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On the significance of transient heat release rate excursions above a set limit

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Abstract

When a heat release rate limit for a consumer product is set by a regulatory agency, it is of interest to know whether small excursions above that limit, such as may occur due to production line variability, represent a disproportionate increase in fire hazard. This paper presents a methodology to examine this issue. The heat release rate curve of the object is described by a Gaussian time variation; a perturbation peak, also Gaussian, is added to this main peak. The impacts of the perturbation peak on the build up of hazardous conditions in a room fire (where the object is the only item burning) and on the threat of ignition of secondary items are examined. For the peak heat release rate domain studied here, only the ignition threat is significantly affected by the perturbation peak. The results quantify the trade-off between the height of the perturbation peak and its duration for a fixed percentage of increase in the room area threatened by secondary object ignition. The results show that the increased threat is of the same order as the relative perturbation in heat release rate.
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Keywords: Furnishings; Heat release rate; Ignition

1. Introduction

It is a common practice among various regulatory bodies to set an upper limit on the acceptable heat release rate (HRR) of various objects as assessed in some appropriate flammability test method. Thus, for example, the California Bureau of Home Furnishings (CBHF), in California Technical Bulletin 133, sets an upper limit of 80 kW for the HRR of chairs to be used in public occupancies. The US Consumer Product Safety Commission has recently set an upper limit of 200 kW for mattress/foundation sets used in residences (CFR 1633). These test methods apply one or more gas burners to the surface of the object to assess its HRR response, which is then measured by oxygen consumption calorimetry.

It is soft furnishing items such as beds and furniture, which are involved in a substantial fraction of the annual fire deaths in the United States; thus these items are a principal concern of the present study. However, the results should apply more broadly to situations where similar HRR limits are prescribed.

Subsequent to localized ignition by the gas burner(s), flames spread over and into the structure of the test object increasing the area that is burning and the overall HRR until, at some point, fuel consumption begins to cut back on the overall burning rate and the HRR declines, heading ultimately to zero. Thus, the burning process is inherently transient and the HRR behavior involves one or more substantial peaks. For various furniture items tested in Ref. [1], the burning durations ranged up to 20 min or more, but the time above a HRR half the peak value was more like 2–5 min. For bed assemblies (with ignition of the bed clothes) based on designs aimed at passage of the CFR 1633 criterion, the time above the half peak value is of the order of 5 min, though here there tends to be two peaks of such duration [2]. It is the highest peak HRR value seen over some test interval, e.g., 30 min, that is required to be no greater than an upper limit value such as one of those mentioned above.

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Because the typical soft furnishing item has an intricate structure, fire growth on it can be quite complex and somewhat variable from one nominally identical sample to the next. There may be one or more broad HRR peaks and each may be punctuated by short-lived "supplemental" peaks that send the overall HRR upward briefly. The prescribed HRR limit may be exceeded only by some short-lived transient HRR spike that is the result of some chance confluence of events in the burning of the object. Because of sample variability, such complexities are often not quantitatively repeatable.

The possibility of such short-lived, supplemental HRR spikes poses the question as to whether they represent a real threat. That is, does such a peak significantly increase the threat to the surroundings beyond that posed by the overall broader peak on which it rides? Alternatively, we might ask: can such a HRR spike that exceeds the set limit of a test method be deemed tolerable if its duration and/or intensity above the limit are less than some level? The very non-linear nature of fire growth and its impacts within a compartment means that the answer is not obvious. This is the issue addressed in this study. The results shed light on the nature of a regulatory HRR limit.

To proceed, it is necessary to develop an assessment methodology for the threat posed by a short-lived HRR spike. By short-lived here we mean a peak whose duration is short compared with the overall duration of the main HRR peak of the object being tested. Also, we focus on peaks, which are "supplemental" in that they add atop this broader, main HRR peak. To be of interest and of significance in relation to exceeding a set HRR limit, they must be near in time to the peak of the main fire. We do not address the related question of when the main peak itself lacks the duration or intensity to be a threat (see Ref. [4]).

We address the threat issue by considering the burning object in the context of a room. There are two types of threat a burning object in a room poses. First, it is a source of hot, toxic gases that accumulate in an upper layer and second, the burning object may, as a result of the radiation its fire emits, ignite surrounding objects (potentially leading to flashover). For the situations considered here, we will show that the main concern with the threat posed by short-lived HRR peaks is through their effect on the ignition of other objects. We will infer a relation between HRR peak duration and height that corresponds to a fixed level of increase in ignition threat.

Because the focus here is on the significance of HRR spikes in relation to a prescribed HRR limit, we focus on a particular domain for that limit, i.e., ca. 200 kW. As noted above, 200 kW is the limit for mattresses in CFR 1633. This is near the limit (250 kW) given for both upholstered furniture and mattresses in the NFPA Life Safety Code for various public occupancy buildings. A rationale for lowering the allowable peak HRR from residential bed fires to this range of levels is given in Ref. [4]; the arguments used there, based primarily on the "radiative ignition reach," are applied and extended here. To a first approximation, this same rationale and limit apply to furniture.

2. Analysis methods and results

2.1. Role of the hot, upper smoke layer

We consider first the effect of a HRR spike on the development of the hot smoke layer in a room. The NIST Consolidated Fire and Smoke Transport model (CFAST) is well suited to investigate this aspect of the overall effect of a HRR transient. As described below, the main fire peak and the HRR spike will both be taken to be Gaussian in time. We comment later on possible effects of this and other specific assumptions in the analysis.

The normal smoke-layer development (i.e., with no HRR spike on top of a Gaussian main fire peak) is as follows. The fire plume initially entrains room air quite strongly due to its nearly full room height. The initial plume flow is sufficient to potentially fill the room with smoke quite rapidly (roughly 10 s for a medium-sized room and a fire even as small as 50 kW) but, of course, the filling of the room cuts the entrainment length and, therefore, the entrainment rate and the total plume flow. Furthermore, as the room tries to fill, the flow out of an open door grows rapidly.[1] The net result is that the layer height drops to roughly half the room height in a few tens of seconds and then decreases at a much lower rate. That subsequent lower rate of drop is set by the filling of the surrounding rooms and the entrainment rate of the plume (which is approximately proportional to the 1/3 power of HRR). Here the CFAST calculations have been done for a six-room, single-floor house with a floor area of 109 m^2 (1173 ft^2); the fire is in a bedroom just off a central hallway. For a given peak HRR (here 200 kW), the filling time of the house depends somewhat on the time-width of the Gaussian main fire peak, since this determines the total heat evolved. For a main fire peak which has a half-height, full-width (HHFW) of 500 s, CFAST shows that the fill time of the house is about 500 s; for a HHFW of 250 s, it is comparable but filling is incomplete (i.e., the smoke layer does not reach the floor). This incomplete filling is significant in the present context, as will be seen below.

For fires of ca. 200 kW or less, the upper layer is not very hot in any absolute sense though it can reach lethal conditions. The layer reaches the neighborhood of 200 °C in the room of fire origin and, if its lower edge drops low enough, it cannot be avoided by crawling beneath it. It is the temperature level of the upper layer, not its toxic gas content, which poses the threat in this low HRR domain [3,4,5]. Very low-reaching upper layers (and the attendant difficulty of escape) need not necessarily occur if the total heat released is limited; certain bed fire cases (mainly

[1] We do not address the very different situation that occurs in a closed room. Such fires tend to be extinguished by a lack of oxygen but can create lethal conditions nonetheless.

consuming just the bedclothes) discussed in Ref. [4] involved relatively short-lived HRR peaks of about 200 kW size. CFAST showed that the smoke layer in this same multi-room context would remain above 0.7 m and escape would be possible if one stayed low. We return to this point below.

To simplify the present analysis, the existing fire is assumed to be a 1-m-diameter pool fire 1/2 m above the floor level and it is given a Gaussian time history. Soft furnishing fires tend to be centered some distance above the floor and can be distributed in a complex (and time-dependent) manner in space; concentrating the fire as a single pool should tend to give the highest upper-layer temperature in the analysis here. Then the HRR for the main fire is given as follows:

$$HRR(\mathrm{kW}) = 200\exp\left\{-\left[(t-t_0)/t_{\mathrm{MP}}\right]^2\right\}, \tag{1}$$

where t is the time, t_0 is the time after the start of the analysis at which the main peak occurs and t_{MP} is a characteristic time determining the width of this main HRR peak. For the CFAST runs, the value of t_0 is chosen such that the peak occurs at $1.73t_{\mathrm{MP}}$; this starts the analysis at a time when the HRR of the main fire is early in its peak (at 5% of its peak value) and is increasing toward its peak.

The HRR spike to be imposed on this main fire peak is also taken to be Gaussian in its time dependence. When a spike is present, the overall HRR is described by the following:

$$HRR(\mathrm{kW}) = 200\left\langle \exp\left\{-\left[(t-t_0)/t_{\mathrm{MP}}\right]^2\right\} + f\,\exp\left\{-\left[(t-t_0)/t_{\mathrm{FP}}\right]^2\right\}\right\rangle. \tag{2}$$

Here f is the fractional height of the HRR spike or fluctuation peak (as a fraction of the main peak) and t_{FP} is its characteristic time. Note that the same value, t_0, is used for the placement of both peaks, i.e., the peaks are taken to coincide; this is the worst, or very near the worst, case for additivity of the effects of the fluctuation peak.

This is the HRR inserted into CFAST in the context of the small bedroom noted above, with a fully open door. The room size is 3.08 m × 3.44 m × 2.44 m high (10 ft × 11.3 ft × 8 ft high). The smallness of the room enhances its response to the HRR fluctuation. CFAST then predicts the evolution of the upper-smoke-layer temperature and the layer thickness. It also tracks the potential consequences of exposure to the upper layer in terms of the fractional effective doses of heat and toxic gases.

Eq. (2) has two parameters pertaining to the HRR fluctuation peak, its intensity relative to the main peak and its time width. As noted in the Introduction, we are interested in combinations of these parameters, which represent some fixed percentage of increase in the threat (in this case, to room occupants) as a result of the HRR fluctuation added to the top of the main fire peak. Rather than simply examining the effect of each parameter separately, we treat this as an "experimental design" problem and do a two-level full factorial analysis [6]. This allows us to obtain an "empirical" equation for the effect of each variable plus any interaction they may have when both are changed at the same time. The equation is valid in the neighborhood of the parameter space in which it is generated. In this case, this type of analysis calls for four runs of CFAST, constructed as follows:

t_{FP} = low value, f = low value
t_{FP} = low value, f = high value
t_{FP} = high value, f = low value
t_{FP} = high value, f = high value.

Here the levels chosen for these two parameters are: 14.4 and 28.8 s for t_{FP} (these correspond to a full-time width at half the fluctuation peak height—denoted here as HHFW—of 24 and 48 s, respectively); 0.075 and 0.15 for f. Since we are interested in departures from the base case (with no HRR fluctuation), that case must also be run. The full set of five CFAST runs was performed for main peak time-width parameter values that were varied to yield main peak HHFW values varying from 100 to 500 s.

Fig. 1a shows the CFAST prediction for the temperature of the upper layer and the height of the lower "surface" of this upper smoke layer as a function of time for the base case, unperturbed fire with a main peak HHFW of 250 s. As described above, the layer moves quickly downward for the first 20 s or so then plateaus abruptly. By roughly 120 s it is again moving downward slowly as the entire house fills with smoke. For this fire, which is virtually over at 520 s, the smoke layer plateaus again at about 0.4 m above the floor. Note that there is an extended period of time during which escape is possible, and even when this fire is virtually over it would be possible to escape exposure to the smoke layer by crawling beneath it. The HRR perturbation peaks described above have essentially no effect on this mode of escape.[2]

Fig. 1b shows the base-case fire with a HHFW value of 100 s. Here the possibility of escaping exposure to the hot smoke layer is quite obvious—it never goes below a height of 1.4 m above the floor. Here again we found that the perturbation peaks have essentially no effect on this mode of escape. In the other extreme, here represented by a main HRR peak HHFW of 500 s (Fig. 1c), the situation does indeed becomes more threatening in that the smoke layer drops to about 0.2 m above the floor; this would be difficult to avoid even by crawling. There is still a significant amount of escape time prior to this; it is essentially unchanged by the presence of the HRR perturbations. The times to incapacitation or lethality, based on the upper-layer exposure for this case (indicated on Fig. 1c), are completely insensitive to the presence of the HRR

[2]The perturbations slightly lower the smoke layer at the time of their peak but the effect disappears by the time the smoke layer is at its lowest point late in the fire. The perturbations slightly increase the temperature of the smoke layer but this does not affect escape beneath it.

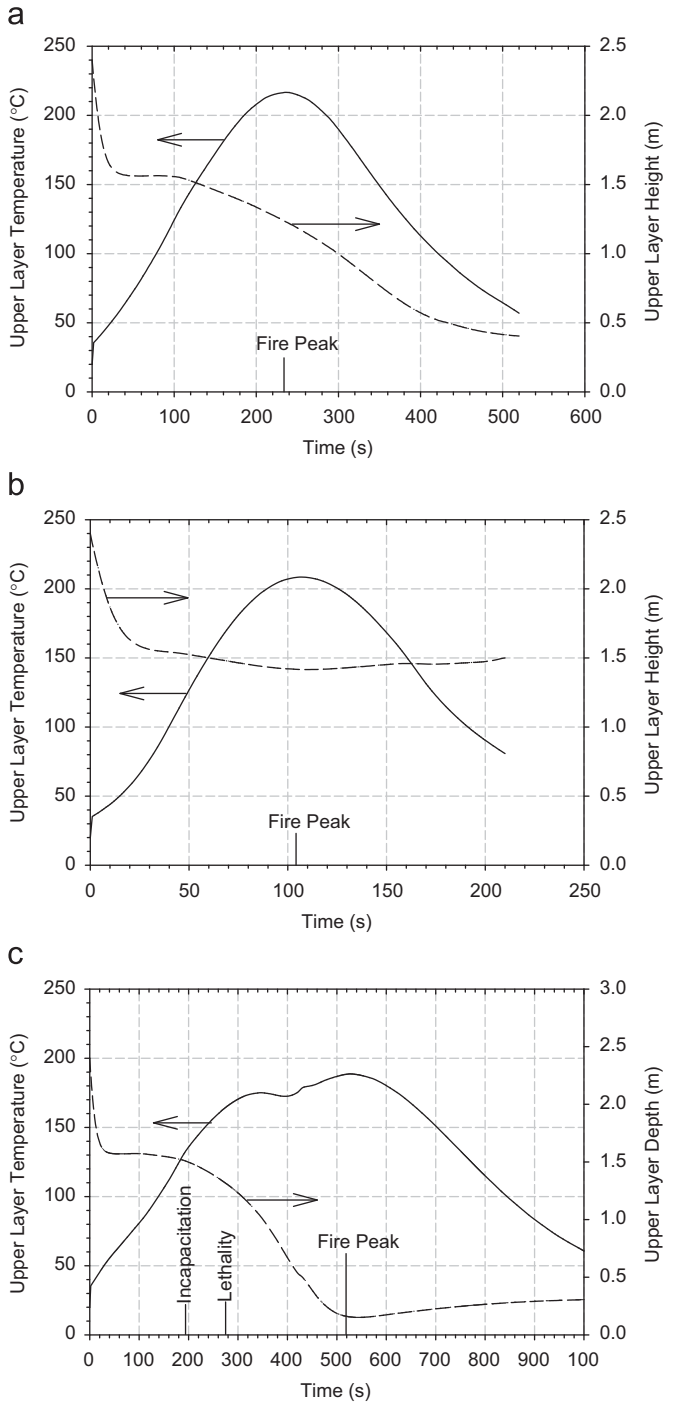

Fig. 1. (a) Condition in room of fire origin base-case: HHFW = 250 s (arrow refers to appropriate axis for each curve). (b) Condition in room of fire-origin base case: HHFW = 100 s. (c) Condition in room of fire-origin base case: HHFW = 500 s.

perturbation peaks since they occur well before these perturbations even start. The first of these times is that at which a person exposed to the upper layer smoke would become incapacitated, according to the ISO Document 13,571 criteria. As noted above, the cause of the incapacitation is heat (the combined effects of convection and radiation) and the effect is cumulative over the entire exposure time. Incapacitation is taken as occurring at 0.3 of a fatal dose.

Overall, it appears that the implications of the noted HRR perturbations to the main 200-kW HRR peak are negligible in as far as escape from the hot smoke layer is concerned. For fires of relatively short duration, the smoke layer stays high enough to permit escape and that escape is essentially unaffected by those HRR perturbations. Longer-duration fires ultimately can trap persons who do not leave during the available escape time but that escape time, is not changed significantly by the presence of the HRR perturbations.

Since the effects of the HRR perturbations here are not significant, the complete analysis to develop a relation between the two perturbation parameters and their measured impact has not been carried out. This is done, however, below in the context of the effect these perturbations have on the ignition of secondary objects in the room via radiation from the primary fire plume.

2.2. Role of potential ignition of secondary objects

As noted in the Introduction, the other possible effect of a HRR fluctuation or spike is the threat of ignition of other objects in the vicinity of the fire. The basic problem here is similar to that described in NFPA 555 [7]. The fire is surrounded by the radiant field from its plume.[3] The flux level decreases with distance in accord with the decreasing radiative view factor between the object and the plume. Here, in keeping with NFPA 555, we take the worst-case view factor, that at the mid-height of the plume; this provides the maximum "reach" of the ignition threat. The base-case fire thus provides a flux field, which will be perturbed (extended outward) by the HRR spike. In effect, the spike increases the plume height; this, in turn, increases the view factor at any given location and therefore the heat flux. This increase means that the potential for radiative ignition has been extended outward somewhat. Countering this is the fact that the spike is relatively short-lived and any object seeing the increased radiant flux requires time to heat up. Thus the consequences of the spike for the increased ignition reach can only be predicted with the aid of an ignition model for the secondary object.

Since the response of an ignition target to a heat-flux fluctuation depends on the nature of that secondary object, there is no unique answer concerning the absolute increase in maximum ignition reach caused by a HRR spike. Here we adopt the approach used in Ref. [4] by looking at a few surrogate materials. In that reference, we presented piloted ignition data for six materials representing the surfaces of a wide variety of secondary ignition objects. Here we use data for two of those materials but one is used in two ways

[3]It was found in Ref. [4] that the piloted ignition reach of the radiation field from a mattress fire substantially exceeds the reach of the flames on the mattress, thus we consider only radiative ignition here and not flame contact ignition.

to represent two types of ignition targets. Thus we used the properties of a 100% cotton fabric, which was the most ignitable material in Ref. [4], as a surrogate for the surface of a piece of upholstered furniture when its rear surface has negligible heat losses (due, conceptually, to a layer of polyurethane foam behind the fabric). That same fabric is a surrogate for a hanging fabric such as a window drape or clothing draped over an item of furniture when it is assumed to have radiative and convective heat losses from the back. Both of these cases are treated as thermally thin. Finally, we looked here also at a thermally thick case based on the piloted ignition data for a 1.27-cm-thick piece of white pine; this is a surrogate for the surface of a piece of wooden furniture. The heat conduction process in a thermally thick material somewhat alters its response to a spike in its surface heat flux (as compared to a thermally thin material). By looking at materials with this range of characteristics, we gain assurance as to the greater generality of our conclusions.

It should be noted here that we are referring to "potential" ignition because the ignition process being modeled here is piloted ignition. This is a conservative assumption since the non-piloted ignition reach of a fire will, in general, be less than the piloted ignition reach. Piloted ignition is a real threat—ignition of the chosen material can occur out to the maximum distances computed (see below), given the chance appearance of a spark or floating ember. Thus it makes sense to focus on it as a worst case.

The ignition models used here are simple and straightforward (see Ref. [4] for full details). Both use the assumption that a material has a unique ignition temperature. The material is assumed to be chemically inert until its surface reaches this unique ignition temperature, then it evolves fuel gases at a rate sufficient to yield an ignitable gas mixture above the surface and so piloted ignition will occur immediately. This is, of course, an approximation to the real complexities of temperature-dependent material degradation and gasification, but this type of model has been used successfully in many aspects of fire research. Here it gives a very good approximation to the ignition delay time versus incident radiant heat flux as measured in cone calorimeter experiments with the above materials [4]. In matching this model to the experimental data, the surface temperature at ignition and the effective thermal inertia of the solid are treated as fitting parameters. These same parameter values are then applied here (in the context of the same models) in computing the maximum ignition reach, for the particular material, around a 1-m diameter pool fire.

Both models include radiative and convective losses at front and back surfaces (the rear surface losses are turned off for the upholstered furniture surrogate, as discussed above). The thermally thick model includes one-dimensional heat conduction below the irradiated front surface. The incident radiant flux follows Eq. (2); if the spike amplitude is zero ($f = 0$) this becomes the same as Eq. (1)

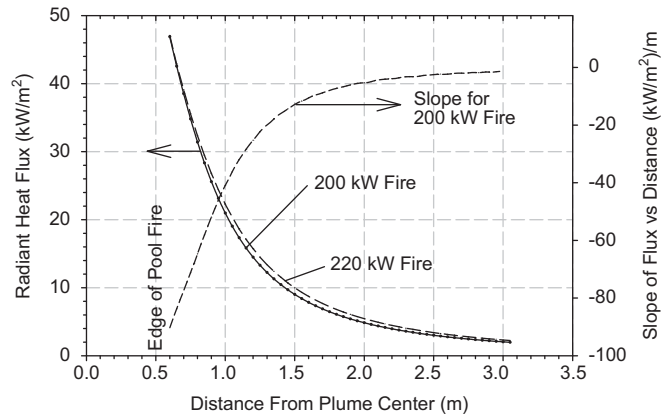

Fig. 2. Calculated radiant heat flux around a 1 m diameter, 200 kW pool fire (worst case flux to target at plume mid-height).

and describes the base case. The same "experimental design" approach is used as that in the previous section, i.e., a set of four perturbed cases is run with the same values as above for parameters f and t_{FP}.

Fig. 2 shows the radial flux distribution, at mid-plume height, around the 1-m diameter, 200 kW pool fire. This is based on the Shokri and Beyler emissive-power formula for the pool fire, as quoted in NFPA 555. We note that the original Shokri and Beyler paper [8] shows substantial scatter in the data for pool fires in this diameter range; however, the measured radiant fluxes from burning computer monitors [9] were generally consistent with levels predicted by this emissive power formula.

Fig. 2 also includes the radiant-flux distribution for a 220 kW fire to show the approximate level of perturbation in flux versus distance involved for the cases examined here. It clearly is not large; it also is not independent of distance from the pool fire center. In the radial distance range that will be found below to be most relevant for the secondary ignition targets considered here (ca. 1.2–1.6 m), the 10% change in fire HRR yields an approximately 10% change in radiant heat flux. We will assume such a one-to-one relation here so that the fractional size and characteristic width of a HRR spike carry directly over to the radiant-flux peak it engenders.

From the model(s) of ignition we will obtain the minimum peak heat flux (from the main fire) that will (when added to any flux spike) just yield piloted ignition of each of the materials. From the difference between the base case (unperturbed) and the four perturbed cases above, we find a relation for the incremental decrease in this minimum flux (as a function of f and t_{FP}). Ultimately, we want to obtain the incremental increase in distance from the fire over which piloted ignition of the target materials are just possible. This will be converted to a percentage increase in the area around the fire, which is at risk; this is the actual metric to be used to judge the significance of a HRR spike. To do this we need the slope of flux versus distance from center of the 200 kW fire; this is also shown in Fig. 2.

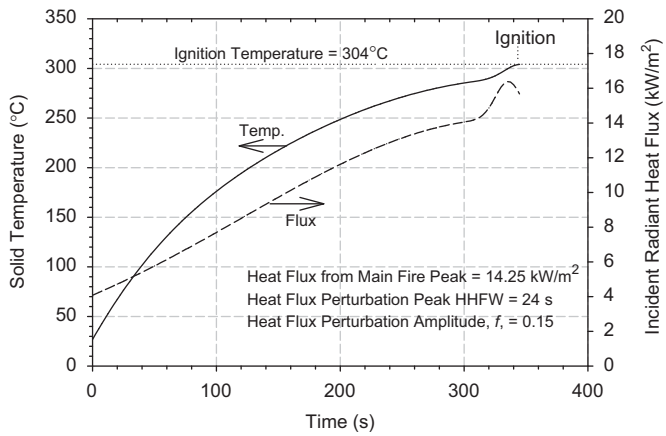

Fig. 3. Example of computed temperature–time curve at margin of ignitability. Cotton fabric with front and rear heat losses.

In seeking the minimum main fire radiant heat flux level that will just yield piloted ignition (i.e., just reach a surface temperature equal to the ignition temperature of the material), we ran the ignition model repeatedly with varied levels of the incident heat flux. Since the models require only a few seconds to integrate the transient energy equation describing the solid temperature, this was readily feasible. The minimum flux was typically resolved to 1/4 kW/m^2 or better.

The HHFW value for the main HRR peak was 500 s for most of the cases run here. Unlike the smoke-layer height examined with CFAST above, the ignition problem that is the focus here is minimally sensitive to the main fire peak width, as will be seen below.

Fig. 3 shows an example of the incident flux and resulting surface temperature history that just results in ignition for a particular set of perturbation parameters applied to the cotton fabric having both front and rear heat losses (drapery surrogate). The specific perturbation parameters shown here correspond to the lower value for the HHFW of the perturbation peak but the higher value of its amplitude. The figure shows that the monotonic rise of fabric temperature as a result of the rising main flux peak is rather mildly perturbed when the flux spike sets in just past 300 s; however, without this perturbation, this case would not have yielded ignition. The temperature boost via the flux spike is, of course, a function of the thermal mass of the fabric, which here is moderate. Ignition (a surface temperature for this fabric of 304 °C) is reached about 10 s after the main and perturbation fluxes have (together) reached their maximum. The main flux peak value of 14.25 kW/m^2 is seen from Fig. 2 to correspond to a distance from the pool fire center of 1.21 m. For this particular material and rear boundary condition, the minimum flux with no perturbation (i.e., the base case) was 15.55 kW/m^2, which occurs at a distance from the pool fire center of 1.16 m. Thus, the incremental effect of this flux spike was, in this case, an increase in the maximum piloted ignition reach of 0.05 m. This corresponds to an increase in the area around the fire at-risk for piloted ignition of 10.9%.

Note that we ignore the upper smoke layer in examining the effects of a HRR spike on the secondary object ignition. For a nominal 200 kW fire, the smoke layer, as it reaches 200 °C, is emitting about 3 kW/m^2. The average differential in this maximum radiant flux due to the HRR spikes with the characteristics given above is about 3/4 kW/m^2, and this occurs only in the final 20%–25% of the ignition process. A diminished radiative view factor for this upper layer radiation (as compared to that for the fire plume radiation) makes this effect even smaller. Thus, the main effect of the upper layer radiation for the low HRR fires considered here is a small shift to shorter ignition times, and a slight increase in maximum ignition reach for all cases in the factorial analysis due to the base case 3 kW/m^2 (diminished by the view factor and the short application time).

From the five model runs that give maximum ignition reach (for the base case and four perturbed cases), we obtain a set of four incremental departures from the base value of the minimum flux for ignition of the material being addressed. Using the "design of experiments" analysis method [6], we obtain a relation between this flux increment and the HRR spike parameters. Thus for the cotton fabric treated as a drapery surrogate, we obtain

$$\Delta\dot{q}_{\min} = 0.025 - 0.00208(HHFW) - 6.67f - 0.0834(HHFW)f \quad (3)$$

Here $\Delta\dot{q}_{\min}$ is the change in minimum flux for ignition of the target material relative to the base case with no HRR (or heat flux) perturbations; the base-case minimum flux for ignition here is 15.5 kW/m^2. The HHFW of the perturbation HRR peak, is in seconds and $\Delta\dot{q}_{\min}$ is in kW/m^2.

Each change in the minimum flux of the main fire peak corresponds, via the slope curve in Fig. 2, to a change in radial distance from the fire and implicitly a change in the area at risk of piloted ignition around (external to) the pool fire. Thus, one can treat this area variable similarly and obtain the following equation for the percentage change in area around the fire at risk of piloted ignition.

$$\%\ Area\ change = -0.178 - 0.00710(HHFW) + 43.8f + 0.862(HHFW)f. \quad (4)$$

By similar means, one obtains the following equations for the cotton cloth with no rear heat losses (upholstered furniture surrogate) and for the 1.3-cm-thick white pine (wooden furniture surrogate), respectively.

$$\%\ Area\ change = 1.04 - 0.0434(HHFW) + 3.20f + 1.28(HHFW)f \quad (5)$$

$$\%\ Area\ change = 0.692 - 0.0368(HHFW) - 12.0f + 0.834(HHFW)f. \quad (6)$$

Each of these equations is a relation, for its respective material, between the two parameters of the heat flux or

HRR spike, given a fixed level of percentage change in area at risk of piloted ignition.

Area at risk of ignition around a fire is taken here as a measure of the threat such a fire poses of igniting other objects. The larger this area, the larger the chance that there will be some secondary object within the "ignition reach" of the fire. By looking at the percentage change in this area, we are normalizing the absolute change by the base-case area to get a measure of how much the ignition threat is changed from that base case.

Plots of the above equations are shown in Fig. 4a–c. All of the graphs have the same range of values on each axis and we have confined that range to the general neighborhood in which the above equations were obtained. Each graph shows what one would expect: an inverse dependence between allowable amplitude of a HRR spike above the set limit (here 200 kW) and the duration of that spike in terms of its HHFW. This latter parameter refers to that portion of a spike above the main fire HRR peak of 200 kW. Each separate curve corresponds to the indicated fixed percentage increase (due to the HRR perturbation) in the area around the pool fire, which is at risk of piloted ignition of the indicated material. By inference, the same levels of increased risk of piloted ignition carry over to real rooms containing the types of objects for which the present materials are surrogates.[4]

In Fig. 4, the further a given % *Area change* line moves toward the upper right-hand corner, the more forgiving is the ignition process, i.e., the greater can be the duration of a given HRR spike above the 200 kW limit without enlarging (by X%) the area around the fire which is at risk of piloted ignition of the material to which the graph applies. Comparison of Fig. 4a–c shows that the cotton fabric with rear heat losses (drapery surrogate) is the least forgiving since, for this case, the % *Area change* lines fall farthest toward the lower left-hand corner. The minimum heat flux for ignition for the base case (no HRR spike) with this situation was approximately 15.5 kW/m^2, which occurs about 1.2 m away from the pool center (see Fig. 2). For comparison, the base-case ignition reach values for the other two material ignition situations were as follows: cotton fabric with no rear surface heat losses (upholstered furniture surrogate), 7.9 kW/m^2 reached at 1.6 m from the pool fire center; 1.3-cm-thick white pine (wood furniture surrogate), 18.2 kW/m^2 reached at 1.07 m from the pool fire center.

2.3. Secondary ignition-parametric sensitivities

It must be borne in mind that the above relations are derived from looking at the secondary ignition problem in

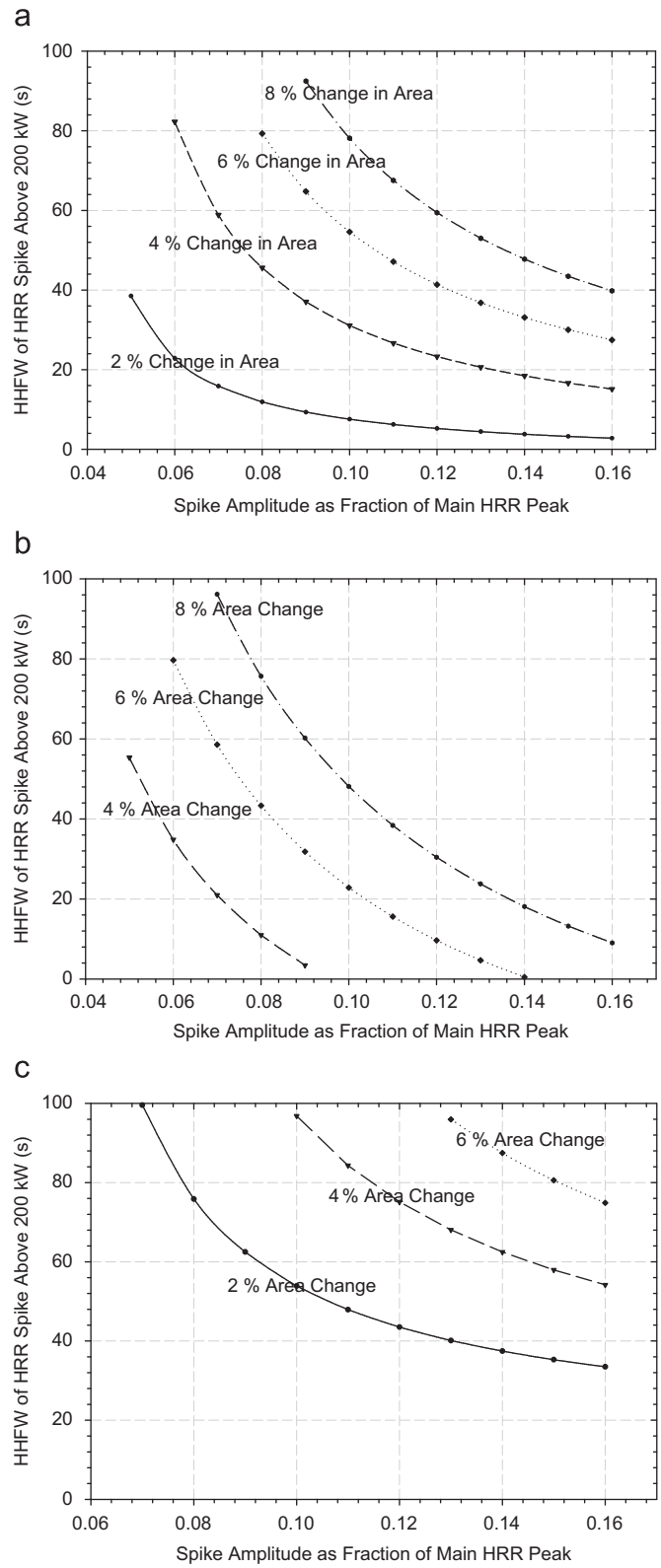

Fig. 4. (a) Trade-off of HRR spike half-height width and amplitude for several fixed percentage changes caused by spike in ignition area around fire; case of cotton fabric with no rear heat losses as the ignition target. (b) Trade-off of HRR spike half-height width and amplitude for several fixed percentage changes caused by spike in ignition area around fire; case of cotton fabric with no rear heat losses as the ignition target. (c) Trade-off of HRR spike half-height width and amplitude for several fixed percentage changes caused by spike in ignition area around fire; case of 1.3-cm-thick white pine as the ignition target.

[4]This argument applies best to the overall population of rooms that may be at risk of a fire. Individual objects with finite size (e.g., an upholstered chair) in particular rooms tend to have a discontinuous risk of ignition if any part of their periphery lies within the maximum radius of piloted ignition of that object. This issue is discussed somewhat further in Ref. [4].

a specific context—a 1-m pool fire of 200 kW peak intensity. This context should be quite relevant, since this peak HRR is in the area of concern for regulators and the physical fire size is relevant to furnishings. We consider below some possible variations in the parameters of the problem to see if the above results are reasonably general.

If the peak HRR from the main fire were substantially increased above the 200 kW range, the reach of the radiative heat flux versus distance in Fig. 2 would be increased accordingly. For example, if the 200 kW fire becomes a 400 kW fire, the Shokri–Beyler formula shows that the radial distances at which the above minimum fluxes for ignition are reached move outward about 1/4–1/2 m and the slopes (decrease of flux with distance) at these locations change only a few percent. Thus, the radial increments outward in ignition reach as a result of the same relative-size HRR spike are essentially unchanged from the above results. The biggest change is in the area by which these increments are normalized to obtain percent area change. This area increases significantly to drive the percent area increase values below those for the 200 kW cases. Thus the larger fire, even though it threatens a larger area, is more forgiving of HRR spikes than the 200 kW fire considered here, because the percent change in ignition-threatened area is less. If, on the other hand, the main fire HRR peak is reduced to 100 kW, the maximum ignition reach is reduced, but once again the changes in ignition threat area brought on by HRR spikes are comparable to those calculated from the above equations (the 100 kW values for changes in threatened ignition area are about 20% less than those for the 200 kW fire). This suggests that the above results are fairly general. However, there is one note of caution on the smaller fireside. While the use of a 1-m diameter, 100 kW fire is justifiable, it is not clear that its plume behavior or radiant emissive power would follow the Shokri–Beyler formula put forth in NFPA 555. Experience with soft furnishings, which have such low HRR values indicates that they tend to have multiple small fire plumes rather than a single plume like a liquid pool fire and this would alter the radiant flux distribution about the fire.

When the peak HRR of the fire is substantially higher than the ca. 200 kW range which was the focus here, there is increasing coupling between the smoke layer and the secondary ignition process. The HRR spikes cause increasingly significant changes in the upper-layer temperature and thus its radiant flux to objects below the smoke layer (or in it) and these changes have their own additive effects to those caused by the changing fire plume size. The optical thickness of the smoke increases and the plume within the smoke layer is obscured. The overall radiative heating problem can become much more complex and require treatment by a more general gas-phase fire model such as the NIST Fire Dynamics Simulator.

The temperature response of an ignition target material to a spike in the radiant flux on its surface depends on the heat balance to which that surface is subjected. A thermally thin material has a characteristic response time as follows

$$\tau = \rho C \ell \bar{T} / \dot{q}. \tag{7}$$

Here $\rho C \ell$, the product of the density, heat capacity and thickness, is called the thermal mass, $\bar{T}$ is the temperature of the material when the flux spike strikes it and $\dot{q}$ is the magnitude of the flux spike. Obviously, the response time could be decreased (and the temperature response increased) if the thermal mass were minimized. The maximum ignition reach for such materials would fall further out on the flux curve in Fig. 2. We have not considered such very-light-weight fabrics of minimal thermal mass, because they are not found in the secondary targets (upholstered furniture, drapery) whose ignition could mean a real enhancement of overall compartment HRR and progression in a room fire toward flashover. In any event, the above results suggest that it is not the material condition giving the farthest ignition reach which is most constraining as to allowable HRR spikes.

We also varied other parameters in the above calculations to ascertain their influence on the results derived here. These were the characteristics of the main fire peak, in particular, its time width and its time of occurrence relative to the start of the solution process for temperature versus time. The HHFW of the main HRR peak was doubled, to 1000 s, and halved, to 250 s. For the white pine, which has a memory of heating history via its in-depth temperature profile, the changes in the base-case (no HRR or flux spike) minimum flux for ignition were quite distinct, going up from 18 to 22 kW/m^2 when the main peak width was halved and going down from 18 to 14.8 kW/m^2 when the peak width was doubled. Nevertheless, these are minor changes in this context, having no appreciable effect on the sensitivity to flux spikes since they represent small shifts along the flux versus radial distance curve in Fig. 2. (In any event the wood behavior is not the limiting case for the issues considered here). The thermally thin fabric behavior is nearly insensitive to the main fire HHFW or the time of its occurrence; the minimum flux for ignition shifts <0.2 kW/m^2 when either of these parameters is halved or doubled. Thus, the relations shown in Fig. 4 between the HRR spike amplitude and spike HHFW should apply to a wide range of fires, such as bed and upholstered furniture fires, when the allowable peak HRR is restricted to ca. 200 kW magnitude.

There is some sensitivity of the development of the upper layer temperature to the shape of the HRR versus time curve; this has been shown in the case of large fires leading to flashover [10]. Thus, using CFAST, the minimum HRR required to achieve an upper layer temperature of 600 °C was found to vary by 30% with large changes in peak shape (at fixed total heat content). This effect appears to be due to a shifting balance of energy sources and sinks for the upper layer. The Gaussian peak shape used here knows nothing of these effects which imply varying flux–time relations seen by the ignition target objects. Real fires also show complex time variations in HRR, also implying

varying flux-time relations. The preceeding results imply that the ignition behavior of the thermally thin cotton fabric would not be much influenced by these variations. Thus the results in Fig. 4b which are for the limiting case, should be reasonably general.

A couple of other considerations should be mentioned. When the cotton fabric is subjected to both front and rear heat losses (as opposed to front surface losses only), its minimum flux for ignition essentially doubles; this is simply the result of the doubled heat loss from a unit area of the fabric. Since we take the HRR and heat flux spikes to be a fraction of the base case, the absolute size of the heat flux spike is doubled for the case with heat losses from both front and back surfaces (again, as compared to the case with front surface losses only). In the context of the transient ignition model, this has the net effect that the allowable decreases in the requisite minimum heat flux for ignition (brought on by the presence of a HRR or flux spike) are nearly tripled. The changes in slope of flux versus distance at the two maximum ignition reaches (on Fig. 2) compensate for this almost completely, yielding very comparable values of incremental increases in radial ignition reach (distance from the center of the fire). The actual percentage increases in ignitable area are, however, about 50% larger for the case with front and rear heat losses and this leads to the domination of this case in determining the relation between the acceptable HRR spike amplitude and time width.

A thermally thick material can be more responsive to heat flux spikes than a thermally thin material with front and rear surface losses. However, when its density and heat capacity are comparable to the thermally thin material, as here, then heat conduction into its depth becomes an additional damper of thermal responsiveness. Thus, the thick white pine both requires the highest minimum flux for ignition and has the smallest response to the HRR and attendant heat flux spikes. This puts it out of contention for determining the relation between the acceptable HRR spike amplitude and time width.

3. Discussion

In viewing the results of Fig. 4b as a guide to the potential effects of HRR spikes on real world room fires, a few considerations should be kept in mind.

First, it should be noted that real heat release rate calorimeters have a finite response time, typically of the order of 10 s, which can modify a HRR spike in an object being measured [11,12]. Thus, a HRR peak with a HHFW in the 10 s range is being decreased in amplitude and broadened in time by the measurement system so one should proceed with caution in interpreting such peaks. Improvements in calorimeter response time could alleviate this issue.

The percent area change in Fig. 4b has to be put into perspective. This does not represent the probable increase in ignitions over the population of all rooms in which a 200 kW fire occurs. First, Fig. 4b represents a very specific type of ignition exposure. Figs. 4a and c clearly indicate that combinations of HHFW and spike amplitude yielding, for example, a 4% area increase for the cotton fabric with rear losses (as seen in Fig. 4b) would yield an appreciably lesser ignition threat area increase for other materials and objects. Thus, there could be no significant effect of a HRR spike at all in a room in which there is no object having a material and exposure condition like that represented by Fig. 4b. Also, there would be no significant effect in particular cases where the increased ignition reach brought on by the HRR spike did not encompass any new objects in a room (or, for that matter, if it merely reached slightly farther out on an object already encompassed). The average real world effect, in terms of increased incidents of enhanced fire growth due to HRR spikes falling in the size-duration domain defined by Fig. 4b, is thus expected to be appreciably less than that implied by the percent change in threatened area. The curves in Fig. 4b are closer to an upper limit for this threat increase.

There are further factors at play in the real world of secondary ignitions as a result of a HRR spike. These concern the relative likelihood of piloted versus non-piloted ignition around an existing fire and how that likelihood may depend on such factors as the distance from the fire and the nature of the material in the primary fire (whether it can shed "embers" that could act as ignition pilots). There is not sufficient information in the literature to make quantitative judgments about such factors but they all point towards the fact that use of Fig. 4b to judge the real world threat of HRR spikes is likely to be conservative.

Given the most conservative line in Fig. 4b (that for a 4% increase in area threatened by piloted ignition) and avoiding HHFW values of <10 s for the reason stated above, one sees the following: there is likely to be very little real world impact if a product exhibits HRR fluctuations above 200 kW varying from 16 kW with a 10 s duration to 10 kW with a 55 s duration. In this sense, a HRR limit can be seen as being somewhat flexible and forgiving.

There are additional considerations that both regulators and product manufacturers must factor in with regard to a HRR limit. Neither is likely to have a large enough HRR test sample size (number of replicates) to have a really good estimate of the average and of the standard deviation in peak HRR behavior for a given product. This scatter in test behavior comes both from the product variability and lab-to-lab measurement variability. The cost of testing limits the number of test replicates; thus CFR 1633, for example, requires only three replicates. This puts pressure on the manufacturer (whose products will be tested at random by the regulator) to push his sample average peak HRR well below the HRR limit value and/or to make his product very reproducible. The latter option is not very realistic in a newly regulated industry. As an example, pushing the three-sample average peak HRR down to 100 kW and finding a sample standard deviation in that peak HRR of 50 kW (which may be optimistic) implies

(from Student's t-distribution) that about 10% of the population of such products will exceed 200 kW in peak HRR and about 5% will exceed 250 kW. The results above suggest that going 10% over the limit (if restrained in duration in accord with Fig. 4b) is not likely to yield appreciable effects in the real world of accidental fires. Exceeding it by 20% will probably be detrimental. A regulator can minimize this loss of effectiveness due to sample variability by setting the HRR limit lower.

4. Conclusions

We have addressed the issue of the possible impact on the real-world fire threat of transient peaks in HRR that exceed some limit set by a regulator. For the relatively low HRR limits that apply (or are recommended) in the United States for soft furnishings items, there are two modes of threat enhancement that need to be considered: decreased escape time from the hot smoke layer in a room and increased radiative ignition reach of the fire plume toward secondary flammable items in the room. We found here that only the second threat is significant. We assessed this latter threat by considering the response of surrogate materials (modeling the ignition response of such items as an upholstered chair or drapery) to a Gaussian HRR spike atop a broader Gaussian fire. We find that the response, in terms of percent increase in area around the main fire that is subject to piloted ignition of the worst-case surrogate material, is of the same order as the increase in HRR represented by the spike. We argue that, on average, the threat in the overall population of secondary objects in the real world is appreciably less than for this worst case, and thus the threat posed by limited (e.g., $\leqslant 10\%$ for $\leqslant$ a few tens of seconds) excursions in HRR, above the set limit, is minimal.

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