Riskcon engineering

# Preliminary Hazard Analysis

## 17 Thornells Road, Tyabb

Maoneng Australia Pty Ltd
Document No. RCE-20087_Maoneng_PHA_Final_15Dec20_Rev(0)
Date 15/12/2020

# Preliminary Hazard Analysis

17 Thornells Road, Tyabb

Maoneng Australia Pty Ltd

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## Quality Management

| Rev | Date | Remarks | Prepared By | Reviewed By |
|---|---|---|---|---|
| A | 16 November 2020 | Draft issue for comment | Renton Parker | Steve Sylvester |
| 0 | 15 December 2020 | Issued Final | | |

# Executive Summary

## Background

Maoneng Australia Pty Ltd (Maoneng) has proposed to develop a battery energy storage system (BESS) at 17 Thornells Road, Tyabb, Victoria (the project). The objective of the project is to provide support to the existing National Electricity Network by storing electricity until it is needed and stabilising rapid fluctuations events. The project will comprise up to 240 MW of battery storage along with associated infrastructure (i.e., substations, transformers, etc.). This report examines the potential for fire risk from lithium-ion chemistry should a battery failure occur.

EMM Consulting Pty Ltd (EMM) has engaged Riskcon Engineering Pty Ltd (Riskcon) to prepare this PHA for the project.

## Conclusions

A hazard identification table was developed for the Mornington BESS project to identify potential hazards that may be present at the site as a result of operations or storage of materials. Based on the identified hazards, scenarios were postulated that may result in an incident with a potential for offsite impacts. Postulated scenarios were discussed qualitatively and any scenarios that would not impact offsite were eliminated from further assessment. Scenarios not eliminated were then carried forward for consequence analysis.

Incidents carried forward for consequence analysis were assessed in detail to estimate the impact distances. Impact distances were developed into scenario contours and overlaid onto the site layout diagram to determine if an offsite impact would occur. The consequence analysis showed that no scenarios would have the potential to impact off site; hence, no incidents were carried forward for detailed frequency analysis.

Notwithstanding this, a frequency assessment was prepared to highlight that the risk at the site boundary would be zero (0) as the consequence contours would not impact over the site boundary. As the risk was calculated to be zero (0) it would be below the acceptable criteria and would be considered a permissible development.

In addition, incidents exceeding 23 kW/m$^2$ were reviewed which indicated that the contours from such incidents would not impact over the site boundary and therefore incident propagation would not be expected to occur and would be below the acceptable criteria.

Based on the analysis conducted, it is concluded that the risks at the site boundary are not considered to exceed the acceptable risk criteria; hence, the project would only be classified as potentially hazardous and would be permitted within the current land zoning for the site.

## Recommendations

Notwithstanding the conclusions drawn, the following recommendations have been made and should be undertaken to cover the battery and inverter equipment as well as common hazards for a mechanical site prior to the commencement of operations at the BESS project to the extent dangerous goods exceed any thresholds:

- A Dangerous Goods (DG) risk assessment shall be prepared for the site.
- A DG register shall be prepared for the site.
- A site manifest shall be prepared at the site in accordance with Schedule 3 of the Victorian Dangerous Goods Regulation (VDGR).

- The site shall notify the Regulator (i.e. WorkSafe Victoria) of the presence of DGs.
- A site layout shall be prepared for the site in accordance with Schedule 3 of the VDGR.
- A placard schedule shall be prepared for the site to ensure the correct placards are installed.
- An Emergency Response Plan (ERP) shall be prepared for the site and submitted to the Fire & Rescue Victoria (FRV).
- An Emergency Services Information Booklet (ESIB) shall be prepared for the site and submitted to the FRV.
- The transformers shall be designed according to the requirements detailed in AS 1940-2017 "The storage and handling of flammable and combustible liquids" to minimise the potential for fire or explosion to occur within the transformers.

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## Abbreviations

| Abbreviation | Description |
|---|---|
| ADG | Australian Dangerous Goods Code |
| AS | Australian Standard |
| CBD | Central Business District |
| DGs | Dangerous Goods |
| ERP | Emergency Response Plan |
| ESIB | Emergency Services Information Booklet |
| FPQ | Fire Protection Quantity |
| FRV | Fire & Rescue Victoria |
| HIPAP | Hazardous Industry Planning Advisory Paper |
| PHA | Preliminary Hazard Analysis |
| Pmpy | Per million per year |
| SEP | Surface Emissive Power |
| SEPP | State Environmental Planning Policy |
| SSC | Spread Sheet Calculator |
| VDGR | Victorian Dangerous Goods Regulation |
| VF | View Factor |

# 1.0 Introduction

## 1.1 Background

Maoneng Australia Pty Ltd (Maoneng) has proposed to develop a battery energy storage system (BESS) at 17 Thornells Road, Tyabb, Victoria (the project). The objective of the project is to provide support to the existing National Electricity Network by storing electricity until it is needed and stabilising rapid fluctuations events. The project will comprise up to 240 MW of battery storage along with associated infrastructure (i.e., substations, transformers, etc.). This report examines the potential for fire risk from lithium-ion chemistry should a battery failure occur.

EMM Consulting Pty Ltd (EMM) has engaged Riskcon Engineering Pty Ltd (Riskcon) to prepare this PHA for the project.

## 1.2 Objectives

The key objectives of this PHA are to:

- Complete the PHA according to the Hazardous Industry Planning Advisory Paper (HIPAP) No. 6 – Hazard Analysis (Ref. [1]);
- Assess the PHA results using the criteria in HIPAP No. 4 – Risk Criteria for Land Use Planning (Ref. [2]); and
- Demonstrate compliance of the site with the relevant codes, standards and regulations (i.e. Planning and Environment Regulation, OHS Regulation, 2017 Ref. [3]).
- Conduct a review of the Fire Protection Quantity (FPQ) under the Victorian Dangerous Goods (Storage and Handling) Regulations 2012 (VDGR, Ref. [4]).

## 1.3 Scope of Services

The scope of work is to complete a PHA study for the Maoneng project located at 17 Thornells Road, Tyabb to assist in demonstrating the project is safe as part of the approval process. The scope does not include any other assessments which may be required as a result of this study nor any other Maoneng facilities.

# 2.0 Methodology

## 2.1 Multi-Level Risk Assessment

The Multi-Level Risk Assessment approach (Ref. [5]), although published by the NSW Department of Planning, Industry and Environment, it has been used as the basis for the study to determine the level of risk assessment required. The selection of this framework is due to the absence of a suitable Victorian guideline or policy. The approach considered the development in context of its location, the quantity and type (i.e. hazardous nature) Dangerous Goods stored and used, and the project's technical and safety management control. The Multi-Level Risk Assessment Guidelines are intended to assist industry, consultants and the consent authorities to carry out and evaluate risk assessments at an appropriate level for the project being studied.

There are three levels of risk assessment set out in Multi-Level Risk Assessment which may be appropriate for a PHA, as detailed in **Table 2-1**.

**Table 2-1: Level of Assessment PHA**

| Level | Type of Analysis | Appropriate If: |
|---|---|---|
| 1 | Qualitative | No major off-site consequences and societal risk is negligible |
| 2 | Partially Quantitative | Off-site consequences but with low frequency of occurrence |
| 3 | Quantitative | Where 1 and 2 are exceeded |

The Multi-Level Risk Assessment approach is schematically presented in **Figure 2-1**.

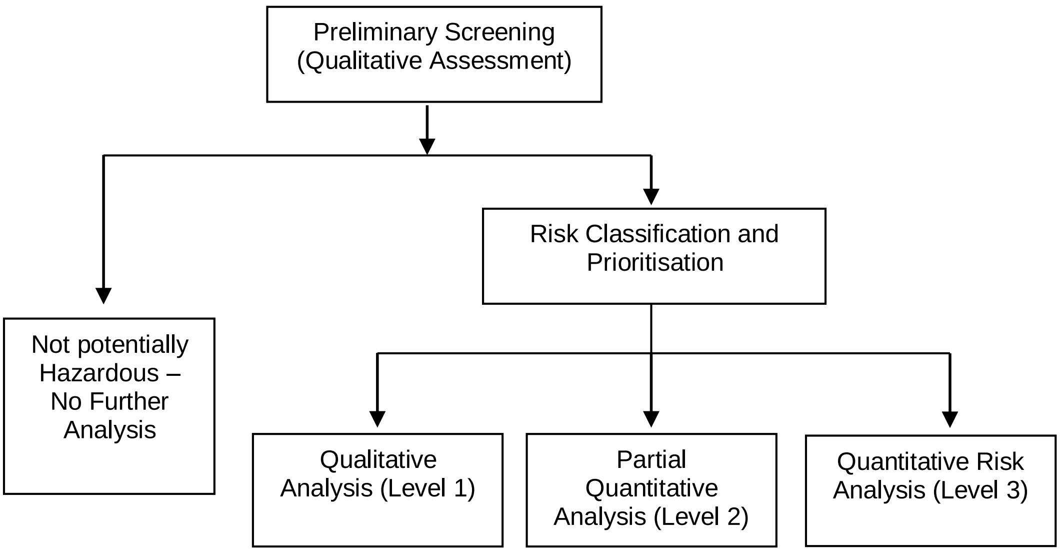



**Figure 2-1: The Multi-Level Risk Assessment Approach**

Based on the type of DGs to be used and handled at the proposed project, a **Level 2 Assessment** was selected for the Site. This approach provides a qualitative assessment of those DGs of lesser quantities and hazard, and a quantitative approach for the more hazardous materials to be used on-site. This approach is commensurate with the methodologies recommended in "Applying SEPP 33's" Multi Level Risk Assessment approach (DPIE, 2011). The selection of this framework is due to the absence of a suitable Victorian guideline or policy.

## 2.2 Risk Assessment Study Approach

The methodology used for the PHA is as follows;

**Hazard Analysis** – A detailed hazard identification was conducted for the site facilities and operations. Where an incident was identified to have a potential off-site impact, it was included in the recorded hazard identification word diagram (**Appendix A**). The hazard identification word diagram lists incident type, causes, consequences and safeguards. This was performed using the word diagram format recommended in HIPAP No. 6 (Ref. [1]).

Each postulated hazardous incident was assessed qualitatively in light of proposed safeguards (technical and management controls). Where a potential offsite impact was identified, the incident was carried into the main report for further analysis. Where the qualitative review in the main report determined that the safeguards were adequate to control the hazard, or that the consequence would obviously have no offsite impact, no further analysis was performed. **Section 3.1** of this report provides details of values used to assist in selecting incidents required to be carried forward for further analysis.

**Consequence Analysis –** For those incidents qualitatively identified in the hazard analysis to have a potential offsite impact, a detailed consequence analysis was conducted. The analysis modelled the various postulated hazardous incidents and determined impact distances from the incident source. The results were compared to the consequence criteria listed in HIPAP No. 4 (Ref. [2]). The criteria selected for screening incidents is discussed in **Section 3.1**.

Where an incident was identified to result in an offsite impact, it was carried forward for frequency analysis. Where an incident was identified to not have an offsite impact, and a simple solution was evident (i.e. move the proposed equipment further away from the boundary), the solution was recommended, and no further analysis was performed.

**Frequency Analysis** – In the event a simple solution for managing consequence impacts was not evident, each incident identified to have potential offsite impact was subjected to a frequency analysis. The analysis considered the initiating event and probability of failure of the safeguards (both hardware and software). The results of the frequency analysis were then carried forward to the risk assessment and reduction stage for combination with the consequence analysis results.

**Risk Assessment and Reduction –** Where incidents were identified to impact offsite and where a consequence and frequency analysis was conducted, the consequence and frequency analysis for each incident were combined to determine the risk and then compared to the risk criteria published in HIPAP No. 4 (Ref. [2]). Where the criteria were exceeded, a review of the major risk contributors was performed, and the risks reassessed incorporating the recommended risk reduction measures. Recommendations were then made regarding risk reduction measures.

**Reporting** – on completion of the study, a draft report was developed for review and comment by Maoneng / EMM. A final report was then developed, incorporating the comments received by Maoneng / EMM for submission to the regulatory authority.

# 3.0 Site Description

## 3.1 Site Location

The site is located at 17 Thornells Road, Tyabb which is approximately 70 km south east of the Melbourne Central Business District (CBD). **Figure 3-1** shows the regional location of the site in relation to the Melbourne CBD.


**Figure 3-1: Site Location**

## 3.2 Adjacent Land Uses

The land is located in an industrial area surrounded by the following land uses, which are adjacent to the site as shown in **Figure 3-2** are:

- North – Residential (rural)
- South – Food processing warehouse (industrial)
- East – Residential (rural)
- West – Tyabb Terminal Station

## 3.3 Detailed Description

The purpose of the project is to provide support to the National Electricity Network by arbitraging electricity demand fluctuations by storing electricity during off peak periods or when there is surplus supply and discharging the stored electricity when demand is highest (i.e. generator trips /

shutdowns) or in peak periods. This is achievable due to the high response times achieved through lithium ion battery storage which can fill peak demands due to the quick dispatchability of battery storage. The project will have capacity to store up to 240 megawatts (MW) of energy and conceptually comprises the following key components:

- batteries housed within fully enclosed battery containers, with associated inverters and transformers and an underground cable network;
- an onsite 220 / 33 kilovolt (kV) or 66/33 kV substation;
- a switch room;
- a control room;
- an underground or overhead transmission line connecting the on-site substation to the adjacent Tyabb Substation;
- internal access roads;
- a temporary construction laydown area;
- an operations and maintenance building; and
- security fencing and fire safety equipment.

The project will connect into the grid via the Tyabb terminal station which is located directly to the west of the proposed project. The electricity will pass through either a 66 kW or a 220 kV underground capable from the terminal station into the 33/220 kV substation where it will be converted and distributed to the battery nodes located around the site as shown in **Figure 3-2.**Energy would flow back into the grid via this same route but in reverse.

## 3.4 Quantities of Dangerous Goods Stored and Handled

The DGs stored at the site are for various customers and may fluctuate with customer requirements. The classes and quantities to be approved in the project are summarised **Table 3-1**. Indicative locations of the DGs have been provided in **Figure 3-2.**

**Table 3-1: Maximum Classes and Quantities of Dangerous Goods Stored**

| Class | Description | Quantity |
|---|---|---|
| 2.2 | R-134a / R-410a | 1,000 L |
| 9 | Lithium Batteries | 9,000^ tonne |
| C1 | Transformer oils | 33,000* kg |
| C1 | Diesel | 5,000 L |

^Based upon upper estimates from design documents

*Estimated based upon similar switch rooms on other sites

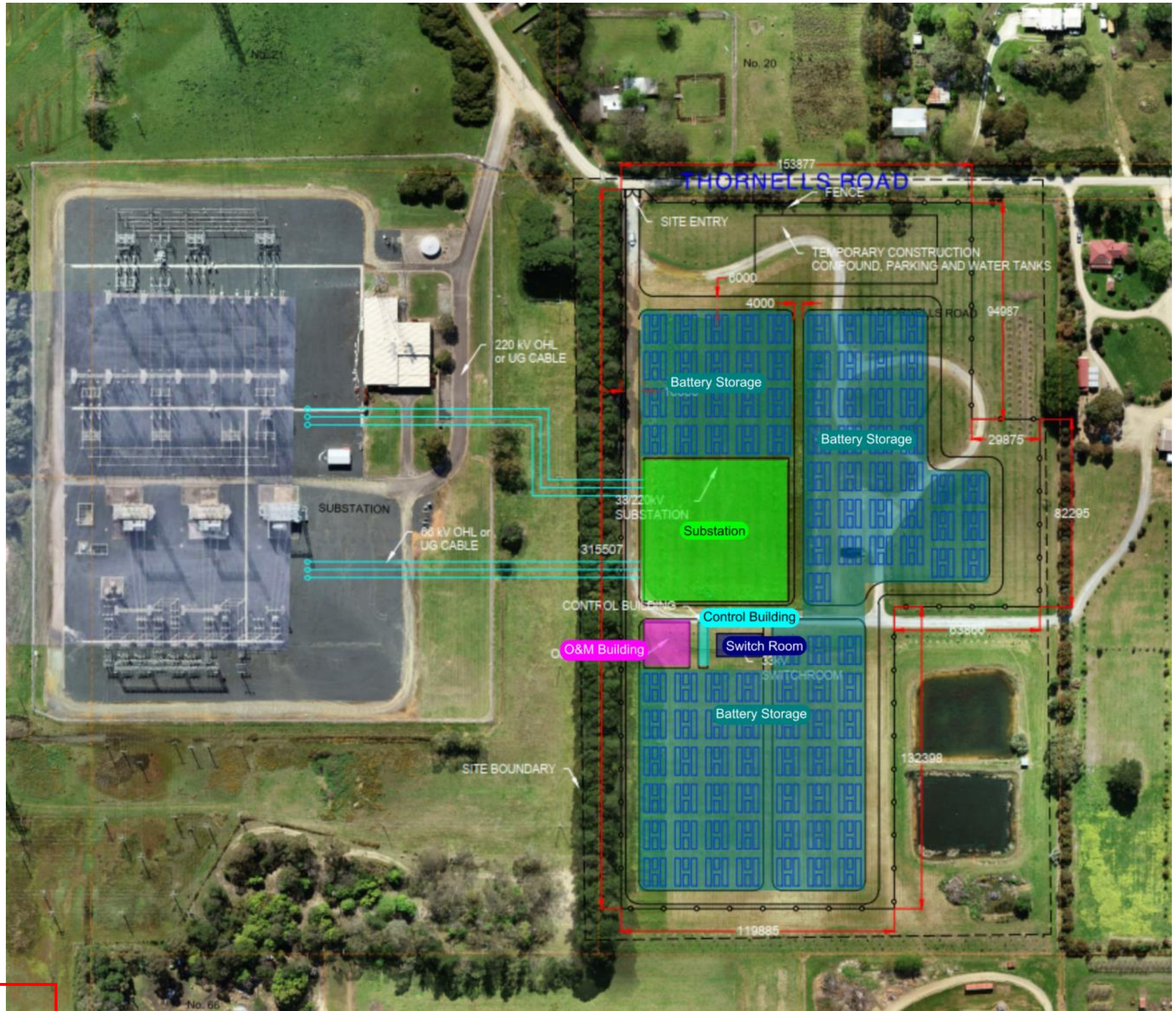



Figure 3-2: Site Layout

# 4.0 Fire Protection Quantity Assessment

## 4.1 Introduction

The Victorian Dangerous Goods (Storage and Handling) Regulations (VDGR, Ref. [4]) covers the storage and handling of materials classified as Dangerous Goods (DGs). These Regulations provides an assessment of the required documentation to be prepared for a site based upon a threshold based approach for each class of DG stored at a site. As shown in **Section 3.4** a range of products will be stored as part of site operations which are classified as DGs; hence, the site is subject to the VDGR. The main purpose of the assessment is to determine whether additional overview is required from a regulatory perspective in terms of Fire & Rescue Victoria (FRV) involvement. This is determined by the threshold "Fire Protection Quantity" (FPQ) within the VDGR. Provided in the following section is an assessment of the FPQ and the associated implications for the site approval process.

## 4.2 Assessment

As noted, the assessment is based upon thresholds provided in the VDGR. The applicable thresholds for the site have been extracted from the Regulation to assess where the site will sit within the regulatory framework for DGs. The results of the assessment are shown in **Table 4-1**.

**Table 4-1: Fire Protection Quantity Assessment**

| Class | Description | Quantity | Placard | Manifest | FPQ | Determination |
|---|---|---|---|---|---|---|
| 2.2 | R-134a / R-410a | 1,000 L | 5,000 L | 10,000 L | 20,000 L | n/a |
| 9 | Lithium Batteries | 9,000 T | 5 T | 10 T | 20 T | FPQ |
| C1 | Transformer oils | 33,000* kg | 10,000 L | 100,000 L | 100,000 L | Placard |
| C1 | Diesel | 5,000 L | 10,000 L | 100,000 L | 100,000 L | n/a |

Based upon a review of **Table 4-1** the site would be classified as a FPQ site.

## 4.3 Implications

The assessment determined that the site would be classified as a FPQ site which requires referral to FRV which would occur regardless due to the presence of buildings at the site. Typically, this would require a design assessment of the project to demonstrate compliance with an applicable DG design standard. However, the site is being triggered by the batteries which are classified as a Class 9 DG which technically only exists during transport and not storage. Nonetheless, the VDGR include this as an assessable quantity.

The design standard for Class 9 batteries, AS/NZS 4681:2000 (Ref. [6] is extremely dated and only covers DGs stored in buildings as the risks for external storage are relatively minor. Furthermore, the standard was based upon battery designs from 2000 which did not include the protection incorporated in modern batteries (i.e. temperature and voltage monitoring, cooling, etc.) and were based upon chemistries more likely to result in thermal decomposition (i.e. lithium metal). Therefore, there is no real design guidance available for such battery installation (i.e. Mornington BESS) from a DG perspective.

The risks are mitigated via the design of the battery modules themselves and the availability of fire protection at the site. FRV will expect to see some ability (i.e. presence of hydrants) to fight a fire at the site should one occur; however, this would be best discussed with FRV based upon the remoteness of the site (i.e. a site not within the immediate turnout area of a fire station).

Additional implications include those relating to the documentation which is required to be prepared by the VDGR. Documentation required for a site exceeding manifest levels is as follows:

- Risk assessment
- Register
- Manifest
- Notification to the Regulator
- Emergency Response Plan
- Emergency Services Information Booklet
- Placard schedule
- Site layout

Each of these items have been discussed further in the following subsections in terms of what they entail and whether they will be submitted to a Regulator (i.e. WorkSafe Victoria) for approval.

### 4.3.1 Risk Assessment

A risk assessment is required by Clause 27 of the VDGR which requires the risks associated with an activity or storage to be controlled. The DG risk assessment is the documentation prepared to demonstrate the risks have been assessed with the required controls incorporated into the site design / operation to an acceptable level as required by the Regulation. This document is not submitted to a Regulator, but is a requirement of the operator to demonstrate they have fulfilled their obligations under the VDGR. This document is likely to only be reviewed by a Regulator if they attend the site as part of an inspection or due to an incident at the site requiring their involvement.

### 4.3.2 Register

A register is required under Clause 60 of the VDGR and is a summary of the DGs stored on site along with the Safety Data Sheets (SDS) for the products stored. The register also links into the findings of the risk assessment closing the loop from the summary document to the risk assessment. The register is not submitted to a Regulator for review but is required to fulfil the operators obligations under the VDGR.

### 4.3.3 Manifest

The manifest is required under Clause 45 of the VDGR. The document is another summary document which is submitted along with the notification to the Regulator. The purpose of the manifest is to provide information about the types and quantities of DG stored to FRV should an incident occur at the site.

While the document is submitted to the Regulator it is typically for information purposes and does not require approval by them.

### 4.3.4 Notification to the Regulator

The notification is required by Clause 66 of the VDGR and is the driving link between the manifest and the Regulator. It is a form which details the specifics of the DG depots at a site and how they interlink with the manifest. The notification is used to form a database of sites which store DGs exceeding the manifest level. While the notification is not typically reviewed, the operator will receive an acknowledgement from the Regulator which they use to demonstrate they have notified the Regulator as required by the VDGR.

### 4.3.5 Emergency Response Plan

The Emergency Response Plan (ERP) is required by Clause 55. The purpose is to outline the potential emergencies (i.e. fire, bush fire, natural disaster, etc.) and the associated mitigation and response measures. The document is site specific and is submitted to the FRV for review and approval.

### 4.3.6 Emergency Services Information Booklet

The Emergency Services Information Booklet (ESIB) is an accompanying document to the ERP and is essentially a summary document of the ERP. This is submitted to the FRV for review and approval.

### 4.3.7 Placard Schedule

The site is required to be placarded under Clause 47 and the placard schedule is a document which details where the placards are required to achieve compliance with the VDGR. The placard schedule is not submitted to the Regulator but is used to ensure the correct placards have been installed.

### 4.3.8 Site Layout

The site layout is required by Clause 8 of Schedule 3 of the VDGR and accompanies both the manifest and the notification. The purpose of the layout is to show where the DGs are stored around the site along with other points of interest to FRV including; power isolation points, valve isolation points, drains, etc. to assist them in coordinating a response (i.e. isolate power prior to attacking a fire) or prevent contaminated water from being discharged from the site.

### 4.3.9 General

The documentation listed above is not required prior to construction but would be required to be in place 2 weeks prior to occupation.

# 5.0 Hazard Identification

## 5.1 Introduction

A hazard identification table has been developed and is presented at **Appendix A**. This table has been developed following the recommended approach in Hazardous Industry Planning Advisory Paper No .6, Hazard Analysis Guidelines (Ref. [1]). The Hazard Identification Table provides a summary of the potential hazards, consequences and safeguards at the site. The table has been used to identify the hazards for further assessment in this section of the study. Each hazard is identified in detail and no hazards have been eliminated from assessment by qualitative risk assessment prior to detailed hazard assessment in this section of the study.

In order to determine acceptable impact criteria for incidents that would not be considered for further analysis, due to limited impact offsite, the following approach has been applied:

- *Fire Impacts* - It is noted in Hazardous Industry Planning Advisory Paper (HIPAP) No. 4 (Ref. [2]) that a criterion is provided for the maximum permissible heat radiation at the site boundary (4.7 kW/m$^2$) above which the risk of injury may occur and therefore the risk must be assessed. Hence, to assist in screening those incidents that do not pose a significant risk, for this study, incidents that result in a heat radiation less that at 4.7 kW/m$^2$, at the site boundary, are screened from further assessment.

  Those incidents exceeding 4.7 kW/m$^2$ at the site boundary are carried forward for further assessment (i.e. frequency and risk). This is a conservative approach, as HIPAP No. 4 (Ref. [2]) indicates that values of heat radiation of 4.7 kW/m$^2$ should not exceed 50 chances per million per year at sensitive land uses (e.g. residential). It is noted that the closest residential area is approximately 80 m from the site, hence, by selecting 4.7 kW/m$^2$ as the consequence impact criteria (at the adjacent industrial site boundary) the assessment is considered conservative.

- *Explosion* - It is noted in HIPAP No. 4 (Ref. [2]) that a criterion is provided for the maximum permissible explosion over pressure at the site boundary (7 kPa) above which the risk of injury may occur and therefore the risk must be assessed. Hence, to assist in screening those incidents that do not pose a significant risk, for this study, incidents that result in an explosion overpressure less than 7 kPa, at the site boundary, are screened from further assessment. Those incidents exceeding 7 kPa, at the site boundary, are carried forward for further assessment (i.e. frequency and risk). Similarly, to the heat radiation impact discussed above, this is conservative as the 7 kPa value listed in HIPAP No. 4 relates to residential areas, which are over approximately 80 m from the site.

- *Toxicity* – Toxic substances have been proposed to be stored at the site; hence, toxicity has been assessed.

- *Property Damage and Accident Propagation* - It is noted in HIPAP No. 4 (Ref. [2]) that a criterion is provided for the maximum permissible heat radiation/explosion overpressure at the site boundary (23 kW/m$^2$/14 kPa) above which the risk of property damage and accident propagation to neighbouring sites must be assessed. Hence, to assist in screening those incidents that do not pose a significant risk to incident propagation, for this study, incidents that result in a heat radiation heat radiation less than 23 kW/m$^2$ and explosion over pressure less than 14 kPa, at the site boundary, are screened from further assessment. Those incidents exceeding 23 kW/m$^2$ at the site boundary are carried forward for further assessment with respect to incident propagation (i.e. frequency and risk).

- _Societal Risk_ – HIPAP No. 4 (Ref. [2]) discusses the application of societal risk to populations surrounding the proposed project. It is noted that HIPAP No. 4 indicates that where a development proposal involves a significant intensification of population, in the vicinity of such a project, the change in societal risk needs to be taken into account. In the case of the project, there is currently no significant intensification of population around the proposed site; however, the adjacent land has been rezoned residential; hence, there will be a residential zoned housing area located approximately 80 m from the site. Therefore, societal risk has been considered in the assessment.

## 5.2 Properties of Dangerous Goods

The type of DGs and quantities stored and used at the site has been described in **Section 3**. **Table 5-1** provides a description of the DGs to be stored and handled at the site, including the Class and the hazardous material properties of the DG Class.

**Table 5-1: Properties* of the Dangerous Goods and Materials Stored at the Site**

| Class | Hazardous Properties |
|---|---|
| 2.2 – Non-Flammable, Non-Toxic Gas | Non-flammable, non-toxic gases are those which do not pose a flammable or toxicity risk and are therefore relatively benign. However, such gases may pose asphyxiation risks as they can exclude oxygen at the point of release creating an oxygen deficient environment. |
| 9 – Miscellaneous DGs | Class 9 substances and articles (miscellaneous dangerous substances and articles) are substances and articles which, during transport present a danger not covered by other classes. Releases to the environment may cause damage to sensitive receptors within the environment. It is noted that the Class 9s stored within this project are lithium ion batteries which may undergo thermal runaway (i.e. escalating reaction resulting in heat which ultimately leads to failure of the battery and a fire). |
| Combustible Liquids | Combustible liquids are typically long chain hydrocarbons with flash points exceeding 60.5$^{o}$C. Combustible liquids are difficult to ignite as the temperature of the liquid must be heated to above the flash point such that vapours are generated which can then ignite. This process requires either sustained heating or a high-energy ignition source. |

* The Australian Code for the Transport of Dangerous Goods by Road and Rail (Ref. [7]

## 5.3 Hazard Identification

Based on the hazard identification table presented in **Appendix A**, the following hazardous scenarios have been developed:

- Li-ion battery fault, thermal runaway and fire.
- Electrical equipment failure and fire.
- Transformer internal arcing, oil spill, ignition and bund fire.
- Refrigerant gas release and asphyxiation hazard.
- Release of diesel, ignition and pool fire.

Each identified scenario is discussed in further detail in the following sections.

## 5.4 Li-Ion Battery Fault, Thermal Runaway and Fire

Lithium ion (Li-ion) batteries are composed of a metallic anode and cathode which allows for electrons released from the anode to travel to the cathode where positively charged ions in the solute migrate to the cathode and are reduced. The flow of electrons provides the source of energy which is discharged from a battery and used for work. In a Li-ion battery, the lithium metal composites (a composite of lithium with other metals such as cobalt, manganese, nickel, or any combination of these metals) oxidises (loses an electron) becoming a positively charged ion in solution which migrates through the battery separator to the cathode. At the same time, the lost electron travels through the circuit to the cathode. The lithium ions in solution then recombine with the electron at the cathode forming lithium metal within the cathodic metal composite. This process is shown in **Figure 5-1**.

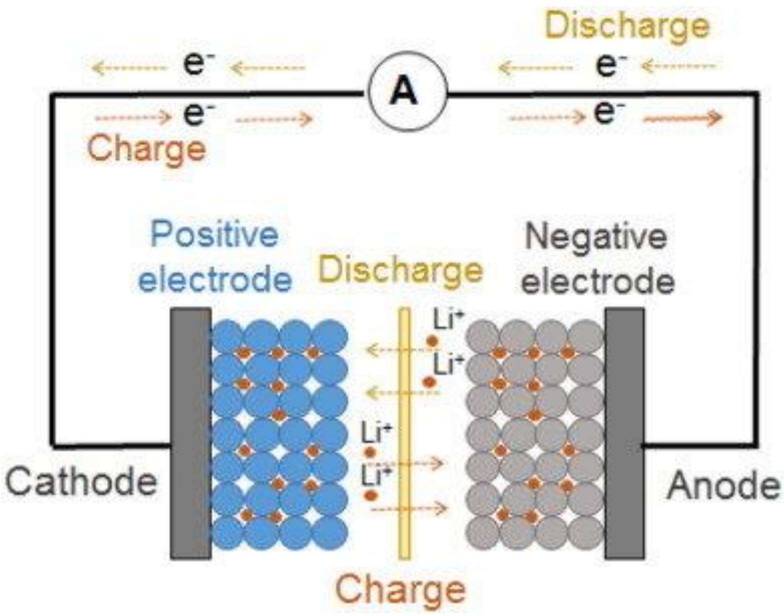



**Figure 5-1: Cathode and Anode of a Battery (Source Research Gate)**

Initial lithium batteries were designed around lithium metal (i.e. no composite structure) due to the high energy density yielded by the metal. However, when overcharging a battery, lithium ions can begin to plate on the anode in the form of lithium dendrites. Eventually, the dendrites pierce the separator within the battery resulting in a short of the battery which could result in heat, fire, or explosion of the battery. The technology evolved to move away from lithium metal to lithium ions (held within composite materials) which reduced the incidence of lithium dendrites forming resulting in an overall safer battery.

Despite the improvement in battery technology, there are several degradation mechanisms that are still present within the battery which can result in thermal runaway. These include:

- Chemical reduction of the electrolyte at the anode
- Thermal decomposition of the electrolyte
- Chemical reduction of the electrolyte at the cathode
- Thermal decomposition by the cathode and the anode
- Internal short circuit by charge effects

These effects arise primarily as a result of high discharge, overcharging, or water ingress into the battery which results in a host of bi-products being formed within the battery during charge and discharge cycles.

As a result, lithium ion batteries are equipped with several safety features to prevent the batteries from charging or discharging at voltages which result in battery degradation which lead to shorting of the battery and thermal runaway. Safety features generally include:

- Shut-down separator (for overheating)
- Tear-away tab (for internal pressure relief)
- Vent (pressure relief in case of severe outgassing)
- Thermal interrupt (overcurrent/overcharging/environmental exposure)

These features are designed to prevent overcharging or excessive discharge, pressurisation arising from heat generated at the anode or from battery contamination. Protection techniques for Li-ion batteries are standard; hence, the potential for thermal runaway to occur in normal operation is incredibly low with the only exceptions being where batteries are manufactured poorly or due to manufacturing faults, or battery damage (i.e. battery cell is ruptured as this can short circuit the battery resulting in thermal runaway).

Given the ubiquitous nature of lithium ion batteries, thermal runaway is not considered a credible threat when used in a battery storage. In terms of physical damage, the batteries are contained within in modules which are located within a fenced area; therefore, there is a low potential for damage to occur to the batteries which may initiate an incident.

Notwithstanding this, there is the potential for thermal runaway to occur which may consume the whole battery module which may result in offsite impacts or propagation risks to adjacent modules. Therefore, this incident has been carried forward for further analysis.

## 5.5 Electrical Equipment Failure and Fire

Electrical equipment is located within the switch room which may fail resulting in overheating, arcing, etc. which could initiate a fire. In the event of a fire, it may begin to propagate to adjacent combustible materials (i.e. wiring). It is noted that electrical equipment fires typically start by smouldering before flame ignition occurs resulting in a slow fire development.

The type of equipment used within the project is ubiquitous throughout the world and across industry segments and is therefore not a unique fire scenario. Based upon fire development within switch rooms the fire would be considered to be relatively slow in growth and would be unlikely to result in substantial impacts in terms of offsite impact or incident propagation. Therefore, this incident has not been carried forward for further analysis.

## 5.6 Transformer Internal Arcing, Oil Spill, Ignition and Bund Fire

Transformers contain oil which is used to cool the units during operation. If arcing occurs within the transformer (e.g. due to a low oil level), the high energy passing through the coolant vaporises the oil into light hydrocarbons (methane, ethane, acetylene, etc.) resulting in rapid pressurisation within the reservoir. To minimise the likelihood of such occurrence, transformers are fitted with a low oil pressure switches and a pressure surge switch (Buckholtz relay). These devices identify potential oil and pressure events within the transformer, isolating power and alarming operators.

Notwithstanding the protection systems, if the pressure rise exceeds the structural integrity of the reservoir, and the installed pressure relief devices, the reservoir can rupture allowing the release of oil into the bund. The rupture also allows oxygen to enter the reservoir. The temperature of the gases is above the auto ignition point, but this does not occur until oxygen is present. When oxygen enters the reservoir, the gases auto ignite which generates sufficient heat to ignite the oil in the bund.

As there is the potential for a fire to occur within the substation transformers, this incident has been carried forward for further analysis.

The transformers haven't been subject to detailed design at this stage; hence, the following recommendation has been made:

- The transformers shall be designed according to the requirements detailed in AS 1940-2017 "*The storage and handling of flammable and combustible liquids*" to minimise the potential for fire or explosion to occur within the transformers.

## 5.7 Refrigerant Gas Release and Asphyxiation Hazard

The refrigeration system will be used to providing air conditioning and temperature control in the control room and other areas requiring temperature control. A simplified explanation of how a refrigeration system operates to cool an area is provided below.

A refrigeration system contains four essential components:

1. Compressor
2. Expansion valve
3. Refrigerant
4. Heat exchanging pipework

**Figure 5-2** has been provided to aid in the description of how the refrigeration system operates to cool a specific area. The refrigeration system cycles the refrigerant gas through the system.

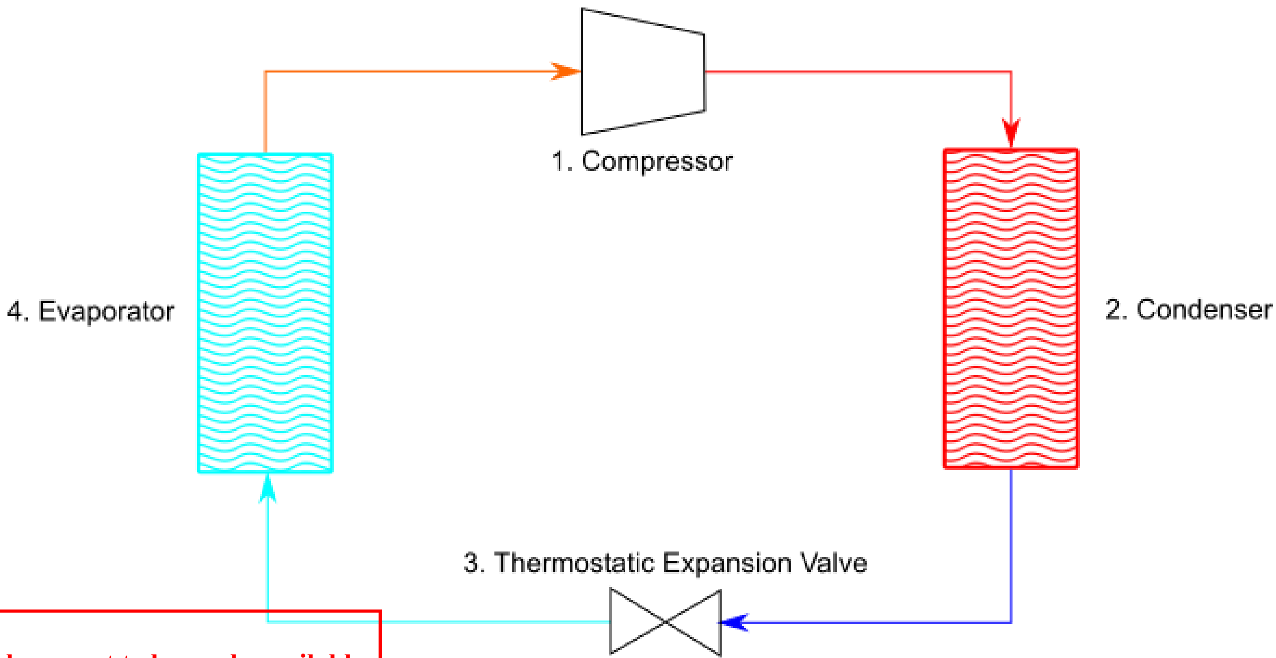



**Figure 5-2: Refrigeration Flow Diagram**

1. Refrigerant gas from the evaporator enters the compressor where it is pressurised (red) which increases the temperature of the gas. The gas travels along the pipework to the condenser.
2. The condenser is coiled to provide a large surface area to allow the hot gas to dissipate heat. As the gas releases heat through the coils, the gas condenses into a pressurised liquid (dark blue).
3. The pressurised liquid enters the thermostatic expansion valve where it expands across the valve seat, resulting in a sudden drop of pressure of the liquid refrigerant and rapid expansion which cools the liquid (light blue).
4. The cooled refrigerant enters the evaporator which is coiled to provide a large surface area to facilitate exchange of heat from the area to be cooled into the refrigerant. As the refrigerant absorbs heat it boils into a gaseous state.
5. On completion of the cycle, the refrigerant is drawn into the compressor and the cycle repeats.

Refrigeration systems are commonly used in all air conditioning systems which are not subject to frequent releases and if they do occur the leaks are minor resulting in minimal amounts of escaped gas. Therefore, a rupture release would not be considered to be a credible scenario given the ubiquitous nature of these systems. In the event a small release occurs it will be dissipated quickly via wind movement around the refrigeration unit prevent accumulation. Furthermore, such a release would be insufficient to impact offsite; hence, this incident has not been carried forward for further analysis.

## 5.8 Release of Diesel, Ignition and Pool Fire

Diesel will be used on site equipment primarily during construction but may be present during operations where equipment needs to be moved / relocated / site vehicles. The diesel will likely be stored in a portable refuelling tank which typically are double skinned (i.e. integrally bunded) tanks complying with AS 1940-2017 (Ref. [8]). The presence of two tanks (i.e. inner and outer tank) results in the potential for external leakage to be incredibly low as this requires the failure of both tanks simultaneously. Therefore, a full release of diesel fuel from the tanks would not be expected to occur.

Nonetheless, if a substantial release did occur, combustible liquids do not emit flammable vapours which results in the ignition probability being incredibly. To ignite the spill, a sustained ignition source with sufficient energy would be required to be exposed to create sufficient heat to vapourise the liquid to initiate combustion. Should this occur, the fire would grow to the dimensions of the spill which would be unlikely to be sufficient to result in an offsite impact.

Due to the low likelihood of release, ignition and consequences impacts from a diesel pool fire an offsite impact is not considered to be a credible scenario; hence, this incident has not been carried forward for further analysis.

# 6.0 Consequence Analysis

## 6.1 Incidents Carried Forward for Consequence Analysis

The following incidents were identified to have potential to impact off site:

- Li-ion battery fault, thermal runaway and fire.
- Transformer internal arcing, oil spill, ignition and bund fire.

Each incident has been assessed in the following sections.

## 6.2 Li-Ion Battery Fault, Thermal Runaway and Fire

There is potential that a Li-Ion battery may fault resulting in thermal decomposition and fire which may spread throughout the whole fire unit if not isolated / protected. A detailed analysis has been conducted in **Appendix B** and the radiant heat impact distances estimated for this scenario are shown in **Table 6-1**. The radiant heat contours associated with a fire occurring within a Li-Ion battery module are shown in **Figure 6-1**. It is noted the contours are located at units in the worst case location with respect to the site boundary.

**Table 6-1: Radiant Heat from a Li-Ion Battery Fire**

| Heat Radiation (KW/m$^2$) | Distance (m) |
|---|---|
| 35 | 3.3 |
| 23 | 4.9 |
| 12.6 | 7.8 |
| 4.7 | 14.8 |

As can be seen in **Figure 6-1** the radiant heat contours at 4.7 kW/m$^2$ do not impact over the site boundary; hence, the potential for a fatality to occur offsite would not be expected to occur.

The 23 kW/m$^2$ contour is associated with incident propagation which also does not impact over the site boundary. Therefore, incident propagation offsite would not be expected to occur from a Li-Ion battery module fire. It is noted that the contour may impact the adjacent Li-Ion battery units; however, it is noted the analysis is incredibly conservative as it assumes the whole area of a unit is on fire which ignores the gaps between individual units within the module cluster. Furthermore, it doesn't take into account the barrier to direct radiant heat exposure as the units are enclosed and typically have temperature control. Therefore, incident propagation between units would also not be expected to occur.

In the event radiant heat did impact the battery enclosure the protection systems present within the battery units (i.e. temperature and voltage monitoring and isolations) would activate preventing propagation of the incident into adjacent units.

As the contours for fatality and incident propagation do not impact over the site boundaries this incident has not been carried forward for further analysis.


**Figure 6-1: Li-Ion Battery Module Fire Radiant Heat Contours**

## 6.3 Transformer Internal Arcing, Oil Spill, Ignition and Bund Fire

There is potential that arcing may occur within the transformers which may lead to generation of gases and pressure above the structural integrity of the oil reservoir which may rupture leaking oil into the bund. As a result of the arcing and rupture, the oil may ignite leading to a bund fire within the dimensions of the bund. A detailed analysis has been conducted in **Appendix B** and the radiant heat impact distances estimated for this scenario are shown in **Table 6-2**. The radiant heat contours associated with a fire occurring within a transformer bund are shown in **Figure 6-2**. It is noted the contours are located at the worst-case location within the substation with respect to the site boundary.

**Table 6-2: Radiant Heat from a Transformer Bund Fire**

| Heat Radiation (kW/m$^2$) | Distance (m) |
|---|---|
| 35 | 3.3 |
| 23 | 4.9 |
| 12.6 | 7.8 |
| 3.0 | 14.9 |

As can be seen in **Figure 6-2** the radiant heat contours at 4.7 kW/m$^2$ do not impact over the site boundary; hence, the potential for a fatality to occur at off site would not be expected to occur.

The 23 kW/m$^2$ contour is associated with incident propagation which also does not impact over the site boundary. Therefore, incident propagation offsite would not be expected to occur from transformer bund fire.

As the contours for fatality and incident propagation do not impact over the site boundaries this incident has not been carried forward for further analysis.

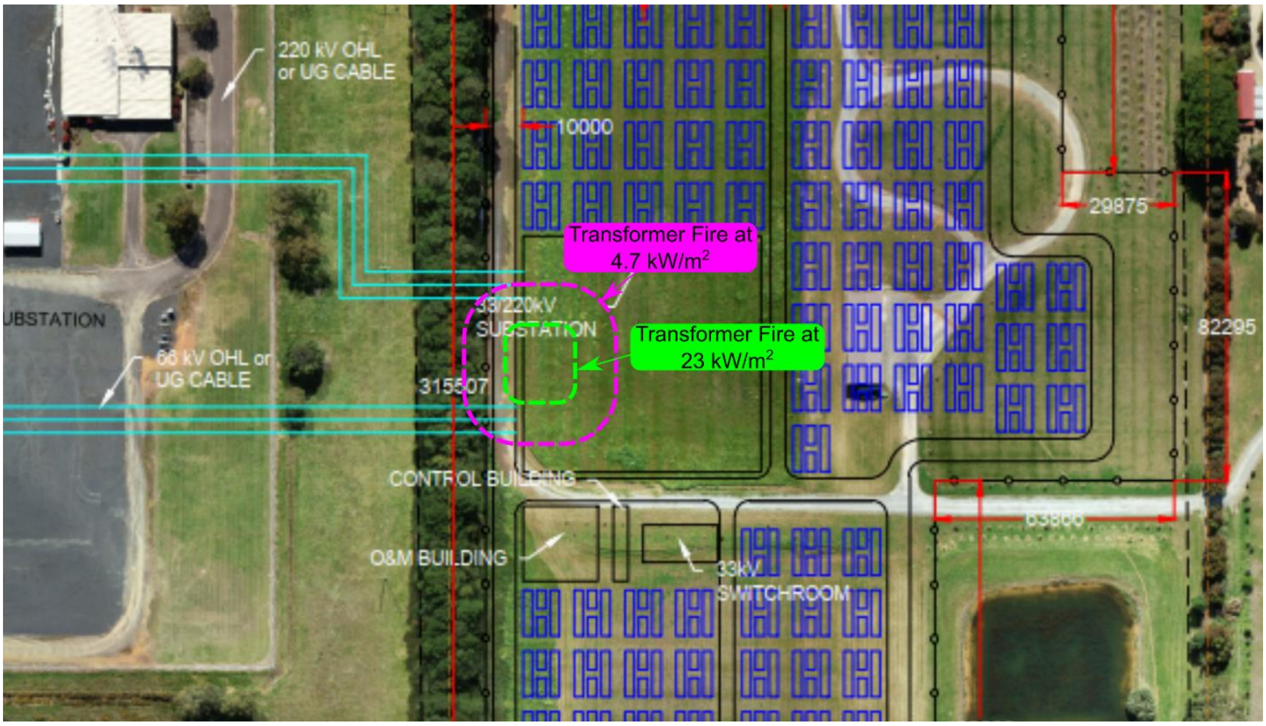



**Figure 6-2: Transformer Bund Fire Radiant Heat Contours**

# 7.0 Frequency Analysis

## 7.1 Incidents Carried Forward for Frequency Analysis

No incidents were identified to have an offsite impact; hence, no frequency analysis has been conducted as the offsite impact would be zero (0).

## 7.2 Total Fatality Risk

As noted there is no potential for offsite impact in terms of incident propagation or fatality; hence, the fatality risk would be zero (0); nonetheless, the results have been summarised in **Table 7-1**.

**Table 7-1: Total Fatality Risk**

| Incident | Fatality Risk |
|---|---|
| Li-Ion Fire | 0 |
| Transformer Fire | 0 |
| **Total** | **0** |

## 7.3 Comparison Against Risk Criteria

The acceptable criteria have been taken from the NSW Department of Planning, Industry and Environment *Hazardous Industry Planning Advisory Paper No. 4 – Risk Criteria for Land Use Safety Planning* (Ref. [2]) and used for guidance as Victoria does not have any published criteria for offsite risk. The acceptable risk criteria published in the guideline relates to injury, fatality and property damage. The values in the guideline present the maximum levels of risk that are permissible at the land use under assessment.

The adjacent land use is classified as an industrial site (under the guidelines). For industrial facilities, the maximum permissible fatality risk is 50 chances pmpy. The assessed highest fatality risk is 0 pmpy at the closest site boundary; hence, the highest risk is within the permissible criteria and therefore all other risk points beyond the boundary would be within the acceptable criteria.

Based on the estimated injury risk, conducted in the analysis above, the risks associated with injury and nuisances at the closest residential area are not considered to be exceeded.

## 7.4 Incident Propagation

The same guidelines provide acceptable risk criteria (Ref. [2]) for incident propagation as 50 chances pmpy. A review of the scenarios that may lead to incident propagation shows that the 23 $kW/m^2$ contour was not observed to impact offsite; hence, the potential for incident propagation is zero (0) which is less than the acceptable risk criteria for incident propagation.

# 8.0 Conclusion and Recommendations

## 8.1 Conclusions

A hazard identification table was developed for the Mornington BESS project to identify potential hazards that may be present at the site as a result of operations or storage of materials. Based on the identified hazards, scenarios were postulated that may result in an incident with a potential for offsite impacts. Postulated scenarios were discussed qualitatively and any scenarios that would not impact offsite were eliminated from further assessment. Scenarios not eliminated were then carried forward for consequence analysis.

Incidents carried forward for consequence analysis were assessed in detail to estimate the impact distances. Impact distances were developed into scenario contours and overlaid onto the site layout diagram to determine if an offsite impact would occur. The consequence analysis showed that no scenarios would have the potential to impact off site; hence, no incidents were carried forward for detailed frequency analysis.

Notwithstanding this, a frequency assessment was prepared to highlight that the risk at the site boundary would be zero (0) as the consequence contours would not impact over the site boundary. As the risk was calculated to be zero (0) it would be below the acceptable criteria and would be considered a permissible development.

In addition, incidents exceeding 23 $kW/m^2$ were reviewed which indicated that the contours from such incidents would not impact over the site boundary and therefore incident propagation would not be expected to occur and would be below the acceptable criteria.

Based on the analysis conducted, it is concluded that the risks at the site boundary are not considered to exceed the acceptable risk criteria; hence, the project would only be classified as potentially hazardous and would be permitted within the current land zoning for the site.

## 8.2 Recommendations

Notwithstanding the conclusions drawn, the following recommendations have been made and should be undertaken to cover the battery and inverter equipment as well as common hazards for a mechanical site prior to the commencement of operations at the BESS project to the extent dangerous goods exceed any thresholds:

- A Dangerous Goods (DG) risk assessment shall be prepared for the site.
- A DG register shall be prepared for the site.
- A site manifest shall be prepared at the site in accordance with Schedule 3 of the Victorian Dangerous Goods Regulation (VDGR).
- The site shall notify the Regulator (i.e. WorkSafe Victoria) of the presence of DGs.
- A site layout shall be prepared for the site in accordance with Schedule 3 of the VDGR.
- A placard schedule shall be prepared for the site to ensure the correct placards are installed.
- An Emergency Response Plan (ERP) shall be prepared for the site and submitted to the Fire & Rescue Victoria (FRV).
- An Emergency Services Information Booklet (ESIB) shall be prepared for the site and submitted to the FRV.

- The transformers shall be designed according to the requirements detailed in AS 1940-2017 "*The storage and handling of flammable and combustible liquids*" to minimise the potential for fire or explosion to occur within the transformers.

## 9.0 References

[1] Department of Planning, Industry and Environment, “Hazardous Industry Planning Advisory Paper No. 6 - Guidelines for Hazard Analysis,” Department of Planning, Industry and Environment, Sydney, 2011.

[2] Department of Planning, Industry and Environment, “Hazardous Industry Planning Advisory Paper No. 4 - Risk Criteria for Land Use Safety Planning,” Department of Planning, Industry and Environment, Sydney, 2011.

[3] WorkSafe Victoria, “Occupational Health and Safety Regulation,” WorkSafe Victoria, Melbourne, 2017.

[4] WorkSafe Victoria, “Victoria Dangerous Goods Regulation 2012 under the Victoria Occupational Health and Safety Regulation 2017,” WorkSafe Victoria, Melbourne, 2012.

[5] Department of Planning, Industry and Environment, Multi-Level Risk Assessment, Sydney: Department of Planning, Industry and Environment, 2011.

[6] Standards Australia, “AS/NZS 4681:2000 - The Storage and Handling of Class 9 (Miscellaneous) Dangerous Goods and Articles,” Standards Australia, Sydney, 2000.

[7] National Transport Commission (NTC), “Australian Code for the Transport of Dangerous Goods by Road & Rail, 7th Edition,” 2011.

[8] Standards Australia, AS 1940-2017 - Storage and Handling of Flammable and Combustible Liquids, Sydney: Standards Australia, 2017.

[9] Standards Australia, “AS/NZS 3000:2007 - Wiring Rules,” Standards Australia, Sydney, 2007.

[10] I. Cameron and R. Raman, Process Systems Risk Management, San Diego: Elsevier, 2005.

[11] F. P. Lees, Loss Prevention in the Process Industries, London: Butterworth-Heinemann, 2005.

## Appendix A

# Hazard Identification Table

## A1. Hazard Identification Table

| Area/Operation | Hazard Cause | Hazard Consequence | Safeguards |
|---|---|---|---|
| Battery Storage | • Failure of lithium ion battery protection systems | • Thermal runaway resulting in fire or explosion<br>• Incident propagation through battery cells | • Batteries are tested by manufacturer prior to sale / installation<br>• Overcharging and electrical circuit protection<br>• Battery monitoring systems<br>• Thermal and smoke detection<br>• Batteries composed of subcomponents (i.e. BBU, cells) reducing risk of substantial component failure<br>• Batteries are not located in areas where damage could easily occur (i.e. within the fenced property)<br>• Hydrant protection<br>• Electrical systems designed per AS/NZS 3000:2007 (Ref. [9]) |
| Switch rooms, MMR rooms, communications, data halls, etc. | • Arcing, overheating, sparking, etc. of electrical systems | • Ignition of processors and other combustible material within servers and subsequent fire | • Hydrant protection<br>• Fires tend to smoulder rather than burn<br>• Isolated location<br>• Switch room contained within a structure |
| Substation | • Arcing within transformer, vaporisation of oil and rupture of oil reservoir | • Transformer oil spill into bund and bund fire | • Bunded<br>• Fire protection (hydrants, extinguishers)<br>• Isolated location |
| Refrigerant gases | • Failure of flanges, valves, compressors, etc. and release of gas | • Non-flammable, non-toxic gases pose no fire issue<br>• Potential oxygen exclusion and asphyxiation risk | • Relatively low volume of gas used<br>• Robust and commonly used systems which are not prone to large leaks |

| Area/Operation | Hazard Cause | Hazard Consequence | Safeguards |
|---|---|---|---|
| | | | • Open outdoor area provides natural ventilation preventing accumulation of gases |
| Diesel | • Release of combustible liquid and ignition | • Pool fire at the point of release | • Combustible liquids do not give off flammable vapours at atmospheric conditions<br>• Low ignition probability<br>• Relatively small release of diesel<br>• AS 1940-2017 compliant storages |

# Appendix B

## Consequence Analysis

## B1. Incidents Assessed in Detailed Consequence Analysis

The following incidents are assessed for consequence impacts.

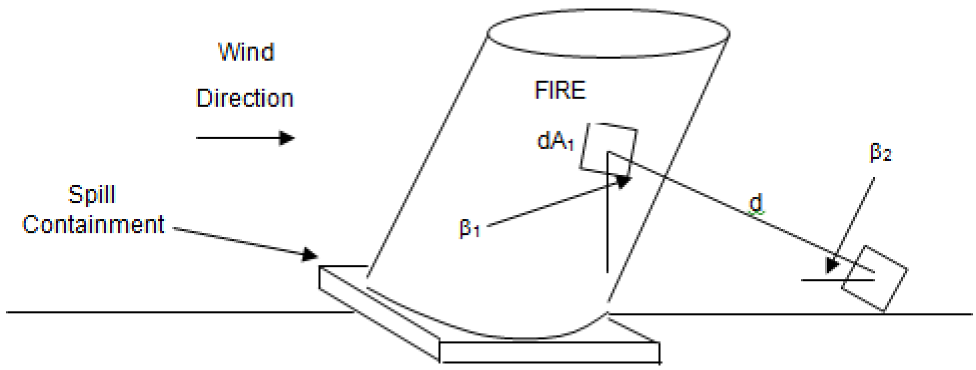
- Li-ion battery fault, thermal runaway and fire.
- Transformer internal arcing, oil spill, ignition and bund fire.

Each incident has been assessed in the sections below.

## B2. Spreadsheet Calculator (SSC)

The SSC is designed on the basis of finite elements. The liquid flame area is calculated as if it is a circle to find the radius for input into the SSC model.

The SSC is designed on the basis of finite elements. The liquid flame area is calculated as if it is a circle to find the radius for input into the SSC model. **Appendix Figure B-1** shows a typical pool fire, indicating the target and fire impact details.




**Appendix Figure B-1: Heat Radiation on a Target from a Cylindrical Flame**

A fire in a bund or at a tank roof will act as a cylinder with the heat from the cylindrical flame radiating to the surrounding area. A number of mathematical models may be used for estimating the heat radiation impacts at various distances from the fire. The point source method is adequate for assessing impacts in the far field; however, a more effective approach is the view factor method, which uses the flame shape to determine the fraction of heat radiated from the flame to a target. The radiated heat is also reduced by the presence of water vapour and the amount of carbon dioxide in air. The formula for estimating the heat radiation impact at a set distance is shown in **Equation B-1** (Ref. [10]).

$$Q = EF\tau \qquad \textbf{Equation B-1}$$

Where:

- Q = incident heat flux at the receiver (kW/m$^2$)
- E = surface emissive power of the flame (kW/m$^2$)
- F = view factor between the flame and the receiver
- $\tau$ = atmospheric transmissivity

The calculation of the view factor (F) in **Equation B-1** depends upon the shape of the flame and the location of the flame to the receiver. F is calculated using an integral over the surface of the flame, S (Ref. [10]). The formula can be shown as:

$$F = \int\int_{S} \frac{\cos\beta_1 \cos\beta_2}{\pi d^2}$$ **Equation B-2**

**Equation B-2** may be solved using the double integral **or** using a numerical integration method in spread sheet form. This is explained below.

For the assessment of pool fires, a Spread Sheet Calculator (SCC) has been developed, which is designed on the basis of finite elements. The liquid flame area is calculated as if the fire is a vertical cylinder, for which the flame diameter is estimated based on the fire characteristics (e.g. contained within a bund). Once the flame cylindrical diameter is estimated, it is input into the SSC model. The model then estimates the flame height, based on diameter, and develops a flame geometric shape (cylinder) on which is performed the finite element analysis to estimate the view factor of the flame. **Appendix Figure B-1** shows a typical pool fire, indicating the target and fire impact details.

The SSC integrates the element $dA_1$ by varying the angle theta $\theta$ (the angle from the centre of the circle to the element) from zero to 90° in intervals of 2.5 degrees. Zero degrees represents the straight line joining the centre of the cylinder to the target (x0, x1, x2) while 90° is the point at the extreme left hand side of the fire base. In this way the fire surface is divided up into elements of the same angular displacement. Note the tangent to the circle in plan. This tangent lies at an angle, gamma, with the line joining the target to where the tangent touches the circle (x4). This angle varies from 90° at the closest distance between the liquid flame (circle) and the target (x0) and gets progressively smaller as $\theta$ increases. As $\theta$ increases, the line x4 subtends an angle phi $\Phi$ with x0. By similar triangles we see that the angle gamma $\gamma$ is equal to 90- $\theta$ - $\Phi$ . This angle is important because the sine of the angle give us the proportion of the projected area of the plane. When $\gamma$ is 90°, sin($\gamma$) is 1.0, meaning that the projected area is 100% of the actual area.

Before the value of $\theta$ reaches 90° the line x4 becomes tangential to the circle. The fire cannot be seen from the rear and negative values appear in the view factors to reflect this. The SSC filters out all negative contributions.

For the simple case, where the fire is of unit height, the view factor of an element is simply given by the expression in **Equation B-3** (Derived from **Equation B-2**):

$$VF = \Delta A \frac{\sin\gamma}{\pi \times X4 \times X4}$$ **Equation B-3**

Where $\Delta$A is the area of an individual element at ground level.

*Note: the denominator (π. x4. x4) is a term that describes the inverse square law for radiation assumed to be distributed evenly over the surface of a sphere.*

Applying the above approach, we see the value of x4 increase as $\theta$ increase, and the value of sin($\gamma$) decreases as $\theta$ increase. This means that the contribution of the radiation from the edge of the circular fire drops off quite suddenly compared to a view normal to the fire. Note that the SSC adds up the separate contributions of **Equation B-3** for values of $\theta$ between zero until x4 makes a tangent to the circle.

It is now necessary to do two things: (i) to regard the actual fire as occurring on top of a fire wall (store) and (ii) to calculate and sum all of the view factors over the surface of the fire from its base to its top. The overall height of the flame is divided into 10 equal segments. The same geometric technique is used. The value of x4 is used as the base of the triangle and the height of the flame, as the height. The hypotenuse is the distance from target to the face of the flame (called X4'). The angle of elevation to the element of the fire (alpha $\alpha$) is the arctangent of the height over the ground distance. From the cos($\alpha$) we get the projected area for radiation. Thus there is a new combined distance and an overall equation becomes in **Equation B-4 (**(Derived from **Equation B-3**):

$$VF = \Delta A \frac{\sin\gamma \times \cos\alpha}{\pi \times X4 \times X4}$$ **Equation B-4**

The SCC now turns three dimensional. The vertical axis represents the variation in $\theta$ from 0 to 90$^o$ representing half a projected circle. The horizontal axis represents increasing values of flame height in increments of 10%. The average of the extremes is used (e.g. if the fire were 10 m high then the first point would be the average of 0 and 1 i.e. 0.5 m), the next point would be 1.5 m and so on).

Thus the surface of the flame is divided into 360 equal area increments per half cylinder making 720 increments for the whole cylinder. Some of these go negative as described above and are not counted because they are not visible. Negative values are removed automatically.

The sum is taken of the View Factors in **Equation B-3**. Actually the sum is taken without the ΔA term. This sum is then multiplied by ΔA which is constant. The value is then multiplied by 2 to give both sides of the cylinder. This is now the integral of the incremental view factors. It is dimensionless so when we multiply by the emissivity at the "face" of the flame (or surface emissive power, SEP), which occurs at the same diameter as the fire base (pool), we get the radiation flux at the target.

The SEP is calculated using the work by Mudan & Croche (Ref. [11] & Ref. [10]) which uses a weighted value based on the luminous and non-luminous parts of the flame. The weighting is based on the diameter and uses the flame optical thickness ratio where the flame has a propensity to extinguish the radiation within the flame itself. The formula is shown in **Equation B-5**.

$$SEP = E_{max}e^{-sD} + E_s(1 - e^{-sD})$$ **Equation B-5**

Where;

$E_{max}$ = 140

S = 0.12

$E_s$ = 20

D = pool diameter

The only input that is required is the diameter of the pool fire and then estimation for the SEP is produced for input into the SSC.

The flame height is estimated using the Thomas Correlation (Ref. [10]) which is shown in **Equation B-6**.

$$H = 42d_p\left[\frac{\dot{m}}{\rho_a\sqrt{gd_p}}\right]^{0.61}$$ **Equation B-6**

Where;

$d_p$ = pool diameter (m)

$\rho_a$ = density of air (1.2 kg/m$^3$ at 20$^o$C)

$\dot{m}$ = burning rate (kg/m$^2$.s)

g = 9.81 m/s$^2$

The transmissivity is estimated using **Equation B-7** (Ref. [10]).

$$\tau = 1.006 - 0.01171(\log_{10} X(H_2O) - 0.02368(\log_{10} X(H_2O))^2 - 0.03188(\log_{10} X(CO_2) + 0.001164(\log_{10} X(CO_2))^2 \quad \textbf{Equation B-7}$$

Where:

- $\tau$ = Transmissivity (%)
- X($H_2O$) = $\frac{R_H \times L \times S_{mm} \times 2.88651 \times 10^2}{T}$
- X($CO_2$) = $\frac{L \times 273}{T}$

and

- $R_H$ = Relative humidity (% expressed as a decimal)
- L = Distance to target (m)
- $S_{mm}$ = saturated water vapour pressure in mm of mercury at temperature (at 25$^o$C $S_{mm}$ = 23.756)
- T = Atmospheric temperature (K)

## B3. Radiant Heat Physical Impacts

**Appendix Table B-1** provides noteworthy heat radiation values and the corresponding physical effects of an observer exposed to these values (Ref. [2]).

**Appendix Table B-1: Heat Radiation and Associated Physical Impacts**

| Heat Radiation (kW/m$^2$) | Impact |
|---|---|
| 35 | • Cellulosic material will pilot ignite within one minute's exposure<br>• Significant chance of a fatality for people exposed instantaneously |
| 23 | • Likely fatality for extended exposure and chance of a fatality for instantaneous exposure<br>• Spontaneous ignition of wood after long exposure<br>• Unprotected steel will reach thermal stress temperatures which can cause failure<br>• Pressure vessel needs to be relieved or failure would occur |
| 12.6 | • Significant chance of a fatality for extended exposure. High chance of injury<br>• Causes the temperature of wood to rise to a point where it can be ignited by a naked flame after long exposure<br>• Thin steel with insulation on the side away from the fire may reach a thermal stress level high enough to cause structural failure |
| 4.7 | • Will cause pain in 15-20 seconds and injury after 30 seconds exposure (at least second degree burns will occur) |
| 2.1 | • Minimum to cause pain after 1 minute |

## B4. Li-Ion Battery Fault, Thermal Runaway and Fire

The battery units are spaced out throughout the site to provide energy storage when drawing energy from the grid and discharging back to the grid. For conservatism, a Li-Ion batter fire has been based upon a fire originating within a battery pack and propagating to the closest batteries. The area covered by a full battery module is approximately 110 m$^2$. This are has been used as an input for the fire dimensions and converted to a circular diameter to input into the SEP and SSC models.

$$D = \sqrt{\frac{4 \times 110}{\pi}} = 11.8\,m$$

The following data was input into the SSC:

- Fire diameter – 11.8 m
- Burning rate – 0.022 kg/m$^2$.s (selected to model combustible materials)

The above information was put into the spreadsheet calculator which calculated the following outputs:

- SEP – 49.0 kW/m$^2$
- Flame height – 10.2 m

The results of the analysis are shown in **Appendix Table B-2.**

**Appendix Table B-2: Heat Radiation Impacts from a Li-Ion Battery Fire**

| Heat Radiation (KW/m$^2$) | Distance (m) |
|---|---|
| 35 | 3.3 |
| 23 | 4.9 |
| 12.6 | 7.8 |
| 4.7 | 14.8 |

## B5. Transformer Internal Arcing, Oil Spill, Ignition and Bund Fire

Transformers contain oil to provide cooling and insulation. If arcing occurs within the transformer, the oil will rapidly heat generating gases above their auto ignition point. The pressure of the gases may rupture the reservoir allowing oxygen to enter resulting in the gases auto igniting. The oil is released from the reservoir and is ignited by the burning gases.

It has been assumed that the transformer has bund dimensions of approximately 12.5 m x 9 m which is based upon similar projects; hence, if a spill from the transformer was to occur it would fill the base of the bund resulting in a pool fire with the dimensions of the bund. These dimensions have been used to calculate a circular diameter to input into the SEP and SSC models.

$$A = L \times W = 12.5 \times 9 = 112.5\,m^2$$

$$D = \sqrt{\frac{4 \times 112.5}{\pi}} = 12\,m$$

The following data was input into the SSC;

- Fire diameter – 12.0 m

- Burning rate – 0.022 kg/m$^2$.s (combustible liquid, Ref. [11])

The above information was put into the spreadsheet calculator which calculated the following outputs:

- SEP – 48.5 kW/m$^2$
- Flame height – 10.25 m

The results of the analysis are shown in **Appendix Table B-3.**

**Appendix Table B-3: Heat Radiation Impacts from a Transformer Bund Fire**

| Heat Radiation (KW/m$^2$) | Distance (m) |
|---|---|
| 35 | 3.3 |
| 23 | 4.9 |
| 12.6 | 7.8 |
| 4.7 | 14.9 |