REVIEW ON FOUR STANDARD TESTS ON FLAME SPREADING

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ABSTRACT

Four flame spread tests on materials and components were surveyed in this paper. They are ASTM E1321-97a, BS476: Part 7: 1997, ASTM E84-99/NFPA 255 and ISO 9705: 1993(E). The scale of these tests, the heat sources concerned, testing requirements, environment, experimental setups, results and classification systems were reviewed. Selected results on materials assessed by the four tests using data reported in the literature are illustrated. Preliminary studies indicated that ISO 9705: 1993(E) is a test suitable for assessing flame spreading of materials and components.

1. INTRODUCTION

Passive building fire safety and the provision of fire services installations are basically designed following the prescriptive codes issued by the government Buildings Department (BD) [1-3] and Fire Services Department (FSD) [4]. However, prescriptive codes might not be suitable for buildings with new design features. Therefore, 'engineering approach' in Hong Kong [5] (or engineering performance-based fire codes in overseas) are used. Though the codes are different in different countries, flame spreading over lining and finishes materials is a key element [6].

When an item such as a foam furniture catches fire and starts burning, adjacent items might be ignited to give higher heat release rates [7]. Flame spreading of building materials and components should therefore be specified carefully. It seems that this part is not described clearly in the local codes [1-4] where only the BS476: Part 7 on surface spread of flame test [8] was specified. But this test is basically for assessing building materials, not on the entire building element. Therefore, specifications on suitable tests on flame spreading should be described more clearly in the local codes.

In this paper, four standard tests on spread of flame were reviewed with the aim of illustrating how flame spreading behaviour of materials and components can be tested. Those four standard tests are:

- ASTM E1321-97a Standard Test Method for Determining Material Ignition and Flame Spread Properties [9]

  This is an American national standard issued by the American Society for Testing and Materials (ASTM), USA, which is also referred to as the Lateral Ignition and Flame Spread Test or LIFT. The test adopted an apparatus evolved from the International Standards Organization (ISO)/International Maritime Organization (IMO) research and the scientific analysis process initiated by the Federal Aviation Administration (FAA) and carried out at the National Institute for Standards and Technology (NIST) in 1985 as discussed in the literature [9]. There are two protocols, with one for determining the ignition parameters of the materials and the other one for obtaining the lateral (opposed) flow flame spread properties.

- BS476: Part 7: 1997 Method of test to determine the classification of the surface spread of flame of products [8]

  As reviewed [10], the test was developed by FOC Fire Testing Station at Borehamwood, and then introduced by the British Standards Institution (BSI). The original development of BS 476: Part 7 was initiated by some disastrous fires caused by rapid flame spread along wall linings. The test method was designed to simulate a corridor situation with a fire at one end, the radiant panel being the fire and the sample the wall lining [11]. This test is specified by the local government [4] for assessing the fire spreading of materials.

- ASTM E84-99 or ANSI/NFPA 255-2000 – Standard test method for Surface Burning Characteristics of Building Materials [12,13]

  This "tunnel test" was originally developed at the Underwriter's Laboratories (UL) and adopted by the UL, National Fire Protection Association (NFPA) and the ASTM as standards, UL 723 in 1950 [14], NFPA 255 in 1955 and ASTM E84 in 1961 respectively.

The test, with the flame source comparable to a fire in a large waste container or a small upholstered chair [15], was designed to simulate the growth stage of a fire when interior finishes are ignited and consumed [16]. ASTM E84 and NFPA 255 are used by the regional and local building-code authorities in the USA [10]. ASTM E84 has been approved by the model-building codes [17-19] and NFPA 255 has been specified in the Life Safety Code (LSC) [20].

- ISO 9705: 1993(E) Fire Tests – Full-scale room test for surface products [21]

  As reviewed by Williamson and Dembsey [22], the room/corner scenario was introduced in the 1950s in both the United States and Australia. Later, online measurement of the rate of heat release was made using the oxygen consumption method [7,23,24]. Much of the work leading finally to the ISO standard was published in the literature [25,26]. The test for studying the reaction-to-fire properties of surface products has become an international standard, ISO 9705 since 1990 [27].

2. SCALE OF TESTS

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.

The size of the testing sample for lateral flame spread test is 155 mm × 800 mm (0.12 m^2) for ASTM E1321. The specimen shall be thermally thick and tested at full thickness for materials or composites thinner than 50 mm. The required dimension of the specimen for BS 476: Part 7 is 885 mm × 270 mm (0.24 m^2). The specimen should be tested at full thickness provided that it can be fitted into the specimen holder, if not, the unexposed face should be cut away to reduce the thickness to a minimum of 50 mm. For bench tests, the variations in the burning rate of products are smaller than those for full-scale tests. Further, the cost is lower as the required equipment is relatively not so expensive. Since the entire building element cannot be tested, it is always difficult to convince people that bench-scale test will give results representing the practical world. The results may differ significantly, depending on the test conditions, including temperature and heat flux. It is even established that no known bench-scale test is directly correlated with the data on flame spreading of real products [28]. However, a basis for comparison can be provided.

ASTM E84/NFPA 255 was developed as a more realistic and comprehensive test. The results have performance similar to that observed during accidental fires for some materials and thermal exposure. A large testing specimen of exposed area 3.34 m^2 (514 mm × 7.32 m) was used for allowing realistic fire involvement of material surfaces and the development of physical and structural failures that may influence the flammability performance during the testing period. The tunnel fire exposure is provided by a 1.37 m long test flame, covering 0.65 m^2 of the exposed specimen surface. Thermal exposure and area coverage of the materials are sufficiently large to give progressive surface burning and combustible volatile generation characteristics of the materials under evaluation. A moving wind-aided flame front is resulted.

ISO 9705 is a full-scale burning test. The products are tested inside a room, 3.6 m by 2.4 m and 2.4 m high. They can be covered on the walls (excluding that contains the doorway) and the ceiling, or just be covered on either one of them and tested with standard ceiling or wall materials. The maximum size of the testing sample is 31.7 m^2. This test represents a real scale fire in a small room with combustible linings [29]. The results achieved are very close to that encountered in an actual fire. However, there might be large variations in full-scale burning rate among products, say, of the order of a factor of 100, showing a lower repeatability and reproductibility [28]. Also, a higher cost and more preparation works are required for carrying out such a test.

3. HEAT SOURCE

A radiant panel and an ignitor (or a pilot flame) are used in both ASTM E1321 and BS476: Part 7 while gas burners are used in ASTM E84/NFPA 255 and ISO 9705. However, the specified radiation heat flux of the radiant panel or the heat output of the burners for each test are different and the heating profiles vary. The specimens are subjected to a large gradient of external heat flux, resulting in transient heating of varying rates at different parts of the surface [10].

- ASTM E1321

  The specimen is subjected to a gradually changing heat flux. The peak value of this flux is not a single, fixed value but is to be determined from the ignition test. The irradiance at 50 mm position from the hot end, which could be varied from 20 kWm^{-2} to 65 kWm^{-2} by controlling the fuel-air flow rate to the panel, is approximately 5 kWm^{-2} higher than the minimum heat flux necessary for ignition.

- BS476: Part 7

  Irradiance would be changed with the distance along a reference line from the inside edge of the specimen holder, i.e. 32.5 kWm^{-2} for 75 mm, 21 kWm^{-2} for 225 mm, 14.5 kWm^{-2} for 375 mm, 10 kWm^{-2} for 525 mm, 7 kWm^{-2} for 675 mm and 5 kWm^{-2} for 825 mm. The specified irradiance has a tolerance of ± 0.5 kWm^{-2}.

- ASTM E84/NFPA 255

  The rate of heat release is about 5000 Btu/min (88 kW) on the exposure side of the tunnel. Gas temperature near the specimen surface is up to 900°C.

- ISO 9705

  Two heat sources are recommended. The one more commonly used gives a thermal power of 100 kW, equivalent in intensity to a severe waste paper basket fire [30] during the first 10 min, and 300 kW for a further 10 min. The other one provides a maximum net heat output of 162 kW and gross heat output of 176 kW. The heat output shall be adjusted to 25%, 50%, 75% and 100% of the maximum net heat output at 0 s, 30 s, 60 s and 90 s after ignition respectively.

4. TESTING ENVIRONMENT

To control the testing environment and other ambient factors affecting the specimen and testing procedure, several parameters are specified and monitored during the test.

- ASTM E1321

  The space volume shall be bigger than 45 m^3 with a ceiling height higher than 2.5 m. The apparatus shall be located with a clearance of at least 1 m separation to the walls of the room. The air supply rate shall be about 8.33×10^{-3} m^3s^{-1}. The pressure and ambient temperature are controlled at about 20 to 30 Pa and 25 ± 5°C respectively.

- BS476: Part 7

  The testing environment should be free from draughts. The test should be performed in a space with a volume bigger than 400 m^3 to prevent building up of excessive heat. The minimum clearances from the radiant panel shall be 5 m in front; 1 m behind; 4 m from the floor to ceiling level; and 2.5 m on either side, measured from the panel centre.

  Effluent gases from the radiant panel and specimen shall be extracted without affecting the testing condition of the apparatus during the test.

- ASTM E84/NFPA 255

  The testing environmental conditions under control include air velocity (taken as the arithmetic average values at seven points along the tunnel) of 73.2 ± 1.5 $m \cdot min^{-1}$ and air supply at a temperature of 23 ± 2.8°C, with 50 ± 5% relative humidity. Pressure shall be maintained at the manometer reading of 9.53 mm, with no excessive air leakage. The test chamber shall be cooled down to 40.5 ± 2.8°C before putting in the new testing sample.

- ISO 9705

  The testing room shall be placed in a draught free heated space which is large enough to produce no influence on the test. The temperature shall be set to 20 ± 10°C. The horizontal wind speed shall be controlled at less than 0.5 ms^{-1} at a horizontal distance of 1 m from the centre of the door.

5. FLAMING ENVIRONMENT AND TESTING POSITIONS

The configurations of the four tests are shown in Fig. 1 for ASTM E1321, Fig. 2 for BS476: Part 7, Fig. 3 for NFPA 255 and Fig. 4 for ISO 9705.

Radiant panels are adopted in ASTM E1321 and BS476: Part 7. There shall be no visible flame on the surfaces of the panels. An ignitor or a pilot flame is used for igniting the material. For both ASTM E84/NFPA 255 and ISO 9705, the flame shall be in direct contact with the specimen surfaces.

In ASTM E1321, the vertically mounted specimen is exposed to the radiant heat source inclined at 15 ± 0.25° to it. The pilot assembly used in ASTM E1321 is a horizontally oriented, non-impinging gas (acetylene/air) flame. The flame is about 180 mm in length and it burns parallel to a flange mounted at the top of the specimen holder. The sample is preheated in the absence of the pilot burner for a period of time determined through the ignition test, to ensure the existence of thermal equilibrium under flame spread conditions [31].

In BS 476: Part 7, the vertical specimen holder assembly is located at 90 ± 2^o to the radiant panel.

In ASTM E84/NFPA 255 test, the specimen shall be installed in the horizontal ceiling position, perpendicular to the test flame. This orientation may place some limitations on the types of material that can be realistically mounted. Mounting methods should be carefully selected so as not to affect the final result.

The material to be tested by ISO 9705 shall as far as possible, be mounted in the same way as in practical use, vertically or horizontally.

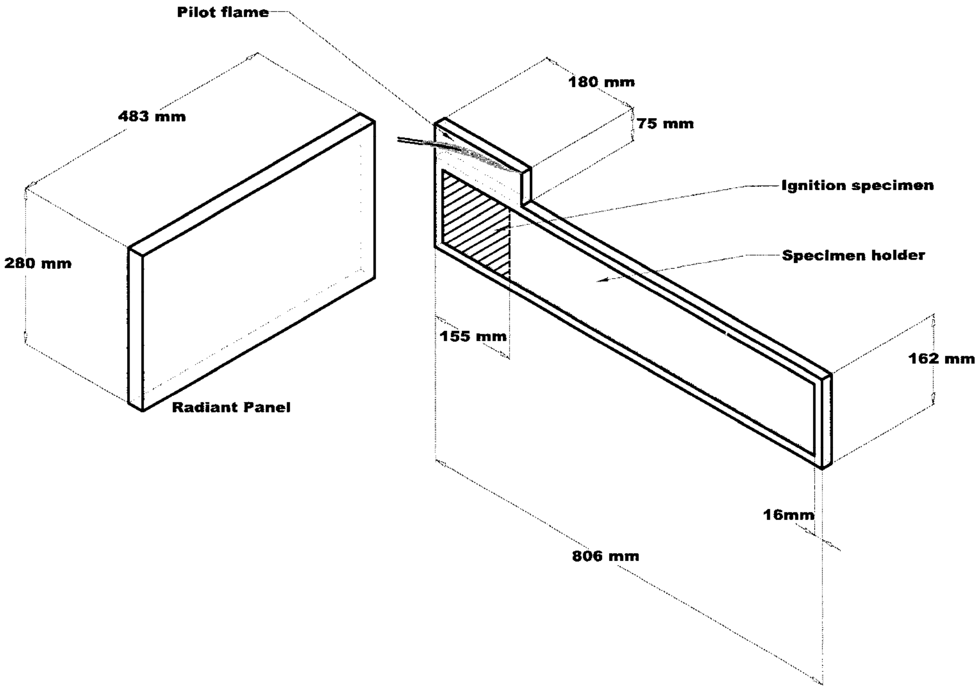

Fig. 1: Configuration of ASTM E1321

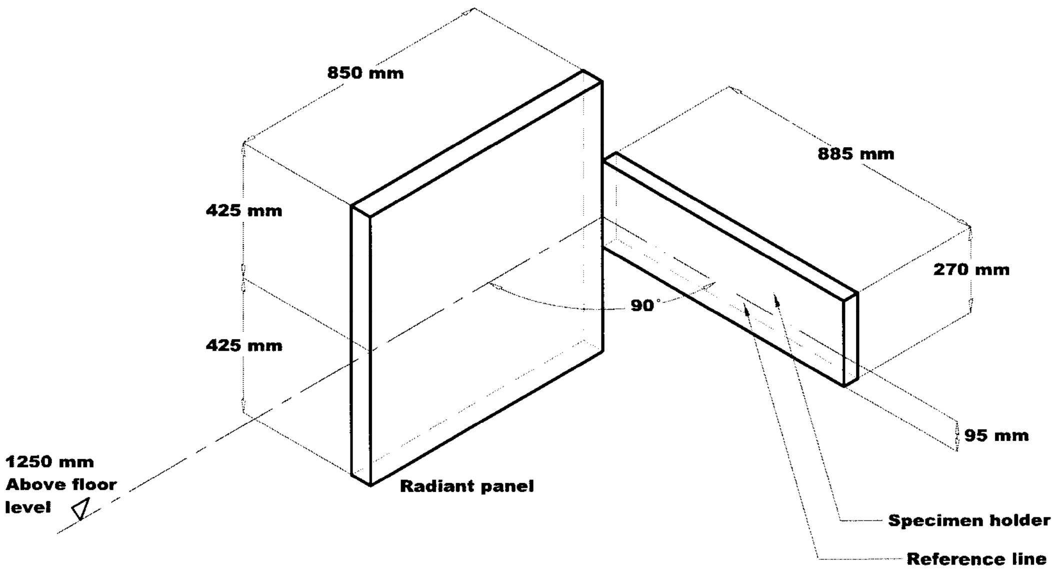

Fig. 2: Configuration of BS476: Part 7

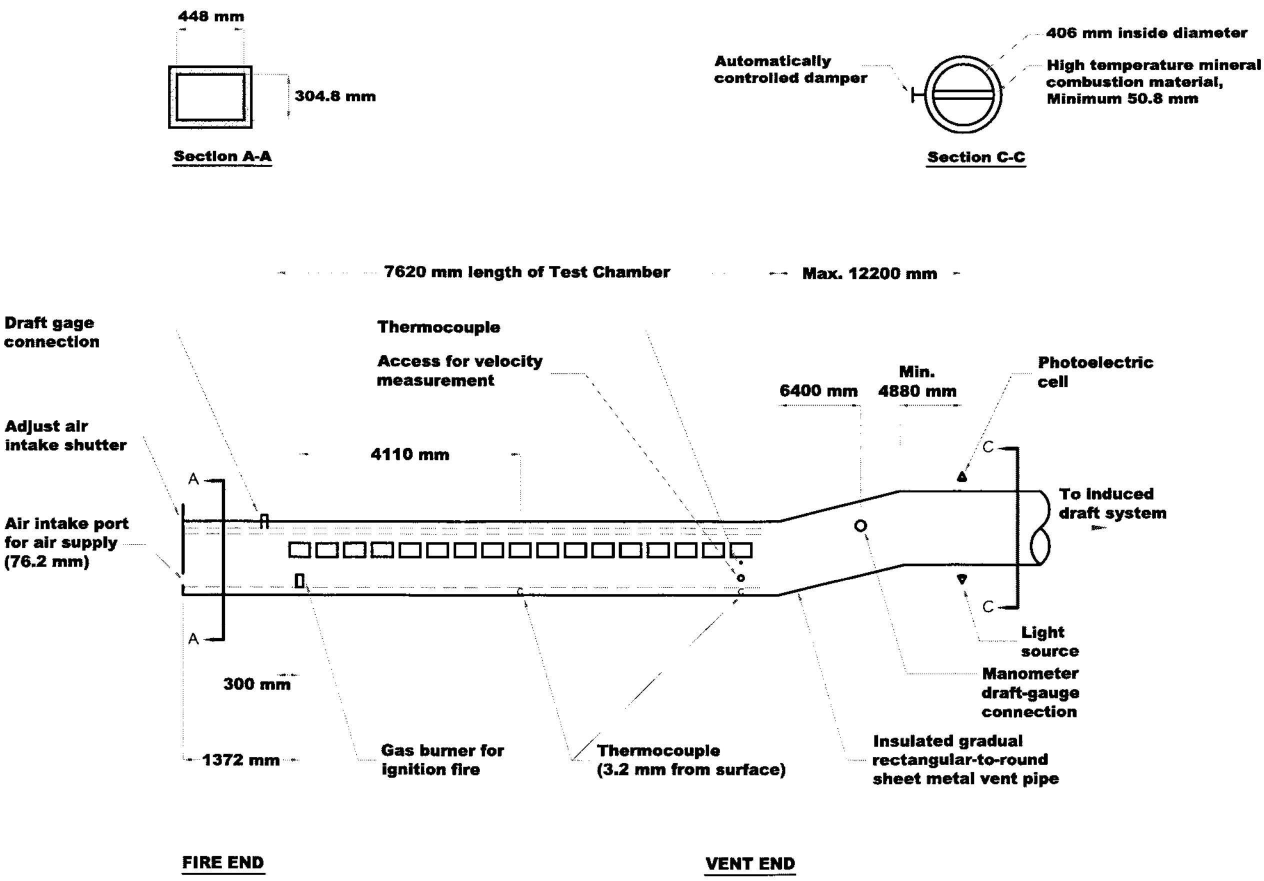

Fig. 3: Configuration of NFPA 255

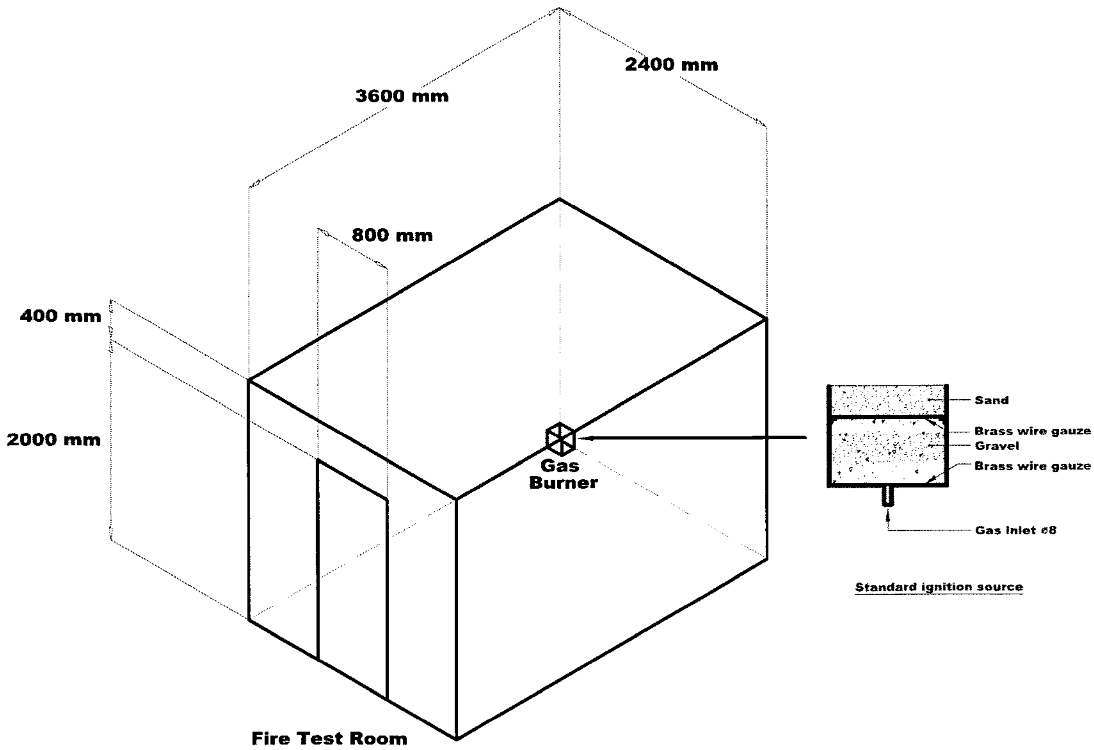

Fig. 4: Configuration of ISO 9705

6. TEST RESULTS

- ASTM E1321

  The following are measured:

  - Surface flux
  - Flame front arrival time along specimen surface
  - Flame front velocity

  A straight line shall be fitted to the correlated flame spread data for further derivation of the following flame spread parameters:

  - Flame spread parameter, C (flame spread velocity)
  - Minimum flux necessary for ignition, $\dot{q}''_{o,ig}$
  - Minimum surface temperature necessary for ignition, T_{ig} (conditions necessary for combustion)
  - Minimum flux necessary for flame spread, $\dot{q}''_{o,s}$
  - Minimum temperature necessary for flame spread, $T_{s,min}$
  - Flame heating parameter, Φ (available flame energy for spreading)

- BS476: Part 7

  The following are recorded:

  - Time at which the flame front along the horizontal reference line crosses each vertical reference line.
  - Maximum flame spread distance and time of occurrence.
  - Any spread of flame that extends for less than 50 mm whilst the pilot flame is still on.
  - Behaviour of the product, flashing and transitory flaming phenomena.
  - Debris (flaming or not) falling away from the specimen, intumescences and/or deformation of the specimen.

- ASTM E84/NFPA 255

  The following are recorded:

  - Peak flame spread distance (i.e. observed distance minus 1.37 m, end of the ignition fire) and time of occurrence.
  - Photoelectric cell output immediately prior to the test and at least every 15 s during the test.
  - Burning characteristics of the specimen during test exposure, e.g. delamination, sagging, shrinkage, fallout, etc.
  - Smoldering and other conditions within the test duct when the test is ended.

- ISO 9705

  The following are recorded:

  - Rate and distance of flame spread
  - Time for ignition
  - Flames emerging through the doorway
  - Floor heat flux
  - Exhaust air flow rate
  - Heat release rate
  - Production of carbon monoxide (CO) and carbon dioxide (CO_2)
  - Hazard of reduced visibility

  Optional measurements include:

  - Surface temperature of the product.
  - Vertical temperature profile in the doorway.
  - Mass and convective heat flow through the doorway.
  - Toxic hazard, e.g. hydrocarbons (CH_n), nitrogen oxides (NO_x) and hydrogen cyanide (HCN).

7. CLASSIFICATION SYSTEM

- ASTM E1321

  There is no established pass/fail criterion for the ignition and flame spread test results generated from the ASTM E1321 [32]. Indeed, the material parameters obtained can be correlated by using a simplified theory for flame spread. Hence the results can be considered suitable for use in mathematical models for fire growth and prediction of performance of materials [10,31].

- BS476: Part 7

  Travelling distances of the flame front after 1.5 min and 10 min (disregarding any flaming which occurs from the material that has slumped, melted or fallen below the position of the horizontal reference line) are measured. The results are used to classify the sample as Classes 0, and 1 to 4. At least five of the six test specimens with valid test results shall have the spread of flame (in mm) not exceeding the corresponding limits specified for the designated class as shown in Table 1. The remaining specimen shall not exceed this limit by more than the tolerance given.

As specified in the local code [4], for premises including basements, commercial buildings, domestic buildings, hotels and institutional buildings, Class 1 or 2 rate of flame spread should be provided, or be brought up to that standard by the use of an approved fire retardant product for:

- all linings for acoustic and thermal insulation purposes in ductings and concealed locations, and
- all linings for acoustic, thermal insulation and decorative purposes within protected means of escape.

• ASTM E84/NFPA 255

The flame front distances at every 0.6 m or time intervals not more than 30 s are measured. The data collected are plotted against time to obtain the flame spread time-distance curve. The total area A_T under the curve, ignoring any flame front recession, is used to determine the Flame Spread Index, FSI:

$$FSI = 0.515\, A_T \quad \text{for} \quad A_T \leq 29.7 \text{ min-m} \qquad (1)$$

$$FSI = 4900/(195 - A_T) \text{ for } A_T > 29.7 \text{ min-m} \quad (2)$$

Smoke generated during the tests is also compared. Smoke data collected from the photoelectric cells are plotted as a light absorption-time curve. The area under the curve shall be divided by that under the curve for red oak and multiplied by 100 to give an index. This index shall be compared with those of the benchmark materials, i.e. red oak (index of 100) and inorganic-reinforced cement board (index of 0) to provide a relative ranking.

As mentioned earlier, ASTM E84 has been referenced and specified by the U.S. model building codes [17-19]. All the three codes use similar definitions for classification of interior wall and ceiling finishes. Under Standard Building Code [17], Class A materials have an FSI of 25 or less; Class B materials have an FSI ranges from 26 to 75 while for Class C, it varies from 76 to 200. Smoke density for all the three classes should not be greater than 450. These three categories are referred to as Classes I, II and III in both Uniform Building Code [18] and BOCA National Building Code [19].

In the LSC, NFPA 255 is specified for testing of interior wall and ceiling finishes in new construction and existing buildings. The classification system is the same as those adopted in the model building codes and materials are grouped into Classes A, B and C.

The building codes in North America generally limit the maximum flame spread properties of interior finish materials for different building uses as follows [33]:

- Fire-isolated passageways (exits) : Class I
- Corridors providing access to exits : Class II
- Assembly areas : Class II
- General areas : Class III

It is specified in the LSC that one step-down of class can be used in areas where an approved automatic sprinkler system is installed, i.e. Class C materials shall be permitted if Class B is required and Class B ones can be used in locations where Class A is required.

• ISO 9705

There is no classification and product rating scheme defined officially for this test. However, by evaluating some of the critical performance aspects, a ranking system can be derived. As discussed in the literature [28], the following can be used to presume the hazards of materials:

Table 1: Classification of spread of flame under BS 476: Part 7

Class	Spread of flame / mm			
	At 1.5 min.		Final	
	Limit	Limit for one specimen in sample	Limit	Limit for one specimen in sample
Class 0	Not ignited			
Class 1	165	165 + 25	165	165 + 25
Class 2	215	215 + 25	455	455 + 45
Class 3	265	265 + 25	710	710 + 75
Class 4	Exceeding the limits for Class 3			

- 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)
- amount of smoke evolution

The time to flashover was considered as the criterion for classification [e.g. 28,33] as such phenomenon can be an indicator of the material's ability to spread flame and contribute to fire growth. The shorter the time to flashover, the greater the flame spread property of the material. Four levels of room fire performance focusing on this critical condition were suggested in the literature [33] for the regulation of materials as shown in Table 2.

There are many works and experiments carried out in the Nordic countries which are very useful for the evaluation of a new system [34]. For example, a five-scale classification system was proposed by Sundström and Goranssön [35,36] from the Swedish National Testing and Research Institute (SP), as shown in Table 3. Heat release rate, smoke production and the time to flashover were their major concerns. Fig. 5 is a graphical illustration of the system criteria for peak heat release rate [36].

Table 2: Proposed classification system for ISO 9705 by Gardner and Thomson

Level	Building use	Restriction to materials
A	Fire-isolated passageways (exits)	No flashover after 10 min
B	Assembly areas and corridors providing access to exits	Flashover after 6 min
C	General areas	Flashover after 4 min
D	- Not permitted -	Flashover in less than 4 min

Table 3: Proposed classification system for ISO 9705 by Sundstrom and Goransson [1988]

Class	Minimum time (min)	Heat release rate (kW)			Smoke production rate (obm^{3}s^{-1})		Corresponding material	Typical example
		Burner excluded peak	Burner included peak	Burner excluded average	Peak	Average		
A	20	300	600	50	10	3	Products showing very limited burning	Mineral wool; Gypsum plaster board
B	20	700	1000	100	70	5	Products approaching but not giving flashover during the entire 20 minutes test period	Light wall-papers on gypsum plaster board
C	12	700	1000	100	70	5	Products leading to flashover but only after more than 2 minutes of exposure to the increased burner output of 300 kW	Fire resistant coating on wood; Gypsum plaster board on polystyrene foam
D	10	900	1000	100	70	5	Products flashing over shortly after increasing the burner output to 300 kW	Heavy wallpaper
E	2	900	1000	-	70	-	Products flashing over after more than 2 minutes at a burner output of 100 kW	Solid wood products

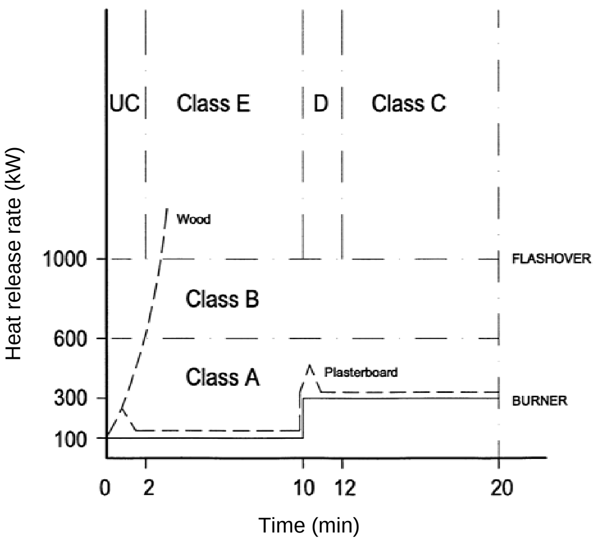

Fig. 5: Classification criteria for peak heat release rate for ISO 9705 proposed by Sundström

In the classification system, both the peak and average values of heat release rate are considered, such that a limit is put to long lasting fires which give off a significant amount of total energy. Also, some credits are given to those products that burn out quickly even though the peak heat release is high.

To justify the suitability of their proposed system, eleven products were tested and classified. The results were compared with those present European regulations used in England, France, Germany, Italy and Denmark under their EUREFIC programme [37]. It was found that there was no general agreement between the classification systems, except for the Class A and well known products like plasterboard and plywood, which show a better level of agreement. A comparison of the proposed EUREFIC system by SP with BS 476: Part 7 is summarized in Table 4. From the comparison, a draft transfer of classification from the EUREFIC system to BS 476: Part 7 was done and shown in Table 5.

Table 4: Comparison of the EUREFIC system for ISO 9705 and BS 476: Part 7

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

Table 5: Draft transfer of EUREFIC classification system to BS 476: Part 7

EUREFIC level without smoke	BS476: Part 7
A B C	1
D E	3
U	4

This system is still opened for a more detailed analysis as it is too far from enough to draw a final conclusion from such a small set of results. It was also commented that for practical purposes, it may not be necessary to have five classes in a new classification system [34]. On the other hand, this fact shows that the system is flexible and it can differentiate various products and can therefore be related to various existing national systems.

There is another proposal regarding the classification system in USA. On 1 January 1996, the High Speed Craft Code (HSC) concerning the construction of high-speed crafts by combustible materials entered into force as part of the Safety of Life at Sea (SOLAS) convention. In the code, it is specified that bulkhead linings and ceiling materials should be tested using the ISO 9705 in order to classify the materials into either fire restricting or non-fire restricting. A fire restricting material should meet the acceptance criteria as published in the resolution MSC.40 (64) [38] of the IMO [32]:

- Test average heat release rate over the entire test time shall not exceed 100 kW,
- Maximum 30-second average heat release rate shall not exceed 500 kW,
- Test average smoke production rate shall not exceed 1.4 ms^{-1},
- Maximum 60-second average smoke production rate shall not exceed 8.3 ms^{-1},
- 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.

A few shortcomings with the standard were found on proceeding the ISO 9705 tests by the U.S. Coast Guard Research and Development Centre [32]. There are no clear specifications, except the calibration procedure which provides an examination of the effect of the duct flow rate (at 300 kW only) on the exhaust duct volumetric flow rate or range of flow rates. In fact, it was believed that the exhaust volumetric flow would affect the heat release rate measurements and the effect is usually greater at lower flow rates and heat release values. The heat release rate might give unreal spikes when the duct volumetric flow rate is suddenly increased, while rapid increase in duct flow rate may occasionally be necessary when a sudden increase in smoke production is experienced.

The IMO failure criterion concerning the flame spread to the area below 0.5 m was another concern. Tests on nine composites representing a range of fire restricting and non-fire restricting materials were carried out with the 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 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-minute testing period. Thin wallpaper type coverings can be an exception as flame could rapidly spread with a small amount of heat and smoke released. Such flame spreading criterion was suggested to be re-examined. Also for the falling droplets/debris criterion, it was experienced in the testing of paperbacked textile wallcovering, in which the wallpaper tended to separate from the substrate and fall to the floor. This behaviour is restricted according to the IMO criterion, however, it was believed that the quantity of falling debris was very small and flaming ceased in a few seconds which do not produce any significant problem in such application.

A partially lined room was suggested to be adequate to assess the fire-restricting nature of a wall covering material. According to their observations, only the panel sections adjacent to the burner, those at the top of side walls as well as those on the ceiling were burnt in most cases, with the remainders did not contribute significantly to the fire. Using a partially lined room may help to reduce the cost of performing such experiments and the amount of materials to be provided by manufacturers.

- After the above review of the classification systems of the four tests, it is found that depending on the measurements and observations during the tests and/or derivations from the results, relative ranking scales could be defined. However, these ranking scales are arbitrary. Results achieved from one test do not necessarily agree with another one. All the four tests are used to measure and describe the response of a certain material, product or assemblies to heat and flame under different controlled conditions. Performance of those products or assemblies under an actual fire might be different.

8. COMPARISON OF RESULTS OF THE FOUR TESTS

Results from the four flame spread tests are illustrated by surveying the results appeared in the literature [27,29,31,33,39-42]. Materials surveyed are:

- Timber product
- Gypsum board
- Cement
- Plastic
- Foam
- Fibre, and
- Wool

Results are shown in Table 6 [29,31,33,39-42]. Note that those data are not obtained by testing the same materials in the four tests. Results are just shown to illustrate the data format. Some materials in different forms, types or with different finishes have been tested by more than one test. The following are observed:

- Gypsum board

  Different gypsum boards have been tested according to the four testing standards. The testing results are summarized below:

  - Gypsum board
    $C = 3.5\ (s/mm)^{1/2} \cdot cm^2W^{-1}$
    under ASTM E1321
    Class 0 under BS476: Part 7
  - Painted gypsum board
    Q_p = 430 kW under ISO 9705
  - Gypsum board with PVC covering
    Q_p = 1000 to 2100 kW under ISO 9705
  - Gypsum board with textile covering
    Q_p = 1000 to 2650 kW under ISO 9705
  - Fire-rated gypsum board
    $C = 2.1\ (s/mm)^{1/2} \cdot cm^2W^{-1}$
    under ASTM E1321
    FSI = 15 under ASTM E84

- Timber product

  Data on testing of timber product by all the four tests were collected:

  - Ordinary plywood
    $C = 0.8$ to $1.8\ (s/mm)^{1/2} \cdot cm^2W^{-1}$
    under ASTM E1321
    Class 3 under BS476: Part 7
    Q_p = 360 kW to 2500 kW under ISO 9705
    FSI = 46 to 170 under ASTM E84
  - Plywood with fire retardant
    Class 1 to 2 under BS476: Part 7
    FSI = 4 to 26 under NFPA 255
  - Hardboard
    $C = 1.3$ to $5.8\ (s/mm)^{1/2} \cdot cm^2W^{-1}$
    under ASTM E1321
    Class 2 to 3 under BS476: Part 7
    FSI = 86 to 113 under ASTM E84

Repeatability and reproductibility of testing methods should be considered:

- Repeatability is the precision under conditions where independent test results are obtained with the same method on identical test items in the same laboratory by the same operator using the same equipment within short intervals of time [43].

- Reproductibility is the precision under conditions where test results are obtained with the same method on identical test items in different laboratories with different operators using different equipment [43].

The reproductibility of the ISO 9705 was investigated in the literature [27], but no appropriate data in repeatability was provided. Samples of four different products including birch plywood, melamine-faced particle board, fire-retarded plywood and fire-retarded extruded polystyrene were tested in five laboratories. Results on the time to release 1000 kW of heat are shown in Table 7. Note that nonsystematic results were found on testing fire-retarded extruded polystyrene. A possible reason was due to small differences in glueing the product on the walls and parts of the products fell from the substrate in some tests. From the results, it was derived that 95% confidence interval of the mean of the time to critical fire size, taken as “heat released of 1000 kW” in this paper, is from 2% to 27%. However, it is too early to draw a conclusion of the reproductibility of such test by just comparing the results of three to four tests. Further investigation and analysis on the possible sources of variations is necessary, though the results are probably not worse than that of other large-scale tests [27].

It must be noted that the reproductibility of the tests also depends on the quality of the tests carried out by individual laboratories and their ability to repeat and reproduce the testing conditions.

Table 6: Survey on flame spread testing results of materials

Type	Material	Test Results									
		ASTM E 1321				BS476: Part 7	ISO 9705				ASTM E84/ NFPA 255
		$\dot{q}''_{o,s}$ / Wcm^{-2}	$\dot{q}''_{o,ig}$ / Wcm^{-2}	C/ (s/mm)^{½} cm^{2}W^{-1}	T_{ig}/ °C	Class (Year)	Q_p / kW	t_p / s	R_f / kWm^{-2}	t_f / s	FSI
Timber Product	W1: Wood panel	0.4	1.6	1.1							
	W2: Chipboard	0.7	2.8	1.2	390						
	W3: Chipboard	0.4	1.6	2.2							
	W4: Chipboard acoustic panel					2 or 3 (1971)					
	W5: Chipboard acoustic panel, with fire retardant surface treatment					1 (1971)					
	W6: Hardboard					3 (-)					
	W7: Hardboard					3 (1971)					
	W8: Hardboard	0.1	1.5	1.8							
	W9: Hardboard	0.4	2.7	1.3	380						
	W10: Hardboard, standard										113
	W11: Hardboard, exterior										86
	W12: Hardboard, 6.35 mm thick	0.4	1.0	5.8							
	W13: Hardboard, 3.175 mm thick	0.1	1.3	2.2							
	W14: Hardboard, 3.4 mm thick, with gloss paint	1.1	1.8	4.1							
	W15: Hardboard, with nitrocellulose paint	0.4	2.1	2.0							
	W16: Hardboard, with wallpaper					3 (-)					
	W17: Hardwood dance floor, with intumescent fire retardant paint					1 (1971)					
	W18: Hardboard, with fire retardant paints					1 (1971)					
	W19: Particle board										104
	W20: Particle board					3 (1971)					
	W21: Particle board, 1.27 cm thick	0.9	1.7	3.2							
	W22: Particle board (Douglas Fir), 1.27 cm thick	0.6	1.7	2.0							
	W23: Particle board, fire rated									630	
	W24: Particle board, fire rated						1800	760			
	W25: Particle board, fire rated						440	110			
	W26: Particle board, fire rated						747	1085	18	-	
	W27: Particle board, fire rated, type B1						1000	630	22	730	
	W28: Plywood						2400	170			
	W29: Plywood						570	150			
	W30: Plywood						920	140			
	W31: Plywood						2000	140			

		Test Results									
		ASTM E 1321				BS476: Part 7	ISO 9705				ASTM E84/ NFPA 255
Type	Material	$\dot{q}''_{o,s}$ / Wcm^{-2}	$\dot{q}''_{o,ig}$ / Wcm^{-2}	C/ (s/mm)^{½} cm^{2}W^{-1}	T_{ig}/ °C	Class (Year)	Q_p / kW	t_p / s	R_f/ kWm^{-2}	t_f / s	FSI
Timber Product (Cont'd)	W32: Plywood						2500	205			
	W33: Plywood						360	100			
	W34: Plywood						1000	150	15	142	
	W35: Plywood					3 (-)					
	W36: Plywood (back side)	0.8	2.9	0.8	400						
	W37: Plywood, 0.635 cm thick	0.4	1.2	1.8							
	W38: Plywood, 1.27 cm thick	0.3	1.4	1.5							
	W39: Plywood (Birch)									162	
	W40: Plywood (Blackbutt)										46
	W41: Plywood (Hoop pine)										168
	W42: Plywood (Luaun - WEY)										170
	W43: Plywood (Victorian ash)										91
	W44: Plywood, with oil-based/polymer paints					3 (-)					
	W45: Plywood, with vinyl	1.5	2.9	1.7	400						
	W46: Plywood (Hoop pine), with fire retardant and untreated face veneers										26
	W47: Plywood (Hoop pine), with fire retardant										4
	W48: Plywood, with fire retardant					1 or 2 (-)					
	W49: Sawn board (Black butt)										48
	W50: Sawn board (Brush box)										45
	W51: Sawn board (Cypress pine)										51
	W52: Sawn board (Douglas fir - COFI)										69
	W53: Sawn board (Jarrah)										26
	W54: Sawn board (Radiata pine)										85
	W55: Sawn board (Radiata pine - COFI)										77
	W56: Sawn board (Victorian ash)										51
	W57: Sawn board (Western red cedar - COFI)										69
	W58: Sawn board (Hardwood and softwood species)					2 or 3 (1971)					
	W59: Sawn board (Radiata pine), with fire retardant coating										6
	W60: Sawn board (Hardwood and softwood species), with fire retardant coating					1 (1971)					
	W61: Melamine faced high density non-combustible board						460	716	7	-	

Table 6 (Cont'd): Survey on flame spread testing results of materials

		Test Results									
		ASTM E 1321				BS476: Part 7	ISO 9705				ASTM E84/ NFPA 255
Type	Material	$\dot{q}''_{o,s}$ / Wcm^{-2}	$\dot{q}''_{o,ig}$ / Wcm^{-2}	C/ (s/mm)$^{1/2}$ cm^{2}W^{-1}	T_{ig}/ °C	Class (Year)	Q_p / kW	t_p / s	R_f / kWm^{-2}	t_f / s	FSI
Gypsum Board	G1: Gypsum board, 1.27 cm thick	0.9	3.5	3.5							
	G2: Plasterboard					0 (1971)					
	G3: Asbestos insulating board					0 (1971)					
	G4: Gypsum paper plaster board, painted						430	620			
	G5: Gypsum paper plaster board, painted						426	625	9	-	
	G6: Gypsum board, with wall paper	0.7	1.0	5.8							
	G7: Gypsum board, with PVC wall carpet						2100	700	-	-	
	G8: Gypsum board, with PVC wall covering									635	
	G9: Gypsum paper plaster board, with PVC wall carpet						1000	655	21	654	
	G10: Gypsum board, with textile wall covering									660	
	G11: Gypsum board, with textile wall covering						2650	680			
	G12: Gypsum paper plaster board, with textile wall covering						1000	660	20	670	
	G13: Gypsum board, fire-rated, 1.27 cm thick	1.1	2.8	2.1							
	G14: Gypsum board, fire rated										15
Cement	C1: Cement building board					1 (-)					
	C2: Asbestos cement					1 (-)					
	C3: Lightweight concrete board, fiberglass reinforced										5
	C4: Portland cement plaster, fibre reinforced										0
Plastic	P1: Polyester	≤ 0.2	2.8	1.1	390						
	P2: PMMA	≤ 0.2	2.1	1.6	310						
	P3: PMMA, Type G, 1.27 cm thick	0.1	1.6	2.0							
	P4: PMMA polycast, 1.59 cm thick	0.3	1.0	3.4							
	P5: PVC sheeting, 1.6 mm (1/16 in.) thick					2 (1971)					
Foam	FO1: Foam, rigid, 2.54 cm thick	0.6	2.0	0.6							
	FO2: Foam, flexible, 2.54 cm thick	0.2	1.2	1.2							
	FO3: Polycarbonate, 1.52 cm thick	2.2	3.0	1.5							
	FO4: Polyisocyanurate, 5.08 cm thick	0.9	1.7	0.4							
	FO5: Polyisocyanurate										75
	FO6: Urethane foams and protective coating of polyisocyanurate foam					1 (1971)					
	FO7: Polyuretane, 5.08 cm thick	0.2	0.9	1.0							

Type	Material	Test Results									
		ASTM E 1321				BS476: Part 7	ISO 9705				ASTM E84/ NFPA 255
		$\dot{q}''_{o,s}$ / Wcm^{-2}	$\dot{q}''_{o,ig}$ / Wcm^{-2}	C/ $(s/mm)^{1/2} cm^2W^{-1}$	T_{ig}/ °C	Class (Year)	Q_p / kW	t_p / s	R_f/ kWm^{-2}	t_f/ s	FSI
Foam (Cont'd)	FO8: Polyurethane foam, with plastic faced steel sheets						1000	195	14	205	
	FO9: Polystyrene foam, fire rated						1000	80	36	90	
Fibre	F1: Mineral fibre					1 (-)					
	F2: Mineral fibre					1 (1953)					
	F3: Fibre insulating board	0.6	1.4	3.4							
	F4: Fibreland	≤ 0.2	1.9	0.57	290						
	F5: Fibreboard, low density	0.1	1.2	1.3							
	F6: Fibreboard, medium density									178	
	F7: Fibreboard, medium density, with plastic coating									122	
	F8: Fibreboard, coated	1.2	1.9	3.0	300						
	F9: Fibre insulating board, with flat oil					2 (1971)					
	F10: Fibre insulating board, with 3.2 mm thick plaster					0 (1971)					
	F11: Fibreglass board					1 (1971)					
	F12: Fibreglass insulation					1 (1971)					
	F13: Fibreglass shingle	1.8	2.7	1.5							
	F14: Fibreglass board, with cavity wall insulation					1 (1971)					
Wool	WO1: Carpet, acrylic	0.8	1.8	1.7							
	WO2: Carpet, courtelle					4 (1971)					
	WO3: Carpet, evlan					4 (1971)					
	WO4: Carpet, nylon					4 (1971)					
	WO5: Carpet, terylene					4 (1971)					
	WO6: Carpet, wool	1.2	1.6	1.2							
	WO7: Carpet, wool, stock	2.1	2.5	1.5							
	WO8: Carpet, wool					4 (1971)					
	WO9: Carpet, 50/50 courtelle/evlan					4 (1971)					
	WO10: Carpet, 40/40/20 courtelle/evlan/nylon					4 (1971)					
	WO11: Carpet, 85/15 evlan/nylon					4 (1971)					
	WO12: Carpet, nylon/wool blend	1.4	1.6	3.2							
	WO13: Carpet, 80/20 wool/nylon					4 (1971)					
	WO14: Carpet, fire rated wool					1 (1971)					

Table 6 (cont'd): Survey on flame spread testing results of materials

Type	Material	Test Results									
		ASTM E 1321				BS476: Part 7	ISO 9705				ASTM E84/ NFPA 255
		$\dot{q}''_{o,s}$ / Wcm^{-2}	$\dot{q}''_{o,ig}$ / Wcm^{-2}	C/ $(s/mm)^{1/2}$ cm^2W^{-1}	T_{ig}/ °C	Class (Year)	Q_p / kW	t_p / s	R_f / kWm^{-2}	t_f / s	FSI
Wool (Cont'd)	WO15: Carpet, fire rated wool, needlefelt					1 (1971)					
	WO16: Carpet, fire rated wool, needlefelt					1 (1971)					
	WO17: Carpet, fire rated wool, polypropylene, wilton loop pile					4 (1971)					
	WO18: Carpet, fire rated wool, woven fabric					1 (1971)					
	WO19: Carpet, fire rated wool, jute backing, axminster					1 (1971)					
	WO20: Carpet, fire rated wool, jute backing, axminster					1 (1971)					
	WO21: Carpet, fire rated wool, jute backing, face-to-face wilton					1 (1971)					
	WO22: Carpet, fire rated wool, jute backing, face-to-face wilton					1 (1971)					
	WO23: Carpet, fire rated wool, jute backing, face-to-face wilton					2 (1971)					
	WO24: Carpet, fire rated wool, jute backing, hard twist wilton					1 (1971)					
	WO25: Carpet, fire rated wool, jute backing, loop pile wilton					1 (1971)					
	WO26: Carpet, fire rated wool, jute backing, multi frame wilton					1 (1971)					
	WO27: Carpet, fire rated wool, jute backing, shag pile					4 (1971)					
	WO28: Carpet, fire rated wool, jute backing, single frame wilton					1 (1971)					
	WO29: Carpet, fire rated wool, jute backing, single frame wilton					2 (1971)					
	WO30: Carpet, fire rated wool, jute backing, single frame wilton					1 (1971)					
	WO31: Carpet, fire rated wool, jute backing, single frame wilton					1 (1971)					
	WO32: Carpet, fire rated wool, jute backing, tufted loop pile					1 (1971)					

Type	Material	Test Results									
		ASTM E 1321				BS476: Part 7	ISO 9705				ASTM E84/ NFPA 255
		$\dot{q}''_{o,s}$ / Wcm^{-2}	$\dot{q}''_{o,ig}$ / Wcm^{-2}	C/ (s/mm)$^{1/2}$ cm^{2}W^{-1}	T_{ig}/ °C	Class (Year)	Q_p / kW	t_p / s	R_f/ kWm^{-2}	t_f/ s	FSI
Wool (Cont'd)	WO33: Carpet, flame-resist-treated wool, jute backing, tufted loop pile					3 (1971)					
	WO34: Carpet, fire rated wool, jute and cotton backing, hard twist wilton					1 (1971)					
	WO35: Carpet, fire rated wool, jute and linen backing, single frame wilton					1 (1971)					
	WO36: Carpet, 75/25 fire rated wool/nylon, jute backing, woven loop pile					4 (1971)					
	WO37: Carpet, 85/15 fire rated wool/nylon, jute backing, woven loop pile					4 (1971)					
	WO38: Rockwool fibre insulation					1 (1971)					
	WO39: Faced rockwool						1690	90			
	WO40: Wood wool slab (BS 1105)					1 (1971)					
	WO41: Mineral wool, combustible faced						1000	80	19	205	
	WO42: Mineral wool, combustible faced									80	
	WO43: Mineral wool ceiling										0 to 25
	WO44: Mineral wool, with textile paper	0.2	1.7	1.2							
	WO45: Mineral wool, with plastic faced steel sheet						287	732	6	-	

Table 7: Interlaboratory test results for ISO 9705

Product	Time to release 1000 kW	Deviation	Remarks
Birch Plywood	137 ± 37 s	± 27%	Flashover was reported in all tests
Melamine-faced particle board	199 ± 18 s	± 9%	Flashover was reported in all tests
Fire-retarded plywood	635 ± 15 s	± 2%	Reproductibility was evaluated by considering a lower level of 700 kW
Fire-retarded extruded polystyrene	Nonsystematic results		

The average and the 95% confidence interval of the mean is given, i.e. in large series of tests the mean of the times would fall within the indicated limits around the average with a 95% probability.

Table 8: Comparison of ISO 9705 and ASTM E1321 results

Material	Heat Release Rate kW		Smoke Production m^2s^{-1}		Time to Flashover (TFF) min	Flame Spread Parameter (C) $m^2\sqrt{s}/kW\sqrt{mm}$	Critical Ignition Flux ($\dot{q}''_{o,ig}$) kWm^{-2}	Minimum Flux for Spread ($\dot{q}''_{o,s}$) kWm^{-2}	Minimum Temperature for Spread ($T_{s,min}$) °C	Flame Heating Parameter (ϕ) $(kW \cdot m^{-1})^2 \cdot m^{-1}$
	30s Avg.	Net Avg.	60s Avg.	Net Avg.						
FR phenolic	197.7	47.7	9.4	2.2	No flashover	Material failed to ignite under maximum operating flux of panel (61.9 kWm^{-2})				
Fire restricting material	143.9	25.7	0.8	0.2	No flashover	Material failed to ignite under maximum operating flux of panel (61.9 kWm^{-2})				
FR polyester	1515.8	138.8	49.4	10.3	6.2	0.22 0.44*	19 15.8*	12.83 16.24*	325 406*	19.47 4.79*
FR vinylester	1435.8	196.8	54.7	14.8	5.3	0.42 0.24*	21.7 16.5*	16.94 16.55*	428 419*	6.26 18.37*
FR epoxy	686.3	113.6	42.9	10.2	16.5	No ignition under flux level of 27.8 kWm^{-2} and impinging pilot				
Coated FR epoxy	166.1	28.6	5.8	2.1	No flashover	No ignition under flux level of 57.8 kWm^{-2} and impinging pilot				
Paperbacked textile wall Covering[#]	140.8	20.7	0.3	0.2	No flashover	Material failed to ignite due to physical reaction of the covering/substrate to the radiant panel (Wallcovering melted rapidly, exposing noncombustible substrate which did not support ignition)				
Polyester	1734.6	273.9	22.3	4.9	1.8	0.16 0.16*	15.3 19.1*	8.27 6.04*	234 177*	19.11 18.92*
FR modified acrylic	963.1	131.7	8.7	1.1	11.1	0.17 0.26*	22.4 17.4*	12.37 11.39*	307 284*	32.88 13.56*

Notes: * Flame spread data obtained from IMO A.653/ASTM E1317 testing analyzed under ASTM E1321 procedures for reference.
Adhered to inorganic reinforced cement board.

9. CONCLUSION

The four tests on assessing the flame spreading were reviewed with the objective of introducing and comparing the concepts, scale, heat source, testing environment, flaming environment and test position, test results, and classification of materials. Performance of some materials reported in the literature under these four tests are also reported, compared and analyzed.

Since flame spreading is a very complex phenomenon, full-scale burning tests, like ISO 9705, would give sufficient data. However, the costs of fire tests of materials, the tight budget and fast track of design and construction of a project might not allow assessing materials with such tests. As reported in the literature [44,45], it is possible to skilfully combine the results from the cone calorimeter [46] with ASTM E1321 to give realistic data that would be correlated with the results from those full-scale burning tests or even real fire situation. Reviewing all these in more detail, however, are the subjects of separated forthcoming papers.

NOMENCLATURE

A_T total area under the flame spread time-distance curve (ASTM E84/NFPA 255)
C flame spread parameter (ASTM E1321)
Q_p peak heat release rate (ISO 9705)
$\dot{q}''_{o,ig}$ minimum flux necessary for ignition (ASTM E1321)
$\dot{q}''_{o,s}$ minimum flux necessary for flame spread (ASTM E1321)
R_f heat flux to floor at 1000 kW or peak heat release rate
T_{ig} minimum surface temperature necessary for ignition (ASTM E1321)
$T_{s,min}$ minimum temperature necessary for flame spread (ASTM E1321)
t_f time to flashover (ISO 9705)
t_p time to reach peak heat release rate (ISO 9705)
Φ flame heating parameter (ASTM E1321)

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