RECOMMENDATION OF TESTS FOR ASSESSING FLAME SPREAD OF MATERIALS IN HONG KONG

by

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Performance-based design for passive building fire safety provisions is accepted by the authority in Hong Kong since 1998. This is also known as the "fire engineering approach", though the performance-based fire code is not yet available. To cope with the use of new building materials, appropriate flame spread tests on materials and components should be specified. After reviewing four standard tests in the literature, i. e. ASTM E1321-97a, BS476: Part 7: 1997, ASTM E84-99/NFPA 255, and ISO 9705: 1993(E), it appears that ISO 9705: 1993(E) is suitable for assessing the flame spread of materials.

Key words: *fire, flame spread, standard tests, assessment, materials*

Introduction

Passive building design for fire safety is specified by prescriptive codes issued by the Buildings Department (BD) [1-3] of the local government. Apart from specifying the fire resistance period of wall, flame spread over materials was not clearly described. Note that flame spread over lining and finishes materials is one of the key elements [4] in providing fire safety. Upward flame spread along a wall lining and horizontal flame development beneath a combustible ceiling would give flashover rapidly.

Provision of fire service installations in Hong Kong is controlled by the Fire Services Department (FSD) [5]. BS 476: Part 7 [6] on surface spread of flame test was specified for some application such as finishes materials in their fire service installations code [5]. But this test is basically for assessing building materials, not the entire building element. It is not feasible to assess modern sandwich panels [7].

Suitable tests on flame spread should be specified for assessing modern materials and components, especially in applying "fire engineering approach" [8, 9]. This is similar to engineering performance-based fire codes (EPBFC) overseas [10]. At the moment, EPBFC is not yet available but the government would consider the performance-based designs of fire safety provisions through this fire engineering approach [8, 9].

Heat release rate of materials [11] is the most important parameter in fire hazard assessment while implementing performance-based design. Fire properties of materials

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can be assessed by studying the relationship between flame spread and heat release rate. Note that "fire properties" can be interpreted [12] as input material data for fire models. Those values might not be unique and depend on the burning conditions. Appropriate tests with mathematical models have to be used for predicting the real-scale fire.

In fact, flame spread tests should be specified in the karaoke establishments bills [13] developed after a big karaoke arson fire. Karaokes are typically partitioned into many boxes with long corridors by timber partition materials [14]. Timber materials are still more commonly used [15] than gypsum plasterboards even now as they are cheaper and easier to install. Those timber products can be ignited easily under a flashover fire even with retardants [16]. Upward and horizontal flame spread over the linings and wall might give a heat release rate high enough to flashover. Items placed adjacent to the partition wall might be ignited. Further, the partition wall would fall, lose the compartmentation effect and block the way. The partition walls are required to have a fire resistance period of 1 hour in new codes [1-3]. As pointed out [17], lining materials that can be easily ignited in a fire but cannot sustain flame spread after removing the fire source would imply some degree of fire safety. Flame spread over the partition materials should be watched to give compartmentation effect. This point will be studied in this paper.

Previously, four standard tests on spread of flame commonly used were preliminary reviewed [15]. The aim was to see whether recommendations can be made to the Authority on specifying the flame spread behaviour of materials and components. Those four standard tests are:

– ASTM E1321-97a – Standard Test Method for Determining Material Ignition and Flame Spread Properties [18], also referred to as the Lateral Ignition and Flame Spread Test or LIFT,
– BS476: Part 7: 1997 – Method of test to determine the classification of the surface spread of flame of products [6],
– ASTM E84-99 or ANSI/NFPA 255-2000 – Standard test method for Surface Burning Characteristics of Building Materials [19, 20], and
– ISO 9705: 1993(E) Fire Tests – Full-scale room test for surface products [21].

Comparison of the four tests

A comparison of the four tests was summarized before [15]:

– Both ASTM E1321 and BS476: Part 7 are bench-scale tests for assessing specimens of smaller size relative to the actual construction. It is difficult to assess full-scale effects such as structural performance of a material or construction component in real fires. Thermostructural failures and falling of non-structural members [22] in actual fire conditions might affect the flame spread.
– Horizontal flame spread is tested with materials mounted in vertical position for ASTM E1321 and BS476: Part 7. This may not be good for materials mounted horizontally such as carpets. Even for testing walls, the spread of flame is along the vertical direction [23]. Further, materials are tested in a ceiling position for ASTM E84/NFPA 255.

- ASTM 1321, BS476: Part 7 and ASTM E84/NFPA 255 allow testing one product by itself, or attached to an adjacent product, at one time. Flame spread from the wall to the ceiling or from the ceiling to the wall cannot be studied. In actual fires, fuel droplets would fall from the burning fuel, say the ceiling, onto the wall or floor. This, together with the radiative heat flux from the hot gas layer, would give a faster fire spreading rate [24].
- A wall surface exposed to an advancing heat and flame front is simulated in BS476: Part 7. The fire is fairly well developed. It only provides a measurement of the rate of development of the flame across the materials, which are not the first items ignited and no thermal feedback from ignition is considered [25].
- The lengthy preheat time of ASTM E1321, say from 7 to 10 minutes, of the specimen may allow surface pyrolysis which will then have time to change from the actual conditions after the pilot flame is inserted. Such changes can lead to poor ignition of the sample and altering its burning behaviour. This can be evidenced by the propensity for oscillating flames rather than sustained flaming, after ignition [26]. As a result, values measured in assessing flame spread depend on the consistency of flame propagation. Erratic flame fronts may lead to uncertain sets of data and affect the repeatability of the test. It was recommended [26] to eliminate the preheat period and to run the tests using the International Maritime Organisation (IMO) Res. A653(16) [27] or ASTM E1317 [28] surface flammability test protocol, which operates at a higher heat flux level without preheating the specimen, and then use the ASTM E1321 procedures for further analysis.
- For ISO 9705, wall and ceiling materials can be tested in their normal mounted conditions. Flame spread from one wall or falling burning objects to adjacent walls and ceiling can be observed. From the experiments reported on investigating the burning behaviours of materials under different configurations [29], the results on testing the walls and ceiling separately and putting them together are different. Typical results on the heat release rate curves of plywood and fire-retarded plywood were reported [29]. The heat release rates of testing materials with fire retardant for wall only, or for ceiling only, would be much lower than the materials without fire retardant. However, for the arrangement with both wall and ceiling, the heat release rates for the materials with fire retardant were only slightly less than those without fire retardant. In other words, the effect of putting on fire retardant to reduce the heat release rate is not significant. Updated cone results [7] illustrated that burning materials with and without fire retardants under high heat fluxes are similar. Such results can only be illustrated by modifying ISO 9705 extended to postflashover fire, not stopped at flashover.

The test results and the classification system are:

- ASTM E1321
  There is no established pass/fail criterion for the ignition and flame spread test results generated from ASTM E1321. The material parameters obtained can be used in mathematical models for fire growth and prediction of performance of materials [30, 31].
- BS476: Part 7

– Materials are classified into Classes 1 to 4 depending on the flame front distances at 1.5 and 10 min. of the test.
– ASTM E84/NFPA 255
The travelling distances of the flame front (at every 0.6 m or time intervals not more than 30 s) are measured and plotted against time to obtain the flame spread time-distance curve. The total area A_T under the curve is used to determine the Flame Spread Index, FSI, which can be compared with the benchmark materials to provide a relative ranking.
– ISO 9705
There is no classification or product rating scheme defined officially in the standard. Proposed systems overseas are discussed in the later section.

Both ASTM E1321 and BS476: Part 7 are bench-scale experiments. ASTM E84/NFPA 255 is a relatively large test, while ISO 9705 is considered as a full-scale burning test. These four standard tests were developed based on different scenarios. Materials were therefore only assessed under the conditions designated. Practical ranking or classification systems were deduced from the testing results. Attempts were made to derive correlations among the measured data appeared in the literature [15]. However, correlation expressions derived are not convincing due to the difficulties in searching for tested data on the same materials under the four tests.

Recommendation of using ISO 9705

More realistic fire performance data than tests for individual components can be obtained [32]. It appears that ISO 9705 is a suitable testing method for assessing flame spread for Hong Kong [33] with justifications as follows:

– *Measurement of heat release rate and smoke production*
The answer to the question "How big is a fire?" is on estimating the heat release rate from burning the building materials. This was identified to be the most important parameter in hazard assessments. On the other hand, most of the people killed in a fire were due to smoke. Therefore, the smoke production rate is also important. These two important parameters can be measured by ISO 9705. Not only that, the temperature, thermal radiation levels, concentration of gases, and production of toxic gases can all be measured accurately.
– *Possibility of flashover*
Time to flashover can be measured by this test [33]. Note that the room size for the ISO 9705 test is very close to the minimum size of a building. A lining fire might develop faster in a larger room.
– *Scale of test and orientation*
Flame spread depends on the conditions of the surrounding fluid. Air cavity and substrates for some products may become the heat sink. With ISO 9705, it is possible to test the lining and surface finish products that cannot be tested properly in smaller scale tests. Different orientations, such as wall and ceiling, of the specimen as well as its real configuration of installation can be included.

Review on classification systems based on ISO 9705

There are recommendations on classifying and rating products based on ISO 9705. A ranking system can be derived by evaluating some of the critical performance aspects. As discussed in the literature [34], the following can be used to presume the hazards of materials such as sandwich panels:
– peak heat release rate,
– total heat release,
– time to flashover (during 100 kW burner exposure in the first 10 minutes or during the subsequent period of 300 kW burner output), and
– amount of smoke evolution.

The time to flashover was considered as the criterion for classification [*e. g.* 34, 35]. The ability of a material in sustaining flame spread and its contribution to fire growth can be assessed. Four levels of room fire performance, A, B, C, and D were suggested [36] for the regulation control of materials:
– A: for fire-isolated passageways (exits), no flashover after 10 minutes,
– B: for assembly areas and corridors providing access to exits, flashover after 6 minutes,
– C: for general areas, flashover after 4 minutes, and
– D: not permitted, flashover in less than 4 minutes.

Good efforts were made in the Nordic countries on evaluating a proposed system [37]. A five-scale classification system was proposed [38, 39]. Heat release rate, smoke production and the time to flashover are considered with a graphical presentation of the system [39]. In the classification system, both the peak and average values of the heat release rate are considered. A limit is put on long lasting fires which give off a significant amount of total heat. Credits are given to those products that burn out quickly even though the peak heat release is high. To evaluate the system, eleven products were tested and classified under the proposed system. The results were compared with the regulations used in England, France, Germany, Italy, and Denmark under their EUREFIC programme [39, 40]. It was found that there was no general agreement between the classification systems, except for class A and products like plasterboard and plywood. A comparison of the proposed EUREFIC system by SP with BS 476: Part 7 is summarized in tab. 1. This classification system is open for a more detailed assessment. Having five classes in a new classification system might not be practical, but can give flexibility [39]. It can differentiate various products and can therefore be related to various existing national systems.

There is another classification system based on ISO 9705 in the USA. The High Speed Craft code (HSC) was implemented on January 1, 1996, as part of the Safety of Life at Sea (SOLAS) on the construction of high-speed crafts by combustible materials. In that code, bulkhead linings, compartment linings, and ceiling materials are required to be tested using ISO 9705. Materials are classified into either fire restricting or non-fire restricting. A fire restricting material is defined as a material having low flame spread characteristics, limited rate of heat release, and low smoke production [41]. It should meet the acceptance criteria as published in the resolution MSC.40(64) [42] of the IMO [26]:

– average heat release rate over the entire testing time shall not exceed 100 kW,
– maximum 30 s average heat release rate shall not exceed 500 kW,
– average smoke production rate shall not exceed 1.4 m/s,
– maximum 60 s average smoke production rate shall not exceed 8.3 m/s,
– no flame spread to the area below 0.5 m from the floor at a distance greater than 1.2 m from the corner, and
– no flaming "droplets or debris" may reach the floor, except in the area within 1.2 m from the corner.

Table 1. Comparison of the EUREFIC system for ISO 9705 and BS 476: Part 7 [Hovde 1991, Bluhme 1991]

BS 476: Part 7	Proposed EUREFIC classification system	Product	Remarks
1	A B C	A1: Painted gypsum paper plasterboard	–
		A2: Melamine faced high density non-combustible board	–
		A3: Plastic faced steel sheet on mineral wool	–
		A4: FR particle board	–
3	D	D1: Textile wallcovering on gypsum paper plasterboard	–
		D2: FR particle board type B1	–
		D3: PVC wallcarpet on gypsum paper plasterboard	Class 2 (BS 476: Part 7) if flashing and transitory flaming are taken into account
	E	E1: Ordinary plywood	–
		E2: Plastic faced steel sheet on polyurethane foam	Class 3 (BS 476: Part 7) if flashing and transitory flaming are taken into account
4	–	U1: Combustible faced mineral wool	–
Invalid	U	U2: FR extruded polystyrene foam	–

However, some shortcomings with the ISO 9705 standard were identified while carrying out the tests [26]. There are no clear specifications on the exhaust duct volumetric flow rate or range of flow rates, except the examination of the effect of the duct flow rate (at 300 kW only) in the calibration procedure. The exhaust volumetric flow is believed to affect the measurements of heat release rates, especially when the flow rates and heat release values are low. The heat release rate might give unreal spikes when the duct volumetric flow rate is suddenly increased. Rapid increase in the duct flow rate is found when there is a sudden increase in the smoke production rate.

The IMO failure criterion concerning the flame spread to the area below 0.5 m is another concern. Tests on nine composites representing a range of fire restricting and non-fire restricting materials were carried out with ISO 9705. The flame spread failure criterion was found to be not so representative since the upper limits of the smoke and heat release rate are usually exceeded before the flames spread to the 0.5 m level when flashover occurs. On the other hand, the flames are usually confined to the wall and ceiling areas in the immediate vicinity of the burner flame if flashover does not occur during the 20 min. testing period. Thin wallpaper type coverings might be an exception as flame would spread rapidly with a small amount of heat and smoke released. The flame spread criterion was suggested to be re-examined.

There are also some reservations on the falling “droplets” or debris criterion. In testing paperbacked textile wallcovering, wallpaper would be separated from the substrate and fall to the ground. Materials showing this behaviour would be regarded as “non-fire restricting”. However, the quantity of falling debris would be very small and so flaming would cease in a few seconds. This would not produce any significant problem in such application.

A room partially filled with wall-covering materials was suggested to be good enough to assess the fire-restricting nature of that material. It was observed that only the panel sections adjacent to the burner, at the top of the sidewalls and on the ceiling were burnt in most cases. Remainders of the materials did not contribute significantly to the fire. Such partially lined room would reduce the testing cost and the amount of materials to be provided by manufacturers.

Other alternatives

An agreement was made in June 1994 on the harmonization of test procedures and classification system for surface lining materials used in buildings by the member countries in the European Community. Reaction to fire for construction products will be classified with a Euroclass system into six different classes, A to F [43]. A new intermediate-scale test method developed and approved by the European Committee for Standardization in 2001 – the Single Burning Item (SBI) test was specified as the main test procedure for flame spread. The test was also established as a British Standard BS EN 13823 [44] in 2002. In the new 2000 edition of the UK Building Regulations [45], the SBI test was included for assessing flame spread over internal linings. Building products should fulfill the requirements of the SBI test and the Euroclasses, unless appropriate test and classification methods are yet available where the existing national test, BS 476: Part 7 can be used until such a time that a generally accepted guidance is published by the Office of the Deputy Prime Minister. Since it has just been developed and assessed recently, the ISO 9705 Room/Corner test was taken as a reference scenario [46] and to be used to specify the levels for the classification. The Lateral Flame Spread (LFS) is concerned [47]. In the test, the requirement of upward flame spread expressed as a value of length during a specified time (F_s) should be fulfilled. In addition to the SBI test, all materials should be tested by the Non-combustibility test (EN ISO 1182) [48], the Gross Calorific Value test (EN ISO 1716) [49] as well as the Ignitability test (EN ISO 11925-2) [50]. Based on the results, materials are classified into six groups from A to F [51], with class A further divided into A1 and A2.

Another set of tests and classification system was considered [47] to be used for interior linings in order to meet the performance-based building regulations and international demands for harmonization in Japan. The test with a cone calorimeter [52] was proposed to be used together with the ISO 9705 room/corner test by taking it as a reference scenario. Three proposals were provided [47].

A reduced-scale model box (RMB) test [53] was proposed for assessing fire spread. It is a 1/3 scale model of the room/corner test used to determine the behaviour of quasi non-combustible materials [47]. Attempts have been made to derive the correlation equations between the results of the RMB test and the ISO 9705 full-scale test [54].

Results [47] measured by the ISO 9705 test and the RMB test were roughly compared [15]:

- RMB: no flashover,
- ISO 9705: no flashover,
- RMB: peak heat release rate <100 kW,
- ISO 9705: time to flashover >10 min.,
- RMB: peak heat release rate >200 kW, and
- ISO 9705: time to flashover <5 min.

Further studies on additional parameters are required.

Comparison with ASTM E84/NFPA 255

ASTM E84/NFPA 255 “tunnel test” is widely accepted and the FSI rating system is readily understood in the USA. However, it was not designed as a stand-alone test to describe the combustibility of a material [55], but rather, to evaluate the FSI of interior finishes and to compare the performance of different materials with the benchmark materials without necessarily be indicative of the behaviour of the material in its end-use application. At the same time, designers use a wide range of materials for interior finishes and decoration in the modern building designs nowadays. In some cases, particularly those composite and decorative materials with unusual geometries or configurations, the tunnel test is inappropriate [56].

It was found that although some wallcoverings may achieve a low flame-spread rating in the ASTM E84 test conditions, the materials may actually spread flame readily and cause fires to grow quickly in the larger-scale and more realistic room/corner test [57]. In the 1989 Atlanta high-rise office building fire, an electrical arc ignited multiple layers of wallcoverings and fire rapidly spread in the exit corridor. Although the listed ratings of the individual wallcoverings were acceptable for the occupancy, locations, and exit corridors, the combination of materials performed much differently in fire conditions [58].

The U. S. Building codes place some restrictions on interior finishes in buildings by limiting the flame spread rating of a material permitted for a given type of construction and occupancy. Textile wallcoverings installed in an unsprinklered occupancy are required by Model building codes [59-61] and the Life Safety Code (LSC) [62] to be tested in a room/corner fire test [32]. Complete assembly with all layers and substrates are required by the LSC to be tested. However, the ASTM E84 test method is not designed to test wall assemblies. Some modifications of extending the skirt on the removable tunnel lid were required [32] to ensure an adequate seal in the liquid trough and prevent the escaping of heat and smoke, so that the tunnel test can be used for interior finish materials on their intended substrate and wall assembly.

Considering the testing positions of materials, the National Standard of Canada for building materials also employs a similar tunnel test [63, 64], in which the building materials can be mounted on the ceiling or floor depending on their physical (whether it can support its own weight) and burning (melting or dripping) characteristics. However, for ASTM E84, samples can only be tested in the ceiling-mounted position [65].

As reported, carrying out an ASTM E84/NFPA 255 "tunnel test" is less expensive than the ISO 9705 room corner fire test in the USA [32]. But if a new rig is to be developed, there might not be much difference in the initial installation cost, staff training cost, operation and maintenance cost. Bearing in mind that there might be numerous new materials to be developed in China. Developing such a testing facility should be a good investment.

ASTM E1321 together with the cone calorimeter

As discussed, ISO 9705 is relatively expensive to run and only one scenario can be modeled at a time. Large quantities of testing materials are required. Results of the cone calorimeter have been widely proved to be correlated with the ISO 9705 results. For developing new materials, it can be used together with the LIFT apparatus (ASTM E1321) to predict the full-scale flame spread of materials.

An empirical relationship was developed [66] for predicting the time to flashover in the full-scale room/corner tests for the surface lining materials. That was further modified [67] to give some new correlations based on the heat release rate measurements in the cone calorimeter. The time to flashover was expressed [68] as a function of the material parameters from the cone calorimeter and LIFT.

Studies have also been carried out by the USA [26, 69] to assess the ability of the small-scale test results to predict the full-scale fire performance of compartment linings in room/corner configurations. A proposal was submitted to IMO by Finland on qualifying the fire-restricting materials on the basis of the cone calorimeter data, in which it showed that a maximum 60 s sliding average heat release rate of 60 kW/m^2 or less in the cone calorimeter at a heat flux of 50 kW/m^2 would be equivalent to meet the ISO room test criteria for heat release rate [26]. This proposal was assessed and found to be feasible to develop accurate acceptance criteria from the ISO 5660 cone calorimeter test. Their overall evaluation suggested that using the cone calorimeter results, LIFT test results and mathematical modeling results can predict the ISO 9705 results; and the realistic scenarios including different ignition sources, ceiling heights, room sizes, and ventilation rates.

It was proposed [70] to use the cone calorimeter and LIFT results to simulate the behaviours of materials in the ISO 9705 test using the SPREAD algorithm [71, 72]. Modifications were made to change the sidewall algorithm to a corner one. Results illustrated that the heat release rate curves from the model are similar to those measured from the experiments. This type of model has been proved to have potential for practical application.

Conclusions

As reported earlier [15, 33] on comparing with three other tests, ISO 9705 is recommended for testing the flame spread of materials as explained in this paper. In contrast to overseas, the local government can draft codes on flame spread without worrying about disturbing the local testing facilities. Taking ISO 9705 as the first choice might give good data.

On ranking materials from ISO 9705, there are classification systems proposed in other countries. However, only the IMO acceptance criteria [42] are formally adopted in the HSC, though some decisive conditions were not agreed on [26]. Other systems are still open for further analysis and improvement. The local government may take those overseas experiences as references. Further, in-depth studies on a wider range of products are recommended. The results should be compared with BS 476: Part 7 [6] and the other generally recognized rankings [*e. g.* 34, 38-40] in order to develop the most suitable classification system for the local construction industry.

There are always arguments saying that ISO 9705 is expensive to be carried out. However, in comparing with the local cost of buildings, a residential building at mid-levels would still cost HK$ 5,000 (US$ 600) per square foot. People cannot argue on the cost for such a test. Further, higher education institutes would serve the industry by testing these materials and components at reasonable costs to help providing fire safety. However, smoke emissions might bring about environmental problems. Developing such a full-scale burning facility in a remote area is strongly recommended. But that does not imply that installing a smoke treatment plant is unnecessary.

Other tests with SBI [45], RMB [47], and combining the LIFT test [18] with the cone calorimeter results [52] might also be considered in performance-based design. Those tests might be used as alternatives in later stages of development.

References

[1] ***, Code of Practice for the Provision of Means of Access for Firefighting and Rescue Purpose, Building Authority, Hong Kong Special Administrative Region, 2004

[2] ***, Code of Practice for the Provision of Means of Escape in Case of Fire, Building Authority, Hong Kong, 1996

[3] ***, Code of Practice for Fire Resisting Construction, Buildings Department, Hong Kong, 1996

[4] Bukowski, R. W., Babrauskas, V., Developing Rational, Performance-Based Fire Safety Requirements in Model Building Codes, *Fire and Materials, 19* (1994), 2, pp. 173-191

[5] ***, Code of Practice for Minimum Fire Service Installations and Equipment and Inspection and Testing of Installations and Equipment, Fire Services Department, Hong Kong, 1998

[6] ***, Fire Tests on Building Materials and Structure, Part 7. Method of Test to Determine the Classification of the Surface Spread of Flame of Products, BS476: Part 7: 1997, British Standards Institution, London, 1997

[7] Chow, W. K., Fire Hazard Assessment on Polyurethane Sandwich Panels for Temporary Accommodation Units, *Polymer Testing, 23* (2004), 8, pp. 973-977

[8] ***, Guide to Fire Engineering Approach, Practice Note for Authorized Persons and Registered Structural Engineers PNAP 204, Buildings Department, Hong Kong, 1998

[9] Chow, W. K., Fire Safety in Green or Sustainable Buildings: Application of the Fire Engineering Approach in Hong Kong, *Architectural Science Review, 46* (2003), 3, pp. 297-303

[10] ***, Application of Fire Safety Engineering Principles to the Design of Buildings, BS7974: 2001, British Standards Institution, London, 2001

[11] Babrauskas, V., Grayson, S. J., Heat Release in Fires, Elsevier Applied Science, London, 1992

[12] Cleary, T. G., Quintiere, J. G., A Framework for Utilizing Fire Property Tests, *Proceedings* (Eds. G. Cox, B. Langford), 3rd International Symposium, Fire Safety Science, Edinburgh Scotland, UK, 1991, pp. 647-656

[13] ***, Legislative Council, Karaoke Establishments Bill. Press Release, Hong Kong Special Administrative Region Government, 2000

[14] Chow, W. K., Lui Gigi, C. H., A Fire Safety Ranking System for Karaoke Establishments in Hong Kong, *Journal of Fire Sciences, 19* (2001), 2, pp. 106-120

[15] Leung, C. W., Fire Spreading of Materials and Its Contribution to Compartment Fire, Ph. D. thesis, The Hong Kong Polytechnic University, Hong Kong, 2006

[16] Chow, W. K., Han, S. S., Chow, C. L., Fire Behaviour of Timber Products with and without Fire Retardant, *Journal of Applied Fire Science, 11* (2002-2003), 3, pp. 209-227

[17] Hasemi, Y., Yoshida, M., Hayashi, Y., Yabuta, T., Correlations between Bench-Scale Test and Room Corner Test Based on a Flame Spread Modelling: Interpretation of Small and Intermediate Scale Fire Testing, NISTIR 6588, 15th Meeting of the US-Japan National Research, Panel on Fire Research and Safety, San Antonio, Tex., USA, 2000, Vol. 1, pp. 51-61

[18] ***, Standard Test Method for Determining Material Ignition and Flame Spread Properties, ASTM E1321-97a, American Society for Testing and Materials, West Conshohocken, Pa., USA, 1997

[19] ***, Standard Test Method for Surface Burning Characteristics of Building Materials, ASTM E84-99, American Society for Testing and Materials, West Conshohocken, Pa., USA, 1999

[20] ***, Standard Method of Test of Surface Burning Characteristics of Building Materials, NFPA 255: 2000, National Fire Protection Association, Quincy, Ma., USA, 2000

[21] ***, Fire Tests – Full-Scale Room Test for Surface Products, ISO 9705: 1993(E), International Standards Organization, Geneva, Switzerland, 1996

[22] Babrauskas, V., Wickström, U., The Rational Development of Bench-Scale Fire Tests for Full-scale Fire Prediction, *Proceedings*, 2nd International Symposium on Fire Safety Science, Hemisphere Publishing Comp., New York, USA, 1989, pp. 813-822

[23] Walker, A.G., Flammability Testing in Europe, *Fire and Materials, 4* (1980), 3, pp. 149-153
[24] Murrell, J. M., Barnfield, J. R., The Role and Application of Standard Tests, *Fire and Materials, 13* (1988), 1, pp. 141-147
[25] Allender, P. J., Specification of Combustible Materials for Passenger Train Design, *Fire and Materials, 8* (1984), 3, pp. 113-124
[26] Janssens, M. L., Garabedian A., Gray, W., Establishment of International Standards Organization (ISO) 5660 Acceptance Criteria for Fire Restricting Materials Used on High Speed Craft. Final Report, No. CG-D-22-98, U. S. Coast Guard Research and Development Center, Southwest Research Institute, San Antonio, Tex., USA, 1998
[27] ***, Recommendation on Improved Fire Test Procedure for Surface Flammability of Bulkhead, Ceiling, and Surface Finish Materials, IMO Resolution A 653(16), International Maritime Organization, London, 1989. Reproduced in the FTP Code, pp. 61-93
[28] ***, Standard Test Method for Flammability of Marine Surface Finishes, ASTM E1317-97a, American Society for Testing and Materials, West Conshohocken, Ma., USA, 1997
[29] Dowling, V. P., McArthur, N. A., Webb, A. K., Leonard, J. E., Blackmore, J. M., Large-Scale Fire Tests on Three Building Materials, *Proceedings*, 3rd International Conference on Fire Research and Engineering, Society of Fire Protection Engineers, Chicago, Ill., USA, 1999, pp. 217-227
[30] Bhatnagar, S. K., Varshney, B. S., Mohanty, B., An Appraisal of Standard Methods for Determination of Flame Spread Behaviour of Materials, *Fire and Materials, 16* (1992), 3, pp. 141-151
[31] Quintiere, J., Harkeroad, M., New Concepts for Measuring Flame Spread Properties, Fire Safety Science and Engineering, ASTM STP 882 (Ed. T. Z. Harmanthy), 1985, pp. 239-267
[32] Dyar, C. G., Boser, R., Testing Low-Flame-Spread Wallcoverings on Typical Construction Substrates in ASTM E84, *Fire Technology, 32* (1996), 3, pp. 231-238
[33] Chow, W. K., Han, S. S., Superposition of Heat Release Rate Curves for Combustibles with Bench-Scale Tests, *Polymer Testing, 25* (2006), 1, pp. 75-82
[34] Babrauskas, V., Sandwich Panel Performance in Full-Scale and Bench-Scale Fire Tests, *Fire and Materials, 21* (1997), 2, pp. 53-65
[35] Chow, W. K., Based Fire Codes, *International Journal on Engineering Performance* (Special issue on full-scale burning tests), *6* (2004), 3, pp. 88-180
[36] Gardner, W. D., Thomson, C. R., Flame Spread Properties of Forest Products – Comparison and Validation of Prescribed Australian and North American Flame Spread Test Methods, *Fire and Materials, 12* (1988), 2, pp. 71-85
[37] Hovde, P. J., Comparison between Nordtest and ISO Fire Test Methods. Evaluation of Classification Systems, *EUREFIC Seminar Proceedings*, Copenhagen, 1991, Interscience Communications, London, pp. 47-54
[38] Sundström, B., Goranssön, U., Possible Classification Criteria and Their Implications for Surface Materials Tested in Full Scale According to ISO DP 9705 or NT Fire 025, SP Report 1988: 19, Fire Technology, SP, Swedish National Testing Institute, Sweden, 1988
[39] Sundström, B., Classification of Wall and Ceiling Linings, *EUREFIC Seminar Proceedings*, Copenhagen, 1991, Interscience Communications, London, pp. 23-36
[40] Bluhme, D. A., Correlation of Test Results with Other European Test Methods, *EUREFIC Seminar Proceedings*, Copenhagen, 1991, Interscience Communications, London, pp. 55-63
[41] Grenier, A. T., Janssens, M. L., Nash, L., Developing Cone Calorimeter Acceptance Criteria for Materials Used in High Speed Craft, *Fire and Materials, 24* (2000), 1, pp. 29-35
[42] ***, Standard for Qualifying Marine Materials for High Speed Craft as Fire-Resisting Materials, Resolution MSC.40(64), International Maritime Organization, London, 1994
[43] ***, European Commission, Commission Decision of September 9, 1994, Implementing Article 20 of Directive 89/106/EEC on Construction Products, Official Journal of the European Communities, No. 6, Brussels, 1994

[44] ***, Reaction to Fire Tests for Building Products. Building Products Excluding Floorings Exposed to the Thermal Attack by a Single Burning Item, BS EN 13823:2002, British Standards Institution, London, 2002
[45] ***, The Building Regulations 2000. Approved Document B: Fire Safety, Office of the Deputy Prime Minister, London, 2000
[46] ***, European Commission, Update No. 9 on Progress Regarding Fire Related Issues, Document, Brussels, 1998
[47] Hedskog, B., Ryber, F., The Classification Systems for Surface Lining Materials Used in Buildings in Europe and Japan – A Summary and Comparison, Report 5023, Department of Fire Safety Engineering, Lund Institute of Technology, Lund University, Lund, Sweden,1998
[48] ***, Reaction to Fire Tests for Building Products. Non-Combustibility Test, BS EN ISO1182: 2002, British Standards Institution, London, 2002
[49] ***, Reaction to Fire Tests for Building Products. Determination of the Heat of Combustion, BS EN 1716: 2002, British Standards Institution, London, 2002
[50] ***, Reaction to Fire Tests. Ignitability of Building Products Subjected to Direct Impingement of Flame. Single-flame Source Test, BS EN ISO 11925-2:2002, British Standards Institution, London, 2002
[51] ***, Fire Classification of Construction Products and Building Elements. Part 1: Classification Using Test Data from Reaction to Fire Tests, BS EN 13501-1: 2002, British Standards Institution, London, 2002
[52] ***, Fire Tests – Reaction to Fire – Part 1: Rate of Heat Release from Building Products (Cone Calorimeter Method), ISO 5660-1: 1993, International Standards Organization, Geneva, Switzerland, 1993
[53] ***, Certification of Quasi-Noncombustible Materials and Fire Retardant Materials, Notification No. 1321 of the Ministry of Construction, 3rd ed., The Building Center of Japan, Tokyo, 1994
[54] Yoshida, M., Hasemi, Y., Tanaike, Y., Tasaka, S., Saito, F., Fangrat, J., Comparative Studies in the Reduced-Scale Model Box and the Room Corner Test, *Proceedings*, 8th International Interflam Conference, Edinburgh, Scotland, UK, 1999, 1, pp. 23-33
[55] ***, Standard Test Method for Surface Burning Characteristics of Building Materials (E84-91a), Annual Book of ASTM Standards, Section 4, Part 7, American Society for Testing Materials, Philadelphia, Pa., USA, 1993, pp. 299-313
[56] Torvi, D. A., Lougheed, G. D., Carpenter, D. W., Senez, P. L., Locke, H. A., Evaluating Materials and Fire Protection Systems Using Full-scale Fire Tests, *Proceedings*, 3rd International Conference on Fire Research and Engineering, Society of Fire Protection Engineers, Chicago, Ill., USA, 1999, pp. 363-374
[57] Belles, D. W., Fisher, F. L., Williamson, R. B., How Well Does ASTM E84 Predict Fire Performance of Textiles and Wallcoverings, *Fire Journal, 84* (1988), 1, pp. 25-27, 29-30, 74
[58] Isner, M. S., Five Die in High-Rise Office Building Fire, *Fire Journal, 84* (1990), 4, pp. 50-59
[59] ***, Standard Building Code (SBCC), Southern Building Code Congress International, Birmingham, Al., USA, 1997
[60] ***, Uniform Building Code, The International Conference of Building Officials, Whittier, Cal., USA, 1997
[61] ***, BOCA National Building Code, The Building Officials and Code Administrators International, Inc., Country Club Hills, Ill., USA, 1999
[62] ***, Life Safety Code Handbook, National Fire Protection Association, Quincy, Ma., USA, 1991
[63] ***, Standard Method of Test for Surface Burning Characteristics of Building Materials and Assemblies, ULC Standard CAN4-S102-M83, Underwriters' Laboratories of Canada, Scarborough, Ont., Canada, 1983

[64] ***, Standard Method of Test for Surface Burning Characteristics of Flooring, Floor Covering, and Miscellaneous Materials and Assemblies, ULC Standard CAN4-S102.2-M83, Underwriters' Laboratories of Canada, Scarborough, Ont., Canada, 1983
[65] Mehaffey, J. R., Flammability of Building Materials and Fire Growth, *Proceedings*, Building Science Insight '87, Institute for Research in Construction, National Research Council Canada, Ottawa, NRCC 2827, 1987, pp. 21-23
[66] Ostman, B., Nussbaum, R., Correlation between Small-Scale Rate of Heat Release and Full-Scale Room Flashover for Surface Linings, *Proceedings* (Ed. Wakamatsu *et al*.), 2nd International Symposium on Fire Safety Science, International Association of Fire Safety Science (IAFSS), Tokyo, Hemisphere Publishing Comp., New York, USA, 1987, pp. 823-832
[67] Ostman, B., Tsantaridis, L., Correlation between Cone Calorimeter Data and Time to Flashover in the Room Fire Test, *Fire and Materials, 18* (1994), 4, pp. 205-209
[68] Karlsson, B., Modeling Fire Growth on Combustible Lining Materials in Enclosures, Report TVB-1009, Department of Fire Safety Engineering, Lund University, Lund, Sweden, 1992
[69] Beyler, C. L., Hunt, S. P., Lattimer, B. Y., Iqbal, N., Lantenberger, C., Prediction of ISO 9705 Room/Corner Test Results, Volume I, Final Report No. CG-D-22-99, U. S. Coast Guard Research and Development Center, Groton, Ct., USA, 1999
[70] Wright, M. T., Barnett, J. R., Dembsey, N. A., Flame Spread on Cored Composite Panels for Use in High Speed Craft, *Proceedings*, 3rd International Conference on Fire Research and Engineering, Society of Fire Protection Engineers, Chicago, Ill. , USA, 1999, pp. 228-239
[71] Mitler, H., Steckler, K., Spread – A Model of Flame Spread on Vertical Surfaces, Technical Report NISTIR 5619, Department of Commerce, National Institute of Standards and Technology, Gaithersburg, Md., USA (written 1993, issued 1995)
[73] Mitler, H., An Algorithm to Describe the Speed of a Wall Fire Under a Ceiling, Technical Report NISTIR 5547, Department of Commerce, National Institute of Standards and Technology, Gaithersburg, Md., USA, 1994

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