which ensues when more fuel is burning at the same time. Had the ignition location been, for example, in the top center of the horizontal area of the bed having only a single layer of covers, the heat release history would have been substantially different; the peak would have occurred later (much later for some bedclothes materials) and could have been different in magnitude. The relative magnitudes of the heat release peaks from the various bedclothes combinations might also be changed as a result of such a change in ignition location.

The chosen scenario yielded a fairly rapid onset of intense thermal loads being imposed on the mattress. The burning zone that spreads along the vertical sides of the mattress imposes a high local heat flux to the mattress which moves along with the velocities reported in Figs. 2-5 to 2-8. Also, the fire reached the pillow fairly early, yielding a large flame zone with an expected strong heating of surrounding areas of the mattress.

The total thermal threat that must be endured by a mattress depends not only on the peak heat flux but also on the duration of that flux. Fast spread of the flames over a given point on the mattress tends to shorten the heat exposure duration but this could be more than compensated for by a wide burning zone. The width of the burning zone tends to increase with the total thickness (or mass) of burning material over the region of interest though, on the sides of the mattress, the gravity effect noted above allows more rapid, through-the-depth burning and thus a shorter burning zone. Unfortunately, the data obtained in this part of the study cannot discern the effective width of the heat flux distribution affecting a given mattress area as the covers burn over it (on the sides or on the top of the mattress). This is because of possible flame heat flux blockage by the mass of material between the visible flame zone and the mattress surface. The width of the high flux zone and other data on the heat load striking the mattress surfaces were obtained in the next part of the study, described in Chapter 3.

The area beneath the pillow is somewhat different from other parts of the mattress in consistently having a thick fuel load per unit area due to the presence of the pillow. The fire tended, to some extent, to spread over the pillow, then down into it. The most important feature here was the thick layer of polyester fiberfill which melted down to form an irregular pool of burning material on top of the mattress. Fairly intense burning persisted over the central pillow area for
2-3 min after it had reached this melt pool stage. The relatively tall flames (up to about 50 cm to 60 cm) could be expected to radiate strongly both toward the polyester melt pool and to more bare areas near it. Thus this is a very challenging area to the mattress. The latex pillow burned even longer and more intensely but it did not appear to melt down in the process so the residual, char-like burning mass tended to protect the mattress area beneath it. The periphery of the pillow area might be expected to see significant radiant heat fluxes since this material gave sooty, strongly radiating flames.

It is possible for the local thermal threat to a mattress from burning bed covers to be changed significantly by different arrangements of these covers. This was explored to a limited extent in the next stage of this study.

Heat Flux to Nearby Surfaces. The peak heat fluxes to the two gages adjacent to the mattress were highly variable (few kW/m^2 to 80 kW/m^2 over the range of bedclothes combinations) and non-reproducible in successive replicate tests. For the most part, both of these attributes reflect the smallness of the flux sensor (6 mm dia., ¼ in) and its relation to the variable flame zone passing by its fixed location. Figures 2-9 and 2-10 show, as an example of one of the most intense cases, the replicate test results for bedclothes combination #4. The time of occurrence of the peaks in these figures is not significant. For example, the side peak could have been measured much earlier on the ignited side of the bed rather than on the side opposite the igniter.

In general, on the head end there were two sources of the heat flux, the fitted sheet (a relatively small fuel mass) on the vertical surface of the mattress and the pillow, whose nearest surface was a few centimeters from the gage. Flames on the fitted sheet (which did not always spread to this area) had the potential to engulf the gage in a relatively small flame zone which would yield a relatively small radiation contribution and a moderate total heat flux (convection plus radiation). If the pillow were burning strongly nearby at the same time, the additional radiation it provided would boost the total flux further. The net result was peak total fluxes for this gage which ranged from about 5

kW/m^2 to 75 kW/m^2. The high end of this range occurred only in brief spikes which could have been due to some solid, hot material contacting the gage surface (the reading would thus be invalid); the peak levels that were more sustained (tens of seconds) were usually in the
20 kW/m^2 to 30 kW/m^2 range. Such a flux and duration could be expected to ignite many low density materials (fabrics, foams, etc.) placed at the gage location but would not ignite full density solids such as wooden furniture elements [8, 9].

On the side of the bed near the center of the folded back covers, there was, for some bedclothes combinations, much more fuel whose flames could immerse the flux gage. The larger flame volume accompanying the thicker fuel layer led to a relatively larger radiation contribution supplementing the convective flux that resulted from flame contact. The side gage results in Figs. 2-9 and 2-10 show that this could lead to a few tens of seconds of exposures to fluxes of 50 kW/m^2 and above. This is capable of igniting plywood, for example [9]. There may well have been other areas adjacent to this region of the burning bedclothes where these flux levels were sustained longer, creating the possibility of igniting other, denser wooden materials that might be found in furniture or decorative finish items.

Note that proximity to the burning bed counts heavily here. Any object not contacted by the flames would see a significantly lesser heat flux (by radiation only). It would also be lacking a pilot flame for ignition and so would require a higher heat flux to induce spontaneous ignition.

Flames from the burning of the overhanging covers did play on the bottom of the mattress to a limited degree for some of the bedclothes combinations, but only on the side of the bed away from the igniter since it had no block in place to mimic a foundation below the mattress. The heat fluxes here could be moderately intense but the flame contact was erratic and tended to be relatively short. Any mattress capable of resisting the heat exposure that the top of a mattress sees could likely resist the bottom exposures seen here. Limited data on the bottom surface fluxes are reported in the next chapter.

Bedclothes Combinations Selected for Further Study. The goal in the next step of the study was to focus on six bedclothes combinations for which measurements of heat fluxes to the mattress surfaces were to be made. From these data, gas burners to simulate the local impact of realistic bedclothes combinations were to be devised. The six combinations were selected as follows. As a first step, all of the combinations with charring components (cotton or wool) were eliminated since the char is both protective and likely to add an element of greater scatter to the flux behavior (it breaks up erratically). To catch the low end of the expected ignition threat to the mattress, combinations #2 and #12 were included. The behavior of the pillow areas was expected to be largely autonomous from the other covers. With these, the two distinct cases of heat flux to the pillow area of the mattress were included (from polyester fiberfill and latex foam pillows, which then do not need to be focused on for the remaining combinations) as are the two lightest layered cases for other areas of the bed. To catch the expected high end to the sides and horizontal surfaces of the mattress, combinations #4 and #5 were included. Finally, two presumed intermediate cases which have differing spread rates for the overhanging covers, combinations #3 and #7, were included in the heat flux study summarized in the next chapter.

Table 2-1a. Bedclothes Combinations for Inert Mattress Tests

Unless otherwise stated, sheet below means a polyester/cotton blend (50/50); pillow means a polyester fiberfill pillow plus a polyester/cotton pillow case; NOTE: "two sheets" means one fitted sheet plus one flat sheet.

1) Two sheets and one pillow
2) Two sheets, a mattress pad[9] and one pillow
3) Two sheets, a mattress pad, one pillow, one acrylic blanket
4) Two sheets, a mattress pad, one pillow, one acrylic blanket, one medium weight comforter
5) Two sheets, a mattress pad, one pillow, one acrylic blanket, one heavy weight comforter
6) Two cotton sheets, a mattress pad, one pillow with cotton pillow case, one cotton blanket, one medium weight comforter
7) Two sheets, a mattress pad, one pillow, one polyester blanket
8) Two sheets, a mattress pad, one pillow, one polyurethane blanket
9) Two sheets, a mattress pad, one pillow, one cotton blanket
10) Two sheets, a mattress pad, one pillow, one polyester blanket and a medium weight comforter
11) Two sheets, a mattress pad, one pillow, one wool blanket and one heavy weight comforter
12) Two sheets, one latex foam pillow

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[9] The mattress pad covered the top surface of the mattress only. It was held down on the four corners by elastic straps. The pad contained a layer of polyester fiberfill within a polyester/cotton shell.

Table 2-1b. Mass of Bedclothes Components

(Note: Range shown is that seen for all components of a given type. For some components only two samples were used in this study; for others, such as the sheets and pillows, the numbers used were substantially larger.)

Bedclothes Component	**Weight Range (kg)**
fitted sheet (polyester/cotton)	0.364 - 0.398
fitted sheet (cotton)	0.467 - 0.468
flat sheet (polyester cotton)	0.532 - 0.536
flat sheet (cotton)	0.640 - 0.647
pillow case (polyester/cotton)	0.104 - 0.107
pillow case (cotton)	0.127 - 0.130
pillow (polyester fiberfill)	0.563 - 0.585
pillow (latex foam)	0.963 - 0.975
mattress pad	0.383 - 0.552
acrylic blanket	1.182 - 1.210
polyester blanket	0.890 - 0.976
polyurethane blanket	1.045 - 1.046
cotton blanket	1.297 - 1.317
wool blanket	1.716 - 1.789
medium weight comforter	1.252 - 1.283
heavy weight comforter	1.524 - 1.584

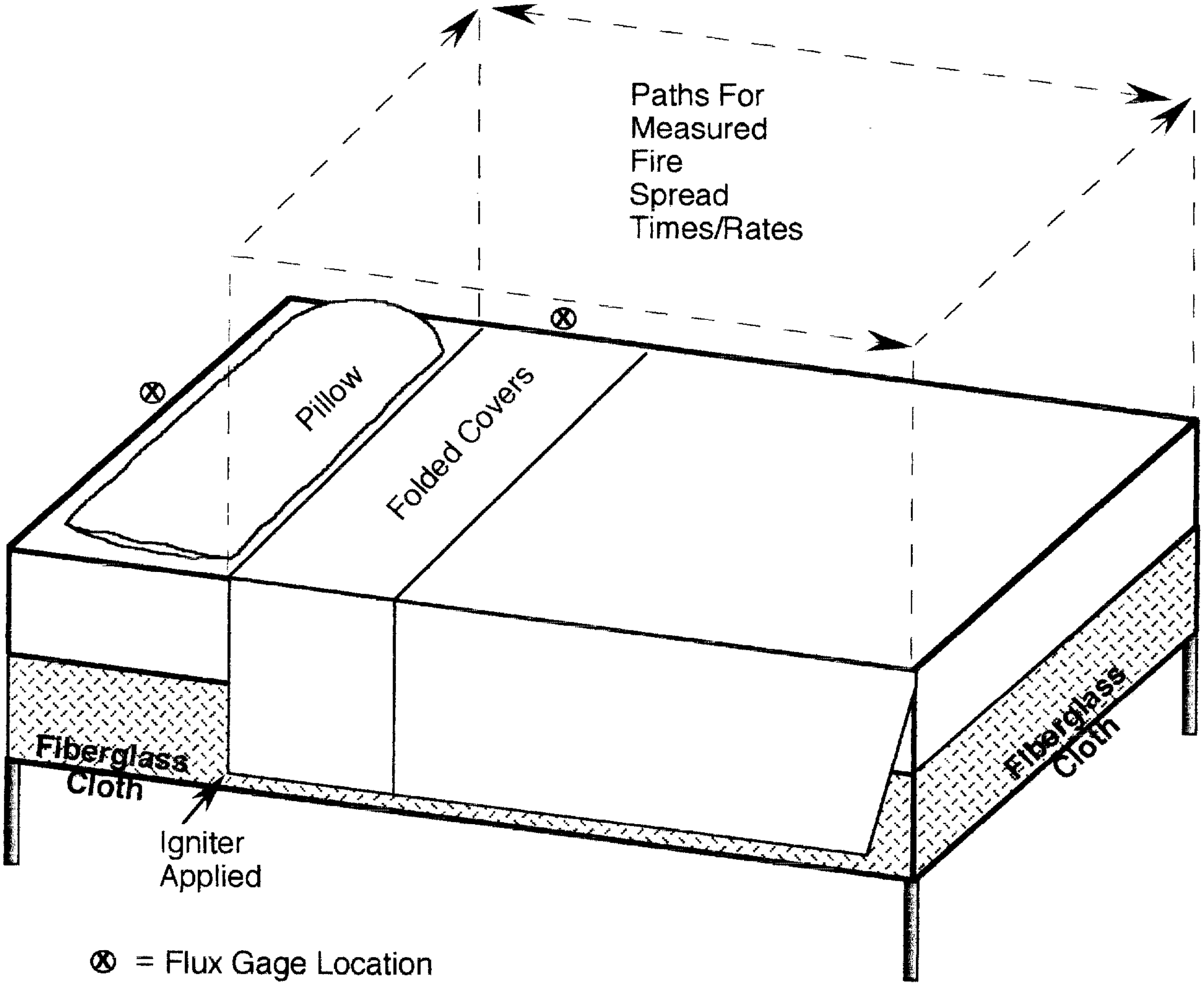


Figure 2-1. Schematic of bed showing ignition location and measured fire spread paths along top edge. Fiberglass cloth (or non-asbestos paper) was on two sides shown only.

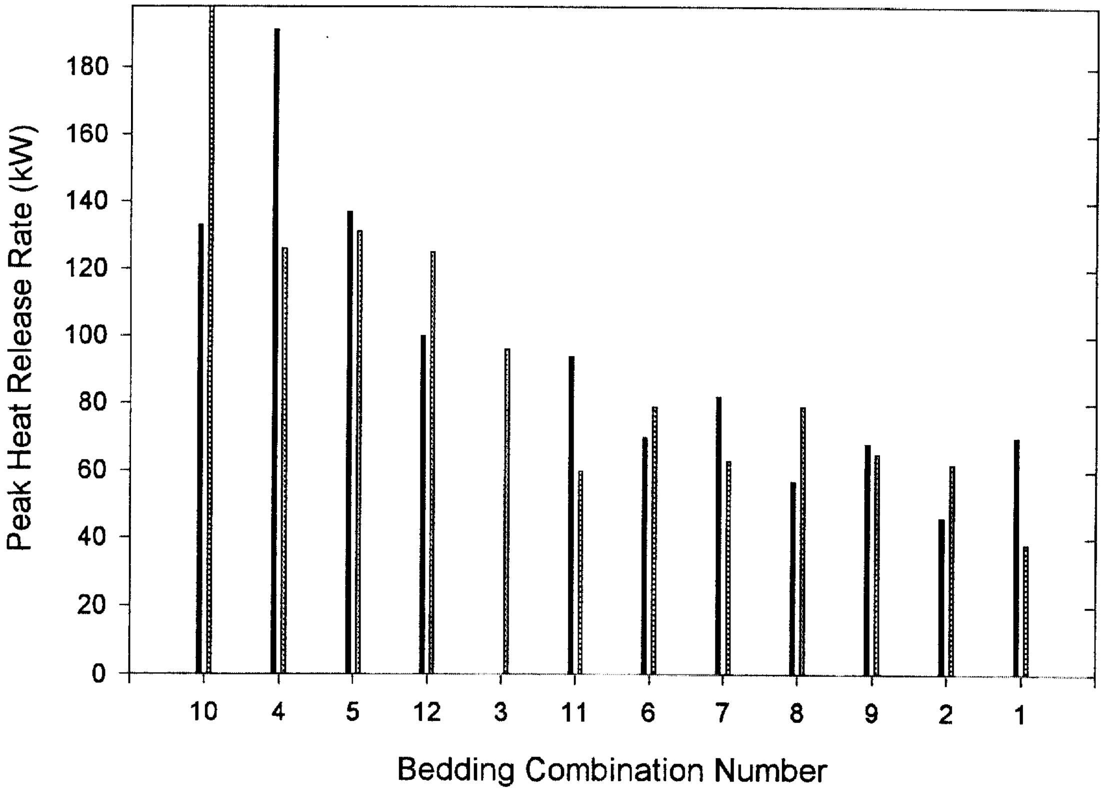


Figure 2-2 Peak heat release rate measured in two tests for each bedding combination; arranged in order of the average result from the two tests

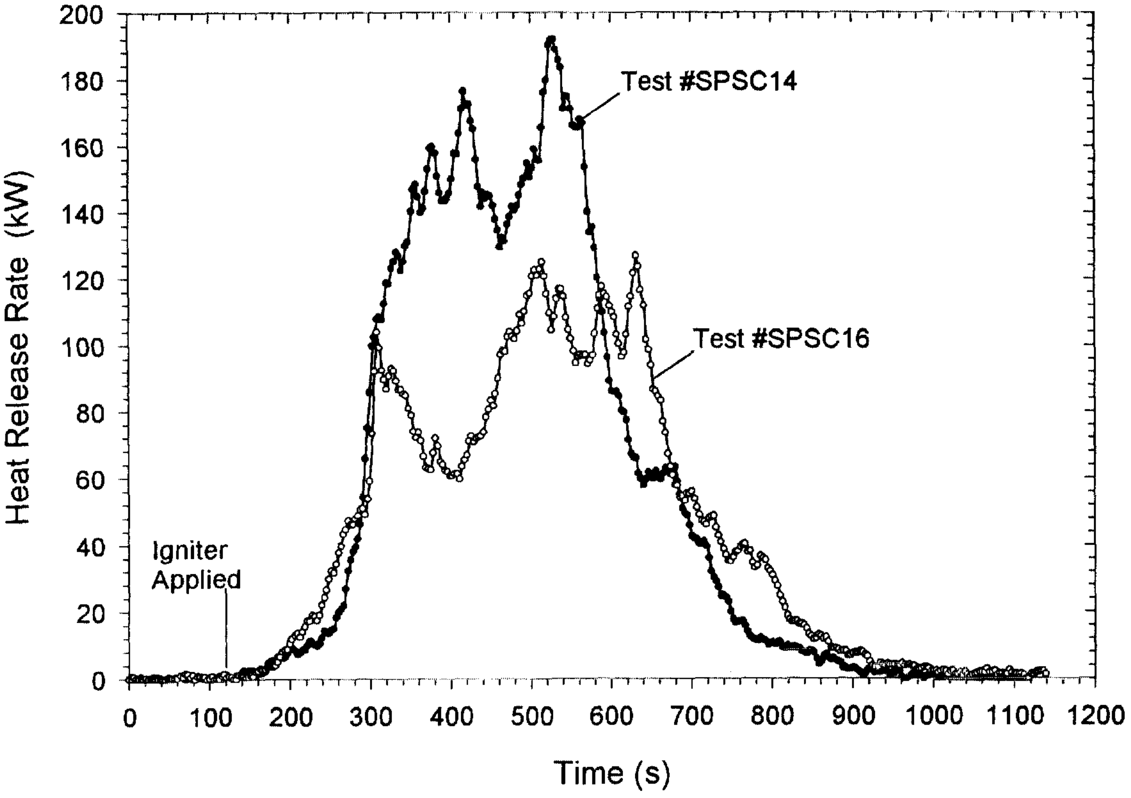


Figure 2-3 Heat release rate vs. time for bedding combination #4; results for replicate tests

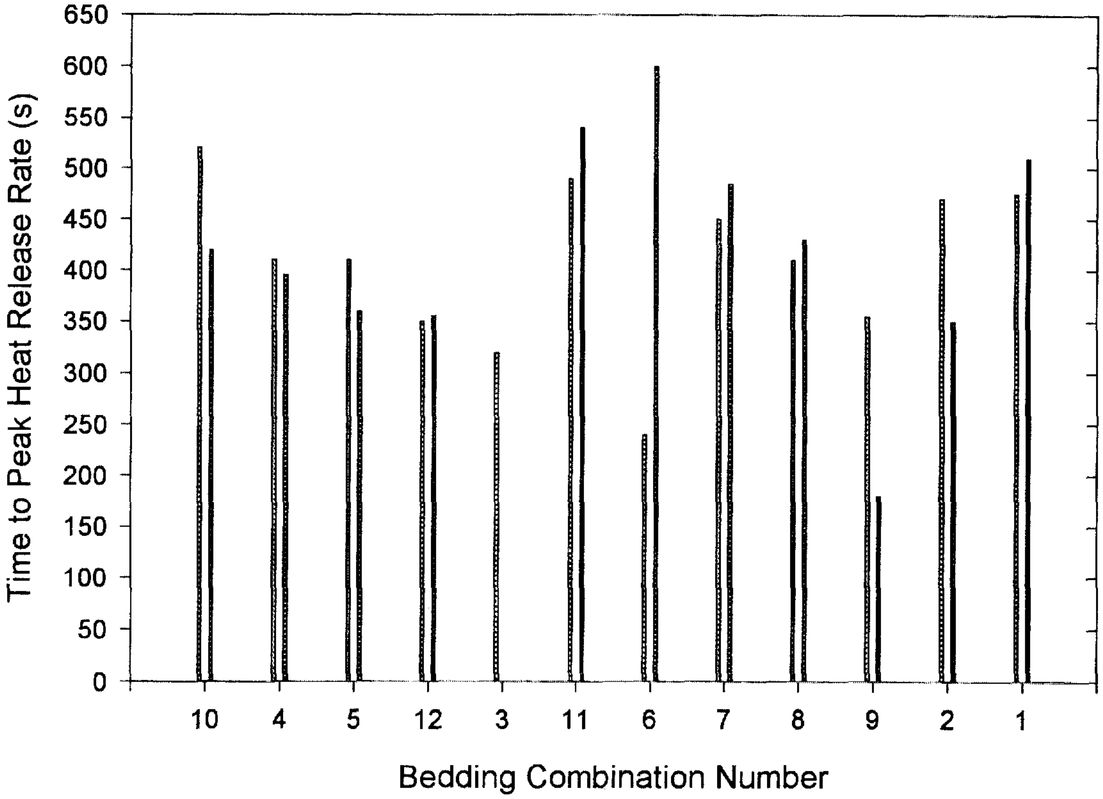


Figure 2-4 Time to peak heat release rate for twelve bedding combinations; arranged in same order as for peak heat release rate (Fig. 2-2)

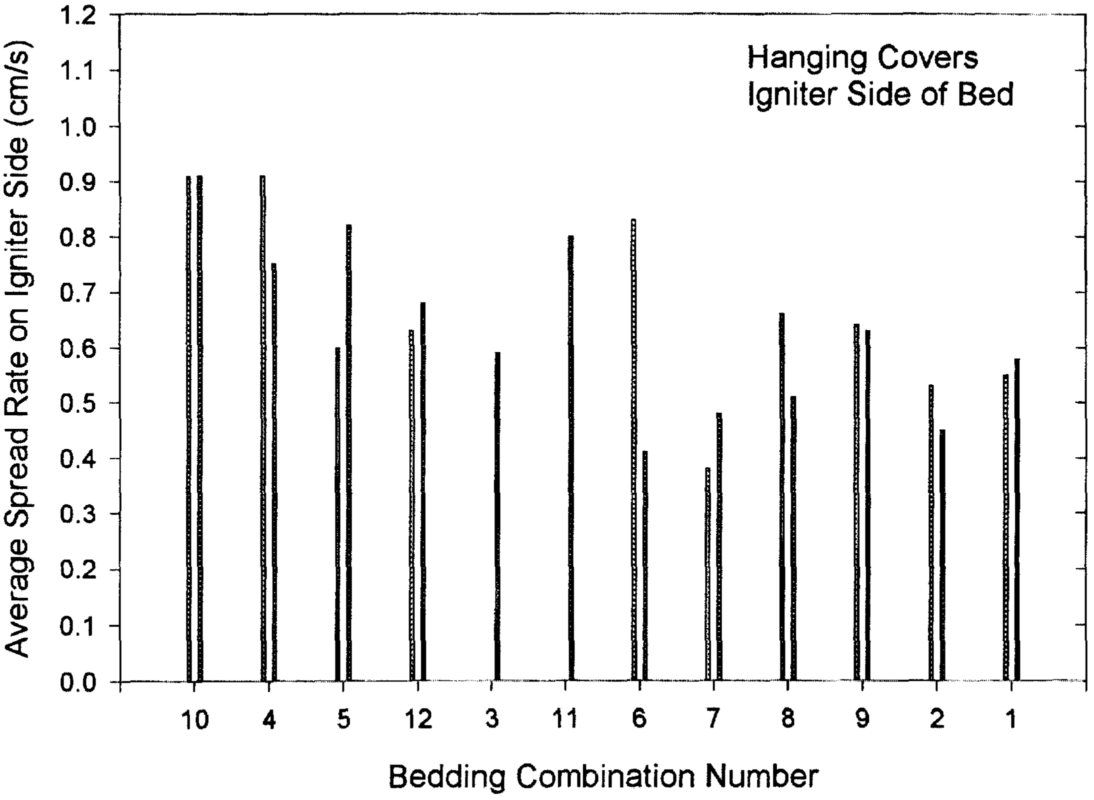


Figure 2-5 Average lateral fire spread rate on hanging covers; igniter side of bed; bedding combinations arranged in same order as for peak heat release rate (see Fig. 2-2)

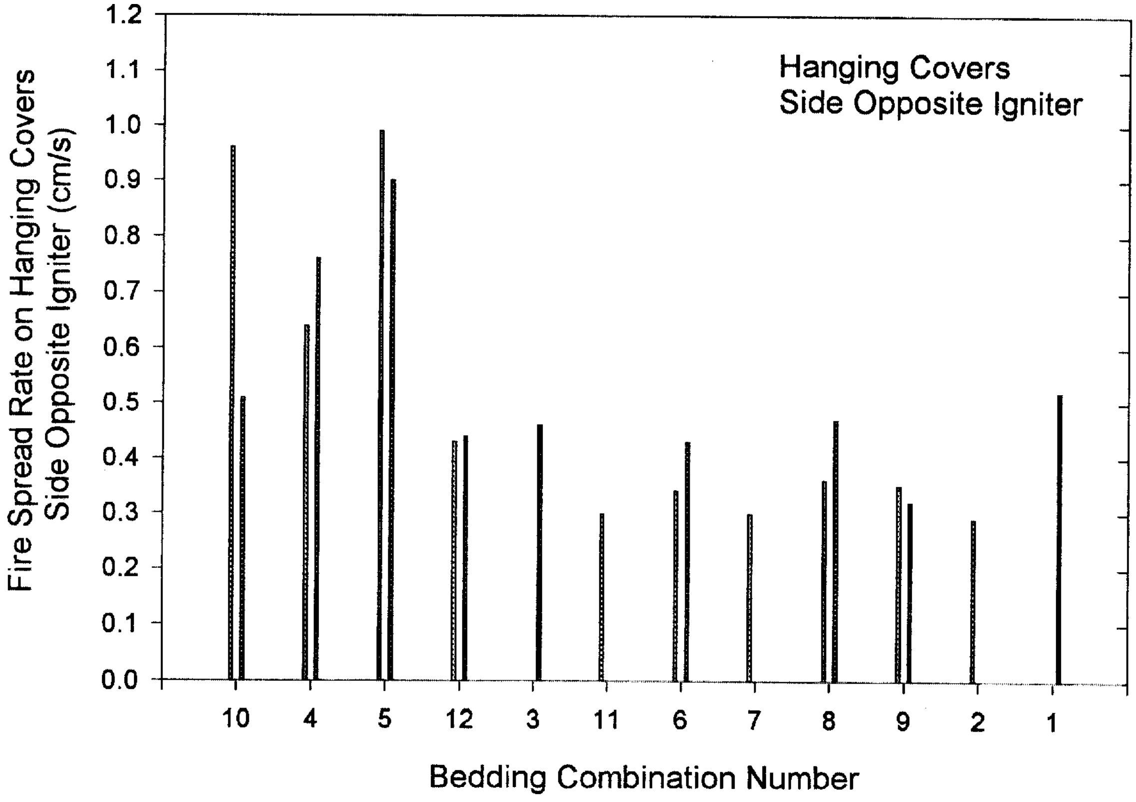


Figure 2-6 Average lateral fire spread rate on hanging covers; side opposite igniter; bedding combinations arranged in same order as peak hea release rate (see Fig. 2-2)

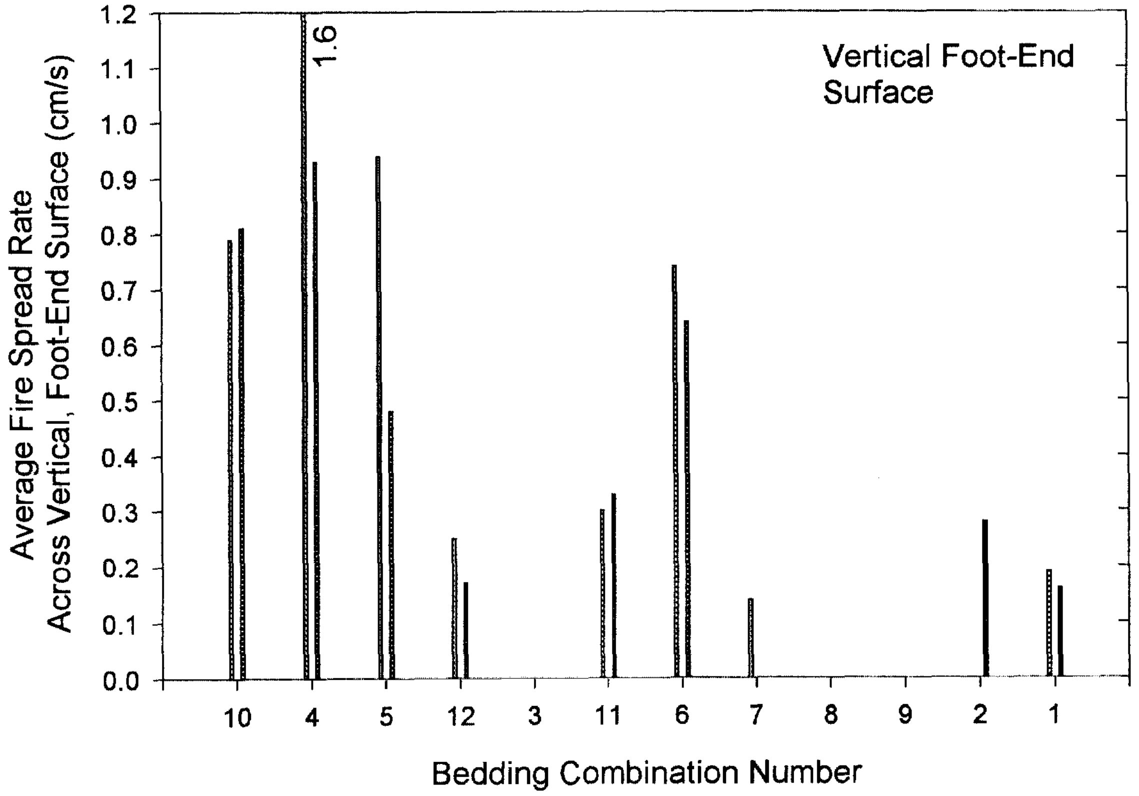


Figure 2-7 Average fire spread rate across vertical, foot-end surface; bedding combinations arranged in same order as peak heat release rate (see Fig. 2-2)

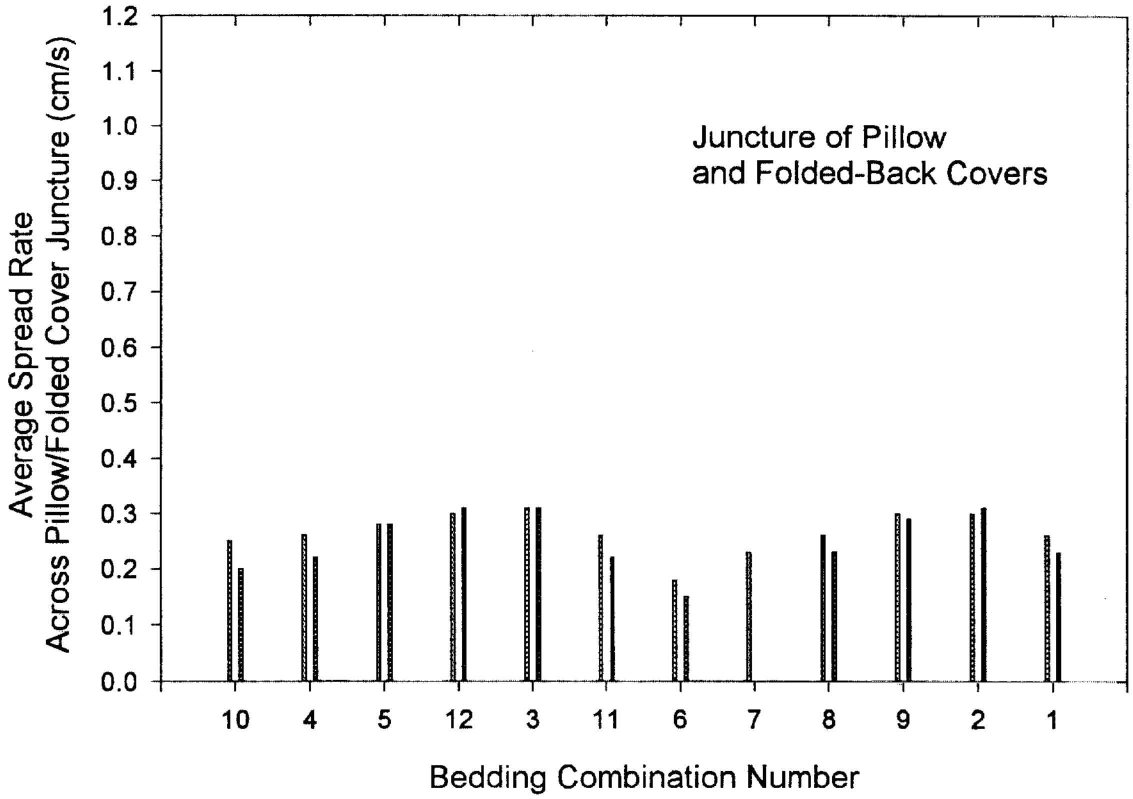


Figure 2-8 Average lateral fire spread rate across juncture of pillow and folded-back covers; bedding combimations arranged in same order as peak heat release rate (see Fig. 2-2)

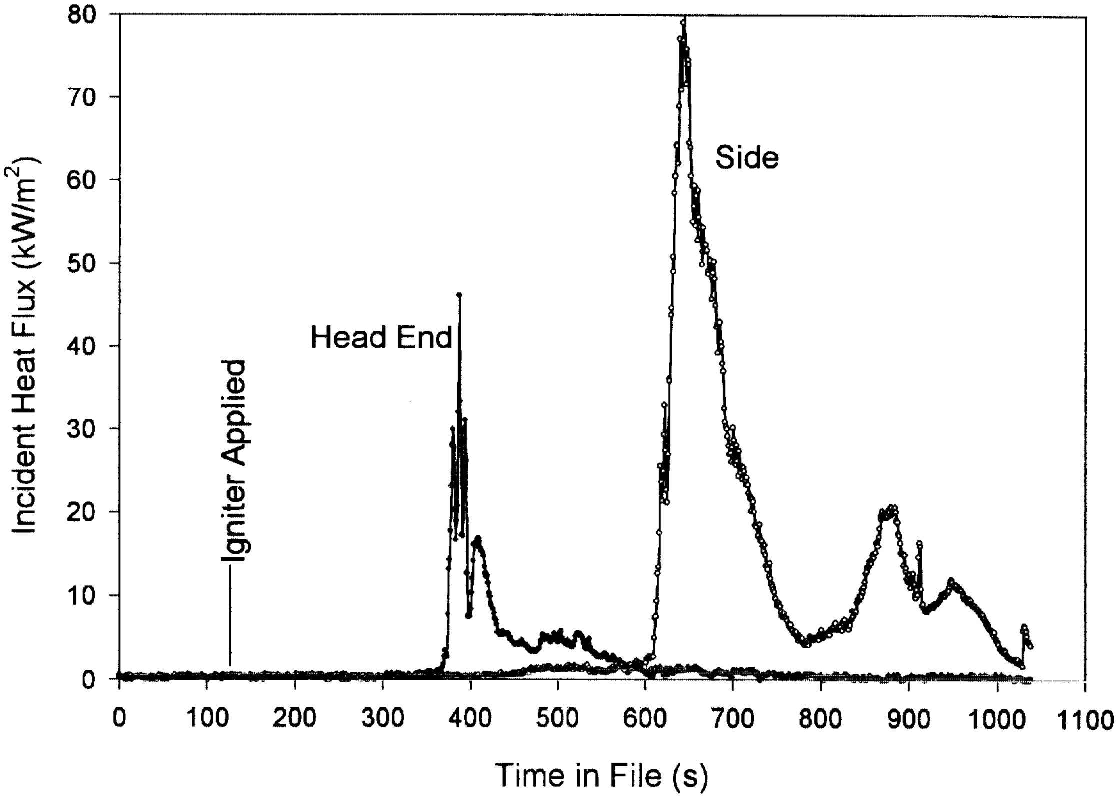


Figure 2-9 Incident heat flux on gages at two locations adjacent to the bed; bedding combination number 4.

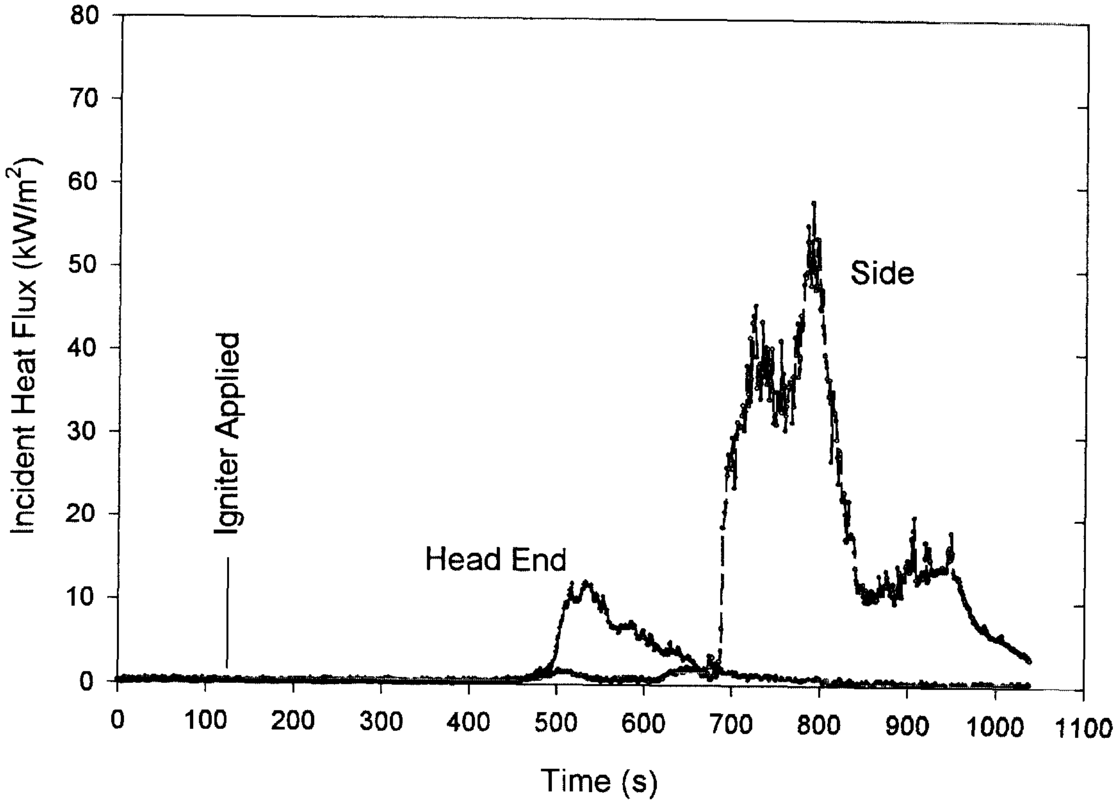


Figure 2-10 Incident heat flux on gages at two locations adjacent to bed; bedding combination number 4.

Chapter 3. Measurements of Heat Flux to an Inert Mattress

Recall that a goal of this study is to develop gas burners which provide a reproducible thermal load similar to that imposed on a mattress by burning bedclothes materials. In order to design ignition sources that can mimic this local thermal impact, it is necessary to measure the heat flux imposed by those bedclothes as they burn. By *local* impact is meant the heat flux versus time experienced by *typical fixed locations* on the surface of the mattress, not the *totality* of heat flux exposure experienced by the whole mattress as the bedclothes are consumed. This result is expected to vary significantly with the bedding combination in question because the size and duration of flames at any locale on the mattress depend on the nature of the bedding materials and their total mass.

The heat flux information of interest consists of flux versus time, along with a measure of the surface area seeing this thermal load. As will be seen below, this is reduced here to estimating the heat flux above certain fixed levels along with the time period that the flux remains above this level and the local area affected for this time.

Obtaining a detailed map of the time-varying heat flux at a large number of points on the surface of the mattress could be complex and expensive if normal flux gages were used for this task. The use of sufficient gages to generate a highly detailed map might well disturb the pattern (and would also be prohibitively expensive). To overcome this difficulty, an alternative technique has been used, which relies on the use of an infrared imaging camera to obtain large amounts of information on heat flux patterns in pictorial form. This is a refinement of a technique developed by NIST in assessing the California Technical Bulletin 133 test for upholstered furniture [14].

Description of Experiment. Figure 3-1 is a sketch of the experimental set-up. The inert "mattress" upon which the bed covers were burned was distinctly different from that used in the previous chapter since the former design was not suited to the present purpose. Here it consisted of a steel angle-based framework (twin bed size) whose top and sides were covered with a very thin layer of stainless steel foil (0.0025 cm thick). The various bedding combinations were assembled on this "bed" in the normal manner. Thus the material with which the bedclothes were in contact while burning was this foil, which substituted for the normal mattress surface.

As the bedclothes burned they imposed their heat load onto the steel foil surrogate for the mattress surfaces, causing its temperature to rise at any given point in proportion to the heat flux received by that point (see Appendix A). An infrared imaging camera viewed the back side of the steel foil on one side and a part of the top of the mock-up (see Fig. 3-1). The camera was an Inframetrics model 525, sensitive from 8μm to 14 μm. To facilitate this view from a distance dictated by the camera's optical characteristics, the mock-up was raised so that the top of the mock-up was 2.1 m (6.75 ft) above the floor. The camera looked up at a fixed angle of about 40° to the horizontal. The camera sat on top of a slide so that it could be moved laterally (by hand during a test) to see the head end, middle or foot end of the mock-up as the flames moved around on the bedclothes.

Figure 3-2 shows a photo of a portion of the underside of the mock-up (the head and middle sections). Four heat flux gages can be seen there mounted out on the end of spring-loaded arms which keep them in good contact with the steel foil as it expands when heated. Each flux gage sensor surface was centered on a small hole in the steel foil and was nearly flush with the foil so that it saw any heat flux impinging on the outside surface of the foil. A total of six Schmidt-Boelter flux gages was installed with four on the top and two on the side away from the IR camera. The white lines visible in the picture brought 85 °C water to the gages; the gages were calibrated at this temperature. Note that the bulk of the surface area of the steel foil was unobscured so that the IR camera could view its glowing in the infrared. Also visible in Fig. 3-2 is one of two small fans used to pull heated air out from the space enclosed by the mock-up to keep the background temperature of the foil more in line with that during the IR camera calibration process (described below).

It is evident in Fig. 3-2 that the flux gage sensors (6 mm dia.) monitored only a very tiny fraction of the total surface area of the mock-up which was exposed to the burning bedclothes. They literally provided only point data whereas the IR camera viewed a substantial fraction (ca. 60 %) of the entire affected area of the mattress mock-up. The camera could view one entire vertical side surface and ca. 75 of the horizontal top of the mattress mock-up. The gages thus served as a spot check of the primary heat flux results obtained from the IR images in a manner described below.

Bare stainless steel foil is a poor absorber or emitter of infrared radiation. Thus it was necessary to coat the foil on both sides. The interior surface of the foil was painted with Dupli-Color High Heat Paint (DH 1602) which was baked with a heat gun until it turned a stable deep brown color. This treatment was applied only once, before the start of the test series. The exterior of the steel foil was painted with Krylon Flat Black Paint (1602). It was baked using a 500 W lamp to the point where the paint was dull black and essentially stopped smoking. This coating was re-applied after each test because the melted/burned materials sticking onto it during a fire test modified it significantly and/or covered it. Thus it was necessary to clean the outside surface of the steel foil after every test to prevent material build-up which would have altered the thermal response characteristics of the foil (see Appendix A). This proved to be an extremely tedious process; it involved the use of paint stripper and mechanical scraping that stretched the steel foil somewhat (though without evident effect on its heat response).

The relationship between brightness of the IR image and heat flux to the front side of the steel foil was calibrated in a separate facility which provided much cleaner heat flux data. This consisted of a shorter version of the same type of steel frame covered on one horizontal and one vertical surface with the same stainless steel foil. The foil was coated and baked-out on both sides in the same manner as described above. A single heat flux gage, mounted as above, was used to measure the total flux to the outside surface of the steel foil due either to an electric heater or a gas flame. Both sources imposed mixed convective/radiative heat loads on the foil as is to be expected from the burning bedclothes. The IR camera viewed the back of the foil and its isotherm function was used to measure the brightness of the image (relative to background) very near the flux gage. This was done separately for the vertical foil surface and the horizontal foil surface since they differ in their heat loss rates. Appendix A discusses the heat balance on the steel foil. Figures 3-3a and 3-3b show the resulting calibrations which were used below to infer peak heat flux levels from the burning bedclothes.

Inspection of Figs. 3-3a and 3-3b shows that the calibration data are somewhat noisy. The chief source of noise was probably the fact that in the calibration set-up there were spatial variations in the heat flux which made for difficulties in getting a precise reading near the flux gage. The noise introduced an approximately ±5 % uncertainty in the flux measurements since the IR brightness could only be read to an uncertainty of about ± 0.05 isotherm units. The need, in the actual experiments, to repeatedly re-coat and re-bake the exposed side of the foil surface, with its attendant uncertainty in the effective heat capacity of the coating layer and thus the response time of the foil (see Appendix A) brings the uncertainty to an estimated ±10 % (though this added uncertainty applies mainly to short-lived, i.e., 10 s to 15 s, heat flux peaks).

For the measurements of heat flux patterns imposed by bedclothes, the bedclothes were placed onto the twin bed mock-up, layer by layer, in the same manner as they would be on a normal mattress. An additional factor explored here, however, was the effect of disturbing the bedclothes so that they did not lay flat and neat as they did in Chapter 2. It should be noted that some types of bedclothes arrangements are likely to be worse than others in terms of their effect on the heat flux to the mattress. Thus simply forming the bedclothes into a large pile on top of the mattress is not likely to be severe on the mattress since the flames would mainly be on the outer surface of such a pile and thus be insulated from the mattress, heating it primarily around the pile periphery. Here the emphasis was on configurations which allowed more air into a gap between the bulk of the bedclothes and the fitted sheet. This was intended to allow flames in the gap, to thus bypass the insulative effect of the thick covers and to form a radiating cavity near the mattress, thereby boosting the heat flux to it.

Three specific arrangements were used simultaneously (though not in every test): (1) A tent-like cavity between the bedclothes and the fitted sheet in the fold-over region, at its juncture with the pillow. This was supported with a wire frame roughly 20 cm wide at its open end by 15 cm high; it tapered to zero height at 30 cm (pointed toward the foot end of the bed mock-up). (2) A vertical ripple in the overhanging covers on the side away from the IR camera, always in the single bedclothes thickness region. The ripple caused the hanging covers to loop out away from the side of the mock-up a distance of the order of 15 cm. (3) A collapsed "tent" in the single thickness region of the bedclothes on top of the mock-up. This was formed by pulling the covers up from the IR camera side of the mock-up, forming a roughly triangular vertical arch and letting this collapse to a height of 20 cm to 25 cm. These localized disruptions also resulted in "ridges" in the bedclothes over much of the top surface of the mock-up.

The bedclothes were ignited in one or two locations using a propane torch. When the wire-supported "tent" was present in front of the pillow, the material around the opening of this disruption was ignited first. The igniter was then applied also to the same location as was used in Chapter 2 (i.e., at the bottom of the folded-over bedding, on the end toward the head of the "bed"). When there were no disruptions in the bedclothes arrangement, this was the only location ignited.

Since the IR camera could see only a portion of the underside of the mock-up from any fixed position (somewhat more than one third of the length), it was necessary to move it laterally (along the longitudinal direction of the mock-up) in order to follow the heat patterns from the moving flame zones. It was generally possible to get full data on the local duration of these zones, especially on the vertical side where the duration was relatively short. On the top of the mock-up, there were a few occasions where the full duration of a local flux peak was missed because the camera had to be moved to follow some other simultaneous event.

Because of the time-consuming efforts required to clean the steel foil between tests, it was decided to obtain data on the pillow region only with bedclothes combinations #2 and #12, i.e., with the two types of pillow material and also with combination #5 (in one test). Thus in five of the total of twelve tests (six bedclothes combinations with two replicates of each), the pillow region behavior was recorded with the IR camera. For the remaining seven tests the camera was directed at regions other than that below the pillow.

The tests were conducted in a randomized order. The IR camera and one Hi-8 camera were paired on the same mounting. The latter camera was present to resolve any ambiguities in the IR images but it proved unnecessary. A second Hi-8 camera recorded a view of the burning bedclothes from the side opposite that having the IR camera. The IR camera output was recorded on VHS tape.

Infrared Data Analysis. Analysis of the infrared camera tapes was a tedious task due to the complexity of the results they recorded. Recall that the goal was to obtain adequate information on peak heat fluxes, flux duration and localized area affected by this flux. The IR tapes show diffuse gray glowing zones of constantly changing shape and of widely varying intensity which moved over the observed surfaces at rates which also vary widely. The brightest regions, corresponding to the highest heat fluxes, were of primary interest.

The tapes were analyzed as follows. The first 8 min of each test were digitized at the rate of one frame per second of test time using 8-bit resolution. These parameters were dictated by available memory limitations but it was generally sufficient to capture the bulk of the bedclothes fire process. The digital images were then displayed using NIH

Image, a freeware image analysis program. Since the IR camera's isotherm measuring function had been used at frequent intervals throughout the test to measure bright spots on the image, it was possible to construct from this a calibration between the brightness of a given image pixel and isotherm level. Using the data in Figs. 3-3 a&b, one could then relate pixel brightness to heat flux. The threshold function of the image analyzer program was then used to impose an artificial color onto any pixels above a desired brightness, corresponding to a flux level of interest. Thus, for example, all areas of the image with an incident flux level at or above 65 kW/m^2 were colored red while the remainder of the image stayed varying shades of gray. It then remained to quantify the real surface area on the mock-up that this red area corresponded to and, furthermore, to quantify how long this red area persisted. The conversion to real mock-up surface area was complicated by the fact the top and sides of the mock-up were seen at differing angles imposing geometric distortions onto the image being viewed. Known elements of the underside of the mock-up (e.g., the structural framework) could be discerned in many of the images. By use of their known dimensions and spacings it was possible to construct a grid pattern calibrated with real dimensions that was used to determine areas from the displayed images. The duration of a given hot region interacted somewhat with its apparent area since the fire causing the hot areas was moving and this was difficult to readily account for with the available software. The uncertainties in these two quantities (hot spot area and duration) are estimated to be ± 20 %, mainly for this reason. Because of the time requirements to perform these analyses for all twelve tests (separate analyses were required for horizontal and vertical surfaces), the heat flux threshold values were limited in eleven of the tests to 65 kW/m^2 and 50 kW/m^2. For one test (with the heaviest bedclothes combination, #5), data were also obtained at threshold heat flux values of 35 kW/m^2 and 20 kW/m^2.

In counting the various hot spot areas for a given heat flux threshold, a minimum duration requirement was imposed which varied with the flux. The minima were as follows:

Flux Threshold (kW/m^2)	Minimum Duration (s)
65	3
50	5
35	10
20	25

These were chosen on the basis of the time needed to ignite various fabric/foam combinations as reported in Ref. 6. The typical ignition times were equal to or longer than the above numbers. Shorter heat flux exposures are ignored because they have little chance of igniting a real mattress (and, in any event, the gas burners discussed in the next chapter are applied for longer times).

Heat Flux Pattern Results and Discussion. Figures 3-4a and 3-4b show the measured combinations of area and duration at a flux of at least 65 kW/m^2; the scales differ in the two figures. Both horizontal and vertical surface data are included for all six bedclothes combinations. Note that if a symbol is absent for a given bedclothes combination, it is because that combination did not produce any significant area above the flux threshold with a duration of at least the cut-off time noted above. The first thing to note is that there is considerable variability in both the size of hot spots and their duration, even for a particular bedclothes combination. This reflects the wide variability in proximity and contact between the burning bedclothes materials and the adjacent "mattress" surface. The burning process itself causes the materials to undergo substantial changes in shape in an erratic manner. Both flames and hot, possibly molten, materials transfer heat to the mattress surface. The heat flux from the flames varies with the angle at which they impinge on a surface and with the presence of any intervening material which may be temporarily insulative.

The second point to note is that the vertical side data are much more sparse than are the horizontal surface data. There simply were not many spots on the side surface which reached the 65 kW/m^2 threshold value. The few that showed up were short-lived and small in area. The reason here is presumably related to the gravity issue discussed above. The materials are not held in as close contact with the side surface of the mock-up as they are with the top surface. Thus the heat flux to the side surface is less. The duration is less because, as noted in Chapter 2, the flame spread rate is faster. In contrast, the top surface shows numerous spots at 65 kW/m^2 or above. In fact, a check showed that some spots reached more than 70 kW/m^2.

Early in the development of this flux measurement method, it was also used to examine, to a limited extent, the heat flux pattern imposed on the bottom outer surface of a mattress by the burning of the hanging bed covers. The results were in all respects similar to the more extensive data for the vertical side of a mattress.

Figure 3-4a shows a boxed area marked "pillow area with heavy covers." This box encompasses data points derived from the single test with bedclothes combination #5 in which the pillow area of the horizontal surface was monitored along with the other areas. The prolonged, intense burning that sometimes occurred was near the juncture of the pillow and the doubled layer of covers. It is probable that if that area had been monitored in other tests, more data points would have showed up in this region. Thus the single triangular point at 45 s would not be isolated. This is relevant to the exposure times chosen for the gas burners, as discussed in the next chapter.

Figures 3-5 a&b show the thermal load data obtained for horizontal and vertical surfaces when the heat flux threshold was lowered to 50 kW/m^2. Again note that the abscissa scales on the two graphs differ. On both graphs there is an increased number of data points, especially at larger areas and longer times, as compared to Figs. 3-4 a&b. This reflects the fact that many of the same hot spots as above were involved in the monitoring process and there was a natural tendency for the burning zones which caused them to generate local areas of higher flux and larger areas around these, having a lesser flux, where the flames were in less close contact with the mock-up surface. Also, since the flames were unlikely to remain close to the surface during the entire burning process at any given location, the duration of the high flux spots tended to be less than that of the lesser flux spots.

Figure 3-6 a&b show all of the data obtained as a function of the four levels of heat flux threshold examined (20 kW/m^2, 35 kW/m^2, 50 kW/m^2, 65 kW/m^2) for bedclothes combination #5. Again there was a tendency for the largest hot spots to be those corresponding to the lowest heat flux. The tendency for these lower fluxes to also persist for a longer time was more mixed here; it is clearly the case on the side of the "mattress" but not necessarily so for the top surface with this bedclothes combination.

The data suggest a time-dependent heat flux history at any given point, as is to be expected from the fact that the burning zone is moving progressively over each locale. Thus, as the burning zone approaches a given point, the heat flux there begins to rise, reaches a peak and then recedes as the burning zone moves on. As will be seen in the next chapter, this behavior cannot readily be mimicked with a gas burner, except by a square-wave exposure.

Examination of the data in terms of the location and frequency of the hot spots relative to the presence or absence of disruptions in the bedclothes arrangement indicates a tendency for there to be more of the most intense hot spots in the presence of the wire tent. Recall that this was a support placed under the fold-over region of the covers, in front of the pillow. Effects from the other modes of bedclothes disruption were much harder to discern, though the collapsed tent on the foot end may have had an occasional tendency to intensify the local heat flux.

The heat flux gage data were difficult to interpret in a definitive manner. An example is shown in Fig. 3-7 for a test with the heaviest bedclothes combination (#5). The gages were used as a check on the IR data but they sampled very few spots and those spots were smaller (6 mm dia., ¼ in) than the IR camera could resolve at its stand-off distance. Furthermore, the gages react strongly to contact from hot, condensed phase material with a strong upward spike or they can be easily obscured by a small (1-2 mm dia.) piece of insulating material flaking off a piece of burning bedclothes material.

The flux gages have a much faster time response than does the stainless steel foil, so they follow the local history with a much higher time resolution (0.1 s versus 5 s to 10 s response time). Thus the gages show a much more erratic looking flux history than one would infer from the steel foil. This noisy variability in the local flux is probably correct but is also largely irrelevant. The real mattress surface responds more slowly and it is a more time-averaged history which drives the local mattress surface temperature. The results in Fig. 3-7 do confirm the general increasing-peak-decreasing character of the local heat flux history, as described above but one sees that there can be more than one peak at a given locale.

The peak flux values varied more broadly than the levels seen with the IR camera. In twelve tests, there were a total of two spikes recorded on horizontal surface gages in excess of 100 kW/m^2; these lasted only a few seconds. The side surfaces also showed higher spikes than did the IR camera but again for very brief periods. Recall that short peaks were not counted in the IR data even when they were seen but the slower response of the steel foil makes them unlikely to be seen.

One pertinent point does emerge from the flux gage results that is less clear in the IR results above. It was not unusual for the total duration of heat flux exposure to be 200 seconds or even more, even though the time at higher fluxes (e.g., > 50 kW/m^2) may have been much less. This tendency for a continued lower level of heat input from the bedclothes (which can be seen in Fig. 3-7) may have been relevant to the fate of one of the mattress designs discussed in the Chapter 5.

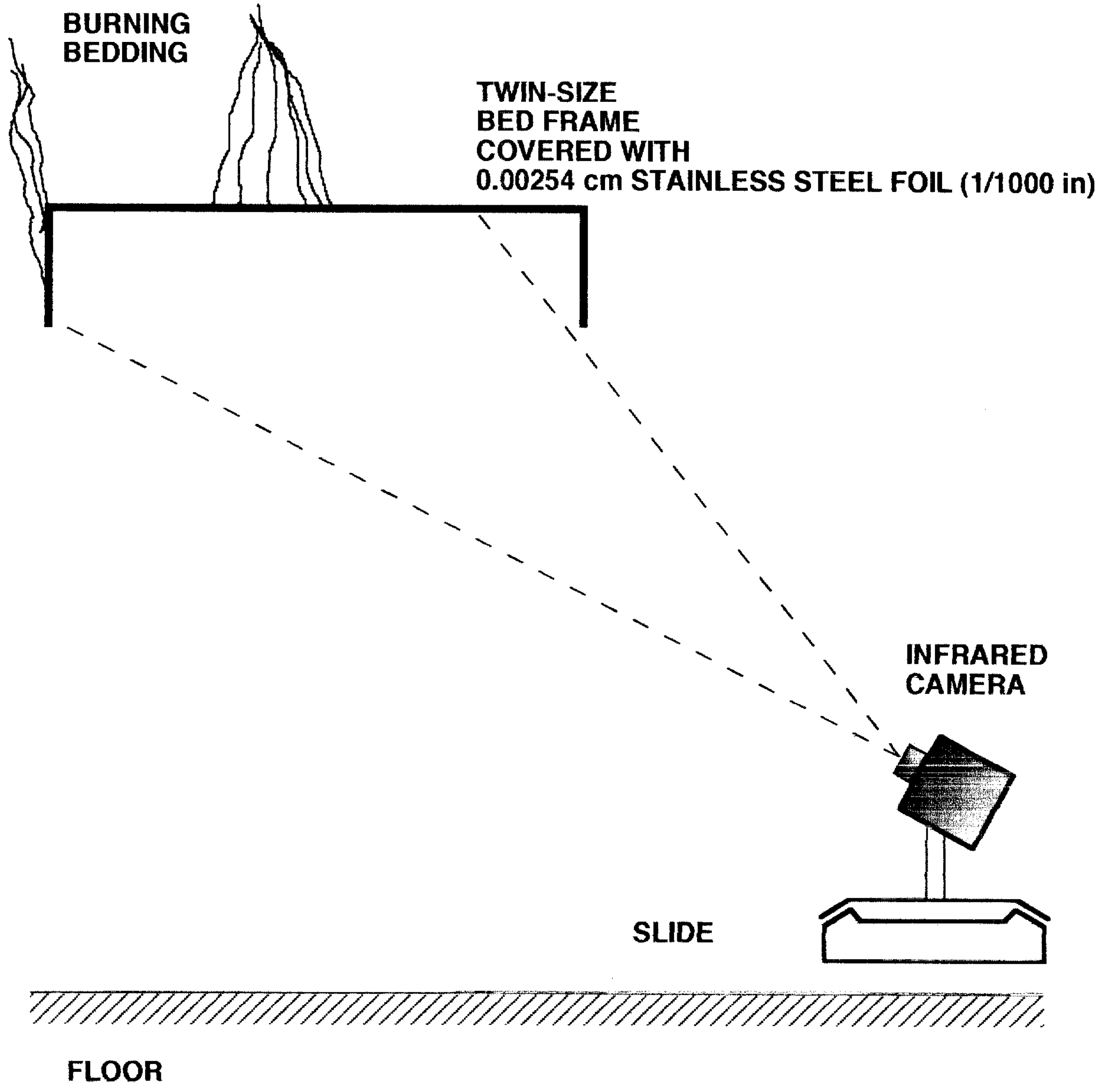


Figure 3-1. Sketch of set-up for characterization of heat flux patterns imposed on inert mattress surfaces by burning bedding.

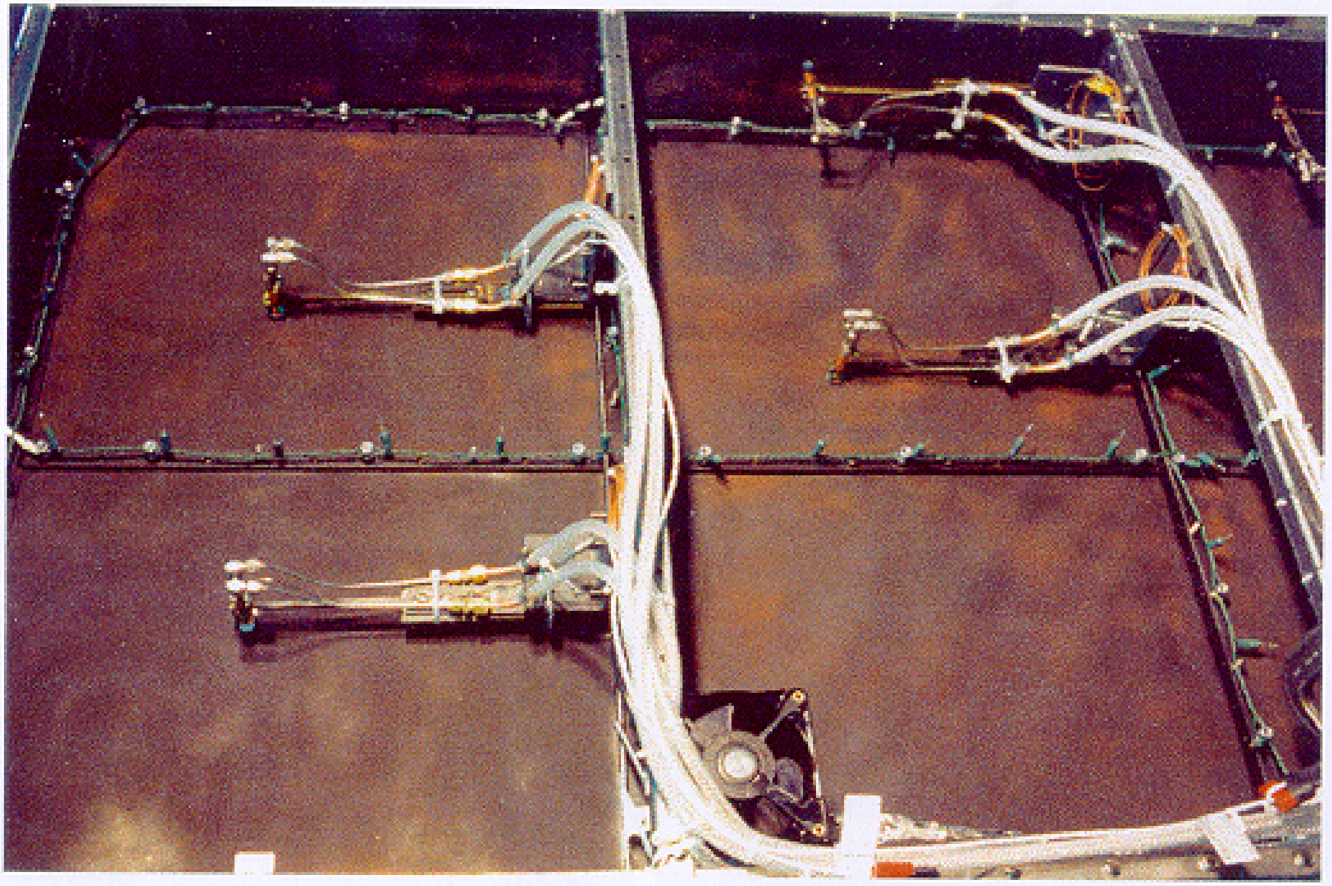
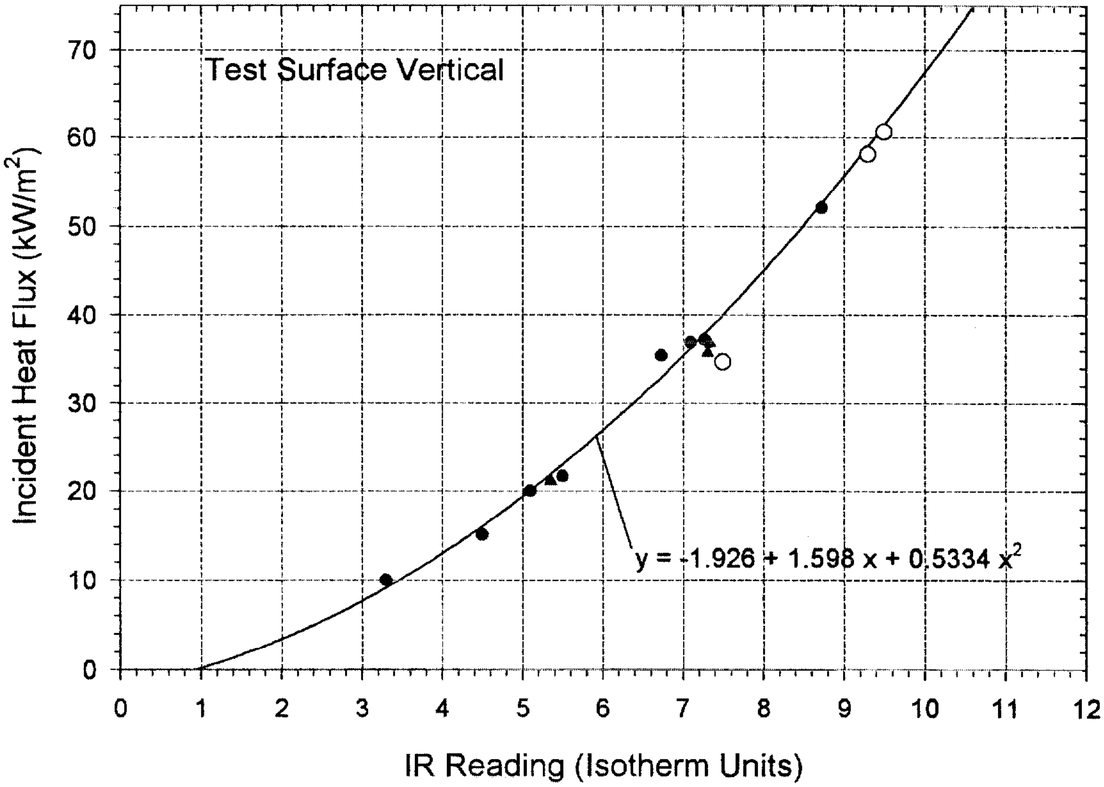


Figure 3-2 Photo of underside of inert mattress showing placement of four of the six spring-loaded heat flux gages.



CIRCLES: Obtained with electric heater as flux source

TRIANGLES: Obtained with propane flame as flux source

Figure 3-3a Calibration of infrared camera image brightness as a function of incident heat flux onto front side of vertical stainess steel foil

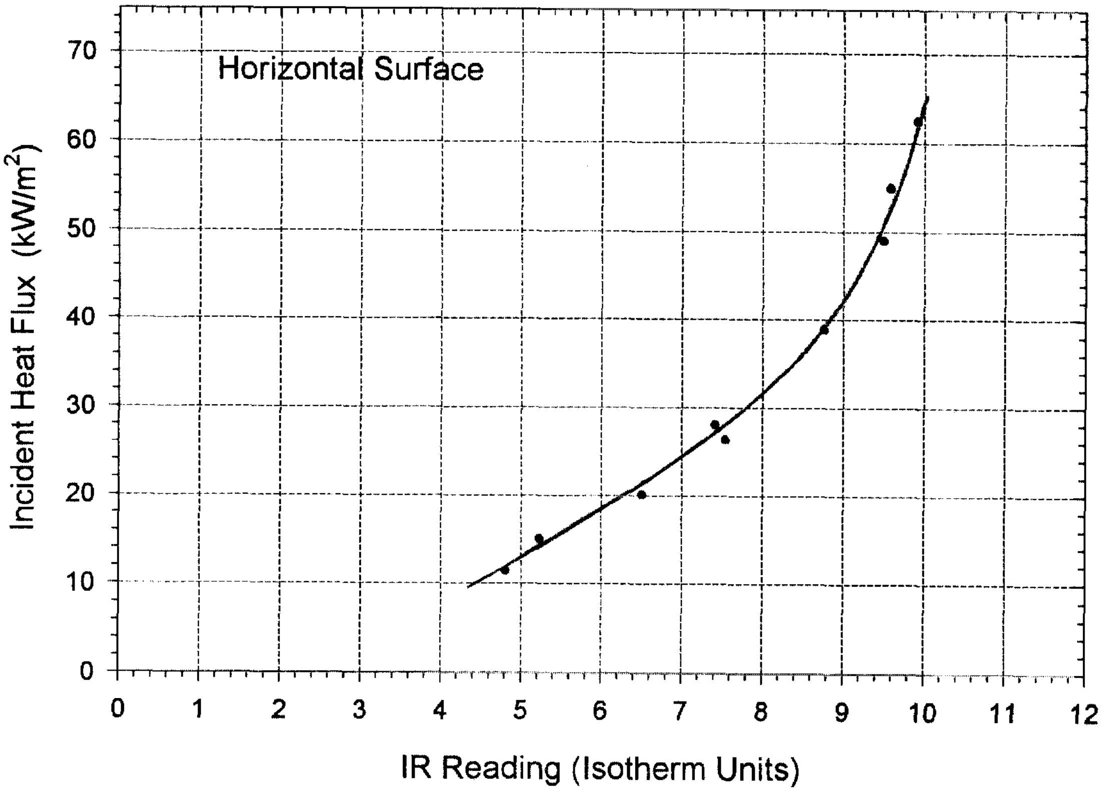


Figure 3-3b Calibration of infrared camera image brightness as a function of incident heat flux onto top side of horizontal stainless steel foil.

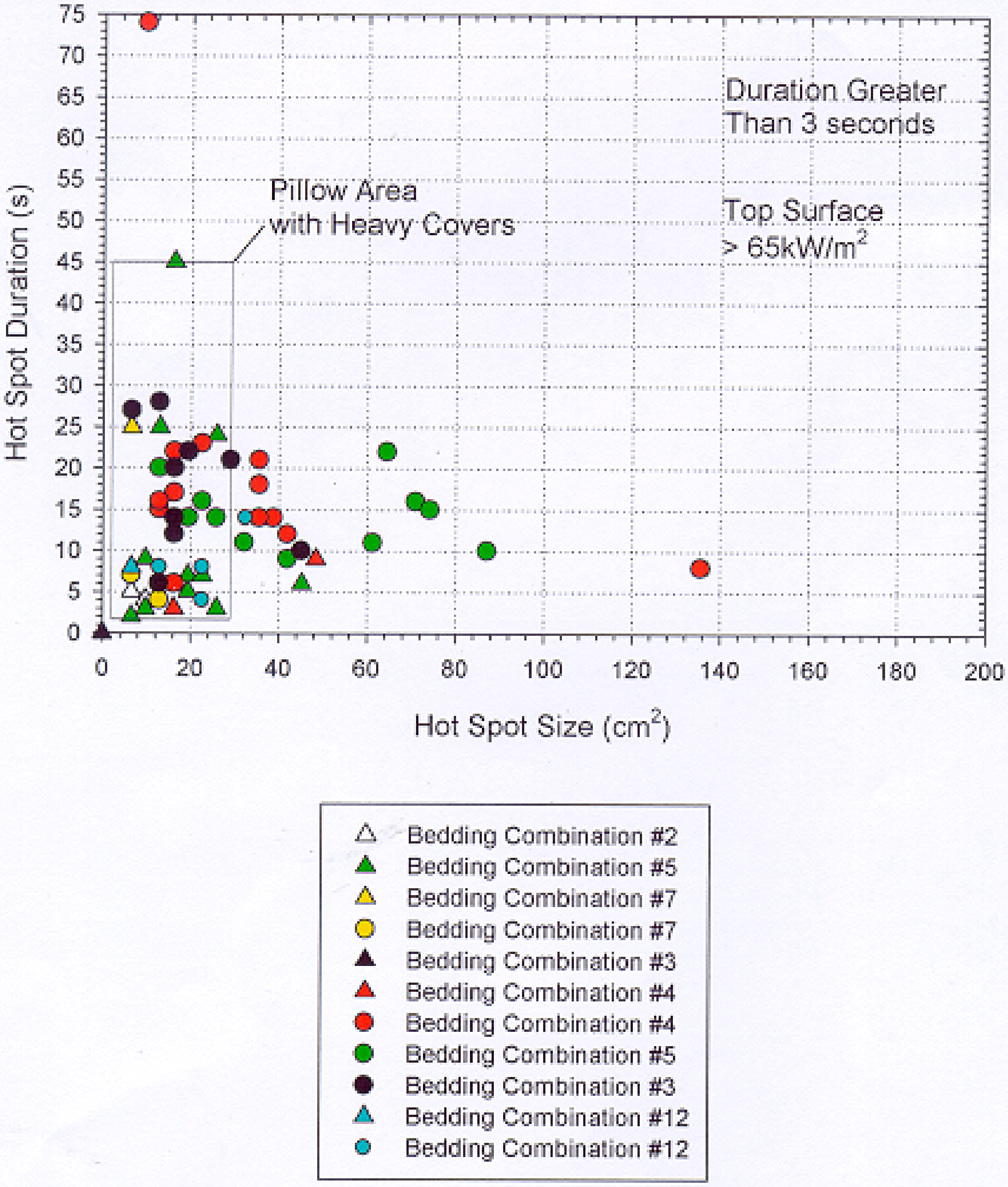


Figure 3-4a Measured characteristics of hot spots from burning bedding imposing a heat flux > 65 kW/m^2 on the top surface of a mattress

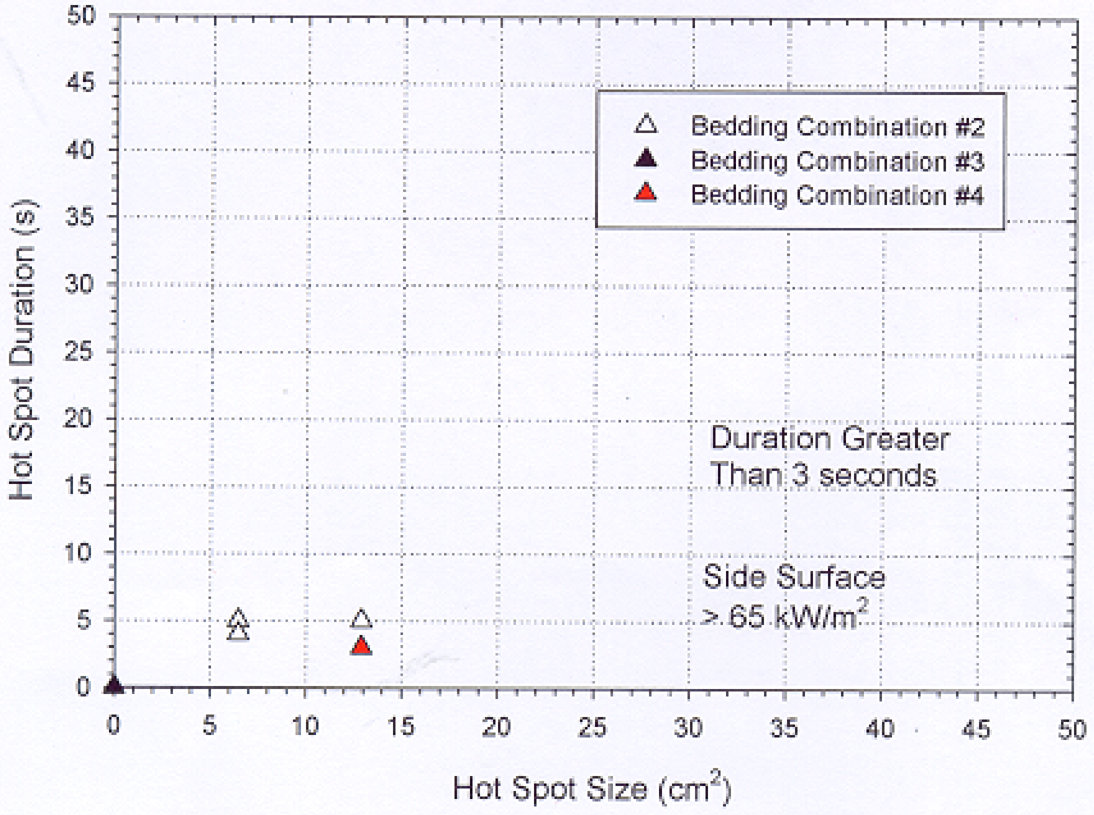


Figure 3-4b Measured characteristics of hot spots from burning bedding imposing a heat flux > 65 kW/m^2 on the side surface of a mattress

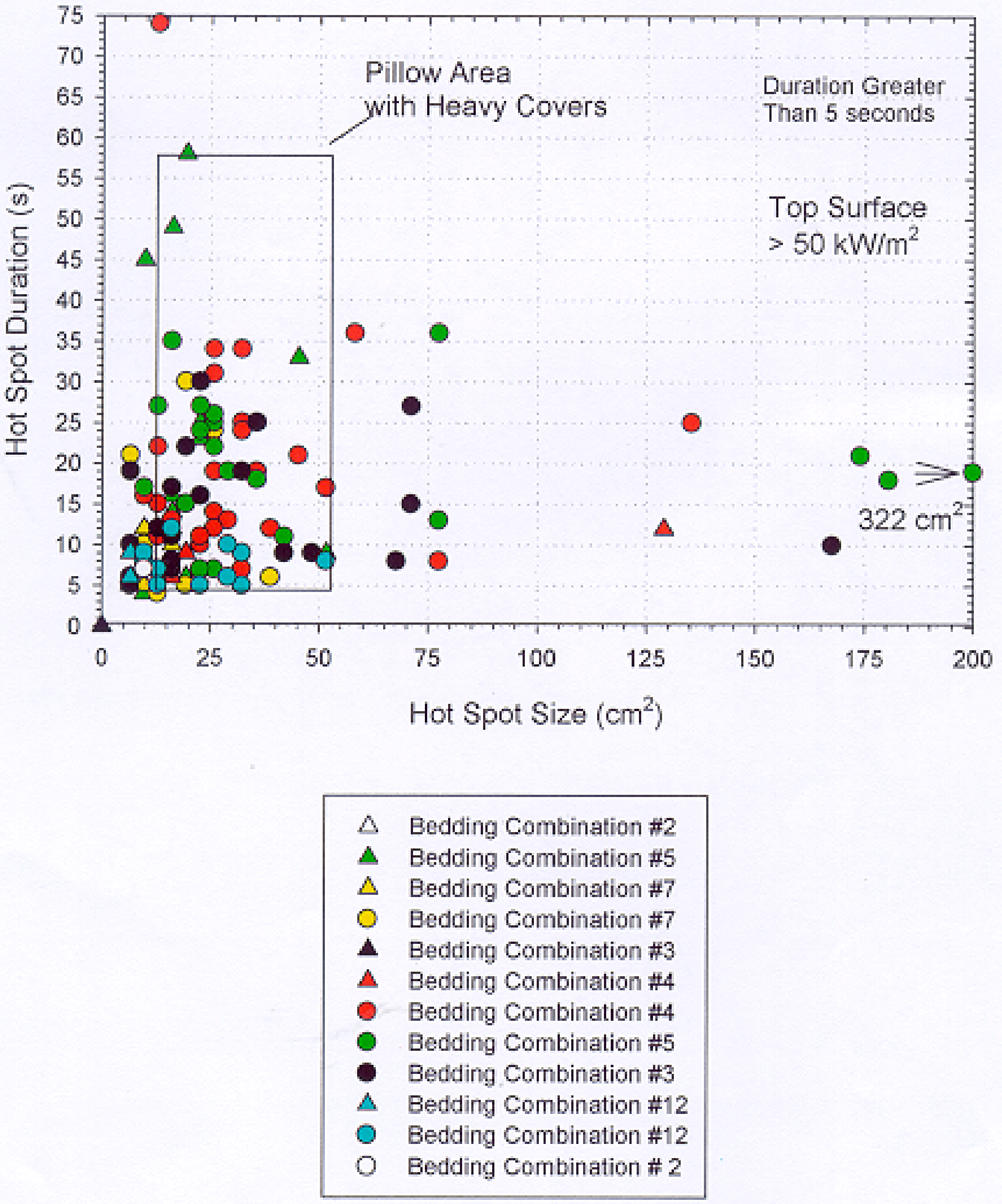


Figure 3-5a Measured characteristics of hot spots from burning bedding imposing a heat flux > 50 kW/m^2 on the top surface of a mattress

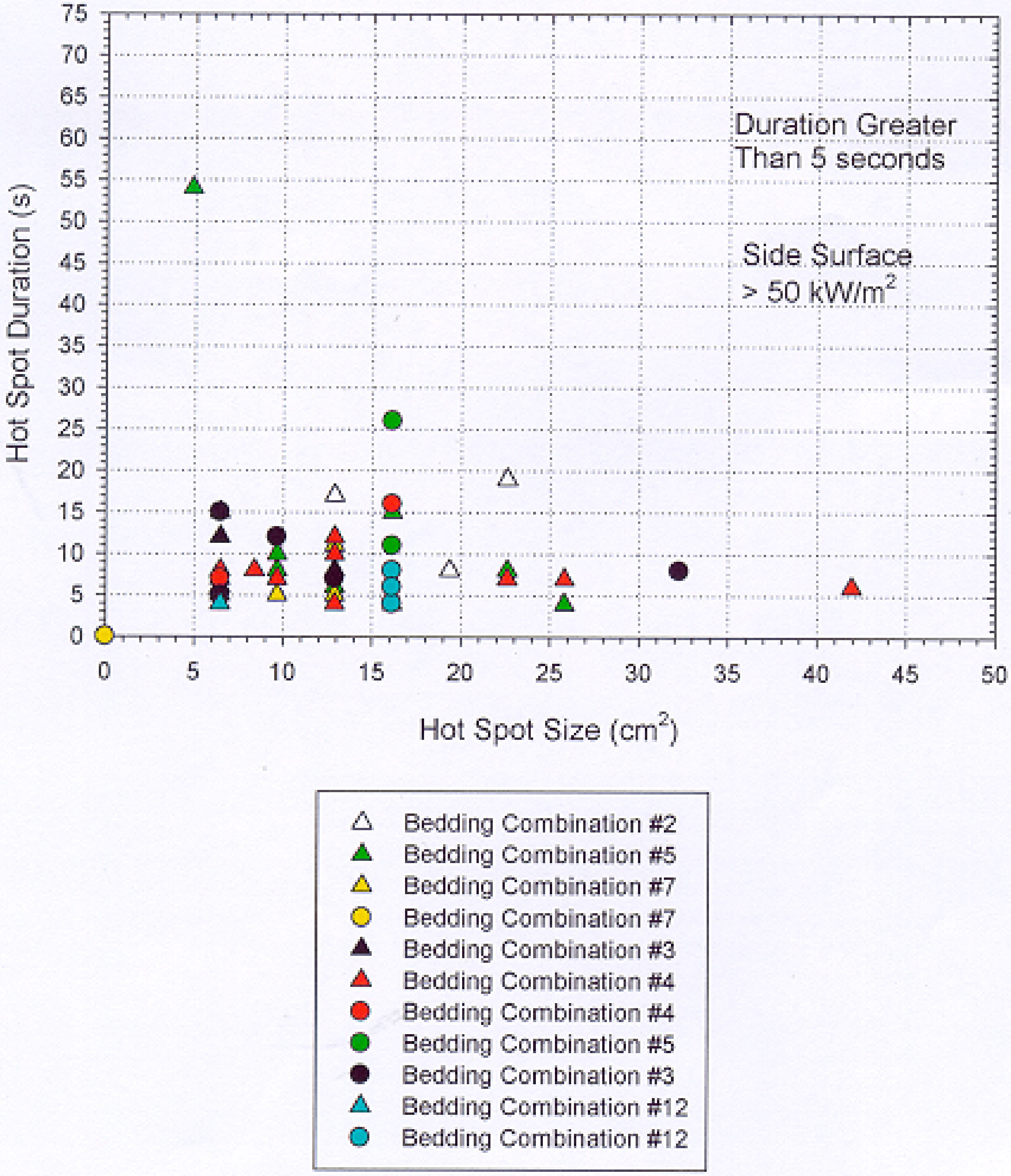


Figure 3-5b Measured characteristics of hot spots from burning bedding imposing a heat flux > 50 kW/m^2 on the side surface of a mattress

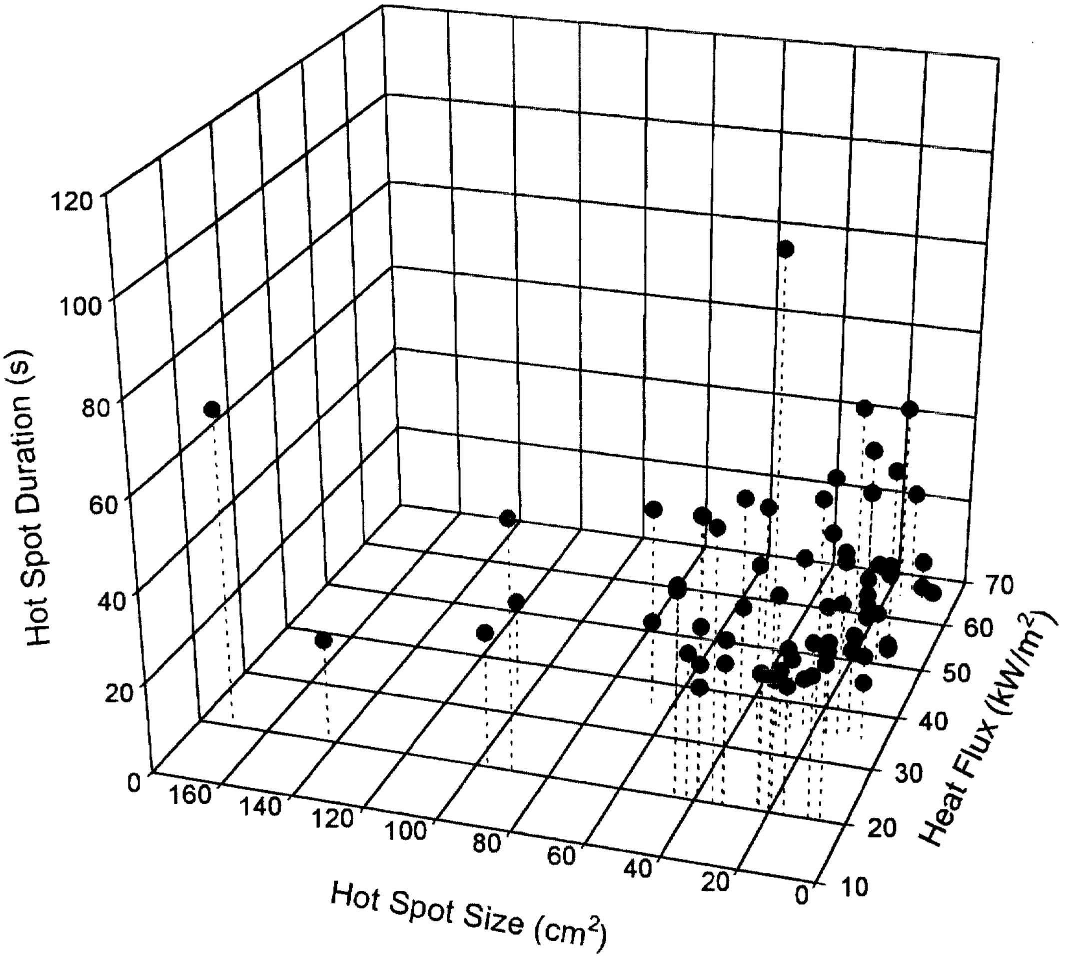


Figure 3-6a Measured characteristics of heat flux patterns on top of mattress from burning of bedding combination number 5.

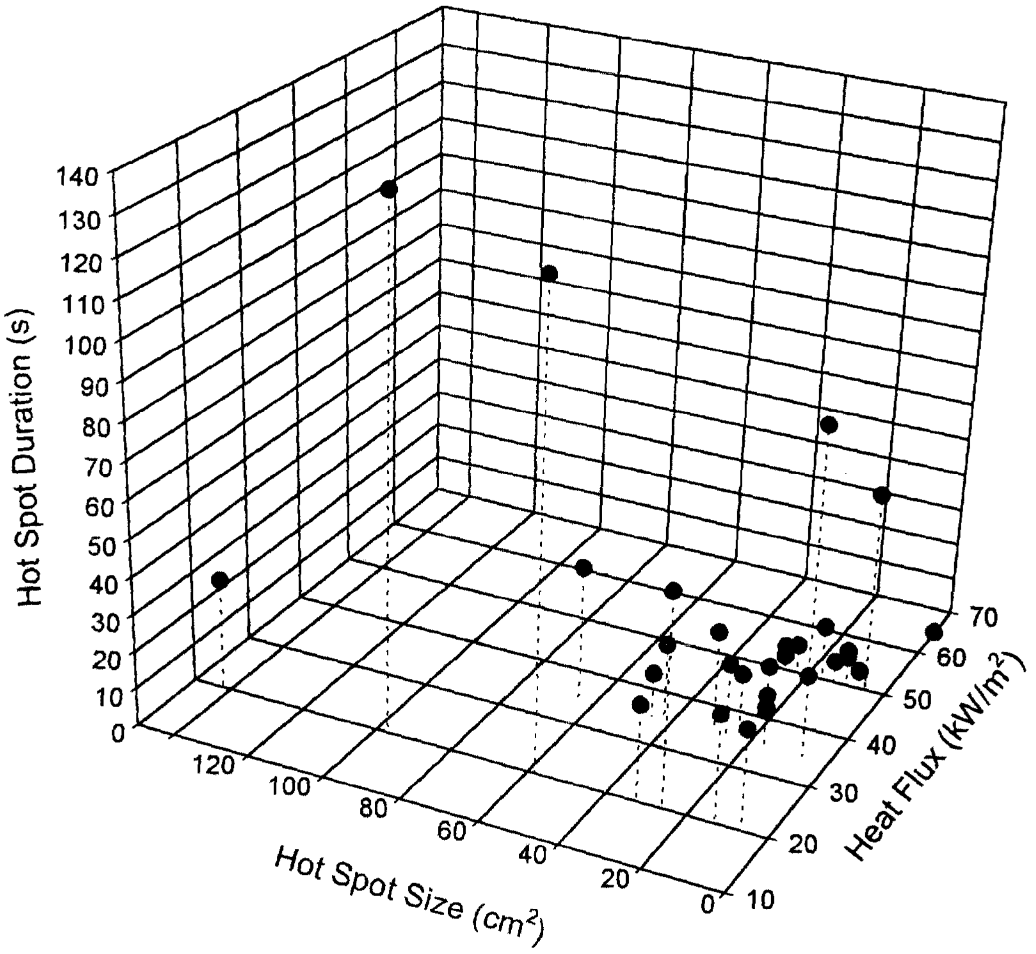


Figure 3-6b Measured characteristics of heat flux patterns on side of mattress from burning of bedding combination number 5.

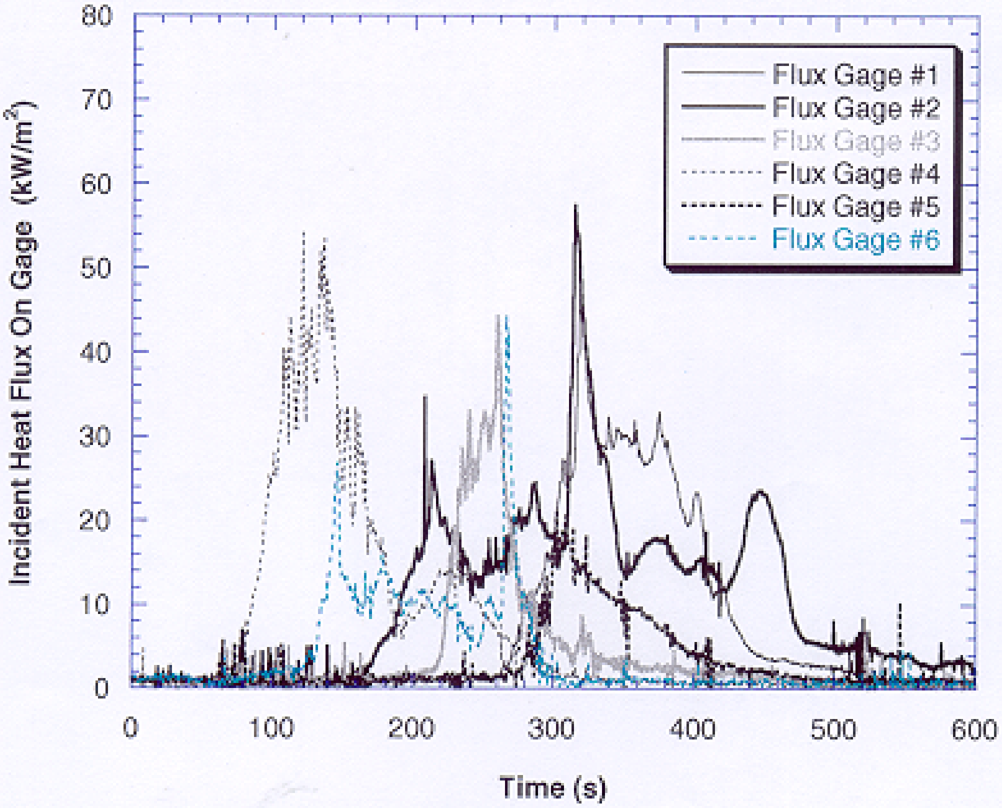


Figure 3-7. Heat flux vs time as seen by the six heat flux gages embedded in the surface of the inert mattress; bedding is combination #5.

Chapter 4. Gas Burner Design and Performance

Introduction. It should be evident from the preceding results on heat flux patterns from burning bedclothes materials that these are highly variable ignition sources as far as a mattress is concerned. Even a single type of bedclothes placed onto a mattress in a very controlled manner appears to impose a heat load whose characteristics vary rather randomly from place to place as the bedclothes burn.

It is highly desirable to have a testing tool for mattresses which can serve as a substitute for the bedclothes, imposing a heat load which is comparable in severity so that the mattress behavior which results is essentially that which the burning bedclothes would produce. However, simplicity and reproducibility are key assets for this substitute heat source. This demands certain compromises. The bedclothes present a moving heat source and this movement depends on where and how the bedclothes were ignited. In general, this movement is not an essential determinant of the response of the mattress, however.[10] Thus this aspect can be eliminated in the interests of simplicity. The bedclothes may also simultaneously heat a strip that stretches over the width or length of the top of the mattress plus the height of one or more sides. This also is not generally an essential determinant of the mattress response.[11] Rather what counts in both of these cases is that the mattress be subjected on representative sections of its construction to the maximum thermal load it would normally see from the bedclothes. In this sense the area that is subjected to a heat source needs only to be large enough to be representative of any spatially-varying construction details.[12]

The simplest device which can mimic the thermal loads seen in the previous chapter is a gas burner. With care such a device can be used to repeatably expose any desired section of a mattress to a fixed heat flux for a well-defined time. There is a need for two gas burners, however. The top (or bottom) and the sides are constructed differently. Furthermore, the data in the previous chapter indicate that the top and sides of a mattress see differing thermal loads for differing times. A mattress can be tested with the two burners simultaneously. They can be near each other or not.

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[10] The detailed behavior of the mattress does respond to the moving nature of the burning bedding heat source. Thus the timing and exact height of the heat release peak from a mattress would vary with whether the heat source was stationary or moving. However, the overall response, in terms of the ability of the mattress components and assembly to resist fire involvement and fire growth is expected to be relatively insensitive to the issue of heat source movement. Because a burning mattress + foundation + bedding is a complex system, this cannot be categorically stated to be true in all cases.

[11] In Chapter 5 an exception to this is discussed.

[12] It is recognized that if the mattress burns locally during the application of an external heat source (as is likely) then the total heat release rate seen during that exposure is proportional to the total area being heated. The concern here, however, is with what the mattress does subsequent to this heat exposure. This is less sensitive to the area being heated and more sensitive to the design details. Again, there was one exception, discussed in Chapter 5.

A simple gas burner is not a highly flexible device. It presents two limitations which follow from its nature. The typical burner consists of a Tee-shaped head; a line of holes along the top of the Tee spreads the gas evenly and anchors an array of identical flame jets which impinge on the surface of interest. The peak heat flux that is imposed on the surface depends on the distance between the Tee head and the surface; the greater the distance, the lower the peak flux. The peak flux drops sharply for positions outside of the flame zone.

When bedclothes are burning on top of a mattress, gravity keeps them in contact with the mattress surface. Even if the composition of the surface is such that it shrinks severely under the heat load, the burning bedclothes stay with it, imposing their full heat load. If a gas burner is fixed in space relative to the original mattress surface, shrinkage of that surface will lessen the heat load in an unrealistic manner. The behavior on the side is potentially similar, though usually not as severe (the thin materials there cannot shrink very much). To overcome this limitation, it is necessary to add an element of complexity to the gas burner assembly. Thus the burners used here were mounted on pivots and weighted slightly so as to follow, at a fixed standoff distance, the shrinking mattress surface.

The other limitation with such a burner is that the heat flux is not readily controllable except by positioning. The gas burns in the surrounding air and this dictates the flame temperature. If the air supply was under separate control, the flame temperature could also be controlled, allowing heat flux variability. However, to do so over a significant range calls for a complex burner containing a stoichiometric burning section followed by a dilution section. Three flows must be precisely controlled for each burner. This was deemed impractical for the present application. As a result, the burners used here can only impose a fixed heat flux; only the duration is readily varied. Thus the gradually increasing and decreasing peaks such as were seen in Fig. 3-7 are replaced by square waves. At time zero the flux comes on at a fixed value; it remains at this level until the burner is shut of by cutting off its gas supply.

Details of Burner Design and Placement. Figure 4-1 shows sketches of the two gas burner heads used in the mattress tests of the next chapter. They differ only in length with the shorter burner being applied to the side of a mattress. A rather close hole spacing was chosen for the gas jets in order to come somewhat nearer the limiting case of a two-dimensional jet flame. Slower entrainment in a two dimensional jet extends its length in comparison to a three dimensional jet [11]. An extended flame should have a less rapid decrease of heat flux with distance from the burner. The extended flame also makes the test more severe since it causes flames to penetrate any holes that develop in the mattress surface. It is not clear to what extent such penetration occurs during the burning of real bedclothes since the bedclothes themselves obscure the view.

The burners were oriented perpendicular to the surfaces which they were to heat. As it happened, when the burners were made in the NIST shop, the holes were all inadvertently drilled with an orientation pointing about 5° off the plane of the Tee. This actually served to broaden the heat flux peak somewhat, a desirable effect (more akin to the bedding heat flux peaks), since the jets did not impinge at a 90° angle on the mattress surface. At the same time, the impingement angle provided a near stagnation point flow with its attendant high heat fluxes, as was needed here to simulate those from the burning bedclothes. Since the only effect of the 5° off-plane hole alignment is a desirable broadening of the flux peak, it has been adopted here as part of the burner design.

The burner-to-heated surface spacing was controlled by a pair of adjustable stand-offs which protruded forward from a collar on the gas supply arm of the Tee. Actual contact with the heated surface was by a pair of rectangular stainless steel pads, each of which had an area of 3.2 cm^2 (1/2 in^2). The pads were oriented outward away from the flame impingement area.

Figure 4-2 shows a diagram of the flow control system used for each of the burners. Propane (99 %) was chosen as the gas since it is readily available in liquified form. Flow rate was set with a multi-turn valve and indicated by a rotameter. The duration of flow was controlled via a solenoid valve operated from a pre-set interval timer. Achievement of reliable ignition at the start of a test required the use of a small pilot flame (also propane) placed just forward of the burner. Its flame was kept small so that it did not heat the mattress surface significantly by itself.

The burners were placed on the end of rather long arms (ca. 1.2 m, 4 ft)) so that their pivot points were far from the mattress surface. This minimized the change in orientation relative to the surface when the burners moved toward it in response to its shrinkage. Each burner was counter-weighted so that it tended naturally to fall against its respective surface with a force of 170 g to 200 g (6 oz to 7 oz), as measured with a spring gage. To facilitate reproducible positioning and orientation of the burners with respect to the somewhat amorphous mattress surfaces, a piece of sheet metal was placed over the area to be heated. This had a 90° bend so that it could be used for both the top and side burner setups. The flat sheet metal surface was a reference plane allowing the operator to align the burner parallel to its surface at the desired stand-off distance. A copper tube segment in each burner feed line facilitated bending of the line to get good parallel orientation to the top or side surfaces of the mattress.

The bend line in the piece of sheet metal also served as a reference for the placement of the burners. The top burner was placed mid-length along the long direction of a mattress with one end of the burner tube over the sheet metal bend line. The burner thus extended perpendicular to the side of the mattress, inward over the top of the mattress its full 30.5 cm (12 in) length. This length spanned one or more cycles of the quilt pattern on the mattress top to assure that a representative area was being heated.[13] It also impinged on the edge seam which has a very different construction. The side burner was oriented vertically and was typically placed 18 cm (7 in) to one side of the top burner with the top

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[13] This was chosen as a burner size criterion rather than a specific area such as that seen in the last chapter since, to a first approximation, hot spot area does not determine mattress response.

end of its tube 2.5 cm (1 in) below the bend line on the piece of sheet metal. The relative lateral placement of the two burners put them just beyond a spacing where their flames would interact. The vertical placement of the side burner left 7.6 cm (3 in) of its length below the lower edge of the 20 cm (8 in) thick mattresses whose tests are described in the next chapter; this was done to expose the foundation as well as the mattress, as described in the next chapter. At the same time, since buoyancy caused the side burner flames to bend upward, they impinged not only on the full height of the mattress side but also on the upper and lower edge seams. Thus the edge seam was subjected to three areas of flame impingement in a single test.

Calibration of the Burner Heat Flux. Prior to any mattress testing, the burners were calibrated to determine the manner in which their heat flux varied with distance from the burner tube. For this purpose a single Schmidt-Boelter heat flux gage was mounted with its sensor surface flush to a metal plate. The gage was cooled with water at 85 °C to prevent water condensation from the propane burner flame; the gage had been previously calibrated at this water temperature. The plate was oriented either vertically for the side surface burner or horizontally upward for the top surface burner. The heat flux to the sensor surface was measured as a function of the relative positions of the burner and the sensor. The burner heating could cause the plate to warp and the gage to recess below its surface. Also soot accumulation on the gage surface could lower the net heat flux. Thus the tests had to be conducted intermittently with plate cooling and sensor cleaning in between each measurement.

The propane flow rate was chosen primarily on the basis of flame length projected out from the burner head. The goal was to have a flame which extended out 75 to 100 mm (3 in to 4 in) from the front of each burner tube. Along with moving the burners to follow a shrinking surface, this provision was intended to preclude an unrealistic lowering of the flux to a mattress surface should the material shrink unevenly away from the flames. Also, the longer flames again decrease the variation of heat flux with distance from the burner so as to make positioning less critical. Note that the actual gas flow rate, though it dictates a heat release rate from the burner, has little relevance except in setting the heat flux at a given distance. (Thus it is important that the flow rate be held at the same level throughout any test series.) The flow rates used here were 10 NTP L/min to the top burner and 11 NTP L/min to the side burner.[14] This yields a total heat release rate of about 30 kW.

Most of the tests were done with the burners oriented perpendicular to the surface having the flux gage. (Recall that the flame jets then impinged at about an 85° angle.) Small variations (5° to 10°) in the burner orientation angle had no definite effect on the peak flux but perpendicular jet impingement did result in a very narrow peak. Thus it is preferable

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[14] If the burner system were used on thicker mattresses, it would be preferable to maintain the exposure of the full mattress side , as is done here. Thus the side burner would need to be longer (to assure also that the foundation is exposed to the burner flames). The propane flow rate per unit length should be maintained at the same level as here to assure the calibration of heat flux vs. distance from the burner is unchanged.

to retain perpendicular burner alignment and take advantage of the peak broadening mentioned above in connection with the fact that the burner holes were drilled about 5° off-plane. (Note that this does mean that the flame impingement area will not be exactly in front of the burner's apparent aim point on the mattress surface. This should cause no problem in usage.)

Figures 4-3 and 4-4 show the variation in peak heat flux with distance between the sensor and the front of the two burner tubes. Figures 4-5 and 4-6 show the lateral variation in the flux patterns imposed on the surface when the burners are at the distances shown. Figures 4-3 and 4-4 indicate that in spite of the efforts to decrease the sensitivity of peak heat flux to burner distance from the surface, the behavior is still rather sensitive. A 2 mm change can alter the flux by 10 %. Thus, in the tests described in the next chapter, an effort was made to hold the burner positioning to within 1 mm from test to test.

Figure 4-5 shows that the position of the flux peak shifts laterally on the surface as the burner distance from the surface is varied. This is a result of the ca. 5° (from the vertical) impingement angle at which the flame jets approach the surface. The shift is irrelevant to the burner's performance.

Although the data are incomplete, both Figs. 4-5 and 4-6 indicate that the flux distribution on the mattress surface is rather narrow. For example, in Fig. 4-5 the distribution for a spacing of 39 mm (the value used for the top surface burner in the mattress tests described in the next chapter), appears likely to fall to ½ of the peak value at about 1.5 cm (0.6 in) to either side of the peak.

Burner Flux and Duration for Mattress Tests. The data in the previous chapter are the basis for choosing the values of peak heat flux and flux duration on both the vertical side and horizontal top of the mattresses tested as described in the next chapter. As noted there, the data show a wide range of scatter, varying both with time for a given type of bedclothes and with the nature of the bedclothes combination itself. The tendency here has been to try to move toward (but not necessarily achieve) a worst case. Several bedclothes combinations showed >65 kW/m^2 peak heat fluxes on the top surface (Fig. 3-4a). It was noted that these peaks could sometimes exceed 70 kW/m^2. Thus here a burner spacing of 39 mm was chosen which imposes a peak heat flux of about 73 kW/m^2 onto the top surface of a mattress. The peak flux on the side was distinctly less, rarely exceeding 65 kW/m^2 (Fig. 3-4b) but several bedclothes combinations exceeded 50 kW/m^2 (Fig. 3-5b). Thus a spacing for the side burner of 42 mm was chosen which imposes a peak heat flux of 55 kW/m^2.

As to heat flux duration, these same figures provide a guideline. For the top surface, Fig. 3-4a shows only one point at 45 s duration. However, recall that it was noted that if the pillow region had been monitored in all of the tests, more points were to be expected within the box shown there. Thus a 45 s exposure duration was chosen as one case. Since one point showed up at 74 s in Fig. 3-4a, a value of 70 s was chosen as a second, more severe exposure condition with some justification in the data. By similar reasoning exposure values of 25 s and 50 s were chosen for the side burner, based on Fig. 3-5b. In the mattress tests reported in the next chapter, the short exposures were used in one set of tests and the long exposures were used in another set. Note that a feature which is missing here is a gradual tailing-off of the flux over a substantial time at the end of these peak durations. There is no way to produce this type of result without a complex programming either of the flow to the burner or the position of the burner relative to the surface.

Figure 4-7 is an overview of the gas burners in place at Omega Point Laboratories for the tests described in the next Chapter. On the left is a sleep set resting on a short bed frame which, in turn, rests in a pan on top of a scale. On the right is the support and pivot structure for the two burners; note the two cylindrical brass counterweights which dictate the force with which the burners rest against the mattress surfaces. The support structure also incorporates the controls for the propane flows to the burners and their pilot lights.

Vertical Gas Burner

Material: Stainless Steel Tubing
1.27 OD with 0.0889 cm wall
(0.5 in OD x 0.035 in wall)

HOLES ARE NOMINALLY
0.127 cm (0.050 in) or CLOSEST DRILL SIZE
HOLES ALL POINT TO LEFT
AT 5° OUT OF PLANE

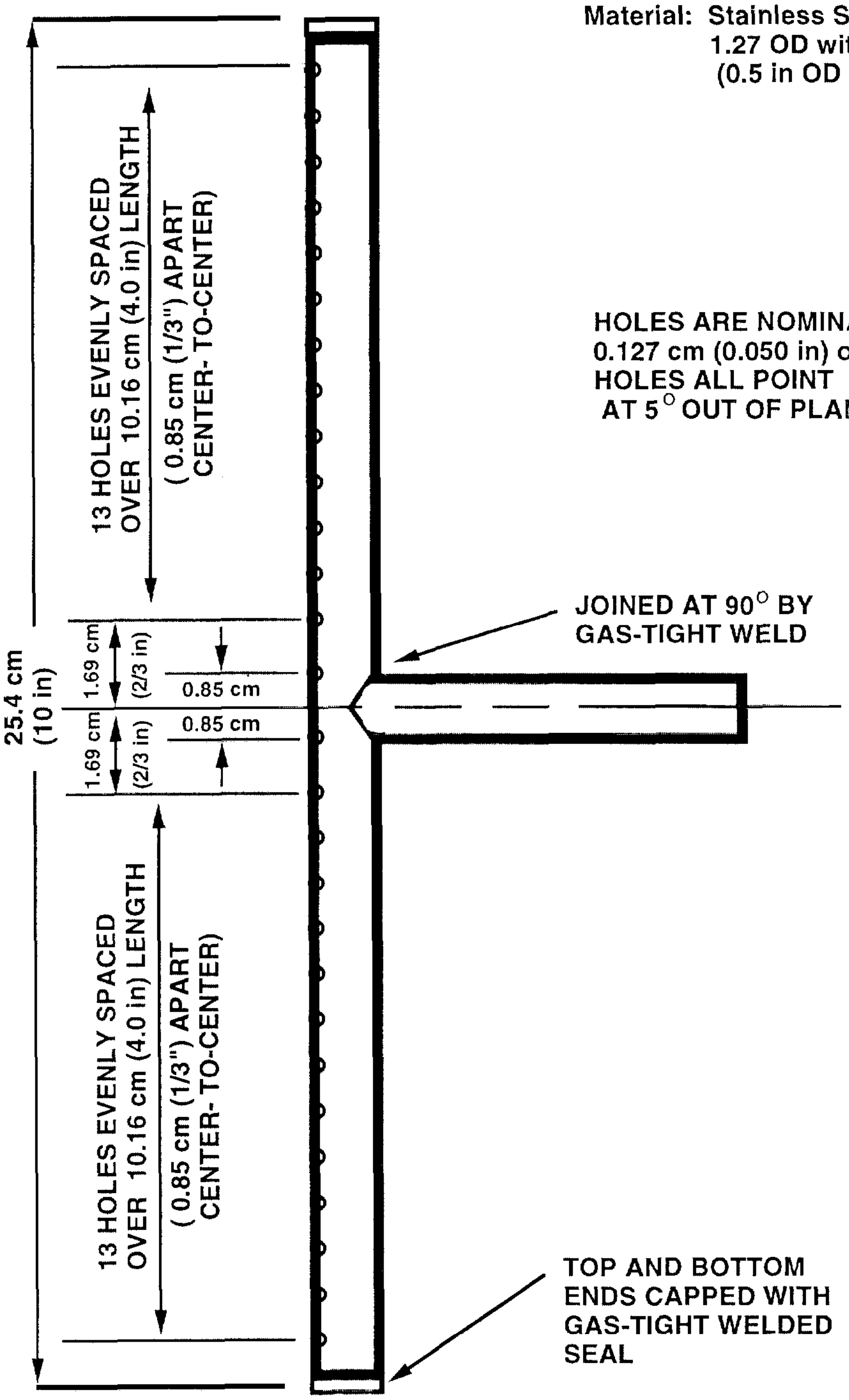
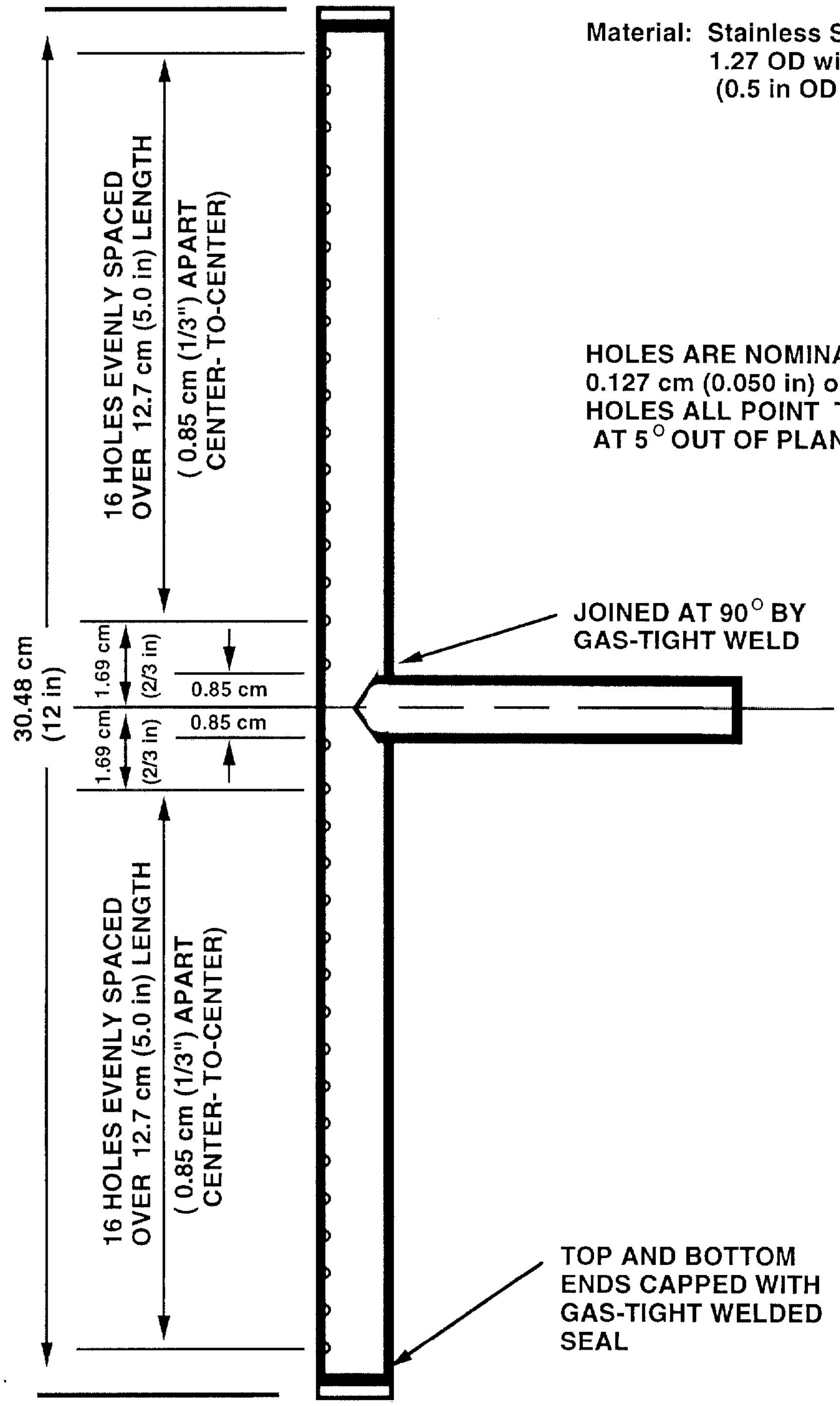


FIGURE 4-1a

Horizontal Gas Burner

Material: Stainless Steel Tubing
1.27 OD with 0.0889 cm wall
(0.5 in OD x 0.035 in wall)



HOLES ARE NOMINALLY
0.127 cm (0.050 in) or CLOSEST DRILL SIZE
HOLES ALL POINT TO LEFT
AT 5° OUT OF PLANE

JOINED AT 90° BY
GAS-TIGHT WELD

TOP AND BOTTOM
ENDS CAPPED WITH
GAS-TIGHT WELDED
SEAL

FIGURE 4-1b

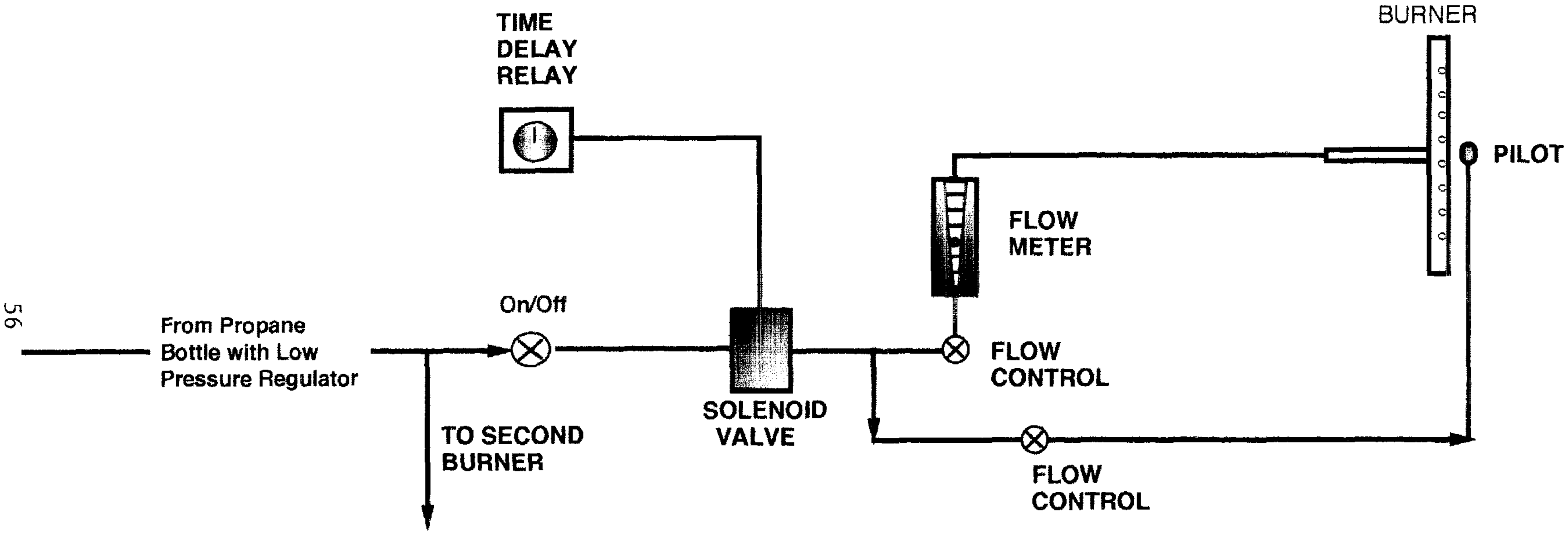


FIGURE 4- 2. Schematic of propane flow system; independent systems were attached to each burner.

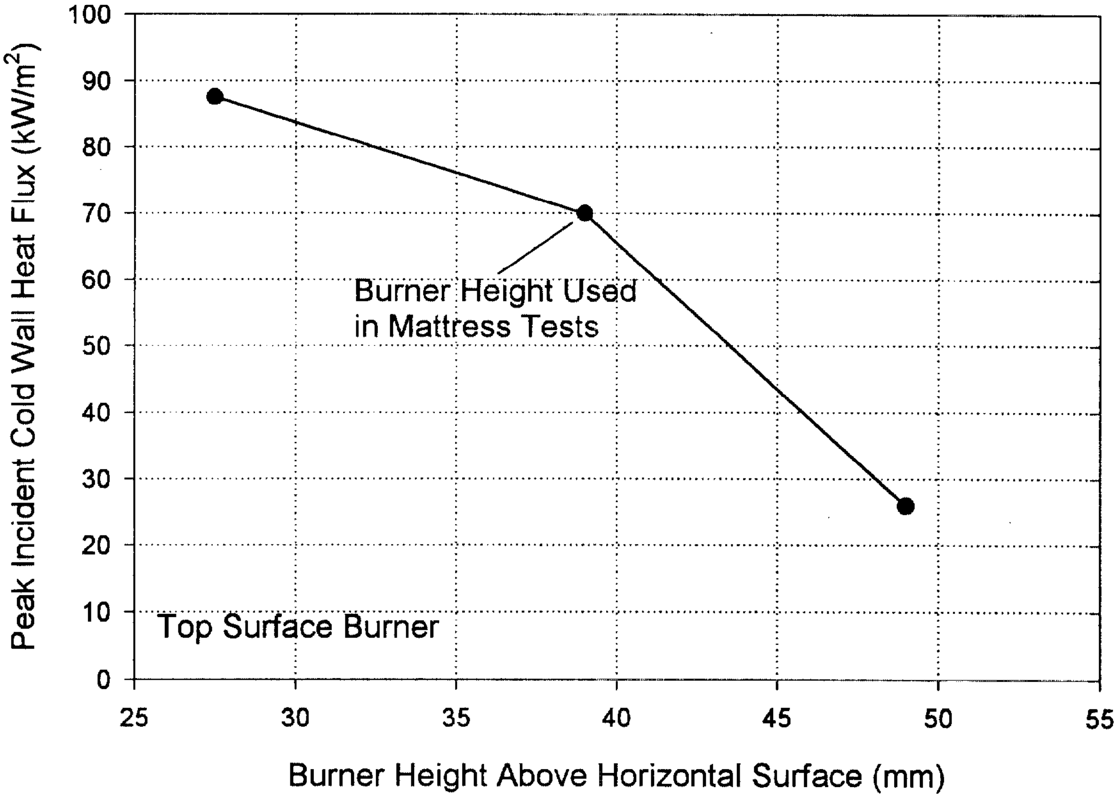


Figure 4-3 Variation of peak burner heat flux with burner spacing above the mattress surface; top surface burner.

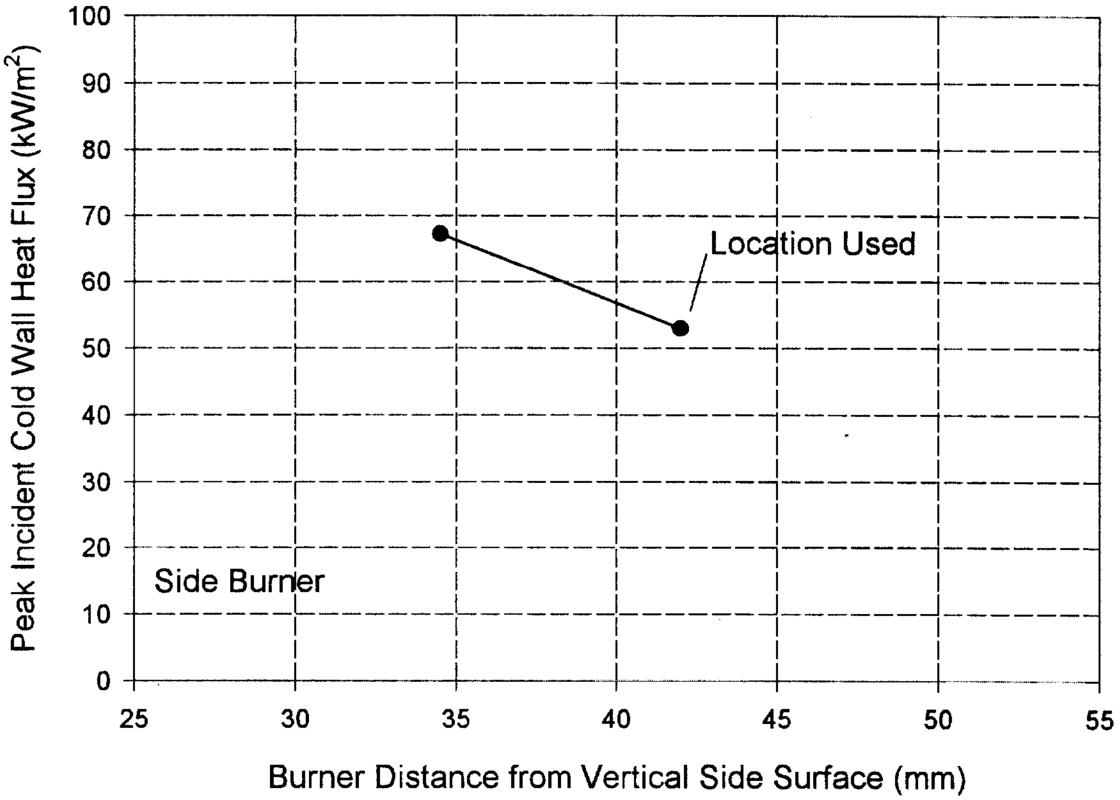


Figure 4-4 Variation of peak burner heat flux with burner spacing from the vertical side surface of a mattress; side surface burner.

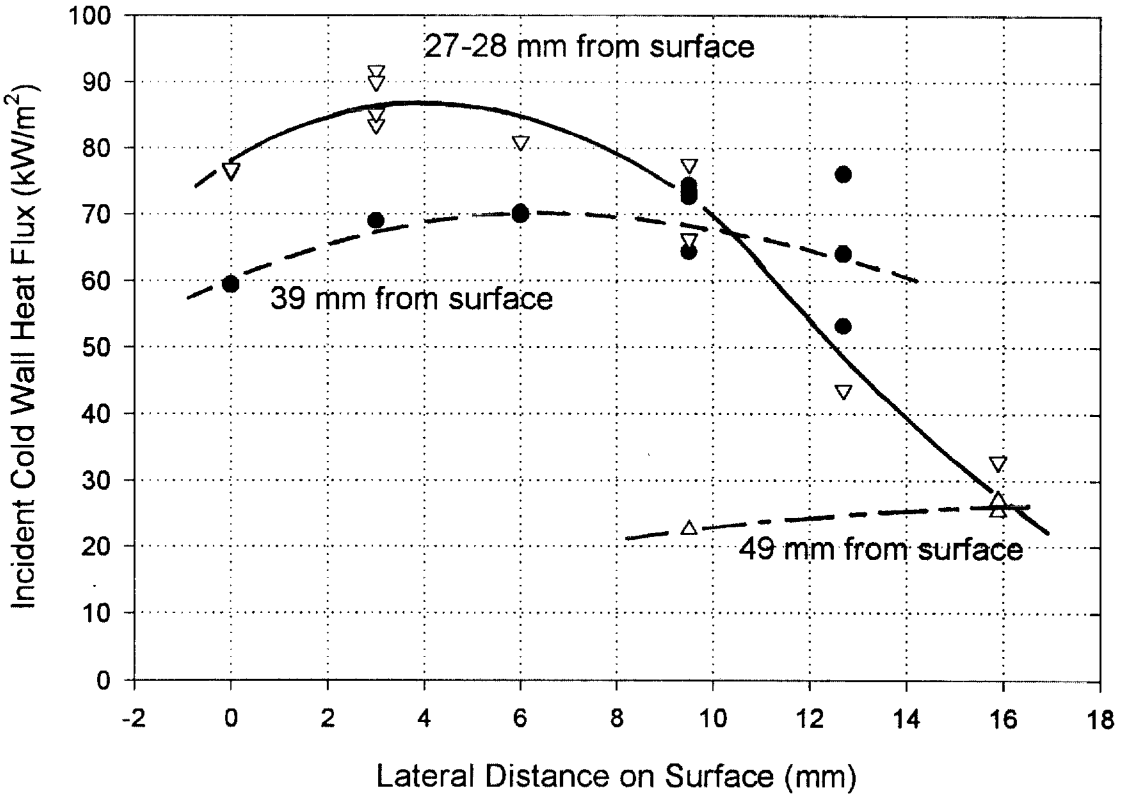


Figure 4-5 Lateral variations of incident heat flux imposed by top burner on surface with three different spacings of burner above surface

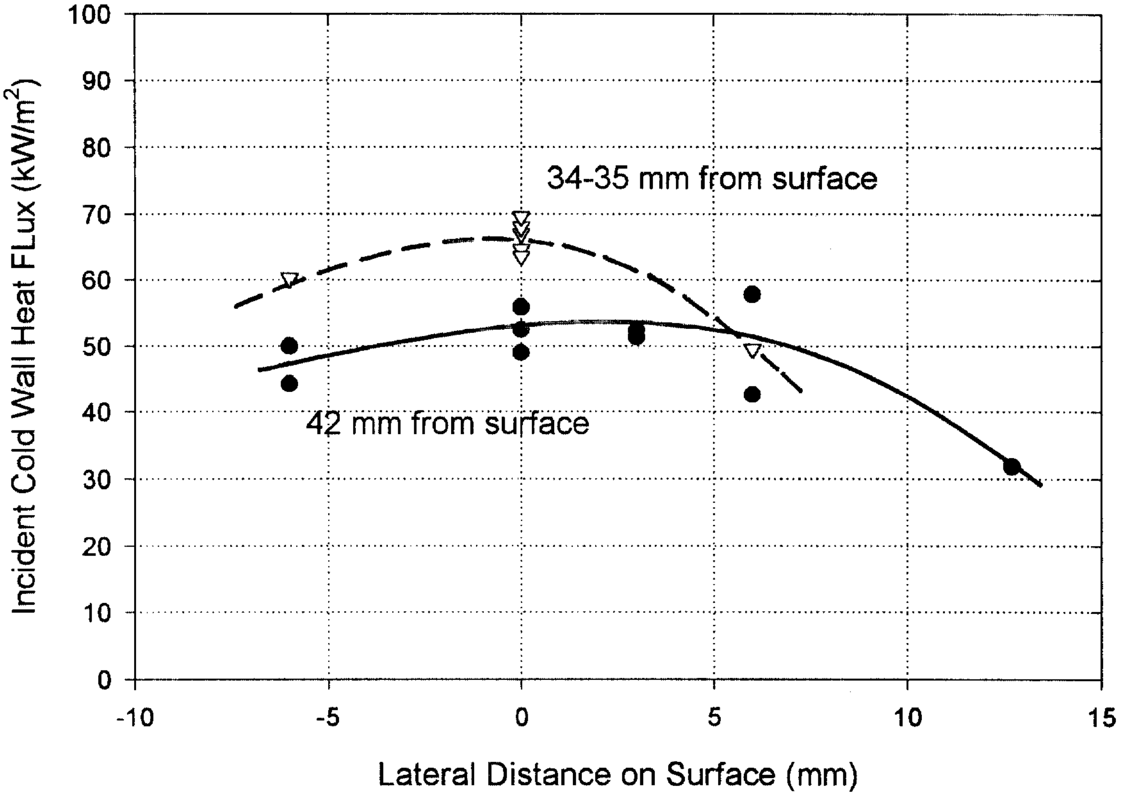


Figure 4-6 Lateral variations of incident heat flux imposed by side burner on surface with two different spacings of burner from surface.

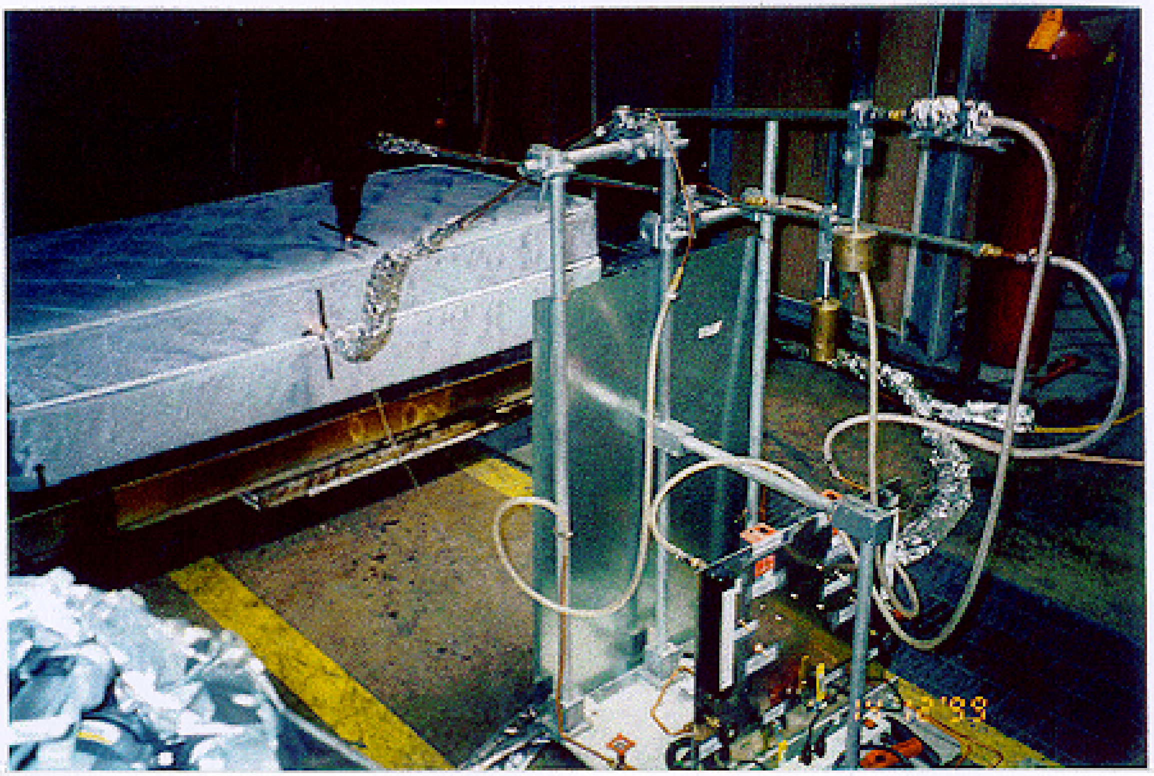


Figure 4-7 Overview of test set-up with gas burners. Sleep set on left rests on top of a scale. Gas burners are in position with pilot lights on. Gas burner support and control apparatus is on right.

Chapter 5. Tests of Improved Mattress Technologies

Introduction. In this stage of the study, the pair of gas burners described in the previous chapter was applied to a series of mattresses. This series of mattresses included one sample that was representative of the current residential market technology. The series also included mattress designs that incorporated a variety of currently available technologies that are intended to reduce flammability. The goal was to ascertain the robustness with which the gas burners can "predict" the response of a mattress to burning bedclothes. Thus it was necessary that the burners be tested over a wide range of mattress assembly designs and fire behaviors. For comparison, the same set of mattresses was also subjected to burning bedclothes.

The reader should bear in mind that these tests were all performed in an open facility, not a room. Experience has shown that heat feed back from a room environment can increase the heat release rate, particularly as one approaches the level which can cause flashover in the room [17, 18].

The mattress designs used here were intended to provide a range of mattress fire performance for the purpose of determining if gas burner designs could be developed to simulate burning bedclothes on sleep sets and to assess the potential level of fire safety improvement attainable with current, marketable flammability modifications in sleep sets. The specific designs tested are not commercially available and were not optimized to cover all of the state-of-the-art products available, nor do they represent any specifically recommended mattress design or technology.

Mattress Designs. Table 5-1 summarizes the five sleep set designs tested in this study; see Fig. 5-1 for a sketch showing the placement of the various components in the mattress and foundation. Mattress #1 is typical of current residential mattresses; none of the materials contains flame retardant additives. Note that this type of mattress passes Federal Standard 16 CFR-1632 for cigarette ignition resistance [12] which means that it is resistant to smoldering ignition. Mattress #2 utilizes a ticking which passes MVSS 302; this limits its allowable rate of horizontal flame spread in specific laboratory conditions [13]. In addition all of the polyurethane foam is of a grade which is generally considered to be moderately flame retarded.[15] Mattress #3 has a special ticking which is composed of a fire barrier fabric. All of the interior materials are the same as in Mattress #1 but the thread used to close the seams in the ticking is more fire resistant than normal thread. Mattress #4 replaces all of the polyurethane foam in Mattress #1 with a flame-retarded polyester batting. In addition, a fibrous barrier layer is built into the back of the quilt layer and the mattress border. The edge seam thread is a fire-resistant material. Mattress #5 uses a combination of less flame retarded polyurethane foam (compared to that in Mattress #2) and boric acid treated cotton batting.

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[15] This foam is a grade frequently used in upholstered furniture to help pass California Technical Bulletin 133 [12]; it contains melamine as a flame retardant.

It should be noted that the various technologies represented here have been suggested by available materials and by limited studies of mattresses for specialized markets [7, 15]. The consumer acceptability of designs 2 through 5 has not been determined.

All of the mattresses were tested on top of foundations (i.e., complete sleep sets were tested). The foundations contained an open wood frame base to which were attached steel wire supports that served as spacers and support for the top platform. This platform consisted of a steel frame covered by thin pad (ca. 6 mm thick, ¼ in) and a top fabric layer. The wood and steel were the same for all of the mattresses but the border materials matched those in the specific mattresses with which they were tested. Thus the particular ticking on the side of the foundation was the same as that in the mattress it supported, as was the padding under the ticking. The top pad of all of the foundations was intended to be the same but there was an indication that Mattress #4 contained the same material as in its mattress topper pad instead.

These full scale fire tests were conducted at Omega Point Laboratories in Elmendorf, Texas since the NIST facility has been temporarily closed. The tests were carried out by NIST personnel but Omega Point was responsible for acquiring the heat release rate and weight loss data. The tests were conducted under a hood instrumented for heat release rate measurements via oxygen consumption, generally in accord with ASTM E-1590 [16]. Thus the foundations and mattresses (sleep sets) were placed on top of a short twin-size bed frame; this, in turn, rested on top of a 12.7 mm (1/2 in) thick layer of gypsum wall board placed inside of a steel pan which rested on a scale. The system was calibrated at 40 kW and 150 kW each morning before the start of testing. It should be noted that the larger fires (≥ ca. ½ MW) yielded enough smoke spillage from the hood that the system was likely to have underestimated the heat release rate peak by a margin which is not known. However, the peaks reported here are not greatly different than those reported elsewhere for twin size mattresses; thus it is estimated that the error is of the order of 10 % and should not affect any conclusions made here.

All materials were conditioned in a room whose relative humidity varied between 30 % and 40 %; the test room humidity was generally in the 20 % to 30 % range. The test materials were removed from the conditioning room 10 to 15 min before a test was conducted.[16] The tests were videotaped using one Hi-8 camera and one digital video camera. Both viewed the fire from the same side of the mattress but from different angles.

A set of twenty burner exposure tests was conducted first. Thus each sleep set combination was subjected twice to the short burner exposures (top, 45 s; side, 25 s) and twice to the long burner exposures (top, 70 s; side, 50 s). The tests were conducted in a randomized order. In each test the results were recorded until the subsequent fire had nearly fully died out (after consuming the mattress) or until it was fully clear that no

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[16] These conditions are drier than those used in Chapter 2 to test the bedclothes alone. Lower ambient humidity leads to a lesser amount of water adsorbed in the fabrics and this will, in turn, allow somewhat faster rates of flame spread. The differences are not believed to be sufficient as to cause any significant changes in the overall results or conclusions from this work.

further burning was going to occur.

Subsequently, a set of ten tests was conducted in which each sleep set design was covered with bedclothes combination #4 (see Table 2-1a) and the bedclothes were ignited. The ignition location was the same as that used previously for bedclothes (i.e., at the bottom of the forward end of the folded-back bed covers). A butane lighter was applied there for 30 s to initiate the fire. These tests included two "wire" tents similar to those used in the heat flux tests of Chapter 3. One was placed on the longitudinal midline of the bed, at the juncture of the folded covers and the pillow. The second was placed on the camera side of the bed, at the side edge of the mattress, under the "foot" end of the folded back covers. The tall, "open" end of this wire tent support rested in the groove created by the upper side seam of the mattress.

Test Results and Discussion

(a) Gas Burner Tests. Table 5-2 summarizes the peak heat release rate and its time of occurrence for the gas burner tests of the five mattress designs. Inspection of the Table reveals a wide range of variation among the mattress designs in the peak heat release rate and time required to reach this peak . Recall that the time to the peak is a measure of the time available for intervention in the developing fire and thus is an important measure of hazard, along with the value of the peak itself. However, the absolute time to the peak was shortened in the first set of tests by the fact that a large ignition source was imposed immediately at time zero. Note that these tests involved bare mattresses, without bedclothes, so that the numbers seen here do not readily carry directly over to a real bedroom fire.[17] Appendix B gives a detailed description of the fire growth behavior that underlies the heat release rate results in Fig. 5-2.

The intention is that the gas burners be capable of predicting the fire behavior of a mattress design when it is subjected to a realistic fire involving burning bedclothes as the heat source. It is not to be expected that the peak heat release rate will be the same since the bedclothes add significant heat of their own (and this addition certainly counts in assessing the likelihood of flashover in a compartment). Furthermore, since the relative timing of the burning of various system components can affect the magnitude of the heat release peak (see Appendix B), there may be positive or negative effects on the sleep set heat release rate contribution to the whole when burning bedclothes replace the gas burners as the ignition source. It is also not to be expected that the time to the heat release rate peak will be the same since the burning bedclothes constitute a moving heat source, constantly impacting new areas of the mattress, in contrast to the static burners which persisted for much less total time. Nevertheless, the burners would, if fully successful, indicate whether a mattress plus bedclothes fire will be large, medium or small (in relation to the heat release that would flash over a small bedroom, i.e., ca. 1.1 MW).

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[17] Note also that these tests were performed in a large open space that precluded either oxygen depletion or radiative feedback from an accumulating hot smoke layer, both effects that can occur in a bedroom. Parker [17] found the feedback effects to become significant at a heat release rate of about 600 kW in the ASTM standard room.

In addition, they should also give some useful indication of the speed of achievement of the peak since this is relevant to escape and suppression.

In effect, the next step, discussed below, amounts to a calibration of the relationship between the gas burners and burning bedclothes as heat sources. The relation may depend to some extent on the combination of materials which are chosen.

(b) Burning Bedclothes Tests. The chosen bedclothes set here is combination #4 which was second highest in heat release rate on an inert mattress. It was also the source of some of the more severe heat flux impact numbers.

Table 5-3 lists the peak heat release rate values and time to this peak for replicate tests of the five mattress designs having bedclothes combination #4 placed on them. Appendix B gives a detailed description of the fire growth behavior that led to these heat release rate results, as well.

Figures 5-2 and 5-3 summarize the issue of a correlation between the burner results and the bedclothes results. All data points are the average over the number of tests run with the given configuration; no distinction is made, with the burner results, between short and long exposures. The error bars are the calculated standard deviations of the points.

In Fig. 5-2 it is apparent that there is a reasonable correlation, for four of the mattress designs, between the peak heat release rate seen with the pair of burners and that seen with bedclothes combination #4. Note that the straight line relation passes through the vertical ordinate at a finite heat release peak value; this is dictated by the heat release from the bedclothes alone (on an inert mattress; see Fig. 2-2) so one can see that the relation must change, at least due to that reason (and perhaps others) if the bedclothes set were changed. Mattress 4, based on the polyester fiberfill technology, is an exception to the linear relation; it yielded a much greater heat release rate peak with the bedclothes than the burner result for this mattress predicts. The phenomenon behind this, an abrupt overpressurization which opened the mattress seams (only when it was subjected to burning bedclothes, not the gas burners), is described in detail in Appendix B.

In Fig. 5-3, the same four designs tend to show a monotonic relationship between time to the heat release rate peak for the two modes of thermal stress of the mattress designs. Now, however, the relation is not linear. Given the large standard deviation on the points for Mattresses 2 and 4 (arising from the burner results), it is evident that the relation is only roughly pinned down. Here too, the intercept on the vertical ordinate is necessarily finite because it is dictated by the time required for the bedclothes alone to burn atop an inert mattress (see Fig. 2-3). Once again, Mattress #4 is an exception; the large heat release rate peak it yielded with the bedclothes occurred much later than the relation in Fig. 5-3 would predict.

The uncertainties in the heat release rate peak in Fig. 5-2 tend to be roughly comparable for the burners and the bedclothes as heat sources. For the time to the peak, in Fig. 5-3, the uncertainties for Mattress 2 and 5 are much larger with the burners than with the bedclothes. This is in spite of the fact the burners are a much more consistent heat source on the mattress area where they are applied. The reason for the increased variability seems to be that fire growth in a mattress is an unstable process readily altered by slight variations in construction, materials and, perhaps, laboratory conditions. The burners start the process then let it go on its own. The bedclothes, on the other hand, are continually applying their heat to new areas in a partially controlling manner with regard to the overall fire growth process. This helps damp out variations which the mattress might provide.

From the above results it is apparent that the varied mattress designs succeeded in posing a widely varying set of fire situations as tests for the gas burners. The gas burner results successfully correlated the bedclothes results over a very wide range of heat release rate. However, the results did reveal that burning bedclothes can yield behavior (internal overpressurization) which the gas burners do not emulate. The combination of burning bedclothes plus sleep set is a significantly more complex system than the combination of gas burners plus sleep set. Thus it will be necessary to be attentive to this as a source of potential divergence with other mattress designs. As a result, it is probably best to include some final testing with burning bedclothes to complement gas burner tests.

Ways in Which to Use Gas Burners. The gas burners could be used to examine the fire response of an individual material, a combination of materials, a mock-up assembly or a complete mattress.

When used with anything less than a full mattress, the results are necessarily limited in what they can predict. For example, if using the burners to test a barrier material, one could expose a sheet of the material to one of the burners for the times utilized above (e.g., 70 s at the closer spacing yielding the higher heat flux). If the material permits flame penetration in this time, it will most likely be unsatisfactory. If it does not permit flame penetration in this time, it would be informative to lengthen the flame exposure to find the total time which the material can remain intact. If the material passes at 70 s or even longer, it may not yield satisfactory performance in a mattress unless all necessary seams can be kept closed. The experience here with Mattress 5 suggests that this is judged more reliably with an assembly which includes all materials (including structure-defining metal components) since some may sustain flaming and prolong the thermal attack on the seams beyond the burner exposure time. Again it may be informative to push harder and extend the burner exposure time to find how much greater than 70 s the failure time is. The preceding experience suggests that this procedure will suffice with some material combinations but not all. There is still the possibility of seam rupture due to an overpressure event of the type seen with Mattresses 3 and 4 (see Appendix B). It may not be necessary to resort to a full bed fire with bedclothes in order to test for such a failure. If the internal pressures in these events were characterized, they could probably be simulated effectively (and more safely) using an air pressure system. This would require further study. It is worthwhile to resolve this issue in some such manner since this behavior was the only phenomenon which disrupted the relationship between the burner results and the bedclothes results. This would obviate the necessity to check for such behavior using a bedclothes fire with its attendant issues of variability due to materials and configuration.

The ultimate way in which to use the gas burners is with a complete mattress in conjunction with a heat release rate calorimeter, as was done here, since it is heat release which is the primary measure of mattress contribution to fire hazard. However, this measurement requires a specialized facility. A much simpler, first-cut measurement is suggested by the results in Fig. 5-4. The peak rate of heat release from the bedclothes/mattress fires is seen to vary in an approximately linear manner with the maximum rate of weight loss from the mattress resulting from gas burner exposure. Thus simply weighing a mattress as a function of time during a gas burner test provides a first estimate of heat release rate peak.[18] In doing so, however, one needs to be careful to measure the slope of this somewhat noisy curve at a time which coincides with the apparent visual peak in flame volume.

Heat release rate is the product of mass loss rate and heat of combustion of the materials burning. Heat of combustion can vary significantly with the nature of the polymers involved or with the presence of gas phase flame retardants. Thus there is a fundamental reason why the relation in Fig. 5-4 must really be a band, not a line. Nonetheless this approximate relationship should be sufficient to aid the development process of improved mattresses. Again, the final proof of performance to be expected with bedclothes comes in a heat release rate test of the mattress design with the gas burners but this can come after a process that resolves intermediate design issues in a more convenient manner.

Note that Mattress 4 is an exception in Fig. 5-4 for the same reason it was in Fig. 5-2. Thus if the issue of seam rupture via overpressurization could be resolved separately using measurements of the type discussed above, then Mattress 4 would be expected to drop down near the data point for Mattress 3.

Possible Areas for Further Work. There are a variety of issues alluded to in varying degrees in this chapter and in Appendix B which would benefit from further study.

- **Hazards in room.** There is a need to consider in detail the issue of the hazards within the room of origin and beyond, produced by a bed assembly fire. These issues were considered in the context of furniture fires in the final report from the European CBUF program [17]. They include the probability of ignition of other objects and the build-up of smoke and toxic gases within the room as a function of fire size, room size and ventilation conditions. The results of that study could be adapted to the present problem and perhaps expanded somewhat to help define the level of hazard a given bed fire presents and to quantify the extent that it is decreased at various levels of improved mattress performance. The NFIRS fire incident data base, compiled by the Federal Emergency Management Administration, could provide indications of the potential for fire casualty reductions as a function of bed fire intensity.

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[18] Clearly it is still necessary to have a facility in which such a fire can be handled safely.

- **Bed size effect.** A corollary aspect of this room hazard issue is that of the effect of mattress size on heat release rate behavior. There are little or no quantitative data available on how the size and timing of the heat release rate peak from a mattress (or from bedclothes) increase with the size of a mattress (both lateral dimensions and thickness). Such data are essential to a proper assessment of bed fire hazards.

- **Role of flooring.** The potential role of flooring materials in foundation fire development is mentioned in Appendix B. There are no data available at this point and a limited, experiment-based survey seems desirable.

- **Foundation improvement.** As suggested by the discussion in Appendix B, it would also be of interest to determine whether simply using a well-protected foundation would substantially lower the overall heat release rate peak with some of the alternative mattress designs.

- **Resistance of seams to over-pressurization.** The possibility of developing a test for mattress resistance to internal overpressurization was mentioned above. This would require a number of full-scale mattress fires with bedclothes. The mattresses would be instrumented for internal pressure and temperature. The pressure data would provide a basis for designing an air pressure-based, pressurization resistance test which would have to mimic the transient nature of the overpressurization. The temperature data would allow assessment of the internal consequences of the overpressurization event to help establish whether internal burning invariably follows and under what conditions it may grow.

Table 5-1 Component Materials in Mattress Designs (Refer to Figure 5-1 for Component Locations)

	MATTRESS 1	MATTRESS 2	MATTRESS 3	MATTRESS 4	MATTRESS 5
Ticking	Std. damask	MVSS 302 damask	Combined fabric/barrier	Std. damask	MVSS 302 damask
Quilt	19 mm (3/4 in) std. PU foam (19.2 kg/m^3, 1.2 lb/ft^3) in quilt	19 mm (3/4 in) moderately FR PU foam in quilt	Same as Mattress #1	0.23 kg/m^2 (3/4 oz/ft^2) FR polyester batt with barrier batt backing	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)	25.4 mm (1 in) moderately FR PU foam	Same as Mattress #1	0.31 kg/m^2 (1 oz/ft^2) FR polyester batt	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	Thermo-plastic Mesh Pad	Thermo-plastic Mesh Pad
Spring Unit	Twin Innerspring	Twin Innerspring	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	6 mm (1/4 in) moderately FR PU foam under MVSS 302 damask	Same as Mattress #1	0.23 kg/m^2 (3/4 oz/ft^2) FR polyester batt with barrier batt backing	Boric acid treated cotton batt under MVSS 302 damask
Thread	Standard	Standard	Combustion modified	Aramid, in edge only	Standard
Foundation Border	Same as mattress	Same as mattress	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	0.62 kg/m^2 (2 oz/ft^2) polyester fiber pad[19]	0.62 kg/m^2 (2 oz/ft^2) polyester fiber pad

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[19] This was the intended material; there was an indication that the mattress topper was used instead.

Table 5-2. Peak Heat Release Rate and Time to Reach Peak; Mattresses Subjected to Two Burner Exposure Durations[20]

(Lowest value in each column is average of values above it)

MATTRESS 1	MATTRESS 2	MATTRESS 3	MATTRESS 4	MATTRESS 5
960kW/270 s	1040 kW/890 s	30 kW/ ign.	30 kW/ ign.	310 kW/1320 s
Data Lost	1050 kW/900 s	ca. 35 kW/ ign.	30 kW/ ign.	400 kW/1090 s
940 kW/190 s	1010 kW/1200 s	ca. 40 kW/ ign.	30 kW/ ign.	340 kW/1230 s
920 kW/215 s	1230 kW/730 s	30 kW/ ign.	30 kW/ ign.	500 kW/710 s
940 kW/225 s	1080kW/930 s	35 kW/60 s[21]	30 kW/60s	390 kW/1090s

Table 5-3 Heat Release Peak and Time to Peak; Mattresses Covered with Bedclothes Combination #4

(Lowest value in each column is average of values above it)

MATTRESS #1	MATTRESS #2	MATTRESS #3	MATTRESS #4	MATTRESS #5
990 kW/320 s	1350 kW/470 s	190 kW/340 s	680 kW/730 s	310 kW/300 s 420 kW/825 s
1100 kW/305 s	1280 kW/470 s	190 kW/350 s	625 kW/650 s	220 kW/350 s 560 kW/810 s
1045kW/310s	1325 kW/470 s	190 kW/345 s	650 kW/690s	265 kW/325 s 490 kW/820 s

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[20] The upper two entries in the column for a given mattress design are for the shorter burner exposure durations (45 s on top; 25 s on side); the lower two entries are for the longer durations (70 s on top; 50 s on side)

[21] For simplicity, the peak occurring during burner exposure is taken to occur at 60 seconds.

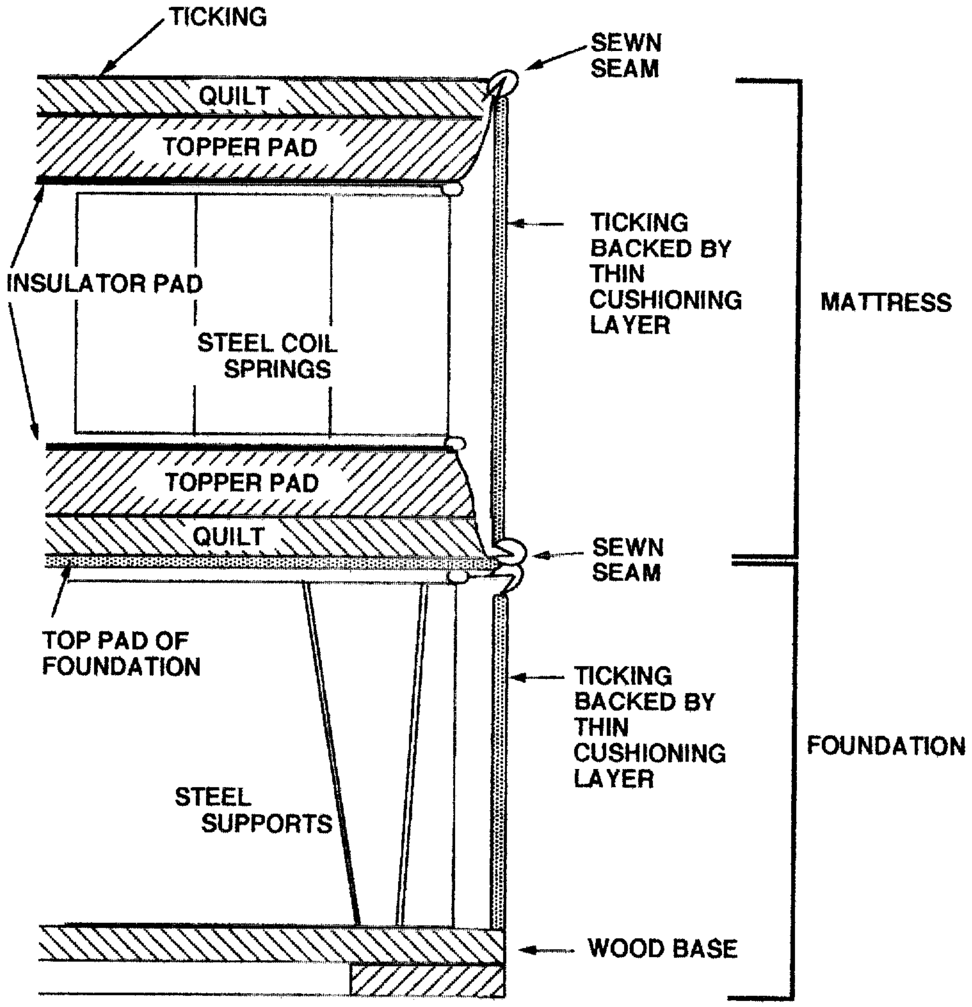

Figure 5-1. **Cross-sectional view of mattress and foundation structure (not to fixed scale).**

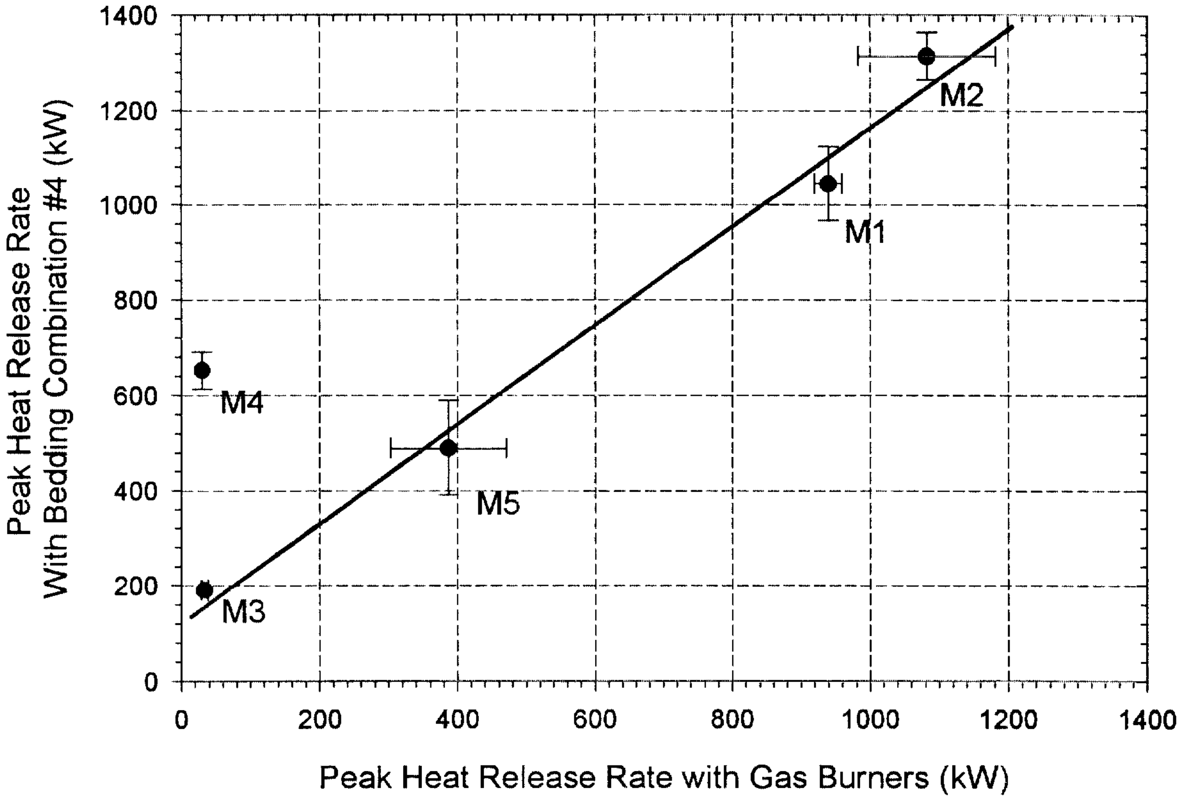

Figure 5-2 Correlation, for peak heat release rate, between gas burner results and burning bedding results for the five mattress designs; bedding was combination number 4.

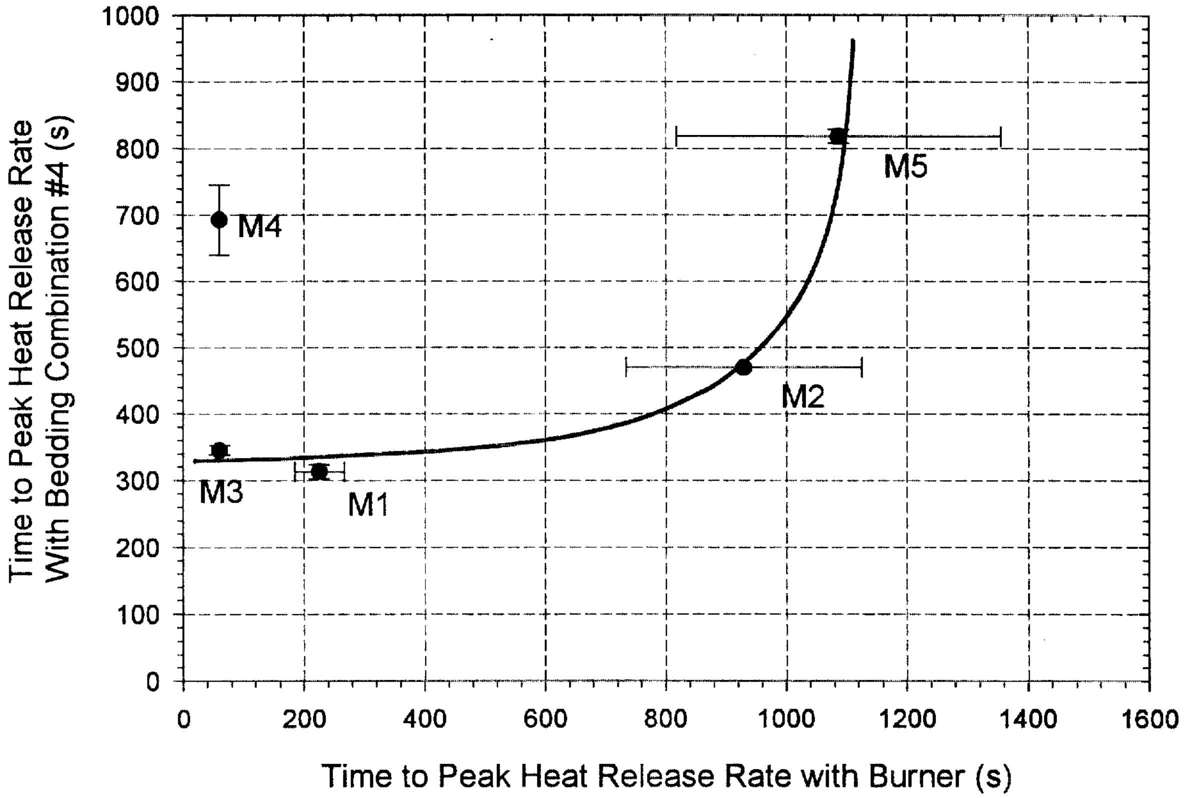

Figure 5-3 Correlation, for time to peak heat release rate, between gas burner results and burning bedding results for the five mattress designs; bedding was combination number 4.

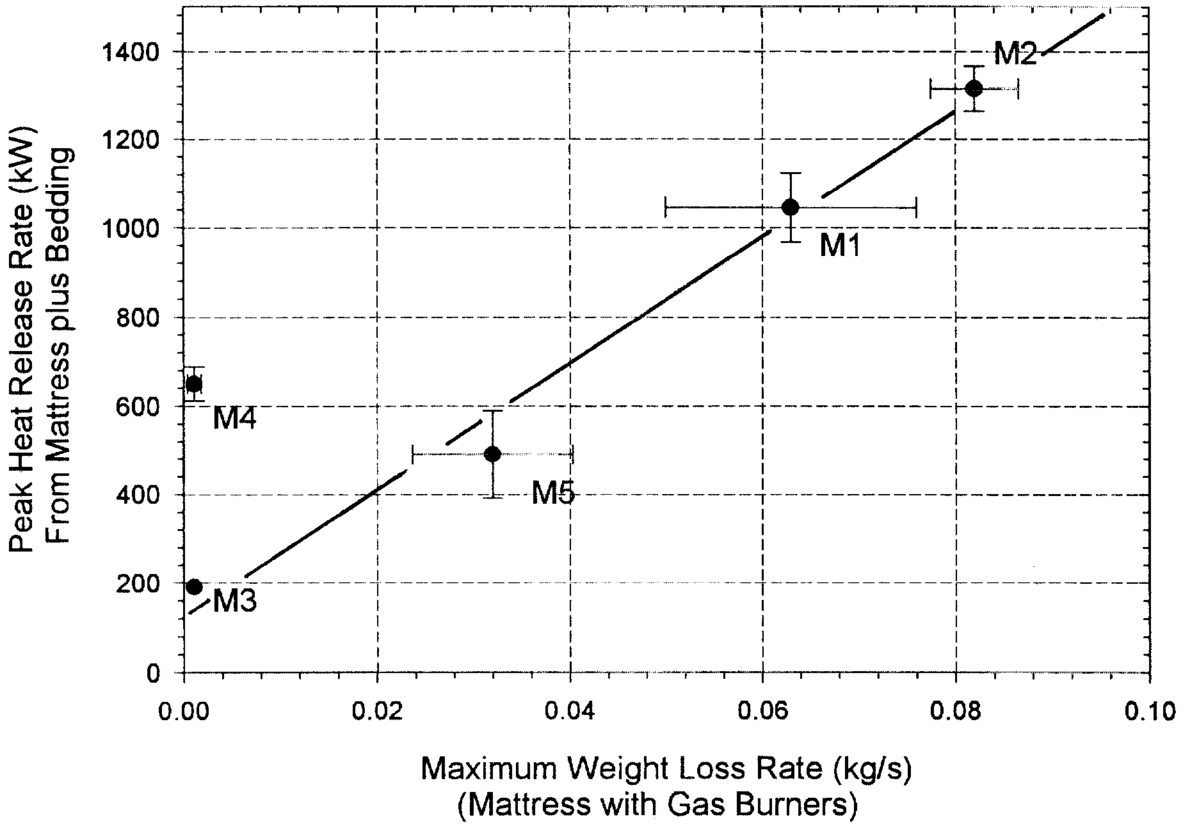

Figure 5-4 Correlation between maximum weight loss rate seen with gas burners and that seen with the bedding combination number 4; five mattress designs.

Acknowledgments

This study was sponsored in large measure by the Sleep Products Safety Council and supplemented by NIST funds. All bedclothes materials were donated by manufacturers through the American Textile Manufacturers Institute. The final mattress tests, with and without bedclothes, were conducted by the authors at Omega Point Laboratories in Elmendorf, TX.

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Appendix A
Thermal Behavior of Thin Stainless Steel Foil

The factors determining the temperature response of the stainless steel foil used in the bedclothes heat flux measurements (Chapter 3) can be quantified by means of a simple transient heat balance on the foil. The infrared camera responds to the brightness of the foil in the 8 μm to 14 μm range. This is essentially determined by the temperature of the foil since the camera sees the blackened inner surface of the foil and its emissivity is fixed. The foil receives heat on one side (toward the burning bedclothes) in the form of convection and radiation; it losses heat on the side toward the IR camera by the same two mechanisms. The extreme thinness of the foil means that it will have only a negligible temperature gradient across its thickness and minimal tendency to transfer heat laterally. Therefore it is treated as being thermally thin with no lateral heat conduction. Since the foil has a finite mass per unit area, it responds as follows.

$$(\rho C\ell)\, dT / dt = q(t) - h(T - T_A) - \varepsilon\sigma(T^4 - T^4_A) \qquad (A-1)$$

where the following apply to the mass average of the foil plus its coatings on both sides: ρ is density, C is heat capacity; l is the thickness of the coated foil, T is foil temperature, t is time, q(t) is a time-varying heat flux (convection plus radiation) to the outer surface of the foil (imposed by burning bedclothes or some other source), h is the coefficient for convective heat transfer from the side of the foil facing the IR camera, ε is the emissivity of the foil surface (toward the IR camera), σ is the Stefan-Boltzmann constant and T_A is the ambient temperature.

If the imposed heat flux, q(t), is a step function going from zero to a finite, steady level, the above equation must be solved to predict the resulting foil temperature as a function of time. The result will be that the foil rises to some new temperature, above ambient, after a finite time and then stays there as long as the imposed flux stays steady. At the steady temperature condition, the left hand side of Eq. A-1 is zero so the solution of the remaining algebraic equation determines the temperature as a function of the steady heat flux level. One can see that it depends on the heat transfer coefficient, h. The value of this coefficient varies with the orientation of the foil surface (horizontal vs. vertical). Since foil temperature determines foil brightness in the infrared, it becomes necessary to calibrate the heat flux vs. IR brightness level separately for each of the two orientations found on a mattress surface.

If the imposed heat flux is now a time-dependent function which first increases, reaches a peak and then decreases to zero, the foil temperature will follow it perfectly only if the characteristic time for the rate of change of flux is slow compared to the foil response time (as measured by the step function above). As the rate of flux change increases, the peak foil temperature will decrease, ultimately going to no change at all for a very fast heat flux peak.

These response issues were explored by solving Eq. A-1 numerically. However, it is difficult to pin down some of the parameter values which go into this equation. Consequently, these issues were also explored experimentally by moving an electrical strip heater past the steel foil at various constant speeds. Figure A-1 shows the results. Note that the speed range for the movement of the heater is essentially the same as that seen in Chapter 2 for the flame spread rate over various bedclothes materials. The degradation in the response of the steel foil is minimal, implying that this is not a substantial source of distortion in the heat flux data. The modeling did, however, make it clear that it is necessary to keep the mass per unit area of the foil system to a minimum. Thus it was necessary to clean the foil after every test to eliminate a build-up of fire degradation products and to bake out the foil after re-coating so as to minimize any endotherm that might result from solvent evaporation.

The response of the steel foil was checked during the bedclothes heat flux tests by recording the IR increase in brightness when portions of the steel foil were abruptly exposed (on the side away from the camera) to radiation from a pre-heated photo flood lamp. These tests showed a 90 % or better response in about 8 s to 10 s. Note that this does mean that short (e.g. < 5 s) heat flux patterns would be underestimated in their flux intensity by this system but such short flux exposures are of minimal interest here.

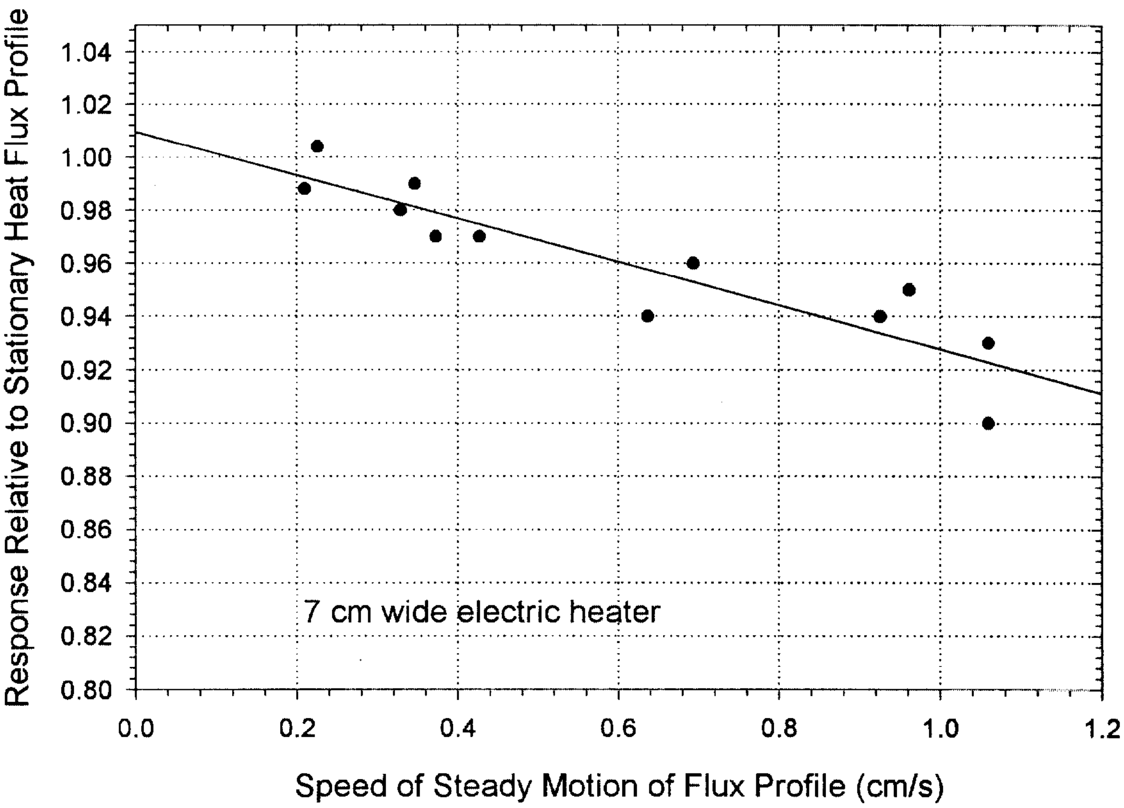

Figure A-1 Measured decay of IR camera response due to movement of an imposed heat flux profile; 7 cm wide electric heater over horizontal 0.00254 cm (0.001 in.) stainless steel foil.

Appendix B
Summary of Fire Behavior of Tested Mattresses With Gas Burners and with Bedclothes

The results of the mattress tests, described in Chapter 5, are reported here in some detail to provide some insights into how and why the various designs gave the heat release rate results seen. Some implications of the results are then discussed.

(a) Gas Burner Tests. Mattress 1 was the base case, typical of current market technology. Although the heat release data were lost in one test due to a computer lock-up, the results for the remaining three tests were fairly consistent. All cases yielded a rapid build-up to a fire just under one MW in peak intensity. There is some indication in Table 5-2 that the longer burner duration led to the heat release rate peak occurring somewhat sooner. The peak heat release variations are probably not significant in a statistical sense.[1]

Fire growth in this sleep set configuration was consistent in its path. The side burner flame penetrated the relatively thin materials there in about ten seconds, initiating flaming on the upper surface of the lower topper pad and soon burning through the upper pads of the top of the mattress immediately in front of the side burner. The upper burner simultaneously initiated flaming on top of the upper quilt layer. Lateral growth of these burner initiated flame-zones within and on top of the mattress promptly followed. It appeared that the internal flame zone spread the most rapidly, followed fairly closely by the flames on top of the mattress. The internal flame zone consisted of interacting flames on the inner surfaces of both the upper and lower topper pads. Flaming drips from the upper to the lower pad helped keep the lower flame front near the upper front, as did radiative interchange. This lateral spread engulfed the entire mattress volume yielding the bulk of the heat release contributing to the reported peaks.

The peak heat release rate in a fire is a product of the rate of heat release from unit area of burning material and the total area which is burning. The local heat release rate per unit area depends on the nature of the material and on the net heat flux it is seeing from its own flames and any surrounding, radiating material. The parallel surfaces configuration which define the interior volume of a mattress provide an environment where radiative interchange is enhanced thus boosting the local heat release from the materials which line this volume.

The foundation forms a second, similar volume except that its bottom is only partially closed, by the wood framework. The foundation is thus another potential contributor to the heat release peak; its contribution is limited by the lesser amount of padding materials it contains and the relatively slow burning of its wood content.

Here flames did immediately begin to spread down and across the border material on the

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[1] Recall also that the calorimeter being used here was subject to some loss of smoke which implies that the peak values above about ½ MW are low by some unknown percentage.

igniter side of the foundation but this yielded minimal heat release due to the small amount of material involved. The foundation got fully involved only when radiation and some flaming drip material coming from burning on the underside of its top pad (plus, perhaps, the mattress fire penetrating the lower mattress pads) ignited the wood frame extensively. By this time the mattress fire was past its peak. The peak fire in this second "compartment" thus lagged behind the first (the mattress) and the total fire heat release peak was less than it would have been if the two peaks had coincided.

Mattress 2 was similar to Mattress 1 except that all of the polyurethane foam was moderately flame-retarded and the ticking was rated to pass MVSS 302, implying it was subject to slower flame spread in certain test conditions. Table 5-2 indicates a seemingly anomalous result - the heat release rate peaks were consistently higher than those seen from the unretarded foam construction of Mattress 1. Note, however, that the peaks all occurred at a much later time. There is no clear indication of a trend in the results with burner duration.

These results reflect a distinctly different mode of fire growth, as compared to Mattress 1. Once again the side burner penetrated the side material in about 10 s but now the exposed surface of the topper pads (top and bottom) inside the mattress resisted significant fire involvement, reflecting the flame-retarded nature of the foam in them. The predominant modes of subsequent flame spread were laterally on the mattress sides and downward on the similar material forming the side of the foundation. However, this spread left behind continuing flaming at the side juncture of the mattress and the foundation. The evident source of continuing flaming here was the polyester fiber pad on top of the foundation. Flames tended to spread on its underside and come up the opened side of the mattress/foundation assembly where they were recorded by the video cameras. A photo of the underside of this pad area documented the existence of this mode of flaming. Varying behavior of the flaming on the underside of the this pad appears to account for the variation in the times to reach a peak in the heat release for the four burner tests with this mattress. The first clear consequence of these spreading flames was spreading ignition of the wood frame at the base of the foundation, mainly by radiation. These flames reinforced the flames above them on the underside of the pad. This took varying times to develop in separate tests. Then at differing locations along the ignited side and differing times into the test, these flames resulted in ignition of the outer edge region of the top of the lower topper pad in the mattress. Evidently continued heating of the flame-retarded foam from below brought it to a temperature where its retardant was rendered less effective.

The process that followed was complex. Flames grew simultaneously in both the mattress interior and in the foundation. The foam forming the top and bottom topper pads that lined the mattress interior appeared to be overwhelmed by the preceding pre-heating and by the heat coming from the flames growing on the area first ignited by flames from below. Flaming melt drip material (upper to lower topper pads) was a clear contributor to the spread of flames in the mattress interior. However, fire growth in the foundation, with the bulk of its materials unretarded, was as fast, if not faster. What appeared to be coupled flames zones spread together along the length of both the mattress and foundation compartments so that both were burning intensely at the heat release peak. In this manner, because the area involved in flaming at the peak exceeded that with Mattress 1, the heat release rate peak with this flame-retarded construction exceeded that from the analogous non-retarded construction. It is not certain but it is probable that this design would have behaved significantly better in these gas burner tests if the fiber pad in the foundation had not ignited.[2]

Mattress 3 contained most of the same materials as did Mattress 1 except that its ticking was a fire barrier material. Also note that the sides of its foundation were covered with the same barrier material. The data in Table 5-2 indicate that little happened to this mattress during and subsequent to the double gas burner exposure. The observed heat release peak was primarily due to the igniter and thus occurred during the burner application (as indicated by "ign." in Table 5-2). There was some heat release from foam vapors coming into the burner flames through the barrier but it was at such a low level as not to be reliably quantified by the calorimeter. After the burner exposure ended there was some continuing weak flaming, especially on the top of the mattress. This could last for several minutes before dying out. It left a blackened shallow depression in the top of the mattress. In one case this encompassed an area on the top of roughly 0.2 m^2 (ca. 2 ft^2); other cases were smaller in area.

The barrier evidently succeeded in its primary goal, preventing the establishment of flames on the polyurethane foam immediately inside of it. Certainly the end results, the dying out of all exterior flames and the lack of any further evidence of continuing burning imply that flames never started on the inside of the barrier. The foam was extensively degraded by heat transferred through the barrier. Sectioning of the mattress showed foam surfaces that were consistent in appearance with pyrolysis or with flaming. As will be seen below with the bedclothes initiated fires, even when flames do get inside such a barrier the results in terms of heat release rate may be minimal. The barrier necessarily has seams which are its most vulnerable point[3]. The seams which were impacted by the burners here were at the upper and lower edges of the mattress. As was noted in Chapter 4, the seams were subjected to burner flames in three locations simultaneously in the burner set-up used here (though two of these are for the shorter duration of the side burner). While the tape edge covering burned away, the seams themselves did not open. The nature of the "combustion modified" thread used to close the seams is not known but is presumably organic. Thus it can be expected to fail eventually during sustained heating, but localized seam failures are not necessarily the precursors of a large fire.

Mattress 4 was unique in that it contained no polyurethane foam. Instead the cushioning role was played by a flame-retarded polyester batt which also covered the sides of the

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[2] The foundation also contributed substantially when burning bedding was the heat source but the sequence of events differed in relative timing (see below).

[3] Some barrier materials are organic and are subject to burn through in situations where the heating is sustained for a long enough period. The barrier used here appeared to have a fiberglass base which did not show any signs of penetration.

mattress and foundation. All of these layers included a denser, fibrous backing layer (ca. 3 mm thick), evidently organic, which, when exposed to flames, charred with minimal shrinkage, thus forming a barrier. Note that the upper and lower surfaces of the interior volume of the mattress were lined with exposed FR polyester batting, not with the barrier which was on the inner surface of the quilting layer. Note also that the thread used to close the seams in the barrier was a strongly charring organic material (a polyaramid).

In all four gas burner exposures conducted here, this mattress construction showed minimal fire involvement. Any heat release contribution beyond that of the burner could not be reliably measured by the calorimeter, as indicated in Table 5-2. Subsequent to the burner exposure, small flames persisted on the top of the mattress for a few minutes (one case for 17 ½ min) before dying out. These and the burner flames locally consumed the ticking; they either consumed or simply shrank the FR polyester batting immediately below it, causing a depression in the mattress. The action appeared to stop at the fibrous barrier layer which remained intact with no evident holes. The behavior on the side of the mattress and foundation was similar but ended much sooner, typically after one minute and the tape on the seams was the most persistent element of this. The minimal fire behavior here is to be contrasted below with the large fire which accompanied the exposure to burning bedclothes.

Mattress 5 utilized a combination of somewhat flame-retarded polyurethane foam (rated to pass California Technical Bulletin 117, a small flame exposure test) and boric acid treated cotton batting[4]. Here the cotton, which forms a char layer upon flame exposure, was intended to form a barrier on the sides of the mattress and foundation. In contrast to Mattress 4, this barrier layer was not between the quilt layer and the topper pad but rather formed the bottom of the topper pad. This meant that the interior volume of the mattress was lined with cotton batting. Note that the seams were held together by ordinary thread.

The fire behavior of this combination was rather complex and variable. The fire spread on the top of the mattress as a growing "ring", consuming the ticking, foam and upper portion of the cotton batting (leaving it charred). The flames were limited in size (ca. 15 cm to 20 cm high) and the resultant heat release rate was small (ca. 50 kW). However, these combustible materials made possible a continuing attack on the seams which held the mattress side cotton layer in place. Flames persisted at both the top and bottom seams on the ignited area of the mattress with the result that sooner or later (this varied from test to test), the seams opened and flames spread onto the exposed cotton surfaces in the mattress interior. This happened anywhere from one to three minutes into the test and was largely a result of the spreading fire along the top edge of the mattress. Flame penetration into the mattress interior was not directly fatal, however, since the cotton there burned fairly slowly (especially if the seam opening was such that it limited the air supply into the mattress interior) and the heat release rate typically increased by less than a factor of two. However, this did preheat all materials in the layer formed by the

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[4] Boric acid is primarily a smolder retardant for cellulosic materials but it also aids the flame barrier effect here by making the cotton char more resistant to oxidation and thus burn through. In this way it can also slow the flaming combustion of the thick cotton layer cotton somewhat.

juncture of the mattress and foundation. Also, the flaming mattress side material eventually (sometimes quickly) fell down and ignited the side material on the foundation. This allowed its flames to ignite the underside of the pad forming the top of the foundation. Radiation from this in turn ignited the wood base in the foundation and the stage was set for a coupled fire growth process involving spread along the length of the foundation and the top of the lower pad of the mattress. This led to the observed heat release rate peak which varied substantially in size. The combination of delayed timing (i.e., the fire did not grow large until the top of the mattress was already largely consumed) and the flame-retarded or charring nature of the bulk of the burning materials kept the heat release peak to moderate size.

(b) Burning Bedclothes Tests. The behavior of the individual mattress designs under the influence of a bedclothes fire is summarized below.

Mattress 1, the design based on current residential practice, yielded a slightly larger fire with bedclothes than without. The result was somewhat less than the sum of the separate peaks from bedclothes (ca. 160 kW) and mattress alone but the difference may not be statistically significant. The behavior that led to the peak was somewhat different than was seen with the burners alone. In particular, it appeared that the spread of fire within the mattress was initially somewhat slowed by the presence of the bedclothes since they inhibited air access there. Recall that when there were no bedclothes, the top of the mattress opened continuously as the flames advanced on the upper and lower inner mattress surfaces. Here the bedclothes layers posed an additional barrier to the opening of the mattress top. However, as the flaming process in the mattress was spread by the flames continually moving along the bedclothes hanging over the side of the bed, this became less of an inhibitor. The fire did still grow fastest in the mattress/bedclothes assembly with the foundation initially lagging. However, at the heat release peak, the foundation contributed strongly, as well.

The heat release rate peak for Mattress 1 is right in the range to just produce flashover in a small bedroom (1.1 MW for a 2.44 m cube; 8 ft cube). Since the peak values here are somewhat underestimated due to smoke spillover, the flashover threat is almost certainly real.[5] Recall also that the presence of heat feedback from a hot smoke layer in a room would increase the peak heat release rate, again pushing toward flashover. Flashover strongly increases the threat to persons beyond the room of fire origin.

Mattress 2, in which all of the polyurethane foam was moderately flame-retarded, gave a large but late fire with the gas burners. Here the fire was again intense, as measured by peak rate of heat release, (in fact, the most intense seen in all of the mattress testing) but it peaked sooner with the bedclothes than with the burners as the heat source. The peak was somewhat greater than the sum of the mattress and bedclothes peaks (1315 kW average vs. 1240 kW average) but again the difference is comparable to the uncertainties in the data. With the gas burners as the heat source, the fire in the mattress interior waited until

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[5] But note that the heat release rate necessary to cause flashover increases as the size of the room increases.

flames had spread on the underside of the top pad of the foundation and pre-heated the lower foam padding of the mattress. Here there was much less of a delay getting flames established on the interior foam surfaces of the mattress. This appeared to be due to two effects. First, the folded-back bedclothes on the igniter side seemed to provide some heat (radiation) to the lower, interior foam pad adjacent to it for a period of about three minutes. The longest gas burner exposure in this area was 50 s. The longer flux duration from the bedclothes here was probably much less intense than the gas burner level over much of its length. Second, it appeared that flaming material from the pillow and/or bedclothes may have dropped through the top of the mattress onto this lower, interior foam pad. A moderately intense fire spread through the mattress but it grew to an intense peak when the foundation became fully involved and bathed the mattress in its flames. As before, it appeared that the path to foundation involvement was by flame spread on the underside of its top pad, initiated by flames from material (mattress, bedclothes, foundation ticking) on the ignited side of the assembly. In turn, the wood frame of the foundation became involved by a combination of radiation from the burning pad above it and flaming melt/drip material from above.

The heat release rate peak from Mattress 2 with burning bedclothes was above the 1.1 MW threshold for flashover of a small bedroom. It was higher than that from the reference case. The moderately flame-retarded foam did, however, lead to a significant delay in the time of the heat release rate peak. This would allow a greater time for escape and/or a fire suppression response.

Mattress 3, with its fire barrier ticking, gave little more than the heat release peak from the bedclothes themselves. However, one of the mattresses exhibited a phenomenon also seen below with another design. At about 290 s into the test, with bedclothes flames stretching from the far side of the pillow (away from the ignition side), across the top of the mattress and down the hanging covers near the foot end of the ignition side, an abrupt ignition event occurred in the mattress interior. This was clearly due to a deflagration wave that flashed through a mixture of pyrolysis gases and air in the mattress interior, abruptly boosting the internal pressure. Flames emerged for roughly one second from all exposed mattress surfaces and the mattress itself swelled then settled back. This could have been due to auto-ignition of the internal gas mixture or to piloted ignition through some small hole, perhaps in a ticking seam. It gradually became apparent that the foam in the mattress interior was burning but in a very unstable manner, presumably due to its very limited air supply rate. Flames propagated rapidly (tens of cm/s) through fuel/air mixtures in waves which immediately died out then re-appeared. This continued after all of the bedclothes were consumed, yielding a heat release rate of about 20 kW. There was no evidence of growth in this heat release rate when the internal fire was extinguished with water thirty minutes after the start of the test. The other test with this design and burning bedclothes as the heat source showed no signs of this internal deflagration phenomenon and the heat release rate died out as the bedclothes died out.

Mattress 3 represents essentially no increased fire threat beyond that presented by the bedclothes themselves. The peak from the bedclothes, here about 160 kW, presents no direct threat of flashover for even a small bedroom.[6] Its ability to ignite other objects has not been considered here beyond the flux measurements in Chapter 2 but those results imply only a short range threat. Of course the flames do represent a severe burn threat to any nearby persons.

The two tests with Mattress 4, the design based on FR polyester fiberfill rather than polyurethane, gave the same internal deflagration phenomenon in quite comparable circumstances to those above. Thus with the bedclothes burning in a very similar manner (from the far side of the pillow, across the top and down onto the hanging bedclothes near the foot end), 300 s to 400 s into the test, an abrupt internal pressurization occurred in the mattress. This caused it to swell, emit flames from most exposed surfaces and then settle back to a seemingly unaltered state. Here, however, this event was soon followed by a strong increase in white smoke from the top seam on the ignition side of the mattress and flames could soon be seen in the mattress interior. Recall that the top and bottom interior surfaces were formed by FR polyester batting, not the barrier mat which was sandwiched between polyester batts in both upper and lower mattress pads. Aside from the considerable smoke coming from the mattress interior, there were no further signs of a worsening fire for several minutes. Then it became apparent that the wood base foundation was becoming involved, apparently via flaming melt/drip material (there were no visible holes in the barrier material on the sides of the foundation through which to see). The fire then grew rapidly stronger with what appeared to be coupled spread in the foundation and mattress interiors (much of the barrier on the side and top of the mattress stayed in place obscuring the view). The replicate test of this configuration gave essentially the same result.

This mattress clearly exhibited a behavior in the bedclothes tests which differed qualitatively and quantitatively from that seen with the gas burners. The overall result followed from the internal overpressurization which very likely opened a seam in the barrier layer. It is less clear why this led to a large fire for this design but not for Mattress 3, described above. There are a couple of possibilities. First, the seam rupture was more extensive and thus allowed more air into the interior so that when flames from the bedclothes penetrated the opening, an interior fire could grow with less restraint. Second, the interior fire produced flaming melt/drip material which made its way into the foundation and ignited the wood there. Neither possibility can be confirmed from the evidence on the video tapes since the charred bedclothes materials obscured much of the mattress.

The source of the differing outcomes with this design, between gas burner exposure and burning bedclothes exposure, was clearly the internal deflagration. Auto-ignition or piloted ignition of internal gases in the mattress are both favored by the larger, simultaneously heat-exposed area on the mattress imposed by burning bedclothes (as compared to the gas burners); so also is a greater concentration of these internal gases. Barrier rupture by such a phenomenon is a possibility with any barrier-wrapped mattress

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[6] Again note that a small fire can pose a toxicity threat if the bedroom door is closed.

design. Since the gas burners, as used here, did not predict it, such a design may have to be tested with bedclothes to be sure of the ability of the barrier to remain intact sufficiently to inhibit a rapid mattress fire. Note that the burner exposure is still relevant as an intermediate step in testing a design since it gives information on the ability of the barrier and its seams to resist burn-through or heat-induced seam failure. It may also be possible to do separate testing of seam behavior, as discussed below.

The magnitude of the heat release rate peak obtained with Mattress 4 and burning bedclothes was intermediate in size (ca. 650 kW) and delayed in time (nearly 700 s) compared to the reference mattress. Both of these trends indicate a lesser hazard. The heat release rate peak is well below the 1.1 MW level which is a flashover threat in a small bedroom. However, a fire this size does represent a significant threat of ignition to any other nearby objects. Thus one can anticipate that the threat to life is decreased by the lower, later peak since it allows more time for escape and fire suppression response. In the absence of a suppression response, however, it still represents a significant hazard to life and to the structure.

Mattress 5, which contained a combination of TB 117 polyurethane foam and boric acid treated cotton batting, produced results with burning bedclothes that fell on the prediction line shown in Fig. 5-2. This design uses the cotton batting as a type of barrier to flame penetration into the mattress (and foundation) interior. It has the advantage that the interior surfaces of the mattress are all cotton, which, due to its charring nature, burns more slowly than polyurethane foam. As was seen with the gas burners, however, the barrier properties of cotton batting are of moderate effectiveness. Here the flames on the side of the mattress (from bedclothes, from the side covering of mattress or foundation, or from the TB 117 polyurethane foam exposed on the edge of the lower mattress pad) got inside the mattress in 6 min to 7 min.[7] Typically the side batting separated at an upper or lower seam, allowing the flame penetration. Since the cotton inside the mattress burns rather slowly, what ensued was a moderate fire in the mattress (plus the fire in the bedclothes which was supplemented by the burning foam on top of the mattress). The internal fire continued for several minutes, consuming a significant fraction of the cotton batting in the mattress. Ultimately, the foundation became involved, initially at the foot end. This was probably the result of flames from the hanging bedclothes igniting the underside of the top pad of the foundation, which then ignited the wood frame at its base. This was the sequence in other tests but here the charring cotton batting on the side of the foundation precluded a clear view of this. Flames then spread, from foot end to head end, along the length of the foundation and its flames helped strengthen flaming in the remaining material of the mattress and bedclothes. The result was the second and larger heat release rate peak which is the one recorded in Figs. 5-2 and 5-3.

Mattress 5 plus bedclothes gave a moderate size heat release rate peak, somewhat smaller than that from Mattress 4. Furthermore, it was slow to be reached. Note, however, that the earlier initial heat release rate peak from this design is substantial, as well. None of

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[7] At roughly the same time, the combined heat release rate from the pillow, bedding and top surface foam formed an initial peak in overall heat release rate which is also reported in Table 5-3.

the peaks was in the range that would pose a direct threat of flashover in a small bedroom. However, the risk of secondary ignition of other nearby objects is substantial with peaks of a few hundred kilowatts. This does not necessarily mean that flashover will ensue unless there is a nearby object with heat release behavior similar to a bed (e.g., another bed or an upholstered chair). Even then the timing of the ignition of the other object has a strong influence since it must add its heat release to the burning bed at the right time to get a combined heat release rate over the flashover level.

From the above we can summarize the findings on the performance of the various alternative mattress designs, as follows.

- Mattress 2. This design, based on the same construction as the reference mattress but containing only moderately flame-retarded polyurethane foam, succeeded only in delaying a large fire. The delay was significant, however, and, in some cases might allow an effective fire suppression response to intervene.

- Mattress 3. This design effectively precluded an appreciable heat release rate from the flammable materials within the barrier layer (the ticking). Thus the only significant heat release rate was from the bedclothes. The results in Chapter 2 show that the bedclothes heat release rates are well below levels which pose a flashover threat. In one test with bedclothes, an overpressurization event occurred which did lead to weak burning inside the mattress. It is possible that different circumstances could lead to more rapid burning if the seams were more extensively opened.

- Mattress 4. This design allowed complete combustion of mattress and foundation after the barrier layer was breached in both bedclothes tests by an internal overpressurization event. The resulting heat release rate peak was moderate but larger than that from Mattress 5; it also occurred somewhat sooner than for Mattress 5.

- Mattress 5. This design allowed complete combustion of both mattress and foundation but at a relatively moderate rate and with delayed heat release rate peaks. Since the polyurethane foam was outside of the cotton batting "barrier", the layer on top of the mattress was completely consumed as the bedclothes burned over it. Thus the heat release rate peak would grow larger if this layer were made thicker. That foam layer (now facing the foundation) was a participant in the flaming which breached the cotton batting on the sides of the mattress. It may also have been a participant in the spread of flames into the foundation. To delay the breaching of the side barrier on the mattress, it may be necessary to use a more flame-retarded foam in the quilt layer so that it burns for less time along the lower edge of that side barrier; this would also lessen the heat release rate contribution from the quilt layer on top of the mattress.

Other Implications of the Results. Another fact which emerged clearly here was that the foundation can play an appreciable role in overall fire growth for various mattress designs. The top pad and wood frame in these foundations formed a formidable coupled heat source once they became involved. That heat source sits right under the mattress and so can force it to burn more intensely than it would otherwise. As often happened here, the foundation and mattress can burn together to yield the heat release rate peak. If the involvement of the foundation were slowed, that would have slowed the time to a peak here (with the obvious exception of Mattress 3 and, perhaps also, Mattress 2). If it were eliminated, the peaks seen here would be substantially lowered for all but Mattress 3. It appeared that the top pad of the foundation was leading the involvement process.

An issue of concern in relation to the foundation is that, in real usage, it is essentially open to the floor below it. This implies that the floor and/or its covering may interact with the fire growth process in the foundation. In this study the "floor" was a sheet of gypsum board; the paper facing sometimes burned but its effect appeared minimal; in any event the board was changed only every 4 to 5 tests. In a residential setting, the floor could include carpet, underlay and wood. If flaming melt/drip material falls on it, the result may be a more intense fire under the mattress.

The gas burner results with the mattresses alone were successful predictors of the bedclothes fire situation for four out of the five designs. The exception involved a phenomenon which was not induced by the burners, internal deflagration and accompanying over-pressurization which split the mattress seams. The reason that this was not seen with the burners was probably that they do not heat a sufficient area of the mattress at one time as to have a good chance of causing internal ignition of gas/air mixtures accumulating inside the mattress.[8] This deficiency might be overcome by greatly increasing the size of the burners but they would become unwieldy and major consumers of propane in the process. For all of the other mattress designs and even for Mattress 4, the burners did a reasonable job of predicting the bulk of the mattress response to burning bedclothes. A partial exception seemed to be Mattress 2 where the bedclothes, with their longer heating from the folded-back region[9] and flaming melt drips, produced flame involvement in the mattress interior more readily than the burners did; even so it fell on the line in Fig. 5-2. This relative timing effect is probably why the line in Fig. 5-3 is curved as much as it is.[10] The gas burners should be useful devices for assessing the behavior of candidate improvements in mattress designs but a check with bedclothes is still probably a wise path before final design decisions are made. Note that

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[8] The burners may not gasify sufficient material within the mattress interior to cause a flammable mixture there. The bedding, in heating a much larger surface of the mattress at one time, clearly has a much better chance to produce an ignitable mixture. Auto-ignition of such a mixture, which would not require any holes in the barrier, is also favored by the larger volume of heated gases which the bedding could produce.

[9] A possible way to simulate this longer heating at a lower heat flux level would be to add a second gas burner next to each primary burner but spaced further from the surface to lower its imposed heat flux. At the end of the primary burner exposure the gas flow could be switched to the secondary burner for a continued, lower level exposure. The cost here is increased complexity. An alternative to finding the effect of longer heat exposure is to employ the two burners as used here but for longer times. At some point this becomes overkill because the high flux for a long time exceeds the conditions imposed by burning bedding.

[10] It should be recognized that the results in burner "calibration" results in Figures 5-1 and 5-2 are dependent somewhat on bedding combination, bedding arrangement and ignition location. Thus the lines become bands whose width can only be judged with increasing numbers of fire tests.

the preceding results also imply that it is best to test the combination of mattress and foundation (the sleep set) at all levels of development; the pair of gas burners developed here are useful for that purpose.