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CONCERNS ON ESTIMATING HEAT RELEASE RATE OF DESIGN FIRES IN FIRE ENGINEERING APPROACH

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ABSTRACT

A number of big building fires broke out in Hong Kong in the past few years. Especially after the great fire on Fa Yuen Street, more attention should be paid to fire safety in construction projects, which go through Fire Engineering Approach (FEA) or performance-based design (PBD). The heat release rate of a design fire is the most important parameter in hazard assessment to determine the fire safety provisions for buildings which have difficulties to comply with the fire code. However, a very low design fire less than 5 MW is usually assumed in many FEA/PBD projects. This is assumed even in large crowded spaces, such as public transport terminals and shopping malls.

According to the surveys done by different research groups in the past 25 years, local buildings usually store much more combustibles, an amount that exceeds the upper limit of 1135 MJm^{-2} imposed by the codes. This included factory buildings, retail shops, karaokes, higher education institutes, residential buildings and shopping malls. The heat release rate resulted from igniting the combustibles would be much higher than the value assumed in the FEA/PBD report. A post-flashover fire due to whatever reason would give even higher heat release rate. There are even no sprinklers in many public places such as crowded subway stations. If a huge fire broke out in such places, the difficult task of controlling fire would be left to firemen.

Data on heat release rate for local combustible products is not yet available. In most of the FEA/PBD projects, estimations were calculated under low radiative heat flux, which are very crude assumptions. Most of these calculations are not supported by full-scale burning tests, and some calculations were even wrong in taking average heat release rate as the peak heat release rate. Correct calculation is necessary for implementing the new generation of building fire safety codes in big post-flashover fires. Highlights in the estimation of probable heat release rate by burning combustibles will be discussed in this paper. Sample calculation of achieving low values of heat release rate to convince the authority will be illustrated. Such mistake should be avoided to estimate reasonable design fire in FEA/PBD. Adequate fire safety provisions, including hardware passive building designs, active fire protection systems and software fire safety management, can therefore be set up.

1. INTRODUCTION

As previous studies [1-3] about factories, karaoke lounges, retail shops and higher education institutes show, buildings in Hong Kong usually store large amount of combustibles. The same applies to residential buildings as surveyed recently [4]. The fire load density is much higher than the one specified in the codes [5,6]. This would give higher fire risk and was clearly indicated in several big fires [7,8], with the recent one on Fa Yuen Street in the end of November, 2011 [9]. Consequent to the big Garley Building fire [7], fire safety regulations were upgraded to some extent.

For buildings having difficulties to comply with the prescriptive building fire safety codes [e.g. 6,10-13], fire engineering approach (FEA) [14,15] or performance-based design (PBD) [16,17] can be applied. This applies [18] to both new building projects with special architectural features; and upgrading fire safety provisions for existing buildings. Some engineers are not willing to provide the necessary fire safety provisions simply for reducing the cost as required by the clients [19]. A common assumption made in such FEA/PBD projects is to operate the designed fire safety provisions when the fire is not yet developed to an agreed value. In case the fire breaks out, the responsibility of suppressing big post-flashover fires is then left to the firemen. Furthermore, there was no evidence to show how safety and health of the firemen would be affected in such FEA/PBD reports, if the buildings failed to comply with code specification. Even in overseas PBD guides developed in the past two decades, occupational health and safety issues have not been specifically addressed, following normal practice of assessing that the design complied with fire safety code [e.g. 16,17]. The importance of protecting firemen in PBD was just discussed more seriously in the Asia-Oceania meeting on railway fires [20].

Taking long travel distance of FEA/PBD projects as example, firemen have to walk a longer distance with limited supply of oxygen from their portable breathing apparatus, which operates for only 30 minutes. They have to carry heavy equipment, including air bottles, to the fire site first. They then have to carry disabled or injured occupants out of the fire site. High amount of combustibles would give very big fires, particularly in open kitchens [18] of small flats in tall residential buildings. Several firemen were already killed in big fires in recent years [21] !

Obviously, firefighters all over the world are well-trained to fight against any big fires, but there is an important question on such FEA/PBD projects [22]:

Is it fair to expose our brave firemen to such hazardous environment in buildings without adequate fire safety provisions, just for the sake of reducing construction cost [19]?

Such notions are commonplace for short-term property investment, but it remains a mystery that many buildings, which will be operated in long term, are also built based on such thinking. Examples include underground subway stations, long tunnels and even big airport terminals mainly owned by the government.

The heat release rates resulted from burning the combustible items should be estimated properly for adequate fire safety provisions [23]. It is an important parameter affecting the course of a fire. However, pyrolysis and the burning rate cannot be predicted realistically from material properties of stored combustibles. There are limitations on developing a model integrating the intermediate combustion reactions, turbulent mixing of gasified fuel vapour with air and thermal radiation feedback [24]. The peak heat release might be able to give approximate predictions for some fuels, but the approach still has to be observed closely with experimental data [25]. Therefore, only smoke movement in big halls can be predicted properly by fire models. Some fire consultants even said that heat release rate of design fire would not affect Available Safe Egress Time (ASET). It is because fire models cannot predict burning process and smoke toxicity accurately without using experimental empirical parameters for stored combustibles at the moment. Therefore, all FEA/PBD projects with such wrong application of fire model must be reviewed as soon as possible.

The input heat release rate is taken as important data for using fire models in fire hazard assessment tool [26]. However, very few experimental data is available from systematic full-scale burning tests [27], especially for local products and building configurations. Fire engineers (who should understand the difference between fire and smoke spread) used to argue with the authority to get very low design fire in FEA/PBD projects, leading to serious concerns [28]. It is observed that large atriums store high amount of combustibles. As pointed out by the Fire Services Department, over 20 MW of heat was observed in post-flashover big fires. Such value is much higher than 5 MW, the value assumed in the design fire, and some even go as far as assuming lower than0.5 MW! The heat release rates estimated from the existing models might deviate from those of an actual fire. There is contention on the scale of a design fire.

As pointed years ago, issues and problems that need to be addressed [29] are:

- Review on the characteristics of combustibles identified in a building, i.e. furniture, audio-visual equipments, electrical appliances, partition walls and carpets.
- Carrying out full-scale tests to set up a database on the heat release rates of local combustibles by the oxygen consumption method.
- Assessing the heat release rate models for burning combustible items by experimental data.
- Carrying out more research on modelling the fire environment in a room to come up with realistic fire models.

However, no progress was made in these areas, despite many overseas studies [20]. That is because:

- Research fund was significantly cut in many countries. Consequently, very few research positions with low pay are available.
- There is a high demand from the industry on carrying out FEA/PBD projects. Research assistants with limited training on fire science and engineering are then recruited by these companies.

Consequently, fire research progressed slowly with very limited research output. Industry even employed research students who just completed their master or doctoral degree. When compared to the graduates 15 years ago, they might not have acquired good understanding of fire science and engineering technology. But it is encouraging that more government officers are eager to study for a master and doctoral degree, thinking that such training is essential in promoting safety. Officers are much better trained in fire engineering when compared with 20 years ago. It is now very hard to gain the official approval with a ‘one-page’ FEA/PBD report on wood structures.

Nevertheless, all those project reports on FEA/PBD should be reread carefully [22,30]. Closing down all spaces – which are not equipped with adequate fire safety provisions will not be an option. However, such FEA/PBD projects must be inspected carefully after many fires. Fire officers are carrying out annual investigation to make sure that the assumptions made in the report are actually the case. In some crowded areas in some cities, building owners are required to designate two security guards – who have good fire training – to be on duty for 24 hours a day. The guards should be on duty in all such storage areas, where heat release rate might be much higher than the assumed value, such as 5 MW, as submitted in the FEA/PBD report. Fire safety provisions in open kitchens in residential flats of supertall buildings with excessive fire load density [4] must be upgraded immediately.

2. APPROPRIATE APPROACH WITH FIRE TESTS

There are many world class buildings and infrastructure in Hong Kong. The height of the tallest building is over 400 m, the underground railway stations are located 40 m below the ground, and a 29 km-long long tunnel is operating in Hong Kong. The safety problems should be addressed properly, and very few studies on heat release rate measurement for local combustibles had been carried out.

However, there are extensive measurements on the fire aspects of different combustibles all over the World. Combustibles such as furniture [31,32], surface and lining materials [e.g. 33] with the oxygen calorimetry [23,34] were tested at the Swedish Testing and Research Institute (SP), Sweden; Building and Fire Research Laboratory (BFRL), National Institute of Standards and Technology, USA; Fire Research Station (FRS), Building Research Institution, UK (in their Cardington full-scale burning facilities); and other big laboratories in USA, Japan, Australia and New Zealand. There are a lot of works on the burning of single items [23,31-33], fire models [26], and on burning some compartments such as libraries, retail shops [35] and office workstations [36] in advanced countries. The research programme Combustion Behaviour of Upholstered Furniture (CBUF) in Europe [31] is an obvious example. Even Mainland China, Korea and Japan have set up large databases on combustibles, including train compartments [e.g. 20].

Even though the author pointed out this ten years ago after the big train fire in Korea and the arson fire in Hong Kong, surprisingly, nothing was developed in Hong Kong. Possible heat release rates were seldom measured systematically [22,37] in other countries. At most, only an empty train car without luggage was estimated [37,38] to give low value of 17 MW, but it was not clear whether the heat release rate [38] was deduced from full-scale burning tests or estimation. It is also not clear why the draft version was recommended heat release rate was 6.5 MW [13] on train fires by the same group in the draft version. Note that the suggested heat release rate was about 20MV in systematic quality experiments on empty train car fires in Korean and Japan [10].

Combustibles of similar characteristics but with different materials and manufacturing process would give very different heat release rate upon burning. External thermal radiative heat flux is another key factor. Similar studies on local products under high heat flux should be carried out. As pointed out by the author about 10 years ago [27], heat release rate of burning real train cars in Hong Kong were not tested in systematic long-term research projects, and it lagged far behind many other countries in the Far East.

3. CONCERNS ON COMMON CALCULATION METHODS ADOPTED

A design fire with lower heat release rate would predict a less hazardous environment by fire models. Therefore, small design fire in FEA/PBD projects, including big airport terminals, was used to be proposed without any experimental justification in full-scale burning tests. Engineers always argue with government officers in countries where there is a low chance of being prosecuted of professional negligence as in Italy [39]. But if the real fire of heat release rate is much bigger than that of the design fire, the fire safety provision will not function as expected. Consequently, it could lead to disasters, which endanger the life of occupants, damage property, disturb normal operation and environmental protection. More importantly, the life of firefighters might be at risk!

There are concerns over the following three methods which are adopted to estimate heat release rate of design fire.

- Method 1

The calculation based on procedure such as on p. 82 and 83 of reference [40] is not clearly explained. The peak heat release rate Q_{peak} (in kW) was calculated by the mass loss rate m_f of the fuel (in g/m^2s), instantaneous combustible surface area A_f (in m^2), and effective heat of combustion h_c (in MJ/kg) as:

$$Q_{peak} = m_f \times h_c \times A_f \quad (1)$$

Data on heat release rate density q_d (in kW/m^2) of materials was published in literature [32,41-43] and the following equation was used:

$$q_d = \frac{Q_{peak}}{A_f} \tag{2}$$

Putting in equation (2) gives:

$$q_d = m_f \times h_c \tag{3}$$

Values of q_d and m_f were copied directly from literature without using the data of local products concerned. It should be noted that furniture with the same appearance might not be made of the same materials. Values of Q_{peak} on the combustibles are then used to give the total heat release rate.

For example, value of q_d for polyurethane foam without fire retardant is 466 kW/m^2 [32], and h_c is 46 MJ/kg. A long chair of surface area 0.33 m^2 would give a low peak heat release rate Q_{peak} of only 154 kW. However, that piece of polyurethane foam measured overseas in the literature [32] might not be the same as the local polyurethane foam [29,41].

- Method 2

Another method listed [40] is to estimate Q_{peak} by the heat load H (in kJ) and the fire load FL (in kg) as:

$$H = FL \times h_c \tag{4}$$

By assuming that the heat release rate curve Q(t) (in kW) at time t (in s) after ignition in a room follows a NFPA-t^2 fire [42] with growth factor t_g (25 s, 150 s, 300 s and 600 s for ultra-fast, fast, medium and slow fires respectively).

$$Q(t) = 1000\left(\frac{t}{t_g}\right)^2 \tag{5}$$

Taking time t_p (in s) for heat release rate to climb at Q_{peak} , heat release up to peak H_p (in kJ) is calculated by :

$$H_p = \int_0^{t_p} Q(t)dt \tag{6}$$

By assuming without explaining that H_p is H/2, combining equations (4), (5) and (6) gives:

$$\int_0^{t_p} 1000\left(\frac{t}{t_g}\right)^2 dt = \frac{FL \times h_c}{2}$$

Integrating gives:

$$\frac{1000}{t_g^{\,2}}\frac{t_p^{\,3}}{3} = \frac{FL \cdot h_c}{2}$$

Rearranging gives:

$$t_p = \left(\frac{3}{2}\frac{t_g^{\,2}}{1000}FL \cdot h_c\right)^{1/3} \tag{7}$$

Value of Q_{peak} is then calculated by taking t as t_p:

$$Q_{peak} = 1000\left(\frac{t_p}{t_g}\right)^2$$

Putting in t_p gives:

$$Q_{peak} = \frac{1000}{t_g^{\,2}}\left(\frac{3}{2}\right)^{2/3}\frac{t_g^{\,4/3}}{1000^{2/3}}FL^{2/3}h_c^{\,2/3}$$

$$= 1000^{1/3}\left(\frac{3}{2}\right)^{2/3}\cdot\frac{FL^{2/3}}{t_g^{\,2/3}}h_c^{\,2/3}$$

$$= 1000^{1/3}\left(\frac{3}{2}\cdot\frac{FLh_c}{t_g}\right)^{2/3}$$

This gives:

$$Q_{peak} = 13\left(\frac{H}{t_g}\right)^{2/3} \tag{8}$$

However, it is not clear why H_p is taken as H/2. Even such a proposed figure is accepted, limiting value of Q_{peak} to 1 MW (or 1000 kW) means that H is also limited. Taking an ultra-fast t^2-fire with t_g of 75 s, the upper limit of fire load FL_u for polyurethane foam of h_c 46 MJ/kg can be calculated by equation (8):

$$1000 = 13 \times \left(\frac{FL_u \cdot 46}{75}\right)^{2/3}$$

or

$$\left(\frac{1000}{13}\right)^{2/3} = \frac{FL_u \cdot 46}{75}$$

This gives:

FL_u = 29.5 kg

Therefore, only small amount of combustibles, such as 29.5 kg of polyurethane foam, is allowed to store in the room to give a Q_{peak} of 1 MW.

- Method 3

Another method is based on testing a protocol which is compiled with overseas standards [43]. Again, the tests must be carried out by burning local products with procedure suitable for local demand. It should not just follow overseas standards without any justification as raised by the author [41]. It should be noted that the level of education and civic awareness in some Far East countries are very different from advanced countries. Willingness to queue up while waiting for bus is a good example.

The above three methods are commonly used to calculate the peak heat release rate and the values calculated are lower than the design fire, say 1 MW. It should be noted that values of Q_{peak} reported in the literature [40,43] were not measured for local furniture. It is necessary to demonstrate that combustible items such as furniture used in the area concerned must be identical to those being tested. However, such data for local products was not shown.

Furthermore, average heat release rate Q_{av} calculated from the fire load FL and burning duration t_B (in s) by the following equation should not be mixed up with Q_{peak}.

$$Q_{av} = \frac{FL \cdot h_c}{t_B} \qquad (9)$$

The above equation does not give the peak heat release rate.

Research group led by the author [e.g. 18,28] found out that very high peak heat release rate was observed while burning local combustible products in post-flashover fires. Radiative heat flux is another factor affecting the combustible behaviour of furniture. Fire retardants applied to the combustibles, such as polyurethane foam sofa, would be ignited, burnt vigorously and emit toxic gas under high radiative heat flux. Therefore, better equipment must be provided to firemen, who go to the fire site with burning polyurethane foam.

All the above methods on calculating heat release rate should be reviewed with experimental support.

4. APPROPRIATE APPROACH AND NECESIITY OF FULL-SCALE BURNING TESTS

Academics have come up with a more appropriate approach, which is based on reported heat release rate curves [44]. It is necessary to determine the design fire by deducing the heat release rate curves while burning local products. Take a karaoke lounge with furniture such as polyurethane sofa, cushions, coffee table, chairs, partitions, surface lining materials and floor coverings or carpets as an example. Burning furniture of heat release rate Q_{furn}, surface lining materials of heat release rate Q_{surf} and carpets of heat release rate Q_{cap} would give the total heat release rate in the karaoke Q_K at time t [45] from the principle of superposition [46] as:

$$Q_K = Q_{furn} + Q_{surf} + Q_{cap} \qquad (10)$$

Heat release rate curves Q_{furn}, Q_{surf} and Q_{cap} should be measured experimentally in an oxygen consumption calorimeter for local products. Taking domestic upholstered furniture in Europe reported in the CBUF project [47] as an example, Q_{furn} (in kW) at time t (in minute) is:

$$Q_{furn} = 2500 \exp[-0.4\,(t-3)^2] \qquad (11)$$

For Class I lining in Swedish system, Q_{surf} (in kW) with a burner of strength between 100 kW and 300 kW placed next to it can be fitted by:

$$Q_{surf} = 300 \exp[-0.6\,(t-1.7)^2] \qquad (12)$$

Q_{surf} for burning Classes II and III linings might be a fast t^2-fire for an adjacent burner of strength 100 kW to 160 kW, i.e.:

$$Q_{surf} = 160\, t^2 \qquad (13)$$

Burning carpets might give Q_{cap}, which could lead to an ultra-fast t^2-fire:

$$Q_{cap} = 640\, t^2 \qquad (14)$$

Therefore, the total heat release rate Q_{K1} (in kW) for a fire in a room in karaoke lounge with lining materials classified as Class I under the Swedish system with carpet ignited at time t_{ic} is:

$$Q_{K1} = 2500 \exp[-0.4\,(t-3)^2] + 300 \exp[-0.6\,(t-1.9)^2] + 640\,(t-t_{ic})^2 \qquad (15)$$

Bear in mind that the surface lining would be ignited at 0.2 minute when Q_{furn} reached 100 kW.

For surface lining materials classified as Swedish Classes II or III, the total heat release rate in burning a karaoke box Q_{K2} (in kW) is:

$$Q_{K2} = 2500 \exp[-0.4 (t-3)^2] + 160 (t-0.2)^2 + 640 (t-t_{ic})^2 \quad (16)$$

A pictorial presentation of the 5-minute burning curves of the carpet (i.e. t_{ic} = 5 minutes) is shown in Fig. 1. This illustrates the choice of lining materials is important after a piece of furniture is ignited. For using Class I lining materials, the carpet might not be ignited as Q_{K1} dropped to 1000 kW in 5 minutes.

Estimation by equation (10) is only an approximation. Heat release from the first object would affect the burning behaviour of the second object. The phenomenon is complicated and empirical relations from full-scale burning tests need to be derived [46]. For example, whether the carpet would be ignited in 5 minutes is a question and can only be determined by full-scale burning tests.

Further, the radiative heat flux encountered is an important element in studying a post-flashover fire. Heat release rate curves measured by a cone calorimeter would be different under different radiative heat fluxes. Therefore, modelling heat release rate of the karaoke lounge by the principle of superposition with equation (10) is a very crude estimation. Full-scale burning facilities, which measures heat release rate by the oxygen consumption method [23], must be used to justify the model.

As reported by Hertzberg et al. [48], design fire is a crucial and decisive parameter to predict room fire development in performance-based design on fire safety provisions. No simple tools are available for prediction at the moment. On the other hand, CFD models are not yet developed [24] to study fire. At most, the model is only applicable to smoke control design in big halls. Even so, hot smoke tests are required to justify the predictions. The academics should develop semi-empirical methods as reported [48], which is supported by large volume of experimental data from bench-scale tests and cone calorimeter. Intermediate-scale tests with single burning item (SBI) test or Reduced Model Box (RMB), full-scale burning tests with room calorimeter and real-scale tests with large exhaust hood are also worth exploring and used together with two-zone models [26,49].

As measured experimentally by oxygen consumption method, burning cable would give 300 kW to 600 kW; burning printer would give 80 kW, 600 kW for computer monitor, and 100 to 250 kW for TV sets. Therefore, it is very difficult to control the peak heat release rate in a small room to 1 MW, even though only products in Europe are used. The situation was even worse for an empty train compartment. Real-scale tests were conducted on only part of a 9 m^3 small train compartment which is only equipped with two side-by-side seats. In this setting, the peak release rate would only amount to 0.5 MW to 2 MW !

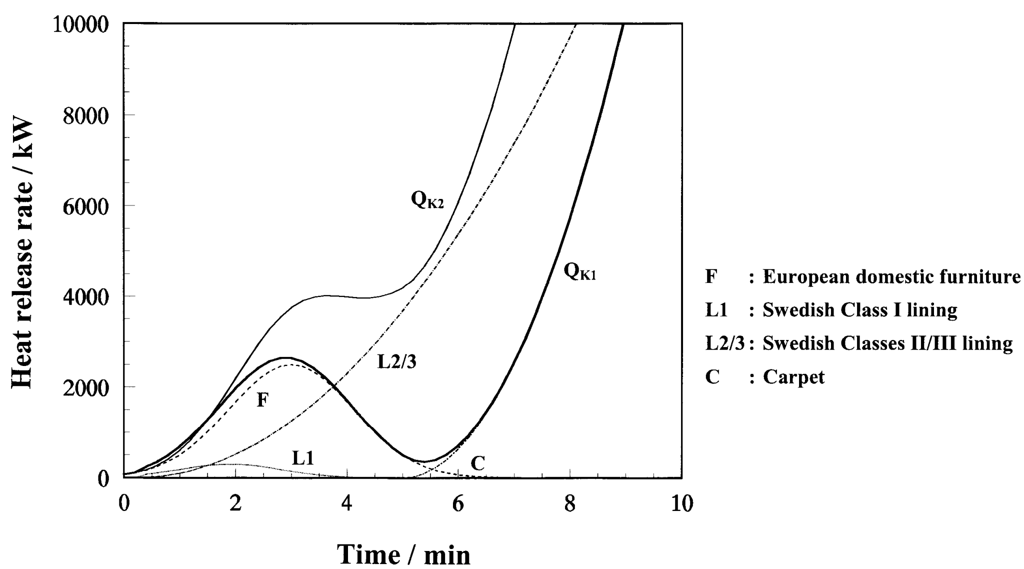

Fig. 1: Example of estimating heat release rate in a karaoke box (Chow, 2001)

5. CONCLUSIONS

Heat release rate [23,34,50] is the most important parameter in fire hazard assessment. A better understanding of heat release rate would provide more information for predicting the following [e.g. 32]:

- Fire environment, such as the smoke layer temperature, smoke layer interface height, radiative heat flux, rate of smoke flowing out and air intake rate, through the openings.
- The likelihood of flashover.
- Upward flame over walls.
- Ignition of other items which are placed adjacent to a burning item.

Furthermore, concentrations of toxic gases in the smoke layer can be predicted if relevant information such as the combustible product yields is measured. The results will be useful in recommending appropriate fire safety provisions for buildings which store high amount of combustibles.

Fire safety regulations on new architectural features, supertall buildings, large halls, long tunnels and underground subway stations cannot be set up without research support. Geometrical configurations and heat release rate database for local combustible products must be clearly set up. Fire safety provisions in very deep underground subway stations cannot just rely on estimating ASET with low design fire [51], and it is criticized as a flawed application [52-54].

Queries should be directed to fire safety provisions, and check if they follow prescriptive codes. In some buildings, partitioning without fire resistance in large halls, storing high combustibles in residential buildings with open kitchens and extended distance in large halls and long tunnels are common practices and features. There is an overriding concerns [55] about how such design would affect fire fighting strategy and potential health impact to firemen. It should be reminded that this point was only briefly discussed in many overseas PBD guides [16,17]. Very few FEA/PBD reports in the past two decades addressed the issues of firefighting and protecting firemen. Firemen have to carry heavy portable breathing apparatus and fire fighting equipment into the fire site, while walking a longer distance than the code specified, in a setting which lacks adequate fire resisting partitions. They have to bring out injured occupants and the disabled, and air bottles can only operate for 30 minutes. Impact on firefighters was not thoroughly analyzed in the FEA/PBD projects while fire safety provisions deviated from the code requirements. For example, requiring firemen to walk a much longer distance while carrying portable breathing apparatus and even injured occupants would definitely affect rescue and fire-fighting. The firefighters' health will certainly be affected. However, key information on heat release rate of local products is still absent in many countries and cities of the Far East, including Hong Kong. Carrying out full-scale burning tests [27,56-58] requires resources, but obviously, such studies are necessary to guarantee safety, particularly in setting up new codes with contradictory low figures on design fires [13,20,38]. All existing projects with heat release rates, which are estimated without strong justification by full-scale burning tests, must be revised to ensure appropriate fire safety provisions in buildings storing high amount of combustibles [1-4,59].

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