

Penrose substation fire inquiry report

9 November 2015

Note: This paper has been prepared for the purpose of the Security and Reliability Council (SRC). Content should not be interpreted as representing the views or policy of the Electricity Authority.

Function of the SRC

The function of the Security and Reliability Council (SRC) under the Electricity Industry Act 2010 (the Act) is to provide independent advice to the Electricity Authority (Authority) on:

- the performance of the electricity system and the system operator
- reliability of supply issues.

Background

Section 18(1) of the Act provides that on written request by the Minister of Energy and Resources (the Minister), the Authority must review and report on any matter relating to the electricity industry that is specified by the Minister.

On 7 October 2014, the Minister wrote to the Authority requesting under section 18 that the Authority undertake an inquiry into the Penrose substation fire that occurred on 5 October 2014. The fire severely damaged electricity supply equipment at Penrose substation and caused a significant power outage that left some Auckland customers without electricity for more than two days.

The report that the SRC has been asked to consider is the Authority's response to the Minister's request.

Scope of SRC advice required

In making his request under section 18 of the Act, the Minister asked a specific set of questions. Section 18 also allows the Authority to consider any matters that fall outside the scope of the review but that the Authority considers should be included. The inquiry report will be released by the Minister once he has had a chance to consider it. It is not the Authority's role to publish the report and **the SRC is expected to not discuss the contents of the draft inquiry report outside the SRC until the Minister publishes it.**

When considering those matters, the SRC should bear in mind that it is not being asked to reach any particular verdict.

In addition, the report includes comments relating to safety considerations. While included in the report, this matter is outside of the SRC's statutory function. Accordingly, the SRC's advice should not discuss safety.

Vector and Transpower will attend the first hour of the meeting to present on the context of the Penrose fire. This presentation is in lieu of a site visit. Vector and Transpower will not attend the substantive discussion of the report.

The SRC may wish to consider the following questions. In answering these questions the SRC may comment on the analysis and recommendations included in the report, as well as other issues that the SRC feel important but are not included in the report. In order for the Authority to understand any views expressed by the SRC, it would be helpful if the rationale for these views was included in the advice.

To assist the Authority in meeting deadlines with the Minister, the Authority requests that the SRC finalise its advice and provide it to the Authority by 5pm on the day following the meeting (10 November).

Q1.	Does the SRC consider that the report answers the Minister's security and reliability questions?
Q2.	Does the SRC consider that there are security and reliability issues not covered by the report that could be usefully covered?

- Q3.** Does the SRC consider that there are security or reliability implications arising from the inquiry that need further attention outside of the inquiry report? If so, whose attention should be drawn to these implications?
- Q4.** What advice, if any, does the SRC wish to provide to the Authority?

Attachments

The following reports are attached to this paper:

- The Authority's *Penrose substation fire 5 October 2014*
- Vector and Transpower's *Penrose Substation Fire Investigation Report*
- Cable Consulting International Limited's *Investigation into a Fire in a Cable Trench in Penrose Substation*

Post-script note:

The Security and Reliability Council received the draft version of the following report at its 9 November 2015 meeting.

The final version of this report is available from <http://www.ea.govt.nz/monitoring/enquiries-reviews-and-investigations/2014/section-18-review-of-auckland-power-outage-5-october-2014/>

Penrose substation fire 5 October 2014

Report on the inquiry conducted by the
Electricity Authority under section 18 of the
Electricity Industry Act 2010

3 November 2015

Version control

Version	Date amended	Comments
1.0	6 October 2015	Consultation draft for Vector, Transpower and NZFS feedback
2.0	3 November 2015	Post-consultation draft

Draft

Inquiry into the Penrose substation fire and power outage 5-7 October 2014

Section 18(1) of the Electricity Industry Act 2010 provides that on written request by the Minister of Energy and Resources (the Minister), the Electricity Authority (the Authority) must review and report on any matter relating to the electricity industry that is specified by the Minister.

On 7 October 2014, the Minister wrote to the Authority requesting under section 18 that the Authority undertake an inquiry into the Penrose substation fire that occurred on 5 October 2014. The fire severely damaged electricity supply equipment at Penrose substation and caused a significant power outage that left some Auckland customers without electricity for more than two days.

This report is the Authority's response to the Minister's request.

1 Executive summary

The impact of the Penrose fire on customers was significant

- 1.1 In the early hours of Sunday 5 October 2014, a fire was identified at Transpower New Zealand Limited's (Transpower's) Penrose substation. The fire resulted in a major outage to electricity supplies in parts of Auckland.¹
- 1.2 The fire was caused by the electrical failure of a cable joint in a medium voltage power cable owned by Vector Limited (Vector). The fire led to a widespread loss of supply due to the location of the cable joint within an in-air cable trench containing a total of 3.99km² of power cables in 38 separate lengths (including 19 high-voltage cable circuits, 15 cable joints and a number of control cables).³
- 1.3 The power cables in the cable trench directly supplied over 39,000 electricity customers in Auckland. However, a total of 75,339 customers were affected by the fire because further electrical circuits had to be switched off to enable access for fire-fighting personnel. Electricity was progressively restored throughout Sunday and Monday and supply was restored to the final customers on the afternoon of Tuesday, 7 October 2014.
- 1.4 The response of the New Zealand Fire Service (NZFS), and of Vector and Transpower personnel, was successful in bringing the fire under control and significantly limiting the potential consequences.⁴ The fire had the potential to cause much wider damage and disruption to power supplies than in fact occurred.
- 1.5 The Authority's estimate of the economic cost to customers due to the loss of supply is between \$47 million and \$72 million.⁵

The Minister requested this inquiry under section 18 of the Electricity Industry Act 2010 (the Act)

- 1.6 The Hon Simon Bridges, Minister of Energy and Resources, noted the significance of the loss of supply in terms of disruption and cost and requested that the Authority carry out an inquiry into the outage. Specifically, the Minister asked the Authority to address the following questions:
 - a) what caused the loss of supply or contributed to it, including potentially systemic factors such as risk management systems, asset health monitoring and maintenance practices, network design and regulatory incentives and controls?

¹ Abbreviated terms are defined when first used. Section 11 provides a glossary of terms.

² Vector and its cable expert CCI have stated different trench cable km over the course of the inquiry. The 3.99km is the latest length that has been advised by Vector.

³ The term 'in-air' is used in this report to mean that the cable trench was not backfilled with solid material; the cables were accordingly laid 'in-air'. Figure 4 shows a typical cross-section of the cable trench and its contents.

⁴ Vector was not involved in the management of the substation site during the fire but did provide assistance in undertaking distribution network switching and control.

⁵ This estimate is based on the Value of Lost Load (VoLL) which is a survey-based estimate of electricity users' willingness to pay to avoid an outage. The analysis supporting the estimate is included in section 8.

- b) what fire hazard mitigation systems were in place; and did they operate as intended?
 - c) what actions were taken during the course of the outage in respect of:
 - (i) ensuring the safety of people and equipment?
 - (ii) communicating with affected and interested parties (including emergency services) about the impact of the event and timeframes for restoration of supply?
 - (iii) mitigating the loss of supply and expediting restoration?
 - d) what the estimated economic impact of the outage was on customers?
 - e) what actions will be taken or are recommended, as a result of the outage and subsequent investigations, to improve the resilience of power supplies and management of outages?
- 1.7 The Minister made his request under section 18 of the Electricity Industry Act 2010 (the Act).
- 1.8 During the course of the inquiry, the Authority worked with the parties involved to answer the Minister's questions.
- 1.9 Vector and Transpower announced a joint investigation into the fire on 8 October 2014. The Authority's inquiry commenced on the same date.⁶ The Authority worked closely with Vector and Transpower and drew on the information and analysis provided in their joint investigation report.⁷ The Authority also drew on the findings of independent experts engaged by Vector and Transpower.
- 1.10 On 24 July 2015, Vector and Transpower gave the Authority a draft report of their findings. In addition, Vector provided the Authority with a draft report on the findings of Cable Consulting International Limited (CCI) on 7 August 2015.⁸ As at the date that this report was completed, the Authority had not received finalised versions of either of those reports. The Authority received a final version of the NZFS Fire Investigation Report on 21 August 2015.

The inquiry considered a range of information

- 1.11 Establishing exactly how the fire started and the sequence of events that followed required technically specialised and complex work, particularly given the extent of the fire damage. The Authority's inquiry drew from, and relied on, a significant quantity of information and expert analysis produced by the investigation. In addition, the Authority drew from other publically available information.⁹

⁶ This report refers to the 'Vector/Transpower joint investigation' as 'the investigation'. The Authority's inquiry is referred to as 'the inquiry'.

⁷ Transpower New Zealand Limited and Vector Limited, *Penrose Substation Fire – 05 October 2014 – Investigation Report*, Final Draft, undated, provided under cover of a letter to Carl Hansen on 1 September 2015. This inquiry report refers to the joint Vector/Transpower investigation report as 'the investigation report'.

⁸ CCI is an international company with expertise in high-voltage electricity cables. Vector and Transpower engaged CCI to undertake a detailed investigation of the fire-damaged cables at Penrose substation.

⁹ References to the relevant sources of information referred to in this report are provided in the relevant sections of this report.

- 1.12 At the outset, the Authority established a protocol with Vector and Transpower for sharing information and exchanging views. The Authority attended workshops with Vector and Transpower throughout the inquiry. The workshops provided opportunities for the Authority to clarify points of interest at relevant points in the investigation. The workshops also provided the opportunity for Vector and Transpower to provide information and ensure the Authority was kept updated in a timely manner.
- 1.13 The Authority was provided with information and documentation describing Vector and Transpower's risk and asset management systems. The Authority considers that the systems presented align with international standards and practice.¹⁰ These systems have been independently reviewed and are subject to periodic review. The Authority considers that, through consistent application of their risk and asset management systems, both Vector and Transpower will be operating to good electricity industry practice.
- 1.14 While the Authority drew significantly on information provided by the joint investigation, the Authority has formed its own views. The main focus areas of the inquiry were:
- a) establishing why the power outage occurred and why the disruption was extensive, including to:
 - (i) obtain accurate information from reliable sources
 - (ii) identify who was responsible for managing the substation and cables
 - (iii) identify what caused the fire to start and spread
 - (iv) identify what contributed to the power outage
 - b) considering the reasons why risks associated with the cable trench at the Penrose substation had not been identified, including to:
 - (i) assess the relevant risk and asset management systems
 - (ii) consider how the risk and asset management systems had been applied in practice at Penrose
 - (iii) identify why the fire was able to start and spread
 - c) assessing how the relevant parties responded to the fire, including how well the affected customers were kept informed of the status of restoration efforts
 - d) identifying improvements and making recommendations to reduce the potential for similar events in the future.
- 1.15 A draft of this report was provided to Transpower, Vector, and NZFS for comment on 6 October 2015. The Authority received a submission from NZFS, and a joint submission from Transpower and Vector, on 20 October 2015.
- 1.16 In cases where the Authority was satisfied that the submissions pointed out factual inaccuracies in the draft report, or where the Authority otherwise accepted the points that were raised, the report has been corrected or amended to reflect

¹⁰ Transpower informed the Authority that it considers risk management to be a subset of asset management.

that. Where the Authority disagreed with an issue raised in submissions, the report has been amended to state where that is the case.

The inquiry took a standard risk assessment approach

- 1.17 Both Transpower and Vector use risk and asset management systems that align with relevant international standards and good electricity industry practice. The Authority took into account international standards relevant to risk and asset management and used the basic components of these systems to form a structure for the inquiry.
- 1.18 The first step in risk management assessment is to identify risks. Accordingly, early engagement with Vector and Transpower sought to determine whether they had previously identified the risk of a cable trench fire at Penrose substation.

The risk of a cable trench fire at Penrose had not been identified

- 1.19 Before the fire, neither Vector nor Transpower had identified:
 - a) the risk of fire ignition from failure of a power cable in the Penrose cable trench (the ignition risk) or
 - b) the risk posed by multiple power cables co-located in the Penrose cable trench (the co-location risk).
- 1.20 Consequently, neither Vector nor Transpower took steps to prevent a fire in the cable trench at Penrose or lessen the supply interruption impact of such a fire on customers.
- 1.21 A 33 kV indoor switchgear building and transformers are located close to the location of the fire. If the fire had destroyed these facilities, the impact would have been much greater.¹¹

The electrical failure of a cable joint ignited the fire

- 1.22 The Remuera K10 cable was one of the original cables installed in the cable trench in 1966.
- 1.23 In 2001, a Vector maintenance contractor discovered bitumen leaking from a cable joint located in the Penrose cable trench section of the Remuera K10 feeder. To address the issue, the contractor removed the joint and spliced a new section of cable into the existing cable. The repair required a short section of new cable and, because the new and old cables were of a different type, two new transition cable joints.
- 1.24 One of the transition joints electrically failed on 4 October 2014 and this is believed to have provided the source of ignition for the fire.

Other factors contributed to the fire

- 1.25 Although electrical failure of the cable joint ignited the fire, a significant contributing factor to the spread of the fire and the widespread loss of supply was the co-location of 38 lengths of power and a number of control cables in the Penrose cable trench. The large number of cables located in close proximity

¹¹ kV is the standard industry abbreviation for 1,000 volts, eg 33 kV is 33,000 volts.

within the Penrose cable trench provided fuel for the fire. The air in the cable trench surrounding the cables provided the oxygen to sustain the spread of the fire.

- 1.26 Due to the confined space available in the cable trench for making the joints, the spliced cable that Vector installed in 2001 was longer than the section of cable it had replaced. This meant that the cable had to be returned to the trench in a bow shape rather than a straight line. CCI identified this as one of a number of contributing causes to the failure of the transition joint.
- 1.27 In the executive summary of its report, CCI sets out 14 main conclusions from its investigation of the cable trench installation. The Authority considers the forensic investigation undertaken by CCI was detailed and high quality. Accordingly, subject to the discussion in this report, the Authority has relied on and drawn from CCI's report and accepts its 14 main conclusions.
- 1.28 CCI concluded that the cause of the transition joint failure was a vulnerability of the transition joint design. CCI concluded that the jointing quality was satisfactory. CCI states that a number of technical factors contributed to the cable joint failure. These factors included the lack of a straight alignment of the joint and the cable, and the lack of cable cleats and joint supports.¹²
- 1.29 CCI considered that the number of cables in the cable trench contributed to the rate of spread of the fire, that by 2001 limited space remained in the trench, and that at the time of the fire in 2014, too many cables had been installed in the trench.¹³
- 1.30 The security and integrity of the cable trench and cables were critical to maintaining a reliable electricity supply to a large number of electricity customers in Auckland.

The Authority considers Vector and Transpower should have identified the risk

- 1.31 The investigation report states that Vector could not have been expected to have the knowledge to specifically identify the risk of a joint failure causing fire in the cable trench as cable faults are very rare, and details of any incidents that have occurred globally have not been made public.¹⁴
- 1.32 However, the Authority found that Transpower was aware of the potential for cable installations to cause fires and had asset management documentation requiring cable installation design to consider and appropriately mitigate fire risks from potential cable failure.
- 1.33 The Authority considers that Vector and Transpower should have been aware of the factors that had the potential to affect the integrity of the cable trench and the cables that it contained and therefore should have identified the risk. This is because Vector and Transpower identify similar risks in other contexts, there are examples from overseas of cable insulation failures causing substation fires, there are international standards that mitigate the consequence of trench fires

¹² CCI report, section 15.2

¹³ CCI report, Executive Summary, page 5 and section 4.6

¹⁴ Investigation report, section 8, paragraph 18

and cable joint failures, and there are products available to manage the risk of cable joint failures causing fires. This information is all available in the public domain.

- 1.34 In their submission on a draft of this report, Vector and Transpower disputed the Authority's conclusion that they should have identified the risks related to the co-location of multiple cables in the cable trench. The Authority reconsidered its conclusion in light of that submission, but has not changed its view. This is explained further in section 5 of this report.

The Authority considers there were opportunities to identify and manage the cable trench risk

- 1.35 Each cable added to the cable trench since its installation in 1966 provided an opportunity to review the risk posed by an increasing concentration of important cables in the cable trench.¹⁵ When Vector added new cables to the cable trench, the focus appears to have been on the individual project risk.¹⁶ Transpower and Vector did not consider the co-location risk implications of the overall cable trench installation.
- 1.36 Other opportunities arose to identify the risk associated with the concentration of cables in the trench, such as the biennial State of the Network Review commissioned by Vector for the Auckland Energy Consumer Trust (AECT), and Transpower's high impact, low probability (HILP) study at Penrose substation in 2013.
- 1.37 The Penrose cable trench was not a standard cable trench – the investigation found that the cable trench at Penrose was quite different from other cable trenches. Despite this, Vector and Transpower had not considered applying a different design standard to the Penrose trench based on its criticality to electricity supplies over a wide area.¹⁷ The Authority's view is that Vector should have considered the specific features of an installation like the Penrose cable trench, including its criticality to electricity supply, before allocating it to an asset group or type. The categorisation should have also been periodically reviewed, especially when changes to the installation were undertaken, as they were at Penrose over a long period.
- 1.38 The Authority considers that all electricity lines businesses should review their asset policies and application to ensure that supply-critical components are appropriately categorised.¹⁸ This particularly relates to assets at grid connection substations, where multiple asset owners are always involved.

¹⁵ The cables are considered to be important because failure of a single cable could impact on the security of electricity supplies to electricity customers and failure of more than one cable could lead to loss of electricity supply to a large number of consumers.

¹⁶ Investigation report, section 7.6.2

¹⁷ The fire demonstrated the potential for damage to occur to all cables in the trench and the consequences, therefore the trench and its contents together were critical components of Vector's network.

¹⁸ In this report, 'supply-critical' is used as a reference to an attribute of a component, or a combination of components, in the supply system where failure of that component or components would result in a major supply interruption.

The application of risk and asset management systems can be improved

- 1.39 The Authority has considered both Vector's and Transpower's asset and risk management systems. The Authority considers that the documentation relating to these systems is consistent with good electricity industry practice. The Authority also investigated how these systems were applied in practice at the Penrose substation.
- 1.40 Specifically to the Penrose substation fire, the Authority considers that the risk identification stage of the risk management systems was not applied sufficiently well by Vector and Transpower, leading to opportunities to identify the cable trench risks being missed. As a consequence, Vector and Transpower did not take actions to remove or mitigate this risk.
- 1.41 The Authority notes that both Vector and Transpower intend to review their risk management practices to incorporate lessons from the Penrose fire. The Authority supports these initiatives.

Communications with customers worked well

- 1.42 Customer, media and public communications about the supply interruptions commenced early and utilised a range of media and communication methods. In the early stages, Transpower, and subsequently Vector, kept customers informed about the status of supply interruptions. Vector provided updates throughout the period of supply interruptions.
- 1.43 The Authority has not identified any concerns or issues about the management of medically dependent or vulnerable consumers related to the Penrose fire event.

The management of Penrose and other substations can be improved

- 1.44 It is neither feasible nor efficient to eliminate all risk from electricity network businesses. Identified risk controls and mitigations should undergo analysis of costs and benefits. Treatments for identified HILP risks in particular can accrue high costs.
- 1.45 The Penrose fire incident has presented Vector and Transpower with an important opportunity to reassess risks at Penrose and other network locations. The investigation report recommends that the cable trench and cable configuration be re-designed. In its report, CCI recommends that several actions be taken at Penrose and other substations.
- 1.46 Vector is using a range of methods to reinstate its cables in a more permanent arrangement at Penrose substation. These methods should address the risk of fire ignition due to cable joint failures in in-air situations and the risk posed by co-location of multiple cables in an in-air trench.
- 1.47 In their investigation report, Vector and Transpower identify four key lessons:
 - 1. *Cable joints installed in air with other cables in close proximity can cause sustained fires when they fail;*
 - 2. *Risk management processes did not identify very low probability events that had not previously occurred on the network;*
 - 3. *The nature of the incident identified opportunities for improvement of standard operating procedures; and*

4. *The asset and risk management processes at the physical interface between Transpower and Vector's networks need to be improved.*¹⁹

- 1.48 The investigation report and the CCI report include a number of recommendations relating to four identified areas. The Authority supports the recommended actions included in the investigation report and the CCI report.
- 1.49 The Authority considers that the lessons and recommendations from the investigation, if implemented, will deliver improvements in the identification and management of HILP risks at Vector and Transpower. The Authority notes that Vector and Transpower have completed a number of recommendations and are progressing implementation of the others.

The Authority recommends a number of additional actions

- 1.50 To support the recommendations made in the investigation report and the CCI report, the Authority makes the following recommendations:

Recommendations relating to the Minister's first question

Recommendation 1 – Lessons from the Penrose incident must be shared with industry stakeholders. Significant fire events at high-voltage substations are rare events and provide valuable opportunities to review policies and procedures

Recommendation 2 – Supply-critical components should be given higher risk management priority than non-critical components, even if the probability of occurrence is low

Recommendation 3 – The particular characteristics of each asset and co-located groups of assets must be considered in determining the risk profile of the asset

Recommendation 4 – In-air cable joints must be identified and the associated fire risk mitigated

Recommendation 5 – Asset boundaries require improved management between asset owners to ensure clear division of responsibility

Recommendation 7 – Planning standards should be reviewed by Vector to ensure the standards are appropriate

Recommendation 8 – Future State of the Network reviews should be re-scoped to ensure the reviews are effective

Recommendation relating to the Minister's third question

Recommendation 9 – An independently peer reviewed, post-event safety review must be undertaken to identify improvement opportunities.

¹⁹ Investigation report, section 9.2

- 1.51 The Authority considers that many of the recommendations are relevant to all electricity lines businesses.

The improvements must be completed

- 1.52 For customers to have confidence in the reliability of their electricity supplies, the Authority considers it important that:
- a) Vector and Transpower afford a high priority to reporting progress towards completion of the recommendations
 - b) there is transparent external monitoring of the progress achieved towards implementing the remedial actions identified in the investigation and in this inquiry.
- 1.53 The Authority recommends that Vector and Transpower submit to the Authority for approval an implementation plan by 31 December 2015. After the plan is approved, Vector and Transpower should submit progress reports to the Authority every six months until all actions have been completed (the monitoring period). Vector and Transpower should engage with the Authority during the monitoring period as may be required by the Authority from time to time.
- 1.54 The Authority will monitor progress made towards completion of the recommended improvement actions and will report to the Minister if there are any deviations from the implementation programme.

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Part One Background to the inquiry

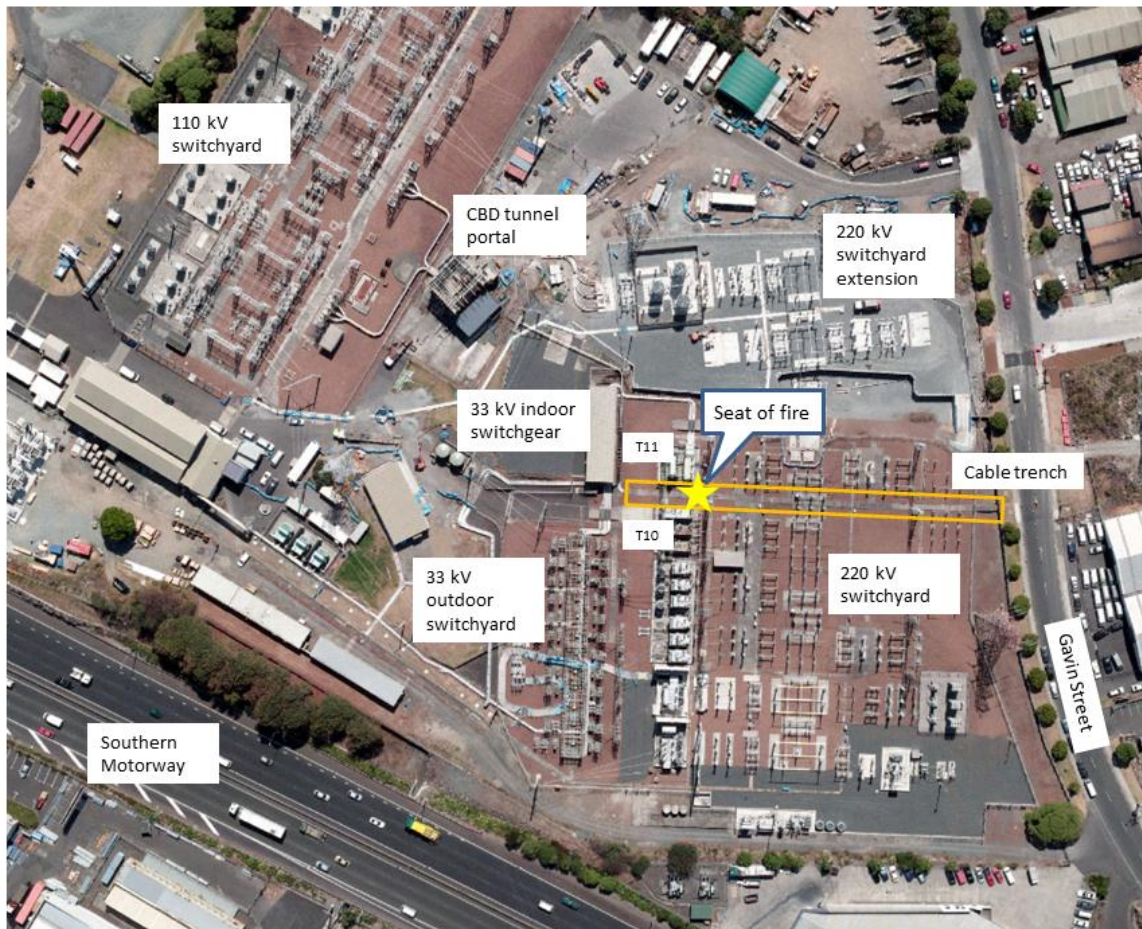
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2 Why the Authority has carried out this inquiry

A fire at Penrose substation on 5 October 2014 caused a widespread power outage in Auckland

- 2.1 Penrose substation is a major national grid substation located in the industrial suburb of Penrose alongside the Auckland Southern Motorway, approximately 10 kilometres southeast of the city centre (Figure 1). Transpower, the national grid owner and operator, owns Penrose substation.

Figure 1 – Penrose substation layout



Source: Investigation Report (Figure 5)

Note: T10 and T11 are labels for transformer banks

- 2.2 Late in the evening on Saturday 4 October 2014, a fire started at Penrose substation. At 2:04 am on Sunday 5 October, Transpower's NGOC controller observed a number of unusual alarms from equipment at Penrose substation and called out a substation maintainer to Penrose to investigate.
- 2.3 At 2:17 am on Sunday 5 October, a member of the public reported to emergency services of hearing explosions coming from the substation. NZFS responded and reported seeing thick smoke coming from the outdoor switchyard located behind the substation perimeter security fence.

- 2.4 The first NZFS fire appliance arrived at the Penrose substation perimeter security gate at 2:26 am. The substation maintainer arrived at 2:41 am and reported seeing thick black smoke in the vicinity of the 220/33 kV supply transformer T11.
- 2.5 Once safe access was arranged to the security fenced area, Transpower and NZFS personnel traced the source of the smoke to a fire near the 33 kV switchroom adjacent to transformer banks T10 and T11.
- 2.6 Later investigation by Transpower and NZFS personnel determined that the fire started inside a cable trench containing 38 lengths of power cable and a number of control and communications cables.²⁰ The power cables are owned by Vector, the local distributor of electricity and gas in Auckland. The cable trench also included a switchyard lighting cable owned by Transpower.
- 2.7 The fire destroyed all of the cables in the cable trench. The power cables are sections of the primary high-voltage circuits that supply over 39,000 customers through distribution 'zone' substations in:
- a) the residential suburbs in the Eastern Bays, Remuera and Epsom
 - b) the commercial/retail suburb of Newmarket
 - c) the industrial area through Penrose, Westfield and Mt Wellington.
- 2.8 To allow safe access to fight the fire, Transpower de-energised all 33 kV and 22 kV supplies at Penrose substation. Consequentially, by 3:08 am, 75,339 customers supplied from Penrose were without power, equating to a loss of around 116 MW of load from the network.²¹
- 2.9 Figure 2 shows the area affected by the power outage.

Figure 2 – Supply area affected by the Penrose substation fire



Source: Investigation Report (Figure 3)

²⁰ There are several cable trenches and above ground cable-racks installed at Penrose substation. The covered, concrete-lined cable trench in which the fire started runs west to east through the 220 kV switchyard, and is highlighted with a yellow border in Figure 1. At the time of the initial firefighting by NZFS, it was not clear that the fire had actually started inside the cable trench.

²¹ MW is the standard industry abbreviation for 1,000,000 watts, a unit of power

- 2.10 After the fire was extinguished, NZFS handed control of the site back to Transpower. Vector and Transpower were then able to start restoring electricity supplies. Supply was restored to 72% of affected customers within 24 hours of the outage and to 98% by 8:00 am on Tuesday. However, the extent of the fire damage meant that supply to some customers was not restored until the afternoon of Tuesday 7 October 2014.
- 2.11 To put the significance of the outages into context, Vector disclosed in its Annual Compliance Statement (published on 29 May 2015) that the Penrose fire resulted in power outages totalling 218.4 SAIDI minutes over the period 4–7 October 2014.²² This equates to 44% of Vector's total unadjusted SAIDI for the reporting year to 31 March 2015.
- 2.12 Once supply to all affected customers had been restored, Vector and Transpower announced a joint investigation into the incident. In addition, the Minister asked the Authority to conduct an inquiry into the incident.
- 2.13 The next sections outline the scope of the Authority's inquiry.

The Minister requested an inquiry by the Authority

- 2.14 The Minister wrote to the Authority on 7 October 2014, noting the significance of the 5 October power outage in terms of disruption and cost. Citing questions that the outage raised over the reliability of power supply, the Minister requested that the Authority carry out an inquiry into the outage and report its findings to him.²³
- 2.15 The Minister made his request under section 18 of the Electricity Industry Act 2010 (the Act). Section 18(1) of the Act provides that on written request by the Minister, the Authority must review and report any matter relating to the electricity industry that is specified by the Minister.
- 2.16 The Minister requested that the Authority work with all parties to address the following questions:
- a) What caused the loss of supply or contributed to it, including potentially systemic factors such as risk management systems, asset health monitoring and maintenance practices, network design and regulatory incentives and controls?
 - b) What fire hazard mitigation systems were in place; and did they operate as intended?
 - c) What actions were taken during the course of the outage in respect of:
 - (i) ensuring the safety of people and equipment?

²² SAIDI means System Average Interruption Duration Index and is a statistic reported annually by electricity distributors under the Electricity Information Disclosure Requirements administered by the Commerce Commission. The Penrose fire event constituted 44% of Vector's total unadjusted SAIDI for the reporting year ended 31 March 2015 (ie SAIDI before making adjustments for major events). For further information about the information disclosure regime, see <http://www.comcom.govt.nz/regulated-industries/electricity/electricity-information-disclosure/current-electricity-information-disclosure-requirements/>. Vector's 2014/15 compliance statement is available at <http://vector.co.nz/electricity-disclosures/price-quality-path>.

²³ Letter from Hon Simon Bridges, Minister of Energy and Resources, to Dr Brent Layton, Chair of the Electricity Authority, 7 October 2014. A copy is attached as Appendix A.

- (ii) communicating with affected and interested parties (including emergency services) about the impact of the event and timeframes for restoration of supply?
 - (iii) mitigating the loss of supply and expediting restoration?
 - d) What the estimated economic impact of the outage was on customers?
 - e) What actions will be taken or are recommended, as a result of the outage and subsequent investigations, to improve the resilience of power supplies and management of outages?
- 2.17 The Minister also requested that the scope of the inquiry include any policy implications. Accordingly, the Minister requested that the Ministry of Business, Innovation and Employment (MBIE) be kept fully informed throughout the process of the inquiry.

What the Authority is required to do under section 18 of the Act

- 2.18 On receiving a written request by the Minister under section 18 of the Act, the Authority must review and report on any matter relating to the electricity industry as specified by the Minister.
- 2.19 If, in the course of a review, the Authority considers that there are matters that fall outside the scope of the review, but which it should nevertheless report on to the Minister, the Authority may include a report on those matters in the final report or in a separate report.
- 2.20 Section 15 of the Act provides the Authority with a single statutory objective:
- To promote competition in, reliable supply by, and the efficient operation of, the electricity industry for the long-term benefit of consumers.*
- 2.21 The questions to be addressed by the inquiry are consistent with the Authority's statutory objective.

The Authority commenced an inquiry

- 2.22 Following receipt of the Minister's letter, the Authority:
- a) established an internal inquiry project team within its market performance group
 - b) appointed two directors of Strata Energy Consulting Limited (Strata) as its specialist technical advisors
 - c) met with representatives of Vector and Transpower to establish a protocol under which the inquiry would be conducted.
- 2.23 This report sets out the findings of the inquiry conducted by the Electricity Authority under section 18 of the Electricity Industry Act (2010) (referred to as 'the inquiry').

How the Authority has worked with Vector and Transpower

- 2.24 The Minister requested that the Authority work with all parties involved to address the Minister's questions.

- 2.25 The Authority identified that the parties involved included Vector, Transpower and NZFS. At an initial meeting, Vector and Transpower representatives advised the Authority that the two businesses intended to work closely together to conduct an investigation and to produce a joint investigation report. Vector and Transpower also advised the Authority that NZFS was investigating the fire and would provide a fire investigation report. The NZFS investigation was separate from and independent of the Vector and Transpower investigation.
- 2.26 Vector and Transpower recognised it would be necessary to draw on expert analysis and work through a significant quantity of information to comprehensively investigate the fire.
- 2.27 The Authority informed the Vector and Transpower representatives that it required their close cooperation so that it could:
- a) efficiently and effectively access information as the joint investigation progressed
 - b) ask timely follow-up questions as the Authority's inquiry progressed in parallel
 - c) discuss emerging themes and appropriate detail relevant to the Minister's questions in a timely manner
 - d) expedite the Authority's report to the Minister.
- 2.28 The Vector and Transpower representatives undertook to conduct an inclusive investigation process with the Authority's inquiry team, including:
- a) providing guided access to the site of the fire at an early stage for the Authority's inquiry team members
 - b) sharing draft and updated reports on specialist topics relevant to the investigation as they were produced
 - c) providing prompt responses to the Authority's formal questions
 - d) meeting with the Authority at appropriate times to share recently compiled information and discuss current topics of significance to the inquiry.
- 2.29 The Authority considers the respective investigation teams and the Authority have operated in accordance with the inquiry protocol throughout the investigation process.

Vector and Transpower commissioned supporting investigations

- 2.30 In addition to their joint investigation report, Vector and Transpower have provided reports on two supporting investigations. These are:
- a) Cable Consulting International Ltd, *Draft Notes: Investigation into a Fire in a Cable Trench in Penrose Substation*, Final Draft, 13 August 2015 (referred to in this inquiry report as the 'CCI report')
 - b) Edif ERA, *Analysis of Samples Taken From Cable Trench at Penrose Substation*, August 2015.
- 2.31 CCI carried out a detailed forensic examination of the damaged cables and cable joints, including work in New Zealand and the United Kingdom. Based on CCI's recommendation, Vector and Transpower engaged Edif ERA to undertake

specific tests and inspections of the cable and joint samples extracted from the cable trench.

NZFS investigated the cause of the fire

- 2.32 NZFS undertook its own investigation to determine the cause of the fire, which benefited from the assistance of the investigation team, including the cable expert. NZFS subsequently provided the following report to the Authority: New Zealand Fire Service, *Fire Investigation Report*, 11 August 2015 (final) (referred to in this inquiry report as the 'NZFS report').

The referenced reports have been provided to the Authority

- 2.33 In carrying out the inquiry, the Authority has drawn from each of the referenced reports and from a number of supplementary reports on specific topics. All reports directly referenced throughout this inquiry report are listed in section 12.

The inquiry took many months to complete

- 2.34 The inquiry started in October 2014. The Authority initially expected to provide a report to the Minister by the end of April 2015.
- 2.35 However, three investigation reports essential to the inquiry were provided to the Authority significantly later than expected. The timing of those reports was outside of the Authority's control. Those reports are:
- a) a 'working draft' of the CCI report was received by the Authority on 7 August 2015 and a 'final draft' of the report on 26 August 2015
 - b) a 'final' version of the NZFS report was received by the Authority on 20 August 2015
 - c) Vector and Transpower provided a series of early drafts of their investigation report from 26 June 2015. The (undated) 'final draft' of the investigation report was received on 1 September 2015.
- 2.36 As at the date that this report was completed, the Authority had not received finalised versions of the CCI report or the investigation report.
- 2.37 The inquiry has relied on the CCI report and the NZFS report to establish the initial cause of the fire and determine how it travelled along the cable trench.

3 Background information about Penrose substation

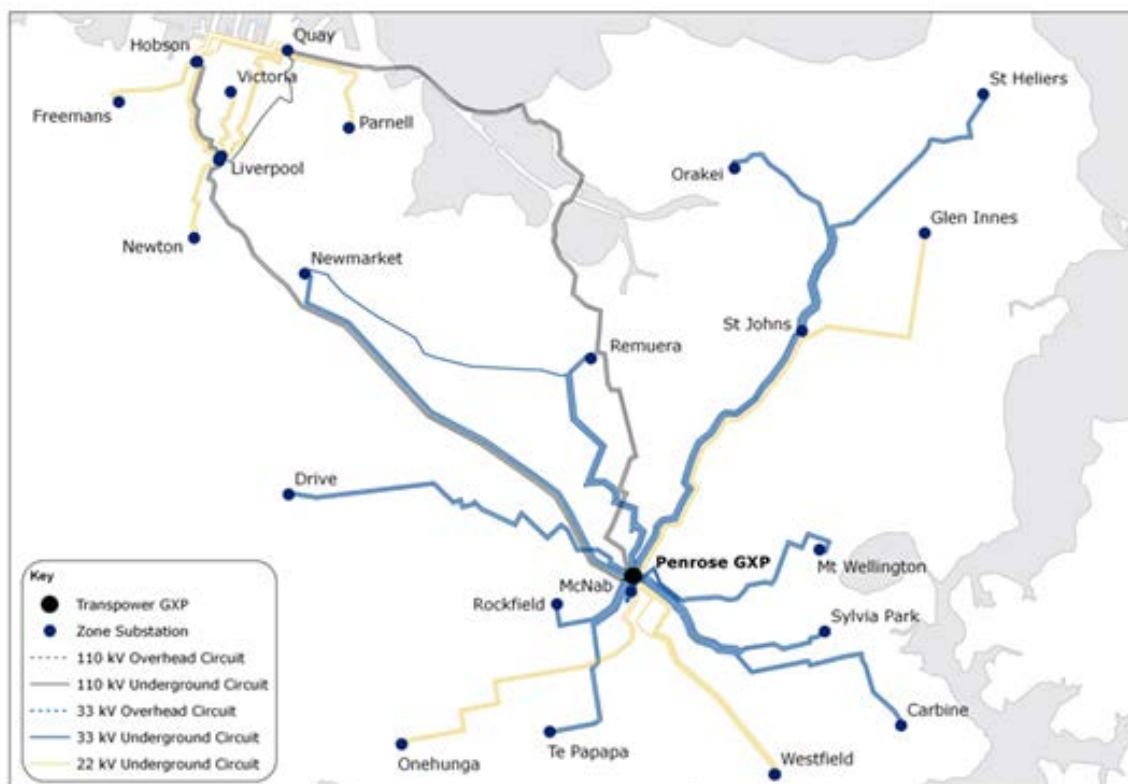
Penrose substation is a major national grid supply point into central Auckland

- 3.1 Penrose substation is a major electricity grid exit point (GXP) on the national grid owned and operated by Transpower. The extra high-voltage (EHV) transmission network into Auckland and across the Auckland isthmus provides connections through Penrose substation at 220 kV and 110 kV.
- 3.2 The national grid also supplies electricity into Vector's distribution network at Penrose, servicing a wide area of south-central Auckland starting at the south-

eastern perimeter of the central business district (CBD) and running south and east as far as Westfield and Onehunga.²⁴

- 3.3 A large part of Vector's distribution network is supplied from Penrose substation at 110 kV, 33 kV and 22 kV to supply electricity customers throughout its south-central Auckland network – see Figure 3.

Figure 3 – Vector network area and zone substations supplied at various voltages from Penrose GXP



Source: Vector

Penrose substation has a long history of development

- 3.4 Vector and Transpower have documented the history of development at Penrose substation in the investigation report and in the supplementary report *Penrose substation fire 05 October 2014 – History of Penrose substation, 3 February 2015*. The main points of relevance to the cable trench fire on 5 October 2014 are set out in the following paragraphs.
- 3.5 Penrose substation was originally commissioned in 1925 as part of the initial reticulation of Auckland from the earliest Waikato hydropower developments. Electricity supply capacity from Penrose substation has grown steadily to the point that Penrose is amongst the very largest GXPs supplied by the national grid.

²⁴ KiwiRail also takes supply from Penrose at 25 kV for electrification of the commuter rail network in Auckland. Southpark is a further direct supply customer supplied from Penrose.

- 3.6 Penrose substation has undergone a number of significant developments in the last 15 years. This has significantly increased supply capacity into Vector's network and improved supply security throughout and north of the Auckland isthmus.
- 3.7 Notable recent developments include:
- a) in 1999, the capacity of the 220/33 kV supply transformers was doubled to 400 MVA²⁵
 - b) completed in 2001, the Auckland CBD supply upgrade added new 110 kV circuits from Penrose to Vector CBD zone substations via Vector's CBD cable tunnel
 - c) in 2001, the Penrose 220 kV bus was upgraded (sectionalised) to improve transmission and supply security
 - d) in 2010, a second 220/110 kV interconnecting transformer was installed to increase the security and capacity of supplies from the 110 kV bus
 - e) in 2011, a new 220/33 kV 200 MVA supply transformer was added to improve the security and capacity of supplies from the 33 kV bus
 - f) in 2014, the major 220 kV transmission upgrade into and across Auckland was completed. This involved a Penrose termination of new 220 kV circuits from Pakuranga and the CBD (via the Vector cable tunnel and on to the North Shore to link up with the grid at Albany).
- 3.8 Planned but not completed by October 2014, two further security upgrades are expected to improve security of supply at Penrose, particularly the 33 kV and 22 kV supplies. These are:
- a) a further 220 kV bus security upgrade at Penrose, by reconfiguring the existing single bus layout to form a four-section ring bus, which is also intended to provide regional transmission security benefits
 - b) replacement of the remaining outdoor 33 kV switchyard with a modern indoor switchgear installation.

Penrose substation has a complex layout

- 3.9 GXP's allow a transmission customer's electrical equipment (underground cables and overhead lines) to connect to Transpower's electrical equipment (switchgear). The physical point at which the transmission customer's electrical equipment connects to the grid is referred to as a 'point of connection'. Points of connection are located within Transpower's national grid substations.
- 3.10 Indoor and outdoor switchgear installations that operate at a standard supply voltage agreed with the transmission customer (eg, 110 kV, 33 kV, 22 kV, and 11 kV) control the flow of electricity between the grid and the customer's network. This switchgear is usually owned by Transpower and this is the case at Penrose. The transmission customer lays its underground cables or runs its overhead lines on the site to connect to the switchgear.

²⁵ MVA is the standard industry abbreviation for 1,000,000 volt-amperes, a unit of energy. For the purposes of this report, MVA and MW can be considered to be approximately equivalent terms.

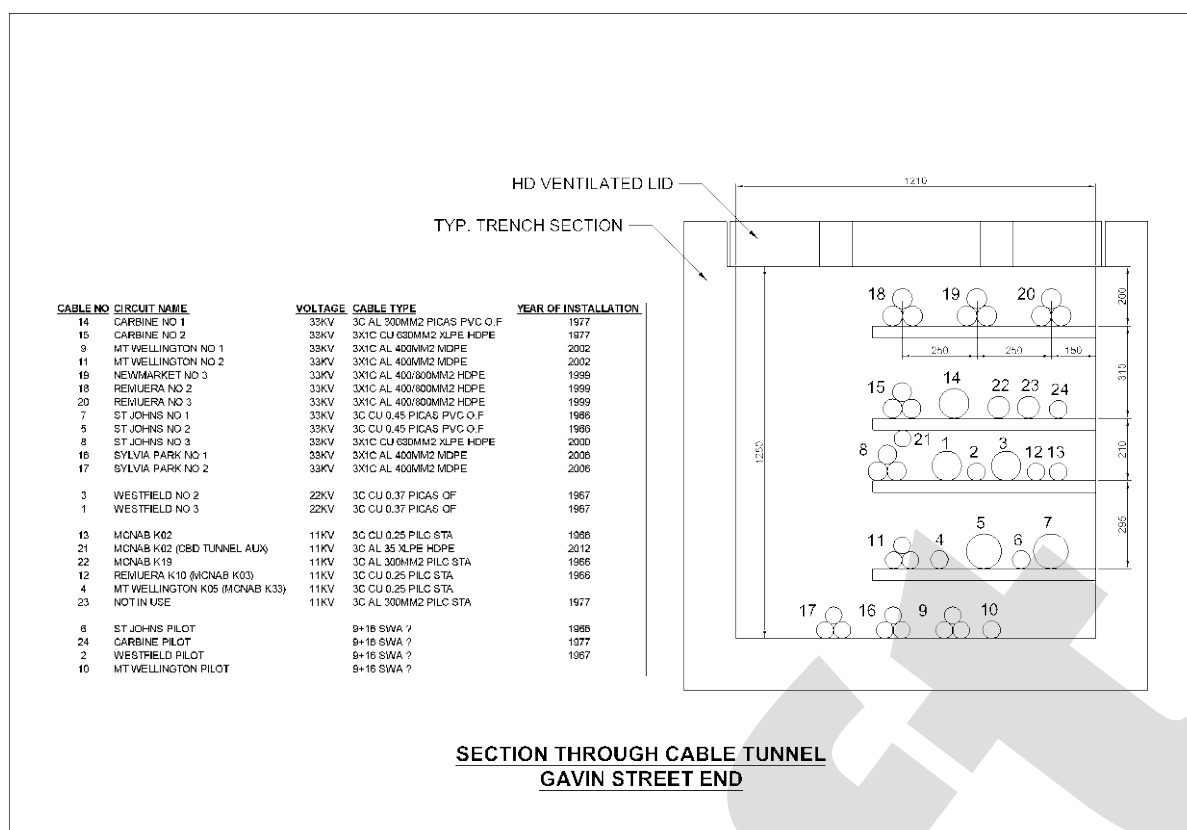
- 3.11 The relatively large number of connections within Penrose substation between the grid and Vector's distribution network, and the basalt rock on which the substation is built, have contributed to the configuration of Vector's power cables at the site.

A concrete-lined cable trench contained many cables

- 3.12 The original development of the outdoor 220 kV and 33 kV switchyards at Penrose in 1966 included construction of a concrete-lined cable trench running west to east across the 220 kV switchyard.²⁶
- 3.13 The cable trench has ground-level removable lids and is owned by Transpower. It is used:
- a) by Vector to provide a route for a number of its 33 kV, 22 kV, communications and control cables from points of connection within the substation to Gavin Street
 - b) by Vector as part of a through-route for a number of 11 kV cables that traverse the Penrose substation site (note that the 11 kV cables are not supplied from points of connection at Penrose substation – these cables are supplied from nearby Vector zone substations)
 - c) by Transpower for a power cable used to supply switchyard lighting.
- 3.14 Figure 4 shows a cross-section of the cable trench and cables at the Gavin Street end.

²⁶ The cable trench runs west to east (left to right) through the outdoor 220 kV switchyard from the 33 kV indoor switchgear building to Gavin Street. Interconnecting (220/110 kV) and supply (220/33 kV) transformers are located at the western edge of the 220 kV switchyard. Refer to Figure 1 for the location of the cable trench within the substation.

Figure 4 – Cable trench cross-section as at October 2014



Source: Transpower/Vector

- 3.15 At the time of the fire, the cable trench contained:
- twelve 33 kV circuits, two 22 kV circuits
 - six 11 kV circuits²⁷
 - several communications, control, and pilot (communication cables associated with specific cables) cables
 - a switchyard lighting power supply cable.
- 3.16 Figure 4 shows the Vector power and pilot cables only.
- 3.17 The combined equivalent single length of all the power cables in the cable trench was found by CCI to be 3.99 km.²⁸ The power cables in the cable trench had 15 in-air cable joints installed in their length.
- Transpower is the owner and operator of land and facilities at Penrose substation**
- 3.18 Transpower is the owner and operator of Penrose substation. In that capacity, and of particular relevance to the October 2014 fire, Transpower is responsible for:

²⁷ Five of which were in service and one (cable 23 in Figure 4) marked as 'not in use'.

²⁸ CCI report, section 2.4

- a) site security and safety – the substation is a nationally and regionally significant extra high-voltage facility
- b) identification and management of risks and hazards to people and equipment
- c) management of access and occupation agreements/arrangements with owners of facilities installed (or to be installed) at the substation, including monitoring compliance with the agreements
- d) management of its equipment, including the cable trench but not including Vector's cables
- e) development of the substation to meet future transmission requirements.

Vector is the local distributor that takes supply from Penrose substation

3.19 Vector distributes electricity in Auckland and owns electrical equipment located on Transpower's land at Penrose substation. In that capacity, and of particular relevance to the fire event, Vector is responsible for:

- a) ownership and operation of power and control cables
- b) the security and safety of its cables – Penrose substation is an important GXP with regional significance within Vector's network
- c) identification and management of risks and hazards to people and equipment related to the location of its cables within the substation
- d) compliance with the terms of relevant access and occupation agreements/arrangements with Transpower, including the requirement to:
 - (i) apply good industry practice to the management and development of its assets
 - (ii) obtain Transpower's formal approval before installing new assets
- e) management of its assets, including the cables it owns within the cable trench but not including Transpower's cable trench itself or the switchyard lighting cable
- f) development of its network to meet future network requirements.

3.20 The peak electricity demand supplied at 33 kV and 22 kV from Penrose is around 350 MW.²⁹ The Penrose supply area includes a wide range of customers typically found in large inner-urban and fringe CBD zones. These include residential, commercial and industrial customers.

Vector has rights to occupy parts of Penrose substation such as cable routes

3.21 Rights of occupation for transmission customers and access to their assets, are routinely agreed between Transpower and transmission customers, such as Vector. Access and occupation agreements covering transmission customers'

²⁹ 33 kV peak demand is estimated from information provided in Transpower's 2015 Transmission Planning Report and includes demand supplied at 22 kV, since 22 kV demand is supplied via 33/22 kV transformers from the 33 kV bus. At the time of the outages (ie overnight), the demand on 33 kV and 22 kV supplies from Penrose was significantly less than the peak demand figure quoted here.

connection assets have evolved over several decades as the industry structure has evolved.

- 3.22 In 1966, the Auckland Electricity Power Board (AEPB) installed power and control cables that exited Penrose substation to Gavin Street in the newly constructed cable trench. The AEPB is a predecessor of Vector and operated as an electrical supply authority. At that time, the Electricity Supply Regulations provided for installation, operation and maintenance of the cables. These arrangements carried through until 1 January 1993, when the Electricity Act 1992 afforded the cables statutory protection as 'existing works'.
- 3.23 In October 1999, Transpower constructed the first indoor 33 kV switchgear building and entered into a 'licence to occupy' agreement with Vector. The agreement allowed Vector to install new cables at the Penrose substation and inspect, renew, maintain and operate those cables for an initial 20-year period. While the license also allowed for the replacement of some existing cables in the cable trench, it did not affect the status of the cables already laid in the cable trench, which were protected as existing works under the Electricity Act 1992.
- 3.24 In 2000, Vector entered into a connections contract with Transpower for Penrose substation. The connections contract included an access and occupation schedule, which granted Vector a licence to occupy, and access, certain parts of Penrose substation to install, operate and maintain specified facilities for the conveyance of electricity.³⁰
- 3.25 However, Vector and Transpower disagree about what contracts apply with respect to access and occupation at Penrose substation:³¹

Transpower's view is that when the Connections Contract was entered into the intent was for all existing and future Vector assets at Penrose to be covered by it, to the exclusion of previous agreements.

Vector's view is that the current version of the Connections Contract does not cover all existing Vector assets at Transpower's Penrose substation. Vector agrees that greater certainty is required, and that the Connections Contract should be updated to reflect all existing and future Vector assets.

The list of Facilities at Penrose in the Access and Occupation Schedule is incomplete and inaccurate. Some Facilities are not described correctly¹⁶ and Vector's 11 kV cables installed in the Cable Trench in the 1960s and 1970s (including the cable on which the joint that faulted was installed) are not listed.

Neither Transpower nor Vector has records showing unequivocally that the Access and Occupation Schedule has been updated since the original 2000 version.

- 3.26 The most recent agreement entered into that provides for access and occupancy is the 2000 Connections Contract. In the 2000 Connections Contract, Vector

³⁰ Investigation report, section 6.2

³¹ Investigation report, section 6.2.1. Note that footnote 16, included in the quoted text, is a footnote from the referenced report.

must comply with operating standards related to safety, security, access and operating practice.³² However, these standards do not apply to the design of Vector's assets at Penrose substation, which are required to comply with 'good industry practice'.

- 3.27 Relevant to an electricity distributor such as Vector, good industry practice is generally accepted to be the exercise of that degree of skill, diligence, prudence, foresight and economic management that would reasonably be expected from a skilled and experienced electricity network owner engaged in New Zealand in the distribution of electricity.³³

Access arrangements for NZFS personnel are provided in TP.SS 07.40

- 3.28 Transpower's approved service specification governing station security and entry control is TP.SS 07.40.³⁴ The purpose of this service specification is:

*To specify the responsibilities of personnel entering Transpower stations and communication sites, and to stipulate the entry protocols, safety management and security requirements for those stations and sites.*³⁵

- 3.29 The section related specifically to entry by NZFS personnel states:

10. FIRE BRIGADE ENTRY

10.1 General

10.1.1 Fire Service personnel are prohibited by their management to enter a restricted area to attend fires unless they are accompanied by the holder of a valid Competency Certificate.

*10.1.2 The RAE Competency Certificate holder accompanying the fire brigade must obtain a permit where required to ensure any fire brigade activities in the vicinity of high-voltage equipment can be carried out safely.*³⁶

³² 2000 Connections Contract for Penrose substation, Access and Occupation Schedule, clause 5.1

³³ For example, this is essentially the same definition provided in Part 1 of the Code.

³⁴ Transpower, *TP.SS 07.40 Station security – procedures*, issue 13, February 2012

³⁵ TP.SS 07.40, clause 1

³⁶ TP.SS 07.40, clause 10. RAE means Restricted Areas Entry.

4 What happened on 4–5 October 2014?

4.1 The following references have informed the following description of events that occurred in the lead up to discovery of the fire at Penrose substation:

- a) section 3.2 of the investigation report
- b) the NZFS report
- c) the CCI report.

4.2 A timeline of key events is included in Appendix B.³⁷

An 11 kV feeder fault occurred at 11:21 pm on 4 October 2014

4.3 At 11:21 pm on Saturday 4 October 2014, a fault caused the Vector 11 kV feeder designated Remuera K10 to trip.³⁸ That feeder supplies electricity to customers in parts of Remuera and Ellerslie, and includes sections of overhead line and underground cable. At the time of the fire event, Remuera K10 was supplied from Vector's Remuera zone substation.

4.4 Remuera K10 includes a section of cable installed in the cable trench at Penrose substation. The feeder does not supply loads within the substation but uses the cable trench as a through-route from one side of the substation to the other.

4.5 The investigation concluded that the fault in the section of Remuera K10 located in the cable trench caused the Penrose substation fire.³⁹

4.6 At the time this fault occurred, the Vector Electricity Operations Centre (EOC) controller considered that the Remuera K10 trip had resulted from a routine feeder fault. To locate the cause of the fault, the EOC controller dispatched a faultman to carry out a line patrol. Remuera K10 has a history of faults caused by tree branches contacting the overhead lines.

4.7 Following established procedure, the faultman started patrolling from Remuera substation, following an outward route along the overhead line. The faultman observed the status of fault passage indicators installed on the feeder during his line patrol.⁴⁰ He concluded that the fault was most likely located within an overhead section along Michaels Avenue between Marua Road and the Ellerslie Panmure Highway.

4.8 However, as the faultman found no physical evidence of the fault during the line patrol, and given the history of tree-related faults on the overhead line sections of

³⁷ Some event times cited in the various reports are time-stamped to the nearest second, however the times stated in this report omit the seconds and state only hours and minutes. A consequence of this adjustment is that some of the times and durations cited in this report are plus or minus 1 minute, depending on the reference used.

³⁸ When electrical equipment 'trips', circuit breakers automatically open to de-energise the faulted equipment (in this case, an 11 kV feeder). Vector and Transpower have reported numerous equipment trippings in the sequence of events associated with the fire. Some of these were as a consequence of fire damage to control cables.

³⁹ This is corroborated by the CCI report and the NZFS report.

⁴⁰ Fault passage indicators are installed on feeders to assist with fault location. They indicate to a faultman if high fault currents have passed by the point at which they are installed.

the feeder, the EOC controller concluded that the fault was a transient fault.⁴¹ In accordance with established operating procedure, the EOC controller then manually reclosed the feeder at 1:21 am on Sunday 5 October 2014 (ie two hours after the feeder had originally tripped). The feeder immediately tripped again.

- 4.9 At this point, the EOC controller considered the most likely cause of the fault was a faulty cable termination. The EOC controller then transferred some residential load from Remuera K10 to an alternative feeder to restore supply to those customers.
- 4.10 The EOC controller and the faultman then carried out a sequence of switching operations along the remainder of the Remuera K10 feeder. This was done to isolate the fault location to a smaller section of the feeder.
- 4.11 While these switching operations were underway, supply to the whole of Remuera zone substation was lost. Information received by the EOC controller regarding the fire meant that EOC attention shifted to the developing situation at Penrose substation.

Attention was drawn to Penrose substation by alarms and a neighbour's call to emergency services

- 4.12 The following description of events that occurred as the fire took hold at Penrose substation is taken largely from section 3.1 of the investigation report.
- 4.13 From 2:04 am on 5 October 2014, Transpower's remote monitoring and control system recorded a series of unusual alarms from equipment at Penrose substation. The initial alarms were associated with the 220/33 kV supply transformer T11 (refer to Figure 1 and note the proximity of T11 to the indicated seat of the fire).
- 4.14 At 2:09 am, Transpower's National Grid Operations Centre (NGOC) dispatched a substation maintainer to investigate the cause of the alarms. T11 subsequently tripped at 2:10 am, followed in quick succession by number of 33, 22, and 11 kV feeder and transformer trippings. This sequence resulted in an escalating series of power outages to customers.
- 4.15 A neighbour at a property adjacent to Penrose substation called emergency services at 2:17 am to report hearing explosions coming from the Penrose substation.⁴² NZFS dispatched fire appliances in response to the call and notified NGOC. The first fire appliance arrived at the perimeter security gate in Gavin Street at 2:26 am.
- 4.16 The maintainer met the first-response fire appliances and opened the Gavin Street perimeter security gate at 2:41 am. The maintainer reported seeing thick smoke near the 220/33 kV supply transformer T11. This quickly developed into flames visible above ground between the adjacent transformers (T10 and T11) and the 33 kV indoor switchgear building (located next to the 220 kV switchyard).

⁴¹ A transient fault is a fault that self-clears due to the high fault current, eg a tree branch that is burned clear of the live overhead conductors.

⁴² The investigation has determined that the 'explosions' most likely resulted from a number of outdoor 33 kV circuit breaker (CB) trippings logged between 2:11 am and 2:16 am.

- 4.17 A live, extra high-voltage switchyard (in this case containing 220 kV and 33 kV equipment) is a hazardous environment. Firefighting in a live switchyard is a hazardous activity. Transpower's site access procedure accordingly requires that emergency services personnel are accompanied by an RAE Competency Certificate holder.⁴³
- 4.18 At 2:50 am, NGOC informed EOC that all 33 kV equipment in the 220 kV switchyard would be de-energised to provide safe access for firefighting by NZFS personnel. This required planning and executing a long sequence of switchgear operations by the NGOC controller. Once those operations were completed, all 33 kV and 22 kV supplies at Penrose were de-energised. This resulted in the interruption of electricity supply to 75,339 customers.
- 4.19 The area around the fire adjacent to the 33 kV switchroom was declared safe to enter at 3:22 am. By this time, the fire was burning freely against the exterior wall of the 33 kV switchgear building.
- 4.20 A comment in the executive summary section of the NZFS report states:
- The first fire appliance arrived at 2:26am but it was not until 3:23am when an initial fire attack occurred in the area of the switchgear building.*
- 4.21 This means that NZFS access to the security fenced switchyard area occurred 57 minutes after the first fire appliance arrived at Penrose substation.
- 4.22 TP.SS 07.40 requires that the RAE Competency Certificate holder accompanying the fire brigade must obtain a permit where required to ensure any firefighting activities in the vicinity of high-voltage equipment can be carried out safely.⁴⁴ No permit was issued at this point.⁴⁵
- 4.23 While the NZFS report stated that an initial fire attack commenced in the area adjacent to the 33 kV switchgear building at 3:23 am, this was the time NZFS first entered the security fenced switchyard area. The application of foam commenced at 3:32 am.
- 4.24 At 3:35 am, the firefighters withdrew due to concerns that the cables exiting the cable trench might still be energised. At this time, the onsite Transpower personnel asked the Vector EOC controller if there was any back-feed from the Vector network into the 33 kV circuits at Penrose substation.⁴⁶
- 4.25 At 3:55 am, NZFS noted that power was confirmed as being isolated and that firefighting was underway with two foam deliveries in use. This point was 89 minutes after the first fire appliance arrived at Penrose substation.

⁴³ Investigation report, paragraphs 3.28 and 3.29

⁴⁴ TP.SS 07.40 clause 10.1.2

⁴⁵ Transpower has informed the Authority that, in its opinion, issue of a permit is only required if 'work' is to be undertaken on electricity equipment (e.g. if a cable was to be cut). In light of this submission, the Authority reviewed the relevant service specification and considers that, if Transpower's view is correct, then the procedure is at best unclear and should be reviewed. This issue is discussed further in section 7.

⁴⁶ Transpower and Vector disagree with NZFS on some of the facts relating to this part of the sequence of events. At the date of this report, no consolidated version of events, agreed by all the parties involved, has been made available to the Authority. This is discussed further in section 7.

The fire continued to spread inside the cable trench across the 220 kV switchyard

- 4.26 After NZFS brought the fire adjacent to the 33 kV switchgear building under control, the fire continued to burn and spread eastward along the cable trench through the 220 kV switchyard towards Gavin Street. The 220 kV switchyard was still energised at this point. NZFS had been made aware of the energised status of the 220 kV switchyard at 3:34 am when Transpower notified NZFS not to go past the line of the transformers (ie not to go any further into the 220 kV switchyard) because that area was still energised.
- 4.27 To enable firefighting in the cable trench from the edge of the transformers across the 220 kV switchyard, the onsite Transpower manager requested NGOC to shut down the 220 kV switchyard at 4:26 am.
- 4.28 At 4:30 am, NGOC initiated switching operations to de-energise the entire 220 kV switchyard. These operations were completed at 4:35 am. The investigation report states:
- Arcing and corona discharging was also occurring in the 220 kV switchyard. Damage from flashovers could have impeded restoration of electricity supply once the fire was extinguished. To avoid equipment damage and to allow NZFS better access, the entire 220 kV yard was de-energised.*
- 4.29 The NZFS report states that:
- Re-entry to the switchyard area did not occur until 4:37am when confirmation was received of the power being isolated.*
- The delay in being able to recommence firefighting did allow fire spread from where the fire originated to along the length of the trench.*
- 4.30 After the firefighters entered the de-energised 220 kV switchyard, they were able to control the fire in the cable trench running eastward from the transformers towards Gavin Street by 6:45 am.
- 4.31 The cable trench was flooded with water at 8:00 am to cool any hot spots and eliminate the risk of re-ignition. NZFS transferred control of the site back to Transpower at 9:57 am but remained at Penrose on standby.

Part Two Responses to the Minister's questions

Draft

5 Why the power outage occurred

5.1 This section answers the Minister's first question:

What caused the loss of supply or contributed to it, including potentially systemic factors such as risk management systems, asset health monitoring and maintenance practices, network design, and regulatory incentives and controls?

5.2 In summary, the inquiry has concluded that:

- a) a cable trench that traverses the Penrose 220 kV switchyard had too many cables installed in it⁴⁷
- b) a cable joint failure ignited the fire in the cable trench, which was identified in the early hours of 5 October
- c) the cable joint design and method used to install the cable joint in 2001 were factors that contributed to its failure
- d) the manual reclose of the Remuera K10 feeder at 1:21 am on 5 October accelerated the fire
- e) the failure to apply risk and asset management policies and procedures meant that the risk of fire in the Penrose cable trench was not identified
- f) the co-location of the cables in the trench contributed to the spread of the fire and meant that the fire affected more feeders, which threatened Transpower's assets and resulted in a widespread outage.
- g) there are no systemic issues related to regulatory incentives and controls.

5.3 The Authority considers that Vector and Transpower should have been aware of the factors that had the potential to affect the integrity of the cable trench and the cables that it contained and therefore should have identified the risks.

5.4 This section explains the basis for these conclusions.

A cable trench traversed the Penrose 220 kV switchyard that had too many cables installed in it

5.5 As summarised in section 3, a concrete-lined cable trench was installed as part of a major 1966 development to connect 220 kV national grid lines at Penrose substation. The cable trench runs for 103.9 metres west to east across the substation's 220 kV switchyard.

5.6 The cable trench was used:

- a) by Vector as a route for a number of its 33 kV, 22 kV and associated pilot cables from points of connection within Penrose substation to Gavin Street
- b) by Vector as part of a through-route for some 11 kV cables that traverse the Penrose substation site
- c) by Transpower for a power cable used to supply switchyard lighting.

⁴⁷ CCI report, section 15.6.3

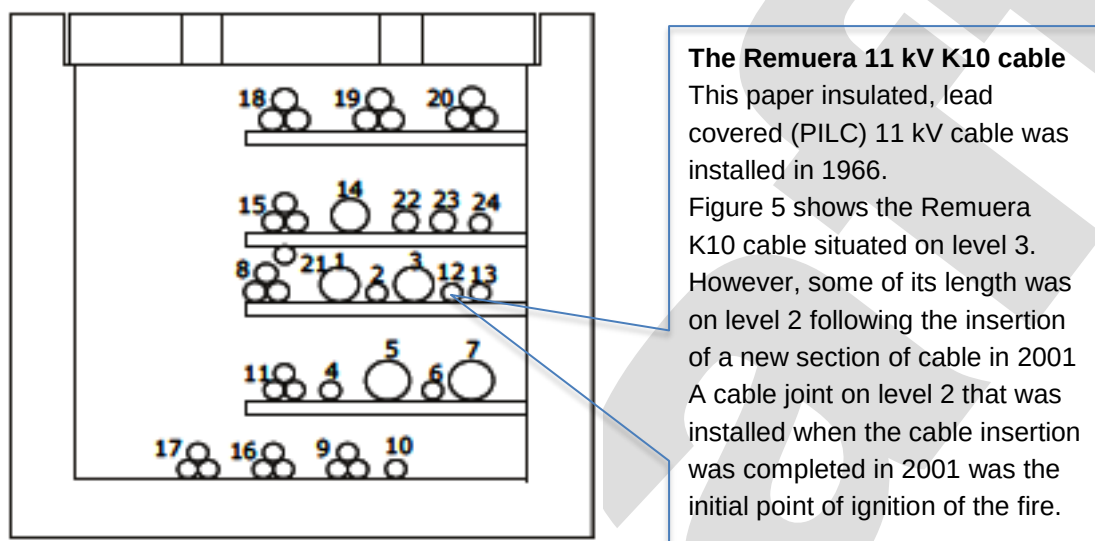
5.7 CCI considered the cable trench to be a 'significant in-air application' containing:

1. 19 power cable feeders,
2. a total combined cable length of 3.99 km comprising 38 lengths each of 103.9m,
3. 15 joints (4 x 11 kV PILC, 3 x 33 kV XLPE and 2 x 11 kV PILC/XLPE) and
4. a significant volume of flammable material comprised of over-sheathing and hydrocarbon insulation and low viscosity cable oil in the cable and within the oil reservoir tanks.⁴⁸

5.8 In its report, CCI states that, by 2001, limited space remained in the trench⁴⁹ and that at the time of the fire in 2014, too many cables had been installed in the trench.⁵⁰ CCI notes that, while the co-location of a large number of cables did not directly cause the joint failure, it did contribute to the stress placed on the cable joint and the rate of fire spread.⁵¹

5.9 Figure 5 shows the cables in the cable trench in 2014, and the location of the cable that contained the joint that failed. The material used in the cables provided the fuel for the fire.

Figure 5 – Cross-section of the Penrose substation trench Gavin Street end



Source: Investigation report

5.10 The cable trench is covered with ground-level removable concrete lids. At the time of the fire, the cable trench had no fire barriers or fire, heat or smoke detectors. No fire suppressant systems had been installed. Figure 6 is a photograph of the cable trench taken in 2001. Note that more cables were added to the trench after this photograph was taken.

⁴⁸ CCI report, section 15.6.1

⁴⁹ CCI report, section 4.6

⁵⁰ CCI report, section 15.6.3

⁵¹ CCI report, section 15.6.3

Figure 6 – Penrose cable trench in 2001



Source: CCI report

A cable joint failure ignited the fire in the cable trench which was identified early on 5 October

- 5.11 In 2001, Vector observed that an existing 11 kV PILC straight joint was leaking bitumen. The cable formed a section of the Remuera K10 feeder circuit. The cable joint was located in a section of the circuit that ran inside the Penrose substation cable trench.
- 5.12 To fix this issue, a Vector maintenance contractor cut out a section of the cable that included the leaking joint and spliced in a new length of cable, requiring two new joints. The new cable was a more modern type, with cross-linked polyethylene (XLPE) insulation. Joints installed to connect two different types of cable are called 'transition joints' – in this case, a 'PILC to XLPE' transition joint.
- 5.13 The two new joints were installed in the confined space of the cable trench, and the spliced XLPE cable was longer than the section of PILC cable it replaced. This meant that the Vector contractor had to lay the cable in a bow shape rather than in a straight alignment.
- 5.14 The CCI report confirms that one of the two transition joints in the Penrose cable trench section of the Remuera K10 feeder failed while in service and provided the initial source of ignition for the fire.
- 5.15 Figure 7 is a cutaway diagram of an 11 kV, three-core, heat-shrink sleeve PILC to XLPE transition joint.

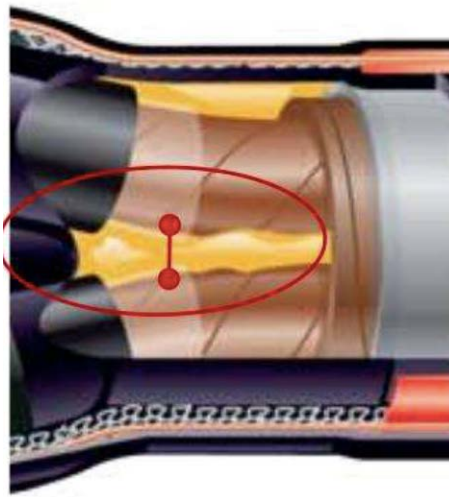
Figure 7 – PILC to XLPE transition joint example



Source: CCI report⁵²

- 5.16 CCI's detailed examination identified that a power arc occurred in the 'crutch' of the transition joint at the location shown in Figure 8.⁵³ CCI concludes that the fire is likely to have ignited from the 11 kV power arc that would have resulted as the insulation material in the joint failed.

Figure 8 – The arc position in the failed transition joint



Source: CCI report⁵⁴

- 5.17 Once the fire had started, it spread to the west towards the 33 kV indoor switchroom and east towards Gavin Street. The acceleration of the fire and the manner in which it spread along the trench were assisted by:
- a) the in-air environment of the trench, which provided oxygen to fuel the fire
 - b) the contents of the trench, which contained fuel for the fire (e.g. wood, oil, plastic)
 - c) the manual re-close of Remuera K10 at 1:21 am, 120 minutes after the feeder originally faulted and tripped

The method used to install the cable joint in 2001 contributed to its failure

- 5.18 CCI examined the burnt remains of the failed joint, and the second intact transition joint, and concluded that Vector had completed each of the two joints in

⁵² CCI report, Figure 98

⁵³ CCI report, section 6.3

⁵⁴ CCI report, Figure 31

accordance with the manufacturer's instructions. Note that this comment is about how each of the joints were individually completed.

- 5.19 Following detailed forensic inspection of the two transition joints, CCI concludes that:

The cause of the transition joint failure is the vulnerability of the transition joint design, with respect to the electrically stressed insulation in the crutch between the PILC cable cores.⁵⁵

- 5.20 CCI also concluded that, from the examination of the unfailed transition joint, the jointing quality was satisfactory.⁵⁶

- 5.21 CCI identifies likely contributing factors as:

- i) The concentration of thermo-mechanical disturbance of the crutch insulation resulting from:
 - a. Lack of straight alignment of the joint and cables (the joint was positioned at the start of a curve in the cable).*
 - b. Lack of cable cleats and joint supports.**
- ii) Ingress of moisture into the crutch insulation at the lead sheath cut*
- iii) Drying-out of the impregnating compound from the paper insulation*
- iv) Migration of void filling mastic to the paper insulating tapes in the crutch*
- v) The jointing process of inserting 'void filling mastic' insulation into the PILC crutch of the transition joint, this being difficult and variable and risked damage to the cable insulation.⁵⁷*

- 5.22 That is, one of the likely contributing factors to the ignition of the fire was the installation of the spliced cable section in a bow shape, which placed stress on the correctly completed transition joint. As CCI notes, this contributed to the failure of the transition joint and ignition of the fire.

- 5.23 CCI notes:

By the year 2001 when the two PILC to XLPE transition joints were installed as a repair measure in the Penrose trench the Author was aware that transition joints had a higher failure rate than conventional PILC straight joints. The Author notes that failure rates were not available in the public domain.⁵⁸

The manual reclose of the Remuera K10 feeder at 1:21 am on 5 October accelerated the fire

- 5.24 The cable trench section of the Remuera K10 feeder was not included in the line patrol that was carried out before the manual reclose at 1:21 am. The CCI report considers it likely that the fire accelerated when Vector manually reclosed Remuera K10.
- 5.25 All electrical networks have protection systems installed that automatically detect electrical faults and rapidly trip the appropriate circuit breaker(s) to isolate the

⁵⁵ CCI report, section 15.2

⁵⁶ CCI report, section 15.2

⁵⁷ CCI report, section 15.2

⁵⁸ CCI report, section 15.2

faulted equipment. Vector and Transpower's protection report confirms that the feeder protection system for Remuera K10 operated as designed.⁵⁹

- 5.26 The cable fault that occurred at 11:21 pm was cleared in 0.561 seconds. After the manual reclose of the feeder at 1:21 am, the fault cleared in 0.550 seconds. The CCI report considers that reclosing the feeder circuit breaker onto a failed cable joint would have significantly increased the severity of joint damage and collateral circuit damage and increased the risk and rate of acceleration of the fire.

Potentially systemic factors related to risk management

- 5.27 The Joint Australian New Zealand International Standard ISO 31000:2009 Risk Management - Principles and Guidelines (ISO 31000) is a reference and guide on good practice risk management. Both Vector and Transpower align their risk management with ISO 31000.
- 5.28 The Authority considers that, consistent with the international standard ISO 31000, risk management processes should:
- a) identify potential risks
 - b) assess the probability and impact of an identified risk
 - c) rank the priority of identified risks
 - d) form and implement plans to control or mitigate identified risks.
- 5.29 Managing an electricity network requires a network owner to identify and assess many complex risks and combinations of risks.
- 5.30 The Authority concludes that, prior to the Penrose fire, neither Vector nor Transpower had identified:
- a) the risk of fire ignition from failure of a power cable in the Penrose cable trench (the ignition risk) or
 - b) the risk posed by multiple power cables co-located in the Penrose cable trench (the co-location risk).
- 5.31 Therefore, steps were not taken that could have prevented the widespread supply disruption or mitigated the extent of the disruption.
- 5.32 The investigation report concludes that Vector could not have been expected to identify the risk of fire in the cable trench and supports this conclusion:⁶⁰
- a) by noting that no previous cable failures had occurred within the cable trench
 - b) by referencing international experience researched since the fire, which points to a very low incidence of fires related to cable joints in in-air situations
 - c) by noting that details of any cable fires that have occurred globally have not been made public.
- 5.33 Vector also informed the Authority that no fires had arisen from transition joint faults elsewhere on its network.

⁵⁹ Transpower New Zealand Limited and Vector Limited, *Penrose Substation Fire – 05 October 2014 – Summary of Protection Operations report*, 22 May 2015, section 3.2

⁶⁰ Investigation report, section 7.6.2 and section 8, paragraph 15

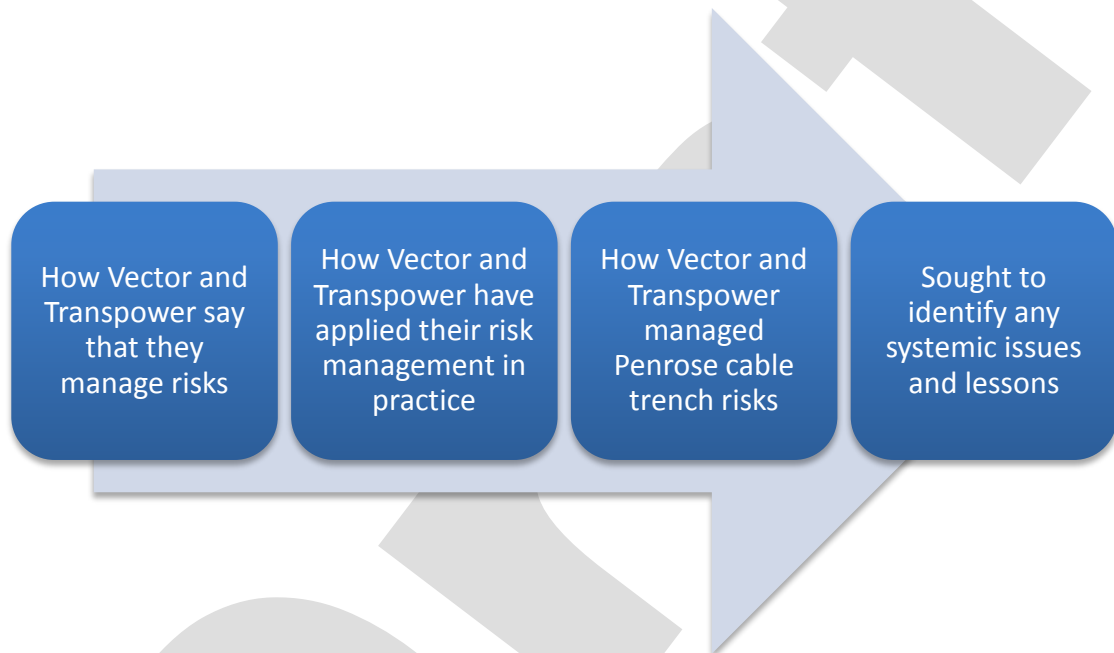
- 5.34 However, the Authority considers that both Vector and Transpower should have been aware of the factors that had the potential to affect the integrity of the cable trench and the cables that it contained and therefore should have identified the risk to electricity supplies and to the integrity of the substation. The basis for this view is explained further below.
- 5.35 In reaching its view on the risk management aspects related to the Penrose fire event the Authority has relied on and accepts CCI's conclusion that:

*At the time of the fire, too many cables had been installed in the trench.
This did not contribute to the cause of the joint failure, but did contribute to the rate of fire spread.⁶¹*

The Authority's approach when considering potentially systemic factors in risk management

- 5.36 The inquiry took the initial step of establishing whether Vector and/or Transpower had identified the risks associated with the cable trench at Penrose substation. As Vector and Transpower told the Authority that neither had identified the risks, the Authority moved on to consider why the risks had not been identified.
- 5.37 In order to answer the question as to why the cable trench risks had not been identified the Authority used a 'top-down' review of governance and management to establish what the businesses say they do and then compare this with what was seen to have been applied in practice. This approach is described in Figure 9.

Figure 9: The Authority's top down review process



- 5.38 Vector owns and manages the power cables installed in the cable trench at Penrose. Accordingly, the Authority assessed Vector's management practices in relation to its role as asset owner. As owner of the Penrose substation,

⁶¹ CCI report, Executive Summary, conclusion 13

Transpower has obligations to manage risks that could threaten the integrity of the substation and the safety of people at the substation. Accordingly, the Authority assessed Transpower's risk management practices in relation to its obligations at the Penrose site.

5.39 When undertaking its assessment of the management of the cable trench risks at Penrose substation the Authority:

- a) used ISO 31000 as a reference and guide on good practice risk management. As noted above, both Vector and Transpower align their risk management with ISO 31000.
- b) took account of Vector and Transpower's documentation including risk policies, strategies, and asset management strategies and plans.
- c) considered the biennial State of the Network reports provided to AECT by external expert consultants, the CCI report and additional advice on transition joint fire risk knowledge⁶²
- d) participated in discussions at workshops to gain an understanding of how Vector and Transpower applied their risk management policies and strategies in practice at the Penrose substation
- e) took into account the draft investigation report and supplementary documentation provided by Vector on its risk management methods
- f) considered the Authority's technical advisor's views on how risk management is applied in electricity network businesses both in New Zealand and internationally
- g) considered other information gathered from public sources.

The risk was identifiable but was not identified

5.40 CCI identified that the Penrose cable trench was 'a significant in-air application'. The Authority agrees with CCI's finding and, in addition, considers that a contributor to the loss of supply was the co-location of a very large number of supply-critical cables within an in-air trench, some of which had cable joints installed.

5.41 That is, setting aside the risk of a specific type of cable joint failure causing ignition, Vector and Transpower did not identify a generic risk to electricity supplies and the consequences of all the cables in the Penrose cable trench being disabled simultaneously. This is confirmed in the investigation report which states:

No specific risk reviews were carried out with respect to the cables in the cable trench. Risk assessments were made for each network project that involved new cables being installed in the trench, but these were focused on the construction and environmental risks pertaining to the specific project. In these projects the trench simply formed a small

⁶² Cable Consulting International Ltd, Draft Notes: Investigation into a Fire in a Cable Trench in Penrose Substation, Final Draft, 13 August 2015

*section of the cable route and the associated construction risks were considered minor.*⁶³

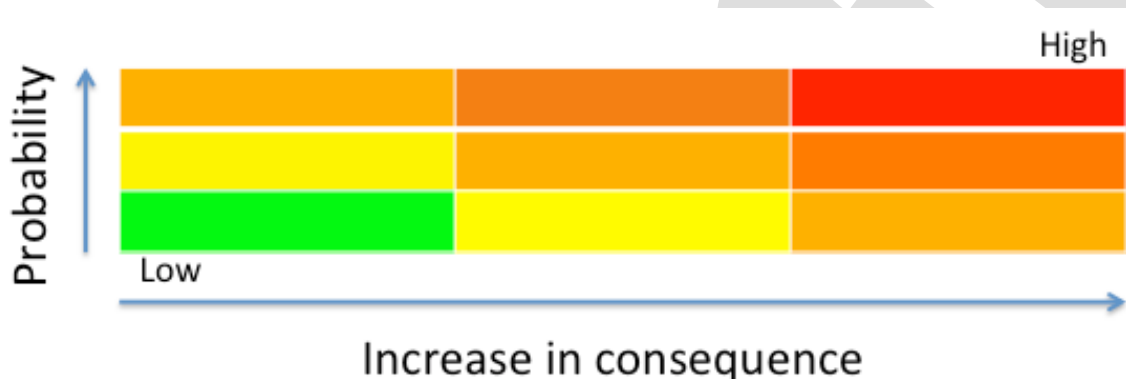
5.42 The Authority considers that the specific risk to electricity supplies posed by the co-location of a large number of supply-critical cables within an in-air trench at Penrose substation should have been identified and assessed. There were several opportunities to identify the risks, including:

- a) on each occasion when cables were added or jointed in the cable trench
- b) during periodic maintenance inspections
- c) during Transpower's HILP study for Penrose substation, carried out in 2013
- d) when biennial reviews of the state of the network were undertaken for the AECT.

5.43 A common aspect of Vector's and Transpower's risk management frameworks is that both probability and consequence of a potential risk must be considered. This approach should ensure that specific assets, or groups of assets, that are critical to the operation of the network, are considered, regardless of how small the probability of an occurrence is.

5.44 Figure 10 shows how, at a high level, risks can be considered on the basis of probability and consequence.

Figure 10 – Risk priority assessment matrix



Source: Investigation report

5.45 Had the above approach been applied to the risk to electricity supplies resulting from the co-located power cables within the Penrose cable trench, the Authority considers it likely that the ignition risk would have been assessed as:

- a) high consequence (impact)
- b) low probability.

5.46 Such risks are generally termed 'HILP events'. Assessing the risk as a HILP event would have led to further detailed consideration of specific risk controls and mitigations. Nevertheless, as noted above, Vector and Transpower have both confirmed that the risk of a very large number of power cables co-located within the cable trench at Penrose substation had not been identified in their respective risk management systems.

⁶³ Investigation report, section 7.6.2

- 5.47 The investigation found that, on the occasions when Vector laid additional cables in the cable trench, the focus was on specific project risks rather than combined or grouped cable trench risks.⁶⁴ The Authority considers that correct application of the risk management framework means that it should have been applied to the trench as a whole. The Authority considers that this is likely to have contributed to the fact that neither Vector nor Transpower identified the wider cable trench risk, ie the co-location risk.

Transpower had identified but not acted on a relevant generic risk

- 5.48 In its response to a question from the Authority, Transpower described how it identifies, assesses and manages risks, as follows:

Detailed risk registers are prepared by various teams within Transpower as part of a 'bottom-up' approach to grid asset risk identification and management. These bottom-up risk registers are aggregated to Division risk registers which are in turn consolidated into the Corporate Risk Register.

The lower level risk registers focus on initial capture of risks. Following a preliminary assessment, the higher severity risks are populated with risk controls and treatments, and considered for escalation to the relevant aggregated Division risk register.

The aggregated Grid Performance risk register is presented regularly to meetings of the Grid Performance leadership team, and top risks from the Division are communicated to the Transpower staff Risk Committee. This is a cross-Divisional team. They are responsible for the compilation of the Corporate Risk Register. The Transpower Board regularly reviews the top risks in the Corporate Risk Register.⁶⁵

- 5.49 In the same response, Transpower also gave details of a specific risk entry it considered relevant to the Penrose fire:

Grid Performance NNI Register – NNI 23

Failure of equipment (eg cables and joints) owned by connected customer on Transpower site causes safety hazard and fire/explosion damage to critical Transpower assets leading to loss of supply.

- 5.50 Transpower risk register entry NNI 23 is relevant to the Penrose fire because:
- a) the cables were owned by a connected transmission customer (ie Vector)
 - b) the cables were located on a Transpower site (ie Penrose substation, in the cable trench that crosses the 220 kV switchyard)
 - c) the fire caused a safety hazard that destroyed sections of other Vector and Transpower cable assets
 - d) before it was contained, the fire threatened to damage supply-critical Transpower assets (switchgear, transformers, a 33 kV switchgear building and associated auxiliary equipment in and near the 220 kV switchyard)

⁶⁴ Investigation report, section 7.6.2

⁶⁵ Transpower New Zealand Limited, *Asset Management Practices, Version 2*, dated 4 May 2015.

e) the fire led to a widespread loss of supply.

- 5.51 Transpower's response goes on to explain the status of risk NNI 23 at the date of the Penrose fire:

This risk statement from the NNI register, as at October 2014, was a product of the initial risk identification process outlined above. A preliminary risk assessment had been undertaken, scoring this risk as 'Medium' risk level, before controls (ie the inherent risk level). Priority for further risk analysis, including documenting risk controls and treatments, was based on the initial risk assessment.

In general, priority for further risk analysis was given to risks assessed with inherent risk levels of 'High' or 'Extreme'. As a consequence, risk controls and treatments for the risk statement NNI-23 had not been documented as at October 2014, and this risk had not been escalated to the aggregated Grid Performance risk register.

- 5.52 In summary, at the time of the Penrose fire, Transpower had identified a generic risk (ie a risk not related to a specific site) that failure of a connected customer's assets located at a Transpower site could lead to damage of supply-critical Transpower assets and cause a loss of supply. Transpower rated this risk as having an inherent risk level of medium.
- 5.53 Transpower had entered this bottom-level risk into its risk management register but, by October 2014, had not progressed beyond the stage of identification and initial assessment.

Transpower's Penrose HILP study should have identified the risk to electricity supply

- 5.54 In 2013, Transpower undertook a programme of HILP event studies at a number of its high priority substations, including at Penrose substation.⁶⁶ The purpose of the studies was to identify HILP risks, propose mitigations, and make recommendations to carry out works or to progress further investigations.
- 5.55 The HILP study did consider the cable trenches at Penrose, and suggested that consideration should be given to undertaking a:
- ... programme to replace timber cable trench covers in the 220 kV yard with concrete covers.⁶⁷*
- 5.56 In a study commissioned by Transpower and undertaken by Marsh Risk Consulting (Marsh) as part of the HILP study at Penrose substation, cable trenches were identified as a HILP risk. Marsh identified that damage to cables in the cable trench along the southern fence line in the 220 kV yard would contribute to the potential for a high impact event.⁶⁸
- 5.57 The HILP study considered the cable trench risk could arise from damage to the cables from external events such as vehicles breaking through the wooden covers and damaging cables.

⁶⁶ Penrose Substation High Impact Low Probability (HILP) Event Study June 2013

⁶⁷ Penrose Substation High Impact Low Probability (HILP) Event Study June 2013, Section 4.8

⁶⁸ Penrose Substation High Impact Low Probability (HILP) Event Study June 2013, page 11

- 5.58 Despite the broad scope of the HILP study, it did not identify potential risks related to the use of the cable trench by Vector for its cables. The discussion of cable trench risks was limited to potential damage to one specific trench. The study did not identify the potential risks to the safety and security of Penrose substation related to the contents of the cable trench.

Vector's State of the Network reviews identified the risk event of simultaneous failure of two cables but not simultaneous failure of 38 cables

- 5.59 The AECT deed requires that Vector management obtain a biennial report from an independent expert on the state of the Auckland electricity reticulation assets. This is called the 'State of the Network' review. The scope of the review is to prepare a report on:
- a) the state of Vector's electricity assets across its Auckland and Northern networks with regard to maintenance programmes and the appropriateness of expenditure levels
 - b) any need for the upgrading of Vector's electricity assets, taking into account what is already being planned by Vector management
 - c) the capacity of Vector's electricity assets in relation to forecast demand
 - d) any security risks to Vector's electricity assets.
- 5.60 Vector's expectation was that the review would cover:

*... existing Vector plans and policies, forecasts, and expenditure profiles, as well as field inspections of typical Vector assets and interviews with technical and management staff. Vector will assist with the provision of the required information and to facilitate interviews and field visits.*⁶⁹

- 5.61 State of the Network reviews have been undertaken since 2009. In two of the biennial reviews, a risk related to installing two cables in common trenches at zone substations was identified. However, none of the State of the Network reviews have identified or discussed the Penrose cable trench specifically.

In summary, Vector and Transpower should have identified the risk

- 5.62 Vector should have identified the criticality to electricity supplies of the cables co-located in the cable trench. As noted above, the risks could have identified on a number of occasions, including:
- a) when cables were added to the cable trench
 - b) when maintenance, such as cable jointing, was undertaken within the cable trench
 - c) during periodic risk reviews and during biennial state of the network reviews.
- 5.63 Transpower should have identified the risk to the integrity of the Penrose substation due to the co-location of a large number of power cables within the Penrose cable trench. As the national grid owner, Transpower should be aware

⁶⁹ Auckland Energy Consumer Trust, *Electricity Network Review – Request for Proposal 2010*, Scope

of all risks relating to the integrity of national grid facilities, particularly those relating to security of supply and the safety of people and equipment.

- 5.64 Both Vector and Transpower have said they intend to review their risk management practices to incorporate lessons from the Penrose fire. The Authority strongly supports these initiatives and recommends that electricity network businesses more generally review their risk management procedures and ensure the procedures are followed in practice.

Vector and Transpower's submission

- 5.65 Vector and Transpower, in their submission on a draft of this report, gave significant emphasis to their view that the Authority's conclusion that they should have identified the risks related to the co-location of multiple cables in the cable trench was wrong. Accordingly, the Authority has reconsidered that conclusion in light of Vector and Transpower's submission.
- 5.66 The Authority's understanding of Vector and Transpower's submission on risk identification relating to the Penrose cable trench is summarised as follows:
- the relevant risk event is a transition joint-related fire
 - the co-location of cables relates to the potential consequences that may arise from any risk event
 - there is no risk "inherent in co-locating multiple power and control cables" in the Penrose substation cable trench
 - the specific fire risk relating to the transition joint was not identified and therefore no risk mitigation actions were taken
 - publically available 'risk intelligence' on in-air transition joint failures posing a fire risk was not available to Vector and Transpower
 - even if the potential high consequences of a failure of co-locating cables in a common trench had been identified, because the risk of a transition joint fire risk was unknown, nothing would have been done
 - limited publically available information means that Vector and Transpower cannot be expected to have identified the fire event risk in the Penrose cable trench.
- 5.67 In summary, the Authority understands that Vector and Transpower consider that the Authority has incorrectly categorised the co-location of multiple cables in the trench as a separate risk rather than a consequence of a risk. Even if the consequences of a loss of the cable trench had been identified, Vector and Transpower consider that they still would not have identified the fire risk and therefore could not have been expected to consider risk mitigation actions.

The Authority's assessment of Vector and Transpower's submission

- 5.68 When formulating its view in the draft report given to Vector and Transpower, the Authority applied its understanding and interpretation of ISO 31000, which defines risk as the *effect of uncertainty on objectives*.
- 5.69 ISO 31000 defines **risk assessment** as
overall process of risk identification, risk analysis and risk evaluation

5.70 ISO 31000 defines **risk identification** as the *process of finding, recognizing and describing risks*

Note 1 Risk identification involves the identification of risk sources, events, their causes and their potential consequences.

Note 2 Risk identification can involve historical data, theoretical analysis, informed and expert opinions, and stakeholder's needs.⁷⁰

5.71 In light of Vector and Transpower's alternative interpretation of 'risk', 'risk identification' and 'risk assessment' the Authority has reconsidered its interpretation of ISO 31000, and in doing so has taken particular note of the following definition of **risk** provided in ISO 31000:

Note 1 An effect is a deviation from the expected

Note 2 Objectives can have different aspects (such as financial, health and safety, and environmental goals) and can apply at different levels (such as strategic, organization-wide, project, product and process)

Note 3 Risk is often characterized by reference to potential events and consequences, or a combination of these.

Note 4 Risk is often expressed in terms of a combination of the consequences of an event (including changes in circumstances) and the associated likelihood of occurrence.

Note 5 Uncertainty is the state, even partial, of deficiency of information related to, understanding or knowledge of an event, its consequence, or likelihood.⁷¹

5.72 When undertaking a risk assessment, the system under consideration and the system's objectives must be defined. The Authority considers that, for the scope of this inquiry, it is reasonable to assume that:

- a) in the case of Vector, the system starts at the Penrose substation and ends where consumers take supply. The objective is safe, secure, and reliable power supply to consumers
- b) in the case of Transpower, the system has an end point at the Penrose substation and the objective is safe, secure, and reliable supply to Vector, its customer.

5.73 The definition of risk provided in ISO 31000 specifically deals with the uncertainty of risk. Note 5 states that uncertainty includes deficiency of information and knowledge. Vector and Transpower appear to be submitting that knowledge of a specific risk source is a prerequisite to identification of a risk.

5.74 Notes 3 and 4 specifically recognise that risks can be characterised as a combination of risks and events and, in particular, the consequences and probability of an event. The Authority considers that Vector and Transpower have incorrectly expressed the risk of loss of supply at the Penrose cable trench as only relating to the possibility of transition joint failure.

⁷⁰ ISO 3 1000 Section 2.15

⁷¹ ISO 3 1000 Section 2

- 5.75 Consistent with guidance provided in ISO 31000, the Authority considered how uncertainty could arise in relation to the objectives stated above. This requires consideration of the system components and, in each case, asking what could happen to introduce uncertainty for the safety, security, and reliability of electricity supplies. One such part of the system is the cable trench. This is a critical part of Vector's network, and it runs alongside Transpower transformers and control cables.
- 5.76 The Authority has chosen to consider the risk of the cable trench as a whole (the co-location risk) and the specific fire risk (the ignition risk).
- 5.77 The Authority chose to focus on the co-location risk because it is common to separate elements of the power system to reduce risk. For example, separation is part of the permanent restoration at Penrose, and modern switch room basements are designed using fire barriers between independent parts. Separation is an effective treatment of any risk that affects one part of the system, (for example, separation would address vandalism and directional drilling risks). Because co-location risk is commonly managed in the industry, and Vector and Transpower's design standards show that both were aware of this type of risk, the Authority has concluded that they should have identified the co-location risks associated with the Penrose cable trench.
- 5.78 Accordingly, the Authority's view remains that the identification and assessment of the co-location of supply-critical components based on the consequences and probability of failure is appropriate and consistent with the guidance in ISO 31000.
- 5.79 The Authority considers that, when applying risk management practices, it would not have been necessary for Vector and/or Transpower to have knowledge of a specific source of ignition to manage the risk of fire – it is only necessary to know that fire is a possibility. The evidence set out in this report shows that both Vector and Transpower knew about the risks to co-located cables, and therefore could have managed the risks and avoided the impact the fire had on consumers.
- 5.80 The Authority's view is that, by applying the ISO 31000 guidelines:
- a) it was possible for Vector to have identified the criticality of the cable trench contents to maintaining reliable and secure electricity supplies to a large number of its customers. It was also possible to identify potential events other than a transition joint fire that could cause such an event
 - b) it was possible for Transpower to have identified the potential risks to critical substation assets and the associated risks to maintaining secure and reliable supplies to its customers.

The submission is inconsistent with Vector and Transpower practice

- 5.81 In its reconsideration of its interpretation of ISO 31000, the Authority reviewed past Vector and Transpower risk management practices with regard to potentially high impact events that have low probability of occurrence (HILP events). That review demonstrates that it is common practice for risks associated with supply-critical components to be characterised and expressed in terms of consequences of an event and the associated likelihood of occurrence.

Transpower HILP studies

- 5.82 Transpower undertook a series of HILP studies commencing in 2013. The first HILP study was for Islington substation in Christchurch. The HILP study identified that *the control building fire risk was found to be of particular concern* and noted that:

The control building not only houses the control and protection relays, but SCADA and communications equipment, staff kitchen/office areas, and workshops.

- 5.83 For Islington, Transpower identified a generic fire event risk in the control room building. The identification and consideration of the potential HILP event risk did not require a specific fire risk source to be identified. Nor did the HILP risk assessment rely on information intelligence of previous destructive control room fires.
- 5.84 Transpower also undertook a HILP study at Penrose substation in 2013. Amongst other HILP risks, Transpower identified a HILP event risk relating to fire spreading between supply-critical transformers. The HILP study report recommended that *there is a risk-based case to seriously consider fire barriers for transformers T8, T9 and T10 in order to limit fire spread to adjacent transformers.*
- 5.85 The Penrose transformer HILP event risk is an example of where Transpower has identified a generic transformer fire risk that does not rely upon knowledge of a specific component that might fail and ignite a fire. This appears to be analogous to the identification of a generic risk of a joint or cable fire event in the Penrose cable trench that can affect other cables and also other equipment such as transformers in the immediate vicinity.
- 5.86 Transformer T10 is located next to the cable trench close to the position where CCI identified the fire as having ignited. This means that the HILP study identified the risk of a transformer fire spreading to other transformers, but did not consider the potential for it to spread to the cable trench or vice versa.
- 5.87 The HILP study clearly shows that the cable trench was a significant risk to the integrity of Transpower's assets at Penrose with the potential to have an adverse and serious impact on its ability to supply its customers.
- 5.88 Unfortunately, despite the broad scope of the HILP study, it did not identify potential risks relating to the use of the cable trench by Vector for its cables.

Vector HILP studies

- 5.89 Vector has undertaken HILP assessments of its network that identified several potential HILP events and expressed these by reference to their consequences and probability.
- 5.90 In its 2013 Asset Management Plan (AMP) Vector identifies events that could lead to extensive loss of supply.

There are a number of credible but highly unlikely contingency events that may occur on a distribution network that would almost inevitably give rise to extensive and extended outages. These are the so-called HILP (high-impact, low-probability) events that would have a widespread impact, but would be inordinately expensive to avoid (if indeed possible) and where the likelihood of their occurring is so low this expenditure cannot be realistically

justified. HILP events that Vector, therefore, accepts which could lead to major power outages include:

- Destruction of the Penrose/Liverpool tunnel and all circuits within. This would leave the CBD supply exposed;*
- Failure of a tower or structure on the double circuit 110kV overhead line feeding Wairau substation in the North Shore, which would leave a shortfall in supply capacity for the North Shore;*
- Loss of multiple transmission/sub-transmission cables in a common trench.*
- Vector has a number of double circuits feeding zone substations which share a common trench. In theory, a single event could, therefore, damage more than one circuit;*
- Complete failure of a 110kV, 33kV, 22kV, or 11kV busbar at a substation, which would affect multiple circuits; and*
- Total loss of a zone substation (single or multiple transformers) through a force majeure event such as an earthquake, volcanic activity, flood or plane crash.⁷²*

5.91 The first and third bullet points show that Vector was aware of the potential threat to electricity supplies arising from the loss of multiple cables in a common trench or tunnel.

5.92 In the fourth bullet point, Vector identifies that a theoretical single event could damage double circuits in a common trench at zone substations. It is not unreasonable to conclude that Vector should also have looked at the situation at the other end of the cables where many circuits were contained in a single trench.

5.93 Included in Vector's list of HILP events are several that are less significant in terms of consequence to customers than the loss of the Penrose cable trench.

5.94 The AMP goes on to state:

For all these cases, the risks are managed to the fullest practical extent possible and contingency plans are in place to minimise the impact of the event

5.95 Vector's approach in its AMP does not depend on identifying component specific risks (e.g. transition joint fire) but on more generic risks expressed as a combination of consequences and the associated likelihood of occurrence.

5.96 The Authority's reconsideration of this issue has reinforced its original recommendation that supply-critical assets must be identified and their assessment given a high priority.

Transpower did know about the fire risk posed by cable installations

⁷² Vector 2013 AMP Section 5 Page 16

- 5.97 As discussed earlier in this section, Transpower had identified the generic risk related to cables and joints on Transpower sites it considered relevant to the Penrose fire:

Grid Performance NNI Register – NNI 23

Failure of equipment (eg cables and joints) owned by connected customer on Transpower site causes safety hazard and fire/explosion damage to critical Transpower assets leading to loss of supply.

- 5.98 Transpower's 2013 Asset Capability Statement (ACS) on Power cables shows that it had detailed knowledge of cable-related fire risks and the potential for fire to spread:

When cable insulation fails, there is normally an arc flash and a resultant fireball resulting from the ejected materials. In the case of oil-filled cables this can be especially severe because the oil, being pressurised, continues to feed the fire. As the failed cable contains many flammable elements, it can become a source of fuel for a continuing fire (or trigger a fire in adjacent combustible materials). It is this continuing fire that presents a safety risk to people and equipment.

- 5.99 The description of a potential cable-related, arc-ignited, fire event in the ACS is very similar to the actual event at Penrose substation.

- 5.100 Transpower's ACS document also states that it is important that "cable installation design considers and appropriately mitigates fire risks from potential cable failure".

- 5.101 The Authority therefore disagrees with Transpower's submission that it did not have knowledge of cable and cable joint fire risks.

Could Vector have known of the generic risk of a cable trench fire?

- 5.102 During its investigation, Vector asked CCI to undertake a review of publications to establish the level of information available on in-air cable installation related fires. CCI's conclusion was:

From a review of publications, while in-air cable installations have been reliable, there has been an appreciable, low incidence of major cable fires. A few of the major cable fire reports and cable system failure reports were found in the public domain. In general i) the cause of a fire, the remedial measures and the lessons learnt are not given in sufficient detail and ii) it is only possible to find information if the incident has received wide publicity.⁷³

- 5.103 The Authority accepts CCI's conclusion in relation to the scope and questions that it was asked to address.

- 5.104 The Authority's understanding of CCI's conclusion is that, while in-air cable fires have been rare, they are known to have occurred. CCI's study of information in the public domain did not generally provide details of the causes of the fires and lessons obtained from the events unless they had a high public profile.

⁷³ CCI report, Executive Summary, conclusion 14

5.105 The Authority has undertaken its own desk-based high level internet research of available information and from this it concurs with CCI's conclusion that, while there appear to have been few reports of major cable fires, there is sufficient information available for such events to be considered to be appreciable.

5.106 For example:

*On February 15 1999 an electrical failure and subsequent fire occurred at Azopardo substation which affected 160,000 customers. The fire was caused by a failed cable joint which ignited a fire which destroyed all the cables in the affected area of a tunnel.*⁷⁴

*On December 20, 2003, a [12kv] cable failure inside of Mission Substation in San Francisco caused a fire that led to the interruption of service to over 100,000 customers. Pacific Gas and Electric's investigation of the event found that, over time, the particular application of PILC cable (40 years in a vertical position) caused the cable to lose its insulating capability.*⁷⁵

5.107 As discussed above, Transpower had a detailed knowledge of potential cable related fire risk, even though cables make up a relatively minor proportion of Transpower's assets. Cables are a much larger proportion of Vector's assets and Vector would have been expected to have at least the same level of knowledge as Transpower.

5.108 If Vector had not developed its knowledge of cable-related fire risks to the same level that Transpower had, given the importance of power cables to Auckland's electricity supplies, the Authority recommends that it do this as a priority.

5.109 Accordingly, the Authority remains of the view that Vector could and should have identified the Penrose cable trench as a supply-critical component and had knowledge of the generic risk sources from cable related fires. Had this occurred, in accordance with Vector's AMP statement, Vector would have ensured that "*the risks are managed to the fullest practical extent possible and contingency plans are in place to minimise the impact of the event.*"

Could Vector have known of the specific transition joint related fire risk?

5.110 Vector's and Transpower's submission suggests that the only relevant risk source is transition joint failures that result in fires. The submission argues that such failures are rare, and therefore Vector "*could not have been expected to have the knowledge to specifically identify this risk (fire from cable fault).*"⁷⁶

5.111 Limited desk-top research undertaken by the Authority has revealed that publically available information is present regarding transition joint fires. For example Substation Reliability Experts, Inc. has developed a standard solution to address similar situations to the Penrose cable trench:

⁷⁴ Second-generation Reforms in Infrastructure Services By Federico Basañes, Robert D. Willig, Inter-American Development Bank

⁷⁵ Extract from Pacific Gas and Electric's investigation

https://www.pge.com/regrel-public/GRC2007NOI/GRC2007-Ph-I_Test_PGE_20050000-00-Exh004-Ch06.doc

⁷⁶ Investigation report page. 4

Cables located in the vicinity of cable joints are at an increased risk of catching fire. Cables running throughout the plant serve as a pathway for fire spread.

SRE Solution:

This standard is used to apply a protective wrap to power cable joints and power cables in the vicinity of joints. The intent of this procedure is to reduce the effects of an arc blast upon power distribution cables and to reduce the spread of fire after a “flash” event. The EP3990 wrap material is not designed to contain an arc blast. The intent of the wrap is to mitigate the impact of flame, hot gasses and molten materials upon surrounding power cables.⁷⁷

- 5.112 Regarding fire risks related to transition joints in in-air situations, UK Power Networks standard EI 02-0031 installation of power cables and joints (21/11/2013) in air states:

Underground cables and cable joints are designed to be buried direct in the ground. Installation in air should be avoided to limit the possible effects of a fire, caused by a failure and its subsequent spread, unless no other engineering solution is possible.

5.1 Transition Joints between Existing Solid PILC and new XLPE Cables

Experience has shown that this particular type of joint is more prone to an electrical failure than other types due to a mix of old and new technology and particularly the condition of the existing PILC cables. Therefore, the use of such joint in an in-air situation should be avoided unless no other economic engineering solution is achievable.

- 5.113 The Authority's limited research is insufficient to support a conclusion that Vector should have been aware of a specific risk from transition-joint fires. However, there is evidence that others in the electricity industry were aware of an issue with transition joints.
- 5.114 Further research on this subject has not been undertaken as the Authority considers that knowledge of this specific risk was not a prerequisite to identifying the cable trench as a supply-critical component and HILP event risk.
- 5.115 As set out above, the Authority considers that it is not credible for the only risk relating to nearly 4km of high voltage cables, oil cable cooling systems, many cable joints, low voltage lighting cable and system control circuits, to be a specific type of failure of a transition cable joint.
- 5.116 The Authority therefore does not accept Vector and Transpower's submission that knowledge of the specific transition joint risk was a prerequisite to the identification and management of the supply-critical cable trench.

⁷⁷ Cable Wrap Protection, Substation Reliability Experts, Inc., 2175 Dunavant Street · Charlotte, NC 28203, www.srexperts.com

Potentially systemic factors related to asset management systems, processes and practices

Asset failures can be predicted and investments supported

- 5.117 The CCI report describes CCI's view of how Vector should apply probability analysis in its asset management practices:

It is recommended that in performing the first stage of a risk assessment a sensitivity study be performed in which failure accelerating factors are applied to the fault rates for the main generic types of joints and cables to represent design, condition, age and proportion of the load to their rated current carrying capacity. Such factors should be applied in particular to the more vulnerable components such as transition joints and to older PILC joints. In the second stage of the risk assessment it is recommended that the consequence of failure be assessed (such as fire spread and disruptive violence to other assets).⁷⁸

- 5.118 Over the last 20 years, forecasting the risk of failure of an asset over its lifetime has become standard asset management practice in the electricity industry. Information gathered internationally on failure rates has enabled asset failure rate curves to be developed and applied when making asset management decisions.⁷⁹ Using probability forecasting techniques, asset managers are able to predict when assets are likely to fail and use this information to develop appropriate replacement, refurbishment and maintenance strategies. Cable failure rates increase as cables approach the end of their expected lives. Identifying the point at which the risk of failure becomes higher than the cost of replacing or refurbishing the asset is a core asset management activity.
- 5.119 A simple cost benefit analysis calculation has demonstrated that there would have been significant net economic benefit for work to reduce the cable trench risk.⁸⁰ Further discussion on the cost benefit calculation is provided in section 8.

Categorisation of assets did not take sufficient account of the characteristics of the cable trench

- 5.120 The Authority has assessed the potential for systemic issues within the asset management practices adopted by Vector and Transpower. The approach the Authority took in this assessment was a 'top-down' review of governance and management to establish how the businesses document their asset management plans (AMPs).⁸¹ Electricity industry AMPs document what businesses intend to

⁷⁸ CCI report, section 15.6.1

⁷⁹ For example, a continuous probability distribution curve called a Weibull curve has been used since the 1950s. It is used in Reliability Centred Management (RCM) to forecast asset reliability over an asset's lifecycle. This is sometimes referred to as a 'bath-tub' curve due to its shape. See: <http://www.weibull.com/hotwire/issue14/relbasics14.htm>

⁸⁰ Such a calculation would require identification of an appropriate failure probability value. An example of such a value is provided in the CCI report, in section 15.6.1.

⁸¹ Information disclosure requirements under subpart 9 of Part 4 of the Commerce Act 1986, include the requirement for electricity distribution businesses to publish AMPs. An AMP is intended to be the principal document that drives an electricity distribution business's asset investment planning.

do. Information provided in the AMPs can be compared with observations about what businesses actually do in practice.

- 5.121 Vector has a well-documented asset management system that aligns with industry standards and is independently reviewed periodically. A review of Vector's recent AMPs reveals that cable trenches are not specifically addressed.
- 5.122 The Penrose cable trench was a special cable trench because it had some features comparable to an extension of a switchroom basement or cable tunnel. For example, it contained a large number of power and control cables laid in close proximity. Categorising and treating the power and control cable installation as a cable trench meant that Vector did not consider the specific features of the Penrose cable trench that meant its security was critical to the maintenance of electricity supplies. As a result, Vector did not routinely undertake monitoring or maintenance inspections. CCI found that some cables were not secured (cleated) properly. The investigation confirmed that the trench covers were rarely lifted and were not lifted during Transpower's HILP study.
- 5.123 In its 2013 AMP, Vector described the enhanced Condition-Based Risk Management (CBRM) framework to be implemented. Included in the purpose of the CBRM framework is:

*... a criticality-assessment framework that rates the importance of all assets in terms of the potential impact failure or mal-function of the asset would have on public and operator safety, on network reliability and on operational effectiveness. The criticality assessment takes into account factors such as asset location (geo-spatial analysis), network capacity impacted by failure of the asset and the likely customer impact as a result of the failure of the asset. The criticality information forms the basis for assessing the impact that the failure of an asset will have.*⁸²

- 5.124 Vector should have captured the supply-criticality of the Penrose cable trench and its cables within the purpose of the CBRM framework. If this had occurred, Vector would have been able to control the associated risks. In its 2013 AMP, Vector notes that the initial stages of the implementation of the CBRM programme focused on overhead line assets because these are vulnerable assets in Vector's network. Prioritising in this way meant that Vector's identification of the Penrose trench and cables would occur later in its CBRM roll-out.
- 5.125 The AMPs cover the information and communication technologies (ICT) that have become vitally important components of network management. When considering cyber security risks Vector considered the following:

*Communication protocols are one of the most critical parts of power system operations, responsible for retrieving information from field equipment and, vice versa, for sending control commands.*⁸³

⁸² Vector Electricity AMP 2013, section 6.1.3

⁸³ Vector Electricity AMP 2013, section 5.12.6

5.126 Vector's AMP does not identify the fact that control cables at the Penrose GXP are critical to the proper functioning of the ICT system or that these cables are run in the same trench as the power cables.

5.127 The CCI report recommends for new installations that:

*... data and pilot and control cables be fire segregated from the power cables, preferably outside the trench.*⁸⁴

5.128 Completing the roll-out of Vector's CBRM framework, including identifying supply-critical assets, is an important step in asset management. The collection of reliable asset data on large complex electricity networks is challenging and can take several years to complete. Prioritising the roll-out of the CBRM is essential and Vector's initial focus on the more vulnerable overhead assets is understandable. However, the Authority considers that Vector should have categorised the cable trench in such a way as to reflect its criticality to electricity supplies and ensure that it was able to prioritise the associated risks appropriately.

Vector and Transpower failed to meet all of their access and occupation responsibilities

5.129 The access and occupation arrangements related to Vector's cables in the Penrose cable trench are described in section 3.

5.130 The Authority found that Vector and Transpower failed to meet all of their responsibilities under the prevailing access and occupation arrangements relevant to the cable trench at Penrose substation because:

- a) the original schedule of cables was not accurate, as it did not identify all cables in the cable trench
- b) as cables were added to the cable trench over time, cable asset documentation (eg, drawings and schedules) in respect to the access and occupation documentation, were not accurately maintained by either party
- c) neither party followed formal request and approval processes for recent cable additions
- d) Transpower did not undertake compliance reviews of the requirements of the access and occupation arrangements.

5.131 The Authority considers that Vector and Transpower asset managers had an inadequate understanding of the requirements of the Penrose access and occupation arrangements. For example, early in the inquiry, the Authority encountered uncertainty from Vector and Transpower as to which party owned the cable trench and what formal agreements were in force with respect to Vector's cables within the cable trench. Inconsistencies between Vector's and Transpower's views regarding access and occupation responsibilities are discussed in the investigation report:

⁸⁴ CCI report, section 15.4.1

Transpower's view is that when the Connections Contract was entered into the intent was for all existing and future Vector assets at Penrose to be covered by it, to the exclusion of previous agreements.

*Vector's view is that the current version of the Connections Contract does not cover all existing Vector assets at Transpower's Penrose substation. Vector agrees that greater certainty is required, and that the Connections Contract should be updated to reflect all existing and future Vector assets.*⁸⁵

- 5.132 In addition, the investigation report states that there has been "*limited centralised awareness within Transpower of the Vector cables in the trench at Penrose*".⁸⁶
- 5.133 These findings highlight the need for greater attention to formalised asset management practices at network asset boundaries.
- 5.134 The Authority considers that these findings indicate issues that may be relevant to all electricity lines businesses. To address this, the Authority considers that Vector and Transpower should comprehensively review their asset management practices at all points of connection between their respective networks. In addition, Transpower should also review its asset management practices at all network asset boundaries.

Potentially systemic factors related to network design

An appropriate planning criteria was not applied to the cable trench

- 5.135 The design of electricity network architecture includes consideration of an appropriate level of built-in redundancy. This anticipates that electrical equipment can fail for a variety of reasons, and seeks to ensure continuity of supply in such circumstances.
- 5.136 The level of network redundancy provided is specified in a network business's planning criteria. Elements of the planning criteria are justified on economic grounds, related to the value that customers place on having a continuous supply of electricity.
- 5.137 Planning criteria incorporate the concept of a 'single credible contingency', similar in concept to a 'common-mode failure risk'. For example, the loss of a sub-transmission circuit supplying a zone substation is a risk (ie a single credible contingency) that is commonly anticipated.⁸⁷ When the peak load on the zone substation grows over time to a specified level, the supply continuity risk is mitigated by providing two circuits, each of which is capable of carrying the peak demand on the zone substation. With two sufficiently separated circuits operating in parallel, a loss of supply is avoided if a fault occurs and one circuit is tripped.
- 5.138 Applied to the specific situation of the sub-transmission cables in the Penrose cable trench, it is evident that Vector's planning criteria did not consider that the loss of all power cables within the trench was a single credible contingency.

⁸⁵ Investigation report, section 6.2.1

⁸⁶ Investigation report, page 40

⁸⁷ Sub-transmission circuits relevant to the Penrose fire are circuits that operate at 22 kV and 33 kV. Distribution circuits operate at 11 kV.

Separation of circuits (eg in different trenches) supplying common loads would have significantly mitigated the risk to electricity supplies due to the destruction of any one cable trench. This would have meant that supply would have been restored far more quickly to Auckland consumers.

- 5.139 The cable trench contained both sub-transmission and distribution cables. Vector's asset strategy for the Remuera K10 11 kV distribution cable was different from that applied to the higher voltage sub-transmission cables in the cable trench.
- 5.140 Vector applied a 'run to failure' strategy to the 11 kV PILC cables and a 'predictive time to failure' approach for the 22 kV and 33 kV cables.⁸⁸ By laying 22 kV and 33 kV cables in the same cable trench, Vector effectively linked the security of the higher voltage 22 kV and 33 kV cables to the run to failure risk of the 11 kV PILC cables. As discussed earlier, 'failure' in this case can result from a failed cable joint and a faulty cable joint can fail and produce a power arc if its insulation breaks down.⁸⁹ Given the context of the Penrose in-air cable trench a fire is more likely to result from an arc event due to the presence of combustible material present (e.g. plastic, oil, wood and oxygen).
- 5.141 Failure to identify the single credible contingency risk inherent in the Penrose cable trench is a shortcoming in the application of Vector's network planning criteria related to identification of single contingency risks. All network businesses should undertake processes to review periodically network planning criteria related to situations that would create a single contingency risk.

Sufficient separation of assets was not provided

- 5.142 The cable trench contained a variety of cables of different types. In addition to the power cables, the cable trench contained control and communication cables that perform important monitoring, protection and control functions.
- 5.143 The CCI report considers that:

... by 1999, when the first XLPE cables with PE over-sheaths and wire screens were installed in the Penrose trench, the manufacturing and supply industries were aware that:

- (i) cables for in-air use were available with improved fire retardant over-sheaths
- (ii) fire segregating measures between circuits were an available option
- (iii) fire detection and extinguishing measures were an available option
- (iv) PE over-sheath and XLPE insulation materials propagate fire
- (v) PVC over-sheath material at elevated fire temperatures of > 400°C can propagate fire
- (vi) Oil-filled cables were a fire-spread hazard for in-air applications.⁹⁰

⁸⁸ As advised by Vector by email to the Authority *Re 11kV cables* on 24 September 2015.

⁸⁹ Transpower ACS Power Cables Fleet Strategy, TP.FS 04.01, Issue 1, October 2013, section 2.2.1

⁹⁰ CCI report, section 15.4.1

5.144 In addition, the CCI report notes that:

*However, the Author accepts that industry engineering recommendations and specifications did not, and still do not, clearly communicate fire precaution knowledge for new circuits, nor give clear advice for existing installations on what retrospective action, if any, should be taken.*⁹¹

5.145 The CCI report recommends that where new XLPE cables are installed in-air:

- (i) XLPE insulated cable circuits that do not have fire retardant over-sheaths not be installed in close proximity above, or adjacent to, other circuits.
- (ii) Wire screened XLPE cables not be installed close to other cables and services without having fire retardant over-sheaths/coatings, fire segregation and increased spacings. Should a cable failure occur, a power arc is likely to emerge through the screen wires and spread fire to adjacent cables not having fire retardant coatings.
- (iii) Data and communication cables not be installed between power cables, as this risks i) acting as a fire bridge between power cables, ii) early loss of signals in a fire, iii) disturbing the power cables and joints during installation and iv) impairing the power cable heat dissipation in normal service. It is recommended that data and pilot and control cables be fire segregated from the power cables, preferably outside the trench.⁹²

5.146 The Authority considers that, when making decisions to purchase and install XLPE cables after 2000, Vector should have researched and taken into account manufacturer's information and canvassed industry knowledge. However, the Authority acknowledges, given CCI's advice, that this information may not have been made available to Vector.

5.147 CCI has made important recommendations that could be relevant to all network businesses.

Network protection could not identify the fault location

5.148 The investigation concluded that the protection schemes at Penrose performed as designed with two exceptions.⁹³ The protection operation indications did not show that the fault was in the Penrose section of the Remuera K10 feeder. However, it is normal practice that protection schemes do not provide an indication of the location of faults.

5.149 The manual reclose of Remuera K10 at 1:21 am was undertaken following a line patrol of the overhead sections. The faultman undertaking the line patrol concluded that:

⁹¹ CCI report, section 15.4.1

⁹² CCI report, section 15.4.1

⁹³ Investigation report, section 3.2

*... the fault was in the overhead section ... based on information from fault passage indicators.*⁹⁴

5.150 The practice of only inspecting overhead sections⁹⁵ and the absence of a fault location indication meant that the faultman did not identify the cable fault in the cable trench during the initial line patrol.

5.151 The Authority notes Vector's recommendation to make:

*... specific amendments to the procedures in light of the incident.*⁹⁶

The Authority has been informed by Vector that these amendments have now been completed.

Potentially systemic factors related to regulatory incentives and controls

Vector and Transpower have not commented on regulatory constraints

5.152 The Commerce Commission regulates Vector and Transpower under Part 4 of the Commerce Act 1986. Transpower is regulated under individual price-quality regulation. Vector is regulated under default or customised price-quality regulation.

5.153 Price-quality regulation is designed to ensure that electricity distribution businesses such as Vector:

*... have similar incentives and pressures to suppliers operating in competitive markets to innovate, invest and improve their efficiency. It also aims to limit the ability of suppliers to earn excessive profits, while also ensuring that consumer demands on service quality are met.*⁹⁷

5.154 The Authority has reviewed:

- a) a number of Vector's AMPs
- b) Vector's State of the Network reports
- c) Transpower's Penrose site strategy document
- d) Transpower's Penrose HILP report
- e) the investigation report.

5.155 No issues have been identified by the Authority regarding regulatory constraints that would prevent either Transpower or Vector from addressing asset risks at Penrose substation.

5.156 In discussions, Vector and Transpower did not raise any comment or raise concerns relating to price-quality regulation, as applied by the Commerce Commission. The Authority considered if price-quality regulation could have been

⁹⁴ Investigation report, section 3.2

⁹⁵ Including cable risers and ground mounted switchgear.

⁹⁶ Investigation report, section 3.2

⁹⁷ <http://www.comcom.govt.nz/regulated-industries/electricity/electricity-default-price-quality-path/>

a contributing factor to the Penrose fire. The Authority found that the price-quality regulation provides for both Vector and Transpower to secure sufficient revenue to make investments and maintain their assets. The Authority concluded that price-quality regulation was not a contributing factor to the Penrose fire.

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6 Assessment of the fire hazard management systems at Penrose substation

6.1 This section covers the Minister's second question:

What fire hazard mitigation systems were in place; and did they operate as intended?

6.2 The inquiry has found that:

- a) fire hazard mitigation systems were not installed in the Penrose cable trench
- b) fire hazard mitigation systems are not routinely installed in cable trenches
- c) the Penrose cable trench was an unusual installation
- d) the repair of fire damaged equipment provides an opportunity to improve fire hazard management.

6.3 This section explains the basis for these conclusions.

Fire hazard mitigation systems were not installed in the Penrose cable trench

6.4 No fire hazard mitigation systems were installed inside the Penrose cable trench or in the vicinity of the cable trench.⁹⁸

6.5 The investigation report states:

*Transpower and Vector use a range of design standards in planning and developing their networks. These ensure assets are designed to appropriately mitigate risks such as fire risk.*⁹⁹

6.6 The Authority considers that the Penrose event has demonstrated that the design standards were either not applied, or were not sufficiently scoped, to include the fire hazard risk inherent in the Penrose cable trench.

6.7 As noted above, Vector and Transpower disagree with the Authority's conclusion that they could have been expected to identify the risk.

Fire hazard mitigation systems are not routinely installed in cable trenches

6.8 The investigation included a survey of international practices related to hazard detection and containment systems in cable trenches. It found that terms such as culverts, ducts, troughs and channels are commonly used as an alternative to 'trench'.

6.9 The survey undertaken for the investigation identified that:

*... no network companies were found to have installed fire detection or suppression systems in structures like the cable trench.*¹⁰⁰

⁹⁸ The investigation report does not directly state that no fire hazard mitigation systems were in place but this has been confirmed in discussions with Vector and Transpower.

⁹⁹ Investigation report, section 7.3.3

¹⁰⁰ Investigation report, section 7.6.3

- 6.10 However, the Penrose cable trench had features that made it quite different to general cable trenches. It was situated in a major substation and contained important supply cables that were critical to maintaining electricity supplies to a large number of customers.
- 6.11 The survey did identify actions taken with respect to the fire risk in such structures, which is the result of the risk management practices of the network businesses. The survey did not specifically research how other network businesses would have identified and managed the risks associated with co-locating multiple supply-critical cables in a common trench.
- 6.12 Applying international risk and asset management standards and modern asset management systems allows supply-critical components to be identified and managed. Whilst adopting such standards does not guarantee that all risks will be identified, the Authority considers that Vector and Transpower, having adopted these standards and systems, should have identified the Penrose cable trench as a critical network component and as a potential HILP event risk.
- 6.13 As noted above, Vector and Transpower disagree with the Authority's conclusion that they could have been expected to identify the risk.

The Penrose cable trench was an unusual installation

- 6.14 As discussed in section 5, the Penrose cable trench was unusual in that it contained so many supply-critical circuits in an in-air cable trench. Distribution cables that were run-to-failure were co-located with sub-transmission cables that are managed to a higher security standard. In this respect, identifying this installation as a cable trench was insufficient to reflect its criticality to power supplies and its potential risk to safety.
- 6.15 The Authority considers that had Vector and Transpower fully assessed the characteristics of the Penrose cable trench the risks to supply would have been identified and assessed. The actions taken by Vector and Transpower since the fire show that there were a number of practical actions that Vector and Transpower could have taken to reduce the risks to supply. For example, Transpower informed the Authority that cable joints it had subsequently identified in cable basements, were now covered with sand bags.¹⁰¹ This is a low cost but effective interim measure to mitigate the risk of joint failures causing a fire.

Fire hazard mitigation measures should have been considered

- 6.16 The Authority acknowledges that international practice related to risk management of cable trenches is inconsistent. There is evidence that some network businesses have adopted practices that would prevent cable joint fires. For example, a number of Australian network businesses now do not allow cable joints to be installed in sections of cables laid in in-air situations.
- 6.17 Some network businesses were aware of the potential risks from cable joints in in-air situations, however this information does not appear to have been widely shared across the electricity industry. No evidence has been provided to the inquiry that Vector researched this area prior to the October 2014 fire.

¹⁰¹ For example under floor channels within a substation building such as a switchroom

- 6.18 Fire hazard mitigation measures are likely have been economically viable given the potential consequences of a fire. As the investigation has shown, it took nearly 7.5 hours to locate and contain the fire after the initial cable joint fault on the Remuera K10 feeder.¹⁰²
- 6.19 The Authority considers that a fire hazard mitigation system would have led to early detection and extinguishment of the fire, possibly eliminating (or at least reducing) the damage to the adjacent cables and substation equipment.

The Penrose fire provides an opportunity for improved fire hazard management across the industry

- 6.20 The Authority considers that the Penrose fire provides important lessons about asset management, relevant to all network businesses. The lessons should be reviewed by network businesses for relevance to their individual situations.
- 6.21 For existing installations where cable joints are installed in in-air situations, interim fire prevention measures should be considered, such as sand-bagging. Longer term fire hazard mitigation approaches, such as segregation of cables, application of fire retardant paint and cable sheaths and periodic inspection and monitoring, should also be considered.

¹⁰² See sequence of event timings and durations in Appendix B, Table 4

7 Safety, communication and mitigating loss

7.1 This section covers the Minister's third question:

What actions were taken during the course of the outage in respect of:

(a) ensuring the safety of people and equipment?

(b) communicating with affected and interested parties (including emergency services) about the impact of the event and the timeframes for restoration of supply?

(c) mitigating the loss of supply and expediting restoration?

7.2 This section first considers parts (b) and (c), then returns to questions related to safety.

7.3 The inquiry has found that:

- a) Vector and Transpower managed affected customer and public communications well
- b) Vector and Transpower managed the process of supply restoration well, given the extent of the damage
- c) Vector and Transpower have not completed safety-focused reviews with sufficient formality and urgency
- d) some safety issues have not been identified by Vector and Transpower
- e) the Penrose substation fire provides valuable lessons regarding safety and coordination with emergency services during incidents at substations
- f) Vector and Transpower must share the lessons with other stakeholders
- g) an independent review of safety should be undertaken.

Vector and Transpower managed communications with affected customers well

7.4 The investigation report states that there was extensive communication during the outage to a wide range of stakeholders, including affected customers, emergency services, council and government.¹⁰³

7.5 The first customer communication was an update on Transpower's Facebook page at 3:20 am on 5 October. The first media statement was issued at 3:50 am. As the events unfolded, primary responsibility for external communications passed from Transpower to Vector.

7.6 In total, eighteen customer updates were provided by Transpower and Vector during the event. This provided a source of frequently updated information for stakeholders.

7.7 Vector and Transpower provided customer and public updates using a broad range of communication channels, including:

¹⁰³ More detailed information on external communications is available in the report: Vector, *Penrose Substation Fire – 05 October 2014 – Customer Management*, Issue 1, 10 March 2015.

- a) websites
 - b) Facebook pages
 - c) Twitter accounts
 - d) Vector's contact centre (calls and email)
 - e) calls to electricity retailer call centres
 - f) direct contact with larger consumers by Vector account managers
 - g) Vector's recently developed smartphone outage application
 - h) media releases
 - i) media interviews by Vector and Transpower CEOs.
- 7.8 Vector provided additional information to retailers to assist them in managing medically dependent and vulnerable consumers.
- 7.9 The Electricity and Gas Complaints Commissioner noted that no complaints had been lodged with the service related to the Penrose fire.¹⁰⁴
- 7.10 While it is not possible to canvass every impacted stakeholder, the Authority has identified no concerns regarding the management of stakeholder communications related to the Penrose fire event. The Authority considers the joint communications effort fronted initially by Transpower and subsequently by Vector:
- a) was well planned and coordinated between Vector and Transpower, with clear role responsibilities
 - b) used a wide range of channels to ensure the latest information was available to stakeholders, including use of digital media
 - c) was mindful of medically dependent and vulnerable consumers.
- 7.11 Nevertheless, major event management is only rarely experienced. The Authority considers the Penrose fire event provides valuable lessons for all electricity lines businesses and retailers, particularly related to:
- a) joint planning for responding to major events
 - b) inter-business coordination as events unfold, to ensure consistent, up-to-date status information is constantly available for the duration of the event
 - c) application of the widest range of communications channels.

The process of supply restoration was well managed given the extent of the damage

- 7.12 The investigation report states that operational co-ordination between Vector and Transpower during re-livening and repair works functioned effectively.¹⁰⁵

¹⁰⁴ Confirmed in telephone discussion between Judi Jones, Electricity and Gas Complaints Commissioner, and Bill Heaps, Strata Energy Consulting.

¹⁰⁵ More detailed information on supply restoration is available in the report: Vector, *Penrose Substation Fire – 05 October 2014 – Customer Management*, Issue 1, 10 March 2015.

- 7.13 Control of the site passed from NZFS back to Transpower at 9:57 am on 5 October. The investigation report states that established site procedures were used, such as site access and issuing of permits for work.¹⁰⁶
- 7.14 Restoration of supply to all affected customers required effective co-ordination between Transpower, Vector and their respective contractors. This was initially achieved through regular onsite meetings and close co-ordination with EOC and NGOC.
- 7.15 Vector and Transpower established restoration priorities, initially focused on restoring supply to the 220 kV Penrose bus with sufficient capacity to supply the anticipated loads.¹⁰⁷
- 7.16 All equipment was inspected before it was re-livened and restoration followed a planned process to ensure it was carried out safely with no further equipment failures. The switchyard was vacated of all personnel before each major item of equipment was energised. The first equipment inspections were completed at 10:41 am on 5 October, allowing step-by-step restoration of 220 kV and 33 kV supplies.
- 7.17 Communications during the restoration phase were affected by degradation of mobile phone services from around 11:00 am.
- 7.18 Restoration was suspended for approximately one hour around 1:47 pm when smouldering timber re-ignited. NZFS was called to deal with this, requiring de-energisation of some already re-livened equipment to ensure safe access for firefighters.
- 7.19 In parallel with Transpower's restoration work, Vector commenced assessment of the extent of damage to feeder cables to identify the undamaged feeders that could be safely re-livened.
- 7.20 33 kV bus re-livening commenced at 2:52 pm, allowing Vector to commence re-livening of the undamaged feeders to zone substations. By 6:21 pm, Vector had re-livened seven zone substations, restoring supply to over 36,000 customers in Epsom, Newmarket, Glen Innes, Penrose and Westfield.
- 7.21 Transpower continued restoring the Penrose 220/33 kV supply transformers to provide additional capacity and improve supply security. After smoke residue had been cleaned off equipment, the T8 220/33 kV supply transformer was re-livened at 4:26 pm.
- 7.22 The restoration process was expedited by Transpower operating equipment above normal ratings for short periods. This allowed Vector to restore supply to some customers earlier than would otherwise have been possible, while Transpower continued inspecting 220 kV equipment.
- 7.23 Throughout Sunday night, Vector EOC controllers extensively reconfigured the Vector network to enable back-feeds from alternative zone substations into de-

¹⁰⁶ Investigation report, section 3.4

¹⁰⁷ Supply *capacity* can usually be provided by one circuit, however full supply *security* is only provided when an additional circuit or circuits is/are livened to provide redundancy, so that a subsequent single circuit fault does not result in a loss of supply.

energised areas.¹⁰⁸ This allowed supply to be restored to a further 18,786 customers overnight on 5/6 October.

- 7.24 Transpower brought additional staff to Auckland from other areas to enable 24-hour work during the recovery phase. Specialist engineering resources were also deployed to Penrose substation to assist with damage assessment and restoration.
- 7.25 Transpower's next priority was to achieve full restoration of the Penrose 220 kV switchyard, to improve supply security to the Auckland CBD via the Auckland tunnel 220 kV cable to Hobson Street substation.¹⁰⁹

With some 220 kV and 33 kV supply capacity restored, progressive restoration of Vector's network could proceed

- 7.26 The investigation report states that the repair works to restore supply to the remaining 20,257 customers were extensive and complex.¹¹⁰
- 7.27 All circuits in the cable trench were fire-damaged beyond repair. Recovery initially focused on repairing five cables, each supplying a different de-energised zone substation. With one cable restored to provide capacity to each zone substation, the remaining destroyed cables were then repaired to restore normal supply security.
- 7.28 As the cable trench was extensively damaged by the fire, Vector and Transpower identified alternative temporary routes through the substation for the new cables. These were agreed between the parties by the evening of 5 October. Vector commenced cable repair work at 9:00 pm.
- 7.29 Each repair required the damaged section of cable to be cut out and a replacement section of new cable spliced in. Crews worked continuously to complete repairs. Working conditions over the initial 24 hours of the repair operation were challenging, with periods of severe rain, high wind and hail through the night of 6 October.
- 7.30 Repairs to the first two cables were completed by early morning on 7 October. A third cable was re-livened by 1:35 pm on 7 October and this enabled full supply restoration to all affected customers shortly afterwards.
- 7.31 Repairs to all remaining damaged cables were completed by 15 October. The repair effort was a 24-hour operation for the first week before reverting to a daily operation to relieve worker fatigue.
- 7.32 Over fifty people were dedicated to working on the recovery effort, requiring over 4,000 hours of effort. No safety incidents were reported in this time. In total over:
 - a) 8 km of temporary cables was installed
 - b) 60 new cable joints were installed

¹⁰⁸ Vector's network design enabled extensive use of back-feeds to restore supply to affected customers from adjacent areas that were unaffected. This was carried out in stages starting on the morning of 5 October. Over 23,000 customers (nearly one third of affected customers) were restored using back-feeds.

¹⁰⁹ Normal supply security was eventually restored to Penrose substation at 9:22 pm on 8 October.

¹¹⁰ Investigation report, section 3.5

- c) 1,000 cable supports were used
- d) 2,000 cable clamps were installed
- e) 5,000 sand bags were used on the site.

Supply restoration to customers

- 7.33 The investigation report states that Vector focused on safely restoring all customers as quickly as possible.¹¹¹
- 7.34 Restoration of customers was carried out in the following order:
- a) re-livening customers supplied by undamaged cables
 - b) switching the distribution network to back-feed customers from adjacent unaffected substations
 - c) repairs to damaged cables.
- 7.35 The investigation report states that:
- a) 36,296 (48%) of customers were restored by 6:21 pm on 5 October
 - b) 54,113 (72%) of customers were restored by 8:00 am on 6 October
 - c) 73,552 (98%) of customers were restored by 8:00 am on 7 October
 - d) all customers were restored by 2:08 pm on 7 October.

The Authority's conclusions relating to the process of supply restoration

- 7.36 The investigation report expresses the following view about the restoration effort after the site was handed back to Transpower at 9:57 am on the morning of 5 October:

The incident was a large and complex event that placed extreme demands on Transpower and Vector. The joint response is considered to have been effective because:

- a. *There were no reported injuries or safety incidents affecting the public, Transpower and Vector staff, their contractors, or members of Emergency Services;*
- b. *Relivening and repairs were completed without delay once control of the site was returned to Transpower. Transpower and Vector promptly mobilised all necessary resources, and drew on existing spares holdings to achieve this;*
- c. *Customers were kept well informed during the outage through regular updates delivered across a wide range of communication channels; and*
- d. *No other equipment at the substation was damaged during the restoration and recovery efforts.*¹¹²

¹¹¹ Investigation report, section 3.6

¹¹² Investigation report, section 8, paragraph 14

- 7.37 The Authority considers that Transpower and Vector carried out equipment repairs and supply restorations quickly. The Authority appreciates that Transpower and Vector were required to make a vast number of decisions under urgency and a significant repair effort involving prioritisation and management of a large workforce was required.
- 7.38 The need to bring NZFS back to the substation on the afternoon of 5 October had a relatively minor impact on the repair and restoration effort, but indicates the level of vigilance required at all times.
- 7.39 The Authority notes that there were no reported injuries or safety incidents affecting the public, Transpower and Vector staff or contractors, or emergency services personnel.¹¹³ However, the Authority has a number of concerns relating to safety risk management during the firefighting phase and the supply restoration phase. These are addressed in the following sections.

Safety-focused reviews have not been completed with sufficient formality and urgency

- 7.40 The Authority notes that ensuring the safety of people and equipment is not one of its functions and accordingly falls outside the Authority's core expertise. However, the Authority makes the following observations with a view to this topic being considered more fully by other parties, as outlined below.
- 7.41 It is important that experiences at the time of an event are documented and evaluated as early as possible. This allows all relevant detail to be documented when it is fresh in mind and ensures that improvements are identified and implemented as soon as possible. This is particularly important for identifying lessons that may reduce the risk of injury to firefighters and electricity industry personnel attending future substation fires.
- 7.42 Transpower has confirmed to the Authority that it has not undertaken a formal review of the conduct of the Penrose fire event with NZFS and Vector. The investigation has relied on interviews with Transpower and Vector staff and contractors in reaching the conclusion that there were no safety issues.¹¹⁴ Transpower has also provided copies of correspondence that it had with NZFS.
- 7.43 Taking into account the seriousness of the fire, the potential lessons that could be drawn, and the level of review undertaken to date by Transpower and NZFS, the Authority considers that a formal assessment of the safety procedures for dealing with substation fires should be undertaken.
- 7.44 The Authority also considers that the informal approach described to it by Transpower lacks the necessary rigour to capture important lessons on safety performance. At a minimum, the Authority considers that Transpower, as the substation owner, should have led a comprehensive review of safety to personnel and equipment with NZFS and Vector as soon as possible after the fire. The relevant documents provided by Transpower together with its descriptions of what has been undertaken to date have convinced the Authority that a formal

¹¹³ Investigation report, section 8, paragraph 14 (a)

¹¹⁴ Confirmed during a teleconference with Vector and Transpower staff and Strata directors on 26 August 2015.

assessment of the safety procedures for dealing with substation fires should be undertaken.¹¹⁵

Some safety issues have not been identified and reviewed by Vector and Transpower

- 7.45 The Authority has identified a number of issues it considers should have been comprehensively reviewed and reported on. The issues include the following:
- a) Transpower's documented procedure requires that a permit be issued prior to allowing fire service access for firefighting, yet a permit was not issued.¹¹⁶ Transpower and Vector dispute this interpretation of the wording of the procedure. Transpower's view is that no permit was required. The Authority's view is that whether a permit is required or not is secondary to the fact that the standard itself is unclear and needs to be reviewed as part of a wider review of safety at the Penrose site during the fire.
 - b) The contents of the cable trench were accurately recorded in GIS. However, at the time of the initial fire attack, neither Transpower nor Vector on-site and control room personnel appeared to have an accurate understanding of the combined contents of the cable trench. Vector EOC is unlikely to have been aware of any cables that Transpower had placed in the trench and Transpower appears to have had an inaccurate knowledge of the Vector cables in the trench. Accordingly, it remains unclear how it was determined that all circuits in the cable trench had been de-energised and made safe for firefighting to commence. The NZFS memorandum highlights this issue when describing the need for firefighters to withdraw due to concerns that not all electrical circuits had been switched off.¹¹⁷ Further, feedback on a draft of this report from the NZFS quotes from post incident debrief notes that "*[an NZFS staff member] was designated safety officer and described his actions. He was advised by a workmen [sic] from either Vector or Transpower, who stated that he couldn't be 100% sure that power was off in the affected area. [NZFS staff member] then ordered the firefighters to withdraw from the area and advised the OIC of this.*"
 - c) NZFS initiated its fire attack at 3:32 am after Transpower advised at 3:22 am that power was switched off in the area adjacent to the 33 kV switchgear building. However, NZFS stated that its frontline personnel were soon withdrawn '*... due to uncertainty that power was actually off and isolated*'.¹¹⁸ The Authority considers that there is significant doubt about the facts related to this part of the fire response. The investigation report does not directly refer to this incident and the Authority's subsequent discussions with Vector and Transpower have revealed that Vector and Transpower disagree with the NZFS report of events. Nevertheless, Transpower's reported sequence of

¹¹⁵ NZFS memorandum (9 October 2014) and NZFS letter (undated) and emails all providing time stamped event sequences.

¹¹⁶ Transpower, *Operating and Emergency Management Procedure TP SS 07.40 Station security procedures*, Issue 13, dated February 2012, paragraphs 10.1.1 and 10.1.2

¹¹⁷ NZFS memorandum (9 October 2014), second page

¹¹⁸ Letter from Director, Office of the Chief Executive, NZFS to Manager Market Monitoring, Electricity Authority, 15 September 2015

events notes that a query was raised with Vector at 3:35 am as to whether there was any back-feed into the substation from Vector's 33 kV network. At 3:38 am Vector EOC confirmed to Transpower NGOC that there was no back-feed. These logged event entries would appear to support the NZFS view that firefighting stopped for a period and that there was doubt onsite as to whether all energised equipment in the vicinity of the fire had been isolated prior to the commencement of firefighting.¹¹⁹ However, there continues to be disagreement about this aspect of the incident. In particular, there appears to continue to be disagreement as to who raised the concern about whether the power was off and isolated, on what basis the concern was raised, and who ordered the firefighters to withdraw.

- d) The NZFS letter referenced in list item (c) states:

The Fire Service experienced problems knowing who to ask for advice, as there was more than one electricity agency taking responsibility for the site in attendance (i.e. both Transpower and Vector). Conflicting advice from different representatives at various levels, within each organization caused confusion in identifying if extinguishing options could be performed safely.

As stated in item (c), Vector and Transpower have disagreed with this report of events in a follow up discussion with the Authority subsequent to receipt of the NZFS letter. Regardless of the dispute over the facts, the summary of minutes taken of the incident debrief undertaken by NZFS on Monday 10 October 2014 clearly records that the NZFS personnel who attended the fire had concerns regarding the uncertainty as to whether the power had been switched off, and that they experienced problems knowing who to ask for advice.

- e) The cable trench was contaminated with heavy metal residues and unexpected presence of arsenic.¹²⁰ It is also likely that the oils and residue from plastics had contaminated the trench. The Authority was told that a disadvantage of the rapid expansion foam used to contain the fire in the trench is that it leaves caustic residues.
- f) The Authority was informed that after the fire, NZFS filled the cable trench with water to cool it down. The controls used for disposal of the water to avoid broader contamination are important, but have not been addressed in the investigation report.
- 7.46 In its letter to the Authority, NZFS provides a synopsis of minutes from a post-event debrief. This synopsis contains some errors of fact, for example, there is no common oil supply for the cables and transformers at Penrose. There is also confusion in the letter about whether the onsite electricity personnel NZFS liaised with were Transpower or Vector staff.
- 7.47 Some confusion is understandable for NZFS frontline personnel that are not familiar with the electricity industry. Feedback on this report from the NZFS states

¹¹⁹ The Authority has compiled a sequence of time-stamped events from event logs provided by Vector, Transpower and NZFS – see Table 4 in Appendix B.

¹²⁰ As noted to the Authority during its first visit to the Penrose substation on 28th November 2014

that “*The Fire Service’s letter of 15 September was intended to reflect the understanding and perception of firefighters and officers who attended the Penrose substation fire at the time and shortly afterwards at the debrief; namely that its personnel were unsure who was responsible for the site, and making decisions about the isolation of power at different parts of the site.*” The Authority’s view is that these likely errors of fact do not detract from the main conclusion the inquiry has reached regarding safety, which is that the absence of a post-incident review is a significant gap.

7.48 Once it became clear that there was a difference of views about safety during the fire at the Penrose substation, the Authority wrote to the NZFS copied to Vector and Transpower suggesting that they undertake a review to capture the lessons from the fire. This suggestion has been adopted by the parties involved.

7.49 Due to the absence of a formal post-incident review involving all onsite personnel, the Authority considers there are important unanswered questions. These include the following:

- a) Were the firefighters adequately briefed on extra high-voltage substation site risks prior to the initial attack? Particularly, site risks associated with:
 - (i) the extent of high-voltage and extra high-voltage equipment de-energisation
 - (ii) the presence of hazardous materials.
- b) At the time of the fire, who possessed authoritative knowledge of the cable trench contents, sufficient to warrant safe access for NZFS personnel to commence firefighting activities?
- c) The Authority notes that no permit was issued in accordance with TP.SS 07.40 prior to commencement of firefighting. Transpower initially informed the Authority that this was because safety ‘earth-stick’ connections could not practically be placed on or around burning equipment. As noted in paragraph 4.22, Transpower subsequently informed the Authority that, in Transpower’s opinion, the issue of a permit was not required to allow access for fire services to fight fires.¹²¹ The Authority undertook a further review of TP.SS 07.40 and reconsidered the two clauses specifically relating to fire service access to substations:

10.1.1 Fire Service personnel are prohibited by their management to enter a restricted area to attend fires unless they are accompanied by the holder of a valid Competency Certificate

10.1.2 The RAE Competency Certificate holder accompanying the fire brigade must obtain a permit where required to ensure any fire brigade activities in the vicinity of high voltage equipment can be carried out safely.

Regarding determining when a permit is required, section 6.3 of Transpower’s Fire Services Familiarisation Checklist provides the following guidance:

¹²¹ Meeting at the Electricity Authority’s offices on 13th October 2013

If Access is required to work within the minimum approach distance of conductors the Equipment must be isolated and then earthed to the station earth grid. Then an access permit can be issued for work. When the work is complete and everyone has signed off the permit can be cancelled.

During the inquiry, Transpower's responses to questions on the requirement to issue a permit for fire service access have been inconsistent. The Authority considers that Transpower must undertake a review of TP.SS 07.40, and its application, with the objective of removing ambiguity and obtaining a robust procedure in light of what has been learned from the Penrose fire.

d) What are the facts associated with the apparent need to stop firefighting and question the possible presence of 33 kV back-feeds into the substation from Vector's network (around 3:32-3:38 am)?

e) Did the firefighters employ appropriate tactics and are there any lessons for fighting possible future substation fires involving high-voltage equipment?

The NZFS report states that the NZFS investigation team interviewed the NZFS Operational Commander on the choice of firefighting tactics and observations during the incident.¹²² However, no further details are provided in the NZFS investigation report on the findings from this interview.

f) Did flooding the cable trench with water introduce an additional risk associated with dispersal of hazardous fire by-product contaminants into the ground?

g) Were procedures for handing over control of a fire site involving high-voltage equipment from NZFS to Transpower established prior to the fire? If so, were the procedures followed during the Penrose substation fire event?

Were there sufficient safeguards in place to manage post-fire risks? For example, risks related to possible fire re-ignition (as in fact occurred) and contact by onsite personnel with hazardous substances? The Authority received from Vector a copy of an occupational hygiene assessment report commissioned by Vector. That report considers contaminant risks to personnel working onsite since the fire.¹²³ The occupational hygiene assessment concludes that there is a very low risk to short or long term health from the contaminants found on the site at the time the assessment was taken.

7.50 The Authority has not been able to answer the questions raised in the preceding paragraph as many of these questions emerged late in the inquiry process and are outside the Authority's area of expertise. The Authority considers there are sufficient unanswered questions as to justify a comprehensive joint review, and a possible joint standard, related to managing the risks associated with firefighting

¹²² NZFS report, Process of Investigation, page 11

¹²³ Paragon Health & Safety Consultants, *Occupational Hygiene Assessment – Penrose Substation*, 25 November 2014

activities involving electricity network facilities. Such a review should include at least the areas identified in the following paragraph.

- 7.51 The Penrose fire was a significant and unusual fire event that must be fully reviewed to identify opportunities for improving management of substation fire risks and controls. The Authority considers that a post-event evaluation must include:
- a) the adequacy of fire prevention planning between NZFS and Transpower
 - b) the accuracy and adequacy of information available to NZFS on arrival at the substation
 - c) how NZFS gained access to the site and the reasons for any delays
 - d) how well coordination and communication occurred between NZFS and Transpower prior to and during firefighting activities
 - e) identification and management of safety hazards on arrival and during the fire, including possible hazards associated with the fire suppressants used
 - f) the appropriateness of methods used to control/extinguish the fire, taking into account the hazardous substation environment
 - g) the process of handing over control of the fire site between NZFS and Transpower
 - h) a comprehensive peer review by an independent expert.

The Penrose substation fire provides valuable lessons that must be shared with other stakeholders

- 7.52 Fires in electricity substations are rare but very dangerous events. This is particularly the case for major substations containing high-voltage equipment. Capturing and sharing lessons from actual events provides an important opportunity to minimise the risks to people and equipment from future fires.
- 7.53 The Authority has reviewed the investigation report, the CCI report and the NZFS report, including draft versions of the first two reports.¹²⁴ None of the post-event evaluation points listed in the previous section have been addressed in those reports.
- 7.54 The Authority considers that a comprehensive and transparent review of the safety aspects of the Penrose substation fire should be undertaken by Vector and Transpower. The review must include engagement with NZFS. To provide assurance that all aspects have been fully covered, the review should be peer reviewed by an appropriate independent safety expert.
- 7.55 Vector and Transpower must share the lessons from the safety review with appropriate stakeholders. To achieve the widest dissemination, lessons must be communicated to all stakeholders, including to other electricity distributors and relevant industry associations.

¹²⁴ The NZFS report was reviewed and approved by NZFS Area Manager for Auckland City on 11 August 2015.

NZFS has made important points in their submission

- 7.56 The Authority provided NZFS with a draft of its inquiry report and NZFS provided comments on two issues relating to perceptions that firefighters had at the time of the fire event. NZFS acknowledges that Transpower holds a different perspective of its management of the event.
- 7.57 NZFS note that *"while Transpower and Vector may be clear about the organisation to which the staff or contractor's on site were aligned, that was not the experience of the Fire Service during the event."*
- 7.58 The Authority agrees with NZFS that the differences in the firefighter's experience and Transpower's is important and, when reviewed, is likely to reveal important lessons.
- 7.59 NZFS has restated its understanding that *its staff were withdrawn from firefighting for a period because it was not certain that power in the affected areas was off and isolated*. NZFS's understanding is different to Transpower's description of this issue.
- 7.60 The Authority remains of the view that this is a very important safety related issue that must be fully reviewed. The key point for Transpower to take on board is that NZFS firefighters that attended the fire had the perception that supplies may not have been isolated. A review must focus on why the NZFS firefighters had this perception and not on proving that the perception was wrong.
- 7.61 The Authority notes that NZFS, Vector, and Transpower have responded to the concerns raised by the Authority during the inquiry and are in the process of arranging a workshop to consider the event and identify lessons that could lead to improvements when responding to future incidents.
- 7.62 The Authority welcomes the commencement of the joint workshop.

8 An assessment of the economic impact of the fire

8.1 This section covers the Minister's fourth question:

What [was] the estimated economic impact of the outage ... on customers?

8.2 The inquiry has found that:

- a) the magnitude of the supply outage was significant
- b) the economic cost to electricity customers is estimated to be between \$47 million and \$72 million
- c) the economic cost would have exceeded this value but for the performance of NZFS, Vector and Transpower personnel in bringing the fire under control and restoring supply
- d) investment to reduce the cable trench risk would have been justified but was not carried out.

The magnitude of the supply outage was significant

8.3 Under clause 11 of the Commerce Commission's Electricity Distribution Services Default Price-Quality Path Determination 2012,¹²⁵ Vector is required to submit annual compliance statements to the Commerce Commission. Vector publishes its statements on its website.

8.4 The Commission uses Limits (annual SAIDI and SAIFI values) to assess a distribution business' performance.

8.5 On its website, Vector has published its compliance statement for the year ended 31 March 2015.¹²⁶ The compliance statement states that Vector exceeded its allowance, and therefore failed to meet its annual reliability assessment requirement, for SAIDI in the year to 31 March 2015.

8.6 Vector also exceeded its annual reliability assessment requirement for SAIDI for the previous assessment period ending 31 March 2014, but did not exceed the reliability requirement in any of the preceding three years.

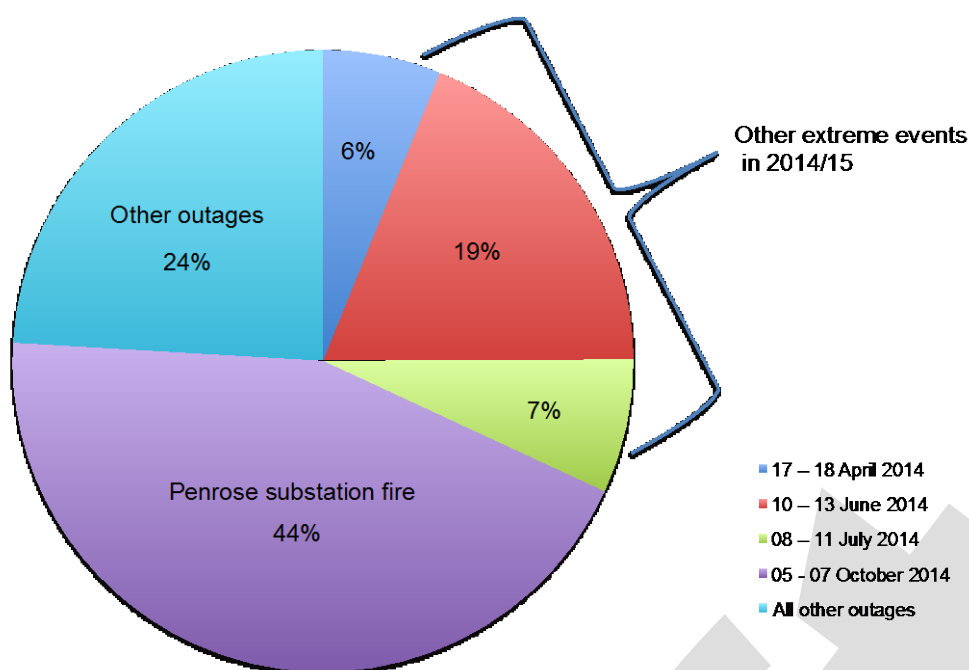
8.7 In the assessment year ended 31 March 2015, Vector classified four events as major event days. Three of the major events were related to extreme weather events and one to the supply interruptions that resulted from the Penrose substation fire.

8.8 Figure 10 highlights the proportion of the supply interruptions on Vector's network caused by the four major events in the year to 31 March 2015. The impact of the Penrose fire in terms of loss of supply to customers can be clearly seen.

¹²⁵ The Commerce Commission issues the price-quality determination pursuant to Part 4 of the Commerce Act 1986. This requires non-exempt suppliers of electricity lines services to provide information to relevant parties for the assessment of their performance against the price path and quality standards.

¹²⁶ <http://vector.co.nz/documents/101943/659865/Electricity+Compliance+Statement+May+2015.pdf>

Figure 11 – Contributions to Vector's SAIDI for the year ended 31 March 2015



Source: Data from Vector's 2015 Electricity Compliance Statement

The economic cost to electricity customers is likely to have been high

- 8.9 The first step to calculate the economic cost requires an assessment of the amount of energy (load) that would have been used by customers if the fire and the resulting power outages had not occurred.
- 8.10 Owing to the limited information available, it has been necessary to make assumptions when estimating the total amount of unserved load.
- 8.11 To test the sensitivity of assumptions about the amount of unserved load for different customer groups, the Authority has produced a range of estimated results using three alternative assessment methods. Table 1 summarises the methods and the assessed unserved load.

Table 1 – Estimated load not served (MWh)¹²⁷

Customer group	Method		
	Based on Penrose GXP volumes	Based on Penrose and neighbouring GXP volumes	Based on available individual customer metered volumes
Residential	1,286	641	999
Small non-residential	635	336	472
Medium non-residential	547	511	527

¹²⁷ MWh is the standard industry abbreviation for 1,000,000 watt-hours, a unit of energy. 1 MWh = 1,000 kilowatt-hours = 1,000 'units' of electricity. 'Units' are an amount of energy that customers should be familiar with from electricity invoices.

Large non-residential	1,463	1,461	1,462
Total	3,930	2,949	3,461

- 8.12 Over many years, electricity industry stakeholders have assessed the value of lost load (VoLL) multipliers. VoLL multipliers represent an average value that a group or category of electricity customers place on electricity not supplied (or 'lost load').
- 8.13 The total lost load is initially broken down into four Vector customer categories. The lost load is then reassigned to the four customer groups for which VoLL multipliers are available so that the total cost of non-supply can be estimated.
- 8.14 VoLL multipliers (Table 2) have been sourced from a report prepared by the Authority.¹²⁸ The report provides VoLL multipliers (in units of \$/MWh) for the following four customer groupings:
- Residential
 - Small non-residential (< 200,000 kWh per annum)
 - Medium non-residential (200,000 to 1,000,000 kWh per annum)
 - Large non-residential (> 1,000,000 kWh per annum).

Table 2 – VoLL multipliers (\$/MWh)

Residential	\$ 11,980
Small non-residential	\$ 56,815
Medium non-residential	\$ 27,992
Large non-residential	\$ 3,906

- 8.15 The lost load per customer group is then multiplied by the corresponding VoLL multiplier to provide an estimate of the dollar value of the load not supplied. This represents an estimate of the economic value of the load not supplied due to the outages that resulted from the Penrose fire.
- 8.16 Table 3 provides a breakdown of the results for each customer group.

Table 3 – Estimated cost of load not supplied (\$)

Customer group	Method		
	1. Based on Penrose GXP volumes	2. Based on Penrose and neighbouring GXP volumes	3. Based on available individual customer metered volumes
Residential	\$ 15,401,215	\$ 7,677,016	\$ 11,973,289
Small non-residential	\$ 36,063,111	\$ 19,070,178	\$ 26,834,430
Medium non-residential	\$ 15,320,679	\$ 14,309,842	\$ 14,763,539
Large non-residential	\$ 5,713,028	\$ 5,706,634	\$ 5,709,570
Total	\$ 72,498,033	\$ 46,763,670	\$ 59,280,828

¹²⁸ Electricity Authority, *Investigation into the Value of Lost Load in New Zealand - Report on methodology and key findings*, 23 July 2013, Table 1 - VoLL for Auckland respondents, 8 hour outage

- 8.17 Table 3 indicates that the estimated economic cost to customers from the outages that resulted from the Penrose fire is in the range \$47 million to \$72 million.

The economic cost to customers could have been much higher

- 8.18 The investigation report and the NZFS report confirm that, just prior to commencement of firefighting at 3:23 am, there was an imminent risk of the fire spreading to the Penrose 33 kV indoor switchgear building. Recorded images of the fire show that flames were lapping the side of the building and that the spouting downpipe was on fire. The initial firefighting attack sought to extinguish the fire at the switchgear building.
- 8.19 The point of ignition of the fire was between two large power transformers. Owing to the damage to the control cables near the fire, control signals automatically sent to the substation during the early stages of the fire led Transpower to suspect that one of the transformers could have been on fire.
- 8.20 If the switchroom had been even partly destroyed, supply interruptions would likely have taken significantly longer to restore. Had this occurred, the potential costs of extended supply interruptions could have exceeded the estimated economic costs summarised in Table 3.

Investment to reduce the cable trench risk would have been justified

- 8.21 CCI has calculated the cumulative number of faults for the Penrose cable trench at 1.2 over the 48 years it has been in service. CCI notes that this number of faults is 'small, but not zero'. This means that a failure of a cable in the trench could have been expected to occur once every 40 years ($= 48/1.2$ - this value is often referred to as the 'mean time between failures' or MTBF).¹²⁹
- 8.22 Using a lower-end value for the estimated cost of the fire to electricity customers of \$50 million, a discount rate of 7% and the MTBF of 40 years results in a present value of \$3.3 million. This indicates that \$3.3 million of investment in prevention actions could have been economically justified for the cable trench on the basis of the cost to customers due to a failure and fire every 40 years. This calculation assumes that a failure will lead to a fire. Given the context of the cable trench with sufficient fuel and oxygen and the failure likely to consist of an arc, the Authority believes that this is a reasonable assumption.
- 8.23 As the potential consequences of the failure and fire could have been much higher, and taking into account the costs of restoration are not included in these calculations, the justifiable investment value is likely to be much higher than the estimated \$3.3 million. This means that there would have been low economic barriers for work to reduce the cable trench risks if Vector or Transpower had identified the need for them.

¹²⁹ Cables deteriorate over time and as they age the probability of a fault increases. This is particularly the case as cables approach the end of their expected lives.

9 Other matters considered during the inquiry

- 9.1 This section covers the Minister's question relating to policy implications and also considers areas not explicitly covered in the Minister's letter but relevant to the Penrose fire.

No policy-related issues were identified during the inquiry

- 9.2 During the inquiry, the Authority has considered if any policy issues contributed to the cause or effects of the Penrose substation fire.
- 9.3 The Authority has also considered if issues relating to the structure of the electricity industry may have adversely affected communications with customers during the event. The Authority has not identified any issues relating to the interactions between customers, electricity retailers and Vector. As discussed in section 7, the Authority has found that communications throughout the event with customers, media and the public appear to have worked well.
- 9.4 As discussed in paragraphs 5.152 to 5.156, the Authority has identified no issues with price/quality regulation relating to the fire.

Part Three Recommendations to improve the resilience of power supplies

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10 Actions being taken by Vector and Transpower to improve resilience

10.1 This section covers the Minister's fifth question

What actions will be taken or are recommended, as a result of the outage and subsequent investigations, to improve the resilience of power supplies and management of outages?

10.2 The inquiry has found that:

- a) Vector and Transpower have identified, and are implementing, a number of actions to improve systems and practices
- b) the actions being taken by Vector and Transpower are appropriate and necessary – several actions have already been completed
- c) the Authority has identified additional actions that Vector and Transpower should take
- d) the Authority should monitor and report on how Vector and Transpower implement the actions, to provide assurance that security of supply will be improved.

The investigation has recommended several actions

10.3 Through their joint investigation, Vector and Transpower have identified 'key learnings' (lessons) applicable to each business individually, and jointly where collaboration will be required to implement remedial actions.

10.4 Vector and Transpower have identified four high-level key learning areas:¹³⁰

- a) *Learning 1: cable joints installed in air with other cables in close proximity can cause sustained fires when they fail*
- b) *Learning 2: risk management processes did not identify very low probability events that had not previously occurred on the network*
- c) *Learning 3: the nature of the incident identified opportunities for improvement of standard operating procedures*
- d) *Learning 4: the asset and risk management processes at the physical interface between Transpower's and Vector's networks need to be improved.*

Vector's and Transpower's actions from Learning 1

10.5 The investigation has recommended that:

- a) *Vector and Transpower implement changes at Transpower's Penrose substation as part of the recovery works, including installing replacement cables in two trenches containing segregated ducts for each cable to effectively eliminate reduce the risk of fire causing multiple cable failures.*

¹³⁰ Investigation report, section 9.2. The items listed in paragraphs 10.4-10.13 are quoted from the investigation report. They have been reformatted only to match the style used in this inquiry report.

- b) *Vector and Transpower review locations where power cables are installed in open air environments to identify any risks associated with assets at the following locations:*
 - (i) *Transpower/Vector points of connection (GXPs)*
 - (ii) *Vector's network*
 - (iii) *Transpower sites*
 - (iv) *take appropriate actions to mitigate these risks.*
 - c) *Vector review and update its relevant policies, procedures and practices with respect to cables, and cable joints installed in air.*
 - d) *Transpower incorporate lessons from the Penrose cable fire into asset management practice, including design standards. Include mitigation of risks from failures of cable joints in open air.*
- 10.6 The investigation has recommended that the following actions are undertaken:
- a) *design a new permanent solution at the Penrose substation*
 - b) *construct the solution*
 - c) *inspect all areas on the Vector network where there are multiple cables in open air, including Transpower, and third party substations, assess the consequence of failure and identify actions to mitigate risks identified from the inspection*
 - d) *inspect all critical Transpower substations to identify cable joints in air, assess the consequences of failure, and identify actions to mitigate risks identified from the inspections*
 - e) *complete all actions identified to mitigate the risks*
 - f) *Vector amend its maintenance schedules to include inspections of all open air cable installations*
 - g) *review and amend Vector policies, procedures and practices that deal with cable system design, installation and maintenance*
 - h) *review and amend Transpower asset management standards that deal with cable system design, installation and maintenance.*

Vector's and Transpower's actions from Learning 2

- 10.7 The investigation has recommended that:
- a) *Vector review and update its risk management framework, and risk identification processes*
 - b) *Transpower incorporate lessons from the Penrose cable fire into risk review processes.*
- 10.8 The investigation has recommended that the following actions are undertaken:
- a) *Vector review and amend its asset risk management framework*
 - b) *Vector amend its procurement processes and contracts to request suppliers to make Vector aware of any significant issues with product failures*

- c) *Vector create a dedicated role within its networks business focused on managing asset risk identification and management processes*
- d) *Vector continue to develop its assessment of asset risk profiles to ensure the criticality of assets is considered*
- e) *Vector review risk identification processes across the Vector group to ensure any lessons from the incident are applied*
- f) *Transpower review the scope of risk studies, including HILP event studies, to ensure coverage of assets owned by connected parties on Transpower land.*

Vector's and Transpower's actions from Learning 3

10.9 The investigation has recommended that:

- a) *Vector update its standard operating procedures to apply key lessons from the incident*
- b) *Transpower update its standard operating procedures to apply key lessons from the incident.*

10.10 The investigation has recommended that the following actions are undertaken:

- a) *Vector update its standard operating procedures for locating faults on feeders with cable sections installed in air*
- b) *Transpower review its communications and existing arrangements with the NZ Fire Service, to identify opportunities for improvement*
- c) *Vector review its communications and existing arrangements with the NZ Fire Service, to identify opportunities for improvement.*

Vector's and Transpower's actions from Learning 4

10.11 The investigation has recommended that:

- a) *Vector and Transpower review contractual terms and management processes at points of connection to ensure key lessons from the incident are incorporated*
- b) *Transpower improve its business process for assessing and approving customer requests for access and occupation of Transpower land*
- c) *Transpower establish an on-going process to provide assurance about the status and condition of customer assets on Transpower land and the potential risks to the grid.*

10.12 The investigation has recommended that the following actions are undertaken:

- a) *Vector and Transpower review contractual terms and management processes at points of connection*
- b) *Transpower review the business process for assessing and agreeing to customer requests for access and occupation of Transpower land. Ensure that a risk assessment is part of the process*
- c) *Transpower establish an on-going process to provide assurance about the status and condition of customer assets on Transpower land and the potential*

risks to the national grid. This process is to focus on critical sites, and to include agreement of risk mitigation plans with customers.

Vector and Transpower have started work to improve resilience

10.13 The 'final draft' investigation report, received by the Authority on 1 September 2015, states that the following improvements have already been completed, or are in progress:¹³¹

- a) *At Penrose a permanent solution for cables damaged in the fire has been designed and agreed between Transpower and Vector. The replacement cables will be installed in fire segregated ducts along two independent routes.*

This work will be carried out in conjunction with a separate Transpower project to install a new indoor 33 kV switchroom. The timeframe for completion of this work is June 2016 and is determined by a need to co-ordinate with the indoor switchroom project. Tenders have been let for this work.

- b) *Transpower and Vector have each undertaken surveys of their sites to identify situations where failure of cables in air could lead to significant consequences. These surveys have not identified any issues of immediate concern. However, at several Transpower sites, interim risk mitigations for cable joints have been implemented as a precautionary measure.*

Vector has developed action plans based upon its site surveys and prioritised these. Works on all critical (priority 1) sites have been completed.

- c) *Transpower has developed a process for a comprehensive review of Access and Occupation schedules, to update the records of customer assets on Transpower land, and to evaluate the risks associated with those assets. The documentation updates and risk reviews for the most critical sites are scheduled to be completed within 12-18 months.*

- d) *Improvements to risk identification and review processes are underway within both organisations, together with enhancements to relevant asset management standards and operating practices.*

- e) *Vector has amended its operating procedures for locating faults on feeders with cable sections installed in air, and has commenced training of staff.*

- f) *Transpower has developed a process for a comprehensive review of Access and Occupation schedules to update the records of customer assets on Transpower land, and evaluate the risks associated with those assets. This process has commenced. The documentation updates and risk reviews for the most critical sites are scheduled to be completed within 12-18 months.*

10.14 The investigation report states that "Transpower and Vector will track progress on actions through established internal processes". The investigation report provides details of Vector's and Transpower's internal assurance processes.¹³²

¹³¹ Investigation report, section 10

¹³² Investigation report, page 68

10.15 An update on progress with implementing the above actions was provided to the Authority by Transpower and Vector on 23 October 2015. The progress report is attached at Appendix D.

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11 The Authority's recommendations

- 11.1 The Authority considers that the recommendations and actions proposed by the investigation are sound and must be implemented to achieve improved supply resilience.
- 11.2 As the inquiry was conducted in parallel with the investigation, some overlap of the recommendations has occurred. The Authority intends that its recommendations should support the recommendations made in the investigation report and the CCI report. The Authority's recommendations also include timeframes for completion of key actions and provide for the monitoring of progress towards achieving them.
- 11.3 Many of the recommendations are relevant to all electricity lines businesses.

Recommendations relating to the Minister's first question

Recommendation 1 – Lessons from the Penrose incident must be shared with industry stakeholders

- 11.4 The detailed background, failure mechanisms and key lessons of the Penrose fire have potential values for other electricity lines businesses. The Authority recommends that Vector and Transpower share the findings of this inquiry and the investigation with other electricity lines businesses.
- 11.5 Where barriers exist to the sharing of information, Vector and Transpower must tell the Authority about the nature of the barriers and the limitations placed on information sharing.

Recommendation 2 – Supply-critical components should be given higher risk management priority than non-critical components, even if the probability of occurrence is low

- 11.6 The Authority recommends that Vector reconsider how it prioritises risks for its asset management programme so that it gives priority to supply-critical network components. Vector should undertake this review immediately and implement recommendations on improvements before 31 March 2016.
- 11.7 As discussed in section 5 of this report, Vector has previously given priority to overhead components of its network.¹³³ However, failure of supply-critical network components can have the most significant impact on customers and Vector should give a high priority to identifying and managing those failures, even if the probability of such failures may be low.

¹³³ Section 6.1.3 of Vector's 2013 Asset management plan states that *work on developing a CBRM framework for Vector's electricity assets commenced during FY11, focusing on overhead line assets.*

Recommendation 3 – The particular characteristics of each asset must be considered in determining the risk profile of the asset

- 11.8 The Authority recommends that Vector and Transpower review their fire risk mitigation standards and asset management policies to better align with the key characteristics of specific installations. Vector and Transpower should undertake this review immediately and implement recommendations on improvements before 31 March 2016.
- 11.9 For example, a Transpower standard exists that considers fire risk in cable basements but it does not anticipate other in-air installations (ie in-air cable trenches) that have essentially the same characteristics and pose similar risk profiles.

Recommendation 4 – In-air cable joints must be identified and the associated fire risk mitigated

- 11.10 To address explicitly the risk of fire ignition from cable joints, the Authority recommends that Vector and Transpower review their standards for existing power cable joints in in-air situations. For new installations, joints in in-air situations should be avoided where practicable. Vector and Transpower should undertake this review immediately and implement recommendations on improvements before 31 December 2015. The Authority understands that Vector and Transpower have already initiated programmes in line with the above recommendation.
- 11.11 A number of relatively low-cost fire mitigation solutions have been identified by the investigation in its survey of electricity lines businesses. These options should be fully considered and, where appropriate, implemented.

Recommendation 5 – Asset boundaries require improved management between asset owners to ensure clear division of responsibility

- 11.12 The Authority recommends that Vector and Transpower pay greater attention to formalised asset management practices at all boundaries where assets connect to the grid. Vector and Transpower should undertake an immediate review of their asset management policies and implement recommendations on improvements before 31 March 2016.
- 11.13 If the findings from the review indicate a systematic issue beyond Penrose substation, the Authority recommends that Vector and Transpower undertake a comprehensive review of asset management practices at all points of interconnection between their networks. In addition, Transpower should review asset management practices at all network asset boundaries.

Recommendation 6 – Access and occupation arrangements must be reviewed and complied with

- 11.14 All of Transpower's access and occupancy arrangements and procedures through which third parties are allowed to locate assets and equipment at important substations must be fully reviewed and include a periodic compliance review. Transpower should undertake this review immediately and implement recommendations on improvements before 31 March 2016.

- 11.15 The Authority recommends that Transpower review its arrangements regarding access and occupancy, and compliance with those arrangements. Transpower should undertake this review immediately and implement recommendations on improvements to its standard contract before 31 December 2015. The Authority recognises that completion of individual contracts between Transpower and its customers may take some time to complete and some form of prioritisation may be required.
- 11.16 The inquiry found that the arrangements, through which Transpower had provided Vector with access to locate its cables in the Penrose trench were not well understood by either Vector or Transpower. For example, important schedules recording the cables in the trench were inaccurate and had not been updated, and approvals for locating additional cables in the trench had not been documented. These issues must be addressed and corrected in the review.

Recommendation 7 – Planning standards should be reviewed by Vector to ensure the standards are appropriate

- 11.17 The Authority recommends that Vector review its network planning standards with respect to the definition of a single credible contingency event relevant to the multiple power cables co-located within close proximity. Vector should undertake this review immediately and implement recommendations on improvements before 31 March 2016.
- 11.18 Thirty eight power cables supporting 19 supply-critical circuits co-located within an in-air trench was a primary risk factor in the Penrose fire incident. The cable trench was effectively a single contingency risk for the 19 supply-critical circuits. Such supply-critical circuits should have had at least one level of redundancy inherent in the network design.
- 11.19 Included in the lengths of power cables were 11 kV power cables that Vector managed using a 'run to failure' maintenance approach. Locating 'run to failure' cables in an in-air situation in close proximity to other assets that have a higher standard applied to them was a critical factor in extent of supply disruption that resulted from the Penrose fire. Vector must reconsider the application of its network planning standards for these situations.

Recommendation 8 – Future State of the Network reviews should be re-scoped to ensure the reviews are effective

- 11.20 Vector and the AECT should review the scope of the biennial State of the Network Reviews to ensure that the reviews achieve what was intended, and that any limitations are fully understood.
- 11.21 The Authority recommends that the scope of future State of the Network Reviews include supply-critical network components, and an assessment of how the associated risks are being managed.
- 11.22 Vector and the AECT should undertake the review immediately and include recommendations on improvements in the 2016 State of the Network review and report.

Recommendation relating to the Minister's third question

Recommendation 9 – An independently peer reviewed, post-event safety review must be undertaken to identify improvement opportunities

- 11.23 An early post-event review involving Vector, Transpower and NZFS should have taken place. The lack of such a review has raised, at a late stage in the inquiry, important questions about communications and safety management during and after the fire. Resolution of inconsistencies between the perspectives of Vector, Transpower and NZFS could reveal important lessons and opportunities for improvement in emergency management procedures.
- 11.24 The Authority notes that in the final stages of this inquiry, Transpower has said that it is considering a safety review that will bring together Vector, Transpower and NZFS in a review of the safety and inter-agency aspects resulting from the Penrose fire.
- 11.25 The Authority considers that the review must include engagement with relevant field and office personnel from Vector, Transpower and NZFS, especially the onsite personnel involved on 5 October 2014. The results must be widely disseminated with relevant stakeholders. This review will provide opportunities to consider and improve safety and fire control management for emergency responses involving high-voltage electrical facilities.
- 11.26 The Authority recommends that the safety review be externally peer reviewed by an appropriate independent safety authority and the outcomes publicised by 31 March 2016.

The actions must be completed

- 11.27 For customers to have confidence in the reliability of their electricity supplies, the Authority considers it important that:
- a) Vector and Transpower afford a high priority to reporting progress towards completion of the recommendations
 - b) there is transparent external monitoring of the progress achieved towards implementing the remedial actions identified in the investigation and in this inquiry.
- 11.28 The Authority recommends that Vector and Transpower submit to the Authority for approval an implementation programme by 31 December 2015. After the plan is approved, Vector and Transpower should submit progress reports to the Authority every six months until all actions have been completed (the monitoring period). Vector and Transpower should engage with the Authority during the monitoring period as may be required by the Authority from time to time.
- 11.29 The Authority will monitor progress made towards completion of the recommended improvement actions and will report to the Minister if there are any deviations from the implementation programme.

12 Glossary of abbreviations and terms

Act	Electricity Industry Act 2010
AECT	Auckland Energy Consumer Trust
AEPB	Auckland Electricity Power Board
AMP	Asset Management Plan
Authority	Electricity Authority
CB	Circuit breaker
CBD	Central Business District
CBRM	Condition-based Risk Management
CCI	Cable Consulting International Ltd
CCTV	Closed-circuit television, a security monitoring camera system installed at Penrose substation
CIGRE	International Council on Large Electric Systems
Code	Electricity Industry Participation Code 2010
EHV	Extra high-voltage
EOC	Vector's Electricity Operations Centre
GXP	Grid Exit Point
HILP	High impact, low probability
kV	Kilovolts (= 1000 volts), a unit of electrical voltage
Minister	Hon Simon Bridges, the Minister of Energy and Resources
MW	Megawatt, a unit of electrical power
MWh	Megawatt-hour, a unit of electrical energy
MTBF	Mean time between failures
MVA	Megavolt-ampere, a unit of electrical power
NZFS	New Zealand Fire Service
NGOC	Transpower's National Grid Operations Centre
PE	Polyethylene
PILC	Paper insulated, lead covered, a type of high-voltage power cable
RAE	Restricted Areas Entry
SAIDI	System Average Interruption Duration Index
Supply-critical	An attribute of a component, or a combination of components, in the supply system where failure of that component or components would result in a major supply interruption.
SRC	The Security and Reliability Council
Transpower	Transpower New Zealand Limited

Vector	Vector Limited
VoLL	Value of Lost Load
XLPE	Cross linked polyethylene, a type of high-voltage power cable

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13 References quoted and inquiry engagement with Vector and Transpower

References

- 13.1 Vector and Transpower have provided to the Authority a suite of documents and reports at various times throughout the inquiry.
- 13.2 The references listed below are the documents that have been directly quoted in this inquiry report.

Joint Transpower/Vector references

Transpower New Zealand Limited and Vector Limited, <i>Penrose Substation Fire – 05 October 2014 – Investigation Report</i> , Final Draft, undated, provided under cover of a letter to Carl Hansen on 1 September 2015
Transpower New Zealand Limited and Vector Limited, <i>Penrose Substation Fire – 05 October 2014 – Summary of Protection Operations report</i> , 22 May 2015

Transpower references

Transpower New Zealand Limited, <i>Station security – procedures TP.SS 07.40</i> , Issue 13, February 2012
Transpower New Zealand Limited, <i>Standard Maintenance Procedure – Fire Service Site Familiarisation (SI0045) SMP No: 02.41.025</i> , Issue 2, 19 November 2013
Transpower New Zealand Limited, <i>Penrose Substation High Impact Low Probability (HILP) Event Study</i> , June 2013, Report No: NP573
Transpower New Zealand Limited, <i>Penrose substation fire 05 October 2014 – History of Penrose substation</i> , 3 February 2015, working draft version 1
Transpower New Zealand Limited, <i>Transpower ACS Power Cables Fleet Strategy</i> , TP.FS 04.01, Issue 1, October 2013

Vector references

Vector Limited, <i>Penrose Substation Fire – 05 October 2014 – Customer Management</i> , Issue 1, 10 March 2015.
Paragon Health & Safety Consultants, <i>Occupational Hygiene Assessment – Penrose Substation</i> , 25 November 2014
Auckland Energy Consumer Trust, <i>Electricity Network Review – Request for Proposal 2010</i>
Vector Limited, <i>Penrose Substation Fire – 05 October 2014 – Summary of Protection Operations report</i> , 22 May 2015

General references

Cable Consulting International Ltd, <i>Draft Notes: Investigation into a Fire in a Cable Trench in Penrose Substation</i> , Final Draft, 13 August 2015
Edif ERA, <i>Analysis of Samples Taken From Cable Trench at Penrose Substation</i> , August 2015
Electricity Engineers' Association, <i>Guide to Electrical Safety for Emergency Services Personnel</i> , Second Edition, Issue 1, April 2009 ISBN 0-473-11349-X
Electricity Engineers' Association, <i>Guide to Electrical Network Safety for Emergency Services Personnel</i> , Third Edition, May 2015 ISBN: 978-0-473-32447-6

New Zealand Fire Service, <i>Fire Investigation Report</i> , 11 August 2015 (final)
Electricity Authority, <i>Investigation into the Value of Lost Load in New Zealand - Report on methodology and key findings</i> , 23 July 2013
Letter from Director, Office of the Chief Executive, NZFS to Manager Market Monitoring, Electricity Authority, 15 September 2015
Letter from Hon Simon Bridges, Minister of Energy and Resources, to Dr Brent Layton, Chair of the Electricity Authority, 7 October 2014

Engagement with Vector and Transpower

- 13.3 The Authority's inquiry team has met with Vector and Transpower representatives to discuss the Penrose fire event on several occasions.
- 13.4 The meetings labelled 'workshops' below included discussion of a range of topics relevant to the progress of the investigation and the inquiry.
- 13.5 The main meetings were as follows:
- a) 14 November 2014 – initial meeting to coordinate investigation and inquiry activities
 - b) 28 November 2014 – a site meeting held at Penrose substation to provide site familiarisation and observe post-fault activities and initial investigation topics
 - c) 19 December 2014 – workshop 1
 - d) 10 February 2015 – workshop 2
 - e) 8 April 2015 – workshop 3
 - f) 27 May 2015 – meeting to discuss lessons and recommendations
 - g) 16 June 2015 – meeting to discuss Vector external communications
 - h) 4 August 2015 – workshop 4
 - i) 28 August 2015 – second site visit to Penrose substation to view the status of repairs and meet afterwards at Vector's Auckland offices for workshop 5
 - j) 13 October 2015 – meeting at Electricity Authority offices between officials to discuss Vector and Transpower submissions on the Authority's draft report
 - k) 14 October 2015 – meeting at Transpower offices between the Chief Executives of the Authority, Vector, and Transpower to discuss Vector and Transpower's submissions on the Authority's draft report.

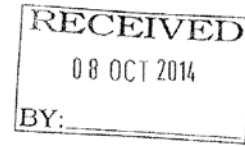
Appendix A The Minister's letter

A.1 A copy of the Minister's letter to the Authority is reproduced below.



Office of Hon Simon Bridges

MP for Tauranga
Minister of Energy and Resources
Minister of Labour
Associate Minister for Climate Change Issues



7 October 2014

Dr Brent Layton
Chair
Electricity Authority
PO Box 10041
Wellington

Dear Brent

The fire at the Penrose sub-station on 5 October which caused a power outage affecting around 85,000 households and businesses in parts of Auckland was a significant event. Many thousands of homes and businesses were left without power for over two days causing significant disruption and cost.

This raises questions about the reliability of power supply. It is therefore important there be a full inquiry so the public can be confident that risks of power supply interruption are adequately managed.

I am writing to request, under section 18 of the Electricity Industry Act 2010, that the Authority undertakes an inquiry of the Penrose outage and report its findings to me.

The Authority should work with all parties involved to address the following questions:

1. What caused the loss of supply or contributed to it, including potentially systemic factors such as risk management systems, asset health monitoring and maintenance practices, network design, and regulatory incentives and controls?
2. What fire hazard mitigation systems were in place; and did they operate as intended?
3. What actions were taken during the course of the outage in respect of:
 - a. ensuring the safety of people and equipment?
 - b. communicating with affected and interested parties (including emergency services) about the impact of the event and timeframes for restoration of supply?
 - c. mitigating the loss of supply and expediting restoration?
4. What the estimated economic impact of the outage was on customers?

5. What actions will be taken or are recommended, as a result of the outage and subsequent investigations, to improve the resilience of power supplies and management of outages?

I also request that the scope of the inquiry includes any policy implications and, because of this, that the Ministry of Business, Innovation and Employment be kept fully informed throughout the process of the inquiry.

Yours sincerely

A handwritten signature in black ink, appearing to read 'S Bridges', followed by a long horizontal line extending to the right.

Hon Simon Bridges
Minister of Energy and Resources

Appendix B Timeline of events

B.1 The following timeline of events has been compiled from several references. These are:

- (a) the investigation report
- (b) the CCI report
- (c) the NZFS report

Table 4 – Timeline of events

Duration [Stage 1]	Duration [Stage 2]	Time	Source	Event
T1 = 0:00		4/10/14 23:21	EOC	Remuera K10 trips - Stage 1 starts
2:00		5/10/14 1:21	EOC	manual reclose of Remuera K10, immediately tripped
2:11		5/10/14 1:32	CCTV	light smoke observed adjacent to 33 kV switchgear building
2:43		5/10/14 2:04	NGOC	unusual alarms noted at Penrose substation
2:46		5/10/14 2:07	EOC	Carbine #2 protection blocked due to failed pilot cable
2:48		5/10/14 2:09	NGOC	substation maintainer dispatched to Penrose
2:49		5/10/14 2:10	NGOC	T11 trips, then 4 x 33kV feeder trippings over the next 5 minutes
2:56		5/10/14 2:17	NZFS	a substation neighbour reports hearing 3 loud explosions at the substation
2:56		5/10/14 2:17	NZFS	NZFS dispatches fire appliances and notifies NGOC
3:00		5/10/14 2:21	NGOC/EOC	more pilot cable failures and 33/22 kV transformer trippings
3:02		5/10/14 2:23	NGOC	notified EOC that a number of assets had tripped and explosions reported to NZFS
3:05	T2 = 0:00	5/10/14 2:26	NZFS	first NZFS appliance arrives at Penrose gate (2nd arrived at 2:28 am) - Stage 2 starts
3:11	0:06	5/10/14 2:32	CCTV	pronounced smoke & light reflections (fire) observed
3:20	0:15	5/10/14 2:41	Transpower	maintainer meets NZFS onsite and opens perimeter security gate; NZFS personnel enter substation
3:23	0:18	5/10/14 2:44	EOC	more cable circuit trippings over next 4 minutes
3:29	0:24	5/10/14 2:50	NGOC	notified EOC that all 33 kV equipment would need to be de-energised
3:34	0:29	5/10/14 2:55	NZFS	message logged that the fire appeared to be in an oil-filled underground cable
3:37	0:32	5/10/14 2:58	NGOC	switching operations commence to de-energise 33 kV and T10; completed at 3:17 am
3:41	0:36	5/10/14 3:02	NZFS	commenced bringing in foam equipment
3:56	0:51	5/10/14 3:17	NGOC	switching operations complete (19 CBs opened) - all 33 + 22 kV equipment de-energised
4:01	0:56	5/10/14 3:22	Transpower	notified NZFS that equipment is de-energised near the 33 kV building area
4:11	1:06	5/10/14 3:32	NZFS	NZFS commences firefighting on the cables exiting the cable trench near the 33 kV building
4:11	1:06	5/10/14 3:32	CCTV	dense smoke and free fire observed
4:13	1:08	5/10/14 3:34	Transpower	Transpower Regional Services Manager arrives, locates in the NZFS command vehicle
4:13	1:08	5/10/14 3:34	Transpower	notified NZFS not to go past the transformers into the 220 kV switchyard because it is energised
4:14	1:09	5/10/14 3:35	Transpower	Transpower queries whether there is any backfeed from the Vector network. Fire fighting is temporarily suspended.
4:17	1:12	5/10/14 3:38	EOC	advises NGOC that there are no backfeeds into the 33 kV system
4:19	1:14	5/10/14 3:40	Transpower	Transpower Regional Services Manager advises EOC that Vector cables are on fire in the cable trench
4:29	1:24	5/10/14 3:50	Transpower	Transpower Senior Maintenance Manager arrives at site
4:34	1:29	5/10/14 3:55	NZFS	message logged that power confirmed isolated, 2 x foam deliveries in use
5:00	1:55	5/10/14 4:21	Vector	Transpower Regional Manager advised Vector GM Network Operations that cable trench containing Vector cables is on fire
5:05	2:00	5/10/14 4:26	Transpower	Transpower manager requests complete shutdown of the 220 kV switchyard
5:09	2:04	5/10/14 4:30	Vector	oil mechanic shuts off oil flow into oil-filled cables
5:09	2:04	5/10/14 4:30	NGOC	commences switching to shut down the 220 kV switchyard
5:14	2:09	5/10/14 4:35	NGOC	switching operations complete (4 x CBs opened)
5:14	2:09	5/10/14 4:35	NZFS	request for hazardous guideline for "hydro treated naphthenic distillate"
5:16	2:11	5/10/14 4:37	NGOC	advises NZFS that the 220 kV switchyard is de-energised
5:16	2:11	5/10/14 4:37	NZFS	NZFS enters 220 kV switchyard area to continue fire fighting
5:24	2:19	5/10/14 4:45	Vector	oil mechanic shuts off oil flow into St John's (4:45 am) and Westfield (5:00 am) cables
5:26	2:21	5/10/14 4:47	NZFS	logged situation report: 2 fires, 33 kV switchgear building fire contained, fire in cable trench & firefighting not commenced because not confirmed as being isolated
7:24	4:19	5/10/14 6:45	NZFS	fire contained
8:39	5:34	5/10/14 8:00	NZFS	flooded trench to cool the contents
10:36	7:31	5/10/14 9:57	NZFS	site control handed back to Transpower; NZFS remained on standby - Stage 3 starts

Appendix C Methodology for determining the economic cost of the electricity supply outage to customers

- C.1 To estimate the total amount of unserved energy as a result of the outage, it was necessary to make some assumptions due to the limited information available. Hence, several different approaches were taken yielding a range of estimated results.
- C.2 In estimating the total amount of unserved energy as a result of the outage, several different approaches were taken based on the information available, thus yielding a range of estimated results.
- C.3 The total lost load is initially broken down into four Vector customer categories. The lost load is then re-assigned to the four customer groupings for which VoLL multipliers are available so that the total cost of non-supply can be estimated.
- C.4 The following data sources were available:
 - (a) Half-hourly GXP load for Penrose 33 kV and 22 kV and other nearby GXPs
 - (b) Half-hourly load for Industrial and Commercial (I&C) customers with Time of Use (TOU) meters
 - (c) Half-hourly load and customer category for customers with AMS (advanced) meters (approximately 17% of the remaining customers in the affected area)
 - (d) Monthly load and customer type for all Installation Control Points (ICPs) in the affected area (ie, the area normally supplied from the Penrose 33 kV and 22 kV GXPs)
- C.5 The Vector database classifies customers according to four categories as follows:
 - (a) Residential
 - (b) Business
 - (c) Industrial and Commercial (non-TOU)
 - (d) Industrial and Commercial (TOU)
- C.6 VoLL multipliers have been sourced from a report prepared by the Electricity Authority . The report provides \$/MWh VoLL multipliers for the following four customer groupings:
 - (a) Residential
 - (b) Small non-residential (< 200,000 kWh per annum)
 - (c) Medium non-residential (200,000 to 1,000,000 kWh per annum)
 - (d) Large non-residential (> 1,000,000 kWh per annum)
- C.7 The following three approaches were taken:
 - (a) Method 1: Compare GXP loads on affected days with corresponding days in neighbouring weeks (Penrose 33 kV and 22 kV only).

- (b) Method 2: Compare GXP loads on affected days with corresponding days in neighbouring weeks (Penrose 33 kV and 22 kV as well as neighbouring GXPs to which load was transferred during the outage).
- (c) Method 3: Compare ICP loads on affected days with corresponding days in neighbouring weeks where half hourly data is available and extrapolate over the affected area.

C.8 In all cases TOU data for I&C customers was used directly.

Data

VOLL Multipliers \$/MWh

Residential	\$ 11,980
Small non-residential	\$ 56,815
Medium non-residential	\$ 27,992
Large non-residential	\$ 3,906

Estimated Cost of Non-Supply

Customer group	Method		
	Based on Penrose GXP volumes	Based on Penrose and neighbouring GXP volumes	Based on available individual customer metered volumes
Residential	\$ 15,401,215	\$ 7,677,016	\$ 11,973,289
Small non-residential	\$ 36,063,111	\$ 19,070,178	\$ 26,834,430
Medium non-residential	\$ 15,320,679	\$ 14,309,842	\$ 14,763,539
Large non-residential	\$ 5,713,028	\$ 5,706,634	\$ 5,709,570
Total	\$ 72,498,033	\$ 46,763,670	\$ 59,280,828

Method 1: Compare GXPs only

C.9 The following steps were taken in the analysis:

- (a) Estimate the normal total Penrose GXP load for each day of the week by averaging total Penrose GXP loads for corresponding unaffected days of the week over the period 28 September through 21 October 2014.
- (b) For the I&C TOU category, estimate the normal (ie the counterfactual) load for each day of the week by averaging the metered loads for corresponding unaffected days of the week over the period 28 September through 21 October 2014.
- (c) Assign the remaining normal total Penrose GXP load for each day of the week, after deducting the normal I&C TOU load, to the other three customer categories (Residential, Business, and I&C non-TOU) according to proportions derived as follows:
 - (i) Aggregate total metered ICP loads for the months of September and November 2014 into the four customer categories.
 - (ii) Estimate the percentage of weekly I&C TOU load that normally falls on each day of the week based on unaffected days over the period 28 September through 21 October 2014.

- (iii) Assume the percentage of weekly I&C non-TOU load that normally falls on each day of the week is the same as for I&C TOU load.
- (iv) Estimate the percentage of weekly residential load that normally falls on each day of the week based on available residential AMS data for unaffected days over the period 28 September through 21 October 2014.
- (v) Estimate the percentage of weekly business load that normally falls on each day of the week based on available non-residential AMS data for unaffected days over the period 28 September through 21 October 2014.
- (vi) Assign total load for each customer category from paragraph (i) to each day of the week using the percentages from paragraphs (ii) through (v).
- (vii) Calculate the normal ratios of the Residential, Business, and I&C non-TOU loads for each day of the week from paragraph (vi).
- (d) Obtain total Penrose GXP load for each day of the outage (Sunday 5 October through Tuesday 7 October 2014).
- (e) Obtain total I&C TOU load for each day of the outage (Sunday 5 October through Tuesday 7 October 2014).
- (f) Calculate percentage of I&C TOU load served on each day of the outage from (e) and (b).
- (g) Initially estimate total I&C non-TOU load for each day of the outage using the percentage of load served from I&C TOU data.
- (h) Initially estimate total Residential load on each day of the outage using the percentage of load served from available residential AMS data.
- (i) Initially estimate total Business load on each day of the outage using the percentage of load served from available non-residential AMS data.
- (j) Scale the initial estimates of Residential, Business, and I&C non-TOU loads for each day of the outage so that the sum of the four categories matches the total GXP load from (d).
- (k) Calculate total load not served for each customer category by subtracting estimated actual loads from estimated normal loads (ie. subtracting (e) and (j) from (b) and (c).
- (l) For each of the three non-residential customer categories (ie. Business, I&C non-TOU, and I&C TOU), calculate the percentage of the load which falls into each of the three non-residential VoLL groupings (ie. small, medium and large), based on 12 months of metering data.
- (m) Split the total load not served for non-residential customer categories into small, medium and large using the percentages from 12.
- (n) Apply the VoLL multipliers to each VoLL grouping to obtain estimated cost of non-supply.

Method 2: Compare GXP loads for Penrose and neighbouring GXPs

C.10 The following steps were taken in the analysis:

- (a) Same as Method 1
- (b) Same as Method 1
- (c) Same as Method 1
 - (i) Obtain total Penrose GXP load for each day of the outage (Sunday 5 October through Tuesday 7 October 2014), same as Method 1.
 - (ii) Estimate the normal GXP load for PAK0331, ROS0221 and MNG0331 (the neighbouring GXPs to which load was transferred during the outage) for each day of the week by same method as for Penrose.
 - (iii) Obtain GXP load for each day of the outage for PAK0331, ROS0221 and MNG0331.
 - (iv) Augment total Penrose GXP load for each day of the outage with the amount by which PAK0331, ROS0221 and MNG0331 were above average (ie $1 + 3 - 2$)
- (d) Same as Method 1
- (e) Same as Method 1
- (f) Same as Method 1
- (g) Same as Method 1
- (h) Same as Method 1
- (i) Scale the initial estimates of Residential, Business, and I&C non-TOU loads for each day of the outage so that the sum of the four categories matches the augmented total Penrose GXP load.
- (j) Same as Method 1
- (k) Same as Method 1
- (l) Same as Method 1
- (m) Same as Method 1

Method 3: Compare ICP loads and extrapolate

C.11 The following steps were taken in the analysis:

- (a) Same as Method 1
- (b) Same as Method 1
- (c) Same as Method 1
- (d) (this step not required)
- (e) Same as Method 1
- (f) Same as Method 1
- (g) Same as Method 1
- (h) Same as Method 1

- (i) Same as Method 1
- (j) (this step not done – ie, category load estimates were not scaled to match GXP load)
- (k) Same as Method 1 except that load not served for any customer category on any day is limited to non-negative values (this had a minor effect on Residential and Business load on the last day of the outage (Tuesday 7 October).
- (l) Same as Method 1
- (m) Same as Method 1
- (n) Same as Method 1

Draft

23 October 2015

Transpower/Vector Progress Update on Implementation of Actions arising from the joint investigation

Progress on each of the actions identified to implement the recommendations arising from the joint investigation is outlined in the table below. This update is at 23 October 2015.

ACTION	STATUS
1 Design a new permanent solution at the Penrose substation.	Completed
2 Construct the solution.	Underway and on track to be completed by June 2016 in conjunction with a project to convert the 33kV outdoor switchyard to an indoor switchroom. Tenders for the duct installation are currently being assessed. Tender documents for the cable installation are being prepared. Removal of damaged cables is complete and the trench is being cleaned in preparation for the installation of ducts.
3 Inspect all areas on the Vector network where there are multiple cables in open-air, including Transpower and third party substations,	Completed

assess the consequences of failure and identify actions to mitigate risks identified from the inspections.	
4 Inspect all critical Transpower substations to identify cable joints in air, assess the consequences of failure, and identify actions to mitigate risks identified from the inspections.	Completed
5 Complete all actions identified to mitigate the risks.	Vector – All high priority (phase I) mitigation work has been completed. One phase II site is yet to be completed due to co-ordination with a separate project. All lower priority works are in progress and expected to be completed by 30 June 2016. Transpower - At several Grid Exit Points, the connected customer has undertaken to implement interim risk mitigations, such as the application of intumescent paint or sandbags to cable joints in air. Some sites have already been finished, and progress with the remainder is being followed up, to ensure all identified work is completed.
6 Vector amend its maintenance schedules to include inspections of all open-air installations.	Completed
7 Review and amend Vector policies, procedures and practices that deal with cable system design, installation and maintenance.	Two key standards relating to cable joints in air have been updated. Some additional work is underway for remaining updates.
8 Review and amend Transpower asset management standards that deal with cable system design, installation and maintenance.	Scoping of this work has commenced.
9 Vector review and amend its asset risk management framework.	In progress
10 Vector amend its procurement processes and contracts to request suppliers to make Vector aware of any significant issues with product failures.	In progress.

11	Vector create a dedicated role within its networks business focussed on managing asset risk identification and management processes.	Completed
12	Vector continue to develop its assessment of asset risk profiles to ensure the criticality of assets is considered.	In progress
13	Vector review its risk identification processes across the Vector group to ensure any lessons from the incident are applied.	In progress
14	Transpower review the scope of risk studies, including HILP event studies, to ensure coverage of assets owned by connected parties on Transpower land.	Scope for HILP risk studies has been amended. Work is proceeding to define and implement improved processes for identification, communication and assessment of risks at sites. This will include coverage of assets owned by others on Transpower land.
15	Vector update its standard operating procedures for locating faults on feeders with cable sections installed in air.	Completed
16	Transpower review its communications and existing arrangements with the NZ Fire Service to identify opportunities for improvement.	A joint operational review of the incident with NZ Fire Service has been agreed. An independent facilitator is in the process of being engaged.
17	Vector review its communications and existing arrangements with the NZ Fire Service to identify opportunities for improvement.	A joint operational review of the incident with NZ Fire Service has been agreed. An independent facilitator is in the process of being engaged.
18	Vector and Transpower review contractual terms and management processes at points of connection.	In progress
19	Transpower review the business process for assessing and agreeing to customer requests for access and occupation of Transpower land. Ensure that a risk assessment is part of the process.	Scoping of this work has commenced, and will be informed by outcomes and learnings from the updating of Access and Occupation schedules outlined in the following row.
20	Transpower establish an on-going process to provide assurance about the status and condition of customer assets on Transpower land and the potential risks to the national grid. This process to	Transpower has developed a process for a comprehensive review of Access and Occupation schedules to update the records of customer assets on Transpower land, and evaluate the risks associated with those assets. This

focus on critical sites, and to include agreement of risk mitigation plans with customers.

process has commenced. The documentation updates and risk reviews for the most critical sites are scheduled to be completed within 12-18 months

Post-script note:

The Security and Reliability Council received the draft version of the following report at its 9 November 2015 meeting.

The final version of this report is available from <http://www.ea.govt.nz/monitoring/enquiries-reviews-and-investigations/2014/section-18-review-of-auckland-power-outage-5-october-2014/>

Penrose Substation Fire

05 October 2014

Investigation Report



CONFIDENTIAL AND DRAFT

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Acknowledgement

Transpower and Vector regret the disruption to customers during the 5 October 2014 outage. Everything was done to ensure the network was repaired as quickly as possible, however we do understand and acknowledge the impact the outage had on homes and businesses.

Transpower and Vector acknowledge the dedication and commitment of their employees and service providers, and the NZ Fire Service, in responding to this incident.

This report details findings and recommendations from a joint Transpower and Vector investigation into the fire at Transpower's Penrose Substation.

Both Transpower and Vector have taken the learnings from the investigation to assist in detecting and mitigating similar risks in the future.

Vector Limited is a publicly-listed company that owns and operates the electricity network in Auckland.

Transpower New Zealand Limited is a State Owned Enterprise that owns and operates the New Zealand transmission grid.

Executive Summary

Incident

In the early hours of the morning on Sunday 5 October, New Zealand Fire Service (NZFS) and Transpower personnel were called out to Transpower's Penrose substation. Upon arrival at the substation, they observed thick smoke which was subsequently found to be coming from a fire in a concrete cable trench containing Vector cables and a Transpower lighting cable.

Investigation

Transpower and Vector have conducted a joint investigation into the incident. It covered:

- the cause;
- extent and impact of the outage;
- risk mitigations, and whether these operated according to design, and
- key learnings and recommendations for the future.

The investigation included engaging an independent international power cable expert, and laboratory testing of cable and joint samples.

Cause

The cause of the fire was the failure of a cable joint in a Vector distribution (11 kV) cable within a concrete cable trench running east-west across the Transpower 220 kV switchyard at Penrose. The joint failed at 23:21 on Saturday 4 October 2014

The cable joint that failed is a common type used in electricity networks internationally.

Extent and Impact of the Outage

The fire spread to all of the cables in the concrete cable trench. This led directly to the loss of electricity supply to 39,043 Vector customers.

To provide safe access for the NZFS personnel to fight the fire, a large part of the Penrose substation also had to be de-energised. As a result, a total of 75,339 customers were without power from 03:08 on 5 October 2014. Supply to the Auckland CBD was not affected.

Vector made extensive use of backfeeding within its network to restore supply to affected customers. This limited the number of customers without supply for more than 24 hours to 20,257.

Cable Trench

The large concrete cable trench at Penrose is unusual. There are no directly similar installations at other Transpower substations. Distribution cables are normally buried, but at Penrose the sub-surface material is hard volcanic rock. The trench was constructed in the 1960s to provide an efficient means for a large number of distribution cables to traverse the site, avoiding difficult multiple excavations for individual cable routes. This resulted in multiple cables installed in air. Prior to the 2014 incident, there had been no faults of cables in the trench.

The investigation surveyed network companies in New Zealand, Australia and the United Kingdom, and this confirmed structures such as short tunnels, culverts and trenches are used for installation of cables in locations where burying the cables is not practicable. Within these structures it is common to have multiple cables installed.

Risk Mitigations

Transpower, Vector, and their external experts, had not identified a risk of fire in the cable trench. The investigation did not reveal any records of cable fires from joint failures on Vector's network before the incident. The surveys of network companies confirmed that cable fires from joint failures are very rare. Information on cable fires that have occurred was found to not be publicly available.

In the few cases where cable fire reports have been presented in industry forums, the cause of the fire, remedial measures and lessons learnt are not given in sufficient detail to inform others. A specific review of Penrose site risks carried out by Transpower in 2012 did not identify the cables in the trench as a concern.

The scale of the incident meant emergency response plans were activated, and these operated effectively.

Restoration of Supply to Customers

Transpower and Vector promptly mobilised all necessary resources, and accessed existing spares holdings to complete repairs without delay.

Customers were kept well informed during the outage through regular updates delivered directly across a wide range of channels.

Restoration of full supply to customers took place over three days as temporary cables were installed. As a result:

36,296 (48%) of customers were restored by 18:21 Sunday

54,113 (72%) of customers were restored by 08:00 Monday

73,552 (98%) of customers were restored by 08:00 Tuesday

75,339 (100%) of customers were restored by 14:08 Tuesday

Safety

There were no reported injuries to members of the public, Transpower and Vector staff, their contractors, or emergency services personnel during the incident and the extensive recovery works. Action by retailers was taken to identify and manage the needs of known medically dependant consumers affected by the outage.

Recommendations for Transpower and Vector

Recommendations are based on learnings from the joint investigation, including the independent cable expert's report. It is recommended that:

Transpower and Vector jointly:

1. Implement changes at Transpower's Penrose substation as part of the recovery works, including installing replacement cables in two trenches containing segregated ducts for each cable, to effectively eliminate the risk of fire causing multiple cable failures.
2. Transpower and Vector review locations where power cables are installed in open air environments to identify any asset risks and take appropriate actions to mitigate these risks.
3. Review contractual terms and management processes at points of connection to ensure key learnings from the incident are incorporated.

Vector:

1. Review and update its relevant policies, procedures and practices with respect to cables, and cable joints installed in air.
2. Review and update its risk management framework, and risk identification processes, to incorporate key learnings from the incident.
3. Update its standard operating procedures to apply key learnings from the incident.

Transpower:

1. Improve the process for considering customer requests for access and occupation of Transpower land along with the potential risks throughout the lifetime of the assets.
2. Incorporate learnings into asset management practice, design standards and risk management policies.
3. Update standard operating procedures to apply key learnings from the incident.

Implementation of Recommendations

Significant progress has been made on implementing the recommendations set out above.

At Penrose, a permanent solution for cables damaged in the fire has been designed and agreed between Vector and Transpower. The replacement cables will be installed in fire segregated ducts along two independent routes across the 220 kV switchyard. This work is being carried out in co-ordination with a project to install a new indoor 33kV switchroom and is scheduled to be completed by June 2016.

Transpower and Vector have each undertaken surveys of their sites to identify situations where failure of cables in air could lead to significant consequences. These surveys have not identified any issues of immediate concern. However, at several sites, interim risk mitigations for cable joints have been implemented as a precautionary measure.

Transpower has developed a process for a comprehensive review of Access and Occupation schedules, to update the records of customer assets on Transpower land, and to evaluate the risks associated with those assets. The documentation updates and risk reviews for the most critical sites are scheduled to be completed within 12-18 months.

Improvements to risk identification and review processes are underway within both organisations, together with enhancements to relevant asset management standards and operating practices.

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1 Introduction

At 02:17 on 5 October 2014, a member of the public rang Emergency Services to report hearing explosions coming from Transpower's Penrose substation. Penrose substation is a large unmanned substation located in the industrial suburb of Penrose, approximately 10 km south-east of the centre of Auckland. When the NZ Fire Service (NZFS) arrived at the substation, they witnessed thick smoke in the 220 kV switchyard. This was subsequently discovered to be due to a fire in a cable trench¹ containing Vector cables and a Transpower lighting cable.

Fire damage to the cables in the trench led to feeder trippings that interrupted supply to over 39,000 customers. Transpower then shut down the affected part of the substation to allow NZFS personnel safe access to fight the fire.

As a result, by 03:08 on Sunday 5 October, 75,339 Vector customers supplied from Penrose were without power. Electricity supply was restored to 54,113 (72%) customers within 24 hours and 72,744 customers (97%) within 48 hours. However, the extent of the damage caused by the fire meant that supply to the final customers was only restored in the afternoon of Tuesday 7 October.

Immediately after supply was restored to all customers, Transpower and Vector announced a joint investigation into the Penrose fire and outage, with the investigation to cover:

- The cause of the event on 5 October 2014;
- Extent and impact of the outage;
- Risk mitigations and whether these operated according to design; and
- Key learnings and recommendations for the future.

Transpower and Vector each appointed independent investigators, and jointly engaged Brian Gregory (of Cable Consulting International), a leading international cable expert, to assist with the investigation. Results of this investigation are presented in this report.

In addition, the Minister of Energy and Resources requested the Electricity Authority (EA) to carry out an inquiry. Transpower and Vector have co-operated fully with the EA's investigators. This report has been provided to the EA as an input into their investigation.

A number of reports have been prepared as part of the investigation. These cover areas relevant to the investigation, including customer engagement, asset and risk management, and a history of the development of the Penrose site and surrounding network. Appendix A provides a list of these reports.

¹ The fire occurred in the cable trench that runs east-west across the 220 kV switchyard, references to a cable trench are to this particular trench unless specifically noted otherwise

2 Customers

This section provides an overview of service to customers and the impact of the incident on customers.

A separate background report on Customer Engagement has been prepared and provides further background to this section of the report.

2.1 Service to Customers

Transpower and Vector are responsible for the physical delivery of electricity to customers as shown in **Figure 1**. Vector's electricity network is used to transport electricity to over 540,000 customers² in Auckland via over 18,000km of overhead lines and underground cables.

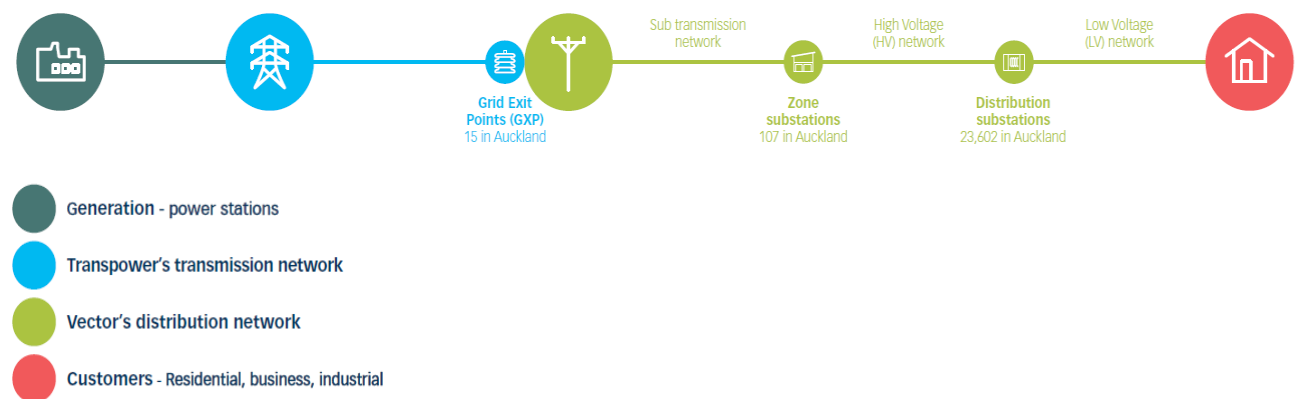


Figure 1 Electricity System

In recent times, the reliability of the service received by Vector's customers has ranged between 99.97 to 99.98%³. This is a near continuous supply of electricity to customer's homes and businesses.

Whilst customers receive a very high level of reliability; Vector does not, and cannot, provide a 100% continuous supply of electricity due to:

- Upstream failures in the electricity system;
- External influences on its network beyond Vector's control (extreme weather, third party damage to the network, i.e. car vs. pole); and
- The failure of equipment on the network

Vector's aim is to provide a high level of reliability at an affordable cost.

² The number refers to the number of ICPs connected to Vector's network. An ICP (Installation Control Point) is a customer connection to the Vector network. An ICP can be a residential property, a small business or a larger commercial or industrial site. Where the term customer is used in this paper it refers to an ICP.

³ These include Transpower and Vector outages and are a reflection of the high level of reliability of both networks.

The level of reliability experienced by Vector's urban customers is comparable to other major overseas cities, such as Sydney and London.

There are certain points in the electricity system, as in all infrastructure networks, where a failure can result in disruption of supply to large numbers of customers. Although such failures are infrequent, they can occur. Since the Penrose incident, significant failures have occurred in London and Washington DC.

On 1 April 2015, an electrical fire in an underground utilities tunnel in Holborn, London, resulted in affected customers being without electricity for up to three days. On 7 April 2015, an explosion and fire at a Maryland power substation resulted in widespread power outages in Washington DC affecting tens of thousands customers intermittently across the city.

2.2 Customers Supplied by Penrose Substation

Penrose substation is the largest of the ten connections between the national transmission grid and Vector's electricity network across the Auckland region.

Penrose substation has two separate switchyards (110 kV and 220 kV). Customers in the residential suburbs in the Eastern Bays, Remuera and Epsom, the commercial/retail suburb of Newmarket, and the industrial area through Penrose, Westfield and Mt Wellington are supplied from equipment in the 220 kV switchyard. Customers in the Auckland CBD and neighbouring suburbs are supplied from the 110 kV switchyard via cables installed in Vector's CBD tunnel⁴. There are multiple corridors for Vector's supply cables to exit the Penrose substation. A schematic of the Penrose substation is shown in Figure 2.

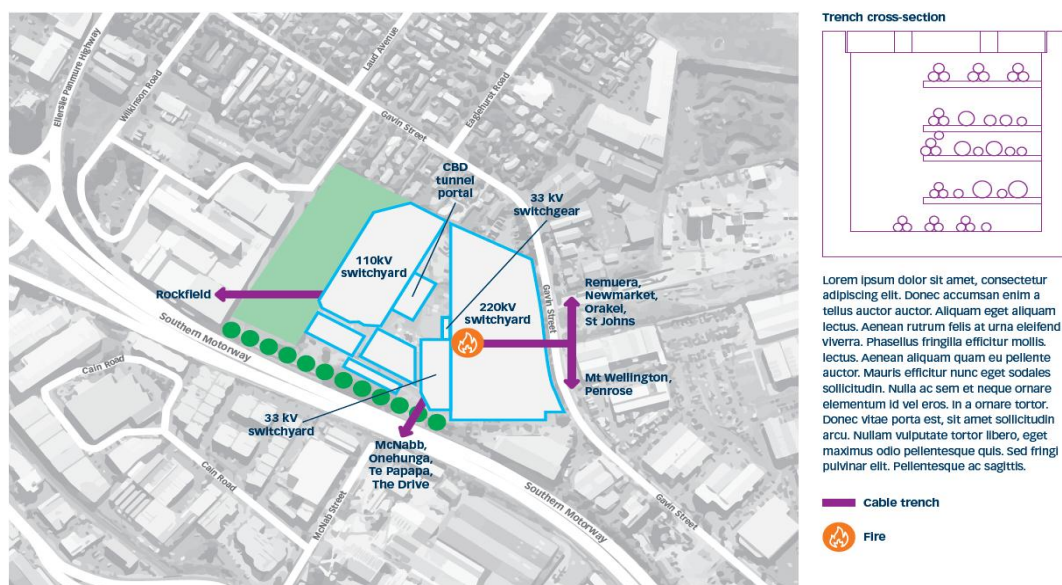


Figure 2 Penrose Substation

⁴ This is under normal network configuration. The CBD can also be supplied from other Transpower substations at Mt Roskill and Hobson Street.

2.3 Customer Impact

The fire damaged a number of cables, causing them to trip. Transpower then shut down the 220 kV switchyard to allow NZFS to safely enter the substation and extinguish the fire. As a result, 75,339⁵ customers were without power from 03:08 on Sunday, 5 October 2014. Supply to the approximately 36,000 customers in the CBD was not interrupted.

Supply was also interrupted to KiwiRail and Southpark - Transpower's direct-connect customers at Penrose. Figure 3 shows the general area of customers affected by the incident.



Figure 3 General area of customers affected by incident

The mix of customers affected is summarised below in **Table 1** both in terms of customer numbers and total size (load).

Customer Type	Number of Customers	Daily Load (MWh)
Residential	64,146 (85%)	1,200 (31%)
Small business	9,498 (13%)	529 (13%)
Industrial and large commercial	1,695 (2%)	2,214 (56%)

Table 1 Customers Affected by Penrose Fire

⁵ Some early media reports stated that up to 85,000 customers were without power.

3 Incident and Restoration

This section covers the incident (including events leading up to the incident), the operational response to the incident, and recovery efforts to restore supply to all customers. Recovery efforts include initial re-livening of the site and repairs to damaged cables. A summary timeline of the incident and response is shown in Figure 4.

This section also describes how the operational response was managed in terms of communication to affected customers, safety, and preventing further damage to equipment after the initial incident.

3.1 Incident

From 02:04 on 5 October 2014, the Transpower remote control system recorded a series of unusual alarms from equipment at Penrose substation. Many of the first alarms were associated with the 220/33 kV supply transformer T11. At 02:09, Transpower's National Grid Operations Centre (NGOC) called out a Transpower Maintainer to go to the substation to investigate the cause of the alarms. T11 subsequently tripped at 02:11 and the Vector Electricity Operations Centre (EOC) was advised.

A member of the public rang Emergency Services at 02:17 on 5 October 2014 to report hearing explosions coming from the Penrose substation.⁶ NZFS immediately dispatched appliances in response to the call, and notified NGOC. The fire appliances arrived between 02:26 and 02:28.

The Maintainer met the first response fire appliances at the substation entrance and opened the security gates at 02:41.

The Maintainer reported seeing thick smoke in the vicinity of the 220/33 kV supply transformer T11 when he arrived. This quickly developed into above ground flames, between the adjacent transformers T10 and T11, and the 33 kV indoor switchgear building located in the 220 kV switchyard.

Transpower's site access procedure requires emergency services personnel to be accompanied by an authorised person, because a live, high voltage switchyard is a hazardous environment. Fire fighting in a live switchyard is particularly hazardous.

⁶ The loud noise of four circuit breaker trippings between 02:11 and 02:16 was most likely the source of the "explosions" that the resident in Gavin Street heard which caused him to call emergency services.

Your text here

Figure 4 Time Line

Figure 5 gives an aerial view of the Penrose substation.

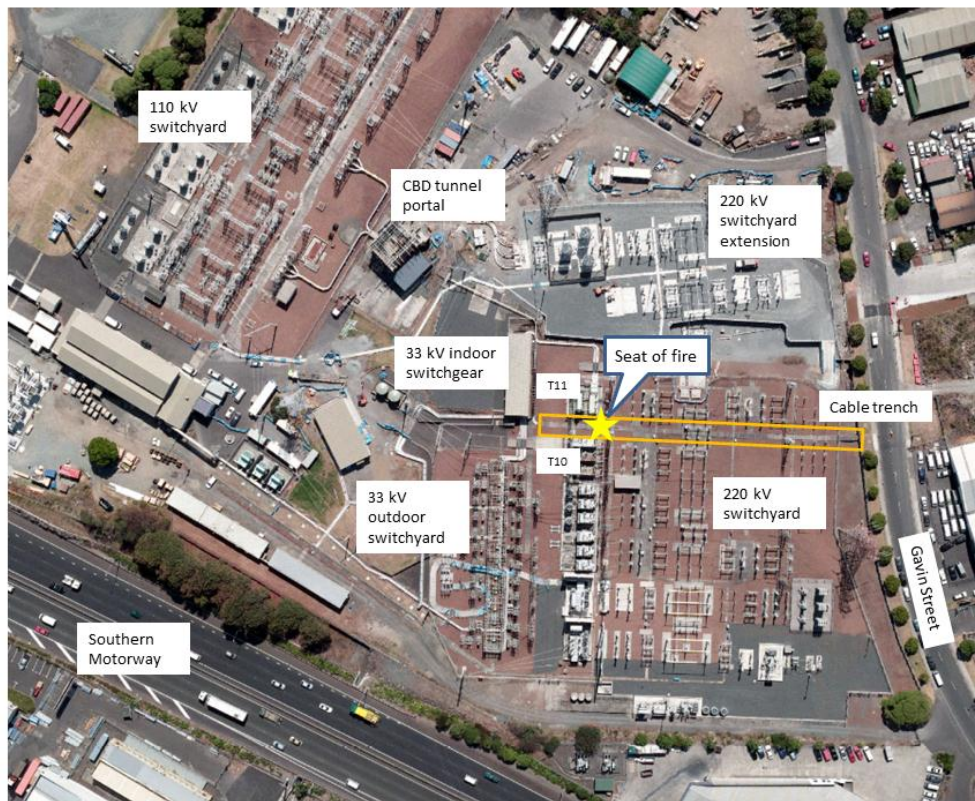


Figure 5 Penrose Site

At 02:50, the Vector EOC was informed by Transpower's NGOC that all 33 kV equipment in the 220 kV switchyard at Penrose substation was being de-energised to enable safe access for NZFS. This required a large number of individual operating actions to safely remove all 33 kV equipment from service.

NZFS was told that the area was safe to enter at 03:22, and firefighting commenced with the application of foam at 03:23. By this stage, flames in the trench had spread from the area between the transformers to near the 33 kV indoor switchgear building, and were threatening the building.

The fire adjacent to the switchgear building was quickly contained, preventing extensive and irreparable damage to the equipment inside. At this point, it became clearer that the Vector cables in the cable trench were on fire and had suffered damage.

The fire continued to spread eastwards along the cable trench towards Gavin Street. Arcing and corona discharging was also occurring in the 220 kV switchyard. Damage from flashovers could have impeded restoration of electricity supply once the fire was extinguished. To avoid equipment damage and to allow NZFS access, the entire 220 kV yard was de-energised.

No further customers were impacted by this decision because the 110 kV supply to the CBD from Penrose remained in service during the incident. Risk to the CBD during this event was mitigated by the availability of alternative Transpower and Vector supplies into this area.

At 04:37, fire fighters entered the 220 kV switchyard. The fire was contained by 06:45. NZFS transferred control of the site back to Transpower at 09:57, and remained on standby for any flare-ups.

A Sequence of Events of the incident is set out at Appendix B.

3.2 Events leading to the incident

At 23:21 on Saturday 4 October 2014, there was a feeder fault in a Vector 11 kV feeder (designated Remuera K10) supplied from the Remuera zone substation. The feeder supplied parts of Remuera and Ellerslie in the vicinity of Ladies Mile, Marua Road and Michaels Avenue and is comprised of sections of overhead line and underground cable. It included a section of cable installed in the cable trench at Penrose substation.

The investigation into the Penrose incident subsequently revealed that it was this feeder fault that caused the fire. Further details on the investigation are provided in Section 4.

At the time, the Remuera K10 event was considered by the Vector EOC controller to be a routine feeder fault. Accordingly, the EOC controller notified the faults dispatcher, who called out a faultman to carry out a line patrol and visual inspection to locate the fault. The feeder comprises sections of overhead line and underground cable, and has a history of faults caused by tree branches on the overhead lines.

The faultman started his route patrol from the Remuera substation, following the overhead line towards the end of the feeder as is standard practice. He was in regular contact with the controller during the patrol.

The line patrol suggested the fault was in the overhead section along Michaels Avenue between Marua Road and the Ellerslie Panmure Highway based on information from fault passage indicators. As no physical evidence of the fault had been identified during the line patrol, and given the history of vegetation related faults⁷ on the overhead line sections of the feeder, the controller concluded it was a transient fault. The controller therefore manually reclosed the feeder.⁸ The feeder was closed at 01:21 on Sunday morning and tripped immediately.

At that stage, a cable termination was considered to be the most likely cause of the fault. The residential load in Celtic Crescent was transferred to the McNab K06 feeder to restore supply to those customers, and the remainder of Remuera K10 feeder was sectionalised, so that the location of the fault could be isolated. While this was occurring, the supply to Remuera zone substation was lost, and resources were then diverted to Penrose.

A review of the actions undertaken to locate and isolate the Remuera K10 feeder fault has been completed as part of the investigation. The review concluded that these actions were carried out in accordance with Vector's standard procedures at the time and recommended specific amendments to the procedures in light of the incident.

3.3 Operational Response

This section describes the actions taken by Transpower and Vector in their respective control rooms. It also covers actions from NZFS in fighting and extinguishing the fire and handing control of the substation back to Transpower.

3.3.1 NGOC and EOC Actions

Transpower (NGOC) and Vector (EOC) control rooms both became aware of the incident independently of each other due to alarms from their respective supervisory control and data acquisition (SCADA) systems.

The first contact between them was a phone call from NGOC to EOC at 02:09. At this point, it was considered to be an issue with a Transpower transformer (T11) as a number of alarms had been received relating to its condition. A subsequent phone call from NGOC at 02:23 informed the EOC that a number of assets had tripped, and that the NZFS had received a report of an explosion at Penrose substation.

⁷ Such as vegetation or tree branches which had hit the lines and fallen to the ground.

⁸ In accordance with Vector standard operating procedure at the time.

Both control rooms escalated the incident in accordance with their normal processes. Senior managers travelled to their respective control rooms to oversee incident response, and Transpower and Vector personnel were dispatched to the substation.

At 02:50, Transpower informed Vector that the 33 kV equipment in the 220 kV switchyard would be de-energised to allow safe access for NZFS. This was completed at 03:17. At this point, all supply to the Vector network at 33 kV and 22 kV was disconnected.

During this period, there was uncertainty as to what was on fire and which assets were affected.

A Transpower Manager arrived at Penrose Substation at 03:34 to oversee management of the site, and based himself in the NZFS Command Vehicle. At approximately 03:40, he advised Vector that the fire was in a cable trench containing Vector cables. Once it was confirmed that Vector assets were damaged, a Vector Manager travelled to Penrose substation to liaise with Transpower on site.

While the NZFS was controlling the fire, Transpower and Vector mobilised resources in preparation for reliving and recovery works.

The resources for reliving were in place before NZFS handed control of the site back to Transpower. Vector's operations engineers reviewed plans for backfeeding supply into the affected areas in preparation for restoring supply to customers. Once the extent of damage was confirmed and recovery activities prioritised, these plans were actioned.

3.3.2 NZ Fire Service

NZFS was contacted at 02:17 by a member of the public with a report of explosions. Three fire appliances were initially dispatched from Ellerslie, Remuera and Mt Wellington stations. They arrived between 02:26 and 02:28, and gained access to the substation at 02:41 when the Transpower Maintainer arrived. They were not able to access the affected area of the 220 kV switchyard until power was isolated. The initial assessment was that a fire was occurring on top of the cable trench.

At 02:58 switching commenced to de-energise the live 33 kV equipment and at 03:02 NZFS commenced bringing in foam equipment. All cable failures that directly caused a loss of supply had occurred by 03:06 well before NZFS fire control activities commenced at 03:32.

All live equipment near the west end of the trench was de-energised by 03:17. At 03:22 NZFS was advised it was safe to enter the area adjacent to the 33 kV switchgear building. Foam was then applied to extinguish the fire in this area.

The fire continued to burn in the opposite direction along the trench to the east, in the 220 kV switchyard. The smoke was causing arcing and corona discharge in live 220 kV equipment. NZFS were unable to enter this area until it was de-energised. Following consideration of the impact on supply to the broader Auckland area, the entire 220 kV switchyard was de-energised at 04:37 to allow NZFS to continue fighting the fire along the trench.

Extinguishing the fire in the trench took some time, as difficulties were initially encountered removing the concrete trench covers. High expansion foam had to be used as the cables were on different levels. Two foam generators were required to prevent re-ignition as firefighters moved along the trench. The fire was finally contained at 06:45. At 08:00 NZFS flooded the trench with water to cool the area and prevent flare ups.

Additional fire appliances and other resources had been mobilised during the firefighting. At the peak there were;

- 6 Fire Appliances,
- 1 Command Unit,
- 1 Foam Tender,
- 1 Aerial Appliance, and
- 32 Fire Fighters

Due to the size and complexity of this incident, the NZFS dedicated substantial resources to safely extinguishing the fire.

At 09:57, control of the site was transferred back to Transpower. The NZFS remained on standby to manage any potential flare ups.

3.4 Relivening

Operational co-ordination between Transpower and Vector during relivening and repair works functioned effectively. As it was a Transpower site, once control of the site was handed back to Transpower from NZFS, established site procedures were used, such as site access and permitting for works. Within these existing procedures Transpower and Vector recognised the need to quickly restore customers and took a pragmatic stance without compromising safety or risking damage to assets on site. Co-ordination activities involved Transpower, Vector and their respective contractors and were dealt with during the initial restoration process via regular update and planning meetings on site.

Restoration priorities were established between Transpower and Vector once control of the site was transferred back to Transpower. The initial focus of restoration work concentrated on securing a supply into the Penrose 220 kV bus with sufficient capacity to supply the anticipated loads.

All equipment had to be inspected before it was re-livened, and restoration had to follow a gradual process, to ensure it was carried out safely and no further equipment failures occurred. As a further safety precaution, personnel were cleared from the switchyard before each major item of equipment was energised.

The first equipment inspections were completed at 10:41 allowing step-by-step restoration of the 220 kV supply to commence. The first of the 220/33 kV supply transformers (T7) was energised at 11:48.⁹ This was followed by progressive inspection and reliving of the remaining grid equipment in the 220 kV and 33 kV switchyard.

Communications during the restoration phase were affected by degradation of the cellphone service from around 11:00. Restoration was suspended for approximately one hour around 13:47 when the NZ Fire Service had to be called to deal with smouldering timber that had re-ignited. Some equipment that had already been livened had to be de-energised again, to ensure safe access for fire fighters.

In parallel with the Transpower restoration work, Vector was assessing the extent of damage to feeder cables and determining the feeders that could be safely restored.

Livening of the 33 kV bus commenced at 14:52. Vector then started restoring supply to distribution zone substations fed by cables that had not been damaged in the fire. By 18:21, Vector had relivened seven of its zone substations, restoring supply to over 36,000 customers in Epsom, Newmarket, Glen Innes, Penrose and Westfield.

Transpower continued restoring the Penrose 33 kV supply transformers to provide additional capacity and improve the security of supply. After smoke residue had been cleaned off equipment, the 220/33 kV transformer T8 was livened at 16:26.

The restoration process was expedited by Transpower operating equipment above normal ratings for short periods. This allowed Vector to restore supply to customers earlier, while Transpower continued inspecting 220 kV equipment.

Throughout Sunday night, Vector's control room carried out extensive reconfiguration of its network to backfeed supply into affected areas. This resulted in a further 18,786 customers being restored overnight on Sunday (nearly half of the customers supplied by the damaged cables in the trench).

Additional Transpower staff were brought to Auckland from other areas to enable 24 hour coverage during the recovery phase. Specialist engineering resources were also deployed to the site to assist with the damage assessment and restoration.

Full restoration of the 220 kV switchyard was the next priority, to provide extra supply security for the CBD from Transpower's Pakuranga substation via Penrose, into the Hobson Street substation. Full supply security to the Penrose Substation was restored at 21.22 on Wednesday 8 October.

⁹ This was a critical milestone, because it restored local service power supply to the substation. The essential controls, protection and monitoring equipment of the entire substation had been operating on battery backup for 8 hours until this point.

3.5 Cable Repairs

The repair works to restore supply to the remaining 20,257 customers were large and complex, and carried out with urgency. All fourteen sub-transmission circuits in the cable trench were damaged beyond repair and needed replacing. The recovery initially focused on repairing five cables, each supplying a different zone substation, to restore supply to customers. The remaining eight cables were then repaired to restore full security.

The recovery effort was affected by significant construction works in progress at the substation prior to the incident, and the additional hazards associated with working on a construction site. There was also a need to co-ordinate site activities and access with Transpower personnel carrying out cleaning of smoke damaged equipment immediately after the fire.

While NZFS was fighting the fire, Vector organised the personnel and resources necessary to carry out the repairs, in anticipation of gaining access to the site. As the cable trench was damaged and could not be used by Vector, alternate temporary routes through the substation had to be agreed for the new cables. These were agreed between Transpower and Vector by Sunday evening. The first access permit was issued by Transpower at 21:00.

Each repair required a damaged section of cable to be cut out and a replacement section of new cable joined. Vector was able to access all necessary materials (cables, joint and accessories) from its strategic spares holdings and from suppliers, to enable repairs to commence as planned.

Crews worked continuously to complete repairs. Working conditions over the initial 24 hours of the repair operation were challenging, with periods of severe rain, high wind and hail during Monday night.

Repairs to the first two cables were completed by early morning on 7 October, and a third cable by 13:35 that day enabling supply to be restored to all customers shortly thereafter. Repairs to all remaining cables were completed by 15 October. The repair effort was a 24-hour operation for the first week before reverting to a daily operation to manage fatigue impact.

Over fifty people were dedicated to working on the recovery effort and over 4,000 man hours were worked without any safety incidents. In total over:

- 8 km of temporary cables was installed;
- 60 joints were made;
- 1,000 cable supports were used;
- 2,000 cable clamps were installed; and
- 5,000 sand bags were used on the site.

3.6 Customer Restoration

Vector's focus was on safely restoring all customers, as quickly as possible.

Restoration of all customers was achieved by relivening customers supplied by undamaged cables, backfeeding to supply customers from adjacent substations, and repairs to damaged cables.

36,296 (48%) of customers restored by 18:21 Sunday

54,113 (72%) of customers restored by 08:00 Monday

73,552 (98%) of customers restored by 08:00 Tuesday

All customers were restored by 14:08 on Tuesday 7 October

Vector's network design enabled extensive use of backfeeding to restore supply to affected customers from adjacent areas that were unaffected. This was carried out in stages starting on the Sunday morning. Over 23,000 customers (nearly one third of those affected) were restored this way, meaning power was restored to them earlier than waiting for repairs to be completed.

Restoration milestones are set out in **Table 2**.

Date/Time	Description	Customers Restored (cumulative)
Sun 5 Oct 09:57	NZFS return control of site to Transpower	
12:50	Some customers in Onehunga, Newmarket and Mt Wellington restored via backfeeding	4,451 (6%)
14:52	Inspections and safety checks completed. 33 kV bus relivened.	
18:21	Restoration of all substations with undamaged cables	36,296 (48%)
Mon 6 Oct 09:06	Backfeeding to restore supply to customers in St Heliers, Onehunga, Mt Wellington and Remuera	55,082 (73%)
Tue 7 Oct 07:41	Restoration of St Johns, Orakei, St Heliers, and Sylvia Park substations using repaired (new) cables	73,292 (97%)
14.08	Restoration of supply to all customers ¹⁰	75,339 (100%)

Table 2 Customer Restoration Milestones

¹⁰ A few customers were on their own generation at this point and required short arranged outages to reconnect to Vector's network.

3.7 Customer Communications

There was extensive communication during the outage to a wide range of stakeholders, including affected customers, Emergency Services, council and government.

The first customer communication was an update on Transpower's Facebook page at 03:20 on Sunday 5 October. The first media statement was issued at 03:50. In total, eighteen customer updates were provided by Transpower and Vector during the incident, ensuring a steady stream of information was available to customers. Transpower and Vector's communication protocols and plans worked effectively.

Customer updates were delivered via a broad range of communication channels, including Vector's recently developed Smartphone outage application, which enabled rapid and wide dissemination of the latest information.

Vector also provided additional information to retailers to assist them in managing medically dependent customers. Further details on customer communications are provided in the background report on Customer Engagement.

3.8 Safety

Safety is always the highest priority during incidents, but never more so than when fire is involved and Emergency Services are required to enter electrical substations. Every effort was made to restore supply to customers as quickly as possible without compromising safety.

The fire was contained without threat to nearby businesses and homes. There were no reported injuries or safety incidents affecting members of the public, Transpower and Vector staff, their contractors, or members of Emergency Services during the incident and the extensive recovery works. The site access procedures and operating protocols worked effectively.

During the first week after the fire, short sections of the cable trench were uncovered where the NZFS had gained access to fight the fire. This introduced a potential exposure to personnel from contaminants. The recovery works were carried out well away from this area. The exposure risk was identified early during the site inspection and additional precautions were then taken for personnel working near the cable trench. Personnel that entered the trench wore full cover disposable overalls and P3 respirators. The trench was covered and sealed as the inspection progressed.

Tonkin and Taylor carried out a site inspection and sampling of potential ground contamination, and the results confirmed the additional precautions were appropriate. Paragon Health and Safety also confirmed there were low to very low risks from exposure to contaminants. Results of health testing of workers at the site showed no issues of concern.

Public safety was managed through various mechanisms. When power was first lost, Transpower's NGOC contacted NZ Police at 02:30 to advise them of the incident. Emergency Services were also provided with regular updates of the situation in accordance with standard operating procedures. NZ Police managed traffic at the site and throughout the affected area, as traffic lights were out of service. The NZFS checked local residents were not affected by the fire and smoke.

Communications to the broader public were provided using a range of mechanisms as described in the Customer Communications section 3.7.

3.9 Damage to Equipment

The fire irreparably damaged all the cables in the cable trench, some Vector cables in racks adjacent to the end of the trench, and Transpower control cables that passed across the trench in several places. There was also smoke residue on 220 kV insulators, and scorching to the external cladding of the 33 kV switchgear building.

Protection schemes ensure that electrical equipment is isolated to minimise damage during electrical faults. The protection schemes at Penrose performed as designed with two exceptions¹¹.

There is a risk when re-livening equipment that undetected damage may lead to faults that cause more significant damage. For some critical assets, the repair times can be months and therefore extensive checks are made to ensure equipment is undamaged before re-livening. As a result of the careful approach taken in restoring supply, there was no additional equipment damage at Penrose substation other than that sustained during the fire.

When reconfiguring the network to restore supply by backfeeding, there was the potential to overload assets and cause damage. The morning and evening peaks caused short-term overloading in the Glen Innes area, which was managed through rolling outages. There were two localised cable faults in this area.

¹¹ For two of the faults caused by the fire, the main protection did not operate because the fire had damaged communication cables. These faults were cleared by the backup protection, which did not operate exactly as expected. While this did not contribute to the extent of the outage, the operation of the backup protection will be reviewed as part of the current project to replace the outdoor 33 kV switchyard.

4 Investigation

4.1 Methodology and Process

Transpower and Vector commissioned a joint investigation into the incident, appointing independent investigators to determine the cause and identify key learnings for the future.

The joint investigation has focused on the cause of the incident and to assist in this process, Brian Gregory (Cable Consulting International), a cable expert from the United Kingdom, was engaged.

The methodology adopted by the investigation team is described in the flow chart in Figure 6. The investigation is intended to identify what happened and, to the extent possible given the damage, why it happened. The historical development of the site, and Transpower and Vector asset management practices provide context. The operational response from Vector, Transpower and NZFS determined customer restoration timeframes. From all these elements lessons can be learned for the future.

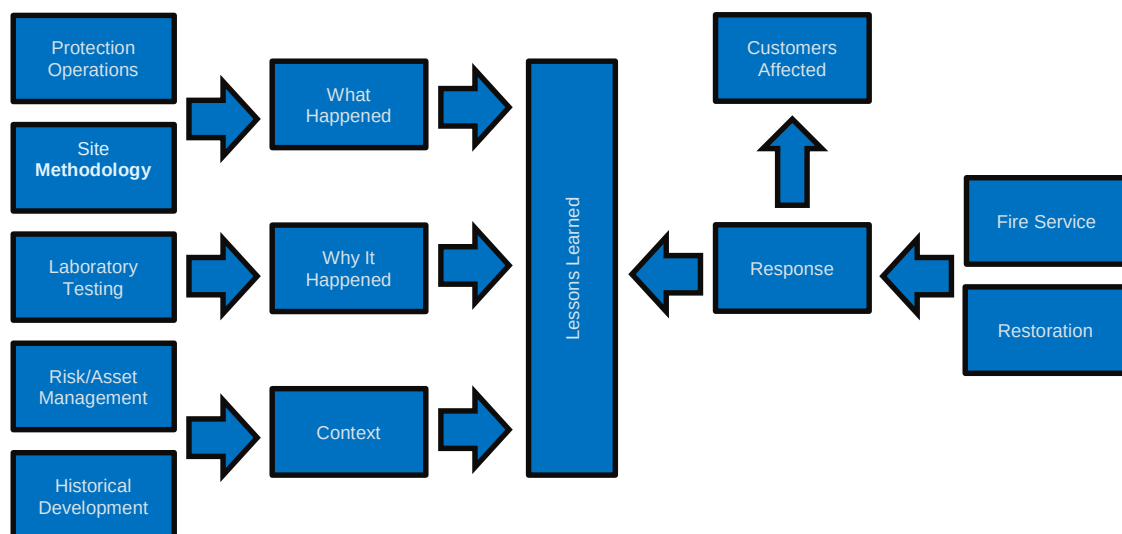


Figure 6 Investigation Methodology

The investigation commenced with an inspection of the damaged cables led by Brian Gregory. The NZFS investigator also participated in the inspection, to give the investigation team the benefit of his extensive experience in determining the seat of a fire.

A summary of the report from the NZFS is included in Section 4.2, with a full copy available on the NZFS website, www.fire.org.nz.

A key input to the investigation has been an analysis of the equipment electrical protection operations that occurred as the fire damaged the energised cables in the cable trench, causing electrical faults. This information has assisted the investigation team to understand the sequence of events and how the fire has developed. The protection analysis is summarised in section 4.3.

The inspection of the cables in the cable trench was carried out in a careful and methodical manner, to ensure all relevant information was identified. Sections of the damaged cables were recovered, with some inspected at the substation. The recovered cable samples were then sent to the EDIF ERA Laboratory in Leatherhead, United Kingdom for detailed analysis and inspection. Brian Gregory oversaw this examination, and based on the test results, his own analysis, and inspection, prepared his report which is summarised in section 4.4.

4.2 NZFS Report

The executive summary from the New Zealand Fire Service report 'Fire Investigation Report – 19 Gavin St, Ellerslie, Auckland' is reproduced below. A full copy is available on the NZFS website, www.fire.org.nz. The report determines the cause of the fire to be accidental. There are no recommendations made within the report.

A fire involving high voltage power cables in a concrete lined trench located at Transpower's Penrose substation had occurred. This caused a major power outage to some areas of Auckland which were supplied with power from the substation. Fire spread also damaged some high voltage cables outside the trench and a small area outside of the switchgear building.

NZFS received a 111 call from a neighbour of the substation at 2:18 a.m. on 5 October 2014.

Fire crews arrived to discover a fire in a section of a cable trench within the switch yard area, however due to the power not being isolated at that stage, firefighting was unable to commence.

The first fire appliance arrived at 2:26 a.m. but it was not until 3:23 a.m. when an initial fire attack occurred in the area of the switchgear building, preventing serious fire damage to the switchgear building.

Following the initial fire attack which extinguished the fire threatening the switchgear building, which was within the switchyard area, fire crews were forced to withdraw. This was due to a concern that power had not been isolated from all areas around the fire. Re-entry to the switchyard area did not occur until 4:37 a.m. when confirmation was received of the power being isolated.

The delay in being able to recommence firefighting did allow fire spread from where the fire originated to along the length of the trench.

While some fire damage occurred to areas outside the cable trench, most fire damage was contained to the cable trench.

An investigation team, including a NZ Fire Service Specialist Fire Investigator, a UK cable expert, Vector and Transpower Engineers as well as private Fire Investigators appointed by insurers was set up. A team approach is internationally recognised as best practice when investigating major fires.

As part of the investigation, fire damaged cables from the area and point of origin, were removed for the cable expert to carry out a closer inspection. Samples of cables not affected by the fire were also removed for inspection.

A number of the cables removed were also taken to the UK for a more in depth investigation by the cable expert.

The Teams origin and cause investigation confirmed the fire originated in the cable trench near the T11 transformer. A transition joint in the Remuera 11 kV feeder cable in this area failed causing an initial release of a large amount of heat, which caused the outer covering of the feeder cable to gradually heat up and ignite. Due to the large number of power cables surrounding this transition joint, once the outer covering had ignited, the fire then gradually spread to the other cables. The concrete lids covering the trench allowed the heat from fire to build up heat within the trench and assisted the fire spread along the trench.

The cause has been classified as accidental due to a failure within a transition joint of the Remuera 11 kV feeder cable

A report from the UK cable expert will be produced covering the cause of the failure.

4.3 Protection Analysis

Protection schemes ensure that electrical equipment is isolated to minimise damage during electrical faults. They monitor current and voltage levels and disconnect equipment if the levels exceed pre-set limits.

Modern protection schemes use microprocessor based electronic devices that provide multifunction capability, with integrated primary and backup protection, fault data recording and remote access for information retrieval. The data obtained from these devices greatly assisted the investigation to identify the sequence of events described in Appendix B.

The faults in the 11 kV cable that started the fire were correctly detected by protection, and circuit breakers opened to clear the faults in the expected time.

As the fire developed, more of the cables in the cable trench were damaged. The cable damage caused electrical faults in the cables, which were detected by the protection schemes. Therefore, the sequence of protection operations informed the order that the cables were damaged and accordingly how the fire developed. This is discussed in more detail in the cable expert report.

4.4 Cable Expert Report

The executive summary from the Cable Consulting International report 'Investigation into a Fire in a Cable Trench at Penrose Substation' is reproduced below. This report was commissioned by the joint investigation team to provide an independent assessment of the cause of the incident.

A number of recommendations are made and these have been incorporated into the overall recommendations from the investigation (Section 9).

Transpower and Vector agree with CCI's findings and intend to work with CCI to implement the recommendations made in the report.

On 5th October 2014 a fire was reported at the Penrose Substation. The fire damaged a large number of Vector cables that were installed in a cable trench in the 220 kV switchyard. The damage to the cables resulted in the loss of supply to Auckland's eastern suburbs.

The Author was engaged by Transpower and Vector to investigate the cause of the fire. This report presents the findings of the investigation, and the Author's recommendations for the future installation of cables in similar environments.

The Author has carried out a comprehensive investigation into the cause of the electrical failure and the resulting fire, at both the Penrose substation and the Edif ERA Laboratory in Leatherhead, Surrey. Further analysis and interpretation of results has been performed at the CCI offices in Underriver, Kent. The Author has been afforded full access to the cables and the cable trench, and all background information, as well as the required testing and analysis facilities, to enable this investigation to be undertaken.

The investigation has covered:

- Cause of the fire
 - Examination of the cables in the cable trench
 - Examination of samples of cables retrieved from the cable trench, both at Penrose substation and at Edif ERA
- Cause of the transition joint failure
 - Detailed examination of the 11 kV PILC to XLPE transition joints
 - Analysis of the electrical stress distribution in the 11 kV PILC to XLPE transition joint
- Assessment of the condition of cables and joints in the cable trench
 - Assessment of the condition of all cables in the cable trench, based on samples of cables retrieved from the Gavin Street end of the cable trench which was least affected by the fire
 - Analysis of the current rating of the cables in the cable trench
- Assessment of the fire development
 - Analysis of the locations of the electrical faults on cables that occurred as a result of the fire
 - Analysis of the energy in the electrical arcs
- Analysis of the fire performance of the cable types installed in the cable trench
- Review of published information related to cable fires and fire performance of cable types

The Author's main conclusions are:

1. The fire was initiated by a power arc in an 11 kV PILC to XLPE transition joint in the Remuera K10 circuit. The energy from the first power arc had the capability to violently burst open the polymeric heat shrink sleeves

and copper knit mesh cloth and so admit air into the joint. The arc produced a high temperature that was capable of igniting the flammable joint materials in the presence of air, these being the polymeric sleeves, the PILC cable core insulation (hydrocarbon compound impregnated paper insulation) and the XLPE cable insulation.

2. The fire was accelerated by a second power arc when voltage was reclosed onto the failed joint, and by the subsequent failures of the 33 kV XLPE cables that have wire screens and flammable polyethylene over sheaths. The OF cables did not contribute until the end when aluminium sheaths ruptured and significantly increased fire severity. Each cable type was flammable and a severe fire was inevitable.
3. The cause of the transition joint failure is the vulnerability of the transition joint design, with respect to the electrically stressed insulation in the crutch between the PILC cable cores. This is the position where the power arc occurred. It should be noted that none of the insulation of the failed joint survived the fire and this conclusion is based on the examination of the unfailed transition joint.
4. The older, belted, unscreened, three-core PILC cable type is inherently incompatible in design and material types with the newer screened XLPE single core cable and its materials. In a joint, the transition between the unscreened and screened cable systems occurs in the crutch of the PILC paper insulated cores and this is the key reason for the generic vulnerability of a transition joint.
5. The contributory causes of transition joint failure are:
 - a. Thermo-mechanical disturbance. The joint was positioned on a curved cable and was not cleated or supported.
 - b. Water entry into the paper insulation at the crutch of the PILC cores. The water seals were short in length and on surfaces that allowed variable adhesion.
 - c. PILC impregnating compound drying-out of the paper core within the joint.
 - d. Migration of the void filling compound to the paper insulating tapes underneath the lead sheath.
 - e. Damage to the paper tapes due to the difficulty of effectively inserting high permittivity void filling compound.
6. The original 11 kV PILC joints would not have caused a fire on failure. The conventional PILC joint designs have low electrical design stresses and are mechanically robust. A synergy was seen to exist between the PILC cable and the conventional cast-iron joints. During the filling of the joint the hot bituminous insulating compound had mixed with the oil-rosin cable impregnant. It had penetrated long distances along the cable core interstices and paper tape butt gaps, thereby filling and insulating any air voids that are normally formed during jointing.
7. The progression and location of each cable failure had not been influenced by fire-fighting. All of the cable failure incidents had occurred by 3:04:29, which was before the Fire Service was admitted to the Penrose Switchyard and commenced applying foam at approximately 3:23 am.
8. The fire performance of the three cables types is described below.

- a. The polyethylene sheathed, wire screened, 33 kV XLPE cables exhibited the poorest cable fire performance. The polyethylene and XLPE insulation have a high heat release during combustion and thus spread combustion more readily. The cables dripped burning globules and strings of molten polyethylene to spread fire to cables below. The wire screen cable design does not have a metallic sheath or armour, and therefore the cable has limited protection to an external fire.
 - b. The oil cables had remarkably good fire performance with only one cable suffering an electrical fault. The corrugated aluminium sheaths were seen to have withstood the fire with less damage than other cable types. Their good fire survivability time is attributed to the high thermal capacity and high melting points of the extruded aluminium sheaths.
 - c. The 11 kV PILC cables had the best fire performance. The good fire survivability is attributed to the two robust layers of steel tape armour (high thermal capacity and high melting point), the good high temperature performance of the paper insulation and its low insulation design stress. The downside of PILC fire performance is that the lead sheath melts at low temperature and flammable impregnating compound then drips out, prospectively spreading fire to the cables below.
9. The OF and PILC cables did not contribute to the early development of the fire and the spread to the XLPE cables.
 10. A detailed examination of the XLPE, OF and PILC cables has shown them to all be in good condition. Based on the results of the tests the residual life of the XLPE, OF and PILC cables are predicted by Edif ERA to be 20, 15 and 10 years respectively. Edif ERA noted that some XLPE cables had experienced temperatures above their maximum design operating temperature.
 11. The operating temperatures of all the cable circuits and all the types of cables within the cable trench in both the Summer and Winter seasons has been satisfactory, being below their maximum design operating temperatures for continuous operation with sufficient margin to allow for variations in the trench geometry.
 12. The temperature calculations show that the reason samples of XLPE cable insulation had experienced temperatures above their maximum design operating temperature was not due to overheating in normal service operation. It is concluded that the cause was heating by hot air from the fire.
 13. At the time of the fire, too many cables had been installed in the trench. This did not contribute to the cause of the joint failure, but did contribute to the rate of fire spread. Fire tests have shown that there is a critical mass and critical spacing dimensions at which cable fires accelerate.
 14. From a review of publications, while in-air cable installations have been reliable, there has been an appreciable, low incidence of major cable fires. A few of the major cable fire reports and cable system failure reports were found in the public domain. In general i) the cause of a fire, the remedial measures and the lessons learnt are not given in sufficient detail and ii) it is only possible to find information if the incident has received wide publicity.

The Author recommends that:

1. Risk assessments be performed on in-air installations to identify the possibility of electrical failure of the cable lengths and joints.
2. The location of other transition joints installed in air on the network be reviewed.
3. For in-air applications, a technical specification is prepared for transition and straight joints, which includes demonstrated low fire propagation and power arc containment test performances.
4. For new XLPE insulated cable circuits, in significant in-air applications:
 - a. Cables be specified with a Low Smoke Zero Halogen sheath.
 - b. Joints of any type be excluded from the in-air installation.
 - c. Wire screened XLPE cable circuits be installed with a minimum separation to other cables to be advised by fire test houses and cable manufacturers.
 - d. Data and communication cables be installed in a separate fire segregated route.
5. If transition joints installed in air are unavoidable, they be installed within an arc resistant housing.
6. For each significant in-air application:
 - a. The rating capacity be calculated and retained on file and be updated as part of the approval process for any new circuit.
 - b. The in-service temperature be monitored at regular intervals, and correlated to the calculated cable ratings.
7. Voltage not be reclosed onto a failed circuit containing cables installed in air without taking precautions to manage the risk of fire ignition and propagation.
8. The joint design and jointing process be made more consistent with respect to a) the water seals and b) the void filling mastic.
9. Alternative designs of transition joints be assessed.
10. Cable support designs be reviewed for all in-air cable installations.
11. Joint failure statistics be compiled and regularly reviewed.

5 History of Development at Penrose

Penrose substation was established in the 1920s in what was then a rural area on the southern fringe of Auckland. The city has since grown to envelop the site. Penrose is a major supply point for the growing Auckland region. It supplies the largest load of any Transpower urban supply point.

Penrose has been expanded many times since its establishment. The development of the site can be broken into three periods:

- Early history (pre 1966);
- 220 kV Development (1966-1976); and
- Developments since 1976.

A separate background report on the History of Penrose has been prepared and provides further background to this section of the report.

5.1 Early History (pre 1966)

Penrose substation was established in 1925 by the Public Works Department. It was initially connected by a 50 kV transmission line from the south with Auckland Electric Power Board (AEPB, the predecessor to Mercury Energy and Vector) taking supply at 6.6 kV and then at 22 kV.

Penrose was one of a number of substations established to supply power to Auckland. These substations were established on the outskirts of the city at the time. Figure 7 is an aerial photo of the Penrose substation in 1949 showing the substation in open land, with both the southern motorway and Gavin St yet to be constructed. The current site is shown in Figure 5.

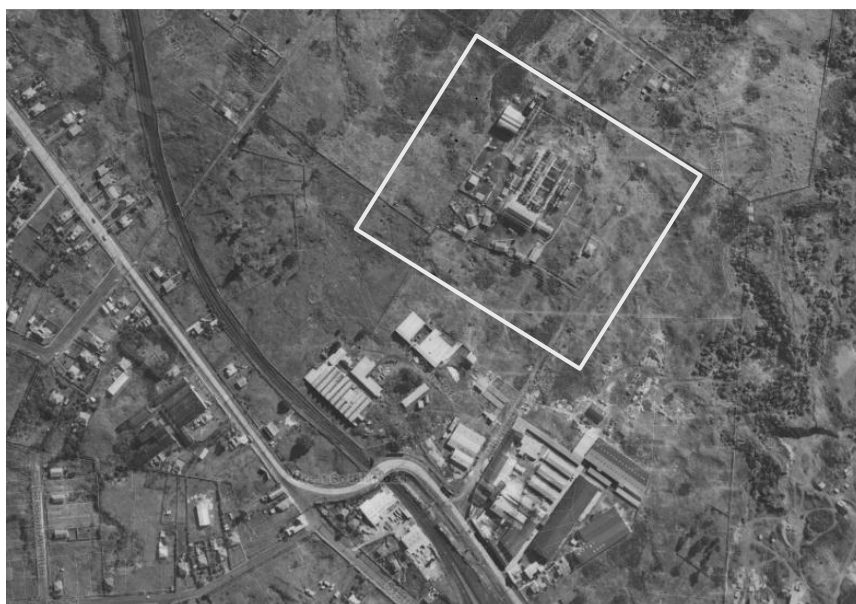


Figure 7 Penrose in 1949

Over the period 1930 to 1963, additional transmission lines were built to increase supply into Penrose, and a number of feeders were connected by the AEPB to supply new substations. The timing of these is shown in Figure 8. In 1953, the southern motorway was constructed running past the western boundary of the site, limiting future access and egress routes to/from the site. Around this period, commercial and residential developments had taken place on the northern and eastern boundaries of the site effectively confining the substation footprint.

5.2 220 kV Development (1966 - 1976)

To meet Auckland's continuing growth, Penrose was upgraded to 220 kV in 1966 with the construction of a new double circuit transmission line from Otahuhu Substation. The redevelopment of the substation to establish the new 220 kV and 33 kV switchyards required a significant increase in the footprint of the substation, which was expanded eastwards towards Gavin Street.

The substation expansion necessitated the acquisition of a small strip of land owned by the AEPB adjacent to the original 110 kV substation. This land was used by the AEPB as a corridor for the Mt Wellington subtransmission cables and an overhead line (believed to be an 11 kV feeder linking the Remuera and McNab zone substations). The arrangement for the acquisition of this corridor led to the construction of the cable trench. Further details of the cable trench are provided in Section 5.4.

The timing of developments at the substation related to the 220 kV upgrade, as well as the further development of AEPB substations from Penrose, is outlined in the timeline shown in Figure 8. The 220 kV upgrade provided a large increase in capacity which served to meet Auckland's growth for the next two decades.

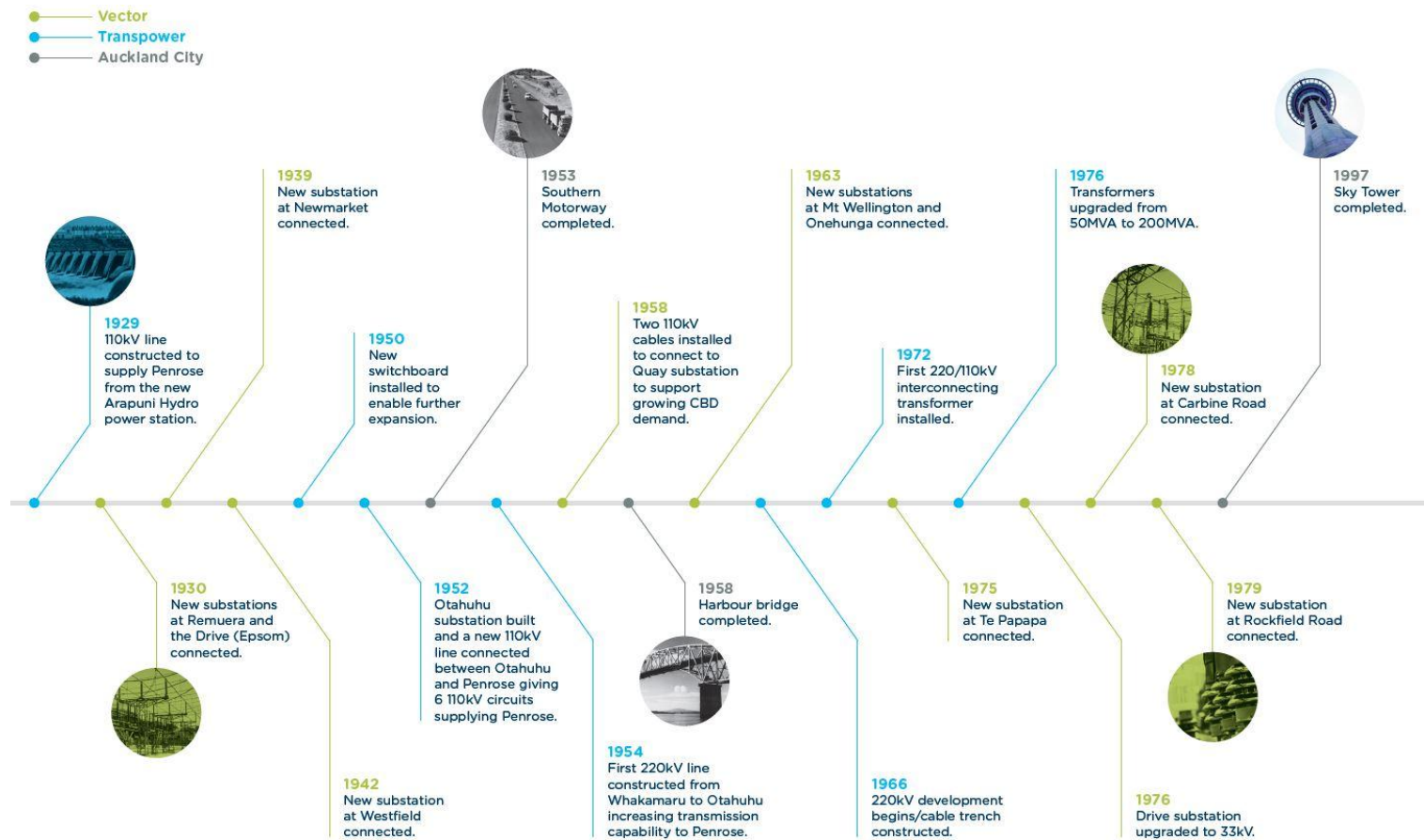


Figure 8 Timeline of Development of the Penrose Substation

5.3 Developments Since 1976

The 22 kV and 33 kV supply arrangements were adequate until the early 1990s when it became apparent that further development of the 33 kV supply from Penrose would soon be necessary.

In 1996, Mercury Energy (Mercury), the successor of AEPB formally requested an increase in capacity from 200 MVA to 400 MVA. In response, Transpower presented three options. From the available options, Mercury chose to install a new 200 MVA transformer and a 33 kV indoor switchroom. Following the construction of the new switchroom, some of the existing 33 kV feeder cables were transferred from the outdoor switchyard to the new indoor switchboard. These feeders were oil cables – a type of cable construction that was no longer available. Accordingly oil stop joints were constructed in Gavin Street and the cables were joined to sections of new XLPE insulated cables run in the cable trench in place of the original cables to terminate onto the new switchboard.

Shortly afterwards, Vector upgraded the substations at Newmarket and Remuera to 33 kV. This included the installation of new cables from Penrose substation, which were installed in the cable trench to exit the site via Gavin Street.

The supply to Mt Wellington substation was upgraded in 2001 and McNab substation in 2008. A new substation was established at Sylvia Park as part of the commercial development in 2006.

Between 2001 and 2014, significant network reinforcement work was completed by Transpower and Vector in the Auckland region. Details are provided in section 7.4.2. Many of these projects required work at the Penrose substation but did not result in any changes to cables in the cable trench, other than the relocation of an 11 kV cable. These transmission projects have significantly improved security of supply to the Auckland region and meant the CBD was not impacted at all by the incident.

5.4 Cable Trench

The concrete trench was constructed around 1966 as part of the development of the 220 kV and 33 kV switchyards. Limited details on its design and construction have been located, other than a 1966 internal NZED memo. This indicates the trench was built to relocate AEPB cables to enable ownership of the AEPB land adjacent to the trench to be transferred to NZED. The proposal was for NZED to fund 50% of the trench cost.

The memo also states an intention that all future AEPB cables and services are to be installed in the trench¹². No evidence as to any final agreement was located.

¹² All cables to supply Vector zone substations in the eastern suburbs have been installed in the trench. Cables supplying zone substations to the north and west of Penrose use other routes to exit the substation.

Penrose is sited upon basalt rock¹³ which makes direct burying cables significantly more difficult than in soil. The concrete cable trench was constructed to provide a practical means of conveying a significant number of distribution feeder cables across the switchyard from the station boundary.

The trench is an open concrete walled structure approximately 1.4m deep, 1.2m wide, and 100m long, covered with heavy concrete lids. The construction of the trench would have required extensive civil work due to the hard rock. The difficult construction conditions encouraged the use of a single trench and influenced its size and design. The trench contains racks on four levels, and was clearly designed to accommodate additional cables to those originally installed.

The concrete trench is owned by Transpower. With the exception of a Transpower lighting cable and some earthing conductors, all other cables, and associated fittings and racks in the trench are owned by Vector.

Upon its completion, a number of existing AEPB cables were relocated to the trench, as well as new cables for substation upgrades and new substations. These included three 11 kV cables used to connect McNab substation with AEPB substations at Remuera and Mt Wellington. These feeders enabled load transfer between zone substations.

By the end of 1967, AEPB had five 33 kV, two 22 kV and three 11 kV cables, plus three pilot cables, in the cable trench, as shown in Figure 9.

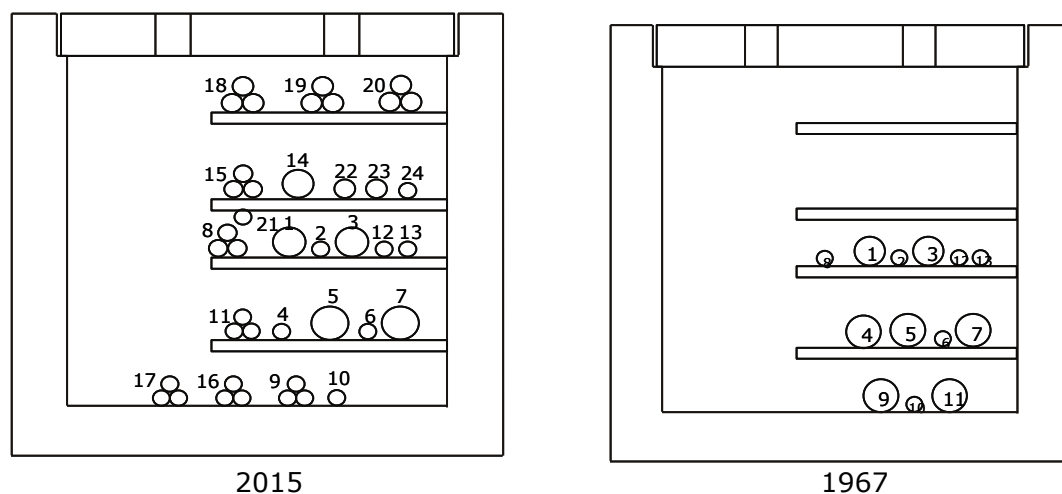


Figure 9 Trench Cross Section

¹³ Basalt rock is very hard and difficult to excavate. Excavation methods include the use of rock breakers (heavy machinery) and explosives.

The ground conditions and other site related factors, contributed to the ongoing use of the trench as an egress point from the site. Since its construction, all cables to supply Vector zone substations in the eastern suburbs have been installed in the trench. At the time of the fire, there were twelve 33 kV circuits, two 22 kV circuits and six 11 kV circuits, as well as a Transpower switchyard lighting cable and earthing conductors, and Vector fibre optic cables in the trench. Details of all cables installed in the trench are in Appendix C.

5.5 Works in Progress at the Time of the Incident

Development work is ongoing at the Penrose substation. At the time of the incident, work was in progress at Penrose by Transpower to install a 220 kV cable to create a 220 kV ring bus to further increase security of supply. By July/August 2014, a new concrete trench had been constructed passing beneath the cable trench where the fire occurred.

During the 220 kV switchyard expansion works, vibration monitoring was installed for a short period during rock-breaking work to indicate if there was a potential for damage to adjacent switchyard equipment. Vibration monitoring was carried out from 28 May to 7 June 2014 during rock breaking for the new retaining wall (near where the new 220 kV ring bus cables would penetrate the wall, opposite T11). No significant vibrations were detected.

During the construction of the 220 kV ring bus cable project, temporary props were provided beneath the cable trench carrying the Vector distribution cables. On site investigations after the fire also confirmed that there had been no settlement of the concrete trench due to excavations underneath it.

As part of a nationwide equipment renewal programme, Transpower has planned to replace the Penrose outdoor 33 kV switchyard with an indoor switchboard, in conjunction with Vector. Detailed design and primary equipment procurement has been completed. Construction of a new 33 kV switchgear building was scheduled to commence during summer 2014-15.

6 Access and Occupation Arrangements

Transpower's customers, including Vector, need to connect to the National Grid at Transpower's substations. To do so, some customer assets need to be located at Transpower substations, including the cables necessary to get to the physical point of connection with Transpower assets.

This section covers the arrangements in place for Vector's assets located at Penrose substation.

6.1 Pre 2000

When Transpower came into existence in 1987, there were at least a dozen cables already in the Cable Trench¹⁴ which had been put there by Vector's predecessor (AEPB), including the cable that faulted.

The AEPB was created under the Auckland Electric-power Board Act 1921 (AEPB Act). Under the AEPB Act, the AEPB was given the right to construct electric works as a supply authority licensee.

The electric works installed in the Cable Trench between 1966 and 1 January 1993 were all installed by AEPB as a supply authority licensee and subject to the obligations in the Electricity Supply Regulations in relation to installation, operation and maintenance.

Following the enactment of the Electricity Act 1992, any electric works installed prior to 1 January 1993 were deemed "existing works" and afforded statutory protection. This allowed AEPB's successors, Mercury Energy Limited and then Vector, to continue to have such assets on Transpower's property and to access, maintain (including replace) and operate those assets. Transpower cannot require those assets to be removed or relocated except with Vector's consent.¹⁵

In 1999, Transpower and Vector entered into a Licence to Occupy dated 21 October 1999 (Licence) for a 33 kV indoor switch room project whereby Transpower granted Vector a licence to install new cables at the Penrose substation, and inspect, renew, maintain and operate those cables for a twenty year term (with a right of renewal for a further 20 years). The Licence also shows a cable ladder system, which follows a separate, Transpower-approved route to the west of the 33 kV indoor switchgear building. The Licence did not modify any rights relating to the cables in the Cable Trench other than the specific 33 kV cables which were being re-terminated from the 33 kV outdoor switchyard to the new 33 kV indoor switch room as part of the project.

¹⁴ The Cable Trench is not the only route Vector uses for its cables at Penrose substation. There are other access routes to the North and West, all of which were approved by Transpower (or its predecessors)

¹⁵ Section 35 of the Electricity Act allows a landowner to request that existing works be moved, reconstructed or replaced, but the works owner's consent is still required (not to be unreasonably withheld) and the landowner must meet the cost of the move, reconstruction or replacement.

6.2 Connections Contract

In 2000 Vector entered into a Connections Contract with Transpower. The Connections Contract, together with Vector's existing works rights under the Electricity Act, still govern Vector's access and occupancy at Penrose.

6.2.1 Access and Occupation Schedule

The Connections Contract includes an Access and Occupation Schedule which contains Vector's rights of access to and over Transpower's land at Penrose. The Access and Occupation Schedule grants Vector a licence to occupy and access certain parts of Transpower's Penrose substation in order to install, operate and maintain certain "Facilities" (owned by Vector) for the conveyance of electricity. The Access and Occupation Schedule requires Vector to operate and maintain its Facilities in accordance with "Good Industry Practice". Vector is required to follow Transpower site access procedures to gain access to the site and to carry out work on site.

All of the assets covered by the Licence are listed in the Access and Occupation Schedule. That suggests the intention at the time was to replace the Licence with the Access and Occupation Schedule.

Transpower's view is that when the Connections Contract was entered into the intent was for all existing and future Vector assets at Penrose to be covered by it, to the exclusion of previous agreements.

Vector's view is that the current version of the Connections Contract does not cover all existing Vector assets at Transpower's Penrose substation. Vector agrees that greater certainty is required, and that the Connections Contract should be updated to reflect all existing and future Vector assets.

The list of Facilities at Penrose in the Access and Occupation Schedule is incomplete and inaccurate. Some Facilities are not described correctly¹⁶ and Vector's 11 kV cables installed in the Cable Trench in the 1960s and 1970s (including the cable on which the joint that faulted was installed) are not listed.

Neither Transpower nor Vector has records showing unequivocally that the Access and Occupation Schedule has been updated since the original 2000 version.

6.2.2 New and Relocated Facilities

Transpower's approval is required before Vector can install new Facilities or relocate existing ones to a different Facilities Area.

¹⁶ For example, the list refers to three 2 kV feeders (Remuera 1, 2 & 3), which should be referred to as 33 kV feeders, and to one 22 kV feeder (Quay Street 4), which was decommissioned in the 1950's.

In deciding whether or not to give its approval, Transpower is concerned with ensuring its own assets and operations are protected, including its development plans and options at the relevant site. Transpower is not concerned with ensuring the customer's assets or operations are protected, or looking into whether the customer's network design is prudent, except to the extent necessary to ensure Transpower does not incur any new material risks. Transpower does not "sign off" generally on all the choices the customer makes about the electrical and physical design of its Facilities. That is the customer's responsibility.

Sometimes there will be a conflict between Transpower's interests at a site and a customer's requirement to secure corridors within the site for the installation of its feeders to enable connection to the National Grid. This is most likely to occur at physically constrained sites such as Penrose. In that situation Transpower, as the landowner, is able to protect its interests by refusing permission for the customer's proposal if necessary. It will then be for Transpower and its customer to work together to find a mutually acceptable solution.

Notwithstanding the prescriptive processes in the Connections Contract, it appears the parties have historically used less centralised processes for the approval of the physical location of Vector's cables at Penrose. Transpower's records contain only one formal application from Vector for new connections or changes to the location of its Facilities at Penrose.¹⁷

Transpower has published documents describing the current process for customers requesting approval to install or modify their assets at Transpower's sites.

6.3 Roles and Responsibilities

Transpower and Vector are each responsible for the performance of their respective networks, and the asset management practices adopted, including risk management, planning, development, operation and maintenance.

Transpower is responsible for the integrity of its sites, but is dependent on connected parties like Vector following good industry practice and processes. In its role as grid owner and owner of the site, Transpower needs to be aware of risks to grid assets that may arise from assets owned by others on its sites. There has been limited centralised awareness within Transpower of the Vector cables in the trench at Penrose.

Vector is responsible for obtaining Transpower approval for new assets or for any changes it proposes at Transpower sites.

¹⁷ From January 2014 (relocation of several 33 kV and fibre optic cables due to Transpower's new 33 kV switchgear building). Transpower's records also contain less formal application correspondence from March 1999 (relocation and new connections for the 33 kV cables covered by the Licence) and 2011 (relocation of McNab K02 11 kV due to Transpower site extension).

7 Asset Management

Asset management is a core activity for Transpower and Vector. Effective asset management helps ensure that electricity is provided safely and reliably at service levels that meet the needs and expectations of customers.

Asset management incorporates consideration and mitigation of risk as part of an optimised decision making approach throughout the asset life cycle. It is not possible or economic to entirely eliminate all risks to network reliability. Effective asset management requires an appropriate balance between performance, cost and risk. Excessive investment in risk mitigation leads to unnecessarily high costs for customers. The management of risk, as it applied to the Penrose substation and the cable trench, is covered in this section.

Transpower and Vector own and manage assets which have long lifespans, fifty years and more. Asset management practices and standards are continually evolving meaning what was constructed historically may differ from current standards. Normal practice is to apply new or current design standards when existing assets are replaced, and to manage any legacy risks through established risk management processes.

7.1 Transpower Asset Management System

A separate report on Asset Management has been prepared by Transpower that provides further background to this section of the report.

Transpower's asset management system has been independently certified against the PAS55:2008 standard. Independent reviews of Transpower's asset management have also been undertaken by the Office of the Auditor General. Further reviews have been undertaken by technical advisers to the Commerce Commission, as part of their review of Transpower's expenditure proposals submitted as part of individual price-quality path regulation. These independent reviews have acknowledged the progress that Transpower has made in improving its asset management approach in recent years.

The following sections focus on transmission asset management planning and feedback processes.

7.1.1 Grid capacity and security

The key risks considered in the long range network planning process are risks to reliability, security, availability and customer service levels. Long range plans for the capacity and security of the transmission network are reviewed annually. The process includes updating forecasts of future demand and generation.

Transpower works with connected parties to prepare these forecasts and the expected performance of the network is then studied under a range of scenarios, to identify risks, investment needs and options. The analysis of risks and investment needs includes a criticality framework, as a proxy for the consequences of failure.

Major new investments in the core grid that are needed to increase capacity or maintain security are subject to one-by-one regulatory approval by the Commerce Commission.

The planning and development of the transmission system in the Auckland region, as outlined in more detail in section 7.1.4, is an example of recent major investments in the grid.

7.1.2 Connection assets

The network planning process also includes review of the capacity and security of Transpower assets at the point where the connection is made to distribution networks.

Investments in new, or upgraded, grid connection assets are subject to specific funding agreements with the relevant connected parties. This means that the connected parties make the risk trade-off between the capability of the connection assets, and the costs of the grid connection service. Based on this trade-off, they can choose connection asset configurations of higher or lower security levels.

Transpower provides the connection assets in accordance with investment agreements, and manages the performance and safety risks associated with those assets.

The network planning process integrates plans for the main grid and for grid connection assets. The outputs from this work are published each year in Transpower's Annual Planning Report.

7.1.3 Replacement and refurbishment

Major transmission assets can have a lifetime of 50 years or more. However, asset related risks can increase over time, to the point where replacement or refurbishment becomes necessary.

An example of replacement and refurbishment work is the nationwide programme for replacement of existing outdoor 33 kV switchyards with indoor equipment to improve safety. The nationwide programme is prioritised taking criticality into account. Most of the outdoor 33 kV switchyards in the Auckland region are being replaced in agreement with Vector, including the remaining outdoor 33 kV switchyard at Penrose.

7.1.4 Substation site planning and development

Asset management planning and development at substation sites incorporates requirements from both the grid planning and equipment replacement perspectives outlined above.

Transpower prepares site strategies for substations to provide strategic direction for the development of the site. The site strategies highlight key issues that must be considered, including future customer requirements. The strategies provide a means of co-ordinating long term investments to achieve efficiencies and improve integration. The current programme of developing and documenting site strategies commenced in June 2012. Site strategy documents have now been published for more than 60 substations.

7.2 Vector Asset Management System

A separate report on Asset Management was prepared by Vector and provides further background to this section of the report. Vector's asset management framework and underlying systems, processes, and practices are mature, well developed, and consistent with a major infrastructure asset manager.

The key document in which Vector's asset management practices are described is Vector's Asset Management Plan (AMP). This is underpinned by other business documents, including standards, policies, procedures, risk schedules and various asset information systems and databases. Vector's AMP is updated annually to outline Vector's asset management policies, responsibilities, targets, investment plans and strategies to deal with the future of the electricity network. The AMP is publicly disclosed, and available on Vector's website.

Vector's asset management practices are regularly reviewed and updated, both internally and externally. External reviews include regulatory reviews, and reviews by Vector's insurers, covering different aspects of the AMP. Vector's Asset Management Plan and network expenditure are regularly reviewed by technical advisors to the Commerce Commission as part of the current regulatory process.

Since 2005 Vector's asset management planning and practices, have been independently reviewed, at least bi-annually, by a number of internationally recognised experts. In recent years Vector has engaged Siemens, Sinclair Knight Merz, and PA Consulting to carry out this work. The scope of these reviews is broad, covering all Vector assets. The use of internationally based experts is, in part, to provide a comparison between practices in other jurisdictions.

These reviews are conducted to provide guidance to Vector's board and management on the appropriateness of Vector's asset management practices. In addition, the reports are also provided to the Auckland Energy Consumer Trust (AECT) in fulfilment of Vector's obligations to its major shareholder to demonstrate good custodianship of the electricity network assets¹⁸.

The reports all generally endorsed Vector's asset management practices. A number of observations were made, all of which were carefully considered by Vector management and the Vector board.

7.3 Reviewing Risks

Transpower and Vector each have risk management frameworks designed to identify, assess, monitor and treat risks to acceptable levels taking into account consequence, likelihood, and existing risk controls within the business. Risk controls also include emergency preparedness, and business continuity plans designed to manage the business in the event of a major event and effectively restore business operations.

7.3.1 Transpower Risk Reviews

The Transpower risk management feedback processes of most relevance to the Penrose cable fire are:

- Site Risk Reviews; and
- Studies of High Impact Low Probability (HILP) Events.

7.3.1.1 Site Risk Reviews

Substation risk reviews provide essential feedback for asset management planning and strategy. There are a wide range of processes in place that contribute to the understanding of site risk such as:

- Inspections carried out by maintenance service providers
- Engineering inspections, including post-event reviews
- Studies of High impact, low probability event risks (see next section)
- Specific reviews associated with Site Strategy development
- Development and review of grid risk registers

Risk assessment is often informed by actual incidents. There have been few incidents of failure of customer assets on Transpower land. The Penrose cable fire is the only incident Transpower is aware of that has led to serious consequences.

¹⁸ Vector is required under the Deed Requiring Essential Operating Requirements (DREOR) to conduct an independent review of its asset management practices every 2 years and provide this report to the AECT.

In 2014, a generic risk was identified of the potential for damage to the grid and safety risks arising from the failure of customer assets on Transpower land. The trigger for the identification of this risk was the failure of a Vector outdoor circuit breaker at a Transpower site. Following this failure, there was a nationwide programme to manage risks with similar circuit breakers.

There had been no other significant problems caused by the failure of customer assets on Transpower land over many years, and the generic risk was therefore not accorded high priority for mitigation, compared with other identified risks.

7.3.1.2 High Impact Low Probability (HILP) events

Understanding and assessing possible HILP events is an important element of Transpower's asset management planning. A methodology for HILP event studies has been developed and published in a peer reviewed paper and presented at an international forum. A HILP study for Penrose was carried out in 2013 as outlined in section 7.5.2.

7.3.2 Vector Risk Management

A separate report on Vector's Risk Management framework was prepared by Vector and provides further background to this section of the report. Vector's aim is to maintain robust risk management practices consistent with the AS/NZ ISO 31000:2009 risk management standard.

Vector's risk management framework is regularly reviewed and updated, both internally and externally. Vector's insurers have carried out independent risk reviews on key risks as part of the insurance process.

Vector's network business unit maintains a key risks profile containing strategic and critical operational risks relevant to its business. Network risks are identified via a number of ways, including:

- Condition assessment of assets through failure trend analysis, physical inspections and testing;
- Reporting of incidents involving harm or potential harm to personnel or the public;
- Equipment failures on the Vector network;
- Information from industry associations, suppliers and manufacturers; and
- Use of external experts.

Vector has identified a number of HILP events. Given the significant consequences of these events, Vector seeks to minimise the impact through a combination of controls to limit the impact of an event and specific contingency plans to restore supply.

The development of network emergency plans are part of Vector's response capability which forms a key part of Vector's risk management framework, particularly for situations where elimination of risks is not feasible. An example is the loss of a zone substation. Vector has individual contingency plans for each of its 107 zone substations.

Vector has not developed contingency plans for the loss of a GXP. It is impractical for Vector to develop these plans as there is insufficient capacity within Vector's network to transfer loads of this magnitude between GXPs. Furthermore, such plans are dependent upon the nature of any specific event, and can vary considerably from event to event.

7.3.3 Fire Risk Mitigation

Fires in electricity substations are very rare events. However, fire can lead to serious damage to equipment, interruption to customers, and safety hazards.

Transpower and Vector use a range of design standards in planning and developing their networks. These ensure assets are designed to appropriately mitigate risks such as fire risk.

There have been major changes in design standards and practices for fire risk mitigation in substations over the past 50 years. Recent designs for substation equipment incorporate increased resilience against common mode failures resulting from fire. In particular, recent designs incorporate greater use of fire-cells and physical segregation. Key elements of current "best practice" substation fire risk mitigation for new installations include:

- Bunded areas around power transformers to contain oil spills;
- Fire walls around power transformers;
- Fire segregation for high voltage power cables;
- Indoor switchboards segregated into multiple fire-rated sections;
- Indoor switchgear built to withstand the effects of internal arc faults;
- Indoor switchgear equipped with high speed protection systems that detects arc faults;
- Highly sensitive smoke detectors installed in control and relay rooms;
- Active fire suppression systems provided for some key locations; and
- Transpower is planning to install hypoxic air fire prevention systems at some critical locations.

It is not practical or economic to apply these latest fire risk mitigation standards immediately to all existing substations. In some cases, it is feasible and economic to retrofit fire protection systems. Examples include the retrofitting of fire walls around existing power transformers, or the provision of external arc flash protection systems for some older indoor switchboard installations.

7.3.4 Contingency planning and emergency preparedness

Electricity networks are exposed to hazards from external events, such as extreme weather, and third party damage. Electricity network equipment itself is generally highly reliable, but occasional failures do occur. All these factors can threaten reliability of supply.

It is not possible to entirely eliminate all risks to network reliability. This means that a prompt and efficient response, after the event, is the most appropriate way of managing certain kinds of incidents or events.

Both Transpower and Vector have extensive arrangements in place to provide 24 hour call out response to faults. The call out fault response is supported by access to a large pool of highly competent industry trades, technician and professional engineering staff. In addition, there are a wide range of other measures in place to ensure a timely and effective response to unexpected events. These include:

- Extensive holdings of spare parts, and complete replacements for some types of equipment;
- Holdings of major strategic spares, such as replacement power transformers and relocatable switchboards and generators; and
- Effective relationships with local suppliers, transport contractors, equipment hire companies and specialist service providers.

In the Penrose incident, despite the unusual nature of the event, and the extent of damage caused by the fire, the existing arrangements for contingency planning and emergency response enabled effective response and recovery.

7.4 Auckland Regional Network

The Transpower network in the Auckland region is illustrated geographically in **Figure 10**.

The Auckland region has some of the highest load densities in the country. Transmission lines supply the Auckland and Northland regions from the south at 220 kV, distributing power at major substations around Auckland and providing through transmission to Northland.

The electricity network supplying Auckland has been upgraded in stages over many years, to meet the growth in the region. Prior to 2014, almost all the electricity used north of the Auckland Harbour Bridge was supplied over one double-circuit line. This put the load at risk from low-probability incidents such as a tower failure, or a fault on one circuit while the other circuit was out for maintenance.

As a result of recent major transmission upgrades, there is now a high capacity 220 kV ring between Otahuhu, Pakuranga and Penrose, and a high capacity 220 kV loop from Otahuhu and Penrose through the Henderson and Albany substations in the North Isthmus. There is also a 110 kV transmission network supporting the 220 kV network.

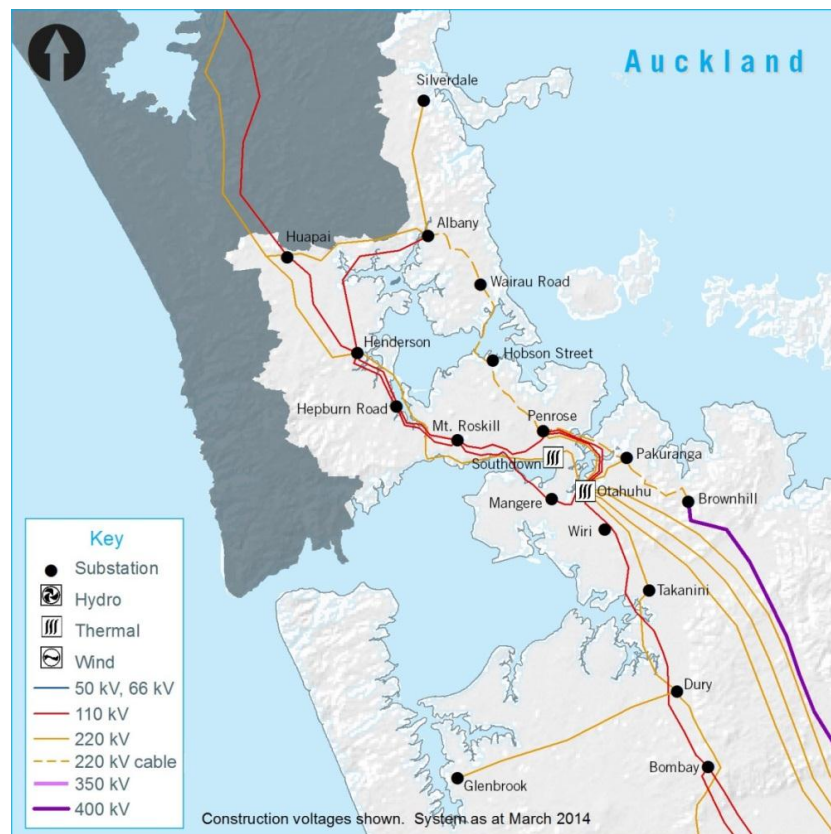


Figure 10 Auckland Region

7.4.1 Regional Outages (Since 1998)

There have been five significant incidents in the 16 years prior to the October 2014 incident at Penrose affecting customers in the Auckland region due to power system failures within and into the region. Each incident has had a different cause, and affected different groups of customers. Details of each incident are given in **Error! Reference source not found.**

There have also been two power system failures external to the Auckland region that affected customers throughout the North Island, including customers in Auckland, for 2 to 3 hours¹⁹. These outages were part of normal contingency arrangements designed to maintain stability of the electricity system, and were not related to the power supply into or within the Auckland region.

After each incident there have been extensive reviews resulting in a number of recommendations. For example a Ministerial Inquiry was conducted into the loss of supply to Auckland's CBD in 1998. These recommendations have included a number of major projects which have either eliminated or significantly reduced the risk, and severity, of a re-occurrence of similar outages. The projects are described in Section 7.4.2.

¹⁹ Some media reports include these outages when looking at power cuts in Auckland.

Date	Incident	Response
Feb 1998	Four Vector 110kV cables supplying Auckland's CBD failed resulting in a loss of supply to for 5 weeks until a temporary supply was established.	Vector improved security into the CBD through a new supply from Mt Roskill in 1999 at a cost of \$25 million. In 2001, Vector completed a major project that was already in progress at the time of the incident, involving construction of a 9.2 km tunnel from Transpower's Penrose substation through to Hobson substation. Vector invested over \$120 million in the CBD tunnel, cables and substation upgrades.
Jun 2006	A D shackle holding an earth wire broke, resulting in a partial outage of Transpower's Otahuhu substation. South and central Auckland (around half the city) was without power for up to six hours.	In 2009, Transpower completed a \$106 million new 220 kV enclosed gas insulated switchgear (GIS) facility at Otahuhu substation separate from the existing 220 kV switchyard. The region's dependence upon Otahuhu was further reduced by connecting the new 220 kV transmission line from Whakamaru into Pakuranga substation in 2012.
Feb 2009	A 33 kV supply transformer failed at the Penrose substation while another transformer was out of service undergoing refurbishment. This resulted in the loss of supply to 74,000 Vector customers.	Following this incident, Transpower installed an additional \$5 million transformer at Penrose. Transpower has also established a number of spare transformers that can be used nationwide, in the event of a similar failure.
Oct 2009	A forklift carrying a shipping container accidentally hit a 220 kV circuit running from Otahuhu to Henderson. The other circuit was out of service for maintenance at the time, which meant that the main electricity supply route north was lost. 280,000 customers throughout Northland and north and west Auckland were without power for 3 hours.	In 2014, Transpower completed the North Auckland and Northland (NAaN) project to reinforce supply to West Auckland, the North Shore and Northland, using corridors established by Transpower and Vector, including Vector's CBD tunnel. This development improved security of supply by forming a secure and high capacity transmission ring around central Auckland, and providing an alternative supply route north.
Feb 2011	A fire near Hamilton under one of the 220 kV lines into Auckland resulted in reduced supply capacity into the region with some customers being without power for an hour in Northland, and Vector shutting off all hot water heating.	In 2012, Transpower commissioned a major project that was already under construction at the time of the incident. This project created a new 186 km double circuit transmission line between Whakamaru and Pakuranga meaning there are now five separate 220 kV lines supplying the Auckland region.

Table 3 Significant Events Affecting Auckland Region Supply

7.4.2 Major projects (Since 1998)

Four major projects have been implemented since 1998 to address the future capacity requirements of the Auckland region and mitigate network security risks. In a number of cases projects were modified in response to the significant incidents noted in section 7.4.1. The combined value of these projects was over \$1.6 billion.

The projects were:

- In 2001, Vector completed a 9.2 km tunnel from Transpower's Penrose substation into Auckland's CBD to provide improved security into the CBD at a total project cost of over \$120 million;
- In 2009, Transpower completed a \$106 million new 220 kV gas insulated switchgear (GIS) facility at its Otahuhu substation;
- In 2013, Transpower completed a new 186 km long double circuit transmission line between Whakamaru and Pakuranga. This \$894 million project included 220 kV underground cables for the final 11 km into Pakuranga substation. Pakuranga was upgraded from a 110 kV to a 220 kV substation at the same time. This project created a major new transmission route into Auckland, and also reduced the dependence of the Auckland region on the Otahuhu substation; and
- In 2014, Transpower completed the North Auckland and Northland (NAaN) project. 37 km of underground 220 kV cable was commissioned between the Pakuranga, Penrose, and Albany substations, crossing the Auckland harbour bridge. This \$424 million project made use of corridors established by Transpower and Vector, including using Vector's CBD tunnel. This development improved security of supply within Auckland by forming a secure and high capacity transmission ring around central Auckland, and reinforced supply to West Auckland, the North Shore, and to Northland. The project includes new grid exit points connecting to Vector's sub-transmission system at Hobson Street in the CBD, and at Wairau Road on the North Shore, with significant associated work by Vector.
- In 2014 Vector spent \$73 million upgrading Hobson Street and Wairau Road substations to enable connection of the new transmission link created by the NAA project.

Details of how each of the above projects has reduced the risk from previous significant incidents are given in Table 3.

In addition to these projects, in the period since 1995, there have been 30 other Transpower projects that have either reinforced supply into the Auckland region, or increased capacity at individual grid exit points in the region.

In the same period Vector has made significant investment in its subtransmission network. This has included normal replacement works and investment to meet Auckland's growth. Whilst this investment has been Auckland wide a number of projects have been carried out in the area supplied from the Transpower Penrose substation. These projects include new supplies to Newmarket, Remuera and Mt Wellington and a new substation to supply Sylvia Park.

Vector regularly invests over \$100 million p.a. on its network. In the last six years Vector's investment has been nearly \$1 billion.

7.5 Penrose Substation

The history of the development of the Penrose substation is described in Section 5. The Penrose substation is a major supply point for the Auckland region and has the largest load of any Transpower urban grid exit point. It is assigned the highest level in Transpower's criticality framework.

7.5.1 Penrose Substation Site Strategy

A Transpower site strategy was published in June 2012. The strategy development process includes consultation with customers.

The significant projects identified in the Penrose strategy that were in progress at the time of the incident included:

- Extension of the 220 kV bus to become a ring bus. The ring bus will provide improved resilience; and
- Replacement of the existing outdoor 33 kV switchyard with an indoor switchroom, with indoor switchgear separated into fire segregated cells.

7.5.2 Penrose Substation Risk Reviews

A HILP study for Penrose substation was carried out for Transpower in 2013 which included a site review by Marsh. The study confirmed the need to enhance seismic resilience of the critical control buildings, to upgrade building fire protection, and retrofit fire separation barriers for major power transformers. These initiatives are in the process of being implemented. The HILP study did not identify the specific risk of fire in the cable trench carrying distribution cables across the 220 kV switchyard.

7.5.3 Future Development

Vector's Asset Management Plan outlines several near-term and long-term developments affecting customers supplied from the Penrose substation.

In the near-term, the Glenn Innes subtransmission cables are scheduled to be replaced in 2016/17. Currently these are supplied from the Penrose 22 kV bus. A number of options are being considered including replacing the existing cables like-for-like, supplying Glen Innes from St Johns 33 kV bus or by installing cables from Pakuranga GXP.

The Penrose load is significant and is expected to increase further with forecast growth. As part of Vector's long term network development plan two new GXP's have been investigated, one at Southdown and a second at Newmarket. Both of these GXP's will displace load currently supplied via the Penrose 33 kV bus at Penrose. Vector's long-term development plans are dependent upon a number of factors, including whether customer load continues to grow as forecast. Neither of these GXP's are scheduled to be constructed within the plan's 10 year planning horizon.

7.6 Penrose Cable Trench

The construction of the cable trench is covered in Section 5.4. Since its construction the cable trench has been used as the only corridor out of the Penrose substation for 33 kV subtransmission cables supplying zone substations in the eastern suburbs. The cable trench has also been used to enable distribution feeders from McNab²⁰ substation to supply areas of Remuera and Ellerslie on the eastern side of the motorway.

The area within the substation is considered a controlled environment, where there is negligible risk of third party damage to the cables.

Access to the cable trench is very restricted, with only crawl space available when the covers are in place. Given the hazards of live power cables and the confined space, personnel access is prohibited unless the covers are removed. Therefore inspections of the cable trench and the cables has been limited to occasions when new, or replacement, cables have been installed.

An earlier inspection by Vector in 2001 had identified an 11 kV cast iron PILC cable joint that was leaking bitumen. The maintenance contractor inspected the joint and decided to replace it. The standard repair was carried out, which involved cutting out the faulty joint and installing a short length of new cable with two new joints. By this time XLPE cable was being used on the network, and therefore XLPE cable was installed with two PILC to XLPE transition joints. It was one of these transition joints that failed in October 2014.

Transition joints are used by network companies to enable repairs and extensions to existing PILC cables and joints. The cable joint that failed is a type commonly used in electricity networks in New Zealand and internationally.

7.6.1 International Practice

Most cables entering substations are either direct buried or installed in individual ducts. Increasingly, cables supplying inner city substations are installed in deep tunnels, which are designed for full personnel access. There are also smaller, shallow tunnels, or culverts, within some cities, which provide egress for a large number of cables to supply the high density local loads from the inner city substations.

²⁰ McNab substation is located to the west of the motorway.

Occasionally, network companies install short tunnels or culverts at other substations, where normal methods of access are difficult or the land is not owned by the utility, but these are not common.

Vector contacted a number of New Zealand network companies to review their practices for structures like the cable trench and found that none had comparable structures. As a result Vector commissioned surveys of network companies in Australia and the United Kingdom to review normal industry practice for the installation of power cables in structures like the cable trench. The surveys identified a wide range of different structures used by network companies, from deep tunnels to shallow troughs. Most of the large tunnels are used solely for transmission cables. Many of the smaller tunnels contain a number of cables comprising a range of different cable types and voltages, including XLPE, PILC and oil filled cables.

Generally, tunnels do not have fire detection or suppression systems. Some network companies have started to paint cables with fire retarding paint, but this is normally only for transmission cables. No smaller structures, like the cable trench, have fire detection, or suppression systems, installed.

In substation buildings, fire detection systems are generally installed to comply with building regulations, but active fire suppression systems are not widely used. Active fire suppression systems are used by network companies with indoor transformers, and at large inner city substations with indoor switchgear.

In congested cities like London, structures like the cable trench are relatively common, often dating back to the 1930s. Sometimes they are larger, and are combined with other utility services, such as gas pipelines or sewer systems. There are also similar structures in Sydney that contain numerous medium voltage cables and often other services such as high pressure gas mains. None of these structures have fire suppression systems.

Historically, network companies had no restriction on the installation of joints in basements or tunnels. Some now avoid joints in close proximity to other cables. If the use of a joint cannot be avoided, they will adopt passive protection measures, such as fire blankets, to protect the cables. No utility had a separate programme to replace or protect existing joints, choosing to carry out fire mitigation measures as part of other works.

7.6.2 Cable Trench Risk Reviews

No specific risk reviews were carried out with respect to the cables in the cable trench. Risk assessments were made for each network project that involved new cables being installed in the trench, but these were focused on the construction and environmental risks pertaining to the specific project. In these projects the trench simply formed a small section of the cable route and the associated construction risks were considered minor.

Procurement and installation of cables is done to network standards. Vector's network standards are regularly updated to incorporate learnings, including feedback from manufacturers and suppliers. Vector has not received any information from manufacturers and suppliers alerting them to the risk of transition joint failures causing fires.

Joint failures are rare²¹. Joint failures causing fires are very rare. Transpower and Vector have no record of fires caused by joint failures prior to this incident.

The survey of utility practice confirmed this. It found that:

- In New Zealand and Australia, three similar joint failures were identified. These failures have occurred over the last ten years with the latest occurring in February 2015. As a result of these failures, the network companies have either made, or, in the latest case, are considering making, changes to their standards related to the installation of joints in air. In all of these incidents the cause was not made public; and
- In the United Kingdom, one utility first became aware of the risk circa. 2006 when an 11 kV joint faulted and caused a fire that damaged several nearby cables. The joint failure occurred in an excavation that had been left open during ongoing works. As a result of this incident, the utility produced the first issue of its standard for the installation of cables and joints in air. In 2012, the utility had a failure of a transition joint in the basement of a zone substation, which again caused a cable fire and damaged several other circuits. The utility updated its standard as a result of this incident. Neither the incidents nor the updated standards were made public.

In the United Kingdom, there have been a number of "manhole fires", where electrical faults have resulted in explosions under pavements, particularly in London. These appear to be related to link box faults, which have been associated with water ingress and gas leakage into the pits. These are quite different to the Penrose incident.

7.6.3 Cable Trench Fire Risk Mitigations

No network companies were found to have installed fire detection or suppression systems in structures like the cable trench.

It is apparent from the surveys that, where network companies have become aware of the risk of fires from joint faults, they have changed their standards so that, as much as practicable, new joints are not installed in air. If new joints must be installed in air, specific precautions are taken to mitigate the risk of fire. No network companies have initiated a separate programme of retrospectively applying protection measures to existing joints, preferring instead to apply the new standards as part of other works at the substations.

²¹ Based on Vector's actual joint failure rates the expected time between joint failures on an average Vector cable circuit for distribution cables are 1 per 22 years. The expected time for an average subtransmission circuit is 1 per 79 years.

The specific precautions adopted have generally involved painting cables and cable joints with fire retarding paint. Some network companies have specified a type of joint with a fire retardant outer shell, which can be filled with resin.

8. Findings

Cause

1. The cause of the fire was an electrical failure in a cable joint in a Vector distribution (11 kV) feeder cable within a cable trench containing Vector power cables and a Transpower lighting cable, running east-west across the Transpower 220 kV switchyard. The joint failure occurred at 23:21 on Saturday 4 October 2014 resulting initially in the loss of supply to customers in Remuera and Ellerslie.
2. A manual reclose of the distribution feeder, following a line patrol, caused a second fault at 01:21 on Sunday 5 October 2014. The reclose accelerated the fire, but did not affect the scale or duration of the outage.

Investigation

3. The cable joint that failed is a type commonly used in electricity networks in New Zealand, and internationally. These joints are supplied in standard kits by a range of manufacturers.
4. The joint was installed in 2001 as part of a replacement of a PILC cable joint that was leaking bitumen. The replacement involved cutting out the leaking joint, and installing a short length of new XLPE cable, and two new PILC to XLPE transition joints.
5. The failed transition joint was largely destroyed by the fault and the subsequent fire. However, the fault location was clearly identified by the arc erosion on all three copper conductors of the PILC cable.
6. Given the significant damage to the failed transition joint, the second (identical) transition joint was examined to identify any contributory factors to the failure. There was no evidence of an electrical fault on the second transition joint and fire damage was limited to the outer heat shrink layers.
7. The inspections of the two transition joints could not identify any single factor that caused the transition joint failure, but a number of potential contributory factors were identified.

The investigation found that:

- a. Based on the inspection of the failed transition joint:
 - i. The fault occurred in the crutch between the PILC cable cores; and
 - ii. The transition joint had been installed on an angle, without cable cleats and joint supports, making it susceptible to moisture ingress at the cable crutch.

- b. Based on the inspection of the second (unfailed) transition joint:
 - i. The jointer had correctly followed the manufacturer's jointing instructions in making the joint;
 - ii. The transition joint is susceptible to moisture ingress at the PILC end of the joint;
 - iii. The impregnating compound had dried from the paper insulation, causing the insulating tapes to be thermally degraded;
 - iv. Void filling mastic had migrated onto the paper insulating tapes in the crutch; and
 - v. The paper insulation in the crutch is susceptible to damage when the void filling mastic is inserted.
- 8. The investigation concluded that the cause of the transition joint failure was the vulnerability of the transition joint design with respect to the electrically stressed insulation in the crutch between the PILC cable cores. This is a generic issue faced by all manufacturers when designing transition joints that connect two different cable types.
- 9. The investigation determined that the fire spread initially to the control cables and XLPE insulated power cables. The oil cables did not contribute to the early development of the fire.
- 10. The detailed examination of the cables extracted from the cable trench revealed them to be in good condition, with ample remaining life expectancy. An analysis of the cable loading has demonstrated that the cables have been operated within their maximum design operating temperatures with an acceptable margin.

Impact

- 11. At the time of the fire, the cables in the cable trench supplied 39,043 customers (around 7% of Vector's total customers). Fire damage to the cables in the trench led directly to the loss of supply to those customers.
- 12. Transpower had to de-energise the area of the Penrose substation where the cable trench is located, to enable safe access for NZ Fire Service to fight the fire. As a result a total of 75,339 Vector customers were without power from 03:08 on Sunday 5 October. Supply from Penrose was also interrupted to Transpower customers KiwiRail and Southpark.
- 13. Reliving restored supply to 36,296 (48%) customers within 16 hours. Extensive use of backfeeding within Vector's network restored a further 18,786 customers (25%), limiting the number of customers without supply for more than 24 hours to 20,257 (27%). All customers were restored within 59 hours.

Response

14. The incident was a large and complex event that placed extreme demands on Transpower and Vector. The joint response is considered to have been effective because:
- a. There were no reported injuries or safety incidents affecting the public, Transpower and Vector staff, their contractors, or members of Emergency Services;
 - b. Reliving and repairs were completed without delay once control of the site was returned to Transpower. Transpower and Vector promptly mobilised all necessary resources, and drew on existing spares holdings to achieve this;
 - c. Customers were kept well informed during the outage through regular updates delivered across a wide range of communication channels; and
 - d. No other equipment at the substation was damaged during the restoration and recovery efforts.

Risk Mitigations

15. Prior to the fire, Vector, Transpower, and their external experts, had not identified a risk of fire in the cable trench. There had been no cable failures within the cable trench prior to the incident, nor did the investigation find any records of fires caused by joint failures in Transpower and Vector's networks prior to the incident.
16. In 2014, Transpower had identified a generic risk related to customer assets on Transpower land causing damage to grid assets. Transpower had also conducted a HILP study at the Penrose substation in 2013. Neither of these risk review processes specifically identified the risk of fire in the cable trench.
17. Vector commissioned surveys of network companies in Australia and the United Kingdom to review normal industry practice for the installation of cables in structures like the cable trench. The surveys found:
- a. The preferred method for the utilities, as it is for Vector, is to install the cables in the ground, either directly or in ducts;
 - b. Network companies occasionally construct short tunnels, culverts or trenches at substations, where normal methods of access are difficult, or the land is not owned by the utility. Multiple cables of various voltage levels, types and ages are installed in such structures;
 - c. No fire detection or suppression systems are installed in the smaller structures, like the cable trench;

- d. Most larger tunnels do not have fire detection or suppression systems installed;
- e. A few network companies have started to paint cables with fire retarding paint, but this is normally only for transmission cables.

Based upon the survey information the investigation concluded the cable trench design, and practices for installing cables in the cable trench, were in line with industry practice.

18. The surveys, and the Cable Expert investigation, found that fires from cable faults are very rare. It was also found that details of any incidents that have occurred globally have not been made public. In the few cases where cable fire reports have been presented in industry forums, the cause of the fire, remedial measures and lessons learnt are not given in sufficient detail to inform others. As a result Vector could not have been expected to have the knowledge to specifically identify this risk.
19. The design and operation of the cable trench is in line with industry practice. The specific risk of a joint failure causing fire in the cable trench was not identified so no controls specific to this risk were in place. Emergency plans were in place to manage outage incidents and these worked effectively.

Other Findings

20. The Cable Expert report concluded too many cables had been installed in the cable trench and this allowed the fire to propagate and sustain itself. Industry standards provide guidelines for testing the fire performance of cables, but do not recommend minimum spacings between cables or the maximum volume of combustible material in a specific installation.
21. The establishment of the cable trench, and its ongoing use as an primary egress point for Vector cables to the east of the substation, was due to a number of factors:
- a) The establishment of the 220 kV switchyard in the mid 1960's, led to the design and construction of the cable trench. The cable trench at Penrose is unusual. There are no directly similar installations at other Transpower substations. Upon its construction the cable trench provided an efficient means for a large number of new and existing cables to traverse or exit the site;
 - b) Significant load growth in Auckland since 1966 required further development of Vector's network which led to further cables being installed over time in the trench; and
 - c) At Penrose the sub-surface material is hard volcanic rock which made alternative corridors costly and difficult to construct.

It was concluded that the availability of, and ease of access to, the cable trench relative to the perceived cost and difficulty of establishing new (and diverse) routes, encouraged its ongoing use.

21. Recently completed major projects such as the Vector cable tunnel, and the Transpower 220 kV cable network installed as part of the North Auckland and Northland (NAaN) project, meant there was no risk of loss of supply to the Auckland CBD during the incident.
22. The management systems for additions and changes to Vector assets on Transpower land have not been applied consistently by Transpower and Vector. There wasn't a formal process to jointly review the status and condition of customer assets on Transpower land.

9. Learnings and Recommendations

A key focus of the investigation has been to identify and implement learnings from the incident. This section details the review process, the lessons learned, and the key recommendations and actions arising from the investigation.

A number of actions are already underway. Progress to date on implementing the recommendations is outlined in section 10.

Transpower and Vector conducted separate reviews, before sharing lessons learned.

9.1.1. Vector Review

A series of workshops were held focussing on three key areas:

- Operational Response;
- Asset Management/Risk Management; and
- Customer Management (including communications).

A separate review of the overall management of the incident was conducted with members of the Vector's Crisis Management Team (CMT) and Emergency Response Team (ERT). Findings from this review were also included in the final review workshop.

A final review workshop was held, involving senior management, to share the collective learnings from the initial workshops and to identify key learnings from the incident.

The reviews also identified a number of minor business improvement opportunities which have been included in the appropriate business areas for implementation, with many actions already completed.

9.1.2. Transpower Review

The early stages of the investigation included a review of operational management during the response and recovery phase. Engineering support provided to the recovery team was also reviewed.

The reviews also identified some business improvement opportunities, and these have been allocated to the appropriate business area for scoping and implementation.

9.1.3. Joint Transpower/Vector Review

Following their own reviews Transpower and Vector shared key learnings, and identified areas where collaboration will be required to implement actions arising from learnings.

Key learnings from the incident are outlined in Section 9.2.

9.2. Key Learnings

Four key learnings were identified:

1. Cable joints installed in air with other cables in close proximity can cause sustained fires when they fail;
2. Risk management processes did not identify very low probability events that had not previously occurred on the network;
3. The nature of the incident identified opportunities for improvement of standard operating procedures; and
4. The asset and risk management processes at the physical interface between Transpower and Vector's networks need to be improved.

These learnings, and recommendations based upon these learnings, are outlined further below. Actions required to implement recommendations are also noted.

The recommendations from the Cable Expert report have been adopted and have been incorporated into the actions outlined in this section. Transpower and Vector intend to work with CCI in implementing these recommendations.

Learning 1 Cable joints installed in air with other cables in close proximity can cause sustained fires when they fail.

The permanent replacement of the temporary cables installed as part of the recovery works at Penrose will mitigate the risk of a similar incident occurring at Penrose.

It is recommended that:

Transpower and Vector implement changes at Transpower's Penrose substation as part of the recovery works, including installing replacement cables in two trenches containing segregated ducts for each cable to effectively eliminate the risk of fire causing multiple cable failures.

The actions to implement this recommendation are:

- To design a new permanent solution at the Penrose substation; and
- Construct the solution.

Inspections will be carried out at points of connection between Transpower's grid and Vector's network, other similar sites on the Vector network, and other Transpower sites to identify cable joints in air in critical locations, and assess the potential impact of failure. Actions will then be taken to mitigate any risks identified from the inspections.

It is recommended that:

Transpower and Vector review locations where power cables are installed in open air environments to identify any risks associated with assets at the following locations:

Transpower/Vector points of connection (GXPs) [Jointly];

Vector's network [Vector];

Transpower sites [Transpower]; and

take appropriate actions to mitigate these risks.

The actions to implement these recommendations are:

- Inspect all areas on the Vector network where there are multiple cables in open air, including Transpower, and third party substations, assess the consequences of failure, and identify actions to mitigate risks identified from the inspections;
- Inspect all critical Transpower substations to identify cable joints in air, assess the consequences of failure, and identify actions to mitigate risks identified from the inspections;
- Complete all actions identified to mitigate the risks; and
- Vector amend its maintenance schedules to include inspections of all open air cable installations.

The inspections cover existing installations. There is also a need to ensure new (future) installations adequately assess the potential risk, and deploy controls to mitigate the risk of fires from joint failures. New installations may arise from new assets being constructed or from repairs to existing assets.

It is recommended that:

Vector review and update its relevant policies, procedures and practices with respect to cables, and cable joints installed in air.

Transpower incorporate learnings from the Penrose cable fire into asset management practice, including design standards. Include mitigation of risks from failures of cable joints in open air.

The actions to implement these recommendations are:

- Review and amend Vector policies, procedures and practices that deal with cable system design, installation and maintenance; and
- Review and amend Transpower asset management standards that deal with cable system design, installation and maintenance.

Learning 2 **Risk management processes did not identify very low probability events that had not previously occurred on the network.**

Prior to the incident Transpower and Vector had no recorded instances of joint failures in open air causing a fire. Joint failures causing fires are very rare, and there are comparatively few joints installed in open air. As a result, both Transpower and Vector had no direct previous experience to draw on to assist in identifying this risk. Information from other network companies, manufacturers, or suppliers globally on the failure of joints in open air was not publicly available.

It is recommended that:

Vector review and update its risk management framework, and risk identification processes.

Transpower incorporate learnings from the Penrose cable fire into risk review processes.

The actions to implement these recommendations are:

- Vector review and amend its asset risk management framework;
- Vector amend its procurement processes and contracts to request suppliers to make Vector aware of any significant issues with product failures;
- Vector create a dedicated role within its networks business focused on managing asset risk identification and management processes;
- Vector continue to develop its assessment of asset risk profiles to ensure the criticality of assets is considered;
- Vector review risk identification processes across the Vector group to ensure any learnings from the incident are applied; and
- Transpower review the scope of risk studies, including HILP event studies, to ensure coverage of assets owned by connected parties on Transpower land.

Learning 3 **The nature of the incident identified opportunities for improvement of standard operating procedures.**

The nature of the incident has highlighted some opportunities for improvement of current procedures.

The Remuera feeder fault review (Section 3.2) identified improvements to Vector's standard operating procedures as they apply to feeders with cable sections installed in air.

The event highlighted the importance of enabling safe access for NZ Fire Service personnel in the event of fire in a substation.

The Electricity Engineers Association's (EEA) Guide to Electrical Network Safety for Emergency Services Personnel²² provides essential background information to

²² Third edition issued in May 2015

assist emergency services to avoid and control hazards from electrical networks. Building on this industry guide, Transpower currently arranges annual site familiarisation visits to its substations for NZ Fire Service. However, the incident has highlighted the need for Transpower to review its existing arrangements with NZFS.

The learnings from the incident are also relevant to Vector sites and Vector has undertaken to engage with NZFS to review its existing arrangements.

It is recommended that:

Vector update its standard operating procedures to apply key learnings from the incident.

Transpower update its standard operating procedures to apply key learnings from the incident.

The actions to implement this recommendation are:

- Vector update its standard operating procedures for locating faults on feeders with cable sections installed in air;
- Transpower review its communications and existing arrangements with the NZ Fire Service, to identify opportunities for improvement; and
- Vector review its communications and existing arrangements with the NZ Fire Service, to identify opportunities for improvement.

Learning 4 The current asset and risk management processes at the physical interface between Transpower and Vector's networks need to be improved.

The incident has highlighted the opportunity for Transpower and Vector to improve the asset management interface with respect to Vector assets on Transpower property.

More robust management will ensure a greater collective focus on managing the connection interface, including greater awareness of the collective risk posed by all the assets - irrespective of ownership - on any site. As part of this process roles and responsibilities will be further refined.

It is recommended that:

Transpower and Vector review contractual terms and management processes at points of connection to ensure key learnings from the incident are incorporated.

Transpower improve its business process for assessing and approving customer requests for access and occupation of Transpower land.

Transpower establish an on-going process to provide assurance about the status and condition of customer assets on Transpower land and the potential risks to the grid.

The actions to implement the above recommendations are:

- Transpower and Vector review contractual terms and management processes at points of connection;

- Transpower review the business process for assessing and agreeing to customer requests for access and occupation of Transpower land. Ensure that a risk assessment is part of the process; and
- Transpower establish an on-going process to provide assurance about the status and condition of customer assets on Transpower land and the potential risks to the national grid. This process is to focus on critical sites, and to include agreement of risk mitigation plans with customers.

10. Implementation of Recommendations

As at the date of this report all actions identified to implement the recommendations are underway. Significant progress has already been made towards completing these actions.

- At Penrose a permanent solution for cables damaged in the fire has been designed and agreed between Transpower and Vector. The replacement cables will be installed in fire segregated ducts along two independent routes.

This work will be carried out in conjunction with a separate Transpower project to install a new indoor 33 kV switchroom. The timeframe for completion of this work is June 2016 and is determined by a need to co-ordinate with the indoor switchroom project. Tenders have been let for this work.

- Transpower and Vector have each undertaken surveys of their sites to identify situations where Transpower and Vector have each undertaken surveys of their sites to identify situations where failure of cables in air could lead to significant consequences. These surveys have not identified any issues of immediate concern. However, at several Transpower sites, interim risk mitigations for cable joints have been implemented as a precautionary measure.

Vector has developed action plans based upon its site surveys and prioritised these. Works on all critical (priority 1) sites have been completed.

- Transpower has developed a process for a comprehensive review of Access and Occupation schedules, to update the records of customer assets on Transpower land, and to evaluate the risks associated with those assets. The documentation updates and risk reviews for the most critical sites are scheduled to be completed within 12-18 months.
- Improvements to risk identification and review processes are underway within both organisations, together with enhancements to relevant asset management standards and operating practices.
- Vector has amended its operating procedures for locating faults on feeders with cable sections installed in air, and has commenced training of staff.
- Transpower has developed a process for a comprehensive review of Access and Occupation schedules to update the records of customer assets on Transpower land, and evaluate the risks associated with those assets. This process has commenced. The documentation updates and risk reviews for the most critical sites are scheduled to be completed within 12-18 months.

Transpower and Vector will track progress on actions through established internal processes.

Transpower

Transpower has an established process called RESOLVE which governs the investigation of significant incidents, and the implementation and tracking of the resulting corrective and preventive actions. The RESOLVE process includes monthly updates on open actions, and the preparation of summary reports on status. This process is administered by the Asset Risk and Investigations Manager. Requests for closure of actions are independently reviewed and the evidence supporting closure is checked.

The RESOLVE process is led by the National Events Review Group. This group of senior managers meets monthly to review progress on open investigations and the status of open actions. The National Events Review group reports to Transpower executive management.

Vector

Vector will monitor actions through its internal audit function. This function is responsible for ensuring that the corrective actions framework is designed and operating effectively. A transparent process across all of Vector's business units is in place and has been approved by the Vector's Board Risk and Assurance Committee.

Any recommendations arising from the Penrose Investigation will be monitored in accordance with this framework and recorded in the group corrective actions register. On a monthly basis the Group Manager Internal Audit and Assurance will follow up with responsible action owners to confirm the status of open corrective actions. This will include confirmation that progress is within expectations and that target dates will be achieved. Any closed actions will be confirmed and where appropriate evidence reviewed to demonstrate successful implementation. In addition to this all completed corrective actions are incorporated into the continuous follow up programme to provide independent assurance that changes to business processes and systems have been embedded.

On a monthly basis the status of the Penrose corrective actions will be communicated to the Executive Risk and Assurance Committee. This reporting will include analysis of open items by priority and ageing, detailed reports on status including updates from responsible action owners and a summary of all closed items during the month. The analysis will then be consolidated into the quarterly internal audit status update to the Board Risk and Assurance Committee.

In addition to this reporting process any overdue actions will be subject to the corrective action escalation procedure. This includes three, six and twelve month escalation triggers to the responsible executive, CEO and Board Risk and Assurance Committee to ensure appropriate governance and focus over the timely implementation of agreed remedial actions.

Appendix A – List of Background Reports

The following is a list of background reports prepared to support the investigation.

Customer Engagement Report (Joint Transpower and Vector report)

NZ Fire Service Fire Investigation Report – 19 Gavin St, Ellerslie, Auckland

Cable Consulting International Report - Investigation into a Fire in a Cable Trench at Penrose Substation

History of Penrose Substation (Joint Transpower and Vector report)

Transpower - Asset Management Practices

Vector - Asset Management

Vector – Risk Management

Appendix B – Sequence of Events

The sequence of events listed below covers the time period from the initial fault (at 23:21 4 October) through to NZFS handing control of Penrose substation back to Transpower (at 09:57 5 October). At this point recovery operations commenced.

Date/time	Description
4/10/2014	
23:21:00	Vector's 11 kV feeder K10 at Remuera substation tripped
5/10/2014	
1:21:00	Vector's 11 kV feeder K10 at Remuera substation tripped after a close order
2:04:29	Sequence of unusual alarms from equipment at Penrose commenced
2:09:00	Transpower NGOC called out the substation maintainer to attend at Penrose
2:10:42	Penrose 220/33 kV transformer T11 tripped
2:11:39	33 kV feeder Remuera No 3 tripped
2:12:31	33 kV feeder Newmarket No 3 tripped
2:14:31	11 kV feeder tunnel auxiliary tripped
2:14:47	33 kV feeder Carbine No 2 tripped
2:16:45	33 kV feeder Remuera No 2 tripped
2:17:35	Member of the public called emergency services, to report three explosions at Penrose
2:22:46	33 kV feeder St Johns No 3 tripped
2:22:46	All 22 kV supply from Penrose interrupted by tripping of three 33/22 kV transformers
2:25:00	NZ Fire Service appliances arrived at Penrose substation gate
2:41:00	Substation maintainer arrived at Penrose substation and opened road gate to allow NZFS access
2:44:58	11 kV feeder McNab K02 tripped
2:48:42	33 kV feeder Carbine No 1 tripped
2:48:46	33 kV feeder Mt Wellington No 2 tripped
2:48:54	33 kV feeder Mt Wellington No 1 tripped
2:50:00	Transpower NGOC advises Vector EOC that it will be necessary to de-energise all remaining 33 kV supplies
2:57:13	33 kV feeder Sylvia Park No 2 tripped
2:57:58 to 3:17:12	All remaining in-service 33 kV equipment and supply transformers de-energised
3:04:59	11 kV feeder McNab K19 tripped
3:22:00	Fire Service advised by Transpower that power is off to switchgear building area

Date/time	Description
3:32:00	Firefighting commences, with foam applied to cables exiting ground near 33 kV switchgear building
4:26:00	Transpower Regional Services Manager requests complete shutdown of the 220 kV yard
4:35:00	220 kV switchyard fully de-energised
4:37:00	Fire Service advised by Transpower that the 220 kV switchyard is completely de-energised. Now able to apply foam along trench eastwards into 220 kV area.
9:57:00	Fire Service transfers control of the site back to Transpower
10:41	Penrose 220 kV busbar test livened
11:48	Penrose 220/33 kV transformer T7 returned to service to restore local service power supplies to the substation
11:54	Penrose 220/110 kV transformer T6 returned to service to restore security to 110 kV supplies to CBD
13:47	Restoration suspended for approximately one hour when the NZ Fire Service had to be called to deal with smoke from smouldering timber
14:52	Penrose 33 kV busbar re-energised
15:17	33 kV feeders Newmarket 1 and Newmarket 2 livened
15:23	Penrose T21 and T22 re-energised, to liven 22 kV switchboard
16:46	Penrose 220/33 kV transformer T8 re-energised, to provide security to 33 kV busbar
16:50	33 kV feeders McNab No 1 and 2 livened
17:03 to 17:33	22 kV feeders Glen Innes, Westfield and Onehunga livened
20:47	33 kV feeder SouthPark livened
6/10/2014	
23:26	33 kV feeder St Johns no 3 livened
23:29	220 kV Bus D relivened, together with cable connections to Hobson St
7/10/2014	
07:26	33 kV feeder Sylvia Park 1 livened
12:56	33 kV feeder Carbine No 2 livened
17:57	33 kV feeder Mt Wellington No 2 livened
23:53	33 kV feeder Remuera No 3 livened
8/10/2014	
21:22	Penrose 220 kV Bus B and C restored, bringing Penrose back to full pre-event security levels.

Appendix C – List of Cables in Cable Trench

Trench Position	Circuit	kV	Cable Type
1A	Remuera No3	33	3x1c Al 400 XLPE HDPE
1B	Newmarket No3	33	3x1c Al 400 XLPE HDPE
1C	FO Duct	-	Telecom FO cables
1D	Remuera No2	33	3x1c Al 400 XLPE HDPE
2A	Carbine	-	Pilot 25C 9+16
2B	Not in use	11	3c Al 300 PILC STA
2C	McNab K19	11	3c Al 300 PILC STA
2D	Carbine No1	33	3c Al 300 PICAS O.F PVC
2E	Carbine No2	33	3x1c Cu 630 XLPE HDPE
2F	Tunnel Supplies	11	3c Cu 35 XLPE HDPE
3A	McNab K02	11	3c Cu 0.25 PILC STA
3B	Remuera K10	11	3c Cu 0.25 PILC STA
3C	Westfield No 2	22	3c Cu 0.37 PICAS O.F PVC
3D	Westfield	-	Pilot 0 + 32C
3E	Westfield No 3	22	3c Cu 0.37 PICAS O.F PVC
3F	St Johns No3	33	3x1c Cu 630 XLPE HDPE
4A	St Johns No1	33	3c Cu 0.45 PICAS O.F PVC
4B	St Johns	-	Pilot 25C 9+16
4C	St Johns No2	33	3c Cu 0.45 PICAS O.F PVC
4D	Mt Wellington K05	11	3c Cu 0.25 PILC STA
4E	Mt Wellington No2	33	3x1c Al 400 XLPE MDPE
5A	Mt Wellington	-	Pilot 25C 9+16
5B	Mt Wellington No1	33	3x1c Al 400 XLPE MDPE
5C	Sylvia Park 1	33	3x1c Al 400 XLPE MDPE
5D	Sylvia Park 2	33	3x1c Al 400 XLPE MDPE

Post-script note:

The Security and Reliability Council received the draft version of the following report at its 9 November 2015 meeting.

The final version of this report is available from <http://www.ea.govt.nz/monitoring/enquiries-reviews-and-investigations/2014/section-18-review-of-auckland-power-outage-5-october-2014/>

TITLE: **Draft Notes: Investigation into a Fire in a Cable Trench in Penrose Substation**

REPORT: **Final Draft**

CUSTOMER: **Vector and Transpower**

AUTHOR: ***Eur Ing Brian Gregory BSc, CEng, MIEEE, FIET***

DATE: **13th August 2015**

Distribution: **CONFIDENTIAL**

Executive Summary

On 5th October 2014 a fire was reported at the Penrose Substation. The fire damaged a large number of Vector cables that were installed in a cable trench in the 220 kV switchyard. The damage to the cables resulted in the loss of supply to Auckland's eastern suburbs.

The Author was engaged by Transpower and Vector to investigate the cause of the fire. This report presents the findings of the investigation, and the Author's recommendations for the future installation of cables in similar environments.

The Author has carried out a comprehensive investigation into the cause of the electrical failure and the resulting fire, at both the Penrose substation and the Edif ERA Laboratory in Leatherhead, Surrey. Further analysis and interpretation of results has been performed at the CCI offices in Underriver, Kent. The Author has been afforded full access to the cables and the cable trench, and all background information, as well as the required testing and analysis facilities, to enable this investigation to be undertaken.

The investigation has covered:

- Cause of the fire
 - Examination of the cables in the cable trench
 - Examination of samples of cables retrieved from the cable trench, both at Penrose substation and at Edif ERA
- Cause of the transition joint failure
 - Detailed examination of the 11 kV PILC to XLPE transition joints
 - Analysis of the electrical stress distribution in the 11 kV PILC to XLPE transition joint
- Assessment of the condition of cables and joints in the cable trench
 - Assessment of the condition of all cables in the cable trench, based on samples of cables retrieved from the Gavin Street end of the cable trench which was least affected by the fire
 - Analysis of the current rating of the cables in the cable trench
- Assessment of the fire development
 - Analysis of the locations of the electrical faults on cables that occurred as a result of the fire
 - Analysis of the energy in the electrical arcs
- Analysis of the fire performance of the cable types installed in the cable trench
- Review of published information related to cable fires and fire performance of cable types

The Author's main conclusions are:

1. The fire was initiated by a power arc in an 11 kV PILC to XLPE transition joint in the Remuera K10 circuit. The energy from the first power arc had the capability to violently burst open the polymeric heat shrink sleeves and copper knitmesh cloth and so admit air into the joint. The arc produced a high temperature that was capable of igniting the flammable joint materials in the presence of air, these being the polymeric sleeves, the PILC cable core insulation (hydrocarbon compound impregnated paper insulation) and the XLPE cable insulation.
2. The fire was accelerated by a second power arc when voltage was reclosed onto the failed joint, and by the subsequent failures of the 33 kV XLPE cables that have wire screens and flammable polyethylene oversheaths. The OF cables did not contribute until the end when aluminium sheaths ruptured and significantly increased fire severity. Each cable type was flammable and a severe fire was inevitable.
3. The cause of the transition joint failure is the vulnerability of the transition joint design, with respect to the electrically stressed insulation in the crutch between the PILC cable cores. This is the position where the power arc occurred. It should be noted that none of the insulation of the failed joint survived the fire and this conclusion is based on the examination of the unfailed transition joint.
4. The older, belted, unscreened, three-core PILC cable type is inherently incompatible in design and material types with the newer screened XLPE single core cable and its materials. In a joint, the transition between the unscreened and screened cable systems occurs in the crutch of the PILC paper insulated cores and this is the key reason for the generic vulnerability of a transition joint.
5. The contributory causes of the transition joint failure are:
 - a. Thermo-mechanical disturbance. The joint was positioned on a curved cable and was not cleated or supported.
 - b. Water entry into the paper insulation at the crutch of the PILC cores. The water seals were short in length and on surfaces that allowed variable adhesion.
 - c. PILC impregnating compound drying-out of the paper core within the joint.
 - d. Migration of the void filling compound to the paper insulating tapes underneath the lead sheath.
 - e. Damage to the paper tapes due to the difficulty of effectively inserting high permittivity void filling compound.

6. The original 11 kV PILC joints would not have caused a fire on failure. The conventional PILC joint designs have low electrical design stresses and are mechanically robust. A synergy was seen to exist between the PILC cable and the conventional cast-iron joints. During the filling of the joint the hot bituminous insulating compound had mixed with the oil-rosin cable impregnant. It had penetrated long distances along the cable core interstices and paper tape butt gaps, thereby filling and insulating any air voids that are normally formed during jointing.
7. The progression and location of each cable failure had not been influenced by fire-fighting. All of the cable failure incidents had occurred by 3:04:29, which was before the Fire Service was admitted to the Penrose Switchyard and commenced applying foam at approximately 3:23 am.
8. The fire performance of the three cables types is described below.
 - a. The polyethylene sheathed, wire screened, 33 kV XLPE cables exhibited the poorest cable fire performance. The polyethylene and XLPE insulation have a high heat release during combustion and thus spread combustion more readily. The cables dripped burning globules and strings of molten polyethylene to spread fire to cables below. The wire screen cable design does not have a metallic sheath or armour, and therefore the cable has limited protection to an external fire.
 - b. The oil cables had remarkably good fire performance with only one cable suffering an electrical fault. The corrugated aluminium sheaths were seen to have withstood the fire with less damage than other cable types. Their good fire survivability time is attributed to the high thermal capacity and high melting points of the extruded aluminium sheaths.
 - c. The 11 kV PILC cables had the best fire performance. The good fire survivability is attributed to the two robust layers of steel tape armour (high thermal capacity and high melting point), the good high temperature performance of the paper insulation and its low insulation design stress. The downside of PILC fire performance is that the lead sheath melts at low temperature and flammable impregnating compound then drips out, prospectively spreading fire to the cables below.
9. The OF and PILC cables did not contribute to the early development of the fire and the spread to the XLPE cables.
10. A detailed examination of the XLPE, OF and PILC cables has shown them to all be in good condition. Based on the results of the tests the residual life of the XLPE, OF and PILC cables are predicted by Edif ERA to be 20,

15 and 10 years respectively. Edif ERA noted that some XLPE cables had experienced temperatures above their maximum design operating temperature.

11. The operating temperatures of all the cable circuits and all the types of cables within the cable trench in both the Summer and Winter seasons has been satisfactory, being below their maximum design operating temperatures for continuous operation with sufficient margin to allow for variations in the trench geometry.
12. The temperature calculations show that the reason samples of XLPE cable insulation had experienced temperatures above their maximum design operating temperature was not due to overheating in normal service operation. It is concluded that the cause was heating by hot air from the fire.
13. At the time of the fire, too many cables had been installed in the trench. This did not contribute to the cause of the joint failure, but did contribute to the rate of fire spread. Fire tests have shown that there is a critical mass and critical spacing dimensions at which cable fires accelerate.
14. From a review of publications, while in-air cable installations have been reliable, there has been an appreciable, low incidence of major cable fires. A few of the major cable fire reports and cable system failure reports were found in the public domain. In general i) the cause of a fire, the remedial measures and the lessons learnt are not given in sufficient detail and ii) it is only possible to find information if the incident has received wide publicity.

The Author recommends that:

1. Risk assessments be performed on in-air installations to identify the possibility of electrical failure of the cable lengths and joints.
2. The location of other transition joints installed in air on the network be reviewed.
3. For in-air applications, a technical specification be prepared for transition and straight joints, which includes demonstrated low fire propagation and power arc containment test performances.
4. For new XLPE insulated cable circuits, in significant in-air applications:
 - a. Cables be specified with a Low Smoke Zero Halogen sheath.
 - b. Joints of any type be excluded from the in-air installation.

- c. Wire screened XLPE cable circuits be installed with a minimum separation to other cables to be advised by fire test houses and cable manufacturers.
 - d. Data and communication cables be installed in a separate fire segregated route.
- 5. If transition joints installed in air are unavoidable, they be installed within an arc resistant housing.
- 6. For each significant in-air application:
 - a. The rating capacity be calculated and retained on file and be updated as part of the approval process for any new circuit.
 - b. The in-service temperature be monitored at regular intervals, and correlated to the calculated cable ratings.
- 7. Voltage not be reclosed onto a failed circuit.
- 8. The joint design and jointing process be made more consistent with respect to a) the water seals and b) the void filling mastic.
- 9. Alternative designs of transition joints be assessed.
- 10. Cable support designs be reviewed for all in-air cable installations.
- 11. Joint failure statistics be compiled and regularly reviewed.

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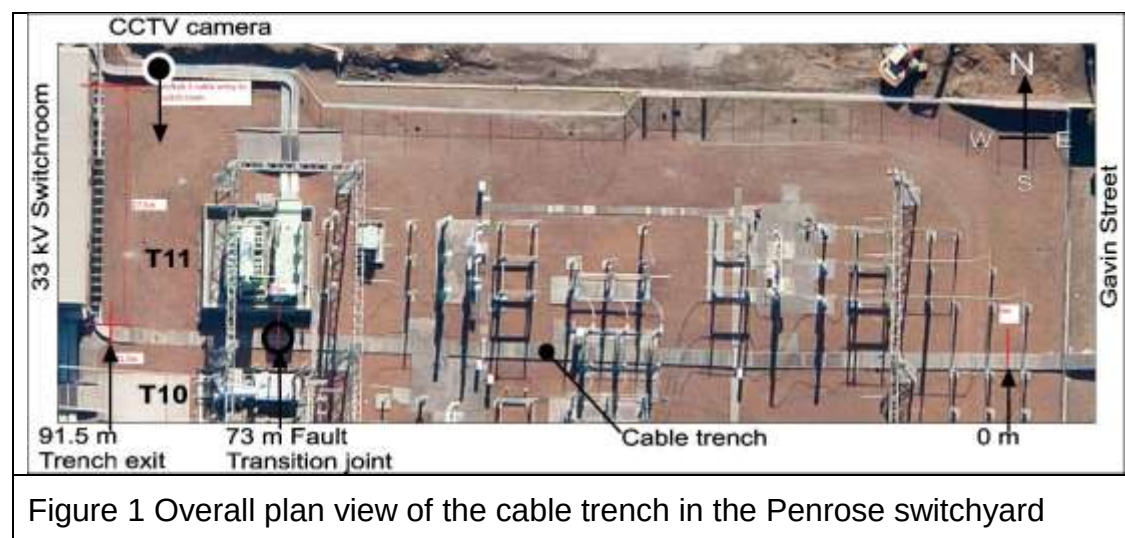
1 Background

On Sunday 5th October 2014, a fire was reported at the Penrose Substation. The fire damaged a number of Vector cables that were installed in a cable trench in the 220 kV switchyard. The damage to the cables resulted in the loss of supply to Auckland's eastern suburbs. The area affected by the fire is shown in Figure 1.

The Author was engaged by Transpower and Vector to investigate the cause of the fire and to provide recommendations regarding the future installation of cables. The Author is Technical Director for Cable Consulting International and is a world expert in cable systems, having previously been Chief Engineer and Chief Development Engineer of BICC Cables.

The Author arrived in Auckland on 10th October and inspected the cables in the cable trench along with the Fire Service investigator and the insurance assessors. The cable trench had remained sealed until this inspection was carried out. The Author was afforded full access to the cables and the cable trench, and all background information, as well as the requisite testing and analytical facilities, to enable this investigation to be undertaken.

This report presents the findings of the Author's investigation, including the inspection and examination of the cables and joints at Penrose and in the United Kingdom, and the Author's conclusions based on the analysis and interpretation of the results.



2 Trench Reference Co-ordinates for the Investigation

2.1 Trench Dimensions

The cable trench runs across the 220 kV switchyard from the East at Gavin Street to the West at the 33 kV Switchroom, Figure 1. A plan of the location of the East end of the trench showing the zero 'chainage' reference position is given in Figure 2. The zero position is 13.5 m from where the cable emerges from the laid-direct section at Gavin Street. The West end is shown in Figure 3. The chainage measurements in this report refer to the distance to the West from the zero chainage reference position. The chainage to the point where some of the cables exit to above ground near the 33 kV Switchroom is 91.5 m and the total cable trench length to this point from Gavin Street is 105 m.

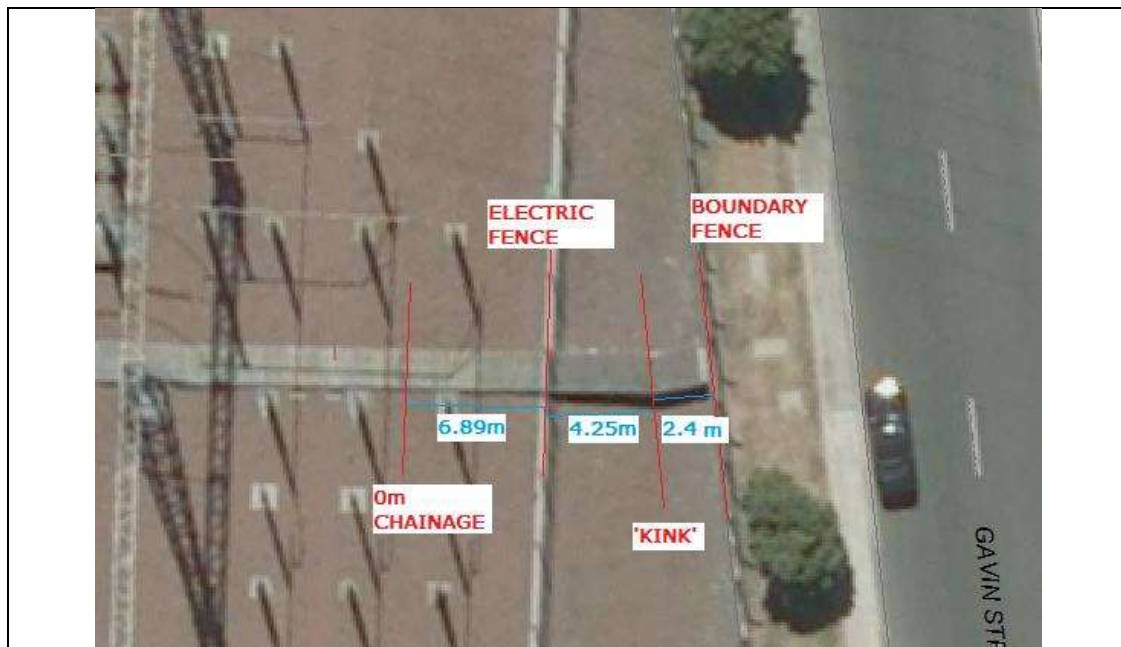


Figure 2 Location of the East end of the cable trench near Gavin Street

In addition to the 33 kV cables that exit to above ground at the 33 kV Switchroom some cables continued underneath the West boundary of the compound and become laid-direct, amongst these are two 22 kV OF (oil filled) cables (Westfield 1 and 2). Three 33 kV OF cables (Carbine 1, St Johns 1 and 2) turned south at the trench West end into a smaller South running trench and then rose above ground to be terminated into cable outdoor sealing ends, adjacent to which cable oil feed tanks (reservoirs) were located. There were no fire barriers to segregate the cable exit to above ground at the 33 kV Switchroom, or between the East-West and North-South trenches.

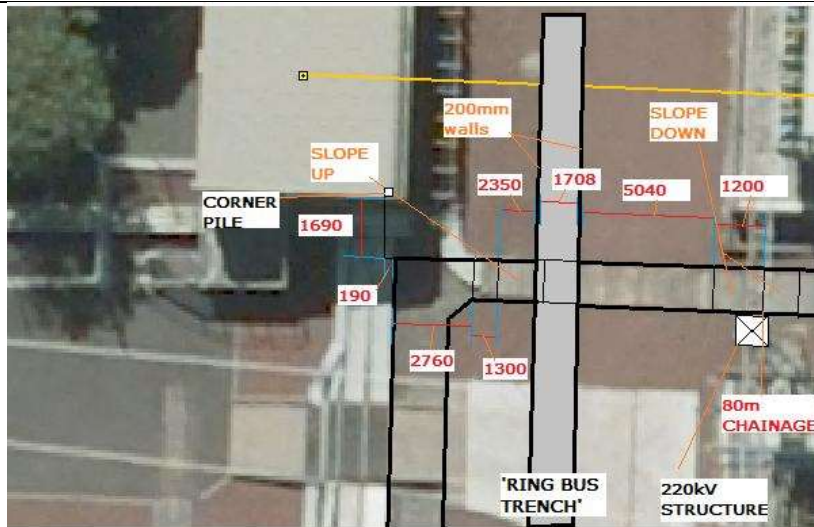


Figure 3 Location of the West end exit of the cable trench within the Penrose Substation near the 33 kV Switchroom (top left)

A larger concrete 220 kV Ring Bus trench is shown to pass below the cable trench. At the time of the fire this trench was under construction with an open top and did not contain 220 kV cables. A temporary timber bridge was present near the 33 kV cable exit that provided access for personnel to the Switchyard.

The trench cross-sectional dimensions, the support arm lengths and the centre-line spacings are given in Figure 4.

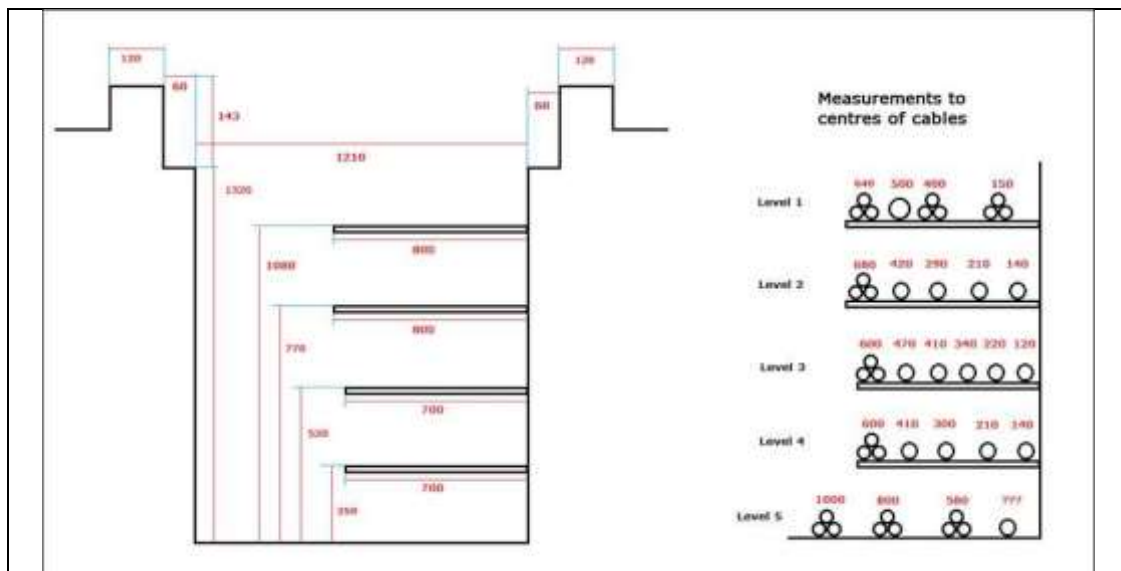


Figure 4 Trench dimensions and cable centre-line spacings at 65 m

The concrete slabs that form the trench cover each have two 45 mm diameter cylindrical holes. The original purpose of the holes is not known. The holes will help to partly ventilate the hot air produced by the cable heat losses. The holes were used by the fire-fighters and by Northpower to lift and remove the slabs.

Inside the trench a small access-way is present of height 1,320 mm and width 410 mm width adjacent to the South wall. At the time of the fire an XLPE cable trefoil circuit, 33 kV Sylvia Park N° 2, was present on the floor of the access way.

An example of the spacings between the cable support arms is shown in Figure 5 for the chainage distances 60 m to 64.5 m. The average spacing is 1.125 m.

Figure 5 also shows which of the 33 kV XLPE circuits in trefoil formation were cleated to the cross arm supports. It is shown that the five trefoil circuits are cleated to every second support arm on Levels 1, 2 and 3, but that the three cables forming the 33 kV Mt Wellington 2 circuit at the end of the arm on level 4 is not cleated.

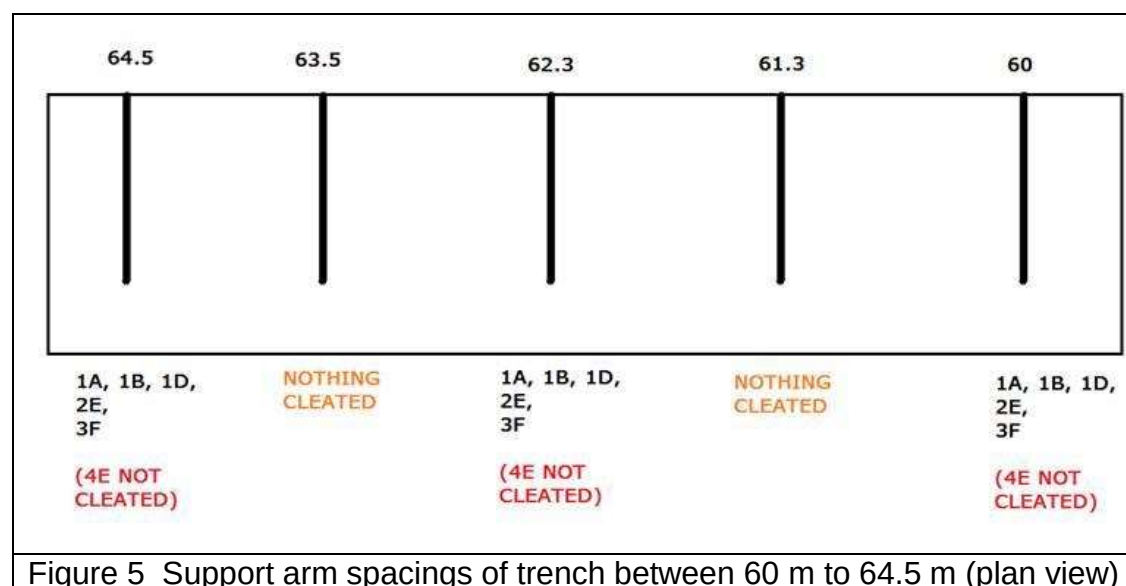


Figure 5 Support arm spacings of trench between 60 m to 64.5 m (plan view)

2.2 Designation of Cable Circuits

Figure 6 shows the circuit locations in the trench cross section at the 73 m chainage position and the alpha-numeric reference designations that they were given for the purpose of the investigation.

For example, '3A0' at 73-74 m chainage is the designation for the position of a traditional 11 kV PILC straight joint in a cast-iron shell. Figure 6 shows the circuit

to be 11 kV PILC McNab K02. This cable circuit runs throughout the length of the trench at the same cross-section position:

1. '3' indicates the circuit is on the third support arm down from the top
2. 'A' indicates the circuit is the first cable from the North wall of the trench
3. '0': indicates it is a self-contained three core cable. Had the circuit comprised three XLPE single core cables, each cable would have been designated X, Y or Z as shown in Figure 6.

The above cross-section designation relates to the support arm level that the cable occupies for all the trench length.

There are two exceptions where the cables change their cross-section positions:

1. The first is the location of the two main subjects of this document these being the transition joints between 11 kV PILC and XLPE cable in the Remuera K10 circuit at 73 m and 79m on Level 2. This cable runs on Level 3 through the main run of the trench and so carries the designation '3B0'. The cable rises to Level 2 between 71.5 m and 81 m chainage, Figure 6. It is this 11 kV Remuera K10 circuit that was the first to fail. The failed transition joint is located at 73 m chainage. This location is described in Section 10 and shown diagrammatically in Figure 41.
2. The second is a cable transposition near to Gavin Street and is not important to this investigation.

In this document the designation 'failed joint' refers to the transition joint in the 11 kV PILC Remuera K10 circuit at 73 m and 'unfailed joint' to the transition joint in the same circuit six metres to the West at 79 m.

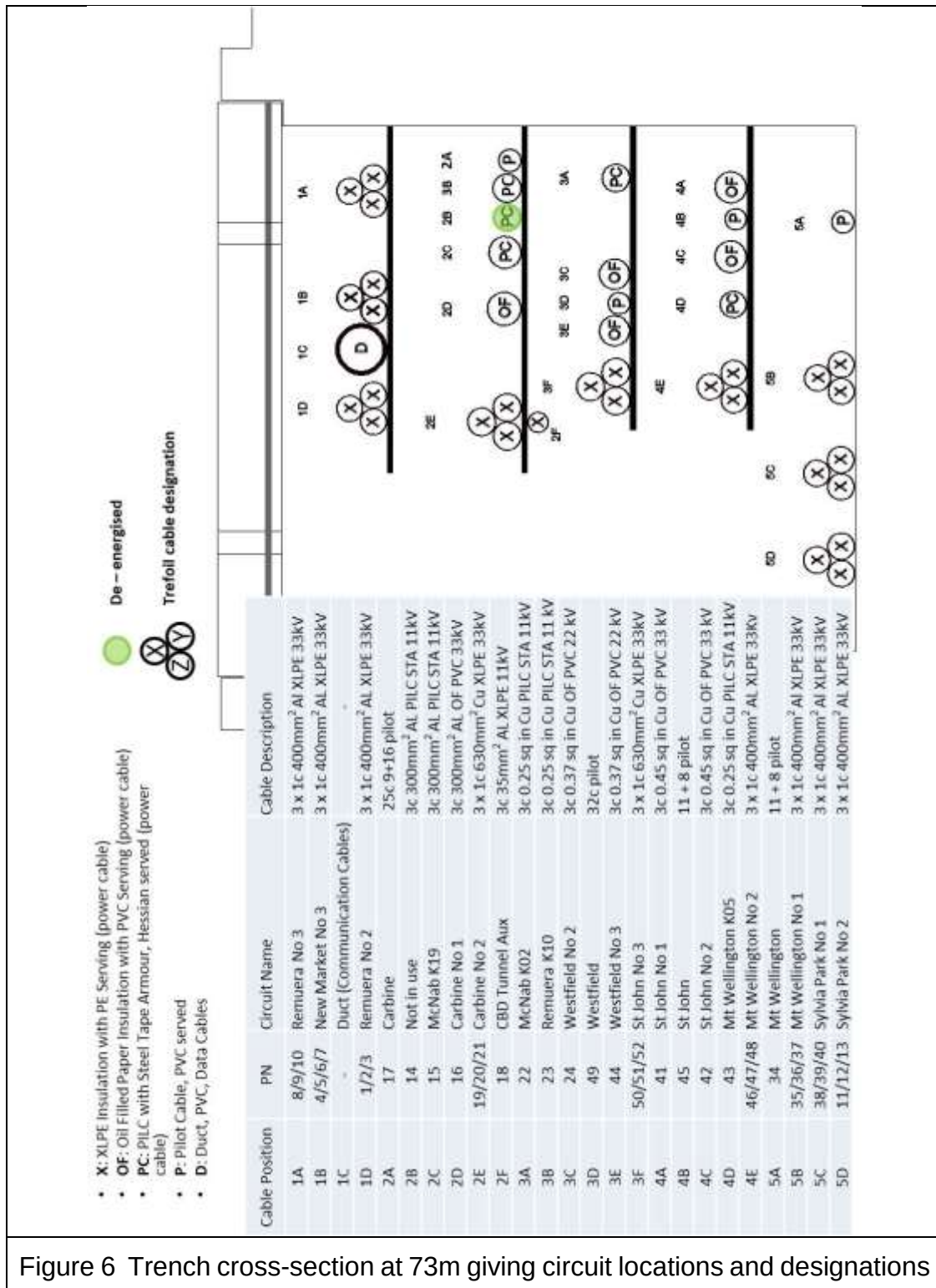


Figure 6 Trench cross-section at 73m giving circuit locations and designations

2.3 Photographs of Trench Cross-section

A photograph taken during the inspection of the trench on 1st August 2001, thirteen years before the fire is shown in Figure 7. The photograph is taken looking eastwards close to the exit into Gavin Street, which can be seen in the background. The view is near the 'zero metre' chainage reference point taken during the investigation for length measurement.



Figure 7 Photograph of the cable trench in 2001, near zero m, before the fire

Four power cable circuits are seen to be present on Level 2. As explained in Section 10 the first electrical fault occurred on Level 2, but further westwards at chainage position 73 m.

Starting from the left hand wall end of the support arm the Level 2 cables are:

- 2A0: Carbine, pilot cable, uncleated.
- 2B0: 11 kV 3/C PILC cable, uncleated (not in use in 2014 at the time of the fire).
- 2C0: McNab K19, 11 kV 3/C PILC cable, uncleated.
- 2D0: Carbine 1 circuit, 33 kV 3/C oil-filled cable, uncleated.
- 2E: Carbine 2 circuit, 3 x 33 kV S/C XLPE cables, cleated in trefoil.

The cables can be seen to be supported on timber battens bolted to a horizontal arm of galvanised angle-iron. The arm is bolted to a galvanised vertical angle-iron with gusset strengthening pieces. The steel vertical is bolted to two studs that are fixed into the North wall (left hand side). The trench access-way is on the South wall (right hand side).

Levels 1 and 2 appear to be fully occupied with cables.

One cable can be seen at the end of Level 3, (3F: St Johns 3 circuit, 33 kV, 3 x S/C XLPE cables, in trefoil).

The visible end of Level 4 is empty.

The visible part of Level 5, the floor of the access way, is empty (in other photographs cables are present on the floor, but are closer to the North wall).

A photograph of the cable trench after the electrical failure on the 4th October 2014 is shown in Figure 8. The photograph is at the position of the first electrical fault at 73 m chainage. The view is of the cable circuits on the top layer. Starting from the left hand wall end of the support arm the cables are:

- 1A0: Remuera 3 circuit, 3 x 33 kV S/C XLPE cables, cleated in trefoil.
- 1B0: New Market 3 circuit, 3 x 33 kV S/C XLPE cables, cleated in trefoil.
- 1C0: Duct for data cables. The duct and plastic cable have melted. The glass fibres remain.
- 1D: Remuera 2 circuit, 3 x 33 kV, S/C XLPE cables, cleated in trefoil.

The electrical fault occurred on Level 2 in a transition joint in Remuera K10, an 11 kV 3/C PILC cable, located below 1B0, the New Market 3, 3 x 33 kV S/C XLPE cable circuit. The remains of the transition joint can be seen on Level 2.

The trefoil cleats on Level 1 can be seen to have been i) broken open as a consequence of the fault current electromagnetic forces and ii) melted from the heat of the fire. The cables in three of the groups on Level 1 have been laterally displaced from their trefoil formation by the electromagnetic force.

Two cable circuits can be seen on Level 5, the floor of the access way, amongst the carbonised debris, these being Sylvia Park No 1 and 2: 3 x 33 kV, S/C XLPE cables.

One phase of a 33 kV S/C XLPE cable had fallen from a higher level onto the cable circuit on the floor.



Figure 8 Photograph of cable trench at 73 m taken after the fire in October 2014

2.4 Summary of Trench Contents: Circuits and Cables

At the time of the fire in October 2014 the 103.9 m long trench contained 38 power cables, 4 pilot cables and a number of ducts and optical fibre cables as listed below. The combined equivalent single length of all the power cables is 3.84 km. One 11 kV PILC cable was not in use making 19 operational circuits. The combined equivalent single length of all the operational power cables is 3.83 km.

1. Power cable circuits: 20* (19 in use), comprising 38 individual cables:
 - a. Groups of three single core cables: 9, 27 single core cable
 - b. Three core cables: 11
 - i. 11 kV PILC: 5*
(*one out of use)
 - ii. 22 kV oil filled cable (OFC): 2
 - iii. 33 kV oil filled cable (OFC): 3
 - iv. 11 kV XLPE: 1
2. Pilot and communication cables: 4
3. Optical fibre cable (3 DTS: in Remuera 2 and 3 and Newmarket 3) 3
4. PVC 110 mm OD duct on Level 1,

containing multiple optical fibre cables:	1
5. HDPE 54 mm OD ducts	2
6. Earth conductors (interpreted to be one long conductor and short transverse conductors):	1
7. Substation lighting cables:	1

Table 1 Circuits in order of date of installation and cable manufacture

Trench Position	kV	Circuit	Cable Type	Year Install	Sample PN				Year Cable
3A	11	McNab K02	3c Cu 0.25 PILC STA	1966	22				1965
3B	11	Remuera K10	3c Cu 0.25 PILC STA	1966	23				1965
4A	33	St Johns No1	3c Cu 0.45 PICAS O.F PVC	1966	23				1965
4B	-	St Johns	Pilot 25C 9+16	1966	45				*
4C	33	St Johns No2	3c Cu 0.45 PICAS O.F PVC	1966	42				*
4D	11	Mt Wellington K05	3c Cu 0.25 PILC STA	1966	43				1965
3C	22	Westfield No 2	3c Cu 0.37 PICAS O.F PVC	1967	24				*
3D	-	Westfield	Pilot 0 + 32C	1967	49				*
3E	22	Westfield No 3	3c Cu 0.37 PICAS O.F PVC	1967	44				*
2A	-	Carbine	Pilot 25C 9+16	1967	*				*
2B	11	Not in use	3c Al 300 PILC STA	1977	14				1977
2C	11	McNab K19	3c Al 300 PILC STA	1977	15				1977
2D	33	Carbine No1	3c Al 300 PICAS O.F PVC	1977	16				1977
1A	33	Remuera No3	3x1c Al 400mm XLPE HDPE	1999	8	9	10		1999
1B	33	Newmarket No3	3x1c Al 400mm XLPE HDPE	2000	4	5	6	7	1999
1C	-	FO Duct	Telecom FO cables		*				*
2E	33	Carbine No2	3x1c Cu 630 XLPE HDPE	1999	19	20	21		1999
1D	33	Remuera No2	3x1c Al 400mm XLPE HDPE	1999	1	2	3		1999
3F	33	St Johns No3	3x1c Cu 630 XLPE HDPE	2000	50	51	52		1999
5A	-	Mt Wellington	Pilot 25C 9+16		*				*
*5B	33	Mt Wellington No1	3x1c Al 400mm XLPE MDPE	2002	35	36	37		1999
*4E	33	Mt Wellington No2	3x1c Al 400mm XLPE MDPE	2002	46	47	48		1999
5C	33	Sylvia Park 1	3x1c Al 400mm XLPE MDPE	2006	38	39	40		2006
5D	33	Sylvia Park 2	3x1c Al 400mm XLPE MDPE	2006	11	12	13		2006
2F	11	Tunnel Supplies	3c Cu 35mm XLPE HDPE	2012	18				2012
Note *: 5B and 4E 33 kV 3 x 1c XLPE cables replaced the gas filled cable circuits listed below in 2001/2									
*5B	33	Mt Wellington No1	3c Gas Filled cable - removed	1966					1966
*4E	33	Mt Wellington No2	3c Gas Filled cable - removed	1966					1966

2.5 Circuits in Order of Date of Installation and Manufacture

Table 1 shows the following years of installation:

- 10 circuits in 1966/67: 3 x 33 kV OF, 2 x 22 kV OF, 3 x 11kV PILC (including Remuera K10, 3B0) and 2 x 33 kV Gas Filled (replaced in 2002)
- 3 circuits in 1977: 2 x 33kV OF and 2 x 11kV PILC (one not in use).
- 5 circuits in 1999/2000: 5 x 33kV S/C XLPE
- 2 circuits in 2002: 2 x 33kV S/C XLPE
- 2 circuits in 2006: 2 x 33kV S/C XLPE
- 1 circuit in 2012: 1 x 11kV 3/C XLPE

In 1999 a new 33 kV Switchroom was constructed and two of the original 33 kV OF three core cable circuits were replaced with 33 kV XLPE single core cables in trefoil formation to terminate onto the new switchboard.

3 Diagrams of Cable and Joint Types

Table 1 shows that there have been four types of power cables installed in the trench, the designs of which bear testimony to the passage of technology in cable design since the installation of the first cables in 1966. The cable and joint designs are shown diagrammatically and described in Section 18, Appendix B.

The types are summarised below:

- PILC (Paper Insulated Lead Covered), 11 kV three core cable having sector shaped conductors and compound impregnated paper tape insulation. The cable is of the 'belted' type in which, for economy and compactness, the individual core insulation does not have separate insulation and earth screens. The cables are mechanically protected by steel tape armour.

A traditional PILC straight joint matches the same principle of unscreened belted insulation as the cable, except it replaces the paper belt insulation with semi-setting bituminous compound. Similarly it was provided with a robust cast-iron joint shell for mechanical protection.

- SCOF (self-contained oil filled) cable, abbreviated in this document to OF. In the trench 22 kV and 33 kV three cores designs were installed, both having robust corrugated aluminium sheaths and extruded PVC

oversheaths. Although not identical, the designs were closely similar to each other.

OF straight joints are not described as none have been found in the trench to date.

- XLPE (cross-linked polyethylene) cables. The 33 kV cables are of single core design complete with their own triple extruded insulation and semiconducting screens, wire screen earth return conductor and polymeric oversheath. Each phase circuit was formed by laying the three phase cables in a trefoil-touching formation.

A heat shrink sleeve straight joint design reduces the jointing times and the number of jointing skills required. Air voids around the ends of the connector and at the outer insulation screen cuts, which would otherwise be unacceptable places of electrical weakness are filled with an adhesive 'void-filling mastic' having semi-insulating, high dielectric permittivity, stress-control properties. A package of overlying heat shrink sleeves is laid over the prepared cable core and connector. Each sleeve has different properties. The inner sleeve has high permittivity, the next sleeve insulating properties, the last sleeve of the insulation package is the screen that has semi-conducting properties and overall a hot-melt adhesive lined, protective, waterproof sleeve is applied to overlap the cable oversheaths. Originally sleeves were separate and then with the progression of technology have been combined firstly into dual layers and secondly into triple layers comprising both polymeric and elastomeric insulating layers. The elastomeric sleeve has the advantage that its elasticity permits it to conform better to the geometry of the critical interface between the cable and joint insulation and thus helps to exclude air voids.

4 Site Investigation at Penrose Substation

The Author arrived in Auckland on Friday 10th October 2014.

From Saturday 11th October to Wednesday 22nd October the Author performed an initial investigation and examination of the trench at Penrose Substation and part-dissection of selected cables and joints.

The Author was provided with:

1. Two assisting qualified Engineers, one from Transpower and one from Vector, and two experienced Northpower cable jointers.
2. Access to the cable trench in which the fire had occurred.
3. An examination room in which the samples of cables and joints from the cable trench would be dissected, with the assistance of the Engineers and Jointers.
4. A record of the times of the circuit breaker operations.

During the investigation in the Penrose Sub-Station the Author:

1. Walked externally along trench at ground level with the objective of locating the sites of the electrical failures in the cables; notes and photographs were taken of the extent of the fire damage. The electromagnetic disturbance of the cables identified that the most promising location of the first electrical failure and the fire to have been between 72 m and 74 m.
2. Entered the trench and, with two assisting Engineers, examined the cables on the five levels (four racks and the floor) from 65 m to 84 m, in as much detail as the remains of the burnt cables permitted,

As a safety measure the trench had been designated as a contaminated area and samples of the fire debris were despatched for analysis. The analysis confirmed that the samples contained heavy metals and arsenic. The 'contamination' designation was kept in force on the trench and contents during the investigation. The Safety Officers directed that protective clothing and face masks were to be worn in the vicinity of the trench. To enter the trench it was required that a higher level of protective clothing and a full face mask were to be worn. The samples of cable and joint to be removed from the trench were sealed prior to removal. The examination room at Penrose was prepared for, and designated as, a contaminated area and staff were required to wear protective clothing. The samples were later cleaned and sealed before despatch to the UK for continued dissection and chemical analysis.

4.1 Findings From the External Inspection of the Trench

The records were inspected prior to the inspection of the cables in the trench. The records showed that the circuit breakers had operated to clear electrical faults on 13 out of 19 energised circuits. Two circuits were recorded to have been de-energised when the Penrose 33/22 kV transformers tripped. Four circuits had been de-energised when the 220 kV switchyard was de-energised. Thus 13 locations of faulted cable were known to be present and available for discovery within the trench. The first fault was known to be present in the 11 kV PILC Remuera K10 circuit.

The inspection began at zero chainage at the Gavin Street end of the trench as i) the cables at this location had not been burnt by the fire and so provided a control sample of what the trench had looked like before the fire, ii) the cables had been cut at this location by Northpower and were in the process of being diverted and so had been marked with their circuit names and iii) the Fire Investigation Officer requested this procedure be followed to permit the signs and locations of increasing fire intensity to be systematically noted and followed.

The outer polymeric sheaths and the inner XLPE insulation could be seen to have burnt away leaving just the metallic components in the 33 kV XLPE cables occupying Level 1 over a major proportion of the trench length. The outer copper wires of the earth return conductor and the inner conductor wires (copper or aluminium) could be seen.

Disturbance of the outer conductor screen wires on Level 1 was seen between 72 m and 74 m, Figure 9, (the view is facing North). The disturbance is indicative of the presence of one or more short-circuit power arcs that had severed the wires and electromagnetic forces that had violently displaced both the wires from their concentric formation and the cables from their trefoil formation. It can be seen that the cable cleats on the top support arm to the right of the photograph (at 73 m) had been part burst open by the short circuit forces and part melted.



Figure 9 Disturbance indicative of violent electrical activity at 72 m- 74 m

Within the above disturbed region and underneath the Level 1 cable support arm at 73 m, an 11 kV PILC cable to XLPE cable transition joint could be seen to be present on Level 2. This was later identified to be the Remuera K10 circuit, which, from the circuit breaker records, was reported to have electrically faulted first.

Figure 10 is a detailed, close-up photograph of the 11 kV joint on Level 2 taken downwards through the space between two of the cable circuits on Level 1, (the view is facing South). The Level 1, support arm at 73 m is on the right.

The transition joint was seen to have suffered severe fire damage. All of the consumable materials comprising the paper tape insulation and the overlying layers of heat shrink sleeves had been burnt away; only the metals remained.

Two grey cylinders could be seen, these being the aluminium halves of the transition joint's bimetallic ferrules that would normally connect the aluminium conductors in the XLPE cable to the copper conductors in the PILC cable. The factory made friction welds that normally join the aluminium ferrule to the copper

ferrule were seen to have parted and the copper conductors on the PILC cable side (to the left of the aluminium connectors) were missing.



Figure 10. Close view of failed transition joint between cable Layers 1 and 2

The mesh that can be seen is the remains of the copper earth screen tape that the jointer is required to wrap helically over the heat shrink sleeve insulation to give 100% cover. It can be seen that the copper mesh has been severed open by the fault.

A longitudinal braided copper strap is present, this being the earth continuity conductor that connects the lead sheath of the PILC cable (out of view on the left) to the copper screening wires of the XLPE cable cores (out of view on the right). A small crimped compression ferrule can be seen in the centre of the photograph that connects the braid conductor to the screen wires, this connector was the only surviving component that held the two halves of the joint together.

The failed transition joint in Level 2 was confirmed to be in the 11 kV Remuera K10 circuit and connected the three core PILC cable to a three core XLPE cable. The normal position of the cable for the main run through the trench was on Level 3 and for the investigation is designated 3B. The cable was seen to have been raised to Level 2 at 71.5 m and descended again at 81 m, in which length two transition joints had been inserted: the faulted joint at 73 m and an unfaulted joint at 79 m. The cable is seen to be ascending from Level 3 to 2 in Figure 11. (The cable bridge and control cables are new and replace those that suffered fire damage, their location is at 70.5m).



Figure 11 11 kV Remuera K10 cable rising from Level 3 to Level 2

4.2 Findings From the Internal Examination of the Trench

The trench was entered by the Author and one Engineer. The cables that could be reached on each of the five layers were individually examined by torch and by hand; a photographic record was taken. Due to the dirty condition of the cables and the presence of liquid on the trench floor it was not possible to write notes. Examination notes were dictated to the second Engineer who was positioned at the edge of the trench.

Figure 12 is a photograph taken from within the trench, horizontally between Levels 3 and 2. The three missing conductors were found. Two conductors had been partly severed by power arc burning at the end of the joint adjacent to the PILC cable and were hanging vertically downwards.



Figure 12 Two parted conductors hanging from the failed transition joint

One conductor had been completely severed and had fallen downwards onto Level 3, Figure 13. All three copper ferrules were confirmed to have parted at the central bimetallic connector.



Figure 13 The severed conductor from the Remuera K10 transition joint

The whole Remuera K10 joint, including the two conductors that were hanging down, was bound together with white tape to protect the evidence during removal of the joint.

From the dictated examination notes the cable positions that had prospective arc cavities and electrical fault holes were identified to be cut out for examination, these being:

- 66.5 m - 70.75 m, containing nine possible fault holes.
- 70.75 m - 75 m, containing six possible fault holes, the faulted 11 kV transition joint and a conventional 11 kV straight joint with a cast-iron shell.
- 74 m - 75 m, containing one possible fault hole.
- 78.25 m - 81 m, containing no fault holes and an unfailed 11 kV PILC to XLPE transition joint at 79 m, six metres from the centre of the failed transition joint in the same Remuera K10 cable. Although superficially fire burnt this second transition joint was substantially intact.

It was evident that the prospective fault holes were from the 75 m - 66.5 m region, i.e. close to the failed Remuera K10 transition joint centred at 73m and to the East of it.

4.3 Cutting Cable and Joint Samples out of the Trench

The layer of XLPE cables from L1 were cut out and sealed in plastic tubes for transport to the examination room and examination at a later stage.

This revealed the two 2 m long samples containing the failed transition joint at 73 m (Figure 14) and the unfailed joint at 79 m, which were then cut out for dissection in the examination room.

Cable samples were cut off the ends of all the cables near to the zero metre position at the Gavin Street end of the trench. These samples were for reference as to the dimensions, condition and the absence of signs of ageing and incipient electrical activity. The zero metre position is where, during the remedial work after the fire, it had been judged that the cables emerging from burial in the embankment under Gavin Street were sound. The cables had been cut, turned through 90° and jointed onto new lengths of XLPE cable for diversion around the edge of the Sub-Station compound and into the 33 kV Switchroom.



Figure 14 Level 1 cables removed to reveal the failed transition joint on Level 2 and a conventional cast-iron joint below it on Level 3

4.4 Examination for Extent of Fire Propagation and Cable Burning

After the Author returned to the UK the assisting Engineers performed a 'char' inspection of the cables at the Gavin Street end of the cable trench. This was to emulate the assessment of the fire propagation distance that is performed during a type test in accordance with IEC 60332-3-10 and 60332-3-24^{1,2} on cable oversheath materials. The findings of the inspection at different distances from zero chainage were:

- 6.5 m.
 - The Level 1 cables showed no char damage to the PE oversheath of the 33 kV XLPE cables.
- 13.3 m
 - Level 2 and 3 (including the PVC sheathed OF cable in 2D) were also clear of char at this point.
- 20.3 m.
 - All Level 1 XLPE cables (1A, 1B and 1D) showed evidence of charring on the exposed top and side surfaces.

- All Level 1 XLPE cables (1A, 1B & 1D) showed no evidence of charring on the protected inside surfaces (butted against adjacent cables in the trefoil) or on the bottom (as shown in green below).
- The XLPE cable in position 2E was also tested, and found to be the same as the Level 1 cables.
- The OF (PVC sheathed) cable in position 2D was tested and found to be charred on all surfaces.
- No other cables on Level 2 were tested at this chainage.
- Cables on Level 3 showed no evidence of charring.

At the West end of the trench the length of obviously fire damaged cables extended 6.7 m northwards from the trench exit, 5m of which ran along the wall of the 33 kV Switchroom. It was not possible to perform detailed char measurements as cable had been removed and replaced.



Figure 15 Char of the PE oversheath on Level 1 at 20.3 m

In summary:

- 77.9 m (59%) out of 132.5 m of circuit length in the trench and along the 33 kV Switchroom wall was fire damaged.
- 54.6 m of cable was not fire damaged

77.9 m of fire damaged cable comprised:

- 52.7 m eastwards from the failed transition joint at 73 m chainage. The fire reached 20.3 m chainage as shown by the start of char. The 33.8 m length to the end of the trench at Gavin Street that was not fire damaged,
- 25.2 m westward from the failed transition joint at 73 m chainage:
 - 18.5 m to the trench exit at 91.5 m chainage.
 - 1.7 m from the trench exit to the corner of the 33kV Switchroom.
 - 5.0 m along the side of the 33kV Switchroom.
 - The remaining 20.8 m length along the side of the Switchroom was not fire damaged.

4.5 Condition of the Non Fire Affected Cables within the Trench

Samples of the cables from the Gavin Street end of the trench were dissected in the Penrose examination room:

- The extruded PVC oversheaths and the extruded aluminium sheaths of the 48 year old 22kV and 33 kV oil-filled cables at the near zero metre position, remote from the fire, were found to be in sound condition.
- The bitumen impregnated hessian served oversheaths and the steel tape armour of the 48 and 37 year old 11 kV PILC cables had significantly deteriorated down to the lead sheath in places, however the lead sheaths were sound.
- The composite PE/PVC oversheaths of the up to 15 year old XLPE cables were sound.

4.6 Observations on the Layout of the Cables in the Trench

Photographs of the trench inspection performed in August 2001 showed that there was limited space left. The trench was reasonably clean and in good condition. Table 1 and Figure 7 show that the cable circuits had been installed logically with the first cables being position close to the North wall and the lower Levels 3 and 4 being filled first, followed by Levels 2 and Level 1. In addition to the control cables that are an essential part of the oil filled cable circuits there was a comparatively large duct carrying fibre optic control and communication cables at position 1C and various smaller data cables between the power cables. At that date there were 17 power circuits installed (including two Mt Wellington 33 kV gas filled cables that were replaced in 2001/2002).

In 1999 and 2000 two new circuits of 33 kV single core XLPE cables in trefoil formation were added, Remuera N°3 and Newmarket No3. In 2002 two circuits of 33 kV single core XLPE cable replaced the two Mt Wellington gas filled cables. The trefoil groups of XLPE cable occupy more space on the support arms than the compact three core gas-filled or oil-filled cables. From these dates onwards the support arms were progressively filled with 33 kV XLPE cables, with three circuits being laid on the floor, one of which was in the access way. (It is recorded that original oil-filled cables had previously also been laid on the floor underneath the Level 4 support arm.) At the time of the fire the number of data cables interspersed between the power cables appears to have also increased with at least one being laid on the floor.

The reduced space between cable groups raises the question of whether there was sufficient space between cables for heat dissipation by convection and radiation and whether cables in contact may have transferred some heat to each other by conduction. It is of note that the different cable types have different operating temperature limits for continuous loading and so it is undesirable to permit contact between types:

- PILC: 65°C
- OF: 85°C
- XLPE: 90°C

From a short-circuit point of view, self-contained cables having three cores within one sheath do not need to be restrained by short circuit straps. This is providing the metallic sheaths and armour layers have sufficient hoop strength to withstand the repulsive forces between the phase conductors. Up to 1997 all of the paper cables in the trench were of the three core type in this category.

4E shows that five of the single core XLPE 33 kV cables in trefoil groups had been fitted with trefoil cleats that constrained the cables together and to the support arms. One XLPE circuit, 4E, at the outer end of its support arm, is reported at one location, Figure 5, not to have been cleated. The Author saw evidence that plastic cable ties had been fitted around one trefoil group, presumably to hold them during installation, however they should not be relied upon to hold short circuit forces at elevated temperatures. The Author did not see evidence that short circuit straps had been fitted to the three trefoil cable groups laid on the trench floor, however these cables were covered in debris from the fire.

From a thermo-mechanical point of view each of the cables will expand and contract cyclically in both the longitudinal and lateral directions. The risk exists that, if a geometrical imbalance exists in the 100 m long trench then the movement and force will become concentrated at this location risking cyclic fatigue damage or in the case of a joint disturbance to the insulation.

The Author saw three locations where the cables had significant lateral bows (loops) present, possibly placed there during installation. Two bows were present in the XLPE cables on Layer 1. One bow affected all three cables. A second bow had been formed by a jointer in two cores to make space for a straight joint in the third. The third bow was in the loop formed in the 11 kV three core XLPE cable between the two PILC/XLPE transition joints.

It is expected that thermo-mechanical movement would have been concentrated at the failed joint at 73 m as the bow started mid-way along the joint's length. It is understood that the Remuera K10 circuit had carried load in previous years, but, although in the last year it had been voltage energised, it had not carried load as the circuit had been electrically opened at the McNab Sub-Station end. The exception is that the Remuera K10 circuit had carried load for ten minutes on the morning of 4th October. The other cables that were carrying load would have heated the air in the trench and so have heated Remuera K10 indirectly.

4.7 Examination of Samples to Find Cable Fault Holes

The assisting team at Penrose examined the samples of cables that had been identified and cut out as containing prospective fault holes. The fault hole photographs are referred to in Section 11 and shown in Section 20, Appendix C.

The volume of the arc crater within each conductor was quantified by inserting modelling clay into the crater and then immersing the clay in a water filled measuring jar. The volume was calculated from the mass of water displaced. The arc crater volumes are listed together with the short circuit currents and durations in Section 12, Table 16.

5 Location of Fault Path in the 11 kV PILC to XLPE Transition Joint

The Remuera K10 'failed' joint and 'unfailed' joint were laid side by side in the examination room at Penrose and later in the examination room at Edif ERA Leatherhead.

Despite the failed joint having been severely burnt it was possible to confirm that the two joints had closely similar constructional features, these being the overall length, the braid earth conductors across the joint, use of three roll springs to connect the braid to the lead sheath of the PILC cable, the earth strap to screen

wire crimped connector, the use of copper mesh screening tape and the bimetallic friction welded connectors.

It was a reasonable assumption that both joints were of the same design and had been installed at the same time, by the same jointing team and using the same tooling. The background to this assumption is that an e-mail dating from 2001 indicated that remedial action was needed concerning a conventional cast-iron joint that was found to be leaking bitumen from the filling port of the cast-iron shell. The e-mail and photograph, Figure 16, showed that the joint was in the Remuera K10 cable at, or close to, the top of the slope in the trench, this being at 79 m. It was thus taken that the cast-iron joint had been cut out c. 2001 and had been replaced by two transition joints and the six metre length of 11 kV three core XLPE cable.



Figure 16 Straight joint in Remuera K10 at 79 m; photo taken in 2001

The unfailed joint was taken as the reference to provide dimensions and constructional details for the failed joint. The measuring datum was the nominal centre of the joint, this being close to the position of the friction-welded faces in the bimetallic ferrule.

5.1 Arc Crater in the Conductors of the Failed Transition Joint

There was a pronounced, large arc crater present in the three conductors as shown in Figure 17. During the dissection, its position was measured and

transferred to the unfailed joint to find as closely as possible the centre-line of the electrical fault path that had initiated the power arc.

Figure 18 shows the arc crater after the conductors had been cleaned and re-assembled by the Author at Edif ERA. In both photographs the PILC cable is on the right hand side and the centre of the joint is towards the left hand side. The fault current had been fed from Remuera Substation as the cable was open ended at McNab. The sloped eroded face of the conductors on the left hand side shows that the arc was fed from the right hand side and so looped outwards under electromagnetic forces to the left.



Figure 17 Failed joint: arc crater in the three conductors



Figure 18 Failed Remuera K 10 joint: arc crater in three conductors after cleaning and re-assembly

First it would be necessary to partly dismantle the unfailed joint and uncover the internal geometry that was under the various layers of heat shrink sleeves. The dismantling procedure had the additional objectives of searching for incipient failure mechanisms that could have also been present in the failed joint:

- Incipient electrical distress
- Ageing
- Damage
- Jointing errors

5.2 Arc Burning to the Earth Return Conductors

Subsidiary arc burning, Figure 19, was found on the surface of one of the three braided earth continuity conductors ~270 mm from the centreline of the main arc crater in the power conductors and 110 mm from the faces of the bimetallic connectors. The arc burn extended over a comparatively large surface area of 25mm by 75 mm. The three braided conductors had been laid one on top of the other by the jointer such that the arc current had spot-welded them together when they shared the current. Arc burning was also found on severed edges of the copper mesh earth screen indicating that in all probability the overlying outer protective heat-shrink sleeve had been cut open by the arc.

Figure 19 shows subsidiary arc burning on the earth braid continuity conductor face (right hand side) in relation to the main arc crater (left hand side). The photograph was taken after the main conductors and the earth braid had been cleaned at Edif ERA. The power arc had looped longitudinally away from the

main crater in the power conductors and touched the earth braid in a glancing contact, this being deduced from:

- The arc burning did not result in major erosion of the earth braid conductors. The burning had not severed the conductors and was not deep.
- The arc burning on the braid is not in radial alignment with either
 - The arc crater in the conductor
 - The parted bimetallic connectors
- There is no arc burning on the power conductors in the radial vicinity.
- The original fault was recorded as initially phase to phase and then for the majority of time as three phase. The reclose fault was recorded as three phase.



Figure 19 Failed joint: Arc burning to the earth continuity braided conductors

5.3 Parted Connectors in the Failed Transition Joint

The faces of the parted friction welds were cleaned, matched and photographed, Figure 20, Figure 21 and Figure 22. It was found that:

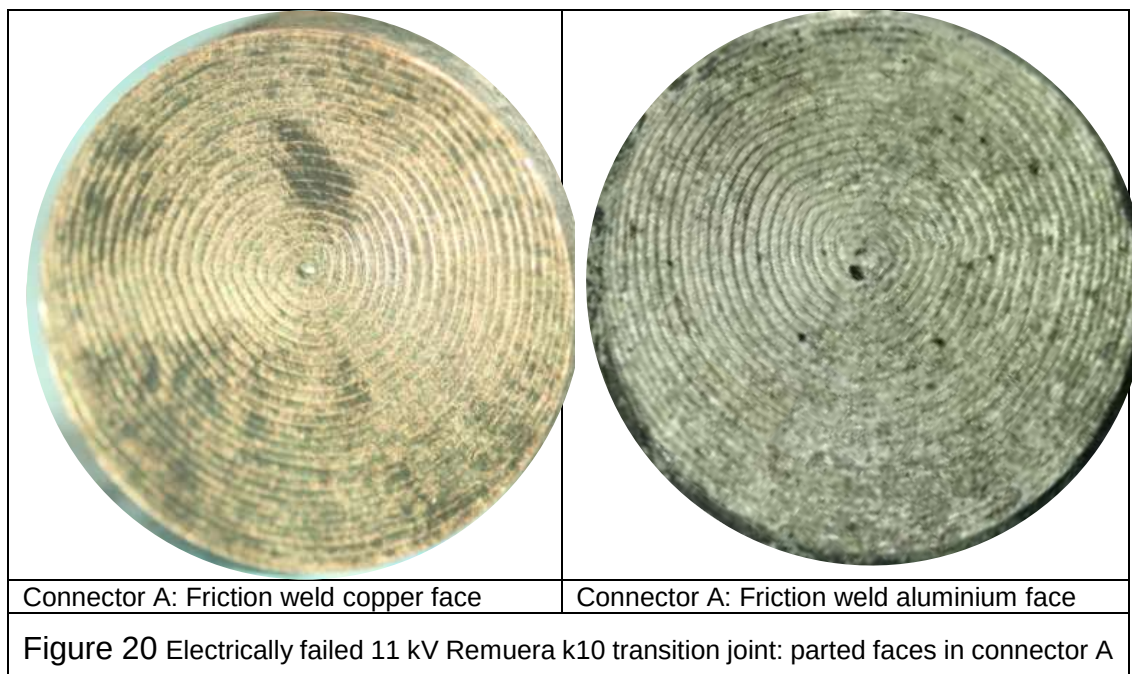
1. There was no direct evidence that the connectors had parted in service or during the electric phase of the failure as i) there was no electrical pitting and arcing and ii) the power arc had occurred in the PILC crutch of the joint and not at the connectors. Arc pitting was absent on the faces, i.e. both low current and high current pitting. Connector B had an aluminium residue present on the copper face that appeared to have been formed by melting, however, there was no evidence of power arc burning and thus it was deduced that this had occurred at the elevated temperature of the fire at the time the connector faces had parted. Although the Remuera K10 circuit had been open-ended at McNab it

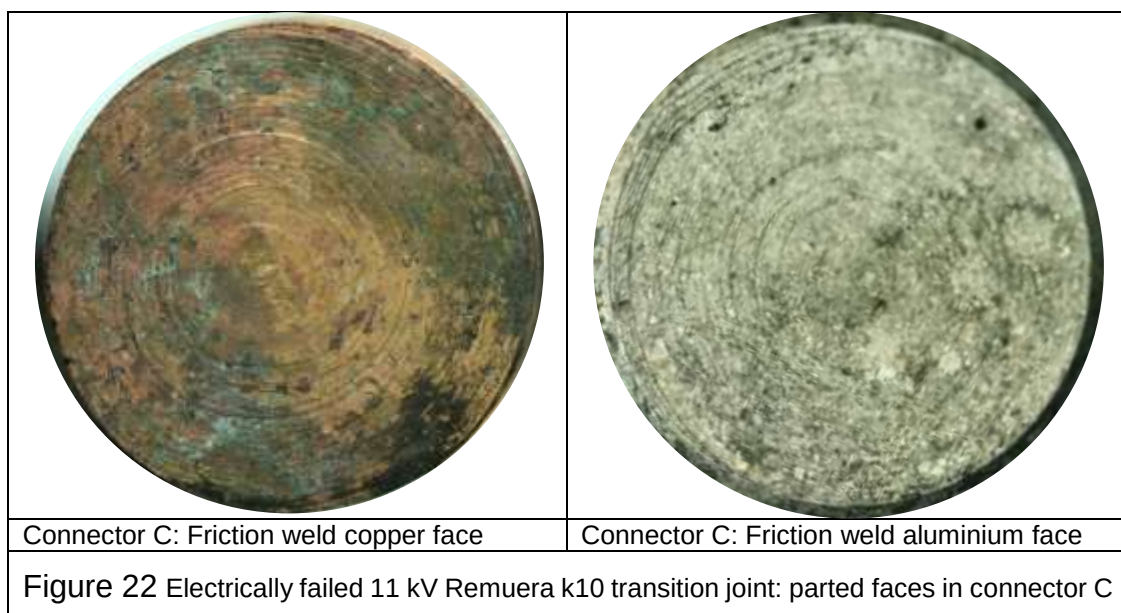
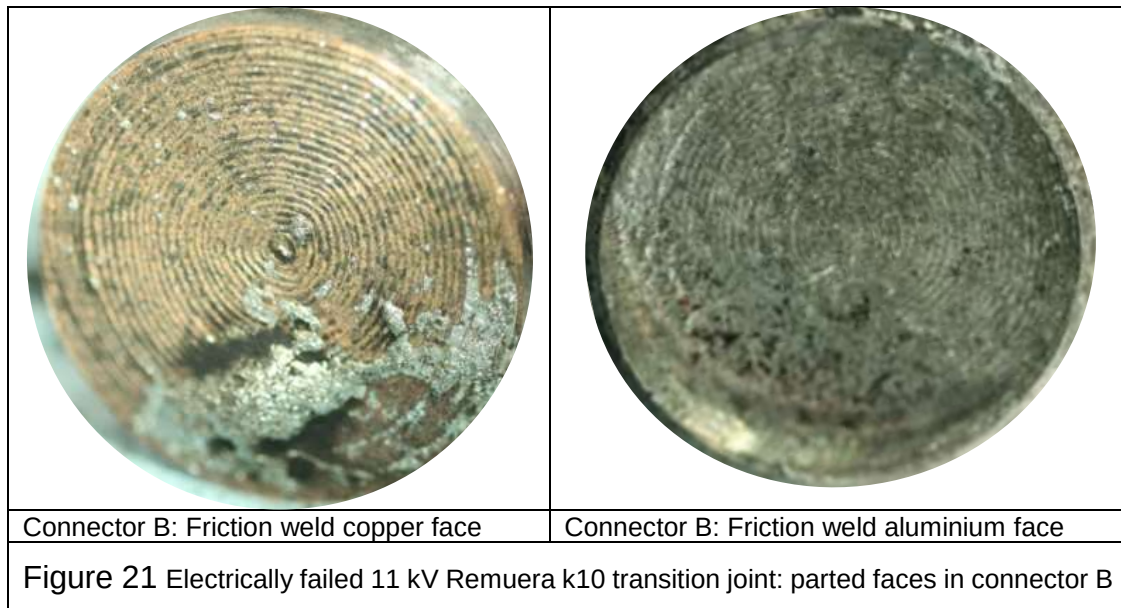
would have carried current earlier on the day of failure when it was switched-in and carried current for 10 minutes and then switched out again. It would in the previous year have carried low level capacitive charging current to energise the insulation capacitance in the length of cable between the joint and the open-point near McNab.

2. The faces each bore unique helical grooves patterns that matched those on the opposite face. The grooves were eccentric and so had not been produced by a lathe tool. It was concluded that the grooves had been produced during the first phase of friction welding when one piece of rotating metal rod is pushed into another, with an eccentric motion, to generate sufficient frictional heat to weld the two dissimilar metals together.

Follow-up Investigation

The parted bimetallic connector from the failed joint and the sound connectors were sent to the laboratories of Edif ERA for examination, testing and metallurgical examination.





5.4 Examination of the Unfailed Transition Joint

Although the fire damage had been less severe at 79 m the outer heatshrink sleeve had suffered fire damage and, although still adhered, had been burnt away along one line of its circumference. It revealed the steel roll springs that were on the lead sheath on the PILC side, Figure 23.



Figure 23 Unfailed joint. The steel roll springs could be seen on the PILC side
The fire has also burnt along the central heat shrink packages to varying degrees to reveal part of the bimetallic connectors, Figure 24.



Figure 24 Unfailed joint. Fire damage to the heat-shrink insulation package
The outer protective heat shrink sleeve was removed to reveal the internal joint components, Figure 25.



Figure 25 Unfailed joint. Outer heat shrink sleeve and copper mesh removed

The arc centre-line measurement was transferred to the heat shrink 'break-out' (glove) in the unfailed joint, Figure 26.



Figure 26 Unfailed joint. The heat shrink 'break-out' covering the PILC crutch

The arc centre-line was denoted by a red pointer and was found to be within the 'break-out' and close to the exit of the core spouts, Figure 27.



Figure 27 Unfailed joint. Arc centre transferred from failed joint

A strip of the semi-conducting heat shrink break-out was removed. The adhesive void filling yellow mastic was removed partly by cutting and partly by pulling. The PILC paper insulation was revealed comprising the core insulation and the end step in the belt's paper insulation. The measured centre-line of the arc in the failed joint was transferred to the unfailed joint (red arrow). This position is close to the end of the yellow barrier tube and adjacent to the termination of the 'belt'. The purpose of the barrier tube is two-fold, i) to prevent loss of the cable's hydrocarbon impregnating compound and ii) to prevent it from degrading the outer polyolefin heatshrink insulation and protective sleeves.



Figure 28 Unfailed joint. Arc centre is in PILC crutch close to oil barrier sleeve

It was found that the yellow void filling mastic inserted by the jointer had adhered to the paper tape insulation and torn it when the 'break-out' was removed, Figure 29.

There were some voids present in the yellow mastic, but it wasn't possible to determine if they had been present before the 'break-out' had been removed. The yellow mastic was noted to have turned brown adjacent to the 'break-out'. The yellow mastic was noted not to have consistently adhered to the lead sheath, this being one of the seals that prevents water ingress into the paper insulation. There were short sealing sleeves present over the ends of the 'break-out' spouts and onto the pressure sleeves. It was found that the overlaps were short and that they had not been uniformly coated with adhesive. Doubt existed that the adhesive seal would have been water-tight.

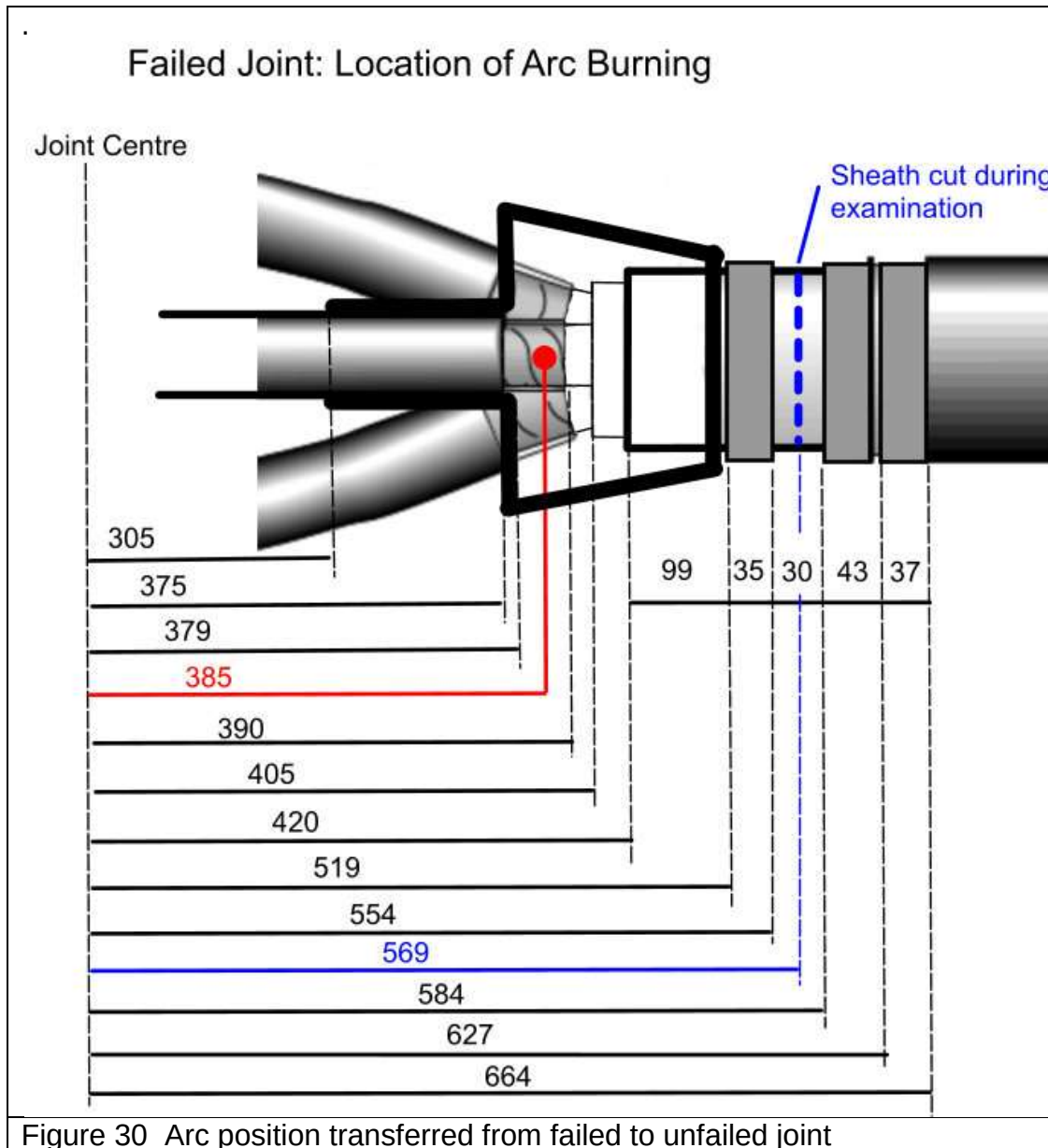
It was possible to determine that the belt paper termination had been cut by the jointer at the specified position, by measuring the length of the belt papers and the length of the jute fillers between the core interstices.



Figure 29 The mastic had not uniformly adhered to the lead sheath

The joint measurements, Figure 30, were found to be closely similar to those given in the Raychem jointing instructions³, thus confirming that the standard of jointing had been satisfactory.

This figure also indicates the position of the arc crater centreline (marked in red) in the failed joint as being 5 mm from the end of the oil barrier tube. However, there are significant uncertainties in the measurement tolerances. Additionally the arc crater had a length of ~62 mm and so it is not possible to know exactly where the electrical fault path that preceded the arc had been. Arc damage tends to move away from the direction of the current feed impelled by electromagnetic forces and so it is probable that the fault path was closer to the belt paper termination at 405 mm or, in the extreme, towards the termination of the lead cut. The lead sheath in the failed joint had been completely melted away so that the position of the arc in relation to the lead cut could not be verified.



The location of the arc and fault positions are shown in Figure 31.

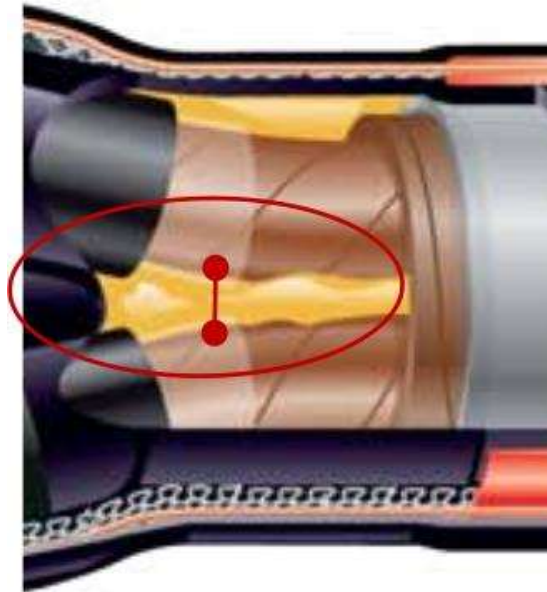


Figure 31 Arc position in the failed transition joint (joint not to scale)

5.5 Other Features Found in the Unfailed Joint

The spring roll connection of the earth braid to the lead sheath of the PILC cable was removed, Figure 32. The jointer had correctly wrapped a copper mesh over the lead sheath. However there were white corrosion products on the lead and green products on the copper mesh and also on the copper braided earth continuity conductor. In the Author's opinion this contact would have overheated and led to failure in a single core joint, in which the contact is required to carry circulating currents in everyday use and short-circuit currents in the event of a system fault. The Author could find no evidence that the connection had overheated and damaged the paper insulation within the sheath. Fortunately in a three core cable there are no circulating sheath currents, however phase to earth system faults can occur that could damage a joint that was otherwise sound. It was concluded that this was not a factor in the joint failure as i) the connector was not located adjacent to the arc cavity in the primary conductors, but at the centre of the joint and ii) the connector appeared to have been mechanically sound before the fire.



Figure 32 White corrosion products at the current contact with the lead sheath

The lead sheath was removed. The belt papers tapes were largely satisfactory and still had sufficient resilience to resist cracking when bent indicating that they had not suffered excessive thermal damage from the fire. The tapes were unwound and very significant blackening uncovered in large interstitial creases immediately above the cores, Figure 33.



Figure 33 Blackening in belt creases above the core interstices

The last belt papers were removed to reveal a large black feature of 86 mm length that straddled the interstices containing the jute string fillers between cores No 2 and No 1. A smaller black feature was present between core 2 and core 3.



Figure 34 Large black feature between core 2 and 1

Figure 35 shows that the feature appeared to be comprise of a black stain that had spread both circumferentially and lengthwise. A deposit or swelling of the paper that is proud of the surface can be seen along the major axis of the insulated cores. The paper tapes can be seen to have cracked and were found to be friable and to have lost their resilience. It thus appeared that the paper tapes within the black feature had either suffered thermal or chemical degradation.



Figure 35 Black feature on the paper insulation of cores No 2 and No 1

Figure 36 shows the removed lead sheath being held back in place. The black feature is underneath the lead sheath and is neither centred on the roll spring position (white region) or on the tip of the lead sheath cut (foreground). The black feature does extend however to within 3 mm of the lead cut.

The cores were opened out. The black feature was not present in the jute string filled central interstice or between the contacting flat faces between the core insulation.



Figure 36 Black feature extends underneath and to the end of lead sheath cut

5.6 Location of Fault Path: Conclusions

It was concluded from the examination in Penrose and later at Edif ERA that:

1. The two black features present in the unfailed transition are indicative of incipient distress in the insulation. It was deduced that the features had pre-existed the fire and not been caused by it, because the overlying belt paper tapes had not been discoloured nor thermally embrittled.
2. The black features are not coincident with the arc crater, but are sufficiently close to it to be listed as a candidate mechanism for the cause of electrical failure. The most likely mechanism being electro-thermal heating due to dielectric losses, this being local heat generation resulting from a high dielectric loss angle/power factor due to local contamination. Possible candidates are 'lossy' materials such as moisture, partial discharge (sparking) by-products and semi-conductive contaminants.
3. The location of the black features in the interstices close to the lead cut and to the crutch of the PILC cores in the joint is significant. The interstice is normally filled with eight jute string fillers and cable impregnating compound. The interstice is a volume space which experiences a significant magnitude of, but not the highest, electrical stress and where longitudinal transport of impregnating compounds or gasses can occur. It

is a space that is expected to vary in volume when the helically laid-up cores thermo-mechanically flex when they are heated. This has been reported⁴ as the possible failure mechanism that prevented the application of the belted design to higher transmission voltages. Within the cable remote from a joint the flexing would be a radial opening-out movement that would introduce voids between the insulated cores. In and adjacent to a joint, and particularly in a transition joint, the mechanical discontinuity would be expected to concentrate the movement and to introduce a longitudinal component and possibly a bending component. This movement would be increased if the joint was not installed in straight alignment with the cable as is the case in the failed joint. The location of the black features in the interstices between the insulated cable cores and the overlying belt paper tape insulation is the position where differential thermo-mechanical movement between the cores and the belt papers would be expected to occur. The boundaries of the interstices are the overlying belt insulation and the two insulated core insulations.

Follow-up Investigation

1. The sample containing the black feature was sent to Edif ERA for analysis.
2. In excess of twelve samples of PILC cable and four PILC traditional straight joints were later examined at Penrose and at Edif ERA for the possible presence of similar features. No other features were found. It was thus concluded that the mechanism that produced the feature was particular to the PILC to XLPE transition joint.

6 Investigations in the UK

From November 2014 to the end of February 2015 the Author attended the laboratories of Edif ERA at Leatherhead, UK, who were contracted to i) examine and analyse the samples returned from the Penrose cable trench and ii) to dissect PILC and XLPE cable joints and certain samples of PILC cable. Prior to despatch from Auckland each sample had been given a reference number with the prefix 'PN'. The list of samples is given in Appendix A.

6.1 Analysis of Cable Samples by Edif ERA

The Author witnessed key stages of, and reviewed, the detailed bench-top analysis by Edif ERA of twenty eight single core 33kV XLPE cables, two three core 11 kV XLPE cables, five three-core 11 kV PILC cables, three three-core OF 33 kV cables, two three-core OF 22 kV cables and four pilot and telephone cables. The results of the analysis are given in Edif ERA's report⁵. The Author is in agreement with the Edif ERA Summary and Recommendations.

6.1.1 Summary from the Edif ERA Report

"This report⁵ was prepared as a supporting document for the joint Transpower/Vector investigation into the fire that occurred in a cable trench at Transpower's Penrose Substation on Sunday 5th October 2014. There are a number of cable trenches and above ground cable racks at the Penrose Substation. The fire occurred in the cable trench that runs east-west across the 220 kV switchyard, and all references to a cable trench in this document are to this particular trench unless specifically noted otherwise."

"Edif ERA was engaged to analyse samples taken from the cable trench. This analysis consisted of a destructive examination of samples of each of the cables as well as various materials tests on the cable components."

"A detailed examination of XLPE, Oil Filled and PILC cables has shown them to all be in good condition. A number of adverse observations have been recorded, but all of these are minor in nature."

6.1.2 Recommendations from the Edif ERA Report

"Based⁵ on the results obtained here the residual life of the XLPE, OF and PILC cables can be predicted to be 20, 15 and 10 years respectively."

"The outer sheath of the XLPE cables reference PN3, 4, 5 and 7 passed the contractual AS/NZS requirement on tensile properties after ageing. For information it would not have met the IEC 60502-2 requirement, which sets a maximum change in elongation after ageing. In Edif ERA's experience the IEC approach is more meaningful as it gives an indication of the thermal stability of the material. The use of the IEC60502-2 should be considered for specifying any future cables." [Author: it is of note that the cables were correctly manufactured to the AS/NZS requirements and so in passing the AS/NZS tensile tests they had fully met their contractual requirement. It is suggested that a proposal be put to the AS/NZS authority to revise the requirement to come into alignment with IEC60502-2]."

“XLPE cables reference PNs 1, 5, 6, 7, 10, 11, 35, 36, 37, 47, 48 and 50 have experienced temperatures above the maximum design operating temperature of 90°C. The temperatures could have resulted from heating by hot air from the fire, or by current loading in service operation. It is recommended that the operating temperatures be checked.”

“With regard to water tree resistance, a two year test is commonly used in the UK and in Europe to ensure resistance to water treeing. The test procedure and performance requirements are specified in BS EN 7870-2 Clause 5.4.8. Edif ERA recommends that future cable suppliers be required to demonstrate that their cables meet the requirements of this standard.”

“Edif ERA notes that the XLPE cable designs have polyethylene outer sheaths, which are not flame retardant. In order to obtain improved fire performance Edif ERA recommends that cables with a Low Smoke Zero Halogen sheath be specified for use in significant in-air applications. These materials are flame retardant, produce low smoke levels when burning and do not contain acid gasses. The relevant performance standards are IEC 60332 for flame propagation, IEC 61034 for smoke emission and BS EN 50267 Part 1 for acid gas content.”

6.2 Examination of Cable Joints at Edif ERA

At Edif ERA detailed dissections were performed on the joints listed in Table 2, these comprised:

- The failed and unfailed 11 kV PILC/XLPE heat shrink sleeve transition joints from Remuera K10
- Three 11 kV PILC straight joints of traditional design having pre-impregnated paper roll insulation in a bituminous-compound filled lead sleeve, which itself is protected in bitumen filled cast iron shell.
- Five 33 kV XLPE heat shrink sleeve straight joints.

The list of joints that were examined is given in Table 2.

Table 2 11 kV and 33 kV joints examined at Edif ERA

PN N°	Description	Trench Position	Length m
53	Unfailed, 11 kV 3C, PILC-XLPE transition joint, Remuera K10	3B0	79
33	Failed, 11kV 3C, PILC-XLPE transition joint, Remuera K10	3B0	73
28	11kV PILC, 3C, cast iron joint, McNab K02	3A0	74
*	11kV PILC, 3C, cast iron joint, Remuera K10	3B0	65
57	11kV PILC, 3C, cast iron joint, Mt Wellington K05	4D0	50
60	11kV PILC, 3C, cast iron joint, Remuera K10	3B0	25
54	33kV XLPE, SC, joint 400-800mm ² , Remuera N° 2	1DY	5
59	33kV XLPE, SC, joint 400-630mm ² , Newmarket 3, YØ	1B-	5
55	33kV XLPE, SC, joint 400-800mm ² , Remuera N° 2	1DZ	5
58	33kV XLPE, SC, joint 400-800mm ² , Newmarket 3RØ,	1B-	5
56	33kV XLPE, SC, joint 400-800mm ² , Remuera N° 3	1AX	5
25	11kV PILC Cable	3B0	70-71

* Sample examined at Penrose. All materials except metals were 100% combusted.

The inspections of the 11 kV Remuera K10 failed PILC/XLPE transition joint 3B0 at 73m and the unfailed transition joint and 3B0 at 79 m in were completed with a representative present from Tyco Electronics, (the successor company to the original supplier Raychem).

Four traditional 11kV PILC traditional straight joints with cast-iron shells were dissected (three at Edif-ERA and 1 at Penrose). It is probable that these joints were installed at, or shortly after, the original PILC cables were installed in 1966.

It is of note that the ~100 m cable length of 11 kV Remuera K10 circuit, 3B0, that contained the failed transition joint originally contained three conventional cast-iron straight joints (at 25 m, 65 m and ~78 m) and that the joint at ~78 m was replaced by two heat shrink sleeve transition joints at 73 m and 79 mm making four joints at the time of the failure. This is a comparatively high number of joints in a short in-air length and indicates i) the cable had experienced unidentified events early in the life of the circuit that required the insertion of three joints and ii) a known event in October 2001 in which one of the cast iron joints was removed and iii) in consequence the number of joints had increased the risk to the reliability of the circuit compared to a straight run of cable.

It was concluded from the detailed inspections performed at Edif ERA that the conditions of the PILC cable and the surviving two conventional cast-iron joints were satisfactory and had not contributed to the cause of the failure and fire. The

removal in 2001 of the conventional cast-iron joint, which had leaked bitumen, and its replacement by two transition joints had indirectly contributed to the failure and fire.

The samples of 11 kV PILC cable listed in Table 3 were taken from either side of the PILC/XLPE transition joints.

Table 3 11 kV PILC and XLPE cable samples examined, 3A0 and 3B0

PN Nº	Description	Trench Position	Length m
30	PILC cable	3A0	81-82
26	PILC cable 3B0	2B0	81-82
53	PILC cable on west of unfailed transition joint 3B0	2B0	80-81
31	PILC cable	3A0	77-78
27	11kV 3C XLPE cable 3B0	2A0	77-78
28	PILC cable on west end of cast iron straight joint	3A0	74-75
28	PILC cable on east end of cast iron straight joint	3A0	72-73
53	PILC cable on west of unfailed transition joint 3B0	2B0	72-73
29	PILC cable	3A0	71-72
25	PILC cable 3B0	2A0	71-72
57	PILC cable on both sides of cast iron straight joint	4D0	50
60	PILC cable on both sides of cast iron straight joint	3B0	25

6.3 Examinations of the Bi-metallic Conductor Connectors at Edif ERA

The three bimetallic connectors in the failed transition joint were found to have parted at the friction weld that connects the copper half of the connector to the aluminium half. This was interpreted not to have been the cause of the fault as i) there was no evidence of arc burning on the parted faces and ii) the power arc erosion had occurred in the crutch of the PILC cores and not at the connector position. The subsequent detailed laboratory examination confirmed that the parting of the connector was a consequence of the fire and had not contributed to the failure or the fire.

It was found that:

- i) At ambient room temperature the connectors in the unfailed joint were sound in both axial tension and in lateral bending.
- ii) A connector from the unfailed transition joint parted under its own weight at just under the melting point of aluminium of 660°C. The

appearances of the parted faces was identical to those found in the failed transition joint.

In parallel to the trials at Edif ERA, Tyco Electronics NZ advised that:

- i) At the time of supply of the heat shrink transition joints in 2001 the connectors had been sourced from a separate company.
- ii) They had performed trials in the past, which showed that friction welded connector interfaces had failed in a closely similar way at 750°C.

It was concluded that:

- i) The bimetallic friction welded connectors, as supplied and in service operation, were sound and had not contributed to the failure of the transition joint.
- ii) Bimetallic friction welded connectors of this type are not an immediate risk to other cable accessories.

6.4 Conclusions of the Cable Joint Examinations at Edif ERA:

As the insulation of the failed joint was completely destroyed in the fire, the adjacent unfailed PILC/XLPE transition joint was inspected to identify potential contributing causes to the failure of the faulted joint.

“Based on the position of the fault, its appearance and from past experience, the PILC/XLPE transition joint fault was an original fault and not a result of the fire.”

“From the profile of the eroded area, the fault position and from previous experience, the PILC/XLPE transition joint fault started in the PILC cable crutch and the arc propagated preferentially away from the cable crutch.”

“The PILC cable crutch is a weak area in any heat shrink joint on a belted PILC cable.”

“The PILC cables had severely corroded steel tape armour but this would not have affected the life of the cables.”

"The cast iron joint shells were corroded and had slight bitumen leaks but this would not have affected the life of the cast iron joints because they have an inner bitumen filled lead sleeve."

"There was a sharp point on one strand of the PILC cable in the PN60 cast iron cable joint. This could have developed into a breakdown fault in perhaps 5 to 10 years (a very rough estimate)."

"There were no other incipient faults in any of the joints sent to ERA for examination."

The black features present in the unfailed transition joint are an explanation for a contributory cause of failure in the nominally identical failed transition joint.

In the Author's opinion the black features are indicative of insulation overheating due to electro-thermal distress resulting from a concentration of electrically lossy contaminants. Possible contaminants are i) materials that were confirmed to have migrated from the high permittivity yellow, void filling mastic and ii) moisture deduced to have entered the paper insulation from heat shrink sleeve water seals that were observed to be imperfect in the unfailed joint.

Other contributory causes of failure are:

- i) Thermo-mechanical movement of the insulation in the crutch region between the PILC cores i.e. radially opening-out of the cores due to thermal expansion and contraction.
- ii) Concentration of thermo-mechanical movement at the mechanical discontinuity formed by:
 - a. The transition joint in the cable run.
 - b. The non-straight alignment of the cable installation on either side of the joint.

The thermo-mechanical movement would have the effect of i) increasing the electrically stressed volume (of impregnating compound and air voids) between the core interstices in which electro-mechanical distress could occur and ii) breaking the thermally embrittled insulating paper tapes.

Evidence was found from methylene blue dye tests on insulating paper tapes of micro-crystalline wax generation caused by partial discharge activity (sparking). This was considered to be quite normal and of a reduced magnitude to that often encountered within in-service, mass impregnated PILC cables and joints.

The insulation design of 11 kV PILC cable systems is considered, in the opinion of the Author, to be based equally on mechanical and electrical requirements such that, although thinner insulation could in theory have been selected, it

would be so thin that it would not have the mechanical robustness necessary to withstand the forces that occur during installation, jointing and in-service operation. The conventional PILC joint designs thus have low electrical design stresses and are mechanically robust. In consequence they do not need the sophisticated insulation electrical stress control geometries provided at higher transmission voltages. The above opinion was confirmed by the examination findings. The dissection of the PILC cables and conventional joints showed that they had sufficient design margins to be able to withstand the following defects with no evidence of electrical distress:

1. Cables: evidence of poor manufacturing quality in some of the 1965 cables, e.g. i) damaged sharp edges of the sector shaped conductors and ii) 100 % registration of three paper tape layers (i.e. the tapes were not overlapped and so had butt gaps of three times the normal radial height).
2. Joints: severe insulation paper tape rucking and edge tearing resulting from the jointer setting the cores into offset bends to provide space for application of the paper roll insulation.

A synergy was seen to exist between the PILC cable and the conventional cast-iron joints. During the filling of the joint the hot bituminous insulating compound had mixed with the oil-rosin cable impregnant. It had penetrated long distances along the cable core interstices and paper tape butt gaps, thereby filling and insulating any air voids that are normally formed during jointing.

The corollary to the above findings is that:

1. The obvious fact that the transition joint had failed indicated that the insulation defects/deterioration that must have initiated failure would have been of greater severity than those seen during the examination in the traditional PILC joints and cables.
2. A synergy was not found to exist between the heatshrink sleeve transition joint and the PILC cable in that:
 - a. The PILC belt tape insulation is removed and is not replaced with a compatible, miscible, self-moulding insulation of equivalent thickness and strength.
 - b. There is no liquid/viscous compound to penetrate into the joint insulation to fill voids that are formed during jointing and in-service operation.
 - c. The joint has no means to hold the PILC cores robustly in straight alignment with the cable and so prevent disturbance of the PILC cores.

Chemical compounds were found in the black features that indicate that they had migrated from the yellow void-filling compound.

Miscibility tests were performed on different concentrations of yellow void filling mastic in insulating oil at different temperatures for different periods of time. It was confirmed that the mastic was not miscible in the oil.

It was confirmed that the black features were particular to the PILC to XLPE transition joint as they were not found during the examination of conventional cast-iron straight joints or in the samples of PILC cables.

6.5 Investigations at CCI

In addition to performing the main investigation described in this document CCI performed:

1. An analysis of the electrical stress distribution in the cable in the region of the black feature found in the core interstices.
2. A calculation of the operating temperature of the cables in the cable trench.
3. A review of published documents that relate to the fire performance of cables in in-air installations.

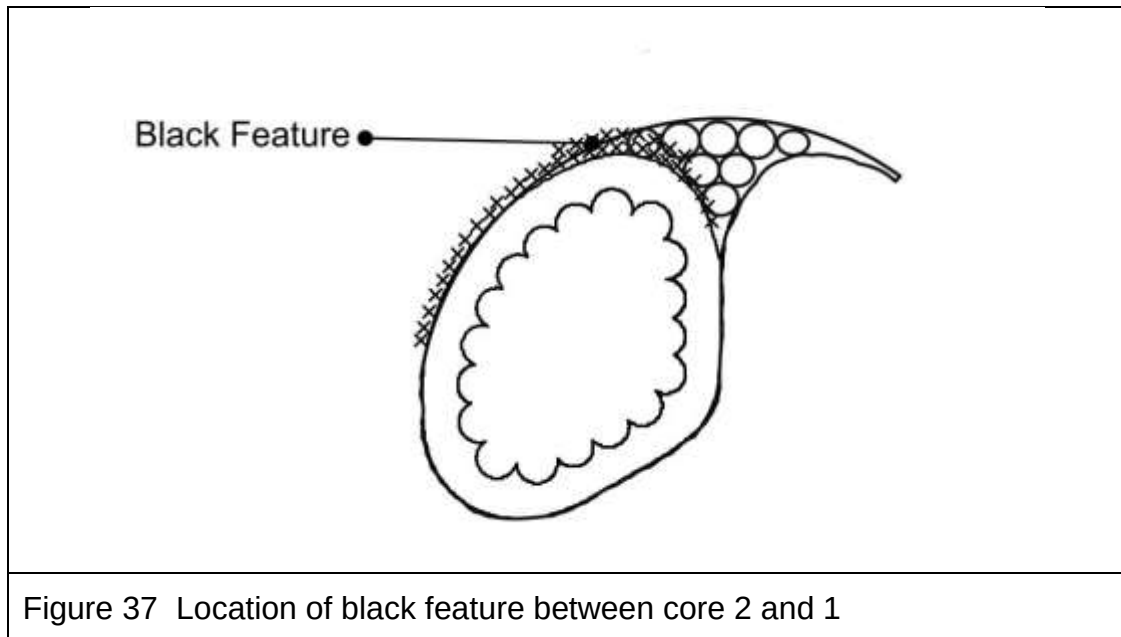
The above items are summarised in the following Sections.

7 Electrical Stress Distribution in the 11 kV PILC to XLPE Transition Joint

Analyses were performed to investigate the stress at i) the black feature found adjacent to the lead cut in the unfailed transition joint and ii) the failure position in the crutch of the PILC cores.

7.1 Stress distribution at the Black Feature

A photograph of the black feature is shown in Figure 35 and its location of the in Figure 37. The 11kV PILC cable is described in Section 18, Appendix B, and is shown diagrammatically in cross-section in Figure 60. The black feature is centred on the shoulder of the core, this being its major axis.



The items of interest to a cable engineer are:

1. Overall stress distribution
2. Location of the maximum stress
3. Magnitude of the maximum resultant stress
4. Black feature:
 - a. Maximum resultant local stress.
 - b. Maximum longitudinal stress tangential to paper surface

'Stress' refers to the electric stress, E (kV/mm), this being the gradient of the voltage (kV) distribution in any direction, x (mm), i.e. $E=dV/dx$. The voltage (or potential) distribution can be visualised in a cable having individual core screens by plotting the 'equipotential distribution' at the point of peak voltage on the sinusoidal voltage waveform. This is a static diagram and so is easy to interpret. Similarly the stress distribution lines can be plotted for the same peak voltage, these being the paths that a unit positive charge, q , would travel impelled by force Eq .

The field plot of the unscreened PILC cable has the complexity that the voltage distribution at any point in the cable cross-section is the resultant from each of the phase voltages, which have phase differences of 120° . Thus the equipotential and stress diagrams are dynamic and continuously rotate.

The stress at every point and every moment in time through the 360° cycle is calculated and displayed and only the maximum values plotted, Figure 38. The values at individual locations are given in Figure 39. The units of stress are

displayed as 10^6 V/m i.e. MV/m, or kV/mm. The voltage and the stress are the RMS values (peak divided by $\sqrt{2}$), which is the usual form for cable engineering.

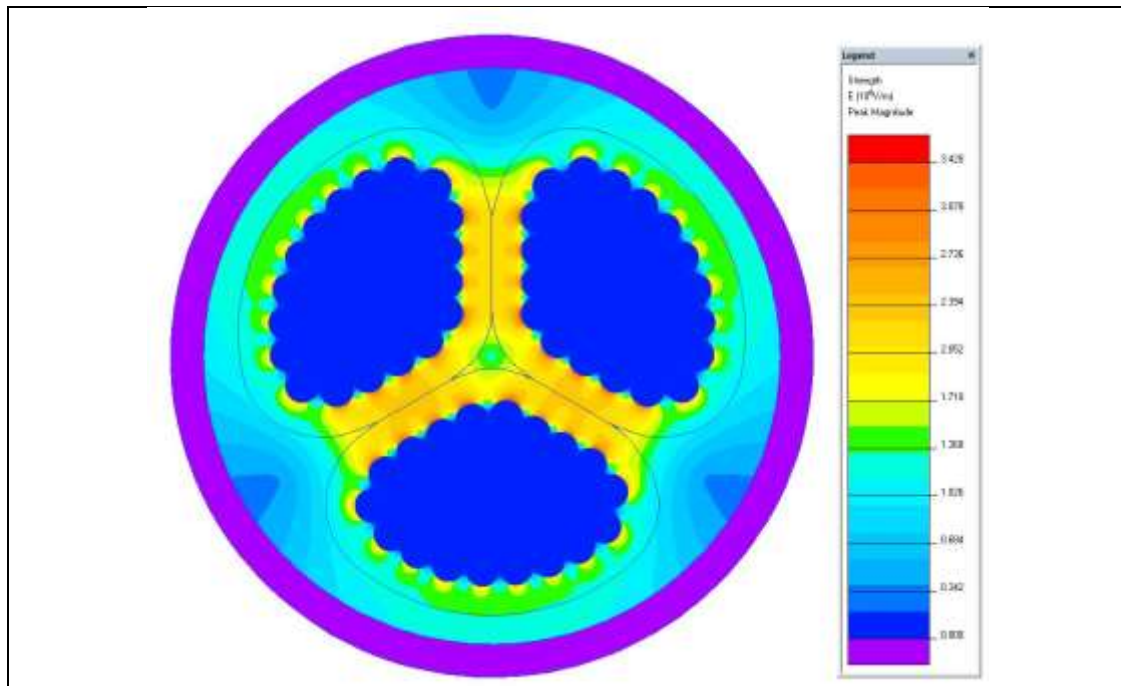


Figure 38 Contour plot of points of maximum stress through a 360° cycle

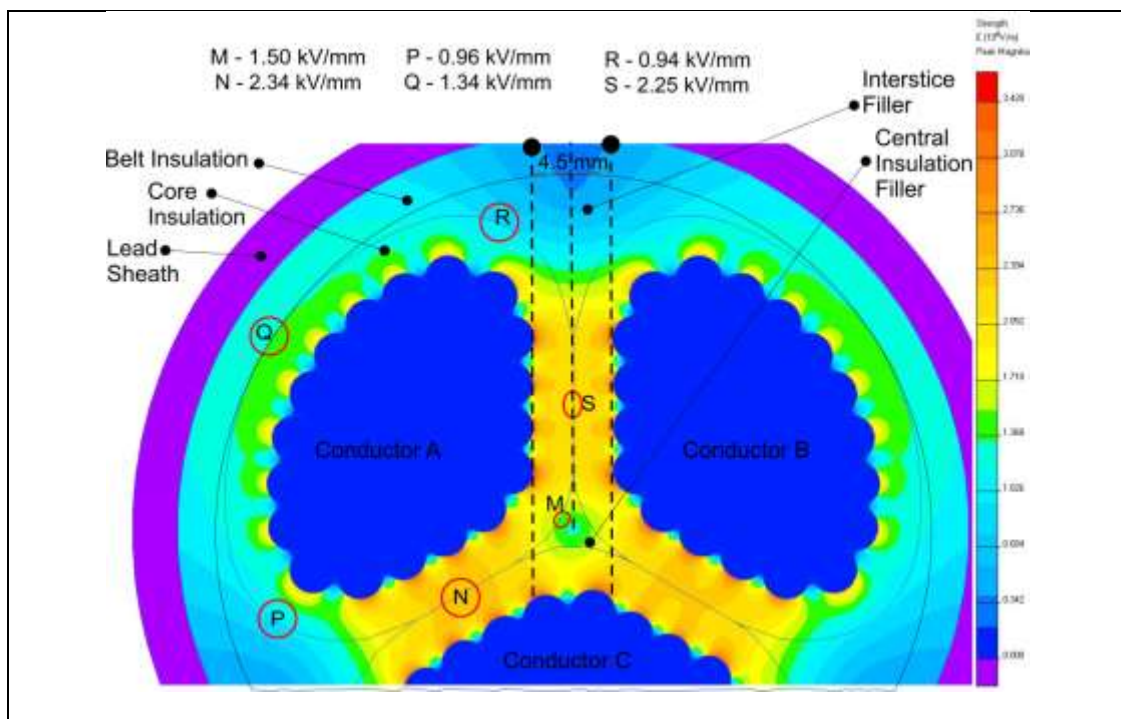
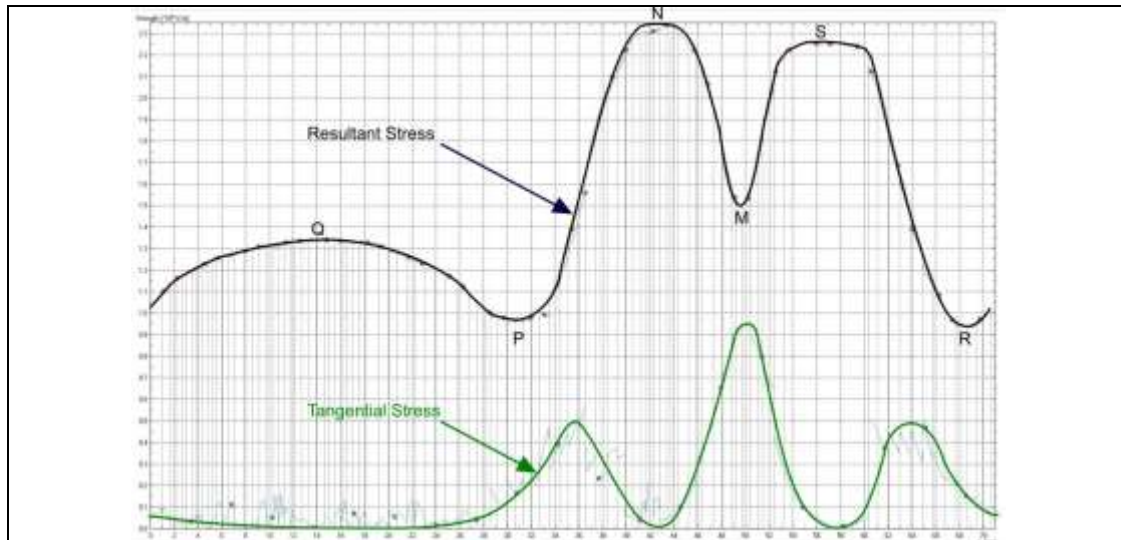


Figure 39 Magnitudes of maximum stress on core through a 360° cycle

Values of the resultant stress around the circumference of the core insulation and of the stress tangential to the surface are given in Figure 40. The peaks of electrical stress are denoted by letters and their geometric positions are shown Figure 39.

**Figure 40** Resultant and tangential stress around the core surface

The results show that:

- The region of maximum resultant stress is not at the black feature on the shoulder of the core, but on the parallel contacting faces between the cores, N and S, where its value is 2.25 kV/mm. The possibility of an electrically weak void being present in this interface within the cable sheath is small. The possibility is significant in the crutch of the transition joint where the cores are opened out and the jointer is required to fill the space with the yellow void filling adhesive mastic.
- A lower magnitude of stress is present in the less well insulated interstices at:
 - The shoulders, P and R, where the resultant stress dips to 1.0 kV/mm and the tangential stress peaks at 0.5-0.6 kV/mm.
 - The central axis, M, where the resultant stress dips to 1.5 kV/mm and the tangential stress increases to 0.9 kV/mm. The possibility of an electrically weak void being present at these interfaces is higher.

The presence of a planar shaped gas void at the shoulder interstice would increase the stress inside the void in proportion to the ratio of relative permittivity of impregnated paper to that of gas i.e. 3.5. Thus the stress in planar void at the shoulder would be 3.5 kV/mm. Small thickness voids at atmospheric pressure would not exhibit partial discharge at this stress. This is confirmed by the findings of the methyl-blue dye tests, which generally showed the absence of PD.

The concentrated variation in stress at the shoulders of the core insulation raises the possibility that this could result in the capture of conducting contaminants that may have been present in the interstices by the mechanism of dielectrophoretic force. This is the force experienced by a solid particle or liquid globule having a different dielectric permittivity to that of the bulk insulation when it is subject to an alternating electric field. The force is proportional to i) the difference in permittivities (a higher permittivity particle/liquid globule being attracted to a region of higher stress), ii) the magnitude of electric stress and iii) the gradient of electric stress. Examples of materials that have a higher permittivity than the paper insulation are i) conducting particles ii) water globules and iii) yellow void-filling compound. The dielectrophoretic accumulation of foreign materials, has in the past resulted in failures within stop joints in oil-filled cables and within oil filled transformers.

8 Calculation of Cable Operating Temperatures

The objectives of the cable operating temperature study were to:

- i) Calculate if any of the 19 cable circuits in the cable trench had operated at equal to, or greater than, their maximum allowable design temperature limits.
- ii) Follow-up the recommendation in the Edif-ERA report recorded in this report in Section 6.1.2:
“XLPE cables reference PNs 1, 5, 6, 7, 10, 11, 35, 36, 37, 47, 48 and 50 have experienced temperatures above the maximum design operating temperature of 90°C. The temperatures could have resulted from heating by hot air from the fire, or by current loading in service operation. It is recommended that the operating temperatures be checked.”

8.1 Temperature Calculation Method

The calculation of the cable conductor temperatures has complexity arising from:

- The number of cable circuits in the air filled trench.
- The geometry of the trench being buried at shallow depth with its roof level with the surface.
- A combination of different heat transfer mechanisms:
 - Conduction through the cable walls
 - Convection and radiation between the cable circuits and between the cable circuits to the walls.
 - Air intake and exhaust through small vents in the roof.
 - Conduction through the surrounding basalt rock to the ground surface.

Doubt existed that the approaches given in IEC 62087 were sufficiently applicable to provide certainty in temperature accuracy.

A simulation method was therefore developed based on 'Abaqus-Standard' FEA software for conduction and for cavity radiation. Two variants were developed to solve the complete thermal model together with the application of a cyclic transient load case. The two methods and the results are described in detail in Section 22, Appendix F.

Both methods gave closely similar answers within a 2 °C conductor temperature difference:

- A co-simulation method that used Abaqus-Standard with Abaqus-CFD to simulate convection.
- Abaqus Standard that used empirical algorithms to simulate turbulent convective heat transfer in-air.

The one hourly loading records for each circuit over a one year period were analysed. A number of possible loading scenarios were applied to the FEA models. The preferred 'pessimistically realistic' load case was to apply a cyclic load based on finding a representative 24 hour maximum load pattern that also had the highest representative peak load a) in Summer with a 23°C ambient and b) in Winter with a 15°C ambient.

8.2 Summary of Temperature Results

The temperatures of the five higher temperature circuits are given in **Table 4** for Winter and in Table 5 for Summer. Table 6 compares the two cable circuits that

were in the lists of higher temperature cables for both the Winter and Summer periods.

Table 4 Winter: Highest Conductor Temperatures under Cyclic Loading

Cable			Conductor Temperatures [°C]		
Position	Type	Circuit	CFD	Empirical	Design
4C	33 kV OF	St John N° 2		59.3	85
3A	11kV PILC	McNab K02		58	65
4A	33 kV OF	St John No 1		57.3	85
2C	11kV PILC	McNab K19		56.8	65
2D	33kV OF	Carbine N° 1		52	85

Table 5 Summer: Highest Conductor Temperatures under Cyclic Loading

Cable			Conductor Temperatures [°C]		
Position	Type	Circuit	CFD	Empirical	Design
2D	33kV OF	Carbine N° 1		59.5	85
2C	11kV PILC	McNab K19		55.0	65
3C	22 kV OF	Westfield No 2		54.5	85
3E	22 kV OF	Westfield No 3		54.0	85
4A	33 kV OF	St John No 1		51.0	85

Table 6 Comparison of Winter and Summer Cyclic Temperatures

Cable			Conductor Temperatures [°C]		
Position	Type	Circuit	Winter	Summer	Design
2D	33kV OF	Carbine N° 1	52	59.5	85
2C	11kV PILC	McNab K19	56.8	55.0	65

The trench roof maximum surface temperatures in winter is 30°C (15°C drop to ambient) and in summer is 36°C (13°C drop to ambient).

8.3 Cable Temperature Conclusions

The Author concluded that:

- i) The operating temperatures of all the cable circuits and all the types of cables within the cable trench in both the Summer and Winter seasons had been satisfactory, being below their maximum design operating temperatures for continuous operation with sufficient margin to allow for variations in the trench geometry:
 - a. The operating temperatures of all the 11 kV PILC cables were satisfactory, being 7 °C to 23°C below their design limit of 65 °C for continuous operation.

- i. The cables closest to their design limiting temperature were the 11 kV PILC cables 2C and 3A, for continuous operation of 65°C.
 - ii. The 11V PILC circuit that was the first to fail, 3B, Remuera K10, had satisfactory low conductor temperatures when it was last on continuous load in 2013.
 - b. The operating temperatures of all the 22 kV and 33 kV OF cables were satisfactory being 26 °C to 38°C below their design limit of 85 °C for continuous operation.
 - i. All of the 22 kV and 33 kV OF cables (2D, 3C, 3E, 4C, 4A), had higher operating temperatures than the 33 kV XLPE cables.
 - ii. The operating temperatures of the OF cables were similar to those of the 11 kV PILC cables.
 - c. The 33 kV XLPE cables were satisfactory having the lowest conductor temperatures of all the different types of cables. These cable sizes in this location thus had the largest margin to allow for future load growth.
- ii) The temperature calculations showed the reason that samples of XLPE cable insulation had experienced temperatures above their maximum design operating temperature of 90°C was not due to overheating in normal service operation. It is concluded that the cause was heating by hot air from the fire. Thus the effect of the fire on the cables had extended from the fire initiation position at 73 m to a chainage position of 5 m.

9 Review of Mechanical Performance

9.1 Review of Thermo-mechanical Disturbance

The Remuera K10 cable had been installed in straight alignment in an informal 'semi-flexible' thermo-mechanical system that rested uncleated on supports at ~1.125 m spacings, Figure 5. The cable had neither been 'rigidly close-cleated' nor 'flexibly sagged' as described in CIGRE TB 194⁶ (i.e. it was not formed into lateral sags between the support arms). Thus the prospective axial thermal expansion in Remuera K10 (and the other cables in the trench) would not have been relieved by uniformly distributed lateral deflection, but would have generated axial compressive forces that tended to move residual thermal strain into randomly occurring geometric lateral perturbations. The six metre long loop of 11 kV three core XLPE cable adjacent to the failed transition joint at 73 m, Figure 41 and Figure 42, is a perturbation that is likely to have cyclically flexed

to absorb and release axial thermal strain from the PILC cable and in so doing to disturb the failed transition joint.

The current loading records showed that in the year 2013-2014 that preceded the failure, although the Remuera K10 cable had been off load since February 2014 (except for three different periods, including a ten minute period on the morning before failure), the cable would have experienced daily thermal expansion and contraction due to the heating of the air in the trench by the other cable circuits. Calculations had shown that the typical trench air temperature and Remuera K10 cable would fluctuate daily by up to 20°C. In years prior to 2014 Remuera K10 had carried load current.

It is considered that the thermo-mechanical flexing had disturbed insulation already at an advanced stage of distress and precipitated the electrical failure.

The Author concluded that thermo-mechanical disturbance of the insulated cores is a contributory cause of the transition joint failure.

9.2 Effect of 220 KV Intertie Construction Work on the Penrose Trench

In the weeks before the electrical failure in the Penrose trench, work had been performed to cut a larger trench in the basalt bedrock that passed immediately below and at right angles to it. The purpose of the trench was to contain a 220 kV Ring-Bus cable circuit. The position of the trench is shown in plan view in Figure 3. The Ring-Bus trench is positioned at 87 m chainage and is thus located 14 m to the west of the failed transition joint at 73 m. The possibility was investigated that vibrations from the rock excavation could have been sufficient to have disturbed the transition joint and contributed to the failure.

In the opinion of the Author the insulation of the transition joint is sufficiently robust not to be at risk of damage by direct vibration of small magnitude. The insulation could be at risk of insulation disturbance as an indirect consequence of the vibration releasing locked-in axial thermo-mechanical strain from the cable. The Author assessed this risk based on an FEA study⁷ of the effect that traffic induced vibration has on the release of constrained thermo-mechanical cable forces in a duct installation. The Author was the principal investigator of this study.

The FEA study⁷ showed that a vibration amplitude of 2.6 mm/s and a frequency of 13 Hz, would be capable of releasing locked-in compressive force and producing axial movement, but only for the special case in which a cable with a smooth polyethylene oversheath is installed inside a smooth plastic duct with a low coefficient of friction (of 0.15). The mechanism of release is to momentarily lift the cable off the duct surface (by 0.08 mm) such that the frictional constraint

momentarily falls to zero permitting the cable to slide, this mechanism being named the 'avalanche' effect.

The Author concluded that the vibration from the inter-tie construction work had not been a major factor in the failure mechanism as:

- i) The vibrational vertical movement would have been too small to lift the PILC cable clear of the trench supports because of the PILC cable's rough surface finish (bitumen impregnated hessian textile tape over steel tape armour).
- ii) Had vibration been a major factor it would prospectively have had a larger effect on the unfailed transition joint, which was located 6 m closer to the source of vibration.

10 Location of Electrical Failure Incidents in the Trench

The evidence from the examinations of the joints and cables performed in Penrose and in the UK permitted a plan view to be constructed, Figure 41. The view is of the Remuera K10 3B0 and McNab 3A0 11 kV PILC cables.

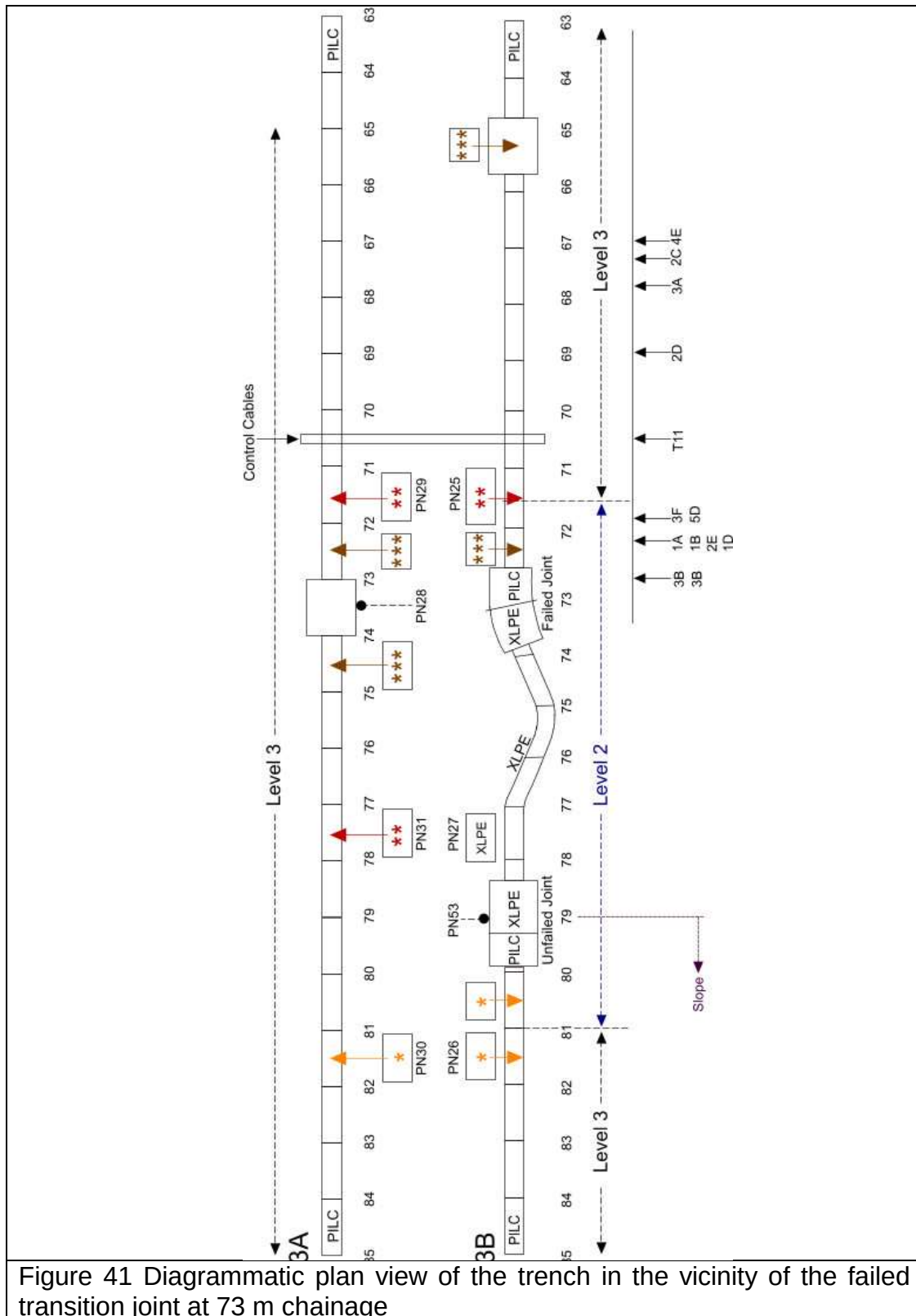


Figure 41 shows the length of trench from 63 m to 85 m. All but one of the electrical fault holes are located between 67 m and 73 m:

- McNab K02, 11 kV PILC cable, which remains in its position, 3A0, on Level 3 next to the North wall throughout the length of the trench.
- 11 kV Remuera K10, 11 kV PILC cable, which, from zero metre chainage, runs on Level 3 immediately adjacent to 3A0. At 71.5 m chainage it rises from Level 2 to Level 3, (note that its designation is not changed). At 73 m (centre-line) the failed transition joint was located on Level 3 between cables 2A and 2B. At this position the failed transition joint connected the three core PILC cable to a three core XLPE cable.

The three core XLPE cable and joint were installed in the shape of a lateral bow, Figure 42, that passed over circuits 2B0, 2C0, 2D0 and 2E (X, Y and Z)) and overhung the trench access way, reaching its peak amplitude at 75m. The loop rejoined its position on Level 2 at 77 m. A second nominally identical transition joint was centred at 79 m, which coincided with change from a horizontal trench run to a downward slope for the trench to pass under the Transformer Way. This joint converted the 6 m length of 11 kV three core XLPE cable back to the main run of 11 kV PILC cable. At 81 m the PILC cable descended back to its original position, 3B0, on the third layer. Dissection of samples of the 3B0 11 kV PILC cable from 0 to 73 m and from 79 m onwards revealed that they were of the oil-rosin type and nominally identical in size and construction having been manufactured by Scottish Cables Ltd in 1965. It was not possible to determine if they were originally part of the same drum length.



Figure 42 Bow shape in the 11 kV three core XLPE cable between 73 m and 77 m chainage

Figure 41 also shows:

- The location of two original PILC to PILC straight joints, having outer cast-iron protective joint shells, one in 3A0 at 73.5 m and one in 3B0 at 65 m. A historical record, text and photographs, refer to a pre-existing cast-iron straight joint, which was determined to be in Remuera K10 on Level 3 at the top of the slope. This is assumed to have been in the horizontal region between 77m and 79 m. Evidence for the joint was confirmed by the finding of bituminous compound within cable sample PN26 at 81-82 m. It is possible that cables 3A0 and 3B0 may each have had one planned joint to connect laid cable drum lengths together.

The finding of two straight joints comparatively close together in cable 3B0 at a 13m spacing (65 m and 77-79 m) indicates that an unidentified event had occurred earlier in its life, for example damage/deterioration/failure of i) an original straight joint that may have required replacement by 'two joints and a cable piece' or ii) the original PILC cable that may have required to be replaced by 'one cable joint and a cable piece'.

- The location of subsequent fault sites in the adjacent circuits.

- The location of a cable bridge across the trench at 70.5 m, which carried control cables for transformer T11.
- The comparative severity of burning in cable samples in 3A0 and 3B0 adjacent to, or in the joints as indicated by the following symbols:
 - ***. The most severe burning with cables having lost their outer servings, the steel tape armour having lost its protective finish and being recently oxidised with red rusty, its lead sheath melted, its paper insulation charred and carbonised and dried impregnating compound is present in some insulation interstitial creases and butt gaps.
 - **. Medium severity burning in which the outer hessian serving is absent, the exposed steel tape armour is red with rust, the lead sheath is intact with some discolouration inside, the insulation is heat affected but intact and the liquid impregnating compound is present in the insulation.
 - *. Lower severity burning in which the outer hessian serving is absent in whole or part, the bituminous lacquer on the steel tape armour is present, the lead sheath is present, the inside of the lead sheath is clean and the liquid compound is present in the paper insulation.
- The sample PN numbers.

10.1 Replacement of Cast Iron Joint in Remuera K10 Cable

It was interpreted that the bowed shape in Remuera K10, Figure 41 and Figure 42 had resulted from the replacement in 2001 of the cast iron joint at ~ 78-79 m in 3B0, which involved:

- i) The change in position of the cut PILC cable ends from Level 3 to Level 2 to provide an improved jointing access height in which to insert two transition joints, one at 79 m and one at 73 m.
- ii) The pulling out of both cable cut ends from near the northern wall and re-positioning them past the southern ends of the Level 2 support arms and into the trench access way. At this position the jointer had access around the cable circumference to assemble and apply hot air to heat shrink the polymeric insulating sleeves onto the transition joints and new 6 m length of three core XLPE 11 kV cable.
- iii) After completing the first transition joint at 79 m the jointer had pushed it and 1.5 m length of adjacent new cable back into straight alignment with the northern wall in the 2B0 position. At the 63 m position the cable ends were left in the trench access way to permit

the second transition joint to be assembled. Because of the 800 mm length of the support arms the jointer was inevitably left with an excess in the length of the three core XLPE cable, which he could not push back to the North wall. He pushed the second transition joint back towards the northern wall and positioned the new XLPE cable in the shape of a bow to accommodate the excess. However the 6 m distance allowed between the two transition joints had been too short and in consequence:

- a. It was not possible to position the joint and cable at 73 m in straight alignment and so part of the transition joint was curved.
- b. The new bowed cable lay on top and crossed all of the existing cables on Level 2 and protruded into the access way.

11 Sequence and Progression of Electrical Incidents

The time sequence of each cable incident is shown in the graph in Figure 43, which plots elapsed time in minutes after the first fault at 23:21:30 versus the chainage position in the cable trench.

In this document an 'incident' is defined as a fault (i.e. an arc cavity in the conductor), a pilot/control cable signal and a consequential automatic or manual de-energisation:

- Each data point represents an incident in which the time of the electrical failure or signal is recorded and the longitudinal position in the trench is known, for example by arc burning or the position of the transformer control cable bridge.
- The horizontal lines are those incidents in which the time is recorded, but in which the longitudinal position is unknown, because arc burning in the conductor had not been discovered at the time of writing this report. For example i) the low voltage signals from the cable system pilot cables (2A and 4B) do not produce obvious power arc damage and ii) a length of the 11 kV, XLPE, 35mm², three core, tunnel supply cable, 2FO, suffered severe fire damage, the cable metallic components were severed/burnt through and the remains of the cable fell amongst the accumulation of debris on the trench floor.

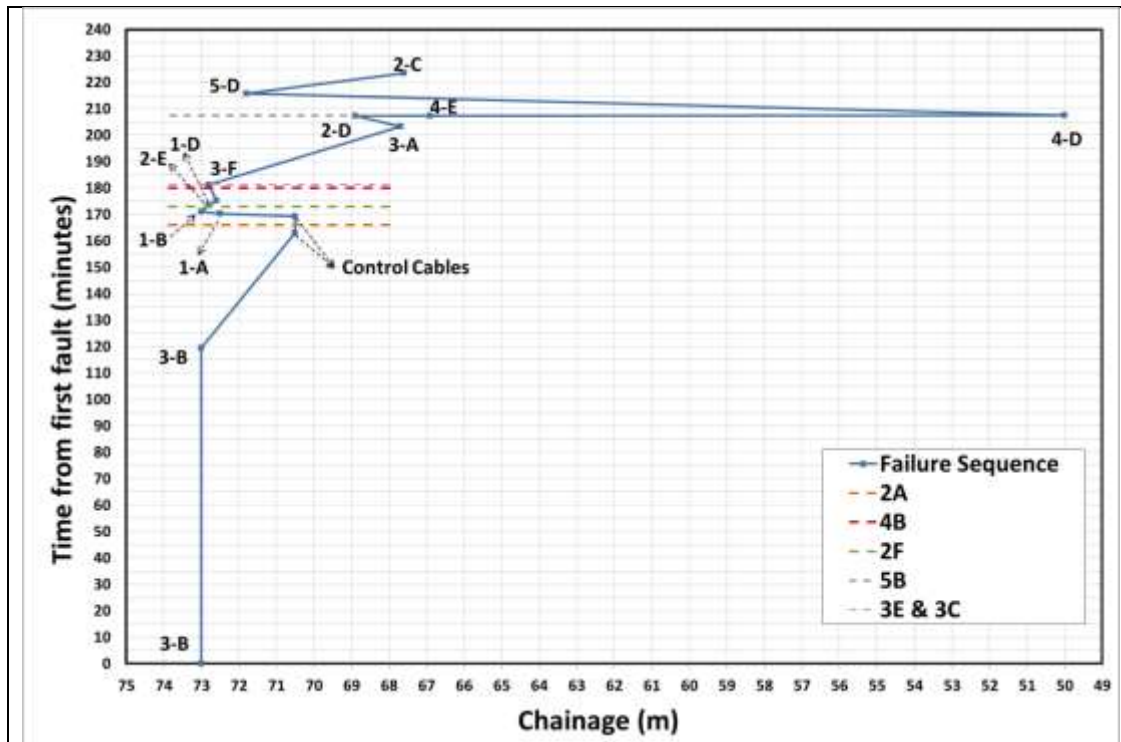


Figure 43 Fault sequence: Elapsed fault times versus their position in trench

Nineteen cable incidents (faults and alarm/pilot signals) occurred over a length from 73 m to 50 m by the time the last tripping occurred at 223.48 minutes after the first fault when 11 kV PILC McNab K19 tripped. This was 104.17 minutes after the reclosure onto the first fault. The incidents occurred in three overlapping 'windows' as defined by the following 'length-time' co-ordinates:

- Window 1:
 - 73 m to 70.5 m.
 - 0 to 200 minutes after the first fault.
 - 12 incidents.

This group of incidents is defined by being immediately adjacent to the failed transition joint in 11 kV Remuera K10, 3B0, at 73m. Two of the early incidents were the T11 control cables on the cable bridge that crossed the cable trench at 70.5m. Fault holes were discovered in five cables and were coincident in location with the failed transition joint 3B0. These cables were above and adjacent to the failed transition joint. This provided clear evidence that the cause of their failure was spread of fire from the electrical failure of the 11kV Remuera K10, 3B0, transition joint.

- Window 2:
 - 71.8 m to 66.9 m. The fire is spreading eastwards.
 - 200 to 223.48 minutes after the first fault.
 - 6 incidents.

The second group has moved preferentially to the East of the 3B0 fault at 73m. This is attributed to the presence of a drop in the level of the cable trench to the West of the 79 m chainage position for the purpose of passing below transformer transportation tracks. It is interpreted that this inhibited the progress of the fire westwards as the hot air from the fire in the cables surrounding the failed 3B0 transition joint rose and so raised the temperature higher at the trench roof to the East than to the lower level trench roof in the West.

- Window 3:
 - 50 m.
 - 207.40 minutes.
 - 1 incident.

This comprises failure of 11 kV Mt Wellington K05 PILC cable, 4D0 at 50 m. It is indicative of an eastwards fire spread after 3A0 over a distance of 18 m. This fire spread is principally attributed to burning PE oversheathed, wire screened 33 kV XLPE cables. However the position of 4D0 on Level 4 close to the trench floor and to the proximity of the ruptured aluminium sheaths in oil filled cables indicates the likelihood of local fire having been spread along the floor by burning oil. The parallel cables, which had previously tripped, had suffered increased fire severity in this region. Arc burning of the conductors and steel tape armour was found. However there was no record from the electrical protection that the feeder had tripped. For the purpose of this report it was therefore taken that the fault occurred coincident with the known time of de-energisation when Mt Wellington substation lost power.

Each incident is described below. The descriptions refer to the sequence of trench cross-section diagrams given in Appendix C, Section 20 and Figure 65 to Figure 97. In each trench cross-section diagram:

- The elapsed time after the first Remuera K10 fault is given.
- The trench longitudinal 'chainage' position of each incident is given.
- A red arrow and a red cable symbol denote the next cable circuit in the time sequence to experience an incident. The arrow does not denote the progressive spread of fire.
- The red cable symbols are retained cumulatively on each diagram to give a general impression of the temporal and spatial spread of the fire intensity.

1st Cable Incident, 3B0, Diagram in Figure 66

Remuera K10, faulted electrically at 23:21:30 in the PILC to XLPE transition joint, 3B0 at 73 m chainage on Level 2.

2nd Cable Incident, 3B0, Diagram in Figure 67

Occurred 119.32 min after the first trip. The Remuera K10 failed PILC to XLPE transition joint, faulted electrically for a second time when the circuit breaker was reclosed. The fault was at the same position in the transition joint 3B0 at 73 m chainage on Level 2. The arc crater in the conductors, Figure 68, is common to the first and second faults, which are indistinguishable.

3rd Cable Incident, T 11 Control Cables, Diagram in Figure 69

Occurred 43.67 min after the second trip. An alarm signal was received from the low voltage control cables for transformer T11 that crossed a cable bridge between the concrete cover tiles that passed over the trench at 70.5 m; 1.5 m to the East of the centre of the failed joint 3B0 and 650 mm from its end. The timber covered metal bridge had no floor, Figure 44, and supported the control cables on lateral metal hangers. Thus the control cables were exposed to the heat and their insulation would have been degraded and melted by the hot air and flames from the transition joint and surrounding cables. It is possible that the increased supply of air through the bridge drew the fire into an eastwards direction.



Figure 44 Control cable bridge at 70.5 m (photo taken in 2001)

4th Cable Incident, 2A0, Diagram in Figure 70

Occurred 2.98 min later. A differential protection blocked signal was received from the Carbine pilot cable, 2A0, which is adjacent to the failed joint on Level 2. This signal indicated fire damage had been caused to the pilot cable.

5th Cable Incident, T11 Control Cables, Diagram in Figure 71

Occurred 3.23 minutes later. A number of alarm signals were recorded from control cables on the bridge, which resulted in the transformer T11 tripping.

6th Cable Incident, 1AZ, Diagram in Figure 72

Occurred 0.95 minutes later. 33 kV Remuera 3, 1AZ, XLPE cable at 72.5 m, faulted and tripped. The fault position (denoted by power arc burning to the metallic components) was located approximately 0.5 m east of the centre of joint 3B). The arc crater is shown in Figure 73. This is still in the immediate vicinity of the transition joint as the joint was 1800 mm long, extending 850mm from its centre on the PILC side and 950mm from its centre on the XLPE side.

This group of three XLPE cables was cleated in trefoil formation to the Level 1 support arm immediately above the failed joint. The group would have been heated directly by flames and hot air for 50.83 minutes after the second arc and 170.15 minutes after the first arc. The XLPE cables had therefore taken a comparatively long time to be thermally degraded to a condition in which electrical failure of the insulation occurred.

The XLPE cables have a 'composite' oversheath comprising two layers, as described in AS/NZS 1429⁸ as being optional for single core cables and mandatory for multi-core. The outer sheath is PE, which has a low oxygen index and therefore can sustain and propagate combustion. The inner sheath is PVC, which has an oxygen index higher than the percentage of oxygen in air. At low temperature and in the absence of flame from a separate source, PVC cannot readily self-sustain combustion and historically was regarded as a 'reduced propagation material'. However PVC does burn at elevated temperatures in the presence of flame and heat and also produces dense corrosive smoke, which is prospectively lethal to people and damaging to certain types of materials. Above 400°C PVC liberates highly flammable gasses and will burn and propagate fire.

The primary cable insulation of XLPE has closely similar fire properties to the PE oversheath, in that it has a low oxygen index and can self-sustain and propagate fire. In addition to propagating fire horizontally through the trench along the surface of the cable, the materials also propagate fire by melting and dripping burning material onto the layers below. Medium/high density PE melts to a viscous liquid at the comparatively low temperature of c.115°C. XLPE changes state from a hard white semi-crystalline plastic at 107°C to a soft transparent elastomer. The temperature at which XLPE degrades and loses its insulating properties is taken to be greater than 250°C for cable short circuit rating purposes.

7th Cable Incident, 1BY, Diagram in Figure 74

Occurred 0.87 minutes later. 33 kV Newmarket 3, 1BY, XLPE cables, faulted and tripped. This cable is next to the previous cable 1AY to have tripped and is above the transition joint 3B0. The arc crater is shown in Figure 75.

8th Cable Incident, 2F0,

Occurred 2.00 minutes later. 11 kV Vector Tunnel Power Supply, 2FO, XLPE three core cable faulted and tripped. The location of the fault was not found as the small 35 mm² copper conductor had melted. It is deduced that to be at the same location as the 33 kV XLPE cable group 2E, i.e. at 72.8m. The cable is cleated immediately below 2E and so it would have experienced radiant heat and burning PE dripping onto it. The cable had a small diameter and insulation thickness and a low metal content and so would have had little fire resistance.

9th Cable Incident, 2EY, Diagram in Figure 77

Occurred 0.27 minutes later. 33 kV Carbine Road 2, 2EY, XLPE cables at 72.8 m, faulted and tripped. The arc crater is shown in Figure 78. It is likely that the PVC duct 1C and XLPE cable 1D were alight and that burning polymer had fallen onto 2E below in Level 2.

10th Cable Incident, 1DY, Diagram in Figure 79

Occurred 1.97 minutes later. 33 kV Remuera 2, 1DY, XLPE cable at 72.6 m, faulted and tripped. The arc crater is shown in Figure 80. It is likely that fire had spread across the top row from 1A to 1B to 1C and then 1D. 2E below had faulted 2 minutes before and this would have accelerated its demise.

11th Cable Incident, 4B, Diagram in Figure 81

Occurred 4.85 minutes later. St Johns Pilot, 4B, signalled a differential protection blocked alarm. The pilot cable is two layers below the failed transition joint with a gap between cables in Level 3. It is likely that burning polymer from the joint and impregnating compound from the PILC cable had spread fire downwards.

12th Cable Incident, 3FX-Y, Diagram in Figure 82

Occurred 1.17 minutes later. St Johns 3, 3FX and Y, at 72.3 m, XLPE cables faulted and tripped. The arc crater is shown in Figure 83. It is likely that burning polyethylene had fallen from 2E, which had faulted 8 minutes before.

13th Cable Incident, 3E0 and 3C0, Diagram in Figure 84

Occurred at the same time as above. 22 kV Westfield N° 2 and N° 3, 3E0 and 3C0, OF cables, were de-energised when Penrose 33 kV to 22 kV transformers tripped for the St John 3 fault. These cables did not fault.

14th Cable Incident, 3A, Diagram in Figure 85

Occurred 21.93 minutes later. 11 kV McNab K02, 3A, PILC cable at 67.6 m, faulted and tripped. This is the first of the second 'Window' of cable co-ordinates to fault. The fault location has now moved away 5.4 metres eastwards from the faulted transition joint 3B0, 73 m, and the interval has increased from less than 6 minutes to 23 minutes. One reason is that the five circuits of faulted XLPE cables (fifteen single core cables in total) adjacent to 3B0 will continue to release high calorific value material into the fire raising its intensity and permitting it to propagate along the cable surfaces. These cables cannot fault for a second time

and so the passage of the fire is only signalled when a live cable is thermally damaged and faults.

15th Cable Incident, 2D0, Diagram in Figure 86

Occurred 4.0 m minutes later and 207.2 minutes after the failure of the transition joint, 33 kV Carbine N° 1, 2D0, OF cable at 68.9 m, faulted and tripped. The arc crater is shown in Figure 87. The fault position is 4.1 m eastwards from the centre of the failed transition joint. This is a significant event as this cable was on the same Level 2 as the failed transition joint and had burning cables above, below and on either side. The oil would have expanded until it exceeded the storage capacity of the oil storage tanks. The pressure would then have risen exponentially to a value capable of bursting the aluminium sheath or one of the accessories. The sheath would become plastic and its hoop strength reduce before the temperature approached the melting point of 660°C (aluminium sheaths are extruded at ~425°C). The sheath is therefore likely to burst in a mechanically weak point somewhere within the fire region. The paper insulation would have been thermally degraded by the high temperature. The drop in pressure and the admittance of air and hot gas into the insulation would cause electrical failure. The addition of hot oil and vapour into the fire would spread the fire along the trench and underneath the cables and so significantly increase its intensity.

16th Cable Incident, 4EY, Diagram in Figure 86

Occurred 0.07 minutes later than 2D0 above. 33 kV Mt Wellington No 2, 4EY, XLPE cable at 66.9 m, faulted and tripped. This was the first oil filled cable to fail in the cable trench. The arc crater is shown in Figure 91. This cable would have experienced burning PE from 3F above it, which had faulted 26 minutes before.

17th Cable Incident, 5B, Diagram in Figure 90

Occurred 0.13 minutes later. 33 kV Mt Wellington No 1 tripped, but no fault current was recorded. A fault position has not been found at the time of writing this report.

18th Cable Incident, 4D0, Diagram in Figure 91

Occurred 0 minutes later (at 207.40 minutes), at the same time as the previous incident, 5B, i.e. 207.40 minutes 11 kV Mt Wellington K05, 4D0, PILC cable at 50 m faulted, as shown by the arc crater in the conductor in Figure 92. However there is no record of this circuit having electrically tripped. It has therefore been taken for the purpose of this report that it faulted at the time of Mt Wellington substation losing power when Mt Wellington No 1 tripped.

This cable falls into the third 'Window' as it is located 23 metres to the East of the failed transition joint at 73 m and 16.9 m to the East of the previous closest fault. It is probable that fire was propagating along the PE sheathed, wire screened 33 kV XLPE cables and along the bottom of the trench aided by the input of the cable oil liberated by the 2D0 OF cable fault at 68.9 m. The cable was de-energised at 207.4.

19th Cable Incident, 5DX, Diagram in Figure 93

Occurred 8.32 minutes later. 33 kV Sylvia Park No 2, 5DX, XLPE cable at 71.8 m, faulted and tripped. The arc crater is shown in Figure 94. This cable had been laid in the access way. It failed close to the fault in the OF cable 2D0 at 68.9m, which had faulted 9 minutes before.

20th Cable Incident, 2C0, Diagram in Figure 95

Occurred 7.77 minutes later. 11 kV McNab K19, 2C0, at 67.9 m, faulted and tripped. The arc crater is shown in Figure 96. The cable is effectively adjacent to (1 m to the East) the faulted OF cable 2D at 68.9 m. It failed 16.28 minutes after cable 2D. 2C0 was next to the faulted transition joint and survived 104.17 minutes after its failure. It is possible that burning oil accelerated its failure.

21th Cable Incident

The following three circuits were manually opened before electrical faults could occur:

- OF Cables:
 - St Johns 2, 33 kV, 4C0 (3:00:34)
 - St Johns 1, 33 kV, 4A0 (3:01:04)
- XLPE Cables:
 - Sylvia Park No 1, 5C(X, Y, Z) (2:59:54)

The 220 kV Switchyard was de-energised at 4:37:00, 315.5 minutes after the 11 kV Remuera K10, 3B0, transition joint first faulted.

12 Fire Initiation

The electrical failure in the Remuera K10 transition joint stands out from the other circuit failures that occurred later as it was:

- The first cable to fault.
- The only fault to have been re-energised and to have suffered a second power arc.
- The only fault to have been within the comparatively weak containment of a transition joint comprising layers of polymeric heat shrink sleeves and copper knitted mesh tapes.

12.1 Source of Fire Ignition

The energy from the first power arc had the capability of violently bursting open the transition joint wrappings (polymeric heat shrink sleeves and copper knitted mesh cloth) and so admitting air into the joint. The arc produces a high temperature that is capable of igniting the flammable joint materials in the presence of air e.g. the polymeric heat shrink sleeves and the materials inside, these being the PILC cable core insulation (hydrocarbon compound impregnated paper insulation) and the XLPE cable insulation. Table 7 gives the ignition and combustion temperature of materials present in cables and joints and compares them with common materials.

The outer heat shrink sleeve would have been split open by the first power arc i.e. by the combination of its transient shock wave and its high temperature. The arc would have heated the copper conductors to above their melting point of 1,084°C this being significantly higher than the temperatures required to melt and burn polymeric and other hydrocarbon materials. For example the melting point of medium/high density cable grade PE is 115°C and of high density PE is 135°C. The short term degradation temperature of XLPE is taken to be $\geq 250^\circ\text{C}$ and the flash ignition temperatures of typical polymeric materials is approximately 350°C, Table 7⁹.

Table 7 Ignition and combustion properties of common materials

Material	Flash Ignition Temperature (°C)	Self-Ignition Temperature (°C)	Limiting Oxygen index (% O ₂)	Heat of Combustion (MJ/kg)
Wool	200	590	24-25	20
Wood	220-264	260-416	22-25	18.5
Cotton	230-266	254-400	18-27	16.7
Polyurethane	310	416	16.5	28
Polypropylene	320	350	18	46
Polyethylene	341-357	349	18	46
Polystyrene	350	490	18	40
Polyvinyl chloride (PVC) plasticised	391	454	47	19
Nylon 66	421	424	20	33
Silicone rubber	490	550	26-39	
Polytetrafluoroethylene (PTFE)	560	580	95	endothermic

A study in Section 23, Appendix F validates the published correlation between the arc crater volume and the magnitude of fault energy (current and time). The temperature of the conductor material is estimated by calculation. It is shown that the temperature of the volume of metal expelled by the arc would have reached a temperature in the region of 6,000 °C. Allowing a 50% factor for the proportion the fault energy converted into heat, a temperature of 3,000°C was obtained. This temperature is three times greater than the melting point of copper and is approximately ten times higher than the temperatures necessary to ignite the hydrocarbon joint and cable materials listed in Table 7. The Author concluded that the power arc fault ignited the fire.

The key difference between the installation of cables in the trench and buried installations is that, although components can still fault and power arcs form, fire cannot be sustained in the absence of air and the oxygen it contains.

Reclosing the circuit breaker onto the failed joint 119.32 minutes after the first electrical failure of the joint would have re-applied voltage to the fault position in the transition joint. At this position the insulating materials had previously been destroyed and occupied by an air-filled void surrounded by electrically conducting materials, such as droplets of metal and carbonised paper and heat shrink sleeve insulation. Without electrical insulation and with the presence of

conducting material the second failure would have been instantaneous, as confirmed by the circuit protection record.

In the Author's experience, the consequences of the second electrical failure would have been significantly more violent in intensity. The arc's shock wave and high temperature would have further opened the damaged joint materials. The ionised gasses forming the arc, unrestrained by the opened heat shrink sleeves and knitmesh screening tapes, would have fanned out of the joint in the shape of a loop²⁰. The arc is impelled outwards by the electro-mechanical forces that accompany the high magnitude fault current. Joint and cable materials that were not already burning would have been readily ignited as they had previously been heated and thermally degraded by the heat and flames from the first fault arc.

Evidence that the arc had looped out to split open the joint's heat shrink sleeves was found where the arc had contacted the outer earth continuity conductors:

- Arc burning, Figure 19, of the copper braid earth conductors that are laid across the length of the joint and used to connect the lead sheath on the PILC cable side to the copper screen wires on the XLPE cable side.
- The melted edges of the copper knitmesh earth screening tape that were found to have been burnt open by the arc.

In support of the formation of an arc loop it was noted that:

- i) The arc burning on the earth conductors was located towards the centre of the joint and was not in line with the arc cavities in the main conductors at the end of the joint.
- ii) The fault was recorded as phase-to-phase and the conductor arc damage was phase-to-phase. There was no evidence that there had been a primary high current arc contact between the conductors and earth conductor.

12.2 Progression of the Fire

The first evidence of fire at Penrose was from a CCTV security camera looking southwards between transformer T11 and the 33kV Switch Room. The hourly photographs are shown and analysed in Section 16, Appendix A and are summarised in Table 9.

- Vision started to be obscured and light reflections dimmed by a light smoke haze 70.72 minutes after the first fault and 48.6 minutes before the second fault, indicating that i) a fire had been ignited by the first fault and ii) its progression was slow.
- Vision was further obscured by light smoke forming a general green haze 130.72 minutes after the first fault and 11.40 minutes after the second fault. This further indicated that progression of the fire from the first fault and acceleration of the fire from the second fault had continued to be slow.
- Clear signs of reflected light are present from the fire deduced to be in the trench between transformers T10 and T11 and swirls of thicker smoke are present at 190.72 minutes after the first fault and 71.40 minutes after the second fault on the transition joint. This confirms that the fire had become established and accelerated between 11.40 and 71.40 minutes after the second fault.
- The fire, accompanied by dense smoke can be seen to have emerged from the exit of the trench adjacent to the 33 kV Switchroom at 250.72 minutes after the first fault and 131.40 minutes after the second fault. This confirms that the fire had progressed from the 73 m chainage position to the exit at 91.5 m within the one hour period. The dense smoke is to be expected from cables having non-fire-performance designs i.e.: having the following combustible materials:
 - Non-fire performance PE oversheaths.
 - Non-fire performance PVC cable oversheaths.
 - Bitumen impregnated hessian outer serving
 - XLPE insulation.
 - Compound impregnated paper tape insulation (PILC cable).
 - Oil impregnated paper tape insulation (OF cable).
 - Free, low viscosity cable oil (OF cable).

From the examination of the CCTV camera photographs described above it was deduced that the fire was ignited by the first power arc, but had burnt slowly and was then accelerated by the second power arc, but still propagated slowly. This deduction was based upon:

- i) The history of the investigation of in-service fires (Section 24, Appendix H) of PVC and later PE oversheathed cables in which it was found experimentally that to obtain consistency of results and replicate service fires for the development of improved materials it was necessary to:
 - a. Reach a critical temperature (>400 °C at which flammable gasses were generated) for which a high heat input and sufficient time were required.
 - b. Select a minimum critical mass/volume of combustible material per metre length such that the flame could generate sufficient heat to demonstrate that it would or would not self-sustain.

- c. Select a cable test configuration of grouped cables representative of the grouping of cables and mass of flammable material present in service.
 - d. Test cables vertically, this having been found to be the most vulnerable orientation in service and on test for flame propagation.
- ii) The formal type testing standard for cables having low propagation properties (e.g. IEC 60332-3-10¹⁰, IEC 60332-3-24¹¹ and the FIPEC report 'Fire Performance of Electric Cables'¹² in the experimental variables listed above were embodied into the test requirements.
- iii) Informal, qualitative fire trials were conducted at the Fire Services facility in Auckland on samples of cable removed from the cable trench. It was found that heat output from a continuously maintained gas torch did ignite the oversheath of the PE sheathed, wire screened, 33 kV XLPE cable, but that it required time. The qualitative trials visualised what had been deduced to have happened from the evidence of the burnt cable in the trench and from the examination of the time stamps on the CCTV photographs:
 - a. In the trench the fire required time to become established, to propagate and to become fierce i.e. the flames did not erupt spontaneously into a fierce, fast propagating fire. In the trials significant heat input was required to self-sustain flames.
 - b. In the cable trench the fire transferred progressively to all the cables except some of those on the floor. Figure 45 visualises how flames and radiated heat transfer fire to a parallel cable. Significant heat input was required to reach a condition which would sustain this fire.



Figure 45 33 kV XLPE cables: ignition of two cables

- c. In the cable trench the flames propagated long distances in both directions. Figure 46 shows flame starting to propagate along the PE/PVC oversheath of a single core 33 kV XLPE cable after the heat source in Figure 45 had been removed.

It is seen that the flames on the parallel cable had not self-sustained and have extinguished.

Portions of burning, partially combusted oversheath have dripped and dropped off the cable onto the floor. Evidence was found in the cable trench that this had spread fire to the cable circuits below. Curtains of i) dripping PE/XLPE were found underneath some of the less severely combusted oversheaths and ii) dripping hydrocarbon compound was found underneath some of the PILC cables from which the lead sheath had melted, but which were still mechanically contained within their double steel armour tapes.



Figure 46 33 kV XLPE cable: flame propagating and PE dropping

Figure 47 shows that the oversheath of the Figure 46 sample had been combusted to expose the copper wire screen. The extruded XLPE core, also combustible, is visible between the wires.



Figure 47 33 kV XLPE cable: oversheath combusted

- d. If a condition occurs of critical volume of combustible material, threshold temperature and ignition, the burning cable contributes its own heat output and the fire becomes self-sustaining and self-propagating. The cable trench contained a significant volume of combustible material, Table 8.

Table 8 Volume of combustible material in the cable trench

Cable Level	Volume of combustible Material [L/m]
1	14.00
2	18.15
3	18.45
4	16.96
5	16.23
Total	83.78

- e. In the cable trench a circuit of 33 kV XLPE single core cables in trefoil formation was present above the failed transition joint. This standard configuration geometrically concentrates both a volume of combustible material and an increased surface area available to absorb heat and to contribute flammable gasses. The volume of combustible material in a trefoil group of 33 kV 400 mm² XLPE cable was measured to be 4.7 L/m. Figure 48 visualises the ignition and flame propagation of a trefoil cable group after the heat source has been removed.



Figure 48 33 kV XLPE trefoil group: flame is sustained

Figure 49 shows the trefoil group after the flame was extinguished. The oversheath comprising an outer layer of PE and inner layer of PVC had been combusted to expose the copper wire screen. On the extreme left of the photograph the oversheath has a matt appearance

indicative of char. The presence of char is specified in the IEC type approval test as a measure for the distance flame has propagated when assessing the performance of a fire performance oversheath. It was used in the investigation to assess how far the fire had propagated along the trench.



Figure 49 33 kV XLPE trefoil group: oversheath combusted

- f. Qualitative fire trials performed on a PVC oversheathed 33 kV OF cable, Figure 50, demonstrated that a significant level of heat was required to ignite the PVC sheath. However, this level also melted the aluminium sheath. It is probable that cable oil leaked from the non-pressurised sample and contributed to the size of the flame. In the cable trench the aluminium sheaths along the majority of their lengths had remained intact. This trial visualised those locations of intense fire in the trench where the aluminium sheath had been melted and ruptured. Figure 51 shows the burnt PVC oversheath, the anti-corrosive bitumen layer and the aluminium sheath, exposed and melted.



Figure 50 33 kV OF cable: PVC sheath and oil burning



Figure 51 33 kV OF cable: oversheath burnt and aluminium sheath melted

12.3 Fire Initiation Conclusion

The Author concluded:

1. The fire was ignited by the power arc generated when the transition joint in Remuera K10, 3B0 at 73 m chainage failed electrically at 23:21:30 hours on 4th October 2014.
2. Two hours later at 01:20:49 hours the fire was accelerated when the circuit breaker was re-closed onto the faulted circuit and a power arc was re-struck in the failed transition joint. More energy and heat was injected by the second power arc.
3. After its ignition, the fire followed a logical progression until its extinction by the Fire Service, i.e. i) preferentially eastwards towards Gavin Street and ii) westwards towards the 33 kV Switchroom.
4. No other source of ignition was found, nor considered to be credible.

13 Fire Performance of the Cables in the Trench

The progression and location of each cable failure had not been influenced by fire-fighting. All of the cable failure incidents had occurred within 223.48 minutes of the first fault in the Remuera K10 cable this being before the Fire Service was admitted to the Penrose Switchyard after approximately 241 minutes.

13.1 Ranked Cable Fire Performance

The 11 kV transition joint PILC to XLPE cable is ranked as having the poorest fire performance as it was ignited and sustained fire long enough to spread fire to the PE sheathed XLPE cables located above it.

The three cable types are ranked below in order of their fire withstand performance in the Penrose trench.

13.1.1 XLPE Cables

The PE sheathed, wire screened, 33 kV XLPE cable circuits exhibited the poorest cable fire performance as defined by having both the shortest times to failure, the highest proportion of circuits to fault and the highest proportion of

material combusted. This is a common design of modern cable that is most often used in laid-direct applications. Eight out of ten XLPE circuits faulted due to fire spread.

The PE sheathed, wire screened, XLPE cables formed the first five 33 kV power circuits to fail as a result of fire spread from the faulted transition joint. These faults were within the 170.15 to 181.27 minutes time period in Window 1, as defined in Section 11 and Figure 43. Remuera N^o 3 was the first at 170.15 minutes. The fifth cable was St Johns N^o 3 at 181.27 minutes. The 11 kV XLPE Tunnel Supply circuit also faulted in this time. In total 12 incidents of cable faults and damaged control cables occurred in Window 1.

The poor fire performance of the PE sheathed, wire screened, XLPE circuits is attributed to:

1. Location: The first three circuits to fail were mounted on the first level such that they were ignited by the faulted transition joint on Level 2. Conversely the two XLPE circuits that did not fail were protected by their position on the trench floor underneath the fourth layer of cables.
2. The properties of the PE sheathed, wire screened, XLPE cable components:
 - a. PE and XLPE have a self-propagating fire characteristic. They sustain combustion at an oxygen level below that present in air i.e. they have a low 'oxygen index'.
 - b. PE and XLPE have a low ignition temperature.
 - c. PE and XLPE have a high heat release during combustion and thus spread combustion more readily.
 - d. PE has the characteristic of dripping burning globules and strings of molten PE to spread fire to cables below. (Strings and curtains of re-solidified PE were found during the examination of the trench).
 - e. The wire screen cable design does not have a metallic sheath or armour. Such components have high thermal capacity and high melting points and so delay the time at which the cable's internal insulation fails electrically and ignites.

3. Design of the XLPE Cable

PE Oversheath and Wire Screen

The arc is likely to burn a larger hole and do more damage to modern wire screened cable designs than to older designs of cables having extruded thick metallic sheaths. This is illustrated by the short-circuit

‘spiking test’, which is sometimes required for 33 kV XLPE cables to ensure that the wire screen has sufficient cross-sectional area and the wire spacing is sufficiently small that i) excessive burn-back length of the wires does not occur and ii) the arc does not extinguish before the fault has been detected and the circuit breaker operated. In this test a spike (steel nail) is previously driven through the insulation to form a short circuit and initiate the arc. The arc is then maintained for the specified duration, (e.g. 3 seconds). The arc usually loops outside the cable during the test. The oversheath and insulation may catch fire and require to be extinguished. A spiking test is described in reference¹³.

In the Author’s opinion, the looped power arc from a faulted PE oversheath, wire screened, XLPE cable is likely to have contributed to the development of the Penrose fire by accelerating the ignition of the adjacent designs of PE sheathed cables. The localisation of the cable faults within ‘Window 1’ is partly attributed to this mechanism.

High Volume of Flammable Material

The 33 kV PE sheathed, wire screened, XLPE cables are installed in trefoil groups, which have a larger diameter and a greater concentration of flammable oversheath material and more surface area than the older three core OF cable types. Fire tests have shown that there is a critical mass and critical spacing dimensions at which cable fires accelerate. Remedial measures are to select a flame retardant sheathing material, to apply an intumescent paint and to segregate circuits by increased spacing (vertically and horizontally) or the use of fire barriers.

13.1.2 Oil-Filled Cables

PVC Oversheath and Extruded Corrugated Aluminium Sheath

The only OF cable to fault occurred in ‘Window 2’ after a total of 207.2 minutes and was located at 2D0 at 68.9 m. The good performance of 2D0 up to that time was remarkable as:

- i) The OF cable was on the same level as the faulted 11 kV transition joint, 3BO, located at 73 m. It is noted that a) the 11 kV three core XLPE cable connected to the transition joint was likely to have been burning and b) it crossed laterally over the top of the OF cable.
- ii) The OF cable had been surrounded by burning and faulting XLPE cables on Levels 1, 2 and 3.

Eventually either the external fire or an internal cable fault and arc breached the aluminium sheath of the OF cable as shown in Figure 87. The increased intensity of the fire damage seen in this trench region is attributed to the release of cable oil and spread of fire. Smaller holes were found to have been melted in the aluminium sheath of 2D0 close to the fault hole as shown in Figure 53.

Although the fire intensity was seen to have been increased in the 'Window 2' zone, it was significantly less than that found between 35m to 45m.

Between 35 m and 45 m, Figure 52, the aluminium sheath of 4C0 had suffered a major rupture, Figure 54. It is thought that this occurred later as 4C0 was manually opened at 3:00:34.

Two of the OF cables remained in service until all of the power had been disconnected at 219.07 minutes and 219.57 minutes, these being the two St John circuits, 4A and 4C. Their survival may be partly attributable to their low position in the trench on Level 4.

The two Westfield circuits 3C and 3E did not fail, but were de-energised at 181.27 minutes when the Penrose 33kV to 22 kV transformers tripped at the same time as the St Johns 3 circuit tripped. A major loss of aluminium sheath was present on the underside of Westfield 3, 3E0, OF cable, at 37-38 m, which, being installed low in the trench, is indicative of an oil fire on the floor.

Elsewhere in the trench the corrugated aluminium sheaths were seen to have withstood the fire with less damage than other cable types. Their good fire survivability time is attributed to the high thermal capacity and high melting points of the extruded aluminium sheaths. In the Penrose fire, a significant number of failures of the XLPE cable circuits and significant fire damage to all the cable types had already occurred before oil was released from ruptured OF cables and increased the fire severity. In consequence fire spread from burning cable oil did not increase the outage repair time. In different circumstances, for example if the first electrical fault had occurred in an OF cable, oil released is likely to spread the fire damage to other circuits present.

At the initial start of a fire a PVC oversheath has low flammability and is non-propagating, but industry tests have shown when the temperature exceeds ~400°C gasses are liberated from the plasticiser that make PVC highly flammable. It was for this reason that the CEGB encouraged the development of oversheathing and insulating materials having low smoke and fume emission and reduced flame propagation.



Figure 52 High fire intensity at 37 m (33 kV XLPE cables on top Level)



Figure 53 Holes in OF cable aluminium sheath, cable 2D0 at 66-71m



Figure 54 Heat deformed and ruptured OF cable corrugated aluminium sheath

13.1.3 PILC Cables

The 11 kV PILC cables were judged to have the best fire performance in the Penrose trench. They had a good fire survivability similar to that of an OF cable, but had the advantage that they did not spread fire by the release of a large volume of flammable cable oil.

In particular:

- i) Three PILC circuits survived until faulting in 203.20 to 223.48 minutes.
- ii) The McNab K19 PILC circuit was the last cable of all to fault in 223.48 minutes despite being positioned high up on the second layer near to the faulted Remuera K10 PILC to XLPE transition joint.

The good fire survivability is attributed to the two robust layers of steel tape armour (high thermal capacity and high melting point), the good high temperature performance of the paper insulation and its low insulation design stress. The downside of PILC fire performance is that the lead sheath melts at low temperature and flammable impregnating compound then drips out, prospectively spreading fire to the cables below. Curtains of re-solidified compound were found in the Penrose trench.

It was concluded that the OF and PILC cables were not contributory to the early development of the fire that occurred from the transition joint and spread to the XLPE cables.

13.2 Variation in Fire Severity Along the Trench

The cable fault incidents had moved Westwards with time from the faulted transition joint at 73 m chainage, no faults were found to the West. The fire had reached a higher intensity to the East and had travelled a longer distance than it had on the West side. Generally the fire on the East side had combusted the cable oversheaths and insulation such that in some locations the 33 kV XLPE cables had no trace of PE or XLPE remaining and the remaining copper screen wires and aluminium conductors had been burnt clean. This was not so on the West of the 73 m position. Remnants of the carbonised cable oversheaths remained and in other places 'curtains' of re-solidified PE strings hung down from below the XLPE cables and strings of waxy cable compound hung down from the PILC cables. The aluminium sheaths of the oil-filled cables were covered by carbonised PVC oversheaths and appeared to be intact. To the East in many places the PVC oversheath had been burnt clean by the fire and in some places the aluminium sheath had been ruptured and melted, which would have released cable oil and increased fire intensity.

When the Fire Service arrived it was reported that the fire had also spread Westwards to have emerged out of the trench exit and to be burning the above-ground cables adjacent to the 33 kV Switchroom.

The reasons for more electrical failures and more severe fire damage being present on the East side of 73 m chainage were:

- At the start of the fire hot air could move freely along the top of the trench on the East side. On the West side hot air movement would have been inhibited by the descent of the trench to pass below transformer tracks.
- The Fire Service upon arrival were able to access, cool and extinguish the fire at the West end of the trench, whereas the East end could not be accessed until after the 220 kV substation had been de-energised. The fire Service reported that fire was moving eastwards.

The most severe fire damage to cables had occurred on the East side at 45 m to 35 m chainage and, in particular where in places:

- The PE oversheath and XLPE insulation had completely burnt away without trace of carbon.
- The copper screen wires were hanging in festoons on the aluminium conductor.

At 45-35 m the lower part of the south wall was uncharacteristically free of soot, this being attributed to a severe cable oil fire on the floor. The cables from 79 m westwards to the 33 kV Switchroom had suffered less damage, in that some

charred residues of the polymeric oversheaths remained and the covering of soot was greater.

At the West end of the trench some of the XLPE cables that exited to run above ground to the 33 KV Switchroom and had suffered severe damage in having all their PE oversheath and XLPE insulation burnt away. This was attributed to the free supply of air that became available at this position. It was noted that the cable exit was open and did not have a fire seal. The exit was in the form of a timber structure that joined onto sun-shielded ducting that was open at the Switchroom end. The burning was less severe than that observed between 45 – 35 m where evidence of a cable oil fire had been present. There was no obvious evidence of an oil fire at this location, however this cannot be ruled out. It was noted from historic photographs and burnt remains that timberwork had been interspersed between some of the concrete roof slabs at a few locations along the trench.

14 Review of Publications on Cable Fires and Cable Fire Performance

A comprehensive review of publications has been performed. The review spans selected items over 130 years from an early experience of cable fire in 1885 to the present date.

Complete lists and summaries of the publications, together with unpublished items from the Author's knowledge are presented in Section 24, Appendix G. The items are presented in ascending date order. The Appendix G publications are divided into:

- Subsection 24.1: Cable fires and fire performance.
- Subsection 24.2: Type test standards for cable fire performance.

References are made to design and test standards and recommendations; if Readers wish to make use of data from these documents they are advised to obtain current issues.

14.1 Sources of Published Information

1. CIRED conference papers (International Conference on Electricity Distribution). The conferences are held at two yearly intervals, the first being in 1971. Cable papers are included in the Session on Components.

2. Jicable conference papers. The conference is held at four yearly intervals and specialises in cable matters at all voltages.
3. CIGRE conference papers. The main conference is held at two yearly intervals. Originally CIGRE specialised in cable systems at 60 kV and above. Now it considers all power cable voltages.
4. CIGRE area conference papers. Conferences are held in different countries, usually on topics of a speciality, local interest, but also to spread knowledge of CIGRE's technical work.
5. CIGRE Technical Brochures, these are the published technical recommendations of a working group. Formal publication was originally exclusively in the CIGRE Electra magazine. The main publication is now in the Technical Brochure and the work summary is in Electra.
6. CIGRE Tutorials, these summarise the work and recommendations of a working group.
7. IEEE conference papers. These are in various journals e.g. ICC conference papers, the 'Transactions on Power' and 'Transactions on Dielectrics and Electrical Insulation'.
8. IEE papers. Up to c.2000 power cable papers were frequently published in the various journals of the IEE (now IET) and in dedicated Conference Proceedings. The IET organise an AC/DC Conference.
9. Electrical engineering text books.
10. IEC Standards.

14.2 Findings of the Publication Review

1. In-air cable installations have been reliable, but there has been an appreciable, low incidence of major cable fires.
2. Generally the cause of a fire, the remedial measures and the lessons learnt are not available in publications in sufficient detail and it is only possible to find information if the incident has received wide publicity.
3. The use of in-air installations in the form of cable tunnels has increased in recent years because of their advantages in passing under obstructions and forming cable routes in congested cities.

4. When a major cable fire has occurred in an in-air installation:
 - a. The rate of flame spread is high.
 - b. The extent of fire damage to adjacent cables and to other assets is high.
 - c. The consequent repair time is long.
 - d. The non-availability of the feeders is long.
 - e. An investigation is undertaken and follow-up action generally occurs in such items as:
 - i. An engineering recommendation (company in-house, national or international).
 - ii. Development of improvements in cable system components,
 - iii. Improvements in cable system type testing techniques.
 - iv. Improvements in installation and maintenance techniques and training.
 - v. Improvements in fire monitoring techniques.
 - vi. Improvements in operational techniques.
5. Examples of incidences of cable fires and, when known, the cause:
 - a. Ignition source external to cable system:
 - i. Fires on a railway embankment as in the 10kV Deptford feeder on 1885.
 - ii. Brown's Ferry, US, Nuclear Power Station. Ignited by a candle flame: 1975.
 - iii. Methil Power Station, Scotland. An oil leak from a turbine gauge caught fire and spread to cables: Pre 1977.
 - iv. A train fire in the Channel Tunnel track-side feeders, the LSF fire performance cables performed well: 1996.
 - v. Vandalism or theft, as in the Dartford Creek Cable Bridge fire in 2009.
 - b. Ignition source internal to the cable system, the most numerical cause is the failure of a joint (*Author: as in the Penrose fire*).
 - i. PVC cable fire in a cable annex of La Spezia Power Spezia Italy ignited in an MV cable termination chamber: 1967
 - ii. 400 kV Woodhead Tunnel, two occasions, the one initiated by a joint failure being in: c.1990.
 - iii. 132 kV Tsing Yi Island bridge jointing chamber: c.1973
 - iv. 110 kV Kista cable tunnel under Stockholm, three occasions, the last being in: 2001.
 - v. London cable pits: 29 disruptive failures of in-air pits containing distribution cables has occurred in a two year

- period, the main cause of failure has been attributed to joint failures: pre- 2014
- vi. 220 kV North China in a cable tunnel: April 2009
 - vii. 220 kV North China, failure of a 15 kV joint, in a cable tunnel: December 2009.
 - viii. China: data from 'many fire accidents'.
- c. Not found from publications at the present date, or under investigation:
- i. China: 'data collected from many accidents'.
 - ii. Kingsway, London, Utilities tunnel shared with gas main: 2015

[Author: The fire at La Spezia in 1967 and IEE publication²⁷ date of 1977 are the key dates that alerted UK Engineers to the risk of PVC cable fires and which then commenced the development and availability of fire retardant (low propagation) and 'low smoke and fume' grades of cable oversheath and insulation. The first cables in the Penrose trench were selected and installed in 1966 some five to ten years before such knowledge became available].

6. A few of the major cable fire reports and cable system failure reports were found in the public domain. In recent years this has happened more regularly, particularly in those countries in which there is a regulatory over-view of the distribution network operator that requires formal justification for the estimated cost of remedial works. A CIGRE working group WG B1-51 was formed earlier in 2015, on a new study topic entitled 'Fire Issues for Insulated Cable Installed in Air'. In addition to their agreed scope of work it is hoped that the WG will be able to list in their published brochure i) the incidences and details of each fire, ii) guidance on what type of new cables to procure for new installations and iii) what remedial actions are available to be selected for existing cable installations.
7. Publications record that PVC extruded cable insulation and oversheaths were initially considered to be fire resistant based on the performance of pressed bench-top samples containing only the base PVC compound heated to a low fire temperature. *[Author: normal grades of non-fire performance PVC cable sheathing were present in all of the cables in the Penrose trench. The 33 kV and 22 kV oil-filled cables had a PVC sheath over the aluminium sheaths. The 33 kV S/C XLPE cables had an HDPE sheath applied over a PVC inner sheath. The pilot cables had a layer of PVC applied over the steel wire armour].* Experience with severe cable fires in power stations in the UK and in Italy in the 1960's and 1970's

showed that this was not the case. It was found that the addition of plasticisers and other process additives caused the compounded PVC to become flammable at elevated temperatures. It was also experienced from the service fires that i) severe damage was done by acidic fumes to control rooms and electronics and ii) the dense smoke and acid fumes were a health hazard in public places such as subway stations and in places of work such as power station control rooms. These adverse experiences led directly to major cable industry developments in:

- a. Fire performance testing methods for i) the materials, ii) the particular cable construction containing the materials and iii) the grouping of the number of cables to be installed and the iv) volume of flammable material in the latter.
 - b. Fire retardant grades of PVC compounds by adding high percentages of active fillers that diluted the concentration of air (and hence oxygen) and inhibited the rate of temperature rise. The liberation of smoke and fume was also reduced, but were still of an unacceptable level for use in public and work places.
 - c. The use of fire performance grades of heavily filled polyolefins, such as MDPE/HDPE. *[Author: all of the 33 kV S/C cables had non-fire performance HDPE inner sheaths and XLPE insulation].* The normal unfilled sheathing grade of MDPE/HDPE was found to be unacceptable as:
 - i. It has no fire retardant properties (in consequence of a low oxygen index i.e. it will burn in oxygen depleted air).
 - ii. It actively contributes a high heat output into the fire, thus spreading the fire to, and along, adjacent cables.
 - iii. It liberated dense black smoke, although it did not contain acidic fumes.
 - d. The downside of heavily-filled oversheathing polyolefin compounds with LSF (low smoke and fume) fire performance is that their mechanical, electrical and water resistant properties are reduced. In such compound developments a balance between fire benefits and property disadvantages has to be reached to suit the particular application. *[Author: care would be required in the selection of a fire performance design of cable oversheath for a short length such as the Penrose trench as the major part of each drum length of cable would be buried in the ground below the water table. One possibility would be to install straight joints at the ends of the trench to connect the different fire performances cable designs].*
8. The evolution of the Type Testing Standards for cable fire performance:
- a. Started to be developed c.1970, by ENEL, (Italian Standards Authority CEI 20:22) and the CEGB, UK, (British Standards). The

French Metro system also developed a standard. These led to the current issues of suites of IEC 60332 (2009) and AS/NZS 4507 (2006) and AS/NZS 1660.5 (2005) test Standards of requirements and test methods.

- b. Has led in Europe to the issue of European norm EN50399 in 2011, which is required for the introduction of classes for reaction to fire performance of cables. Cables that have meet the requirements will bear a CE marking. EN50399 describes the use of IEC 603323-3-10 test equipment together with apparatus to measure the heat release rate and smoke production rate.
9. Experience with development and type testing of fire performance cables has shown that the ignition and propagation of flame is a multivariable problem. The type test standards list the variables and state that meeting the requirement does not mean that the cable will exhibit a satisfactory fire performance in a particular cable configuration in a particular application.
10. Fire tests have shown that key variables in fire ignition and flame propagation are the length of time the cable is heated for, the heat input, the temperature reached and the availability of oxygen. The Author of a paper describing a fire initiated in a North China tunnel by a joint failure ascribed the fire severity to reclosing onto the failed circuit. *[Author: it was deduced from the examination of the failed Penrose transition joint that i) the heat shrink housing would have been opened by the power arc during the initial fault and so oxygen would have admitted from the surrounding air and ii) when the circuit breaker was reclosed onto the circuit the joint was calculated to have experienced a second high injection of heat and high temperature rise, which were sufficient to have accelerated and increased the severity of the cable fire.]*

14.3 Recommendation from the Publication Review

As a result of the publication survey the Author recommends the following fire performance measures for any new significant in-air trench installation:

1. Select cables with fire performance oversheaths that have met the type test requirements when tested to the IEC or AS/NZS test Standards with respect to:
 - a. Low fire propagation. The objective is to reduce the likelihood of ignition and flame spread.
 - b. Low smoke and fume. The objectives are to:

- i. Reduce the risk of Substation insulator damage and flash-overs.
 - ii. Aid the Fire Service in fighting a fire.
2. To exclude joints of any type from the in-air trench. The objective is to remove the main generic cause of cable system failures.
3. To exclude transition joints from the trench. If transition joints are unavoidable, to install them within an arc resistant housing. The objectives are to inhibit the ignition of external fire by containing the power arc and preventing entry of air.
4. Not to close voltage onto a failed circuit. The objectives are to inhibit the ignition of fire by eliminating a re-strike of the power arc and its accompanying disruptive, high pressure wave, high heat output and high temperature.

15 Conclusions and Discussions

15.1 Cause of the Fire

The Author concludes that the cause of the fire in the Penrose trench was the electrical failure of the PILC to XLPE cable transition joint located at 73 m in the 11 kV Remuera K 10 PILC cable circuit.

The manual reclose of the feeder onto the failed transition joint is considered to have accelerated the fire.

15.2 Cause of Transition Joint Failure

The Author concludes that the cause of the transition joint failure is the vulnerability of the transition joint design, with respect to the electrically stressed insulation in the crutch between the PILC cable cores. This is the position where the power arc occurred. It should be noted that none of the insulation of the failed joint survived the fire and this conclusion is based on the examination of the unfailed transition joint.

The Author concludes from the examination of the unfailed transition joint that the jointing quality was satisfactory.

By the year 2001 when the two PILC to XLPE transition joints were installed as a repair measure in the Penrose trench the Author was aware that transition joints had a higher failure rate than conventional PILC straight joints. The Author notes that failure rates were not available in the public domain. Failure rates

were collected, for example, in the UK by the ENA (Energy Networks Association), and are available to member utilities. However, the ENA 11kV PILC joint failure data was found to be insufficiently detailed to have been of assistance. Limited data contributed by Edif-ERA based on fault investigations it has carried out for other parties suggests that the failure rate of PILC transition joints is higher than conventional PILC straight joints.

The Author concludes that the failure mechanism was one of cumulative deterioration with time in service. It was noted that:

- i) The two transition joints had performed satisfactorily for 13 years.
- ii) The unfailed transition joint had incipient electro-thermal distress. This was attributed to local dielectric heating of the PILC paper insulation, which had been contaminated with foreign material.
- iii) The 11kV cable had been energised, but not carried sustained load for eight months prior to failure. It had carried load for ten minutes on the morning of failure. It is considered that this had disturbed insulation already at an advanced stage of distress and precipitated the electrical failure.

The Author considers the contributory causes of transition joint failure to be:

- i) The concentration of thermo-mechanical disturbance of the crutch insulation resulting from:
 - a. Lack of straight alignment of the joint and cables (the joint was positioned at the start of a curve in the cable).
 - b. Lack of cable cleats and joint supports.
- ii) Ingress of moisture into the crutch insulation at the lead sheath cut. This is supported by:
 - a. The stain-like pattern of the black feature in the crutch of the unfailed joint.
 - b. Inadequate heat shrink sleeve water seals in the unfailed joint.
- iii) Drying-out of the impregnating compound from the paper insulation. This conclusion was supported by the finding of dried-out and thermally degraded insulating tapes in the unfailed transition joint. In comparison, the paper tapes in the conventional bitumen filled straight joints were found to have been in good condition and were well impregnated with a mixture of cable impregnant and bituminous joint filling compound, the latter having acted as a reservoir during thermal expansion and contraction cycles in service.

- iv) Migration of void filling mastic to the paper insulating tapes in the crutch. This was supported by the laboratory identification of identical material in the black feature at the crutch position.
- v) The jointing process of inserting 'void filling mastic' insulation into the PILC crutch of the transition joint, this being difficult and variable and risked damage to the cable insulation. This was supported by the findings of the dissection of the unfailed joint.

The Author recommends that:

- i) The location of other transition joints installed in air on the network be reviewed.
- ii) The joint design and jointing process be made more consistent with respect to a) the water seals and b) the void filling mastic.
- iii) Alternative designs of transition joints be assessed.
- iv) Joint failure statistics be compiled and regularly reviewed.

15.3 11 kV PILC to XLPE Transition Joint

The Author considers that fire precaution measures should have been considered when the 11 kV PILC to XLPE transition joint was installed in the in-air Penrose trench. However, it is accepted that the need for such measures would not have been widely known. Personnel would not have been aware of the advisability for the transition joint to have a capability for power arc containment and fire retardancy. It is of note that conventional (and now obsolete) PILC straight joints having a cast-iron protection box inherently had a limited capability, but conventional heat shrink sleeve XLPE straight cable joints do not.

The Author recommends that for in-air applications, a technical specification is prepared for transition and straight joints, which includes demonstrated fire propagation and power arc containment test performances.

The Author has been advised that there are approximately 5,000 transition joints installed on Vector's network, the majority of which are buried. The best failure information available to the investigation was from Edif ERA who advised that, out of 26 failed 11 kV PILC joints it had examined, there were 5.5 times more transition joints than conventional designs of bitumen filled straight joints.

The Author notes that a transition joint is an important and unavoidable strategic cable accessory to a Utility. The availability of the joint permits Utilities to switch from installed 11 kV PILC to new XLPE cable types for diversions and repairs

without having to replace the large asset base of installed PILC cables. The availability of the transition joint inevitably accelerated the disposal of the cable manufacturing equipment for PILC cables and increased Utility dependence on the procurement of XLPE cables as the sole choice. One of the advantages of the XLPE cable system at 11 kV and 33 kV is that the jointing is quicker, lower in cost, and does not involve the health and safety issues associated with i) plumbing onto lead sheaths and ii) filling the joint with hot bituminous compound.

The technical advantages of an XLPE cable are:

- i) It can operate at the higher temperature of 90°C and so has smaller and lower cost conductors than a PILC cable operating at 65°C.
- ii) It does not require the cost of a lead sheath as XLPE insulation is more resistant to water ingress (at voltages of 33 kV and lower).

The Author notes that the older, belted, unscreened, three-core PILC cable type is inherently incompatible in design and material types with the newer screened XLPE single core cable and its materials. In a joint, the transition between the unscreened and screened cable systems occurs in the crutch of the PILC paper insulated cores and this is the key reason for the generic vulnerability of a transition joint. The vulnerability risks identified with the particular heat shrink sleeve transition joint design at Penrose are:

- i) Susceptibility to thermo-mechanical disturbance.
- ii) Water entry into the paper insulation.
- iii) PILC impregnating compound drying-out.
- iv) Migration of the void filling compound.
- v) Damage to the paper tapes due to the difficulty of effectively inserting high permittivity void filling compound.

15.4 Cables

Ten circuits of the older generation of 11 kV PILC cables and 22kV and 33 kV OF cables were installed in the Penrose trench from 1966 to 1977 and operated up to the time of the fire in 2014. No further cables were installed in the Penrose trench until 1999, by which time Utilities had switched from PILC paper cables to extruded XLPE cables and fire retardant oversheaths had become commercially available.

Ten circuits of the newer generation of XLPE cables, having PE oversheaths and wire screens, were installed from 1999 to 2011 (9 at 33 kV and 1 at 11 kV) and operated up to 2014.

15.4.1 New XLPE Cables

The Author considers that fire retardant oversheaths or painted protective coatings should be applied to new XLPE cable circuits installed in-air. Fire retardant oversheaths limit the rate of fire propagation and so provide increased time for fire extinguishing actions, prospectively limiting i) the spread of fire to assets external to the trench and ii) the failures of other cable circuits.

In the Author's opinion, by 1999, when the first XLPE cables with PE oversheaths and wire screens were installed in the Penrose trench, the manufacturing and supply industries were aware that:

- i) Cables for in-air use were available with improved fire retardant oversheaths.
- ii) Fire segregating measures between circuits were an available option.
- iii) Fire detection and extinguishing measures were an available option.
- iv) PE oversheath and XLPE insulation materials propagate fire.
- v) PVC oversheath material at elevated fire temperatures of > 400°C can propagate fire.
- vi) Oil-filled cables were a fire-spread hazard for in-air applications.

However, the Author accepts that industry engineering recommendations and specifications did not, and still do not, clearly communicate fire precaution knowledge for new circuits, nor give clear advice for existing installations on what retrospective action, if any, should be taken.

It is recommended that:

- i) XLPE insulated cable circuits that do not have fire retardant oversheaths not be installed in close proximity above, or adjacent to, other circuits.
- ii) Wire screened XLPE cables not be installed close to other cables and services without having fire retardant oversheaths/coatings, fire segregation and increased spacings. Should a cable failure occur, a power arc is likely to emerge through the screen wires and spread fire to adjacent cables not having fire retardant coatings.
- iii) Data and communication cables not be installed between power cables, as this risks i) acting as a fire bridge between power cables, ii) early loss of signals in a fire, iii) disturbing the power cables and joints during installation and iv) impairing the power cable heat dissipation in normal service. It is recommended that data and pilot and control cables be fire segregated from the power cables, preferably outside the trench.

15.4.2 Original PILC and Oil Filled Cables

The Author considers that fire protection coatings should be applied in retrospect to existing circuits, but notes that generally Utilities have not done this unless a specific incident has occurred to make them aware of the risk.

The Author considers the choice of cable type in 1967 to have been reasonable i.e. i) 11 kV PILC cables with bitumen impregnated, hessian serving, steel tape armour and lead sheaths and ii) 22kV and 33 kV OF cables with corrugated aluminium sheaths and PVC oversheaths. At that time these were highly evolved and service proven cable designs. At that date extruded PVC oversheaths had recently entered service applications. PVC sheathed cables were considered to have low flammability, non-fire propagating properties; this was later found by experience in cable fires at elevated temperatures to be incorrect.

The flammability potential of the PILC cable's bitumen impregnated hessian outer serving had already been recognised in the industry. The Author notes that the PILC cable installation at Penrose was of a standard type in which no special measures to mitigate the risk of fire had been taken. Special measures would have been unusual at that time on 11 kV PILC cables. Special measures used in the UK in certain locations at that time were to apply an asbestos coating. This was later discontinued as being unacceptable for health reasons; in consequence it became a hindrance to maintenance.

15.5 Manual Closing onto a Cable System Fault

The Author considers that feeders should not be manual reclosed onto a cable fault, without having confirmed that the fault was not present in an in-air trench section. Reclosing onto a joint or cable fault significantly increases the severity of joint damage and collateral circuit damage and so increases the risk and rate of acceleration of a fire.

The Author notes, however, that reasonable measures had been taken after the first fault in the Remuera K10 circuit to locate it and that these, due to the fault indicator equipment characteristics, had indicated that the fault was not in the section within the Penrose trench.

The Author understands that Vector's standard operating procedures have been changed to minimise the risk of reclosing onto a cable fault. Feeders that contain in-air cable sections have been specifically identified on the operator console, and the operator will undertake the following additional actions before a manual reclose:

- i) Check any fire detection or protection systems within the cable section for signs of fire.
- ii) Inspect the cable section.
- iii) Isolate the cable section prior to the reclose.

15.6 Suitability of the Penrose In-air Trench Cable Application

The Author's conclusions and recommendations are given on the suitability of the Penrose in-air cable trench application from a cable engineering perspective.

15.6.1 Risk Assessment of the Likelihood of Electrical Failure

The Author recommends that risk assessments be performed on in-air installations to identify the possibility of electrical failure of the cable lengths and joints. In the case of the Penrose trench, although the assessed prospective number of failures is low, the risk of consequent fire spread damage is high.

The Author considers the Penrose cable trench to be a significant in-air application based on it containing i) 19 power cable feeders, ii) a total combined cable length of 3.84 km comprising 38 lengths each of 103.9m, iii) 15 joints (4 x 11 kV PILC, 3 x 33 kV XLPE and 2 x 11 kV PILC/XLPE) and iv) a significant volume of flammable material comprised of oversheathing and hydrocarbon insulation and low viscosity cable oil in the cable and within the oil reservoir tanks.

The calculated, cumulative number of faults for the Penrose cable trench of 1.2 over its 48 year life is small, but not zero. As would be expected the joints contribute a higher proportion towards this figure than the cable:

- i) The indicative number of joint faults is calculated to be 0.9 by taking the number of joints to be 15 and the time in service for each joint and then applying the Vector fault rate for all types of joints on their system over the last ten years of 0.26 per 100 joints per year.

- ii) The indicative number of cable faults is calculated to be 0.5 by taking the number of feeders to be 19 each of 103.9 m length and taking the time in service for each joint and applying the Vector fault rate for all types of cables over the last ten years of 0.2 per 100 km of cable per year. In the absence of more detailed information it is reasonable to reduce this number to allow for the probability that at least 50% of the fault rate value resulted from external means, for example third party dig-ins, thus the indicative number of faults is reduced to ~0.3.

It is recommended that in performing the first stage of a risk assessment a sensitivity study be performed in which failure accelerating factors are applied to the fault rates for the main generic types of joints and cables to represent design, condition, age and proportion of the load to their rated current carrying capacity. Such factors should be applied in particular to the more vulnerable components such as transition joints and to older PILC joints. In the second stage of the risk assessment it is recommended that the consequence of failure be assessed (such as fire spread and disruptive violence to other assets). At periodic intervals the cable network failure data should be divided into similar generic component categories and inspected by such means as Duane Amsaa plots to determine if progressive wearout of the more vulnerable and aged components is in progress.

Limited fault data may be found from CIGRE Technical Brochures such as TB 379¹⁴, 2009, and conference publications such as the 2011 CIRED paper¹⁵ from the Danish Energy Association. The latter describes fault statistics from MV cable systems and has a section on transition joint failures. The paper comments '... it is concluded that the failure rate for transition joints must be significantly higher than for XLPE straight joints'.

15.6.2 Design and Fabric of the Trench

The design of the main fabric and furniture of the trench in 1966 is concluded to have been sound (sturdy and workmanlike), i.e. its concrete walls, floor, roof slabs and galvanised steel support-arm frames.

Although not contributory to the electrical failure, fire seals should have been installed in the cable trench at the following locations to limit the spread of the fire:

- i) The exit from the trench to above ground at the West end leading to the 33 kV Switchroom. This would have prevented the escape of flame to the above ground cables and to the wall of the 33 kV Switchroom.
- ii) The exit at the interface at its West end with the smaller southwards going cable trench leading to outdoor cable terminations and oil

reservoirs for the OF cables. It is believed that the fire was extinguished before it spread into this trench.

The Author considers that timber should not have been used in place of some of the concrete roof slabs, as timber is flammable: i) flame can escape the trench and propagate to external assets and ii) a fresh supply of air can enter and sustain the fire in the trench.

The Author considers that control cables should not have been installed across the Penrose trench. The control cables were not on supports that were fire segregated from the power cables in the trench.

15.6.3 Physical Capacity of the Cable Trench

The Author considers that, at the time of the fire in 2014, too many cables had been installed in the trench. This did not contribute to the cause of the joint failure, but did contribute to the rate of fire spread. The trench contained:

- i) 20 circuits comprising 38 single power cables and additionally a number of control cables.
- ii) No spare space on the four racks or on the ground for either additional circuits, or maintenance on existing circuits.
- iii) A circuit on the ground in the access way.

The Author considers that in-air cable installations should provide for:

- i) Adequate separation between cables to ensure good air ventilation.
- ii) Clear access for maintenance and repair works.
- iii) Physical separation between control and power cables.
- iv) Fire seals at cable exits and entries.

15.6.4 Thermal Capacity of the Cable Trench

An investigation of the thermal capacity was performed to confirm that the cables had not exceeded their rated temperatures.

The Author notes that a rating calculation had been performed in 2001 prior to the addition into the trench of the 33 kV Mt Wellington No 1 and 2 XLPE cable circuits. This was a simple rating calculation based on the assumption that the air in the trench was raised to 40°C by the combined heat generation of all the cables. The calculation was compared to an IEC 60287 semi-empirical

calculation and to an FEA computational flow dynamics model of air convection and ventilation and found to be a reasonable assumption.

It is recommended that for each 'significant' in-air application in the network:

- i) The rating capacity be calculated and the full method and detailed results be kept on file and updated as part of the approval process for a new circuit.
- ii) The in-service temperature be monitored at periodic intervals by a suitable method, such as a DTS (distributed temperature sensing) system, that uses either an optical fibre or thermo-couple sensor.

15.6.5 Thermo-mechanical Installation Design

15.6.5.1 Joint Supports

The Author considers that, in view of the vulnerability of the transition joint, i) a support underneath the transition joint and ii) cleats on either side to prevent thermo-mechanical movement and to keep it in straight alignment should have been installed. (Thermo-mechanical movement is considered a contributory cause of failure).

It is of note that at 11 kV, although good practice, joint supports and cleats have not been installed in all cable applications. PILC straight joints in cast-iron boxes are provided with built-in cable clamps, but it is also good practice to support the weight of the joint (it was not possible in the investigation to determine if the cast-iron joint boxes had been supported before the fire). Heat shrink sleeve, single core, XLPE cable straight joints are lighter in weight and are not always supported.

It is recommended that:

- i) Suitable support designs be reviewed for all types of joints installed in air.

15.6.5.2 Cable Cleats

Although not a factor in the cause of failure, the Author notes that cable cleats had not been installed on the cable support arms to fix the 33 kV, XLPE, trefoil, Mt Wellington 2 circuit.

The use of plastic cable ties risks unacceptable cable movement due to i) thermo-mechanical forces at normal operating temperatures and ii) short circuit forces at the associated elevated temperature limit.

15.7 Other Findings from the Joints and Cables in the Penrose Trench

The following require attention but are not factors in the cause of failure or fire:

15.7.1 Joints

- i) Parted friction-welded, bi-metallic connectors were present in the failed transition joint. These were found to be a consequence of the fire and not a contributory cause of failure. It is noted that these have since been superseded by shear-screw connector designs.
- ii) Variability in the degree of compaction of the transition joint conductor connection was found. It is noted that these have since been superseded by shear-screw connector designs.
- iii) Variability in the 'stripping' of the insulation screen and the preparation of the screen termination was observed in some of the 33 kV XLPE straight joints. It is recommended that jointer training be reviewed.
- iv) The steel 'roll spring' earth return conductor connection onto the lead sheath of the PILC to XLPE transition joint was found to be unsatisfactory. The contact faces of this connection had corroded.

The Author recommends that accessories employing roll spring current connections be identified and mitigating measures taken, noting that:

- a. If a normal earth through-fault current occurred this interface would be at risk of overheating and burning out.
- b. If a 'roll spring' connection is employed on a normal solidly bonded, single core cable system then it would be at risk of overheating and endangering the primary electrical insulation of the joint due to the passage of circulating sheath currents in normal operation.
- v) Variability in the design and compaction of the earth return conductor connectors on single core 33 kV, XLPE, wire screen cables.

It is recommended that connector designs and tooling be reviewed and Engineering and Jointing Staff be trained in the current carrying functions of solidly bonded earth return conductors, noting that:

- a. The passage of normal through-fault current in PILC, three-core cables is likely to over-heat and burn-out high resistance lead sheath connections.
- b. On single-core cables, the connectors also carry the screen wire circulating currents in everyday use. A high resistance contact risks the overheating and consequent failure of the primary joint insulation.

15.7.2 Cables

It was found that the presence of a 33 KV XLPE cable that did not have cross-linked XLPE insulation to be a prospective risk of thermal distortion and failure in future cable operation. The original consignment from the cable supplier has been identified.

The Author recommends that:

- i) A limit be applied to the current rating of the affected circuit(s) to ensure that the cable operating temperature does not exceed 70°C, in place of the specification maximum design limit of 90°C for XLPE cable.
- ii) As part of the purchase procedure for new cables:
 - a. The right to witness tests and to receive reasonable notification be agreed.
 - b. Evidence for the measurement and test results from the specification 'hot set' requirement be sought for the start and end of each extrusion run.
 - c. Traceability of records be required from the extrusion run and XLPE material batches to the despatch drum numbers.
 - d. A record of the drum numbers be added to the circuit records.

Severely corroded steel armour tapes were found on PILC cables in some locations in the trench. Corroded tapes prospectively reduces:

- i) The mechanical protection to the underlying lead sheath, particularly in an in-air application in which cables are subject to thermo-mechanical movements and fatigue strain.

- ii) The PILC cables' ability to carry short circuit through-fault current. The lead sheaths have been calculated to be able to carry the required short circuit level.

Author

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16 Appendix A, CCTV Photographs

A security CCTV camera was positioned looking South over the end section of the cable trench and recorded images at hourly intervals. Table 9 analyses five of the images over a four hour period from 10.72 minutes after the first fault, Figure 55, to 250.72 minutes, Figure 59.



Figure 55 CCTV at 23:32:13, 10.72 m after 1st fault: sharp reflections off T11 side and expansion tank and off side of T10

The observations in Table 9 for Figure 56 show that smoke had obscured both clarity of view and some of the reflections from the Switchyard lights on the sides of the T11 and T10 transformers at 70.72 minutes after the first fault and 48.60 minutes before the second fault occurred. This indicates that some degree of combustion had occurred after the first fault and that fire was in progress.

Table 9 Summary of observations from CCTV images

Observations	CCTV Security Camera Photographs				
	Figure 55	Figure 56	Figure 57	Figure 58	Figure 59
Time after 1 st Fault [min]	10.72	70.72	130.72	190.72	250.72
Time after 2 nd Fault [min]	0	0	11.40	71.40	131.40
T11 reflection right wall	bright	dull	dull	dull	dull mauve
T11 reservoir reflection	bright	dull	dull	dull	obscured
T11 Light to left side	no	no	no	mauve glow	obscured
T10 reflection right wall	bright	none	none	pronounced, extensive, mauve light	dull mauve
Left hand overhead bus bar gantry reflection	clear, pale	clear, pale, larger	clear, pale, larger	pronounced, extensive mauve glow	obscured by smoke
General visibility	clear	clear	general green haze	blue haze	Low, obscured by smoke
Smoke cloud	no	no	no	yes, at end of 33 kV Switchroom	yes, dense smoke cloud
Fire	no	no	no	reflection off fire between T10 and T11	free fire ball, end of 33kV Switchroom
Summary	No evidence of smoke or fire	first loss of clarity due to smoke	further loss of clarity due to smoke	first evidence of light and smoke cloud from fire	fire emerged from trench exit and dense smoke

There was further loss of light transmission at 130.72 minutes, Figure 57, some 11.40 minutes after the reclose onto the fault. No evidence of light from the fire or of dense smoke could yet be seen.

At 190.72 minutes after the first fault and 71.40 minutes after the second, Figure 58 there was clear evidence of i) light reflected from the region of the cable trench that passed between T11 and T10, this being in the general region of the faulted transition joint, 3B0, at 73 m and 2) of a smoke cloud. The fault sequence in Figure 43 shows that the cable failures had been localised around 73 m chainage and were the moving eastwards towards Gavin Street.

Figure 59 shows that at 250.72 minutes the fire had emerged out of the exit of West end of the trench and was close to reaching the corner of the 33 kV Switchroom. The field of view contains dense smoke. The fire had already travelled preferentially 23m to the East of the faulted transition joint towards Gavin Street and the last cable, 11 kV PILC McNab K19, 2C0, had already faulted at 223.48 minutes after the first fault.



Figure 56 CCTV at 00:32:13, 70.72 m after 1st fault: view of T11 and T10 become obscured. Reflection on T10 obscured view of reflection obscured dull reflection off T11



Figure 57 CCTV at 01:32:13, 130.72 m after 1st fault, 11.4m after 2nd: general green haze



Figure 58 CCTV at 02:32:13, 190.72 m after 1st fault, 71.4m after 2nd: mauve light reflections of fire between and above T11 and T10. Halo of smoke.



Figure 59 CCTV at 02:32:13, 250.72 m after 1st fault, 131.4m after 2nd: Free fire from trench exit close to 33 kV Switchroom corner. Dense smoke

17 Appendix B List of Samples Despatched to EDIF ERA**Table 10 Sample List**

PN Number	Cable ID	Length (m)	Collection Date	Cable Type
PN1	1DX	1	17/10/14	1c 400mm ² Al XLPE 33kV
PN2	1DY	1	17/10/14	1c 800mm ² Al XLPE 33kV
PN3	1DZ	1	17/10/14	1c 800mm ² Al XLPE 33kV
PN4	1BX	0.5	17/10/14	1c 800mm ² AL XLPE 33kV
PN5	1BX	0.3	17/10/14	1c 400mm ² AL XLPE 33kV
PN6	1BY	1	17/10/14	1c 400mm ² Al XLPE 33kV
PN7	1BZ	1	17/10/14	1c 400mm ² Al XLPE 33kV
PN8	1AX	1	17/10/14	1c 800mm ² AL XLPE 33kV
PN9	1AY	1	17/10/14	1c 800mm ² AL XLPE 33kV
PN10	1AZ	1	17/10/14	1c 400mm ² AL XLPE 33kV
PN11	5DX	1	18/10/14	1c 400mm ² AL XLPE 33kV
PN12	5DY	1	18/10/14	1c 400mm ² AL XLPE 33kV
PN13	5DZ	1	18/10/14	1c 400mm ² AL XLPE 33kV
PN14	2B0	1	17/10/14	3c 300mm ² AL PILC STA 11kV
PN15	2C0	1	17/10/14	3c 300mm ² AL PILC STA 11kV
PN16	2D0	1	17/10/14	3c 300mm ² AL OF PVC 33kV
PN17	2A0	1	17/10/14	25c 9+16 PILOT
PN18	2F0	1	17/10/14	3c 35mm ² AL XLPE 11kV
PN19	2EX	1	17/10/14	1c 630mm ² Cu XLPE 33kV
PN20	2EY	1	17/10/14	1c 630mm ² Cu XLPE 33kV
PN21	2EZ	1	17/10/14	1c 630mm ² Cu XLPE 33kV
PN22	3A0	1	17/10/14	3c 0.25 sq in Cu PILC STA 11kV
PN23	3B0	1	17/10/14	3c 0.25 sq in Cu PILC STA 11kV
PN24	3C0	1	17/10/14	3c 0.37 sq in Cu OF PVC 22kV
PN25	3B0	1	20/10/14	(Sample 3) 3X1M OF 0.25 SQ IN COPPER PILC CABLE.
PN26	3B0	1	4/11/14	(Sample 4) 3X1M OF 0.25 SQ IN COPPER PILC CABLE.
PN27	3B0	1	20/10/14	(Sample 8) 3X1M OF 0.25 SQ IN COPPER PILC CABLE.

PN Number	Cable ID	Length (m)	Collection Date	Cable Type
PN28	3A0	2	20/10/14	JOINT WITH 2.5 OF 0.25 SQ IN COPPER PILC CABLE (Sample 5)
PN28B	3A0	2	20/10/14	Copper PILC Cable (Sample 5A)
PN29	3A0	1	4/11/14	(Sample 6) 3X1M OF 0.25 SQ IN COPPER PILC CABLE
PN30	3A0	1	20/10/14	(Sample 7) 3X1M OF 0.25 SQ IN COPPER PILC CABLE
PN31	3A0	1	4/11/14	(Sample 9) 3X1M OF 0.25 SQ IN COPPER PILC CABLE
PN32	4EY	1	18/10/14	1c 400mm2 AL XLPE 33kV
PN33	3B0	1	17/10/14	(Sample 2) APPROX 1M OF 0.25 SQ IN COPPER PILC CABLE
PN34	5A0	1	18/10/14	25c 9+16 PILOT
PN35	5BX	1	18/10/14	1c 400mm2 AL XLPE 33kV
PN36	5BY	1	18/10/14	1c 400mm2 AL XLPE 33kV
PN37	5BZ	1	18/10/14	1c 400mm2 AL XLPE 33kV
PN38	5CX	1	18/10/14	1c 400mm2 AL XLPE 33kV
PN39	5CY	1	18/10/14	1c 400mm2 AL XLPE 33kV
PN40	5CZ	1	18/10/14	1c 400mm2 AL XLPE 33kV
PN41	4A0	1	18/10/14	3c 0.45 sq in Cu OF PVC 33kV
PN42	4B0	1	18/10/14	3c 0.45 sq in Cu OF PVC 33kV
PN43	4C0	1	18/10/14	3c 0.25 PILC STA 11kV
PN44	3E0	1	17/10/14	3c 0.37 sq in Cu OF PVC 22kV
PN45	4D0	1	18/10/14	25c 9+16 PILOT
PN46	4EX	1	18/10/14	1c 400mm2 AL XLPE 33Kv
PN47	4EY	1	18/10/14	1c 400mm2 AL XLPE 33kV
PN48	4EZ	1	18/10/14	1c 400mm2 AL XLPE 33kV
PN49	3D0	1	18/10/14	32c PILOT
PN50	3FX	1	17/10/14	1c 630mm2 Cu XLPE 33kV
PN51	3FY	1	17/10/14	1c 630mm2 Cu XLPE 33kV
PN52	3FZ	1	17/10/14	1c 630mm2 Cu XLPE 33kV
PN53A	3B0	1.5m (of 3m total)	20/10/14	(Sample 1a) "Good Joint" PILC to XLPE transition joint (approx 1.5m plus 1.5m cable either side)

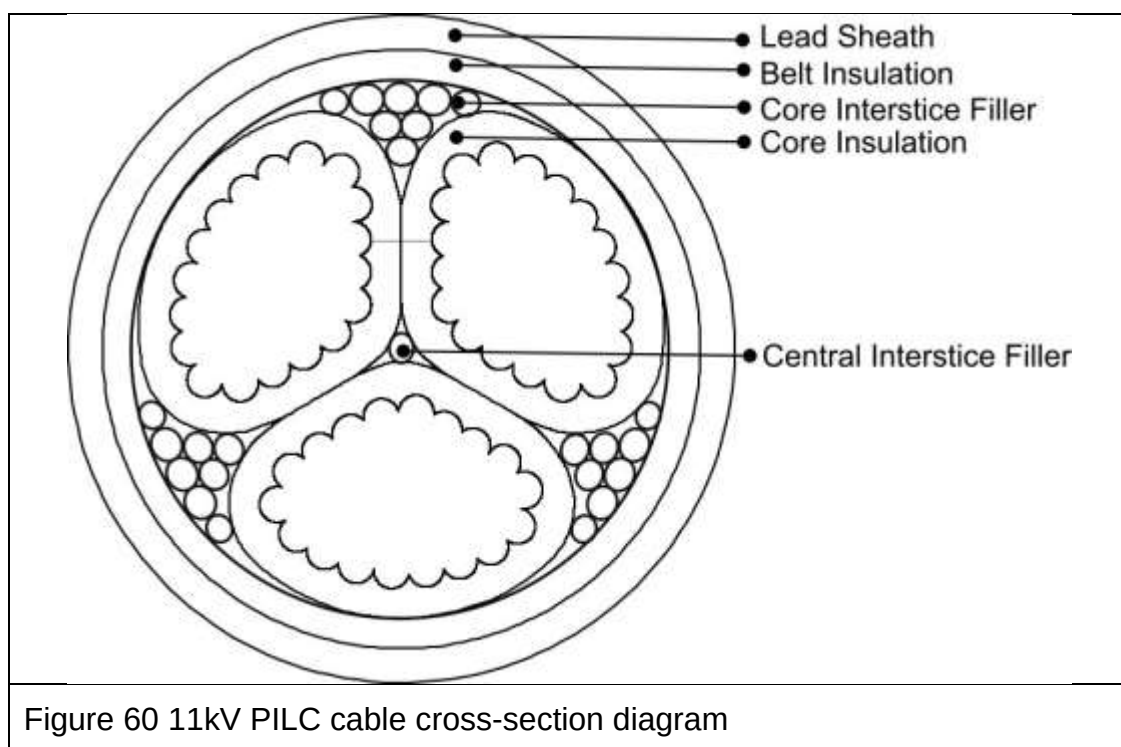
PN Number	Cable ID	Length (m)	Collection Date	Cable Type
PN53B	3B0	1.5m (of 3m total)	20/10/14	(Sample 1b) "Good Joint" PILC to XLPE transition joint (approx 1.5m plus 1.5m cable either side)
PN53C	3B0	(component)	20/10/14	(Sample 1) B4 "Good Joint" Bagged sample - part of joint Remnants of Heat Shrink Casing
PN53D	3B0	(component)	20/10/14	(Sample 1) B1 "Good Joint" Bagged sample - part of joint (Lead Sheath)
PN53E	3B0	(component)	20/10/14	(Sample 1) B2 "Good Joint" Bagged sample - part of joint (Belting Papers - PILC end)
PN53F	3B0	(component)	20/10/14	(Sample 1) B3 "Good Joint" Bagged sample - part of joint Copper braids and spring clip
PN54	1DY	2m inc JOINT	20/11/14	
PN55	1DZ	2m inc JOINT	20/11/14	
PN56	1AX	2m inc JOINT	20/11/14	5M CHAINAGE
PN57	4D0	3.5m inc JOINT	20/11/14	Metal joint shell from ~50m mark.
PN58	1B?	2m inc JOINT	20/11/14	ONLY IDENTIFIED AS 'NEWMARKET 03 RED PHASE'. This is 1B cable. Cannot say whether x, y or z.
PN59	1B?	2m inc JOINT	20/11/14	ONLY IDENTIFIED AS 'NEWMARKET 03 YELLOW PHASE'. This is 1B cable. Cannot say whether x, y or z.
PN60	3B0	2.5m inc JOINT	20/11/14	Metal joint shell from ~25m mark.
PN61	N/A	N/A	20/11/14	Cable cleats from ~72m mark. 6 off.
PN62	N/A	N/A	20/11/14	Scrapings from wall ~72m.
PN63	N/A	N/A	27/11/14	Modelling clay volumes from fault sites (8 off)
PN64	N/A	N/A	30/04/15	Top bolt @ 69.5m
PN65	N/A	N/A	30/04/15	Bottom bolt @ 69.5m
PN66	N/A	N/A	30/04/15	2x nuts @ 69.5m
PN67	N/A	N/A	30/04/15	Bottom bolt & nut @ 69m

PN Number	Cable ID	Length (m)	Collection Date	Cable Type
PN68	N/A	N/A	30/04/15	Top bolt & nut @ 69m
PN69	1BX	0.3m	30/04/15	Additional sample for XLPE testing

18 Appendix C Designs of Cables and Joints in the Trench

There were three types of power cables installed in the trench, the designs of which bear testimony to the march of technology in cable design since the first cables were installed in 1967:

- PILC (Paper Insulated Lead Covered), 11 kV three core cable having sector shaped conductors and compound impregnated paper tape insulation. The cable is of the 'belted' type in which, for economy and compactness, the individual core insulation does not have separate insulation and earth screens. The three insulated cores are laid-up helically in the cable factory and are wrapped overall with a cylindrical layer of paper tapes named the 'belt' insulation. The lead sheath is provided with corrosion protection by layers of bitumen coated cotton tape, paper tapes and hessian tapes that are interspersed between two overlapping layers of robust steel tape armour. The armour is provided with a coating of bituminous lacquer.



A traditional PILC straight joint matches the same principle of unscreened belted insulation as the cable. The lead sheath (the screen) is removed up to the lead cut. The common belt paper insulation is continued for a short distance and is then removed at the 'insulation cut'. The paper core insulation is left on each conductor. The ends of the

conductors are exposed and each conductor is joined by a soldered ferrule. Pre-impregnated paper rolls are then wrapped around each ferrule. The three paper rolls are bound together to give the cores mechanical rigidity to resist cable thermo-mechanical forces. A lead sleeve, which had been parked on one side of the cable is pulled over and the ends are dressed down onto the lead sheath, where they are joined and rendered water tight by plumbing with a lead-tin alloy. The lead sleeves are then filled at elevated temperature with a bituminous insulating compound. This compound forms the same common insulating role as the cable's belt paper insulation. The lead sleeve forms the continuation of the cable's lead sheath earth screen. The filling holes are then sealed by plumbing.

Figure 61 11kV PILC conventional 3/C straight joint diagram BG

- SCOF (self-contained oil filled) cable, abbreviated in this document to OF. The correct name for this cable is SCFF, where FF refers to Fluid Filled in recognition of the introduction of biodegradable dodecylbenzene (DDB) insulating fluid to replace the original type of mineral oil, which had limited biodegradability. Both types of oil are flammable. DDB has a higher autogenous temperature, which had benefits in the application of aluminium sheaths to impregnated cables. In the trench 22 kV and 33 kV three core designs, Figure 62, were installed, which although not identical, were closely similar to each other. The shaped conductors were of the oval type. Each core was provided with its own separate paper tape insulation and earth screen.

Figure 62 33kV OF three core cable cross-section diagram BG ADD CSD

There have been no OF straight joints found in the trench to date and so these are not described.

- XLPE (cross-linked polyethylene) cables. The 33 kV cables are of single core design complete with their own triple extruded insulation and semiconducting screens, wire screen earth return conductor and polymeric oversheath. The cables installed in the trench were of the 'wet' design i.e. they did not have a water-tight metallic sheath. A three phase circuit was formed by laying three cables in a trefoil-touching formation.

Figure 63 33kV XLPE single core cable cross-section diagram BG

- The design of a heat shrink sleeve straight joint is shown in Figure 64.

Figure 64 33kV XLPE single core straight joint diagram BG ADD

20 Appendix D Failure Sequence: Positions in Trench Cross-section

The diagrams give the time and chainage location of each fault. The red arrows show the order and location of failure, not the passage of fire.

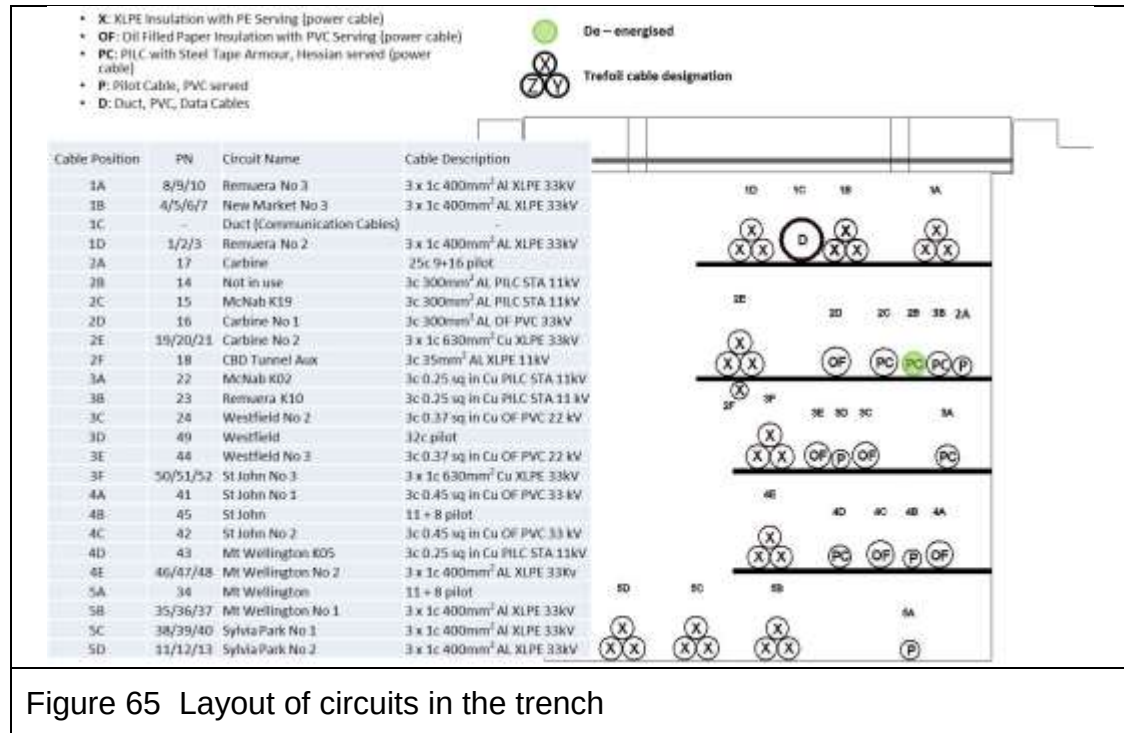


Figure 65 Layout of circuits in the trench

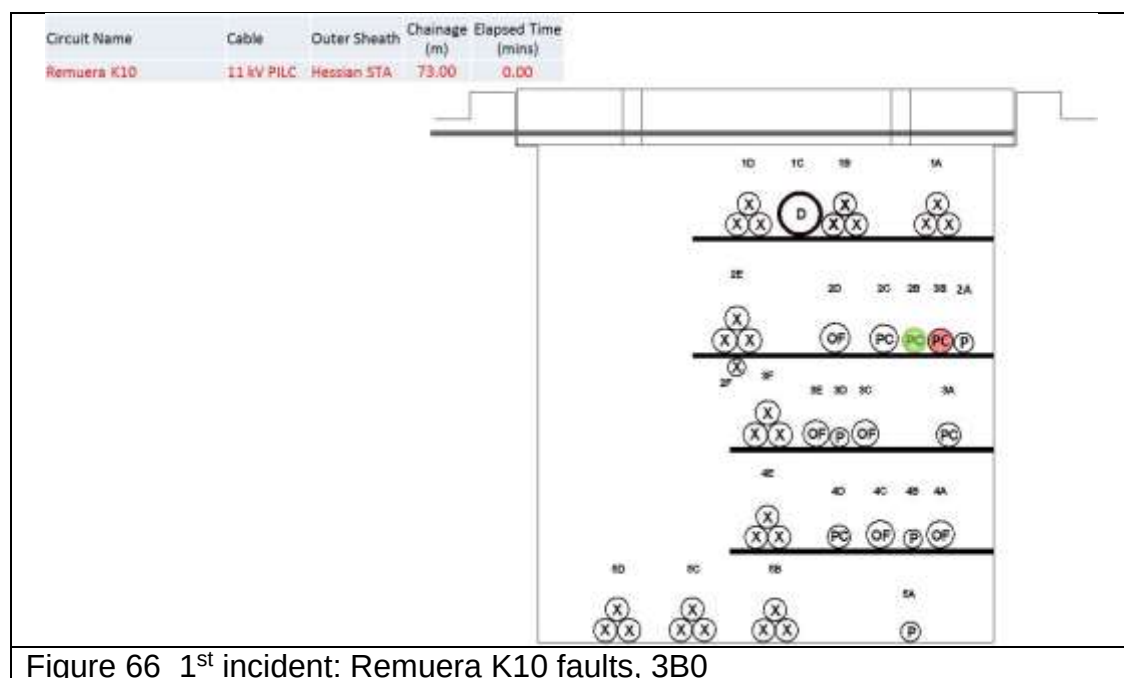


Figure 66 1st incident: Remuera K10 faults, 3B0

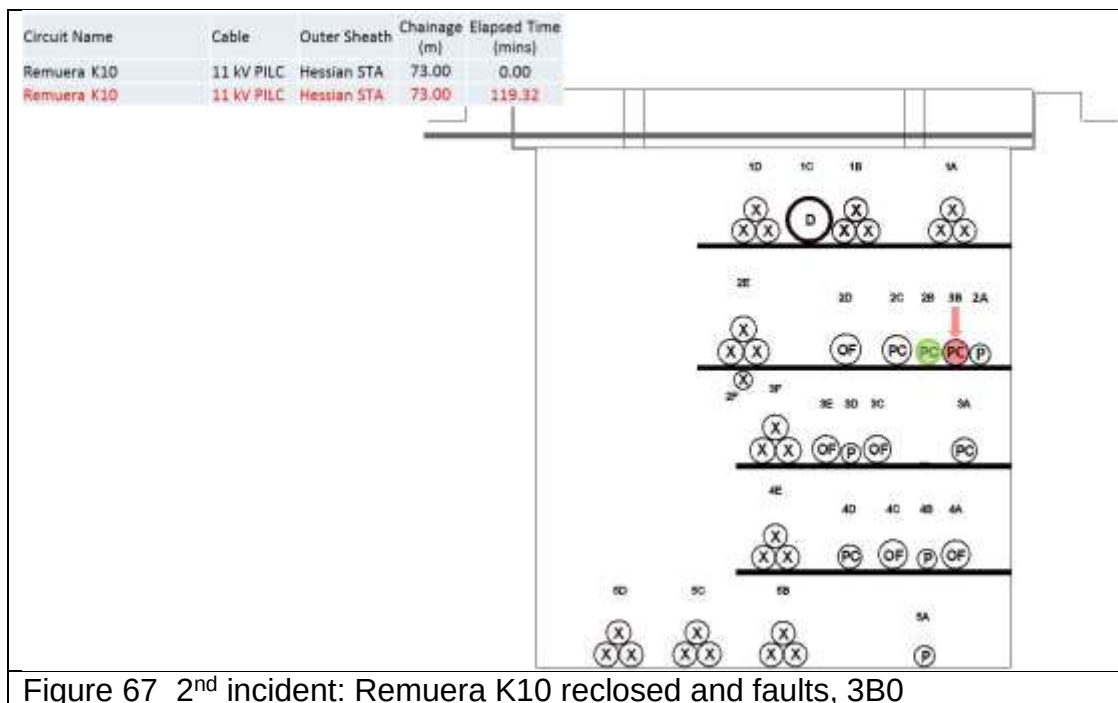


Figure 67 2nd incident: Remuera K10 reclosed and faults, 3B0



Figure 68 Arc crater: 11 kV PILC, Remuera K10, 3B0, 73 m

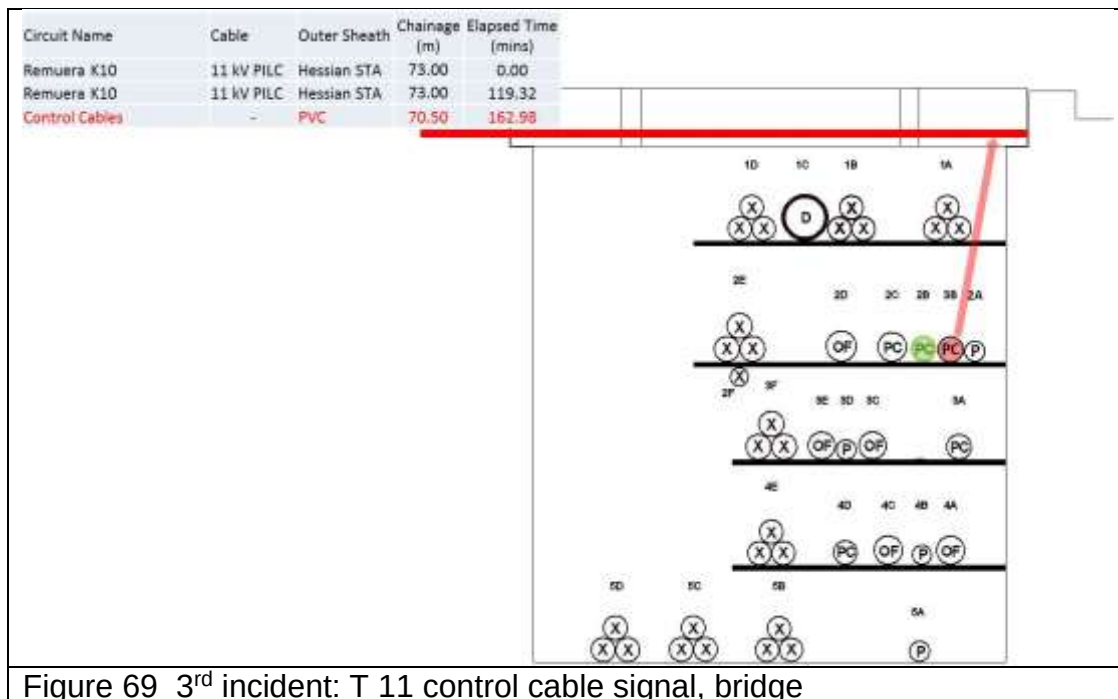


Figure 69 3rd incident: T 11 control cable signal, bridge

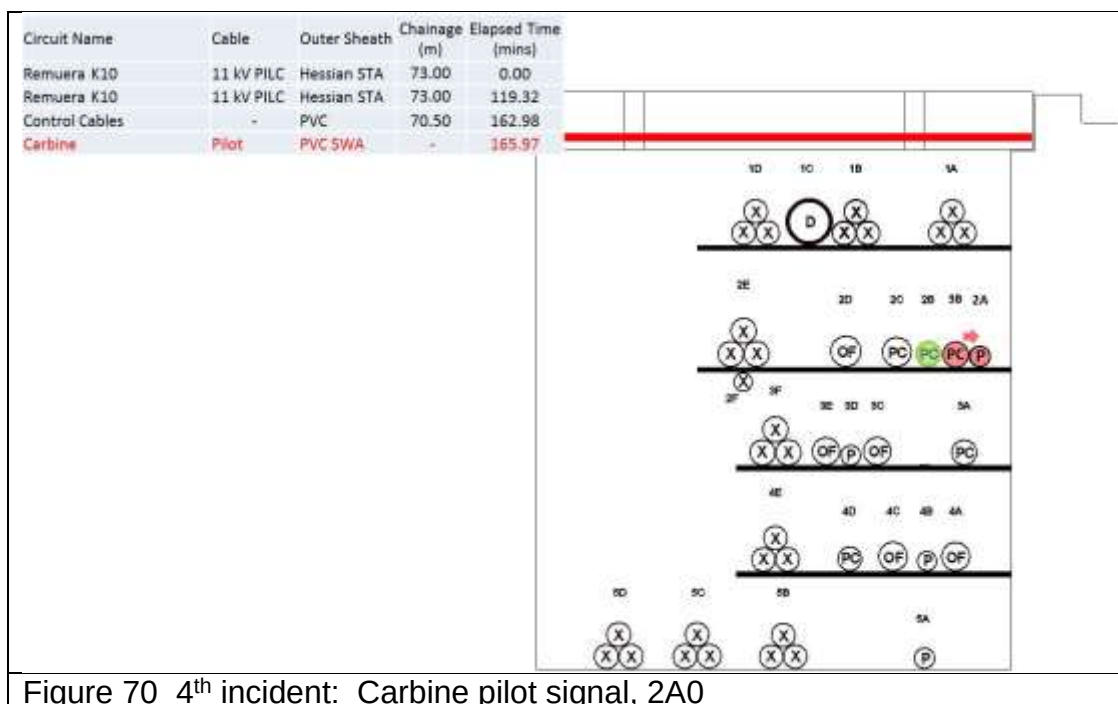


Figure 70 4th incident: Carbine pilot signal, 2A0

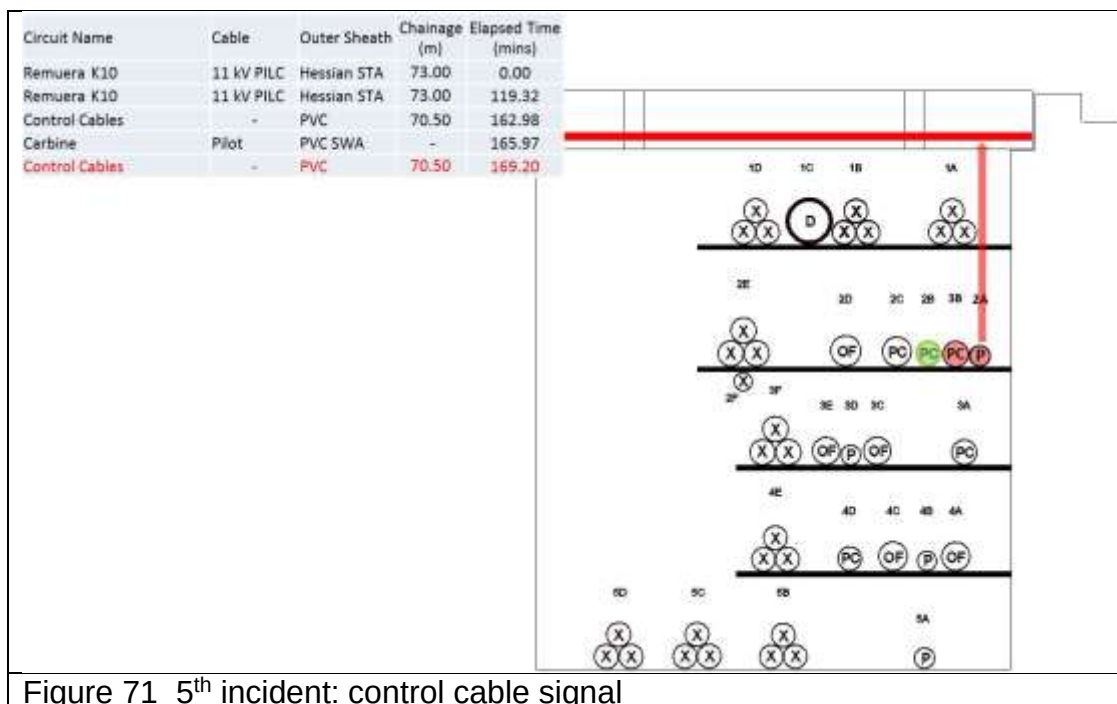


Figure 71 5th incident: control cable signal

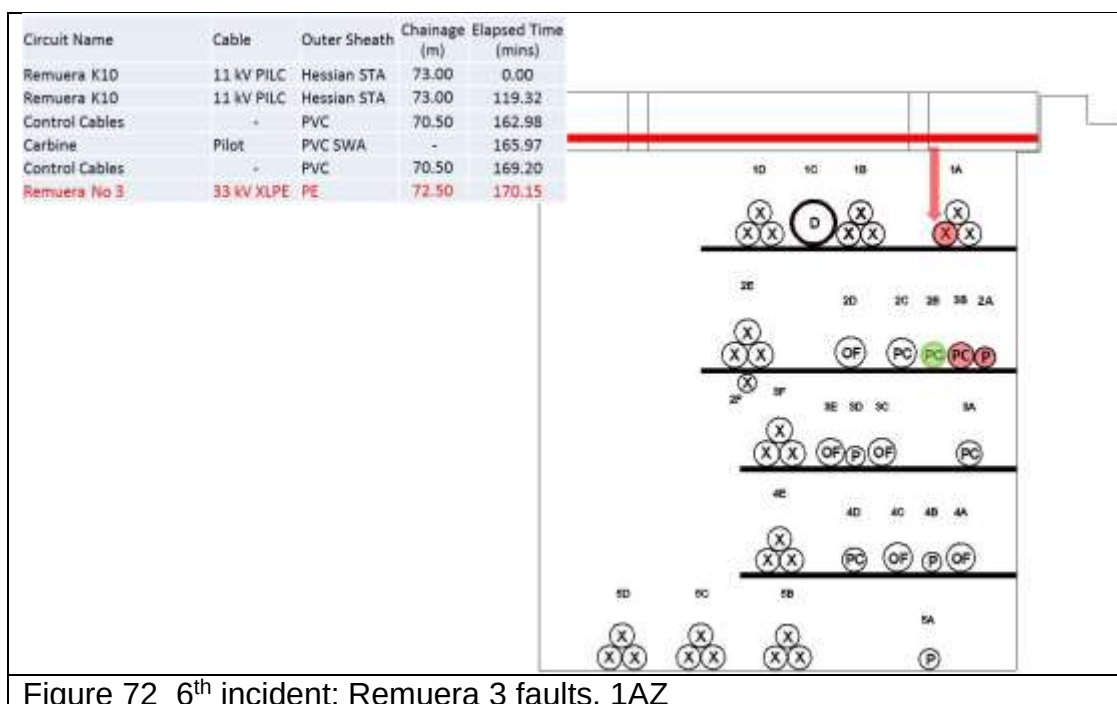


Figure 72 6th incident: Remuera 3 faults, 1AZ



Figure 73 Arc crater: 33 kV XLPE, Remuera 3, 1AZ, 72.5 m

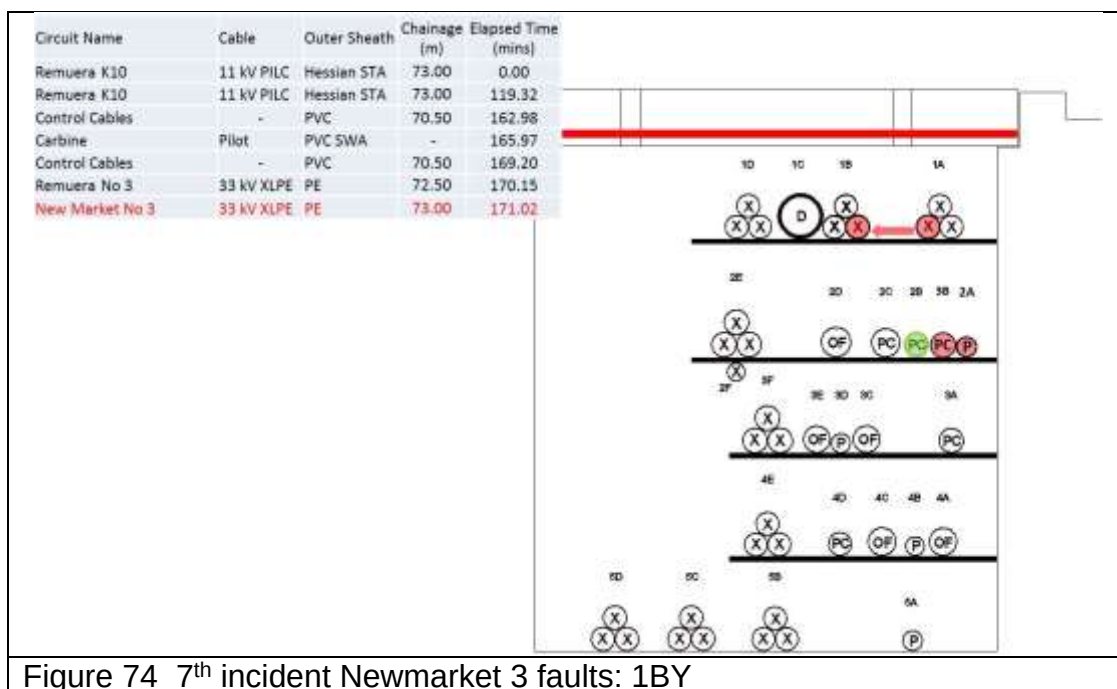


Figure 74 7th incident Newmarket 3 faults: 1BY



Figure 75 Arc crater: 33 kV XLPE, Newmarket 3, 1B, 73 m, Y Phase

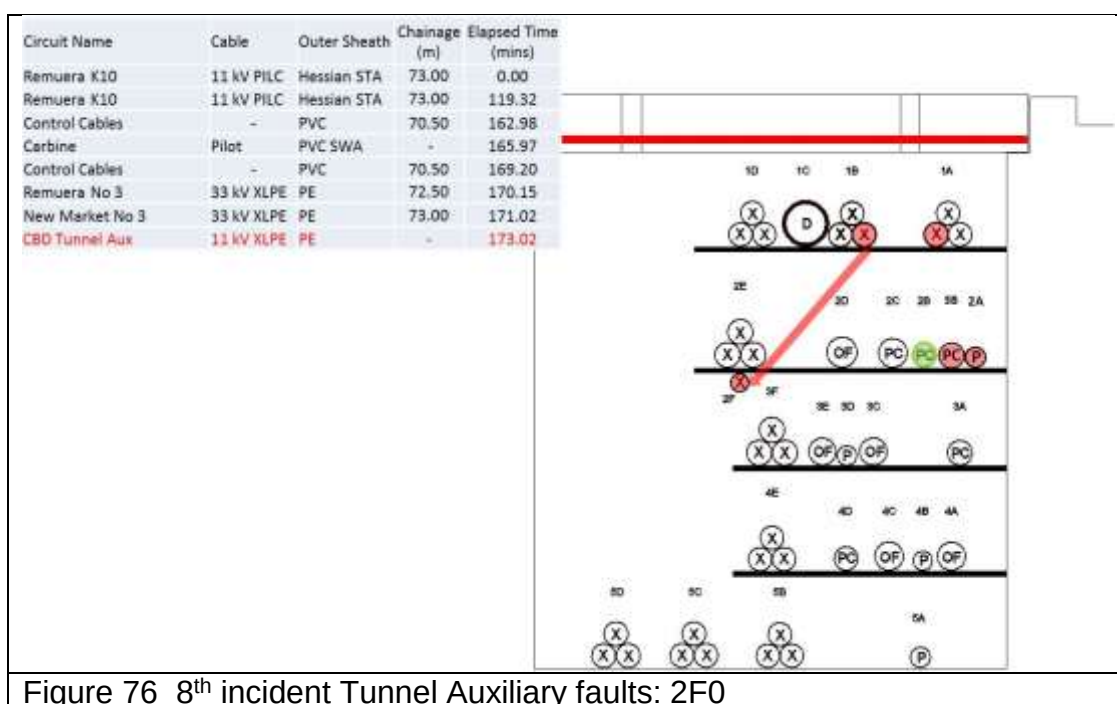


Figure 76 8th incident Tunnel Auxiliary faults: 2F0

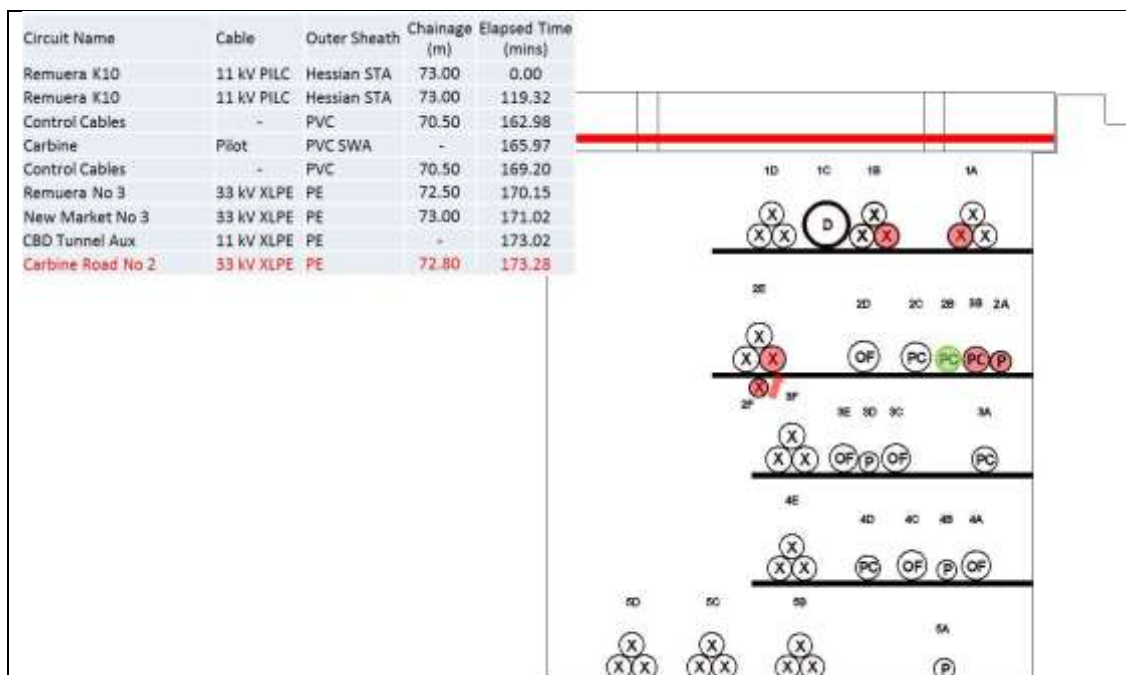


Figure 77 9th incident: Carbine Road 2 faults, 2EY



Figure 78 Arc crater: 33 kV XLPE, Carbine Road 2, 2EY, 72.8 m

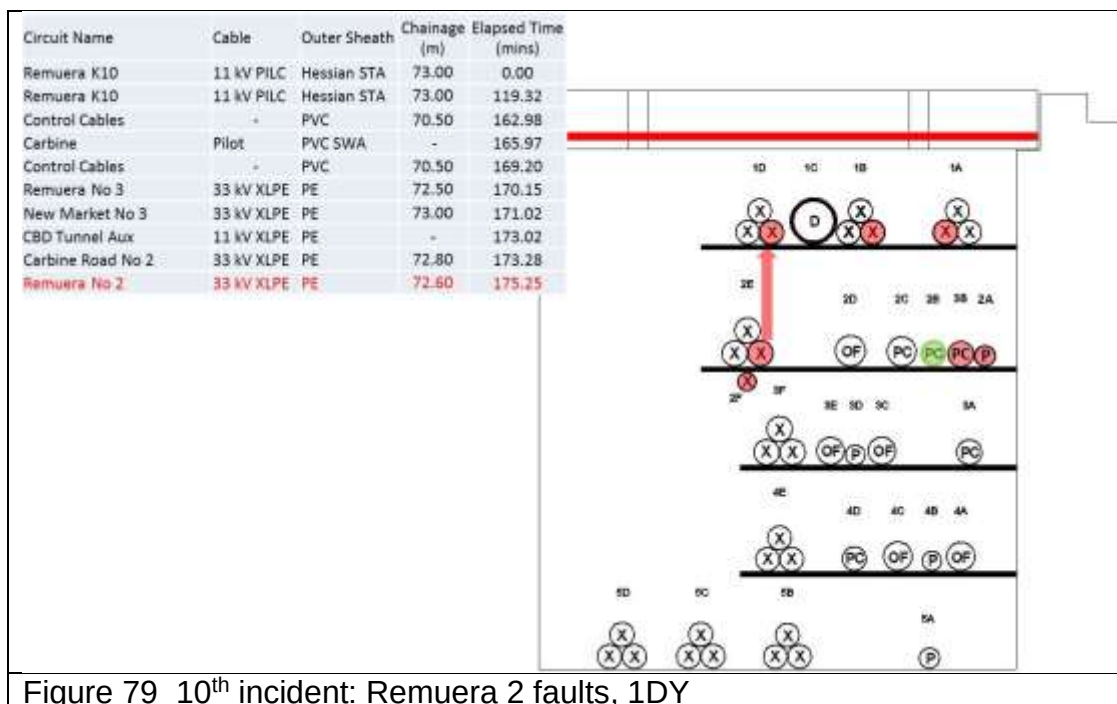


Figure 79 10th incident: Remuera 2 faults, 1DY



Figure 80 Arc crater: 33 kV XLPE, Remuera 2, 1DY, 72.6 m,

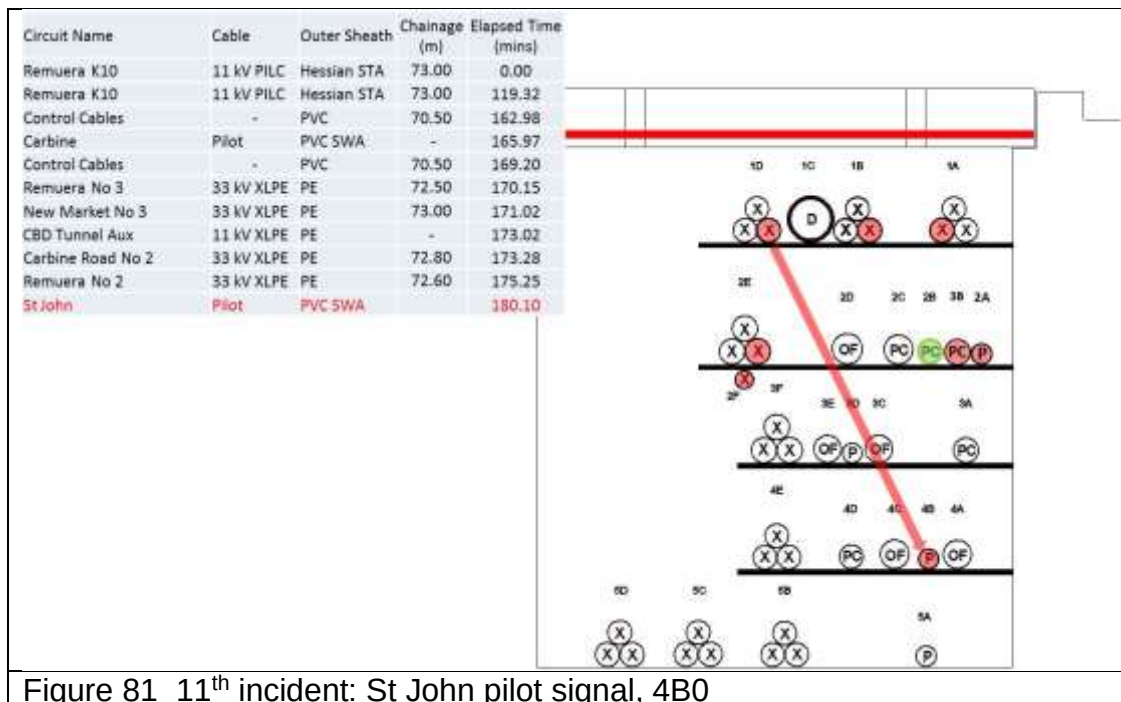


Figure 81 11th incident: St John pilot signal, 4B0

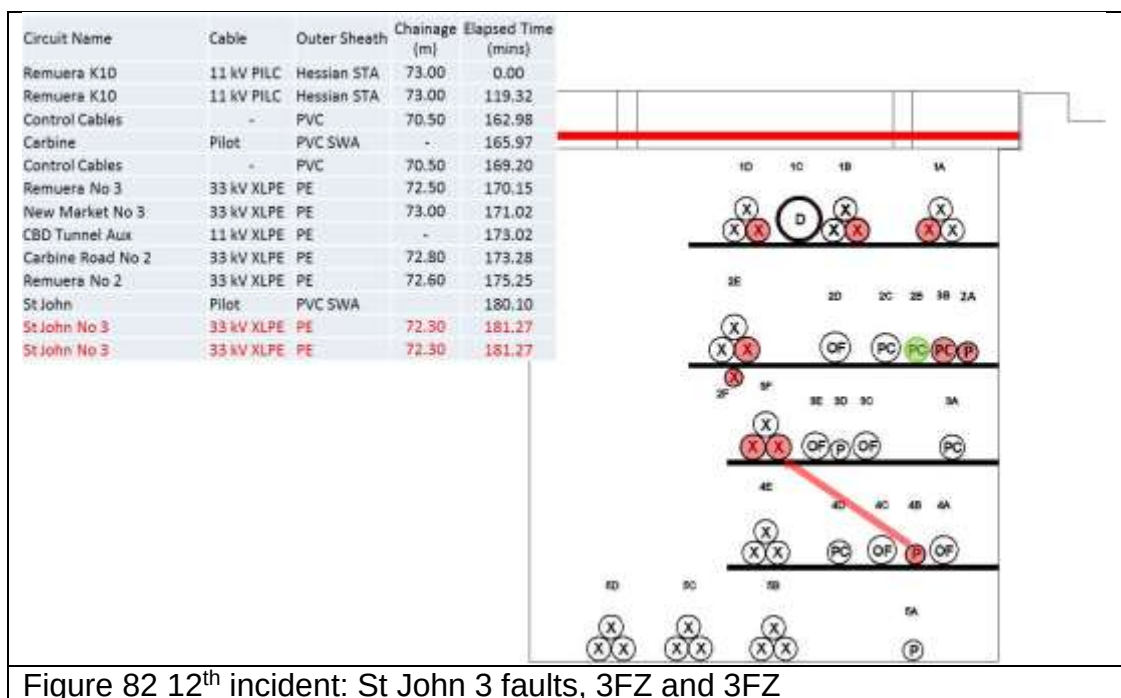


Figure 82 12th incident: St John 3 faults, 3FZ and 3FZ



Figure 83 Arc crater: 33 kV XLPE, St John 3, 3FZ, 72.3 m,

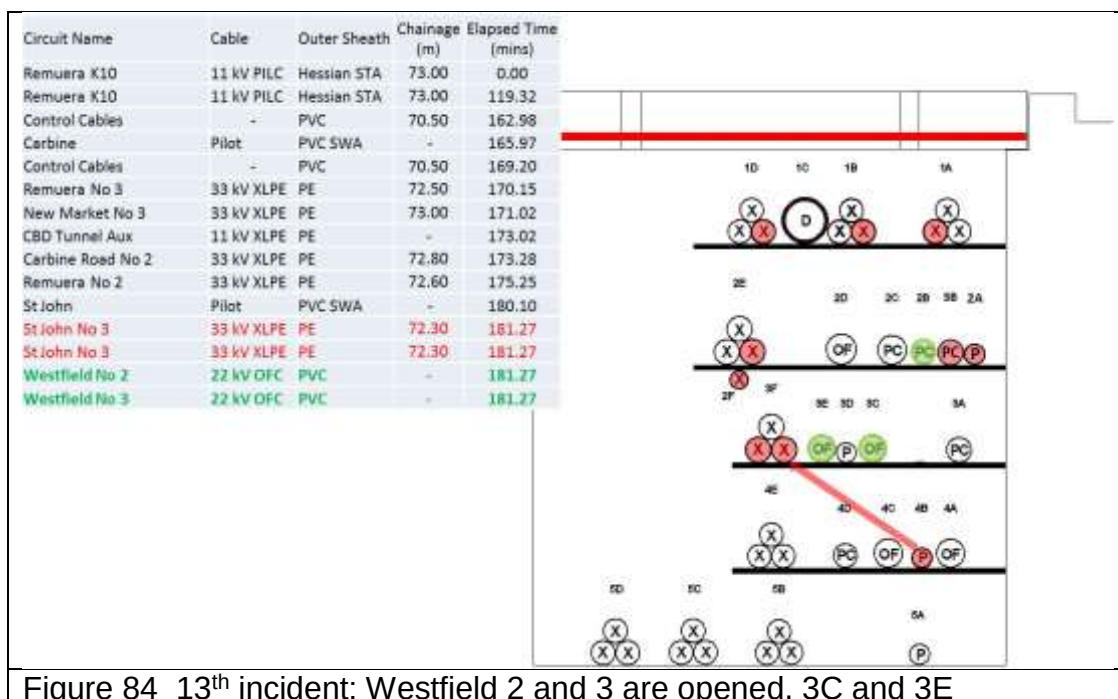


Figure 84 13th incident: Westfield 2 and 3 are opened, 3C and 3E

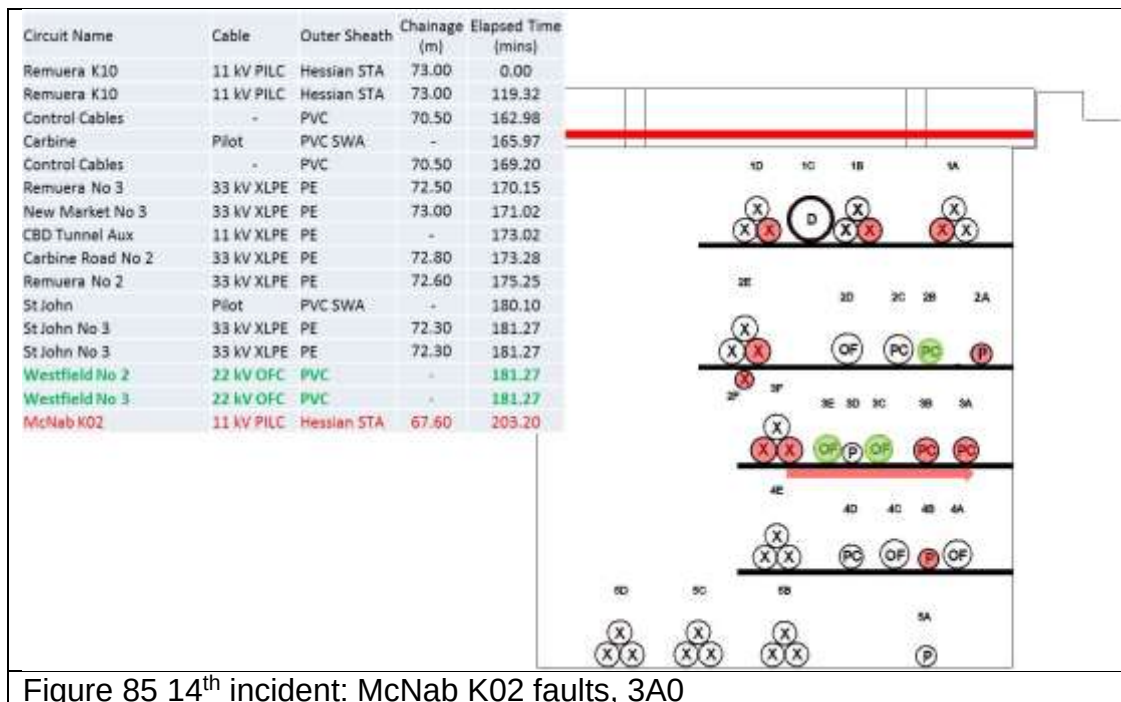


Figure 85 14th incident: McNab K02 faults, 3A0

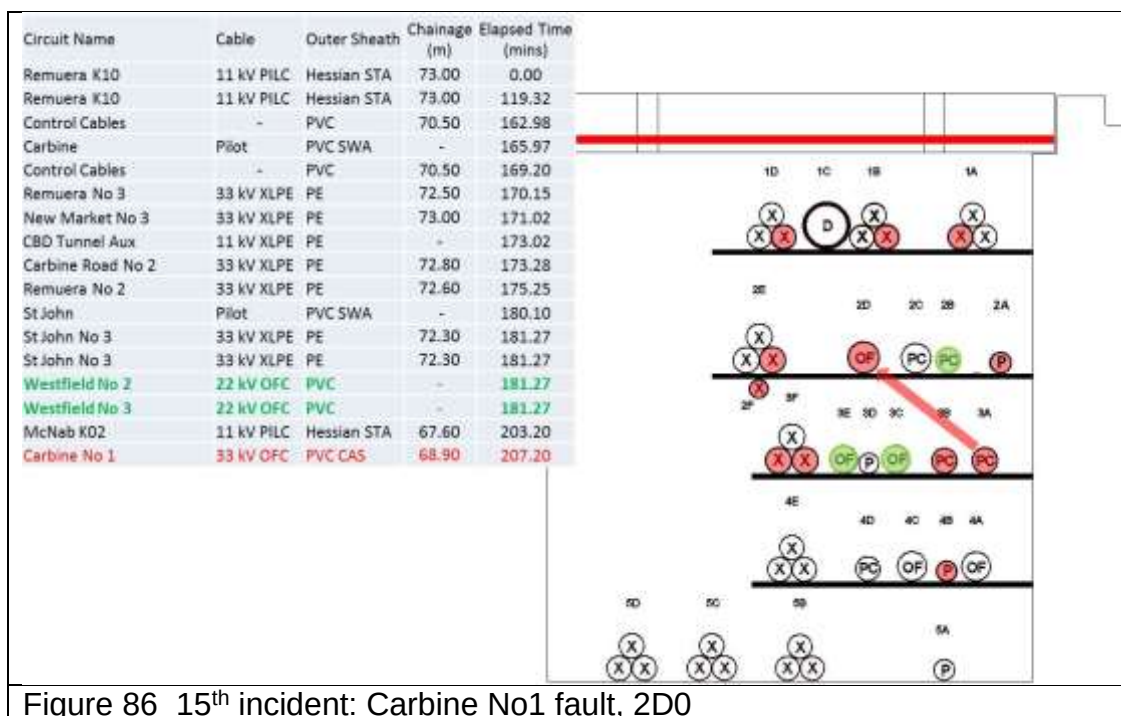


Figure 86 15th incident: Carbine No1 fault, 2D0



Figure 87 Arc crater: 33 kV OF, Carbine 1, 2DO, 68.9 m

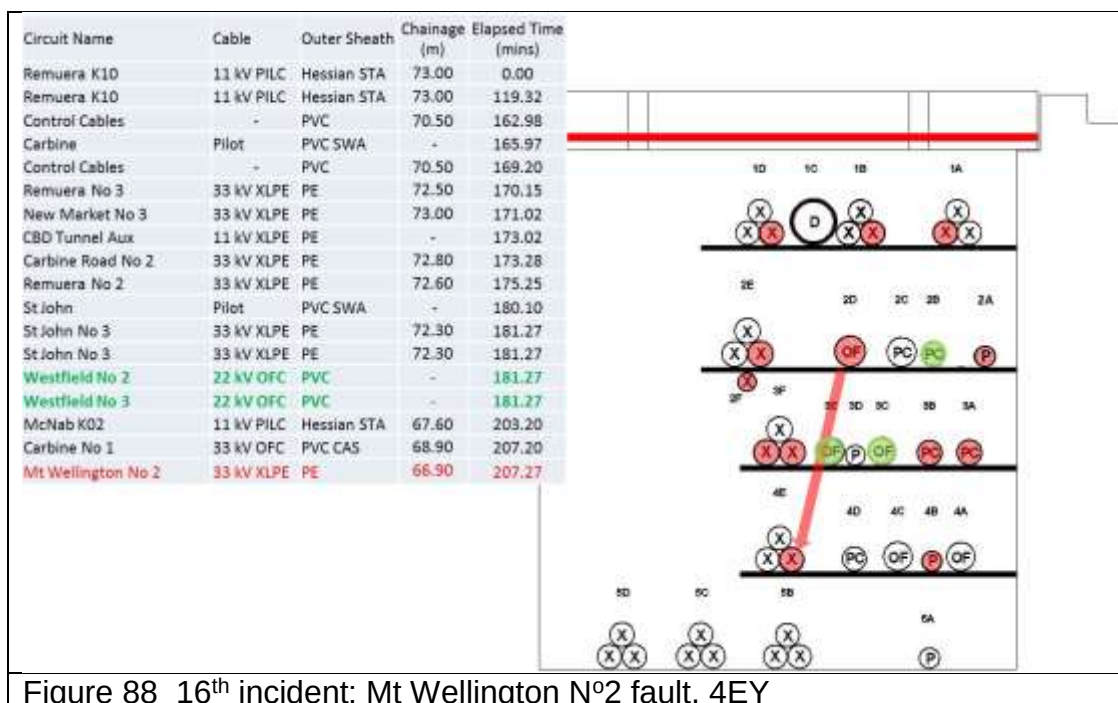


Figure 88 16th incident: Mt Wellington N°2 fault, 4EY



Figure 89 Arc crater: 33 kV XLPE, Mt Wellington N°2, 4EY, 66.9 m

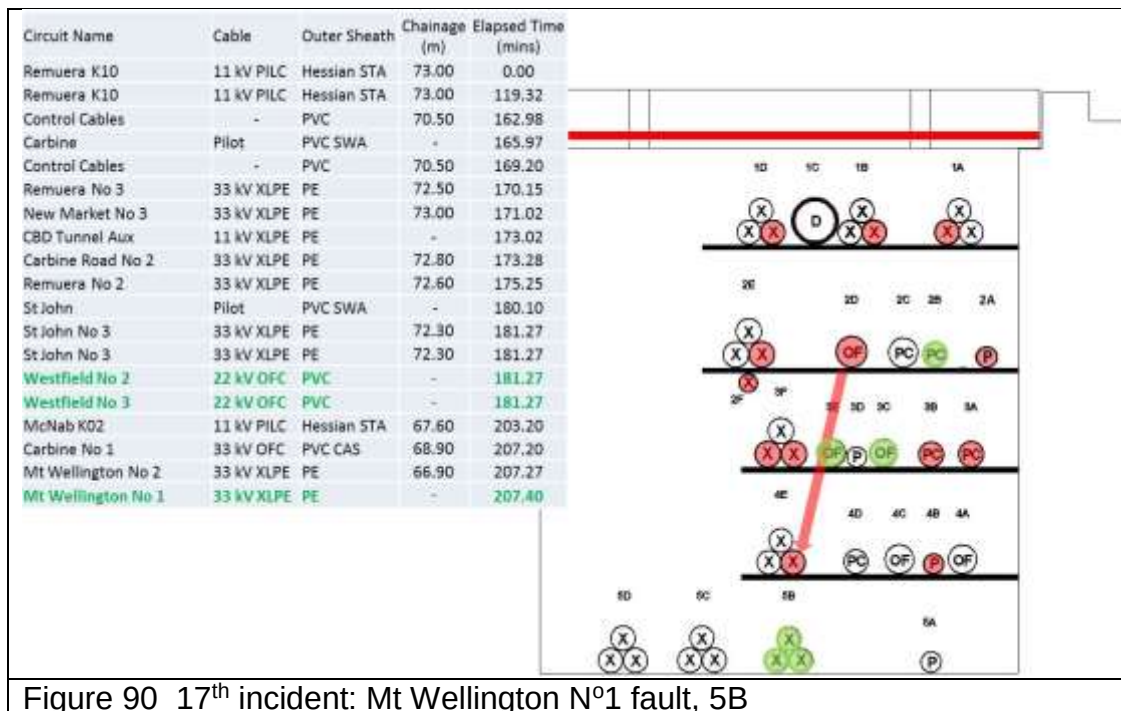


Figure 90 17th incident: Mt Wellington N^o1 fault, 5B

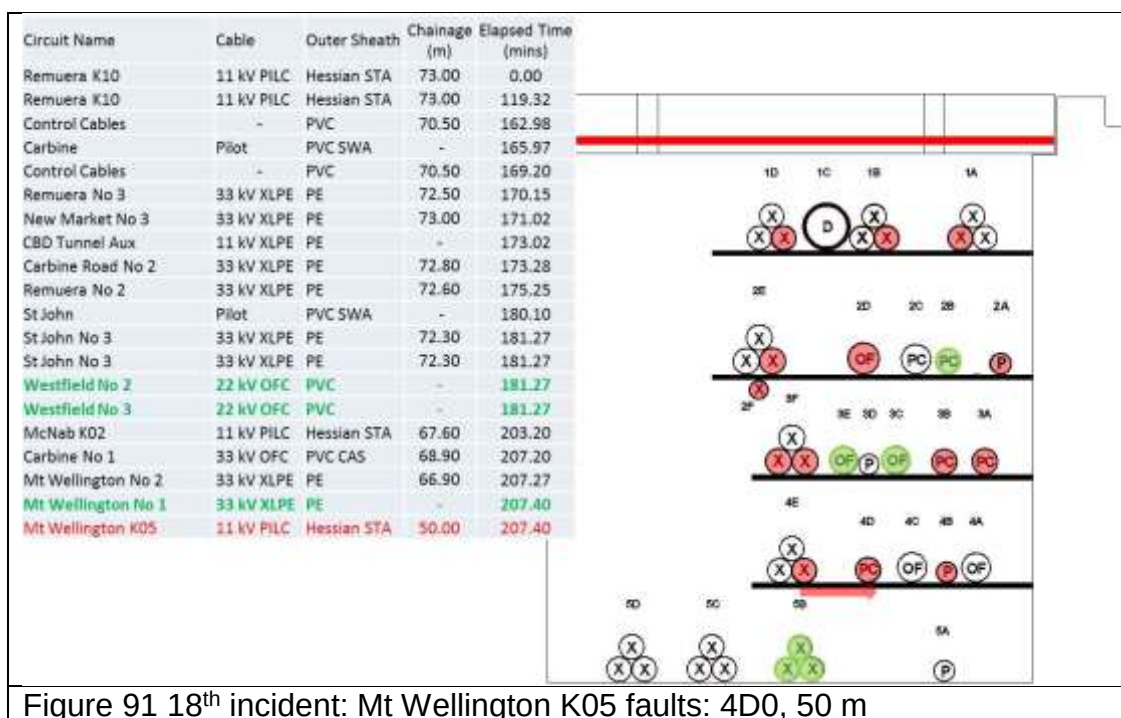


Figure 91 18th incident: Mt Wellington K05 faults: 4D0, 50 m



Figure 92 Arc crater: 11 kV PILC, Mt Wellington K05, 4D0

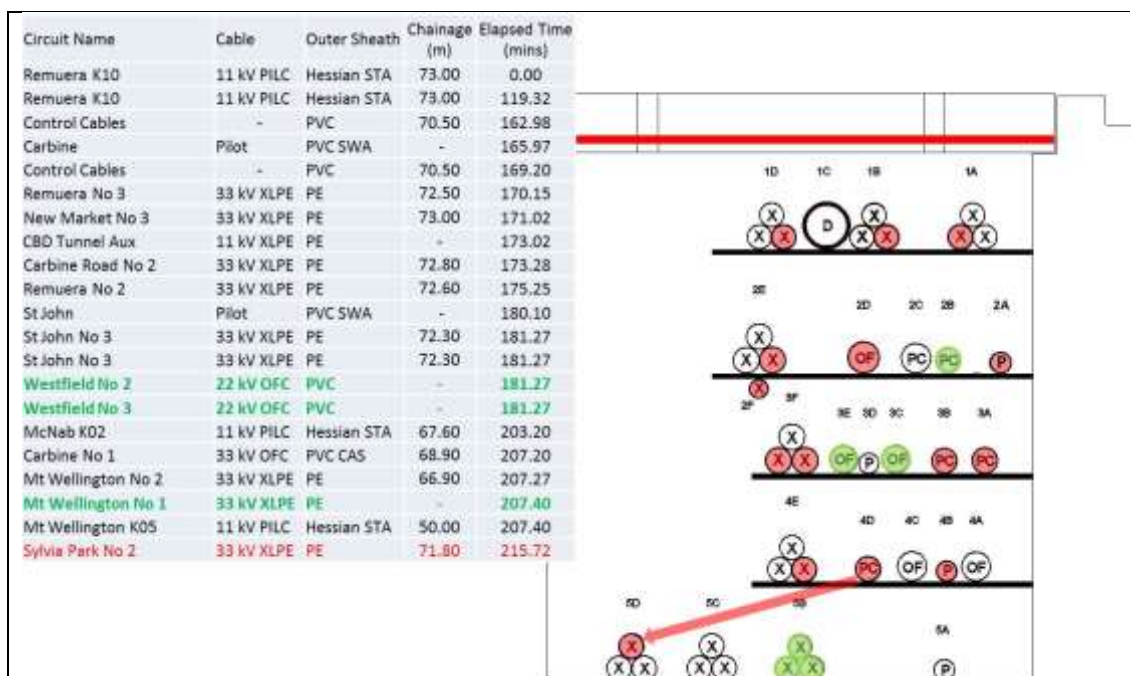


Figure 93 19th incident: Sylvia Park No 2 faults: 5DX



Figure 94 Arc crater: 33 kV XLPE, Sylvia Park No 2, 5DX, 71.8 m

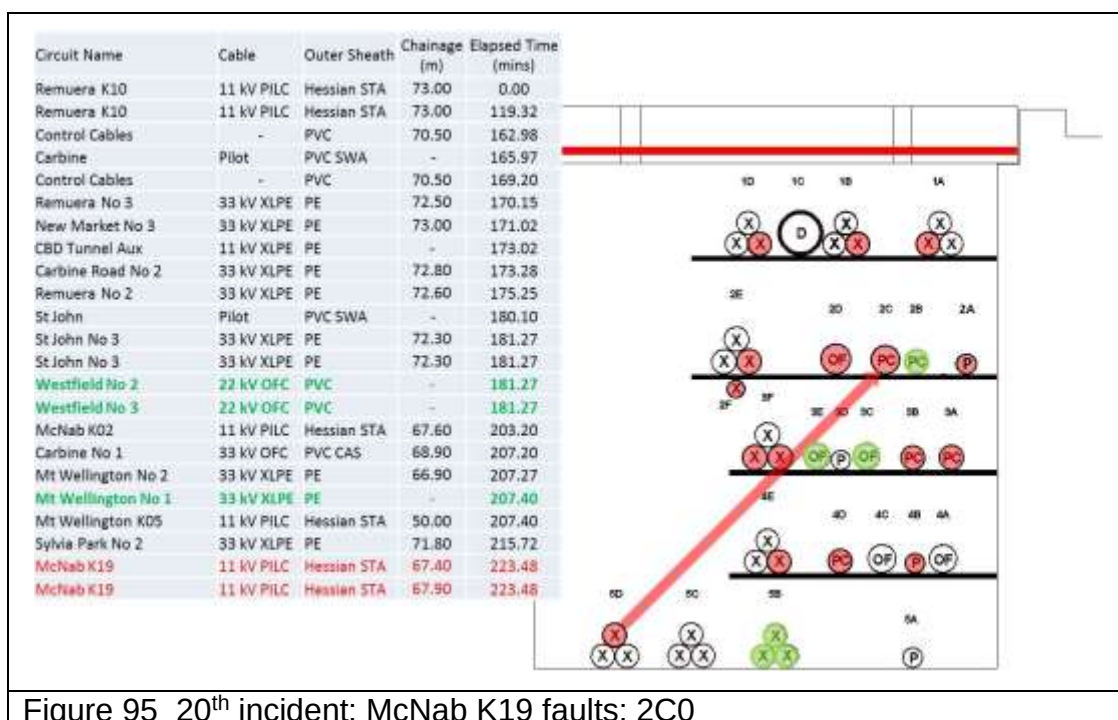


Figure 95 20th incident: McNab K19 faults: 2C0



Figure 96 Arc crater: 11 kV PILC, McNab K19, 2C0, 67.9 m

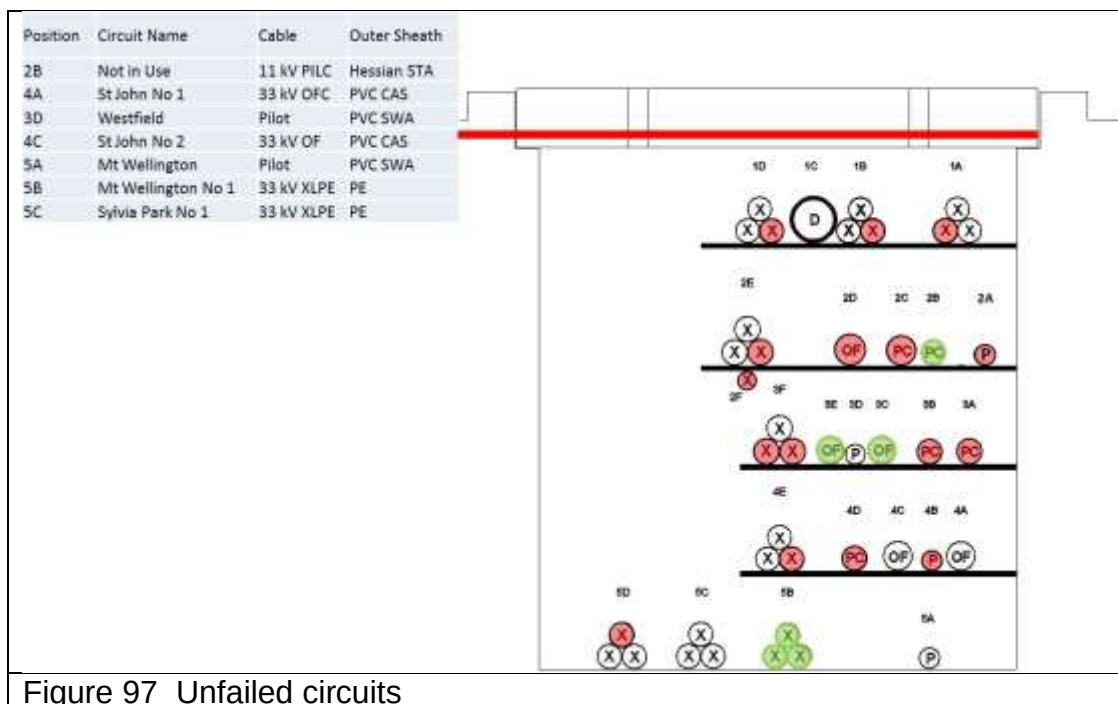


Figure 97 Unfailed circuits

21 Appendix E Design of PILC to XLPE Transition Joint in the Trench

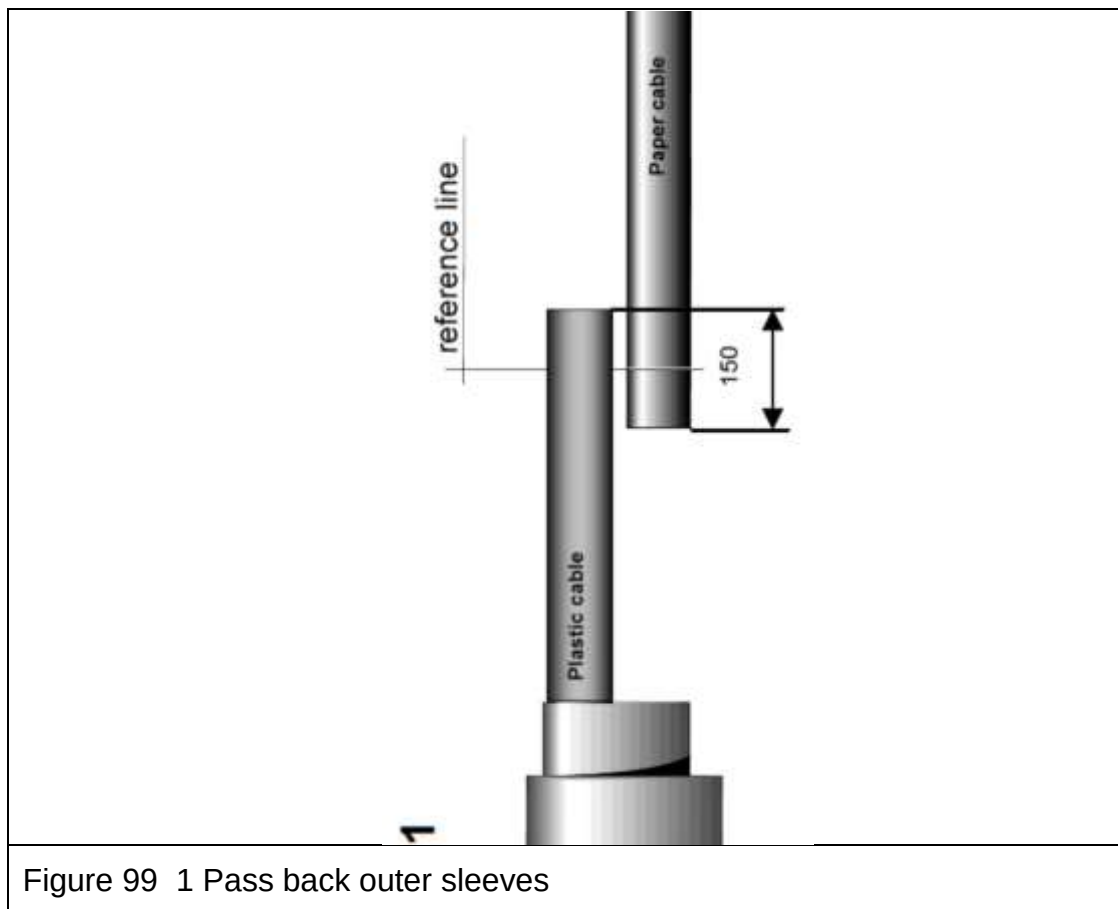
A diagram of a similar Tyco joint is shown in Figure 98



Figure 98 Diagram of an 11 kV three core heatshrink sleeve transition joint PILC to XLPE

The jointing sequence together with measurements taken from the unfailed joint at location 3B0, 79 m, is shown below in the following diagrams.

Measured dimensions from the unfailed joint were added to amended diagrams from the Tyco-Raychem Installation Instruction ESD 0289-9/03-NZ. The measured length in the failed joint between the centre of the joint (interface between copper and aluminium parts of the connector) and the arc burning in the conductors was then transferred to the diagram of the unfailed joint.



2. PILC: Strip serving and steel tape armour

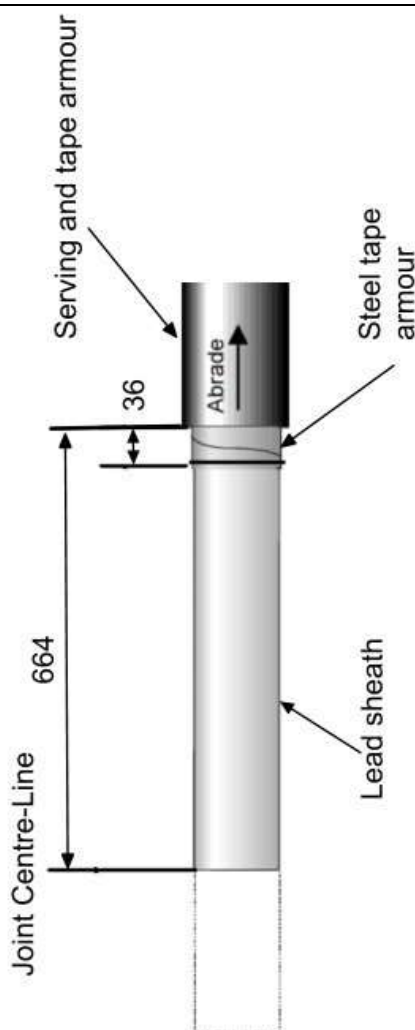


Figure 100 2. Dimensions of stripped serving and armour and bare lead sheath

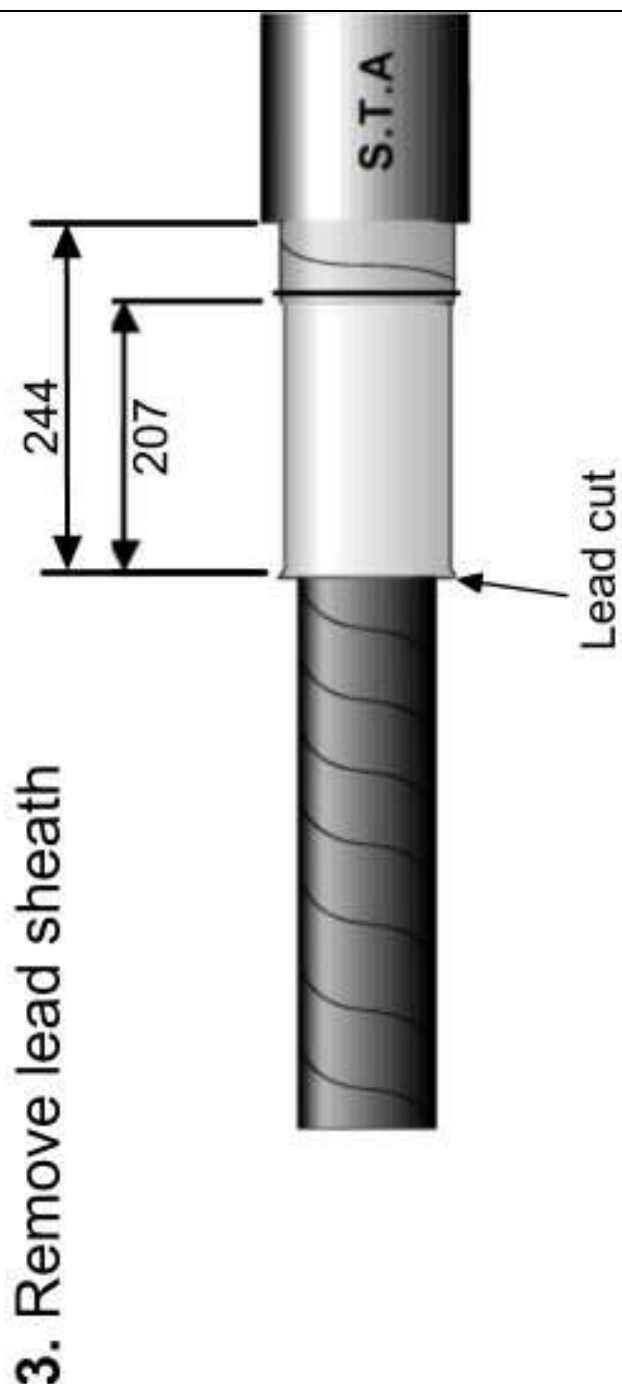
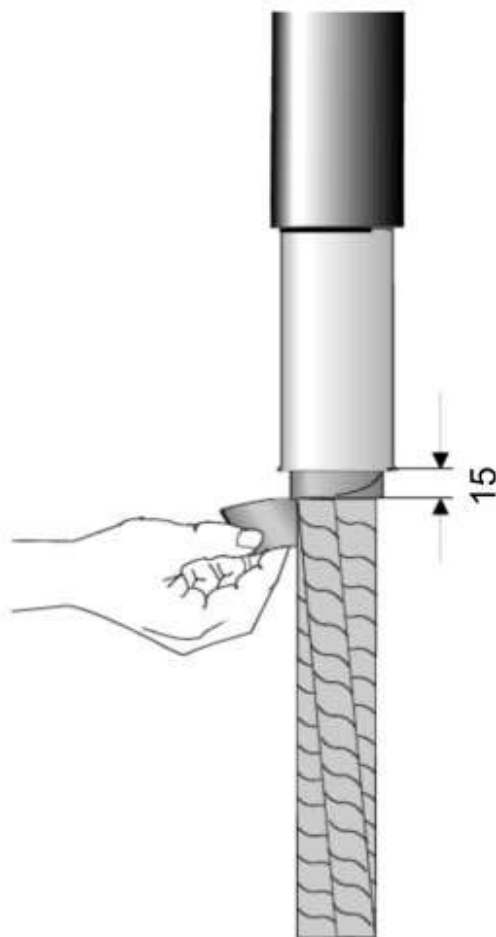


Figure 101 3 Distance between lead and steel tape armour cuts

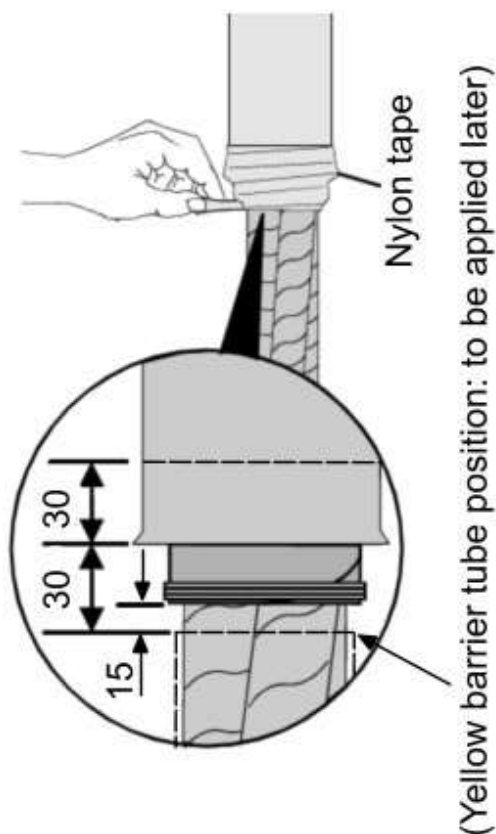
4. PILC: Remove and form step in belt insulation



Note: The yellow void filling tape adhered to and pulled off the belt tapes.
The step length shown of 15 mm is the length of the jute filler protrusion

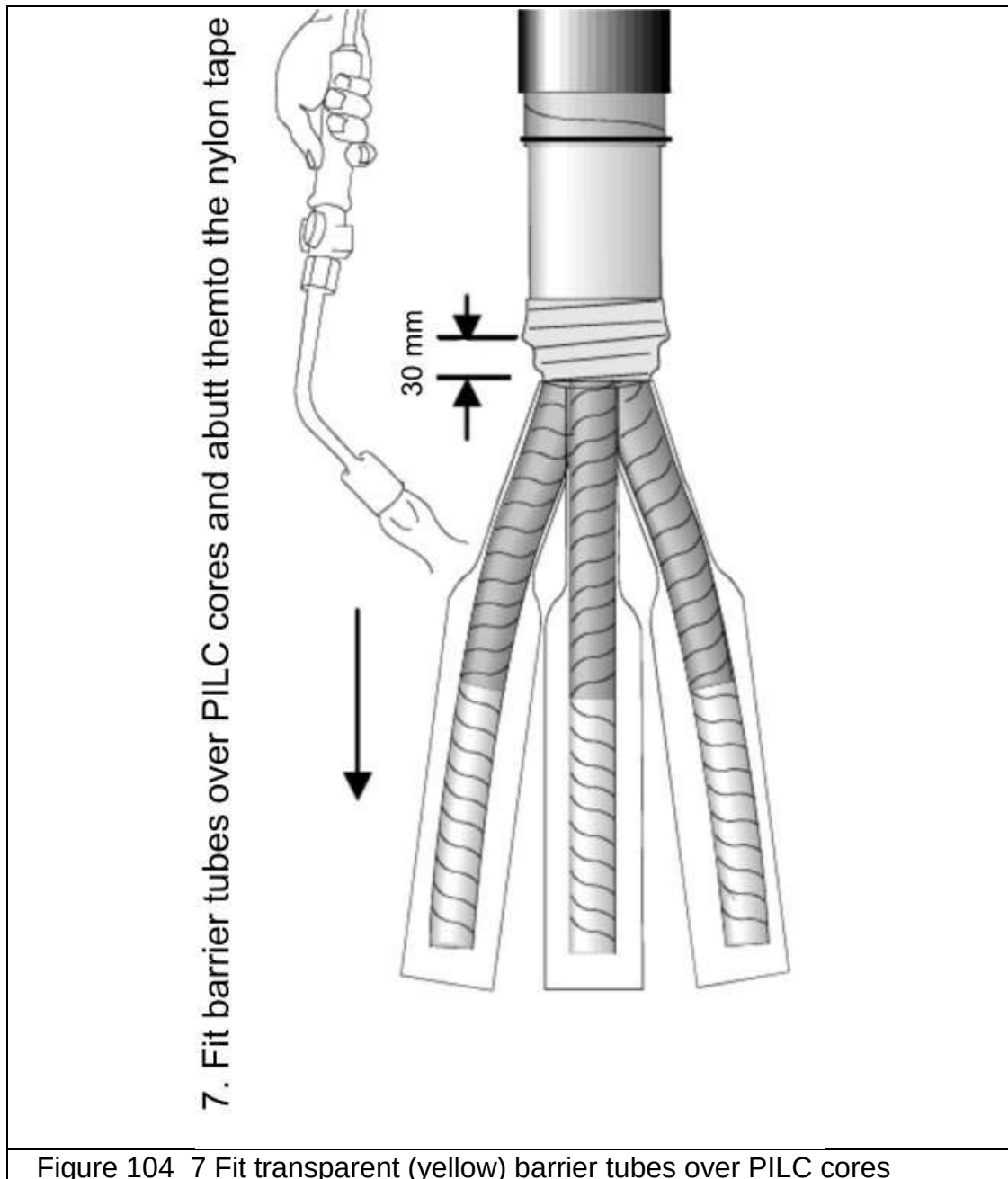
Figure 102 4 Remove and form step in belt insulating tapes

5. Apply protective nylon tape over insulation in crutch



Note: 30 mm is the distance to the start of the yellow barrier tube.
The 30 mm overlap onto the lead sheath is denoted by a grey stain

Figure 103 5 Apply nylon protective tapes over core insulation in crutch



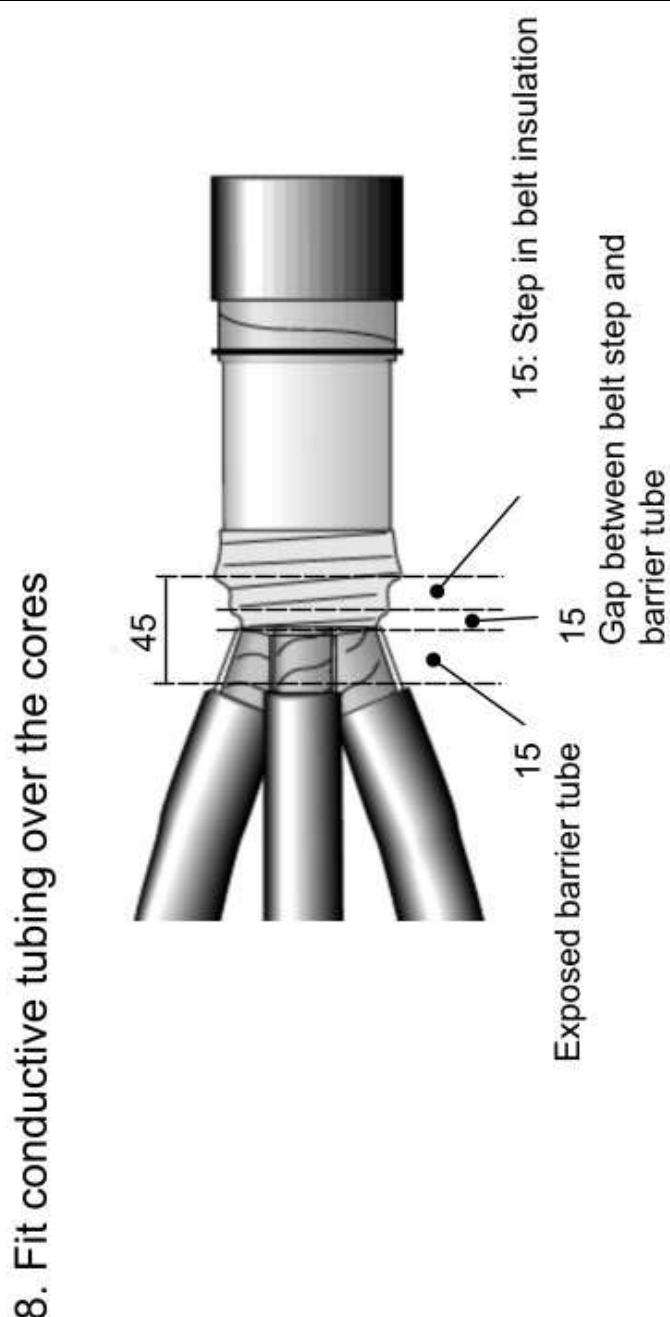


Figure 105 8A Elevation View. Fit conductive tubing (earth screen) over barrier tube

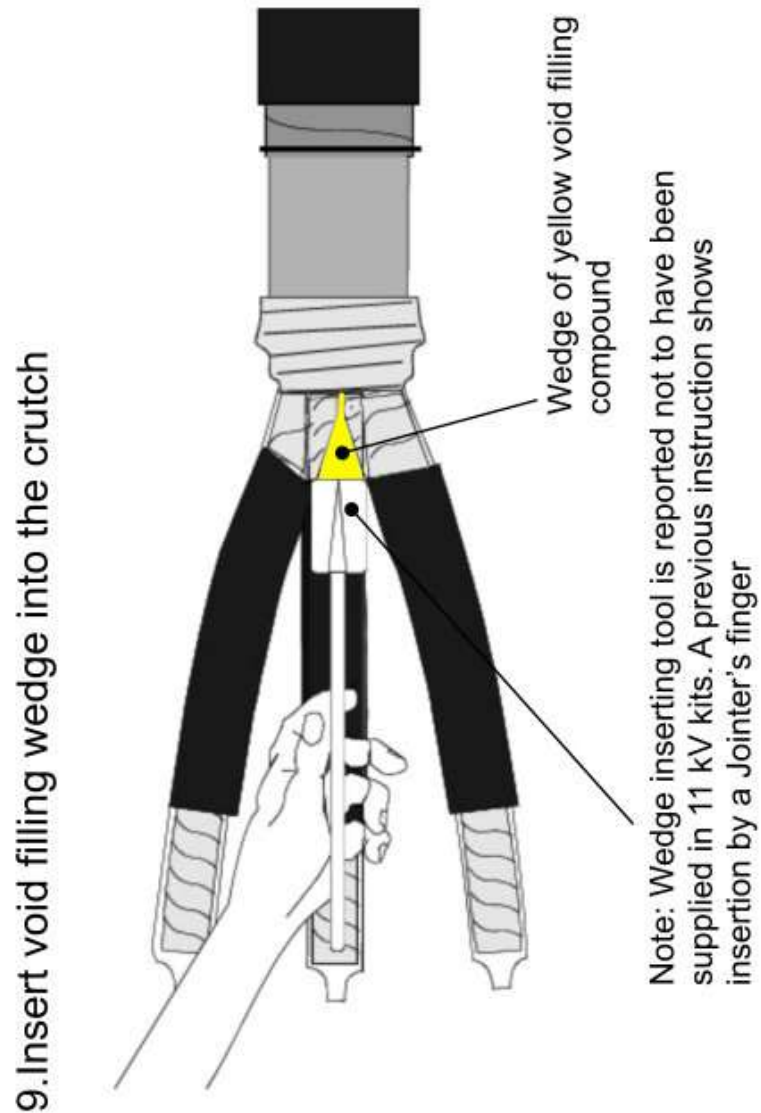
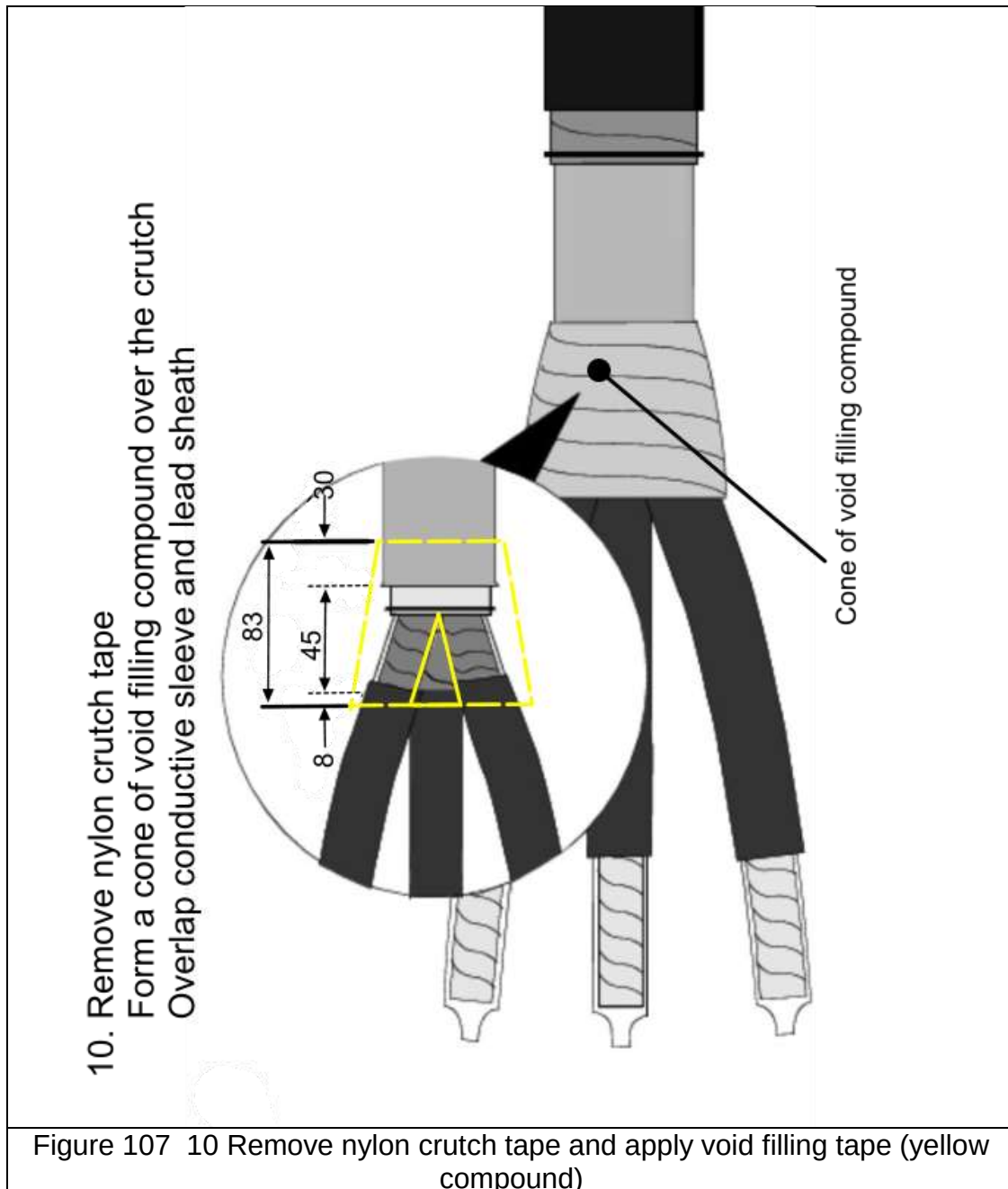


Figure 106 9 Insert void filling wedge (yellow compound) into crutch



11. Fit conducting break-out glove

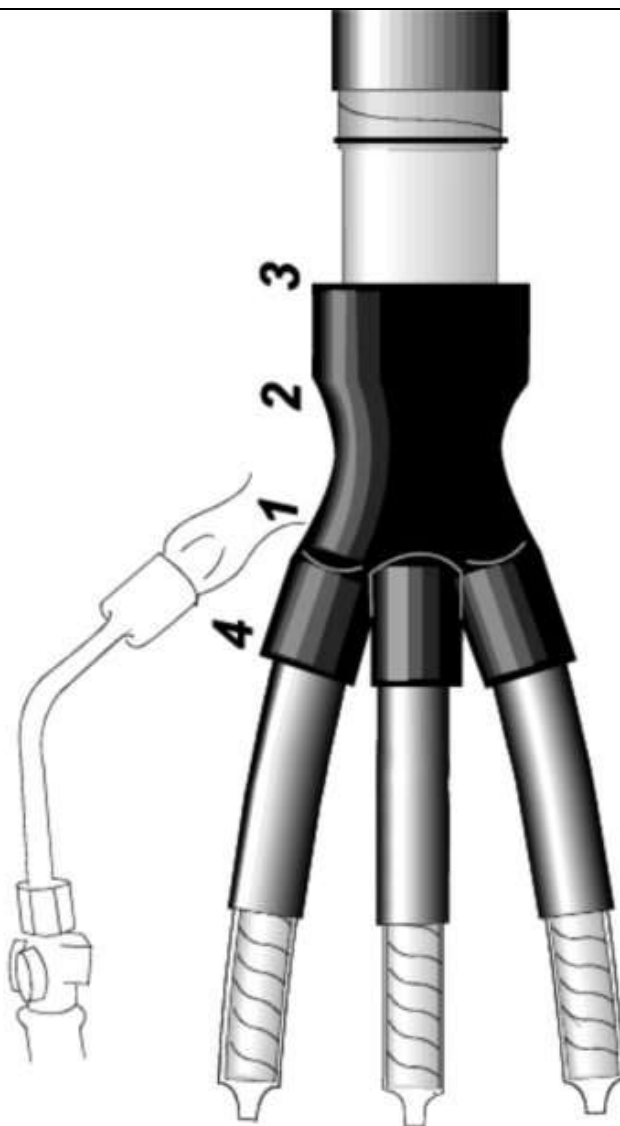


Figure 108 11 A Fit and shrink down conducting brake-out glove (earth screen)

11B. Fit breakout glove over crutch

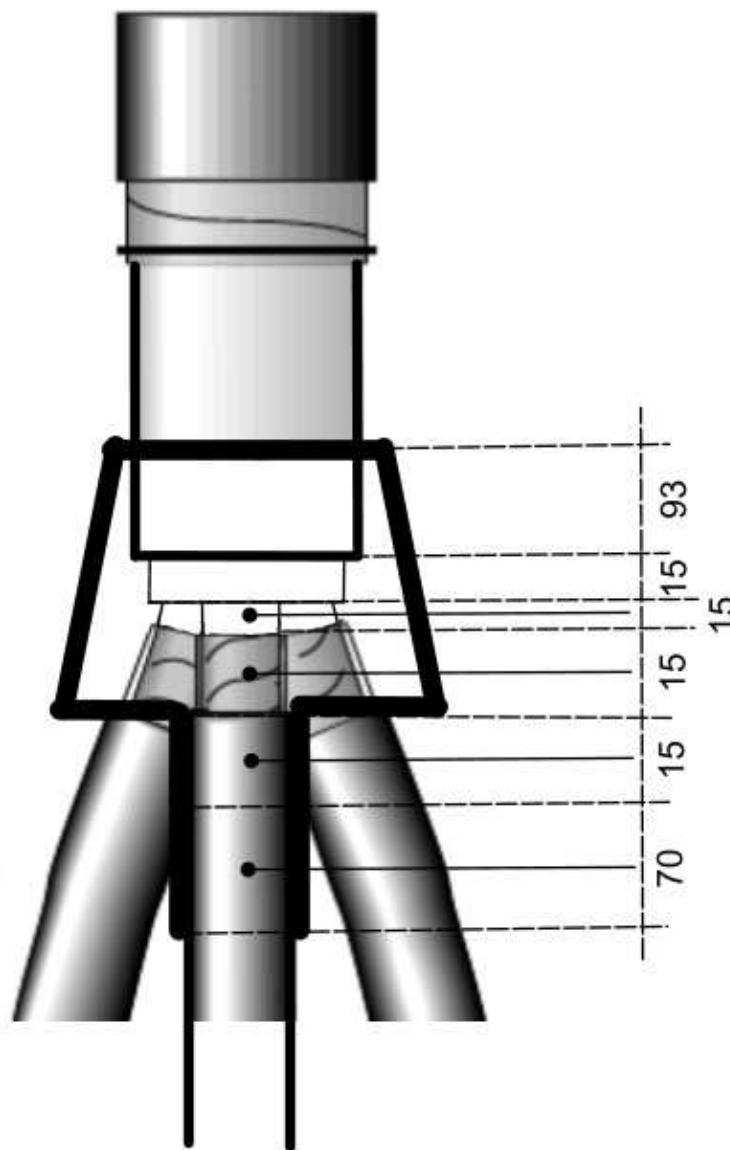
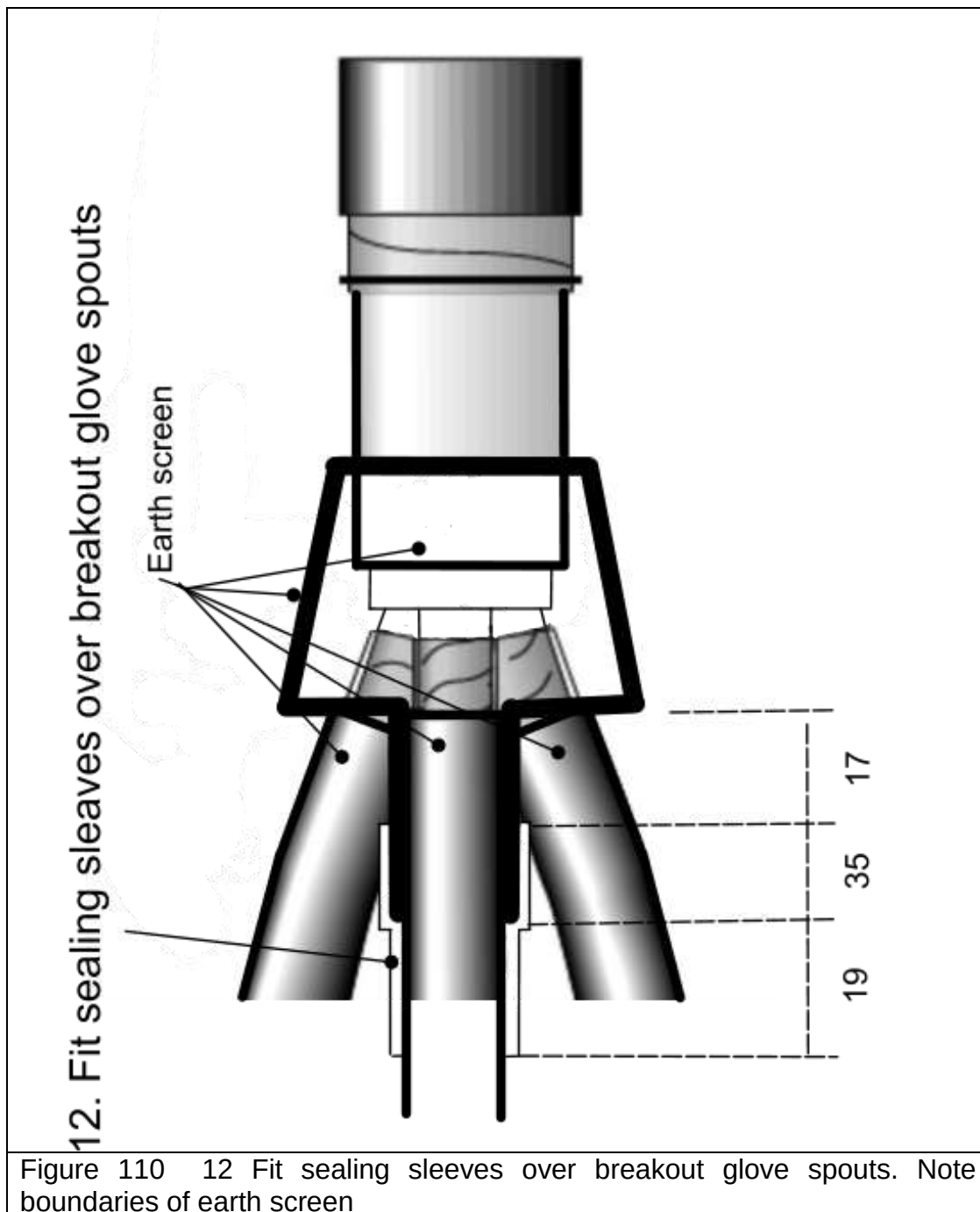
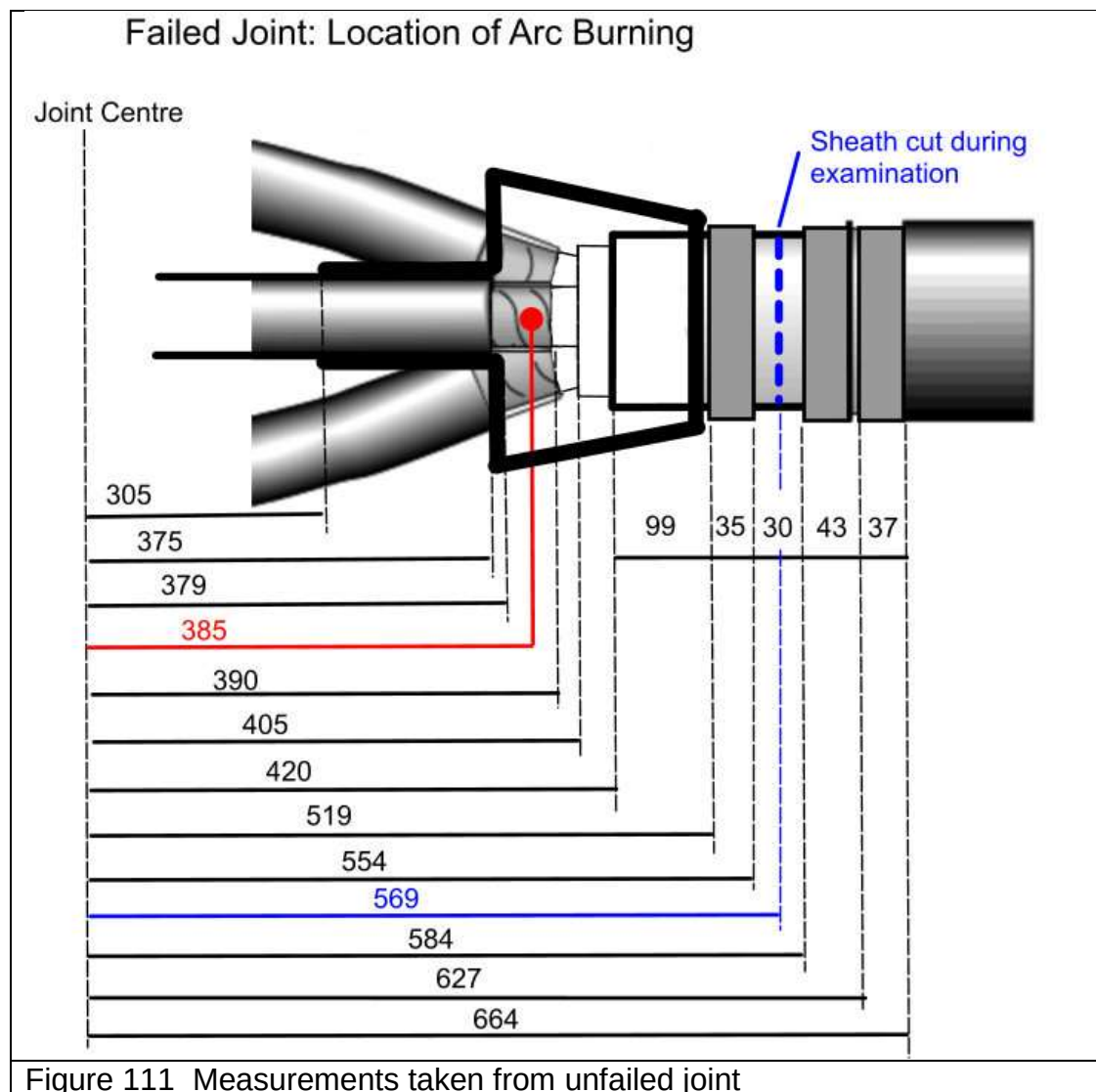


Figure 109 11B Dimensions of component positioning inside break-out glove





22 Appendix F Calculation of Cable Operating Temperatures

The objective of this study was to calculate if any of the cable circuits in the cable trench had operated at equal to, or greater than, their maximum allowable design temperatures. The method was to analyse the historical hourly current loading patterns and to select the patterns having the maximum average twenty four hour current together with a maximum one hour peak value under i) summer and ii) winter loading.

The DSC analysis of samples of the 33 kV XLPE cable insulations performed by Edif-ERA reported in Section 6.1.2 had found that 12 samples cables had exceeded their rated temperature maximum of 90°C. However, other phase cables in the same trefoil groups that formed the circuit had not exceeded this temperature. Significant differences in temperature are not possible with the symmetrical current loading normally present in a three phase system. This led to the conclusion that the elevated temperatures had resulted from hot air generated by the fire. By inspection of the surviving cable oversheaths for the presence of char it was found that flames had travelled to within 15 m of the samples sent to Edif-ERA. This distance was concluded to be sufficiently close to demonstrate that the 33 kV XLPE cables had experienced elevated temperatures above 107°C for a prolonged period of time during the fire.

A second purpose of the rating study was to support the above conclusion by eliminating the possibility that the cables had been overheated in normal service operation.

22.1 Conductor Temperatures Calculation Method

The calculation of the conductor temperatures is complex and non-standard for the following reasons:

- The high number, 19, of loaded cable circuits in close proximity, some being three core and some single core in trefoil formation.
- Heat is dissipated into the air filled trench and onto the concrete lining of the trench by convection and radiation
- The trench is buried at shallow depth with its roof slabs level with the ground surface. The simple cable rating thermal resistance equation is not representative as it assumes i) heat transfer from a point heat source in a buried cylindrical cable at depth below the ground surface and ii) orthogonal geometry for the isotherm and heat flux distributions.
- Air from the trench can be vented to atmosphere through i) distributed holes in the roof slabs of 45 mm diameter and ii) narrow gaps between the slabs.

- The load is cyclic, varying each hour of the day during the seasons of the year. It is thus unrepresentative to calculate the conductor temperature on the assumption that:
 - The load is constant at the value of the peak hourly load. This would yield a pessimistically high temperature.
 - The load is constant at the daily RMS (root mean square) 'loss load' would yield a pessimistically low temperature. This ignores the rapid rise of temperature across the layers of cable that can occur in a one to two hour time period. Small conductor, low voltage cables of the type installed in the cable trench have low thermal time constants and so the temperature drop responds quickly.

Doubt existed that the approaches given in IEC 62087 were sufficiently applicable to provide the certainty in temperature accuracy needed in this study.

A simulation method was therefore developed based on 'Abaqus-Standard' FEA software for conduction and for cavity radiation. Two variants were developed to solve the complete thermal model together under the application of a cyclic transient current loading case.

22.2 Development of the FEA calculation method

1. An FEA model was constructed of each cable, the air filled trench and the ground surrounding the trench. The geometry of the trench cross-section is modelled and assumes that the trench has longitudinal symmetry. The two discrete cylindrical holes in each concrete roof slab and the gaps between the slabs slots were modelled by two rectangular longitudinal slots that had the same air flow impedance and which ran lengthwise in the same position as the cylindrical holes.

The trench is horizontal and longitudinally symmetric westwards from Gavin Street to the 79 m chainage position. To the West of this position the ground surface and trench ramps downwards to a lower level to pass below steel tracks set into the Switchyard surface for transformer transportation. The trench then rises again to its original level before reaching the exit in the vicinity of the 33 kV Switchroom. It is considered that the change in level will result in a chimney effect in which heated air will rise and flow both eastwards and westwards from the deeper level trench into the main run of lower level trench. The complexity of modelling this effect in three dimensions over the full length of the cable trench was beyond the scope and need of this

temperature study. However it was considered to be wise to check that a temperature margin had existed below the maximum design operating temperatures for each type of cable.

2. To overcome the computational disparity between the very short time steps (0.01 seconds) necessary for a CFD (computational flow dynamics) solution for the convection in air and the very long time duration necessary to reach a steady state plateau for transient conduction heat flow through the surrounding ground, of approximately 20 days (1.7×10^6 s), by:

2.1. Solving Abaqus Standard software with transient step-currents applied to the cables with the trench air modelled by empirical heat transfer equations¹⁶ from experimental results in combination with an algorithm written to calculate the average temperature of the body of air in the trench at each computational time step. Figure 112 is the validation model for the empirical equations. A single cable is surrounded by air in a trench with concrete walls. The experimental results for this geometry are available in many heat transfer text books. The surface above the roof is held at 20°C.

Figure 112 shows the temperature rise of the calibration cable with time for a number of different cases. The brown line is the temperature rise of the cable in true 'normal' time, only the first 10,000 seconds are shown. The cable reached its steady state temperature of 72°C after 20 days.

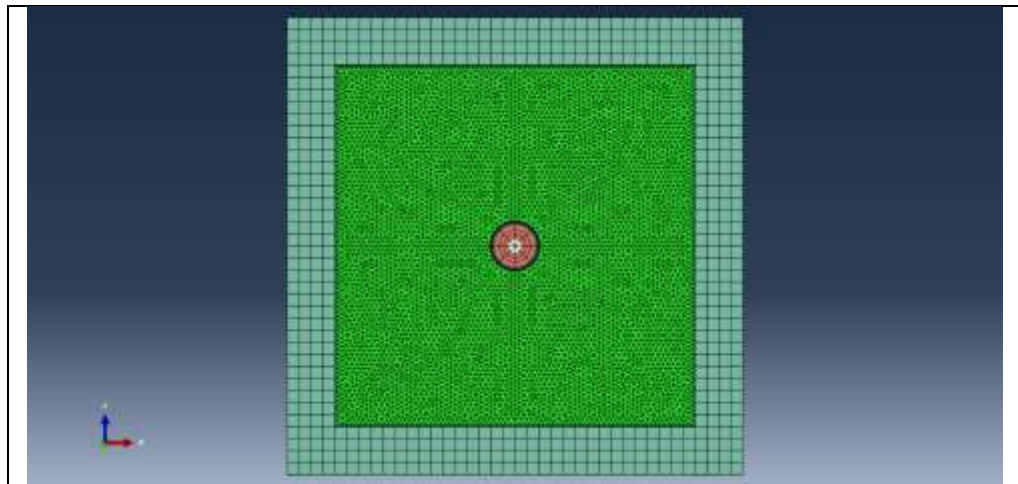


Figure 112 FEA CFD model to validate convection equations

The red line is for the CFD co-simulation (i.e. Abaqus CFD for convection and Abaqus Standard for conduction) solution which reaches a steady state temperature of 74°C. The green line is for the empirical convection

equations embedded into Abaqus Standard, which reaches a steady state temperature of 76°C i.e. an acceptable difference of 2°C.

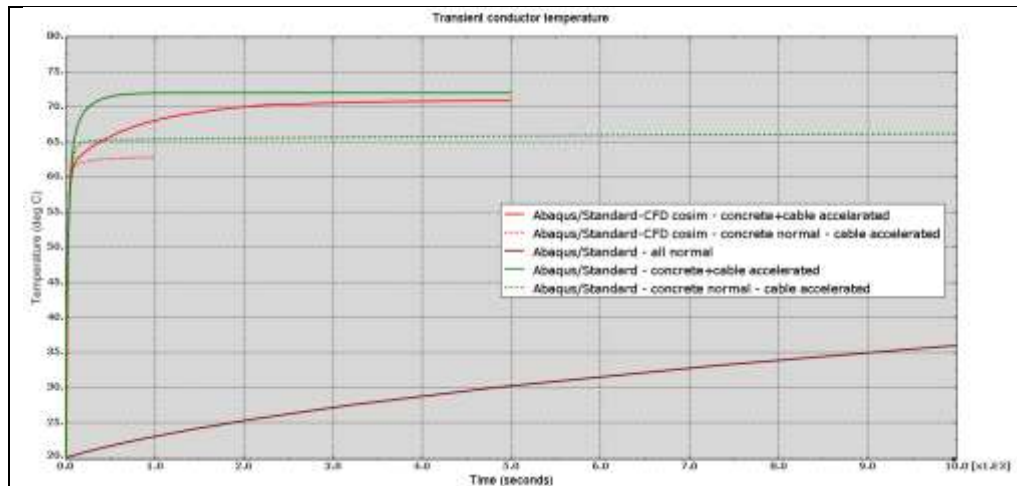


Figure 113 CFD and empirical convection equations: evaluation of steady state temperatures and time acceleration

The densities of the conduction materials in the model were set to a single low value to reduce the number of short duration time steps and permit a 'steady state' convection solution to be obtained. (The disadvantage is that the rate of temperature rise in the conduction materials can no longer be related to the actual temperature rise). This acceleration is shown in Figure 113 for the red and green lines in which the target steady state temperature is reached in 5,000 seconds, this being a very considerable computational acceleration compared to the 'normal' time of 20 days.

The computational time and stability was further improved by using the Abaqus Standard software and empirical equation computed temperature distribution as the starting condition for the Abaqus CFD software solution. The time for the Abaqus Standard run is a few minutes and for the Abaqus CFD is several hours.

The model of the cable trench and all the cables is shown in Figure 114. The ground (basalt rock) surrounding the concrete trench is modelled to a width of ± 50 m and depth of 50 m, which is more than sufficient to obtain an accurate temperature distribution without incurring boundary errors.

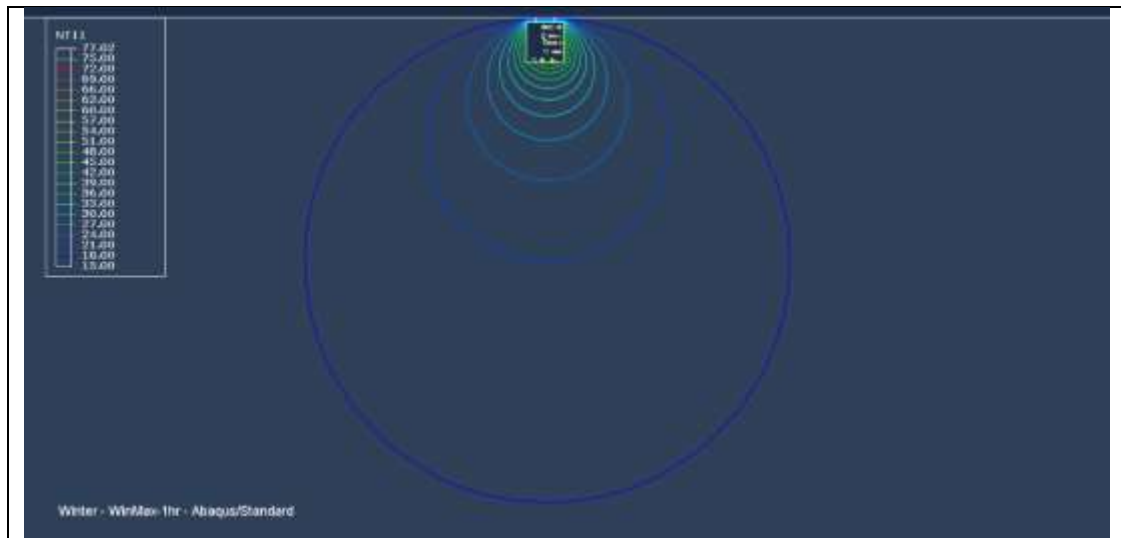


Figure 114 FEA model of the cable trench showing ground isothermal lines

22.3 Current Loading Cases

The following are two examples of current loading cases that were studied to find the 'realistically pessimistic' conductor temperatures.

22.3.1 Summer Continuous Loading at Peak One Hour Current Value

The outputs are shown in Figure 115 to Figure 118. This is a pessimistic loading case in which a continuous current load is applied equal to the maximum hourly peak load recorded on each circuit during the summer season. It is pessimistic as:

- It ignores the benefit of lower current loadings and lower heat output that occur at the other hourly time periods during the day.
- It assumes that the one hour peak loadings on all the circuits occur on the same day.

The summer ambient air temperature was advised to be 23 °C for the purpose of cable rating.

Figure 115 is a velocity vector plot of the convective air flow circulation. The hot air rises from the cables on the support arms on the North (right hand) side of the trench, moves upwards through the gaps present between the cables and with the wall, moves southwards across the roof of the trench with a portion of the hot air venting out and drawing in cold air through the holes in the roof (two

blue vertical rectangles) and then descends on the South wall (left hand side) to flow northwards across the cables on the floor (Level 5).

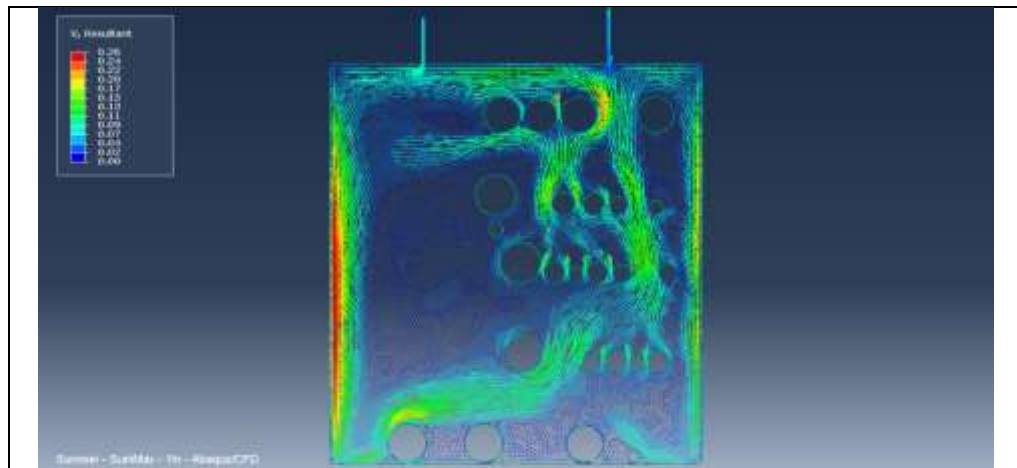


Figure 115 Velocity vector plot of air convection: continuous loading at Summer peak currents

Figure 116 is a convection contour plot that shows the resultant air temperature in the cable trench.

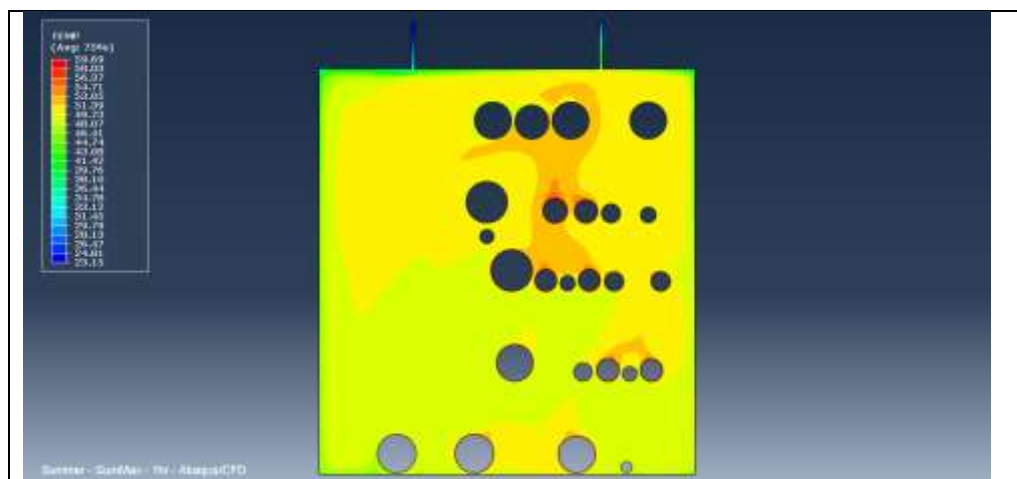


Figure 116 Air temperature contour plot: continuous loading at Summer peak currents

Figure 116 shows:

- i) The highest air temperatures occur above six cables:
 - o Level 2: 2C, 11 kV PILC and 2D, 33 kV OF

- Level 3: 3C, 22 kV OF and 3E, 22 kV OF
- Level 4: 4A, 33 kV OF and 4C, 33 kV OF
- ii) The air temperature in the trench is in the range of 43°C to 59.6°C. The air in the upper half of the trench is greater than 46 °C. Cold air is drawn inwards at 23°C from external ambient air. Thus between day and night the cables will experience a significant range of air temperatures with the extreme for high current carrying cables being 37°C (23°C to 59.6 °C) and for a non-load carrying cable such as 3B being 23°C (23 °C to 46°C).
- iii) The air over the 33 kV XLPE cables is at lower temperatures. The air rising over 3B, the Remuera K10 circuit in which the first failure occurred, was at a lower temperature (in the years prior to 2014 in which it carried load). The lower air temperatures result from the ratio of the low current loading compared to the rated current carrying capacity of the particular conductor size and cable.
- iv) The conductor temperatures are given in Table 11. These were derived from the graphs in Figure 117 and Figure 118. CFD computed values were found to be typically 2-3 °C below the values given by empirical convection equations.

The 33 kV oil-filled cables are at greater than 15°C below their design limit of 85°C limit for continuous operation.

The 11 kV PILC cable 2C is just below its 65 °C limit for continuous operation. However this is an unrealistically pessimistic estimation as the peak current loading used in the calculation is significantly greater than the average 24 hour RMS current loading. For accuracy it is therefore necessary to calculate the true temperature difference by taking into account the cyclic nature of the load.

Table 11 Summer: Highest Conductor Temperatures under Continuous Loading at Peak Current Values

Cable			Conductor Temperature [°C]		
Position	Type	Circuit	CFD	Empirical	Design limit
2D	33kV OF	Carbine N° 1	69	70	85
2C	11kV PILC	McNab K19	64	66	65
3E	22 kV OF	Westfield N° 3	63.5	66	85
3C	22 kV OF	Westfield N° 2	63	66	85
4C	33 kV OF	St John N° 2	62	63	85

A comparison, Table 11, between the CFD heat transfer solution and the empirical convection solution demonstrated that the empirical convection solution gave 'engineering-safe' conductor temperatures, these being higher by 0 to 3 °C. The empirical convection method was faster and so was used in part

for the study. For future rating work the Abaqus Standard software method using empirical convection formulae can be used to model both the true material densities and hence the true rate of heating. The actual 24 hour cyclic load curves can then be applied to investigate the effect of both variations in peak load values and in 24 hour patterns for one circuit or all the circuits.

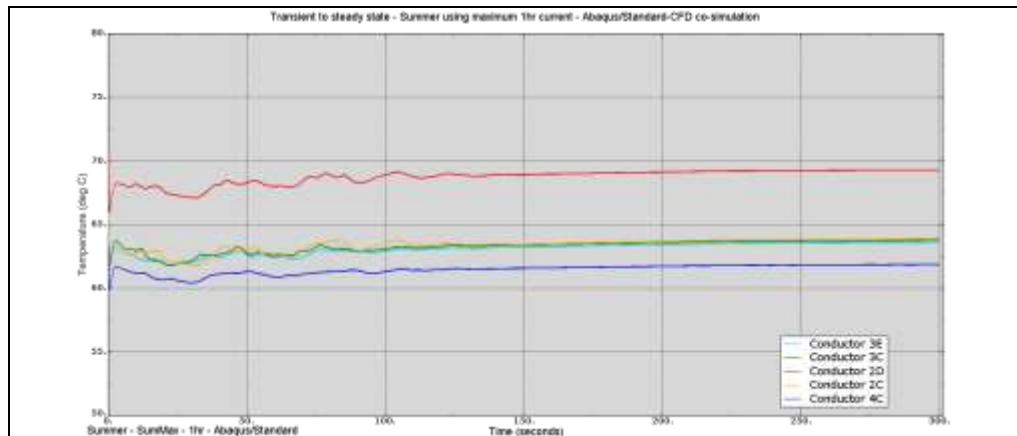


Figure 117 CFD convection: plateau temperatures continuous loading at Summer peak currents.

Note that the zero time in Figure 117 starts from the starting point when the Abaqus Standard solution from Figure 118 was applied.

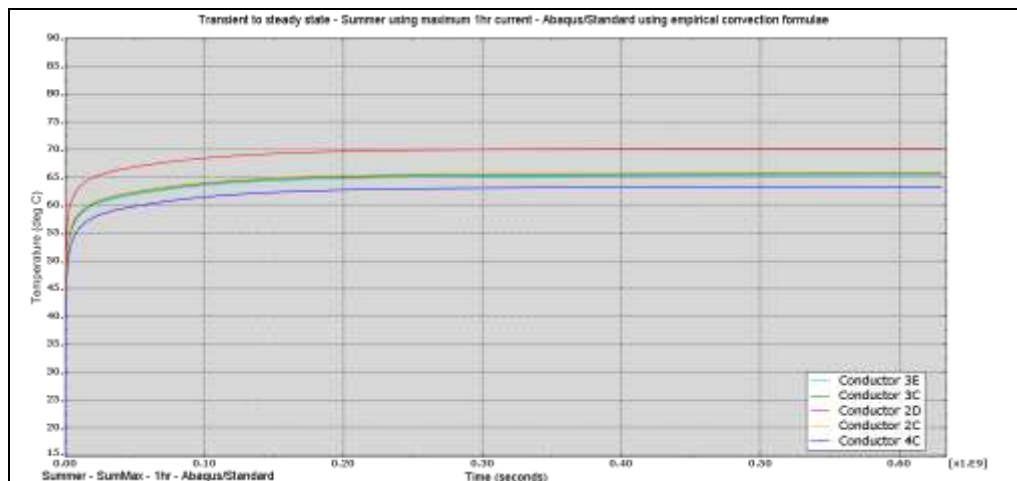


Figure 118 Abaqus Standard and empirical equation convection: plateau temperatures, continuous loading at Summer peak currents.

22.3.1 Winter Loading: Modelling of 24 h Cyclic Load

The study on continuous loading at the one hour peak value found that:

- Current loadings and temperatures were higher in the winter than those in the summer and, allowing for the reduction in ambient temperature from 23 °C to 15°C, the conductor temperatures were also higher in the winter. However it was found that for cyclic loads the maximum operating temperatures were similar.
- The method of applying a continuous current load equal to the one hour peak load was unrealistically pessimistic. Thus the following cyclic rating method was developed.

An examination of the daily load patterns showed that there was a pronounced peak load in each 24 hour period. This permitted the Neher McGrath cyclic rating method¹⁷ to be applied. This is a standard method for the cyclic ratings of buried cables. In this study the method was further developed to suit the geometry of the cable trench.

The daily load curves that had the highest two hour peak current were selected. The two hour duration is compatible with the thermal time constant of the cables in the trench of typically 0.9-1.5 hours. The application of a two hour step load is capable of raising the conductor temperature to ~88% of its steady state plateau value.

The two hour RMS load (i.e. averaged heat loss generation) was calculated from the two individual current values that form the two hour load step.

The 24h RMS current was calculated for each cable circuit.

The full FEA model was solved by the Abaqus Standard software and empirical convection equations for the 24h RMS load current. The steady state temperature distribution around the walls of the trench were recorded. This temperature was taken to remain constant throughout the 24 hour period in consequence of the smoothing effect of the high thermal capacity of the ground.

The peak RMS load currents (for the two hour period) were then applied as a continuous load to the full FEA model. The steady state temperature solution was obtained and inspected. The global thermal resistivities of the trench walls and floor and of the surrounding ground were then iteratively reduced as shown in Figure 119 from a value of 1.0 °C m/W to 0.3125 °C m/W until the temperature of the trench lining became closely similar to that in the 24h RMS current solution (red dotted line). The thermal resistivity of the concrete roof of 1.0 °C m/W was not changed as i) the roof layer is thin and so has a lower value of thermal resistance and thermal capacitance, thus permitting the flow of heat to change

more significantly and ii) a significant proportion of the heat is conducted through the roof to the 15 °C ambient. The individual application of the peak current for a two hour period is taken to have a negligible effect on raising the temperature of the trench walls and floor above their 24h RMS values.

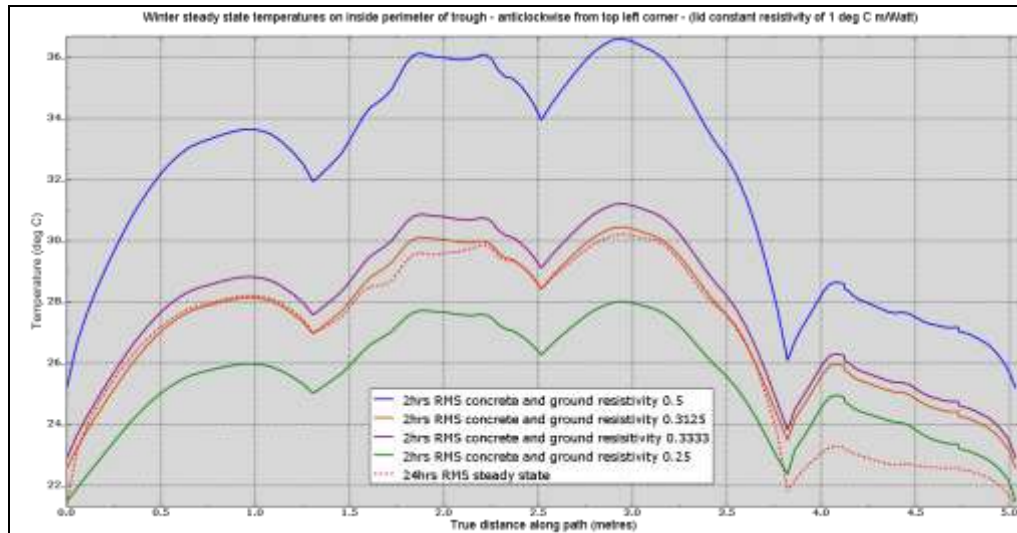


Figure 119 Winter cyclic rating: trench wall temperature distribution

Having achieved the same wall and floor temperatures the resulting conductor temperatures are abstracted, Table 12. Table 12 compares the Abaqus-CFD co-simulation with the Abaqus-Algorithm simulation temperatures.

Table 12 Winter: Conductor and Sheath Temperatures under Cyclic Loading

Cable Position	Cable Type	Circuit	Conductor Temperature [°C]		Max. Cable Surface Temperature [°C]	
			CFD Co-Simulation	Algorithm	CFD Co-Simulation	Algorithm
1A	33kV XLPE	Remuera N°3	44.32	41.59	41.72	38.97
1B	33kV XLPE	Newmarket N°3	40.41	37.23	39.45	36.21
1D	33kV XLPE	Remuera N°2	43.71	41.18	41.49	38.93
2C	11kV PILC	McNab K19	57.82	56.74	49.44	48.30
2D	33kV OF	Carbine N°1	53.80	52.17	47.12	45.62
2E	33kV XLPE	Carbine N°2	38.13	35.54	37.94	35.30
3A	11kV PILC	McNab K02	58.24	57.97	49.32	48.60
3B	11kV PILC	Remuera K10	45.96	44.48	42.98	41.38
3C	22kV OF	Westfield N°2	48.09	46.78	44.02	42.53
3E	22kV OF	Westfield N°3	47.23	46.27	44.22	42.52
3F	33kV XLPE	St John N°3	41.88	39.93	40.76	38.81
4A	33kV OF	St John N°1	56.99	57.32	49.53	48.86
4C	33kV OF	St John N°2	59.17	59.29	50.26	49.24
4D	11kV PILC	Mt Wellington K05	42.19	35.54	40.51	36.15
4E	33kV XLPE	Mt Wellington N°2	38.66	37.30	37.84	36.42
5B	33kV XLPE	Mt Wellington N°1	36.77	37.30	36.15	36.49
5C	33kV XLPE	Sylvia Park N°1	40.60	41.18	38.37	38.69
5D	33kV XLPE	Sylvia Park N°2	34.00	33.94	33.56	33.53

Figure 120 is an inset view of the ground 1.5°C isotherms that surround the trench. Figure 121 is an expanded view of the temperature contour plot for the cable, the trench lining and the surrounding ground.

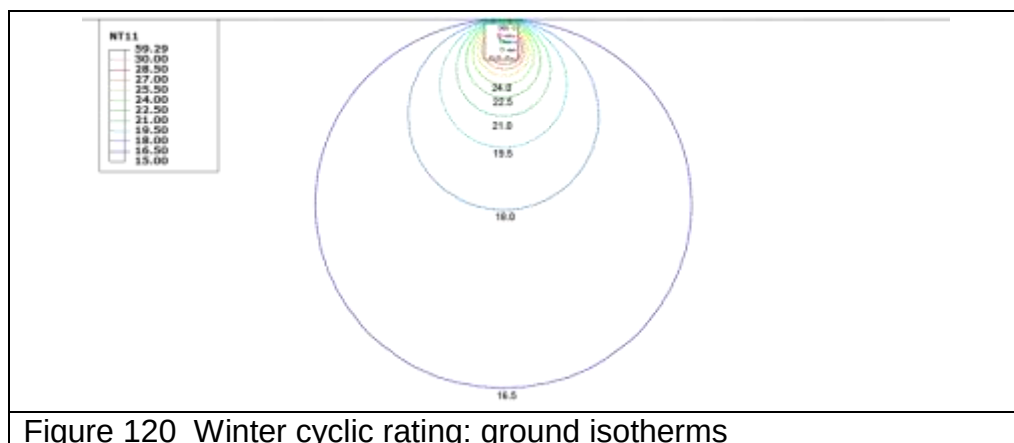


Figure 120 Winter cyclic rating: ground isotherms

Figure 121 (Abaqus Standard-algorithm) shows that the highest temperature profile external to the inner lining of the trench occurs through the concrete roof and is indicative of a higher heat flow. The temperature of the roof inner surface from Figure 119 is 30°C giving a temperature drop of 15 °C to the external ambient of 15 °C.

The mean air temperature in the trench for the 24 hour RMS constant load was 30 °C. The mean air temperature for the 2 hour RMS cyclic rating was 33 °C. Thus the maximum trench air temperature variation that between day and night, assuming a night ambient of 15 °C will be $< (33 - 15) = 18$ °C.

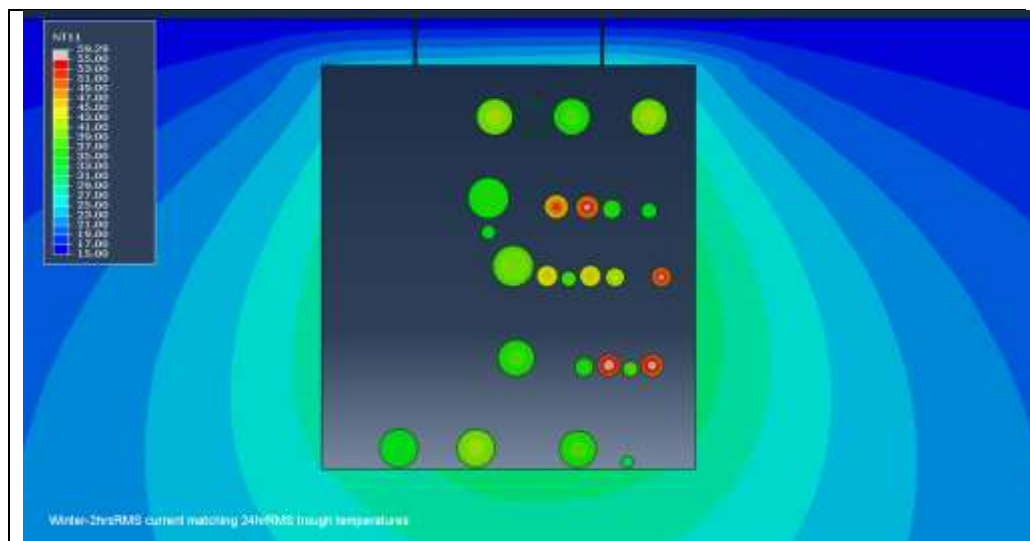


Figure 121 Winter cyclic rating: cable and ground temperatures

Figure 122 shows the steady state conductor temperatures of the five hottest conductors. **Figure 121** shows the temperature profile of the air in the trench (shown as grey), as computed by a convection heat transfer algorithm.

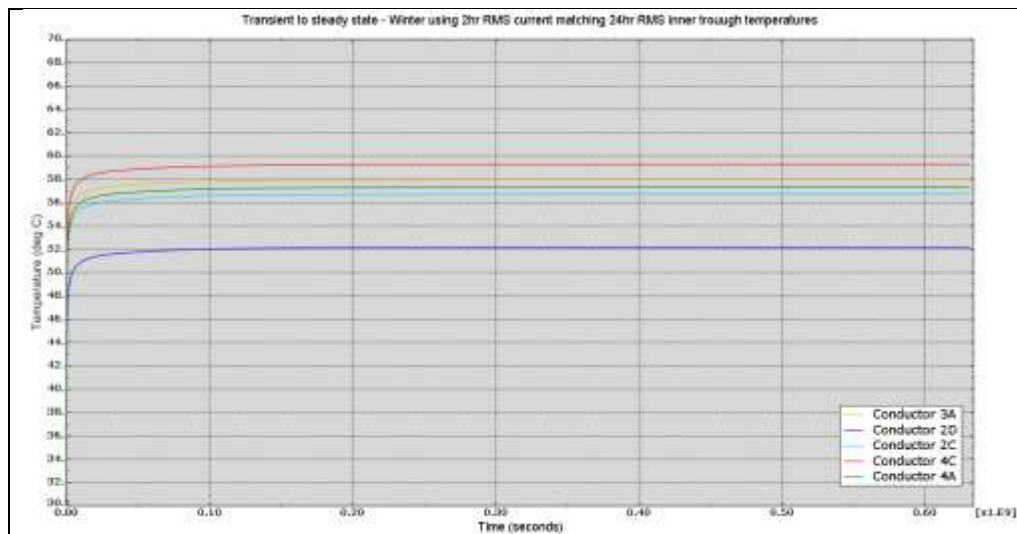


Figure 122 Winter cyclic rating: cable steady state temperatures

Figure 123, Figure 124 and Figure 125 show the air flow and temperature distributions for the full CFD co-simulation solution of the cyclic loading case based on the two hour peak RMS current values applied to each circuit.

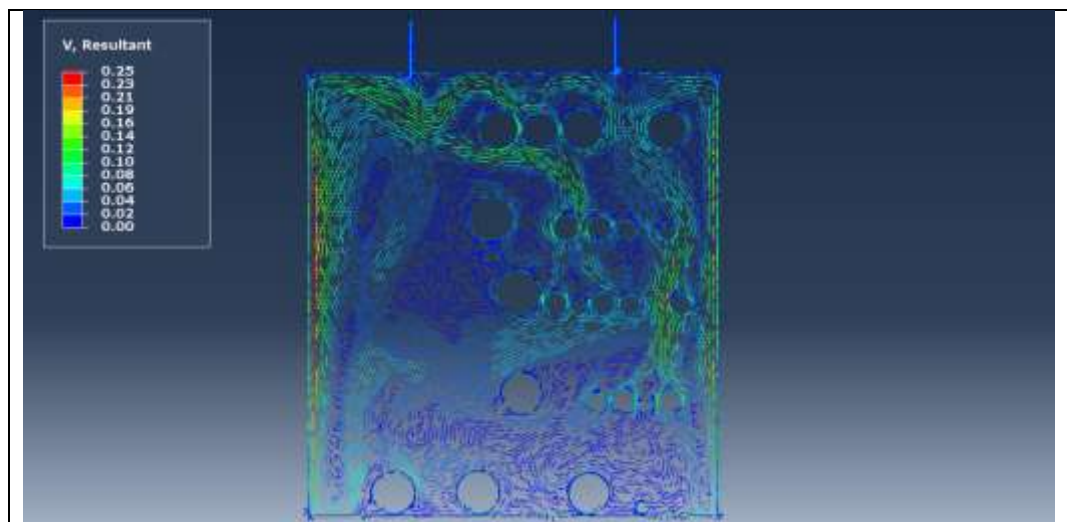


Figure 123 Winter cyclic rating (Abaqus: CFD): Velocity vector plot of air convection

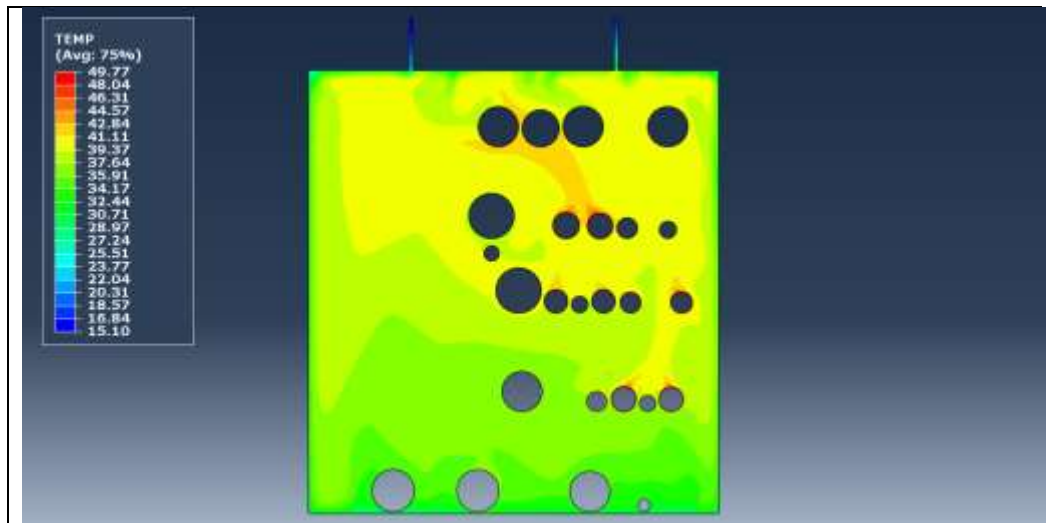


Figure 124 Winter cyclic rating (Abaqus CFD): Air temperature contour plot

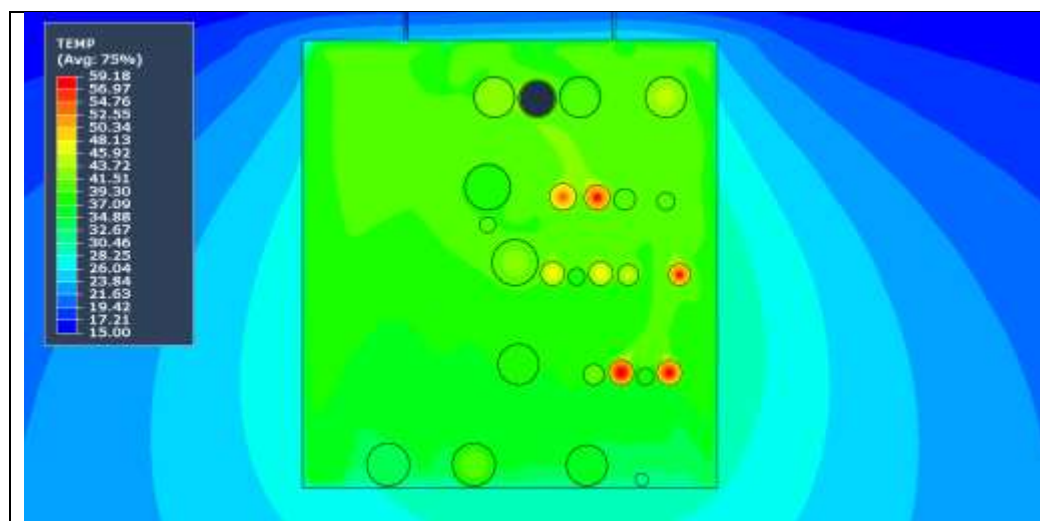


Figure 125 Winter cyclic rating (Abaqus CFD): cable and ground temperatures

The CFD co-simulation showed that:

- Radiation was the most efficient form of heat transfer from the cables:
 - Radiation: 73.8%
 - Convection: 22.0%
 - Air vents: 4.2%
- The Roof and left hand wall (southern) transmitted most heat
 - Roof: 31.0%
 - LH wall: 29.7%

- RH wall: 21.0%
- Floor: 14.2%
- Roof holes: 4.2%

The temperatures from the Abaqus CFD co-simulation computations are shown in Table 13 for the five cables having the highest temperatures. The temperatures in **Table 12** and Table 13 confirm that all the cables are within their safe operating limits:

- 11 kV PILC cables are 7 °C to 23°C below their design limit of 65 °C for continuous operation.
- 33 kV oil-filled cables are 26 °C to 38°C below their design limit of 85 °C for continuous operation.
- The circuit that was the first to fail, 3 B, 11V PILC Remuera K10, has a lower conductor temperature of 46 °C.
- The 33 kV XLPE cables have lower conductor temperatures in the range of 34 °C to 44 °C.

Table 13 Winter: Highest Conductor Temperatures under Cyclic Loading

Cable			Conductor Temperatures [°C]	
Position	Type	Circuit	Empirical	Design
4C	33 kV OF	St John N° 2	59.29	85
3A	11kV PILC	McNab K02	57.97	65
4A	33 kV OF	St John No 1	57.32	85
2C	11kV PILC	McNab K19	56.74	65
2D	33kV OF	Carbine N° 1	52.17	85

22.3.1 Summer Loading: Modelling of a 24 h Cyclic Load

Table 14 gives the summer cyclic loading temperatures for comparison with the winter loadings in Table 13. The operating temperatures are of similar magnitudes.

Table 14 Summer: Highest Conductor Temperatures under Cyclic Loading

Cable			Conductor Temperatures [°C]	
Position	Type	Circuit	Empirical	Design
2D	33kV OF	Carbine N° 1	59.5	85
2C	11kV PILC	McNab K19	55.0	65
3C	22 kV OF	Westfield No 2	54.5	85
3E	22 kV OF	Westfield No 3	54.0	85
4A	33 kV OF	St John No 1	51.0	85

The two cables to be present in both the lists for the higher temperature cables in summer and winter are compared in Table 15.

Table 15 Comparison of Winter and Summer Cyclic Loading Temperatures

Cable			Conductor Temperatures [°C]		
Position	Type	Circuit	Winter	Summer	Design
2D	33kV OF	Carbine N° 1	52	59.5	85
2C	11kV PILC	McNab K19	56.8	55.0	65

Comparing both summer and winter cyclic ratings:

- 11 kV PILC cables are 7 °C to 10 °C below their design limit of 65 °C for continuous operation.
- 22 kV and 33 kV oil-filled cable are 25 °C to 35 °C below their design limit of 85 °C for continuous operation.
- The circuit that was the first to fail, 3 B, 11V PILC Remuera K10, has a lower conductor temperature.
- The 33 kV XLPE cables have lower conductor temperatures.
- The trench roof surface temperatures in summer has a maximum of 36°C (13°C drop to ambient) and in winter 30°C (15°C drop to ambient).

22.3.1 Conclusions on Cable Operating Temperatures

The Author concluded that:

- i) The operating temperatures of all the cable circuits and all the types of cables within the cable trench in both the Summer and Winter seasons had been satisfactory, being below their maximum design operating temperatures for continuous operation:
 - a. The operating temperatures of all the 11 kV PILC cables were satisfactory, being 7 °C to 10°C below their design limit of 65 °C for continuous operation.
 - i. The cables closest to their design limiting temperature were the 11 kV PILC cables 2C and 3A, for continuous operation of 65°C.
 - ii. The 11V PILC circuit that was the first to fail, 3 B, Remuera K10, had satisfactory low conductor temperatures when it was last on continuous load in 2013.
 - b. The operating temperatures of all the 22 kV and 33 kV OF cables were satisfactory being 25 °C to 35°C below their design limit of 85 °C for continuous operation.
 - i. The OF cables that had the highest operating temperatures were 2D, 3C, 3E, 4C, 4A, for continuous operation of 85°C.

- ii) The 33 kV XLPE cables were satisfactory having the lowest conductor temperatures of all the different types of cable.
- iii) The temperature calculations showed the reason that samples of XLPE cable insulation had experienced temperatures above their maximum design operating temperature of 90°C was not by overheating in normal service operation. It is thus concluded that the cause was overheating by hot air during the fire.

23 Appendix G Arc Temperature and Conductor Erosion

The objectives of this section are to use the measured volume of the arc eroded conductor cavities to:

- i) Demonstrate that the 11 kV Remuera K10 joint experienced high arc energy.
- ii) Estimate the temperature of the arc eroded conductor metal.

It should be noted that calculating the behaviour of a power arc is a complex, multi-parameter, non-linear problem for which few of the parameters for it's solution in the geometry of an 11 kV transition joint are known. Hence an academic solution is beyond the reach of this section. For the sake of simple engineering calculations it is usual to take an arc in a particular application to have a near constant, low voltage drop in consequence of its highly non-linear electrical resistance. This section also uses simple engineering approximations.

23.1 Volume of Arc Eroded Cavities

A comparison of the conductor volumes eroded by the power arcs for six of the electrical faults is shown in Figure 126. The volumes were obtained by measuring the clay and plasticine impressions of the fault cavities. The plasticine mould for 3BO accurately depicts the shape and the volume of the cavity. The other clay samples accurately record the volume but not the shape of the cavities.



Figure 126 Clay volumes from the conductor arc cavities

Figure 18 shows the failed joint arc cavity that was eroded in the three conductors by both the first and the second faults.

The first electrical fault, Table 16, was a two phase fault between the red and blue phases for 0.053 s, which then changed to a three phase fault for 0.561 s. The fault current was recorded to be 4,200 A RMS. The second electrical fault was a three phase from the start. The fault duration was 0.55 s and current 4,200A.

Table 16 shows:

- The measured arc erosion volume in the failed 11 kV PILC transition joint 3BO was 27.3 mL, this being produced by two 0.55 s shots of 4,200 A fault current.
- The 3BO transition joint crater volume is very significantly larger than those in the other 11 kV PILC faults i.e. 3A has 4.9 mL and 2C has 1.6 and 3 mL.
- The failed 3BO transition joint is one of the three faults to have large arc crater volumes, the other two being 33 kV XLPE cables; 1A has a volume of 25.8 mL and 3F has 24.4 mL.
- By inspection the volumes are seen to have a dependency on fault current magnitude and duration and hence on arc energy.

Table 16 Details of faults, locations and arc crater volumes

Time of Fault hr min sec	Circuit	Fault Position in Trench		Fault Type	Fault Duration s	Fault Current A	Arc Crater Volume mL
		X-Section	Chainage m				
23:21:30	Remuera K10, 11 kV PILC	3B	73	Two phase Three phase	0.053 0.508	4,200	27.3
01:20:49	Remuera K10, 11 kV PILC	3B	73	Three phase	0.55	4,200	
02:11:39	Remuera 03, 33 kV XLPE	1A	72.5	Single phase-earth	0.215	16,000	25.8
02:12:31	New Market 3, 33 kV XLPE	1B	73	Single phase-earth	0.131	13,962	-
02:14:31	Tunnel Aux 11 kV XLPE	2F	-	-	-	-	-
02:14:47	Carbine Rd 2, 33 kV XLPE	2E	72.8	Single phase-earth	0.364	16,744	16.9
02:16:45	Remuera 02, 33 kV XLPE	1D	72.6	Single phase-earth	0.175	16,500	-
02:22:46	St John 03, 33 kV XLPE	3F	71.1 – 72.8	Single phase-earth Two phase - earth	0.061 0.979 (total of 1.04s)	15,916 - 16,338 & 16,932 - 17,463	24.3
02:44:42	McNab K02, 11 kV PILC	3A	67.7	Two phase - earth	0.199	10,370 - 11,190	4.9
02:48:42	Carbine 01, 33 kV OF	2D	68.9	Two phase - earth	0.412	16,000	-
02:48:46	Mt Wellington 02, 33 kV XLPE	4E	66.9	Single phase - earth	0.196	14,500	-
02:48:54	Mt Wellington 01, 33 kV XLPE	5B	-	-	-	-	-
02:48:54	Mt Wellington K05, 11 kV PILC	4D	-	-	-	-	-
02:57:13	Sylvia Park 02, 33 kV XLPE	5D	71.8	Single phase - earth	0.093	14,546	-
03:04:59	McNab K19, 11 kV PILC	2C	67.4 – 67.9	Two phase - earth	0.319	3,980-4,280	1.6
							3

23.2 Volume of Conductor Metal Lost by Power Arc

The expression to calculate the volume of metal lost was selected from an empirical equation that was fitted by Stanback¹⁸ to experimental results and later used for engineering investigations by Gammon and Matthews²³.

$$V = k \cdot I^{1.5} t$$

Where

V: volume of metal lost for one electrode [m³]

k: constant for copper electrode: $1.185 \cdot 10^{-5}$

t: fault duration [s]

The curves in the graph in Figure 114 were drawn to illustrate the dependence of lost copper volume on fault time and current according to Stanback. For the purpose of the illustration each line represents a constant fault duration together with a multiplying factor to represent the number of power arcs present during fault between the phase conductors and the number of ends of power arcs that contributed to the erosion. The co-ordinates of measured metal lost and fault duration were then plotted in Figure 114 for four faults that had copper conductors and in Figure 128 for three faults that had aluminium conductors.

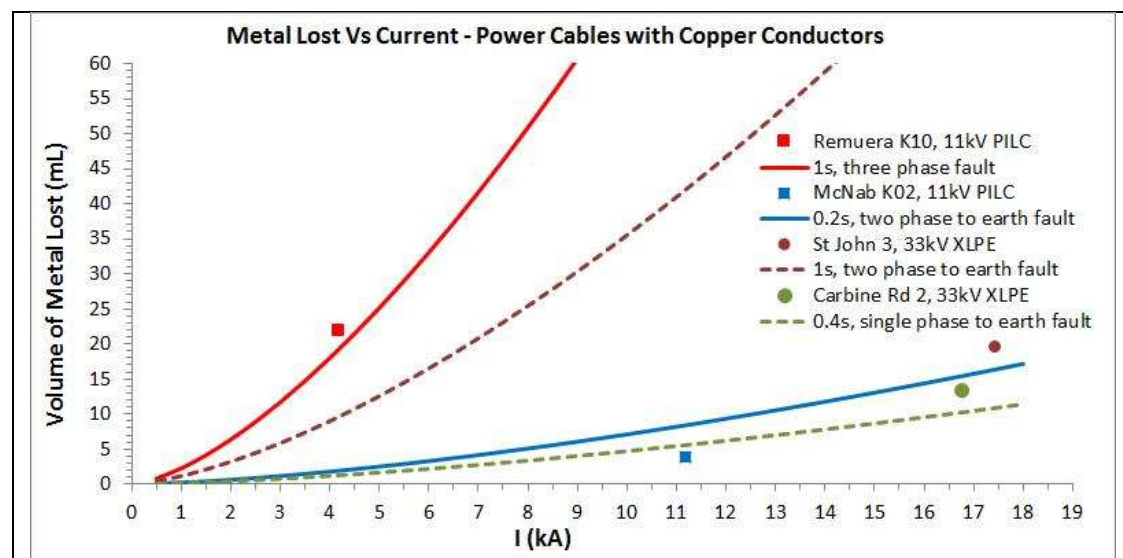
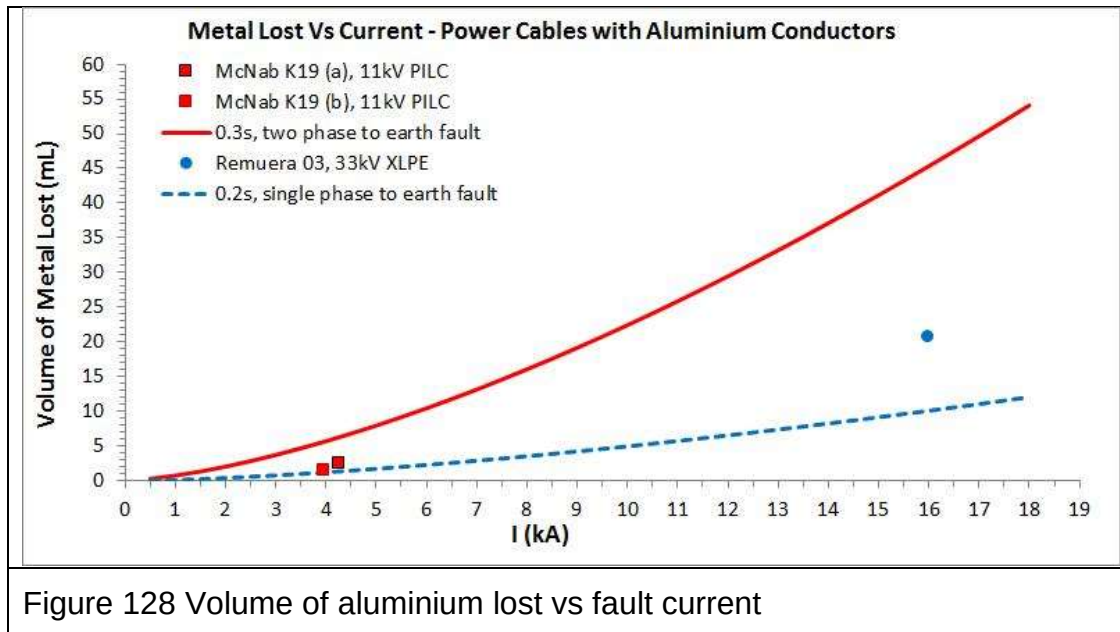


Figure 127 Volume of copper lost vs fault current

The Author concluded that the fault co-ordinates were sufficiently close to the 'Stanback expression' curves to have confidence that:

- The volumes of the metal lost had a logical dependence on the magnitude of fault current and duration

- The two cumulative faults did inject high arc energy into the Remuera K10 transition joint.



23.3 Temperature Rise

The purpose of this section is to estimate the approximate temperature rise Θ that would occur if an isolated solid volume of copper equal to that lost experienced an electric heat input for the short duration of the fault. The purpose is not to calculate the temperature within the arc, which has been reported to be between 5,000 and 20,000K, nor the Ohmic temperature rise within the adjacent conductor, which is routinely limited by design to be less than 160-250 °C depending upon the type of cable. The assumption was made that heat is generated by the power arc and, in the short duration of the fault, heating is 100% efficient, is confined to the measured volume of metal lost and is adiabatic (i.e. no heat is lost due to conduction, convection, radiation, pressure wave etc.). The temperature rise due to Joule I^2R heating of the conductor is neglected as being comparatively small in the short fault duration time.

The simple relationship taken was:

$$\theta = \eta \cdot \frac{k V I t}{m C}$$

Where:

Θ : Temperature rise [°C]
 η : Efficiency of thermal energy input compared with total fault energy [pu]
 k : Integer to allow for number of arc paths present in type of fault
 V : Voltage drop across the power arc [Volt]

I: fault current [Amp]
t: duration of fault [s]
m: mass of metal lost, after allowing for the filling factor of the stranded conductor [kg]
C: specific heat of conductor metal [Joule. Kg⁻¹.°C⁻¹]

Figure 129 plots the calculated temperature rise against the fault current for different fault times for the measured mass of metal lost from four faulted copper conductor circuits.

Figure 129 shows that:

1. Taking 100% efficiency for the conversion of fault into thermal energy the temperature rises were significantly greater than i) the melting point of copper and ii) of the fire ignition temperatures of the insulating and protective layers surrounding the joints and cables, Table 7.
2. Taking a 50% efficiency for conversion of fault into thermal energy the temperature rise in the vicinity of the arc for the Remuera K10 transition joint of ~ 3000°C is much greater than the ignition temperature of the materials.

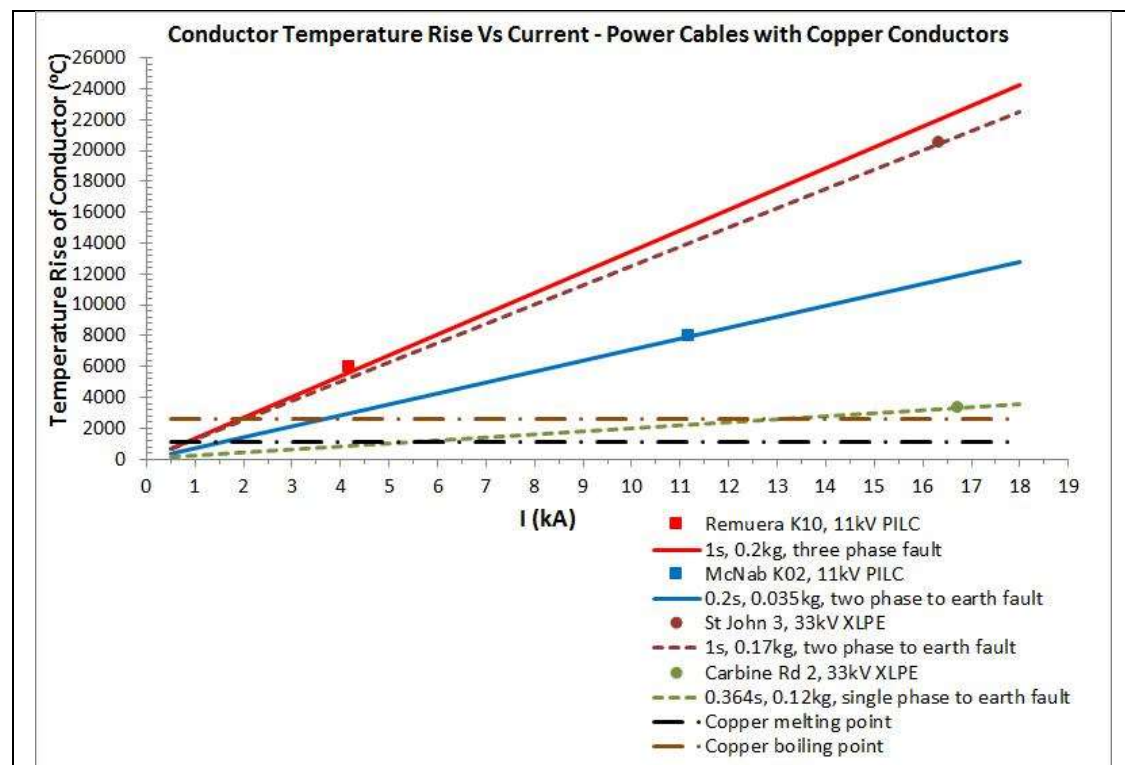


Figure 129 Temperature rise vs fault current for set fault durations

23.4 Selected Publications on Power Arcs

The following selection gives descriptions and engineering information on power arcs applicable to this section.

Wilson W.R, 'High Current Arc Erosion of Electric Contact Materials', 1955

The paper gives loss of metal by evaporation of the electrode to be 0.62 ml/k.Coulomb i.e. 5.5g/k.Coulomb for copper.

'Temperature Measurements in a Free Burning Arc¹⁹', 1976

This paper concentrates on measuring by spectroscopic means the temperature within a low current, 100A, short length welding arc in argon gas. It gives a brief mention of other work on high current power arcs.

'Predicting Damage from 277 V Single Phase to Ground Arcing Faults¹⁸', 1977

The paper records experimental measurements of electrode metal lost due to electric power arcs and then proposes a best fit empirical equation.

'Electric Arcs in Open Air²⁰', 1991

A comprehensive paper giving relationships between:

- arc voltage with current for 100 mm arc gaps in air with copper electrodes and
- Arc power ratios with current for 20 mm gaps with copper or aluminium, which shows that they stay close to unity over a wide range of arc currents and arc power (50W to 30 MW).
- Arc voltage with current for a range of horizontal and vertical gaps from 5 to 500 mm.
- Compares measurement with theory and refers to Lowke's²¹ model

Shows photos of the formation of the loop shape of a free power arc for a 100 mm gap with time up to 1.1 sec.

‘Study of the Electrode Gap Influence on Erosion under the Action of an Electric Arc²²’, 2000.

Measurements are given of arc parameters for electrode gaps of up to 10 mm. *[Author: this is a similar dimension to the 11 kV and 33 kV cable insulation thicknesses].*

‘Study of the Electrode Gap Influence on Erosion under the Action of an Electric Arc²²’, 2000

For short arc gaps and lower currents (0.2 -1 kA)

The arc voltage can be calculated from: $V = (V_i + k * D)$

Where

V: Voltage drop across the arc [V]

V_i: Interface voltage, the sum of the two electrode to air voltage drops, being 20V for a copper electrode in air.

D: Distance between electrodes [mm]

k: a constant, for air it is 4 V/mm

The highest erosion occurs with short gaps of 3 mm where the total metal lost is 0.7 mg. C⁻¹, where a Coulomb is the product of time and current. *[Author this appears to be only approximately 30% of the mass of the arc craters from the cable trench.]*

‘Conventional and Recommended Arc Power and Energy Calculations and Arc Damage Assessment²³’, 2003

The authors of this paper have selected the empirical equations relating metal lost to the fault current and duration and refer to empirical equations in the Stanback¹⁸ paper.

‘Small Scale Arc Fault Testing in Air²⁴’, 2009,

The paper is concerned with modelling the effects that arc energy has on switchgear for example the pressure shock wave. The paper describes that for a three phase fault the total energy is obtained by summing up the three phases and that both voltage and current are functions of the arc length. It considers the share of the arc energy that goes into the pressure build up. It gave experimental results for a full sized measurement in which 38 % of the energy went into the pressure build up and 1/13 scale models in which 16-24% went into the pressure

build up. The arc voltage gradient is given from the results of literature survey that gave similar values and averaged within the range 20-60V/cm length.

'Internal Arc Simulation in MV/LV Substations²⁵', 2009

The paper refers to the requirement for MV switchgear to withstand severe arc faults and to be tested in accordance with IEC 62271-200 and -202. *[Author: there are some similarities between the consequences of an arc in enclosed switchgear and in enclosed cables and joints and so the descriptions are of general interest.]*

The use of CFD software is described to calculate the pressure vs time wave. It is described that a three phase fault is simulated and compared to experimental measurements. There are three pressure rise phases. The first two are shock wave phases. The first being in the sealed switch compartment in which the arc energy produces a rapid pressure rise of ~2 bars in the short front time of 40 ms. The second occurs when the bursting disc of the sealed compartment opens and creates a 'very transient shock wave followed by a decompression'. The third is the thermal phase. Comparisons of measured and calculated pressures are given. The waveform of the fault power is calculated. In the example given of a three phase 20 kA fault (peaking asymmetrically at 40 kA) with an applied system voltage of 45 kV peak, the initial arc power wave initially peaks at 30 MW.

23.5 Conclusions

The Author concluded that:

The recorded fault parameters are sufficiently close to the 'empirical relationship for metal lost by arc erosion to have confidence that:

- The volumes of the metal lost have a logical dependence on the magnitude of fault current and duration.
- The two cumulative faults in the Remuera K10 transition joint injected sufficient energy into the lost metal, assuming it to be an isolated bulk volume, to raise its temperature to approximately 6,000°C allowing for 100% energy conversion, to 3,000 °C allowing for complete cooling between the fault times and to 1,500 °C for an arbitrary 50% energy conversion. The latter is three times greater than the ignition temperatures, Table 7, of the surrounding hydrocarbon materials within the transition joint.

24 Appendix H: Cable Fires, Cable Fire Performance

A review is given with reference to selected publications and to the Author's knowledge of in-service fires and of fire performance testing. The items are given in ascending date order. The review is divided into the following subsections:

- 24.1: Cable fires and fire performance.
- 24.2: Type test standards for cable fire performance.

References are made to design and test standards and recommendations; if Readers wish to make use of these documents they are advised to obtain current issues.

24.1 Cable Fires, Fire Performance and History.

'Development of Power Cables⁴', PV Hunter and J Temple Hazell, 1956.

The text book records that fires of in-air cable installations have occurred since the very first 10 kV AC cable in c1885-89. These cables were installed as part of the 7 mile long Deptford to Grosvenor Gallery feeder in London, laid along the railway embankment, were ignited by sparks from steam locomotives⁴. These early flexible cables were insulated with impregnated jute and covered with a natural fibre serving, which was flammable. Ferranti greatly improved the fire resistance by designing a single phase concentric conductor/earth-return cable self-contained inside its own rigid iron pipe 'sheath' (1885 patent). The cable was insulated with wax impregnated paper, which could only sustain combustion if the iron pipe was ruptured and air entered. The cable was installed in air along the railway embankment and later buried. This was the world's first viable HV 10 kV AC power cable. The cable operated successfully until the circuit was superseded in 1933.

Cables and Fire Hazards, CIRED 1974

The paper²⁶ was presented in Italian at the CIRED meeting in London. The paper describes that the 'CESI' fire propagation test rig was developed following a serious fire in the La Spezia Station, where flame spread was the predominant cause of the destruction of the control panel and the electronic computer. The CESI test rig was designed to compare flame propagation properties under similar conditions of flame propagation in the vertical passages between levels that contained thick bundles of PVC cables, in which rapid propagation of approximately 10 m/minute can occur.

The test results showed that PVC insulated and sheathed cables of different constructions installed in bundles containing 10kg/m of combustible material gave different flame spread distances:

- a. Standard PVC insulated and sheathed cable: 1.45 m
- b. Standard PVC steel wire armoured: 0.7 m.
- c. PVC with a special additive: 0.8 m.

The measurement of Oxygen Index was found to be suitable to confirm reproducible manufacturing quality control results of the fire performance PVC compound. The CESI test rig was suitable to validate the flame propagation performance of the cable construction.

Additionally it was stated that a serious fire had broken out in a US subway system. This would be addressed by the development of a 'smokeless' cable, which would shortly begin.

'Cable Fires in Power Stations'²⁷, 1977

In the IEE Electronics and Power article the CEGB authors describe three power station fires:

- La Spezia Power Station Italy in 1967, in which fire was initiated in a cable termination chamber below MV circuit breaker, which caused PVC cables to catch fire and propagate throughout the electrical annex. The smoke caused the evacuation of the Power Station within 2 minutes. This resulted in complete destruction of the electrical auxiliary equipment including the computer and control room. A photograph shows the collapse of cable trays and major loss of flammable materials by combustion. The remedial works delayed resumption of generation for 9 months. *[Author: 1967 is the key date that alerted the world to the risk of PVC cable fires and which commenced the development of fire retardant and 'low smoke and fume' oversheath grades. The first cables in the Penrose trench were installed in 1966 some five to ten years before such information became available].*
- Methil Power Station Scotland, sometime late 1960's to early 1970's in which an oil leak from a turbine gauge-board caught fire. The fire spread to PVC cables and propagated cable. A photograph shows a large volume of black smoke emerging from the power station, which forced it to be evacuated within 4 minutes of the outbreak. The power station did not return to generation for nine months.
- Brown's Ferry Nuclear Power Station, US, in 1975, in which a candle flame during maintenance work set fire to polystyrene filled cable ducts

and to the cables in them. The fire propagated along the cables. The automatic reactor control was lost and this resulted in a manual trip of the reactor. The station was shut down and there was a considerable delay before it returned to service.

The article says that although it has been known for cable terminations to catch fire, fires started by internal faults in cables are rare. *[Author: joints are not mentioned. However joints and terminations are discontinuities in the system and fall into the same category of cable accessories.]*

The CEEB took the ENEL/CESI specification for fire retardant cable systems and undertook significant research, funding work to improving fire performance of cables, both PVC and polyethylene insulated and sheathed. It is reported that:

- Where the mass of PVC flammable material is < 1 kg/m, it is self-extinguishing. Where the mass is > 1 kg/m, once ignites and at a temperature of ~ 450 °C PVC cable propagates both vertically and horizontally.
- Flame propagation speeds of the order of 20m/min have been recorded. *[Author: 1.2 km/hour i.e. slow walking speed].*
- Before the PVC ignites starting between 150 and 275°C it emits vast quantities of black smoke containing quantities of hydrochloric acid. 10 kg/m of flammable PVC will, when burnt, produce 1,500 m³ of smoke.

The test adopted by ENEL and the CEEB consists in burning a section of cable 'installation' in a vertical position. A cable 'installation' is one in which cable are spaced at between 40 mm and touching. After 1 hour of burning, the damage must not exceed a predetermined distance; for the CEEB this was 1.5 m.

The article also describes:

- The review of existing fire precaution measures such as fire barriers and
- The successful development of fire retardant PVC cable.
- The ongoing development of low smoke and fume cable. At that time it was not clear than low smoke and fume cables could be developed to be economically viable.
- Fire detection sensing cables. It is noted that, from experience the risk is highest when cables are being installed.
- Firefighting. It is considered that the use of non-propagating cable sheaths and smoke control measures make it unnecessary to have the extreme urgency out of fighting cable fires by such measures as water spray equipment.

‘Modern Power Station Practice²⁸, Volume D’, first edition 1963, third edition 1992, Chapter 6, ‘Cabling’ and Sub-Chapter 8, ‘Cable Performance Under Fire Conditions’.

The book was produced by British Electricity International (BEI) with CEGB and industry authors. In Chapter 6 it is stated that until ‘serious fires occurred the late 1960’s PVC had been considered to be a fire retardant cable insulating and sheathing material.’

It is reported that research showed that if there were enough PVC sheathed cables to form a ‘critical mass’ they would burn and propagate fire (previously it had been considered that PVC cables were fire resistant as the base material in the PVC insulating and sheathing compounds had a high oxygen index i.e. they required more oxygen to sustain fire than is available in air).

It was discovered that it is the gasses that are given off by the PVC cable compound, which included additives such as plasticiser, which were highly flammable. Fire temperatures of 1,000°C had been recorded. The CEGB required the development of low propagation sheathing and insulating materials.

As a result, fire performance tests were developed in which a ‘critical mass’ of cable materials was to be subjected to test. The fire performance tests are the basis of the British Standard 4066 and IEC 332^{1,2} tests that are based on it. (Author: *The cable industry committed large resources to testing and development of materials*). It is described that the first fire performance PVC compounds contained a ‘filler’, which reduced the degree of fire propagation by reducing the volume of PVC. However, the filled PVC still emitted dense, corrosive smoke. At that time the CEGB required that all major cable routes in their power stations be enclosed and protected.

The BEI/CEGB book also describes in detail the London Transport Executives ‘3-metre cube test’ used to validate the low smoke and fume properties of fire performance cables for use in the London Underground system

In Sub-Chapter 10 it is stated that although cable components are the major source of combustible material, fires started by internal cable faults are very rare and that with correct design and installation ‘cable faults can be virtually eliminated’.

[The Author is in agreement that, in his 50 years of experience, serious in-air cable fires have been rare. In his opinion this is largely attributable to the inherent robustness of cable systems, to the high quality standards in design, manufacture, testing and installation, to conservatism in the magnitude of current loading applied in service operation and also to good fortune.]

The incidences of serious in-air cable fires have been low, but the impact of the consequence of fire has been high, e.g. in the wide extent of damage to the cable and to the structure/building, in circuit non-availability and in long repair time. In consequence it is normal for serious fires to be investigated.

Unfortunately the findings and lessons learnt from such investigations have not necessarily been clearly recorded in publications, or in Standards to benefit the wider electricity supply and cable industries. There is a need for an industry publication, such as produced by CIGRE]

Tsing Yi Island Kowloon Joint Chamber Fire, c.1973

The Author investigated a cable fire in which four 132 kV circuits of oil-filled cable in an in-air joint chamber containing stop joints had been severely damaged by fire. It was found that the fire had been initiated by the power arc that occurred when a stop joint had failed electrically following the parting of a welded conductor connection. The joint shell had been ruptured and leaking cable oil ignited. The oil spread fire in the chamber and ruptured both the lead sheaths of adjacent cables and lead oil feed pipes from oil reservoir tanks. The concrete walls of the chamber had been severely fire ablated and the steel reinforcing bars exposed.

The Cables Handbook⁹, first edition 1982, third edition 1997. Chapter 6, 'Cables in Fires - Materials and Design Considerations',

This book was produced by the cable company BICC. Dr Alan Friday was a co-author of this Chapter. Dr Friday recently led the Edif ERA team that was involved in the detailed analysis of the Penrose cables and materials from the Penrose trench. The author of Chapter 35, 'Transmission Cable Accessories and Jointing for Pressure-assisted and Polymeric Cables' is Brian Gregory, who is the author of this Penrose cable investigation report. BICC was one of the leading companies that developed cable sheathing materials having low fire propagation and low smoke and fume and performances.

It is recorded that in the 1960's and 1970's there were several fires involving cables at power stations, where the fire propagated along ducts and tunnels at high speeds of up to 10m/min.

Additives, such as antimony trioxide, were developed for inclusion in halogen containing compounds such as PVC and CSP to improve their flame retardancy. However, to comply with specification that set limits on the level of halogen gas emissions, non-halogen containing sheathing compounds were

developed based on EVA, polyethylene and other ethylene co-polymers. These base polymers are unsuitable for use in the unfilled state as they are readily flammable (low oxygen index). To achieve an appropriate level of fire retardancy it is necessary to incorporate high loadings (60-65%) of mineral fillers, the most commonly used being alumina trihydrate and magnesium hydroxide. These additives liberate water in the form of steam when heated to temperatures in excess of 200 and 300°C respectively. The steam dilutes the flammable gasses emitted by the base polymer and cools the surrounding area. The residue of the combustion produces a fire resistant char, which is thermally stable and incombustible. The mechanism of char formation is termed intumescence. These materials are referred to by acronyms such as LSF (low smoke and fume) and LFH (low fire hazard).

Early, heavily filled compounds suffered from a reduction in their physical and electrical strengths and water resistant properties, these being important requirements for cables that are to be partly installed in-air and partly laid-direct in wet ground. Significant development was committed to improve these properties for the present LSF cable and joint materials.

Cables with improved LSF materials were installed in the Channel Tunnel between the UK and France. In November 1996 a fire was initiated on a train in the tunnel and, although all the cables were destroyed at the fire location, the LSF cables did not propagate the fire along the tunnel.

The mechanism of intumescent, char forming fire retardancy is described. Intumescent materials do not impart resistance to fire ignition, but form a fire barrier once the appropriate temperature is reached. Organic additives were more generally considered at the time of the book in 1997. Three basic ingredients are required i) a carbon source, ii a dehydrating agent and iii a blowing agent. When added to a polymer layer it is possible to form an expanded char on exposure to flame. Inorganic additives are an alternative route and these form a hard thermally stable layer. Tapes and paints are available with intumescent properties and have been applied to some cable in-air installations.

The effect of cable design on fire performance is described. Some special low voltage cables are designed to have fire survivability i.e. to continue to operate for a limited time during and after a fire. *[Author: the cable components of interest to the Penrose fire investigation that increase fire resistance time are thick wall, tubular metallic layers that have high melting points, high thermal capacity and high thermal conductivity, for example:]*

- *Two layers of steel tape armour as used on an 11 kV three core PILC cable.*
- *A layer of steel wire armour, as used on a pilot cable.*
- *A thick walled aluminium sheath of the type used to contain the pressure in an oil-filled cable.*

A concentric earth return copper wire conductor of the type applied to some XLPE cables would not be expected to give appreciable fire resistance time as the area of copper is determined by the short circuit current requirement only. In consequence the wires are usually of small radial thickness and are spaced with gaps between them.]

‘Fire Protection Systems and Measures in Substations²⁹’, CIGRE paper 23-01, Section 3.2 ‘Cables’, 1984

CIGRE Working Group SC 23-04 analysed and published the replies to a worldwide questionnaire of utilities.

It is recorded that:

- Few utilities had installed cables having materials with special fire performance additives and these utilities had the objective of improving fire propagation performance.
- The number of utilities using improved fire performance cables had increased from six utilities in 1970-1975 to 11 utilities from 1975 to c.1980.

In addition to IEC standards seven national/utility fire performance requirements for cables were listed, including Australian Standard AS 2373.

Woodhead Tunnel Fire, c.1990

400 kV oil filled cable circuits were installed in the 4.8 km long ex-railway tunnel in the 1960's. In c.1990 a stop joint faulted and a cable oil fire occurred resulting in severe damage. In c.1996 a second fire occurred in the parallel tunnel in which the cable's oil reservoir tanks were located. These fire risk events were one of the reasons that National Grid selecting XLPE cable for installation in the 21 km long Elstree tunnel in London, which was commissioned in 2005.

Cable Fire Evaluation Tests at the Hackney Marsh Fire Test Site, 1990's

In the early 1990's the Author was involved in a CEGB sponsored evaluation test to assess the relative fire performance of replacement designs of 275 kV and 400 kV cables for installation in the air space below the road surface in existing road tunnels. A test enclosure was constructed to simulate a tunnel section. A tray of diesel fuel was positioned under the test cables to burn for a calibrated period (20 minutes) to simulate a vehicle collision on the roadway above the cable chamber

Different types of gas filled cables had previously been installed in some road tunnels and were under consideration for replacement. A 132 kV gas filled cable sample, having an aluminium pressure sheath and insulated with paper tapes pre-impregnated with petroleum jelly was tested. The cable was filled with Nitrogen gas at the normal operating pressure 14 bar. This cable type exhibited excellent fire performance as i) when the aluminium sheath ruptured, the escaping Nitrogen gas inhibited combustion by excluding air, ii) the charred paper tape insulation around the rupture in the aluminium sheath acted as an intumescent layer that inhibited internal fire spread and iii) the absence of liquid impregnant also minimised external fire spread. However, this type of gas filled cable was at that time becoming obsolescent and was not considered suitable for the larger conductor size 275 kV and 400 kV transmission cable applications due to higher dielectric losses and to gas leaks.

Oil filled, paper insulated cables with corrugated aluminium sheaths exhibited a good survivability performance for short fire exposure times as demonstrated by reduced tunnel temperatures and reduced fire propagation, this being attributed to the higher melting point and higher thermal capacity of the aluminium sheath. However, the aluminium sheath ruptured before the end of the test period and the cable oil, leaking under pressure and with feed capacity of the oil reservoir tank sustained and spread the fire such it emerged burning fiercely from the ends of the tunnel.

An oil filled cable was tested that had been impregnated with a specially developed high flash point silicone fluid. However, once the aluminium sheath had ruptured the hot silicone fluid was found to burn as fiercely as a standard oil filled cable and no advantage was apparent.

Conventional oil filled cables were then laid in a CBS (cement bound sand) filled concrete trough installed within the tunnel and the test completed satisfactorily without fire spread or harm to the cable. This installation method had previously been used by the CEGB for oil filled cables installed in the Wimbledon tunnel, Figure 130. The method was later used in the first installations of 132 kV XLPE cable in London Electricity's new cable tunnels. The method was eventually discontinued in favour of fire retardant cable sheaths as the method increased

the risk of damage to the cable during installation, occupied too much of the usable space in the tunnel and had a significant reduction on current rating. Two tests were performed on the then new design of 275 kV cable with extruded XLPE insulation, lead sheath and polymeric oversheath. In the first test the lead sheath melted, the cables ignited and fire propagated along the cables and emerged from the ends of the test tunnel and burnt fiercely. It was deduced that the location of the cables, the magnitude of the fire temperature and heat release from the burning cable were key parameters in fire performance. This was verified by a test in which the XLPE cable was positioned at a lower height in the tunnel with respect to the burning diesel oil. A significantly reduced fire propagation was demonstrated.



Figure 130 Wimbledon tunnel containing a cable trough

Cable Fire Evaluation Tests by BEWAG at IPH Test Centre Berlin, c.1995

Berlin Electricity (BEWAG) sponsored fire tests in preparation for two planned 380 kV cable tunnels. The Author was involved in technical discussions with BEWAG for the prospective manufacture and supply of 380 kV XLPE cables and was shown video footage results of fire evaluation tests. Sections of the tunnel had been assembled at the East Berlin IPH laboratory and the test cables (XLPE and oil-filled cables) were separately installed in different configurations. A conducting pin was driven through the cable in various orientations and a voltage applied to initiate the required fault current magnitude. It was observed that the XLPE cable was punctured and exhibited small flames local to the fault hole, but

did not propagate fire. In some instances burning molten polymer dripped off the cable demonstrating that it was unwise to locate cables in vertical alignment.

The oil filled cable did not always sustain fire, but when it did leaking and burning cable oil spread fire across the floor such that it was necessary to use a fire extinguisher. It was shown that the rotational orientation of the fault puncture hole had an effect on whether fire was sustained. Berlin Electricity selected XLPE insulated 380 kV cable and installed each single phase cable in a vertically sagged formation, with circuits positioned on the opposite sides of the tunnel.

FIPEC Report, 'Fire Performance of Electric Cables – New Test Methods and Measurement Techniques'¹², 2000

This is the final report of the European Commission SMT Programme Sponsored Research Project. The report compares different fire test methods and analyses many fire propagation and smoke emission test results on different size and configurations of cables. The tests were based on the existing IEC vertical test rigs and methods. The report recommends how the test procedures and in particular the measurements can be analysed to derive more information on fire propagation and smoke/fume emission.

'The 2001 Kista Blackout: Corporate Crisis and Urban Contingency'³⁰, 2001

The 2003 book describes the crisis actions that were taken to restore power after a major cable fire in Kista tunnel under Stockholm. It is described that incidents of cable fire had occurred three times in seven years. The 2001 fire incident was the only one in which 110 kV XLPE cables were damaged.

Four racks of power cables were located against one wall of a shared utility tunnel that had been cut out of bedrock. In the 2001 fire incident a phase to ground fault occurred in one of the 11 kV cables and initiated the fire; the cable type is not described. In consequence of the fire all cables at the incident site had to be replaced. The 11 kV cables were located on the top rack. The second rack down contained three 33 kV circuits each in trefoil formation. The third rack down contained one 110 kV cable circuit in trefoil formation. The fourth rack down contained two 110 kV cable circuits in trefoil formation. The 33kV to 110 kV cables are interpreted to have been XLPE insulated.

Cable Systems in Multi-purpose or Shared Structures³¹, CIGRE, 2010

An instigation for the 2010 CIGRE Technical Brochure 403 was to compile the factors and world-wide experience to assist the reader in considering the use of

existing structures such as bridges and tunnels for part of a cable route. A cable circuit in principle could share a structure with major transportation infrastructure with other utilities' services such as gas and water pipes, or with different electricity and telecommunication utilities, for example distribution and transmission cable circuits. Chapter 8, lists examples of 'Multi-purpose or shared structures' in nine countries, including Australia. The Technical Brochure shows the configuration of cables and shared services in the cross-section of the Kista tunnel, Stockholm. Fire related matters are listed in general in sections 3.1.5, 3.2.6, 3.2.7, 4.3, 5.1.2, 5.1.14, 6.4.1 and 6.8.2. *[Author: although headings for fire risk considerations are given, lessons learnt from specific experiences of cable thermo-mechanical disturbance and cable fire are not considered. CIGRE is presently initiating a Working Group to study the fire performance of cables].*

'HFFR' Materials with Improved Mechanical Characteristics for MV Cable Sheathing³² 2003

The paper was presented by authors from a cable manufacturer at the CIRED Barcelona conference in 2003.

HFFR is the acronym for a Halogen-free Flame Retardant compounds for use in cable sheathing and other applications such as flooring. It is described that PVC presents flame-resistant properties due to the existence of chlorine in its molecular structure. However, the cable plasticisers and heavy metals added to PVC sheathing compounds result in i) the loss of the fire resistance and ii) the increase in hazard when it is installed in a closed space. PVC is replaced in MV cables by polyolefin based sheathing compounds.

The paper gives the following speeds of flame propagation along a cable run:

- 200°C horizontal route: 5cm/min.
- 350°C horizontal route: 1.1m/min.
- 250°C vertical route: > 1.3 m/min and is 'almost instantaneous'.

It is described that MV cables with standard, non-fire resistant polyolefin sheaths do not comply with any level of fire resistance. Consequently in the event of a source of fire igniting the material there may be a violent spreading of the flame both along the cable itself and through the drops of melted and ignited material that fall from the area affected by the initial fire.

Curves of the comparative HRR (heat release rate) with heating time of materials put into a cone calorimeter showed that:

- A standard, unfilled, PE material peaked at a HRR of 1,300 kW/m².
- PVC peaks at 200 kW/m². *(Author: it is taken that this is without plasticiser).*

- Two different fire retardant filled polyolefin sheathing compounds peaked at 400 and 200 kW/m².

It is concluded that:

- Only in those cases in which it is highly unlikely that the cables will be affected by fire is it advisable to use non-fire retardant polyolefins. In all other cases it is preferable to use fire retardant compounds.
- It is important to adjust the level of flame retardancy to the minimum necessary in accordance with the type of installation for which the cable is intended, thus optimising the cost and the mechanical characteristics of the compound.

'Fire Prevention Method for 275 kV Oil-Filled Cable in Tepco³³', 2007

The Jicable 2007 TEPCO (Tokyo Electric Power Company) authored paper describes the development of means of limiting fire damage should one of their existing oil filled cable tunnel circuits fault. The consequence of fire is illustrated by a photograph of a short-circuit test in which the cable oil ignited and spread fire.

The paper describes and shows a test set-up comprising the following protective measures:

- i) FRP (fibre reinforced plastic) troughs of fire retardant material with a tightly fitting, rigid U shaped base and similar lid that could be fitted around an existing cable circuit.
- ii) Aramid cloth of high strength and fire retardancy that is zipped together to form a tubular shroud around an existing joint. A pressure relief panel is incorporated into the shroud.

The objective is to contain the disruptive effect of the power arc, to restrict the supply of air and thus inhibit combustion and fire spread. The troughs were to be fitted around existing straight cable runs and aramid bags fitted around geometric discontinuities such as joints and cable bends, for example next to cable terminations. Short circuit testing had been performed to prove prototype designs. *[Author's note: i) FRP troughs have been described as being in use in Japanese tunnel installations for in excess of 15 years and ii) the development and testing of a similar high strength cloth bag has recently been reported by BBC News in which passenger luggage is stored within the bag in an aircraft hold. Explosive tests were performed in an aircraft fuselage, which demonstrated that the bag contained the disruptive effect of a simulated terrorist bomb hidden in the luggage. The shock waves produced by the rapid heating of a power arc are similar to those produced by an explosive.]*

'Fire Hazard of MV/HV Cables Installed in Tunnels³⁴', 2007

The Jicable 2007 paper describes comparative fire tests performed on XLPE insulated cables having standard non-fire performance PE oversheaths and on low fire propagation performance oversheaths. The cable samples were installed horizontally in the FIPEC horizontal test rig set, which had been arranged to simulate cable fire performance in the configuration in which the majority of cable length is installed in a tunnel application. In comparison it is noted that type test Standards validate the performance of non-fire propagating oversheath materials in a vertical test rig, which simulates a cable shaft or cable riser.

The FIPEC experimental set up was modified. In the first test three samples of single core EHV cables, with non-fire performance oversheaths, 4 m long, were installed on horizontal trays with the phase cables one above the other in vertical alignment. This is similar to the arrangement in a vertically sagged tunnel installation on a vertical wall.

The test followed the FIPEC/IEC protocol in which there are three experimental fire steps:

i) In the first step a heat source from a gas burner of 40 kW is applied for 5 minutes. If the flame spread is > 2m along the cable, or the heat release rate from the burning cables is >190kW, the test is terminated.

The non-fire performance EHV cable withstood this step.

ii) In the second step the heat output is increased to 100 kW and held for 10 minutes. The test is stopped if the fire spread is > 2m and the heat release rate is >250 kW.

The non-fire performance EHV cable did not withstand this test. For the EHV, PE oversheathed, XLPE cables it was found that within 4 minutes the heat output rose to the high level of 1,600 kW and the fire propagated along a 3.5 m length. In comparison it was described that in standard vertical fire propagation tests large cables are difficult to ignite. It was interpreted that the larger diameter of the cables and their horizontal alignment, one above the other, produced an enhanced thermal interaction by both heat transfer and by drips of burning PE. This acceleration of the fire did not occur when smaller diameter MV cables were placed horizontally on cable trays at the same spacing.

The three smaller diameter cable samples that had special fire performance oversheaths survived the first, second and third test step, the latter comprising a 300 kW burner output for 10 minutes. Their heat release rate and smoke release rates were very much less than the standard cables that had HDPE and

LLDPE oversheaths. At the end of the test the flame had propagated beyond the 2 m length to 2.6-3.2 m, however the following improved performance was demonstrated by the fire performance oversheathed cables:

- i) Propagation had occurred at a lower speed. The fire performance sheaths survived for the total test duration of 25 minutes, whereas on the EHV cable with non-fire performance material the test was terminated after ~8 minutes.
- ii) The samples had withstood a much higher burner output (300 kW) without exhibiting a high heat release rate.

In summary an EHV cable without a fire retardant oversheath installed in a representative horizontal tunnel configuration exhibited a dramatic fire growth rate and a high heat release. It was concluded that in a real tunnel installation fire fighter access would have been impossible and the fire would have completely consumed the installed cables. Conversely it was demonstrated that fire performance oversheaths exhibited significantly improved fire retardancy as evinced by a reduced flame propagation rate, reduced fire severity (reduced heat release rate) and increased fire survival time.

**'Fire Accidents of the Power Cable Line in Tunnel and Preventative Methods'³⁵ 2009 and
'Fire Accident of High Voltage Cable Lines in Tunnel'³⁶,**

The IEEE 2009 paper and CIGRE presentation describe two incidents of serious cable fires that occurred in cable tunnels in North China in April 2009 and December 2009.

The April 2009 fire destroyed six circuits of single core 220 kV XLPE cable, three circuits of single core 66 kV cable and a fibre optic communication cable.

A joint faulted in a 220 kV XLPE cable circuit with a fault current of 19,390 A. After 60 ms the line breaker tripped and disconnected the circuit. After 1.16s the line breaker reclosed onto the faulted circuit and a fault current of 17,760 A was recorded. It was deduced that bonding lead insulation had been ignited by the passage of a 22,580 A fault current and this in turn had set light to the adjacent 220 kV XLPE cable. One of the 66 kV XLPE cables installed above the 220 kV cable then faulted.

The fire in the tunnel was described as being 'ferocious'. Photographs show flames emerging through ventilation grills into the street above. The conductors of the 66 kV XLPE cables were melted. The temperatures were in excess of the melting points of the metals i.e. 800°C for aluminium and 1083 °C for copper.

The corrugated aluminium sheaths were melted. The concrete was burnt off the walls and ceiling to expose the reinforcing bars.

In the December 2009 incident a fire occurred in an in-air cable trench. Flames are shown to be emerging through ventilation grills into the street above. The fire destroyed 17 m lengths of: two circuits of 110 kV XLPE cable, 7 routes of 15 kV XLPE cable and many routes of signal lines.

In the second incident (or possibly a third incident) the cause of the fire is described to be a faulted 15 kV XLPE joint, which is shown in a photograph.

An analysis had been performed on data collected from 'many fire accidents', which showed that the cause of the fires had been joint faults, or 'other external reasons'.

It was concluded from the investigation that:

- i) The most effective method of fire detection is the on-line detection of the temperature rise of the cable sheath using DTS (distributed temperature sensing by optical fibre cable).
- ii) Early fire warning is the best 'fireproofing' method.
- iii) 'Fireproof methods' for use in a tunnel or trench would be 'air proof block' (fire wall), 'fireproof slot-box' and fire retardant cable sheaths.
- iv) Not to reclose onto a fault.

Dartford Creek Bridge Fire, July 2009

British Power International Ltd submitted to the regulator, Ofgem, a report entitled 'Exceptional Events Report – EDF Energy – Fire Damage to 132 kV and Pilot Cables at Dartford Creek Cable Bridge on 20th July 2009³⁷'.

The report describes that a cable fire had occurred on a cable bridge which carried four in-air, 132 kV oil-filled cable outfeeds from EDFE's Littlebrook Grid Substation to feed Dartford Grid Substation's 11 kV and 33 kV busbars. Two feeders were of 132 kV three core oil-filled design and two were 132 kV single core oil-filled design. The bridge had been commissioned in 1958/59.

All of the feeders tripped within a period of 48 minutes. Supplies were disrupted to 94,600 customers. The fire was attributed to external causes e.g. vandalism or attempted theft as evinced by a number of hand tools were found on site. It was concluded that damage to the cable had resulted from persons unknown setting light to inflammable material at the base of the vertical cableway. An account of the deduced spread of fire between the cables was given.

‘Assessment of the Reaction to Fire Performance of Electric Cables under the EU Construction Products Directive³⁸, 2011

This paper was authored by T Journeaux on behalf of the cable trade organisation Europacable. The author is an expert of standing, who has worked for Prysmian (formerly Pirelli) on the development of fire performance cables and fire testing.

The paper described that a new test method had been developed in consequence of the EU (European Union) introducing classes for reaction to fire performance of cables. The apparatus was developed and CENELEC TC 20 committee issued European Norm EN50399, 2011, which is based on:

- The apparatus of IEC (EN) 60332-3-10.
- The addition of an exhaust duct equipped to measure heat release rate (HRR) and smoke production rate (SPR).

In order to facilitate CE Marking of cables for their reaction to fire performance European Cable manufactures working through Europacable funded a large project named CEMAC II. Part of the project work was divided between Europacable and RTD group led by SP Technical Research Institute, Sweden.

The development work included ‘round-robin’ testing at different laboratories on samples of the same cable; the results are shown graphically in the report.

Test results in all families showed:

- A strong dependence of reaction to fire performance on ‘cable size’.
 - For cables that were not completely combusted, larger cables performed better than smaller cables.
 - For cables that were not completely combusted, the performance was more related to the actual amount of combustible material in the cable test sample.
- Clear differences were observed between cables i) that had not been developed to have fire performance and those ii) that had been developed to have a higher declared performance, based on the IEC standards.

UK Power Networks Ltd Abstracts issued 7th March 2014 to the regulator, Ofgem, "Asset Stewardship Report" entitled "Document 16 Asset Category - Cable Pits, EPN".

The report included the following topics:

- Incidences of:
 - Disruptive displacement of cable pit covers and adjacent ground surfaces.
 - Fire in air filled cable pits.
 - Disruption by power arcs.
 - Disruption by the electrical failure of joints (and cables).
- Types, numbers and ranking of defects found in joints during:
 - Visual inspection of pits.
 - Partial discharge testing.
- Mitigating measures:
 - Replacement of joints.
 - Filling joint shells with resin.
 - Filling cable pits with sand.

It is recorded that:

- Out of a cable pit population of 3,500 population in a 2 year period 29 disruptive failures had occurred in the EPN region (i.e. pit lids had been violently displaced). *[Author this appears to be a rate of 0.85%]*. 4 members of the public had been seriously injured. The total pit population is 52,801.
- In the EPN region 3,500 cable pits were examined and risk assessed:
 - Very high risk pits: 149 (4%)
 - High risk pits: 228 (7%)
 - Medium risk pits: 2,685 (76%)
 - Low risk pits: 438 (13%)

CIGRE Working Group B1-51, 'Fire Issues for Insulated Cable Installed In Air'

A working group for this new subject were approved in February 2015 by the CIGRE Technical Committee. The scheduled date for the final report is to 2017. The scope of work is comprehensive and applies to both distribution and to transmission cable applications. It is proposed to i) concentrate on cables and ii) prepare general rules for joints.

Some of the considerations for the formation of the working group were:

- There is a concern for the fire safety of cables, particularly those installed where it is not practical for fire protection services to give a rapid response. In such situations separate external fire protection measures are available, but can impact on cost. There is a prospective benefit in establishing if more suitable cable designs could provide an adequate self-contained level of fire protection.
- Significant IEC standardisation work on cable fire behaviour has been implemented, but is more applicable to lower voltage, smaller diameter cables. Recent developments of new cable designs and power cable system requirements in terms of flame retardant properties are not yet covered in detail; for these reasons it may sometimes be difficult to apply existing standards to some of the newer transmission and distribution cable designs.

Kingsway Fire London, April 2015

In a news release UKPNL (UK Power Networks Ltd) reported that a fire had broken out in an underground utilities tunnel in Kingsway, London, on the afternoon of April 1, 2015 and that 3,100 customers were affected.

The fire was widely reported in the UK by press, television and internet contributions. Figure 131 shows the area affected by the blackout on the night of 1st April.



Figure 131 Area of Kingsway London affected by blackout

UKPNL reported that:

- The fire had occurred in a shared utility tunnel that contained distribution cables and a gas main.
- The damage was extensive.
- It was the biggest emergency cable replacement project that they had experienced to date, and involved the laying of 13.3km of new cabling

After power was restored to customers UKPNL (electricity) and NG (gas) began an investigation, which is understood to be still in progress.

24.2 Type Test Standards for Cable Fire Performance

IEC 60332, 'Tests on Electric and Optical Fibre Cables under Fire-Conditions'.

IEC 60332 comprises a comprehensive suite of Type Test standards having different Parts, which are divided into different categories, for example IEC 60332-3-22, Edition 1.1 2009-02. Part 3-22 describes the type test requirements on vertically-mounted bunched wires or cables in Category A. IEC 60332 is intended to validate whether a presented test sample from a named manufacturer, having a declared cable construction, containing a named fire performance combustible material and tested in a given test installation configuration meets a 'flame spread performance' requirement. The latter requirement is commonly loosely referred to as a fire retardancy performance or a fire propagation performance. The particular IEC Standard, Part and Category recommends a numerical performance requirement in which the extent of the charred portion towards the upper end of the sample shall not have exceeded a given height.

It is described that 'flame spread' along a vertical bunch of cable samples is a multi-variable phenomenon and so cannot be expected to exhibit the same performance as the test results on a single cable. Thus different Parts are provided for single and bunched cables.

IEC 60332 Parts 1 and 2 specify type test methods for a single cable in a vertical orientation.

IEC 60332 Part 3 specifies type test methods where a number of cables are bunched together to form a test sample installation. The test categories are separated into the following parts:

- Part 3-10: Test apparatus description and dimensions.
- Part 3-21: Category 'A F/R', is intended for special cable designs used in particular installations, for example large diameter single core cables in a grouped formation.
- Part 3-22: Categories A, B, C and D are for general use where different non-metallic volumes are applicable.

IEC 60332 advises that with regard to the cable application:

- The test Categories are not necessarily related to different safety levels in actual cable installations.
- The actual installed configuration of the cables may be a major determinant in the level of flame spread occurring in an actual fire.

The test Categories 'A F/R' and A to D are distinguished by:

- The given test duration.
- The volume of non-metallic material of the test sample.
- The method of mounting the sample for the test.

In all categories:

- Cables having at least one conductor of cross-sectional area greater than 35 mm² are tested in a spaced configuration.
- Cables of conductor cross-sectional area of 35 mm² or less and optical cables are tested in a touching configuration.

AS/NZS 4507:2006, 'Cables-Classification of Characteristics when Exposed to Fire'

The Standard specifies the performance requirements of cables when exposed to fire with respect to specific characteristics and allocates a classification. The standard classifies the following characteristics:

- Reduced flame propagation (RFP): recommends numerical performance requirements for both tests on single cables and on groups of cables in which the extent of the charred portion of the sample shall not have exceeded a given height.
- Reduced hazardous effects (RHE): cables in addition complying with RFP requirements shall be tested in accordance with i) AS/NZS 1660.5.2 for smoke density and achieve a given requirement of minimum light transmittance and ii) AS/NZS 1660.5.4 for acid and corrosive gas emission and achieve and each component shall achieve a given requirement for pH and Conductivity.

- Cable circuit integrity (CI): when tested with AS/NZS 1660.5.5 for fire alone at a flame temperature of at least 750°C, no fuse shall fail nor circuit-breaker be interrupted and the lamp shall not be extinguished.

AS/NZS 1660.5.1.2005, 'Test Methods for Electric Cables, Cords and Conductors', Method 51: Fire Tests –Test for Vertical Flame Spread of Vertically- Mounted Bunched Wires or Cables'

It is stated that this standard adopts the content of IEC 60332-3, all parts and while this standard is technically equivalent to the IEC Standards, it has been structured to include all six parts of IEC 60332-3 in one Australian/New Zealand Standard. This has been necessary due to the fact that AS/NZS 1660.5.1 is referenced as such a number of other Standards.

AS/NZS 1660.5.6.2005, 'Fire Tests-Test for Vertical Flame Propagation for a Single Insulated Wire or Cable'

It is stated that this standard adopts the content of IEC 60332-1, Part 1 and while this standard is technically equivalent to the IEC Standards, it has been structured to include all three parts of IEC 60332-3 in one Australian/New Zealand Standard.

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