Design of Thermally Resistant Buildings for Shelter in Place.

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Following tragic events on petrochemical sites such as BP Texas City in 2005, the last decade has seen intense activity in the petrochemical industries to address the consequence of accidental blast loading on occupied buildings and buildings housing essential infrastructure.

In general, new build permanent and temporary structures are now well protected from blast loading using Blast Resistant Modules (BRM) or bespoke structural solutions. But in many instances, the effects of low probability, high consequence thermal events such as short duration full jet flame impingement, or longer duration pool fire scenarios have not been well understood or considered.

In many cases, no, specific thermal consideration has been made. Or only the performance of the structure under fire has been considered, with little regard for occupant vulnerability to longer duration thermal flux and increases in temperature.

This paper explores the issues which need to be considered when assessing buildings for shelter in place under thermal loading. Four case studies are provided for BRM modular solutions with Passive Fire Protection (PFP), a bespoke new build insitu concrete solution and the assessment of existing blast hardened buildings. Areas where further research and development are needing are also highlighted.

Introduction

Following tragic events on petrochemical sites such as BP Texas City in 2005, [CSB 2007] and Pemex, Mexico, 2012, the last decade has seen intense activity in the petrochemical industry to address the consequence of accidental blast loading on occupied buildings.

In general, new build temporary and permanent structures are now well protected from blast loading using Blast Resistant Modules (BRM) or bespoke structural solutions, and existing structures have been assessed and strengthened where necessary to demonstrate that residual risks are As Low As Reasonably Practicable (ALARP).

However, in many instances, the effects of low probability, high consequence thermal events such as short duration full jet flame impingement, incident flux from non-impinging jet fires and longer duration pool fire scenarios have been less well understood or considered. Often site procedures rely on immediate escape to muster points away from the hazard, but operators are required to remain in control rooms to allow shutdown of the plant and to manage the emergency response. On some smaller sites, escape outside the hazard area is not possible and muster inside protected buildings or refuges is the only option.

In many cases, no detailed thermal consideration has been made in the design of such buildings with vulnerable elements such as windows, HVAC air intakes and other service penetrations, significantly reducing the integrity of the building envelope. Alternatively where fire has been considered, only the integrity and structural stability have been considered, with little regard for occupant vulnerability or comfort from increased internal flux and temperature in longer duration events.

There is very little consolidated industry guidance on the subject which leads to ad hoc project specific decisions having to be made with potentially little consistency across the industry.

Shelter in Place

On sites with major accident hazard potential, there is often a requirement to provide buildings which will protect occupants in the event of an incident. These are normally called "refuges" if a single room or "shelter in place" if a whole building. The key features of a building, which is to be shelter in place from a thermal event, are as follows:

- Building structure, envelope, windows, doors etc shall retain integrity. i.e. remain stable with adequate strength, shall not deteriorate, catch on fire, disintegrate, melt, allow passage of fire or smoke etc.
- Environment shall remain habitable with sufficient insulation provided to maintain a habitable temperature.
- Environment shall remain habitable with sufficient volume of space and floor area per person to avoid overcrowding and ensure there is sufficient oxygen.
- Any external or internal equipment required to maintain environment shall remain operable.

As well as technical aspects, human factors are important, as people must be comfortable and confident they are safe. Industry practice suggests less than 60 min is a reasonable time to expect people to shelter in place, but longer periods are sometimes unavoidable.

Guidance on the provision of a suitable floor area and volume of space per person for a given durations of shelter in place can be calculated from equations provided for toxic refuges in CIA 2010.

Flux and Temperature

When assessing thermal protection of occupied buildings from external fire sources, it is necessary to understand the relationship between flux and temperature, as external hazards are usually communicated to the design team in terms of flux and international codes and standards which set fire resistance performance are based on standard temperature curves. For initial design purposes this can be done using Stefan-Boltzmann Law for black body emissive power which gives good correlation to published furnace test data. It will, however, be conservative as it doesn't take account of convection losses to the external environment which can be allowed for in more detailed calculations.

Proprietary Systems

BS EN 1363 Part 1, 2012, is the new European Standard which has now partially superseded BS476 for the fire testing of building components in cellulose fires. This standard effectively allows the user to carry out a fire test against a standard fire curve and assess the performance of the products against the specific criteria listed below.

INTEGRITY (E) - the ability for the component/ wall build-up to stop the passage of flame or smoke for a defined period of time;

INSULATION (I) - the ability of the component/ wall build-up to reduce the transfer of heat from the fire exposed face to the non-fire exposed face. The average temperature rise on the non-fire face shall not exceed 140°C and the maximum temperature at any point in the component shall not exceed 180°C.

Product compliance with BS EN 1363 is split into standard durations (e.g. 30, 60, 90, 120, 240mins etc) whereas BS476 tests were typically run until the average or maximum temperatures were exceeded. The cellulose fire curve used in these codes and the integrity and insulation requirements are effectively the same as those used in other international standards such as IMO 1993.

Hydrocarbon fire tests can be carried out in accordance BS476: Part 20; 1987 Appendix D and other international standards. Components tested to a hydrocarbon rating are typically designated (H) with a defined duration (e.g. 30, 60, 90, 120, 240mins etc). The required integrity and installation requirements are similar to those indicated above.

Jet fire tests are typically carried out in accordance with ISO 22899-1, which does not set defined average and maximum temperatures on the rear face of the products, it is left to the Specifier to define this criteria. As such, it is possible to have a (J) rated products with an average internal temperature rise of circa. 550°C after the defined duration. This is because this product would be suitable to maintain load bearing capacity of structural steel, but it would not be suitable on its own for use as a building component e.g. the wall of an escape corridor.

There are many types of proprietary PFP systems which have been tested to the above standards, all of which have their advantages and disadvantages which need to be assessed for each project. An example of such a comparison carried out by IKM for a recent project can be found in Table 1. However, due to the cost of carrying out the required testing to bring a product to market, and potential concerns over competitors reverse engineering products, it can often be difficult to obtain fire test data and material properties for some products. This can make assessing the suitability of products for unusual applications, such as shelter in place buildings difficult.

Care should be taken when selecting PFP systems which rely on phase change, such as epoxy intumescent, if the flux level for the site specific hazard is less than the standard temperature curves. There is very little information currently publically available on how many such systems perform at lower flux levels. Other issues such as whether the product may give off hazardous fumes in service e.g. phenolic foams, or may give off hazardous fumes during a fire e.g. epoxy intumescent may also affect product selection.

Bespoke Systems

Proprietary fire protection systems aren't the only way to provide adequate integrity and insulation for a shelter in place building. Many non-combustible building materials can be used to construct bespoke fire resistant building envelopes. The most common examples of these in the major accident hazard industry, would be reinforced concrete (either insitu or precast) used for onshore installations, and stainless steel folded plate with ceramic or mineral fibre insulation used for offshore modules. Well built existing buildings in masonry construction can also provide suitable integrity and insulation for low magnitude short duration events, depending on size and location of openings. Assessment of such Bespoke Systems is also often required to demonstrate tolerable risk levels for existing buildings.

Other Components

The performance of other building components such as windows, doors, HVAC air intake / extract dampers and transit frames for pipe and cable penetrations all need careful consideration. Cellulose and Hydrocarbon fire rated products are available for varying durations for all these components. Jet fire rated windows and dampers are not currently commercially available, so for inherent safety, windows should be removed where there is a jet fire risk, and care needs to be taken in locating air intake and extract, or stainless steel shielding or similar may be utilised where this is not possible.

Habitable vs Survivable

An average temperature rise on the inside face of a building component of up to 140°C at the end of a specified test period does not necessarily mean that the internal building environment will be habitable for shelter in place purposes. It is necessary to consider two connected but distinct fire effects, temperature and flux.

HSE 2010 provides a useful summary of information on human vulnerability to temperature and flux. At less than 70°C the environment will be uncomfortable but not fatal. Between 70°C and 150°C vulnerability is dictated by difficulty breathing and probability of fatality needs to be calculated. At above 150°C vulnerability is dictated by burning of the skin and risk of fatality is significantly increased.

It can be observed from Stefan-Boltzmann's Law that a temperature rise of 140°C (permitted for a proprietary product test), would result in a thermal flux of the order of 1.6-2.0 kW/m2 from the inside face of the panel, which is comparable to the 0.8-1.81 kW/m2 values obtained from tests of various A60 rated products, USCG 1993 (note A60 is comparable to EI60 to BS EN 1363). This can be compared against the limit of 1.6 kW/m2 at which pain would be felt after 60 seconds API 521, with a 50% probability of fatality within 18 minutes (calculated using HSE 2010), but heavy clothing / normal petrochemical Personal Protection Equipment (PPE) will provide some protection.

The above temperature or thermal flux levels may be survivable for short durations if PPE is used, however these do not take cognisance of human factors issues relating to people sheltering in place in a building which is getting hotter and hotter. Typically the natural instinct of people is to escape. Based on IKM's recent research and discussions with industry specialists, there appears to be no industry guidance, and so each project must make its own assessment of what is reasonable. If we consider normal practice for designing hot water radiators for heating buildings they usually operate at temperatures in the range of 40-70°C but only occupy a very small proportion of a buildings surface area. So if we have a wall and roof approaching say 140°C (70°C averaged over the duration of the shelter in place) the internal environment will be far too hot for occupant comfort.

On recent IKM projects we have taken the view that the average temperatures on the inside face of the fire resistant envelope must be kept to approximately 50°C in order to provide a reasonable level of comfort for occupants and to avoid panic (i.e., average room temperature of 20°C, plus 30°C temperature rise, equals 50°C).

Provision of cooling by mechanical systems is normally not viable, as a large cooling load is required which cannot be provided by heat rejection to outside and alternative heat rejection methods such as ground source cooling are not suitable for sudden temperature changes. One solution would be large chilled water buffer vessels or similar, kept cold for the life of the building, to provide sufficient cooling during an incident, but they may never be used. Mechanical systems also require large resilient power supplies to remain operational during an incident. Therefore the cost of providing a suitable mechanical cooling system is disproportionate to the cost of providing additional insulation in the building envelope. In addition, providing additional insulation is inherently safer than providing a mechanical system which could fail to operate correctly during an incident.

Case study 1

Case study one is taken from a project for a new occupied building on an existing major accident hazard site in the UK, which comprises the design of a new high integrity building with blast and thermal protection against Quantified Risk Assessments (QRA) hazard data prepared by others.

Initially the building was designed for consequence based (worst possible) hazard, which required thermal protection for full jet flame impingement of the building (350kW/m^2 flux) for 60 minutes duration. This was later changed to a probability based (worst credible) hazard, of 60kW/m^2 flux. However, when assessing potential fire scenarios it was identified that although the previous 60 minute duration allowed for the one process train which was on fire to be fully purged of flammable product, it was likely that a fire on an adjacent process train would have started prior to extinguishing the first process train. Therefore, to safely remove all inventory from the plant a 120 minutes fire duration was required. For both consequence and probability based scenarios, it was not physically possible to escape to an external place of safety within the site boundary i.e. all areas have hazards in excess of 1.6 kW/m^2, [API 521]. So the building was required to be designed for shelter in place.

Due to the fast track nature of the project and the significant site hazards, a steel blast resistant module (BRM) solution was selected early on in the design as being the preferred solution, but this relied on a PFP system to provide thermal protection. A review of available PFP systems was carried out with advantages and disadvantages summarised in Table 1, unfortunately some systems which appeared to be good solution during initial studies had to be discounted as fire test data couldn't or wouldn't be provided by manufacturers.

The final selected system for the probability based 60kW/m^2 flux was a H120 rated, built up system, the test data for this system indicated that it very nearly met the requirements for H240 and furthermore the fire test data demonstrated that the maximum temperature rise under a hydrocarbon fire test at 120 minutes was only 57 °C, therefore the system could be assessed as meeting the project specific criteria of max 30 °C temperature rise under 60 kN/m^2 flux.

In a similar way suitably rated thermal and blast windows and doors were identified for the project, with the most cost effective solution being a bespoke window with EI180 rated glass which comprised of an 83mm glazing unit built up from 6 layers of toughened glass with 5 gel interlayers, which was demonstrated to have an average internal temperature rise of less than 30 °C after 120 minutes.

With regards to door systems, numerous manufacturers were contacted, but none were currently able to demonstrate compliance with the project specific temperature rise criteria of 30 deg. One manufacturer offered a H120 rated door, but wouldn't provide test data. However, all external access doors were isolated from internal occupants by lobbies which could be formed by an EI60 corridor wall and door. As such, although a H120 external door may have an internal temperature rise approaching 140°C the resulting flux radiated from this door would not reach occupants due to the EI60 rated lobby. It was deemed that this would provide sufficient protection. A similar approach could be used where a small refuge can be protected from high flux and temperature gains by surrounding rooms which don't need to be occupied during an incident.

Case study 2

Case study two is taken from a large project in the Middle East, which comprises the appraisal of numerous existing occupied buildings for blast and thermal protection against QRA data prepared by others. This indicated the following consequence based (worst possible) hazards.

- Blast overpressures up to 850mbar freefield (85kPa, 12 PSI).
- Full jet flame impingement (350 kW/m2) flux, for up to 15 minutes duration.
- Thermal flux from far field pool or jet fires ranging from 30-200 kW/m2, for 1-22 hour duration.
- Buildings within flammable and toxic gas clouds.

Although pool fire scenarios existed for up to 22hrs, it was identified and agreed early on in the project, that full protection for people and infrastructure for this period of time was unrealistic and would come at an unjustifiable capital expenditure. A solution based on safe shutdown of the plant followed by protected evacuation of personnel after 60 minutes using thermally protected escape corridors was selected, which provided a balance of risk and justifiable cost.

At the early stages of the project it was apparent that the one and two storey buildings constructed from traditional non-seismic resistant reinforced concrete frames with masonry infill were significantly understrength for the required blast overpressures. In addition, other building components such as doors, windows, HVAC intakes/extracts and other service penetrations provided negligible protection against blast, fire or ingress of flammable or toxic gas. The client had very onerous requirements for continued operation, so no disruption inside the buildings was permitted. As such, strengthening of the existing structure was quickly discounted in favour of external cocoon protection. Two primary options for the structures were progressed - a structural steel moment frame with external passive fire protection (PFP), and reinforced concrete box either precast or cast in situ. Options considered for the PFP were similar to those described in Case study 1 (see above).

Based on blast and constructability considerations a minimum 300mm thickness of concrete wall was selected. Thermal analysis was carried out using Lusas Finite Element Analysis (FEA) to demonstrate that this wall build-up would provide acceptable performance under the various external fire scenarios. The analysis was reviewed by a third party organisation, using a first-order, iterative, finite difference, one-dimensional heat transfer model, in order to ensure that the thickness of concrete proposed were adequate.

A selection of flame properties was taken from FABIG 2009 which was considered to be suitably validated guidance derived from extensive joint industry large and medium scale jet fire testing. Temperature dependent concrete properties were derived from BS EN 1992-1-2:2004 and Bailey 2011, which were considered to be the current state of the art. This concluded that the 300mm thickness of concrete would maintain the required maximum internal temperature increase of less than 30 °C, provided spalling did not occur. However, the assumption that spalling does not occur under the severe heating scenarios considered for this project is questionable unless significant care is taken in the mix design of the concrete.

Unfortunately there is limited published practical industry guidance on explosive spalling of concrete in severe heating scenarios. Some information is available BS EN 1992-1-2:2004 but this is primarily based on lower intensity cellulose based fires and appears to potentially contradict more recent research. BS EN 1992 -1-2 provides more useful guidance on concrete mix design but although the standard says it covers hydrocarbon fires, it is probably based primarily on lower intensity cellulose fires.

From IKM's project research and discussions with various industry specialists, it was considered that the following should be considered in the concrete mix design:

- Control of moisture content is most important. Explosive spalling is unlikely to occur when the moisture content of the concrete is less than 3 % by weight. Above 3 % a more accurate assessment of moisture content, type of aggregate, permeability of concrete and heating rate should be considered.
- Fume silica should not be used.
- The use of other ad-mixtures such as polypropylene microfibers, to control the escape of moisture in the early stages of the fire, significantly reduce spalling. With adequate performance being achieved with a minimum of 2kg/m^3 of microfilament propylene fibres (circa 16 microns diameter and a length of 6 mm). 5kg/m^3 of fibres is likely to stop spalling completely but the concrete won't be workable.
- Site specific jet, and hydrocarbon fire testing is advisable, once the final mix design, source of aggregate, cement, admixtures etc have been finalised.

Due to the traditional procurement route required by the client, early contractor and supply chain engagement, was very difficult, so carrying out site specific testing was going to be problematic and of limited benefit, so a qualitative risk based approach was adopted.

As inland external concrete in the Middle East can be considered to be dry for the vast majority of the time, it was assumed to be equivalent to exposure class XC1 (dry or permanently wet reinforced concrete) for which BS EN 1992-1-2:2004 indicates the moisture content will be less than 3% and therefore explosive spalling is unlikely to occur. On this basis, a client standard concrete specification was adopted with no site specific fire testing, but with 2kg/m^3 of microfilament propylene fibres, with the contractor to undertake trial mixes to ensure adequate workability for placement and compaction of the concrete. In addition, parametric studies were undertaken to assess the impact of a conservative allowance for up to 100mm [Bailey 2011] of explosive spalling to take place. This identified that although inner face temperatures would increase, they would be below the 140 °C temperature rise allowed for PFP systems and as such would be acceptable, if not desirable, given the additional protection provided by the existing structure within the cocoon.

Once the initial scheme designs were prepared for typical exemplar buildings, a cost and programme estimate was prepared for the project which demonstrated that the insitu reinforced concrete option had significant economic advantages over the Steel-PFP solution. This was primarily due to the high cost of imported steel and PFP in the Middle East when compared to the relatively low cost of labour, concrete and rebar. However the Steel-PFP option was recognised as offering a slight programme advantage over precast concrete and a significant programme advantage over insitu concrete construction. It was also recognised that the reduced programme of the Steel-PFP and precast concrete options were inherently safer as less people needed to be on site for a shorter period of time, reducing the overall risk to people during the construction phase.

Case study 3

Case study three is taken from the same site as case study one, with the design being carried for a new high integrity shelter in place building for a 60 kN/m^2, 120 minute duration thermal event. Again a BRM solution was adopted with PFP external protection. However the building contractor proposed an alternative built system which allowed more work to be carried out in advance offsite, and would produce a more aesthetically pleasing finished building.

The proposed built up system, comprised of an external EI120 rated cladding system which was installed over the BRM structure. Inside the BRM structure there was then supplementary mineral wool insulation installed to ensure that maximum internal temperatures did not exceed the project specified max 30°C temperature rise (i.e., average room temperature of 20°C plus 30°C equals 50°C).

The external cladding system comprised of a 150mm thick EI120 rated steel composite panel, manufactured from two 0.7mm thick steel sheets and separated by a 150mm thick layer of dense mineral wool insulation which is fully bonded to the steel sheets. Extracts of the fire test data were provided by the manufacturer, which demonstrated their compliance with the 120min integrity requirement, but the level of insulation provided was inadequate, on its own, to meet the 30°C temperature rise criteria.

The contractors engineer provided steady state calculations for the overall wall and roof build ups, which comprised of the 150mm EI120 cladding systems and the various air gaps, structural steelwork, additional mineral wool insulation, cement particle board and plasterboard which comprise the total wall and roof build ups. On review by IKM it was noted that the calculation assumed that steady state for the overall temperatures in the wall build up would be reached within the duration of the fire event, with a suggested time to steady state of 10mins proposed based on published literature for internal compartment fires. However, this can be observed as being significantly conservative when compared to the fire test data for the cladding panels. In the test situation the wall panel alone reaches a maximum temperature of 77°C after 120 minutes see Figure 2. Whereas the steady state calculation suggested a temperature of 559°C. From this it can be observed that the time taken to reach steady state will be significantly in excess of the 120 minute fire event. From examination of the test data a linear extrapolation of temperature with time was considered a reasonable, if conservative approximation. On this basis a time to steady state of the order of 11 hours was derived, with an estimated internal temperature rise of the wall after 120mins being circa 6°C. As such, it was concluded that the use of steady state calculations was significantly conservative and habitable conditions could easily be maintained within the building for the duration of the event.

It is noted that the test data used in these extrapolations is for an EI120 cellulose fire curve as opposed to the project 60 kW/m^2 120 minute duration fire event specified. However, although the EI120 curve starts out at a lower flux, it rises to a higher flux early on in the test. By examination of the total energy in the fire event (area under the flux time curve) it can be observed that 60 kW/m^2 120 minute duration has an approximate total energy of 432MJ whereas the cellulose fire curve has a total energy of 833MJ. Therefore it is inferred that the above estimated temperatures will be conservative.

As the overall proposed wall build-up performed significantly better than the project specification, it was proposed as a cost saving measure to investigate the user of lower specification windows. The contractor proposed the use of EI120 rated window system. Based on the test data provided it was observed that the maximum temperature rise experienced in an EI120 test is circa 91°C, see Figure 2. However if the reduction in total energy under a 60 kW/m^2 120 minute fire event is compared to that of an EI120 curve it could be suggested that the temperature rise will only be approximately 50% of the EI120 test result circa 45-50°C. As such although this would be above the project specific requirement of a 30°C temperature rise, when this is combined with the significant reduction in temperature rise for the wall build-up of 6°C, and the relatively small area of the glass, it can be calculated that the overall performance will be acceptable. There would still be potential for uncomfortable / harmful temperatures for someone standing immediately next to the doors and windows, however considering the layout of the building and total shelter in place numbers, there were not any locations within the building where individuals would not be able to move well away from the doors and windows, so the risks were low.

In addition to temperature, flux emitting from the windows also needed to be considered. At 368K (95°C) this flux would be a maximum of 1 kW/m^2 (conservative emissivity = 1.0), which can be observed to be less than the 1.6 kW/m2 safe level with PPE, API 521.

Case study 4

Case study four is taken from an existing major accident hazard site in the UK, which had two existing shelter in place buildings which had been previously assessed for blast loading in the late 1990's and found to be ALARP. However, subsequent QRA's undertaken by others identified that thermal events were significant and were likely to dominate occupant vulnerability and population risk. So a new occupied building assessment was commissioned to demonstrate ALARP against a 60 kW/m^2, 120 minute duration thermal event.

The existing building comprised of a hardened reinforced concrete structure with sacrificial brick cladding. Heat transfer calculations were undertaken for the reinforced concrete walls and roof using transient numerical integration methods and similar input parameter selection methods as indicated in case study 2. These calculations were then benchmarked against the FEA analysis undertaken for case study 2 to ensure adequate reliability. As the reinforced concrete walls were provided with some degree of protection from the external masonry, no allowance for explosive spalling was made. However, as the roof had minimal finishes above the concrete slab, an allowance for explosive spalling to the depth of the top layer of reinforcement was made. This analysis demonstrated that inner face temperatures for the wall would be well within safe habitable limits e.g. less than 30°C temperature rise, but inner face temperatures for the roof to one of the buildings would be higher due to the reduced thickness of concrete. Due to these elevated ceiling temperature and the relatively small size of the building it was calculated that the internal environment in the building would be above the safe habitable limits which might be reasonable for a 120minute shelter in place. As such mitigation measures were proposed to demonstrate ALARP. One option was to remove occupancy from the building by providing a safe means of escape to the other building. The second option was to provide enhanced insulation.

In addition to identifying short comings in the thermal protection provided by the roof structure of one building, there were also significant shortcomings in the windows, doors and service penetrations, with the windows governing occupant vulnerabilities of 1.0 at 60 kW/m^{2}which generated significant Maximum Justifiable Expenditure (MJE) values, which allowed mitigation measures to be put in place to replace all windows and doors with EI120 rated products and all service penetrations to be retrofitted with EI120 rated transit frames and dampers.

Conclusions

There have been numerous examples of low probability high consequence external fire incidents which have resulted in loss of life within occupied buildings and structures, due to there being inadequate integrity and insulation being provided to protect people.

Adequate protection can be provided through the use of proprietary PFP products or bespoke construction solutions such as reinforced concrete, but there is no current industry guidance or agreed practice on the performance requirements to ensure occupant survivability and comfort during a shelter in place event.

Improved information needs to be made available by PFP manufacturers to allow the thermal properties of their products and fire test performance to be interrogated to allow designers and clients to make informed decisions about the suitability of solutions at the early stages of project.

Reinforced concrete can offer a cost effective solution, but improved information on typical mix design fire tests under intense heat loading from hydrocarbon pool and jet fires is required to assess their ability to resist explosive spalling, so that designers and clients can make informed decisions about the suitability of solutions at the early stages of project, before procurement routes, preferred contractors and supply chain partners can be finalised.

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Table 1 – Example Project Comparison of PFP Options

Description	H120 Rating	J30 Rating	J60 Rating	Resistance to lower hazard ranges	Increased Thickness Possible	Material Properties Available for Modelling	No hazardous fumes during fire	No Hazardous fumes in service	No hazardous failure mode during fire	Offsite Prefabrication Possible	Low weight	Approx. Cost (£/m2)
Phenolic Foam Composite	✓	✓	✓	✓	✓	✓	✓	?	✓	✓	✓	650
Zinc Cement Board & Ceramic Fibre	✓	×	×	✓	✓	×	✓	✓	✓	?	✓	
Stainless Steel & Mineral Fibre	✓	✓	×	✓	✓	×	✓	✓	✓	?	✓	700
Epoxy Intumescent	✓	✓	✓	?	?	×	×	✓	✓	✓	✓	
Cement/Vermiculite Spray	✓	✓	✓	✓	✓	?	✓	✓	✓	?	?	
FRP Composite	✓	✓	✓	?	?	×	✓	✓	✓	✓	✓	1300
Insitu Reinforced Concrete	?	?	?	✓	✓	?	✓	✓	?	×	×	450
Precast Reinforced Concrete	?	?	?	✓	✓	?	✓	✓	?	✓	×	650
Water Deluge		Not suitable										
Shielding		Not suitable										

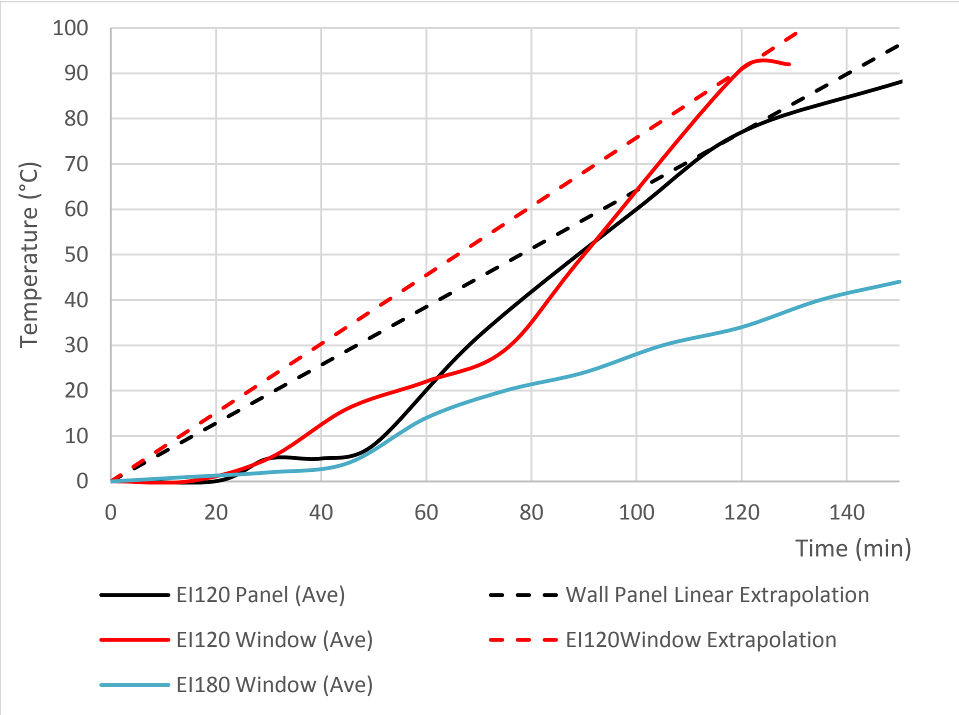

Figure 1 –Wall and Window Fire Test Internal Face Temperatures