Rushes Creek Poultry Production Farm

Rushes Creek Road, Rushes Creek, NSW 2346

Fire Safety Study

Revision: 0

29 June 2021

Project Number: *12545704*

This document is a Fire Safety Study	
Prepared for	ProTen Tamworth Pty Ltd
Project location	Rushes Creek Road, Rushes Creek, NSW 2346
Prepared by	GHD Pty Ltd
Project Reference	12545704
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Document History

Revision / Date	Comment	Author	Reviewed by	Approved by
Rev: A Date: 17/06/2021	Draft Issue for stakeholder comment	**Mark Tsai** BEng (Mech)	**Colin Thomson** CPEng (Fire)	**Carl Voss** MSc (Fire) BEng (Civil) BDC 1843
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Summary of Main Findings and Recommendations

GHD has been appointed by ProTen Tamworth Pty Ltd to undertake a fire safety study for the project located at Rushes Creek Road, Rushes Creek, NSW 2346.

The Rushes Creek Poultry Production Farm was granted Development Consent SSD 7704 on 16 April 2020 by the Minister for Planning and Public Spaces to be established within a rural property approximately 43 km northwest of Tamworth and 33 km northeast of Gunnedah in the New England North West region of New South Wales (NSW).

The development comprises of four individual poultry production units (PPU), where birds are raised for the purpose of producing poultry meat for human consumption. Each farm will contain between 10 to 18 tunnel-ventilated fully enclosed climate controlled poultry sheds, each having the capacity to house 56,500 birds and associated support and servicing infrastructure.

The purpose of the engagement and Fire Safety study is to establish the adequacy of fire safety proposals for the proposed development, ensuring that fire prevention, detection and firefighting measures are appropriate for the specific fire hazards identified at the subject development.

This Fire Safety Study has been developed in accordance with the Hazardous Industry Planning Advisory Paper No.2 – Fire Safety Study Guidelines to a level of detail commensurate with the nature of the project site.

Key Findings

Table 1: Key Findings of Fire Safety Study

Parameter	Finding
Shed Construction	• Dimensions approximately 160.0 m x 18.0 m x 4.7. • BCA Class 8 farm building (subject to performance solution) • Constructed using concrete slab, steel framework, colourbond or zinculume roofing and colourbond steel panel walls insulated with Rigid Polyisocyanurate (PIR) insulation boards. The PIR panels will be encapsulated in aluminium channels. • Sheds will be fully enclosed climate controlled and tunnel ventilated. • Heating provided by wall mounted gas heaters.
Surrounding Residences and Land Use	Surrounding area primarily traditional agricultural production, along with recreational activities associated with Lake Keepit. Low density of surrounding residences with nearest is identified as R25 approximately. 1,025 m from PPU 4. • Nearest populated area, Somerton village to the southeast, approximately 12 km away. • Next nearest populated area, Manilla village to the northeast, approximately 13 km away.

Parameter	Finding
Identified Hazards	• LPG (Class 2.1) – Up to 57,375 L stored at a farm, volume is distributed amongst several tanks in compliance with AS/NZS 1596:2014. • Poultry sheds provided with Polyisocyanurate (PIR)
Prevention / Detection / Protection Required	**LPG Fire** • Installations to comply with AS/NZS 1596:2014 • Outflow of gas to be controlled in accordance with Section 5 of AS/NZS 1596:2014 • Appropriate compliant safety shut down and isolation valves to be installed (Sections 5.3 and 6.7 of AS/NZS 1596:2014) • Inspections, testing and maintenance is to be in accordance with Section 11.5 AS/NZS 1596:2014 • Separation distance between Poultry sheds and LPG tanks is a minimum of 26.5 m apart. Supported by calculations for identified fire scenario and Appendix M of AS/NZS 1596:2014 to not require heat protection at the LPG tanks • Appropriate hazard area classification in accordance with AS/NZS 60079.10.1:2009 • Fire safety systems shall be installed in accordance with Section 13 of AS/NZS 1596:2014
LPG Preliminary Hazard Analysis	The Development is expected to meet all the requirements stipulated by the Department of Planning, Industry and Environment (DPIE) and hence would not be considered, with suitable engineering and design controls in place, to be an offensive or hazardous development on site or would not be impacted by any other hazardous incidents from adjoining facilities offsite.

LPG tank fire exposure protection	• LPG storage will be separated into four areas, one at each of the PPUs and these areas are a minimum of approximately 870 m apart.
	• The location of the above-ground LPG storage tanks will comply with the following requirements for ventilation, access and set up:
	  ○ Above-ground storage tanks will be in the open air, outside buildings;
	  ○ Nearby buildings, fences and the like will permit free access around the tanks and cross-ventilation for the tanks; and
	  ○ The minimum distance to an adjacent LPG tank is equal to the diameter of the largest tank;
	  ○ Groups of LPG tanks at one PPU will be separated by a minimum of 15 m, unless no tanks in either group exceeds

Parameter	Finding
	2m diameter, in which case the distance may be reduced to 10 m. • Separation distance between Poultry sheds and LPG tanks is a minimum 26.5 m apart as supported by calculations for the extreme case fire scenario and Appendix M of AS/NZS 1596:2014 to not require heat protection at the LPG tanks • At least a hose reel complying with AS/NZS 1221 and installed in accordance with AS 2441 shall be provided. • The water supply to the hose reel may be provided by any available on-site reticulated water supply system or from any form of storage system provided that the hose reel is able to deliver at least 0.33 L/s. Where the supply is from a storage system, the duration shall be at least 15 minutes. • The number and location of hose reels shall be such as to ensure that a hose nozzle will reach every point in an area bounded by a line around and 5 m distance from any tank and tanker standing area. • Maintenance shall be in accordance with AS 1851:2012.
Minor potential hazards	
Arcing/Sparks/Explosion of high voltage transformers (including power poles)	• Annual inspections and maintenance of transformer (where required) • Trees, shrubs, grass and the like shall be kept clear from areas surrounding incoming power lines
Gas heater fire	• Heaters are mounted away from the PIR wall by heater mounts, providing an air gap between the body of the heater and the wall. Penetrations of the PIR panel for the insulated air duct into the sheds are to be capped and protected accordingly.
Fires in chemical store	• Incompatible materials shall be kept separate from each other. • No decanting or mixing of chemicals inside the store. • No ignition sources in store with the exception of lighting. • Provision of fire fighting equipment and appropriate training for staff
Bushfires/ grass fires	• Maintain vegetation to a minimum on site. It is noted that tree/shrub plantings are around the perimeter of each PPU, however grass will be maintained and mowed • No combustible material within 3m of the diesel tanks (Section 2.2.5(d) AS1940) • No Combustible materials within 6m of the LPG facility (Section 6.2.5(e) AS/NZS 1596) • Appropriate firefighting equipment is available, operational and staff are trained to use it

Parameter	Finding
Protection and firefighting	Fighting of fire associated with LPG installations depend upon the nature of the surroundings and any associated structures, hazards and activities that may threaten the LPG facility, rather than solely on the quantity of LPG being stored. Any associated buildings and the like will need to have firefighting equipment to comply with building regulations and should be counted as an important part of the overall protection of the site, including the LPG installation. The following protection measures apply to the LPG tanks; • The following are principles detailed in Clause 13.5 of AS/NZS 1596:2014 which are relevant to the LPG tanks; o When an on-site hydrant system is specified, hydrants shall be provided in accordance with Clause 13.7.1 for the tank. o For all other tank installations, at least a hose reel installation in accordance with Clause 13.7.2 shall be available for the tank. Furthermore, provision of firefighting equipment to the neighbouring poultry shed to comply with the BCA provides protection to the LPG tanks: • Provided fire fighters with a fire hydrant system in accordance with H3.9 or AS 2419.1; • Provided with fire extinguishers throughout the development in accordance with BCA Clause H3.11.
Location and type of fire extinguisher at PPUs	• Location and type of fire extinguishers at each PPU shall be in accordance with BCA Clause H3.10 and is illustrated in Figure 14 through to Figure 17
Firefighting water demand and supply	• Fire hydrants are provided to the poultry sheds in accordance with AS 2419.1, modified where acceptable under the Building Code of Australia for Farm Building Use/Performance Solution. Refer Figure 18 through to Figure 21 for proposed locations. • Fire hydrants are served by a pseudo-ring main which utilises the farms water distribution pump pack to charge the pipes, replacing the requirement for two stand-by pumps. • The hydrant system provides 90 m hose coverage from each hydrant (in lieu of 60 m, subject to a separate performance solution)
Firefighting and PPU water availability	• Each PPU has four water storage tanks, each with a capacity of 375 kL. A combined storage capacity of 1500 kL. • Tanks are automatically filled from pressurised lines to remain near full capacity at all times.

Parameter	Finding
	• Tanks are fitted with alarms to sound when water levels drop below two-thirds full. • Water tanks at the four PPU's will be interconnected and able to provide additional water to each other as necessary.
Containment of firefighting water	• Water is the primary suppressant use on site, there is no use of foam or other chemical suppressants other than the fire extinguishers provided on site. • A water management system will be installed at each of the farms to mitigate the impact of surface water run-off from the development. • The sheds will be surrounded by a 0.4 m high dwarf concrete bund wall with strategically located seepage holes to convey excess fire fighting water into gassed swales located between sheds. • Excess firefighting water is conveyed via underground pipes into a table drain located around the perimeter of the farms which then convey water to a detention dam, preventing it from entering the environment. • There is limited potential for contaminated water to be generated.
First aid and emergency planning	• In the event of a fire emergency, fire services shall be notified immediately via 000. Fire Rescue NSW, NSW Police and NSW Ambulance being the first responders are responsible for managing the emergency upon arriving on site. • The site evacuation procedure is documented in the Emergency Plan. • The site office located at each PPU will function as an Emergency Control Centre in the event of an emergency • In addition to the fire protection system detailed throughout the study, the provision of fire aid fire protection equipment is considered. The development shall be provided with equipment summarised in Table 12 • Site managers shall ensure that all employees and contractors are inducted and trained prior to works being commenced on site. • The Emergency Plan shall be reviewed and tested every 12 months as per the requirements of the POEO(G) Regulation.

1. Glossary & Abbreviations

Table 2: Abbreviations and Acronyms

Abbreviations / Acronym	Description
AS & AS/NZS	Australian Standards / New Zealand Standards
BCA	Building Code of Australia
DGs	Dangerous Goods
DPIE	Department of Planning, Industry and Environment
DtS	Deemed to Satisfy
ECC	Emergency Control Centre
EIS	Environmental Impact Statement
FHA	FHA Final Hazard Analysis
FRNSW	Fire and Rescue NSW
FSS	Fire Safety Study
HIPAP	Hazardous Industry Planning Advisory Paper
ISO	International Organization for Standardization
LGA	Local Government Area
LPG	Liquid petroleum gas
L/s	Litres per second
ML	Mega-litres
NSW	New South Wales
PHA	Preliminary Hazard Analysis
PIR	Polyisocyanurate
PPE	Personal Protective Equipment
PRS	Preliminary Risk Screening
PPU	Poultry Production Unit
ProTen	ProTen Tamworth Pty Ltd
SEPP	State Environmental Planning Policy
SLR	SLR Consulting Australia Pty Ltd
SDS	Safety Data Sheets

Abbreviations / Acronym	Description
SSD	State Significant Development

2. Introduction

2.1 Purpose of this Report

GHD has been appointed by ProTen Tamworth Pty Ltd to undertake a fire safety study for the project located at Rushes Creek Road, Rushes Creek, NSW 2346.

The purpose of the engagement and Fire Safety Study is to establish the adequacy of fire safety proposals for the proposed development, ensuring that fire prevention, detection and firefighting measures are appropriate for the specific fire hazards identified at the subject development.

This Fire Safety Study has been developed in accordance with the Hazardous Industry Planning Advisory Paper No.2 – Fire Safety Study Guidelines (Department of Planning, 2011) to a level of detail commensurate with the nature of the project site.

2.2 Scope and Limitations

This report has been prepared by GHD for ProTen Tamworth Pty Ltd and may only be used and relied on by ProTen Tamworth Pty Ltd for the purpose agreed between GHD and ProTen Tamworth Pty Ltd, as set out in section 2.1 of this report.

The services undertaken by GHD in connection with preparing this report were limited to those specifically detailed in the report and are subject to the scope limitations set out in the report.

2.3 Terms of Reference

2.3.1 Regulatory Framework

The Fire Safety Study has been prepared to satisfy condition B40(a) of Development Consent SSD 7704.

> *At least one month prior to the commencement of construction of the development (except for construction of those preliminary works that are outside the scope of the hazard studies), or within such further period as the Planning Secretary may agree, the Applicant must prepare and submit for the approval of the Planning Secretary the studies set out under subsections (a) to (b) below (the pre-construction studies). Construction, other than of preliminary works, must not commence until approval has been given by the Planning Secretary*
>
> *(a) A Fire Safety Study for the development. This study must cover the relevant aspects of the Department's Hazardous Industry Planning Advisory Paper No. 2, 'Fire Safety Study Guidelines' and the New South Wales Government's Best Practice Guidelines for Contaminated Water Retention and Treatment Systems (NSW HMPCC, 1994). The study must meet the requirements of Fire and Rescue NSW.*

This Fire Safety Study has been developed in accordance with the Hazardous Industry Planning Advisory Paper No.2 – Fire Safety Study Guidelines (Department of Planning, 2011) to a level of detail commensurate with the nature of the project site.

2.3.2 Other Relevant Studies

The Fire Safety Study shall be read in conjunction with the following relevant studies;

- The Environmental Impact Statement (EIS) – Volumes 1-3 (SLR, 2018)
- The Response to Submissions (RTS) (EME Advisory, 2019)
- Preliminary Risk Screening (SLR, 2018) (Contained within EIS Volume 3)
- Preliminary Hazard Analysis (SLR, 2018) (Contained within EIS Volume 3)
- Final Hazard Analysis (GHD Pty Ltd, 2021)

2.3.3 Stakeholders

Table 3: Relevant Stakeholders

Role	Stakeholder (organisation)	Named representative
Client	ProTen Tamworth Pty Ltd	Bill Williams
Fire Engineering	GHD Pty Ltd	Mark Tsai Colin Thomson Carl Voss

3. Description of the Facility

3.1 Site Location

The Development Site is located within an area known as Rushes Creek approximately 43 kilometres (km) northwest of Tamworth and 33 km northeast of Gunnedah in the New England North West region of New South Wales (NSW) (see Figure 1) and the Tamworth local government area (LGA).

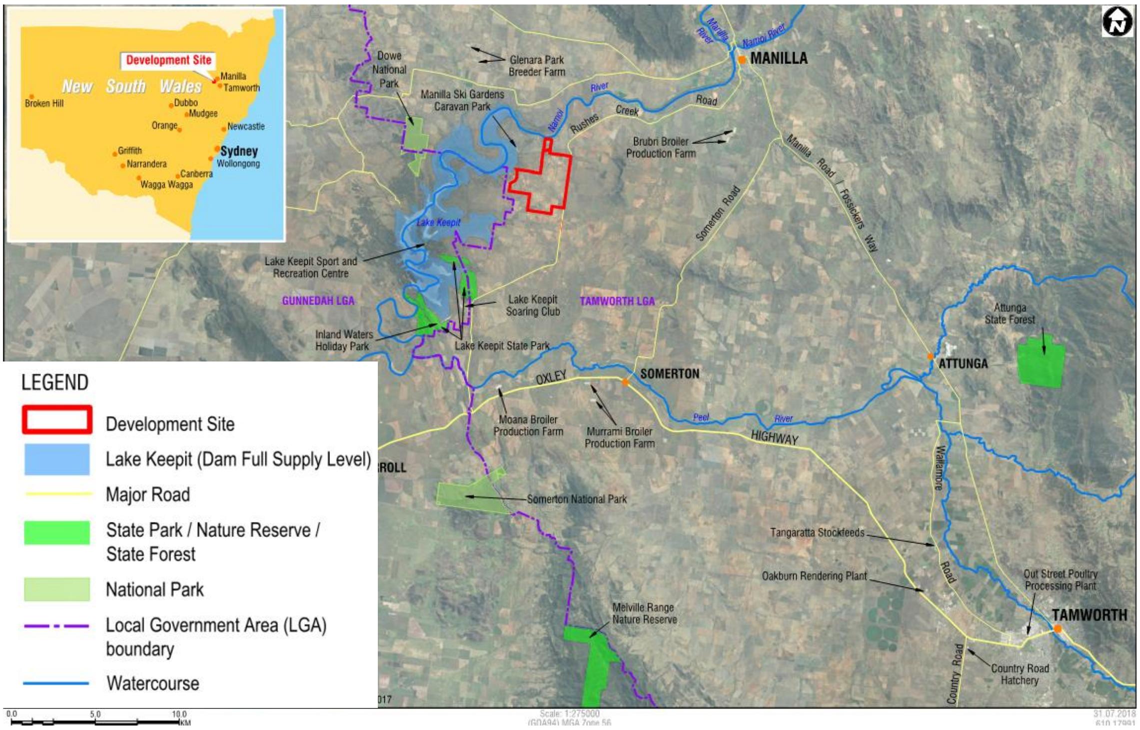

Figure 1: Site Location (SLR, 2018)

3.1.1 Development Overview

The below is from the Environmental Impact Statement developed by SLR, summarised for the purpose of this document. Please see the full Environmental Impact Statement, Volumes 1-3, dated August 2018 for full details (SLR, 2018).

The Rushes Creek Production Farm was granted Development Consent SSD 7704 on 16 April 2020. The long-standing and existing use of the Development Site is traditional agricultural production, including both livestock grazing and cropping. The Development Site comprises approximately 1,016 hectares of land, including cleared grassland with paddock trees and areas of woodland.

The Development will comprise four individual farms or poultry production units (PPUs), each including between 10 and 18 tunnel-ventilated fully-enclosed climate-controlled poultry sheds (54 sheds in total), along with associated support infrastructure and staff amenities.

The Development will have the capacity to house a total population of 3.051 million birds. The proposed numbers of sheds for each farm are as follows:

Table 4: Proposed number of sheds per farm

Farm Number	Number of Sheds
1	10
2	18
3	10
4	16
Total	**54**

The proposed layout of the Development is shown in Figure 2.

In addition to the poultry shedding, the Development will comprise various support/servicing infrastructure, including:

- Eight new residences to house the farm managers;
- Water supply infrastructure to extract, transfer, treat and store water from the Namoi River;
- Electricity supply infrastructure and solar panels at each farm;
- Two new access driveways from Rushes Creek Road and internal access roads;
- A staff amenities and workshop facility at each farm (office space, toilets, change rooms, workshop, chemical store and pump room);
- Dead bird freezers adjacent to the internal access roads near Rushes Creek Road;
- One poultry bedding material storage shed;
- Bulk liquid petroleum gas (LPG) tanks at each farm;
- Generators and generator enclosures/sheds at each farm (emergency use only);
- Vehicle wheel wash facilities;
- Feed silos at each farm;
- Water storage tanks at each farm; and
- Surface water management system at each farm (swale drains, table drains, detention dam and upstream diversions).

The total disturbance footprint is approximately 92.81 ha (Refer Figure 2) and the commercial activities associated with the poultry operation will be largely confined to the individual farm sites and access roads.

It is intended to continue using the land outside of the disturbance footprint within the Development Site for continued agricultural production purposes under some form of lease or share farming arrangement.

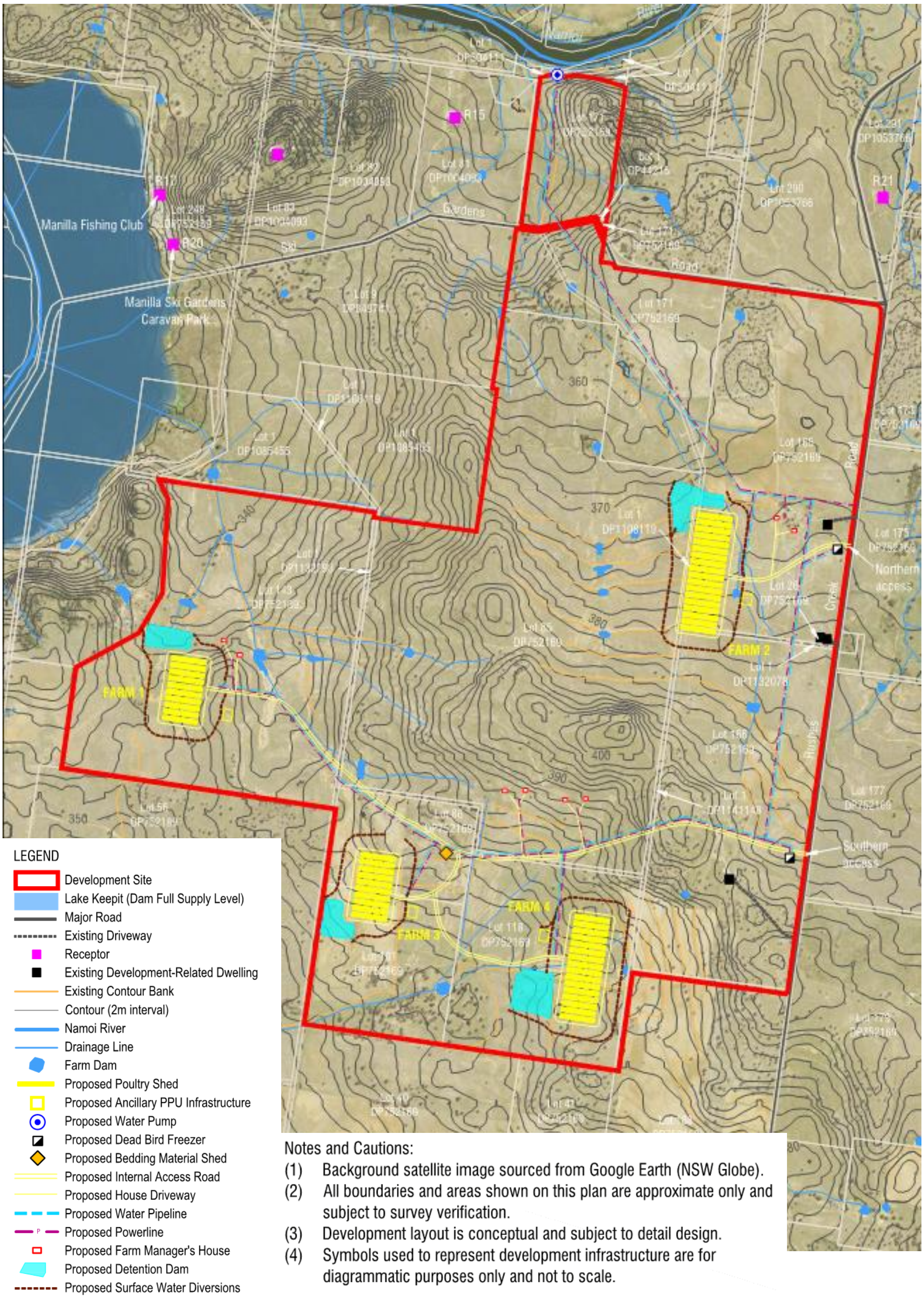

Figure 2: Development Layout (EME Advisory, 2019)

3.1.2 Poultry Sheds

Each of the farms will consist of 10 to 18 poultry sheds, with a total of 54 sheds on the Development Site. The sheds will be distributed laterally and achieve a separation distance of approximately 15 m between sheds.

Each farm will also be provided with a one-way circulation road around the perimeter of the farm to enable entering, exiting and manoeuvring of vehicles.

Based on the civil drawings set, issued by Lance Ryan Consulting Engineers Pty Ltd on 26 March 2019, Rev 4, the individual sheds will measure approximately 160 m in length and 18.0 m wide, equating to a footprint of approximately 2,880 m^2. They are understood to measure approximately 4.7 m to the ridge of the roof and 2.6 m under the eaves.

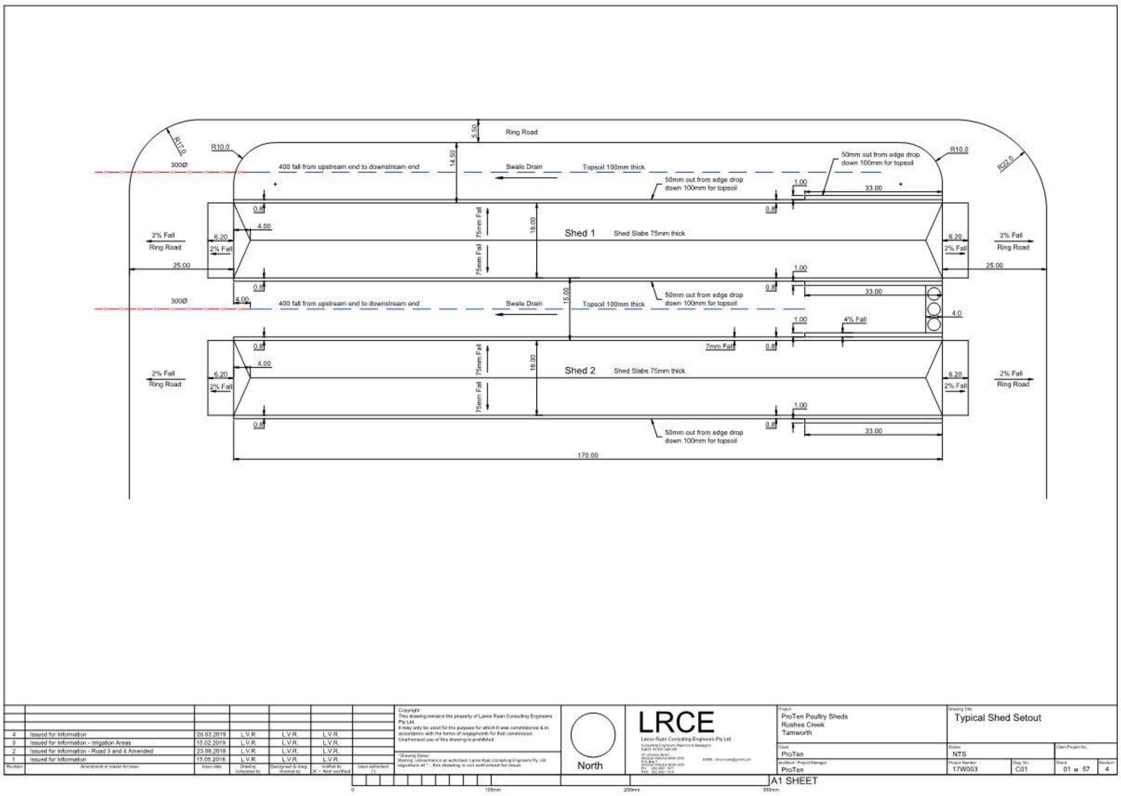

Figure 3: Typical shed layout (Lance Ryan Consulting Engineers Pty Ltd, 2019)

The poultry sheds are considered as “farm buildings” under the BCA and therefore are identified as either a Class 7 or 8 building. The building is understood to be subject to a performance solution to treat the building as a Class 8 farm building in lieu of a large isolated building. The Performance Solution process is separate to this Fire Safety Study, and not discussed further here.

Each shed will be constructed on a concrete slab utilising steel framework, colourbond or zincalume roofing and colourbond steel panel walls insulated with Rigid Polyisocyanurate (PIR) insulation boards. PIR panels will be encapsulated in aluminium channels.

The floor bedding material is understood to consist of soft wood shavings, rice hulls or chopped straw. The flooring will be raw cured concrete and surrounded by a 0.4 m high dwarf concrete bund. All expansion gaps and saw cuts are understood to be Sikaflex filled. An image from one of ProTen’s existing sites (Bective Poultry Production Complex) which is built to a similar specification is shown for reference in Figure 4.

Figure 4: ProTen's Bective Poultry Production Complex (SLR, 2018)

3.1.2.1 Tunnel Ventilation

The sheds are to be fully enclosed climate controlled and tunnel ventilated. The temperature sensors located within the sheds allow ventilation to be adjusted as required.

Heating is anticipated to be required for up to 21 days of each production cycle will be provided by wall mounted LPG heater. The LPG for the heaters is supplied by LPG tanks onsite.

Tunnel ventilation systems will be completely computer controlled and alarm monitored. Back up power is available via emergency diesel standby generators.

3.1.3 Supporting Infrastructure

3.1.3.1 Residential Dwellings

As a result of the scale and 24 hour nature of operation, eight homes are proposed to be constructed on the development to accommodate the farm managers. These buildings are ancillary to the proposed development.

3.1.4 Surrounding Residences and Land Use

The surrounding area is primarily characterised by traditional agricultural production, along with recreational activities around Lake Keepit.

Key surrounding receptors to the Development is summarised in Table 5

Table 5: Key Receptors

Name	Description	Distance
Manilla Ski Gardens Caravan Park and Manilla Fishing Club	Caravan park and camping ground	Approximately 2 km from nearest PPU
Lake Keepit Sport and Recreation Centre	Cabins, conference centre, recreational facilities	Approximately 7 km from nearest PPU
Lake Keepit Soaring Club	Gliding facilities, clubhouse, cabins	> 8 km from nearest PPU

Name	Description	Distance
Inland Waters Holiday Park	Caravan park, cabins, camping ground, recreational facilities	> 9 km from nearest PPU
Somerton	Populated	Approximately 12 km South East of the Development
Manilla	Populated	Approximately 13 km North East of the Development

Three foreshore locations exist around Lake Keepit. These three locations have been designated as a State Park.

The development has a relatively low density of surrounding privately owned residences. The nearest identified is located off Rushes Creek Road, approximately 1,025 m southeast of the nearest PPU (Refer Figure 6)

3.1.5 Distance to Receptors

Figure 5, an excerpt from the EIS, lists the distances between the PPUs and notable surrounding features in the natural and built environments. It is noted that the distances are approximate and were been scaled from satellite imagery and topographic mapping (See Figure 6).

Receptor	Location	Distance from Nearest PPU (m) (nearest PPU)
R1	Dwelling, Rushes Creek Road	4,715 (Farm 2)
R2	Dwelling, Rushes Creek Road	4,585 (Farm 2)
R3	Dwelling, Rushes Creek Road	5,745 (Farm 2)
R4	Dwelling, Rushes Creek Road	5,885 (Farm 2)
R5	Dwelling, Rushes Creek Road	5,395 (Farm 2)
R6	Dwelling, Rushes Creek Road	5,855 (Farm 2)
R7	Dwelling, Moys Lane	5,025 (Farm 2)
R8	Dwelling, Moys Lane	4,225 (Farm 2)
R9	Dwelling, Corella Road	4,385 (Farm 2)
R10	Dwelling, Corella Road	3,890 (Farm 2)
R11	Dwelling, Rushes Creek Road	4,395 (Farm 2)
R12	Dwelling, Rushes Creek Road	4,185 (Farm 2)
R13	Dwelling and small piggery, Rushes Creek Road	3,145 (Farm 2)
R14	Dwelling, Rushes Creek Road	3,625 (Farm 2)
R15	Dwelling, Ski Gardens Road	2,255 (Farm 2)
R16 (potential)	Potential future dwelling, Rushes Creek Road	2,585 (Farm 2)
R17	Manilla Fishing Club, Ski Gardens Road	2,250 (Farm 1)
R18	Dwelling, Ski Gardens Road	2,460 (Farm 1)
R19	Dwelling, Moys Lane	3,775 (Farm 2)
R20	Manilla Ski Gardens Caravan Park, Ski Gardens Road	2,005 (Farm 1)
R21	Dwelling, Rushes Creek Road	1,720 (Farm 2)
R22	Dwelling, Moys Lane	2,765 (Farm 2)
R23	Dwelling, Moys Lane	2,750 (Farm 2)
R24	Dwelling, Rushes Creek Road	1,335 (Farm 2)
R25	Dwelling, Rushes Creek Road	1,025 (Farm 4)
R26	Dwelling, Perrings Road	4,160 (Farm 4)
R27	Dwelling, Perrings Road	4,305 (Farm 4)
R28	Dwelling, Rushes Creek Road	2,480 (Farm 4)
R29	Dwelling, Boundary Road	3,465 (Farm 4)
R30	Dwelling, Boundary Road	3,515 (Farm 4)
R31	Dwelling, Glenbrook Road	5,015 (Farm 4)
R32	Lake Keepit Sport and Recreation Centre, National Fitness Road	6,835 (Farm 1)
R33	Dwelling, National Fitness Road	5,255 (Farm 3)
R34	Dwelling, Rushes Creek Road	3,365 (Farm 4)
R35 (potential)	Potential future dwelling, Bidford Access	3,265 (Farm 4)
R36	Dwelling, Glenbrook Road	4,510 (Farm 2)
Road Traffic Noise Sensitive Receptors		
R37	Dwelling, Rushes Creek Road	12,775 (Farm 4)
R38	Dwelling, Rushes Creek Road	13,495 (Farm 4)

Figure 5: Receptor Distances (Excerpt from Environment Impact Statement Volume 1) (SLR, 2018)

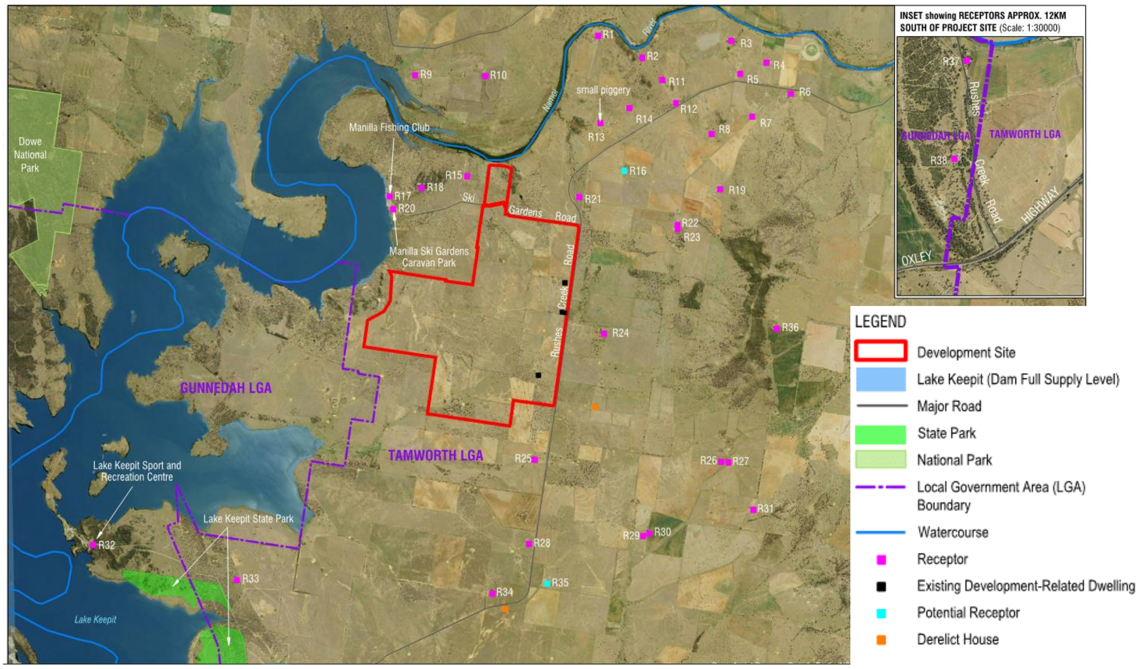

Figure 6: Sensitive Receptors (SLR, 2018)

From the above, the nearest residential receptors are R25 and R24 located off Rushes Creek Road at approximate distances of 1,025 and 1,335 m, respectively, from the development (nearest PPU).

4. Hazards Identified

The identification of fire hazards at the subject development has considered the likes of hazardous materials, process and incidents; in particular those associated with flammables and combustible materials. The likelihood of internal and external causes of incidents are also identified as required.

The site layout is such that PPU’s are located at least 870 m away from each other. Therefore, for the purpose of this study, each PPU is considered a separate area. As the design of each PPU is exactly the same (barring the number of sheds, but including the construction direction, only 1 PPU is described in a generic term and considered the same for all 4 PPUs.

4.1 Inventory of Hazardous Materials, Chemical and Fuels

This section of the report provides information in relation to the inventory of hazardous materials, chemical and fuels at the proposed development. This data is based on the Preliminary Risk Screening and Hazard Assessment conducted by SLR, and can be found in Appendix J of the EIS (SLR, 2018).

4.1.1 Storage of Substances

Figure 7 provides a summary of the developments inventory of hazardous materials, chemicals and fuels, extracted from the abovementioned study.

Substance	Hazardous Class	UN No.	HAZCHEM Code	Total Storage at each PPU	Threshold Quantity	SEPP 33 Threshold Screening
LPG	Class 2.1	1075	2YE	Farm 1 – 38,250 L (38.25 m^3) Farm 2 – 57,375 L (57.38 m^3) Farm 3 – 38,250 L (38.25 m^3) Farm 4 – 51,000 L (51.00 m^3)	16 m^3 (above ground storage)	**Above**
Diesel	Class C1	3082	3Z	Each PPU - 4,000 L (2 x 2,000 L tanks)	100,000 L	Below
Petrol	Class 3 (PG II)	1203	3YE	Each PPU – 700 L (1 x 700 L tank) (0.52 tonnes)	4 tonnes	Below
Sodium Hypochlorite (10-30%) (bleach, disinfectant)	Class 8 (PG III)	1791	2X	Each PPU – 400 L (2 x 200 L drums)	25 tonnes (PG II)	Below
Chlorine dioxide (water supply treatment)	Class 8 (PG II)	1789	2R	Each PPU – 240 L (8 x 30 L drums)		
Microgard 755N or Micro-4 (sanitiser)	Class 9	3082	-	Each PPPU – 25 L (1 x 25 L drum)	10,000 L or kg	Below
Goal (herbicide)	Class 9	3082	2X	Each PPU - 10 L (1 x 10 L drum)		
Agri-Quat (disinfectant, sanitiser)	N/A	-	-	Each PPU – 50 L (2 x 25 L drums)	N/A	N/A
Ditrac (rodenticide)	N/A	-	-	Each PPU - 20 kg (1 x 20 kg container)	N/A	N/A
Glister (herbicide)	N/A	1950	-	Each PPU – 20 kg (1 x 20 kg container)	N/A	N/A
Unicide (sanitiser)	N/A	-	-	Each PPU – 100 L (1 x 100 L drum)	N/A	N/A
Unicide d (sanitizer)	N/A	-	-	Each PPU - 100 L (1 x 100 L drum)	N/A	N/A
Roundup (Glyphosate, herbicide)	N/A	-	-	Each PPU - 25 L (1 x 25 L drum)	N/A	N/A

- Denotes normal fire extinguishing procedures and equipment are appropriate and chemical will not react with the firefighting material.
* Each PPU is located a minimum of 870 m apart therefore the storage for each PPU has been considered on their own and not as one facility.

Figure 7: Inventory of hazardous materials, chemical and fuels (SLR, 2018)

It is noted that chemicals without a hazard classification are not considered hazardous and therefore did not form part of the assessment study.

4.1.2 Dangerous Goods Transport

The dangerous goods transported to the proposed development (maximum per week) is summarised in Figure 8.

ADG Class	Materials	Maximum DGs Vehicle Movements (per week)	Load Type (relevant to the facility)	SEPP 33 Threshold Vehicle Movements (per week)	SEPP 33 Threshold Minimum Quantity (per load)	SEPP 33 Threshold Level Findings
2.1	LPG	1-2	Bulk	>30	2 tonnes	**Above** (in regards to quantity per load only)
3	Petrol	<1	Bulk	>45	3 tonnes	Below
C1	Diesel	< 1	Bulk	N/A	N/A	Below
8	Sodium hypochorite & chlorine dioxide	<1	Packages	>30	5 tonnes	Below

Note: Assumes each dangerous good class is transported separately. Note that LPG is only used at each PPU for a period of up to 21 days during each production cycle. Outside this time LPG will not be used at that PPU.

Figure 8: Dangerous Goods Vehicle Movements (SLR, 2018)

It is noted that the while the number of vehicle movements for the delivery of LPG are well below the SLR screening threshold study, the quantity of LPG delivered per load will likely exceed the screening threshold of 2 tonnes and may be considered potentially hazardous with respect to the transport of LPG.

The vehicle movements for transport of other DG's are well below the respective screening thresholds.

4.2 Identification of fire hazards

The fire safety study is primarily focused on chemicals that pose a fire hazard, propagate a fire or impact fire brigade intervention activities. Therefore, chemicals which do not hold a hazard class are not considered hazardous and do not form the scope of this study.

4.2.1 Storage of Substances

The following substances are only stored in minor quantities, well below thresholds of the SLR screening study and therefore are not considered to present a hazard risk:

- Diesel;
- Petrol;
- Sodium hypochlorite;
- Chlorine dioxide;
- Microgard; and
- Goal

The above substances will be located in dedicated storage areas in appropriately secured, sealed and bunded facilities at each PPU. LPG, diesel and petrol will be stored separately and away from other materials as well as each other. As a result, these substances were not further considered in the Risk Screening study by SLR.

Applying SEPP 33, clearly states *"If combustible liquids of class C1 are present on site and are stored in a separate bund or within a storage area where there are no flammable materials stored they are not considered to be potentially hazardous*." Diesel, which is a Class C1 material, will be stored within bunded areas with a minimum bund volume of 110% of the volume stored and there will be no flammable materials stored in the vicinity.

The total quantities of LPG to be stored at each PPU are above the 16 m^3 (~16,000L water capacity) screening threshold set in Applying SEPP 33 and above the Safe Work Australia manifest quantity of 5,000 L. As a result, the Development may be considered potentially hazardous with respect to the quantity of LPG to be stored at each PPU. LPG therefore has been considered in detail as part of the study.

4.2.2 Dangerous Goods Transport

With reference to Figure 8 where the movement of DG vehicles are summarised, it is noted that whilst the number of vehicle movements for delivery of LPG is well below the screening threshold, the quantity of LPG delivered per load will likely be greater than the screening threshold of 2 tonnes.

The Preliminary Hazard Analysis by SLR acknowledges that whilst the quantity of LPG transported per load to the site will likely exceed the SEPP 33 threshold of 2 tonnes, the number of deliveries will be one to two per week and deliveries are undertaken in a sparsely populated area by rigid vehicles which will limit the capacity of LPG transported. The PHA concludes that on this basis, further consequence analysis for transport risks were not considered necessary.

4.2.3 Hazard Incident Identification

Detailed assessment of potential hazards which could not be eliminated through the SLR Preliminary Risk Screening review is covered in this section of the report. The following substances are treated as a potential hazard after considering the surrounding land uses and potential receptors that may be affected in a hazard event:

- LPG Fire

In addition to an LPG Fire, the hazards associated with a fire occurring at the poultry shed is considered. This is due to a significant amount of PIR panels being installed onto each building and the proximity to the LPG tanks.

Potential Hazardous Incidents identified through the SLR PHA study and the poultry shed fire scenarios are summarised in Table 6. The same table presents controls required to reduce risks to an acceptable level.

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Table 6: Potential Hazardous Incidents

Event	Cause	Potential Consequences	Prevention/Protection Requirements to Reduce Risks to Acceptable Level
Rupture of gas line	Failure of pipe or connection	Leak/release of LPG to atmosphere resulting in ignition	Installations must comply with AS/NZS 1596:2014, specifically Sections 3, 5, 6, 8, 11, 12 & 13. The following sections/clauses are highlighted from AS/NZS 1596:2014, given their relevance to the specific event, noting all relevant sections/clauses must be complied with: • The outflow of gas must be controlled in accordance with Section 5 AS/NZS 1596:2014 • Appropriate compliant safety shut down and isolation valves will be installed (Sections 5.3 and 6.7 AS/NZS 1596:2014). • Ensure that all inspections, testing and maintenance is in accordance with Section 11.5 AS/NZS 1596:2014. • Separation distances are to be maintained as identified in AS/NZS 1596:2014, more specifically separation distances between LPG tanks and any protected place, including poultry sheds, to be at least 26.5 m • Appropriate hazard area classification is accordance with AS 60079.10.1 (Zone 2 hazard area within the space from ground level to 1m vertically above the tank and laterally to a distance of 6m for an 8kL tank (Table ZA.6.5.2.1 AS 60079.10.1:2009)). All electrical equipment used as part of the installation will comply with AS3000. • Fire safety systems will be installed and/or available in accordance with Section 13 AS/NZS 1596:2014 Ensure appropriate staff are trained in how to use firefighting equipment. Appropriate fire drills are conducted to ensure the emergency plan works.

Event	Cause	Potential Consequences	Prevention/Protection Requirements to Reduce Risks to Acceptable Level
Leak during tank filling	Rupture of filling pipe, overfilling tanks, over pressure of lines.	Leak of LPG to atmosphere resulting in ignition	Installations must comply with AS/NZS 1596:2014, specifically Sections 3, 5, 6, 8, 11, 12 & 13. The following sections/clauses are highlighted from AS/NZS 1596:2014, given their relevance to the specific event, noting all relevant sections/clauses must be complied with: • Tank filling requirement must comply with Section 6.6 AS/NZS 1596:2014 • Appropriate compliant safety shut down and isolation valves will be installed (Sections 5.3 and 6.7 AS/NZS 1596:2014). If direct connection filling hose and coupling must be of the type which prevents the escape of more than 0.1L if liquid during disconnection • Fire-sensing elements of the emergency shutdown system shall be located so as to sense and respond to a fire at the filling or loading connection in accordance with Clause 6.7.2 of AS/NZS 1596:2014. • Ensure that all inspections, testing and maintenance is in accordance with Section 11.5 of AS/NZS 1596:2014. • Separation distances are to be maintained as identified in AS/NZS 1596:2014, more specifically separation distances between LPG tanks and any protected place, including poultry sheds, to be at least 26.5 m • Appropriate hazard area classification is accordance with AS 60079.10.1 (Zone 2 hazard area within the space from ground level to 1m vertically above the tank and laterally to a distance of 6m for an 8kL tank (Table ZA.6.5.2.1 AS 60079.10.1:2009)). All electrical equipment used as part of the installation will comply with AS3000.

Event	Cause	Potential Consequences	Prevention/Protection Requirements to Reduce Risks to Acceptable Level
			• Fire safety systems will be installed and/or available in accordance with Section 13 of AS/NZS 1596:2014. Ensure appropriate staff are trained in how to use firefighting equipment. Appropriate fire drills are conducted to ensure the emergency plan works.
Tank failure	Overpressure of tank, due to adjacent fire Tank failure due to corrosion	Leak of LPG to atmosphere resulting in ignition	Installations must comply with AS/NZS 1596:2014, specifically Sections 3, 5, 6, 8, 11, 12 & 13. The following sections/clauses are highlighted from AS/NZS 1596:2014, given their relevance to the specific event, noting all relevant sections/clauses must be complied with: • The tank must be made of steel and comply with the requirements AS 1200 in accordance with Section 5.2.1 of AS/NZS 1596:2014. • Ensure that all inspections, testing and maintenance is in accordance with Section 11.5 of AS/NZS 1596:2014. • Separation distances are to be maintained as identified in AS/NZS 1596:2014, more specifically the separation distance between LPG tank and poultry sheds are proposed to be 26.5 m apart. • Automatic fill shutoff when tank has reached capacity in accordance with Section 6.6 of AS/NZS 1596:2014. • Appropriate hazard area classification is accordance with AS 60079.10.1 (Zone 2 hazard area within the space from ground level to 1m vertically above the tank and laterally to a distance of 6m for an 8kL tank (Table ZA.6.5.2.1 AS 60079.10.1:2009)

Event	Cause	Potential Consequences	Prevention/Protection Requirements to Reduce Risks to Acceptable Level
			• Fire safety systems will be installed and/or available in accordance with Section 13 of AS/NZS 1596:2014. Ensure appropriate staff are trained in how to use firefighting equipment. Appropriate fire drills are conducted to ensure the emergency plan works.
Poultry shed fire (Scenario 1 – Section 5.3.1)	Fire event arising from tunnel fan malfunction, causing a nearby combustible load to be ignited and spreading to PIR panels.	The building dimensions are relatively large in that a building wide flashover event is not expected to occur after an extended duration. Therefore, the fire is assumed to spread to consume ¼ of the buildings PIR panels running parallel to neighbouring poultry sheds. Potential spread of fire to adjacent poultry sheds or LPG storage tanks to be examined.	A fire hydrant system in accordance with AS 2419.1 and/or any approved performance solution shall be provided to service the poultry sheds. Water storage tanks with suitable firefighting water capacity to be provided to serve the pseudo ring main at each poultry shed cluster. Water storage tanks shall be maintained at near capacity at all times and fitted with low level alarms to sound when tanks reach a capacity of two thirds full. Tanks shall automatically be filled from pressurised lines. LPG tank storage shall comply with separation distances as identified in AS/NZS 1596:2014, more specifically the separation distance between LPG tank and poultry sheds are proposed to be a minimum of 26.5 m apart. Ensure appropriate staff are trained in how to use firefighting equipment. Appropriate fire drills are conducted to ensure the emergency plan works. Fire extinguishers shall be provided in accordance with BCA Clase H3.11.

5. Consequence of Incidents

The consequence of the incidents detailed in Table 6 are further assessed in this section of the report.

5.1 Preliminary Hazard Analysis

The potential consequences of incident scenarios assessed in the SLR Preliminary Hazards Analysis are summarised below;

- The operation of the Development will meet the criteria laid down in HIPAP 4 and would be unlikely to cause any risk, significant or minor, to the community.

  Note that this fire safety study further elaborates on various fire scenarios at the development, highlighting the expected impacts.

- There is a requirement to ensure that LPG is stored and used correctly on site, and with compliance with *AS/NZS 1596:2014 The storage and Handling of LP Gas* there is considered to be a low risk to the site users.

- Other spill, fire and incident events are not likely to extend beyond the boundary of the Development Site, with the exception of a major facility fire where, regardless of the type of operation, there will always be a risk of potentially harmful smoke plumes downwind. In the majority of large fires the buoyant nature of a smoke plume means any potentially harmful materials are rapidly dispersed. Any firefighting water can be managed on site without release into the wider environment.

- It is considered that the operations of the Development with the safeguards stipulated would not cause significant off site risks. Whilst the Development is considered to be a hazardous development given the quantity of LPG stored at each PPU, this is easily managed with compliant construction and availability of incident management strategies.

  The surrounding area is lightly populated with the closest residence approximately 1,025 m from the nearest PPU and the nearest population centre, Somerton, approximately 12 km from the nearest PPU.

- The PHA concludes that the Development is expected to meet all the requirements stipulated by the DPIE and hence would not be considered, with suitable engineering and design controls in place, to be an offensive or hazardous development on site or would not be impacted by any other hazardous incidents from adjoining facilities offsite. This Fire Safety Study shall further detail other potential fire hazards in relation to the development.

The PHA has concluded that the risk associated with the use of LPG tanks on the development, when stored and used correctly and with compliance with AS/NZS 1596:2014, there is only a low risk to the site users. Further to this, the fire safety study shall assess the relationship between LPG tanks and poultry sheds given the proposed separation distance when considering worst case fire scenarios at the latter.

The study shall further identify whether the proposed separation distance between LPG tanks and poultry sheds are sufficient such that a fire at the latter should unlikely result in a cascading fire event at the LPG tank. A detailed assessment, including calculations, will be presented in the following sub-sections for the respective hazards identified.

5.2 Fire exposure protection of LPG Tanks

It is understood that each LPG storage location contains a total capacity ranging from 38,250 L to 57,375 L. The assessment shall consider the maximum total capacity of 57,375 L located at farm 2 (Refer Figure 7). The total capacity at any storage location is distributed across several tanks. Tank installations are to comply with requirements of AS/NZS 1596:2014 under Clause 6.2.2:

> *Tanks may be arranged in groups of up to six tanks, with each tank in the group separated in accordance with Table 6.1, Column 2. The following requirements and recommendations apply to tanks in groups:*
>
> *(a) The distance from one such group to another tank or group shall be not less than 15 m except that, where no tank in either group exceeds 2 m diameter, the distance may be reduced to 10 m.*
>
> *(b) Tanks shall not be stacked above one another.*
>
> *(c) The longitudinal axes of thanks in a group should be parallel and should be directed away from any adjacent storages of hazardous, flammable or combustible liquids or gases. Where another arrangement is unavoidable, whereby a tank could be in line with the axis of another tank, the distance between the end of any tank and the end or shell of another tank shall not be less than 3 m or twice the diameter of the larger tank, whichever is greater.*

Furthermore, as indicated in Figure 6, Table 6.1 of AS/NZS 1596:2014, it is required that a minimum distance between adjacent LPG tanks to be the diameter of the largest tank irrespective of tank capacity.

TABLE 6.1

LOCATION OF ABOVE-GROUND STORAGE TANKS

1	2	3	4
Capacity of the tank kL	**Minimum distance to an adjacent LP Gas tank** m	**Minimum distance from the tank to a public place, or a railway line** m	**Minimum distance from the tank to a protected place** m
≥0.5	Diameter of the largest tank	1.5	1.5
1		2	3
2		4 (3)	6 (4.5)
5		5 (3.5)	8 (5)
8		6 (4)	10 (6)
10		7	11
15		8	14
20		9	15
50		10	17
100		11	20
200		12	25
500		22	45

Figure 9: Excerpt from AS/NZS 1596:2014

A fire exposure assessment in accordance with Appendix M of AS/NZS 1596:2014 has also been undertaken to determine the potential effect of a fire in the poultry shed (nearest structure) and its impacts on the LPG storage facility. The assessment determines whether the LPG storage facilities require protection from such fire event.

Parameters utilised in the assessment and the resultant distance ‘D’ (minimum separation distance required) is summarised in Table 7. The typical layout of LPG tank to poultry sheds is shown in Figure 10.

Table 7: Input parameters and calculation results

Parameter	Comments/Results
Required distance between LPG tank and protected place (as required by Table 6.1) *Note that the max total capacity of LPG stored is at Farm 2, 57,375 L.*	17.45 m *Interpolated from data points in Table 6.1*
Distance at which fire source can be ignored	3 x 17.45 = 52.35 m
Actual distance between protected place and LPG tanks	26.5 m (same for all 4 farms)
Assessment Required	Actual Separation Distance < Distance permitted to be ignored; 26.5 m < 52.35 m Yes, further assessment required (per below)
Dimensions of poultry shed *B equals the width of one poultry shed since, shed to shed fire spread is not expected given the 15 m separation. Therefore, worst case is one shed involved in a fire.*	B = 18.0 m H = 4.7 m (to the ridge of the roof)
Net fire area	B x H = 18.0 m x 4.7 m = 84.6 m^2
Distance	$D = 2.2 \times \sqrt{A} = 2.2 \times \sqrt{84.6} = 20.24$ m

TABLE 6.1

LOCATION OF ABOVE-GROUND STORAGE TANKS

1	2	3	4
Capacity of the tank	**Minimum distance to an adjacent LP Gas tank**	**Minimum distance from the tank to a public place, or a railway line**	**Minimum distance from the tank to a protected place**
kL	**m**	**m**	**m**
≥0.5	Diameter of the largest tank	1.5	1.5
1		2	3
2		4 (3)	6 (4.5)
5		5 (3.5)	8 (5)
8		6 (4)	10 (6)
10		7	11
15		8	14
20		9	15
50		10	17
100		11	20
200		12	25
500		22	45

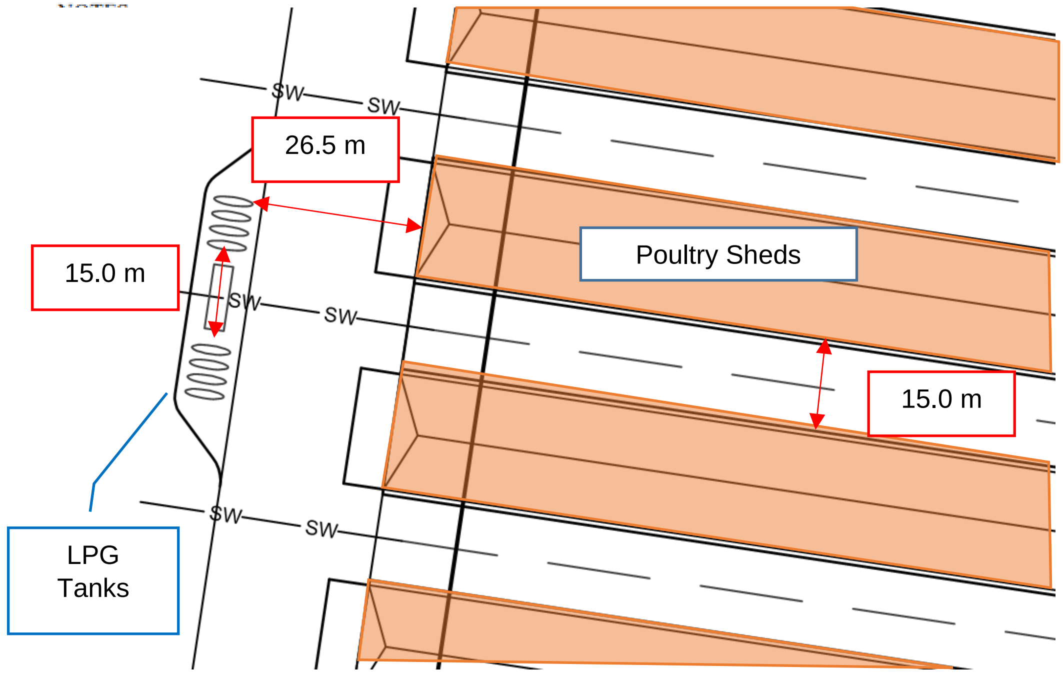


Figure 10: Typical Layout of LPG tanks to poultry sheds

Appendix M of AS/NZS 1596:2014 notes that where distance 'D' is greater than the actual separation distance, additional protection is required to be provided to the LPG tanks to ensure that the tank shell does not exceed 300 °C after 45 minutes of exposure to heat radiation. The temperature of the tank shell will not exceed such temperature if the heat radiation received at the shell's surface does not exceed 10 kW/m^2 as noted in the standard. This estimate is based on a worst case, ie. the tank being effectively empty of LPG liquid and the tanks surface having deteriorated to the point where it cannot reflect heat.

Calculations from Table 7 indicate that the minimum distance D is less than distance of separation (20.24m < 26.5 m), therefore no additional protection is required to the LPG storage tanks.

It is noted that the calculation above assumes that the adjacent building fire will be at 1000°C so the emission from the structure will be 150 kW/m^2. Whilst this is conservative, it does not account for high hazard scenarios whereby a fire at the adjacent building may exceed such assumptions.

As the nearest structure, the poultry shed is clad with PIR, a combustible product, a detailed study of fire scenarios at the poultry shed is considered to validate the findings of the above calculations.

The following section of the report shall assess the extreme fire scenarios that may impact the LPG tanks.

5.3 Poultry Shed Fires

5.3.1 Fire scenario

The fire scenario identified in Table 6 for the poultry shed is further assessed in this section.

The radiant heat levels exhibited in a poultry shed fire will be assessed to determine the likelihood of secondary structures being involved. This study will provide further clarity as to whether the separation distances between structures, particularly LPG storage tanks is sufficient when calculated in accordance with Appendix M of AS/NZS 1596:2014 detailed in Section 5.2.

The poultry sheds are cladded with PIR throughout the building, including the wall directly facing the LPG gas tanks. As with most insulating materials, there are different types of PIR foam, each with differing characteristics and therefore fire behaviour.

As the specific product specifications have not been stipulated for the design at this point, reliance on studies of PIR panels are required to determine their general behaviour in a fire.

While the fire properties may vary, experiments conducted by (Juan P.Hiadlgo, 2017) on the fire performance of PIR found that the results of three PIR specimens sought from various manufacturers yielded very similar results when exposed to radiant heat. Therefore, while the exact product is unknown at this point in time, reliance on results from the experiment is considered acceptable as the fire behaviour of the PIR was demonstrated to behave relatively similar. It was identified that the critical temperature for the onset of pyrolsis of rigid PIR was between 300°C to 370°C.

During the study, when the specimen (100 mm thick) was exposed to a constant irradiance level of 65 kW/m^2, the HRRPUA of the panel (without protective layer at surface) peaked at 160 kW/m^2. This occurred within the first few minutes of exposure (during the flaming combustion stage) as shown in Figure 10, after which it decayed below 60 kW/m^2 represented by the formation of a char layer and transition of the pyrolysis front towards the inner depths.

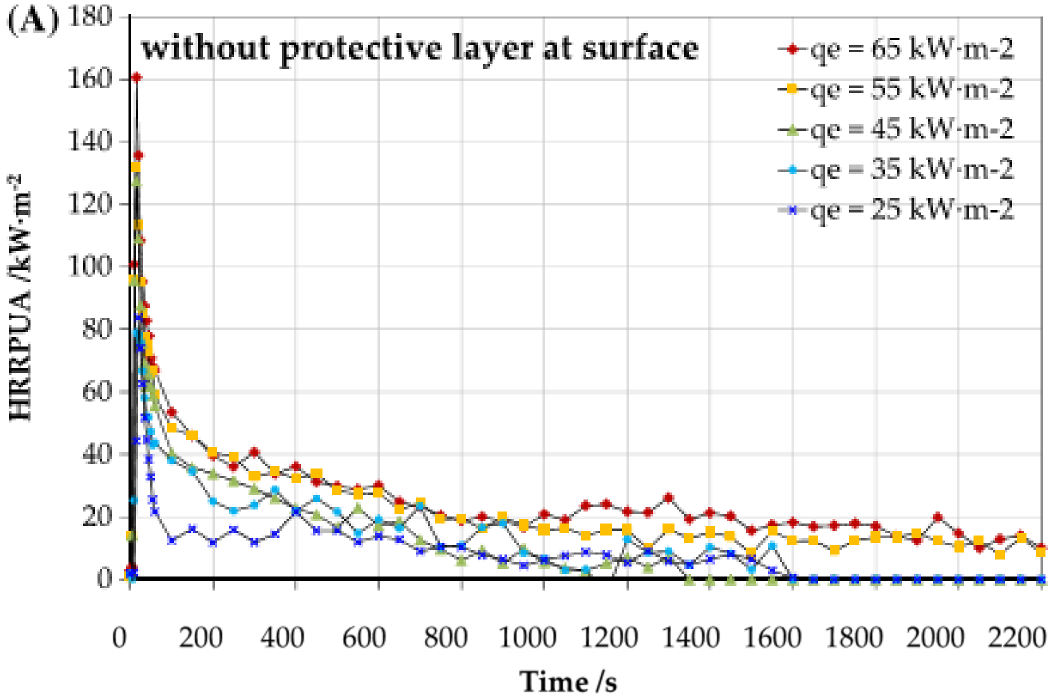


Figure 11: Heat release rate per unit area of 100-mm-thick PIR (Juan P.Hiadlgo, 2017)

It is further noted that under irradiance exposure levels above 55 kW/m^2, the PIR was consumed by the end of the experiment. Under lower levels of exposure, this was not the case. Refer Figure 12 illustrating normalised mass of PIR over time (Juan P.Hiadlgo, 2017).

Details of the study can be found in Appendix B.

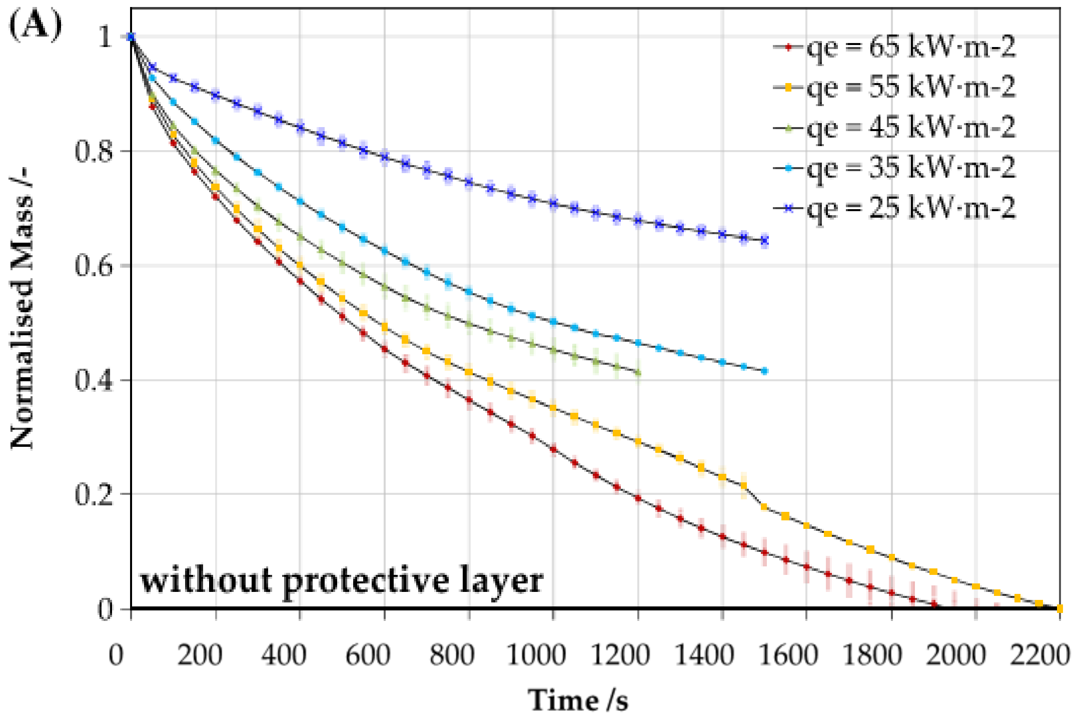


Figure 12: Normalised mass of PIR over time (Juan P.Hiadlgo, 2017)

The risk of ignition and a fully involved fire at the development is relatively low as a result of the operational nature of the facility, local response and material used. However for sensitivity, the following fire scenario at the poultry shed is assessed.

Details for the fire scenarios are summarised in Table 8.

Table 8: Fire Scenarios

Fire Scenario	Comments
Fire event arising from tunnel fan malfunction, causing a nearby combustible load to be ignited and spreading to PIR panels at the closest face to the LPG tanks. The building dimensions are relatively large in that a building wide flashover event is not expected to occur after an extended duration. Therefore, the fire is assumed to spread to consume ¼ of the buildings PIR panels running parallel to neighbouring poultry sheds. Refer Figure 13.	A malfunction in the fan unit results in fire whereby a combustible load located against the internal face of the building is ignited, resulting in the PIR panels being involved. It is assumed that the entire internal and external face of the wall closest to the LPG tank is involved in the fire as a result of openings in the fan units. The entire surface area of the wall will be radiating heat towards the LPG tanks. Area = 18 x 2.2 = 39.6 m^2 W = 18 m, H = 2.2 (wall from topside of dwarf bund to the eaves). It is assumed that the panels involved have an irradiance level of 160 kW/m^2 and is constant for the duration. This is conservative considering the study indicates such levels of radiant heat is only exhibited during the flaming phase and is reduced as char begins to form. Furthermore, the study was conducted on exposed PIR panels without a protective covering which is not the case for the subject buildings. The panels are understood to be encapsulated in aluminium channels. However, the higher level of irradiance may account for other potential combustible loads within the vicinity of the panels. The wall running parallel to the neighbouring poultry sheds are also assumed to be involved in the fire. However due to the large footprint of the building, a building wide flashover is not expected to occur until after a significant time has lapsed. It is assumed that a quarter of the buildings PIR along the wall running parallel to the neighbouring poultry shed (160.0 m / 4 = 40.0 m) is involved based on the location of fire origin.

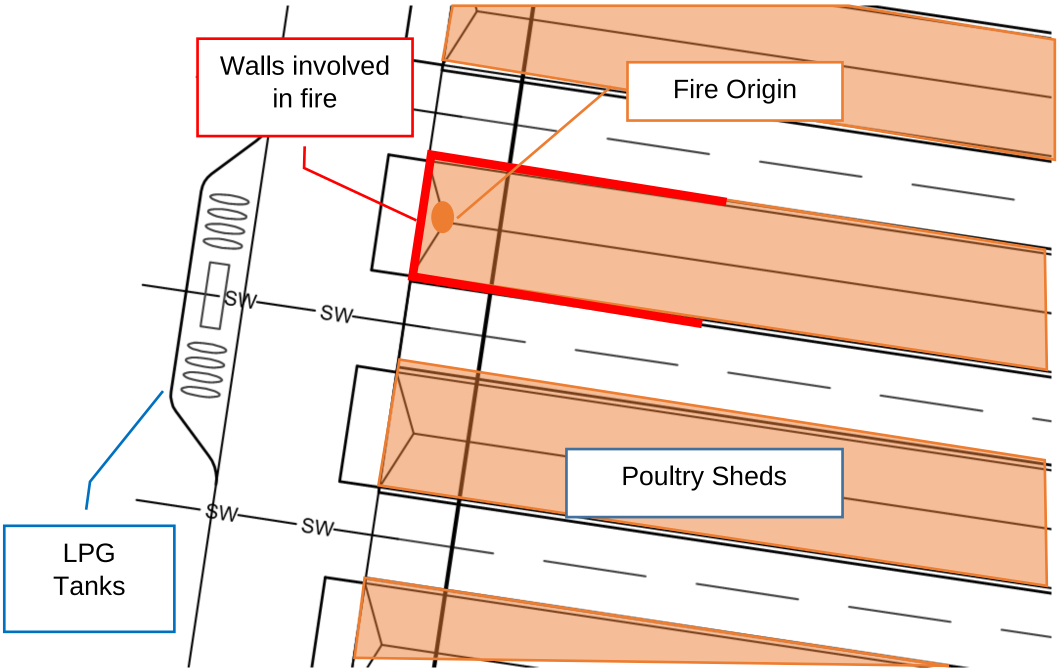


Figure 13: Typical Layout of LPG tanks to poultry sheds

The radiant heat flux received at nearby structures are summarised in Table 9.

Calculations and assumptions are available in Appendix A.

Table 9: Radiant heat flux received from fire scenario 1

Surrounding Infrastructure	Heat radiating surface dimensions	Radiant Heat Flux Received
Poultry shed located 15 m away	Poultry Shed (Side Wall) 40.0 m x 2.2 m (Parallel to adjacent shed)	10.6 kW/m^2
LPG storage tanks located 26.5 m away	Poultry Shed (End Wall) 18.0 m x 2.2 m (Parallel to LPG Tanks) Poultry Shed (Side Wall) 40.0 m x 2.2 m (Perpendicular to LPG Tanks)	3.4 kW/m^2

Table A3 of AS 1530.4-2014 provides typical radiant heat intensities for various phenomena and suggests that piloted ignition occurs at approximately 13 kW/m^2.

As the poultry shed located 15 m away received a radiant heat flux below this threshold, fire spread between the PPU's are not expected.

When determining an acceptable radiant heat flux received at the LPG tanks, reference to the assumptions made under AS/NZS 1596:2014 is applicable. As noted earlier, the standard stipulates that radiant heat flux received at the tank should not exceed 10 kW/m^2 for 45 minutes to maintain the temperature of the tank below 300 °C.

The radiant heat flux received at the LPG tank under the detailed fire scenario is 3.4 kW/m^2 and therefore below the threshold acceptable under AS/NZS 1596:2014. As both the calculation methods; for the fire scenario detailed above, and that in Appendix M of AS/NZS 1596:2014 are deemed acceptable, poultry sheds located 26.5 m from the LPG are acceptable and not expected to promote fire spread.

As the nearest structure, the poultry shed, is considered to exhibit radiant heat flux commensurate with that permitted in AS/NZS 1596:2014 (Refer Section 5.3 for detailed calculations), the LPG tanks are not considered to be exposed to high levels of radiant heat to trigger a secondary fire. As such further catastrophic events such as a Boiling Liquid Expanding Vapor Explosion (BLEVE) events are considered highly unlikely, especially when no other fuel or ignition sources are in the vicinity and fire protection measures provided (Refer Section 7 for fire protection measures).

5.4 Other potential site fires

Whilst an LPG fire is the considered a high risk, lower fire risk hazards that may be present on site. These are summarised in Table 10.

Table 10: Lower risk Fire Hazard Assessment

Event	Cause	Potential Consequences	Prevention/Protection Requirements to Reduce Risks to Acceptable Level
Arcing/ Sparks/ Explosion of High voltage transformers (including power poles)	High voltage transformer breakdown Adverse weather conditions	Arcing/Sparks/Explosion causing fire Network power grid offline Localised fires (could spread to become lager fires) Disruptions to site operations	Annual inspections (and maintenance where required) of transformers Maintenance of ground coverage, trees, shrubs, grass from power sources
Gas heater fire	Gas heater mounted on the walls of the shed malfunctions and initiates a fire	Localised fire involving PIR panels Localised fire could spread to outside area as it develops Loss of production/operation Damage to plant, equipment, buildings etc	Heaters are mounted away from the PIR wall by heater mounts, providing an air gap between the body of the heater and the wall. Penetrations of the PIR panel for the insulated air duct into the sheds are to be capped and protected accordingly.
Failure of High voltage electrical lines	High winds and external debris causing electrical supply lines to break	Electrical supply lines contact with ground (earthing) causing sparks and localised fires Network power grid offline Disruption of operations	Maintenance of ground coverage, trees, shrubs, grass from areas surrounding incoming power lines
Fires in chemical store	Mixing of incompatible materials Electrical ignition sources causing fire	Localised fires inside workshop Localised fires could spread to outside areas Damage to plant, equipment, buildings etc. Loss of production/ operation	Incompatible materials kept separate from each other. No decanting or mixing of chemicals inside the store No ignition sources in store with the exception of lighting. Provision of firefighting equipment and appropriate training for staff.

Event	Cause	Potential Consequences	Prevention/Protection Requirements to Reduce Risks to Acceptable Level
Small fires in workshop	Ignition of combustible/ flammable material arising from hot works (welding, grinding etc.) being undertaken	Localised fires inside workshop Localised fires could spread to outside areas Damage to plant, equipment, buildings etc. Loss of production/operation	Hot works to be undertaken under a permit to work system and properly risk assessed. Good housekeeping removing refuse and/or other combustible material for working areas. Provision of firefighting equipment and appropriate training for staff.
Bushfires/grass fires	Arson Lightning strike/adverse weather conditions Human error	Introduction of ignition sources within the hazard zones. Ignition of flammable and combustible material. Loss of infrastructure and livestock.	Maintain vegetation to a minimum on site. It is noted that tree/shrub plantings are around the perimeter of each PPU, however grass will be maintained and mowed. No combustible material within 3m of the diesel tanks (Section 2.2.5(d) AS1940) No Combustible materials within 6m of the LPG facility (Section 6.2.5(e) AS 1596) Appropriate firefighting equipment is available, operational and staff are trained to use it

6. Fire Prevention Strategies / Measures

Prevention of incidents is the primary key in achieving fire safety adequacy. Through appropriate design and layout of the facility, operating procedure and arrangements, fire incidents can be prevented.

This section of the report shall delve into identifying measures which may potentially minimise the likelihood of fires and/or reduce their severity or extent.

6.1 Management of LPG

The following requirements are expected to mitigate the risk of fire and fire spread to LPG storage tanks.

- LPG storage will be separated into four areas, one at each of the PPUs and these areas are a minimum of approximately 870 m apart.
- The location of the above-ground LPG storage tanks will comply with the following requirements for ventilation, access and set up:
  - Above-ground storage tanks will be in the open air, outside buildings;
  - Nearby buildings, fences and the like will be distanced from the tanks so as to permit free access around the tanks and cross-ventilation for the tanks;
  - The minimum distance to an adjacent LPG tank is equal to the diameter of the largest tank;
  - Groups of LPG tanks at one PPU will be separated by a minimum of 15 m, unless no tanks in either group exceeds 2m diameter, in which case the distance may be reduced to 10 m.
- LPG storage at each PPU will be within the storage and handling requirements of A*S 1596:2014 The Storage and Handling of LPG* for both public places and private places. The location of storage tanks will readily exceed the 10.15 m minimum distance to a public place and 17.45 m to a protected place (poultry shed in this case).
- LPG storage facilities will be designed by Elgas, a long-standing and reputable LPG supplier, and will confirm with AS 1596:2014.
- LPG will be delivered to the development site in specific purpose rigid tankers (ranging in size between 4 tonnes and 12 tonnes) at a frequency of just over 1 delivery each week on average.
- At least one hose reel complying with AS/NZS 1221 and installed in accordance with AS 2441 shall be provided.
- The water supply to the hose reel may be provided by any available on-site reticulated water supply system or from any form of storage system provided that the hose reel is able to deliver at least 0.33 L/s. Where the supply is from a storage system, the duration shall be at least 15 minutes.
- The number and location of hose reels shall be such as to ensure that a hose nozzle will reach every point in an area bounded by a line around and 5 m distance from any tank and tanker standing area.
- Maintenance shall be in accordance with AS 1851:2012.

The design controls to be implemented in accordance with AS.NZS 1596:2014 in conjunction with significant separation distances as determined from the fire scenario assessment (26.5 m between LPG tank and poultry sheds) and is not expected to result in a hazardous development on site and does not pose a significant off site risk..

6.2 Fire Management

In addition to the LPG management requirements detailed above, the following fire prevention strategies will be implemented as to further minimise the likelihood of a fire event and/or reduce a fires severity:

- The buildings will be designed in accordance with the requirements of the Building Code of Australia.
- Electrical installations will be installed and maintained compliant with relevant Australian Standards, including AS 3000:2007 - Electrical Wiring Rules.
- Fire extinguishers will be installed at designated locations compliant with relevant Australian Standards (refer Section 8).
- Fire hydrants will be provided to the poultry sheds in accordance with AS 2419.1, modified where acceptable under the Building Code of Australia for Farm Building Use/Performance Solution.
- Appropriate warning/identification signs will be installed for fuels and fire protection equipment.
- Certified diesel and LPG tanks will be installed.
- Diesel fuel tank bund design will include minimum capacities for the applicable storage size of the fuel tank(s).
- Dissimilar fuels shall be separated in accordance with AS 1940:2017
- Annual maintenance and testing will be undertaken.
- General housekeeping procedures will be regularly undertaken to ensure any trees/shrubs in the vicinity of electrical installations are adequately pruned or removed to maintained clearance and the areas around electrical installations are kept clear of any combustible materials.
- Site-specific training for employees and contractors in the use of fire extinguishing/protection equipment.

6.2.1 Emergency Plan

An Emergency Plan shall be prepared for the development in accordance with the requirements of the Hazardous Industry Planning Advisory Paper No. 1 – Emergency Planning Guideline (NSW, 2011) to a level of detail commensurate with the nature of the development, prior to occupation of the building.

7. Details of Detection and Protection

This section of the study shall consider the requirement for fire detection and protection at the proposed development, taking into consideration the identified risks detailed in Section 4, Consequences in Section 5, the fire prevention strategies/measures in Section 6 and BCA Requirements.

7.1 Background and BCA Requirements

The poultry sheds are considered as “farm buildings” under the BCA. The building is subject to a performance solution permitting the building to be a standard Class 8 farm building in lieu of a large isolated building. In relation to the provision of fire fighting equipment, BCA Clause E1.0 stipulates that;

(a) Where a Deemed to Satisfy Solution is proposed, Performance Requirements EP1.1 to EP 1.6 are satisfied by complying with –

(i) E1.1 to E1.10; and

(ii) …

(iii) …

(iv) …

(v) …

(vi) For farm buildings and farm sheds, Part H3.

As the subject buildings are considered as farm buildings, Part H3 supersede the requirements of E1.0 (Refer BCA Clause H3.8).

Under Part H3, the following clauses are required to achieved in relation to fire fighting equipment on farm buildings.

7.1.1 BCA Clause H3.9 – Fire hydrants and water supplies

In relation to fire hydrants and water supplies, BCA Clause H3.9 states the following;

<u>Note: The bold text is understood to be relevant to the subject design;</u>

(a) A farm building –

(i) with a total floor area greater than 500 m^2; and

(ii) located where a fire brigade station is –

(A) no more than 50 km from the building as measured along roads; and

(B) equipped with equipment capable of utilising a fire hydrant.

must be –

(iii) provided with a fire hydrant system installed in accordance with AS 2419.1, except reference to ‘4 hours’ water supply in clause 4.2 is replaced with ‘2 hours’, or

(iv) located on the same allotment as an access point to a water supply which –

(A) has a minimum total capacity of 144,000 litres; and

(B) is situated so as to enable emergency services vehicles access to within 4 m; and

(C) *is located within 60 m of the building and not more than 90 m from any part of the building.*

(b) *For the purpose of (a)(iv), water supply for a farm building must consist of one or any number of the following;*

(i) *A water storage tank*

(ii) *A dam*

(iii) *A reservoir*

(iv) *A river*

(v) *A lake*

(vi) *A bore*

(vii) *A sea*

(c) *If the whole or part of the water supply referred to in (a)(iv) is contained in a water storage tank, it must be –*

(i) *Located no less than 10 m from the building; and*

(ii) *Fitted with at least one small bore suction connection and one large bore suction connection where-*

(A) *Each suction connection is located in a position so as to enable emergency service vehicles access to within 4 m; and*

(B) *The suction connections are located not less than 10 m from the building and*

(C) *'small bore suction connection' and ' large core suction connection' have the meanings contained in AS 2419.1*

As each poultry shed occupies a total floor area of approximately 2,880 m^2, and is located less than 50 km from the nearest manned fire station (Manilla Fire Station), the requirements of H3.9 are to apply at the development.

It is understood that the building is subject to a performance solution to treat the poultry sheds as a BCA Class 8 farm buildings in lieu of a large-isolated building. As a result, it has been advised that the facilities will be provided with a hydrant system to H3.9 or AS 2419.1.

If a H3.9 compliant system is deemed not appropriate to the sites, it is understood that approval will be sought for an AS 2419.1 performance solution. The AS 2419.1 performance solution would address a modified ring main hydrant system providing 90 m hose coverage (in lieu of 60m), two hours of stored water (in lieu of 4 hours) and utilise the farms water distribution pump pack to charge the ring main (replacing the requirement for two stand by pumps).

7.1.2 BCA Clause H3.10 – Fire hose reels

BCA Clause H3.10 states that;

A fire hose reel system need not be provided to serve a farm building where portable fire extinguishers are installed in accordance with H3.11.

The development will not be provided with fire hose reels.

7.1.3 BCA Clause H3.11 – Portable fire extinguishers

The requirement for portable fire extinguishers are stipulated in BCA Clause H3.11 as follows:

- *A farm building not provided with a fire hose reel system in accordance with E1.4 must be provided with –*
  - *(i) One portable fire extinguisher rated at not less than 5 ABE in each room containing flammable materials or electrical equipment: and*
  - *(ii) One portable fire extinguisher rated not less than 4A60BE adjacent to every required exit door; and*
  - *(iii) Location signs complying with clause 3.3 to 3.9 of AS 2444 above each required portable fire extinguisher.*
- *A farm shed must be provided with not less than one portable fire extinguisher for ever 500 m^2 of floor area or part thereof, distributed as evenly as practicable throughout the building.*
- *A portable fire extinguisher required by (b) must be –*
  - *(i) Of ABE type; and*
  - *(ii) Not less than 4.5 kg in size; and*
  - *(iii) Installed in accordance with Section 3 of AS 2444.*

The poultry sheds will be provided with fire extinguishers in accordance with BCA Clause H3.11.

7.2 Protection and firefighting at poultry sheds

As noted above, the poultry sheds shall be protected in accordance with BCA DtS Provisions, namely;

- Provided fire fighters with a fire hydrant system in accordance with H3.9 or AS 2419.1, modified where acceptable under the Building Code of Australia for Farm Building Use/Performance Solution;
- Provided with fire extinguishers throughout the development in accordance with BCA Clause H3.11.

Note that provision of the above fire safety systems to the poultry shed inherently protects the neighbouring LPG Tanks as further discussed in Section 7.4.

7.3 Fire Detection Systems

Due to the nature of the developments operation, there is minimal staff located on site and therefore no formalised alarm system has been adopted. Should a fire be detected, other staff members are notified via a round robin phone call system and fire brigade is understood to be engaged by dialling 000.

There are no fire detection and/or alarm systems installed throughout the development.

As indicated in the SLR PHA study (SLR, 2018), the development is expected to meet all the requirements stipulated by the DPIE and hence would not be considered, with suitable engineering and design controls in place, to be an offensive or hazardous development on site or would not be impacted by any hazardous incidents from adjoining facilities on site.

7.4 Protection and firefighting LPG

7.4.1 Section 13 AS/NZS 1596:2014

Section 13 of AS/NZS 1596:2014 explains that the fighting of fire associated with LPG installations depend upon the nature of the surroundings and any associated structures, hazards and activities that may threaten the LPG facility, rather than solely on the quantity of LPG being stored.

The standard further notes that the requirements of firefighting is based on surroundings and less on the need of the LPG installation as a gas fire is most often terminated by stopping the gas flow, and almost never by extinguishing a fire. The actual LPG installation may not require a great deal of firefighting equipment if the engineering fire safety requirements of AS/NZS 1596:2014 are in place.

Where an above ground storage tank is located in a Class B site (as in the subject case) in relation to a protected place or public place (refer Section 13.5.1 of AS/NZS 2596-2014), the firefighting requirements for the whole of the site shall be determined from an evaluation of the needs and the available facilities of the particular site.

The following are principles detailed in Clause 13.5 of AS/NZS 1596:2014 which are relevant to the LPG tanks;

- *When an on-site hydrant system is specified, hydrants shall be provided in accordance with Clause 13.7.1 for the tank.*
- *For all other tank installations, at least a hose reel installation in accordance with Clause 13.7.2 shall be available for the tank.*
- *Where the capacity of an individual tank or group of tanks exceeds 50 kL, the installation shall be assessed for heat protection in accordance with Appendix M and treated in accordance with Clause 13.5.2*

The total capacity of LPG storage at Farms 2 and 4 exceeds the 50,000 L limit (57,375 L and 51,000 L respectively). A heat protection assessment has been carried out in accordance with Appendix M of AS/NZS 1596:2014 as well as calculations for a fire event at the nearby poultry shed as detailed is in Section 5.3.

According to the assessment in accordance with Appendix M, 20.24 m is required between the tanks and a protected place (poultry shed). The proposed distance between the LPG tanks and poultry shed is a minimum of 26.5 m, therefore no additional heat protection is required to the LPG. This separation distance is further supported through the assessment of extreme fire conditions in Section 5.3.1. The incident radiant heat flux calculated in the scenario was less than the 10 kW/m^2 stipulated in AS/NZS 1596:2014.

Any associated buildings and the like will need to have fire fighting equipment to comply with building regulations and should be counted as an important part of the overall protection of the site, including the LPG installation.

Therefore the firefighting requirements for the whole site shall be determined from an evaluation of the needs and the available facilities of the particular site, conducted on the basis of the following principles:

- Fire hydrant system provided is commensurate with BCA Clause H 3.9 and relevant Australian Standards, modified where acceptable under the Building Code of Australia for Farm Building Use/Performance Solution.
- Hose reels shall comply with AS 1221 and installed in accordance with AS 2441.

- Fire extinguishers provided in accordance with BCA Clause H3.10 and relevant Australian Standards.

7.4.2 Fire Extinguishers

In accordance with AS/NZS 1596:2014, Section 13.7.5, where fire extinguishers used around LPG, it shall have a minimum rating of 2A 60B(E) and comply with AS/NZS 1841.1, 1841.5 and 1850.

8. Detailed Drawings of Fire Services Layout

The fire services layout is presented in Figure 14 through to Figure 17. The figures illustrate the location of fire hydrants and fire extinguishers at each farm.

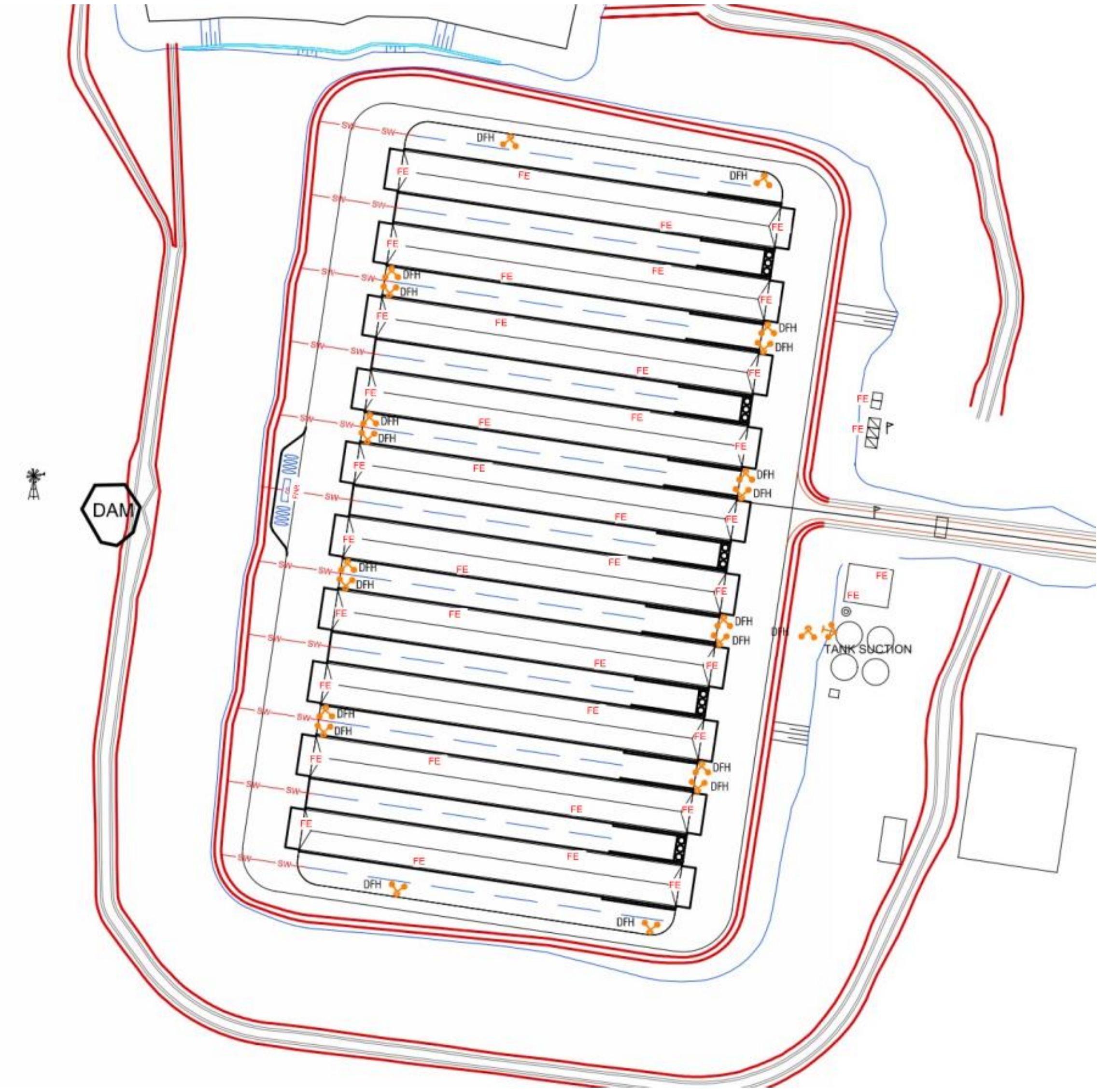


Figure 14: Farm 1 – Fire hydrant and fire extinguisher layout

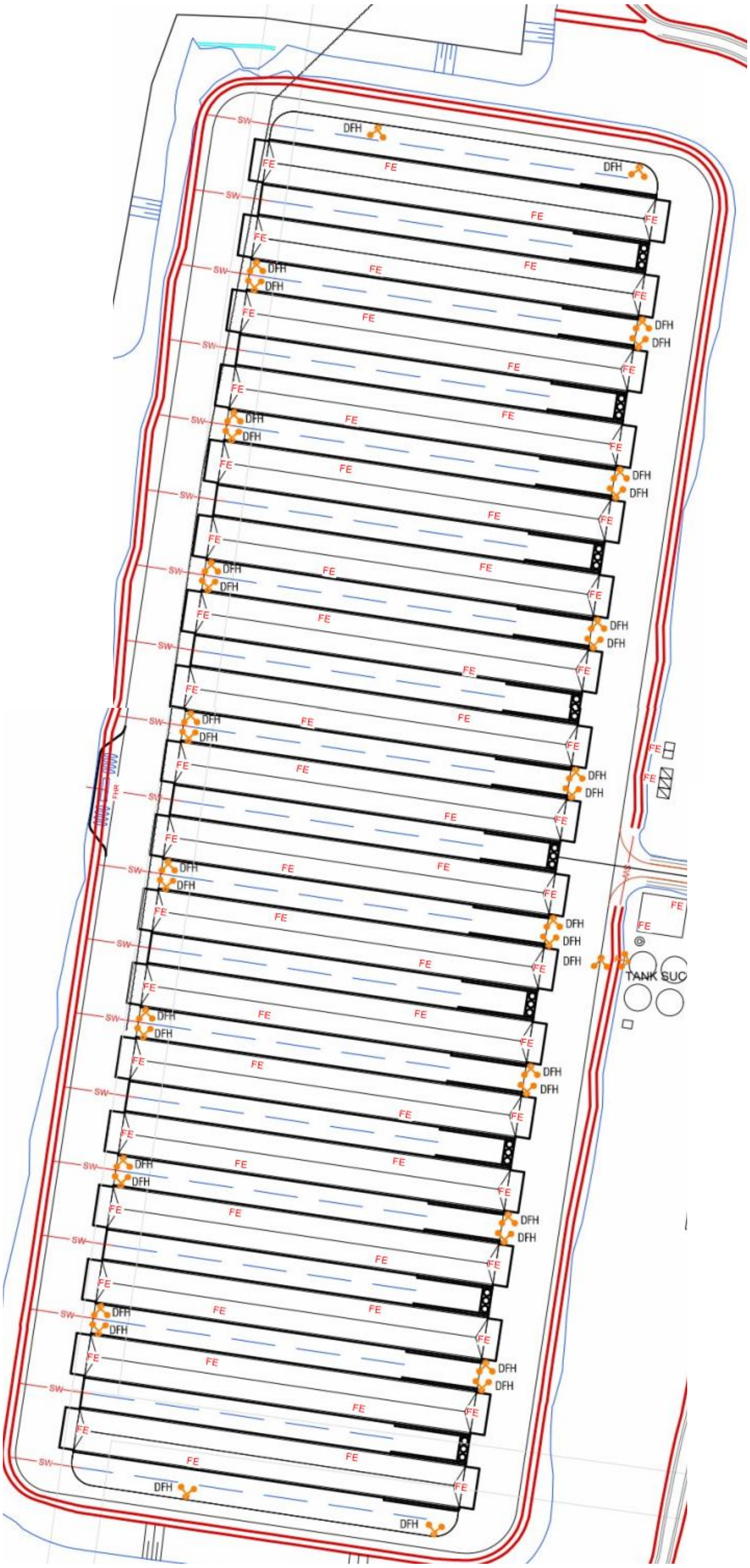


Figure 15: Farm 2 - Fire hydrant and fire extinguisher layout

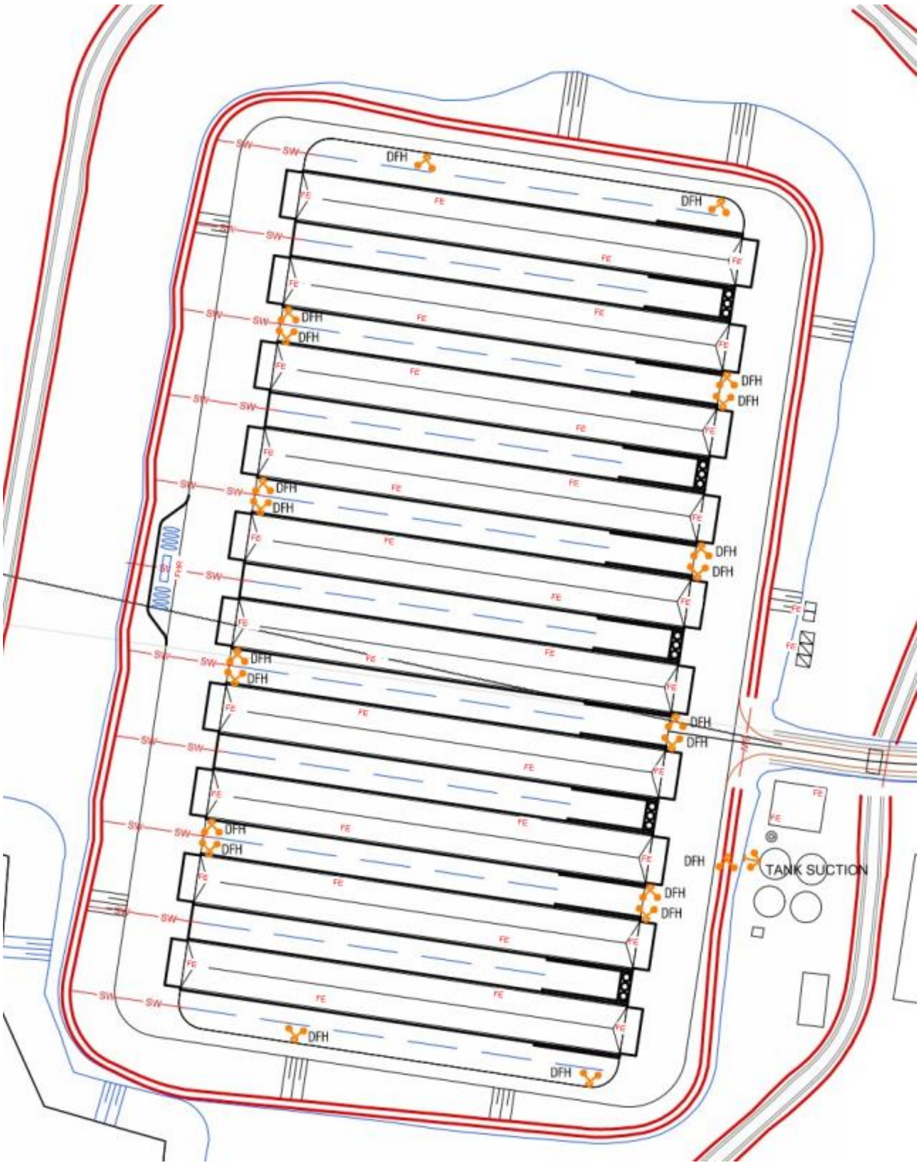


Figure 16: Farm 3 - Fire hydrant and fire extinguisher layout

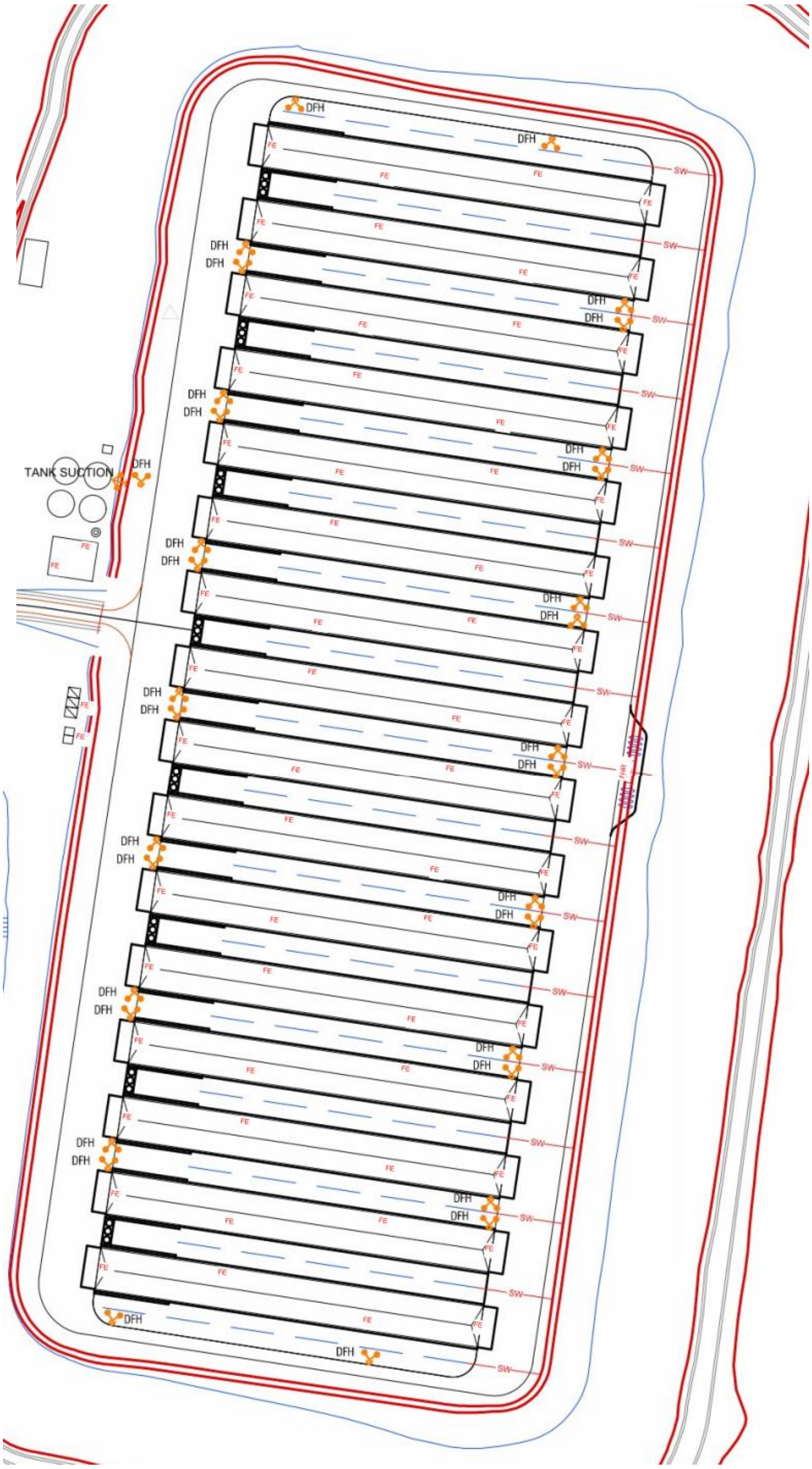


Figure 17: Farm 4 - Fire hydrant and fire extinguisher layout

9. Fire Fighting Water Demand and Supply

As detailed in Section 7, firefighting at the development will be through a H3.9 or AS 2419.1 system, modified where acceptable under the Building Code of Australia for Farm Building Use/Performance Solution. It is noted that the fire hydrants are served by a pseudo-ring main which utilises the farms water distribution pump pack to charge the pipes, replacing the requirement for two stand-by pumps.

With the exception of fire extinguishers, there are no use of form or other chemical suppressants for fighting.

9.1 Location and Coverage

The system provides 90 m hose coverage from each hydrant (in lieu of 60 m, subject to a separate performance solution). Refer to Figure 18 through to Figure 21 for hydrant locations throughout the four PPUs.

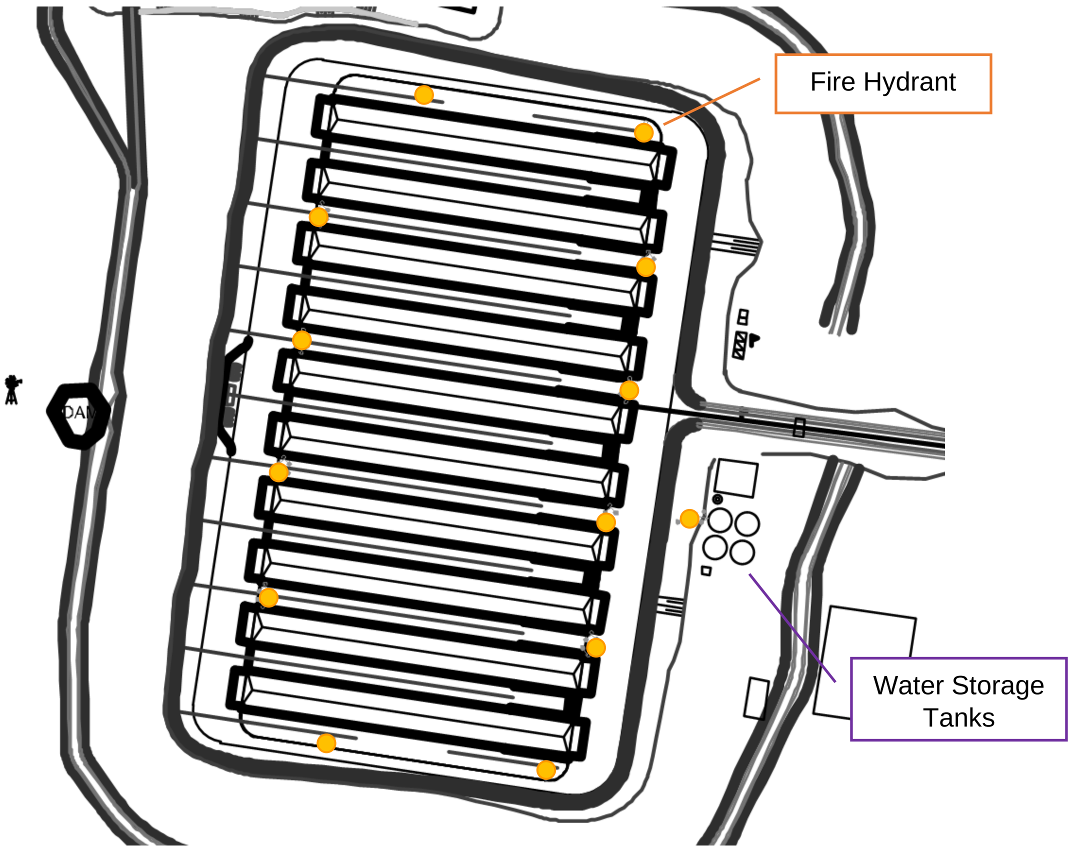


Figure 18: Hydrant Locations - Farm 1

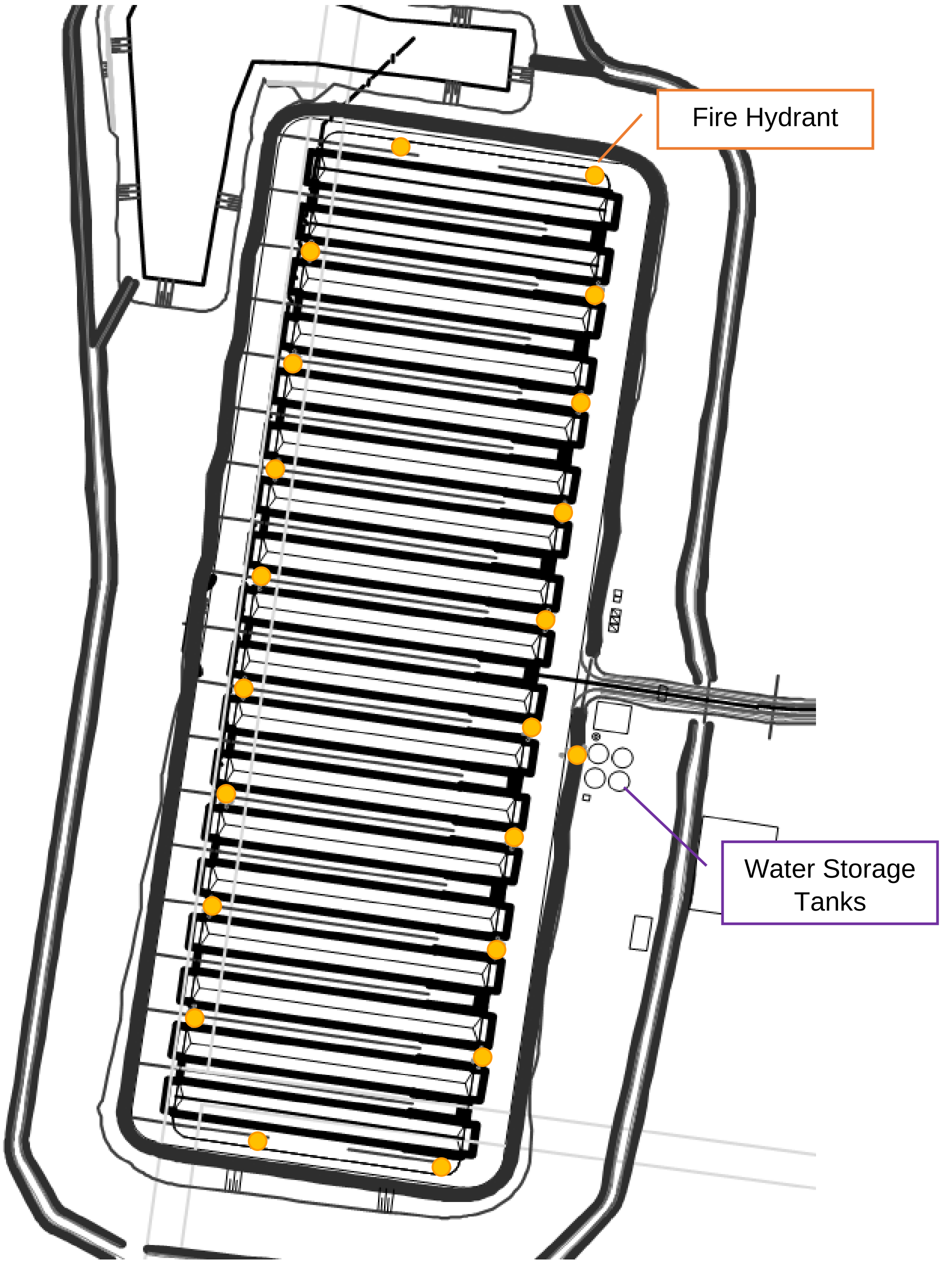


Figure 19: Hydrant Locations - Farm 2

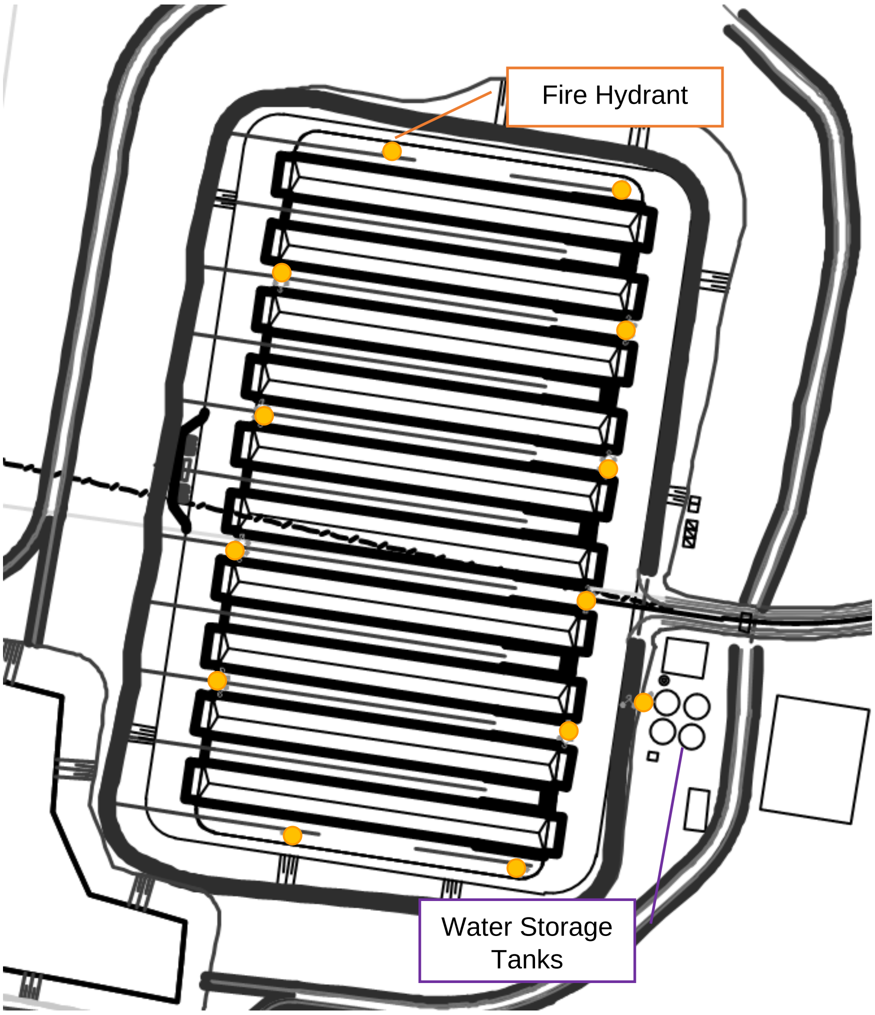


Figure 20: Hydrant Locations - Farm 3

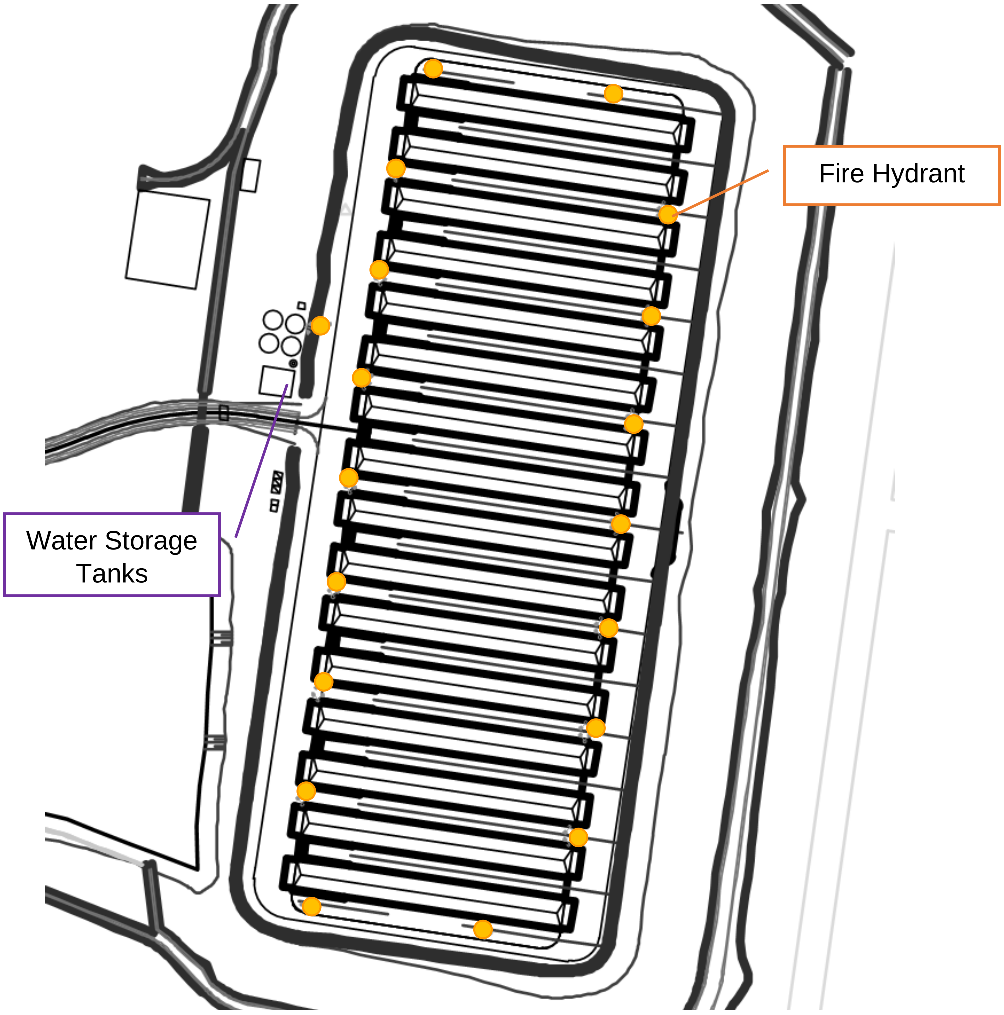


Figure 21: Hydrant Locations - Farm 4

9.2 Water demand calculations

In accordance with AS 2419.1-2005 Table 2.1, the number of hydrants required to flow simultaneously for a BCA Class 8 building that has a floor area between 500 m^2 and 5000 m^2 is two (2). The minimum flow rate for each hydrant is 10 L/s, therefore a demand for 20 L/s over two (2) hours, results in a requirement of 144,000 L of water to be stored.

The pressure provided to the hydrants shall be in accordance with the requirements of AS 2419.1.

9.3 Firefighting water supply

Each PPU will be provided with four zincalume water storage tanks, each tank with a storage capacity of 375 kL. The combined storage capacity at each PPU of 1,500 kL is noted to be sufficient to service the PPU shed ventilation systems and bird consumption for two days.

The tanks are automatically filled from pressurised lines to remain near capacity at all times and low level alarms will be fitted to tanks at approximately two thirds full capacity to alarm should water levels drop below this point.

The amount of water stored at each farm is therefore above the demand requirements of the hydrant system, and being automatically filled ensures that they are suitably available for fire brigade use in the event of a fire.

As each farm is provided with its own water tanks, the water supply at farm for the purpose of fire hydrant operation is independent of each other and therefore in the highly unlikely event of two fires occurring on separate farms, the demand for water at each farm is not impacted.

The location of the water tanks are approximately 200 m from the LPG Tanks such that a fire event occurring at the LPG is not expected to compromise the water supply.

10. Containment of Firefighting Water

As detailed in Section 9, the primary source of firefighting water is provided through the means of a fire hydrant system.

It is noted that an engineered surface water management system will be installed at each of the farms to mitigate the impact of surface water runoff from the development. The systems will be designed to capture the runoff from 200 mm of rainfall (SLR, 2018).

Each poultry shed will be surrounded by a 0.4 m, high dwarf concrete bund wall with strategically located seepage holes to convey excess water from the sheds into grassed swales located between each of the sheds.

Excess water is then able to be conveyed via underground pipes into a table drain located around the perimeter of the farm. Perimeter drains will then convey the water to a detention dam.

The detention dam provided at each PPU is designed to capture all runoff generated from within the farm site from approximately 200 mm of rainfall, which is equivalent to the depth of rainfall for a 1% annual exceedance probability, 72 hour event.

The detention dams at each farm are understood to have the storage capacities as summarised in Table 11 (EME Advisory, 2019).

Table 11: Design capacity of surface water management system

Farm	Approximate storage capacity in volume (m^3)	Approximate storage capacity in Litres (L)
1	33,600	33,600,000
2	50,875	50,875,000
3	36,168	36,168,000
4	50,255	50,255,000

Based on the design capacity of the engineered surface water management system, any firefighting water runoff (144,000 L based on hydrant operation for 2 hours) is expected to enter the controlled surface water management system and captured in the detention dam. The design capacity at each farm far exceeds the potential output from the hydrant system, indicating the system is capable of containing firefighting water, including during rain events. Treatment of water within detention dam is possible if required.

.

11. First Aid Fire Protection Arrangements and Equipment

11.1 Notification of Emergencies

In the event of a fire emergency, fire services shall be notified immediately via 000. Fire Rescue NSW, NSW Police and NSW Ambulance being the first responders are responsible for managing the emergency upon arriving on site.

11.2 Site Evacuation Procedure

The site evacuation procedure shall be developed for the site and shall be applied if a fire event requires the evacuation of the site.

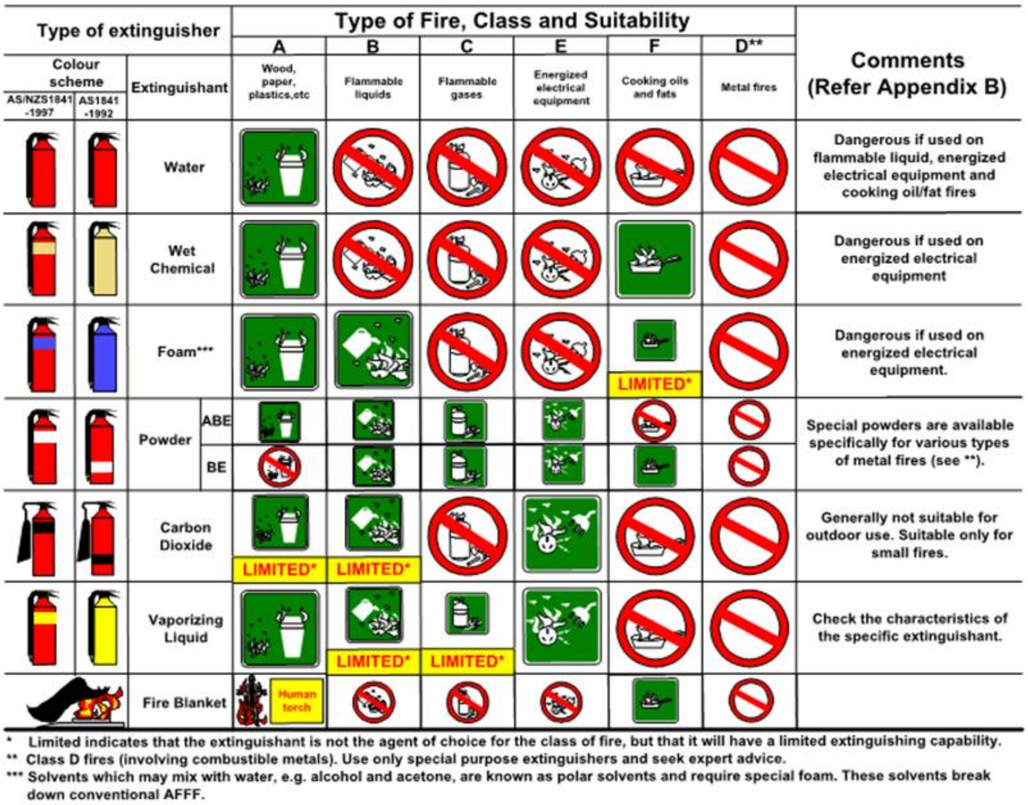
An Emergency Plan shall be prepared for the development in accordance with the requirements of the Hazardous Industry Planning Advisory Paper No. 1 – Emergency Planning Guideline (NSW, 2011) to a level of detail commensurate with the nature of the development

11.3 Emergency Equipment

In addition to the fire protection system detailed throughout the study, the provision of fire aid fire protection equipment is considered. The development shall be provided with equipment summarised in Table 12.

Table 12: Safety Equipment

Item	Location(s)	Maintenance Requirements
Fire extinguishers	As locations as stipulated in AS 2444:2001	As stipulated in AS 1851.1-1995
SDSs	PPU site office and at chemical storage locations	Checked for currency every 12 months
First Aid Kits	PPU site office and as necessary	Checked for currency every 12 months
Spill Kits	Chemical storage facility	Checked for currency and compatibility every 2 years
Personal Protective Equipment	PPU Site Office	As required



Type of extinguisher				Type of Fire, Class and Suitability						Comments (Refer Appendix B)
Colour scheme AS/NZS1841-1997	Colour scheme AS1841-1992	Extinguishant		A Wood, paper, plastics,etc	B Flammable liquids	C Flammable gases	E Energized electrical equipment	F Cooking oils and fats	D** Metal fires	
		Water								Dangerous if used on flammable liquid, energized electrical equipment and cooking oil/fat fires
		Wet Chemical								Dangerous if used on energized electrical equipment
		Foam***						LIMITED*		Dangerous if used on energized electrical equipment.
		Powder	ABE							Special powders are available specifically for various types of metal fires (see **).
		Powder	BE							
		Carbon Dioxide		LIMITED*	LIMITED*					Generally not suitable for outdoor use. Suitable only for small fires.
		Vaporizing Liquid			LIMITED*	LIMITED*				Check the characteristics of the specific extinguishant.
		Fire Blanket		Human torch						

* Limited indicates that the extinguishant is not the agent of choice for the class of fire, but that it will have a limited extinguishing capability.
** Class D fires (involving combustible metals). Use only special purpose extinguishers and seek expert advice.
*** Solvents which may mix with water, e.g. alcohol and acetone, are known as polar solvents and require special foam. These solvents break down conventional AFFF.

Figure 22: Figure A1 of AS 2444

The location fire extinguishers are shown in Section 8.

11.4 Emergency Control Centre

The site office at each PPU shall function as an Emergency Control Centre (ECC) in the event of an emergency. To assist site managers, site wardens and emergency responders, an Emergency Resource Pack containing relevant documentation including but not limited to the following is required to be provided at the ECC:

- The quantity and location of LPG being stored (including details of emergency shutoff)
- Emergency plan,
- Contact details of ProTen and regulatory authority contact details; and
- A manifest of chemicals and quantities stored and their respective safety data sheets (including a plan marking their locations)

11.5 Training and Testing

Site managers shall ensure that all employees and contractors are inducted and trained prior to works being commenced on site.

Emergency training requirements shall be documented in the Emergency Plan.

The Emergency Plan shall be reviewed and tested every 12 months as per the requirements of the POEO(G) Regulation.

12. References

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Standards Australia Limited, 2020. *AS/NZS 1596:2014 - The storage and handling of LP Gas.* s.l.:s.n.

13. Key Assumptions and Limitations

- This report: has been prepared by GHD for ProTen Tamworth Pty Ltd and may only be used and relied on by ProTen Tamworth Pty Ltd for the purpose agreed between GHD and ProTen Tamworth Pty Ltd, as set out in section 1.1 of this report.
- This report and design only covers the "Departures from the DtS" which are addressed by fire engineering Performance Solutions. These have been identified to us by the Regulatory Reviewer. We are not required nor have we undertaken our own Regulatory Review.
- "Departures from the DtS" which are not addressed by fire engineering Performance Solutions are required to meet the Deemed To Satisfy provisions and therefore not covered in this report or design.
- GHD otherwise disclaims responsibility to any person other than ProTen Tamworth Pty Ltd arising in connection with this report. GHD also excludes implied warranties and conditions, to the extent legally permissible.
- The services undertaken by GHD in connection with preparing this report were limited to those specifically detailed in the report and are subject to the scope limitations set out in the report.
- The documentation relied upon has been reviewed only to the degree reasonable as pertaining to GHD's scope, as defined through contract and design intent. It is expressly not GHD's responsibility to,
  - Familiarise ourselves with all information or documentation relating to the project, or the potential fire safety aspect derivatives thereof,
  - Conduct a 'full fire engineering assessment' in any way defined, implied or assumed, for matters outside of GHD's scope,
  - Prepare a holistic fire safety strategy for the building or carry out a full fire engineering assessment of all information and documentation relating to the project, or the potential fire safety aspect derivatives thereof.
- The opinions, conclusions and any recommendations in this report are based on conditions encountered and information reviewed at the date of preparation of the report. GHD has no responsibility or obligation to update this report to account for events or changes occurring subsequent to the date that the report was prepared.
- The opinions, conclusions and any recommendations in this report are based on assumptions made by GHD described in this report. GHD disclaims liability arising from any of the assumptions being incorrect.
- This report is consistent with the fire safety provisions, objectives and limitations of the Building Code of Australia (BCA):
  - We have been informed that building features not part of a Performance Solution will comply with the Deemed to Satisfy provisions of the BCA.
  - This report excludes the analysis and design of fires including incendiary ones involving accelerants, explosives and/or multiple ignition sources, or acts of terrorism.
  - The concepts outlined in this report assume a complete and operational building, and do not address protection of the building during construction, renovation or demolition.

  - Egress and fire safety provisions for persons with disabilities including compliance with the Disability Discrimination Act (DDA) were considered to the same degree as the BCA.
  - Unless stated otherwise, protection of property (other than adjoining property), business interruption or losses, personal or moral obligations of the owner/occupier, reputation, environmental impacts, broader community issues, amenity or non-fire related matters in the building such as health, security, energy efficiency, and occupational health & safety or the re-installation and costs associated with any damages from fire are specifically excluded from this analysis.
  - All essential equipment services and strategies will be maintained, to the operational capacity to which they were designed, installed, commissioned and certified, in accordance with the manufacturer's instructions. Therefore, all essential equipment services and strategies discussed within this report are assumed to function correctly during a fire situation.
- This report is not a compliance or conformance audit for any fire safety system. For example, operational checks of fire safety equipment, verification of construction techniques, fire resistance levels or the witnessing of fire drills or exercises are specifically excluded from the scope of this report.
- The recommendations, data and methodology apply to the subject building and must not be utilised for any other purpose. Any modifications or changes to the building, fire safety management system, or building usage from that described in this report may invalidate the findings, necessitating a re-assessment.
- GHD has prepared this report on the basis of information provided by ProTen Tamworth Pty Ltd and others who provided information to GHD (including Government authorities), which GHD has not independently verified or checked beyond the agreed scope of work. GHD does not accept liability in connection with such unverified information, including errors and omissions in the report which were caused by errors or omissions in that information.
- There is no such thing as a “zero-risk” or “guaranteed safe” building. Even if all of the above listed measures were to be undertaken, there is still a possibility that a fire event may occur.
- It is GHD’s recommendation that this document and the measures proposed herein be discussed by and with relevant stakeholders with the objective to obtain agreement, and ultimately sign-off by relevant parties. Stakeholders envisaged to form part of the signatory group are listed in Table 3.
- GHD has prepared this document for the sole use of ProTen Tamworth Pty Ltd and for a specific purpose, expressly stated herein. No other party should rely on this document without the prior written consent of GHD.
- GHD undertakes no duty, nor accepts any responsibility, to any third party who may rely upon or use this document.
- This document has been prepared based on ProTen Tamworth Pty Ltd’s description of its requirements and GHD’s experience, having regard to assumptions that GHD can reasonably be expected to make in accordance with sound professional principles.
- GHD accepts no liability for information provided by ProTen Tamworth Pty Ltd or other third parties used to prepare this document or as the basis of the analysis. Subject to the above conditions, this document may be transmitted, reproduced or disseminated only in its entirety.

Appendices

Appendix A- Fire Severity Calculations

A.1. Radiant heat incident on neighbouring poultry sheds

Project: **ProTen - Rushes Creek**
Title: Radiation Heat Flux Calculations
Page: 1

Ref	Calculations	Comments
		Version 1.6 R1

Emitting Radiation Calculation

Ref 1

$$\dot{q}''_e = \varepsilon \sigma T^4_{emitter}$$

Input

Emissivity,	ε	1.00		
Stefan-Boltzmann constant	σ	5.67E-11	$kW/m^2/K^4$	
Absolute Temperature of emitter,	$T_{emitter}$	1023.087	°C	

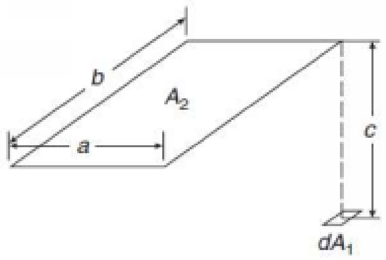
Output

Radiant heat flux emitted,	$\dot{q}''_e$	160.0	kW/m^2	
Distance from boundary		0.00	m	Away from building
Max radiant heat flux emitted at target plane,		3.4	kW/m^2	

Configuration Factor Calculation

Table 1-4.1 in Ref 1

Parallel Configuration

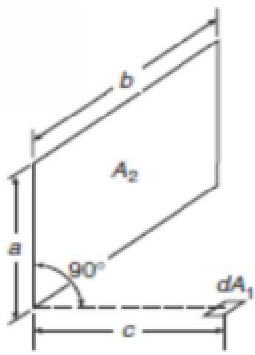


This configuration factor formula is for 1/4 plane element only.

$X = a/c \qquad Y = b/c$

$$F_{d1-2} = \frac{1}{2\pi}\left[\frac{X}{\sqrt{1+X^2}}\tan^{-1}\left(\frac{Y}{\sqrt{1+X^2}}\right) + \frac{Y}{\sqrt{1+Y^2}}\tan^{-1}\left(\frac{X}{\sqrt{1+Y^2}}\right)\right]$$

Perpendicular Configuration



This configuration factor formula is for 1/2 plane element only.

$X = a/b \qquad Y = c/b \qquad A = 1/\sqrt{X^2 + Y^2}$

$$F_{d1-2} = \frac{1}{2\pi}\left[\tan^{-1}(1/Y) - AY\tan^{-1}A\right]$$

GHD	Project: Title:	ProTen - Rushes Creek Radiation Heat Flux Calculations	Page: 2
Ref		Calculations	Comments

Input for Parallel Radiation Calculation

Table 1: Emitting Radiation for Various Windows Parallel to Target

Openings	Width	Height	c_1	$x_{l,b}$	$y_{l,b}$	Include in Analysis
	m	m	m	m	m	
PS end wall	18.00	2.20	26.50	0.00	0.00	Yes

c_1 is the distance from an opening to the boundary

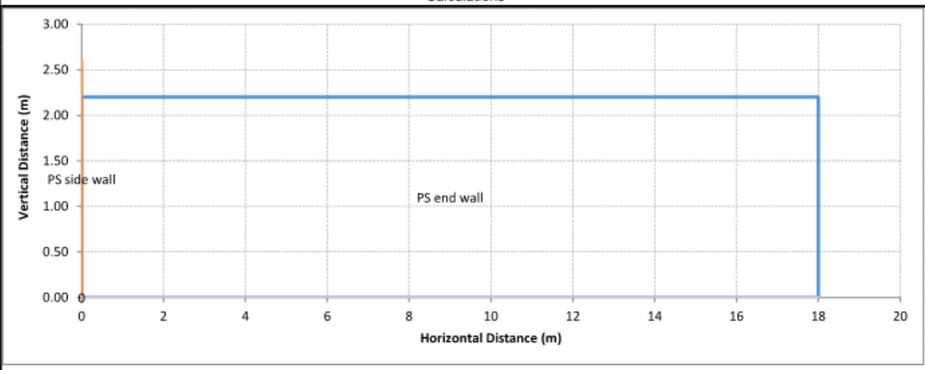
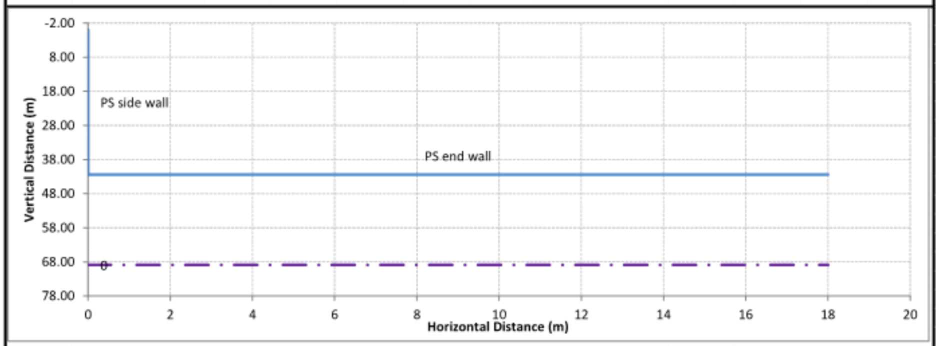
Version 1.6 R1

Input for Perpendicular Radiation Calculation

Table 2: Emitting Radiation for Various Windows Perpendicular to Target

Openings	Width	Height	c_2	$x_{l,b}$	$y_{l,b}$	Hot Source Direction	Include in Analysis
	m	m	m	m	m		
PS side wall	42.40	2.60	26.50	0.00	0.00	+x	Yes

c_2 is the closest distance from an opening to the boundary

GHD	Project: Title:	ProTen - Rushes Creek Radiation Heat Flux Calculations	Page: 3
Ref		Calculations	Comments
		Figure 1: Elevation of Openings Figure 2: Plan of Openings	Version 1.6 R1

A.2. Radiant heat incident on neighbouring poultry sheds

	Project:	ProTen - Rushes Creek	
	Title:	Radiation Heat Flux Calculations	Page: 1

Ref	Calculations	Comments

Version 1.6 R1

Emitting Radiation Calculation

Ref 1

$$\dot{q}''_e = \varepsilon \sigma T^4_{emitter}$$

Input

Emissivity,	ε	1.00		
Stefan-Boltzmann constant	σ	5.67E-11	$kW/m^2/K^4$	
Absolute Temperature of emitter,	$T_{emitter}$	1023.087	°C	

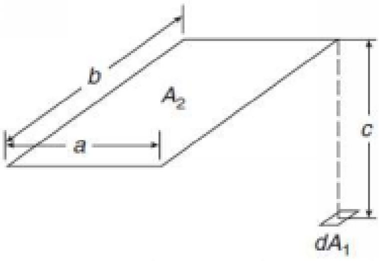
Output

Radiant heat flux emitted,	$\dot{q}''_e$	160.0	kW/m^2	
Distance from boundary		0.00	m	Away from building
Max radiant heat flux emitted at target plane,		10.6	kW/m^2	

Table 1-4.1 in Ref 1

Configuration Factor Calculation

Parallel Configuration

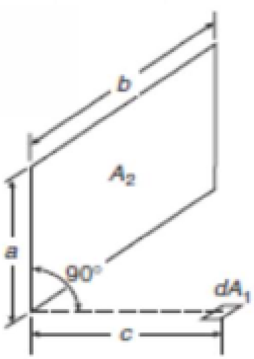


This configuration factor formula is for 1/4 plane element only.

$$X = a/c \qquad Y = b/c$$

$$F_{d1-2} = \frac{1}{2\pi}\left[\frac{X}{\sqrt{1+X^2}}\tan^{-1}\left(\frac{Y}{\sqrt{1+X^2}}\right) + \frac{Y}{\sqrt{1+Y^2}}\tan^{-1}\left(\frac{X}{\sqrt{1+Y^2}}\right)\right]$$

Perpendicular Configuration



This configuration factor formula is for 1/2 plane element only.

$$X = a/b \qquad Y = c/b \qquad A = 1/\sqrt{X^2 + Y^2}$$

$$F_{d1-2} = \frac{1}{2\pi}[\tan^{-1}(1/Y) - AY\tan^{-1}A]$$

Project: **ProTen - Rushes Creek**
Title: Radiation Heat Flux Calculations
Page: 2

Ref	Calculations	Comments
		Version 1.6 R1

Input for Parallel Radiation Calculation
Table 1: Emitting Radiation for Various Windows Parallel to Target

Openings	Width	Height	c_1	$x_{l,b}$	$y_{l,b}$	Include in Analysis
	m	m	m	m	m	
PS side wall	42.40	2.20	15.00	0.00	0.00	Yes

c_1 is the distance from an opening to the boundary

Input for Perpendicular Radiation Calculation
Table 2: Emitting Radiation for Various Windows Perpendicular to Target

Openings	Width	Height	c_2	$x_{l,b}$	$y_{l,b}$	Hot Source Direction	Include in Analysis
	m	m	m	m	m		

c_2 is the closest distance from an opening to the boundary

Ref	Calculations	Comments
		Version 1.6 R1

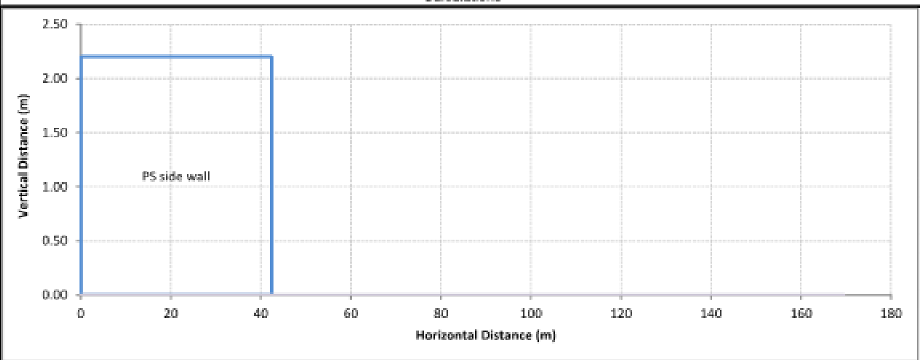


Figure 1: Elevation of Openings

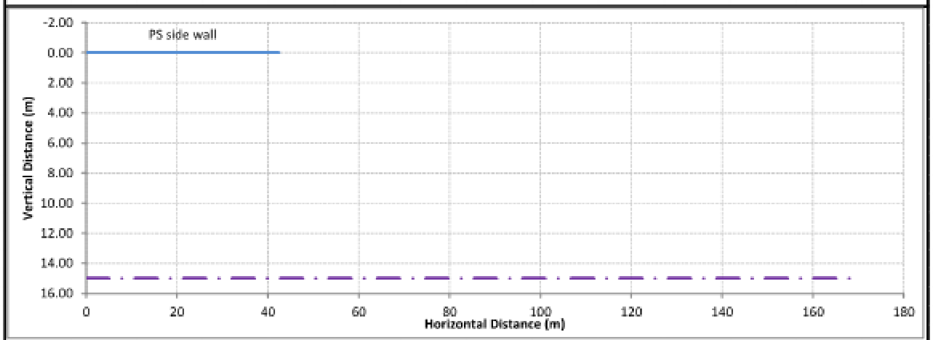


Figure 2: Plan of Openings

Appendix B– PIR Fire Performance Study of Rigid PIR Boards (Non-sandwhiched, with and without protetive layer)

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RESEARCH ARTICLE

WILEY

Fire performance of charring closed-cell polymeric insulation materials: Polyisocyanurate and phenolic foam

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Summary

Results are presented from 2 series of ad hoc experimental programmes using the cone calorimeter to investigate the burning behaviour of charring closed-cell polymeric insulation materials, specifically polyisocyanurate (PIR) and phenolic (PF) foams. These insulation materials are widely used in the construction industry due to their relatively low thermal conductivity. However, they are combustible in nature; therefore, their fire performance needs to be carefully studied, and characterisation of their thermal degradation and burning behaviour is required in support of performance-based approaches for fire safety design. The first series of experiments was used to examine the flaming and smouldering of the char from PIR and PF. The peak heat release rate per unit area was within the range of 120 to 170 kW/m^2 for PIR and 80 to 140 kW/m^2 for PF. The effective heat of combustion during flaming was within the range of 13 to 16 kJ/g for PIR and around 16 kJ/g for PF, while the CO/CO_2 ratio was within 0.05 to 0.10 for PIR and 0.025 to 0.05 for PF. The second experimental programme served to map the thermal degradation processes of pyrolysis and oxidation in relation to temperature measurements within the solid phase under constant levels of nominal irradiation. Both programmes showed that surface regression due to smouldering was more significant for PF than PIR under the same heat exposure conditions, essentially because of the different degree of overlap in pyrolysis and oxidation reactions. The smouldering of the char was found to self-extinguish after removal of the external heat source.

KEYWORDS

charring foams, combustion, insulation materials, performance-based design, pyrolysis, smouldering

1 | INTRODUCTION

Stringent requirements for energy efficiency are driving a trend towards the more widespread use of insulation materials in the built environment. Several types of insulation materials, which are able to meet the multiple design criteria often required for buildings, can be found in the market. A typical classification for insulation materials in the European market, proposed by Papadopoulos et al,[1] distinguishes 4 main groups: (1) inorganic materials such as foams or fibrous materials, (2) organic materials such as expanded foams or fibrous materials, (3) combined materials, and (4) new technology materials. Expanded organic foams such as closed-cell rigid polyisocyanurate (PIR) and phenolic (PF) foams are common combustible insulation materials that are increasingly being used for the design of energy-efficient buildings due to their relatively low thermal conductivity, low density, good durability, and ease of installation.[2] These factors, in conjunction with the

Nomenclature: $E_{CO\rightarrow CO_2}$, heat release per mass unit of oxygen consumed for the combustion of carbon monoxide (J/g); E_{O_2}, heat release per mass unit of oxygen consumed (J/g); ΔH_c, heat of combustion (J/g); m, mass (g/s); $\overline{m}$, normalised mass (−); $\dot{m}$, mass flow rate (g/s); $\dot{Q}$, heat release rate (W); t, time (s); T, temperature (K or °C); X, volume fraction (mol/mol); $\dot{V}$, volumetric flow (m^3/s)

Greek letters: γ, volumetric expansion factor (−); ϕ, oxygen depletion factor (−)

Subscripts: 0, initial; *air*, of air; *eff*, effective; *end*, of the end duration of the test; *e*, of the exhaust or extraction; *i*, of the species i; *loss*, of total loss from the sample; *s*, loss from the sample

Acronyms: DTG, differential thermogravimetric analysis; HRR, heat release rate; HRRPUA, heat release rate per unit area; OC, oxygen consumption calorimetry; PIR, closed-cell rigid polyisocyanurate foam; PF, closed-cell rigid phenolic foam requirement for lower thermal transmittances in building assemblies,[3] lead to these materials increasingly being a preferred option for design.

1.1 | Fire hazards from combustible insulation

The increase in production and extended usage of combustible materials in buildings such as closed-cell cellular polymers has recently given rise to several concerns in the fire safety community.[4,5] This is however not a new problem, and many aspects have already been addressed by several authors and institutions in the past.[6] Indeed, to identify the potential fire hazards to life safety from insulation materials in buildings, numerous authors have extensively studied the fire performance of different types of insulation under different approaches.[6-23] The biggest concern, represented as the flammability and energy release, has classically been addressed using bench-scale experimentation,[13-21] eg, determining the limiting oxygen index according[24] to ASTM D2863 and assessing ignition properties, heat release, and flame spread by using the cone calorimeter[25] or the LIFT apparatus.[26] During recent decades, the fire performance of these materials has been improved by applying flame retardancy techniques, ie, promoting charring behaviour and endothermic reactions in the solid phase, which is typically researched at material scale using thermogravimetry.[7-9] The generation of toxic species due to the combustion and pyrolysis of these plastics has also been raised as a potentially significant concern, and several authors have studied the toxicity of emissions from insulation materials commonly used in buildings.[10-12]

While most of this work has clearly served to rate the hazard from insulation products under specific testing scenarios, several authors highlight that the extrapolation of the performance observed from small-scale testing is hardly applicable to larger scale due to the combination of complex phenomena.[22,23,27,28] Although significant efforts are constantly made to reduce the flammability/combustibility of these materials, there is potential for confusion from the belief that the risk associated with these hazards can be effectively mitigated by obtaining better ratings from standard testing. Harmonisation of standardised testing is intended to offer a plausible representation of the fire hazards from construction products. Yet quantification of the risks associated with the use of combustible insulation in buildings remains as a significant challenge for practitioners.

1.2 | Design tools to quantify the risk from combustible insulation

Recently, new methodologies for the fire safe design of insulation systems have been proposed on the basis of their material behaviour under severe conditions of heat exposure.[29] The methodology proposed by Hidalgo et al considers the mitigation of the fire hazard from combustible insulation materials by designing suitable thermal barriers that control the onset of pyrolysis,[29,30] ie, delaying the onset of hazard generation. Previous work demonstrated that the onset of hazard could be conservatively defined as a "critical temperature."[31] For charring foams, the critical temperature was defined as the temperature at which the peak of the main pyrolysis reaction is obtained by differential thermogravimetric analyses (DTGs) at sufficiently low heating rates and under nonoxidative atmospheres.

The proposed methodology represents a conservative approach for the quantitative fire safe design of construction systems including insulation materials, ie, a framework by which the risk can be quantified. Nevertheless, additional models are required by practitioners and regulatory bodies if quantification of the evolution of hazard after the onset of pyrolysis is to be understood,[32] ie, potential heat release contribution and generation of toxic species from the insulation. The quantification of these hazards is determined by the terms (1) production rate of pyrolysis gases, (2) heat of combustion from pyrolysis gases, and (3) gas species generated by the pyrolysis and combustion. To be able to quantify these parameters and propose a model for performance-based design, a thorough understanding of the material behaviour under conditions of heat exposure is required. This study aims at achieving a thorough understanding of the material behaviour beyond standard testing and parameters, thus identifying the underlying processes that govern those issues, ie, the thermal degradation and thermal evolution of the condensed phase at a relevant scale.

1.3 | Research significance and objectives

In previous work, we presented studies on flammability properties from PIR and PF, as well as their thermal decomposition processes at a material scale by thermogravimetry.[31] The purpose of that work was to determine parameters for the proposed performance-based design methodology.[29] Values of critical temperature established previously, which represent the onset of hazard (pyrolysis), correspond to 300°C to 370°C for rigid PIR insulation and 425°C for the specific PF studied.[31] The present work explores the fire performance of these materials on the basis of their burning behaviour. Variables such as the heat of combustion, emissions of carbon monoxide (CO) and carbon dioxide (CO_2), and consumption of oxygen (O_2) from the combustion are assessed. Thus, the information presented here aims to provide relevant data for the development and application of models capable of predicting the production rate of energy, pyrolysis, and combustion products under different scenarios.

Then the scope of the work presented herein is to present an original methodology to assess the fire performance of representative samples of 2 common commercial rigid closed-cell plastic insulation materials (PIR and PF). This work explores which phenomena should be considered for the development and application of models that can quantify their burning hazard. To achieve this, the following goals are pursued:

1. Macroscopic analysis of the fire performance of these foams by studying heat release rate (HRR), mass loss, and gas emissions from cone calorimeter ad hoc experiments.
2. Mapping of the thermal degradation processes in relation to temperature measurements within the solid phase and correlating the evolution of the thermal profile experienced by the material to results obtained by thermogravimetric analyses presented elsewhere.[31]

The present work is vital for the further development of engineering tools that could assist performance-based designs of building assemblies including combustible insulation. As noted by Hidalgo et al,[29] although the current regulatory fire safety frameworks in the EU[33,34] do not provide a suitable approach for insulation materials, further instrumentation and inclusion of quantitative approaches could complement current standardised testing practices. This approach would help to provide a better understanding and quantification of the fire hazards from insulation materials.

It should be noted that the final fire performance of plastic foams such as PIR and PF strongly depend on the chemical composition and manufacturing process,[35] eg, content of isocyanurate linkages and type of isocyanate-reactive component for PIR, or degree of reticulation for PFs. This information is however largely inaccessible to the public. Since the purpose of this work is to establish a methodology that allows for a comprehensive analysis of phenomena relevant to the eventual fire performance characterisation, 3 current commercially available types of PIR from different manufacturers were selected. These products are certified by their manufacturers to correspond to isocyanurate-based foams (PIR) rather than urethane-based foams (PUR). Only one PF product was selected aiming at a performance comparison with respect to PIR foams; previous thermogravimetric studies have shown essential differences between these products.[31]

2 | EXPERIMENTAL PROGRAMME DESCRIPTION

The experimental programme designed to achieve the objectives noted above was based on the use of the cone calorimeter apparatus,[25] as 2 different series of ad hoc experiments:

1. Piloted experiments and transferring the heat to the sample by radiation from the cone, as presented for the flammability experiments on insulation materials presented elsewhere.[31] The main measurements consisted of mass loss and gas species such as oxygen, carbon dioxide, and carbon monoxide, supported by visual observations.
2. Nonpiloted experiments and transferring the heat to the sample by radiation from the cone. The main measurements consisted of gas species and temperature measurements within the samples, supported by visual observations.

2.1 | Materials

The studied insulation materials comprised 3 types of rigid polyiscocyanurate foam (hereby referred as PIRa, PIRb, and PIRc) and one type of PF. These thermoset plastics are manufactured as rigid closed-cell polymers by blowing a gas through the entire structure of the foam. At present, the blowing agents mainly used are n-pentane, iso-pentane, cyclo-pentane, and various hydrofluorocarbons that have zero ozone depleting potential.[36]

Three different PIR foams from various suppliers were selected to assess the difference in their performance. Polyisocyanurate, which is manufactured based on the mix of an organic isocyanate component and an isocyanate-reactive component, is known to present different possible formulations depending on the isocyanate-reactive component used, which determines its thermal stability.[8] Results in further sections show that the characteristic fire performance from the 3 foams was similar. Therefore, for studying PF, only one product was selected with the intention to assess its characteristic performance with respect to PIR foam.

These materials are often supplied as rigid boards with a protective layer on the surface, which is expected to have some impact on the observed performance during the tests. For the products studied herein, the protective layer corresponds to a low emissivity composite aluminium foil/paper facing. To examine this, samples with and without protective layer were tested. Nevertheless, it should be noted that since this work mainly pursued the characterisation of the material, rather than the product to specific testing methods, the effect of the protective layer must be addressed carefully. Samples with a surface area of 90 mm by 90 mm and 100 mm thick were tested in the 2 series of experiments. Samples with the protective layer removed are shown in Figure 1.

2.2 | Set-up #1: piloted experiments with the heat transferred by radiation

The set-up of these experiments is detailed elsewhere,[31] the results of which are complementary to those presented here. In the previous publication, the measurements were used to assess the critical temperature and thermal inertia of several insulation materials for a performance-based methodology. Temperature measurements were not taken for this experimental programme. The results presented in following sections will rather focus on HRR, mass loss, heat of combustion, and gas emissions. These provide an assessment of the burning behaviour of these foams with no protective layer, thus a characterisation of the material rather than the product.

2.3 | Set-up #2: non-piloted experiments with the heat transferred by radiation

For these experiments, samples were wrapped with aluminium foil at the bottom and lateral sides, with a 6-mm Nickel 200 block at the bottom and altogether wrapped in two 3-mm-thick layers of ceramic insulation paper. The aluminium foil was mainly used to prevent air penetration in the sample from the sides and only allows it from the top. From a heat transfer perspective, the foil is transparent for the conducted heat due to its low thickness and high thermal diffusivity, thus acting as a thermally thin material. The 2 layers of ceramic paper were used to reduce the thermal gradients on the surface of the sample sides. It should be noted that an adiabatic boundary condition at the sides will always be unattainable with this set-up since the conductivity of the ceramic paper is higher than the materials tested.* A schematic drawing of the conceptual set-up and the real set-up is shown in Figures 2 and 3, respectively.

It should be noted that this set-up was used to provide relevant and reliable results that could facilitate future modelling tasks. Thus, the characterisation of the boundary condition at the back face of the material is achieved by using the 6-mm Nickel 200 plate at

*Thermal conductivity of ceramic paper: 0.08 and 0.11 $W{\cdot}m^{-1}{\cdot}K^{-1}$ at 600°C and 800°C, respectively.

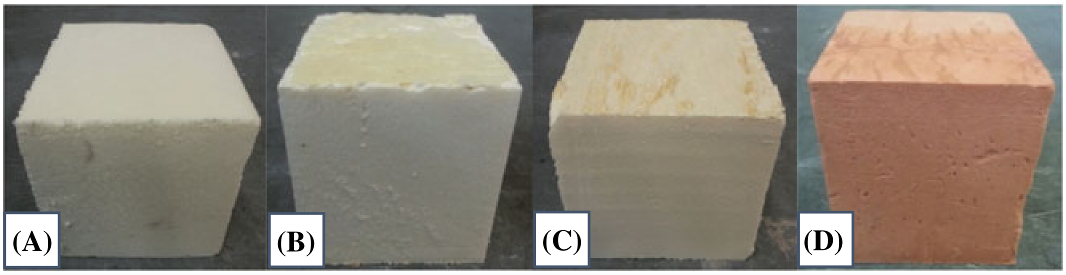

FIGURE 1 Samples of insulation materials before testing. A, PIRa; B, PIRb; C, PIRc; and D, PF. PIR, polyisocyanurate; PF, phenolic foam [Colour figure can be viewed at wileyonlinelibrary.com]

the bottom of the samples. This approach was described by Carvel et al,[37] who recommended the use of a heat sink for material characterisation purposes.

As for the boundary condition at the exposed surface, several values of irradiation from the radiant heater were used. The heat fluxes were selected in such a way that mapping of the different thermal degradation processes was highlighted. The minimum heat flux for each material was defined as a thermal exposure that did not trigger the onset of pyrolysis after reaching thermal equilibrium. Specific values of external heat flux for each material are noted in Table 1.

Experiments were performed at least twice to verify the repeatability of the results and for 2 different configurations, ie, with no protective layer and with a noncoloured protective layer attached to the exposed surface to explore different phenomena and thermal behaviour experienced by the foams.

Measurements of temperature were taken within the sample by using 1.5-mm bead K-type thermocouples. The temperature of the metallic plate at the back was also measured. Thermocouples were installed at the centre of the section and every 2 mm in-depth and in parallel to the exposed surface with the intention of reducing the error in the thermocouple measurement, which is a recommended procedure for materials of particularly low conductivity.[38,39] The first thermocouple was placed within a range of 2 to 3 mm from the surface. No temperature correction was considered by the heat losses introduced by the thermocouple. Additionally, 2 thermocouples were inserted 30 mm horizontally off the second in-depth thermocouple for some experiments. This procedure aimed to clarify whether the heat transfer through the sample was behaving either one-dimensionally or two-dimensionally. The positioning of the thermocouples is shown in Figure 2. A summary of the conditions for all the performed experiments is presented in Table 1.

Gas species such as carbon dioxide, carbon monoxide, and oxygen were measured at the apparatus exhaust duct, which nominal volumetric flow corresponded to 24 L/s. Mass loss was not measured for this experimental programme, as the thermocouples would interfere with the measurements.

3 | ANALYSIS METHODOLOGY

The calorimetry approach considered to evaluate the HRR from the burning of the insulation materials is the species evolution approach based on oxygen consumption (OC).[40] Oxygen consumption rather than carbon dioxide generation calorimetry[41] is used to correlate the HRR due to 2 main reasons: (1) the desiccation system based on calcium sulphate (*drierite*®) tends to absorb carbon dioxide when anhydrous, thus affecting the shape of the measured curve of carbon dioxide, and (2) the variability of energy coefficients for carbon

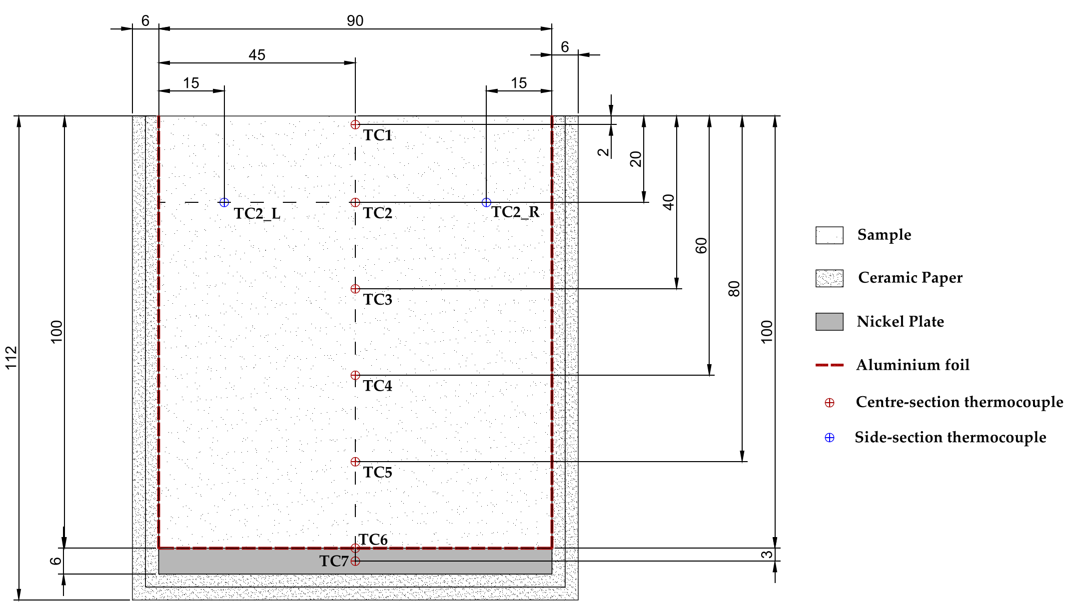

FIGURE 2 Schematics of sample preparation for the set-up #2 [Colour figure can be viewed at wileyonlinelibrary.com]

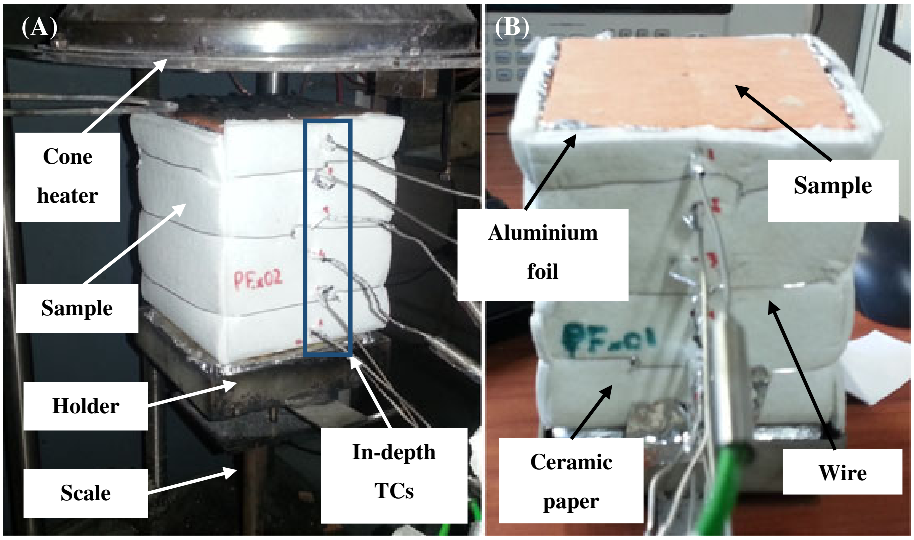

FIGURE 3 A, Sample during testing and B, sample prepared before testing [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Summary of performed experiments (set-up #2)

Material	Configuration	Incident Radiant Heat Flux Range, kW/m^2	Measured Parameters
PIRa Manufacturer-claimed density: 31–34 kg/m^3 Average measured density: 31.2 ± 0.61 kg/m^3	Nominal sample size: 90 mm × 90 mm × 100 mm Exposed surface: (a) With protective layer (b) Without protective layer Wrapping: 2 layers of ceramic paper +1 layer of aluminium foil Back boundary condition: Nickel 200 plate (6 mm) + ceramic board (25 mm) Orientation: Horizontal Pilot: No pilot igniter	10, 25, 35 (2 repetitions)	(1) In-depth temperature (2) O_2, CO_2, and CO gas species
PIRb Manufacturer-claimed density: 32 kg/m^3 Average measured density: 33.0 ± 0.71 kg/m^3		5, 10, 25, 35 (2 repetitions)	
PIRc Manufacturer-claimed density: 30-32 kg/m^3 Average measured density: 33.5 ± 0.65 kg/m^3		5, 10, 25, 35 (2 repetitions)	
PF Manufacturer-claimed density: 35 kg/m^3 Average measured density: 38.1 ± 1.05 kg/m^3		5, 10, 15, 25 (2 repetitions)	

dioxide generation calorimetry tends to be larger than OC.[42] Then the formulation considered for the experiments corresponds to OC calorimetry, noted in Equation 1, which was originally proposed by Janssens[43] and has been revisited by Biteau[42]:

$$\dot{Q}_{OC} = \left(E_{O_2}\cdot\phi - \left(E_{CO\to CO_2} - E_{O_2}\right)\cdot\frac{1-\phi}{2}\cdot\frac{X_{CO}}{X_{O2}}\right)\cdot\frac{\dot{m}_{ex}}{1+\phi\cdot(\gamma-1)}\cdot\frac{M_{O_2}}{M_{air}}\cdot X^0_{O_2}, \tag{1}$$

where E_{O_2} and $E_{CO\to CO_2}$ are the energy released per mass unit of oxygen consumed (W/g) and per mass unit of oxygen consumed for the combustion of carbon monoxide respectively (W/g), $\dot{m}_e$ is the mass flow in the exhaust (g/s), γ is the volumetric expansion factor (−), M_{O_2} and M_{air} are the molecular weight of oxygen and air, respectively, (g/mol), and ϕ is the oxygen depletion factor (−).

The effective heat of combustion $H_{c,\,eff}$ (J/g) is quantified based on calculations of HRR and experimental mass loss, given by the following:

$$\Delta H_{c,eff} = \frac{\int_0^{t_{end}}\dot{Q}_{OC}(t)\cdot dt}{m_{loss}}, \tag{2}$$

where $\dot{Q}_{OC}(t)$ is the HRR (W), t_{end} is the end time of the test (s), and m_{loss} is the total mass loss during the test (g). The notation 'effective' relates to an average value obtained by the combustion of the material. However, the combustion process for most of these foams is nonuniform, with transition from flaming to smouldering, as will be shown in further sections. Then, if Equation 2 is applied for the total test time, the obtained values of heat of combustion will represent a lumped value that considers both flaming and smouldering as a single process. The effective heat of combustion from pyrolysis gases for materials that char and experience smouldering is attempted for an arbitrary period up to 200 seconds during the initial flaming combustion. This period is chosen considering the samples exposed to heat fluxes larger than 35 kW/m^2 (refer to Figure 5). Even though a shorter integration time would be more adequate for 25 kW/m^2, this would lead to large errors due to the short transient behaviour of the flaming combustion. It should be noted that, whereas this is an arbitrary criterion, the objective is to compare this value to the effective value considering the total time of the test.

Mass measurements from the samples are normalised with respect to the initial mass of the sample, m_0 (g), as shown in Equation 3 below:

$$\overline{m}(t) = \frac{m(t)}{m_0}, \tag{3}$$

where $\overline{m}(t)$ and $m(t)$ are the normalised mass (−) and measured mass (g), respectively, at any time. As discussed in further sections, the ceramic paper used to prepare the samples is expected to lose mass during the test, thus including an overestimation of the mass loss. This error is estimated as a maximum of 5% of the initial sample mass, which is assessed by running tests at high heat fluxes until almost all the sample is consumed.

To assess the different thermal degradation processes with respect to temperature measurements, the duration of the tests from experimental set-up #2 was selected in a way such that the maximum thermal gradient could be compared to the residue of the sample. Therefore, samples were cut through their centre section after the end of the test, and the level of thermal degradation achieved at different depths assessed by visual colourimetry. Additionally, the consistency of these results is correlated with thermogravimetric experiments presented elsewhere.[31,35]

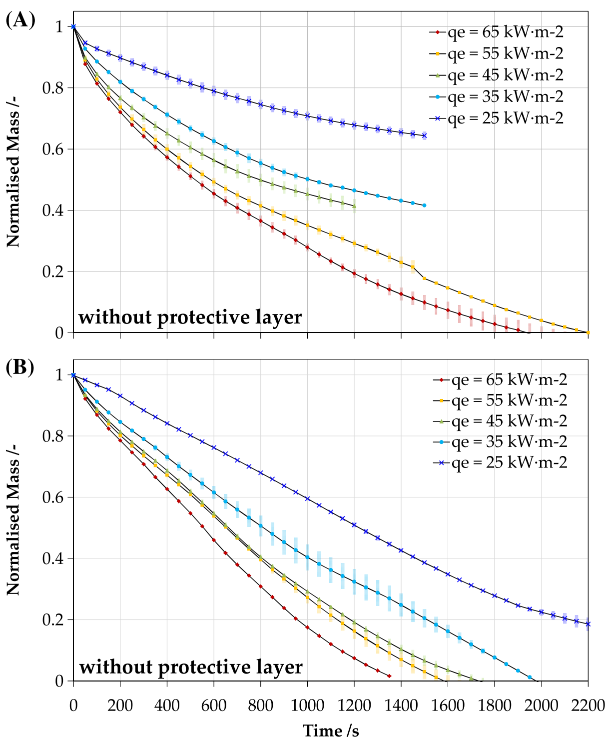

FIGURE 4 Normalised mass (m(t)/m_0) of A, PIRa and B, PF samples without protective layer at different heat fluxes. Shading indicates std. dev. from 2 repetitions. PIR, polyisocyanurate; PF, phenolic foam [Colour figure can be viewed at wileyonlinelibrary.com]

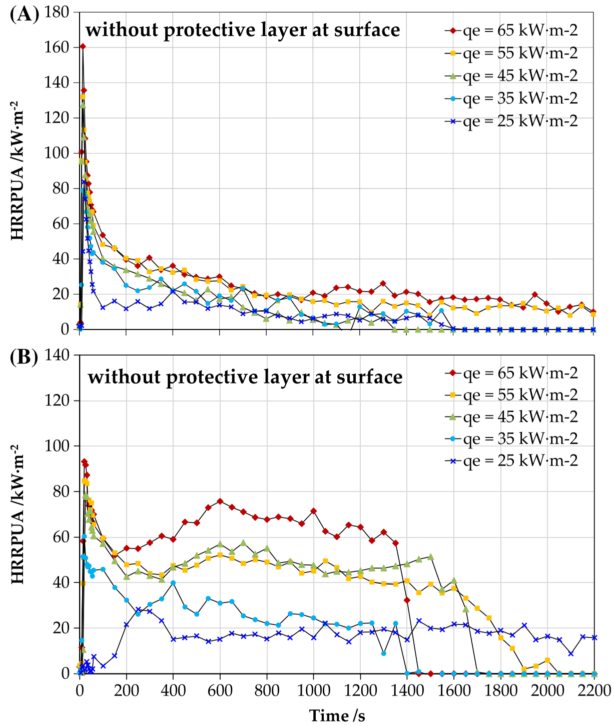

FIGURE 5 Heat release rate per unit area of 100-mm-thick A, PIRa and B, PF samples without protective layer at different external heat fluxes. Average from 2 repetitions. PIR, polyisocyanurate; PF, phenolic foam [Colour figure can be viewed at wileyonlinelibrary.com]

4 | RESULTS AND DISCUSSION

4.1 | Burning behaviour

A summary of the experimental results consisting of mass loss of the samples, HRR per unit area (HRRPUA), and gas species correlations for PIRa and PF is presented below. For simplicity, and since the results from the rest of PIR materials are very similar in performance, only results from PIRa are discussed in this section.

4.1.1 | General observations

The 3 types of PIR were found to behave similarly, with a very fast ignition for every external heat flux larger than the critical. This was followed by a small flame that continued to be reduced until intermittent flaming was only observed by the edges of the sample. Polyisocyanurate foam tended to expand slightly at early stages of the heat exposure. After flaming, a black char layer remained, which tended to glow if the external heat flux was high. The char at the surface continued to get consumed by oxidation, and its thickness started to reduce at different rates depending on the incident radiant heat flux. Flaming at the edges was sporadically observed. The remaining char from PIR was very soft and light. Discolouration of the PIR samples was observed, changing from yellow to orange-brown and finally black colour during the process of thermal degradation. This discolouration is discussed in further sections. It should be noted that the similarity between results from the 3 types of PIR foams is extensively discussed in Hidalgo.[35] Therefore, herein, only main comparative results are presented, and a greater focus is put on PIRa. The reader is

TABLE 2 Calculated effective heat of combustion for plastic foams with no protective layer

Effective Heat of Combustion, kJ/g				
Integration Time	PIRa	PIRb	PIRc	PF
Total test time (t_{end})	19.09 ± 1.99	18.05 ± 2.48	20.52 ± 3.45	20.98 ± 6.01
Up to 200 s (initial flaming)	14.38 ± 0.68	13.22 ± 1.30	16.26 ± 0.84	15.35 ± 0.80

Abbreviations: PIR, polyisocyanurate; PF, phenolic foam.

referred to Hidalgo[35] for assessing the differences in behaviour for 3 different PIR foams.

Phenolic foam was found to have a similar behaviour to PIR, proceeding to char formation after flaming and to smoulder after flame out at the surface. As shown in previous studies,[31] the critical heat flux for ignition is larger than PIR (10-15 kW/m^2 for PIR and 22 kW/m^2 for PF); however, its surface regression by smouldering after ignition was shown here to be much faster. Phenolic foam tended to spall and crack very easily during heat exposure and presented a more brittle behaviour. Popping and snapping sounds could be heard during testing. Discolouration was observed, changing from pink-brown to yellow and finally black colour during the process of thermal degradation. This discolouration is discussed in further sections.

4.1.2 | Normalised mass

Figure 4 shows the average curves of normalised mass from 2 repetitions for PIRa and PF without protective layer at the surface of the samples. For simplicity in the visual assessment of the different evolution of the tests, the mass data are presented as a normalised mass. The normalised mass here refers to the ratio between the mass at any time and the initial mass of the sample before the start of test ($m(t)/m_0$). Therefore, a normalised value of 1 indicates the initial state where the mass of the sample is equal to the initial mass of the sample; a value of 0 indicates that the whole sample has been consumed. For high heat fluxes, samples were tested until near complete consumption of the sample (5% of the mass). Tests at lower heat fluxes (25-45 kW/m^2 for PIR and 25 kW/m^2 for PF) were interrupted earlier, and the sample was removed as no significant flaming was visible anymore. It should be noted that the sample holder materials also experienced loss of mass; therefore, the normalised measurement includes a maximum error or overestimation of up to 5%. This explains why the curves presented in Figure 4 reach an absolute normalised mass of 0 in some instances. Due to the unknown mass loss evolution of the sample holder, a correction has not been applied as this would include further uncertainty in the data outputs.

The mass loss curves of PIR present a reducing slope throughout the tests, indicating that the pyrolysis front was moving through thickness leaving a protective char, thus decreasing the rate of pyrolysis. However, since smouldering was also experienced at the surface of the sample after charring, the change of slope also includes this phenomenon. Phenolic foam mass loss curves are more linear than the ones observed for PIR, while PF mass loss is also observed to be larger than PIR for the same heating conditions. This behaviour is indicative of a more severe consumption of the char at the surface by oxidation (smouldering) for PF. This is consistent with thermogravi-

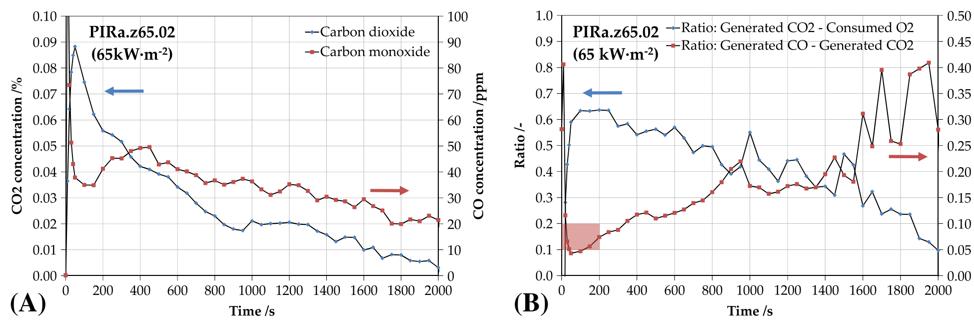

FIGURE 6 A, CO_2 and CO concentrations and B, ratios of generated CO_2 vs consumed O_2 and generated O_2 vs generated CO for PIRa at 65 kW/m^2. The shading denotes the ratio of CO/CO_2 during flaming. PIR, polyisocyanurate; PF, phenolic foam [Colour figure can be viewed at wileyonlinelibrary.com]

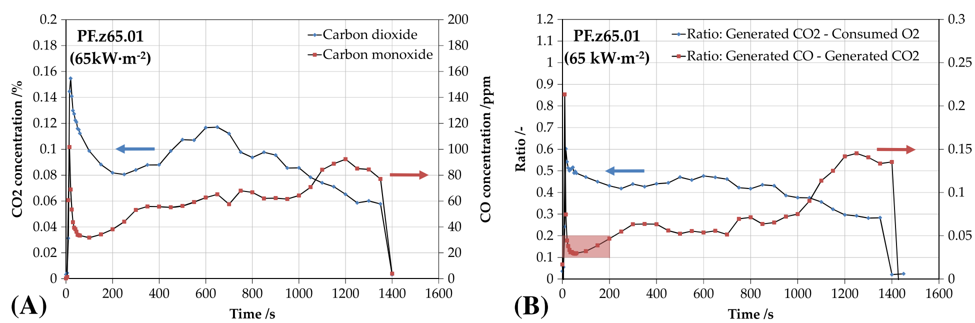

FIGURE 7 A, CO_2 and CO concentrations and B, ratios of generated CO_2 vs consumed O_2 and generated O_2 vs generated CO for PF at 65 kW/m^2. The shading denotes the ratio of CO/CO_2 during flaming. PIR, polyisocyanurate; PF, phenolic foam [Colour figure can be viewed at wileyonlinelibrary.com]

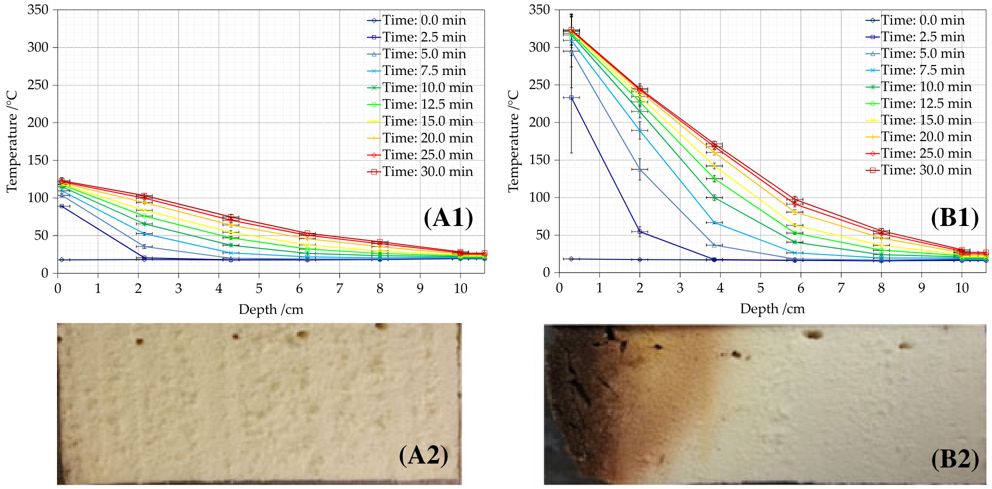

FIGURE 8 In-depth thermal profiles of PIRa at 10 kW/m^2 A1, with and B1, without protective layer. Centre section for the end of the tests A2 and B2. Horizontal error bars: estimated error of ±2 mm in thermocouple positioning. Vertical error bars: standard deviation between 2 repeated tests. PIR, polyisocyanurate [Colour figure can be viewed at wileyonlinelibrary.com]

metric experiments presented elsewhere,[31] which indicated that while PIR presents its main pyrolysis (250°C-350°C) and oxidation (500°C-650°C) domains in 2 different temperature regions, the PF main pyrolysis (400°C-500°C) and oxidation (480°C-550°C) slightly overlap in the same temperature region.

4.1.3 | HRRPUA and effective heat of combustion

Figure 5 shows the average HRRPUA from 2 repetitions for PIRa and PF. In general, PIR samples showed lower HRRPUA than PF throughout the test, except for the peak of HRRPUA. The burning behaviour of PIR and PF showed similar trends, with a large peak of HRRPUA right after ignition, followed by a progressive decay, which is characteristic of charring materials. This is generally expected for any PIR. Nevertheless, PF showed a decay of HRRPUA after the first peak, but an increase for high heat fluxes, which reflects a faster consumption of the char layer.

Table 2 shows the calculated values for the effective heat of combustion for plastic foams PIRa, PIRb, PIRc, and PF. In general, it is observed that the heat of combustion obtained for the pyrolysis gases (flaming) is lower than the effective value obtained considering the total test time.

4.1.4 | Gas species correlations and yields

Figure 6 shows a selection of gas species correlations of specific tests from PIRa and PF, where high heat fluxes are selected to represent clearly the different phenomena taking place. The charts on the left indicate the CO_2 and CO concentrations, while those on the right indicate the ratio of generated CO_2 versus consumed O_2, and the ratio of generated CO versus CO_2.

For PIR and PF, the CO/CO_2 ratio tended to increase greatly during the progress of the test, suggesting a transition from flaming to smouldering combustion, with both phenomena occurring simultaneously during some periods of the test. A ratio between 0.05 and 0.10 is observed during flaming combustion (time before 200 s) for PIR, and between 0.025 and 0.05 for PF; these values are highlighted in Figures 6 and 7, respectively, with a shading. It is difficult to

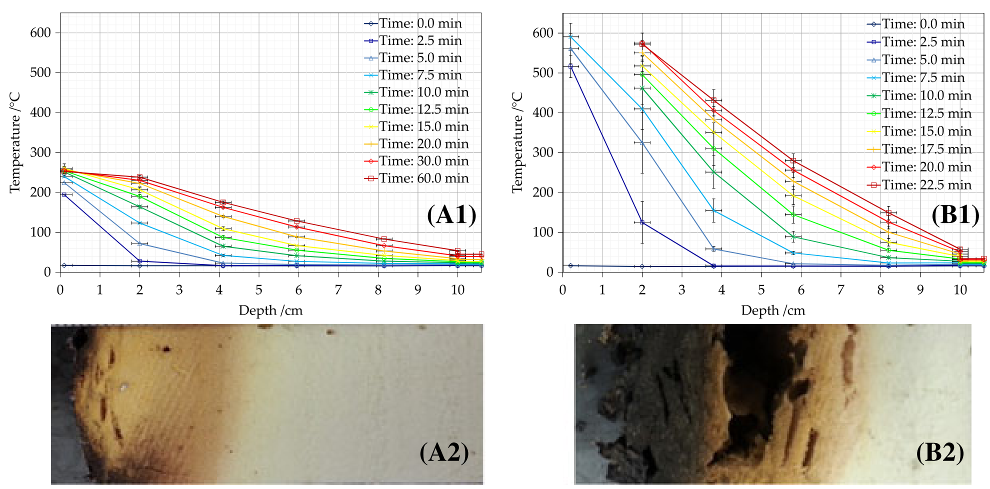

FIGURE 9 In-depth thermal profiles of PIRa at 25 kW/m^2 A1, with and B1, without protective layer. Centre section for the end of the tests A2 and B2. Horizontal error bars: estimated error of ±2 mm in thermocouple positioning. Vertical error bars: standard deviation between 2 repeated tests. PIR, polyisocyanurate [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 10 PIRa sample residue at 25 kW/m^2 without protective layer up to 22.5 minutes A, top view, B, lateral view, and C, lateral view from section. PIR, polyisocyanurate [Colour figure can be viewed at wileyonlinelibrary.com]

establish a constant value since a steady state is not clearly observed. A clear transition from flaming to smouldering combustion cannot be identified as local edge effects are present, thus allowing for flaming at the edges while smouldering occurs at the top surface. The ratio CO/CO_2 continues to increase as the pyrolysis rate and flaming combustion decrease.

Regarding the CO_2/O_2 ratio, a short steady state was initially obtained for PIR, suggesting only flaming combustion from PIR pyrolysates. This continued to decrease during the period of the test indicating the transition to a different burning regime, probably with char being consumed by oxidation and fewer pyrolysis gases being produced due to the spread of the pyrolysis front through thickness. Similar results were obtained for PF, despite the decrease occurring much earlier, followed by a transition to a quasi–steady state. This might be indicative of oxidation of char and flaming of pyrolysis gases occurring simultaneously. At the final stage of the test, this was reduced again, probably mainly due to the oxidation of char.

4.2 | Thermal degradation mapping

4.2.1 | Isocyanurate-based polyurethane foam (PIR)

Figure 8 shows the time history of the in-depth temperature profile for PIRa experiments tested at 10 kW/m^2 with (Figure 8A) and without (Figure 8B) the protective layer at the surface. The in-depth temperature profile is presented for a series of time steps during the test (ie, from 0 to 10 min using a time step of 2.5 min, and from 10 to 30 min using a time step of 5 min). Vertical error bars show the standard deviation from 2 repetitions for each thermocouple position. Horizontal error bars indicate the estimated error in the thermocouple positioning. The results from experiments shown in Figure 8A show good repeatability, while those presented in Figure 8B show worse repeatability, especially for temperature measurements near the surface. This is attributed to the nonuniform thermocouple positioning for repeated experiments, which has a larger impact for measurements near the surface potentially due to the swelling of the material during the thermal decomposition process.

Figure 8A shows a case study where no thermal degradation was observed. Positions close to the surface achieved a quasi-steady temperature in early stages (from 2.5 min), with a maximum value of 123°C ± 4°C. The temperature profile achieved a quasi–steady state after 20 to 25 minutes, with a minimal rate of temperature increase (<1°C/min) for inner positions. The displacement of the thermal gradient towards higher temperatures for inner positions and with steady temperature at the surface is due to the back-boundary layer. The metallic plate, which acts as a heat sink, was slowly increasing in temperature because the thermal wave had reached the sample back face and, consequently, heat was transferred to the plate. The sample section in Figure 8A2 shows that no discolouration was produced in the foam and, consistently, no release of volatiles was observed during the tests.

Figure 8B presents a case study where thermal degradation was observed at the surface of the sample. Thermal gradients were significantly larger than those shown in Figure 8A1, indicating the clear effect of the protective layer on the thermal performance. Positions close to the surface achieved a quasi-steady temperature after 5 minutes, with a maximum value of 323°C ± 20°C, while the temperature profile again achieved a quasi–steady state after 20 minutes, with a minimal rate of temperature increase (<1°C/min) for inner

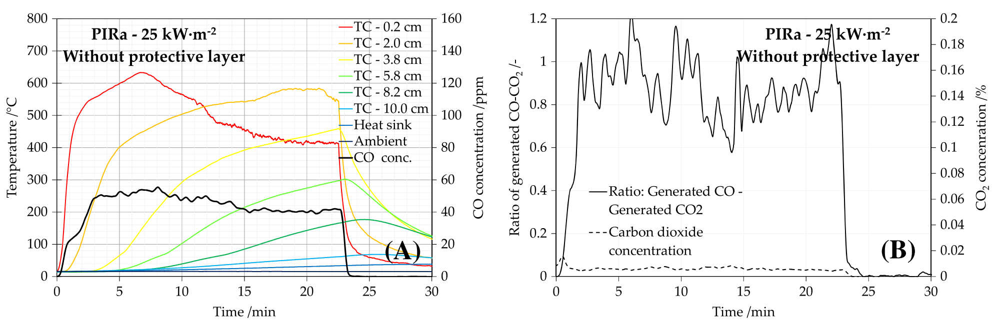

FIGURE 11 Time history of temperatures A, within the solid phase and CO concentration and B, generated CO vs generated CO_2 for PIRa with no protective layer at 25 kW/m^2. PIR, polyisocyanurate [Colour figure can be viewed at wileyonlinelibrary.com]

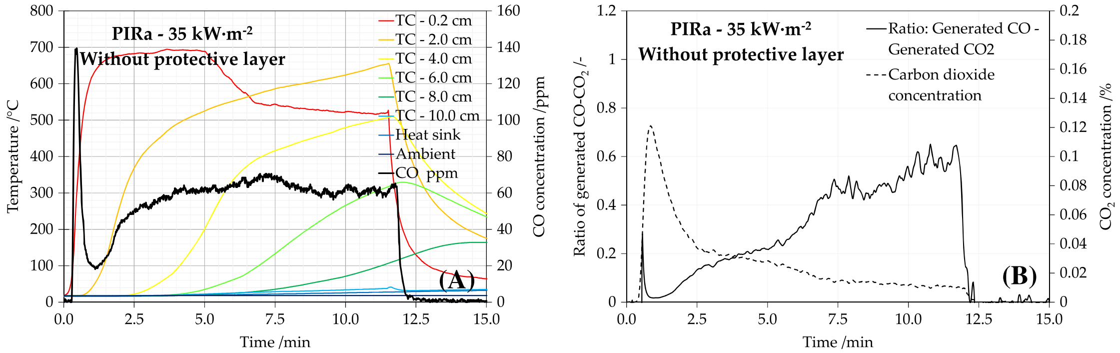

FIGURE 12 Time history of temperatures A, within the solid phase and CO concentration and B, generated CO vs generated CO_2 for PIRa with no protective layer at 35 kW/m^2. PIR, polyisocyanurate [Colour figure can be viewed at wileyonlinelibrary.com]

positions. Three clear tonalities in the discolouration experienced by the sample can be observed in the sample section in Figure 8B2. The discolouration is nonuniform, with higher degradation for regions near the centre line than near the edge. This indicates that the heat transfer was not behaving perfectly in a one-dimensional regime. Some cracking can be observed near the surface, where the discolouration is darker. Additionally, the sample thickness increased by up to 10 mm. A significant release of volatiles was observed after 3 to 4 minutes, but with no ignition during the experiment. Measurements of CO_2 and CO did not present noticeable concentrations compared to the initial baseline; therefore, these are not presented, which confirms that no significant oxidation was produced.

Figure 9 shows the in-depth temperature profiles for PIRa experiments tested at 25 kW/m^2 with (Figure 9A) and without (Figure 9B) the protective layer at the surface. The results from experiments shown in Figure 9A show good repeatability, with vertical error bars being noticeable only for the surface thermocouple. The results from experiments shown in Figure 9B, however, present worse repeatability with the error bars being significantly larger for the 3 first thermocouples. This nonuniformity is attributed to the positioning and, more importantly, to the degradation processes forming cracks within the sample and likely different rate of surface oxidation. Significant differences were observed between the performance of the samples with and without the protective layer, which are attributed to the effect that the protective layer has on the radiation absorption due to its low emissivity, and the blocking of air from contact with the surface, thus reducing or cancelling the surface oxidation for those conditions of heating exposure.

Figure 9A presents a case study where small thermal degradation was observed. Positions close to the surface achieved a quasi-steady

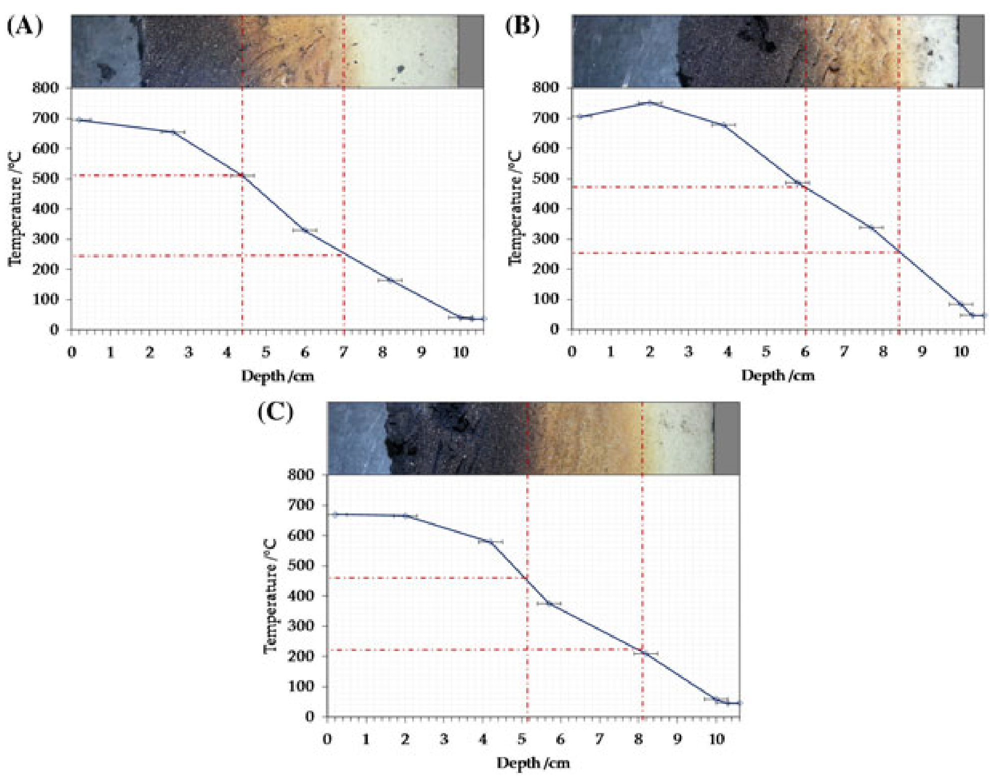

FIGURE 13 Maximum in-depth temperature profile of A, PIRa; B, PIRb; and C, PIRc at 35 kW/m^2 (no protective layer). Horizontal error bars: estimated error of ±2 mm in thermocouple positioning. PIR, polyisocyanurate [Colour figure can be viewed at wileyonlinelibrary.com]

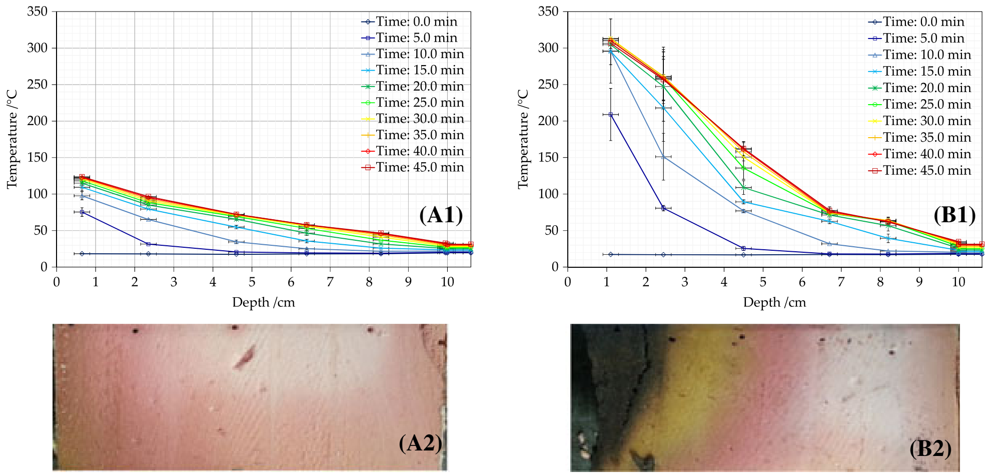

FIGURE 14 In-depth thermal profiles of PF at 10 kW/m^2 with A1, and without protective layer B1. Centre section for the end of the tests A2 and B2. Horizontal error bars: estimated error of ±2 mm in thermocouple positioning. Vertical error bars: standard deviation between 2 repeated tests. PF, phenolic foam [Colour figure can be viewed at wileyonlinelibrary.com]

temperature after 2.5 to 5 minutes, with a maximum value of 252°C ± 5°C, while the temperature gradient achieved a quasi–steady state after 30 minutes, with a minimal rate of temperature increase (<0.5°C/min) for inner positions. Two different tonalities can be observed in the sample section shown in Figure 9A2. This indicates that the heat transfer could be considered as a one-dimensional regime. Small cracks can be observed near the surface. Darker tonalities near the edge of the surface, where the foil ends, might be indicative of an edge effect with lower cooling, therefore presenting higher temperatures. Measurements of carbon dioxide and carbon monoxide did not show concentrations displaced from the baseline, confirming that no oxidation occurred. The sample appeared to have slightly expanded by up to 3 mm.

Figure 9B shows a case study where severe thermal degradation was observed. Positions close to the surface achieved a maximum temperature of 591°C ± 34°C at 7.5 minutes. The lack of measurements from the first thermocouple for the subsequent time steps indicates its detachment from the solid due to consumption of the surrounding material. No steady state was observed for the thermal gradient during the final time steps, with the temperature increasing at a rate of 9°C/min to 10°C/min for inner positions. This rapid rate of temperature change indicates the consumption of material at the surface, thus moving the exposed boundary to lower positions. Three to 4 tonalities can be observed in the sample section shown in Figure 9B2: yellow (virgin material), orange-brown discolouration, and black (char). Small cracks were obtained between the interface of virgin material and orange discolouration, while a series of large cracks can be observed in the brown region, below the char. A thickness regression of approximately 15 mm was obtained, indicating that a significant amount of material was consumed due to surface oxidation.

Figure 10 shows the sample residue from different perspectives for the test presented in Figure 9B (25 kW/m^2 without protective layer for 22.5 min). The surface of the sample presents complex morphology characterised by craters formed by surface oxidation. It can be observed that the char at the edges and lateral sides of the sample presents a smooth morphology, indicating that oxidation did not take place. This is consistent with the set-up that uses aluminium foil to prevent air penetration through the sides, thus limiting oxidation to the top surface.

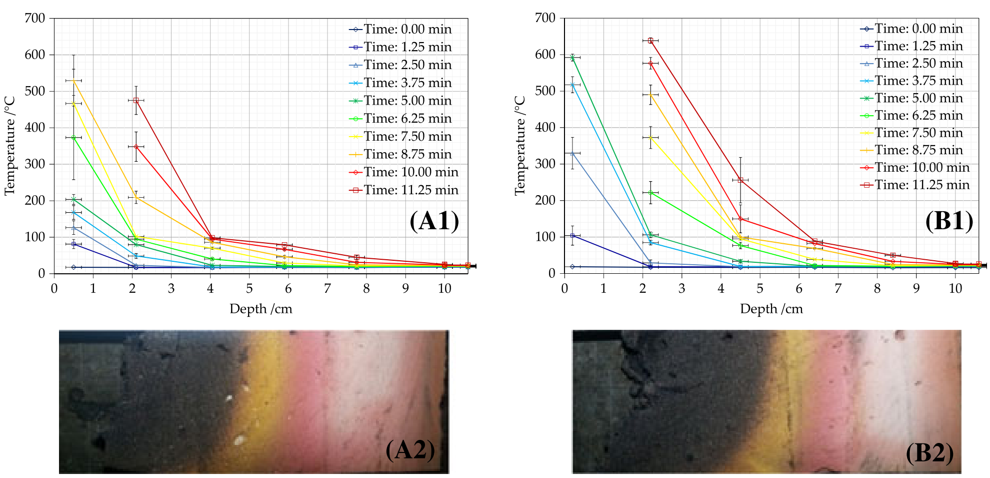

FIGURE 15 In-depth thermal profiles of PF at 25 kW/m^2 with A1, and without B1, protective layer. Centre section for the end of the tests A2 and B2. Horizontal error bars: estimated error of ±2 mm in thermocouple positioning. Vertical error bars: standard deviation between 2 repeated tests. PF, phenolic foam [Colour figure can be viewed at wileyonlinelibrary.com]

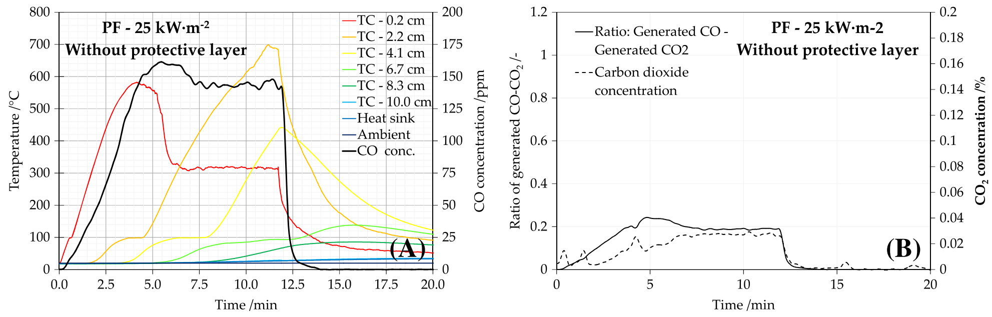

FIGURE 16 Time history of temperatures A, within the solid phase and CO concentration and B, generated CO vs generated CO_2 for PF without protective layer at 25 kW/m^2. PF, phenolic foam [Colour figure can be viewed at wileyonlinelibrary.com]

A large amount of volatiles were released from the start of the test, shown in Figures 9B and 10, but ignition was not achieved. Despite the fact that the heat flux used was above the critical heat flux, a pilot spark was not used. The release of volatiles continued to decrease after 1 minute. Measurements of carbon monoxide are presented in Figure 11A with the time history of temperature measurements. The concentration of CO increased almost from the beginning, probably indicating generation of pyrolysates. The shape of the CO curve changed slope from 2 to 3 minutes, and thereafter the CO generation remained approximately under a steady state during the rest of the test. A slight decrease between 10 and 15 minutes was also observed. These measurements are indicative of smouldering combustion (surface oxidation), with a high CO/CO_2 ratio between 0.8 and 1.2, as shown in Figure 11B. The concentration of CO_2 remained very low in comparison to the generation of CO_2 presented by flaming of PIR pyrolysates in the previous section. Additionally, it is shown that the smouldering was not self-sustained since the thermal gradient and CO generation dropped significantly after the removal of the external heat source. This is due to the closed-cell structure of the foam that does not allow the free circulation of oxygen through the sample, limiting the oxidation to the top surface; therefore, the generation of heat is drastically reduced once the external heat source is removed.

A more severe case study is presented in Figure 12, corresponding to a PIRa sample tested at 35 kW/m^2 without protective layer. The sample auto-ignited after 5 seconds of heat exposure, introducing a different regime that was not observed previously for this experimental series, but for the first series studying heat release. Figure 12A shows the time history of temperatures within the solid phase and the concentration of generated CO. The thermal evolution within the solid was similar to that presented in Figure 11A, but with a faster heating rate. The generation of CO followed a different pattern due to flaming combustion, which was confirmed by the CO_2 concentration presented in Figure 11B. The CO/CO_2 ratio increased over time, indicating simultaneous flaming and smouldering. This is consistent with the behaviour presented in the previous section.

The behaviour from PIRb and PIRc foams was similar to the one presented above. The upper edge of the temperature envelopes for PIRa, PIRb, and PIRc at 35 kW/m^2 is presented in Figure 13, with a section of the sample after the test. The temperature values were interpolated for the interface between the 3 main regions of discolouration (yellow, orange-brown, and black). In general, the first interface was found between 220°C and 260°C, while the second interface was identified between 460°C and 520°C. The first set of temperatures agrees with the value obtained before the onset of the main peak of pyrolysis observed in DTGs under nitrogen atmospheres by Hidalgo et al.[31,35] The second set of temperatures corresponds to the thermal range in which no more significant pyrolysis is obtained under nitrogen atmospheres. Maximum temperatures measured in the solid phase, presented Figure 13, were near 700°C. Thermogravimetric analyses under air atmospheres (50 mL/min flow with 21% of oxygen) showed that the full consumption of mass terminates below 600°C, which indicates that the diffusion of oxygen then dominates the combustion of char at the surface. However, further assessment is required to characterise the mechanisms that govern the combustion of this char.

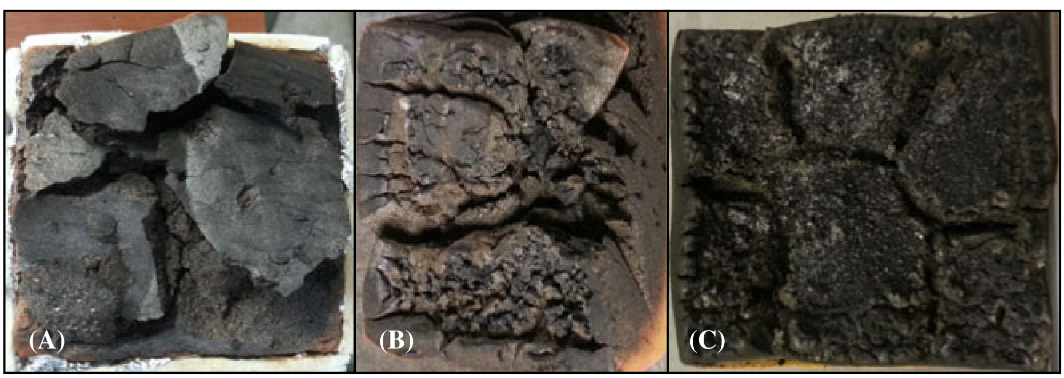

FIGURE 17 PF sample residue at A, 10 kW/m^2; B, 15 kW/m^2; and C, 25 kW/m^2 without protective layer [Colour figure can be viewed at wileyonlinelibrary.com]

4.2.2 | Phenolic foam

Figure 14 shows the time history of the in-depth temperature profile for PF experiments tested at 10 kW/m^2 with (Figure 14A) and without (Figure 14B) protective layer at the surface. The results from experiments shown in Figure 14A present good repeatability in the experiments, while those from experiments shown in Figure 14B present worse repeatability, especially for temperature measurements obtained by the 2 first thermocouples. This is attributed to the nonuniformity of the thermocouple positioning and especially to the thermal degradation observed, with char being detached from the surface.

Figure 14A presents a case study where no clear thermal degradation was observed. Positions close to the surface achieved a quasi–steady state from 10 minutes, with a maximum value of 124°C ± 1°C. The temperature profile achieved a quasi–steady state from 15 to 20 minutes, with a minimal rate of temperature increase (<1°C/min) for inner positions. A change in the slope of the thermal profile was obtained near the second thermocouple once the steady state was achieved. The sample section displayed in Figure 14A2 shows that some discolouration of a darker pink tonality was produced near the surface. Additionally, the sides and bottom of the section have different tonality than the centre, which indicates that material suffers from oxidation at ambient temperatures. No release of volatiles was observed during the tests.

Figure 14B presents a case study where clear thermal degradation was observed at the surface of the sample. Thermal gradients were significantly larger than the ones shown in Figure 14A, indicating the clear effect of the protective layer on the thermal performance again. The temperature close to the surface achieved a quasi–steady state after 10 minutes, with a maximum value of 296°C ± 44°C at this time step. The temperature profile achieved a quasi–steady state from 25 minutes, with a minimal rate of temperature increase (<1°C/min) for inner positions. The in-depth temperature profile during the steady state shows an interesting shape, with 2 different slopes converging at 78°C, indicating temperature dependency of the thermal properties and/or endothermic processes at lower temperatures. This is consistent with the change of slope observed in Figure 14A. Four clear tonalities in the discolouration experienced by the material can be observed in the sample section shown in Figure 14B2. The degradation seems to be nonuniform, with higher degradation for regions near the centre line than near the edge. This indicates that the heat transfer was not behaving perfectly as a one-dimensional regime. Cracks and delamination can be observed within the first 20 mm from the surface, in the char area, as shown in Figure 17A. Delamination is probably due to spalling from the sample; popping and snapping sounds could be heard during the experiment. No significant surface regression or oxidation was observed, but measurements of carbon dioxide and carbon monoxide indicated low concentrations compared to the initial baseline. This is indicative of minor oxidation from the delaminated pieces.

Figure 15 shows the in-depth temperature profiles for PF experiments tested at 25 kW/m^2 with (Figure 15A) and without (Figure 15B) the protective layer at the surface. The results shown in Figure 15A,B present good repeatability except for the first thermocouples. Slightly better performance was observed for the samples with a protective layer (Figure 15A) than those without (Figure 15B), with lower thermal gradients for same times of exposure.

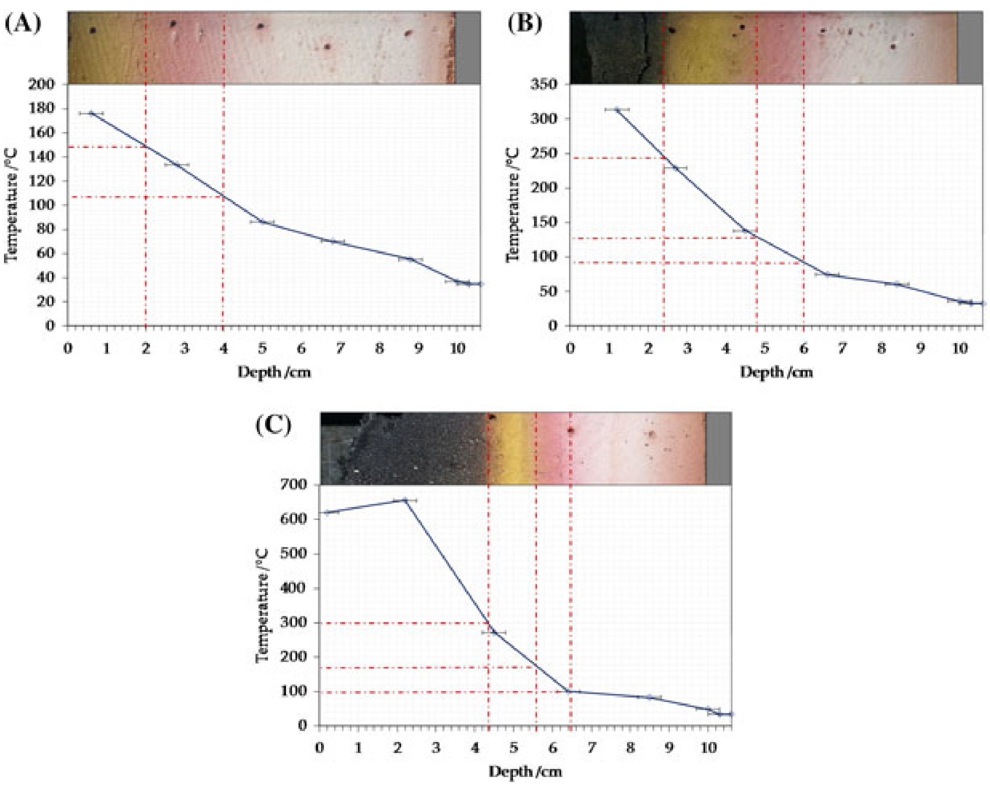

FIGURE 18 Maximum in-depth temperature profile of PF: A, 15 kW/m^2 (foil); B, 10 kW/m^2 (no foil); and C, 25 kW/m^2 (no foil). Horizontal error bars: estimated error of ±2 mm in thermocouple positioning. PF, phenolic foam [Colour figure can be viewed at wileyonlinelibrary.com]

However, the protective layer did not prevent the onset of thermal degradation.

Figure 15A presents a case study where the effectiveness of the protective layer was lost after certain temperature and thermal degradation was eventually achieved. The temperature profile close to the surface showed a moderate rate of temperature increase around 30°C/min to 50°C/min until 5 minutes, achieving a temperature of 204°C ± 14°C, at which point the rate of increase rose significantly since the protective layer started to detach and lift after 4 minutes of heat exposure. As a result, the temperature near the surface achieved a maximum value below 600°C at around 9 minutes, when the thermocouple detached from the initial position due to consumption of the surrounding material. Approximately 20 mm of material was consumed by the end of the tests. Four different uniform tonalities can be observed in the sample section between the edge and the centre line, as shown in Figure 15A2, indicating that the heat transfer could be considered essentially as a one-dimensional regime. No cracks within the core of the sample were obtained, but the top of the sample presented a rough surface with some random cracks. Measurements of carbon dioxide and carbon monoxide showed concentrations displaced from initial baseline, confirming the occurrence of solid-phase oxidation. For simplicity, these results are not presented herein, but for the case shown in Figure 15B, which is equivalent.

Figure 15B shows a case study where severe thermal degradation was observed from early times in the test (2.5 min). The temperature close to the surface achieved a maximum value of 592°C ± 10°C at 5 min. No steady state was observed for the thermal gradient during the final time steps, with the temperature increasing with a rate of 9 to 10°C/min for inner positions. This rate was only observed for positions with a temperature higher than 100°C, indicating a clear endothermic effect at that temperature range. A high rate of temperature increase, without achieving the steady state, indicates the consumption of material at the surface, thus moving the exposed boundary to lower positions. The thermal degradation experienced was similar to that shown in Figure 15A. The surface of the material is presented in Figure 17C, showing crater morphology on the edges and rough surface and random long cracks expanding from the centre to the edges.

Measurements of carbon monoxide are presented in Figure 16A with the time history of temperature measurements. The concentration of CO increased until 5 minutes, when it achieved a steady state at around 150 ppm. These measurements are indicative of smouldering combustion (surface oxidation), suggesting a constant rate of oxidation. Similarly, the CO/CO_2 ratio increased until 5 minutes as shown in Figure 16B, remaining approximately constant at around 0.2. The concentration of CO_2 remained very low in comparison to the generation of CO_2 presented for the flaming of PF in previous sections. Additionally, it is shown that the smouldering was not self-sustained since the thermal gradient and CO generation dropped significantly after removing the external heat source. This is due to the closed-cell structure of the foam that does not allow the free circulation of oxygen through the sample. Additionally, a plateau of temperatures was clearly observed below 100°C in Figure 16A, indicating an endothermic reaction, probably due to water desorption in the polymer.

Images from the surface of the remaining residue for PF experiments without the protective layer at 10, 15, and 25 kW/m^2 are shown in Figure 17. Different patterns indicate the significance of surface oxidation. Figure 17A shows the occurrence of the delamination effect when the achieved temperatures are not high enough to trigger the oxidation of the char created. Figure 17B shows that the oxidation at the surface is not homogenous, indicating the high complexity of the oxidation mechanism, while Figure 17C shows the case of a smouldering process with relatively constant rate of surface regression as shown in Figure 16.

The upper edge of the temperature envelopes for different experiments are presented separately in Figure 18, together with a section of the sample after the test. Temperatures values were interpolated for the interface between the 3 main regions of discolouration (light pink, dark pink, orange-brown, and black). In general, the first interface, which was observed as a plateau of temperature in Figure 18A, was around 100°C, near the change of slope in the thermal gradient. The second interface was identified between 125°C and 160°C, which agrees with the temperature before the first peak of pyrolysis observed in DTGs under nitrogen atmospheres in Hidalgo et al.[32,36] The third interface was identified between 250°C and 300°C, which agrees with the temperature between the first and second peak of pyrolysis observed in DTGs under nitrogen atmospheres. Maximum temperatures measured in the solid phase and shown in Figure 18 were between 600°C and 700°C, while thermogravimetric analyses under air atmospheres showed that all mass consumption ends below 600°C in an air atmosphere. This indicates that the diffusion of oxygen probably dominates the combustion of char at the surface.

5 | SUMMARY

This paper has presented the results from 2 experimental programmes on the basis of ad hoc cone calorimeter tests. This work aimed to investigate the fire performance of charring closed-cell polymeric insulation materials, specifically PIR and PF, so that a comprehensive protocol can be set for assessing the evolution of hazard imposed by the material. The first experimental programme macroscopically analysed the fire performance of these foams by studying HRR, mass loss, and gas species. The second programme mapped the thermal degradation processes in relation to temperature measurements within the solid phase, correlating the evolution of the thermal profile experienced by the material to previous results obtained by thermogravimetry.

The first series of experiments was based on 100-mm-thick samples tested using the cone calorimeter (with spark igniter) and reproducing levels of irradiation from the critical heat flux up to 65 kW/m^2. Calorimetry calculations for PIR and PF samples showed the typical shape obtained from charring materials. A peak of HRRPUA between 120 and 170 kW/m^2 was observed for PIR, with a decay below 60 kW/m^2 represented by the formation of a char layer and the transition of the pyrolysis front towards inner depths. The peak HRRPUA for PF was observed to be in the range 80 to 140 kW/m^2, with a decay and subsequent increase or decrease depending on the external heat flux. Despite its larger critical heat flux for ignition, PF showed larger mass loss and surface regression for the same conditions of heat exposure after a certain time. This is attributed to the overlapping of pyrolysis and char oxidation reactions in a close temperature range for PF, while PIR presents clearly separated temperature ranges for the pyrolysis and char oxidation reactions. The effective heat of combustion for PIR was found to be in the range of 13 to 21 kJ/g, while for PF, the range was 15 to 21 kJ/g. Complimentary gas analyses demonstrated different regimes of combustion for PIR and PF, ie, flaming at the surface with a CO/CO_2 ratio between 0.05 and 0.10 for PIR, and between 0.025 and 0.05 for PF, followed in both cases by smouldering of the char left at the surface, with intermittent flaming at sides and an increasing CO/CO_2 ratio as flaming was reduced. These phenomena may occur simultaneously, depending on the displacement speed of the pyrolysis front and the oxidation rate at the surface.

The second series of experiments was primarily concerned with understanding the thermal evolution and dynamics of the thermal degradation experienced by PIR and PF. This stage was based on 100-mm-thick samples tested with the cone calorimeter (without spark igniter), and reproducing heating scenarios with different severities. Measurements of temperature within the insulation allowed mapping of the different thermal degradation processes, which were previously identified by thermogravimetric techniques. Measurements of gas species (carbon monoxide, carbon dioxide, and oxygen) were also taken to determine whether oxidation processes occurred, ie, flaming from the pyrolysis gases or smouldering from the char generated after pyrolysis.

A technique based on comparing the eventual thermal discolouration through the thickness of a sample was correlated to the upper edge of the temperature envelopes during the test and the thermogravimetric results. Three clear domains were observed in the thermal evolution of PIR and PF, corresponding to the virgin material, pyrolysis region, and char. Polyisocyanurate was found to expand in the regions where it was pyrolysing, creating a series of cracks or gaps within the structure of the foam. Phenolic foam, however, spalled, probably due to the loss of chemically bound water, which was evidenced by plateaus of temperature around 100°C. A clear effect was observed in the thermal performance of the rigid foams such as PIR and PF when samples were tested with the protective layer attached to the exposed surface. This is related to the reduction of the fraction of absorbed heat flux due to the low emissivity of the protective layer, as well as other effects such as the reduction in the rate of oxidation, via avoiding the contact of oxygen with the charred material or the inhibition of a good mixing between air and pyrolysates.

While the pyrolysis was clearly governed by the thermal evolution of the solid phase for these charring materials, the rate of oxidation was identified as a diffusion-controlled mechanism. Indeed, values of temperature higher than those obtained by thermogravimetry under air conditions were observed within the char. The rate of oxidation of the char was also found to be governed by the external heat flux, which also determined the evolution of the pyrolysis front. The smouldering process of the char remaining after pyrolysis from PIR and PF was found to self-extinguish after the external heat source was removed. This indicates that the generated heat from the char oxidation at the surface, with the particular heat losses obtained for the tested conditions, was not sufficient to sustain the process. Additionally, the closed-cell structure does not allow the diffusion of air through the foam, thus limiting the smouldering.

Further work should focus on modelling tasks to characterise the thermal behaviour and pyrolysis of these materials. Additionally, the mechanism of char oxidation should be further investigated.

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