CBUF Model I, Applied to Exemplary New Zealand Furniture

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ABSTRACT

The recent comprehensive study on the combustion behaviour of upholstered furniture sponsored by the European Commission (EC-CBUF) developed a factor-based model for predicting full scale results for the peak heat release rate, time to peak, total heat release and time to untenable conditions. In this paper we examine the applicability of the EC-CBUF Model I to exemplary New Zealand (NZ) furniture items. Eight single seat furniture items have been tested in both the cone and furniture calorimeters. Tests were conducted in accordance with the strict EC-CBUF protocols. Using the results from the cone calorimeter test as input into EC-CBUF Model I, predictions of the full-scale furniture behaviour were made. Comparisons between the full-scale furniture results and the model predictions show that NZ furniture consistently exhibits higher peak heat release rates for similar total heat. Based on these comparisons it is clear that exemplary NZ furniture presents a significantly greater fire hazard than its European counterparts by reaching this higher peak heat release rate in shorter periods of time. Further research is required to determine what modifications are necessary before this model can be applied to NZ furniture.

KEYWORDS: CBUF, combustion, furniture, fabric, foam, model.

INTRODUCTION

Loss of life in domestic and residential type buildings continue to dominate New Zealand's (NZ) annual fire death statistics. Few items within these buildings have the potential to bring about untenable conditions as swiftly as upholstered furniture. Therefore, it is a major goal of safety research to better assess the hazard of furniture fires. Especially, in respect to our ability to predict the hazard.

Full-scale fire testing of furniture as a hazard predictor is much more costly and unwieldy than bench-scale. One of the objectives of modern reaction to fire research is to improve bench-scale based predictive models of full-scale behaviour. Currently the pre-eminent bench scale tool is the cone calorimeter[1]. The first notable predictive model based on the cone calorimeter was developed at the National Institute of Standards and Technology (NIST) (formerly named the National Bureau of Standards) in 1985[2]. This is based on materials and furniture items originating mostly from the 1970s. Since that time, the materials and predictive techniques have changed significantly.

Recent developments were made in the extensive European Commission sponsored study Combustion Behaviour of Upholstered Furniture (EC-CBUF). From this study, three predictive combustion behaviour models are developed and presented in the EC-CBUF Final Report[3].

Model I of the EC-CBUF is a factor based model which uses statistical curve fitting on key variables from the cone calorimeter results along with style factors which accounts for differences in the physical shape of the item. In this paper we examine the applicability of the EC-CBUF Model to exemplary NZ furniture items. Eight single seat furniture items have been tested in both the cone and furniture calorimeters to assess the applicability of the EC-CBUF Model I to NZ furniture. Comparisons are also made with the EC-CBUF results to determine the fire hazard of NZ furniture relative to its European counterpart.

EXPERIMENTAL PROCEDURE AND APPARATUS

The experimental portion of NZ-CBUF involves fire tests on the cone and furniture calorimeters. The University of Canterbury (UC) Cone Calorimeter complies with the standard[4] as amended by Appendix A6 of the EC-CBUF Final Report[3] "Cone Calorimeter testing". The test protocol, specimen preparation, special testing instructions and reporting are all performed according to the strict specification of the EC-CBUF Protocol. Similarly, the UC Furniture Calorimeter complies with the standard[5] as amended by Appendix A7 of the CBUF Final Report[3] "Furniture Calorimeter test protocol". Again, the test protocol, specimen preparation, special testing instructions and reporting are all followed as per the Appendix A7. For complete documentation of the characterisation of the UC Cone and Furniture Calorimeters, refer to Reference [6].

NZ-CBUF FURNITURE ITEMS

The terminology "item" or "sample" are used synonymously throughout this paper to refer to the full-scale generic piece of furniture that the predictions are made. The term "foam" refers to the padding material that in this study was polyurethane manufactured in New Zealand. The covering material referred to as "fabric" are primarily made from synthetic materials.

The items tested in NZ-CBUF consist of eight exemplary armchairs purchased on the open market. They are representative of typical NZ domestic furniture in the low to mid level price range. These are described generally in Table 1. The first five items are of the same manufacture, with only the fabric varying. Table 1 gives material components for the items investigated in this study. Column 1 is the item number used throughout this paper. The size, foam, fabric, and inter-liner are given in columns 2 through to 5 respectively. Additional samples of items 1, 6, 7 and 8 were purchased and disassembled to determine the mass of each component and to obtain foam and fabric for the composite samples required for cone calorimeter tests. Additional fabric for items 2-5 was purchased and composite samples prepared using the extra foam from the disassembled item 1.

TABLE 1: Coding of NZ-CBUF items

	FOAM (MAIN FILLING)		FABRIC (COVER)		INTER-LINER (WRAP)		SEAT
ITEM	CODE	DESCRIPTION	CODE	DESCRIPTION		DESCRIPTION	#
1	A	Polyether foam pad	1	Polyester and other blends	No	N/A	1
2	A	Polyether foam pad	2	Polyester and other blends	No	N/A	1
3	A	Polyether foam pad	3	Polyester and other blends	No	N/A	1
4	A	Polyether foam pad	4	Nylon pile with polyester backing	No	N/A	1
5	A	Polyether foam pad	5	Polypropylene fibre	No	N/A	1
6	B	Polyether foam pad	6	Nylon pile 65/35 polyester cotton base	No	N/A	1
7	C	Polyether foam pad	7	Nylon pile	Yes	Fibre (not specifically FR)	1
8	D	Polyether foam pad	8	Polypropylene fibre	Yes	Fibre (not specifically FR)	1

FIGURE 1: NZ-CBUF item 1 (representative of 1 through 5) and items 6, 7 and 8

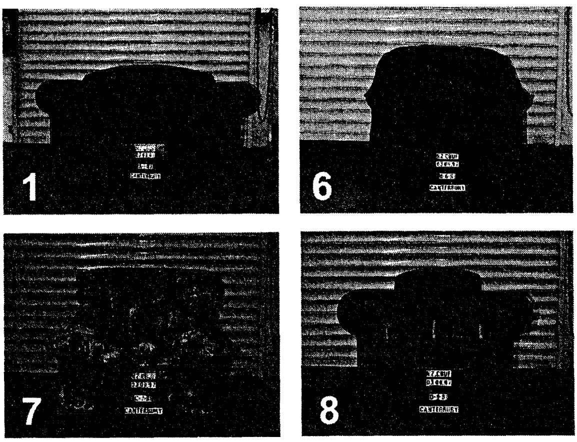


Figure 1 shows the items subsequently cut apart for mass data and cone calorimeter specimens. Item 1 is the two-seat version of the sample tested and is representative also of items 2 to 5, with only the fabric varying.

UNCERTAINTY ANALYSIS

The reported cone and furniture calorimeter results include uncertainty parameters with respect to the HRR. The uncertainties have been calculated in the manner described in more detail, especially for the cone calorimeter, in Reference [7]. The uncertainty of the other measured and calculated properties and the propagation of the uncertainty, from the cone calorimeter results through the EC-CBUF Model I, is not calculated.

EC-CBUF MODEL I PREDICTIONS

EC-CBUF Model I (described in detail in the Final Report[3] and Reference [8]) is a factor-based method that uses a series of statistically correlated factors to predict the peak HRR, total heat release, time to peak, and time to untenability. The model is an improvement on the earlier (1985) factor-based prediction from NIST. The original model was examined for applicability to the EC-CBUF items. It was found to apply only generally and displayed tendencies to under-predict the more modern and varied European furniture. The study undertook further development and refinement of this model. They tested a series of differing furniture styles constructed from the same 'soft' combustible material combinations (soft being the foam, fabric, and inter-liner). An analysis of the results brought about several refinements from the 1985 NIST model to the EC-CBUF Model I. Notably, the mass of soft combustibles replaced the mass of total combustibles, and the power was raised from 1 to 1.25. The time to ignition in the cone calorimeter test was seen as an important variable and included.

The style factor also required significant change to account for the new European furniture. Incorporated in the calculation of the peak heat release rate, time to peak, and untenability time, the style factor accounts for the physical differences that cannot be resolved by the cone calorimeter test method including the ornate and intricate detail that can be found in some furniture. As seen in Figure 1, items 6 and 7 are obviously more ornate than the rectilinear shape seen in items 1 and 8.

TABLE 2: Furniture styles used in the EC and NZ-CBUF programmes

EC-CBUF	STYLE FACTOR A	STYLE FACTOR B	TYPE OF FURNITURE
1	1.0	1.0	Armchair, fully upholstered, average amount of padding
2	1.0	0.8	Sofa, two-seat
3	0.8	0.9	Sofa, three-seat
4	0.9	0.9	Armchair, fully upholstered, high amount of padding

Table 2 provides the style factors needed in the predictive model. It is reproduced in part from a more comprehensive table appearing in References [3] and [8]. Note that that the NZ-CBUF items testes in this series are all single seat armchairs with average to high amounts of padding. Codes 2 and 3 are included for completeness.

Incorporating these new and old variables, Equation 1 emerged as the first correlating variable for the peak heat release rate. It was found that the partially correlating variable x_1 represented well the general trend with the exception of groupings of high peak HRR (over 1200 kW). Considering only these data points, the second correlating variable x_2 emerged in Equation 2.

$$x_1 = \left(m_{soft}\right)^{1.25} \cdot (style\_fac.A) \cdot \left(\dot{q}''_{pk} + \dot{q}''_{300}\right)^{0.7} \left(15 + t_{ig}\right)^{-0.7} \tag{1}$$

$$x_2 = 880 + 500 \cdot \left(m_{soft}\right)^{0.7} (style\_fac.A) \cdot \left(\frac{\Delta h_{c,eff}}{q''}\right)^{1.4} \tag{2}$$

Selection rules are established, that we have termed ‘regimes’, to determine when to use x_1 and x_2, with x_1 displaying a partial dependence.

Regimes:

{1} If, $(x_1 > 115)$ or $(q'' > 70$ and $x_1 > 40)$ or $(style = \{3,4\}$ and $x_1 > 70)$ then, $\dot{Q}_{peak} = x_2$

{2} If, $x_1 < 56$ then, $\dot{Q}_{peak} = 14.4 \cdot x_1$

{3} Otherwise, $\dot{Q}_{peak} = 600 + 3.77 \cdot x_1$

The total heat release (not surprisingly) is determined from the actual mass of the furniture item and small-scale effective heat of combustion. Differentiation is noted between the ‘soft’ and total combustible masses. Experimental observation reveals that the affect of a wooden frame is not seen until nearly all of the 'soft' materials are consumed. Equation 3 was found to represent the total heat release:

$$Q = 0.9 m_{soft} \cdot \Delta h_{c,eff} + 2.1\left(m_{comb,total} - m_{soft}\right)^{1.5} \tag{3}$$

The time to peak is as important as the peak heat release rate in hazard calculations. Equation 4 is developed to predict time to peak HRR from sustained burning (50 kW). It is recognised that often other hazard variables are maximised at or near the time of peak HRR. Note that a different style factor is incorporated into the time to peak calculation.

$$t_{pk} = 30 + 4900 \cdot (style\_fac.B) \cdot \left(m_{soft}\right)^{0.3} \cdot \left(\dot{q}''_{pk\#2}\right)^{-0.5} \cdot \left(\dot{q}''_{trough}\right)^{-0.5} \cdot \left(t_{pk\#1} + 200\right)^{0.2} \tag{4}$$

Equation 5 is developed to predict time to untenable conditions in a standard room. Untenability time is defined as the time from 50 kW HRR to 100 C temperature 1.1 to 1.2 m above floor level. Although results for the time to untenable conditions are presented here for comparison with the EC-CBUF results, compartment fire experiments were not part of this research program.

$$t_{UT} = 1.5 \times 10^5 (style\_fac.B)(m_{soft})^{-0.6} (\dot{q}''_{trough})^{-0.8} (\dot{q}''_{pk\#2})^{-0.5} (t_{pk\#1} - 10)^{0.15} \quad (5)$$

RESULTS

Table 3 summarises the results of the cone calorimeter tests used in the EC-CBUF Model I. Each value represents the average results from at least three specimens of each sample composition. N/A refers to the fact that for sample composite 5 (which corresponds to item 5) a second peak and trough were not clearly discernible from the cone results. Sample 5 burned with a strong single peak.

TABLE 3: Cone calorimeter data used as input to EC-CBUF Model I predictions, including HRR uncertainty

	SAMPLE No.							
PROPERTY, x	1	2	3	4	5	6	7	8
m (g)	22.2	18.6	21.1	21.1	22.7	27.3	21.2	21.1
t_{ig} (s)	8	10	10	19	10	16	17	18
q'' (MJ/m^2)	54.8	35.6	40.0	42.5	61.2	65.6	42.2	46.5
$\delta q''$ (MJ/m^2)	5.0	3.3	3.5	4.2	5.5	5.7	4.0	4.1
$\dot{q}''_{300}$ (kW/m^2)	176	130	174	129	225	207	137	194
$\dot{q}''_{pk}$ (kW/m^2)	467	387	446	500	543	617	326	505
$\delta\dot{q}''_{pk}$ (kW/m^2)	41	33	38	43	43	52	28	43
$\Delta h_{c,eff}$ (MJ/kg)	27.4	21.1	22.4	22	29.4	23.6	20.5	22.2
$t_{pk\#1}$ (s)	33	33	34	39	N/A	40	33	36
$\dot{q}''_{trough}$ (kW/m^2)	335	128	272	149	N/A	208	175	332
$\dot{q}''_{pk\#2}$ (kW/m^2)	466	218	375	253	N/A	355	277	502

Table 4 summarises the non-cone calorimeter data required by EC-CBUF predictive model. This data relates mostly to the mass and style of the furniture item. Of note from Table 4 is that the item from 1 through 5, consisted of essentially the same chair with only varying fabric.

Table 5 summarises the results of EC-CBUF Model I applied from cone calorimeter results and then compares these values to the ones measured in the furniture calorimeter. N/A in the table again refers the fact that a second peak and trough were not clearly discernible from the cone tests of sample composite 5. The x_1 values are included in the table for later comparisons.

TABLE 4: Supplementary data (non-cone test) required for EC-CBUF Model I predictions

PROPERTY, x	ITEM # 1	2	3	4	5	6	7	8
m_{soft} (kg)	5.13	4.80	5.10	5.09	5.23	5.39	5.34	7.13
$m_{comb,total}$ (kg)	25.00	24.67	24.97	24.96	25.10	21.46	22.10	25.04
style code (--)	{1}	{1}	{1}	{1}	{1}	{4}	{4}	{1}
style_fac.A (--)	1.0	1.0	1.0	1.0	1.0	0.9	0.9	1.0
style_fac.B (--)	1.0	1.0	1.0	1.0	1.0	0.9	0.9	1.0

TABLE 5: Comparison of predicted and measured results from the model and furniture calorimeter

PROPERTY, x	ITEM No. 1	2	3	4	5	6	7	8
x_1	79	59	73	59	87	73	47	99
$\dot{Q}_{peak}$ (predicted)	900	823	873	822	928	1230	683	1582
$\dot{Q}_{peak}$ (measured)	1123	795	1233	995	1705	1693	1550	1306
$\delta\dot{Q}_{peak}$ (measured)	108	85	118	102	163	173	119	142
Q (predicted)	313	277	289	287	324	250	243	302
Q (measured)	378	244	299	333	387	262	150	363
δQ (measured)	44	30	34	39	41	38	23	42
t_{peak} (predicted)	90	170	104	153	N/A	111	128	95
t_{peak} (measured)	122	261	132	175	131	92	104	169
t_{UT} (predicted)	40	131	53	108	N/A	61	76	32
t_{UT} (measured)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

FIGURE 2: Predicted peak HRR EC-CBUF Model I versus measured furniture calorimeter

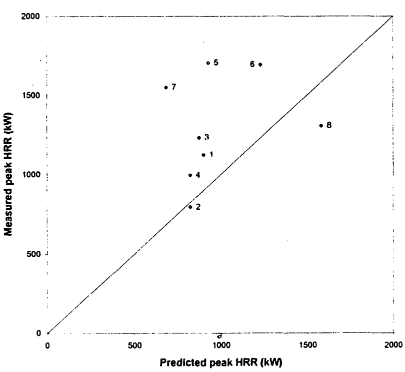


FIGURE 3: Predicted total heat (EC- CBUF Model I) versus measured furniture calorimeter

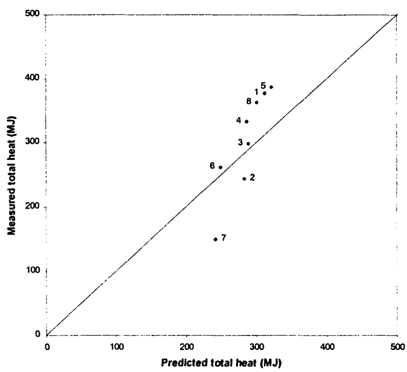


FIGURE 4: Predicted time to peak HRR (Model I) versus measured (furn. calor.). Starting time from 50 kW

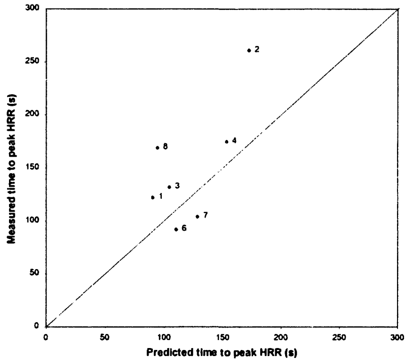


Figure 2, Figure 3 and Figure 4 represent the results of measured peak HRR, total heat and time to peak HRR against predicted values. While the time to untenable conditions in a standard room is also predicted by Model I, it is not experimentally measured in NZ-CBUF.

DISCUSSION OF RESULTS

Unfortunately, the NZ-CBUF sample size is too small to make formal statistical observations (such as a χ^2-Test) with respect to the goodness of the fit of the data to Model I. The 'R^2' coefficient of determination may be calculated for the sample set, however this should be used with caution since it is always possible to improve R^2 unity by simply adding enough terms to the model, without actually improving the fit.

Qualitatively, we observe that the EC-CBUF Model I is not a good predictor of the behaviour of the exemplary NZ furniture tested. The lack of a goodness of fit of the data to the model is especially pronounced in the peak HRR. However, an examination of the relationship of the partial correlating variable x_1 to the measured peak HRR provides an insight to the poor results.

Consider Figure 5. The NZ-CBUF data tends to deny partial dependence. Assuming that there is not the partial dependence. Therefore applying only regime {2} (that is $\dot{Q}_{peak} = 14.4 \cdot x_1$) for style {1} and only regime {3} (that is $\dot{Q}_{peak} = x_2$) for style {4}.

Figure 6 illustrates the result of these assumptions. We can see that while the fit may yet not be good, it has improved significantly. Especially, in respect to furniture item 7 (which was style {4} but only $x_1 = 47$). However, of concern is that two items are significantly under-predicted by the model. This is considered to be an undesirable result in life safety analysis.

FIGURE 5: The relationship of partial correlating variable x_1 in comparison with the measured HRR.

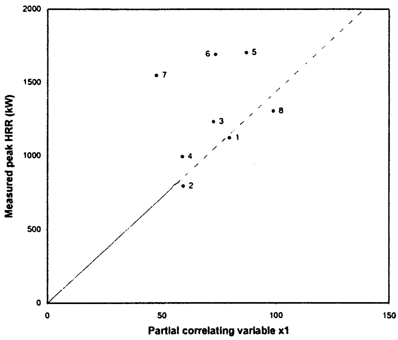
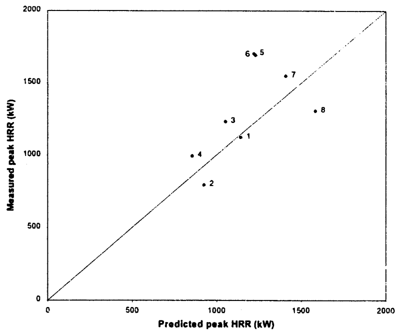


FIGURE 6: Predicted peak HRR (EC-CBUF Model I - modified) versus measured.



Consider Figure 7 and Figure 8. Besides examining the applicability of EC-CBUF Model I, there are other results of interest. For example a pronounced fabric affect is demonstrated in samples 1 to 5. The fabric showed a trend to either melt and peel, or split and remain in place. The latter inhibiting fire development. The two Figures show the HRR time history from the cone (5 minutes) and furniture calorimeter (10 minutes) for this series. The time to peak and magnitude of the peak HRR vary considerably. We note that the time scale begins at 120s in the cone and 180 s in the furniture calorimeters. This is due to respective two and three minute baseline prior to ignition.

FIGURE 7: Fabric effects, 1 to 5 (Cone)

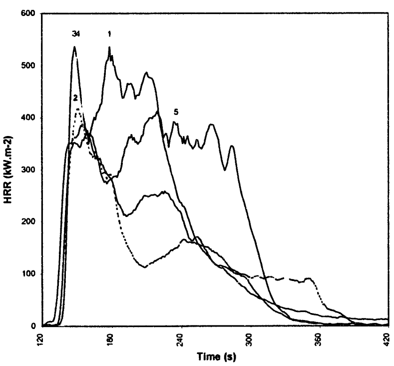


FIGURE 8: Fabric effects, 1 to 5 (Furn.)

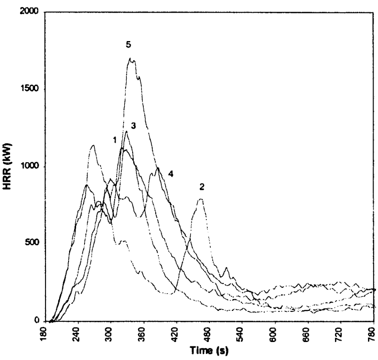


Table 6 compares the results of NZ-CBUF directly with the available EC-CBUF results for the peak heat release rate and total heat release.

For this exercise, 'comparative' EC-CBUF furniture items were selected from the photographic record appended to the Final Report.

TABLE 6: NZ-CBUF (measured) peak HRR, time to peak HRR and total heat, compared against the EC-CBUF data, for comparatively similar furniture items

NZ-CBUF				EC-CBUF		
ITEM #	$\dot{Q}_{pk}$ (kW)	Q (MJ)	t_{pk} (s)	Code	$\dot{Q}_{pk}$ (kW)	Q (MJ)
1	1123	378	122	1.04	784	368
2	795	244	261	1.05	742	463
3	1233	299	132	1.06	1158	412
4	995	333	175	1.07	596	314
5	1705	387	131	1.08	1490	498
6	1693	262	92	1.09	552	144
7	1550	150	104	1.10	866	449
8	1306	363	169	1.11	1259	375
				1.12	652	172
$\bar{x}$	**1300**	**302**	**148**	$\bar{x}$	**900**	**355**

It is observed that relative to EC-CBUF items overall, the NZ-CBUF chairs exhibited significantly higher peak HRR for relatively similar total heat. However, exemplary NZ items do not include combustion modified or high resilience foams or fire resistant fabrics or interliners. In comparison to equivalently composed European items, the peak HRR results were more comparable, although still generally higher.

Unfortunately, data for time to peak HRR for the EC-CBUF items were not reported.

Table 6 indicates exemplary NZ furniture presents a higher fire hazard than its European counterparts. This is seen in the relatively poor fit of the model to measurements, as the NZ samples are considered 'extreme'. In addition, the exemplary NZ furniture fire will grow to a high peak HRR in a short period of time.

CONCLUSIONS

Relative to exemplary European items, the NZ items exhibit higher peak heat release rates for similar total heat. Further, the exemplary NZ furniture presents a higher fire hazard than its European counterparts by reaching this higher peak heat release rate in short periods of time.

The model does not predict 'with goodness' the behaviour of a small (but exemplary) sample of NZ furniture items. Particularly poor, is the prediction of peak heat release rate. The model consistently and considerably under-predicts the peak heat release rate of the NZ items. This is an unconservative result if using this model for predicting the onset of untenable conditions.

The model better predicts the behaviour of style {1} NZ items by ignoring the partial dependence of the correlating variable x_1. Better predictions of the behaviour of style {4} NZ items can be obtained by ignoring the dependence of the correlating variable x_1 and assuming only x_2.

The NZ-CBUF results, both in the bench-scale and full-scale, show considerable covering material (fabric) affects, that at this time has been identified but not quantified.

FUTURE RESEARCH

The NZ-CBUF data set is of limited size, thus, further research is required to expand this data set. Different combinations of common foams and fabrics (statistically sampled) should be tested in the cone calorimeter and furniture calorimeter on a standard frame. The expanded data set will allow more statistically meaningful conclusions to be drawn analytically. In particular, regarding the applicability of EC-CBUF Model I and in general of combustion behaviour. In addition to statistically considering the NZ-CBUF data in isolation, future research should incorporate it into the EC-CBUF data set, with wider comments made and conclusions drawn. EC-CBUF Model II should also be applied to the NZ data. There is a significant need for a detailed uncertainty analysis to determine how the uncertainty of the cone calorimeter results propagates through EC-CBUF Model I. The resulting uncertainty should be reported with all results to indicate to the practitioner the confidence level associated with the predictions.

NOMENCLATURE

δz	uncertainty (absolute) associated with variable "z" i.e. $\delta \dot{q}'', \delta \dot{Q}$
$\Delta h_{c,eff}$	effective heat of combustion of the bench-scale composite sample (MJ.kg^{-1})
$m_{comb,total}$	mass of the total combustible material of the full-scale item (kg)
m_{soft}	mass of the soft combustible material of the full-scale item (kg)
q''	total heat released per unit area of the bench-scale composite sample (MJ.m^{-2})
Q	total heat released of the full-scale item (MJ)
$\dot{q}''_{300}$	HRR per unit area (bench-scale) averaged over 300 s from ignition (kW.m^{-2})
$\dot{q}''_{pk}$	peak HRR per unit area of the bench-scale composite sample (kW.m^{-2})
$\dot{q}''_{pk\#2}$	second peak HRR per unit area (bench-scale) (kW.m^{-2})
$\dot{q}''_{trough}$	trough between two peak HRR, per unit area (bench-scale) (kW.m^{-2})
$\dot{Q}_{pk}$	peak HRR, measured or predicted, of the full-scale item (kW)
$style\_fac$	characteristic style factor A or B of the full-scale item (--)
t_{ig}	time to ignition of the bench-scale composite sample (s)
t_{pk}	time to peak HRR of the full-scale item (s)
$t_{pk\#1}$	time to characteristic 'first' peak of the bench-scale composite sample (s)
t_{UT}	time to untenable conditions in a standard room (s)

x_1 correlating variable in CBUF Model I (--)
x_2 correlating variable in CBUF Model I (--)

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