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# Combustion of Mattresses Exposed to Flaming Ignition Sources Part II. Bench-Scale Tests and Recommended Standard Test

Center for Fire Research
National Engineering Laboratory
U.S. Department of Commerce
National Bureau of Standards
Washington, DC 20234

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Final Report

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# COMBUSTION OF MATTRESSES EXPOSED TO FLAMING IGNITION SOURCES

## PART II. BENCH-SCALE TESTS AND RECOMMENDED STANDARD TEST

Vytenis Babrauskas

Abstract

Ten mattress types were subjected to full-scale fire tests in the earlier part of this project. Burning behavior was determined and hazard was assessed by classifying into performance groups. In the present study bench-scale test procedures were examined for suitability for classifying mattress combustion behavior when exposed to flaming ignition sources. Several tests were examined, and a test protocol was developed based on two procedures -- measurement of rate of heat release and smoke production. These procedures enable the performance classifications, as established by full-scale tests, to be reproduced by convenient laboratory tests. Details are given for conducting the required tests and illustrative performance of some two dozen samples is recorded.

Key words: Bedding; beds; compartment fires; fire tests; health care facilities; heat release rate; hospitals; mattresses; prisons; smoke production.

## 1. INTRODUCTION

In mid-1976 work was started at the National Bureau of Standards (NBS) to characterize the combustion of institutional mattresses when exposed to flaming ignition sources. The initial report [1] was issued in 1977 as Part I and gave the results of the full-scale fire tests and hazard analysis. Ten different mattress types were furnished with identical hospital bedding (see Figure 1 and Table 1) and ignited from a small polyethylene wastebasket filled with trash. The bedding acted as a continued flaming ignition propagator. All of the mattresses passed the mandatory federal cigarette ignition standard [2], but showed substantially varying behaviors in these flaming ignition tests.

This work provided users with a certain amount of guidance, based on behavior simulations for different mattress construction types. Officials of hospitals, prisons, and similar institutions, however, should have available to them a method for testing and rating mattresses which is performance-based (rather than a prescriptive specification) and which can be readily performed by independent testing laboratories. On the face of it, it would seem that a suitable recommendation would be to use the same full-scale test procedure as was defined in Part I [1]. This would not be satisfactory for the following two reasons: (1) the costs of full-scale room tests tend to be very high, making such tests economically

a last resort option; (2) interlaboratory data agreement for full-scale room fire tests has been extraordinarily difficult to achieve, making the data gathered for such tests unsuitable for regulatory use. It is then preferable, if at all possible, to adopt a bench-scale test procedure. Bench-scale fire tests by themselves are not meaningful for hazard analysis unless a satisfactory correlation is available between bench-scale test performance and well-controlled full-scale tests, in which case a sound basis for the utilization of such tests is provided.

The full-scale tests of Part I will be viewed as a proper data base against which to judge bench-scale procedures. The goal of the work in Part II was then to produce a set of simple, reproducible, moderate cost bench-scale test procedures which would give results that adequately correlated to the full-scale findings.

## 2. DESCRIPTION OF TEST MATTRESSES

A description of the ten mattresses tested in full-scale was given in Part I. An additional fifteen specimens were added for the bench-scale series. For convenience, a brief description of all 25 mattresses follows. Their physical properties are listed in Tables 1 and 2.

Mattress M01 was a hospital mattress with solid foam core and retardant treated polyvinyl-chloride (PVC) ticking (the ticking is the outermost mattresses layer, or cover). The polyurethane core consisted of an inner layer and an outer enveloping layer. The inner core foam was retardant treated. The outer core material showed only trace retardants, not at an effective level.

Mattress M02 was a hospital mattress with an innerspring construction and contained unretarded polyurethane foam padding, an unretarded polypropylene interfacing fabric, and a ticking identical to that of Mattress M01.

Mattress M03 was an innerspring hospital mattress with cotton felt padding, an interfacing fabric same as in Mattress M02 and a vinyl ticking identical to that in Mattresses M01 and M02. The cotton padding was retardant treated.

Mattress M04 used a latex foam core (untreated) and a retardant treated vinyl cover. The foam was "pinned" by a regular pattern of holes. This mattress duplicated the mattress used in an Osceola, Missouri, nursing home and which was identified as the principal fuel in a multiple-life loss fire in 1974.

Mattress M05 was a commonly available commercial mattress with a solid foam polyurethane core. The ticking was composed of three layers -- two rayon fabric layers with an intermediate layer of polyurethane foam. The mattress was asymmetrical in that the ticking assembly on top was quilted while on the bottom it was not. None of the materials were retardant treated.

Mattress M06 superficially resembled a cotton innerspring mattress in construction and appearance, but the padding consisted to two layers: a cotton/polyester felt pad and an underpad comprised of cotton, nylon, and polyester fibers. A polyester ticking was used. Only the underpad was retardant treated. (Note that by comparison, an unretarded cotton batting mattress of conventional construction normally cannot pass the cigarette ignition test. Mattress M06, of course, successfully passed the cigarette ignition test).

Mattress M07 was a prison mattress conforming to State of Connecticut Specification 3748-M-339 for mattresses. This specification was issued by the State in 1976 after several fires occurred, involving two fatalities. The mattress was of innerspring construction, using boric acid treated cotton felt batting and a jute pad and covered with a retardant treated cotton ticking conforming Federal Specification CCC-C-436 (Type II).

Mattress M08 was a mattress conforming to U. S. Navy Specification MIL-M-18351, Type III, size 2. Core material was neoprene (polychloroprene) foam and conformed to Specification MIL-R-20092. The above specification references Standard MIL-STD-1623 which is based on the ASTM E162 radiant panel test. The specified neoprene material* is "Type II, Class 4," which requires a flame spread index not greater than 10 on the radiant panel test. The ticking was a retardant treated cotton fabric conforming to Federal Specifications CCC-C-436. The core consisted of three layers of black neoprene foam of different thicknesses and slightly different densities glued together.

Mattress M09 was a prison mattress which was tested because of implication in a recent prison fire. It was comprised of a polyurethane core and vinyl ticking with nylon fabric reinforcement. Only the ticking was retardant treated.

Mattress M10 was a prison mattress of current manufacture which used a black neoprene foam similar to the one in M08 and was retardant treated. A vinyl ticking with nylon fabric reinforcement was used.

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*Neoprene core material in all the test mattresses was retardant treated and could meet this requirement.

Mattress M11 was a used specimen removed from U. S. Coast Guard shipboard service. The mattress consisted of a black neoprene foam core covered with a retardant-treated cotton ticking.

Mattress M12 was considered by the U. S. Coast Guard for shipboard service. The specimen consisted of a buff neoprene foam core covered with a ticking similar to M11.

Mattress M13 was a stock U. S. Coast Guard item. Construction and the ticking were similar to M12; the core material was, however, a black neoprene foam.

Mattress M14 was a prison mattress using a recently developed retardant treated polyurethane foam. A vinyl ticking was used.

Mattress M15 was a pre-production sample of a newly developed mattress using a highly treated and filled hydrophilic polyurethane foam. A vinyl ticking was used.

Mattress M16 was identical to Mattress M14 with the exception of the ticking, which was cotton cloth.

Mattress M17 represented a common commercial mattress construction. It was basically of innerspring cotton batting type, but contained two layers of polyurethane foam underneath the ticking. This use of polyurethane foam as an interliner permits the mattress to pass the cigarette ignition test without need for retardant treated cotton batting.

Mattress M18 was a polychloroprene foam core prison mattress, similar to M08. The foam, however, was buff-colored and was more highly retardant treated than that in M08.

Mattress M19 was a all-polyester batting innerspring unit with a cotton ticking. This was an experimental mattress intended to be compared to all-cotton and mixed fibers batting constructions.

Mattress M20 was a hospital mattress from the same manufacturer and of the same basic size and construction as M01. Here, however, only a single uniform layer of polyurethane foam was used for the core, apparently as a cost-cutting measure.

Mattress M21 was a newly developed hospital mattress making use of an interliner for flame barrier purposes. The construction consisted of a PVC ticking, then a highly retardant treated neoprene interliner. Next a layer of polyurethane foam, then a small amount of cotton batting and finally a jute insulator on top of the innersprings.

Mattress M22 was a pilot production prison unit using a highly retardant treated hydrophilic polyurethane foam of similar, but more recent formulation than M15. A vinyl ticking with nylon fabric reinforcement was used.

Mattress M23 was an athletic mat, consisting of buff-colored PVC-nitrile foam with a skin coat of PVC.

Mattress M24 was jail cell padding material, consisting of black PVC-nitrile foam, covered with a hand laid-up surface covering comprising three fiberglass netting layers encapsulated in a sprayed-on PVC skin coat.

Mattress M25 was the final production version of M22.

Control Mattress A control mattress which would not contribute to the fire was required in order to isolate the effects of bedding combustion. For this purpose a 100 mm thick batt of fiberglass, resting on cement-asbestos board was used. The organic content of the fiberglass batt was burned out prior to testing.

The properties of the bedding used to cover the test mattresses are listed in Table 3.

## 3. FULL-SCALE EVALUATION

To evaluate the hazard, a set of criteria was evolved for the tenability of the room of fire origin. The evaluation was accomplished in two steps. Any mattresses which, by themselves, led to room flashover were considered to be least safe. Flashover was defined as the instant at which the heat flux exceeded 20 $kW/m^2$ at the floor level. This heat flux is sufficient to ignite many combustible materials. Specimens that did not lead to room flashover were then evaluated according to three tenability criteria. The values of the criteria were associated with incipient incapacitation and are the following:

Heat Flux exposure > 2.5 $kW/m^2$ (Note that this is substantially lower than the 20 $kW/m^2$ set as flashover limit above)

Gas Concentrations

$CO_2$ > 8%

$O_2$ < 14%

COHb > 25%

Smoke Obscuration

extinction coefficient > 1.2 $m^{-1}$.

The carbon monoxide effects were evaluated using a formula from Stewart [3] for calculating predicted carboxyhemoglobin (COHb) levels. Details of the development of all the criteria are given in [1]. The analysis of test results was based on the above criteria, and led to establishing four performance groups.

Group A - Mattresses in this group did not exceed any criteria throughout the test.

Group B - Mattresses in this group exceeded the smoke obscuration limit, but did not exceed any other criteria.

Group C - Mattresses in this group exceeded all the tenability limits but did not lead to room flashover.

Group D - Mattresses in this group led to room flashover.

The results showed the following performance:

Group A: M03 and M07, both of cotton innerspring construction.
Group B: M08 and M10, both of neoprene foam construction.
Group C: M02, M05, and M09, all of polyurethane foam construction, and M06 of mixed fibers construction.
Group D: M01, a polyurethane foam specimen, and M04, a latex foam specimen.

The full-scale results are summarized in Table 4.

## 4. BENCH-SCALE TEST PROGRAM

The performance of other mattresses could, in theory, be compared and ranked by conducting additional full-scale tests. Such a course of action cannot be recommended for two reasons: (a) the costs of full-scale tests are very high; and, more importantly, (b) the data may be meaningless unless extraordinary pains are taken to recreate the original test environment. The importance of the latter point was brought out in Part I tests. Reproducibility of tests conducted in the same room by the same operator was good; however, correlation with data taken in a similar, but not identical, room was poor. Thus, it becomes clear that unless a validated standard room fire test becomes available, or until our ability to model room fires improves considerably and the effects of the important variables can be predicted numerically, interlaboratory agreement in full-scale tests should not be expected.

Bench-scale tests, on the other hand are not only much simpler and cheaper to conduct, but can usually be successfully controlled to obtain consistent reproducibility. The prime drawback to bench-scale tests in fire hazard analysis has normally been that their results

were scaled on an arbitrary basis and no comparison with full-scale test data was attempted. This would not be a problem in the present project since an adequate full-scale data base had been established against which the bench-scale predictions could be compared. The following goals were established for the bench-scale tests:

- The tests must be reproducible; their results must duplicate the group ordering of the full-scale tests. (Within - group differentiation was not sought since it was not considered warranted by the precision of the data).

- They should be based, as much as possible, on existing test methods, in order to minimize development time and facilitate commercial testing.

- They should not require specially constructed samples. To the extent possible, specimens are to be cut, through the thickness, from production units and to be tested as natural composites.

Five candidate tests were initially considered: rate of heat release (RHR), smoke density, fuel load (calorific value), flame spread, and ease of ignition. In all cases bench-scale tests were to be performed on mattresses complete with ticking -- while full-scale tests had shown that the type of ticking has but minor effect, the absence of any ticking would significantly change the burning behavior.

### 4.1 Rate of Heat Release Tests in NBS-II Calorimeter

In order to obtain data best amenable to analysis, it was considered desirable to utilize that calorimeter which can most thoroughly characterize the test specimens. The new NBS-II calorimeter was thus selected. This instrument [4] is a larger, more flexible, and more fully instrumented version of the instrument first described by Parker and Long [5]. The operation of the instrument is based on constancy of heat output -- a "substitution" burner is used, the output of which is automatically decreased as specimen heat release increases. Rate of heat release is thus the negative of the substitution burner rate change. The instrument incorporates the following major improvements: (1) A 150 x 300 mm horizontal specimen may now be accommodated, with a uniform radiant heat flux across its surface; (2) the specimen is weighed continuously while under test; (3) an in-place heat flux gage is mounted directly adjacent to the specimen edge, permitting a continuous measurement of the total (external radiant panel + specimen flame) flux; (4) the specimen insertion cooling

transient has been reduced; (5) observation windows now permit viewing the specimens; (6) noise and fluctuation levels in the output signal have been reduced. Details of calibration and operation procedures are given in [4].

Test specimens were prepared by cutting them from the full-size mattresses. Through-the-thickness specimens were cut out in an area away from the mattress edges. Innersprings, if any, were excluded. The specimen size was 150 mm wide by 300 mm long, by approximately 50 mm thick. For mattresses where the total thickness, excluding innersprings, was 100 mm or less, the top 50 mm was used. For mattresses thicker than 100 mm, the thickness of those mattress material layers greater than 20 mm thick was adjusted so that a similar thickness ratio would occur in the test sample as in the production mattress. Mattresses that included interliners for fire barrier purposes were tested by cutting the interliner sufficiently oversized to permit it to be turned over the edges and stapled down. Mattresses containing highly compressed material, such that over 25% thickness expansion occurs when ticking tension is released, were sewn through with metallic thread in sufficient places to attain the production density. Each mattress sample was wrapped in a single sheet of aluminum foil to cover the sides and bottom before testing.

Samples were tested in a horizontal position at three different irradiance values: 25, 50 and 75 $kW/m^2$. These values were chosen to approximately cover the range of irradiance expected in a room fire. An electric spark ignitor located near the edge of the sample and approximately 5 mm above the surface was used for ignition. This has the advantage of negligible heating effects and is easier to maintain than a gas pilot. All specimens were successfully spark ignited; however, certain retardant treated ones took a relatively long time to ignite and then to reach their peak burning rate. Each test was conducted for a maximum of 10 minutes. The start of the test, $t = 0$, was considered to be the moment when the release curve crosses the baseline, going in the positive direction (see Figure 3). Most samples burned to completion before the end of 10 minutes. Cotton and neoprene specimens, however, tended to flame a short while and then switch to slow smoldering and were still smoldering upon removal at the end of the test. Figure 3 illustrates typical rate of heat release results. Most curves showed two peaks, an early one for ticking flaming and a later one for core flaming. For the high rate of heat release specimens the second peak tended to be dominant, while for better performing ones the second peak was smaller or absent. The net result is that times to (highest) peak tended to be inversely related to specimen rate of heat release.

Table 5 summarizes the rate of heat release measurements in the NBS-II calorimeter. Peak added flux values are derived from the peak heat flux gage reading, minus the specified panel irradiance. In most cases three sample of each mattress were tested. For the 3-minute average rate of heat release at 25 $kW/m^2$ irradiance the average coefficient of variation was 0.178. This figure is disproportionately weighted by the very low heat release

specimens which showed a large amount of scatter. A more representative measure is the median coefficient of variation, which was 0.088.

An investigation was next made to determine the effect of sample size on the measurements. Tests on six different specimens were run with smaller samples but under the same operating conditions. A specimen size of 100 mm by 200 mm by 50 mm thick was used. Only a single irradiance value of 50 $kW/m^2$ was applied. Table 6 shows a comparison between these smaller samples and full 150 x 300 mm samples. The peak readings are substantially different for the two conditions. This reflects, probably more than anything else, the difficulty in obtaining reproducible peak height readings in combustion measurements. The three-minute average values are, however, in substantially closer agreement. The peak added flux values are, of course, scale-dependent. Their magnitudes help to explain why the peak rates for the four specimens M06 through M10 are greater than for the other ones. For specimens M04 and M05 the ratio of full to small specimen peak fluxes is nowhere near as great as for the other mattresses. Increased fluxes would tend to boost the release rates for the small specimens. It does not, however, answer the question why the small specimen rates would exceed those of the full ones. Possibly convective effects are still important at the smaller size.

### 4.2 Rate of Heat Release Tests in Modified OSU Calorimeter

The NBS-II calorimeter is viewed as a research tool. Only one such instrument exists; it is neither simple to construct nor to operate. For the present application, a rate of heat release test is desired which would readily be commercially available and be simple to operate. The test apparatus developed at the Ohio State University (OSU) [6] answers that description. The OSU calorimeter does not maintain a constant heat environment, instead, the release rate is determined by a compensated thermopile measurement in the gas outflow stream. While simpler, this apparatus has several shortcomings for mattress testing:

-- the thermopile sensing arrangement does not indicate the full amount of heat liberated by specimens with more radiative flames (as compared to the methane gas calibration standard).

-- sample size and construction are not fully defined.

-- the pilot burner produces more heat than is necessary for adequate ignition.

-- also, the smoke measurement system is not needed since a superior technique (see Section 4.3) is available.

Modifications were made to the procedures described in [6] to overcome these shortcomings and are described in detail in Appendix A. These include the following:

(1) Replacement of the thermopile sensing method by an oxygen consumption technique. The technique involves measuring the oxygen depletion in the exhaust stream as combustion takes place. Once a calibration is made (with a metered supply gas burner) the rate of heat release for any other fuel is proportional to the oxygen depletion. The chemical principle this technique exploits is the near-constancy of the heat of combustion per unit oxygen consumed for almost all fuels. For a device, such as the OSU calorimeter, where the air mass inflow rate is constant, the following expression can be obtained [7], provided $CO_2$ and $H_2O$ products are trapped out of the sampling line before the oxygen meter

$$\dot{Q} = k \frac{[O_2\%]}{1 - 0.0127\ [O_2\%]} \quad \text{(kW)} \tag{1}$$

where $[O_2\%]$ is the volume percent oxygen depletion, baseline minus actual. The calibration constant k is obtained from methane calibration as

$$k = \frac{\dot{Q}_{cal}\ (1 + 0.0127\ [O_2\%]_{cal})}{[O_2\%]_{cal}} \quad \text{(kW/}O_2\%\text{)} \tag{2}$$

The calibration value $\dot{Q}_{cal}$ is obtained from a measured methane flow rate and a known lower heat of combustion ($50.0 \times 10^3$ kJ/kg). In the present test series the calibration was obtained as in Eq. 2, but for simplicity of analysis the small nonlinearity over the expected range of $O_2$ depletion in the denominator of Eq. 1 was suppressed and the RHR expressed as

$$\dot{Q} \simeq k\ [O_2\%] \tag{3}$$

The heat of combustion per unit oxygen consumed is assumed to be identical for methane and for the test specimen (the methane value is about 4% lower than for "typical" plastics [8]). To get the rate of heat release per unit area, $\dot{Q}$ is then divided by the exposed specimen area. Details of the theoretical principles of oxygen consumption calorimetry have been described by Huggett [8].

The primary advantage of the method over a thermopile technique is its suitability for flow-through measurements. The heat sensing technique depends on the assumption that the heat radiated away is negligible and that the heat storage term can be empirically compensated. Unpublished measurements by the author and a study by Krause and Gann [9] both indicate that this problem in the OSU calorimeter is a serious one. Oxygen consumption measurements, on the other hand, are free of these errors since oxygen is neither stored nor radiated away from the calorimeter.

To implement oxygen consumption measurements a highly stable oxygen meter is required. In practice this means that electrochemical units are not suitable and that a paramagnetic unit is required. The meter should be preceded by traps for particulates, $H_2O$, and $CO_2$. To decrease transit time, a large sample flow is pumped from the calorimeter stack and a quantity beyond that needed for the oxygen meter is wasted. An absolute back pressure regulator is desirable at the oxygen meter outlet; otherwise, barometric fluctuations produce variations in pressure which affect the calibration. For sampling in the exhaust duct of the calorimeter to be successful, a location must be used where the stream is well mixed so that oxygen concentration does not vary with small changes in probe positions. With the standard OSU apparatus [6] no such location is available. To implement the technique, therefore, a modification was introduced which consisted of shutting off the air feed to the cooling mantle, which is only needed for the thermopile technique. This eliminates stream-combining turbulence and makes a steady measurement possible. The total flow rate in [6] is set at 40 ℓ/s, of which roughly 3/4 flows through the cooling mantle. Since this air is now not needed, a flow rate of 12 ℓ/s was set, all of which flows through the combustion chamber. Further construction details are given in Appendix A. It should be noted that because of the incompatible flow requirements oxygen consumption and thermopile measurements cannot be made simultaneously in this apparatus in the same run.

(2) The smoke measurement attachment is not used. Smoke density measurements are made, instead, with the technique described in Section 4.3.

(3) A 100 mm by 100 mm standard specimen size is adopted. Detailed specifications are given in Appendix A.

(4) A pilot was desired which produced negligible irradiance to the specimen surface and a negligible heat release rate, yet was stable in the chamber flow environment. A small-diameter oxygen/methane pilot was constructed for this purpose.

One serious problem which could not be readily eliminated was the lack of control over the irradiance. In the NBS-II calorimeter all internal surfaces of the instrument are relatively far away from the specimen. For moderate size specimens, if an irradiance of 25 $kW/m^2$ is measured prior to test, a similar value holds also throughout the duration of a test. In the OSU calorimeter, however, the specimen flames impinge on portions of the apparatus. These portions heat up and contribute an additional irradiance component. The specimen is, thus, not tested under invariant external flux. Since no simple way of minimizing this effect was seen, no changes were made to the standard procedure [6] in this regard.

Results of measurements in the modified OSU calorimeter are shown in Table 7. Since no zero-crossing benchmark is available with this procedure, time t = 0 was defined to be the

time when an $O_2$ depletion of 0.05% first occurred. The median coefficient of variation was 0.111, with the average being 0.134. (The comparable measurements in the NBS-II calorimeter, the values were 0.088 and 0.178.) High coefficients of variation were again mostly associated with low heat release rate specimens. The relative scatter of data with the OSU and the NBS-II procedures, however, cannot be directly compared since the tests were conducted at different stages of instrument development and of operator familiarization.

### 4.3 Smoke Density Tests

Because of the customary difficulties in relating full-scale smoke measurements to small-scale test results, an attempt was made to obtain a smoke parameter which would be as much as possible only a function of the sample material and would be little influenced by test apparatus or test conditions. In Part I of this report the concept of an extinction coefficient was presented as the logical description of the attenuation with a given light path. If a light intensity $I_o$ is present over a smoke-free path of length L, then the effect of smoke in reducing the intensity $I_o$ to a value of I can be expressed as

$$k = \frac{1}{L} \ln \frac{I_o}{I} \tag{4}$$

and k, the extinction coefficient, has units of inverse length, or $m^{-1}$. An analagous quantity using base-10 logarithms is the optical density per meter, D/L.

$$\frac{D}{L} = \frac{1}{L} \log_{10} \left(\frac{I_o}{I}\right) \tag{5}$$

giving a conversion factor of

$$k = 2.303 \frac{D}{L} \tag{6}$$

Furthermore, at a given wavelength or wavelength mix, the extinction coefficient can be factored out to be

$$k = \frac{C}{z\rho_s} \tag{7}$$

where C is the smoke mass concentration ($kg/m^3$), $\rho_s$ is smoke particulate density ($kg/m^3$), and z is a constant for the smoke property of a given material and has the units of volume/extinction area (m).

Consider now an almost-sealed chamber, such as the NBS smoke chamber [10]. The chamber is initially free of smoke. At time t = 0 mass loss and smoke generation begin. A certain fraction, $\chi$, of the specimen mass loss goes into particulates. Then the smoke mass concentration at any given time $t_i$ is

$$C(t_i) = \frac{\chi}{V_{ch}} \int_o^{t_i} \frac{dm_p}{dt}\, dt \tag{8}$$

where $V_{ch}$ is the chamber volume ($m^3$) and $\frac{dm_p}{dt}$ is the mass loss rate (kg/s). From the above relations, the rate of change of k is

$$\frac{dk}{dt} = \frac{\chi}{z\rho_s V_{ch}} \frac{dm_p}{dt} \tag{9}$$

The quantity $\frac{\chi}{z\rho_s}$ serves to characterize the material and will be useful if it turns out not to vary appreciably with time. Since this quantity is effectively an extinction area divided by a unit mass, it is appropriate to call it a "specific extinction area," $\sigma_m$.

$$\sigma_m = V_{ch} \left( \frac{dk/dt}{dm_p/dt} \right) \qquad (m^2/kg) \tag{10}$$

Seader and Chien [11] have defined a similar quantity, derived from base-10 logarithms, called "Mass Optical Density," MOD. These quantities are related according to

$$\sigma_m = 2.303\ (MOD) \tag{11}$$

A similar analysis can be made for the flow-through system comprising the full-scale test room. It is reasonable to assume a two-reservoir model for the room -- a clear, cold lower layer and a warm smoky, stirred upper layer. Then a conservation of smoke mass gives

[mass generated] = [flow out] + [settling + other losses] + [smoke stored]

or,

$$\dot{m}_s = C\left(\frac{\dot{m}}{\rho}\right) + [losses] + V_r \frac{dC}{dt} \tag{12}$$

where $V_r$ is the room volume, $\left(\frac{\dot{m}}{\rho}\right)$ is the doorway volume air flow rate, and C is the doorway outflow smoke concentration. If that flow rate is fast compared to the smoke generation rate, then the last two terms become negligible and an expression for C can be obtained as

$$C = \frac{\dot{m}_s}{(\dot{m}/\rho)} \tag{13}$$

Fang [12] has treated in a similar manner some more complex flow geometries. If we again assume a constant conversion, $\chi$, of pyrolysates into smoke particulates, then the smoke generation rate $\dot{m}_s$ is

$$\dot{m}_s = \chi\, \dot{m}_p \tag{14}$$

Combining the above expressions allows us to determine the full-scale specific extinction area,

$$\sigma_m = \frac{k\ (\dot{m}/\rho)}{\dot{m}_p} \tag{15}$$

The doorway extinction coefficient k, the doorway volume flow rate, and the fuel pyrolysis rate $\dot{m}_p$ are all readily experimentally measureable quantities.

To make the above calculations and compare the full-scale and the smoke chamber $\sigma_m$ values in principle does not even require a steady-state room fire. It does require, however, that the flow velocities be accurately measured, that the upper layer be well stirred (or at least that an appropriate flow-weighted average of the doorway extinction coefficients be available), and that the $\sigma_m$ value be a constant of the specimen.

There would be little hope for a constant $\sigma_m$ in full-scale if it could not be reached in the small-scale chamber. Thus, we have to examine the type of results obtainable from the chamber. For these tests the standard NBS chamber [10] was modified according to the work of Breden and Meisters [13]. The modifications (Figure 4) consist of two changes -- a horizontal sample holder (requiring a new radiant source) and a load cell weighing arrangement. The horizontal sample holder is considered appropriate for these tests since some of the samples melt and drip. To test these in the vertical configuration would be inappropriate since combustion in the vertical holder's dripping trough is very different from that for a horizontal sample.

The test procedure was as follows: samples were prepared similarly to the heat release rate samples, except that the size was 50 mm by 50 mm by 25 mm thick. (Preliminary testing had shown that larger, 75 by 75 mm samples in some cased tended to "saturate" the chamber and give erratic results). The chamber was calibarated and operated according to the standard method [10], with the exception of the modifications mentioned above. A small igniting pilot was used in all cases. The pilotless procedure would not be appropriate for these tests since in the full-scale the burning bedding assures an ignition source. The standard irradiance of 25 $kW/m^2$ was used. A continuous record was taken of the weight loss and the smoke obscuration. The analysis was done according to the equation above for $\sigma_m$. This requires differentiation of the numeric data to obtain the derivatives. While easily done, it results in erratic data, the customary difficulty of numeric differentiation. In view of the expected constancy of the $\sigma_m$ value, a different approach was taken. Secant, rather than tangent slopes were obtained, i.e., the total slopes between the fixed starting time (t = 10 s) and $t = t_i$ were evaluated. A typical $\sigma_m$ curve is shown in Figure 5. It can be seen that the value rapidly rises to a peak, then decays slightly in a shallow plateau. All of the curves obtained had a similar basic shape. The initial low values have two explanations. Moisture is initially driven off. This results in a weight loss but not

any significant obscuration. Also, it does take a finite amount of time after the particles have been liberated for them to mix and fill the light path. The slight decrease in values after the peak can be understood as wall loss and settling effects; these effects predominate in the later part of the test. The conclusion can be drawn from this that the peak $\sigma_m$ value is probably the most characteristic, in fact, of the entire pyrolysis process. Thus, the peak $\sigma_m$ value, as determined by the secant slope method was adopted for this work.

A comparison between the full-scale results and the smoke chamber data is shown in Figure 6. The full-scale specific extinction area was determined according to Equation 15 above. If accurate doorway flow velocities were available the extinction coefficient k would best be determined as a velocity-weighted average over the outflow. However, with the limited instrumentation used here accurate mass balances could not be obtained. (Outflow generally exceeded inflow by about 40%. This difficulty of measurement has been discussed by Tu and Babrauskas [14].) Thus, for the present experiments a simple arithmetic average of the outflow extinction coefficients was taken. Since there is some reason to believe the mass inflow readings may be more accurate than outflow, the $\dot{m}$ value used was based on the inflow. Outflow density was obtained from temperature readings at thermocouple locations 58, 59, 60, and 61 (Figure 2), which were at 0.13 to 1.07 m below the top of the doorway.

The results (Figure 6) show that near the peak burning rate $\sigma_m \simeq 120$ $m^2/kg$, compared to a value of 175 $m^2/kg$ obtained from the smoke chamber. In view of the uncertainties associated with the flow rate measurements, this can be considered moderately encouraging. Away from the peak, the agreement is expectedly less good since the bedding and ignition source make up an increasing fraction of the burning rate. The calculated $\sigma_m$ for the control test is also shown in Figure 6 for comparison. The control test values cannot, however, merely be subtracted out to obtain the mattress contribution since the burning of the mattress changes the time scale of the bedding combustion. A summary of the smoke chamber average $\sigma_m$ results for all the specimens is given in Table 8; for most mattresses three runs were made. The median coefficient of variation was 0.086, while the average was 0.130.

Finally, it is interesting to see whether any conclusions might be made about $\chi$, the pyrolysate-to-smoke-particle conversion efficienty (Eqn. 14). Noting that

$$\sigma_m = \frac{\chi}{z\rho_s} \tag{16}$$

one could determine $\chi$ if $z\rho_s$ were known. Seader and Ou [15] reported the results of a study based on smoke chamber and gravimetric measurements, showing that for piloted ignition conditions and 25 $kW/m^2$ exposure a constant value of $z\rho_s$ is obtained for a wide range of materials. In the units adopted here, $z\rho_s = 1.316 \times 10^{-4}$ $kg/m^2$. This gives

$$\sigma_m = 7600\ \chi \quad (m^2/kg) \tag{17}$$

The maximum $\sigma_m$ measured in this study was 1866 $m^2/kg$, for specimen M23. This equates to an efficiency of 25%. The lowest value was 39 $m^2/kg$, for specimen M07, implying an efficiency of 0.5%.

### 4.4 Heats of Combustion and Fuel Loads

Each component material for the specimens was tested in the oxygen bomb calorimeter, ASTM Method D3286 [16]. The gross heats of combustion have been multiplied by the fractional weight of each component to yield the values in Table 9. A summary of the component heats of combustion is presented in Table 10. Since in the NBS-II calorimeter a simultaneous record of mass loss and heat release rate can be obtained, it becomes interesting to compute effective heats of combustion from these measurements and to compare them to the oxygen bomb value. Table 11 shows the results. Overall, an average of 56% of the upper heat of combustion value is developed. Certain specimens that tend to smolder slowly, primarily the cotton batting and neoprene foam units, show much lower percentages than the remaining specimens. A comparison of the results showed that fuel load alone could not be used to correctly group according to performance, while fuel load used in conjunction with rate of heat release did not improve the characterization.

### 4.5 Flame Spread and Ease of Ignition

Flame spread is usually considered to be an important element of flammability. Likewise, ease of ignition can affect the rate of hazard development. To determine if either of these properties must be considered for mattress hazards, some screening tests were conducted on selected mattress samples. Flame spread behavior was measured on horizontal specimens exposed to a uniform external radiation field. The apparatus used has been described by Kashiwagi [17]. In experiments of this kind fluxes in the range of 0 to 20 $kW/m^2$ can be imposed (the latter limit arising due to flash ignition occurring at $\lesssim$ 20 $kW/m^2$). Here fluxes in the range of 4 - 8 $kW/m^2$ were used. Specimens without any bedding were tested first. The flame spread rate proved to be dominated by the ticking characteristics. Since this was at variance with the full-scale findings, as determined in [1], additional tests were conducted using two bedsheet layers covering the specimen. Under those conditions the ticking material no longer controlled the behavior. The results, however, then appeared to conform more to the rate of heat release findings. Flame spread investigations were not continued further because it was judged that such data would not materially aid in predicting full-scale behavior.

Ease of ignition was tested using a conical radiant heater, patterned after a proposed International Organization for Standardization (ISO) ignitability test [18]. Spark ignition was used in our version of this procedure. An analysis of an exploratory series of tests

showed, however, that nearly the same information that is given by the ignitability tests could, for these mattresses, be obtained from the NBS-II calorimeter by using the time-to-peak data (Figure 7). Thus, for this application a separate ignition test would not be useful.

## 5. ANALYSIS OF FINDINGS

The time to exceed criteria could potentially have been used as the full-scale variable to which bench scale results were to be compared. It was considered not desirable to do this, however, since this variable does not strictly have a continuous scale; i.e., the better performing specimens do not have a value for "time to exceed criteria" since they do not exceed the criteria. For comparison purposes, therefore, the peak full-scale readings were selected. These readings would not have been as desirable for the initial rankings since, as discussed in Part I, there is a fair amount of variability associated with peak readings. For comparison to the bench-scale data, however, they constitute the best available variable.

Next to be resolved was the question of which full-scale variables should be used in the comparison. Floor heat flux readings reflect directly the potential for flashover. They are also obviously a good indicator of the radiant heat fluxes impinging at occupant level. Also, not unexpectedly, a close correlation can be made to the average upper gas space temperatures (Figure 8). Perhaps more unexpected is the close -- although definitely not linear -- correlation between $CO_2$ and floor flux (Figure 9). Even for CO there is a modestly good association with floor flux (Figure 10), although not as good as for $CO_2$. Thus, it becomes appropriate to consider the peak floor flux values as adequately representing flashover potential, heat flux, and gas concentration variables.

No special correlation between smoke obscuration and other measurements was sought since smoke determinations were readily available in bench-scale. Two bench-scale tests, rate of heat release and smoke evolution were thus selected for representing the full-scale results.

Rate of heat release tests in the NBS-II calorimeter yielded numerous data: varying irradiance values, peaks, averages, and times to peak being some factors to be considered. It was easily evident that time-to-peak-RHR would not be an appropriate variable (Figure 11). Peak RHR values were also seen to be of poor predictability. This left some form of average RHR variable to be considered. Hitherto, vague and qualitative arguments [19, 20] have been used to attempt to show that one or another form of averaging is best. For the present study a purely operational approach was deemed best -- that averaging technique was to be selected which gave results best correlated with the full-scale measurements.

Averages were calculated for 25, 50, and 75 $kW/m^2$ irradiance and for 1, 2, 3, 4, and 5 minute intervals (all starting at t = 0). From this comparison it emerged that the 3-minute average values at a 25 $kW/m^2$ irradiance produced the best prediction of full-scale results. The criterion of adequacy was that the bench-scale results would correctly group the mattresses into their full-scale groupings. Within-group ranking was not considered material due to basic limits on precision. It is seen in Figure 12 that the procedure was successful. Groups A/B, C, and D were adequately separated, with some margin available between groups. (Note that the distinction between groups A and B comes only from smoke performance.)

The NBS-II calorimeter is, however, not being proposed as the standard device for determining mattress RHR groupings. The important issue was to determine if the modified OSU calorimeter would be successfully usable in classifying the performance. As a starting point, the same nominal irradiance (25 $kW/m^2$) and the same averaging period (3 minutes) were taken. Figure 13 shows that these were satisfactory choices and the modified OSU calorimeter can be used to discriminate between groups A/B, C, and D. Note that there are no cross-overs across group boundaries and that the groups are well separated. Thus, the chosen irradiance level and averaging period can be used for a standard test. Figure 14 shows a direct comparison of the results. Expected differences would stem from the decreased specimen size in the OSU calorimeter (tending to lower the RHR) and the excess flux imposed from apparatus surfaces (tending to raise the RHR). Since Figure 14 shows a fairly close agreement, it appears that these effects are largely offsetting each other.

For smoke development, it was already established that $\sigma_m$, the specific extinction area, constituted the proper specimen descriptor. Yet, $\sigma_m$ is essentially a measure of the pyrolysate to soot conversion efficiency. The smoke measurements in the test room, on the other hand, essentially reflect a product,

(soot efficiency) x (rate of pyrolysis)

The rate of pyrolysis is established as:

$$\frac{\text{pyrolysis rate}}{\text{unit area}} \quad x \quad \text{(area involved)},$$

which schematically is $\dot{m}''_p A_p$. The complete product then becomes $\sigma_m \dot{m}''_p A_p$ and has the units $m^2/s$. Realistically, the mattress area involved in combustion is not a quantity that is readily determinable. Thus, we undertake to substitute for $\sigma_m \dot{m}''_p A_p$ some simpler expression which can be gotten from the bench-scale tests. An appropriate candidate is $\sigma_m$ x RHR. Since this is a large number, for convenience we define a "smoke parameter" SP as

$$SP = \frac{\sigma_m \text{ x (RHR)}}{10^5}$$

Because of the variable choices taken, the units for SP become kW/kg.

The RHR Factor is taken to be the same 25 $kW/m^2$ irradiance, 3-minute average value as was earlier found suitable for predicting the full-scale heat flux results. This entire expression, while based on proper physical considerations, has to be justified empirically because of the approximations and simplifications involved. Figures 15 and 16 show the results for the SP when the RHR factor in it is based, alternatively, on NBS-II and OSU data. A satisfactory agreement is seen to be achieved in both cases. The Figure 16 results, based on OSU data, can then be used for testing and evaluation.

## 6. CRITERIA FOR PREDICTING FULL-SCALE BEHAVIOR

The RHR and smoke measurement techniques utilized were shown to be suitable for predicting full-scale behavior from bench-scale test procedures. Thus it is recommended that a suitable test method for grouping the performance of institutional mattresses when exposed to flaming ignition sources is one utilizing the procedure given in Appendix A and based on the following criteria.

Group A -- specimens in this group shall have RHR $\leq$ 100 and a smoke parameter SP $\leq$ 0.25.

Group B -- specimens in this group shall have RHR $\leq$ 100.

Group C -- specimens in this group shall have 100 < RHR $\leq$ 200.

Group D -- specimens which have RHR > 200 shall be placed in this group.

It is seen that the smoke parameter is needed only to distinguish between Groups A and B. No limits on the smoke parameter, per se, need to be placed for Groups B, C, and D, although, in practice, Figure 16 illustrates that these groups do exhibit successively poorer smoke behavior.

Table 12 shows the over-all performance results of all the mattresses, including the supplemental ones.

Group A includes, in addition to the original cotton batting specimens, three neoprene mattresses, an all-polyester batting mattress, a neoprene interliner protected mattress, and the latest version of hydrophilic polyurethane foam type unit.

Group B includes, in addition to the original neoprene mattresses, an earlier version of a hydrophilic polyurethane foam type.

Group C includes, in addition to the original polyurethane and mixed fibers mattresses, an ordinary polyurethane foam mattress, a cotton batting mattress with polyurethane topper and some foam mattresses claimed to be retardant treated and highly flame resistant. Also included in this group is a PVC-nitrile foam jail cell padding.

Group D includes a latex foam and a high density polyurethane foam mattress from the original series and also a PVC-nitrile foam athletic mat.

## 7. HAZARD FACTORS ASSOCIATED WITH USAGE CONDITIONS

The minimum group requirements for any given application cannot be properly determined without considering the entire collection of hazards and defense mechanisms. In other words, a fire safety engineering analysis is the context within which furnishings hazard components should be assessed and minimums prescribed. Several specific points of interest, however, merit some discussion.

### 7.1 Arson and Accelerants

Arson and accelerants will, by definition, increase burning rates and hazards associated with mattresses. For this reason it is sometimes suggested that full-scale testing be done under conditions simulating arson, rather than incidental fires. This is appropriate if the goal is to determine the maximum hazard associated with an arson fire, but is not appropriate if, as here, the goal is to evaluate and rank the relative performance of a piece of furnishing. Under the limiting conditions of a large amount of effective accelerant, the accelerant alone is being evaluated. For lesser but still substantial accelerant usages the differences between the furnishings items are simply diminished. On the other hand, the ignition source has to be strong enough to ensure satisfactory and continued ignition. The bedding/wastebasket combination in the full-scale tests and the 25 $kW/m^2$ irradiance in the bench-scale procedures were designed to meet this objective. Thus, the relative ranking of performance will stay similar as the fire scenario threat level is increased, even though all specimens will perform worse. A special consideration may be required in those cases where a specimen uses a barrier interliner to decrease the rate of heat release from the core materials. A decision has to be made whether such units are likely to be stripped prior to being burned.

### 7.2 Storage and Orientation Effects

The full-scale test scenario involved single mattresses placed and oriented in a normal sleeping configuration. Parker [21] found that increased burning occurred when mattresses were tested in a vertical position. A different environment again is involved in storage

rooms, where numerous mattresses may be stored. A specific fire engineering study is needed to assess the adequacy of fire safety in those situations; however, it can again be presumed that mattresses classed by the recommended test into higher groups will perform better.

### 7.3 Fuel Area Effects

The test specimens in the present study were primarily twin-size mattresses, all of similar widths and lengths. Mattress area effects, in consequence, were not relevant. In a given application it can happen that areas are significantly larger or that numerous units are located close to one another, permitting the possibility of continued flame spread. The expected mattress behavior in these circumstances falls into two categories. Mattresses in Group A or B do not spread flame easily. (In full-scale tests their steady, continued burning was ensured by the bedding used.) Thus, if Group A or B mattresses of significantly larger sizes than the test specimens are placed in a room the fire development rate would not be greatly affected. Mattresses in Groups C and D, on the other hand, spread flame much more easily and readily build up an intense fire. Increasing the mattress area in those cases would directly increase fire development rates and, therefore, the hazards.

## 8. CONCLUSIONS

The performance of institutional mattress specimens, when evaluated in bench-scale laboratory tests showed that:

(1) Flame spread and ignition properties do not characterize mattress behavior consonant with full-scale tests.

(2) Rate of heat release and smoke production are the two bench-scale measurements necessary and sufficient to reproduce full-scale findings.

(3) For determining the rate of heat release, both the irradiance level and the averaging period can affect relative performance ranking. Proper conditions are determined by comparison to full-scale results.

(4) Either the NBS-II or a modified OSU calorimeter can be used to obtain suitable rate of heat release data. The NBS-II calorimeter has the advantage of better control while the modified OSU calorimeter is less costly and simpler to operate.

(5) Bench-scale smoke measurements can provide a useful estimate of expected full-scale results if a procedure based on a modified NBS smoke density chamber is used.

(6) Specimen fuel load values can be used to roughly rank performance only (a) within a single specified material type and (b) provided burning rate is relatively high, i.e., not in Groups A or B.

(7) A procedure for proposed standard test has been developed which allows suitable prediction of mattress performance groups.

(8) A large number of additional samples, not tested in full-scale, were evaluated in the bench-scale test procedures. Neoprene foam mattresses are now available with Group A performance, and, for the first time, a special polyurethane foam formulation was seen which gives Group A performance.

It is emphasized that the test procedures developed are for additional flaming resistance requirements and do not replace the mandatory cigarette ignition standard [2].

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TABLE 1
Mattress Sizes and Weights

| Mattress | Size (over-all) | | | Total Weight (kg) | Weight of Combustibles (kg) | Weight of Innerspring (kg) |
|---|---|---|---|---|---|---|
| | Width (m) | Length (m) | Thickness (m) | | | |
| M01 | 0.89 | 2.03 | 0.17 | 14 | 14 | -- |
| M02 | 0.89 | 2.03 | 0.17 | 15 | 6 | 9 |
| M03 | 0.89 | 2.03 | 0.17 | 20 | 11 | 9 |
| M04 | 0.92 | 2.11 | 0.11 | 19 | 19 | -- |
| M05 | 0.95 | 1.88 | 0.13 | 6 | 6 | -- |
| M06 | 0.99 | 1.91 | 0.18 | 20 | 12 | 8 |
| M07 | 0.99 | 1.91 | 0.18 | 25 | 13 | 12 |
| M08 | 0.88 | 1.93 | 0.15 | 18 | 18 | -- |
| M09 | 0.66 | 1.84 | 0.08 | 3.2 | 3.2 | -- |
| M10 | 0.66 | 1.84 | 0.08 | 6 | 6 | -- |
| M11 | 0.71 | 1.91 | 0.10 | 11 | 11 | -- |
| M12 | 0.66 | 1.83 | 0.08 | 11 | 11 | -- |
| M13 | 0.66 | 1.83 | 0.08 | 6.5 | 6.5 | -- |
| M14 | 0.99 | 1.93 | 0.10 | 13 | 13 | -- |
| M16 | 0.99 | 1.93 | 0.10 | 13 | 13 | -- |
| M17 | 0.96 | 1.90 | 0.17 | 19 | 9 | 10 |
| M18 | 0.69 | 1.87 | 0.08 | 14 | 14 | -- |
| M19 | 0.96 | 1.90 | 0.20 | 15 | 8 | 8 |
| M20 | 0.89 | 2.03 | 0.15 | 6 | 6 | -- |
| M21 | 0.91 | 2.03 | 0.16 | 16 | 8 | 8 |
| M22 | 0.73 | 1.84 | 0.18 | 17 | 17 | -- |

TABLE 2. PHYSICAL PROPERTIES OF MATTRESSES

| MATTRESS | INNER-SPRINGS | LAYER | COMPOSITION | TOTAL NUMBER OF LAYERS | THICKNESS (mm) | DENSITY ($kg/m^3$) | $\rho\tau$ ($kg/m^2$) | FLAME RETARDANTS |
|---|---|---|---|---|---|---|---|---|
| M01 | no | Ticking | Polyvinylchloride | 2 | 0.34 | 1100 | 0.378 | yes |
| | | Outer Padding | Polyurethane, (TDI/poly-ether type) | 2 | 36.8 | 25 | 0.921 | slight |
| | | Inner Core | Polyurethane, (TDI/poly-ether type) | 1 | 86.9 | 64 | 5.561 | yes |
| M02 | yes | Ticking | Polyvinylchloride | 2 | 0.34 | 1120 | 0.385 | yes |
| | | Padding | Polyurethane, (TDI/poly-ether type) | 2 | 37.5 | 19 | 0.712 | no |
| | | Interfacing | Polypropylene fabric | 2 | 0.25 | 260 | 0.064 | no |
| M03 | yes | Ticking | Polyvinylchloride | 2 | 0.34 | 1100 | 0.379 | yes |
| | | Padding | Cotton Felt | 2 | 49.6 | 38 | 1.883 | yes |
| | | Interfacing | Polypropylene fabric | 2 | 0.22 | 320 | 0.070 | no |
| M04 | no | Ticking | Polyvinylchloride with cotton backing | 2 | 0.56 | 730 | 0.410 | yes |
| | | Core | Latex (butadiene-styrene) | 1 | 101.6 | 81 | 8.23 | no |
| M05 | no | Ticking | Rayon fabric (outer) (1) | 2 | 0.25 | 620 | 0.154 | no |
| | | Padding | Polyurethane foam | 2 | 0.71 | 110 | 0.078 | no |
| | | | Rayon fabric (inner) | 2 | 0.10 | 200 | 0.020 | no |
| | | Core | Polyurethane foam | 1 | 127. | 20 | | |
| M06 | yes | Ticking | Polyester (2) | 2 | 0.25 | 680 | 0.170 | no |
| | | Padding | Cotton/polyester felt | 2 | 38.0 | 43 | 1.63 | no |
| | | Insulator | Cotton/nylon/polyester pad | 2 | 7.0 | 90 | 0.63 | yes |
| M07 | yes | Ticking | Cotton | 2 | 0.46 | 650 | 0.300 | yes |
| | | Padding | Cotton felt | 2 | 38.1 | 38 | 1.46 | yes |
| | | Insulator | Jute pad | 2 | 6.4 | 120 | 0.788 | no |
| M08 | no | Ticking | Cotton | 2 | 0.46 | 550 | 0.253 | yes |
| | | Core | Polychloroprene foam | 1 | 152. | 67 | 10.18 | yes |
| M09 | no | Ticking | Polyvinylchloride with nylon fabric reinforcement | 2 | 0.36 | 790 | 0.284 | yes |
| | | Core | Polyurethane (TDI/ polyether type) | 1 | 76.2 | 22 | 1.68 | no |
| M10 | no | Ticking | Polyvinylchloride with nylon fabric reinforcement | 2 | 0.33 | 1070 | 0.354 | yes |
| | | Core | Polychloroprene foam | 1 | 76.2 | 50 | 0.253 | yes |
| M11 | no | Ticking | Cotton | 2 | 0.46 | 550 | 0.253 | yes |
| | | Core | Polychloroprene foam | 1 | 98. | 82 | 8.04 | yes |
| M12 | no | Ticking | Cotton | 2 | 0.46 | 550 | 0.253 | yes |
| | | Core | Polychloroprene foam | 1 | 75. | 113 | 8.48 | yes |
| M13 | no | Ticking | Cotton | 2 | 0.46 | 550 | 0.253 | yes |
| | | Core | Polychloroprene foam | 1 | 75. | 62 | 4.65 | yes |
| M14 | no | Ticking | Polyvinylchloride | 2 | 0.40 | 895 | 0.36 | yes |
| | | Core | Polyvinylchloride | 1 | 110. | 52 | 5.67 | yes |
| M15 | no | Ticking | Polyvinylchloride with nylon fabric reinforcement | 2 | 0.33 | 1070 | 0.354 | yes |
| | | Core | Hydrophilic polyurethane foam | 1 | | 187 | | yes |

TABLE 2. (Continued)

| MATTRESS | INNER-SPRINGS | LAYER | COMPOSITION | TOTAL NUMBER OF LAYERS | THICKNESS (mm) | DENSITY ($kg/m^3$) | $\rho\tau$ ($kg/m^2$) | FLAME RETARDANTS |
|---|---|---|---|---|---|---|---|---|
| M16 | no | Ticking | Cotton | 2 | 0.50 | 350 | 0.18 | |
| | | Core | Polyurethane foam | 1 | 110. | 52 | 5.67 | yes |
| M17 | yes | Ticking | Cotton/polyester(2) | 2 | 0.40 | 495 | 0.20 | |
| | | Padding | Polyurethane foam | 2 | 7.9 | 22 | 0.17 | |
| | | Facing | Rayon interliner | 2 | 0.10 | 228 | 0.02 | |
| | | Padding | Polyurethane foam | 2 | 10. | 21 | 0.21 | |
| | | Padding | Cotton batting | 2 | 20. | 46 | 0.92 | |
| | | Insulator | Scrap felt | 2 | 6.0 | 88 | 0.53 | no |
| M18 | no | Ticking | Cotton | 2 | 0.50 | 460 | 0.23 | yes |
| | | Core | Polychloroprene foam | 1 | 80. | 131 | 10.5 | yes |
| M19 | yes | Ticking | Cotton/polyester(2) | 2 | 0.40 | 460 | 0.39 | no |
| | | Padding | Polyester batting | 2 | -- | -- | 0.78 | no |
| | | Netting | Polyolefin | 2 | -- | -- | 0.09 | no |
| | | Padding | Polyester batting | 2 | -- | -- | 0.85 | no |
| | | Netting | Polyolefin | 2 | -- | -- | 0.09 | no |
| M20 | no | Ticking | Polyvinylchloride | 2 | 0.38 | 1020 | 0.39 | |
| | | Padding | Polyurethane foam | 1 | 152. | 18.3 | 2.78 | |
| M21 | yes | Ticking | Polyvinylchloride with nylon fabric reinforcement | 2 | 0.32 | 895 | 0.29 | yes |
| | | Interliner | Neoprene foam with fiberglass backing | 2 | 6.9 | 181 | 1.25 | yes |
| | | Padding | Polyurethane foam | 2 | 17 | 21 | 0.36 | |
| | | Padding | Cotton batting (3) | 2 | -- | 26 | -- | |
| | | Insulator | Jute | 2 | 7.1 | 64 | 0.45 | |
| M22 | no | Ticking | Polyvinylchloride with nylon fabric reinforcement | 2 | 0.43 | 950 | 0.41 | yes |
| | | Padding | Hydrophilic polyurethane foam | 1 | 78. | 150 | 11.7 | yes |
| M23 | no | Skin layer | Polyvinylchloride | 1 | 31. | 124 | 3.84 | |
| | | Foam | PVC-nitrile foam | 1 | | | | |
| M24 | no | Skin layer | Fiberglass with polyvinvychloride | 1 | 22.8 | 151 | 3.44 | |
| | | Foam | PVC-nitrile foam | 1 | | | | |
| M25 | no | Ticking | Polyvinylchloride with nylon fabric reinforcement | 2 | 0.33 | 1028 | 0.34 | yes |
| | | Padding | Hydrophilic polyurethane foam | 1 | 76. | 158 | 12.0 | yes |

(1) Top quilted, bottom not quilted.
(2) Top and bottom quilted.
(3) Only near center of mattress.

TABLE 3. PROPERTIES OF BEDDING

| | Size (WxL) (m) | Composition | Thickness (mm) | Density ($kg/m^3$) | $\rho\tau$ ($kg/m^2$) | Total Weight (kg) |
|---|---|---|---|---|---|---|
| Drawsheet | 1.36 x 1.83 | Cotton | 0.27 | 595 | 0.161 | 0.40 |
| Sheets (two) | 1.83 x 2.64 | 50% Cotton, 50% Polyester | 0.22 | 570 | 0.125 | 0.60 each |
| Spread | 1.93 x 2.79 | 86% Cotton, 14% Polyester | 0.38 | 525 | 0.200 | 1.07 |
| Pillow - filling | --- | Polyurethane | -- | -- | -- | 0.67 |
| - cover | 0.52 x 0.69 | Cotton | 0.40 | 575 | 0.230 | 0.16 |
| Pillow Protector | 0.52 x 0.69 | Polyvinylchloride | 0.14 | 775 | 0.108 | 0.09 |
| Pillow Case | 0.52 x 0.91 | 50% Cotton, 50% Polyester | 0.21 | 595 | 0.125 | 0.12 |

This Table corrects and supersedes Table 5 in Part I Report.

TABLE 4. FULL-SCALE EVALUATION RESULTS

| Group | Mattress | Core Type | Description | Flashover Criterion | Tenability Criteria -- Time to Reach Critical Values | | |
|---|---|---|---|---|---|---|---|
| | | | | Time to Reach Full Room Involvement (s) | Gas Concentration (s) | Radiant Heat Flux (s) | Smoke Obscuration (s) |
| A | M03 | Cotton | Hospital | N.R. | N.R. | N.R. | N.R. |
| | M07 | Cotton | Prison | N.R. | N.R. | N.R. | N.R. |
| B | M10 | Neoprene | Prison | N.R. | N.R. | N.R. | 630 |
| | M08 | Neoprene | Military | N.R. | N.R. | N.R. | 280 |
| C | M09 | Polyurethane | Prison | N.R. | 710 | 670 | 450 |
| | M06 | Cotton/Nylon/ Polyester | Commercial | N.R. | 540 | 500 | 470 |
| | M05 | Polyurethane | Commercial | N.R. | 410 | 380 | 380 |
| | M02 | Polyurethane | Hospital | N.R. | 345 | 300 | 230 |
| D | M04 | Latex | Hospital | 720 | 490 | 460 | 370 |
| | M01 | Polyurethane | Hospital | 470 | 360 | 230 | 300 |

N.R. - Not Reached

TABLE 5. RATE OF HEAT RELEASE MEASUREMENTS IN NBS-II CALORIMETER

| Mattress | 25 kW/m² Flux | | | | 50 kW/m² Flux | | | | 75 kW/m² Flux | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Time to Peak (s) | Peak Rate (kW/m²) | Peak Added Flux (kW/m²) | 3 - Min. Avg. Rate (kW/m²) | Time to Peak (s) | Peak Rate (kW/m²) | Peak Added Flux (kW/m²) | 3 - Min. Avg. Rate (kW/m²) | Time to Peak (s) | Peak Rate (kW/m²) | Peak Added Flux (kW/m²) | 3 - Min. Avg. Rate (kW/m²) |
| M01 | 88. | 1150 | 28.9 | 399 | 58.1 | 1630 | 36. | 448 | 36.6 | 1760 | 35. | 422 |
| M02 | 43.8 | 736 | 21.4 | 138 | 22.8 | 1160 | 25. | 147 | 15.6 | 1260 | 28. | 123 |
| M03 | 7.2 | 184 | 3.4 | 60 | 6.0 | 263 | 2.0 | 134 | 12.6 | 458 | 5.3 | 122 |
| M04 | 96. | 687 | 33.4 | 479 | 48. | 1190 | 36. | 684 | N.A. | N.A. | N.A. | N.A. |
| M05 | 55. | 800 | 23.9 | 179 | 36. | 960 | 25.8 | 208 | 27.6 | 1290 | 28. | 205 |
| M06 | 11.4 | 258 | 10.9 | 127 | 8.0 | 555 | 12.6 | 257 | 4.8 | 710 | 14. | 263 |
| M07 | 3.0 | 380 | 2.9 | 43 | 2.4 | 640 | 12.1 | 88 | 3.0 | 520 | 9.3 | 95 |
| M08 | 16.2 | 226 | 3.2 | 89 | 4.2 | 525 | 10.3 | 209 | 4.8 | 549 | 12. | 221 |
| M09 | 43. | 840 | 25.4 | 152 | 38.6 | 1050 | 30. | 148 | 22.8 | 1440 | 22. | 199 |
| M10 | N.A. | N.A. | N.A. | N.A. | 9.0 | 470 | 3.8 | 204 | N.A. | N.A. | N.A. | N.A. |
| M11 | 16.8 | 149 | 2.8 | 43 | 3.0 | 386 | 6.5 | 124 | 4.2 | 566 | 11. | 198 |
| M12 | 38. | 108 | 2.6 | 22 | 12. | 334 | 1.1 | 158 | N.A. | N.A. | N.A. | N.A. |
| M13 | N.A. | N.A. | N.A. | N.A. | 2.4 | 519 | 8.8 | 143 | N.A. | N.A. | N.A. | N.A. |
| M14 | 135. | 496 | 23.8 | 245 | 145. | 585 | 20. | 400 | 37.8 | 930 | 23. | 338 |
| M15 | 35. | 113 | 4.4 | 51 | 4.8 | 198 | 5.3 | 145 | 2.4 | 318 | 12. | 159 |
| M16 | 112. | 463 | 18.6 | 211 | 96 | 658 | 22. | 291 | 31.8 | 870 | 27. | 293 |
| M17 | 22. | 509 | 15.1 | 112 | 9.6 | 728 | 16.5 | 189 | 11.4 | 1100 | 17. | 224 |
| M18 | 6.4 | 183 | 5.4 | 25 | 1.2 | 294 | 7.9 | 65 | 4.8 | 342 | 5.8 | 136 |
| M19 | 8.0 | 278 | 8.7 | 98 | 10.5 | 380 | 6.1 | 161 | 7.2 | 610 | 12. | 159 |
| M20 | 59. | 772 | 22.6 | 175 | 36.6 | 950 | 22. | 196 | 18.0 | 1410 | 28. | 193 |
| M21 | 9.7 | 224 | 7.1 | 27 | 7.2 | 416 | 5.3 | 163 | 5.4 | 580 | 7.7 | 223 |
| M22 | 66. | 121 | 3.1 | 91 | 27.0 | 244 | 2.7 | 116 | 9.0 | 363 | 7.2 | 129 |
| M23 | 16.3 | 390 | 10.9 | 241 | 16.0 | 554 | 11.1 | 291 | 13.0 | 706 | 14.2 | 348 |
| M24 | 70. | 232 | 6.5 | 124 | 26.6 | 313 | 5.7 | 179 | 23.3 | 499 | 3.4 | 230 |
| M25 | 39.5 | 176 | 2.1 | 63 | 25.6 | 168 | 1.7 | 100 | 12.0 | 322 | 3.3 | 147 |

TABLE 6. EFFECT OF SPECIMEN SIZE ON HEAT RELEASE

(50 $kW/m^2$ Irradiance)

| Mattress | Peak RHR ($kW/m^2$) | | 3-Min Avg. RHR ($kW/m^2$) | | Peak Added Flux ($kW/m^2$) | |
|---|---|---|---|---|---|---|
| | Small Specimens | Full Specimens | Small Specimens | Full Specimens | Small Specimens | Full Specimens |
| M04 | 1400 | 1190 | 800 | 684 | 16.3 | 36. |
| M05 | 1210 | 960 | 205 | 208 | 8.6 | 25.8 |
| M06 | 306 | 555 | 192 | 257 | 1.7 | 12.6 |
| M07 | 204 | 640 | 83 | 88 | 0.8 | 12.1 |
| M08 | 324 | 525 | 206 | 209 | 0.6 | 10.3 |
| M10 | 313 | 470 | 208 | 204 | 0.5 | 3.8 |

TABLE 7. COMPARATIVE RATES OF HEAT RELEASE
(25 $kW/m^2$ Flux, 3-Min. Averages)

| Specimen | NBS-II value ($kW/m^2$) | OSU value ($kW/m^2$) | OSU/NBS-II |
|---|---|---|---|
| M01 | 399 | 344 | 0.86 |
| M02 | 138 | 144 | 1.04 |
| M03 | 60 | 45 | 0.75 |
| M04 | 479 | 624 | 1.30 |
| M05 | 179 | 187 | 1.05 |
| M06 | 127 | 119 | 0.94 |
| M07 | 43 | 46 | 1.07 |
| M08 | 89 | 62 | 0.70 |
| M09 | 152 | 153 | 1.01 |
| M10 | N.A. | 83 | -- |
| M11 | 43 | 50 | 1.16 |
| M12 | 22 | 16 | 0.72 |
| M13 | N.A. | 66 | -- |
| M14 | 245 | 178 | 0.73 |
| M15 | 51 | 52 | 1.02 |
| M16 | 211 | 132 | 0.63 |
| M17 | 112 | 102 | 0.91 |
| M18 | 25 | 22 | 0.85 |
| M19 | 98 | 85 | 0.87 |
| M20 | 175 | 170 | 0.97 |
| M21 | 27 | 21 | 0.78 |
| M22 | 21 | 72 | 0.79 |
| M23 | 241 | 239 | 0.99 |
| M24 | 124 | 104 | 0.84 |
| M25 | 63 | 52 | 0.83 |

N.A. - not available

TABLE 8. SMOKE RESULTS

| | Average $\sigma_m$ ($m^2/kg$) | Smoke Parameter SP* With RHR Factor Based on NBS-II | Smoke Parameter SP* With RHR Factor Based on OSU |
|---|---|---|---|
| M01 | 757 | 3.02 | 2.60 |
| M02 | 833 | 1.15 | 1.20 |
| M03 | 383 | 0.23 | 0.17 |
| M04 | 1504 | 7.20 | 9.38 |
| M05 | 175 | 0.31 | 0.33 |
| M06 | 304 | 0.39 | 0.36 |
| M07 | 39 | 0.02 | 0.02 |
| M08 | 924 | 0.82 | 0.57 |
| M09 | 779 | 1.18 | 1.19 |
| M10 | 1076 | N.A. | 0.89 |
| M11 | 450 | 0.19 | 0.23 |
| M12 | 258 | 0.06 | 0.04 |
| M13 | 1150 | N.A. | 0.76 |
| M14 | 1083 | 2.65 | 1.93 |
| M15 | N.A. | N.A. | N.A. |
| M16 | 993 | 2.10 | 1.31 |
| M17 | 306 | 0.34 | 0.31 |
| M18 | 236 | 0.06 | 0.05 |
| M19 | 249 | 0.24 | 0.21 |
| M20 | 1159 | 2.03 | 1.97 |
| M21 | 857 | 0.23 | 0.18 |
| M22 | 978 | 0.89 | 0.70 |
| M23 | 1866 | 4.52 | 4.46 |
| M24 | 791 | 0.98 | 0.82 |
| M25 | 385 | 0.24 | 0.20 |

$$* - SP = \frac{\sigma_m \times RHR}{10^5}$$

N. A. - not available

TABLE 9. MATTRESS TOTAL FUEL

| Specimen | Fuel (MJ) |
|---|---|
| M01 | 415 |
| M02 | 184 |
| M03 | 225 |
| M04 | 742 |
| M05 | 175 |
| M06 | 268 |
| M07 | 287 |
| M08 | 474 |
| M09 | 95 |
| M10 | 149 |
| M11 | N.A. |
| M12 | 185 |
| M13 | 153 |
| M14 | 294 |
| M15 | N.A. |
| M16 | 296 |
| M17 | 171 |
| M18 | 219 |
| M19 | 213 |
| M20 | 180 |
| M21 | 139 |
| M22 | 186 |

N. A. - not available

TABLE 10. TYPICAL HEATS OF COMBUSTION FOR MATTRESS MATERIALS

| Material | Heat of Combustion, Gross (MJ/kg) | |
|---|---|---|
| | Average | Range |
| Cotton | 18.1 | 17.4-20.4 |
| Cotton/Polyester | 21.2 | 19.7-22.3 |
| Jute | 23.4 | |
| Latex | 40.6 | |
| Neoprene, FR | | |
| Black | 25.8 | 24.8-26.8 |
| Buff, Bulk | 15.6 | 15.3-15.8 |
| Buff, Interliner | 9.7 | |
| Polyester | 25.8 | |
| Polypropylene | 48.5 | 47.5-49.5 |
| Polyurethane | | |
| Non-FR | 30.5 | 26.1-31.6 |
| FR | 24.2 | 24.0-24.3 |
| Hydrophilic | 11.5 | 10.1-12.8 |
| Polyvinylchloride | 25.1 | 22.8-26.0 |
| PVC - Nitrile | 20.5 | 17.3-23.6 |
| Rayon | | 13.6-19.5 |

TABLE 11. EFFECTIVE HEATS OF COMBUSTION AND MASS LOST
(25 kW/m$^2$ Flux, 3-Min. Averages)

| Specimen | Measured $\dot{m}$ (g/s) | Effective $\Delta h_c$ (MJ/kg) | Total $\Delta h_c$ (MJ/kg) | Effective ÷ Total % | Mass Lost After 600s (%) |
|---|---|---|---|---|---|
| M01 | 0.72 | 24.9 | 29.6 | 84 | 89 |
| M02 | 0.25 | 24.8 | 30.7 | 81 | 94 |
| M03 | 0.36 | 7.5 | 20.5 | 37 | 73 |
| M04 | 0.77 | 28.0 | 39.1 | 72 | 89 |
| M05 | 0.35 | 23.0 | 29.2 | 79 | 95 |
| M06 | 0.50 | 11.4 | 22.3 | 51 | 89 |
| M07 | 0.33 | 5.7 | 22.1 | 26 | 76 |
| M08 | 0.43 | 9.3 | 26.3 | 35 | 70 |
| M09 | 0.31 | 22.1 | 29.7 | 74 | 92 |
| M10 | N.A. | -- | 24.8 | -- | N.A. |
| M11 | 0.28 | 6.9 | -- | -- | 59 |
| M12 | 0.24 | 4.1 | 16.8 | 24 | 43 |
| M13 | N.A. | -- | 23.5 | -- | N.A. |
| M14 | 0.87 | 12.7 | 24.3 | 52 | 85 |
| M15 | 0.26 | 8.8 | 13.7 | 64 | 28 |
| M16 | 0.66 | 14.4 | 22.8 | 63 | 90 |
| M17 | 0.42 | 12.0 | 19.0 | 63 | 93 |
| M18 | 0.17 | 6.6 | 15.4 | 43 | 21 |
| M19 | 0.29 | 15.2 | 26.6 | 57 | 93 |
| M20 | 0.41 | 19.2 | 28.0 | 69 | 91 |
| M21 | 0.27 | 4.5 | 17.4 | 26 | 59 |
| M22 | N.A. | -- | 10.9 | -- | 35 |

N. A. - not available

TABLE 12. SUMMARY PERFORMANCE GROUPS

(As determined by the proposed test method, Appendix A)

| Group | Specimen | Heat Release Rate RHR | Smoke Parameter SP |
|---|---|---|---|
| A | M03 | 45 | 0.17 |
| | M07 | 46 | 0.02 |
| | M11 | 50 | 0.23 |
| | M12 | 16 | 0.04 |
| | M18 | 22 | 0.05 |
| | M19 | 85 | 0.21 |
| | M21 | 21 | 0.18 |
| | M25 | 52 | 0.20 |
| B | M08 | 62 | 0.57 |
| | M10 | 83 | 0.89 |
| | M22 | 72 | 0.70 |
| C | M02 | 144 | 1.20 |
| | M05 | 187 | 0.33 |
| | M06 | 119 | 0.36 |
| | M09 | 153 | 1.19 |
| | M14 | 178 | 1.93 |
| | M16 | 132 | 1.31 |
| | M17 | 102 | 0.31 |
| | M20 | 170 | 1.97 |
| | M24 | 104 | 0.82 |
| D | M01 | 344 | 2.60 |
| | M04 | 624 | 9.38 |
| | M23 | 239 | 4.46 |

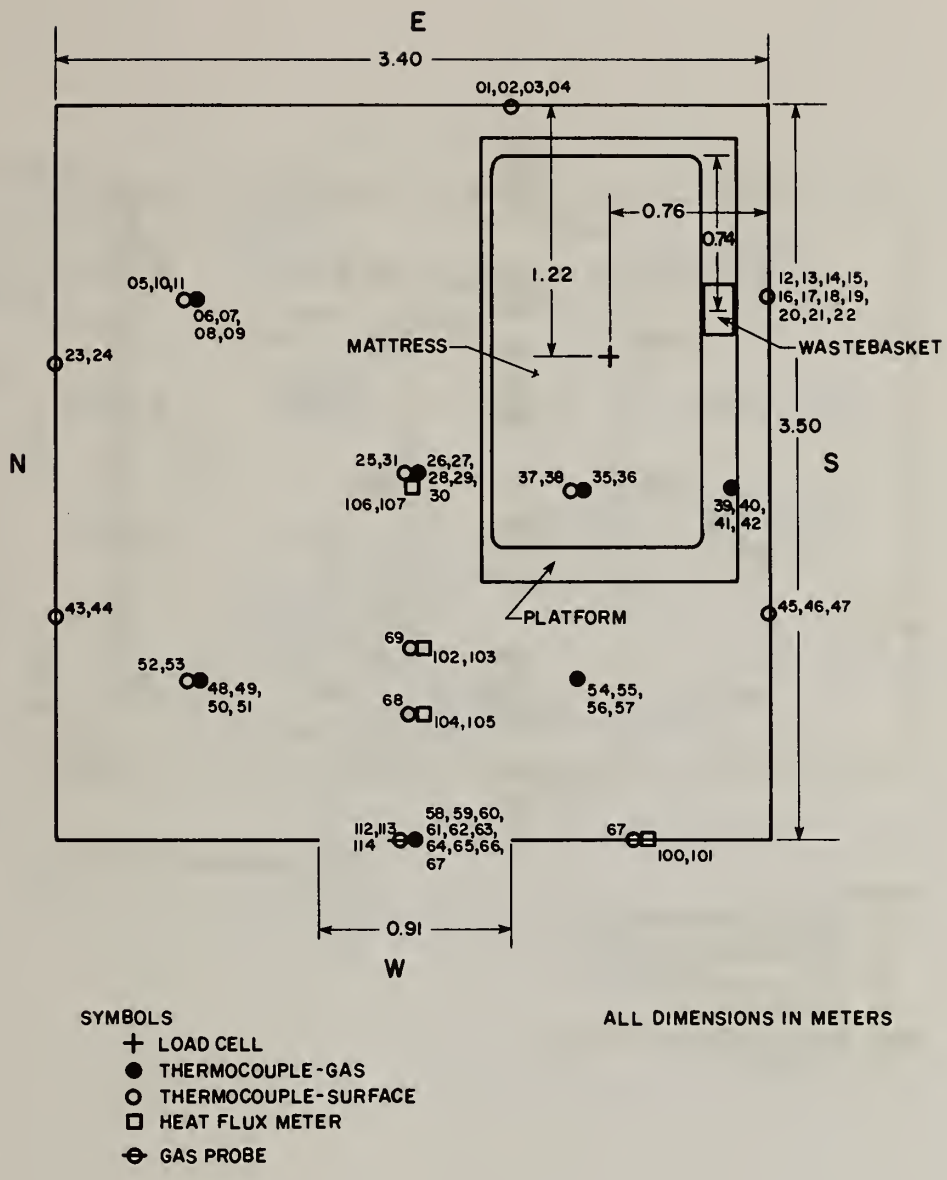


Figure 1. Plan View of Full-Scale Test Room A

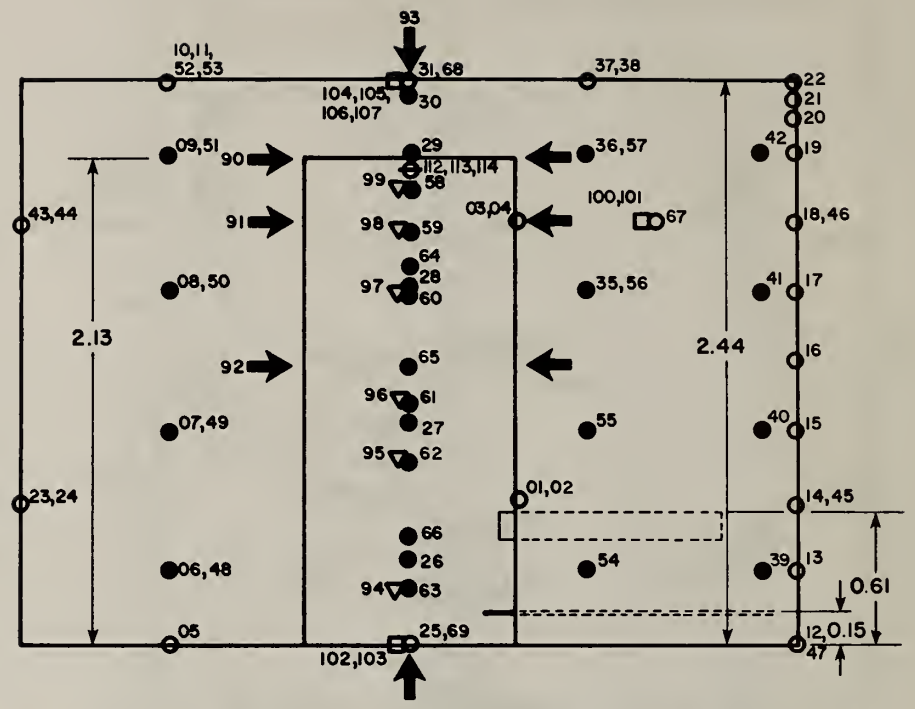


Figure 2. Elevation of Full-Scale Test Room A

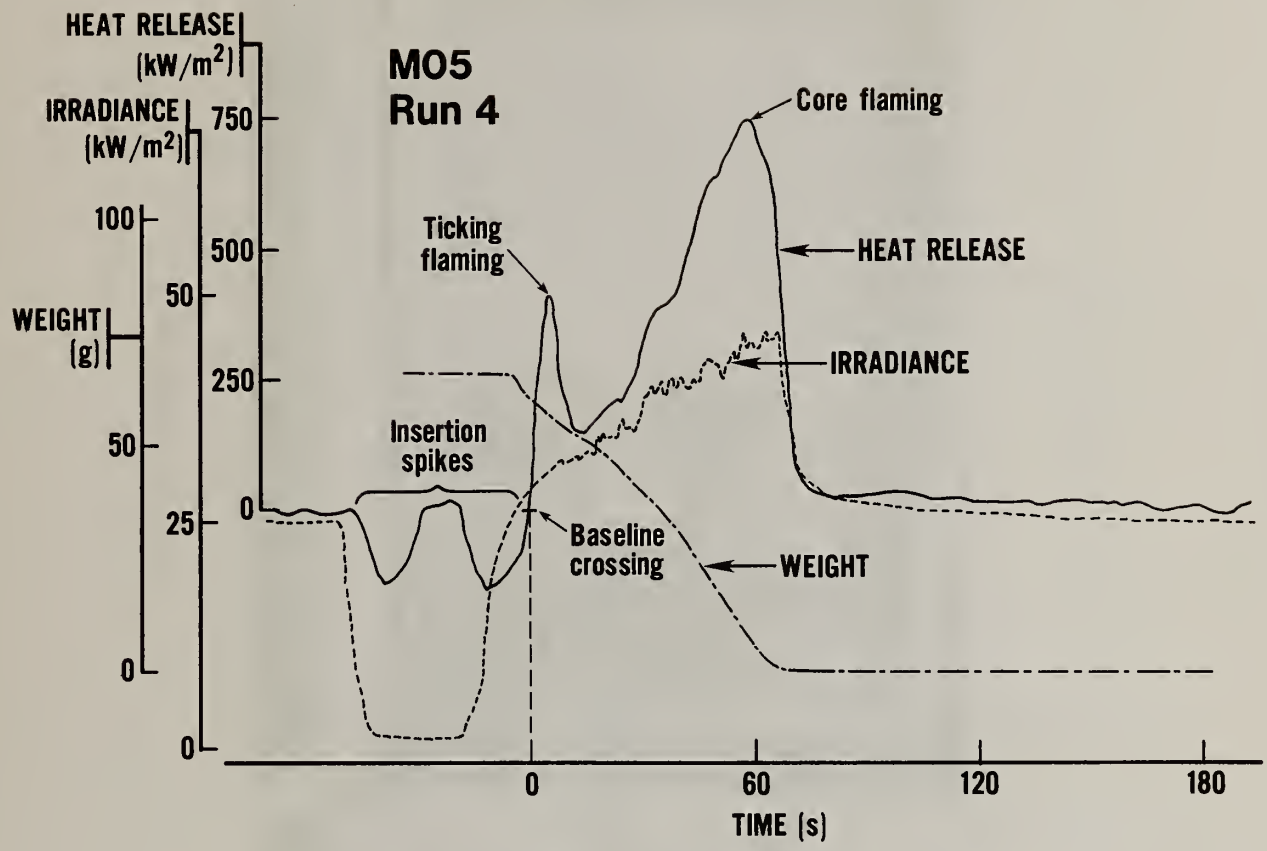


Figure 3. Typical NBS–II Calorimeter Results

Figure 4. View of Smoke Density Chamber with Horizontal Holder Arrangement

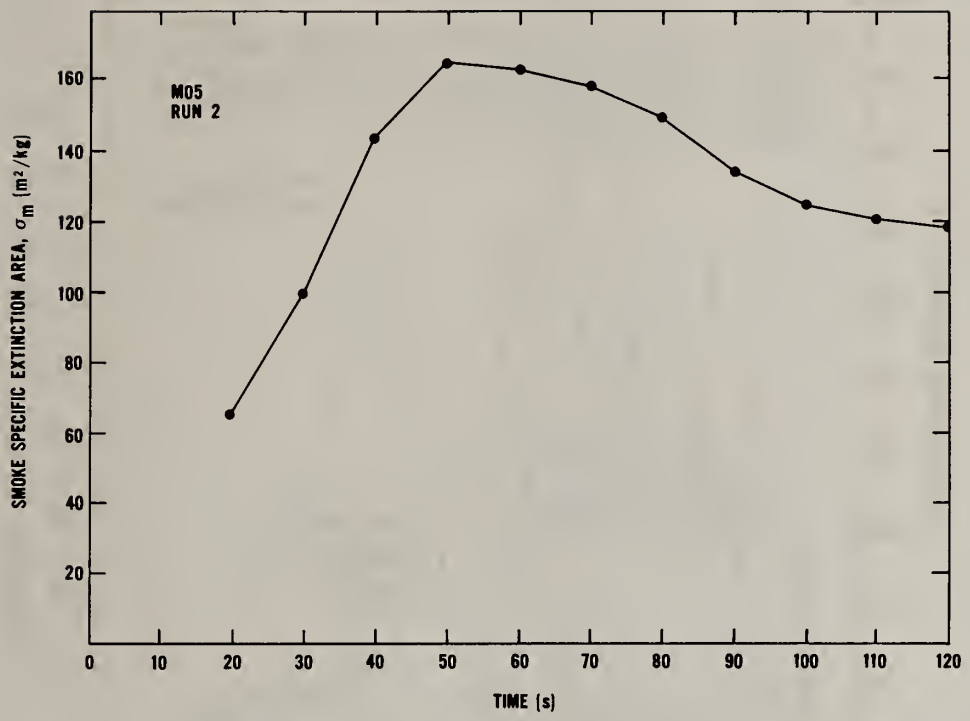


Figure 5. Typical $\sigma_m$ Curve for a Mattress Specimen

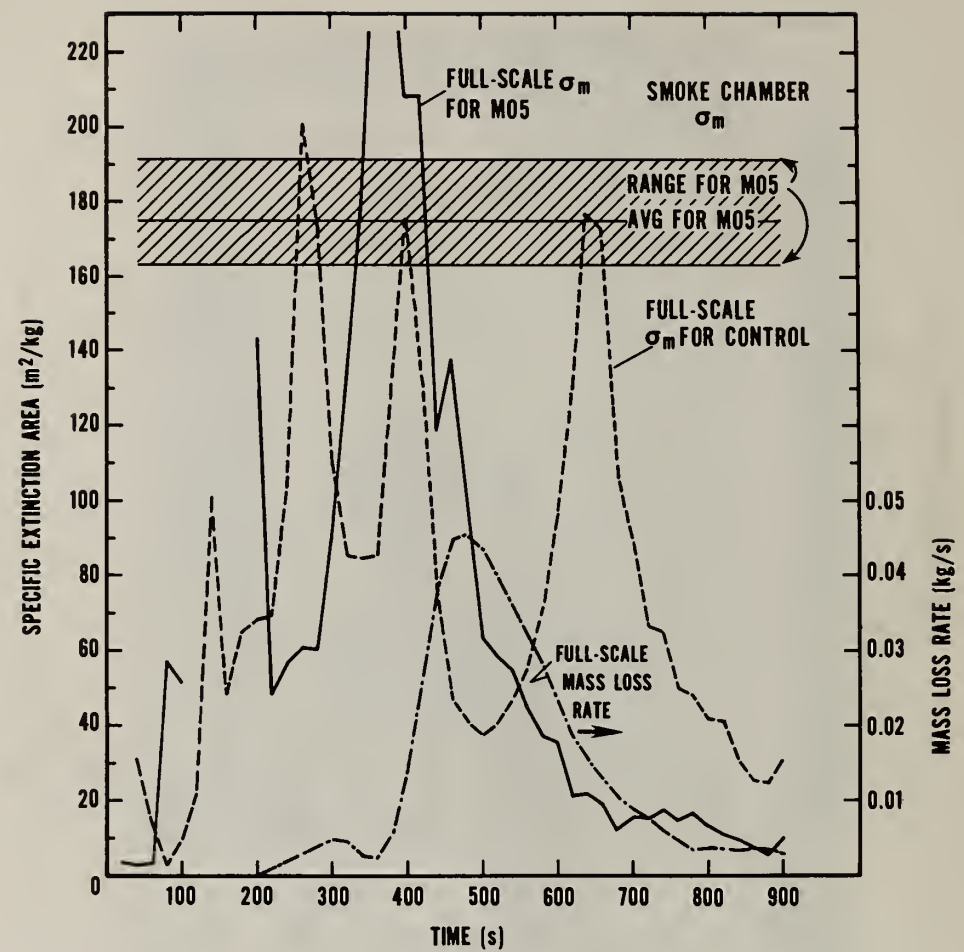


Figure 6. Specific Extinction Area Measurements for Specimen M05

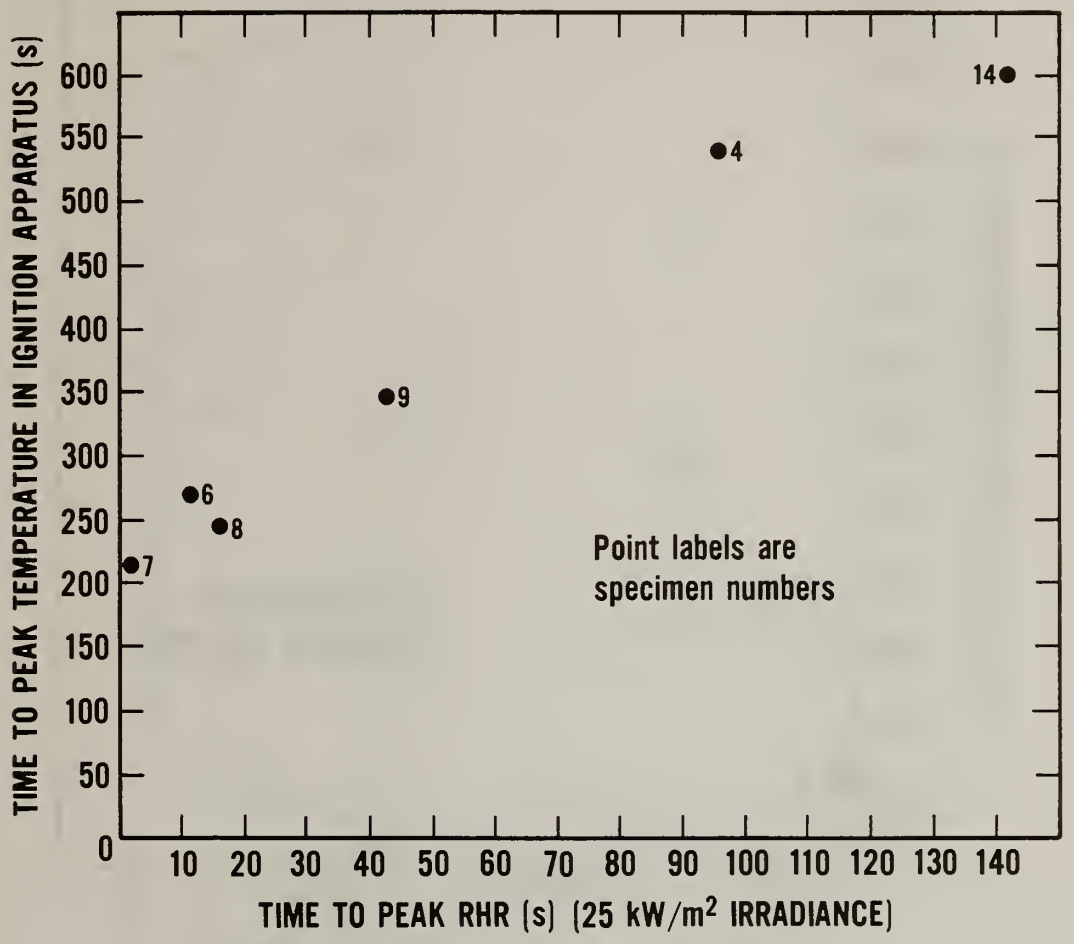


Figure 7. Predictability of Ignition Times from Calorimeter Data

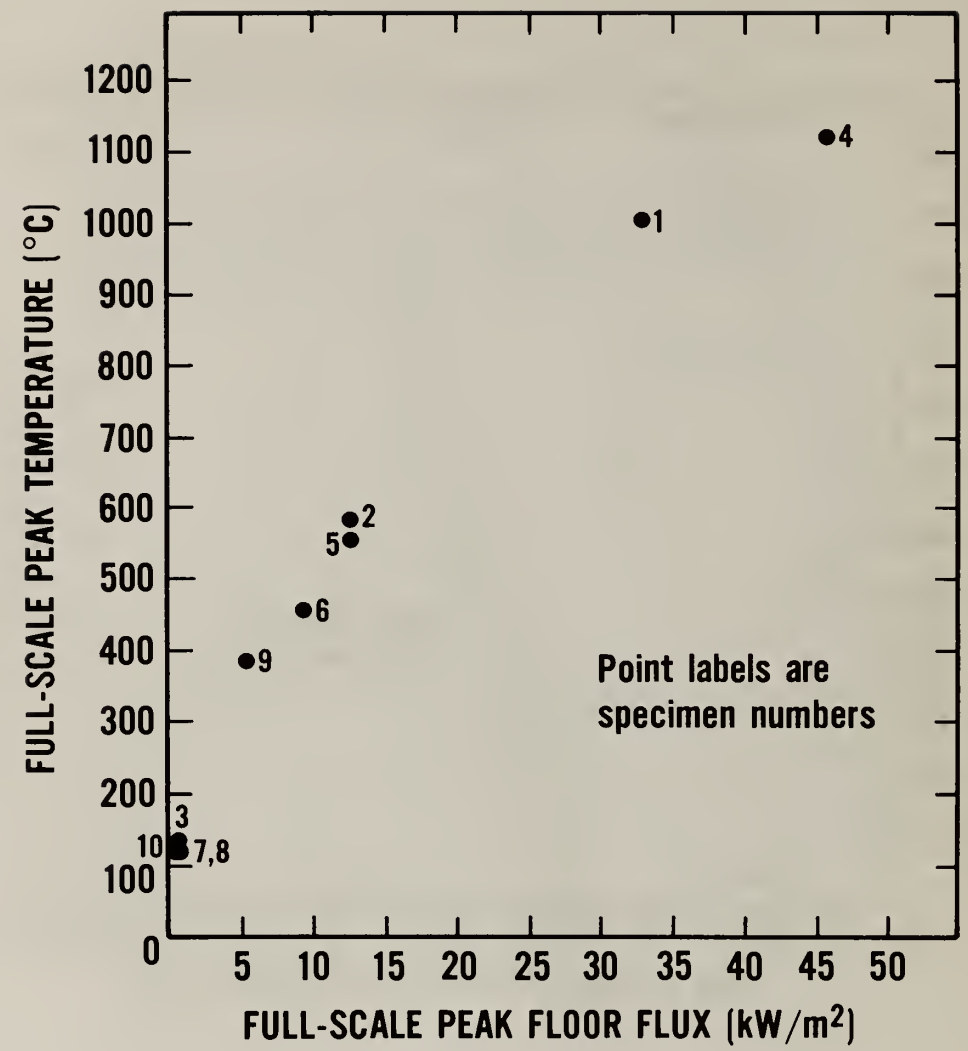


Figure 8. Relationship Between Peak Temperature and Peak Floor Flux

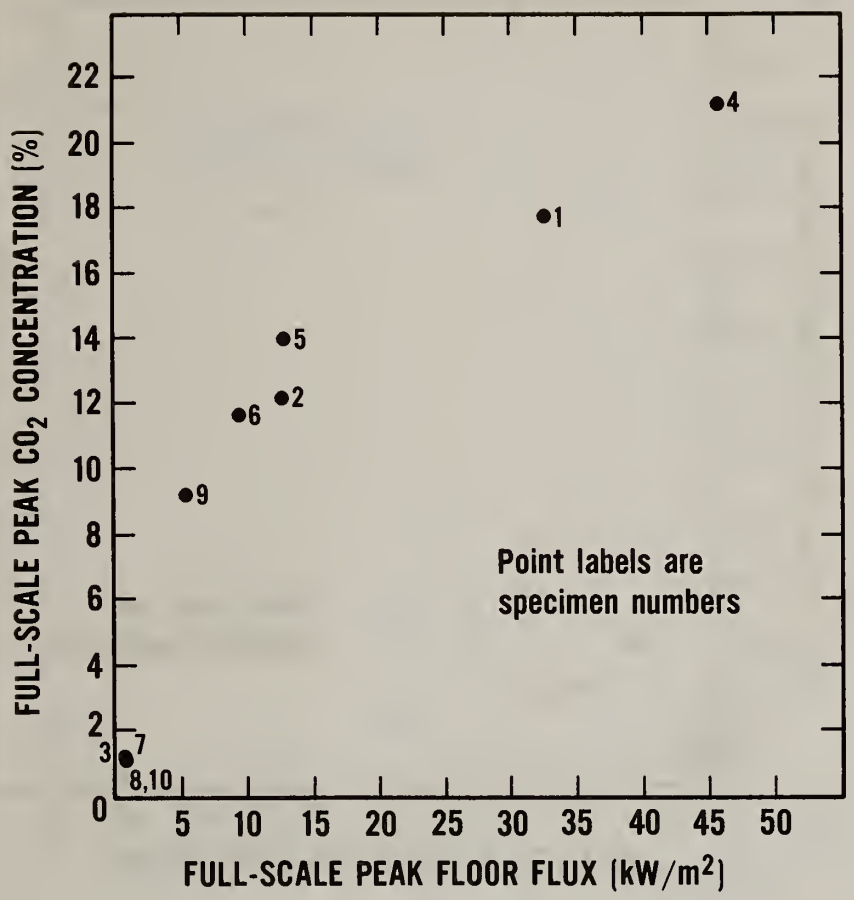


Figure 9. Relationship Between Peak $CO_2$ Concentration and Peak Floor Flux

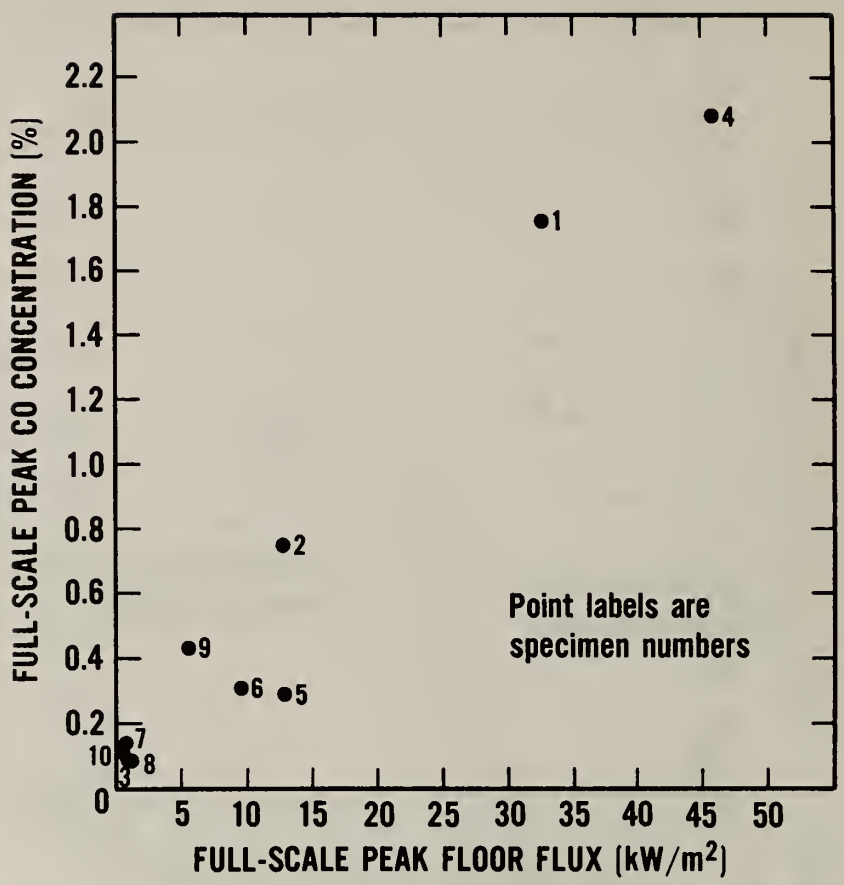


Figure 10. Relationship Between Peak CO Concentration and Peak Floor Flux

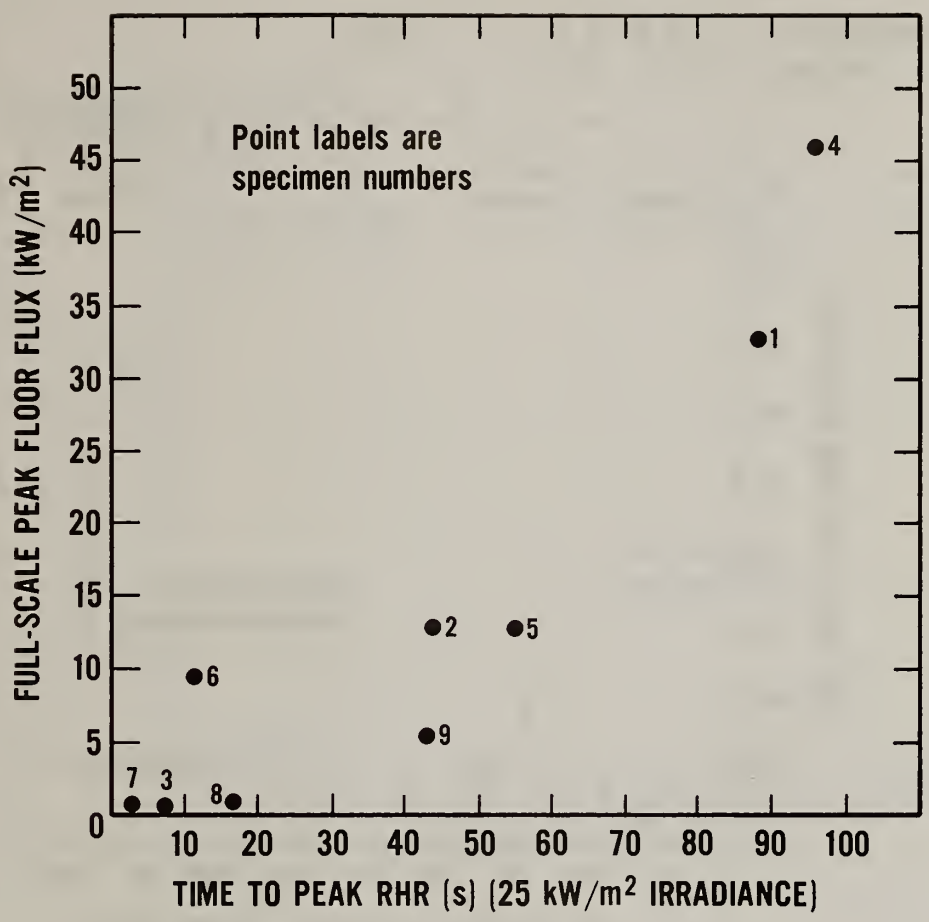


Figure 11. Relationship between Time to Peak RHR and Peak Floor Flux

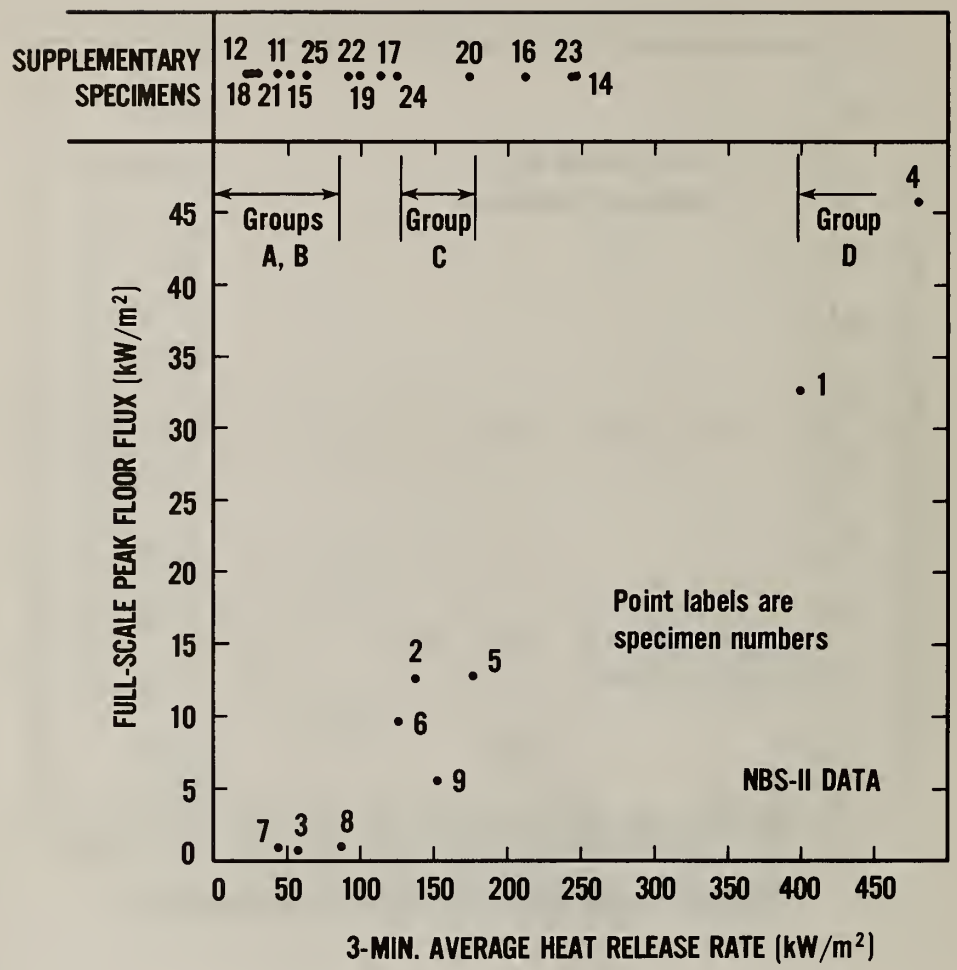


Figure 12. Rate of Heat Release Performance, NBS-II Calorimeter

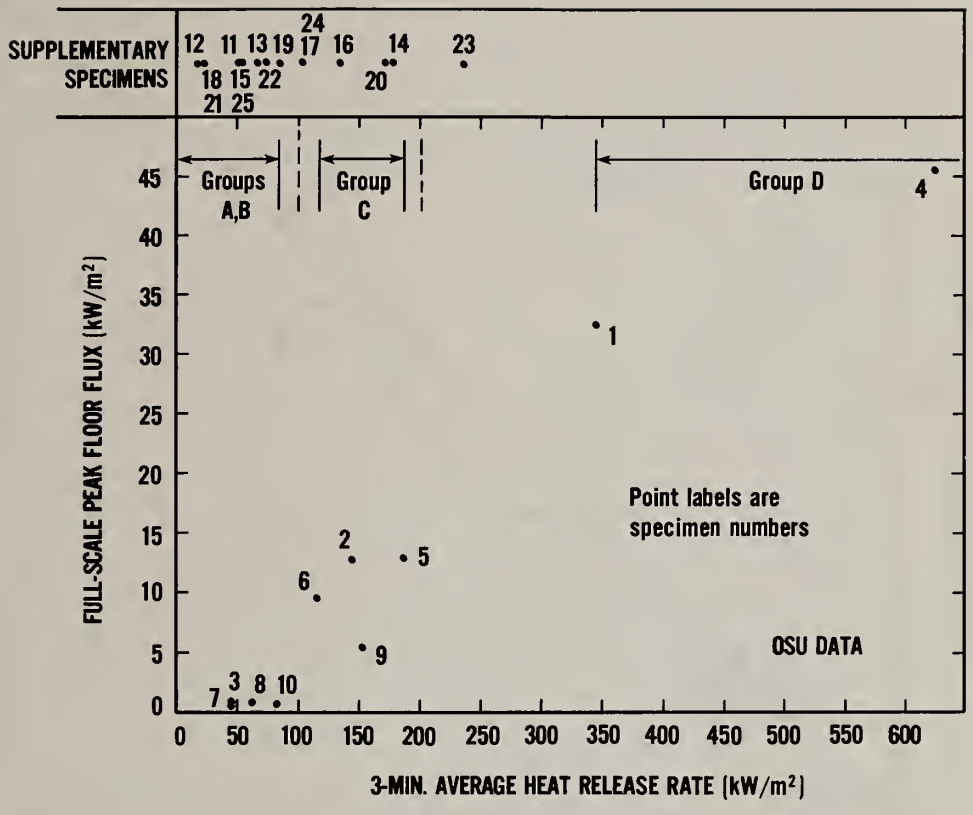


Figure 13. Rate of Heat Release Performance, OSU Calorimeter

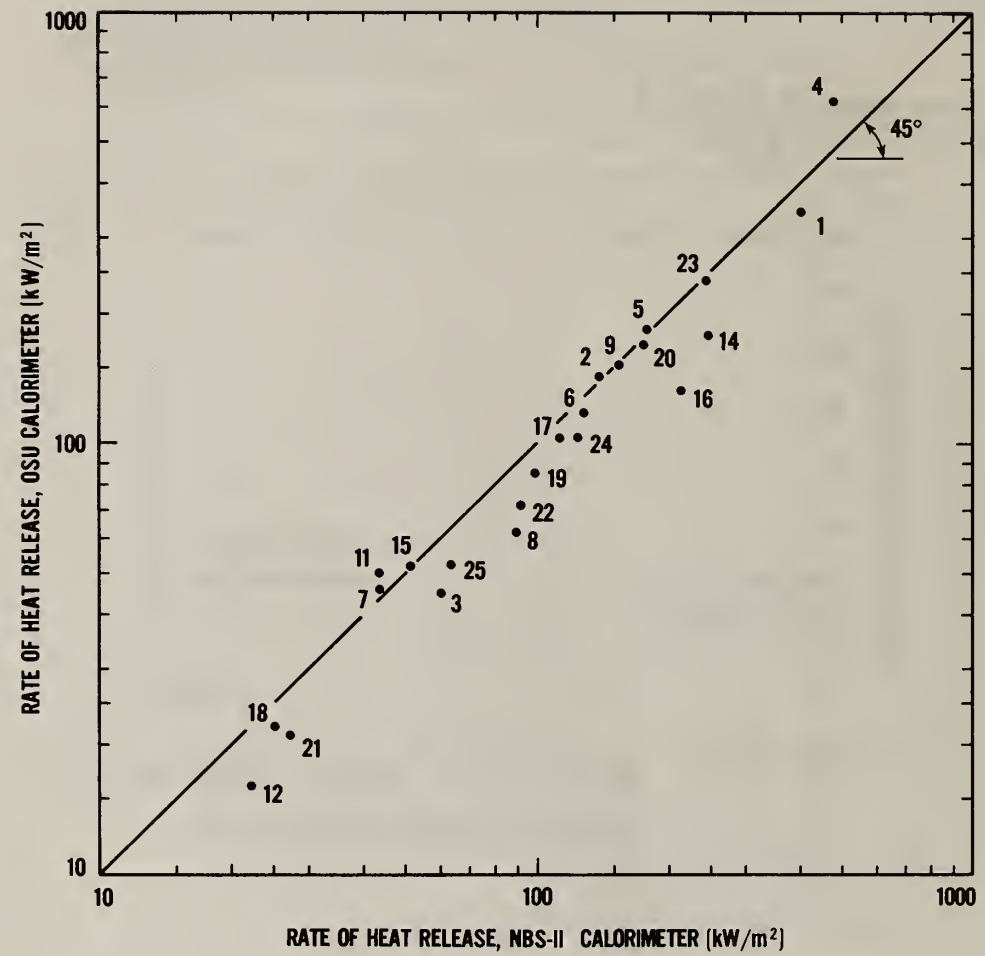


Figure 14. Comparison of NBS-II and OSU Results

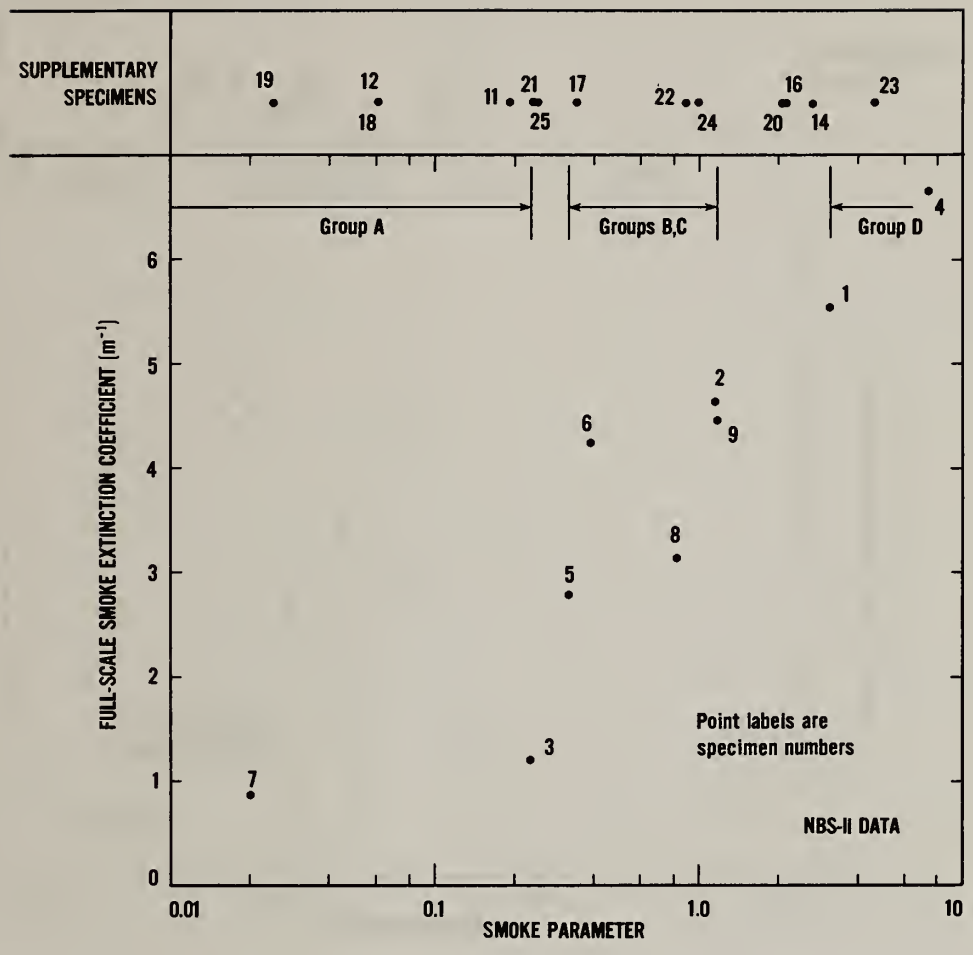


Figure 15. Smoke Performance (RHR Data from NBS-II Calorimeter)

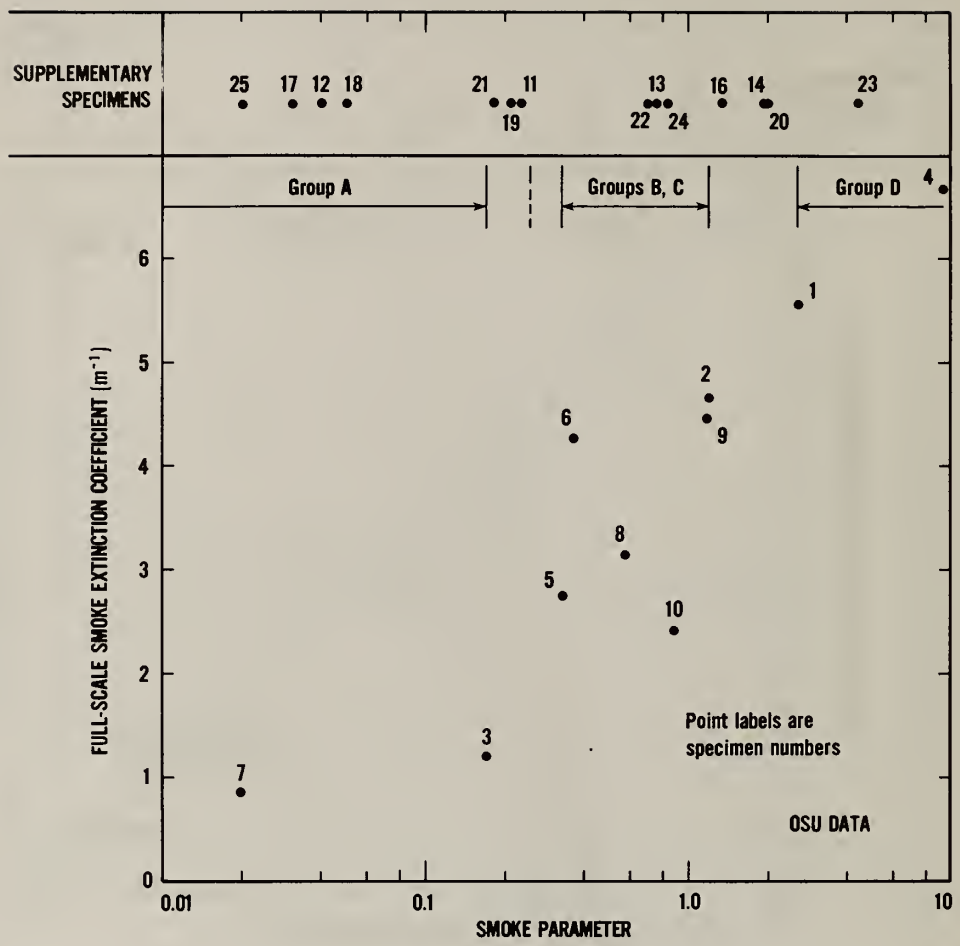


Figure 16. Smoke Performance (RHR Data from OSU Calorimeter)

# APPENDIX A

PROPOSED TEST METHOD FOR INSTITUTIONAL MATTRESS FLAMMABILITY

## 1. Scope

1.1 This method covers the procedures required to assign a performance classification for the flammability of institutional mattresses. Mattress performance is limited to the consideration of heat fluxes and smoke densities produced in a room containing an institutional mattress ignited by a flaming source. Mattresses are classified into one of four groups: A, B, C, or D, described in Section 3.

1.2 To determine the complete performance classification two tests are conducted -- rate of heat release and smoke production. To qualify mattresses for groups B or C only the rate of heat release tests are required.

## 2. Applicable Documents

ASTM Proposed Test Method for Heat and Visible Smoke Release Rates for Materials, ASTM Annual Book of Standards, Part 18 (November 1980).

ASTM Standard ANSI/ASTM E662-79, Standard Test Method for Specific Optical Density of Smoke Generated by Solid Materials.

## 3. Significance

3.1 The test procedures described comprise bench-scale tests designed to correlate with the fire behavior of institutional mattresses measured in full-scale tests. The full-scale conditions [1] consisted of instrumented rooms furnished solely with a test mattress, bedding, and a sustained flaming ignition source. The mattresses were located in a typical sleeping use arrangement.

3.2 Hazard may be increased if mattresses are stored on end, stacked several high, shredded or used in arrangements other than for sleeping use. Existing data suggest that in many cases, however, the relative ranking may be preserved.

3.3 This method does not provide for test of resistance to ignition by cigarettes. Method FF 4-72 [2] should be used to determine cigarette ignition resistance.

3.4 Specimen performance is described primarily by categorization into four groups. The groups have been determined from full-scale fire tests [1]. Appropriate performance in bench-scale tests does not provide assurance that actual fire behavior will be similar to that on which the categorization procedure was developed, due to differences in actual use conditions.

3.5 The four performance groups, based on flashover potential and tenability limits for carbon dioxide, carbon monoxide, oxygen depletion, heat flux, and smoke obscuration, are:

Group A -- Specimens in Group A did not cause any full-scale tenability limit to be exceeded.

Group B -- Specimens in Group B showed elevated smoke production in full-scale tests but did not exceed other tenability limits.

Group C -- Specimens in Group C exceeded smoke production and other tenability limits but did not lead to room flashover.

Group D -- Specimens in Group D exceeded all tenability limits and led to room flashover.

3.6 Repeatability has been determined in one laboratory for tests on the ten specimens included in the full-scale tests and on an expanded set, augmented by an additional 15 specimens. The coefficients of variation for the initial set were 0.102 and 0.093 for the rate of heat release and smoke production tests, respectively. For the augmented set the values were 0.134 and 0.130.

## 4. Rate of Heat Release Tests

4.1 Apparatus. The apparatus shall be similar to that described in the document "Proposed Test Method for Heat and Visible Smoke Release Rates for Materials," with the following exceptions:

4.1.1 The smoke measurement portion of the method shall not be used.

4.1.2 The specimen shall be mounted in the horizontal position; millboard backing and spring support shall not be used.

4.1.3 A non-impinging gas pilot shall be used. A mixture of methane and oxygen shall be fed to a burner tip located approximately 40 mm above the center of the specimen. The burner tip shall have an orifice of 0.75 mm (Smith Welding Equipment* 12-1401-05) or equivalent and shall be oriented at approximately 45° to the specimen. The gas mixture shall be adjusted to provide a small steady bright blue cone.

4.1.4 The radiation reflector shall be stainless steel foil, approximately 0.05 mm thick.

4.1.5 The thermopile measurement system shall not be used; instead, the heat release rates shall be measured by oxygen consumption.

4.1.5.1 An oxygen probe which consists of a stainless steel tube, 6.35 mm outside diameter, 0.89 mm wall thickness, shall be fitted horizontally 25 mm below the stack baffle. The tube shall be approximately 120 mm long and will be attached to a bulkhead fitting through the end chimney wall. Six equally spaced holes, 1.75 mm in diameter, shall be drilled along the length of the top of the tube. The far end of the tube shall be closed off.

4.1.5.2 The supplementary air supply to the top shroud of the apparatus shall be shut off. The total air supply, all of which passes through the combustion chamber, shall be $12 \pm 2$ ℓ/s. (This setting corresponds to approximately 340 mm $H_2O$ indication on the standard orifice flow meter used with the instrument). Short term stability shall be $\pm$ 0.75 ℓ/s between time of calibration and time of test.

4.1.5.3 The oxygen sampling system shall consist of an oxygen meter, pump, filter, drying device and carbon dioxide trap. A paramagnetic type oxygen analyzer has been found suitable (Beckman** 755 or equivalent). The instrument shall at least encompass the range of 15% to 22% oxygen; a commonly available scale of 0-25% is suitable. Electro-chemical or catalytic cells have not been found suitable. Ascarite† has been found suitable for $CO_2$ trapping. To ensure rapid response the sample line length should be minimized. A bypass (dumping) system should be used to provide rapid flow through the sample line while staying within oxygen analyzer flow rate limitation. A flow rate close to the maximum recommended by the manufacturer is normally preferable.

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* Tescom Corporation, Minneapolis, MN

** Beckman Instruments, Fullerton, CA

† Arthur H. Thomas Co., Philadelphia, PA

4.1.5.4 If the oxygen analyzer is sensitive to the partial pressure of oxygen at the outlet, tests shall not be conducted under conditions of rapidly varying ambient barometric pressures. Oxygen analyzer calibration as specified in 4.1.5.5 should be performed before and after each set of tests. Tests will not be considered valid unless the second calibration is within 2% of the first one.

4.1.5.5 Oxygen analyzer calibration. The oxygen analyzer shall be calibrated with ambient air (21.0% dry volume basis oxygen) corresponding to zero depletion and with a bottled oxygen/nitrogen mixture for the second reference. This mixture shall be in the range of 18.0 - 19.8% oxygen by volume. If the instrument response speed is adjustable, it should be set using the calibration burner and adjusted for zero undershoot when gas flow is stopped.

4.2 Heat release rate calibration. Calibration shall be performed before each series of tests and shall be made with a flow of methane through the calibration burner corresponding to a heat release rate of 4.0 to 8.0 kW. The calibration factor shall be determined as

$$k = \frac{\Delta h_c \rho \dot{V}}{[O_2\%]} \quad (1 + 0.0127\ [O_2\%]) \qquad (kW/O_2\%)$$

where $\Delta h_c$ = lower heat of combustion of methane ($50.0 \times 10^3$ kJ/kg)

$\rho$ = density of methane at actual pressure and temperature ($kg/m^3$)

$\dot{V}$ = volume flow of methane ($m^3/s$)

and $[O_2\%]$ = percent oxygen reduction.

The given flow rate should be maintained for approximately 5 minutes to determine a steady value of the response.

4.3 Rate of heat release. The specimen rate of heat release shall be determined from the measured oxygen reduction using the calibration factor determined in Section 4.2. The release rate shall be expressed as

$$RHR = \frac{k[O_2\%]}{A} \qquad (kW/m^2)$$

where A = exposed specimen area ($m^2$).

4.4 Rate of heat release specimens. Specimens are to be cut from finished production mattresses. Three specimens used, 100 mm by 100 mm along the exposed surface and 50 mm thick. Specimens are to be cut, through the thickness of the mattress, from an area least 20 mm away from any edge. If mattress construction is uniform over the entire surface, then specimens may be removed from any convenient location. If construction is variable, three specimens shall be taken and tested from each different area, with results being reported for that area showing the highest heat release rate. The arrangement of layers to produce a total specimen thickness of 50 mm shall be done in the following way. Innersprings and other metal parts, if any, shall not be included and their thicknessses not considered. If the remaining mattress thickness is less than 100 mm, then the top 50 mm shall be used. (The top surface is that normally used facing upward.) If the thickness is greater than 100 mm, then those layers which are thicker than 2 mm shall be trimmed in thickness to be in the same ratio as occurs in the production unit. If the mattress construction incorporates an interliner or other layer for flame barrier purposes, then that layer shall be cut sufficiently larger than 100 x 100 mm to enable it to be wrapped completely down over the sides and stapled underneath the specimen. The topmost layer (ticking) shall be 100 x 100 mm unless it is also included in a flame barrier construction. If the mattress contains highly compressed filling material, such that more than 25% thickness expansion occurs when the mattress is cut, the test specimen shall be sewn through with metallic wire in sufficient places to allow it to assume its production density. The mattress specimen shall be covered along the sides and bottom by a single sheet of aluminum foil, approximately 0.04 mm thick, with the dull side in contact with the specimen.

4.5 Conditioning. Specimens shall be conditioned to equilibrium (constant weight) at an ambient temperature of 23 $\pm$ 3°C and a relative humidity 50 $\pm$ 5%.

4.6 Test Conditions. Test conditions shall be basically as given in the reference document and as modified above. An irradiance of 25 $kW/m^2$ shall be used. Three samples each shall initially be tested. If any result in any set of three replicates is such that it exceeds the minimum by more than 50%, test an additional set of three replicates and report the average of all six results.

4.7 Calculations. The rate of heat release (RHR) shall be determined as required in Section 4.3 and recorded at least every 5 seconds. An average rate of heat release shall be determined for the time period comprising the first 180 s after ignition. Ignition shall be defined as the initial time when an oxygen depletion of $\geq$ 0.05% above the baseline is recorded (the baseline is the undisturbed oxygen reading prior to test).

## 5. Smoke Production Tests

5.1 Smoke production apparatus. Smoke production shall be measured in the apparatus described in ANSI/ASTM E662 with the following exceptions.

5.1.1 Specimens will be tested in a horizontal position, flaming mode, using a load cell for mass loss measurement. Figure A1 shows the arrangement used for accommodating horizontal specimens (Aminco† D1-76000 or equivalent). The development of this modification is given in reference [3].

5.1.2 Specimen size and arrangement shall be as given in paragraph 5.2.

5.1.3 Irradiance shall be measured at the specimen center location with a water-cooled Gardon-type heat flux gauge having a view angle of approximately 180°. The heat flux gauge shall be calibrated for incident radiation at a flux level appropriate to use conditions.

5.1.4 A single tip pilot shall be used, producing a small controlled flame impinging on the specimen center.

5.1.5 Photometer transmission and load cell data should preferably be recorded continuously, but shall be at least once every 10 s.

NOTE: It has been found useful to obtain transmission data with the use of a logarithmic photometer amplifier, Optronic Laboratories* Model 733 or equivalent.

5.2 Smoke production specimens. Three specimens shall be prepared similarly as in paragraph 4.4 except specimen size shall be 50 x 50 x 25 mm thick. Thickness proportioning shall be used if mattress thickness is greater than 50 mm.

5.3 Test conditions. Test conditions shall be basically as given in the reference document and as modified above. An irradiance of 25 $kW/m^2$ shall be used. Three samples each shall initially be tested. If any results in any set of three replicates is such that it exceeds the minimum by more than 50%, test an additional set of three replicates and report the average of all six results.

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†American Instrument Co.

*Optronic Laboratories

5.4 Calculations.

5.4.1 The quantity to be determined from the test is $\sigma_m$, the specific extinction area. This quantity is a measure of the smoke obscuration developed per unit sample mass pyrolyzed.

5.4.2 The starting time, t = 0, is defined to be the time that the specimen is inserted into the apparatus. At each 10 s thereafter the transmission and the mass are recorded. The specific extinction area, $\sigma_m$, is then determined at each 10 s interval according to the relationship

$$\sigma_m = V_{ch} \frac{k - k_{10}}{m_{10} - m} \qquad (m^2/kg)$$

where $V_{ch}$ = chamber volume (0.510 $m^3$), k is the extinction coefficient ($m^{-1}$) at a given time, $k_{10}$ is the extinction coefficient at 10 s after start of test, m is the mass remaining (kg), and $m_{10}$ is the mass at 10 s. The extinction coefficient k is defined as

$$k = \frac{1}{L} \ln \left(\frac{100}{T}\right) = \frac{2.303}{L} \log \left(\frac{100}{T}\right)$$

where L = light beam path length (0.914 m), T is the percent transmission, and ln is the base-e (natural) logarithm. The results are to be tabulated for every 10 s interval from 30 s to 600 s, inclusive. The $\sigma_m$ value reported for each specimen shall be the maximum in this period.

## 6. Performance Classification

6.1 To qualify mattresses for Group B or Group C only the rate of heat release tests, Section 4, are required. Performance group is determined according to the average RHR value, computed for the lot of three or six test specimens according to paragraphs 4.5 and 4.6.

6.2 Specimens with RHR greater than 200 are classified into Group D.

6.3 Specimens with RHR less than or equal to 200 qualify for Group C.

6.4 Specimens with RHR less than or equal to 100 qualify for Group B.

6.5 To qualify mattresses for Group A, both the rate of heat release tests, Section 4, and the smoke production tests, Section 5, are required.

6.5.1 The average RHR is computed for the lot of three or six test specimens according to paragraphs 4.5 and 4.6.

6.5.2 The smoke parameter (SP) is defined as

$$SP = \sigma_m \times RHR/10^5$$

where RHR is determined in Paragraph 6.5.1. The $\sigma_m$ value used in determining the smoke parameter, SP, is the average for the lot of three or six test specimens.

6.6 Specimens with RHR less than or equal to 100 and SP less than or equal to 0.25 are classified into Group A.

## 7. Report

The report shall include the following:

7.1 Description of mattress, including type, manufacturer, size, weight, presence of innersprings and other appropriate identifying features. Include observation if top and bottom constructions are different and if samples are not uniform over their surface area.

7.2 Description of test procedures.

7.3 Number and description of specimens tested.

7.4 The RHR value for each specimen and the average for the lot.

7.5 If smoke production tests were performed, the $\sigma_m$ for each specimen and the average for the lot and the SP value for the lot.

7.6 The performance group.

References

1. V. Babrauskas, Combustion of Mattresses Exposed to Flaming Ignition Sources, Part I. Full-Scale Tests and Hazard Analysis, Nat. Bur. Stand. (U. S.) NBSIR 77-1290 (1977).

2. Standard for the Flammability of Mattresses and Mattress Pads (FF 4-72), 40 FR 59940, CFR Part 1623.

3. L. Breden, M. Meisters, The Effect of Sample Orientation in the Smoke Density Chamber, Nat. Bur. Stand. (U. S.), NBSIR 76-1030 (1976).

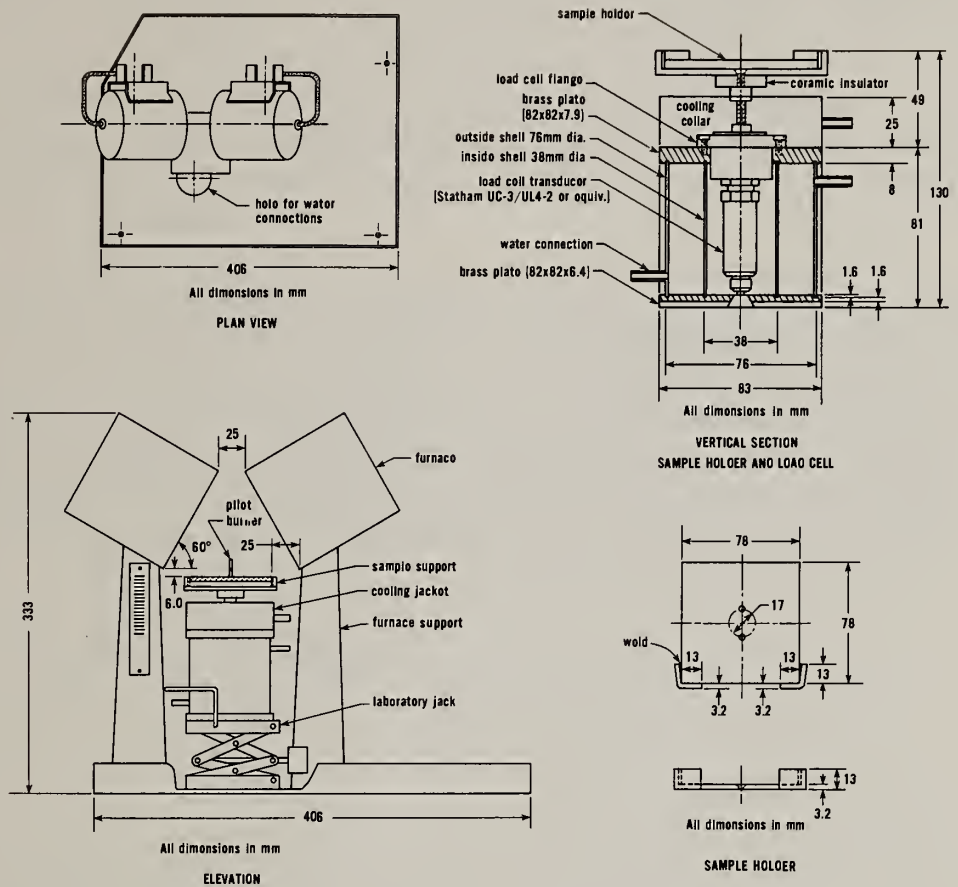


Figure A1. Details of Horizontal Specimen Holder and Load Cell for the Smoke Density Chamber

## APPENDIX B - SUPPLEMENTAL DATA ON HEAT AND MASS FLOWS IN FULL-SCALE TESTS

Data analysis on heat and mass flows in the full-scale tests was not available at the time of the publication of the Part I report [1]. For completeness this analysis for Burn Room A is presented here.

Initial analysis of mass flows was performed using the procedures discussed in detail in [14]. This involves using a doorway velocity profile as measured by six bi-directional velocity probes. This approach showed a poor mass balance, with outflows up to double the corresponding inflows. The analysis in [14] showed two basic difficulties: (a) six probes are insufficient for adequate precision, and (b) the positioning of probes among the flow streamlines is critical (a location has to be established where there is a negligible verticle velocity component).

Relying only on existing data, a different approach was taken instead. Work by Steckler [22] has shown that a good estimate of doorway mass flows can be made by equating the actual doorway temperature distribution to an equivalent two-layer model. It is assumed that the inflow air is of a known temperature $T_\infty$. To be determined are the typical hot upper gas (outflow) temperature, $T_u$, and the neutral plane height, N. Below the height N in the doorway there is only inflow, at the temperature $T_\infty$, while above N there is only outflow at the temperature $T_u$. Two equations are used to solve for the two unknowns N and $T_u$.

$$\int_o^H \rho(h)dh = N\rho_\infty + (H - N)\rho_u$$

and

$$\int_o^H (T(h) - T_\infty)dh = (H - N) \quad (T_u - T_\infty)$$

where T(h) are doorway temperatures measured at height h, H is the doorway height, and the densities $\rho$ are expressed as $\rho = \rho_\infty \frac{T_\infty}{T}$.

The integration is approximated by a summation over, in this case, nine temperature measurement locations. Once $T_u$ and N are obtained, the mass flow rate can be directly obtained using the procedures developed by Rockett [23]. In these calculations a discharge coefficient $C_d = 0.77$ was chosen according to experimental determinations consonant with this approach [22].

Rate of heat release determinations were made using the oxygen consumption principle [8]. Only a single oxygen probe measurement location, near the doorway top, was available. Exploratory probing indicated, however, that oxygen in the upper gas space is quite well mixed and that it is reasonable to assume that all the outflow is at the same concentration as measured by the single probe.

Results for mass flows and rates of heat release are shown in Figures B1 through B11. It should be noted that according to the analysis method adopted mass conservation is implicitly included and, therefore, separate mass inflow and outflow values are not derived.

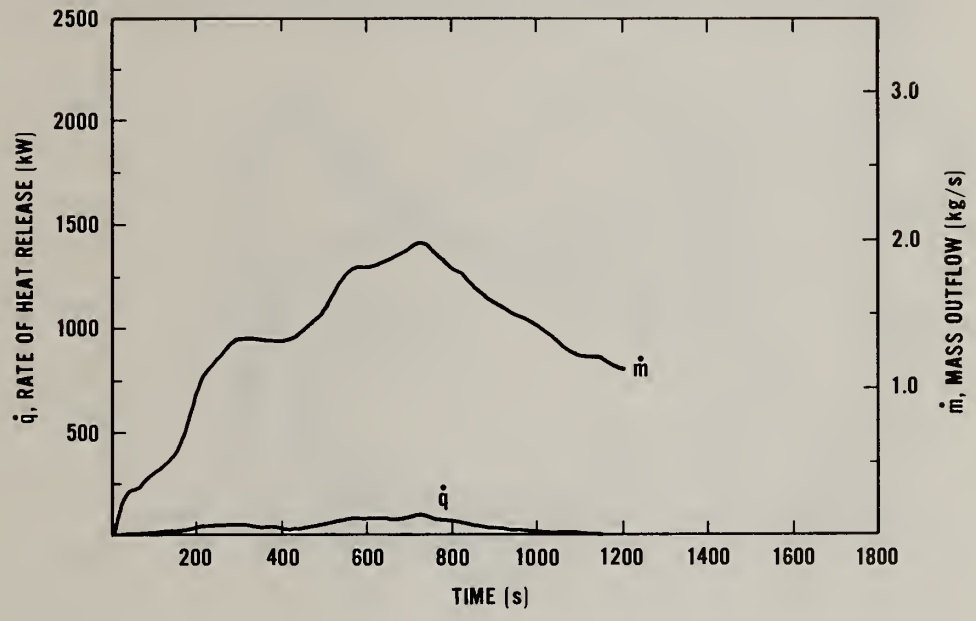


Figure B1. Heat Release Rate and Mass Flow for Control Mattress

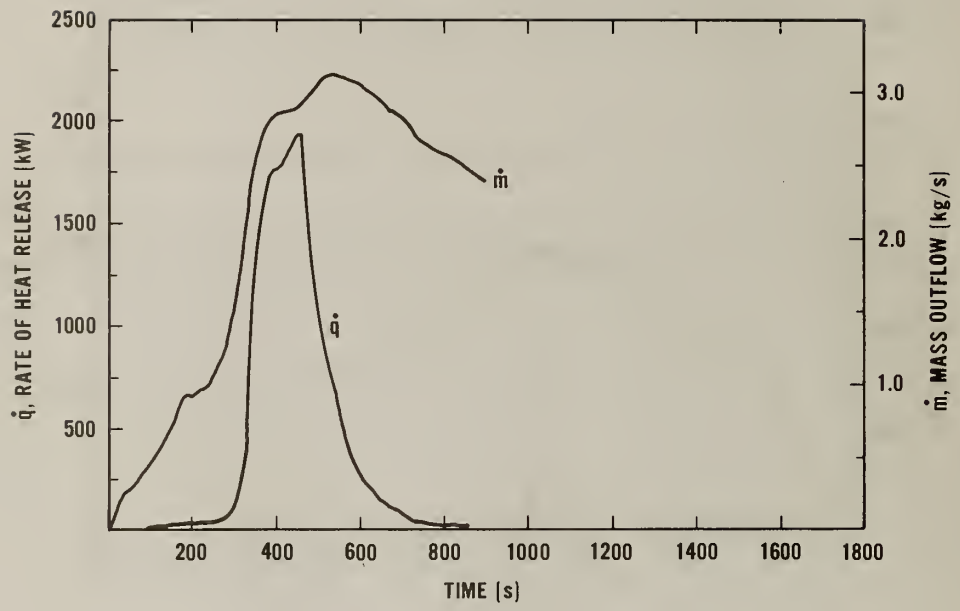


Figure B2. Heat Release Rate and Mass Flow for Mattress M01

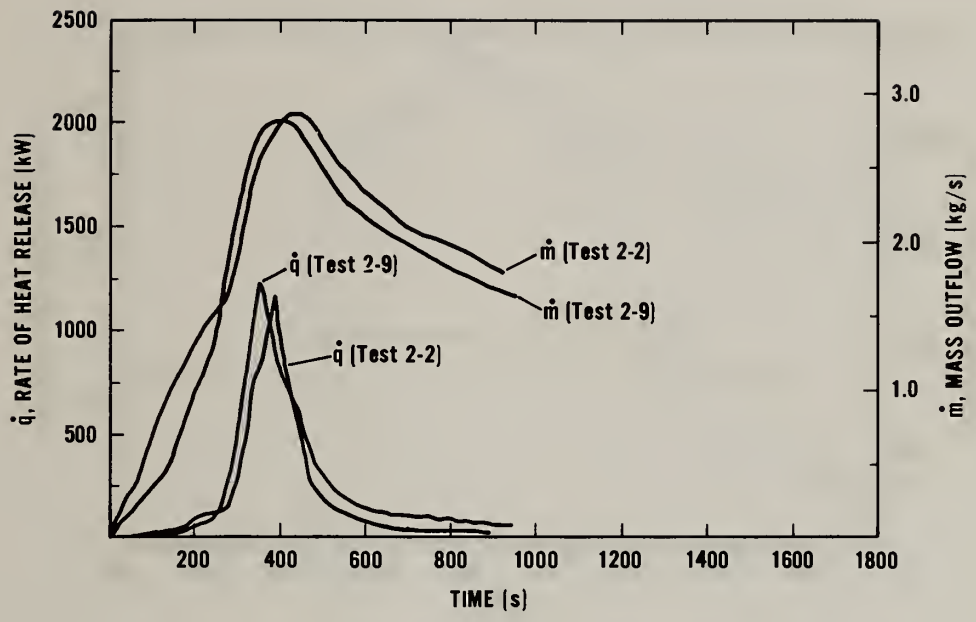


Figure B3. Heat Release Rate and Mass Flow for Mattress M02

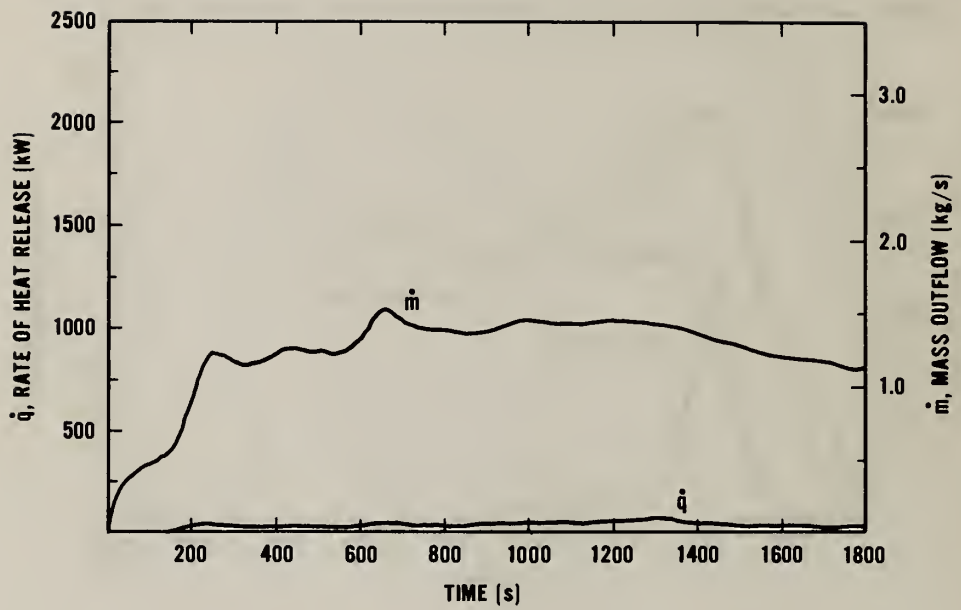


Figure B4. Heat Release Rate and Mass Flow for Mattress M03

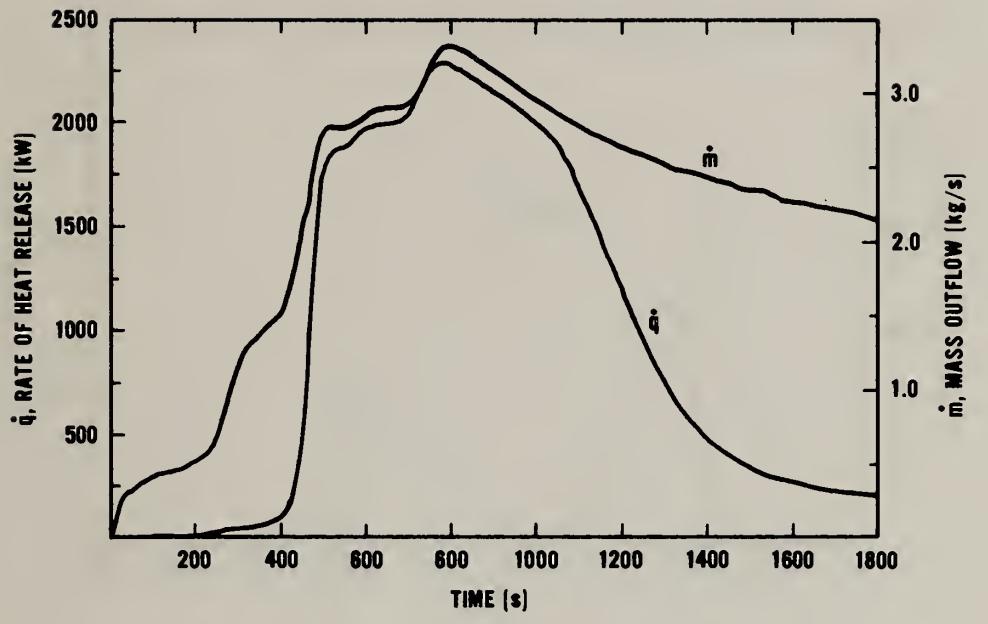


Figure B5. Heat Release Rate and Mass Flow for Mattress M04

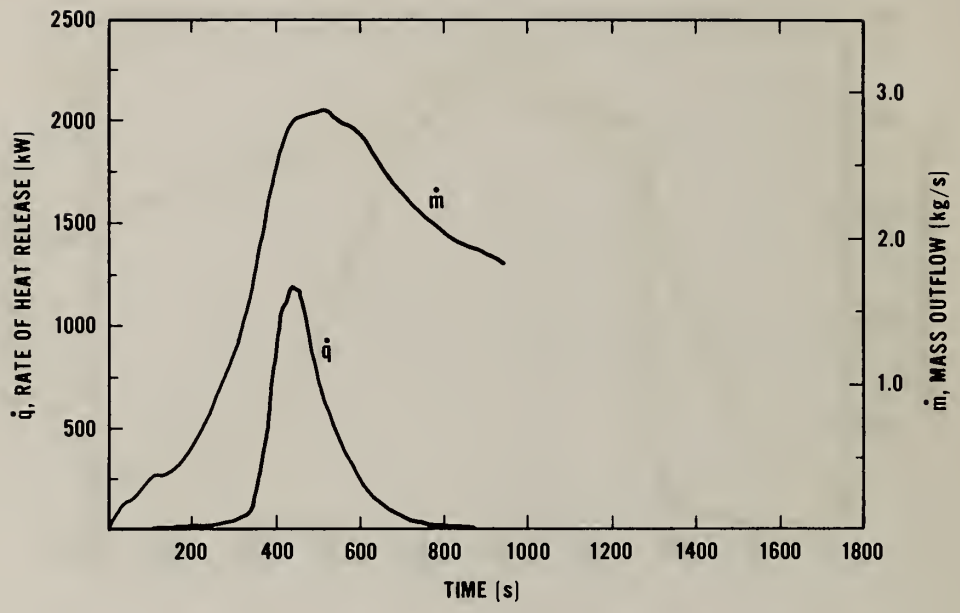


Figure B6. Heat Release Rate and Mass Flow for Mattress M05

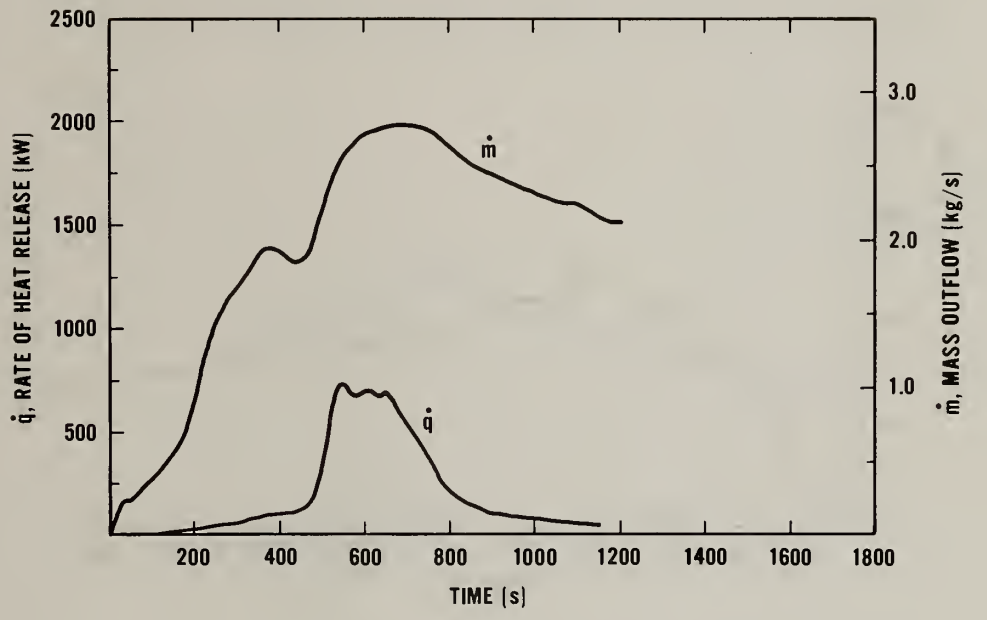


Figure B7. Heat Release Rate and Mass Flow for Mattress M06

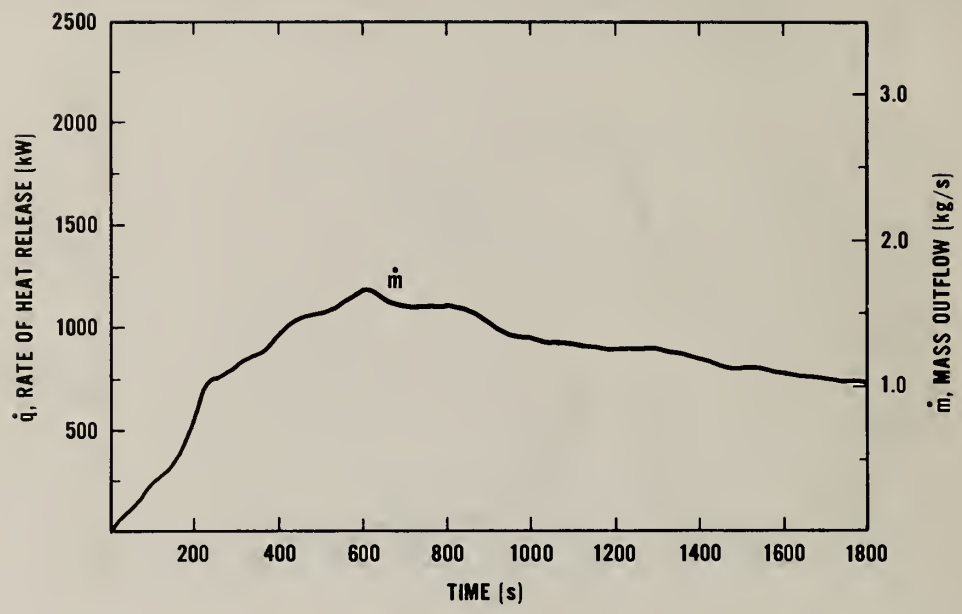


Figure B8. Heat Release Rate and Mass Flow for Mattress M07

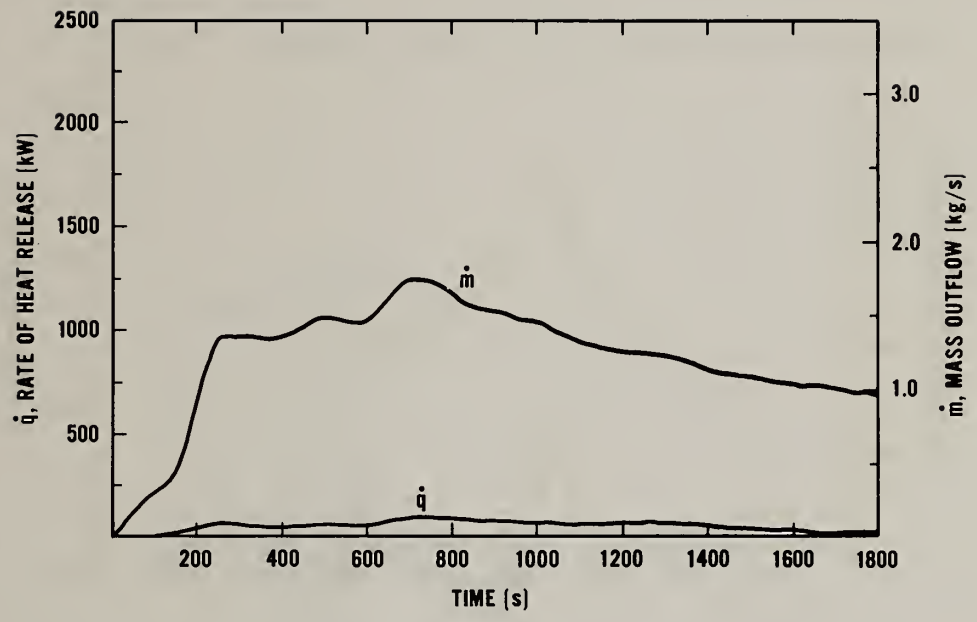


Figure B9. Heat Release Rate and Mass Flow for Mattress M08

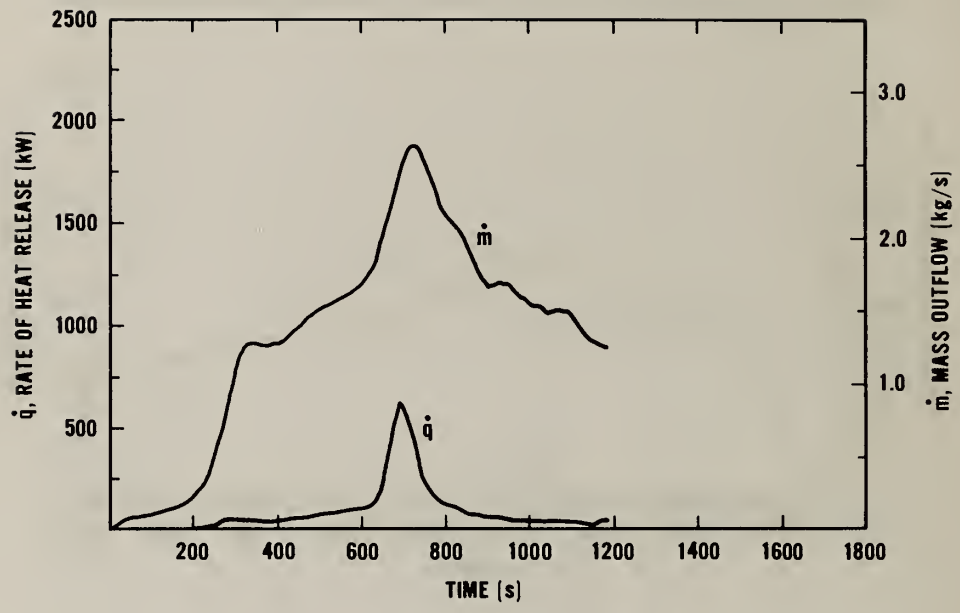


Figure B10. Heat Release Rate and Mass Flow for Mattress M09

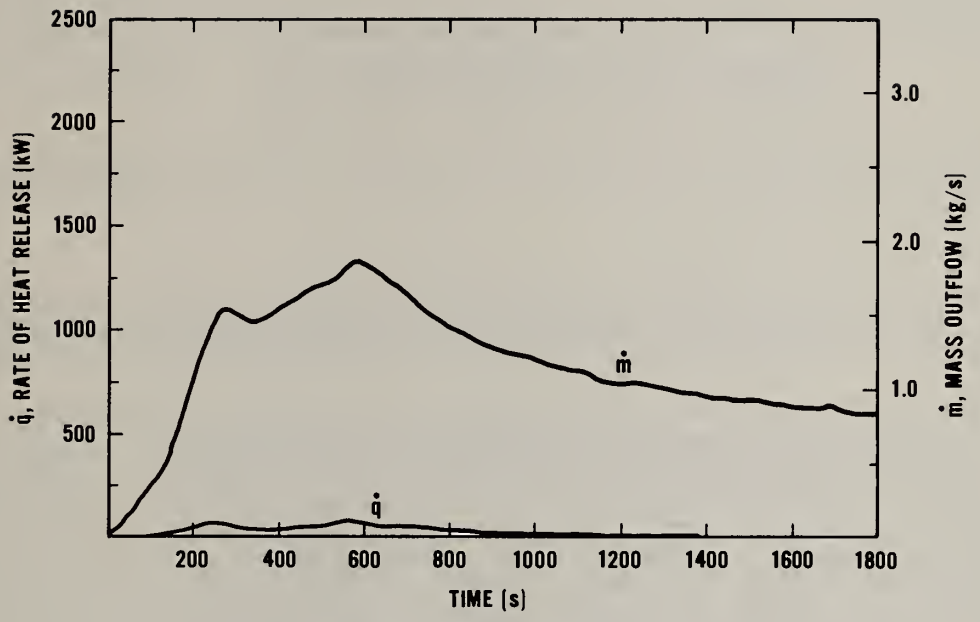


Figure B11. Heat Release Rate and Mass Flow for Mattress M10

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**5. AUTHOR(S)**

Vytenis Babrauskas

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☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

**11. ABSTRACT** *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

Ten mattress types were subjected to full-scale fire tests in the earlier part of this project. Burning behavior was determined and hazard was assessed by classifying into performance groups. In the present study bench-scale test procedures were examined for suitability for classifying mattress combustion behavior when exposed to flaming ignition sources. Several tests were examined, and a test protocol was developed based on two procedures -- measurement of rate of heat release and smoke production. These procedures enable the performance classification, as established by full-scale tests, to be reproduced by convenient laboratory tests. Details are given for conducting the required tests and illustrative performance of some two dozen samples is recorded.

**12. KEY WORDS** *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

Bedding; beds; compartment fires; fire tests; health care facilities; heat release rate; hospitals; mattresses; prisons; smoke production.

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