Sustainable Construction
- A Guide on Fire Protection and Performance-based Fire Engineering
Sustainable Construction

- A Guide on Fire Protection and Performance-based Fire Engineering
The Building and Construction Authority (BCA) has been working closely with industry partners to promote sustainable construction. Sustainable construction refers to the adoption of building designs, construction methods and materials that are environmentally friendly. It also means using materials and resources that have sustainable supplies and are readily available from many sources.

Instead of relying too heavily on raw materials such as sand and granite, we should also consider the adoption of steel, composite materials and other forms of construction such as using drywalls. However one major concern among the building practitioners is the level of fire protection required and the effectiveness of these protective measures. It is therefore important to address these issues and clear the misperceptions that are associated with fire protection for sustainable construction. This publication is timely as the Fire Code had been reviewed and the revised Fire Code was published in June 2007 to address these concerns.

This is the second in the Sustainable Construction series. It aims to provide information on fire safety requirements for buildings adopting steel and other methods of sustainable construction, different passive fire protection methods and the concept of performance-based fire engineering.

Special thanks go to the Working Committee members for their time and effort in preparing this publication. I am confident that it will promote a better understanding of fire safety requirements for sustainable construction and serve as a useful guide for all building practitioners.

Dr John Keung
Chief Executive Officer
Building and Construction Authority
<table>
<thead>
<tr>
<th>Page</th>
<th>Section Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>06</td>
<td>Introduction</td>
</tr>
<tr>
<td>07</td>
<td>Terminology simply explained</td>
</tr>
<tr>
<td>08</td>
<td>Using the Guide</td>
</tr>
<tr>
<td>11</td>
<td><strong>Section 1:</strong> General Requirements</td>
</tr>
<tr>
<td>25</td>
<td><strong>Section 2:</strong> Building Elements</td>
</tr>
<tr>
<td>39</td>
<td><strong>Section 3:</strong> Fire Protection Methods</td>
</tr>
<tr>
<td>63</td>
<td><strong>Section 4:</strong> Performance-based Approach to Fire Safety Design</td>
</tr>
<tr>
<td>76</td>
<td>References</td>
</tr>
<tr>
<td>77</td>
<td>Acknowledgements</td>
</tr>
<tr>
<td>78</td>
<td>Photographs/Graphics Credit</td>
</tr>
</tbody>
</table>
**Introduction**

The Building and Construction Authority has been actively promoting sustainable construction to the construction industry. Various efforts have been put in place to encourage wider use of sustainable materials and products such as steel, drywalls and recycled materials.

One major concern on the use of sustainable construction is the level of fire protection required and the effectiveness of these protective measures. Traditionally, designers follow a set of prescriptive Fire Code requirements in applying the required fire protection. However, in recent years, performance-based fire safety engineering has gained popularity among designers, especially for big and complex buildings as more economic designs can be obtained through analysis and modeling.

This Guide attempts to provide useful information on passive fire protection and fire engineering for building practitioners who are involved in the development, design and construction of buildings using sustainable materials. It comprises four sections. Section One explains the general requirements pertaining to fire resistance. Section Two elaborates the application of metal decking system, drywall system, fire-rated ceiling board system and other dry construction. Section Three highlights the different types of passive fire protection and Section Four explains the concept of performance-based fire engineering.

Detailed engineering analysis and/or calculations and active fire protection measures such as sprinkler system and mechanical ventilation are beyond the scope of this Guide. Designers are advised to refer to technical journals for comprehensive design and analysis.
**Terminology simply explained**

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Combustible</strong></td>
<td>Material that burns intensely, or has rapid rate of flame spread.</td>
</tr>
<tr>
<td><strong>Compartment</strong></td>
<td>A part of a building separated from all other parts of the same building by compartment walls and/or compartment floors. A roof space above the top storey of a compartment is included in that compartment.</td>
</tr>
<tr>
<td><strong>Compartment wall/compartment floor</strong></td>
<td>A wall or a floor which is provided for the purpose of dividing a building into compartments.</td>
</tr>
<tr>
<td><strong>Cubical extent</strong></td>
<td>The cubicle extent of a building or compartment is the volume of space contained within the building or compartment.</td>
</tr>
<tr>
<td><strong>Fire engineering/Fire safety engineering</strong></td>
<td>A branch of engineering discipline that deals with the application of science and engineering principles to protect people and their environments from the destructive effects of fire and smoke.</td>
</tr>
<tr>
<td><strong>Fire protection</strong></td>
<td>Prevention and reduction of the hazards associated with outbreak of fire.</td>
</tr>
<tr>
<td><strong>Fire resistance/Fire rating</strong></td>
<td>The minimum period of time during which an isolated structural or non-structural element may be expected to function satisfactorily while subjected to a standard fire test. The standard fire test referred to by the Fire Code is the British Standards BS 476 Part 20 to 23 or its equivalent.</td>
</tr>
<tr>
<td><strong>Flammable</strong></td>
<td>Material quality that could ignite easily when exposed to flame.</td>
</tr>
<tr>
<td><strong>Relevant Authority</strong></td>
<td>Relevant Authority means the Commissioner of Singapore Civil Defence Force and includes officers authorised by him generally or specifically to exercise the powers, functions and duties conferred by the Fire Safety Act.</td>
</tr>
</tbody>
</table>
Using the Guide

This Guide is divided into 4 sections. Information pertaining to frequently asked questions are listed here for easy reference.

SECTION 1: General Requirements

<table>
<thead>
<tr>
<th>Question</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>What are some of the revisions made to the Fire Code?</td>
<td>12</td>
</tr>
<tr>
<td>Are fire safety requirements more stringent for steel buildings than concrete building?</td>
<td>13</td>
</tr>
<tr>
<td>How to verify that a fire protection system or material has passed the fire resistance test?</td>
<td>14</td>
</tr>
<tr>
<td>Must compartment walls be constructed using concrete or masonry?</td>
<td>16</td>
</tr>
<tr>
<td>Can bare steel structures be used for standalone carpark construction?</td>
<td>20</td>
</tr>
<tr>
<td>What is the minimum requirement of fire resistance for single-storey buildings?</td>
<td>21</td>
</tr>
<tr>
<td>Is submission of fire safety plan to the Relevant Authority required for a landed house?</td>
<td>22</td>
</tr>
<tr>
<td>What is the fire resistance requirement for fully automated mechanised car park?</td>
<td>23</td>
</tr>
<tr>
<td>Do steel-framed buildings require more building inspections for fire protection systems?</td>
<td>24</td>
</tr>
</tbody>
</table>

SECTION 2: Building Elements

<table>
<thead>
<tr>
<th>Question</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Is fire protection required for composite metal decking floor system?</td>
<td>27</td>
</tr>
<tr>
<td>Is there any other alternative dry construction for floor systems?</td>
<td>29</td>
</tr>
<tr>
<td>Can drywall systems be used as party walls?</td>
<td>30</td>
</tr>
<tr>
<td>Are combustible materials allowed to be used in external walls?</td>
<td>33</td>
</tr>
<tr>
<td>Can drywalls be used to construct protected shafts?</td>
<td>36</td>
</tr>
<tr>
<td>Are services allowed within the ceiling space if a fire-rated ceiling board system is used to protect bare steel structures?</td>
<td>37</td>
</tr>
<tr>
<td>Is fire protection required for metal roofs?</td>
<td>38</td>
</tr>
</tbody>
</table>
### SECTION 3: Fire Protection Methods

- What are the available methods to fire protect steel-framed buildings? 40-60
- Is modification to a proprietary fire protection system allowed? 42
- What are the ways to achieve a cost-effective fire protection system? 62

### Fire-rated boards

- Do the fire-rated boards need to be in full contact with the steel element? 43
- Are fire-rated boards suitable for circular steel members? 44
- Is there any restriction to the use of fire-rated board systems? 45
- What are the good practices on storing and handling of fire-rated boards? 46
- Are fire-rated boards allowed at wet areas? 47

### Cementitious spray-fireproofing

- Can cementitious spray-fireproofing be used for all steel sections? 49
- What are the surface preparation works needed to receive the spray-fireproofing? 50,53
- What are the do’s and don’ts when applying the spray-fireproofing? 51,52
- How can the surface appearance of the spray-fireproofing be improved? 53

### Intumescent paint

- How does intumescent paint work? 54
- Do bigger steel sections require a thicker coat of intumescent paint? 55
- Can intumescent paint be applied to external areas? 56
- Is there any restriction to the use of intumescent paint? 57
- What are the surface preparation works needed to receive the intumescent paint? 58
- How to verify the thickness of intumescent paint? 60
Abbreviations

The following abbreviations will be used in this publication:

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTM</td>
<td>American Society for Testing and Materials</td>
</tr>
<tr>
<td>BS</td>
<td>British Standard</td>
</tr>
<tr>
<td>Cl.</td>
<td>Clause</td>
</tr>
<tr>
<td>COC</td>
<td>Certificate of Conformity</td>
</tr>
<tr>
<td>CP</td>
<td>Code of Practice</td>
</tr>
<tr>
<td>DOC</td>
<td>Declaration of Compliance</td>
</tr>
<tr>
<td>EC</td>
<td>European Code</td>
</tr>
<tr>
<td>ISO</td>
<td>International Organisation for Standardisation</td>
</tr>
<tr>
<td>PLS</td>
<td>Product Listing Scheme</td>
</tr>
<tr>
<td>PSB</td>
<td>Tüv Süd PSB Pte Ltd</td>
</tr>
<tr>
<td>QP</td>
<td>Qualified Person</td>
</tr>
<tr>
<td>SS</td>
<td>Singapore Standard</td>
</tr>
</tbody>
</table>
Section 1: General Requirements
One of the main provisions of the Fire Code requires building elements and building materials to achieve the appropriate fire resistance when they formed part of the building compartment. The structural elements of a building are to be constructed with non-flammable or non-combustible materials and with the desired rating in fire resistance.

In considering the types of structural materials to be used in a new building, one must know that the minimum period of fire resistance depends on factors such as the usage, floor area, habitable height and cubicle extent of the building. The required fire resistance does not depend on the type of building materials used in the building.

What are some of the revisions made to the Fire Code?

One of the major changes to the 2007 revision is the relaxation on the use of fire-rated boards and intumescent paint on structural steel beams and columns. In the earlier version, such methods are allowed for the protection of structural steel beams and columns, provided the building does not exceed 24m in height. For buildings exceeding 24m in height, they are allowed to be used only on beams (excluding transfer beams).

In the 2007 revision, fired-rated boards and intumescent paint can be used to protect structural steel columns and beams in all types of buildings with no height restriction imposed. However, in areas that are likely to subject to the risks of explosion or where there is presence of corrosive atmosphere, the QP should consult the Relevant Authority.
Are fire-safety requirements more stringent for steel buildings than concrete buildings?

The fire-safety requirements are similar for both types of buildings. The only difference is the method of protection which depends on whether the building is constructed using steel or concrete.

Fire resistance is a property of a particular building element which measures its ability to resist the spread of fire through the material characteristics of

- stability (resistance to collapse or excessive deflection);
- integrity (resistance to passage of flames and hot gases); and
- insulation (resistance to excessive temperature rise on exposed face).

Usually, fire resistance of a building element is expressed in terms of the minimum period of time during which the building element would function satisfactorily while subject to a standard fire test, measured in BS 476: part 20 to 23.

It is the onus of the designer to accord additional and appropriate level of fire protection to materials used in the building which do not meet the required rating of fire resistance.
How to verify that a fire protection system or material has passed the fire resistance test?

All testing of non-combustible materials and fire-rated construction have to be certified under the **Product Listing Scheme** (PLS) managed by an Accreditation Body. Currently in Singapore, the PLS is managed by Tüv Süd PSB Pte Ltd (formerly known as PSB Corporation).

Any building material/system that is intended for fire safety works listed under the PLS and used in compliance with the requirements stipulated in the Fire Code, would be deemed to be acceptable to the Relevant Authority.

No separate approval is required. The said scheme took effect from 1 April 1998. The following URL provides more information about the PLS:

http://www.tuv-sud-psb.sg/testing/prodcert_prodlst.shtml

These listed fire-rated building materials/systems are usually proprietary systems that have undergone vigorous fire tests to ensure that they are able to function satisfactorily in events of a real fire. Some examples are fire-rated partition system and fire-rated ceiling board system.

A partition system would consist of the steel stud frames with plaster (or gypsum) boards of certain thickness and sound insulation material (such as rockwool). A fire-rated ceiling board system would consist of the ceiling board hangers, the ceiling board and sound insulation material. Therefore, anyone who intends to use a fire-rated material/system should check with the manufacturers to ensure that the **complete system** is adopted.
Products listed in the PLS will be granted a Certificate of Conformity (COC) by PSB. This is a product-based certificate that is given to each individual product. For instance, a supplier who has 3 types of products listed in the PLS will have 3 COCs.

The Declaration of Compliance (DOC) is a project-based document that is given to each individual project after the application of the listed product.

For instance, after the application of intumescent paint onto a building, the manufacturer/applicator will apply to PSB for a DOC.
Compartment walls and floors

Must compartment walls be constructed using concrete or masonry?

A compartment is a part of a building separated from other parts of the same building by compartment walls, floors and other relevant separating structures.

The purpose of dividing a building into compartments is to prevent the spread of fire between specified parts of a building. This is the most basic passive protection device to limit the fire size, contain the fire and prevent the spread of fire and smoke from one part of the building to another. Therefore compartment walls and floors have to be in non-combustible materials to achieve the desired fire resistance rating.

Compartment walls and floors form part of elements of structure which include beams, columns, loadbearing walls and external walls. The desired fire resistance of compartment wall, floor and other relevant separating structures is the minimum period of time during which a particular building element may be expected to function satisfactorily while subject to a standard fire test, currently measured in BS 476: Part 20 to 23.

The same compartment rules apply to both concrete and steel-framed buildings.

It is not necessary for compartment walls to be in concrete or masonry construction. Drywalls that comply with the performance criteria stipulated in the Fire Code can also be used as compartment walls.
Compartmentation requirements for different types of buildings

For residential buildings, compartment walls and floors have to be provided to separate a residential unit or maisonette from any other parts of the same building.

Each residential unit has to be compartmented with a minimum one-hour fire resistance. However, higher fire resistance ratings prevail:

- if the wall forms part of the protected shaft which requires more than one-hour fire resistance,

OR

- if the wall separates the residential section from the section of another purpose group that requires more than one-hour fire resistance.

For a building that houses different purpose groups within the same building, provision of compartmentation is required because of the dissimilar risk of the rooms and spaces.

If it is necessary to provide doors at the compartment wall, the doors are required to have the same fire rating as the walls, unless otherwise stated and permitted under the Fire Code.
For hotels, each hotel bedroom is to be enclosed with one-hour fire resistant construction. This requirement is to protect against fire and smoke spreading into sleeping quarters and the risk of fire starting within the privacy of bedrooms and spreading to other parts of the building.

As internal corridors are requisite means of escape, the internal corridor has to be compartmented from hotel bedrooms with one-hour fire rated compartment walls and half-hour fire doors.
Workers’ dormitories have similar fire resistance requirements as hotels, i.e. each dormitory bedroom has to be enclosed with one-hour fire resistant construction while the internal corridor has to be compartmented from dormitory bedrooms with one-hour fire resistant compartment walls and half-hour fire doors.

However, as cooking facilities are provided at the workers’ dormitory, the kitchen has to be enclosed with one-hour fire resistant construction and half-hour fire doors, and is not permitted to be located within the dormitory bedroom.
Can bare steel structures be used for standalone carpark construction?

Standalone carparks may be constructed with bare steel structures, provided that they satisfy the stipulated conditions in the Fire Code.

For standalone steel carparks, the steel sections must comply with BS 5950 Part 8 or EC-3 Part 1-2 and all the floor beams are to be designed as composite structure within the floor slab.

Lilienthal multi-storey carpark, Hamburg, Germany

Constructor, fabricator and erector of steelworks: Donges Stahlbau GmbH

Standalone steel carpark at Club Street
What is the minimum requirement of fire resistance for single-storey buildings?

For single-storey buildings, the minimum period of fire resistance for elements of structure can be half an hour, provided that they satisfy the stipulated conditions in the Fire Code.
**Is submission of fire safety plan to the Relevant Authority required for a landed house?**

Fire safety plan proposals for small residential developments like detached, semi-detached, terraced and linked houses which do not exceed 3 storeys or levels (including basement and attic) are not required to be submitted to the Relevant Authority for approval as provided for under the Fire Safety (Exemption) Order 1994.

The above exemption, however, does not mean that the QPs (Architects) need not comply with the relevant fire safety requirements in the Fire Code. The fire resistance requirement for such residential houses is usually half an hour for structures above ground and one hour for structures below ground. The QPs are to self-regulate and ensure that:

1. The buildings are designed with proper means of escape
2. Walls and floors are constructed of non-combustible materials, unless otherwise permitted in attics
3. Separating walls between units are properly constructed to prevent fire spread

It is important to note that such detached, semi-detached, terraced or linked houses refer to houses meant for single family occupation only.

---

Small residential developments having more than 3 levels and townhouses are not covered by the Fire Safety (Exemption) Order 1994. Hence, **SUBMISSION OF FIRE SAFETY PLANS TO THE RELEVANT AUTHORITY IS REQUIRED.**
The fully automated mechanised car park (FAMCP) incorporates the revolutionary concept of parking and retrieving a vehicle by mechanical means without the driver entering the parking area.

The FAMCP is classified as a storage building under the Fire Code. Fire resistant walls/floors have to be provided to separate the FAMCP from other usage if it is connected to another building.

The separating walls/floors are required to have a fire resistance of two hours. Other external walls (if required) need to have a minimum one-hour fire resistance.
**Do steel-framed buildings require more building inspections for fire protection systems?**

Under the current Fire Safety Act, public buildings such as offices, hospitals and shopping complexes with an occupant load of more than 200 persons, as well as industrial buildings that fall within the stipulated criteria, are required to obtain a Fire Certificate.

This Fire Certificate has to be renewed yearly. Prior to the application or renewal of the Fire Certificate, inspection has to be carried out to ensure that fire safety systems and measures are properly maintained and in good working condition. **This requirement is the same for buildings constructed using steel or concrete.**

Generally the list of items to be inspected includes active fire protection measures such as sprinkler system and emergency power supply. It also includes passive fire protection systems such as fire-rated boards, spray-on materials and intumescent paints.

*Public buildings such as offices with occupant load of more than 200 persons are required to obtain the Fire Certificate.*
Section 2: Building Elements
The elements of structure – structural frame, loadbearing walls, floors, external walls, separating walls, compartment walls and protecting structure must have a minimum period of fire resistance rating.

Concrete and masonry construction are readily accepted when they are constructed according to “deemed to satisfy” provisions with appropriate covers.

For steel frame structures, they can be designed in composite construction to exploit the inherent fire resistance of the steel structures (please refer to page 61 for a quick guide). The overall stability of the steel or composite frame will have to be checked at the fire limit state if a fire-resistant design is adopted. In cases when designing in composite is not possible, protection such as fire-rated boards, cementitious spray-fireproofing or intumescent paint can be used to achieve the required fire resistance. Section 3 will provide more details of the various types of fire protection.
FLOORS

- **Metal deck with concrete topping**

The metal deck together with the concrete topping acts as a composite slab member. The slab is usually supported by steel beams.

As the metal deck is usually galvanized, designers would need to ensure that any applied fire-proofing (if necessary) is compatible with the galvanizing.

Some metal deck systems allow attachment of suspended loads to the underside of the metal deck. Designers would need to check with the manufacturers on the type of fasteners to be used to support fittings such as pipes and ducting.
Is fire protection required for composite metal decking floor system?

Metal deckings that have been listed as fire rated floor systems under the Product Listing Scheme DO NOT require additional fire protection. These systems have been tested together with the concrete topping as a composite slab and can achieve the required fire resistance. Fire protection would be required for any other non-listed metal decking systems.

Another situation where the metal deck does not require fire protection is when the metal deck is used as a permanent formwork and does not form part of the design of the slab.
Is there any other alternative dry construction for floor system?

Another alternative to achieve dry construction for floors is to use fibre cement floor boards. These boards are supported on steel sections such as C-channels without any concrete topping. Cement screed can be added for tiling purpose. Designers should note that the entire design of the building should satisfy the fire safety requirements of the Fire Code.
WALLS

• Drywall System

In recent years, many forward-looking developers have used the dry wall system as internal partition walls for residential projects. The dry wall system consists of dry boards (non-combustible plaster boards or fibre cement boards) attached to metal studs and sound-insulated by rockwool.

Can drywalls be used as party walls?

Drywall system can also be used as a compartment wall or party wall separating 2 dwelling units, provided that it meets the fire resistance requirement. Designers should select drywall systems that are certified under the PLS.

Drywalls can also be used to construct protected shafts, provided that they meet the performance criteria of:

- **Impact (BS 5588 Pt 5 Appendix A)**
- **Deflection (BS 5234 Pt 2)**
- **Water Absorption and bending strength**
  - (BS 1230 Pt 1 – gypsum plaster board)
  - (ISO 1896 – calcium silicate/cement board)

For use in lift shafts, the drywall system has to meet an additional requirement of cyclic loading and dynamic test as specified under Cl. 3.3 of Building Code of Australia Specification C 1.8.
Typical Drywall System

- Wall track
- Studs
- Acoustic insulation if required
- 1 layer Plasterboard each face
- Fasteners
- Joints to be staggered
- Pack
Thin veneers and wall papers / coverings which are 1 mm thick (or less) and bonded to non-combustible surface (such as drywalls) need not be tested for surface flame spread.

Thin wall finish of maximum 1 mm thick onto non-combustible substrate need not be subjected to surface flame spread requirements.
Are combustible materials allowed to be used in external walls?

External walls located within 1 m of boundaries or exceeding 15 m in height have to be of non-combustible construction and meet the fire-rating requirements of external walls.

Any beam or column forming part of an external wall has to be constructed of non-combustible material as well.

External walls need not be in concrete or masonry construction. Dry construction is permitted, provided that it satisfies the fire resistance and other stipulated requirements.
Materials like timber can be used as external wall systems provided that the external wall is situated 1 m or more from the relevant boundary and the building does not exceed 15 m in height. The setback of 1 m or more from the boundary is to prevent fire spreading from one building to another.

Designers who intend to use any form of plastic material as external walls system would need to seek approval from the Relevant Authority.

This relaxation of rule comes with a condition:

**The external walls must be provided with minimum period of 15 minutes insulation (method of fire exposure - from inside the building) under BS 476: Parts 20 to 23.**
Unprotected openings in external walls refer to windows, doors or other openings, and any part of the external wall which has non-fire-rated cladding attached to its external face.

Unprotected openings are required to be determined and limited to prevent radiant heat from causing fire to start in adjacent buildings. This rule is normally applied to buildings close to boundaries or when adjacent buildings are within close proximity. Appropriate setback distance of buildings from relevant boundaries may be computed as prescribed in the Fire Code.
Protected Shafts

A protected shaft is one which enables persons, objects or air to pass from one compartment to another without loss of integrity.

Protected shafts can be:

- An exit staircase,
- An exit passageway,
- A lift,
- A chute, or
- A duct.

Can drywalls be used to construct protected shafts?

Protected shafts must be constructed of non-combustible materials. Traditionally bricks or reinforced concrete walls are used to construct such shafts. Sustainable materials such as drywalls can also be used to construct the protected shafts provided they are designed to meet the performance criteria stipulated in the Fire Code.
Ceilings

For a steel-framed building, fire-rated ceiling board system can be installed to provide the required fire resistance for bare steel structures.

Are services allowed within the ceiling space if a fire-rated ceiling board system is used to protect bare steel structures?

In such cases, no ducting is permitted within the space above the fire resistant suspended ceiling (which forms part of the fire resistant floor ceiling system) unless the ducting is also fire protected.
Is fire protection required for metal roofs?

For standalone buildings, the metal roof need not be fire protected.

However for buildings of different heights that abut each other,

5m width of the roof over the lower part requires 1 hour fire resistance

OR

9m height of the external wall abutting the lower area requires at least 1 hour fire resistance.

This is to prevent vertical spread of fire through the roof from the lower part of the building to the higher part.

In such cases, fire-rated ceiling board system can be used to provide the necessary fire protection.
Section 3: Fire Protection Methods
What are the available methods to fire protect Steel-framed buildings?

In buildings, fire protection entails a series of measures that lead to the provision of escapes, compartments and suppression systems to either prevent or mitigate an outbreak of fire.

A wide range of materials and products are available to protect structural steelwork from fire. An appropriate type of protection can be selected based on the needs of the development.

The fire protection system can be applied using the profile, box and solid methods. Steel beams that are designed as a composite section with the slab usually require a three-sided protection. Vertical members such as columns usually require a four-sided protection.
Traditionally, designers would provide the fire protection in accordance to the prescriptive fire code. Concrete encasement or concrete infill of hollow steel sections, is one such method of fire protection for structural steelwork.

The advantages of concrete encasement are:
✓ durable and robust; used mostly in cases where resistance to impact damage, abrasion and weather exposure are important
✓ elements can be designed as composite members to enhance the load resistance

The disadvantages are:
✗ building weight increases considerably due to thick encasement
✗ time consuming at site to carry out encasement works
✗ overall section size can be quite large for concrete encasement compared to bare steel and other systems
Besides concrete encasement and concrete infill of hollow steel sections, there are other fire protection systems such as fire-rated boards, spray-on materials and intumescent paint to enhance the fire resistance of structural steel members.

**Is modification to a proprietary fire protection system allowed?**

Most of these fire protection systems are proprietary systems fire-tested in approved laboratories according to standards stipulated by the Relevant Authority, before they can be listed in the PLS.

The fire tests are carried out on a mock-up that is built for the purpose of testing. Therefore the protection system applied at site must be similar to the set-up of the mock-up. For instance, the intumescent paint primer used at the site must be the same as the one used in the mock-up fire test.

Hence, if the proprietary systems have to be modified to suit the project, the system has to be re-tested at an approved laboratory.
Fire-Rated Board Systems

Fire-rated board systems that meet the required fire resistance rating are permitted to be used for protection to structural steel beams and columns in buildings.

Such boards are usually made from calcium silicate or gypsum plaster and are used for cladding steelworks. The boards may vary from 15 mm to 30 mm thick and can provide up to 4 hours of fire-rating.

Jointing and Fixing

Proprietary board systems (including the framing and fixing details) must be installed in accordance with the manufacturer’s specifications.

_Do the fire-rated boards need to be in full contact with the steel element?_

The fire-rated boards need not be in full contact with the steel element. Gaps between the board and steel element are allowed. However, all board joints should be filled with non-combustible materials such as gypsum or cement grout. The purpose of the joint filling is to provide support to the boards to prevent them from being damaged due to impact.
Fire-Rated Board Systems

**Are fire-rated boards suitable for circular steel members?**

Fire-rated boards can also be used to clad circular steel members and any other non-standard steel members.

**Architectural Treatment**

a) **Corner Reinforcement**  
Corner beads made of rigid vinyl create a rust-proof, dent-resistant finished corner. The exposed nose of the bead helps to prevent damage from impact and provides a screed for finishing. It provides a key for the jointing compound and eliminates shadowing and edge cracking.

b) **Control Joint**  
The purpose of the control joint is to relieve stresses of expansion and construction across the joint in large wall areas. Materials such as rolled formed zinc with perforated flangers may be used for this purpose.

c) **Joint Compound**  
All purpose ready-mixed joint compound may be used.
Fire-Rated Board Systems

Is there any restriction to the use of fire-rated board systems?

The Fire Code does not restrict the use of fire-rated boards for any particular type of building.

However, fire-rated boards should not be used to protect structural steel in industrial areas which may be subjected to accidental blasts as the boards may be displaced by the force of the blast. If QPs intend to use the fire-rated boards at areas where corrosive atmosphere may be present, they are to consult the Relevant Authority.

The advantages of fire-rated boards are:
✓ easy to install in a dry process
✓ easy to finish with decorative materials

The disadvantages are:
✗ holes cut into the board (e.g. for services) have to be filled with a compatible fire protection material.
✗ Gypsum plasterboard will lose its insulation property after a fire, so replacement is likely to be required.
Fire-Rated Board Systems

What are the good practices on storing and handling of fire-rated boards?

Store the boards flat and clear of the ground

Protect the boards from weather. Use additional coverings, even if the boards are already in provided packing.

It is recommended that pallets stack to a maximum height of 800 mm high and on firm level ground. If two or more pallets are stacked, the total stack height should not exceed 3200 mm.
Fire-Rated Board Systems

Wherever possible, always lift boards from the stack below rather than slide board on board. This will prevent damage or scratches to the lower boards.

Always carry the boards on edge but do not store on edge.

Limitations

Are fire-rated boards allowed at wet areas?

Generally, boards are not recommended to be used for fire protection of external steelworks, at areas that are permanently wet, or in areas of high humidity.
Cementitious spray applied fireproofing is a form of plaster which requires only addition of water at site to form a consistent, pumpable slurry. It is then conveyed by pumping and dispersed onto building structures by compressed air at the spray nozzle. All these products are factory-mixed formulations consisting of dry ingredients including aggregates or fibres, gypsum or Portland cement, and other binders.

There are a number of spray-applied fireproofing products available in the market. Some products possess fast-setting characteristics that facilitate higher field application efficiency. The fire rating performance of these products is verified through a series of fire tests. Therefore, for the same fire rating requirement, the spray thickness would vary according to the product manufacturer’s specifications.

Environmental conditions such as humidity, temperature and abrasion will affect the working life of the spray-on system, and these points have to be considered by the designer.
Cementitious spray-fireproofing

**Can cementitious spray-fireproofing be used for all steel sections?**

Cementitious spray-fireproofing can be used on structural steel columns, beams, joists, trusses, floor and roof decking. However, for application on columns, the spray-on material will be more susceptible to damage during construction, fitting-out or maintenance. Therefore the site personnel should exercise care to ensure that the applied protection remains in place.

The advantages of spray-fireproofing are:

- Lower cost compared with other passive fire protection system
- Easy to apply onto complicated detailing and connections
- Quicker in application through spraying
- Higher productivity for fast-setting versions

The disadvantages are:

- Application method is wet, and can be messy when the building is in use
- Compared to architectural finishes, the resulting textured surface finish is not as aesthetically pleasing
- Spray-on material needs to be protected from damage during construction, fitting-out or renovations
- Not suitable for off-site application due to the risk of damaging the protection during transportation and erection
Cementitious spray-fireproofing

What are the surface preparation works needed to receive the spray-fireproofing?

Before spraying, the steel to be fire protected has to be free of oil, grease, excess rolling compounds or lubricants, loose mill scale, excess rust, non-compatible primer or any other substance that will impair proper adhesion.

A bonding agent may be required to be applied to the steel substrates to receive the spray fireproofing. Designers should check with the product manufacturer on the requirement.
Cementitious spray-fireproofing

What are the do’s and don’ts when applying the spray-fireproofing?

To prevent damage to the spray-fireproofing, fireproofing to the underside of roof deck assemblies should start only after roofing application is complete and there is no more roof traffic.

Similarly, fireproofing application works should be carried out after the completion of concrete work on steel decking.
Cementitious spray-fireproofing

Installation of trades such as clips, hangars, support sleeves, and other attachments which are required to penetrate the fireproofing should be done BEFORE the application of the fireproofing material.

Installation of services such as ducts, piping, equipment or other suspended items should be done AFTER the fireproofing is completed and inspected.
Cementitious spray-fireproofing

How can the surface appearance of the spray-fireproofing be improved?

1. **Hand troweling** may be applied to some spray-applied fireproofing products to improve the surface appearance of the products.

2. Surface decorative paint may be used as an overspray on spray-applied fireproofing products for sealing, surface colouring or to increase light reflection.

Other important considerations:

a) **Primed/Painted Steel Substrates**

Spray-fireproofing obtains its maximum bond when applied to unprimed/unpainted structural steel. Priming of interior structural steel is generally unnecessary. The use of non-compatible primer may result in bond failure. Designers should consult the product manufacturer for guidance.

b) **Experienced fireproofing applicators**

To ensure the fireproofing is properly carried out, it is recommended that the manufacturer confirm the applicator has been properly trained and has the experience to meet the qualification of an approved applicator for the spray-fireproofing product.

c) **Track records**

The applicator and manufacturer are to provide a list of local project references for review by the designers.
Intumescent Paint

The use of intumescent coating to give fire protection to steel structure is permissible as long as it is applied appropriately and the environment in which the structure is subjected to is non-detrimental to the fire protective properties of the coating. Intumescent paint coatings may be applied to give up to 120 minutes of fire protection.

Only intumescent paint products listed in the PLS are acceptable to the Relevant Authority.

How does intumescent paint work?

In the event of fire, the thin coating of intumescent paint expands up to 50 times to form a layer of insulating foam. The carbonaceous material in the intumescent paint, typically starch, is charred whilst the heat also causes the release of acids. These act to produce large volumes of non-inflammable gases which blow up the charring starch within the softened binder of the intumescent paint into an insulating cellular carbon layer.
**Intumescent Paint**

Generally intumescent paints are applied in three layers – primer, intumescent layer and the finishing coat.

The thickness of the intumescent layers depends on:

(a) steel size

(b) steel type

(c) steel section used as column or beam

(d) fire rating required (e.g. 60 minutes or 120 minute)

(e) exposure (2, 3 or 4-sided) and so on.

---

**Do bigger steel sections require thicker coat of intumescent paint?**

For the same level of fire resistance requirement, a bigger steel section will require a thinner intumescent paint coating as compared to a smaller section.
Intumescent Paint

The intumescent paints have to be tested to BS 476: Part 20/21 and BS 8202: Part 2.

*Can intumescent paint be applied to external areas?*

For intumescent paints intended for external area, they have to pass a 2-year local weathering test in accordance to BS8202: Part 2, prior to listing in the PLS.

One advantage of intumescent paint is that it allows the architects to express the architectural intent of the building through the steel sections. The finish external coats also come in various colours, to suit different designs.

External coats come in various colours

NUS Cultural Hub fire protected by intumescent paint

Steel-framed building adopts a red finishing coat for its intumescent paint
**Intumescent Paint**

*Is there any restriction to the use of intumescent paint?*

The Fire Code does not restrict the use of intumescent paints for any particular type of building. However in buildings where there may be presence of corrosive atmosphere that may affect the effectiveness of protection by the intumescent paints, QPs are to consult the Relevant Authority.

For submission procedures and documents required for submission, please refer to Appendix F of the Fire Code.

---

**Building Owners Take Note:**

**Highly flammable/combustible materials should not be stored within the vicinity of any structural steel members protected by intumescent paint.**

---

The advantages of intumescent paints are:

- Do not require architectural cladding
- Allow building’s structure to be expressed architecturally
- Can be applied off-site

The disadvantages are:

- Require regular inspection and maintenance
- Fire resistance is limited to 2 hours
What are the surface preparation works needed to receive the intumescent paint?

For mild steel, the untreated surface has to be blasted to grade Sa 2.5 (95-99% clean) for priming purpose. This requirement is also stated in the work section on Protective Works for Structural Steelworks in the National Productivity and Quality Specifications (NPQS).

For galvanized steel, the surface must be “etched” using a compatible and approved etching primer.

Galvanized steel must be “etched” using a compatible and approved etching primer
Intumescent Paint

Application Process

Application of primer coat

Application of intumescent layer

Intumescent layer completed

The final product

Application of finishing coat
**Intumescent Paint**

*How to verify the thickness of intumescent paint?*

The thickness of the intumescent paint can be checked by using a Dry Film Thickness (DFT) gauge. Dry film thickness readings should be taken when the intumescent coat is sufficiently hard to prevent the probe indenting the surface, and prior to the application of the finishing coat.

The application of intumescent paint on each member has to be recorded by the applicator in detail. An example of such records submitted to PSB for the purpose of DOC is illustrated below.

<table>
<thead>
<tr>
<th>Ctl marking</th>
<th>Location</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>C3/1-1</td>
<td>0.5m</td>
<td>4.05</td>
<td>3.96</td>
<td>3.97</td>
<td>3.91</td>
<td>4.05</td>
<td>4.04</td>
</tr>
<tr>
<td></td>
<td>1.0m</td>
<td>4.04</td>
<td>3.94</td>
<td>3.98</td>
<td>4.02</td>
<td>3.95</td>
<td>4.03</td>
</tr>
<tr>
<td></td>
<td>1.5m</td>
<td>3.80</td>
<td>3.99</td>
<td>4.07</td>
<td>3.91</td>
<td>3.88</td>
<td>4.06</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>3.98</td>
<td>3.96</td>
<td>3.99</td>
<td>3.95</td>
<td>3.96</td>
<td>4.04</td>
</tr>
</tbody>
</table>

(for simplicity, only a few sides are indicated)
Quick Guide on Fire Resistance for Steel Members

The following table shows the level of fire resistance period which a combination of columns and beams can achieve.

<table>
<thead>
<tr>
<th>Fire resistance (min)</th>
<th>Beam type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>protected</td>
</tr>
<tr>
<td>Column type</td>
<td></td>
</tr>
<tr>
<td>protected</td>
<td>&gt;60</td>
</tr>
<tr>
<td>unprotected</td>
<td>15</td>
</tr>
<tr>
<td>blocked-in</td>
<td>30</td>
</tr>
<tr>
<td>partially encased (unreinforced)</td>
<td>60</td>
</tr>
<tr>
<td>partially encased (reinforced)</td>
<td>&gt;60</td>
</tr>
<tr>
<td>concrete-filled hollow sections</td>
<td>&gt;60</td>
</tr>
</tbody>
</table>

What are the ways to achieve a cost-effective fire protection system?

Cost comparisons made between different systems should be based on total costs, instead of fire protection costs alone. The time required for the fire protection works, the need for additional finishes and future maintenance will have an impact on the overall cost. Nevertheless, the following pointers should be useful in achieving a more cost-effective fire protection system.

(a) Design the members to be built into walls and floors wherever possible
Any exposed face of a steel section will usually require fire protection. Hence to reduce the cost of fire protection, designers should consider building the steel members into walls and floors wherever possible. For example in the case of the Supreme Court, the steel beams and columns are integrated with precast concrete. The use of precast concrete provides both fire protection to the steel members and unblemished off-form surface finish.

(b) Integrate fire protection methods with the architectural intent
Fire protection method should integrate with the architectural finishes. Steel members protected with cementitious spray-fireproofing may retain their rough finishes if they are hidden above the ceiling boards. For aesthetics reasons, hand trowelling may be applied to the spray-fireproofing to improve the surface appearance of the steel elements which are exposed.

Alternatively, intumescent paint may be preferred for exposed columns and beams as it provides a more aesthetically pleasing appearance.

(c) Communicate with the steel fabricators early on the requirements of fire protection
Designers should involve the steel fabricators early and state the fire protection requirements. Fabricators need to know the type and brand of fire protected system prior to preparing the steel surface. For example, some cementitious spray-fireproofing bond better on unprimed/unpainted steel members than primed surface. On the other hand, steel members receiving intumescent paint have to be primed with a compatible and approved primer. Failure to communicate such useful information to steel fabricators early may result in abortive or remedial works, which incurs additional costs.
Section 4: Performance-based Approach to Fire Safety Design
The performance-based approach to fire safety design relies on the use of fire engineering principles, calculations and/or appropriate software modelling tools to satisfy the intentions of the Code of Practice for Fire Precautions in Buildings 2007 (Fire Code).

This new approach provides alternative means of meeting the intentions of the Fire Code.

Building practitioners will have the added flexibility in the application of fire safety for their buildings by having a choice of using the performance-based approach, the prescriptive approach or a combination of both.

**The performance-based approach is unique in that its provisions spell out the intent of the code qualitatively but the means of achieving the desired intent of the code is open to the building practitioner.** The building practitioner will need to substantiate that the proposed solution fully meets the intent of the Fire Code using established fire safety engineering methodology.

The performance-based regulatory system was officially launched on 1 July 2004.
What is the rationale of allowing developers/Qualified Persons (QPs) to choose the type of approach (i.e. prescriptive or performance-based) to fire safety design?

The introduction of a performance-based approach to fire safety design offers building designers greater flexibility in design and possible cost optimisation. The prescriptive approach is more restrictive in the sense that the building designers have to adhere strictly to the requirements stipulated in the Fire Code. The performance-based approach, however, provides a platform for customised building designs so long as fire safety standards are maintained.
Is performance-based approach less stringent than prescriptive approach?

The performance-based approach should not be viewed as less stringent, but it is definitely less restrictive. The use of the performance-based approach to complement the prescriptive approach is widely accepted in many countries, such as Australia, New Zealand, UK, USA, Sweden and Japan. In Singapore, there are several buildings where the performance-based approach has been successfully used, such as the Changi International Airport and the Singapore Expo.
Singapore Expo Convention and Exhibition Centre, the largest most flexible event venue in Singapore. All photos courtesy of Singex Venues Pte Ltd.
When should performance-based approach be adopted?

Only registered Fire Safety Engineers (FSEs) are qualified to assess a performance-based design approach. It is a norm in the industry that the prescriptive approach is used for standard-design buildings whereas the performance-based approach is for more complex buildings. If there is possible cost optimisation or design constraints faced when using the prescriptive method, the decision may then be made to use the performance approach. Ultimately, it is a decision to be made by the developers and QPs.
When are the Fire Safety Engineer (FSE) and Peer Reviewer required?

The Building Developer should engage the FSE on the onset of building project involving performance-based works, during the conceptual design stage, and not as a remedial solution to resolve deadlocks in the approval process.

The Building Developer should engage the Peer Reviewer only after the FSE has completed his Fire Safety Engineering Report (FSER), detailed specifications and drawings and the Building Operations and Maintenance manual (O&M). It is important that the Peer Reviewer does not participate or interfere with the design process prior to this stage. The Peer Reviewer will make his comments in his Peer Reviewer’s Report. In the event that the Peer Reviewer has disagreeable comments on the documents reviewed, the FSE and the Peer Reviewer will need to discuss objectively to resolve the outstanding issues.

The Project QP is responsible to submit all the mentioned documents to the Relevant Authority for final plan approval.
Is it mandatory to engage a Registered Inspector (RI) who is an FSE for performance-based fire safety works?

Yes, it is mandatory to engage an RI who is an FSE for inspection of the completed performance-based fire safety works. These RIs are qualified fire safety engineers and are in a better position to highlight any irregularities in the fire safety engineering works that are implemented on-site for a building.

Is it necessary to engage an FSE to re-evaluate addition and alteration works?

For buildings designed to a performance-based fire safety design, the Building Owner can refer to the O&M manual prepared by the original FSE. The O&M manual would spell out the extent of the performance-based solution in the building. Based on the information provided, the Building Owner has the responsibility to engage an FSE to re-evaluate addition and alteration works where necessary.
Can a building be entirely designed to performance-based solutions?

Theoretically, it is possible to design a building entirely to performance-based solutions. In practice, most performance-based submissions are likely to be a hybrid of performance-based and prescriptive solutions to meet the fire safety requirements stipulated in the Fire Code.

Approach to a Performance-based design

“Performance-based design” is a tool that can be used to look at fire safety from a “whole building” perspective. “Performance-based design” is an engineering approach to fire safety design based on (1) established fire safety goals and objectives, (2) analysis of fire scenarios, and (3) quantitative assessment of design alternatives against the fire safety goals and objectives using engineering tools, methodologies, and performance criteria.
Case Study: The National Library

The National Library is one of the first few buildings in Singapore to have performance-based fire safety design for its structural steel.

Project description:

- 16-storey building with basement, divided into 2 blocks (Function and Programme Blocks)
- interconnected by link bridges on most floors
- library areas, drama centre, associated ancillary areas, and offices
- steel-framed construction for all the above ground floors
Fire Scenarios:

- A fire starts in a given building, and
- Occupants fail to extinguish the fire, and
- Automated fire sprinklers fail to control or extinguish the fire, and
- Fire continues to grow, but only on the storey of origin or on floors connected by a void, until the fire fighters intervene to control and extinguish it.

In the event that a major fire develops and the automated fire sprinklers fail to control or extinguish the fire, the performance-based design is to ensure that the structural adequacy of the building frame is maintained until the fire fighters intervene.
The Approach:

Analyse the risk of fire starting in building.

- Check the effectiveness of the automated fire sprinkler system
- Take measures to increase the reliability of the automated fire sprinkler system
- Study the fire growth and compartment fire conditions, taking into consideration the fire fighters intervention

In terms of structural performance, allow:

- Load-carrying mechanisms for beams and slabs in a structural frame to include membrane action
- Load redistribution from members

The Solution:

The performance-based design allows most of the steel floor beams to be unprotected while maintaining the building’s structural stability in a fire.

This enabled the bare steel structure to be expressed and enabled cost-effective construction of the building.

The performance-based solution also allowed the two blocks to face each other with no additional fixed fire protection systems.

Only selected beams were fire rated. These key steel beams were chosen to be fire-rated for enhanced safety factor and they generally occur in critical areas like corners of the building or in long span areas.
Steel Framing Plan of Typical Floor

The red line indicate the key steel beams with 90-minute fire-rated protection while the secondary steel beams are not fire protected.
References

The following URLs provide information on fire protection and fire engineering.

**Association for Specialist Fire Protection, UK**
http://www.asfp.org.uk/index.html

**Nanyang Technological University Fire Engineering Research Group**
http://www.ntu.edu.sg/cee/research/research_groups/fireresearch/research.htm

**Singapore Civil Defence Force**

**University of Manchester One-Stop Shop in Structural Fire Engineering**
http://www.mace.manchester.ac.uk/project/research/structures/strucfire/

**University of Sheffield Fire Engineering Group**
http://www.fire-research.group.shef.ac.uk/
Acknowledgements

This publication was developed with inputs from members of the Working Committee and fire protection specialists. BCA would like to thank them for their valuable contributions towards the completion of this Guide.

<table>
<thead>
<tr>
<th>Members of the Working Committee:</th>
</tr>
</thead>
<tbody>
<tr>
<td>From Building and Construction Authority</td>
</tr>
<tr>
<td>Mr Lim Tee Yoke (Chairman)</td>
</tr>
<tr>
<td>Ms Goh Siam Imm</td>
</tr>
<tr>
<td>Ms Rose Nguan</td>
</tr>
<tr>
<td>Ms Phua Hui Chun</td>
</tr>
<tr>
<td>From Housing &amp; Development Board</td>
</tr>
<tr>
<td>Er. Teh Poh Suan</td>
</tr>
<tr>
<td>From Nanyang Technological University</td>
</tr>
<tr>
<td>Assoc Professor Tan Kang Hai</td>
</tr>
<tr>
<td>From Singapore Civil Defence Force</td>
</tr>
<tr>
<td>LTC Philip Tham</td>
</tr>
<tr>
<td>Representing Singapore Institute of Architects</td>
</tr>
<tr>
<td>Mr Song Yew Kee (DP Architects Pte Ltd)</td>
</tr>
<tr>
<td>Representing Singapore Structural Steel Society</td>
</tr>
<tr>
<td>Er. Tay Yak Hong (TYH Consulting Engineers)</td>
</tr>
</tbody>
</table>

BCA would also like to thank the following persons/organizations for their consent to use their materials and photographs:

- Arup
- BlueScope Lysaght (Singapore) Pte Ltd
- Boral Plasterboard (M) Sdn Bhd
- Donges Stahlbau GmbH, Germany
- DP Architects Pte Ltd
- Industrial Contracts Marketing (2001) Pte Ltd
- Professor Colin Bailey, University of Manchester and Mr Gerald Newman, The Steel Construction Institute
- Promat Building System Pte Ltd
- Singex Venues Pte Ltd
- The Ascott Group
- TTJ Design and Engineering Pte Ltd
- W.R. Grace (Singapore) Pte Ltd
- Yongnam Engineering & Construction Pte Ltd
Photographs/Graphics Credit:

Copyright to photographs and graphics from the following pages are held with the respective company who has granted permission to BCA for reproduction in this publication.

<table>
<thead>
<tr>
<th>Company</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>BlueScope Lysaght (Singapore) Pte Ltd</td>
<td>27, 28 and 51 (top)</td>
</tr>
<tr>
<td>Boral Plasterboard (M) Sdn Bhd</td>
<td>14</td>
</tr>
<tr>
<td>Industrial Contracts Marketing (2001) Pte Ltd</td>
<td>15, 42 (bottom), 55, 56 (bottom left), 59, and 60</td>
</tr>
<tr>
<td>Promat Building System Pte Ltd</td>
<td>16, 17, 18, 32, 33, 34 (left), 36, 37, 38, 42 (top left and top right), 43, 44, 46, 47, 52 (top) and 54 (bottom)</td>
</tr>
<tr>
<td>TTJ Design and Engineering Pte Ltd</td>
<td>53 (bottom) and 58 (left)</td>
</tr>
<tr>
<td>W.R. Grace (Singapore) Pte Ltd</td>
<td>39, 48 (top), 49 (top) and 51 (bottom)</td>
</tr>
<tr>
<td>Yongnam Engineering &amp; Construction (Pte) Ltd</td>
<td>58 (right top and right bottom)</td>
</tr>
</tbody>
</table>