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Park Service Room Fire Test Simulations Using the Harvard Level 5.2 Computer Fire Model

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
National Engineering Laboratory
Center for Fire Research
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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, ***Secretary***
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, ***Director***

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Park Service Room Fire Test Simulations Using the Harvard Level 5.2 Computer Fire Model

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ABSTRACT

The Fire Center has conducted a series of full-scale tests of hotel-like rooms. The furnishings were a bed with headboard "made up" with bedding, and a wooden sidetable. The ignition source was a wastebasket. The furniture was burned in the new N.B.S. furniture calorimeter and in a 2.44 x 3.66 x 2.44 high room. As an adjunct to analysis of the test results, a series of simulations of the fire tests were run using the Harvard Fire Simulation. This report describes the simulations and their results.

The principal finding of the simulations was that the room had little effect in augmenting the burning of this fuel package. The simulation result was partially due to the burn algorithm used and partially due to the relatively large fire area and short assumed flame radiation extinction length. This finding might not have been true had the individual objects been smaller in area or their flames less opaque. A different burn algorithm might also have produced different results.

INTRODUCTION AND SUMMARY

The Fire Center has conducted a series of full-scale fire tests of hotel-like rooms. The work was sponsored by the U.S. Park Service and the fire tests involved fuel loads representative of those found in tourist accomodations currently available in a number of our National Parks. The furnishings were a bed with headboard, "made up" with bedding, and a wooden side table. The ignition source was a "standard Berkeley wastebasket" [1]. The furniture was burned in the new N.B.S. furniture calorimeter [2] and in a 2.44 x 3.66 x 2.44 m high room. For

some tests the room had combustible walls, in others the walls were plasterboard [3]. As an adjunct to analysis of the test results, a series of simulations of the fire tests were run using the Harvard Fire Simulation level 5.2 [1,4,5]. This report describes the simulations and their results. Only the plasterboard wall - room tests and associated furniture calorimeter tests were considered, as the version of the Harvard simulation available did not include a working algorithm for wall burning.

The specific questions addressed in carrying out the simulations were related to the effects of room size and fuel load. To have investigated these questions experimentally would have involved considerable expense. A set of rooms of varying size would have had to be built and full-scale fire tests, which are inherently expensive in manpower and material, would have had to be conducted. The analytic simulations, on the other hand, can readily study these effects. Six simulations were run:

> A "free-burn" of the wastebasket igniter and a bed-sidetable unit. The free-burn condition was simulated by specifying a very large room with a large, tall door.

> The same fuel in a room similar to that used in the room tests.

> The same fuel in a room of twice the area of the test room. The "double" room had the same ceiling height and door size as the test room.

> The same fuel in a room of four times the area of the test room. Again, the ceiling height and door size corresponded to the test room.

> The wastebasket igniter and two identical bed units in a room twice the area of the test room. In these simulations, the two beds were positioned so that the wastebasket ignited

only one by flame contact. The other ignited if the fire caused by the first bed was intense enough and of sufficient duration to ignite the second bed by radiant and convective heat transfer (no flame contact).

> The same "double fuel package" in a room of four times the area of the test room. The same ignition condition as in the previous case was used.

The fuel package used in the simulation, which will be discussed in detail presently, was adjusted to give approximate agreement between the furniture calorimeter tests and the free-burn simulation. With one exception, specifically discussed, these fuel parameters were then used for all the remaining simulatons. As mentioned above, except for the free-burn simulations, a single door of the same size for all room sizes provided the only ventilation for the simulated fires.

The principal finding of the simulations was that, for the burn algorithm used, the room had little effect in augmenting the burning rate of this fuel package. This differs from the experimental burns where a definite augmentation of rate of heat release was found in the room as compared to the calorimeter burns. The simulation result was partially due to the burn algorithm used and partially a result of the relatively large fire area and short assumed flame radiation extinction length. Under these conditions, the heat flux at the fuel surface, which determines the fuel pyrolysis rate, was determined primarily by the radiation from the flame immediately above the surface. Most of the radiation from the hot gases, upper walls and ceiling, and other fire plumes, did not penetrate through the relatively opaque flames originating from the object itself. Thus the object's surroundings had little effect on its burning behavior. This might not have been the

case had the individual objects been smaller in area or their flames less opaque.

Due to the larger area for heat loss in the larger rooms, gas temperatures in the upper part of those rooms were lower than in the smaller ones for the same fuel load. For the door size used, unburned fuel in the form of soot but no excess gaseous fuel exited from the door for the one-bed fuel load in the smallest room. Ventilation-limited burning did not occur. For the same fuel in the two larger rooms, the slightly lower temperatures resulted in a slightly higher ventilation rate - due to the slightly greater density of the exiting, hot gases. (The reason for this is discussed in [6] and illustrated in [6], figure 4.)

Addition of a second bed in the largest (quad) room had no effect as the second bed did not ignite. In the double room, the second bed did ignite but ventilation-limited burning did not occur. The increase in fire size due to ignition of the second bed was largely offset by exhaustion of the fuel of the initially ignited bed. The rate of heat release for the second bed was qualitatively similar to that for the initially ignited one but, due to the preheating of the second bed prior to its ignition, the time scale for its burning was compressed and its rate of heat release increased.

The concept of superposition of separate item free-burn mass loss rates to estimate the mass loss rate for multiple objects burning in a room

was found to be approximately correct for the cases studied, but may underestimate the mass loss rate to be expected in a severe room fire.

FUEL PARAMETERS

At the time this work was done, the full-scale fire tests that were to be simulated had just been completed. Only preliminary computer runs of the data were available. Documentation for the tests was being prepared, but information was scattered among a number of workers and data notebooks. The amount and type of fuel involved in these tests, as verbally reported to the author and as used in developing these simulations, is listed in table 1. Note, however, that this information may not correspond exactly to that actually applicable and which will be reported in the official test report. Any difference is expected to be minor and would not affect the spirit of the simulations as they attempt to capture the qualitative features of the fires, with only approximate quantitative agreement sought.

The author had witnessed one of the fire tests and viewed video tapes of others. He had discussed the qualitative behavior of the specific tests of interest here with the test chief, Mr. B. Lee. The behavior of the bed was reported to be generally similar in the room and in the furniture calorimeter: After ignition of the wastebasket, the bedding rapidly became involved. Fire spread over the whole surface of the bed and, under the bed, the dust cover on the underside of the mattress burned. This fire soon subsided as the bedding was consumed. Note that the bedding was made-up on the bed and then rumpled to simulate a

"slept-in" condition. This allowed it to burn more independently of the mattress than if it had been in the unrumpled, made-up condition (as had been the case of the bedding in the previous mattress simulations [1]). After passing through a minimum burning rate, the fire grew again as the mattress and bed frame became involved. The fire spread to include the wooden headboard and, eventually, the side table (and, for rooms with combustible walls, the walls).

Figure 1 presents the heat release rate versus time for three furniture calorimeter tests of a bed-sidetable unit ignited by a wastebasket. Note that there is a distinct difference between test FB01 and tests FB04 and FB06*. FB04 and FB06 are about as close as can be expected for repeat full-scale fire tests. Test FB01, although differing significantly from the other two, is qualitatively similar and still within the quantitative agreement often found in repeat full-scale fire tests. A fourth repeat test, FB03, is not shown as figure 1 is already difficult to read. It was close to FB04 and FB06. An average of FB03, 04 and 06 was adopted as the typical behavior to be expected for this fuel and the behavior to be simulated.

Figure 2 shows the result of a simulation of this fuel in a room 24.4 x 36.6 x 24.4 m high, ventilated by a single door 10.76 m wide by 24.03 m high. Thus the simulation is essentially for a "free-burn" or burn

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* Test details are available in [3]. The tests were numbered FB01, 02, ... for free-burns (i.e., those conducted under the calorimeter hood) and RB01, 02, ... for room burns (i.e., those conducted in the enclosure whose vent discharged into the calorimeter hood).

"out of doors" of the fuel. Several implications of this figure are noteworthy.

> The simulation reproduces the two separate peaks. The simulation peaks are somewhat broader than the observed ones and the dip between slightly deeper. The predicted heat release rate beyond the second peak (from 850 to 1100 seconds) is somewhat above the average of the observations.

> The height of the first peak has been adjusted to an approximate average of the observed peaks for FR03, 04 and 06.

> The simulated igniting wastebasket produces a more pronounced peak than the actual one.

The simulation presented in figure 2 uses a total of four objects. Object 1, the igniting wastebasket, is identical to that used in [1]. For the present tests the ignition source was nominally similar to that used in the previous study so the same parameters were used. Objects 2-4 simulated the bed and other furnishings. Object 2 was intended to simulate the light fuel (bedding) responsible for the first peak. It combined a relatively small amount of fuel with rapid fire development. Its area corresponded to that of the bed top surface, increased somewhat to account for the observation that the bedding draped over the sides of the bed and the dust cover on the under side of the mattress burned during the first peak period. Object 3 was to simulate the fuel causing the second peak. It included slightly less than one-half the remaining fuel. Its 16 kg mass was only 60% of the combustible in the mattress and spring. It had a slower growth rate and slightly smaller area to represent the mattress itself and the box spring. Except for the reduced mass, relative to its size, the parameters used to define the burning of the mattress and spring were similar to those found satisfactory in the earlier study for the

simulation of a mattress [1]. Object 4 contained the remaining mattress and spring fuel, as well as the headboard, bed frame and the sidetable fuel. It had a smaller area and was intended to represent the more massive parts of the bed and furnishings. These fuels would presumably become involved later in the development of the fire. Accordingly object 4 was positioned to ignite somewhat after objects 2 and 3.

The exact fuel parameters used are listed in table 2. They were arrived at by a trial and error process. The selection, however, did follow a pattern. The fire growth parameter varies the time between an object's ignition and full involvement and, in particular, the steepness of the rise to peak burning. The object area (provided it has enough mass, as discussed below) sets the height of the peak. The object's mass sets the length of steady burning once the peak has been reached. Finally, for the algorithm used in these simulations, the rate of decay as the fuel becomes exhausted is determined by the burnout time constant. Transition to burnout is set by an input parameter: the fraction of the object's initial mass at which transition occurs. For the algorithm used, the two burnout constants are not modified as the burning conditions vary throughout the simulation. If the object's mass is small relative to its surface area, the burnout phase of its behavior may encroach on the growth phase. In this case there will be no steady burning period and the peak burning rate will depend on the combination of all the parameters. This is the case for objects 2 through 4 of this simulation. For

objects 2 and 3, the growth rate was chosen to give the observed rate of rise ahead of the peak, the burnout time constant chosen to give the observed slope after the peak and the object mass, area and burnout transition chosen to give the desired peak height. In doing this, mass was shifted between the three objects comprising the bed system, but the total mass was always equal to the actual mass. If the burnout phase parameters had been made functions of the heat flux incident on the fuel surface, the extent of the overlap between the growth and burnout phases might have been altered. A small change in the overlap would change the peak burning rate substantially as the steeply rising growth and sharply decaying burnout phases became more separated. The burning area was forced by the bed dimensions but was adjusted within a small range around this value.* The result gave too deep a trough between the two peaks so, in the final choice of parameters, the first peak was broadened somewhat so that the minimum between the first and second peaks was raised. This was accomplished by increasing the bedding mass from 3.2 to 4.14 kg. and lengthening the burnout phase of object 2's involvement by increasing the mass fraction for the

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* As stated earlier, the maximum burning area for object 2 (the bedding) was increased over the bed's surface area to account for the bedding draped over the sides of the bed. This worked well. The area for object 3 (the mattress) was initially taken as the bed"s geometric area. To reproduce the desired peak heat release rate this required a relatively small burn-out rate constant and yielded a broad, flat peak. Reducing the area and increasing the rate constant gave the desired shape. The area, however, was less than the bed's geometric, top surface area. For object 4, the area had to be much less than the geometric area for a satisfactory representation of the data. In interpreting this, it must be remembered that the burn algorithm assumes a circular fire, growing until it covers the entire object. The actual fire may not be circular, but may migrate across the object

transition to burnout. In fitting the second peak, the logarithm of the observed data was plotted against time. Two distinct decay regions were found: between 700 and 900 seconds the rate of heat release dropped rapidly; after 900 seconds, a distinctly slower rate of decay was observed. If a single object were used to simulate the behavior after 500 seconds either the upper part of the peak would be too broad, or the tail (beyond 900 seconds) not well reproduced. In addition, for a qualitatively satisfactory fit to the free-burn data, only about half the total fuel available could be accounted for; if more fuel were used, the second peak was much too broad. By dividing the remaining fuel between two objects (3 and 4) the narrow peak could be simulated while still accounting for all the fuel.

Having arrived at a satisfactory set of free-burn fuel parameters, these were used for the remaining one-bed simulations. For simulations involving two beds a change was necessary. The Harvard simulation used allows for a maximum of five objects. With three objects per bed unit, two beds could not be simulated. It was decided that the behavior after the second peak was of less importance than that prior to and immediately around it. Accordingly, for the two bed simulations, the object representing the late burnout phase was eliminated. Thus five objects, total, were used: the ignition wastebasket (object 1), the

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with an irregular shape. In some cases, parts of the object ignited early in the fire may actually burn-out before other parts become involved. The fire may be moving across the object without growing much in size. This is an explanation for the parameter selection found necessary for object 4. It may not be the only explanation.

first bed (objects 2 and 3; object 4 omitted) and the second bed (two objects identical to objects 2 and 3). Figure 3 compares the free-burn rate of heat release for the 3 object and 2 object bed simulations. One may think of these two object, two bed simulations as though the room contained only the wastbasket and two beds made up with bedding but without headboards. There would be no other furniture in the room.

FIRE TESTS AND TEST ROOM SIMULATIONS

Two nominally identical tests were conducted in the burn room fitted with gypsum walls and ceiling. The observed rate of heat release versus time for these two tests is shown in figure 4. The data shown in figure 4 were computed from the gas mass flow rate and oxygen concentration recorded in the exhaust stack of the hood located outside and above the burn room door. The same procedure was used to compute the heat release rates shown in figure 1 except, in the latter case, the fuel was not burned in the room but, rather, on the floor outside the room and directly under the hood. Thus the data of figure 4 includes heat released by burning occuring outside the room as well as that in the room. Test RB01 shown in figure 4 is qualitatively similar to tests FB04 and FB06 shown in figure 1. However, both peaks of RB01 are distinctly higher for the room burn than any of the calorimeter ("free") burns. The other room burn, RB04, is qualitatively different. It shows three peaks: the first, corresponding in time to the first, RB01 peak, has a much diminished amplitude although it is nearly as high as that of FB06. The second and third peaks of RB04, on the other

hand, are much higher than any of the free-burn tests or the second peak of RB01. These experimental results suggest a definite effect of the room on the total rate of heat release.

Several observations must be made relative to figures 1 and 4. 1) A senior CFR staff member more familiar with the rate of heat release calorimeter than the author pointed out the possibility that, especially during periods of high heat release rate, flames may extend close to the hood surface; the relatively cool hood might cause some quenching. Quenching may have occured in both the free-burn and room tests, but, due to the differing flame geometries, would probably have been more significant for the free-burns. Thus the rate of heat release shown in figure 1 may be somewhat less than a true free-burn would have recorded and the difference between the free-burn and room burn heat release rates may be less than figures 1 and 4 suggest. 2) The peak rate of heat release during the free burn was about 1.2 MW. The flame plume from a pool fire entrains about sixteen times its stoichiometric air requirement between the burning surface and the visible flame tip, or, for this 1.2 MW fire, somewhat over 10,000 scfm of air, the rated capacity of the hood system. Thus, this fire would probably result in a layer of hot gas trapped in the hood between the hood skirt and the exhaust. To the extent that a hot layer formed in the hood, the fire would not be a true free burn, but similar to a fire in a well ventilated room. Thus, the calorimeter burns would have somewhat the character of a room burn; the difference between the "free" burn and room burn tests would be reduced by this. 3) The video

tapes of RB01 were reviewed with particular regard to the amount of flame visible outside the door. It was assumed that any appreciable heat release outside the room door would be obvious as flames. Indeed a large flame plume extended from the door for about 50 seconds at about 250 seconds into the burn. This was preceeded and accompanied by a considerable volume of black smoke. However, during the second period of high heat release, from 700 to 850 seconds, no flames were seen outside the door. The room was relatively free of smoke, but flames extended to and across the ceiling. 4) In discussions of the simulation and test results with CFR staff it has been suggested that the large augmentation of the first peak for RB01 might be due to burning of the paper on the surface of the gypsum wall board. Because of the large amount of smoke and the camera angle relative to the fire, the video tapes shed no light on this speculation. The author can find little test data to confirm or refute this idea. Loftus et al [7] report on the potential heat of gypsum board with and without the paper coating. The net effect of the paper was +18.5 MJ per square meter of gypsum surface. If this heat were released by burning the paper off the room ceiling as a triangular pulse of 60 seconds duration (see figure 4) it would produce a peak rate of heat release of almost 2 MW or about the amount of additional heat needed to account for the observed behavior. If the paper ignited later (at about 610 seconds, just as the mattress began to be significantly involved) for RB04 rather than as the bedding burned (RB01), much of the disparate behavior of these two tests could be reconciled.

In addition to rate of heat release, gas temperatures in the upper part of the burn room provide a useful comparison with the simulation. Although many temperatures may be recorded in the experiment, the simulation calculates only an average value for all the hot gas in the upper part of the room. In choosing a comparison temperature, therefore, either some average must be constructed, or a single thermocouple representative of the average should be chosen. Gas temperatures in the burn room were recorded by a "thermocouple tree" located 0.3 m in from the left wall and 0.3 m back from the front wall. Thermocouples were located at 0.10, 0.44, 0.90, 1.44 and 1.94 m from the ceiling. They showed that the hot-cool interface was about 1.5 m below the ceiling after 200 seconds. Thus the three upper thermocouples would lie in the hot gas layer. The temperatures recorded by these three differ little throughout the test. They also follow closely values recorded by thermocouples located near the ceiling in other parts of the room with the exception of two near the rear wall, left and right of the room centerline. These were about 100 K higher during the peak burning period around 700 seconds. The video tapes of the fire suggest that these two thermocouples were near or in the flame plume attached to the rear wall, extending from the headboard to the ceiling and into the ceiling jet. The same three tree thermocouples also closely followed the readings of the six uppermost thermocouples of a "tree" mounted in the doorway. (Those from 0.1 to 0.81 m below the door soffit.) The thermocouple 0.44 m from the ceiling has been chosen as representative of the average hot layer temperature. Its readings are presented in figure 5. Also shown in

the figure is the simulation's computed hot layer temperature for the four object fuel package in the standard room.

In addition to the "free-burns" described above, simulations were run for three rooms. The basic room, corresponding to the actual fire test room, was 2.44 by 3.66 by 2.44 m high. It had a single vent, a door, 2.03 m high by 0.76 m wide. The other two rooms had the same vent, but were, for the "double" room, 4.88 x 3.66 x 2.44 m high, and the "quad" room, 4.88 x 7.32 x 2.44 m high. In the smallest room, only one bed-sidetable unit was considered, as it would not be possible to fit two such units in the room. This simulation corresponded to the test fires burned with non-combustible walls. The double room could accomodate two full-size beds and some additional furniture, although it would be a bit crowded. The quad room was about the size of a large, contemporary motel room. Furnished with two beds and ancillary furniture it would not be crowded. In the two larger rooms only one bed was ignited by flame contact from the wastebasket. The other bed was positioned so that it could only ignite by radiation from the initially ignited bed and from the hot upper walls, room ceiling and hot gases trapped in the room.

Simulation of the room fire tests based on the four object fuel package discussed above and whose free-burn rate of heat release is shown in figures 2 and 3 gave only slightly augmented heat release rates. The free-burn and room burn results are compared in figure 6. Through the first 600 seconds, the results are virtually identical. The second

peak is about 10% higher for the room than for the free-burn. As shown in figure 5, the hot layer temperature is distinctly lower than the experimental result. The simulation showed no ventilation-limited burning at any time during the fire (there was always more than enough oxygen to burn all the fuel pyrolyzed). The minimum calculated oxygen concentration in the upper part of the room was 12 weight percent. This is consistent with the video tape observation of no flames coming out the door for the time around 700 to 850 seconds, but not for the earlier peak around 250 seconds where a large flame brush extended from the door.

To explore this discrepancy further, the simulation input was modified to yield heat release rates closer to those shown in figure 4. This was accomplished by delaying the burnout transition by increasing the burnout transition mass ratio in proportion to the fraction: object total heat flux divided by the heat flux received from only its own flame (see table 2, note 5). The result is shown in figures 7 and 8. Clearly the observed temperature is better simulated by this. For this simulation, the minimum oxygen concentration in the upper layer was 10.1 weight percent at 690 seconds. The plume air entrainment was 1.63 times the stoichiometric requirement for the burning rate prevailing at that time. Thus the simulation did not show ventilation-limited burning even with the heat release rate increased to the experimental value.

If the heat release rate of figure 4 is correct, then either the

free-burn result inferred from the calorimeter test is too low (due to hood quenching?) or the simulation algorithm used is too insensitive to the room conditions. The detailed simulation data sheds some light on the latter possibility. The rate of growth of fire area and pyrolysis rate per unit area, if not influenced by burnout, depend on the heat flux incident on the fuel surface and thus may be increased by placing the object in a room. During the first peak near 250 seconds object 2 is the only significant contributor to the fire. Object 1 (the igniter wastebasket) had burned out at 130 seconds; object 4 had not yet ignited and object 3's slowly developing fire produced two orders of magnitude less heat than object 2. At 260 seconds, the time that the temperature peaked, object 2's surface received just over 3% of its heat from the hot gas layer and virtually none from the still relatively cool ceiling and upper walls. 97% of the heat flux incident on the surface came from its own flame plume. It seems unlikely that this result would be much changed if the burnout parameters chosen were made more sensitive to the incident flux (and then adjusted to yield the free-burn result, as was done here). Thus the very large augmentation of the first peak observed between the free and room burn experiments cannot be explained by this model*. The second peak occured at 720 simulation seconds. At this point object 2 was nearly burned out and was producing two orders of magnitude less heat than object 3. Object 4 was beginning to be a significant contributor, providing about 16% of the heat released. Object 4 had lost very

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* i.e., some other mechanism, such as the gypsum board paper surface burning discussed above, must be invoked.

little of its initial weight and its burning was not influenced by the burnout aspects of the simulation. It received slightly less than 1/3 its heat from the hot gas layer and ceiling. Thus object 4's rate of heat release could be and was altered by the room. It provided much of the burning rate augmentation found. Object 3 received only 18% of its heat from the hot layer and ceiling so it would not be as strongly influenced by its surroundings as object 4. In addition, at this time, it had lost nearly half its initial weight and was beginning to enter its burnout phase. This, in the present algorithm, is not sensitive to the heat flux incident on the fuel; it is only sensitive to the mass remaining. For this second peak, although the bulk of the heat to the surface of object 3 came from its own flame, there was enough heat from the room to alter its burning rate. Although this did occur, its amount was smaller than it might have been because object 3 was beginning to enter the burnout phase of its simulation. As a result of the algorithm structure, the simulation probably under predicted the effect of the room on object 3.

The level 5.2 Harvard room fire simulation wall heat transfer algorithm assumes a simple wall construction consisting of a single, homogeneous layer of inert material exposed on its cold side to ambient air. This is not appropriate to the test room used in these experiments. The test room walls were a single layer of 0.015 m thick gypsum wall board furred out from cement block (except for the front wall containing the door). Thus the single layer of gypsum, treated by the simulation as the entire wall, was actually only the first layer of a multi-layer

wall. Treating the fire exposed layer as the entire wall may be adequate for the short time during which heat is absorbed by the exposed face but does not have time to penetrate through the first layer. For longer times, the rear face of the exposed layer begins to heat. Then the heat transfer conditions assumed for the back face of the simple wall are no longer appropriate. One might compensate for the overly simple wall conduction algorithm by increasing (artificially) the thermal conductivity of the assumed single layer of wall material. However, this would change the thermal inertia of the material and alter its transient response in an undesirable way.

Examination of figure 7 shows that, for the "altered" simulation parameters, the heat release rate actually exceeded the experimentally determined heat release rate throughout the entire second peak. Nevertheless, figure 8 shows that the predicted room temperature was below the experimental value at and beyond the peak. Numerical experiments done as a part of other simulations suggest that this is partially due to inadequacies of the single layer wall heat transfer simulation. HO5.2 assumes that the lower walls and floor do not heat. This would also result in too large a heat loss late in the fire.

DOUBLE AND QUARDUPLE SIZE ROOM SIMULATIONS

As stated earlier, simulations of the bed-sidetable fuel package were run for rooms of twice and four times the floor area of the test room. The predicted upper layer gas temperature for the three-object bed

simulation in the three room sizes is shown in figure 9. The effect of the increased surface for heat transfer (loss) is clear. Altering the wall conduction algorithm would change this result slightly with all three curves moved up late in the fire. The effect prior to 900 seconds would be small as, up to this time, little heat has penetrated to the rear face of the fire exposed wall layer.

The behavior of a two bed fuel package was simulated for the two larger rooms. In these simulations each bed was simulated by only two objects, those representing the bedding, and the mattress and spring. The object representing the bed frame, headboard and the sidetable was omitted for each fuel package for the reasons explained earlier. The second bed was positioned relative to the igniter wastebasket and primary bed so that it could only ignite as a result of radiant heating from the wastebasket and primary bed fires. Flames from these fires could not contact the second bed. It was close to the primary bed, to simulate the furniture arrangement commonly found in hotel rooms fitted with a pair of similar beds. In the larger room the second bed heated but did not reach its ignition temperature. In the smaller (double size) room the second bed did ignite. It is of some interest that, had its ignition temperature, 450 centigrade, been only slightly higher (10 degrees) it would not have ignited. The mass pyrolysis rate for this simulation is shown in figure 10. Arrows on the time axis point to the ignition times for the two beds. Comparing the mass pyrolysis rate of the primary bed (from 50 to 700 seconds) with that of the second bed (dotted curve from 710 seconds on) shows that they are generally

similar but that the time scale for the second bed's involvement is somewhat compressed and the peak pyrolysis rates raised. This is because the primary bed was cold when ignited whereas the second bed had been preheated until its surface reached ignition conditions. Thus flame spread across the second bed would be rapid and more of the heat flux incident on its surface would be available to pyrolyze fuel, while less would be needed to heat its interior.

It is also seen from figure 10 that the peak mass loss rate for the two bed case is only slightly higher than for one-bed. This is because of the limited fuel available in the first bed. At the time the second bed ignited 56% of the mass of the first bed had already been consumed and, at the time the second bed's bedding peaked (820 seconds), 72% of the mass of the first bed was gone. Had the beds been more massive, or the second bed ignited earlier (for example, because of a lower ignition temperature), a higher total peak mass loss rate would have been achieved. Because the first bed was burning out as the fire on the second bed grew, ventilation-limited burning did not occur in this room with its vent size and with this fuel load. The minimum calculated oxygen mass fraction in the upper gas layer was 13% at 700 seconds, when the first bed burning peaked, and 11.9% at 1090 seconds, just after the second bed burning peaked. The upper gas layer descended to 0.94 m from the floor at 630 seconds. This still gave 0.34 m clearance between the bed surface and the layer, enough for the fire plume to entrain more than enough air for the then current pyrolysis rate. The closest approach to ventilation-limited burning

occured at 1080 seconds when the plume entrained 1.9 times the stoichiometric air requirement.

It has been suggested that free-burn pyrolysis rates for each object in a room can be added to give the post flashover behavior of a multi-object fuel load in the room [8]. The pyrolysis rates for the objects which became involved at flashover would be added to that of the primary fire with their free-burn ignitions shifted to the time of flashover. Figure 10 shows that this would be only approximately true. Even where the room causes little augmentation of the burning for the first object ignited, preheating of subsequently ignited objects may significantly alter their free-burn behavior.

CONCLUSIONS

The experimental data shown in figures 1 and 4 suggests that there was a considerable augmentation of burning as a result of the fire being within a room. While the simulation suggests that some augmentation may have occured, the amount was much less than these two figures indicate. It is proposed that the experimental and simulation fire situations may not be strictly comparable since the gypsum walls and ceiling of the room, assumed inert by the simulation, may have contributed much of the augmentation as their paper surface burned off. Nevertheless, the pyrolysis rates may have been increased more by the room than the simulation showed because of limitations in the simulation's treatment of the burnout phase of an object's burning

cycle. The burnout phase of the algorithm is empirical; no satisfactory physical mechanism has yet been proposed which would cause the observed burnout behavior. Thus it is not possible to suggest a physical mechanism by which burnout might be made sensitive to incident heat flux. The present data provides some basis for a change in the empirically derived algorithm used, but further confirmation should be sought before a change is made.

The simulation did not show any period of ventilation limited burning but the video tapes of the fire did show a considerable flame brush exiting from the room door as the bedding fire peaked. It is suggested that, at this time, the gypsum board's paper surface might have been burning. The appearance of flames out the door might have been simply a consequence of a vigorous fire located so near the vent that its natural flame was too long to be accomodated entirely in the room. Note that appearance of a flame out the door is not necessarily the result of ventilation-limited burning; it may simply be caused by the location and flame size of the fire.

The concept of superposition of free-burn pyrolysis rates to estimate the post flashover burning of multiple objects is only approximately valid. Although the room may not greatly alter the behavior of one object, there can be substantial changes in burning behavior as a result of preheating of objects in the room prior to flashover. This cannot be readily inferred from the free-burn (furniture calorimeter) test data although it might be estimated from material properties using

techniques similar to those embodied in the Harvard burn algorithm.

It should be possible to design a test which would demonstrate the effect, if any, on the rate of heat release, of a substantial flame brush impinging on a gypsum wall-board ceiling. Since the resultant flame might extend a significant distance from the room door for a long enough time to cause ignitions outside the room of origin (even though that room had not flashed over in the conventional sense), it would seem desirable to clarify this point.

The Harvard fire simulation wall-conduction algorithm should be extended to allow more accurate treatment of multi-layer walls including air spaces. H05.2 should also be altered to allow for the heating of the lower walls and floor. The current H05.2 simulation of the burnout phase of an object's behavior may be in error because it is insensitive to incident heat flux.

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Table 1

Fuel Loading in Fire Tests

Fuel Item	Combustible Weight in Kilograms
Filled Wastebasket	0.75
Bedding (1)	3.2
Mattress and Box Spring	24.7
Headboard	14.4
Night Table	10.6
Total Combustible Furnishings	53.7

Notes

1) Two pillows, two pillow cases, two cotton sheets, one blanket

Table 2

Fuel Simulation Parameters

Fuel Item

1 - Wastebasket and contents

Parameter	Value	
X	0.434	m
Y location coordinates	2.13	m
Z	0.32	m
Thickness	0.25	m
Equivalent Radius	0.2	m
Maximum Burning Radius	0.2	m
Density	35.	kg/m**3
Heat of Pyrolysis	3.98E+5	J/kg
Initial mass	0.35	kg
Flame Spread Parameter	2.78E-2	m/sec

2 - Bedding

Parameter	Value	
X	1.22	m
Y location coordinates	2.74	m
Z	0.6	m
Thickness	0.1	m
Equivalent Radius	0.913	m
Maximum Burning Radius	1.263	m
Density	19.32	kg/m**3
Heat of Combustion (1)	3.00E+7	J/kg
Heat of Pyrolysis	2.00E+6	J/kg
Initial Mass	4.14	kg
Ignition temperature	723.	K
Smoke fraction	0.25	gm/gm
Flame Spread Parameter	1.60E-2	m/sec
Burn-out Time Constant	40.	sec
Burn-out Rate Constant (5)	0.52/0.55	

3 - Mattress and Box Spring

Parameter	Value	
X	1.22	m
Y (2) location coordinates	1.44	m
z	0.48	m
Thickness	0.25	m
Equivalent Radius	0.913	m

Maximum Burning Radius	0.843	m
Density	54.0	kg/m**3
Heat of Combustion (1)	3.00E+7	J/kg
Heat of Pyrolysis	2.00E+6	J/kg
Initial Mass	16.0	kg
Ignition temperature	723.	K
Smoke fraction	0.25	gm/gm
Flame Spread Parameter	5.00E-3	m/sec
Burn-out Time Constant	60.	sec
Burn-out Rate Constant (5)	0.5/0.66	

4 - Bed Frame, Headboard, Sidetable

Parameter	Value	
X (3)	2.088	m
Y location coordinates	1.44	m
Z	0.48	m
Thickness	0.25	m
Equivalent Radius (3)	0.43	m
Maximum Burning Radius (4)	0.469	m
Density	54.0	kg/m**3
Heat of Combustion (1)	3.00E+7	J/kg
Heat of Pyrolysis	2.00E+6	J/kg
Initial Mass	32.66	kg
Ignition temperature	723.	K
Smoke fraction	0.25	gm/gm
Flame Spread Parameter	5.00E-3	m/sec
Burn-out Time Constant	600.	sec
Burn-out Rate Constant (5)	0.4/0.72	

Notes:

1) For all objects the program default values were used unless values are given in this table. The default value for the fraction of the heat of combustion actually realized . = 0.65 The heat released by an object is proportional to the product of its heat of combustion and the fraction actually released. Two to three figure accuracy heats of combustion can be found for many materials, but . values for turbulent, diffusion flames amount to little more than educated guesses. Because of the large uncertainty in ., use of exact heats of combustion is not particularly important.

2) Physically, objects 2 and 3 are centered near the same point. They were separated to see if this (a) made any difference to the simulation and (b) alleviated a poor convergence (excessive iterations) near the second peak. It had no effect on either, but the centers were kept separated.

3) Center placed to cause ignition at about 475 sec. This placed the peak burning for this object at close to 900 sec. The equivalent radius and location of object together with its rate of flame spread determine the ignition time for object 4.

4) The simulation is not particularly sensitive to the choice of this radius.

5) Second value used for simulation adjusted to produce the experimental rate of heat release around the second peak of RB01 (result shown in figures 7 and 8).

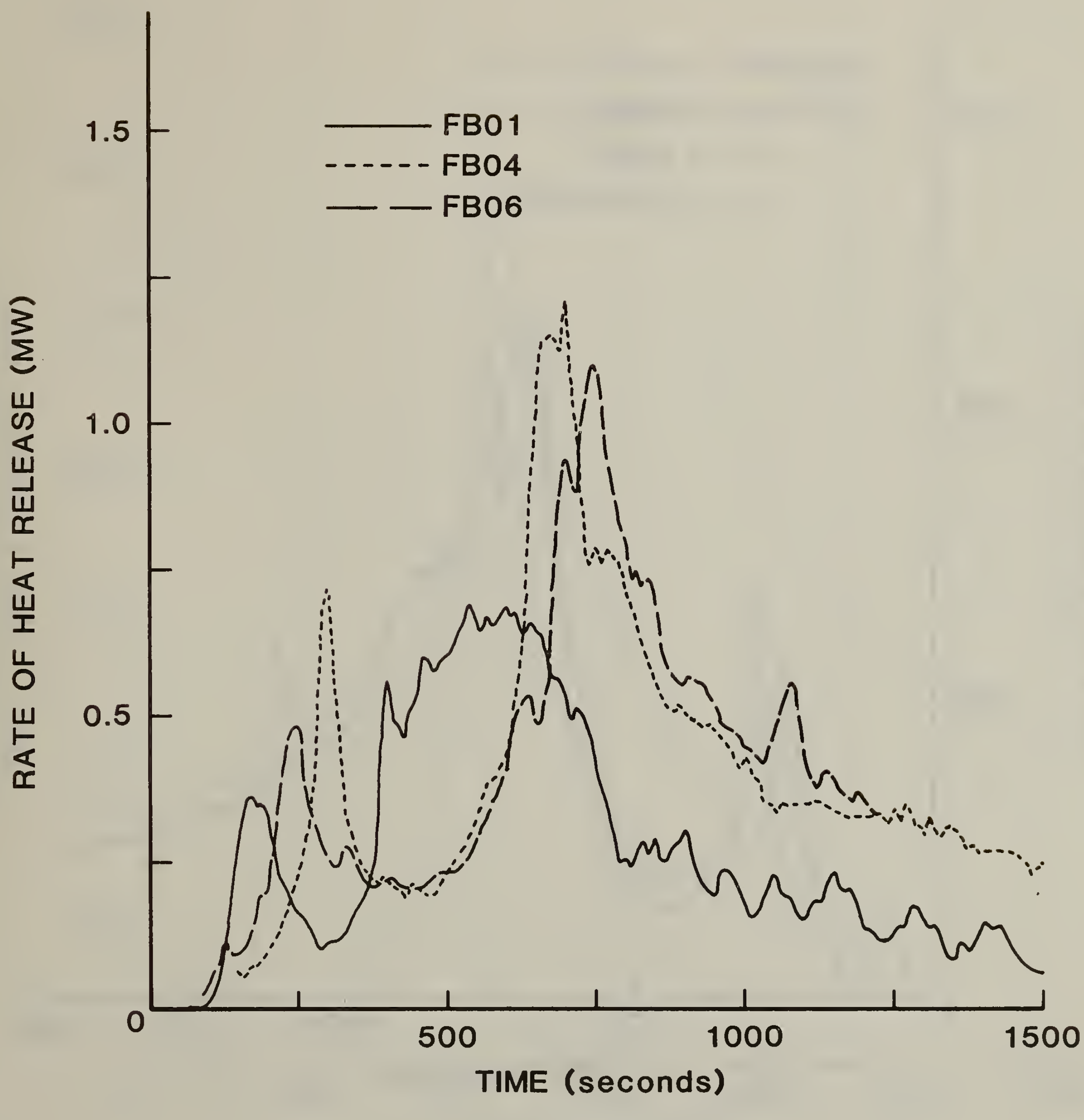

Figure 1. Experimental rate of heat release versus time, furniture calorimeter data, bed with headboard made up with bedding, sidetable: three repeat tests of nominally identical furnishings

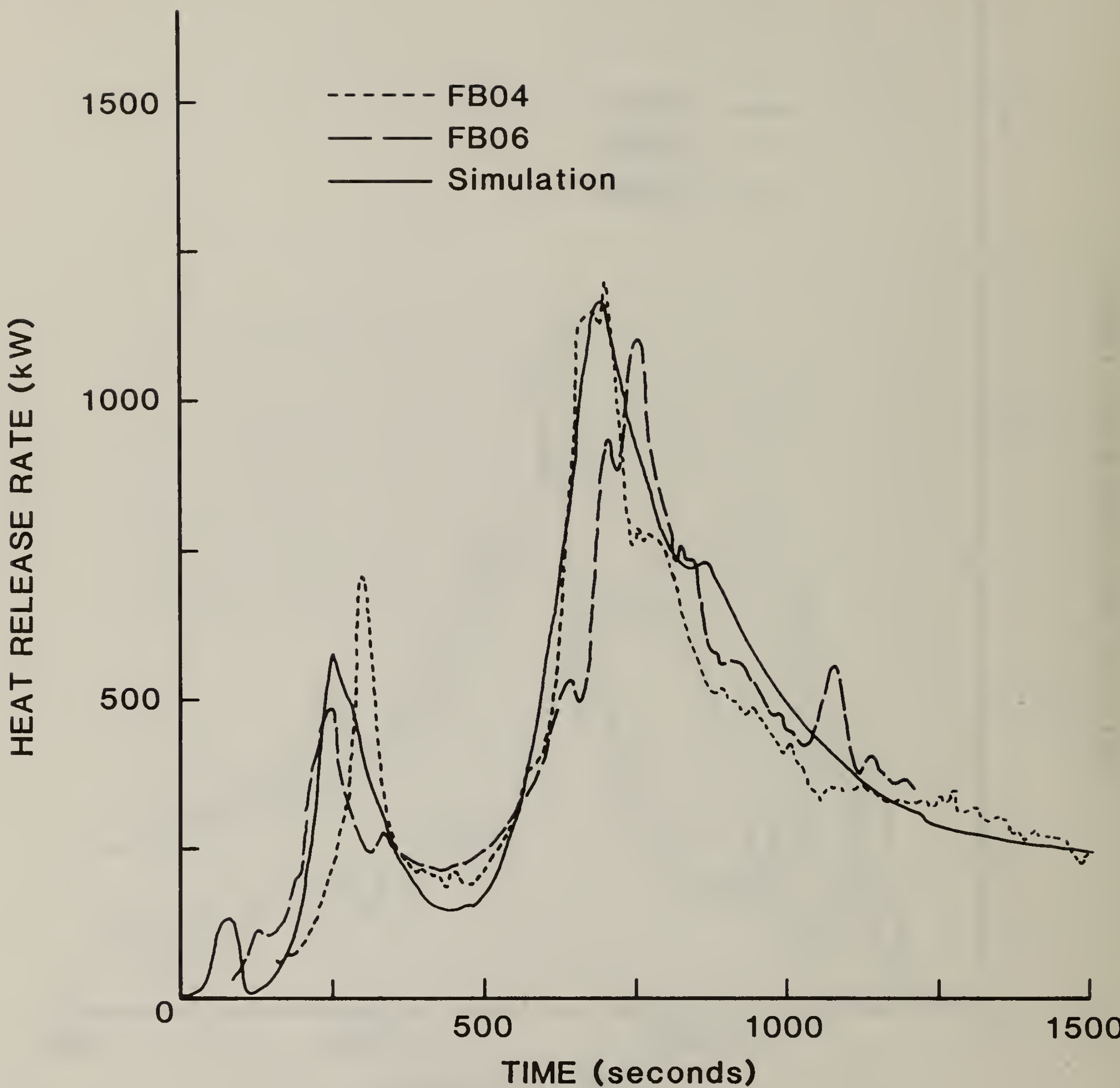

Figure 2. Furniture calorimeter rate of heat release data compared to free-burn simulation

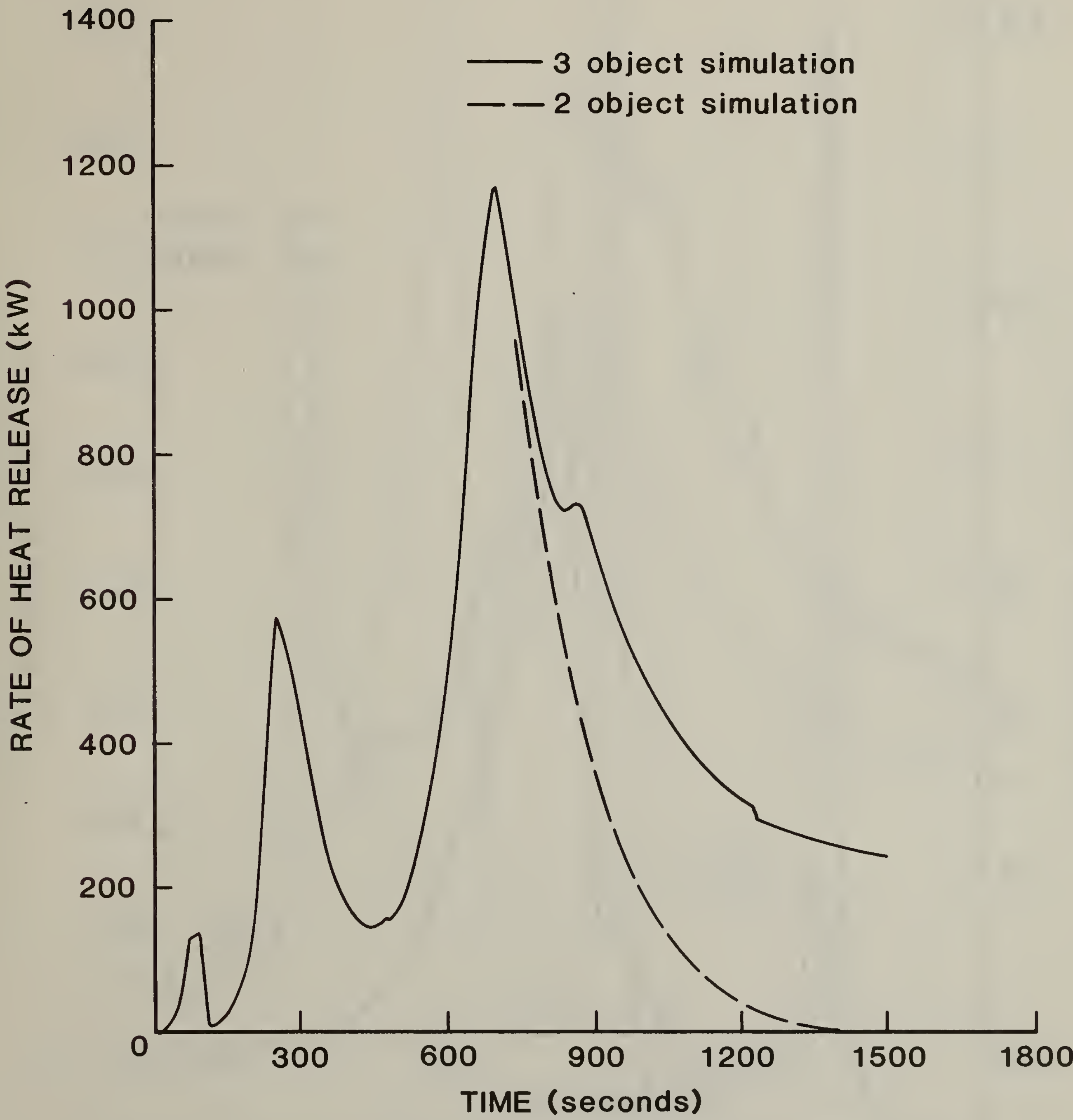

Figure 3. Free burn simulation rate of heat release versus time for 2 and 3 object bed-sidetable simulations

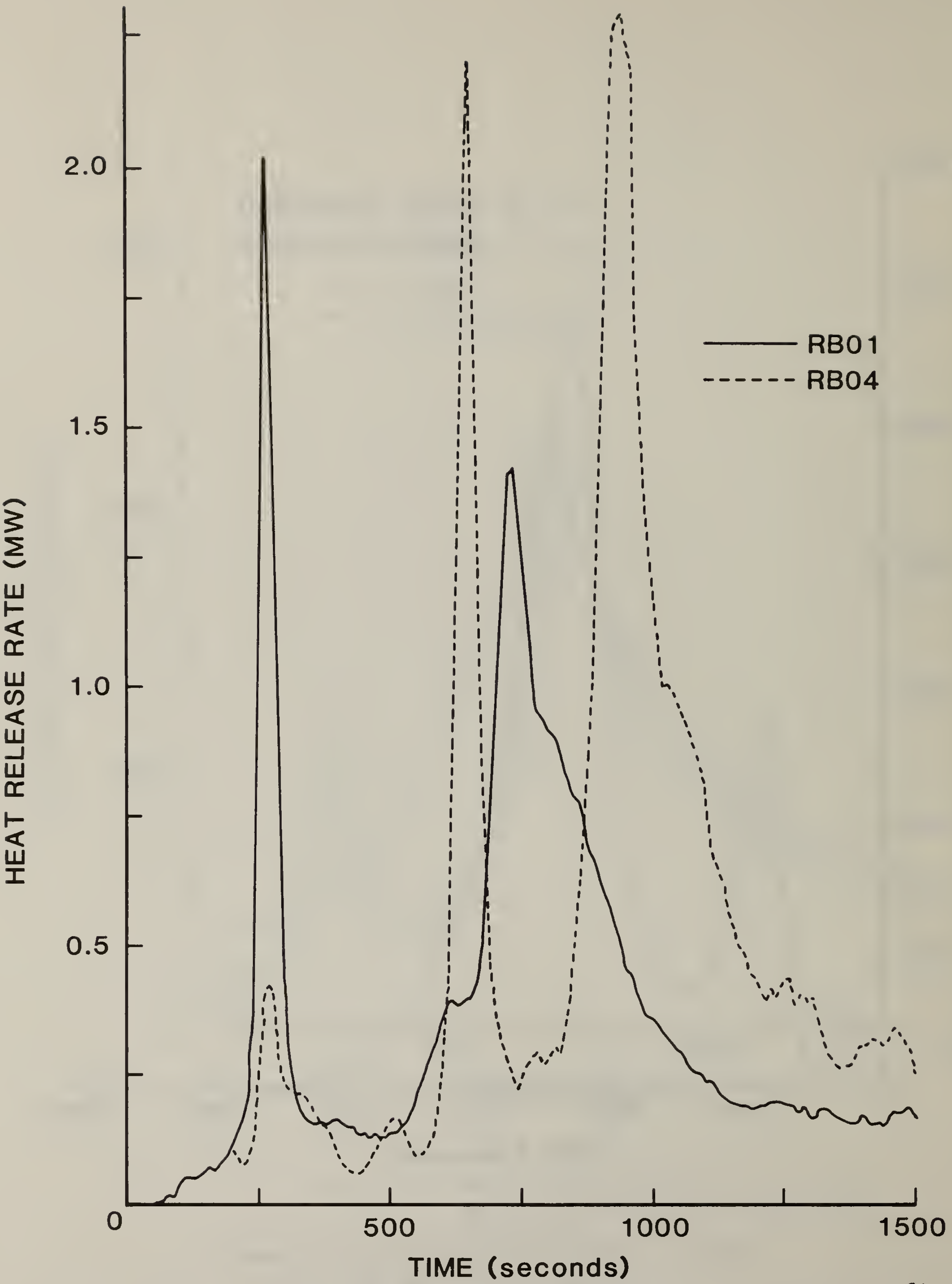

Figure 4. Experimental rate of heat release versus time, room fire test, gypsum walls. Based on hood stack flow and oxygen concentration data: two repeat tests of nominally identical furnishings

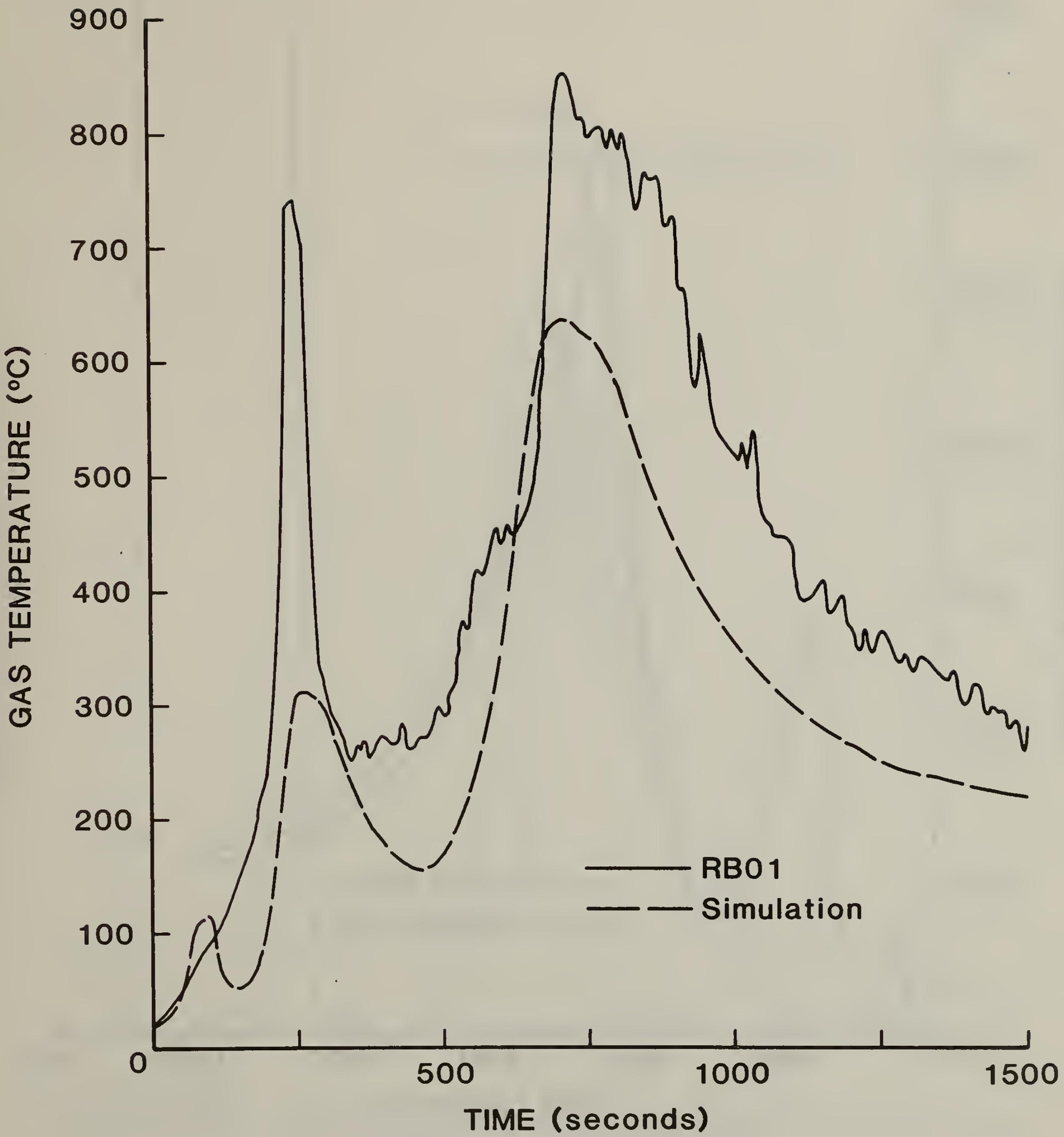

Figure 5. Gas temperature, 0.44 m below the room ceiling, 0.3 m from left wall and 0.3 m from front wall. Also included is the calculated temperature of the upper layer for the 3 object simulation

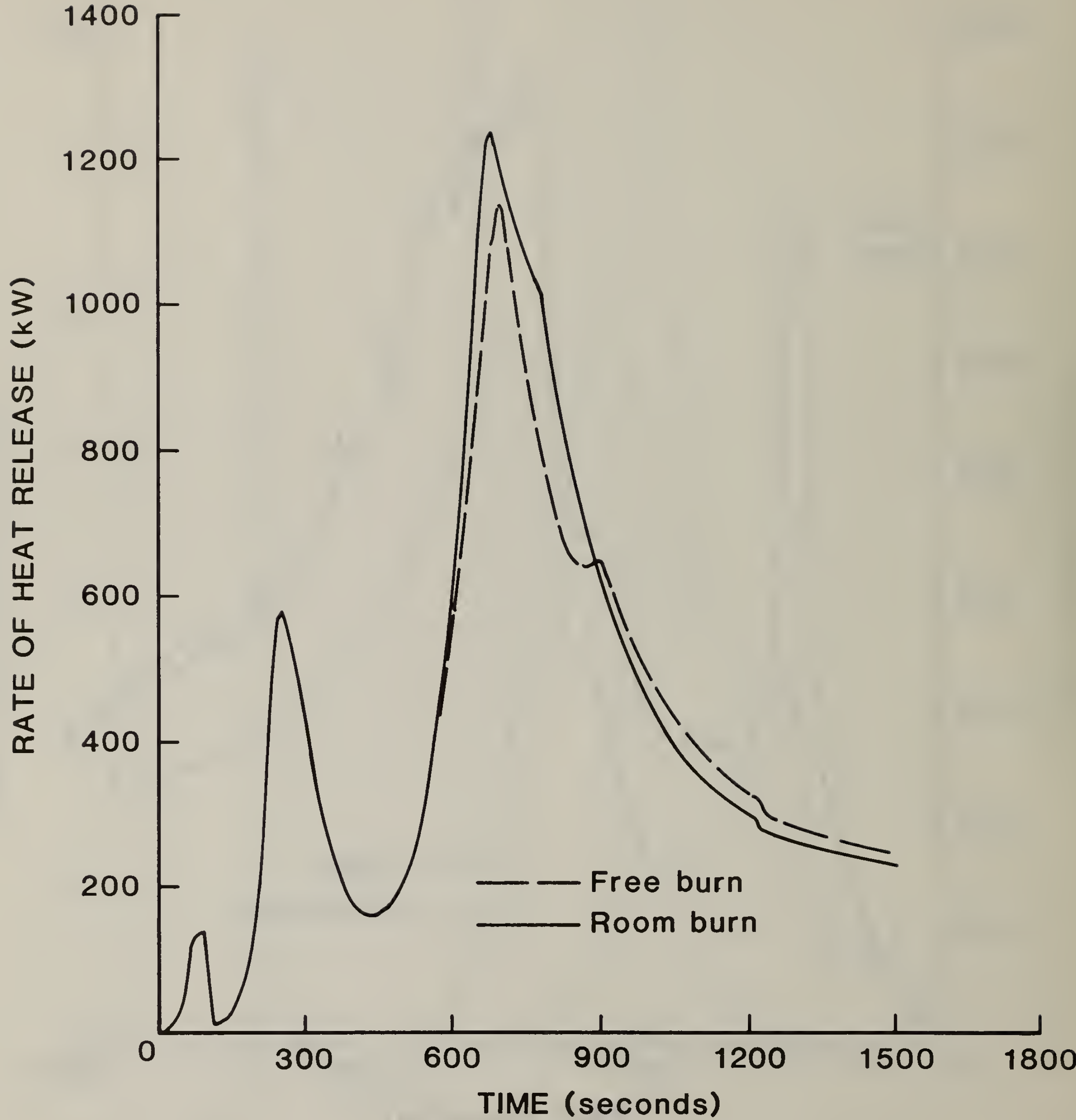

Figure 6. Rate of heat release for the simulated free and room burns

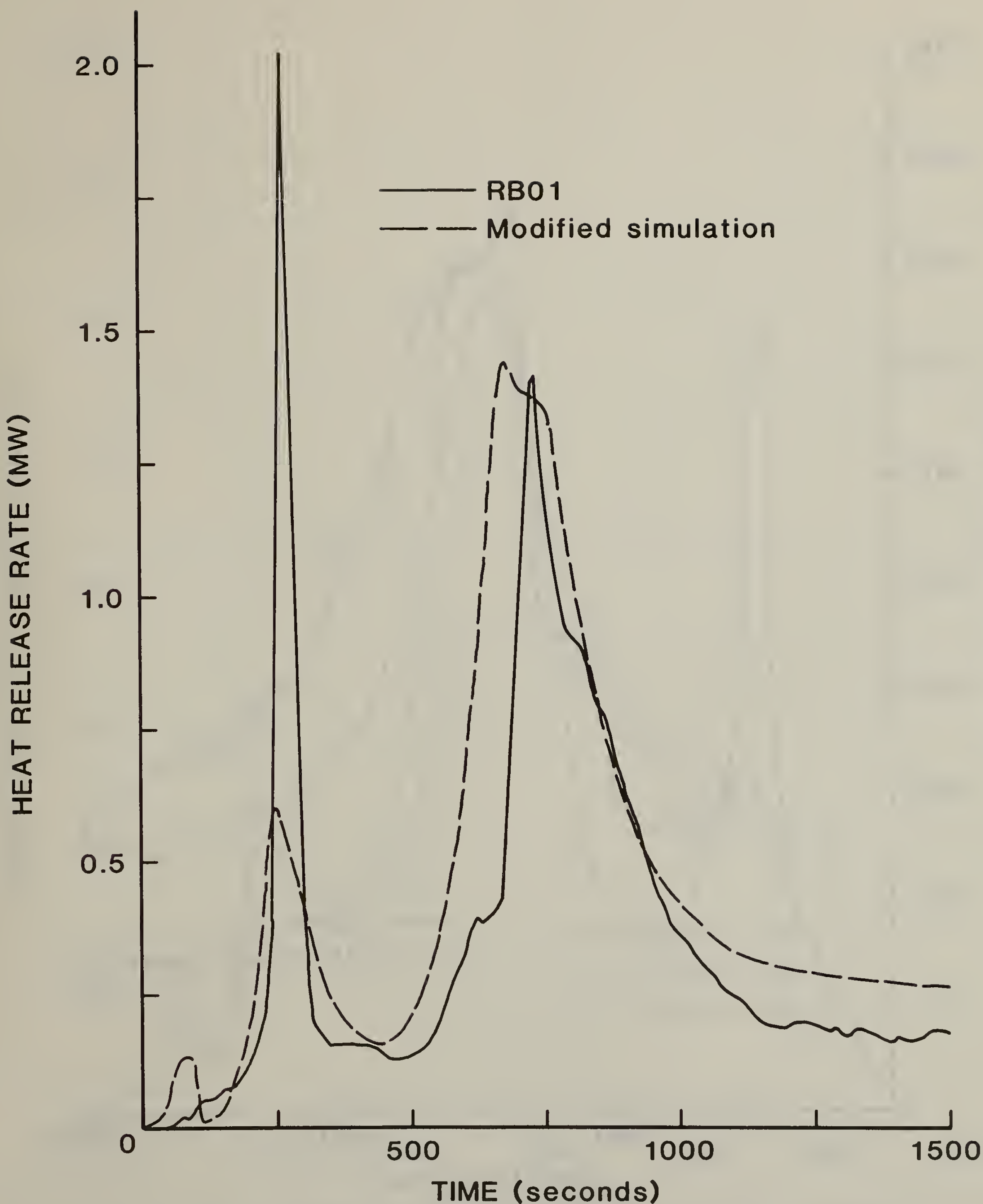

Figure 7. Rate of heat release for the simulated and room burns. Simulated variables changed to reproduce better the heat release of the room burn as recorded by the hood stack sensors

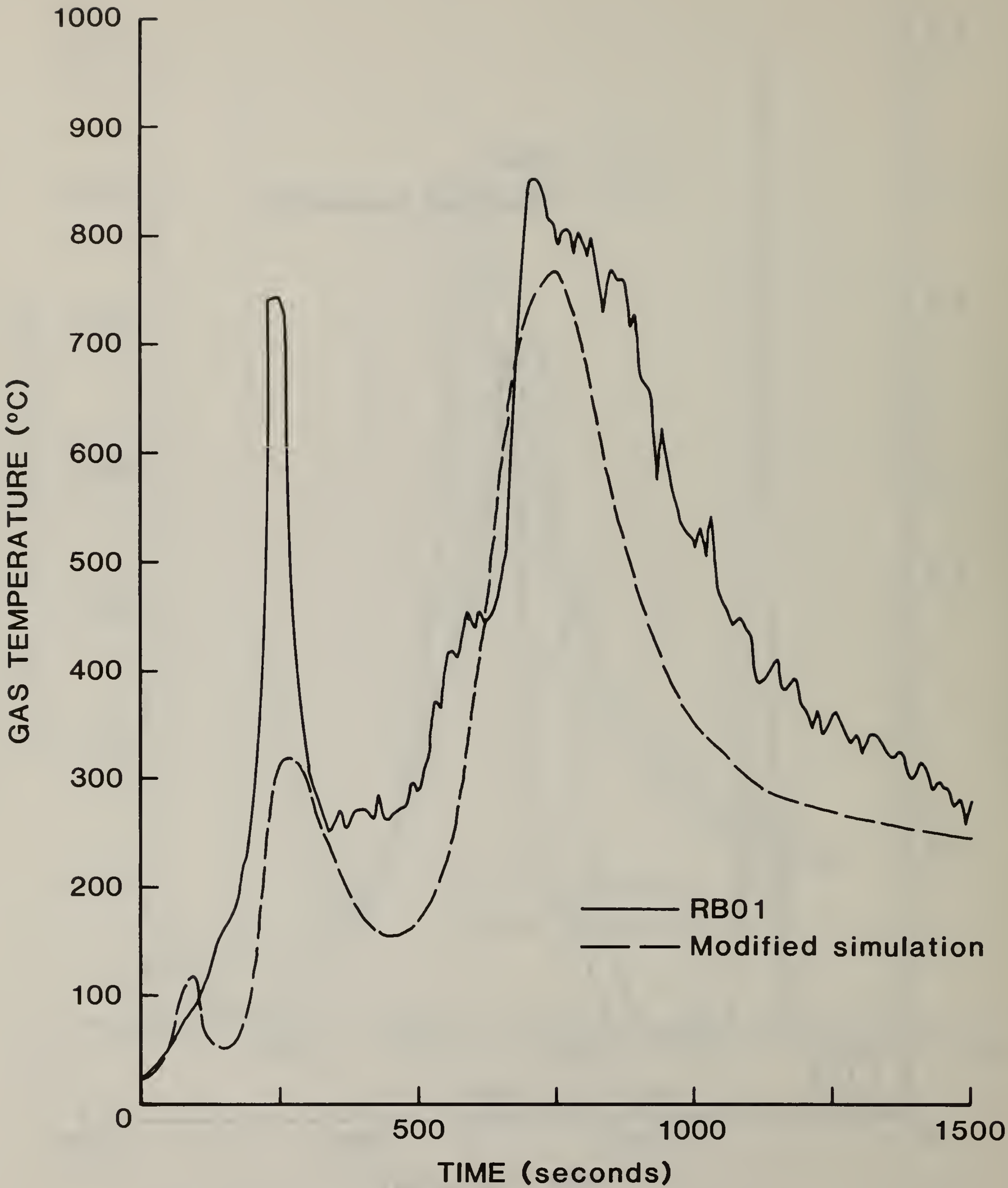

Figure 8. Upper gas temperature for the simulated and room burns. Simulation variables changed to reproduce better the heat release of the room burn as recorded by the hood stack sensors

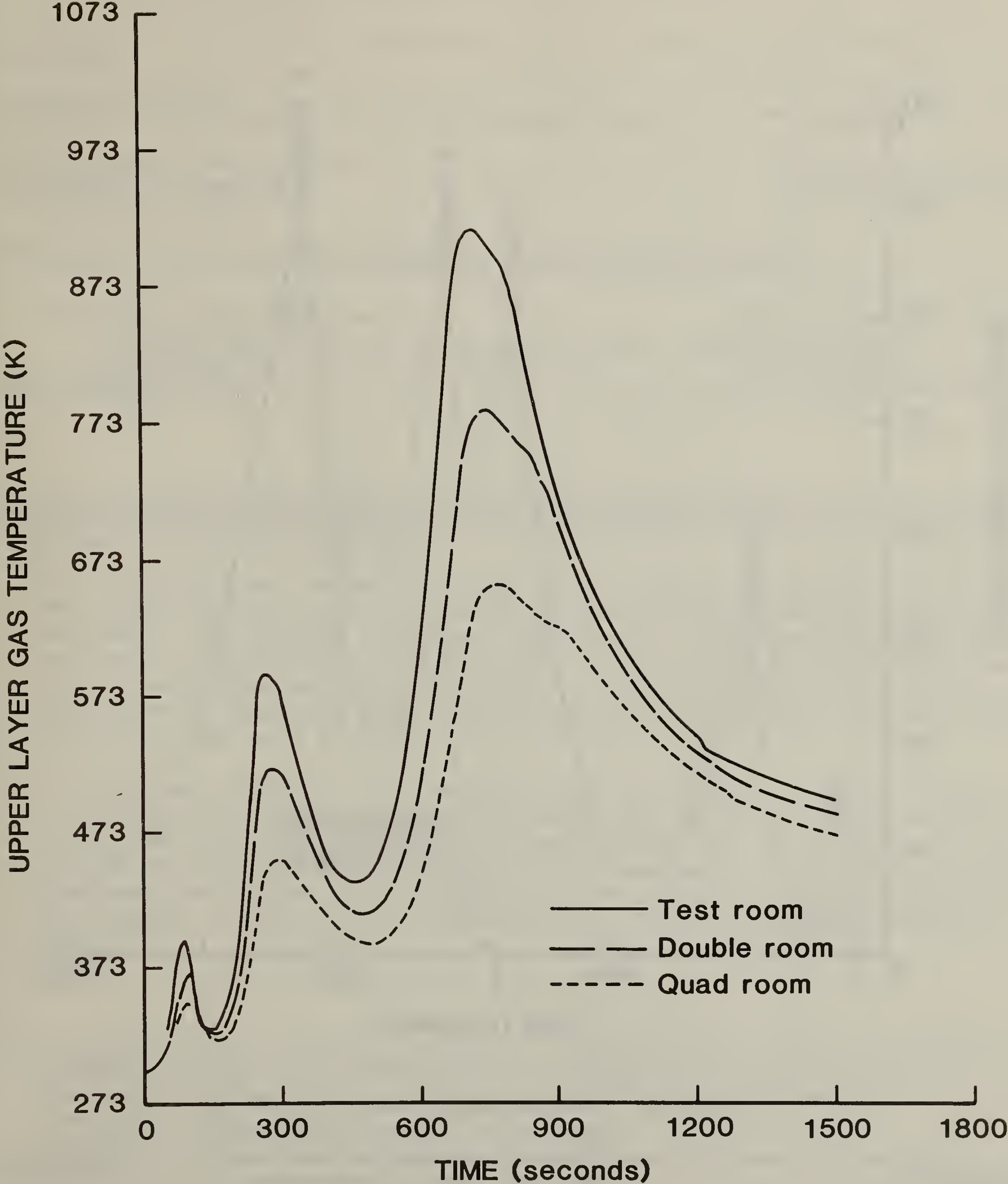

Figure 9. Simulated upper gas temperature for three rooms of differing area, identical vents: three object bed simulation

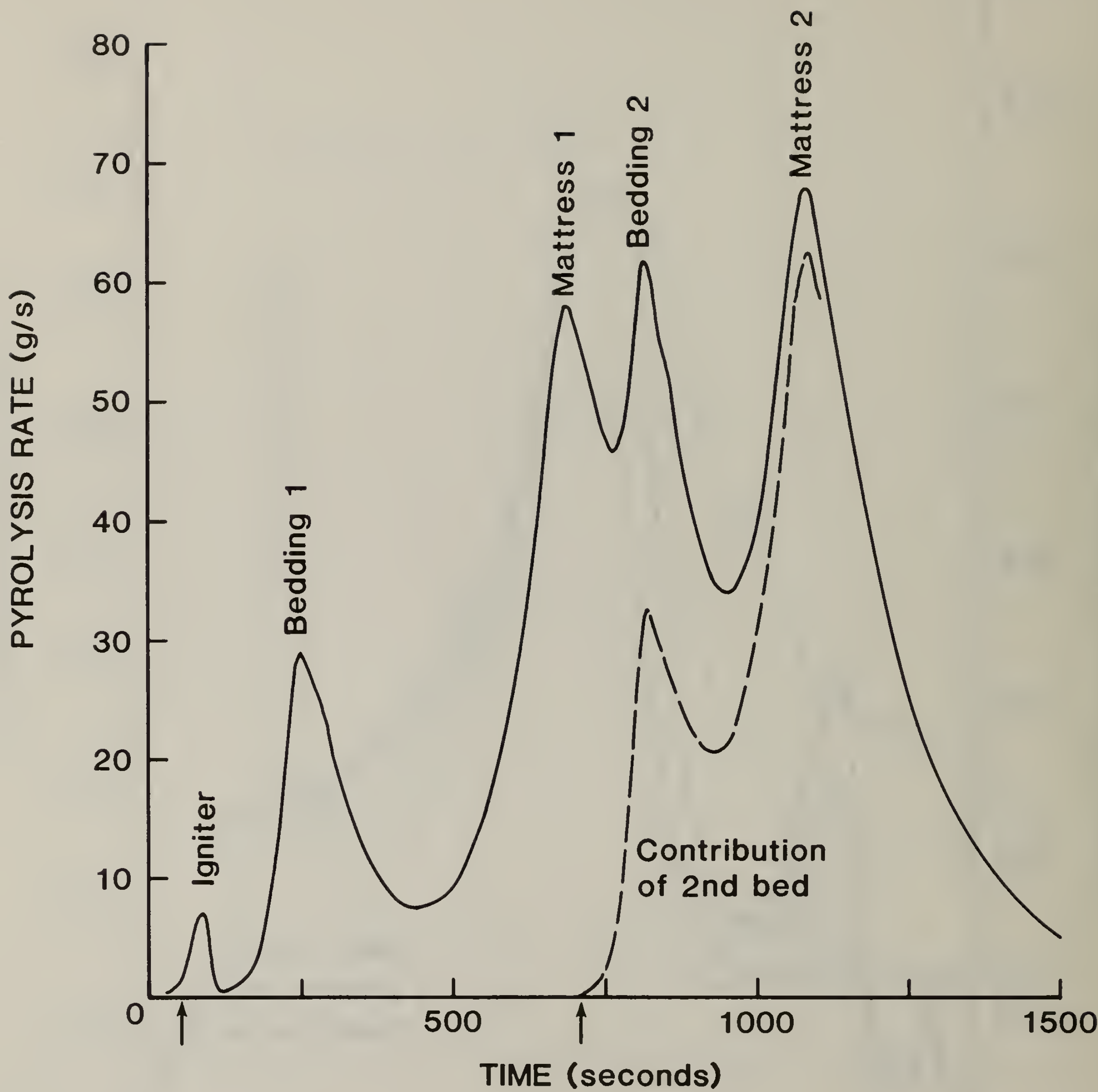

Figure 10. Mass pyrolysis rate, 2 object bed simulation, 2 beds, double room, first bed ignited by flame contact with burning wastebasket, second bed ignited by radiation from upper gas layer, walls and ceiling, and flames from other bed

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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)*

The Fire Center has conducted a series of full-scale tests of hotel-like rooms. The furnishings were a bed with headboard "made up" with bedding, and a wooden sidetable. The ignition source was a wastebasket. The furniture was burned in the new NBS furniture calorimeter and in a 2.44 x 3.66 x 2.44 high room. As an adjunct to analysis of the test results, a series of simulations of the fire tests were run using the Harvard Fire Simulation. This report describes the simulations and their results.

The principal finding of the simulations was that the room had little effect in augmenting the burning of this fuel package. The simulation result was partially due to the burn algorithm used and partially due to the relatively large fire area and short assumed flame radiation extinction length. This finding might not have been true had the individual objects been smaller in area or their flames less opaque. A different burn algorithm might also have produced different results.

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

Full scale fire tests; furniture calorimeter; rate of heat release; room fires

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