



WHEN FAÇADES KILL

A problem of extreme flammability

Facade
Tectonics
space

2018 WORLD CONGRESS
LOS ANGELES

Terri Meyer Boake / University of Waterloo



June 14, 2017 – Grenfell Tower, London



Fire rated Aluminum Composite Panels cost 30% more than flammable ones.
Can you really "value engineer" when it is a matter of life and death?



Recent Tall Building Fires



Sulafa Tower, Dubai

- February 12, 2012. Tamweel Tower, Dubai
- November 25, 2014. Lacosse Apartments, Melbourne
- February 21, 2015. The Torch, Dubai
- December 31, 2015. The Address, Dubai
- July 20, 2016. Sulafa Tower, Dubai
- June 14, 2017. Grenfell Tower, London
- August 4, 2017. The Torch, Dubai

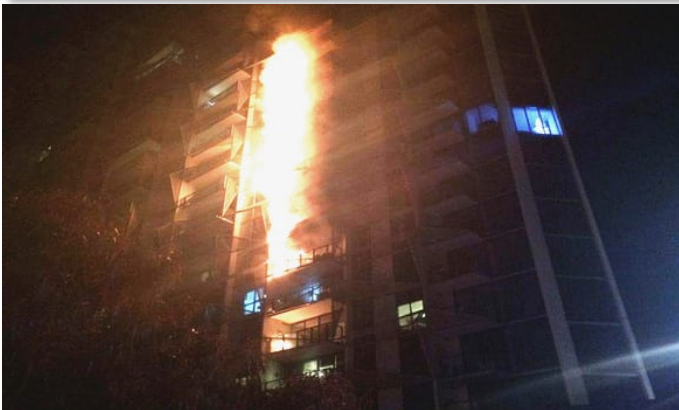
Tamweel Tower, Dubai | February 12, 2012



Scenario

- 34 storey tower, 160 apartments
- Residential, operable windows, balconies
- No deaths or injuries
- Fire started on the outside of the building
- Assumed a cigarette ignited some trash on a balcony and the fire swept up the exterior
- Clad in non fire rated aluminum panels with thermoplastic core
- Residents still not able to move back into the building until late 2017
- Seen as a test case in the UAE for fire related insurance claims and repairs
- *In addition to replacing the cladding they will also be raising the height of the balconies*

Lacrosse Apartments, Melbourne | November 25, 2014



Scenario

- 21 storey tower, 200 apartments
- Residential, operable windows, balconies
- No deaths or injuries
- Fire started on the outside of the building
- A cigarette ignited some trash on a balcony and the fire swept up the exterior
- Fire swept from 8th to 21st floor in 11 minutes
- Clad in non fire rated aluminum panels with thermoplastic core
- The cladding has never been replaced and the building remains occupied
- The Australian government is looking into a process to deal with the many existing buildings with similar cladding

The Torch, Dubai | February 21, 2015, August 4, 2016



Scenario

- 86 storey tower
- Residential, operable windows, balconies
- 4 people with minor injuries
- Fire started on the outside of the building both times
- Clad in non fire rated aluminum panels with thermoplastic core
- Fire #1: Fire alarms did not sound, people notified by occupants of an adjacent tower
- Fire #2: Alarms did sound
- Repairs to the building have yet to be completed

The Address, Dubai | December 31, 2015



Scenario

- 63 storey tower
- Residential/hotel, operable windows, balconies
- Minor injuries
- Fire started on the outside of the building from an electrical fault from a wire for exterior lighting, located on a ledge between the 14th and 15th floors
- Clad in non fire rated Alubond aluminum panels with low density polyethylene core
- Fire alarms did not sound and sprinklers did not go off
- Emaar to receive Dh1.22 billion insurance claim
- Hotel set to reopen late 2017 (unsure if it has)

Sulafa Tower, Dubai | July 20, 2016

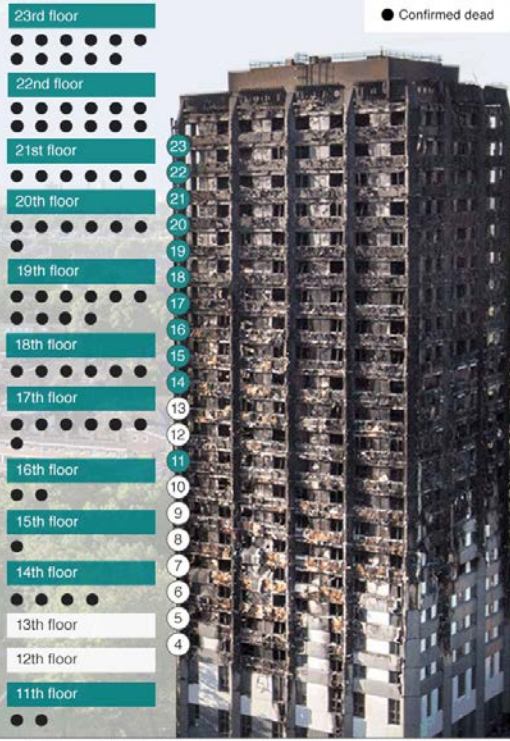


Scenario

- 75 storey tower
- Residential, operable windows, balconies
- No injuries
- Fire started on the outside of the building from a discarded cigarette butt on the 61st floor
- Clad in non fire rated aluminum panels with low density polyethylene core
- Fire alarms did not sound and sprinklers did not go off
- 3 hours to extinguish
- 15 floors damaged
- Flames fanned by high winds

Grenfell Tower, London | June 14, 2017

Where the Grenfell Tower fire victims lived



Scenario

- 27 storey tower
- Residential, operable windows (summer night, open), no balconies
- 71 deaths
- Fire started on the inside of the building from a malfunctioning fridge that burnt through to the cavity
- Spread from 4th floor upwards in 15 minutes
- Re-clad in non fire rated aluminum panels with low density polyethylene core using a rain screen with an additional 150mm polyisocyanurate insulation and a 50mm continuous cavity
- No fire alarms in building
- Single stairwell

Graphic does not include Victoria King, 71, and her daughter, Alexandra Atala, 40, who also died in the blaze, details of where they lived have not been released. Baby Logan Gomes, who was stillborn in hospital on 14 June after his parents escaped the tower block, has also been recorded by police as a victim of the fire. They include people visiting friends and family in the block.

<http://www.bbc.com/news/uk-40301289>

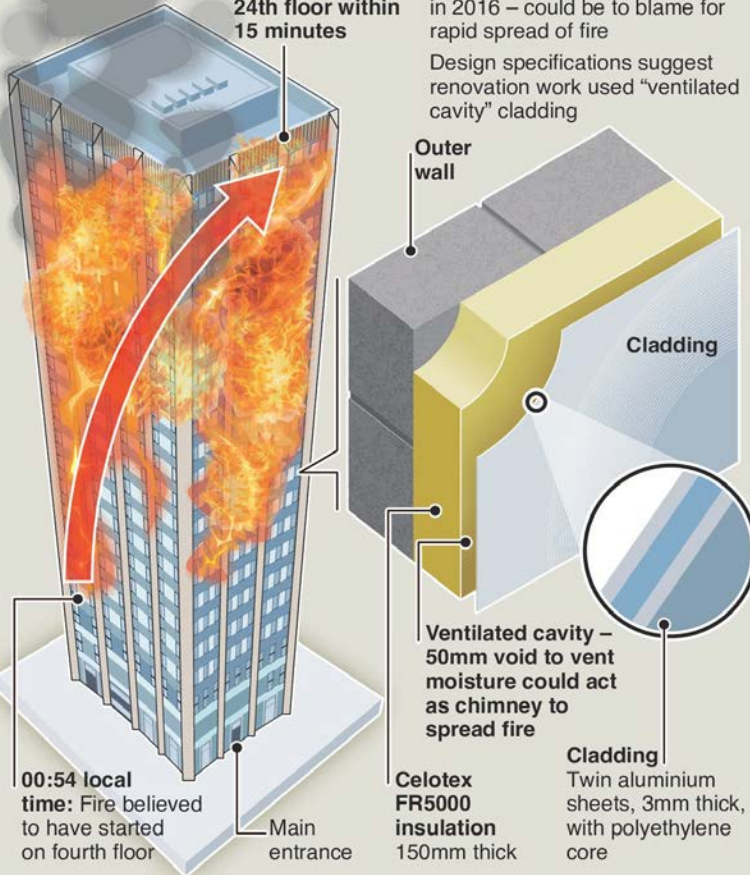
London fire probe focuses on cladding

With 17 confirmed dead but dozens of people still missing, fire chiefs say no more survivors are expected to be found in London's 120-apartment Grenfell Tower

Fire spreads to 24th floor within 15 minutes

Cladding: Added to tower block in 2016 – could be to blame for rapid spread of fire

Design specifications suggest renovation work used “ventilated cavity” cladding



00:54 local time: Fire believed to have started on fourth floor

Main entrance

Celotex FR5000 insulation
150mm thick

Outer wall

Cladding

Ventilated cavity – 50mm void to vent moisture could act as chimney to spread fire

Cladding
Twin aluminium sheets, 3mm thick, with polyethylene core

Grenfell Tower

“The cladding had a metal outer coating and an expanded foam interior. This polyethylene - or plastic - core is less fireproof than other alternatives.

However, even this type of cladding - when properly fitted and with its polyethylene insulation **expertly encapsulated** - should resist fire, the Fire Protection Association (FPA), the UK's national fire safety organisation, said.”

<http://www.bbc.com/news/uk-40301289>

The additional cavity insulation and air space make this fire very different from the UAE fires which did not use the product in this manner.

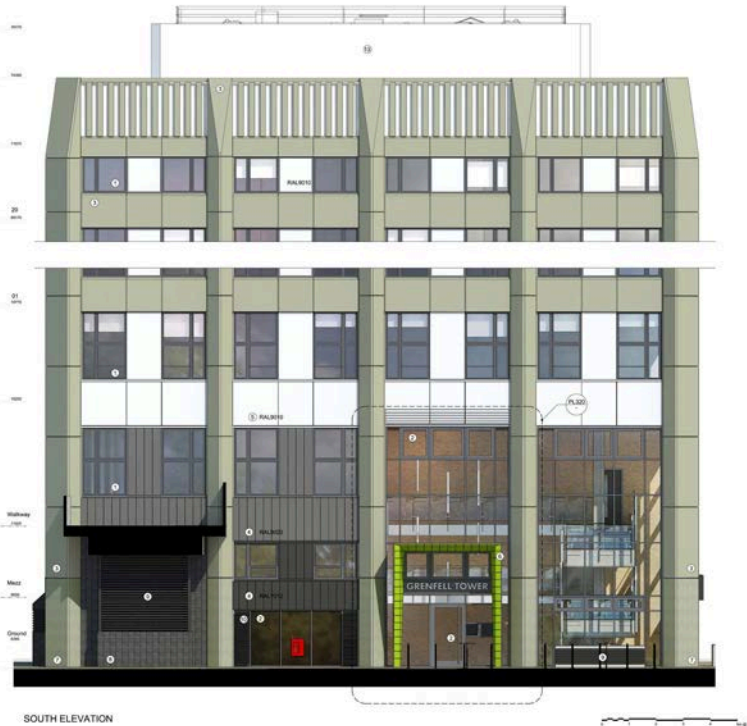
Grenfell Tower

MATERIALS KEY

1. ALUMINIUM FL & T TURN PROFILES
2. ALUMINIUM CURTAIN WALL OPENING LIGHTS & GLAZED DOORS
3. ALUMINIUM CURTAIN WALL OPENING LIGHTS & GLAZED DOORS
4. ALUMINIUM INTERLOCKING PANEL, MANGROSEEN
5. ALUMINIUM GLAZED TITANE MANGROSEEN
6. ALUMINIUM GLAZED TITANE MANGROSEEN
7. GLASS REINFORCED CONCRETE (GRC) PANEL
8. GYPSUMBOARD SLATE BLUE BACKUP BRICK STACK BOND
9. ALUMINIUM VENTILATION LOUVER
10. ALUMINIUM CLADDING AS PART OF OPENING LIGHTS
11. STEEL JOIST RYS
12. ROLLER SHUTTER RYS
13. EXISTING CONCRETE WALL TO ROOF PLANT ROOM



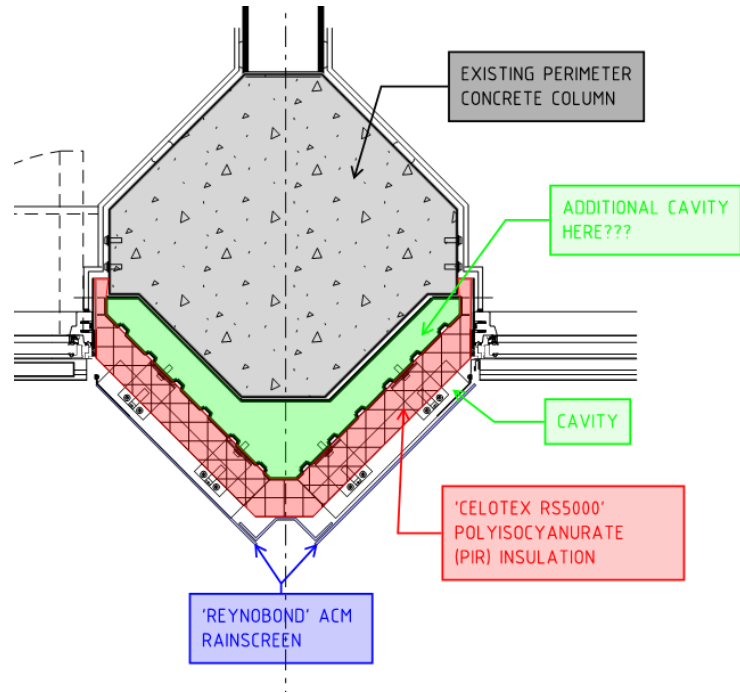
KEY ELEVATION (1:200)



- In a statement on its website, Omnis Exteriors said panels such as Reynobond PE should only be used with “a non-combustible insulation material such as mineral fibre” if they are to be installed on high-rise buildings.
- The fire resistant panel was dropped due to cost reasons
- Massive failures in communication
- Massive investigation underway, changes coming to the British codes.

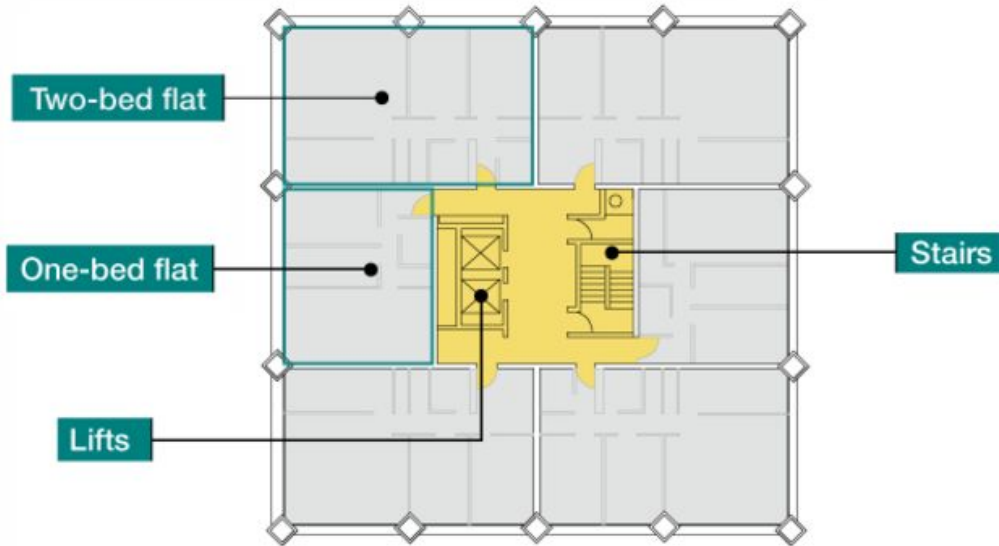


Grenfell Tower



Grenfell physical issues

Typical residential floor in Grenfell Tower



- Only one exit stair for 300+ people
- No sprinkler system

Major Issues in Façade Design

- Deviation from traditional materials
- Out of date fire fighting practice and capabilities
- Variation in global codes, standards and fire test methods
- Confusing state of product naming / lack of clarity on websites and product info
- Role of insulation in *fueling a fire*
- Combustible versus *Flammable*
- Generation of *toxic gasses*
- Height restrictions on flammable/combustible construction
- Rainscreen: the role of the air space in the façade
- Adjacency of buildings (dense urban situations)
- Balconies and operable windows
- Who is responsible?

Deviation from traditional materials



<http://www.dailymail.co.uk/news/article-4606078/Man-faulty-fridge-started-Grenfell-Tower-inferno.html>

- Traditional cladding materials have typically been non combustible (brick, precast, stone, glass, curtain wall)
- The exterior of the building did not tend to burn – the fire load was mostly internal
- High rise residential buildings are typically reinforced concrete
- Traditional insulation such as fiberglass and rockwool are non combustible
- New, lightweight materials behave very differently in fire situations, often contributing greatly to the fuel load
- Newer materials can melt, accelerate a fire and release toxic gasses


Out of date fire fighting practices and capabilities



- 99% of the world's ladder trucks can't reach above the 7th floor whereas MOST high rises are at-least 12 floors and above
- “Shelter in Place” has been successful in preventing deaths from smoke inhalation based on the ability to extinguish the fire in *non-combustible towers (structure AND cladding)*
- Fire fighters are not accustomed to the fire *situations* created by new façade materials
- Fires are burning from the outside to the inside so not triggering alarms quickly
- Fire fighting equipment (fire hose cabinets, etc) designed to put out interior fires – little in place for exterior fires
- Fires burning in concealed tall cavities, initially protected from water by metal cladding
- Fire spread is accelerated by the new materials, many taking as little as 15 to 20 minutes (how long does the fire truck take to arrive?)

Variation in global codes, standards and fire test methods

7 Behaviour in relation to fire

 7.1 When tested to BS 476-6 : 1989, ALUCOBOND panel achieved a fire propagation index (I) of 0 with sub-indices (i₁), (i₂) and (i₃) also of 0 and when tested to BS 476-7 : 1997, the product achieved a Class 1 surface spread of flame.

7.2 When tested in accordance with BS EN 13501-1 : 2007, the ALUCOBOND plus panel, with outer aluminium sheet coated with primer and a two-layered finish coat, when tested for reaction to fire, achieved a classification of B-s1, d0.

7.3 When tested in accordance with BS EN 13501-1 : 2007, the ALUCOBOND A2 panel when tested for reaction to fire, achieved a classification of A2-s1, d0.

7.4 The panels are capable of achieving Class 0 surface or a 'low risk' material in relation to the national Building Regulations.

7.5 These performances may not be achieved by all colours of the panel and the designations of a particular colour should be confirmed by:

England and Wales — test or assessment in accordance with Approved Document B, Appendix A, Clause 1

Scotland — test to conform with Regulation 9, Annex 2C⁽¹⁾, Table, or Annex 2E⁽²⁾

Northern Ireland — test or assessment by a UKAS accredited laboratory or an independent consultant with appropriate experience.

(1) Technical Handbook (Domestic).

(2) Technical Handbook (Non-Domestic).

7.6 The fixing gasket is present in such small quantity as to have negligible effect on the overall fire performance of the cladding.

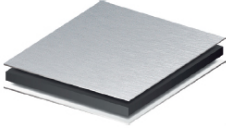
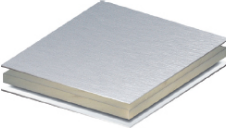
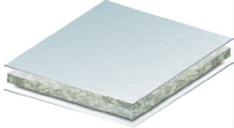
7.7 For resistance to fire, the performance of a wall incorporating the system can only be determined by tests from a suitably accredited laboratory and has not been assessed as part of this Certificate.

7.8 Cavity barriers should be incorporated behind the cladding, as required by the national Building Regulations, but should not block essential ventilation pathways. Particular attention should be paid to preventing the spread of fire from within a building breaching the cladding system through window and door openings.

- Architects work globally
- Standards are not global
- Most tests are done on products and not assemblies
- Missing “bits” are pretty important parts of the safety of the assembly
- Assemblies typically vary from building to building
- Design applications vary

Product Confusion

Table 1 ALUCOBOND composite panels

Characteristic	Panel type		
	Standard ALUCOBOND	ALUCOBOND plus	ALUCOBOND A2
			
Core	Low-density polyethylene (LDPE)	Thermo-plastically bonded aluminium hydroxide	Inorganic filler materials with thermoplastic binder
Length (mm) ⁽¹⁾	3200,4000	3200,4000	3200,4000
Width (mm)	1000,1250,1500 ⁽²⁾	1000,1250,1500 ⁽²⁾	1250,1500 ⁽³⁾
Thickness (mm)	3, 4 and 6	3 and 4	3 and 4
Density (kg·m ⁻³)	900-940	1600-1800	1600-1800
Core colour	Black	Grey	Grey/white

(1) Lengths up to 8000 mm available on request.

(2) 1750 mm width available on request.

(3) 1650 mm width available on request.

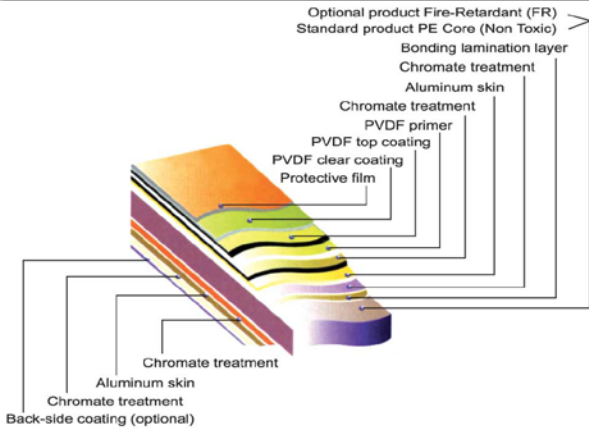
Grenfell is said to have swapped out a more expensive zinc panel for a cheaper aluminum one, that coincidentally also came with a flammable core (the zinc had a fire resistant insulation core)

- Most products go by the name AlucoXXXXX and a cryptic suffix (RE, PE, Plus, A2, etc. who knows what these mean?)
- More concerned with marketing the aesthetics: exterior finish, colors, colorfastness, sizes
- Insulation options are given but with little supporting information
- Many websites do not talk about fire resistance
- Many websites do not cite specific test methods for fire resistance
- Often impossible to tell from the outside of a panel what is on the inside for insulation

Product Confusion



- **Colors**
 - 30 standard colors.
 - Also available in custom colors with minimum quantity.
- **Applications**
 - Wall curtain
 - Parapet and fascia
 - Columns and canopies
 - Advertising plates
 - Interior walls
 - Decorative fins
- **Standard Dimension**
 - 1220mm x 2440mm x 3mm
 - 1220mm x 2440mm x 4mm
- **Available Aluminum Skin Thicknesses**
 - Polyester
 - 3mm: 0.12, 0.15, 0.18, 0.21mm
 - 4mm: 0.21, 0.30, 0.40, 0.50mm
 - PVDF
 - 3mm: 0.21mm
 - 4mm: 0.21, 0.30, 0.40, 0.50mm
- **Special Sizes**
 - Max Width: 2000mm
 - Max Length: 6m
- **Optimal Thickness**
 - 2mm, 5mm, 6mm
- **Finishes**
 - Polyester, PVDF
 - Polyester NANO, PVDF NANO



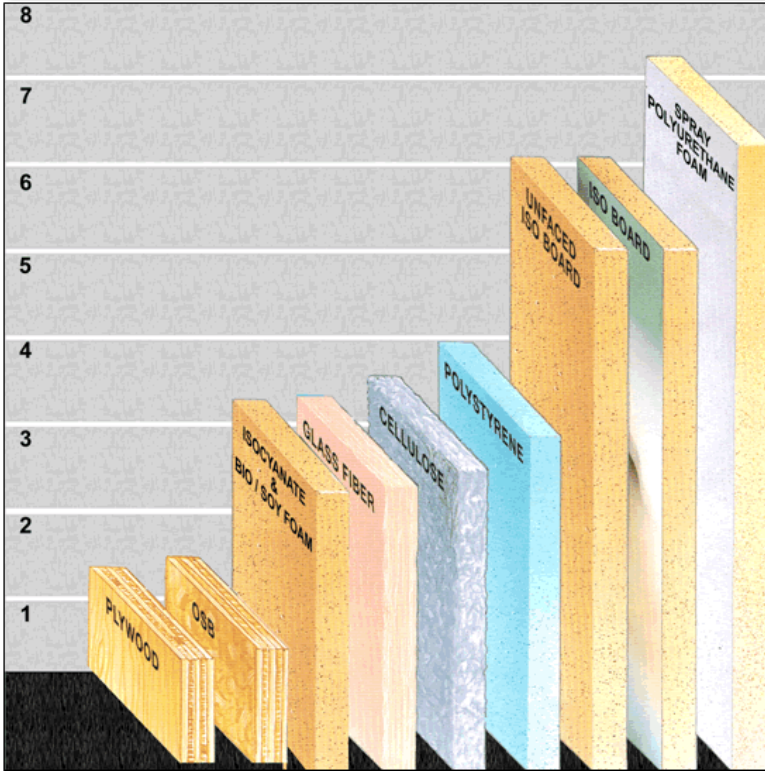
As of the writing of this, Alucobest Panels from China were still being marketed and their website had no information to speak of on fire resistance or limitations of use. These panels are used in the Australian market as well.

Product Confusion



- Most products go by the name AluXXXXX and a cryptic suffix (RE, PE, Plus, A2, etc. who knows what these mean?)
- Alcopanel, Alumech (South Korea), Alucobond (Germany), Alpolic (Japan), Haida, Alucobest (China), Alucowork, Alubond, etc.
- More concerned with marketing the aesthetics: exterior finish, colors, colorfastness, sizes
- Insulation options are given but with little supporting information
- Many websites do not talk about fire resistance
- Many websites do not cite specific test methods for fire resistance
- Often impossible to tell from the outside of a panel what is on the inside for insulation

Role of insulation in fueling a fire



Aluminum composite wall panels insulation core varies from 3 to 6mm (1/8" to 1/4")

SERIOUSLY WITH 6MM OF INSULATION IT'S NOT CONTRIBUTING MUCH TO THE R-VALUE....

Mineral Wool: most fire resistant, withstand up to 1800F

Fiberglass: high heat tolerance but will melt below mineral wool temps

Polyurethane: high flame spread and smoke, melts

Spray foam: is flammable so in many countries has a fire retardant additive (performance then varies by product)

Polystyrene: 212° F (100° C), it begins to soften, to contract and finally to melt. Must be protected by min 1/2" (13mm) gypsum board. Produces dense smoke that will result in carbon monoxide, monostyrene, hydrogen bromide gases

Role of insulation in fueling a fire



<http://www.eng-tips.com/viewthread.cfm?qid=426349>

Low Density Polyethylene Insulation (LDPE):

- The softening of the aluminum combined with the melting of the LDPE insulation led to the panels falling off of the building.
- Fire resistance tests for the panels assume that the panels are sealed so that the edge condition does not expose the interior LDPE core

Role of insulation in fueling a fire



(Photo courtesy of [ChiralJon via Flickr](#).)



Polyisocyanurate:

- possesses the highest level of inherent fire resistance due to its unique structure of strong isocyanurate chemical bonds. These bonds result in improved high temperature resistance (up to 390F, more than twice the temperature resistance of other building insulation foams) which in turn leads to enhanced fire resistance.
- does not melt or drip when exposed to flame but rather forms a **protective surface char**, its fire resistance is further enhanced, especially in terms of flame spread and flashover potential.
- According to the manufacturer, passes both the ANSI UL 1256 and FM 4450 fire tests *without a thermal barrier*.
- Does have issues with generation of toxic gas

Role of insulation in fueling a fire

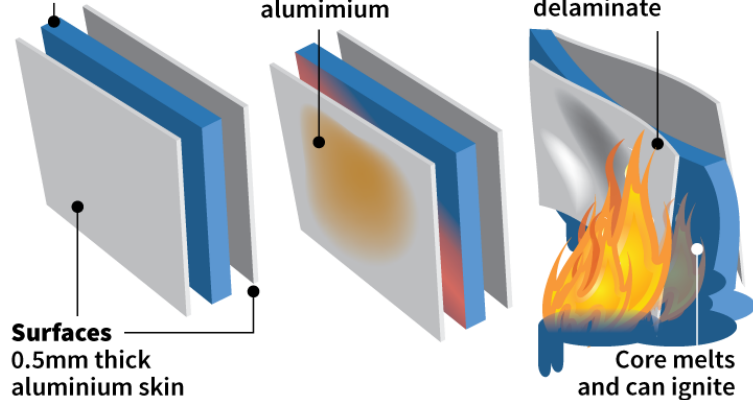
AUE Façade Fires:

Aluminium composite panel Flammable core

Insulating core
2-5mm thick,
100% polyethylene

Heat from a fire will
conduct quickly to the
core through thin
aluminium

Core loses ability to
bind, causing outer
skins to deform and
delaminate



<http://coherence.com.au/curlw/2017/06/high-rise-apartment-fears-after-london-fire/>

Grenfell Insulation:

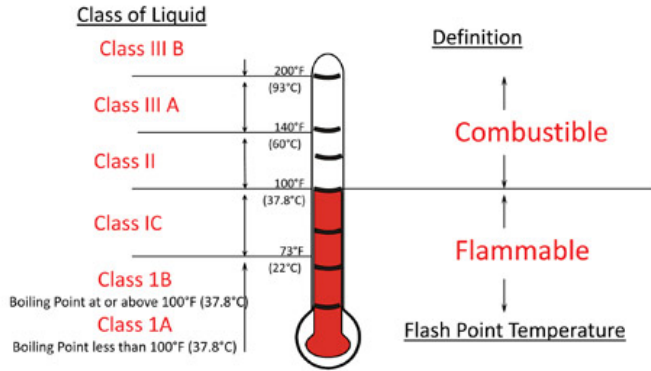
Used an aluminium composite panel over 150mm of Celotex RS5000 insulation

“This new design created an air space between the insulation (Celotex RS5000 PIR thermal insulation) and the aluminum sandwich panel cladding (Arconic's Reynobond ACM - PE core). This air space provided a path for fire spread and a potential chimney effect. Section 715.4 of the 2015 IBC requires all voids in curtain walls to be properly fire-stopped at the floor line. The fire-stop at the floor line was not present as part of the Grenfell Tower cladding project. Building safety experts had warned of using combustible insulation in 2014.”

<https://www.buildingcci.com/blog/07-19-2017/grenfell-tower-fire>

Combustible versus Flammable

NFPA® 30, NFPA® 1, and IFC
Flammable/Combustible Liquid Classification by Flash Point



According to the National Fire Protection Association (NFPA), Combustible substances are those with a flash point of 100 to 150 degrees Fahrenheit. Substances classified as Flammable have flash point temperatures between 20 and 100 degrees Fahrenheit. Thus from the standard/regulatory definitions, Flammable presents a greater fire hazard than Combustible.



February 2007 in Construction Week quoting Wulf Binder, a sales manager working for the aluminium group Novelis Deutschland. “A 5,000 square-metre facade clad with composite panels is equivalent to 19,000 litres of fuel,” he said.

<https://www.thenational.ae/business/property/most-fire-resistant-panels-still-being-ignored-for-uae-towers-despite-spate-of-blazes-1.207550>

Combustible versus Flammable

Type Extinguisher	Fire		CLASS A	CLASS B	CLASS C	CLASS D	Electrical	CLASS F	Comments
	Combustible materials (e.g. paper & wood)	Flammable liquids (e.g. paint & petrol)	Flammable gases (e.g. butane and methane)	Flammable metals (e.g. lithium & potassium)	Electrical equipment (e.g. computers & generators)	Deep fat fryers (e.g. chip pans)			
Water	✓	✗	✗	✗	✗	✗	✗	✗	Do not use on liquid or electric fires
Foam	✓	✓	✗	✗	✗	✗	✗	✗	Not suited to domestic use
Dry Powder	✓	✓	✓	✓	✓	✗	✗	✗	Can be used safely up to 1000 volts
CO2	✗	✓	✗	✗	✗	✓	✗	✗	Safe on both high and low voltage
Wet Chemical	✓	✗	✗	✗	✗	✗	✗	✓	Use on extremely high temperatures

Generation of toxic gasses

Table 6 The yields of toxic products for the smouldering conditions

Material	Smouldering Yields mg/g					
	CO ₂	CO	HCN	NO ₂	HCl	HBr
GW Fiberglass	7.594	1.753	0.392	0.885	0.471	ND
SW Mineral glass	5.687	0.573	0.067	0.429	0.635	ND
PhF Phenolic foam	35.743	11.063	0.232	0.685	ND	ND
EPS Expanded Poly	ND	ND	0.003	ND	1.078	ND
PUR Polyurethane	19.324	1.672	0.056	0.673	2.368	ND
PIR Polyiso	25.390	2.171	0.083	0.328	2.277	ND
ND – below the limit of detection						

It was reported that many of the Grenfell residents may have died from cyanide gas poisoning.

Non combustible insulation such as fibreglass and mineral wool give off comparatively small amounts of toxic gasses as compared to the foams.

Is it height a façade design problem?

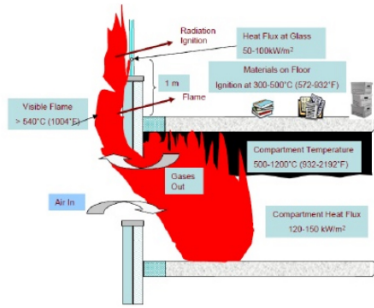
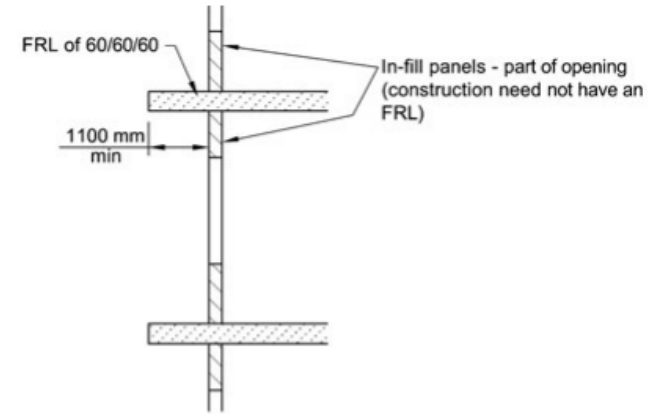
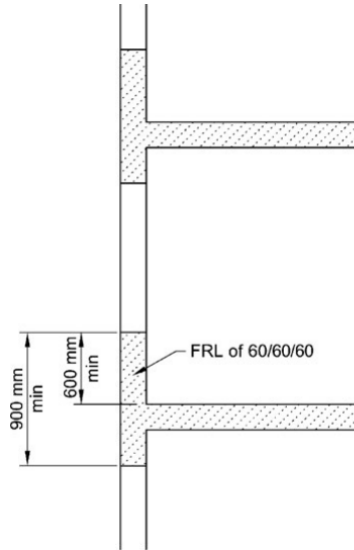


Figure 12.3. Exterior curtain wall and floor fire exposure mechanisms. (Courtesy of Aon Fire Protection Engineering)

In the UAE there was a suggestion of implementing a non combustible fire break of up to 10m in width on high rise towers so that the fire could be prevented from engulfing the entire building.

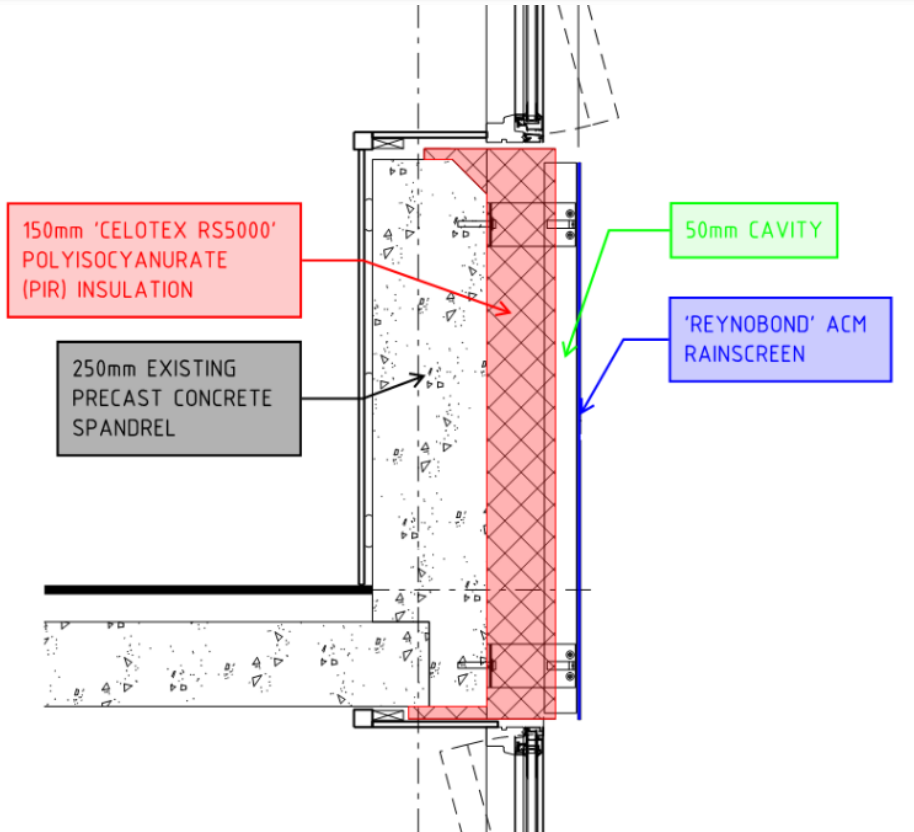


<https://www.buildsurv.com.au/news/2015/4/23/vertical-separation-of-openings-and-spandrel-construction-how-do-they-affect-your-design>

The spandrel panel has been relied on to prevent the spread of fire between floors.

Operable windows make this challenging.

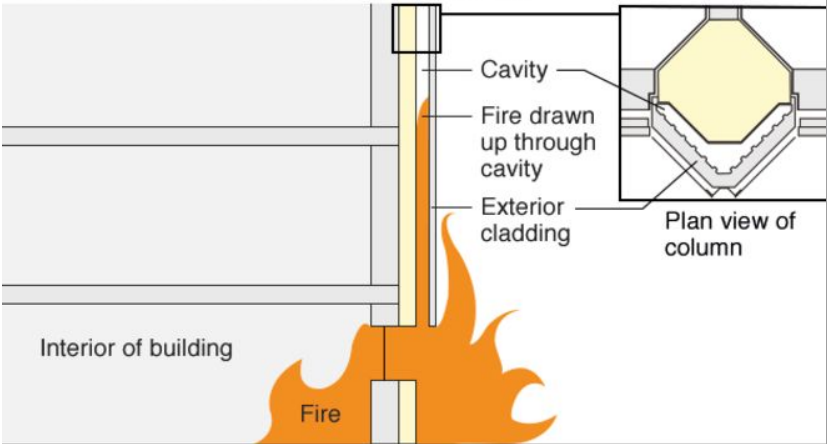
Spandrel panel failure in residential buildings



- Traditional precast concrete spandrel panel was non combustible so the separation of operable windows not a great problem for fire spread
- With a flaming exterior the spandrel panel provided no separation between the operable windows
- This would be a problem on low rise as well as high rise residential buildings.

Rainscreen: the role of the air space in the façade

“Chimney effect” of exterior cladding



Source: Probyn Miers

- A rainscreen façade is a well established practice in Canada, and the need for firestopping to break the continuity of the channel is well known
- This applies to all types of façade cladding materials
- The vertical shafts created by the column covering in Grenfell led to the accelerated spread of the fire
- Essential to properly detail façades with cavity (rather than eliminate the cavity) as it is essential for air pressure equalization to prevent rain penetration
- Also block corners so fire or water is not pushed to adjacent façade cavities
- Cavity insulation should be of a non combustible type or if flammable, properly encapsulated
- Was not an issue in the UAE fires as no cavity there
- More education in detailing is needed

The odd shape of the Grenfell Tower columns meant that there was an airspace in front of and behind the Polyiso insulation layer, likely exacerbating the chimney effect.

Adjacency of buildings



Marina Bay, Dubai

- Tall buildings follow very different setback requirements globally
- **Setbacks** often have been set based on the use of traditional non combustible cladding materials (stone, brick, precast, terra cotta, glass, aluminum)
- These tend not to burn and *waft* down aflame during a fire
- **Wind** exacerbates dispersion of debris
- Separating distances have responded to the effects of radiation temperatures on adjacent buildings
- **Plastics** have been known to be a problem for melting and combustion from adjacent property fires

Adjacency of buildings



The Great Chicago Fire of 1871, and other major urban fires of the period led to laws that prohibited the use of *combustible construction* in urban areas (structure AND cladding).

THE ST. LAWRENCE BURNS



Malak, Ottawa
One of the dwelling house "burns" being filmed by the National Film Board.

Why has this knowledge somehow been completely forgotten as new materials have been developed?

5

The St. Lawrence Burns of 1958 documented the reach of flames and heat from a range of house types (brick and clapboard) and resulted in the 1.2m (4 ft) setback used to allow 7% unprotected openings in residences in Canada.

Balconies and operable windows



<http://www.eng-tips.com/viewthread.cfm?qid=426349>

- All of these tower fires were *residential occupancies*
- The UAE and Melbourne projects all had balconies
- A cigarette fire on a balcony was mentioned as the instigator in many instances
- Most projects had *operable windows* which allowed in Grenfell the fire to immediately spread to the interior
- Operable windows and doors open to the corridor allow for rapid spread of fire
- In the Tamweel fire there is mention of a forthcoming increase in the balcony railing height as a fire prevention
- In theory the balcony should act as a fire break ledge, unless itself clad in flammable materials
- Balconies would also need to be continuous to act as a ledge break

Balconies and operable windows

Dubai Construction Update
Imre Solt - 2012 ©



Tamweel Tower

- In the Tamweel fire there is mention of a forthcoming increase in the balcony railing height as a fire prevention
- In theory the balcony should act as a fire break ledge, unless itself clad in flammable materials
- Balconies would also need to be continuous to act as a ledge break

Sulafa Tower



Major Problem – Existing Buildings



Marina Bay, Dubai

- There have been identified well over 1,000 towers in the UK, UAE and Melbourne alone that used the dangerous material.
- A study done after The Address fire cited that most buildings constructed in Dubai prior to 2012 used the cheaper more flammable cladding.
- Cost identified prior to The Address fire as the primary reason that there was simply no demand for the fire resistant panels (30% premium over the LDPE cores)
- Civil Defense in the UAE is taking a hard line on new construction with new codes and looking at existing projects.

Massive testing in the UK post Grenfell



- One of the issues with the current “witch hunt” that is underway in the UK is that it lacks rigor and transparency.
- Tests are being conducted on the façade material, many failing, but there is no rigor in examine the cavity, air space and insulation behind – which exacerbated the Grenfell fire.

Some ACM Panel manufacturers cease production




≡ **BUSINESS**


Economy | Banking | Aviation | Property | Energy | Technology | Travel and Tourism | Comment | Markets | Money

Alubond stops making plastic-filled cladding used in The Address Downtown Dubai

Alubond will no longer make the controversial panels containing cores known by the industry shorthand of LDPE.

N Sean Cronin
June 12, 2016
Updated: June 12, 2016 04:00 AM

0 shares       



- A number of manufacturers are ceasing production of their PE type products
- But not all
- Fire test procedures are still not uniform nor rigorous
- Cavity insulation specification and design detailing is still subject to failure
- Recladding is an ongoing issue
- Building design, operable windows and use of balconies for smoking remains an issue.

#neveragain



Facade
Tectonics
spa



Fire rated Aluminum Composite Panels cost 30% more than flammable ones. Can you really "value engineer" when it is a matter of life and death?





Continue the Dialogue.

Terri Meyer Boake

- tboake@uwaterloo.ca

Facade
Tectonics
space

2018 WORLD CONGRESS
LOS ANGELES