CCI ***Cable Consulting International Ltd***
PO Box 1, Sevenoaks TN14 7EN
United Kingdom

ER 763
3rd November 2015

TITLE:	**Investigation into a Fire in a Cable Trench in Penrose Substation**
REPORT:	**ER 763**
CUSTOMER:	**Vector Ltd and Transpower New Zealand Ltd**
AUTHOR:	***Eur Ing* Brian Gregory *BSc, CEng, MIEEE, FIET***
DATE:	**3rd November 2015**

Distribution: Vector Ltd and Transpower New Zealand Ltd

Cable Consulting International Ltd
Registered in England and Wales No. 4234974
Registered office: 74 College Road, Maidstone, Kent, ME15 6SL, United Kingdom

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

The CCI 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, UK. Further analysis and interpretation of results has been performed at the CCI offices in Underriver, Kent. The CCI Author has been afforded full access to the cables and the cable trench, and 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 (paper insulated lead covered) cable to XLPE (cross-linked polyethylene) cable 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 CCI 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 (oil-filled) cables did not contribute until the end when aluminium sheaths ruptured and significantly increased fire severity. Each cable type was flammable and, without means to detect and extinguish the fire, 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. 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, 11 kV 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. Drying out of the impregnating compound from within the paper core of the PILC cable inside 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 in cast iron shells 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 firefighting. All of the cable failure incidents had occurred by 3:04:59, which was before the Fire Service was admitted to the Penrose Switchyard and commenced applying foam at approximately 3:32 am.

8. The fire performance of the three cables types is described:
   a. The polyethylene sheathed, wire screened, 33 kV XLPE insulated 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 OF 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 melting points of the extruded aluminium sheaths, high thermal capacity and the exclusion of oxygen from the insulation. The downside of OF cable fire performance is that if the aluminium sheath ruptures the flammable impregnating oil can spread fire to other circuits.
   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 melting point and high thermal capacity), the good high temperature performance of the paper insulation, its low insulation design stress and the exclusion of oxygen from inside the lead sheath. The downside of PILC cable fire performance is that the lead sheath melts at a relatively low temperature compared with aluminium 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 its spread to the XLPE cables.

10. A detailed examination of the undamaged 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 remaining 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 design temperature limits 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 design temperature limits 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 CCI 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 an oversheath having low fire propagation and low smoke zero halogen properties.
    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 on a failed circuit containing cables in air without taking precautions to manage the risk of fire ignition and propagation.

8. The transition joint design and jointing process be made more consistent with respect to a) the water seals and b) the void-filling compound.

9. Alternative and improved 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.

Contents

Figures

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 CCI 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 CCI 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 CCI 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 CCI 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 CCI investigation, including the inspection and examination of the cables and joints at Penrose and in the United Kingdom, and the CCI Author's conclusions based on the analysis and interpretation of the results.

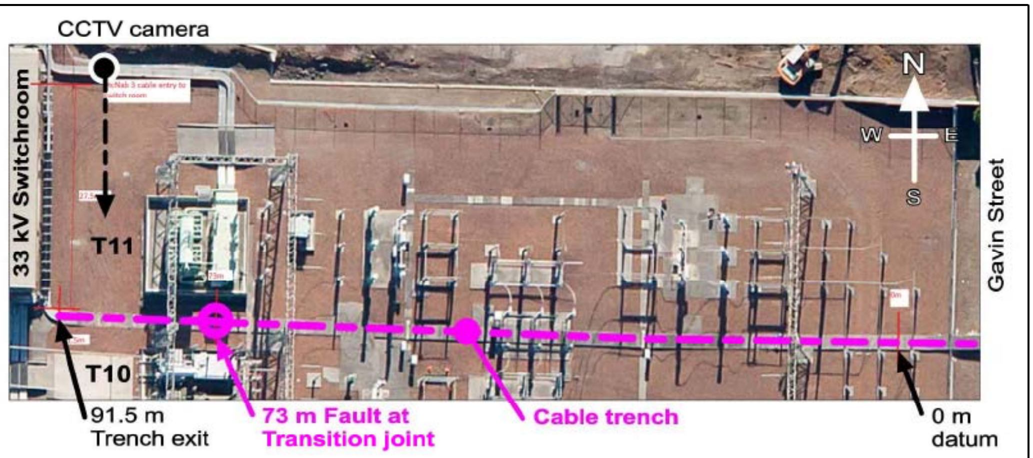


Figure 1 Overall plan view of the cable trench in the Penrose switchyard

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. This was close to the position at which the cable circuits had been judged to be clear of fire damage and where they were cut and jointed onto new diverted cables as part of the immediate remedial works. The zero position is 13.5 m from where the cable emerges from the laid-direct section at Gavin Street.

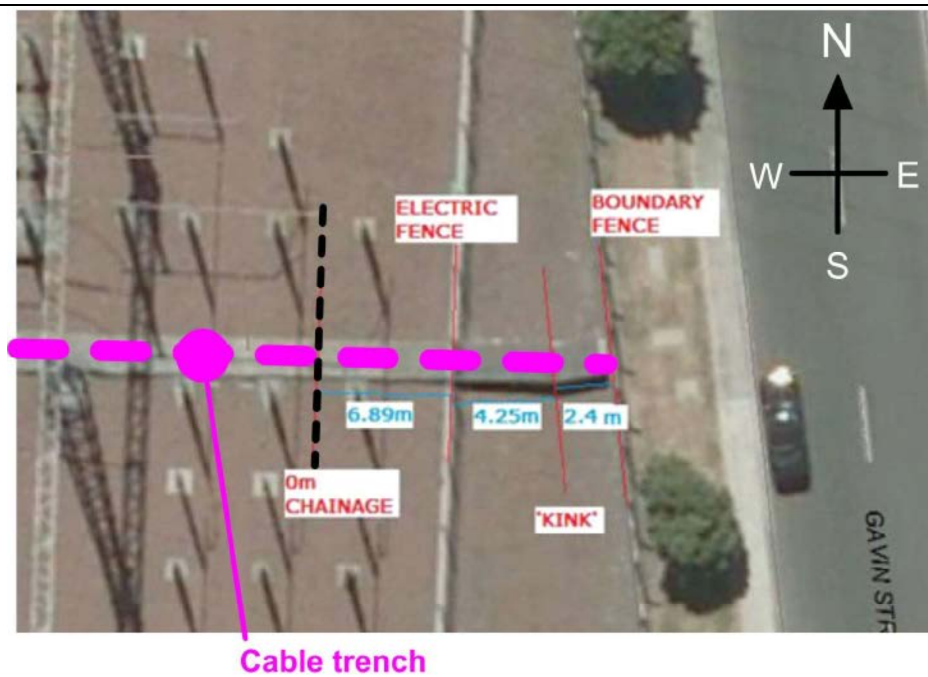


Figure 2 Zero metre chainage at east end of cable trench near Gavin Street

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. A CCTV camera was present in the northwest corner as shown in Figure 1 that looks southwards over this area. Figure 58 in Section 16, Appendix A, shows the CCTV photographs that were recorded before, during and after the fire.

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's western 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.

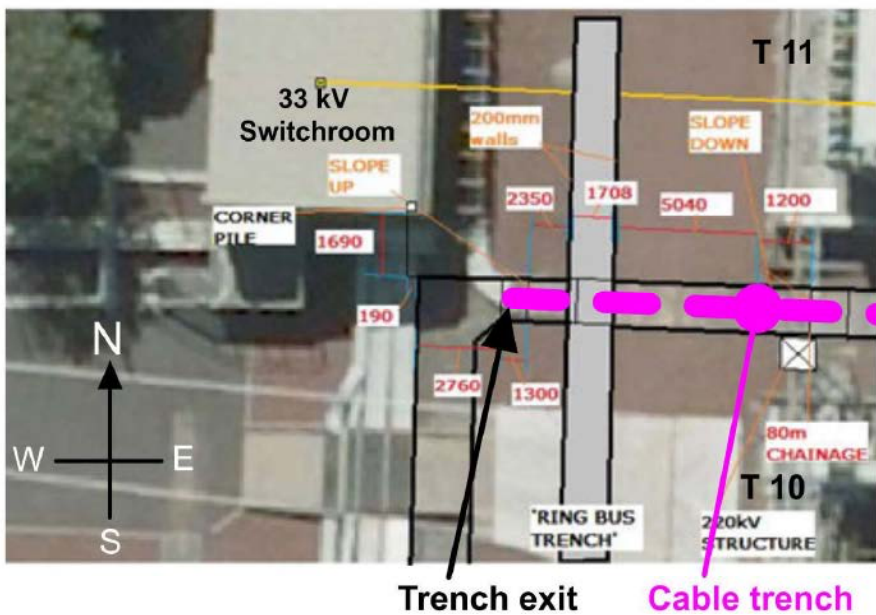


Figure 3 Location of the west end exit of the cable trench within the Penrose Substation near the 33 kV Switchroom (top left)

A larger concrete 220 kV Ring Bus trench seen in Figure 3 passes 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; the view is looking westwards.

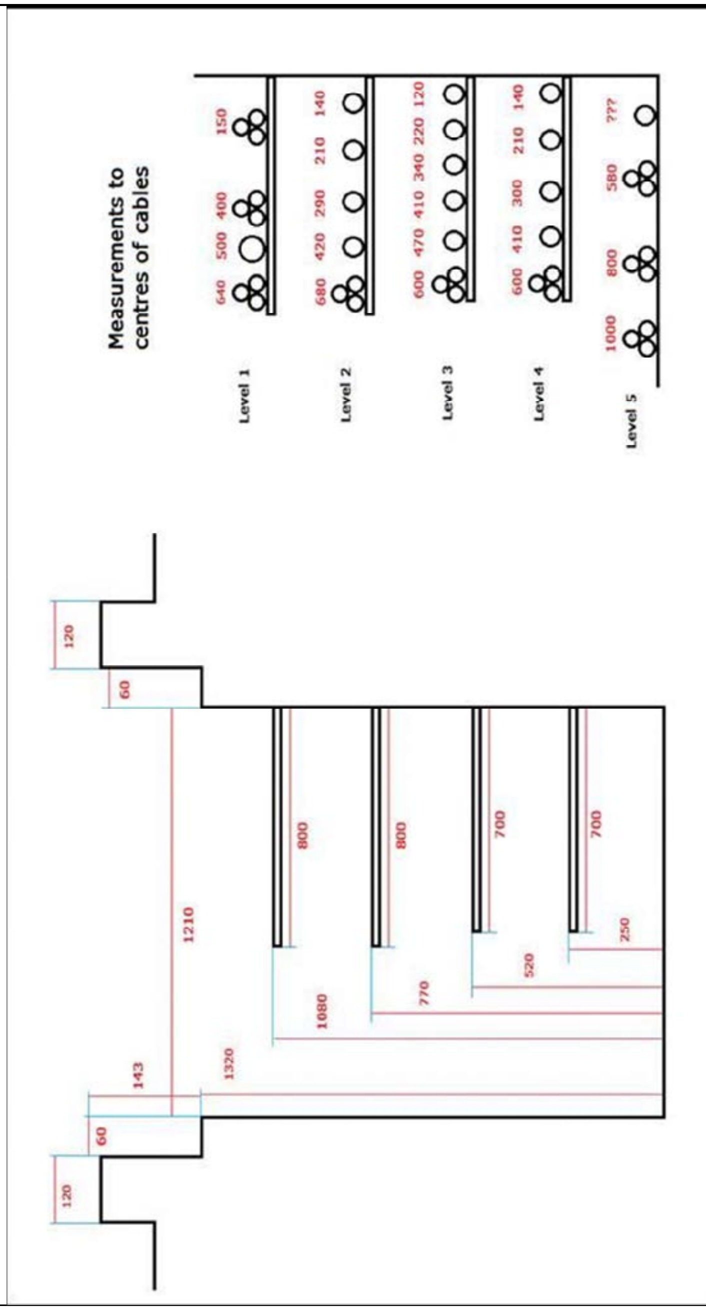


Figure 4 Trench dimensions and cable centre-line spacings at 65 m

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 Northpower to lift and remove the slabs during the investigation.

Inside the trench a small access-way is present of height 1,320 mm and width 410 mm 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 were cleated to every second support arm on Levels I, 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 were not cleated.

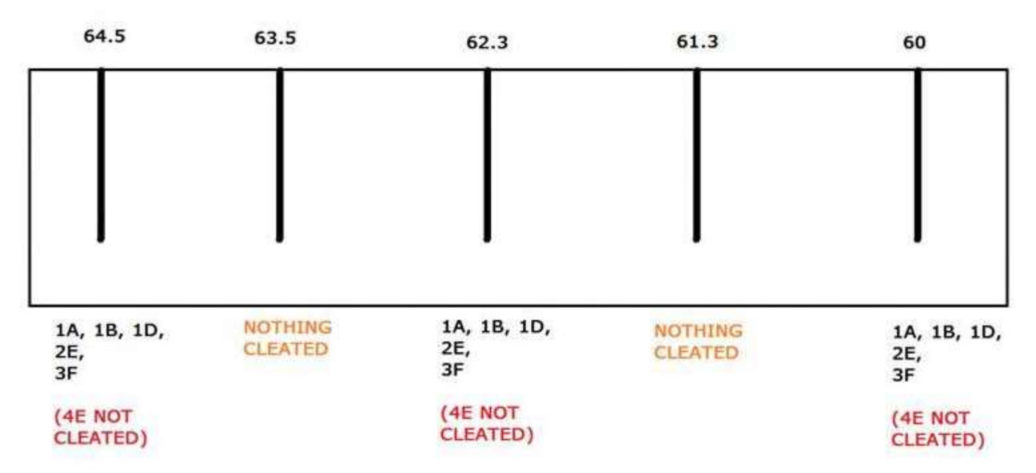


Figure 5 Support arm spacings of trench between 60 m to 64.5 m (plan view)

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. The cross-section designation relates to the support arm level that the cable occupies for the majority of its position in the trench length.

For example, '3A0' at 73 -74 m chainage is the designation for the position of an 11 kV PILC cable. 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 cable on the support arm adjacent to the north wall of the trench.
3. Third symbol:
    3.1. ‘0’, indicates the circuit comprises one self-contained, three core cable type (i.e. in the case of the PILC 11 kV and OF 22 kV and 33 kV cables the three power core phases are contained within one metallic sheath and in the case of the 11 kV XLPE cable the three cores are contained within one PE/PVC oversheath).
    3.2. ‘X, Y or Z’, indicates that the cable is a single core XLPE cable and is part of a trefoil group that forms one circuit, each cable rotational position, if known, would have been designated X (12 °/c), Y (4 °/c), or Z (8 °/c) looking westwards along the trench, as shown in the central inset diagram in Figure 6. All of the single cores cables were 33 kV XLPE.
    3.3. ‘-‘, a hyphen indicates that the cable is a single core XLPE cable and is part of a trefoil group that forms one circuit, but that the particular rotational location of the cable, X, Y or Z, could not be determined.
    3.4. ‘No symbol’, indicates that the cable is a pilot cable.

For example, the position ‘1DY’, is located on the first support arm and is the fourth cable group from the north wall. It is one single core cable in a trefoil cable circuit. It is a ‘Y’ position cable, which indicates that, looking westwards along the trench, it is at the 4 °/c orientation in its trefoil group.

Figure 6 also shows the correlation between the circuit names, their location on the support arms, the type of cable and the identification numbers of the cable samples (PN numbers). The type of cable is designated within the circular cross-sectional symbol for each cable by the following abbreviations:

X: XLPE insulated, single core cables, having copper wire return conductors and a composite polymeric oversheath (extruded PVC inner layer and extruded PE outer layer). Note:
- The X abbreviation for XLPE insulation should not be confused with the ‘XYZ’ rotational position designation as shown in Figure 6.
- The 11 kV three core Tunnel Auxiliary Supply cable also has extruded XLPE insulation and so has been given the X abbreviation.

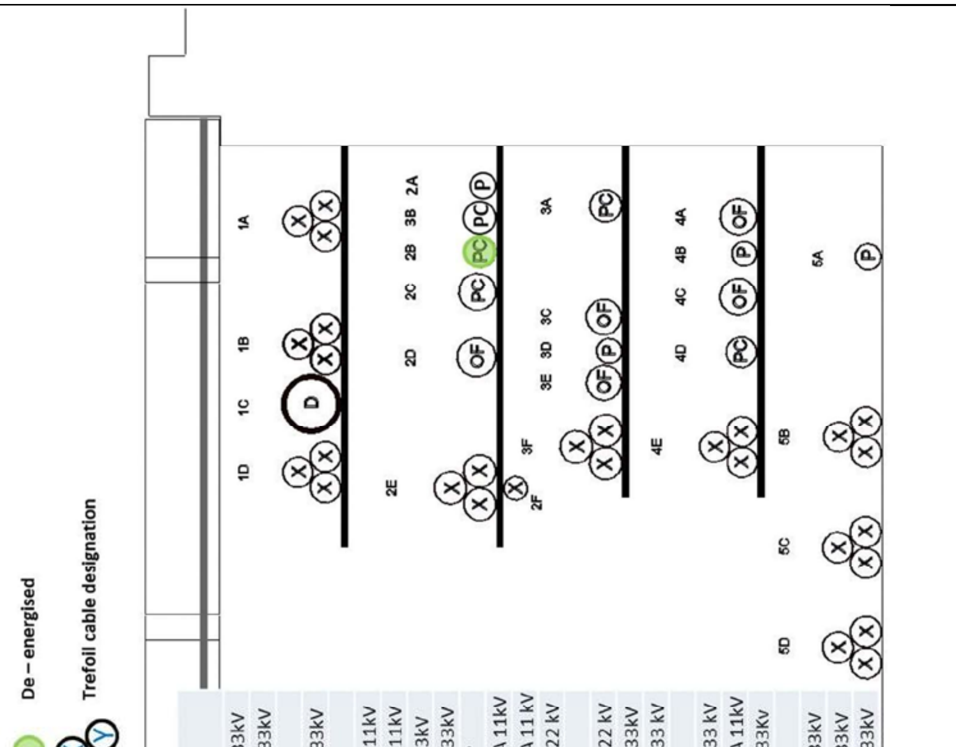
OF: Oil-filled, three-core, self-contained, oil impregnated paper tape insulation, extruded corrugated aluminium sheath and extruded PVC oversheath.

PC: PILC (paper insulated, lead covered), three core cable, having mass impregnated compound paper tape insulation, extruded lead sheath, an armour layer of two steel tapes and an anti-corrosion serving comprising bituminous compound impregnated woven hessian tapes.

P: Pilot cable containing multicore twisted pairs each comprising a copper wire covered with extruded polymeric insulation, a steel wire armour layer and an extruded PVC oversheath.

D: Duct of extruded PVC containing optical fibre data cables.

- **X**: XLPE Insulation with PE Serving (power cable)
- **OF**: Oil Filled Paper Insulation with PVC Serving (power cable)
- **PC**: PILC with Steel Tape Armour, Hessian served (power cable)
- **P**: Pilot Cable, PVC served
- **D**: Duct, PVC, Data Cables



Cable Position	PN	Circuit Name	Cable Description
1A	8/9/10	Remuera No 3	3 x 1c 400mm² Al XLPE 33kV
1B	4/5/6/7	Newmarket No 3	3 x 1c 400mm² AL XLPE 33kV
1C	-	Duct (Communication Cables)	-
1D	1/2/3	Remuera No 2	3 x 1c 400mm² AL XLPE 33kV
2A	17	Carbine	25c 9+16 pilot
2B	14	Not in use	3c 300mm² AL PILC STA 11kV
2C	15	McNab K19	3c 300mm² AL PILC STA 11kV
2D	16	Carbine No 1	3c 300mm² AL OF PVC 33kV
2E	19/20/21	Carbine No 2	3 x 1c 630mm² Cu XLPE 33kV
2F	18	CBD Tunnel Aux	3c 35mm² AL XLPE 11kV
3A	22	McNab K02	3c 0.25 sq in Cu PILC STA 11kV
3B	23	Remuera K10	3c 0.25 sq in Cu PILC STA 11 kV
3C	24	Westfield No 2	3c 0.37 sq in Cu OF PVC 22 kV
3D	49	Westfield	32c pilot
3E	44	Westfield No 3	3c 0.37 sq in Cu OF PVC 22 kV
3F	50/51/52	St John No 3	3 x 1c 630mm² Cu XLPE 33kV
4A	41	St John No 1	3c 0.45 sq in Cu OF PVC 33 kV
4B	45	St John	11 + 8 pilot
4C	42	St John No 2	3c 0.45 sq in Cu OF PVC 33 kV
4D	43	Mt Wellington K05	3c 0.25 sq in Cu PILC STA 11kV
4E	46/47/48	Mt Wellington No 2	3 x 1c 400mm² AL XLPE 33Kv
5A	34	Mt Wellington	11 + 8 pilot
5B	35/36/37	Mt Wellington No 1	3 x 1c 400mm² Al XLPE 33kV
5C	38/39/40	Sylvia Park No 1	3 x 1c 400mm² Al XLPE 33kV
5D	11/12/13	Sylvia Park No 2	3 x 1c 400mm² AL XLPE 33kV

Figure 6 Trench cross-section at 73 m chainage giving cable circuit positions, cable sample numbers (PN), circuit names and cable descriptions

There are two exceptions to the cable position designations, which result from the cable positions changing along the trench:

1. The first is the location of the two main subjects of this document; these being the two transition joints between 11 kV three core PILC and three core XLPE cable in the Remuera K10 circuit at 73 m and 79 m on Level 2. Elsewhere this cable runs on Level 3 along the main length of the trench and so it has been given the designation '3B0'. The cable rises to Level 2 at 71.5 m chainage and at 81 m it descends back to Level 3. At 73 m chainage the 11 kV Remuera K10 circuit, 3B0, is located on Level 2; this is the location of the transition joint in which the first electrical failure occurred. This location is described in Section 10 and shown diagrammatically in Figure 6 and Figure 44.

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 chainage and 'unfailed joint' to the transition joint in the same circuit six metres to the west at 79 m chainage.

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 trench 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 2.

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. A smaller pilot cable is out of view against the north wall (left hand side). As explained in Section 10 the first electrical fault occurred on Level 2, but further westwards at chainage position 73 m.

Starting from the north (left hand side in Figure 7) wall end of the support arm the Level 2 cables are identified from Figure 6 (where the north wall is on the right hand side) to be:

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.

In Figure 7 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 the Level 3 arm, (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 seen present on the floor, but are closer to the north wall).

A photograph of the cable trench with the lids removed 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 north (left hand) wall end of the support arm the cables are:

1A-: Remuera 3 circuit, 3 x 33 kV S/C XLPE cables, cleated in trefoil.
1B-: Newmarket 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 1B-, the Newmarket 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.

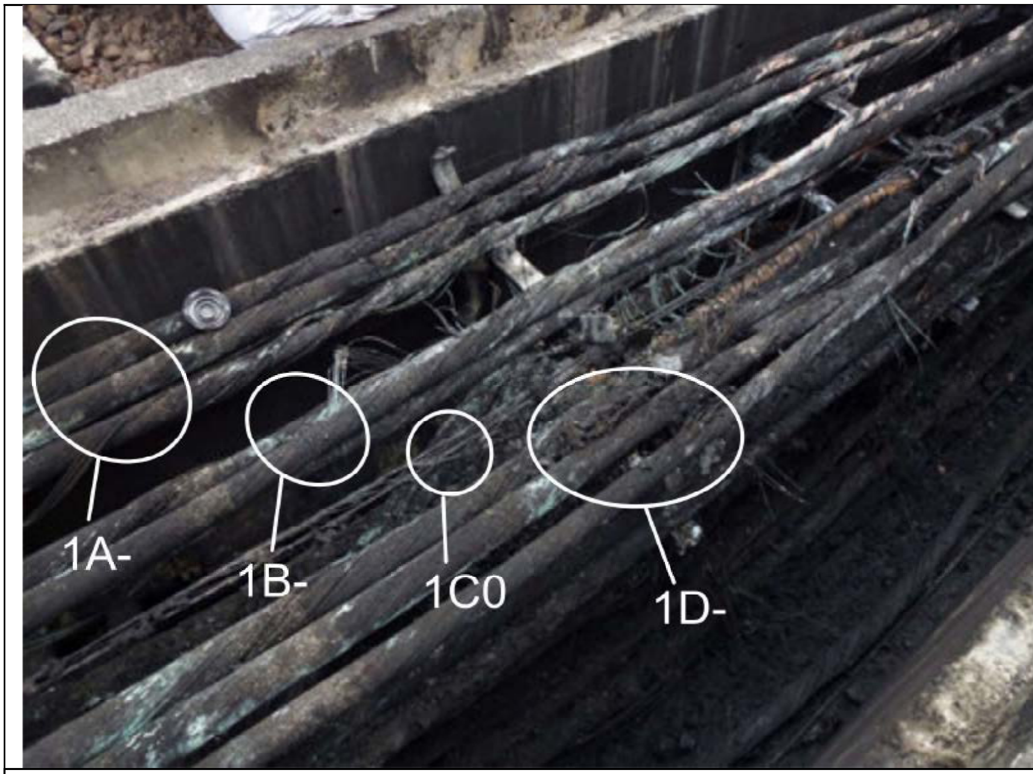


Figure 8 Photograph of cable trench at 73 m, looking eastwards, taken after the fire in October 2014

2.4 Summary of Trench Contents: Circuits and Cables

At the time of the fire in October 2014 the 105 m long trench contained 20 power cable circuits comprising 38 power cables, 4 pilot cables and a number of ducts and optical fibre cables as listed below.

The combined length of all the power cables was 3.99 km.

One 11 kV PILC cable was not in use making 19 operational power circuits. The combined length of all the operational power cables was 3.885 km.

There were 12 other cables and ducts as listed in Items 2 to 7.

1. Power cable circuits: 20 (19 in use), comprising 38 individual cables:

a.	Groups of three single core cables	9	
	Total number of single core cables		27
b.	Three core cables		
i.	11 kV PILC (*one out of use)	5*	
ii.	22 kV oil-filled cable (OF)	2	
iii.	33 kV oil-filled cable (OF)	3	
iv.	11 kV XLPE	1	
	Total number of three core cables		11
	Total number of power cables		38
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	
	Total number of auxiliary cables and ducts		12
	Total number of cables and ducts		50

2.5 Circuits in Order of Date of Installation and Manufacture

Table 1 gives the year of installation for each circuit. The list below summarises the number of new and replacement circuits installed by year.

Year	Circuits Number	Circuits Type	Replaced by XLPE Cable
1966/67	7 (10)	3 x 33 kV 3/C OF 2 x 22 kV 3/C OF 3 x 11 kV 3/C PILC 2 x 33 kV 3/C GF	3F0 replaced in 1999/2000 (includes Remuera K10, 3B0) 4E0 & 5B0 replaced 2001/2002
1977	2 (4)	2 x 33 kV 3/C OF 2 x 11 kV 3/C PILC	2E0 replaced in 1999/2000 (one cable not in use)
1999/2000	5	5 x 33 kV S/C XLPE	
2002	2	2 x 33 kV S/C XLPE	
2006	2	2 x 33 kV S/C XLPE	
2012	1	1 x 11 kV 3/C XLPE	
Total	19 circuits in operation in 2014		

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.

Table 1 Circuits in order of date of installation and cable manufacture

Trench Position	kV	Circuit	Cable Type	Year Install	Sample PN Number				Year Cable
3A0	11	McNab K02	3c Cu 0.25 PILC STA	1966	22	28	29	30	1965
3B0	11	Remuera K10	3c Cu 0.25 PILC STA	1966	23	25	26	27	1965
4A0	33	St Johns No1	3c Cu 0.45 PICAS OF PVC	1966	41				1965
4B	-	St Johns	Pilot 25C 9+16	1966	45				*
4C0	33	St Johns No2	3c Cu 0.45 PICAS OF PVC	1966	42				*
4D0	11	Mt Wellington K05	3c Cu 0.25 PILC STA	1966	43				1965
3C0	22	Westfield No 2	3c Cu 0.37 PICAS OF PVC	1967	24				*
3D	-	Westfield	Pilot 0 + 32C	1967	49				*
3E0	22	Westfield No 3	3c Cu 0.37 PICAS OF PVC	1967	44				*
2A	-	Carbine	Pilot 25C 9+16	1967	17				*
2B0	11	Not in use	3c Al 300 PILC STA	1977	14				1977
2C0	11	McNab K19	3c Al 300 PILC STA	1977	15				1977
2D0	33	Carbine No1	3c Al 300 PICAS OF PVC	1977	16				1977
1A-	33	Remuera No3	3x1c Al 400 XLPE HDPE	1999	8	9	10		1999
1B-	33	Newmarket No3	3x1c Al 400 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 400 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		34				*
*5B-	33	Mt Wellington No1	3x1c Al 400 XLPE MDPE	2002	35	36	37		1999
*4E-	33	Mt Wellington No2	3x1c Al 400 XLPE MDPE	2002	46	47	48	32	1999
5C-	33	Sylvia Park 1	3x1c Al 400 XLPE MDPE	2006	38	39	40		2006
5D-	33	Sylvia Park 2	3x1c Al 400 XLPE MDPE	2006	11	12	13		2006
2F0	11	Tunnel Supplies	3c Cu 35 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 2E- and 3F- 3 x 1c XLPE cables replaced the OF cables listed below in 1999/2000*									
**5B0*	*33*	*Mt Wellington No1*	*3c Gas Filled cable - removed*	*1966*					*1966*
**4E0*	*33*	*Mt Wellington No2*	*3c Gas Filled cable - removed*	*1966*					*1966*
**3F0*	*33*	*St Johns No3*	*3c Cu 0.45 PICAS OF PVC*	*1966*					*1966*
**2E0*	*33*	*Carbine No2*	*3c Al 300 PICAS OF PVC*	*1977*					*1977*

3 Cable and Joint Types

As shown in Table 1, there were four types of power cables present in the trench at the time of the fire; these being 11 kV three core PILC, 22 kV and 33 kV three core OF, 11 kV three core XLPE and 33 kV single core XLPE), the designs of which bear testimony to the passage of technology in cable design since the first 11 kV PILC cables were installed in the cable trench in1966.

The cable and joint designs are shown diagrammatically and described in Section 18, Appendix C. The design of the 11 kV PILC to XLPE transition joint is shown and illustrated in Section 20, Appendix E.

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 was used. This design 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 core designs were installed, both having robust corrugated, extruded, 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 were found in the trench.

- XLPE (cross-linked polyethylene) single core cables. The 33 kV cables are of single core design complete with their own triple extruded insulation and semiconducting screens, copper wire screen, earth return conductor and composite PVC/PE extruded oversheath. Each phase circuit was formed by laying the three phase cables in a trefoil-touching formation.

  A heat shrink sleeve straight joint design was used. Compared to a PILC straight joint this design reduces the number of jointing skills and the jointing time. 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 compound’ 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 is the electrical screen that has semi-conducting properties. Originally sleeves were separate and then, with the progression of technology, were 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. A hot-melt adhesive lined, protective, waterproof sleeve is applied overall, which overlaps and seals onto the cable oversheaths.

- XLPE (cross-linked polyethylene) three core cables. The 11 kV cables are of three core design. Each core is complete with its own triple extruded insulation, semiconducting screens and copper wire screen, earth return conductor. Fibre fillers are laid between the three cores. A composite oversheath of extruded PVC and PE is applied overall.

  11 kV XLPE straight joints are not described as none were found in the trench.

4 Site Investigation at Penrose Substation

The CCI Author arrived in Auckland on Friday 10th October 2014.

From Saturday 11th October to Wednesday 22nd October the CCI Author performed an initial investigation and examination of the trench at Penrose Substation and part-dissection of selected cables and joints.

The CCI 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 Substation the CCI Author:

1. Walked externally along the 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.

Disturbances of the outer conductor screen wires on Level 1 were seen between 72 m and 74 m. The view facing north at this location is shown in Figure 9. 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 formations. The cable cleats on the top support arm to the right of the photograph (at 73 m) had been burst open by the short circuit forces and in some locations melted.

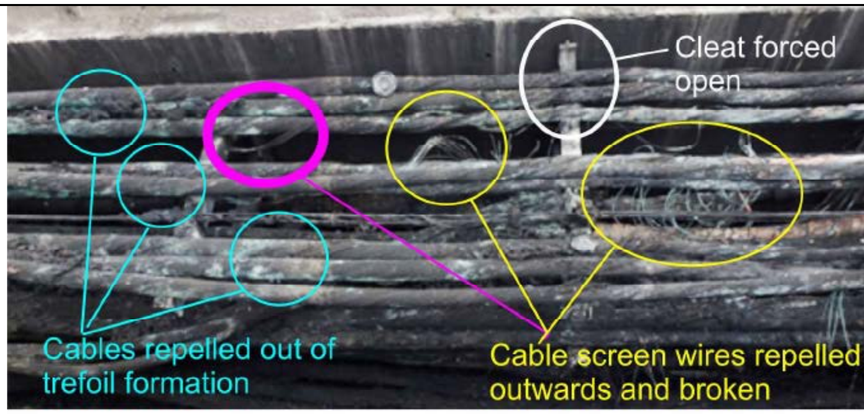


Figure 9 Disturbances indicative of violent electrical activity at 72 m - 74 m

Figure 10 shows the pink ringed detail from Figure 9, looking west along the trench at 94 m chainage where the copper screening wires on the 33 kV XLPE cable 1AZ had been parted by arc burning where they had contacted the top face of the steel support arm on Level 1 (after the PE and PVC sheaths had been burnt away). The parted ends of the wire had then arced to the side face of the steel support arm. A group of larger arc marks is present to the left.

Figure 10 Minor arc burning between steel support and ends of parted copper screen wires on cable 1AZ at 73 m

Within the 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 11 is a close-up photograph of the 11 kV transition 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.

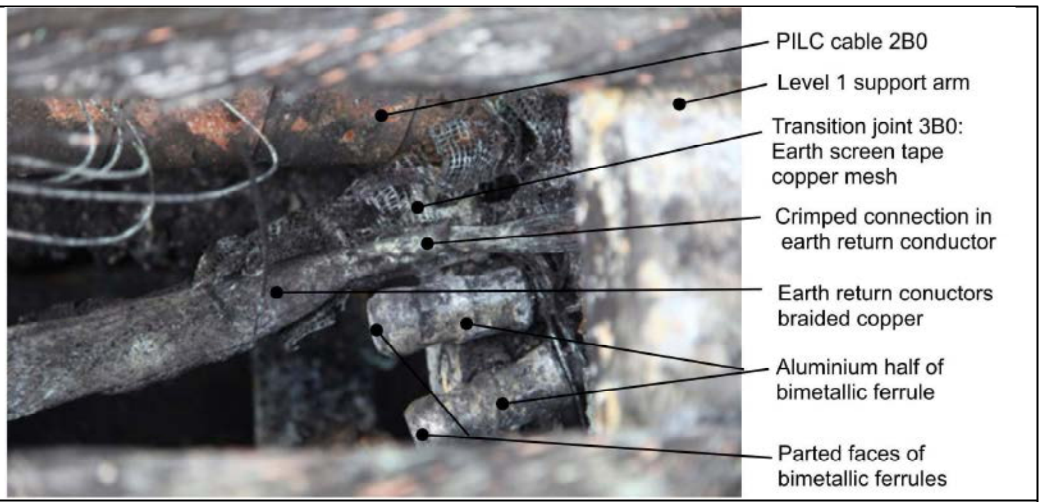


Figure 11 Close view of failed transition joint between cable Layers 1 and 2

The mesh that can be seen is the remains of the copper earth screen tape that would have been wrapped 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 3B0 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 12. (The cable bridge and control cables are new and replace those that suffered fire damage, their location is at 70.5 m). A diagrammatic plan view of the layout is given in Figure 44.

Figure 12 11 kV Remuera K10 cable rising from Level 3 to Level 2

Figure 13 shows a parted cable support frame at 69.5 m chainage. The frame had moved to the south away from the north wall and, in so doing, the southern end had dropped. The cables had not been cleated to this frame and this permitted the frame to move from beneath the cables. The cables moved to the south slightly, but were limited in travel by being cleated to the adjacent support frames either side at 68.5 m and 70.5 m. The northern end of the frame had dragged open part of a cable's wire screen. The latter is normally covered by the PE and PVC oversheaths. This indicated that some or all of the frame's movement had occurred during or after the fire and not before it.

The reason for the collapse of the frame was seen to be either the apparent failure of the stud, or loss of its frame holding nut, as shown in the right hand side of Figure 13. The bottom holding stud (out of view) appeared to have also parted or lost its holding nut. The bottom stud had 'necked' (i.e. had been reduced in diameter) indicating that it had suffered a greater degree of erosion. Both studs were encrusted with matter from the fire, but they could be seen beneath this to have been heavily eroded. The studs were cut off and sent to

Edif ERA laboratories for analysis. Two nuts that had been found on the floor in the vicinity of the frame were sent to assess whether or not they had been fitted to the suspect studs. Reference samples were also sent from a support frame that had been in its correct position.

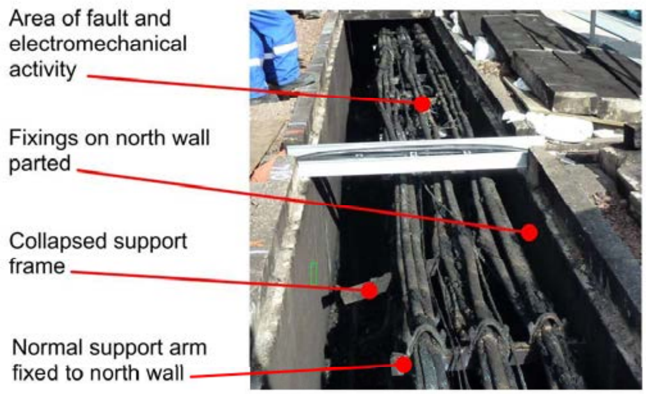


Figure 13 Left: collapsed cable support frame at 69.5 m. Right: plan view of the failed stud between north wall and cable 1AX (frame has moved to left)

4.2 Findings from the Internal Examination of the Trench

The trench was entered by the CCI 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 14 is a photograph taken from within the trench, horizontally between Levels 2 and 3. The three missing copper conductors from the 3B0 11 kV Remuera K10 transition joint 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 14.

Figure 14 Two parted conductors hanging from the failed transition joint

The third conductor had been completely severed and had fallen downwards onto Level 3, Figure 15. It was confirmed that all three copper ferrules had parted at the centre face of the bimetallic connector.

Figure 15 The severed third 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 to 70.75 m, containing nine possible fault holes.
- 70.75 m to 75 m, containing eight possible fault holes, the faulted 11 kV transition joint and a conventional 11 kV straight joint with a cast iron shell.
- 78.25 m to 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 within the 66.5 m to 75 m region, i.e. close to the centre of the failed Remuera K10 transition joint at 73 m and to the east of it.

4.3 Cutting Cable and Joint Samples out of the Trench

The layer of XLPE cables from Level 1 were cut out and sealed in plastic pipes for transport to the examination room and examination at a later stage.

This revealed on Level 2 the two 2 m long samples containing the failed transition joint at 73 m (Figure 16) 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^{o} and jointed onto new lengths of XLPE cable for diversion around the edge of the substation compound and into the 33 kV Switchroom.

Figure 16 Level 1 cables removed. Revealed are a failed transition joint on Level 2 and a conventional cast iron straight joint on Level 3

4.4 Examination for Extent of Fire Propagation and Cable Burning

After the CCI Author returned to the UK the assisting Engineers performed a ‘char’ inspection of the cable oversheaths 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 2D0) were also clear of char at this point.
- 20.3 m.
    - All Level 1 33 kV XLPE cables (1A, 1B and 1D) showed evidence of charring on the exposed top and side surfaces.
    - All Level 1 33 kV 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.
    - The 33 kV XLPE cable in position 2E was also tested, and found to be the same as the Level 1 cables.

- The 33 kV OF (PVC sheathed) cable in position 2D0 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 previously and replaced.

Figure 17 Char of the PE oversheath on Level 1 at 20.3 m chainage

In summary:

- 77.9 m (59%) out of 132.5 m of the cable circuit length in the trench and along the 33 kV Switchroom wall had been fire damaged.
- 54.6 m of cable circuit length was not fire damaged

The 77.9 m of fire damaged cable comprised:

- 52.7 m length 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 33 kV Switchroom.
  - 5.0 m along the side of the 33 kV Switchroom.
  - The remaining 20.8 m length along the side of the 33 kV 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 and visually examined. (The designs of cables are described and illustrated in Section 18, Appendix C).

- The extruded PVC oversheaths and the extruded aluminium sheaths of the 37 to 48 year old 22 kV 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 37 to 48 year old 11 kV PILC cables had significantly deteriorated down to the lead sheath in places, however the lead sheaths and insulation were sound.

- The composite PE/PVC oversheaths and insulation of the up to 15 year old 33 kV 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 available for the installation of future cables. The trench was reasonably clean and in good condition. 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; Table 1 and Figure 7. 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).

From 1999 onwards the support arms and floor 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 previously oil filled and gas filled cables had been laid on the floor underneath the Level 4 support arm.) The trefoil groups of single core 33 kV XLPE cables occupied more space than the compact three core 33 kV oil-filled and 11 kV PILC cables.

In 1999 and 2000 five circuits of 33 kV single core XLPE cables in trefoil formation were installed. Three of the XLPE circuits were new circuits, Remuera Nº3 (1A-), Remuera Nº2 (1D-), and Newmarket Nº3 (1B), these being installed on the vacant top support, Level 1. Two of the XLPE circuits were replacements for two OF circuits, Carbine 2 (2E-) and St Johns 3 (3F-), to allow connection of these circuits onto the new 33 kV switchgear.

In 2002 two circuits of 33 kV single core XLPE cables were placed on Level 4 and Level 5 to replace the two Mt Wellington gas filled cables, which had previously been laid on the floor, Level 5.

In 2006 two circuits of 33 kV single core XLPE cables were added and placed on the floor, Sylvia Park 1 and 2. At the time of the fire the number of data cables interspersed between the power cables also appears to have been increased with at least one being laid on the floor.

The reduced space between cable groups raises the questions 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 inappropriate to permit contact between different cable types as increased mutual heating and electromagnetic induction will occur. The different cable types have different operating temperature limits:

- PILC: 65°C
- OF: 85°C
- XLPE: 90°C

From a short-circuit point of view, self-contained cables having three cores within one metallic 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. Prior to 1999 all of the cables in the trench were of the three core, paper insulated type in this category.

Figure 5 shows that five of the single core, XLPE, 33 kV, cable trefoil groups had been fitted with trefoil cleats that constrained the three cables i) together and ii) 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 CCI Author saw evidence that plastic cable ties had been fitted around one trefoil group, presumably to hold them during installation. Cable ties should not be relied upon to hold short circuit forces at elevated temperatures. The CCI Author did not see evidence that short circuit straps had been fitted to the three trefoil cable groups laid on the trench floor as 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, if a geometrical imbalance location exists in the 105 m long trench, that the movement and force will become concentrated at this location risking cyclic fatigue damage to a cable, or in the case of a joint, disturbance to its insulation.

The CCI 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 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 in cable 3B0 on Level 2, Figure 44 and Figure 45.

It is expected that thermo-mechanical movement would have been concentrated at the failed transition joint in cable 3B0 at 73 m as the bow started mid-way along the joint's length. It is reported that the 11 kV Remuera K10 circuit:

- Had carried load for ten minutes on the morning of 4th October 2014 this being the day in which the first electrical failure occurred at 23:21:30.
- Had been continuously voltage energised from the Remuera Substation end for the previous year, but had not carried load as the circuit had been electrically opened at its McNab Substation end.
- Had carried load in previous years.

For the year in which Remuera K10 was not carrying load the other 18 cable circuits would have heated the air in the trench and so have heated Remuera K10 indirectly causing it to expand and contract. Calculated cable and air temperatures are given in Section 21, Appendix F.

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 prospectively containing fault holes. The fault holes that were found were photographed and are described in Section 11 and shown in Section 19, Appendix D.

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 22, 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. (The design of the transition joint is described and illustrated in Section 20, Appendix E).

Despite the failed joint having been severely burnt it was possible to confirm that the two joints had closely similar constructional features and dimensions, these being the overall length, the braid earth conductors across the joint, the crimped connector between the braided strap (PILC side) and earth return conductor (XLPE side), use of three roll springs to connect the braid to the lead sheath of the PILC cable, 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 email 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 email and photograph, Figure 18, showed that the joint was in the 11 kV Remuera K10 cable at, or close to, the top of the slope in the trench, this being at 79 m chainage, Figure 44. 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 18 Straight joint in Remuera K10 at 79 m: Photo taken in 2001

The unfailed transition 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 19. 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 19 Failed joint: arc crater in the three conductors

Figure 20 shows the arc crater after the conductors had been cleaned and re-assembled by the CCI Author at the laboratories of 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 (right hand side) 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 had looped outwards under electromagnetic forces to the left.

Figure 20 Failed Remuera K10 joint: Arc crater in three conductors after cleaning and re-assembly

In the Examination Room at Penrose the approach was taken to first partly dismantle the unfailed joint and uncover the internal geometry and dimensions of the joint components that were under the various layers of heat shrink sleeves. These would provide the dimensions for comparison with i) the failed joint and ii) the joint supplier's assembly instructions. The dismantling procedure had the additional objectives of searching for incipient failure mechanisms that could have also been present in the failed joint, for example:

- Incipient electrical distress
- Overheating
- Ageing
- Damage
- Jointing errors

5.2 Arc Burning to the Earth Return Conductors

Subsidiary arc burning as shown in Figure 21 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 25 mm by 75 mm. The arc current had spot-welded the three braided conductors together when they shared the current where they had been grouped together for insertion into the connector. 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 21 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 the laboratories of 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 21 Failed joint: Arc burning to the earth continuity braided conductors

5.3 Parted Connectors in the Failed Transition Joint

In the Penrose Examination room the faces of the parted friction welds were cleaned, matched and photographed, Figure 22, Figure 23 and Figure 24. It was found that:

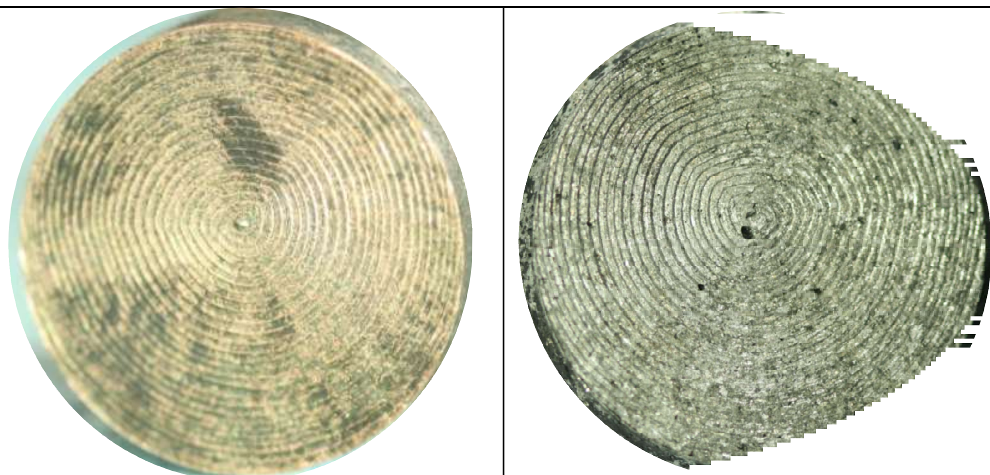
1. There was no direct evidence that the connectors had parted in service or during the electric phase of the failure as i) there was no electrical pitting and arcing and ii) the power arc had occurred in the PILC crutch of the joint and not at the connectors. Arc pitting was absent on the faces, i.e. 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. In the previous year it would 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 groove 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 groves had been produced during the first phase of friction welding when one piece of rotating metal rod is pushed into the other, with an eccentric motion, to generate sufficient frictional heat to weld the two dissimilar metals together.

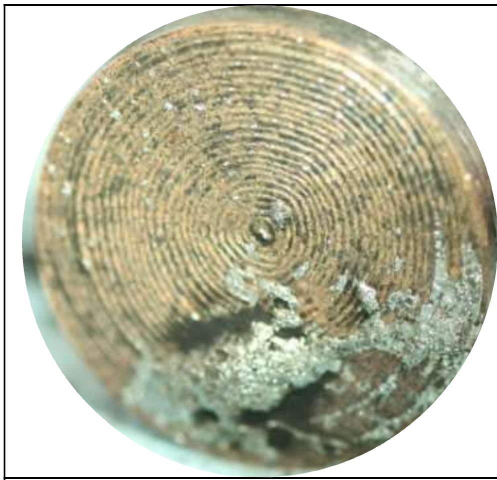
5.3.1 Follow-up Investigation

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 as summarised in Section 6.



Connector A: Friction weld copper face	Connector A: Friction weld aluminium face

Figure 22 Electrically failed 11 kV Remuera K10 transition joint: parted faces in connector A



Connector B: Friction weld copper face

Connector B: Friction weld aluminium face

Figure 23 Electrically failed 11 kV Remuera K10 transition joint: parted faces in connector B

Connector C: Friction weld copper face

Connector C: Friction weld aluminium face

Figure 24 Electrically failed 11 kV Remuera K10 transition joint: parted faces in connector C

5.4 Examination of the Unfailed Transition Joint

For reference the design of the heat shrink joint is described and shown diagrammatically in Section 20, Appendix E. In some locations in this report the abbreviation HS is used for 'heat shrink' and the heat shrink components may be referred to either as 'sleeves', this being the usual terminology in the UK, or as 'tubes' this being usual in the US.

Although the fire damage had been less severe at the 79 m location of the unfailed joint, the outer heatshrink sleeve had suffered fire damage and, although still adhered, had been burnt away along one line of its circumference. The ablation revealed the steel roll springs that were on the lead sheath on the PILC cable side of the joint, Figure 25.

Figure 25 Unfailed joint: The steel roll springs could be seen on the PILC side

The fire had also burnt along the central heat shrink insulation packages to varying degrees to reveal part of one of the bimetallic connectors, Figure 26.

Figure 26 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 27.

Figure 27 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 28.

Figure 28 Unfailed joint: The heat shrink ‘break-out’ glove covering the PILC crutch

The arc centre-line was denoted by a red pointer and was found to be within the ‘break-out’ glove and close to the internal exit of the core spouts, Figure 29.

Figure 29 Unfailed joint: Arc centre transferred from failed joint

A strip of the semi-conducting heat shrink break-out glove was removed. The adhesive void-filling yellow compound was removed partly by cutting and partly by stretching and tearing. 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/insulation tube and adjacent to the termination of the 'belt'. The purpose of the barrier/insulation tube is threefold, i) to prevent loss of the cable's hydrocarbon impregnating compound, ii) to prevent the compound from degrading the outer polyolefin heatshrink insulation and protective sleeves and iii) to part replace the paper tape belt insulation removed from the PILC cable.

Figure 30 Unfailed joint: Arc centre is in PILC crutch close to oil barrier sleeve

It was found that the yellow void-filling compound inserted by the jointer had adhered to the paper tape insulation and during dismantling had torn it when the 'break-out' glove was removed, Figure 31.

There were some voids present in the yellow compound, but it wasn't possible to determine if they had been present before the 'break-out' glove had been removed. The yellow compound was noted to have turned brown adjacent to the 'break-out' glove, possibly indicative of ageing. The yellow compound was noted not to have consistently adhered to the lead sheath, Figure 31, this being one of the seals that prevents water ingress into the paper insulation. There were short sealing sleeves present over the outer ends of the 'break-out' glove 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 31 The compound had not uniformly adhered to the lead sheath

The joint measurements, Figure 32, were found to be closely similar to those given in the installation instructions[3], thus confirming that the standard of jointing had been satisfactory. (Note: the copies of the NZ Assembly Instructions available to the CCI Author were referenced as 9/03 which was taken to be the date of issue of September 2003, which postdates the date of installation and GB Assembly Instructions referenced as 10/97, which predates the date of installation).

Figure 32 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/insulation 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 had preceded the arc was. 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.

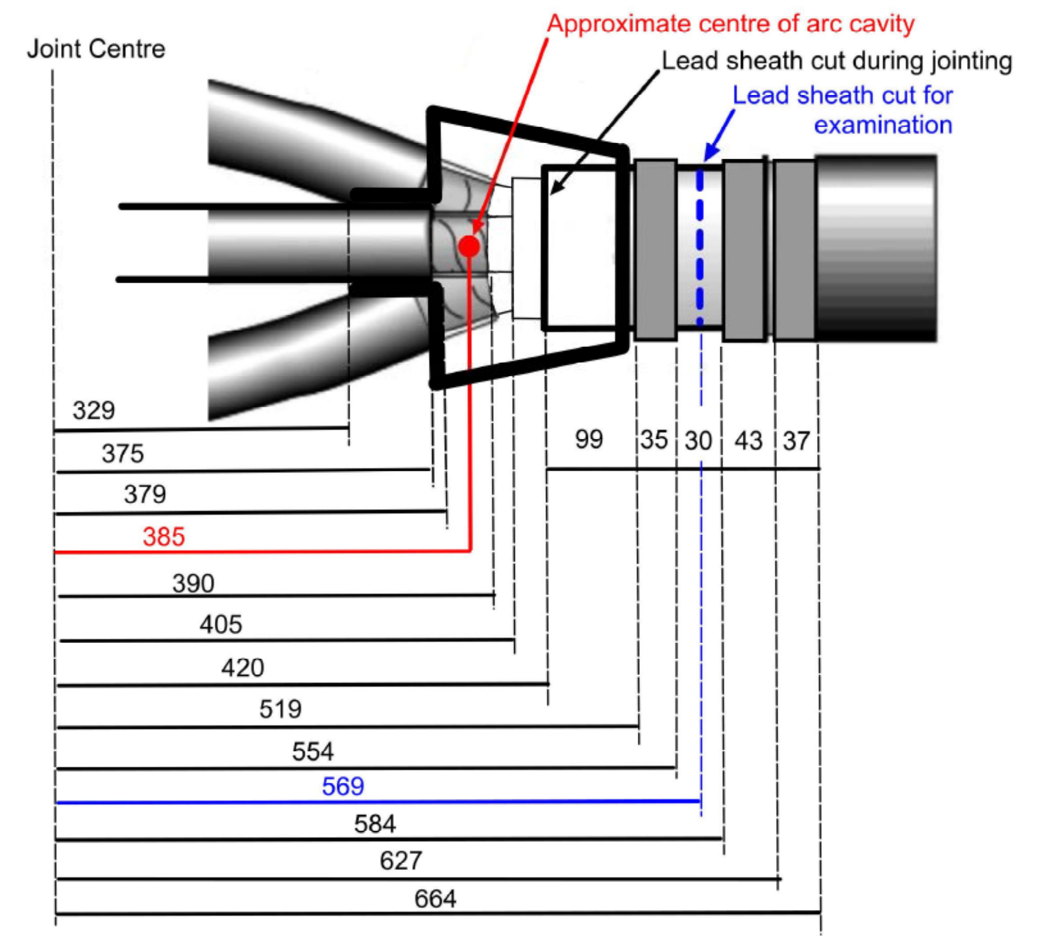


Figure 32 Arc position transferred from failed to unfailed joint

The location of the arc and fault positions is shown in Figure 33. A general view is shown in Figure 114.

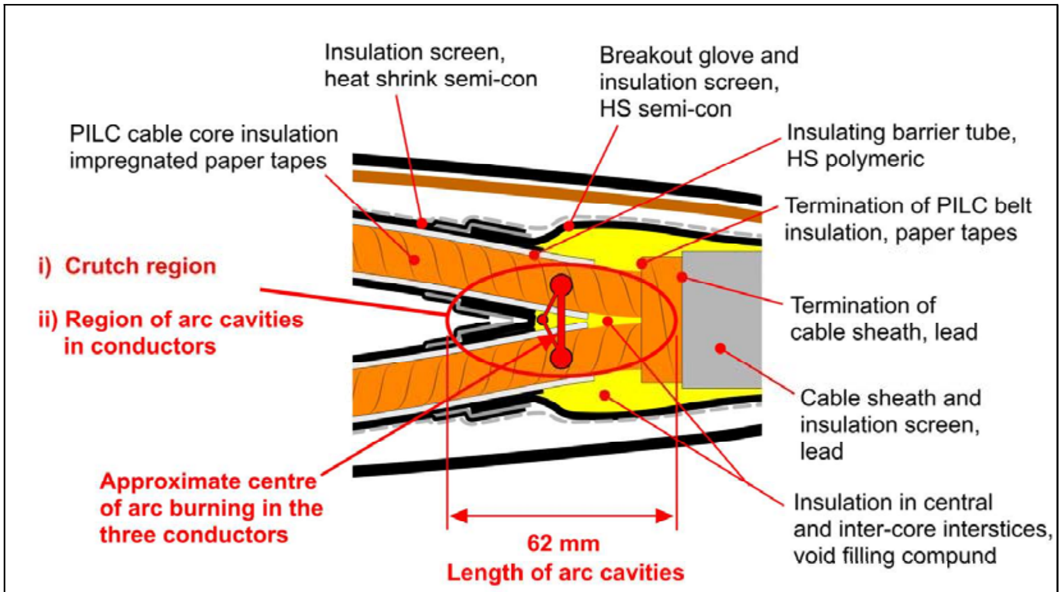


Figure 33 Arc position in the crutch of the failed transition joint (not to scale)

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 34. 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 CCI 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.

In the three core transition joint the CCI 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 through-faults can occur that could damage a joint that was otherwise sound. It was concluded that the corroded electrical contact was not a factor in the joint failure as i) the connector was not located adjacent to the arc cavity in the primary conductors and ii) the paper tape belt insulation immediately below the lead sheath did not show signs of overheating.

Figure 34 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 was uncovered in large interstitial creases immediately above the cores, Figure 35.

Figure 35 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 36 Large black feature between Cores No 2 and No 1

Figure 37 shows that the feature appeared to be comprised 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, electrical or chemical degradation.

Figure 37 Black feature on the paper insulation of Cores No 2 and No 1

Figure 38 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 however extend 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.

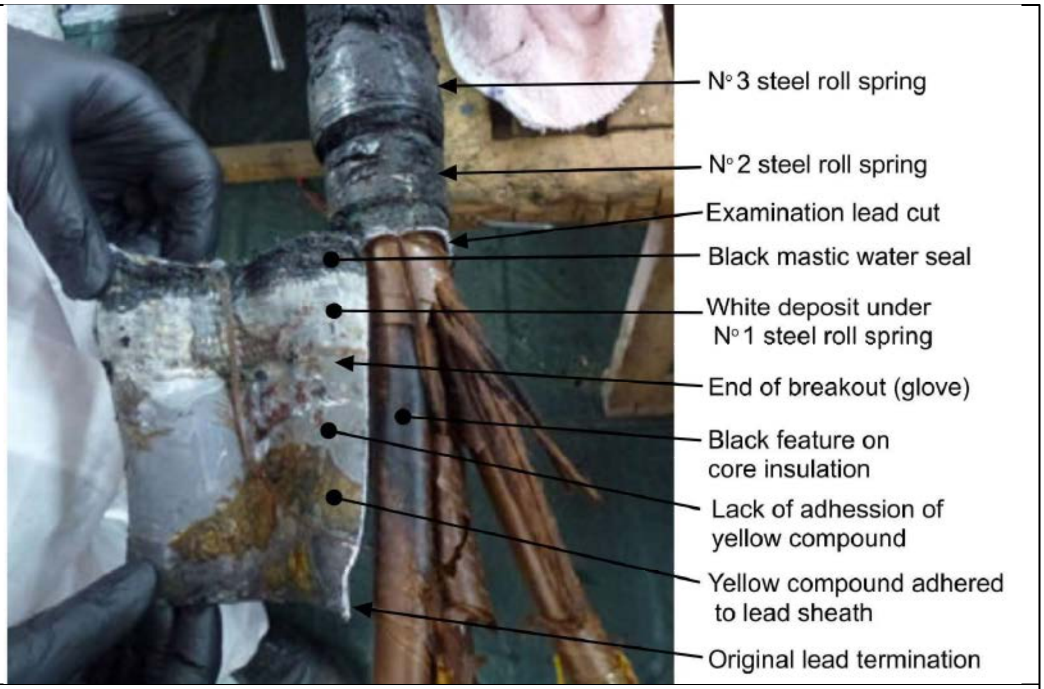


Figure 38 Black feature extends underneath and to the end of lead sheath cut

5.6 Location of Fault Path: Conclusions

The CCI Author concludes from the work in the Penrose Examination room and later in the Edif ERA laboratories that:

1. The two black features present in the unfailed transition joint are indicative of incipient distress in the insulation. It was deduced that the features had pre-existed the fire and had not been caused by it, because the overlying belt paper tapes, which were closer to the high temperatures of the fire had not been discoloured or thermally embrittled.

2. The black features are not coincident with the location of 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 is 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 of the insulation. 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 in-service operation.

   Movement and flexing of the cores has been reported[4] as the possible failure mechanism that prevented the application of the belted cable design to higher system 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 to an asymmetrical 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.

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 black features. No other features were found. It was thus concluded that the mechanism that produced the incipient distress was particular to the unfailed 11 kV PILC to XLPE transition joint. Due to the similarity between the transition joints the probability existed that the incipient distress had also been present in the failed transition joint.

6 Investigations in the UK

From November 2014 to the end of February 2015 the CCI 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 Section 17, Appendix B.

6.1 Analysis of Cable Samples by Edif ERA

The CCI Author witnessed key stages of, and reviewed, the detailed bench-top analysis by Edif ERA of twenty eight single core 33 kV 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 of cable samples is given in Edif ERA report 2015-0027[5]. The CCI Author is in agreement with the Edif ERA Summary, Discussion and Recommendations.

6.1.1 Summary from the Edif ERA Report[5]

"This report 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[5]

"Based 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." [CCI 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 the cables 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 the laboratories of Edif ERA detailed dissections were performed on the returned joints and are recorded in Edif ERA report 2015-0356[6].

The CCI Author participated in eight of the ten joint dissections listed in Table 2:

- The continued dissections of the failed and unfailed 11 kV PILC to XLPE heat shrink transition joints.
- The three dissections of the 11 kV cast iron PILC straight joints.

- Three of the five dissections of XLPE heat shrink straight joints.

Table 2 11 kV and 33 kV joints examined at Edif ERA

PN N°	Description	Trench Position	Chainage Length m
53	Unfailed, 11 kV 3C, PILC-XLPE transition joint, Remuera K10	3B0	79
33	Failed, 11 kV 3C, PILC-XLPE transition joint, Remuera K10	3B0	73
28	11 kV PILC, 3C, cast iron joint, McNab K02	3A0	74
*	11 kV PILC, 3C, cast iron joint, Remuera K10	3B0	65
57	11 kV PILC, 3C, cast iron joint, Mt Wellington K05	4D0	50
60	11 kV PILC, 3C, cast iron joint, Remuera K10	3B0	25
54	33 kV XLPE, SC, joint 400-800mm^2, Remuera N° 2	1DY	5
59	33 kV XLPE, SC, joint 400-630mm^2, Newmarket 3, YØ	1B-	5
55	33 kV XLPE, SC, joint 400-800mm^2, Remuera N° 2	1DZ	5
58	33 kV XLPE, SC, joint 400-800mm^2, Newmarket 3, RØ,	1B-	5
56	33 kV XLPE, SC, joint 400-800mm^2, Remuera N° 3	1AX	5
25	11 kV PILC, 3C, cable at end of Remuera K10 joint sample	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 heat shrink transition joint 3B0 at 73m and the unfailed transition joint 3B0 at 79 m were completed by the CCI Author and by the Edif ERA Investigator with a representative present from Tyco Electronics, (the successor company to the original supplier Raychem).

Four traditional 11 kV PILC straight joints with cast iron shells were dissected (three at Edif-ERA and one at Penrose). It is thought to be probable that these joints had been installed when, or shortly after, the original PILC cables were installed in 1966.

The CCI Author participated in the dissection of the six samples of 11 kV PILC cable that were taken from either side of the PILC to XLPE transition joints listed in Table 3 and participated in, or reviewed the dissection notes, of the six other PILC cable samples listed.

The 105 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). The joint at 78 m was later replaced by two heat shrink sleeve transition joints at 73 m and 79 mm. At the time of the failure there were thus four joints in cable 3B0: two transition joints and two straight joints. This is a comparatively large number of joints in a short cable length and indicates i) the cable had experienced unknown events early in the life of the PILC circuit that required the insertion of three straight joints and ii) a known event in October 2001 in which one of the straight joints was removed. The number and types of joints had increased the risk to the reliability of the circuit compared to a straight run of cable.

Table 3 11 kV PILC and XLPE cable samples examined, 3A0 and 3B0

PN N°	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	11 kV 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

The CCI Author concludes 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.

6.3 Examinations of the Bimetallic Conductor Connectors at Edif ERA

Two aspects of the bimetallic connection were examined i) the bimetallic friction weld and ii) the compression ferrule region. A dissected bimetallic connector is shown in Figure 39.

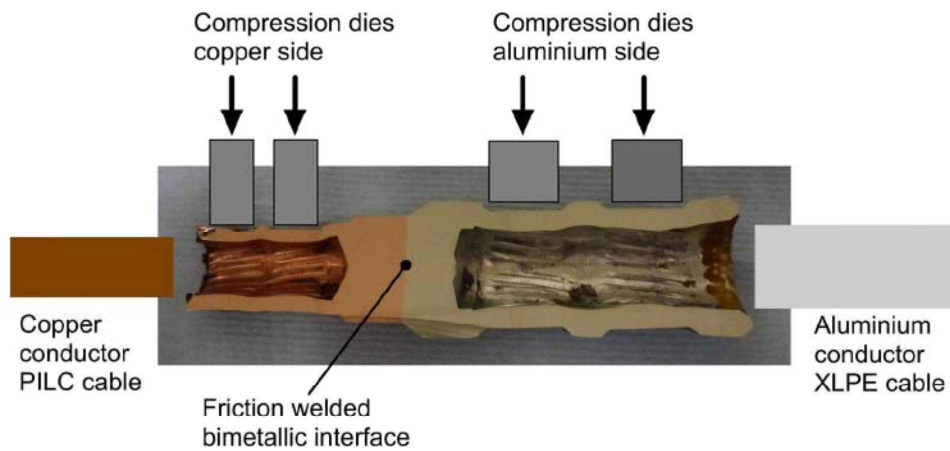


Figure 39 Dissected bimetallic connector

6.3.1 Examination of the Bimetallic Friction Weld

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 failure 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 Edif ERA laboratory examination confirmed that the parting of the connector was a consequence of the fire and had not contributed neither to the failure nor to the fire.

It was found that:

i) At ambient room temperature the bimetallic connectors in the unfailed joint were sound under both axial tension and in lateral bending tests.

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 were 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) Tyco Electronics NZ had previously performed trials, which showed that friction welded connector interfaces had parted in a closely similar way at a similar temperature of 750°C.

The CCI Author concludes 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.

6.3.2 Examination of the Compression Ferrule

Each conductor connection has two compression ferrule regions, each comprising a tubular section. (The Edif ERA report describes the 'compression' as a 'crimp', both have the same meaning in the context of the examination). One tubular section is of larger diameter and houses the aluminium conductor of the XLPE cable. The other tubular section has a smaller diameter and houses the copper conductor of the PILC cable. The conductor is inserted into the tube, which is then compressed inwards onto the conductor. Different sizes of compression dies are required to suit the different diameters of aluminium and copper connector and different types and 'occupancy' of the conductor area. The compression connector is required to have a low electrical resistance and high mechanical strength that stay stable with time in service such that neither overheating nor conductor retraction occur.

The Edif ERA report[6] records the combination of measurements, dissections and inspections that they performed on the three connectors from the failed transition joint and three from the unfilled transition joint. No evidence of overheating or conductor retraction were found.

The CCI Author examined:

i) The connector samples, photographs and test results.
ii) The apparent design 'compaction' (percentage ratio of the volume of metal moved inwards by the compression dies compared to the combined volume of 'air' present within the bore of the ferrule and within the interstices between the conductor wires).

The CCI Author concludes that:

i) The compression connectors had been sound.
ii) The transition joint failure had not been caused by overheating or retraction of the conductors.
iii) The achieved compaction of the aluminium conductor was medium-high, the achieved compaction of the copper conductor was medium-low and that both were acceptable.

6.4 Examination of the Cable Support Frame Wall Studs at Edif ERA

The Edif ERA dissection[6] of the studs confirmed that heavily eroded remnants of the holding nut were present on the top stud, confirming that at least one nut had been in place when the frame had been assembled.

The metallurgical analysis suggested that both studs had been heavily eroded by a power arc. The analysis confirmed that the two nuts found on the floor in the vicinity of the holding frame had neither experienced the heat of the fire nor had been corroded.

The CCI Author concludes that:

i) The collapse of the support frame at 69.5 m was not a contributory cause of failure as the movement occurred during or after the fire and not before it.

ii) The holding frame had been correctly assembled and the nuts found on the trench floor had probably been surplus to requirements.

iii) The support frame holding nuts had been burnt off by power arcs during the fault sequence and the frame had moved during or after the fire. There was no evidence to show that the frame had moved before the electrical fault.

iv) Metallurgical corrosion was not a contributory cause of the stud erosion. The other studs and nuts examined on site were sound and not corroded.

6.5 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.

The CCI Author agrees with the Conclusions stated in the Edif ERA report[6] that:

"Based on the timings of the cable faults that were recorded, the position of the fault, its appearance and from past experience, the PILC/XLPE transition joint fault in the 11kV Remuera K10 circuit was the 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 towards the phase connectors."

"From Edif ERA's previous experience of examining failed PILC cable joints, the PILC cable crutch is a weak area where failures are likely to occur in heat shrink joints on aged belted PILC cables."

"The evidence suggests the nuts found on the floor of the cable trench at 69.5m, the position of the collapsed cable support, were not in place on the studs at the time of the fire."

"The PILC cables in the cable trench had severely corroded steel tape armour but this would not have affected the life of the cables as long as the cables were not subjected to mechanical impacts."

"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."

In the CCI Author's opinion 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 CCI 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 compound and ii) moisture deduced to have entered the paper insulation from heat shrink sleeve water seals that were observed in the unfailed joint to be imperfect.

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 presence of 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 CCI 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 in consequence 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 thermo-mechanical 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 compound in hydrocarbon insulating oil at different temperatures for different periods of time. It was confirmed that the compound 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.

6.6 Investigations at CCI's Offices

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: Section 7.

2. A calculation of the operating temperature of the cables in the cable trench. Section 8 and Section 21: Appendix F.

3. A review of mechanical performance: Section 9.

4. A calculation of the arc temperature and of the volume of metal eroded from the conductors: Section 22, Appendix G.

5. Fire initiation and fire progression along the trench and a review of published documents that relate to the fire performance of cables in in-air installations: Section 12, Section 13 and Section 23, Appendix H.

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 37 and its location in Figure 40. The 11 kV PILC cable is described and is shown diagrammatically in cross-section in Section 18, Appendix C.

The black feature is centred on the shoulder of the core, this being its major axis.

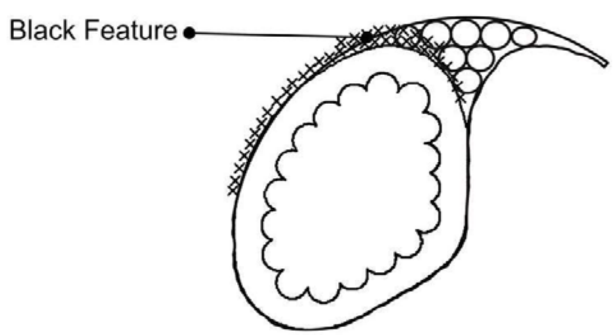


Figure 40 Location of black feature between Core 2 and 1

The items of importance to this investigation 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 i.e. 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.

In a cable having individual core screens (such as a 33 kV XLPE cable or OF cable) the voltage (potential) distribution (also named a 'field plot') can be visualised 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 at the same peak voltage, these being the paths that a unit positive charge, q, would travel impelled by force Eq.

The belted PILC cable does not have individually screened cores and so its field plot has the complexity that the voltage distribution at any point in the cable cross-section is the resultant from each of the three phase voltages, which have phase differences of 120^o. Thus the equipotential and stress diagrams are dynamic and continuously rotate with time.

To produce Figure 42:

- The stress at every point and every moment in time through the 360^o cycle is calculated.

- The maximum values at any moment irrespective of time are selected and plotted. The maximum value at each individual location is shown. The units of stress are displayed as 10^6 V/m, which are equivalent to MV/m, or kV/mm. The voltage and the stress are the RMS (root mean square) values (i.e. peak value divided by $\sqrt{2}$), which is the usual form for cable engineering.

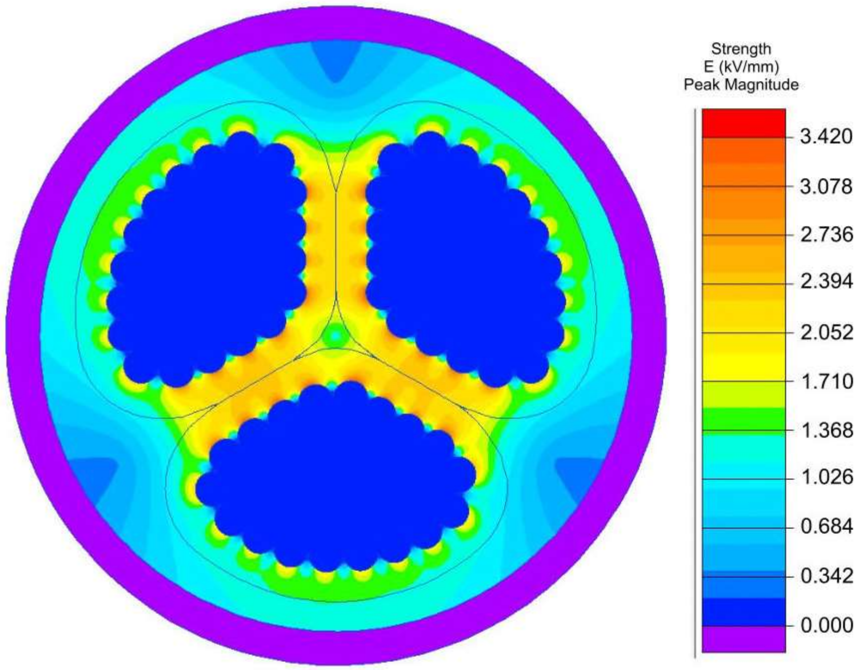


Figure 41 Contour plot of points of maximum stress through a 360^{o} cycle

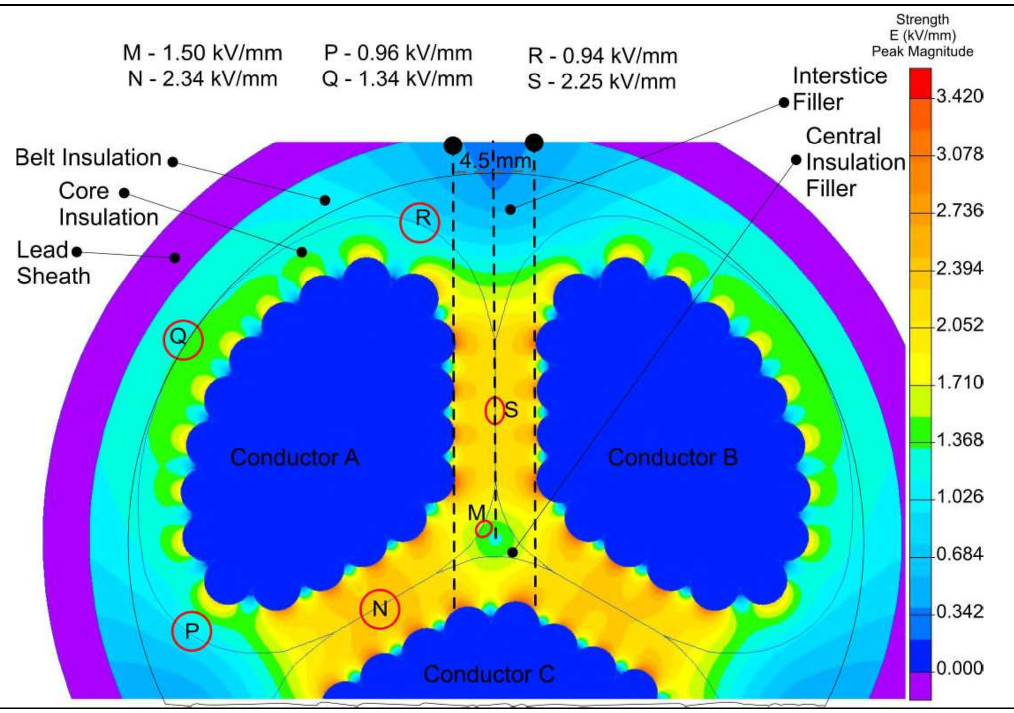


Figure 42 Magnitudes of maximum stress on a PILC core through a 360^{o} cycle

Values of the resultant stress around the circumference of the core insulation and of the stress tangential to the surface are given in Figure 43. The peaks of electrical stress are denoted by letters and their geometric positions are shown in Figure 42.

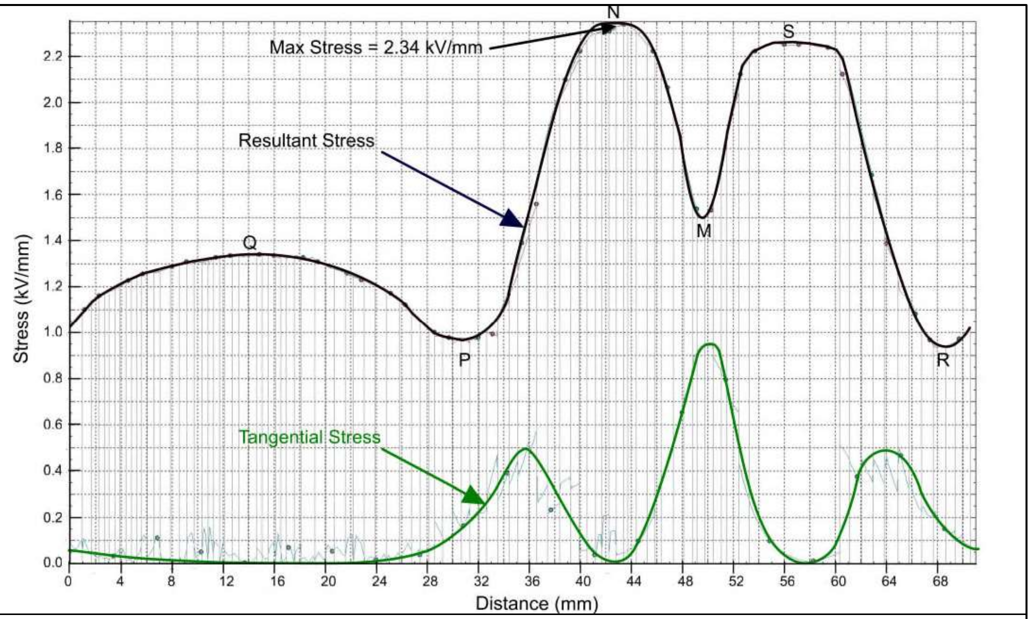


Figure 43 Resultant and tangential stresses around the core surface

The results show that:

- The region of maximum resultant stress is not at the black feature on the shoulder of the core at R and P, but on the parallel contacting faces between the cores, N and S, where its value is 2.34 kV/mm. The possibility of an electrically weak void being present in this interface within the cable is small. The possibility of a void being present 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 compound.

- A lower magnitude of stress is present in the less well insulated interstices. The possibility of an electrically weak void being present at these interfaces is higher 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 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. 3.5:1. Thus the stress in a planar void at the shoulder would be 1.0 kV/mm x 3.5 = 3.5 kV/mm. Large radial thickness voids at atmospheric pressure could exhibit PD (partial discharge) at this stress, but not small thickness voids. Voids in this location could be formed by thermo-mechanical movement of the cable cores. The microscopic analysis and methyl-blue dye tests performed on and adjacent to the black feature at Edif ERA showed no direct evidence of PD, however, due to the masking effect of the degraded black surface and deposited matter the possible presence of PD cannot be ruled out.

The concentrated variation in stress at the shoulders of the core insulation raises the possibility that this could result in the capture of mobile 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 a 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 or 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 relative permittivity than that of the cable insulation, i.e. of 2.3 (impregnating compound) to 3.5 (impregnated paper, are:

- Conducting particles and ionised air voids (high relative permittivity e.g. >1000).

- High permittivity matter such as:

    a. Water globules having a typical relative permittivity of 80.

    b. The yellow void-filling compound (which had a relative permittivity measured at Edif ERA of 11 to 12).

The dielectrophoretic accumulation of foreign materials has in the past resulted in failures within higher system voltage stop joints in oil-filled cables and within oil filled transformers.

The CCI Author concludes:

i) The most likely explanation of the black feature present on the surface of Core 2 of the unfailed transition joint is initiation by the dielectrophoretic accumulation of high dielectric permittivity material. The most likely candidates being yellow compound and water. Evidence of the presence of yellow compound was found by Edif ERA. Evidence of the presence of poor water seals in the joint was found by the CCI Author. Evidence that water can enter the trench was provided by the 2001 trench examination photographs, which showed that a) rain had entered the trench through the holes in and gaps between the roof slabs and b) the floor and lower parts of the wall were damp.

ii) The most likely mechanism of incipient electrical deterioration of the black feature is by local dielectric heating and degradation of the paper insulation (deterioration of the paper was observed by Edif ERA[6]).

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 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 slabs level with the ground surface.
- A combination of different heat transfer mechanisms:
  - Conduction through the cable internal materials.
  - 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 slabs.
  - 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 (finite element analysis) 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 21, Appendix F.

The algorithm method, which was quicker to compute, was judged to be sufficiently accurate. Both methods calculated closely similar temperatures.

- A co-simulation method that used Abaqus-Standard with Abaqus-CFD (computational flow dynamics) to simulate convection.
- Abaqus Standard that used algorithms to simulate turbulent convective heat transfer in-air.

The one hourly loading records for each circuit were provided by Vector and analysed. A number of possible loading scenarios was applied to the FEA models. The preferred 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 temperature and b) in winter with a 15°C ambient temperature.

The calculated temperature for each of the cables in winter is given in Section 21, Appendix F, Table 12.

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	Algorithm	Design
4C0	33 kV OF	St John Nº 2	59.2	59.3	85
3A0	11 kV PILC	McNab K02	58.2	58.0	65
4A0	33 kV OF	St John No 1	57.0	57.3	85
2C0	11 kV PILC	McNab K19	57.8	56.7	65
2D0	33 kV OF	Carbine Nº 1	53.8	52.0	85

Table 5 Summer: Highest Conductor Temperatures under Cyclic Loading

Cable			Conductor Temperatures [°C]	
Position	Type	Circuit	Algorithm	Design
2D0	33 kV OF	Carbine Nº 1	59.5	85
2C0	11 kV PILC	McNab K19	55.0	65
3C0	22 kV OF	Westfield No 2	54.5	85
3E0	22 kV OF	Westfield No 3	54.0	85
4A0	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
2D0	33 kV OF	Carbine Nº 1	52.0	59.5	85
2C0	11 kV PILC	McNab K19	56.7	55.0	65

The maximum winter temperature of the failed 3B0, 11 kV, PILC, Remuera K10 circuit in the last year in which it carried load current, and before the year in which became open ended, had a lower conductor temperature of 46.0°C. Its surface temperature was 43.0°C. The conductor temperature is satisfactory as it is below its temperature limit of 65°C.

The failed 3B0, 11 kV, PILC, Remuera K10 cable would have experienced temperature fluctuations from indirect heating by the other cables in its final year off-load. This would have generated thermo-mechanical expansion and contraction cycles, but of lower magnitude compared to the previous years when carrying load. The typical winter air temperature in the vicinity of 3B0 at peak load was 39°C (± 2°C).

The trench roof maximum surface temperature in winter was calculated to be 24°C (9°C drop to ambient) and in summer was 31°C (8°C drop to ambient).

8.3 Cable Temperature Conclusions

The CCI Author concludes that:

i) The operating temperatures of all the cable circuits and all the types of cables within the cable trench under cyclic loading in both the summer and winter seasons are satisfactory, being below their design limit temperatures:

   a. The operating temperatures of all the 11 kV PILC cables are satisfactory, being more than 7°C below their design limit of 65°C.

      i. The cables closest to their design limiting temperature are the 11 kV PILC cables 3A0 (7°C) and 2C0 (7°C).

      ii. The 11 kV PILC circuit that was the first to fail, 3B0, Remuera K10, had a satisfactory conductor temperature 19°C below its design limit of 65°C when it was last on continuous load in 2013.

   b. The operating temperatures of all the 22 kV and 33 kV OF cables are satisfactory, being more than 25°C below their design limit of 85°C.

   c. The 33 kV XLPE cables are satisfactory having the lowest conductor temperatures of all the different types of cable, being more than 45°C below their design limit of 90°C.

ii) The temperature calculations confirmed the reason that samples of XLPE cable insulation were found by Edif ERA to have experienced temperatures above their design limit of 90°C was not by overheating in normal service operation. The CCI Author thus concludes that the cause is overheating by hot air during the fire.

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 194[7] (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 44 and Figure 45, 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 transition joint insulation.

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 temperature of the trench air and hence the Remuera K10 cable would have fluctuated daily by approximately 20^{o}C. In the years prior to 2014 Remuera K10 had carried load current, but its surface temperature was calculated to have been only 4^{o}C higher.

It is considered that the thermo-mechanical flexing had disturbed insulation already at an advanced stage of distress and precipitated the electrical failure.

The CCI Author concludes 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 CCI Author the insulation of the transition joint is sufficiently robust not to be at risk of damage by direct vibration of small magnitude. However 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 CCI Author assessed this risk based on an FEA study[8] of the effect that traffic induced vibration has on the release of constrained thermo-mechanical cable forces in a cable duct installation. The CCI Author was the principal investigator of this study.

The FEA study[8] showed that a vibration velocity 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 CCI Author concludes that the vibration from the bus 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 laid 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 of the trench in the vicinity of the failure to be constructed, Figure 44. The view is of the two 11 kV PILC cables Remuera K10 3B0 and McNab K02 3A0.

All but one of the electrical fault holes are located between 67 m and 73 m; the exception is a failure in 4D0 at 50 m. Figure 44 shows the length of trench from 63 m to 85 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.

- 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 '3B0' is not changed). At 73 m (centre-line) the failed transition joint was located on Level 2 between cables 2A0 and 2B0. 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 45, that passed over circuits 2B0, 2C0, 2D0 and 2E- and overhung the trench access way, reaching its peak amplitude at 75 m. The loop rejoined its in-line position on Level 2 at 77 m. A second nominally identical transition joint was centred at 79 m on Level 2, which coincided with a 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 Level 3. Dissection of samples of the 3B0 11 kV PILC cable from 0 m 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 in 1965. It was not possible to determine if they were originally part of the same drum length.

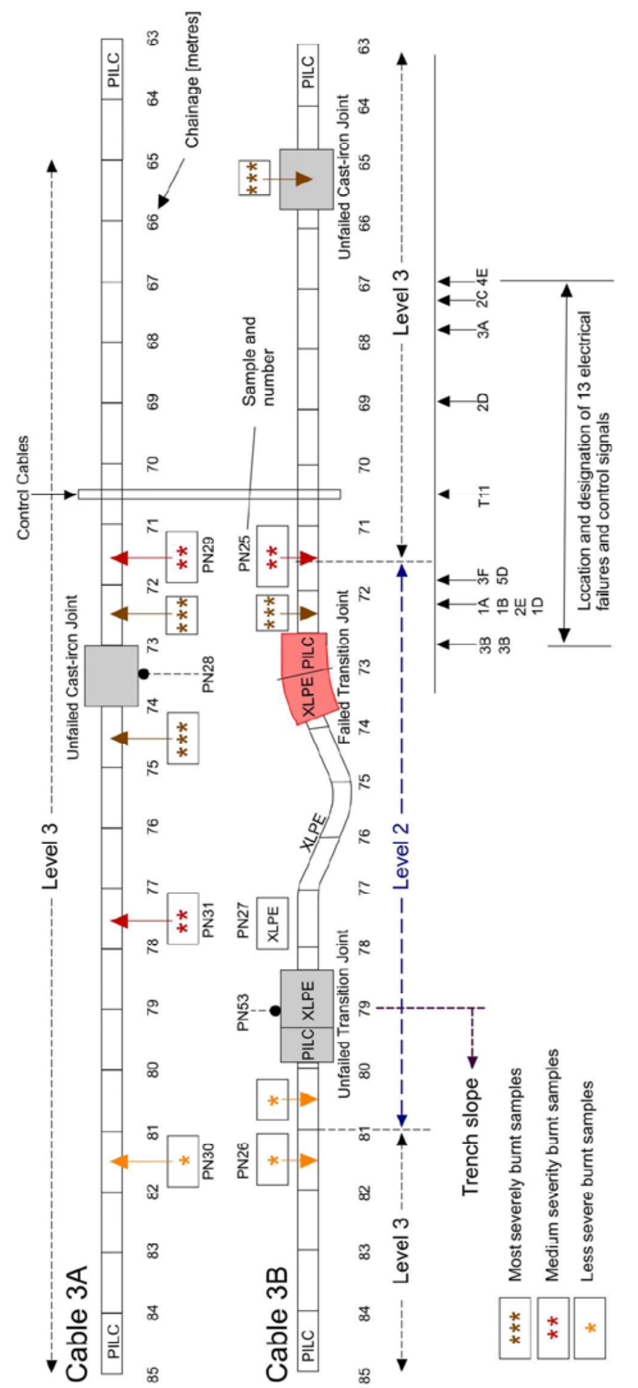


Figure 44 Diagrammatic plan view of the trench in the vicinity of the failed transition joint at 73 m chainage, showing positions of electrical failure and degree of burning damage.

Figure 45 Bow shape in the 3B0 11 kV three core XLPE cable

Figure 44 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-exiting 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 77 m 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 spacing of 13 m (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 rust, 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 the Cast Iron Joint in Remuera K10 Cable

It was interpreted that the bowed shape in Remuera K10, Figure 44 and Figure 45 had resulted from the replacement in 2001 of the cast iron joint in 3B0 at 78 m to 79 m, 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 would have 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 the jointer had pushed it and a 1.5 m length of adjacent new cable back into straight alignment with the northern wall in the 2B0 position. At the 73 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 the jointer could not push back to the north wall. The jointer 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 of, and crossed all 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 46, which plots elapsed time in minutes after the first fault at 23:21:30 on the 4th October 2014 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 broken 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 (2A0 and 4B0) do not produce obvious power arc damage and ii) a length of the 11 kV, XLPE, 35 mm^2, three core, tunnel supply cable, 2F0, 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.

Twenty 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.
    - 13 incidents:
        - 3B0 x 2, 11 kV PILC
        - T11 control cables x 2
        - 2A, pilot
        - 1AX, 33 kV XLPE
        - 1BY, 33 kV XLPE
        - 2F0, 11 kV XLPE
        - 2EY, 33 kV XLPE
        - 1DY, 33 kV XLPE
        - 4B pilot
        - 3FX-Y 33 kV XLPE
        - 3E0 and 3C0, 22 kV OF, de-energised

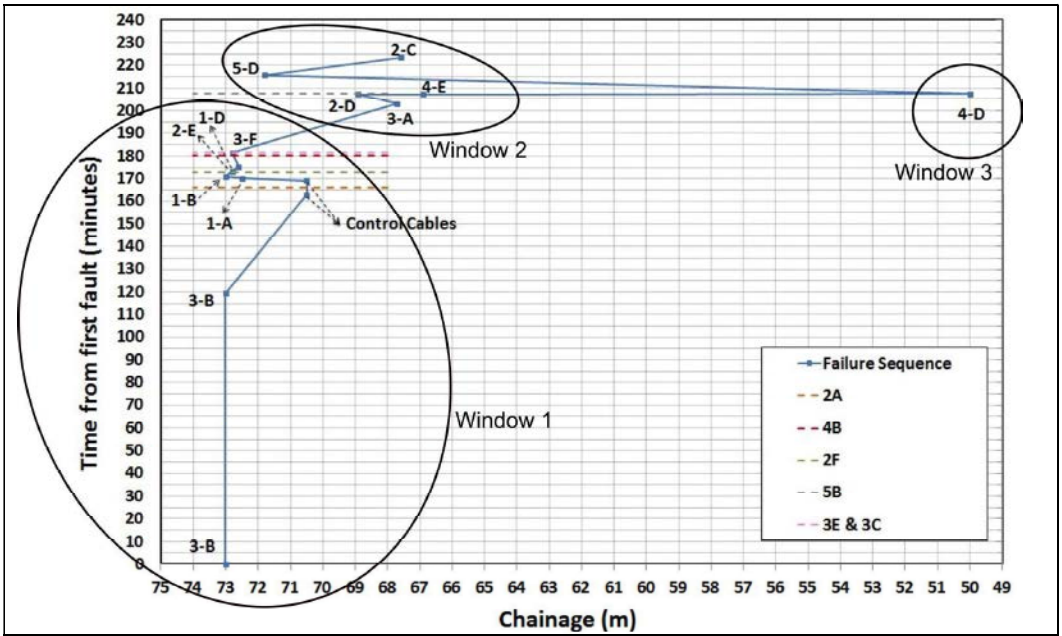


Figure 46 Fault sequence: Elapsed fault times versus their position in trench

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 11 kV 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:
        - 3A0, PILC
        - 2DO, 33 kV OF
        - 4EY, 33 kV XLPE
        - 5B-, 33 kV XLPE
        - 5DX, 33 kV XLPE
        - 2C0, 11 kV PILC

The second group has moved preferentially to the east of the first fault 3B0 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 the transformer transportation tracks. It is interpreted that this drop in level 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 level trench roof to the east than to the lower level trench roof in the west.

- Window 3:
  - 50 m.
  - 207.40 minutes.
  - 1 incident:
    - 4D0, 11 kV PILC

  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 the burning of 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 4D0 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 Section 19, Appendix D, and Figure 80 to Figure 113. 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 81

11 kV PILC 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 82

Occurred 119.32 min after the first trip. 11 kV PILC Remuera K10 faulted electrically for a second time in the PILC to XLPE transition joint when the circuit breaker (Remuera K10) 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 83, is common to the first and second faults, which are indistinguishable.

3rd Cable Incident, T 11 Control Cables, Diagram in Figure 84

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 47, and supported the control cables on lateral metal hangers. Thus the control cables were exposed 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 47 Control cable bridge at 70.5 m (photograph taken in 2001)

4th Cable Incident, 2A, Diagram in Figure 85

Occurred 2.98 min later. A differential protection blocked signal was received from the Carbine pilot cable, 2A, 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 86

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 87

Occurred 0.95 minutes later. 33 kV XLPE Remuera 3, 1AZ, 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 3B0). The arc crater is shown in Figure 88. 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 1429[9] as being optional for single core cables and mandatory for multi-core. The outer sheath is PE, which has an oxygen index of 18% as shown in Table 7 and therefore can sustain and propagate combustion. (The oxygen index is the lowest percentage of oxygen at which combustion of the material can be sustained. The percentage of oxygen in air is 21%.) The inner sheath is PVC, which has an oxygen index of 47% which is greater 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 cable sheathing grades of PVC contain a plasticiser and do burn at elevated temperatures in the presence of flame and heat. PVC sheaths also produce 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 XLPE cable insulation 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^{o}C. XLPE changes state from a hard white semi-crystalline plastic at 107^{o}C to a soft transparent elastomer. The temperature at which XLPE degrades and loses its insulating properties is taken to be greater than 250^{o}C (for cable short circuit rating purposes).

7th Cable Incident, 1BY, Diagram in Figure 89

Occurred 0.87 minutes later. 33 kV XLPE Newmarket 3, 1BY, faulted and tripped. This cable is next to the previous cable to have tripped 1AY and is above the transition joint 3B0. The arc crater is shown in Figure 90.

8th Cable Incident, 2F0, Diagram in Figure 91

Occurred 2.00 minutes later. 11 kV XLPE Vector Tunnel Power Supply, 2F0, three core cable faulted and tripped. The location of the fault was not found as the small 35 mm^2 copper conductor had melted. It is deduced to have been 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 2F0 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 92

Occurred 0.27 minutes later. 33 kV XLPE Carbine Road 2, 2EY, at 72.8 m, faulted and tripped. The arc crater is shown in Figure 93. It is likely that the PVC duct 1C and XLPE cable 1D were alight and that burning polymer had fallen below them onto 2E in Level 2.

10th Cable Incident, 1DY, Diagram in Figure 94

Occurred 1.97 minutes later. 33 kV XLPE Remuera 2, 1DY, at 72.6 m, faulted and tripped. The arc crater is shown in Figure 95. 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 the energy from the power arc would have accelerated the demise of 1DY.

11th Cable Incident, 4B, Diagram in Figure 96

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 dripped and spread fire downwards.

12th Cable Incident, 3FY-Z, Diagram in Figure 97

Occurred 1.17 minutes later. 33kV XLPE St Johns 3, 3F- circuit faulted and tripped at 72.3 m. The first fault was recorded as blue phase to earth for 0.061 s and red and blue phases to earth for 0.979 s. It was deduced that the power arc from the blue phase cable had emerged from between the screen wires and had burnt into the adjacent red phase cable causing it to fault to the earthed screen wires. The arc burning was found in two of the single core cables, Y and Z, which had been cut out separately for examination. The arc burning in cable 3FY is shown in Figure 98 and was recorded to be at 72.8 m. A closely similar arc burn was present in 3FZ at 72.35 m. The difference in position of 450 mm was taken to be a measuring/cutting error and so a common position of 72.3 m was taken. 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 99

Occurred at the same time as incident 12. 22 kV OF Westfield N° 2 and N° 3, 3E0 and 3C0, were de-energised when Penrose 33 kV to 22 kV transformers tripped for the 33 kV St John 3 fault. These OF cables did not fault.

14th Cable Incident, 3A0, Diagram in Figure 100

Occurred 21.93 minutes later. 11 kV PILC McNab K02, 3A0, 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 between incidents (after the 4th incident) has increased from less than 5 minutes to 21.93 minutes. One reason is that the five circuits of faulted XLPE cables (fifteen single core cables in total) adjacent to 3B0 will continue to burn and 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, 3A0, is thermally damaged and faults.

15th Cable Incident, 2D0, Diagram in Figure 101

Occurred 4.0 m minutes later. 33 kV OF Carbine N° 1, 2D0, at 68.9 m, faulted and tripped. This was the first oil-filled cable to fail in the cable trench. The arc crater is shown in Figure 102. The fault position is 4.1 m eastwards from the centre of the failed transition joint and 207.2 minutes after it. The long survival duration of the OF cable is significant 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 to a value capable of bursting the aluminium sheath. The sheath would become plastic and its hoop strength reduce before the temperature approached the melting point of 660°C (aluminium sheaths are typically extruded at 425°C). The sheath is therefore likely to burst at a mechanically weakened 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 cable oil and vapour into the fire would spread the fire along the trench and underneath the cables and so significantly increase the fire intensity.

16th Cable Incident, 4EY, Diagram in Figure 103

Occurred 0.07minutes later than 2D0 above. 33 kV Mt Wellington No 2, 4EY, XLPE cable at 66.9 m, faulted and tripped. The arc crater is shown in Figure 104. This cable would have experienced burning PE from 3F above it, which had faulted 26 minutes before.

17th Cable Incident, 5B-, Diagram in Figure 105

Occurred 0.13 minutes later. 33 kV Mt Wellington No 1, 5B, XLPE cable, 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 106

Occurred 0 minutes later (at 207.40 minutes), at the same time as the previous incident, 5B, 11 kV PILC Mt Wellington K05, 4D0, at 50 m faulted, as shown by the arc crater in the conductor in Figure 107. 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 207.40 minutes.

19th Cable Incident, 5DX, Diagram in Figure 108

Occurred 8.32 minutes later. 33 kV XLPE Sylvia Park No 2, 5DX at 71.8 m, faulted and tripped. The arc crater is shown in Figure 109. This cable had been laid in the access way. It failed close to the fault in the OF cable 2D0 at 68.9 m, which had faulted 9 minutes before.

20th Cable Incident, 2C0, Diagram in Figure 110

Occurred 7.77 minutes later. 11 kV PILC McNab K19, 2C0, at 67.9 m, faulted and tripped. The arc crater in the armour tape is shown in Figure 111 and in the conductor in Figure 112. The long survival duration of this PILC cable of 223.48 minutes is significant 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 cable is effectively adjacent to (1 m to the east) the faulted OF cable 2D0 at 68.9 m. It failed 16.28 minutes after cable 2D0. 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.

21st Cable Incident(s), Diagram in Figure 113

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 circuit 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 knitmesh 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 knitmesh 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 and elastomeric 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 1,085°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 flash ignition temperature of PE (XLPE) is taken to be 349°C and the flash ignition temperatures of other typical polymeric materials is approximately 350°C, Table 7[10].

A study in Section 22, Appendix G, 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 of the fault energy converted into heat, a temperature of 3,000°C was estimated. 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 CCI Author concludes that the power arc fault had ignited the fire.

Table 7 Ignition and combustion properties of common materials

Material	Flash Ignition Temperature (°C)	Self-Ignition Temperature (°C)	Limiting Oxygen index (% 0_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

The key difference between the installation of cables in-air 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 would previously have been destroyed and occupied by an air-filled void surrounded by electrically conducting materials, such as droplets of metal, 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 CCI 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 loop[22]. 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 21, 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 earth return conductor 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 one or more arcs loop it was noted that:

i) The primary and most severe conductor arc damage was phase-to-phase (initially two phase and later three phase, Table 16).

ii) The secondary and less severe arc burning on the earth conductors was located towards the centre of the joint and was not directly in line with the primary arc cavities in the main conductors at the end of the joint. The electrical protection did identify an earth fault for both operations.

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 33 kV Switch Room. Section 16, Appendix A, shows the hourly CCTV photographs and analyses the progression of the fire in Table 9:

- Figure 60. 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.

- Figure 61. 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.

- Figure 62. 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 minutes and 71.40 minutes after the second fault.

- Figure 63. 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 trench 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 outer sheaths (XLPE cable).
  - Non-fire performance PVC:
    - Cable inner sheaths (XLPE cable).
    - Cable sheaths (pilot cable).
    - Cable sheaths (oil filled cable).
    - Data cable duct.
  - Bitumen:
    - Impregnated hessian outer served PILC cable.
    - Coated aluminium sheathed OF cable.
  - 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 had been ignited by the first power arc, but had burnt slowly. The fire had been accelerated by the second power arc, but had still propagated slowly. These deductions were based upon:

i) The review of publications and information on the investigation of cable fires (Section 23, Appendix H) of PVC and 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 (greater than 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 materials present in a service.
d. Test cables vertically, this having been found to be the most vulnerable orientation both in service and on test for flame propagation.

ii) The formal type testing standard for cables having low propagation properties (e.g. IEC 60332-3-10[1], IEC 60332-3-24[2] and the FIPEC report 'Fire Performance of Electric Cables'[11] in the experimental variables that were embodied into the test requirements.

iii) Informal, qualitative fire trials that 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 simulated 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 flame.

b. In the cable trench the fire transferred progressively to all the cables except some of those located on the floor. Figure 48 simulates 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 48 33 kV XLPE cables: Ignition of two cables with gas torch

c. In the cable trench the flames propagated long distances in both directions. Figure 49 shows flame starting to propagate along the PE/PVC oversheath of a single core 33 kV XLPE cable after the heat source in Figure 48 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 mechanism 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 49 33 kV XLPE cable: Flame propagating and PE dropping

Figure 50 shows that the oversheath of the Figure 49 sample had been combusted to expose the copper wire screen. The extruded XLPE core, also combustible, is visible between the wires.

Figure 50 33 kV XLPE cable: Oversheath combusted

d. If a fire condition in-air occurs having a source of ignition, threshold temperature and critical volume of combustible material, the burning cable will contribute its own heat output and the fire will become self-sustaining and self-propagating. The cable trench contained a significant volume of combustible material per metre length as given in 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 the circuit 1A- of 33 kV XLPE single core cables in trefoil formation was present above the failed transition joint. The trefoil formation geometrically concentrates both an increased volume of combustible material and an increased surface area to absorb heat and to contribute flammable gasses. The volume of combustible material in one trefoil group of 33 kV 400 mm^2 XLPE cable was calculated to be 4.7 L/m. Figure 51 simulates the ignition and flame propagation of a trefoil cable group after the heat source had been removed.

Figure 52 shows the trefoil group after the flames were extinguished. The oversheath comprising an outer layer of PE and an inner layer of PVC had been combusted to expose the copper screen wires. 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 51 33 kV XLPE trefoil group: Flame is sustained

Figure 52 33 kV XLPE trefoil group: Oversheath combusted

f. Qualitative fire trials performed on a PVC oversheathed 33 kV OF cable, Figure 53, 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 i) in the early fire stage bitumen leaked from the interface between the oversheath and aluminium sheath and sustained flame ii) in the later fire stage cable oil leaked from the ruptured aluminium sheath 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 simulated those locations of intense fire in the trench where the aluminium sheath was seen to have been melted and ruptured. Figure 54 shows the burnt PVC oversheath, the anti-corrosive bitumen layer and the aluminium sheath, exposed and melted.

Figure 53 33 kV OF cable: PVC sheath burning with gas torch

Figure 54 33 kV OF cable: Oversheath burnt and aluminium sheath melted

12.3 Fire Initiation Conclusion

The CCI Author concludes:

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 were 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 firefighting. 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. The 33 kV XLPE cable design present in the trench is a common design of modern cable that is most often used in buried laid-direct applications. The cable design is described and illustrated in Section18.3, Appendix C. 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 46. Remuera N° 3 was the first at 170.15 minutes. The fifth cable was St Johns N° 3 at 181.27 minutes. The 11 kV XLPE Tunnel Supply circuit also faulted in this time. In total 12 of the 13 incidents in Window 1 were of cable faults and damaged control cables.

The poor fire performance of the PE sheathed, wire screened and XLPE insulated cable circuits is attributed to:

1. Location: The first three circuits to fail were mounted on Level 1 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 layer of cables in Level 4.

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 metallic coverings 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’, described in reference[12], 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.

In the CCI 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, 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. Available 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).

13.1.2 Oil-Filled Cables

PVC Oversheath and Extruded Corrugated Aluminium Sheath.

The cable design is described and illustrated in Section18.2.1, Appendix C.

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, 3B0, 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 102. 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 56.

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 55, the aluminium sheath of 4C0 had suffered a major rupture, Figure 57. It is thought that this occurred late in the fire sequence as 4C0 was manually opened without failure 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, 4A0 and 4C0. Their survival may be partly attributable to their low position in the trench on Level 4.

The two 22 kV OF Westfield circuits 3C0 and 3E0 did not fail, but were de-energised at 181.27 minutes when the Penrose 33/22 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, high thermal conductivity 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. There was no record of received oil alarms warning of low oil pressure, this being attributed to the early fire damage incidents to the pilot cables which carry a signal from oil pressure contact gauges when pressure falls below a pre-set level.

In consequence, burning cable oil did not increase the cable repair time for the outage as the majority of cables had already suffered fire damage. In different circumstances, for example if the first electrical fault had occurred in an OF cable, oil released is likely to have 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 that when the temperature exceeds 400^{o}C gases are liberated from the plasticiser that make PVC highly flammable. It was for this reason and the experience of fires involving the combustion of PVC cables[29] reported in Italy, Scotland and the USA that the CEGB (Central Electricity Generating Board, UK) encouraged the development[30] of oversheathing and insulating materials having low smoke and fume emission and reduced flame propagation, (Section 23, Appendix H).

Figure 55 High fire intensity at 37 m (33 kV XLPE cables on Level 1)

Figure 56 Holes in OF cable aluminium sheath, cable 2D0 at 66 m to 71 m

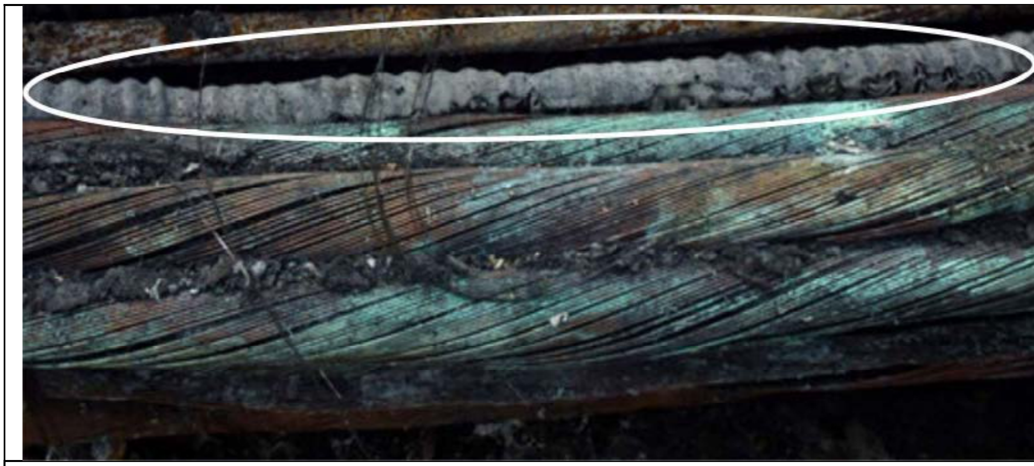


Figure 57 Heat deformed and ruptured OF cable corrugated aluminium sheath

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, and could not, spread fire by the release of a large volume of flammable cable oil. The cable design is described and illustrated in Section18.1.1, Appendix C.

In particular:

i) Three PILC circuits survived until faulting after 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 at 2D0 high up on the second layer near to the faulted 3B0, Remuera K10 PILC to XLPE transition joint.

The good fire survivability is attributed to the two robust layers of steel tape armour (high melting point and high thermal capacity), the good high temperature performance of the paper insulation, its low insulation design stress and the exclusion of oxygen from inside the lead sheath. The downside of PILC cable fire performance is that the lead sheath melts at a relatively low temperature compared with aluminium 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.

The CCI Author concludes 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 eastwards 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 surviving copper screen wires and aluminium conductor wires had been burnt clean. This was not so to 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. It had emerged out of the trench exit and the above-ground cables were burning 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 the 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 switchyard had been de-energised. The Fire Service reported that fire was moving eastwards inside the trench.

The most severe fire damage to cables was seen to have 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 trench 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 had exited to run above ground to the 33 KV Switchroom. These cables 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 was available above ground. 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 sunshield ducting that was open at the 33 kV 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 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 CCI Author's knowledge are presented in Section 23, Appendix H. The items are presented in ascending date order. The Appendix H publications are divided into:

- Subsection 23.1: Cable fires and fire performance.
- Subsection 23.2: 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 (International Conference on Electricity Distribution) papers. (The conferences are held at two yearly intervals, the first having been in 1971. Cable papers are included in the Session on 'Components'.

2. Jicable (International Conference on Insulated Power Cables) papers. The conference is held at four yearly intervals and specialises in power cable matters at all voltages.

3. CIGRE (International Conference on Large High Voltage Electric Systems) 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 regional conference papers. Conferences are held in different countries, usually on speciality topics of 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 is summarised 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 Apparatus and Systems' and 'Transactions on Dielectrics and Electrical Insulation'.

8. IEE papers. Until 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 a 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. 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 period for 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 are:

    a. Ignition source external to cable system:
        i. Fires on a railway embankment, as in the 10 kV 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 or termination, *[CCI Author: as in the Penrose fire].*
        i. PVC cable fire in a cable annex of La Spezia Power Station Italy, ignited in an MV cable termination chamber: 1967
        ii. 400 kV Woodhead Tunnel, two occasions, one was initiated by a stop joint failure 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 still under investigation:
        i. China: 'data collected from many accidents'.
        ii. Kingsway, London, Utilities tunnel shared with gas main: 2015.

[CCI Author: The fire at La Spezia in 1967, CIRED publication[28] date of 1974 and IEE publication[29] date of 1977 are the key dates that alerted UK Engineers to the risk of PVC cable fires and which 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 overview 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 incident, ii) guidance on the selection of fire performance cables for new applications and iii) guidance on remedial actions to improve fire performance of 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 bench-top samples containing only the base PVC compound heated to a low fire temperature. *[CCI 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 1960s and 1970s 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, iii) the grouping of the number of cables to be installed and iv) the volume of flammable material.
    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 was still 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. *[CCI Author: all of the 33 kV S/C XLPE*

cables had non-fire performance HDPE outer sheaths and XLPE insulation]. The normal unfilled sheathing grade of MDPE/HDPE was historically 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 does 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. *[CCI 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 exit of the trench to connect the different fire performance 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 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 met 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 type of ignition source, the length of time the cable is heated, 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 voltage onto the failed circuit. *[CCI 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 been admitted into the joint 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 in the presence of air to have accelerated and increased the severity of the cable fire.]*

14.3 Recommendation from the Publication Review

From the publication survey the CCI 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 (Standards are summarised in Section 23.2) 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 risk to personnel.
        ii. Aid the Fire Service in fighting the fire.
        iii. Reduce the risk of substation insulator damage and flash-overs.
        iv. Reduce the risk of damage to monitoring equipment.

2. To apply an approved layer of fire protective coating if cables with fire performance oversheaths are unsuitable for the particular application. The coating should be performance validated.

3. To exclude XLPE to PILC belted cable transition joints. The circuits for installation into a new trench should be planned to use new XLPE cable types with fire performance oversheaths. Obsolescent cable designs, such as three core, unscreened belted, PILC cable type should not be installed into a new trench and so the type of transition joint present in the 3BO 11 kV Remuera K10 circuit would be unnecessary.

4. Where possible to exclude or minimise the number of straight joints. Straight joints are less vulnerable to failure than three core transition joints, but are more vulnerable than the cable.

5. If straight joints are unavoidable, to select a joint design having fire retardant materials and to install it within an arc resistant environment. The objectives are to:
    a. Achieve flame self-extinction by the use of fire retardant jointing materials and so prevent internal and external fire spread.
    b. Limit the size of the arc rupture hole and so limit the entry of air into the joint. *[CCI Author: The experience of spiking tests on cables is that it may not be possible, or wise, to aim to completely contain an arc of high current magnitude within a strengthened joint shell.]*
    c. Protect adjacent cables from ignition directly by the arc and indirectly from a joint fire by the use of suitable spacing and fire retardant cable materials.

    Suitable performance targets for a straight joint design for installation in-air are:
    a. Demonstrate a consistent electrical, mechanical and watertight test and service performance with time and so reduce the risk of an electrical failure.
    b. Reduce the degree of emergence of the power arc following burn-through of the earth return conductor by providing an ERC (earth return conductor) that:
        - Is uniformly distributed around the joint circumference.
        - Has the same, or greater, cross sectional area per unit of circumference than the area of the cable i.e:

          $A_j \geq \frac{D_j}{D_c} A_c$

          where:

          A_j : area of joint ERC
          A_c : area of cable ERC
          D_j : diameter of joint ERC
          D_c : diameter of cable ERC
    c. Pass the requirements of a suitable short circuit spiking test e.g:
        - Limiting distance for arc emergence.
        - Limiting distance of ERC burn-back.
        - Demonstrated zero flame or flame self-extinction.

6. Not to close voltage onto a failed circuit without taking precautions to mitigate the risk of fire ignition and propagation. 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 CCI Author concludes that the cause of the fire in the Penrose trench was the electrical failure of the PILC to XLPE cable transition joint in the 11 kV Remuera K 10 PILC cable circuit located at 73 m chainage from the reference position at the Gavin Street end.

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 CCI 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. 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 CCI 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 CCI Author was aware that transition joints had a higher failure rate than conventional PILC straight joints. The CCI 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 11 kV 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. Some technical publications have deduced that the qualitative failure rate of transition joints is higher than straight joints.

The CCI 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 contaminated with foreign material, which included yellow void-filling compound and possibly moisture.

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 CCI Author considers the contributory causes of the 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 the finding in the unfailed transition joint:

   a. The stain-like, water pattern of the black feature in the crutch of the unfailed joint.
   b. Lack of a water seal between the outer heat shrink protection sleeve and the PILC cable hessian serving and armour tapes.
   c. A narrow and prospectively incomplete width of mastic water barrier between the lead sheath and the outer protective heat shrink sleeve, this being located in the gap between two of the roll springs.
   d. Incomplete adhesion of the void-filling compound to the lead sheath within the breakout glove.
   e. Incomplete distribution of adhesive between the sealing sleeve, the breakout glove finger and the PILC core screening sleeve.

iii) Drying-out of the cable impregnating compound from the paper insulation. This conclusion was supported by the finding of dried-out and thermally degraded insulating tapes within the heat shrink barrier insulating sleeve 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 compound material into the paper insulating tapes in the crutch. This was supported by the analysis of identical material in the black feature at the crutch position.

v) The jointing process of inserting 'void-filling compound' insulation into the PILC crutch of the transition joint, this being difficult for the jointer to consistently accomplish and risked damage to the cable insulation. This was supported by the findings of the dissection of the unfailed joint.

The CCI Author recommends that:

i) The location of other XLPE to PILC transition joints installed in air on the network be reviewed and risk assessed.

ii) Alternative and improved designs of XLPE to PILC transition joints be assessed for future use.

iii) Future transition joint designs and jointing processes be made more consistent with respect to a) the water seals and b) the PILC crutch insulation (void-filling compound).

iv) Failure statistics for transition and straight joints be compiled and regularly reviewed.

15.3 11 kV PILC to XLPE Transition Joint

The CCI 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. Conventional (and now obsolescent) PILC straight joints having an inner lead sleeve and a cast iron protection box inherently had a limited capability to contain a power arc of low current magnitude. The heat shrink sleeve straight joints on XLPE cable that were observed in the cable trench did not appear to have a capability of withstanding a short-circuit spiking test nor of exhibiting fire retardancy. For example i) the ERC continuity conductors were not uniformly distributed around the circumference, ii) the copper knitmesh screening tape did not have sufficient cross-sectional area to prevent arc burn-through and iii) the polymeric heat shrink sleeves inherently had a lower temperature limit and lower strength capability compared to the temperatures and forces generated by a power arc.

The CCI Author recommends that for in-air applications, a technical specification is prepared for transition and straight joints, which includes a demonstrated power arc containment test (a 'spiking' test) and a fire propagation test.

The CCI 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 CCI 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 below).

The CCI 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 this type of transition joint. The vulnerability risks identified with the particular heat shrink sleeve transition joint design at Penrose were:

i) Susceptibility to thermo-mechanical disturbance in the crutch region.

ii) Water entry into the paper insulation due to inadequate water seals.

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.

vi) Deterioration of the electrical contact faces on the lead sheath ERC by corrosion.

vii) The ERC was not distributed uniformly around the circumference.

viii) The joint materials did not have obvious fire retardancy properties.

ix) The joint materials did not have the capability of containing, or partially containing, a power arc.

15.4 Cables

Twelve circuits of the older generation of 11 kV PILC cables and 22 kV and 33 kV OF cables were installed in the Penrose trench from 1966 to 1977 and nine were 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 2012 (9 at 33 kV and 1 at 11 kV) and operated up to 2014.

15.4.1 New XLPE Cables

The CCI 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 CCI 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^{o}C can propagate fire.

vi) Oil-filled cables were a fire-spread hazard for in-air applications.

However, the CCI 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.

The CCI Author recommends 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 CCI 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 CCI Author considers the choice of cable types in 1966 to have been reasonable; i.e. i) 11 kV PILC cables with bitumen impregnated, hessian serving, steel tape armour and lead sheaths and ii) 22 kV 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 CCI 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 CCI Author considers that feeders should not be reclosed onto a cable fault, without:

i) Having confirmed that the fault was not present in an in-air trench section.

ii) Taking precautions to manage the risk of fire ignition and propagation.

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 CCI Author understands that reasonable measures had been taken after the first fault in the 11 kV 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 CCI 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 CCI 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 CCI Author recommends that risk assessments be performed on in-air installations to identify the likelihood and consequences 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 CCI Author considers the Penrose cable trench to be a significant in-air application based on it containing:

i) 19 operational power cable feeders.

ii) 37 operational lengths each of 105 m with a total combined cable length of 3.89 km.

iii) 15 joints (4 x 11 kV PILC, 3 x 3 x 33 kV XLPE and 2 x 11 kV PILC/XLPE).

iv) A volume of 84 L per metre length of trench of flammable material comprised of oversheathing and hydrocarbon insulation and low viscosity cable oil in the cable (and additionally within the oil reservoir tanks).

The estimated, cumulative number of cable and joint faults for the Penrose cable trench of 1.2 to 1.5 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.

   If the fault rate for transition joints is taken to be 5.5 times greater than all joint types then the indicative number of transition joint failures would be 0.4 and the total number of all joint failures 1.2.

ii) The indicative number of cable faults is calculated to be 0.5 by taking the number of feeders to be 19, each of 105 m length, and taking the time in service for each cable 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 Vector fault rate value resulted from external damage to buried cables, for example by third party dig-ins13. Thus the indicative number of internal cable faults attributable to internal causes would be 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/Crow Amsaa (US army material systems analysis activity) to determine if progressive wearout of the more vulnerable and aged components is in progress.

Limited fault data for 60 kV and above may be found from CIGRE Technical Brochures such as TB 379[13], 2009, (until recently CIGRE has limited its studies to system voltages of 60 kV and above; this limit has since been removed). Limited information may be found from conference publications such as the 2011 CIRED paper[14] from the Danish Energy Association. The latter describes limited fault statistics from MV cable systems and has a section on transition joint failures. The paper includes the qualitative comment that '… 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 physically 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 or delayed 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 deduced that the fire was extinguished before it spread into this trench.

The CCI Author considers that timber should not have been used in place of some of the concrete roof slabs, as timber is flammable. As a result 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 CCI 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 CCI 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 of existing circuits.

iii) A circuit on the ground in the access way.

The CCI Author considers that in-air cable installations should provide for:

i) Fire and power arc separation between power cable circuits.

ii) Limiting the mass of flammable materials to a defined level.

iii) Physical segregation between control and power cables.

iv) Adequate separation between cables to ensure good air ventilation.

v) A strategy for cable repair i.e.

   a. Removal method for damaged or obsolescent cables.
   b. Approved joint types, layout of the joint area, joint clearances to other cables and the method of fixing and supporting joints.

vi) Clear access for maintenance and repair works.

vii) Fire seals at cable exits and entries.

The number of cables in the cable trench is considered to have been too many as it would have precluded items i), ii), iii), iv), v) and vi).

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 CCI Author has seen evidence 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. In the CCI study the air temperature within the trench was calculated using an FEA computational flow dynamics model of air convection and ventilation and was found to be critically dependent on whether the loading was sustained (air temperature range of 43°C to 59.6°C in summer), or cyclic (30°C temperature of trench roof in winter and 36°C in summer).

The CCI Author recommends 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 temperate sensing) system, that uses either an optical fibre or a thermo-couple sensor.

15.6.5 Thermo-mechanical Installation Design

15.6.5.1 Joint Supports

The CCI 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 adequately supported before the fire). Heat shrink sleeve, single core, XLPE cable straight joints are lighter in weight and are not always supported.

The CCI Author recommends that 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 CCI Author notes that cable cleats had not been installed on the cable support arms to fix the 4E, 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.

Electrically insulated cleats and support arms are advised for in-air applications to prevent a power arc passing current through them and igniting other cables. Evidence was found in the trench that the power arc had struck and damaged a steel support frame. Short circuit spiking tests have shown that a power arc emerging from a faulted cable is capable of striking and overheating support metalwork and cleats.

15.7 Other Findings from the Joints and Cables in the Penrose Trench

In Section 15.2 the CCI Author concluded from the examination of the unfailed transition joint that the jointing quality was satisfactory. The following items 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 compression connection was found. It is noted that this type has 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 CCI Author recommends that accessories employing roll spring current connections be identified and mitigating measures taken, noting that:

a. If a normal through-fault current passed through the earth return conductor 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 that are present 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 advised that joints for in-air applications have an ERC that is uniformly distributed around the circumference to contain, or partially contain, a power arc).

vi) 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 CCI 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 70oC, in place of the specification maximum design limit of 90oC 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 despatch drum numbers and installed location be added to the circuit records.

Severely corroded steel armour tapes were found on the PILC cables in some locations in the trench. Corroded tapes prospectively reduce 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. Severely corroded steel tapes also prospectively reduce the fire survivability time of the lead sheath before it melts and admits air and flame to the insulation within.

CCI Author

Brian Gregory

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. The position of the camera is shown in Figure 1. For reference, the daylight location of the equipment in the switchyard is shown after the fire had been extinguished in Figure 58. Note: the time stamp on the bottom left hand corner of the photograph is one hour earlier than local time.

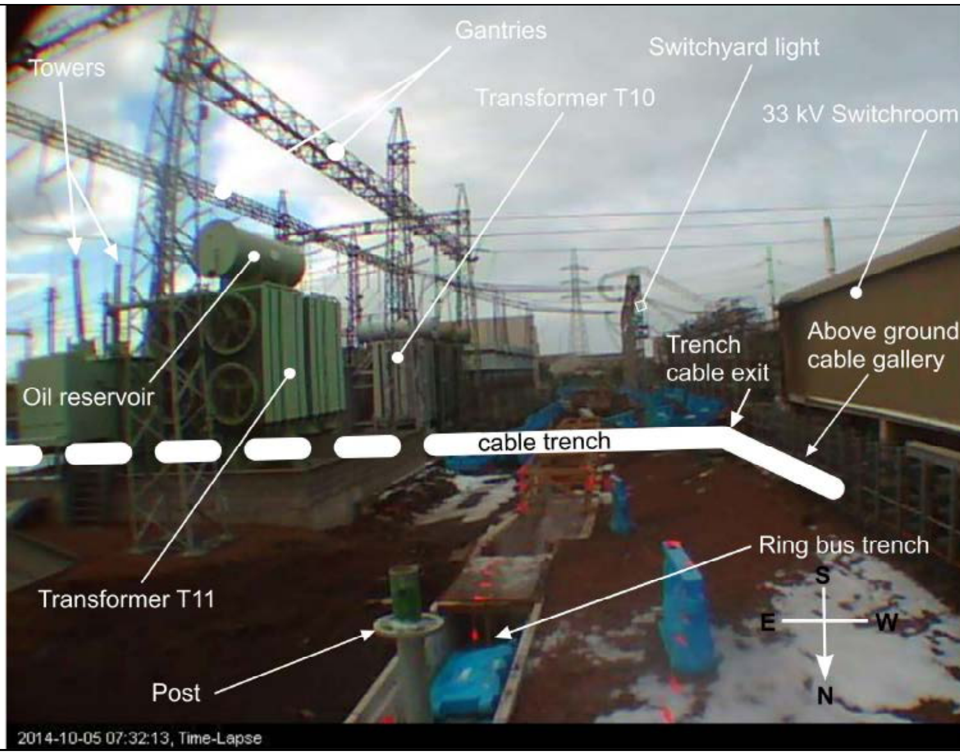


Figure 58 CCTV at 08:32:13, after the fire had been extinguished

Table 9 summarises the analyses of five of the images over a four hour period from 10.72 minutes after the first fault (Figure 59) to 250.72 minutes after (Figure 63).

Table 9 Summary of observations from CCTV images

Observations	CCTV Security Camera Photographs				
	Figure 59	Figure 60	Figure 61	Figure 62	Figure 63
Time after 1st Fault [min]	10.72	70.72	130.72	190.72	250.72
Time after reclose and 2nd 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
Reflections from towers	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 33 kV 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

In Figure 59, 10.72 minutes after the first fault, there are clear reflections of the substation lights from the sides of transformers T10 and T11, the T11 oil reservoir, the 33 kV Switchyard building and the gantries. There is no sign of loss of vision due to smoke. The feature in the centre of the lens is believed to be an insect. A residual smudge from the feature is present in the later photographs

Figure 59 CCTV at 23:32:13, 10.72 min, after 1st fault: sharp reflections off T11 side and expansion tank and off side of T10.

The observations in Table 9 for Figure 60 record that smoke had obscured both clarity of view and some of the reflections from the Switchyard lights on the sides of the T10 and T11 transformers. This indicates that at 70.72 minutes after the first fault and 48.60 minutes before the second fault occurred i) some degree of combustion had occurred after the first fault and ii) that fire was in progress.

Figure 60 CCTV at 00:32:13, 70.72 min after 1st fault: View of T11 and T10 become obscured. Reflection on T10 obscured. Reflection off T11 is dull.

There was further loss of light transmission at 130.72 minutes, Figure 61, some 11.40 minutes after the reclose onto the fault. A green haze had dulled the light and the reflections. No evidence of light from the fire or of dense smoke could yet be seen.

Figure 61 CCTV at 01:32:13, 130.72 m, after 1st fault, 11.4 m after 2nd: general green haze.

At 190.72 minutes after the first fault and 71.40 minutes after the second, Figure 62, there was clear evidence of:

- A mauve 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.
  - The busbar gantries that passed over the trench.
  - The towers to the left of transformer T11.
  - The side of the 33kV switchroom building.
- A smoke halo around the Switchyard light.

The fault sequence in Figure 46 shows that the majority of the cable failures had been localised around 73 m chainage and were the moving eastwards towards Gavin Street (i.e. to the left in this photograph).

Figure 63 shows that at 250.72 minutes after the first fault and 131.40 minutes after the second, the fire had emerged out of the west end exit of the trench and was close to reaching the corner of the 33 kV Switchroom. The field of view contains dense smoke. Additionally the fire had already travelled from the faulted transition joint at 73 m a distance of 23 m to the east towards Gavin Street. The last cable to fault, 11 kV PILC McNab K19, 2C0, had already faulted at 223.48 minutes after the first fault.

Figure 62 CCTV at 02:32:13, 190.72 min after 1st fault, 71.4 min after 2nd: mauve light reflections of fire between and above T11 and T10. Halo of smoke.

Figure 63 CCTV at 03:32:13, 250.72 min after 1st fault and 131.4 min 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 33 kV
PN2	1DY	1	17/10/14	1c 800mm^2 Al XLPE 33 kV
PN3	1DZ	1	17/10/14	1c 800mm^2 Al XLPE 33 kV
PN4	1BX	0.5	17/10/14	1c 800mm^2 AL XLPE 33 kV
PN5	1BX	0.3	17/10/14	1c 400mm^2 AL XLPE 33 kV
PN6	1BY	1	17/10/14	1c 400mm^2 Al XLPE 33 kV
PN7	1BZ	1	17/10/14	1c 400mm^2 Al XLPE 33 kV
PN8	1AX	1	17/10/14	1c 800mm^2 AL XLPE 33 kV
PN9	1AY	1	17/10/14	1c 800mm^2 AL XLPE 33 kV
PN10	1AZ	1	17/10/14	1c 400mm^2 AL XLPE 33 kV
PN11	5DX	1	18/10/14	1c 400mm^2 AL XLPE 33 kV
PN12	5DY	1	18/10/14	1c 400mm^2 AL XLPE 33 kV
PN13	5DZ	1	18/10/14	1c 400mm^2 AL XLPE 33 kV
PN14	2B0	1	17/10/14	3c 300mm^2 AL PILC STA 11 kV
PN15	2C0	1	17/10/14	3c 300mm^2 AL PILC STA 11 kV
PN16	2D0	1	17/10/14	3c 300mm^2 AL OF PVC 33 kV
PN17	2A	1	17/10/14	25c 9+16 PILOT
PN18	2F0	1	17/10/14	3c 35mm^2 AL XLPE 11 kV
PN19	2EX	1	17/10/14	1c 630mm^2 Cu XLPE 33 kV
PN20	2EY	1	17/10/14	1c 630mm^2 Cu XLPE 33 kV
PN21	2EZ	1	17/10/14	1c 630mm^2 Cu XLPE 33 kV
PN22	3A0	1	17/10/14	3c 0.25 in^2 Cu PILC STA 11 kV
PN23	3B0	1	17/10/14	3c 0.25 in^2 Cu PILC STA 11 kV
PN24	3C0	1	17/10/14	3c 0.37 in^2 Cu OF PVC 22 kV
PN25	3B0	1	20/10/14	3 x 1m 3c 0.25 in^2 Cu PILC STA 11 kV
PN26	3B0	1	4/11/14	3 x 1m, 3c 0.25 in^2 Cu PILC STA 11 kV
PN27	3B0	1	20/10/14	3 x 1m, 3c 0.25 in^2 Cu PILC STA 11 kV
PN28	3A0	2.5	20/10/14	Joint with 2.5 m 3c 0.25 in^2 Cu PILC STA 11 kV
PN28B	3A0	2	20/10/14	3c 0.25 in^2 Cu PILC STA 11 kV
PN29	3A0	1	4/11/14	3 x 1 m, 3c 0.25 in^2 Cu PILC STA 11 kV

PN Number	Cable ID	Length (m)	Collection Date	Cable Type
PN30	3A0	1	20/10/14	3 x 1 m, 3c 0.25 in^2 Cu PILC STA 11 kV
PN31	3A0	1	4/11/14	3 x 1 m, 3c 0.25 in^2 Cu PILC STA 11 kV
PN32	4EY	1	18/10/14	1c 400mm^2 Al XLPE 33 kV
PN33	3B0	1	17/10/14	1m, 3c 0.25 in^2 Cu PILC STA 11 kV
PN34	5A	1	18/10/14	25c, 9+16 Pilot
PN35	5BX	1	18/10/14	1c 400mm^2 Al XLPE 33 kV
PN36	5BY	1	18/10/14	1c 400mm^2 Al XLPE 33 kV
PN37	5BZ	1	18/10/14	1c 400mm^2 Al XLPE 33 kV
PN38	5CX	1	18/10/14	1c 400mm^2 Al XLPE 33 kV
PN39	5CY	1	18/10/14	1c 400mm^2 Al XLPE 33 kV
PN40	5CZ	1	18/10/14	1c 400mm^2 Al XLPE 33 kV
PN41	4A0	1	18/10/14	3c 0.45 in^2 Cu OF PVC 33 kV
PN42	4C0	1	18/10/14	3c 0.45 in^2 Cu OF PVC 33 kV
PN43	4D0	1	18/10/14	3c 0.25 in^2 PILC STA 11 kV
PN44	3E0	1	17/10/14	3c 0.37 in^2 Cu OF PVC 22 kV
PN45	4B	1	18/10/14	25c 9+16 Pilot
PN46	4EX	1	18/10/14	1c 400mm^2 AL XLPE 33 kV
PN47	4EY	1	18/10/14	1c 400mm^2 AL XLPE 33 kV
PN48	4EZ	1	18/10/14	1c 400mm^2 AL XLPE 33 kV
PN49	3D	1	18/10/14	32c Pilot
PN50	3FX	1	17/10/14	1c 630mm^2 Cu XLPE 33 kV
PN51	3FY	1	17/10/14	1c 630mm^2 Cu XLPE 33 kV
PN52	3FZ	1	17/10/14	1c 630mm^2 Cu XLPE 33 kV
PN53A	3B0	1.5m (of 3m total)	20/10/14	"Unfailed Joint" PILC to XLPE transition joint (approx. 1.5 m plus 1.5 m cable either side)
PN53B	3B0	1.5m (of 3m total)	20/10/14	"Unfailed Joint" PILC to XLPE transition joint (approx. 1.5 m plus 1.5m cable either side)
PN53C	3B0	(component)	20/10/14	"Unfailed Joint" bagged sample - part of joint Remnants of Heat Shrink Casing
PN53D	3B0	(component)	20/10/14	"Unfailed Joint" bagged sample - part of joint (Lead Sheath)
PN53E	3B0	(component)	20/10/14	"Unfailed Joint" bagged sample - part of joint (Belting Papers - PILC end)

PN Number	Cable ID	Length (m)	Collection Date	Cable Type
PN53F	3B0	(component)	20/10/14	"Unfailed Joint" bagged sample - part of joint. Copper braids and spring clip
PN54	1DY	2m	20/11/14	Straight Joint, 1c 400mm² AL XLPE 33 kV
PN55	1DZ	2m	20/11/14	Straight Joint, 1c 400mm² AL XLPE 33 kV
PN56	1AX	2m	20/11/14	Straight Joint, 1c 400mm² AL XLPE 33 kV, 5 m chainage
PN57	4D0	3.5m	20/11/14	Metal joint shell, PILC, from 50 m mark.
PN58	1B-	2m	20/11/14	Straight Joint, 1c 400mm² AL XLPE 33 kV. Cannot say whether X, Y or Z.
PN59	1B-	2m	20/11/14	Straight Joint, 1c 400mm² AL XLPE 33 kV. Cannot say whether X, Y or Z.
PN60	3B0	2.5m	20/11/14	Metal joint shell, PILC, from 25 m mark.
PN61	N/A	N/A	20/11/14	Cable cleats from 72 m mark. 6 off.
PN62	N/A	N/A	20/11/14	Scrapings from wall 72 m.
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 @ 69.5 m
PN65	N/A	N/A	30/04/15	Bottom bolt @ 69.5 m
PN66	N/A	N/A	30/04/15	2 x nuts @ 69.5 m
PN67	N/A	N/A	30/04/15	Bottom bolt & nut @ 69 m
PN68	N/A	N/A	30/04/15	Top bolt & nut @ 69 m
PN69	1BX	0.3m	30/04/15	Additional sample for XLPE testing

18 Appendix C, Designs of Cables and Joints

The designs of cable and joint types installed in the cable trench are described. It is not the purpose of this Appendix to describe the condition and any constructional features that were found during the examination of the samples; these are described in the two Edif ERA reports.

There were four types of power cables present in the trench at the time of the fire, these being 11 kV three core PILC, 22 kV and 33 kV three core OF, 11 kV three core XLPE and 33 kV single core XLPE), the designs of which bear testimony to the march of technology in cable design since the first 11 kV PILC cables were installed in the cable trench in1966.

18.1 11 kV PILC Three Core Cable System

18.1.1 11 kV PILC Cable Design

The PILC (Paper Insulated Lead Covered) cable, Figure 64, has three sector shaped conductors individually wrapped with paper tape insulation.

The cable is of the 'belted' type in which, for compactness of size and economy, the individual cores partly share a common insulation and a common earth screen. The PILC cable cores do not have individual earth screens.

The dimensions of the insulation thickness are given in BS 480:1966[15] for the 0.25 in^2 copper and 300 mm^2 aluminium conductor sizes present in the cable trench:

- Conductor to conductor: 0.21 in, (5.33 mm)
  Radial core: 0.105 in, (2.665 mm)
- Cond to sheath, earthed star point: 0.15 in, (3.81 mm)
  Belt: (3.81-2.665): (1.145 mm)
- Cond to sheath, non-earthed star point: 0.21 in, (5.33 mm)
  Belt: (5.33-2.665): (2.665 mm)

In the cable factory the three insulated cores are laid-up helically together with insulating, jute string fillers to form a compact cylindrical shape. The laid-up cores are wrapped overall with a cylindrical layer of insulating paper tapes, which is named the 'belt'. The laid-up cores are wound onto a process drum that is loaded and sealed inside a drying vessel. The paper and jute insulation is dried by the application of heat and vacuum. The cable cores are then thoroughly impregnated by filling the vessel under positive pressure with electrical insulating compound that has been pre-heated to reduce its viscosity and aid impregnation.

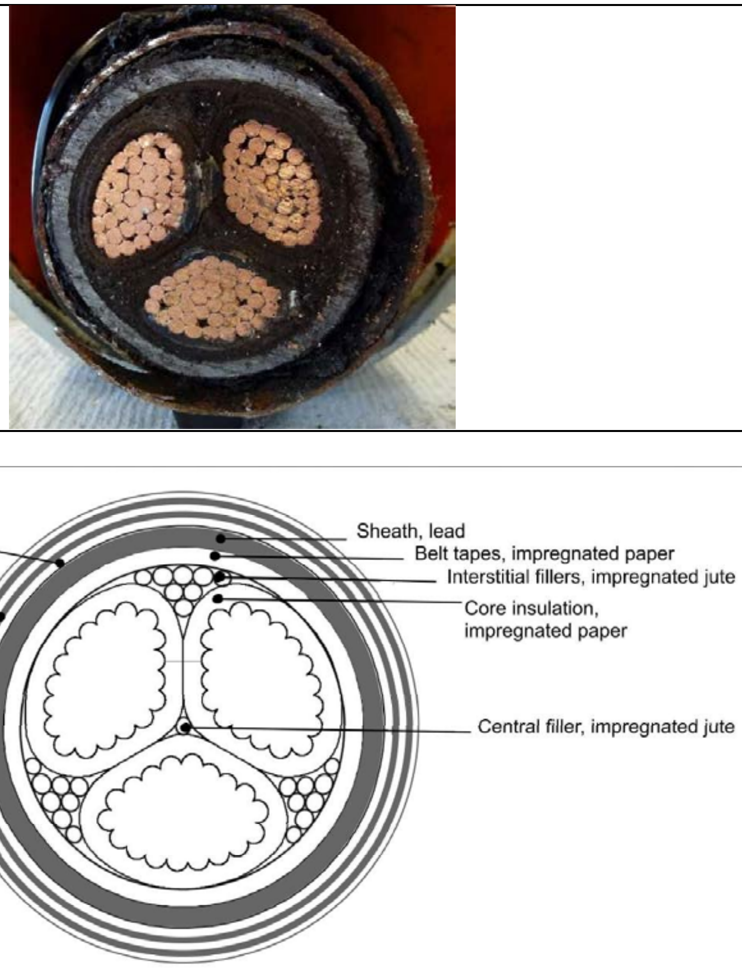


Figure 64 11 kV PILC three core cable cross-sections

The cable and compound are cooled under pressure. The impregnated cable core is removed and a tight lead sheath is extruded over it. The lead sheath ensures longevity of service performance by:

- Preventing loss of compound.
- Withstanding the pressure generated by the thermal expansion of the compound in service, in combination with the outer serving and armour.
- Preventing ingress of moisture into the insulation.
- Being highly resistant to corrosion.

The oldest PILC cable design in the trench was manufactured by Scottish Cables in 1966, as denoted by the marker tape. The cable contained the older type of viscous, oil-rosin compound. The common dielectric earth screen shared by the three cores was formed by the inner surface of the lead sheath. The copper conductors were unscreened, this being normal for early types of PILC cable designs.

The newest PILC cable design in the trench was manufactured by ABCAL, New Zealand, in 1977, as denoted by the marker tape. The cable contained the newer type of MIND compound (mass impregnated non-draining), which comprises a blend of mineral oil and microcrystalline waxes. MIND compound was developed to exhibit a higher viscosity at the cable operating temperature such that gravitational draining would be inhibited in those cables installed on steep slopes. This cable had a separate carbon paper earth screen applied over the belt tape. The aluminium conductors were each screened with a carbon paper tape.

Figure 65 11 kV PILC cable protection over lead sheath: Compounded paper beddings and two steel tapes with interleaved hessian tapes

The lead sheath is provided with a corrosion protection formed of layers of bitumen coated proofed cotton fabric tape, paper tapes and hessian tapes, Figure 65, upper photograph. A layer of gapped steel tape armour is applied, Figure 65, lower photograph. The steel tape is provided with a pre-applied corrosion protection of bituminous lacquer. A layer of bitumen coated hessian tape is then applied. A second steel armour tape is applied gapped in the same lay direction as the first tape such that there is a 100% armour cover over the cable. Further layers of bitumen coated hessian tapes are applied. A layer of chalk wash is applied overall to prevent the turns of cable sticking together on the cable despatch drum.

18.1.2 11 kV PILC Straight Joint Design

The straight joint, Figure 66, is designed to be compatible with the PILC cable's features; i.e. the unscreened cable cores, common belt insulation, complete impregnation with compound, containment in a watertight lead sheath and armour protection.

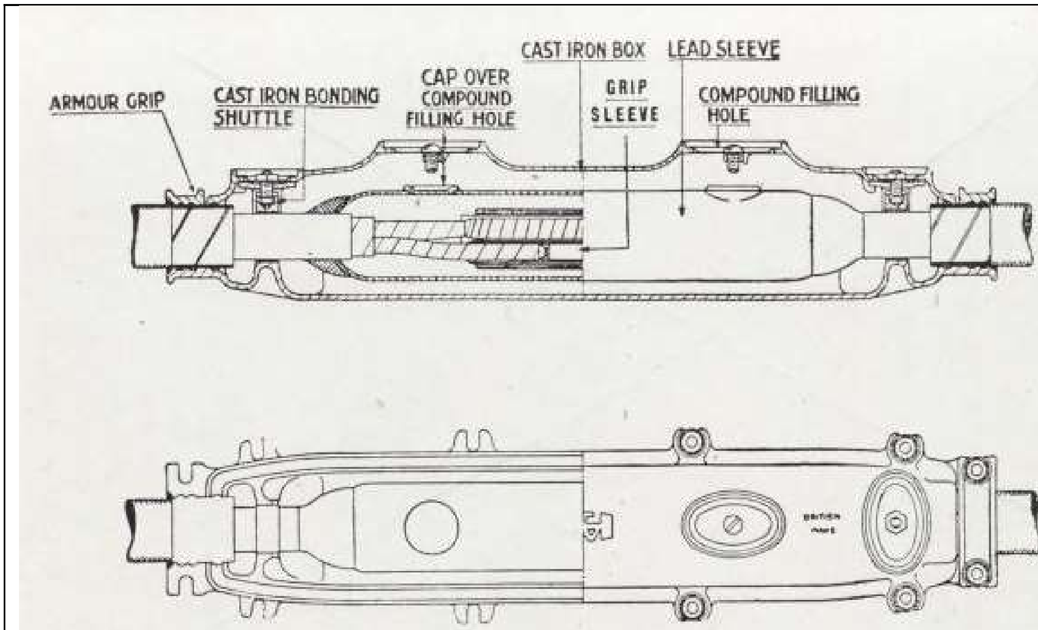


Figure 66 11 kV PILC three core straight joint: Cast iron shell type

The design of the cast iron joint shell shown in Figure 66 is similar, but not identical to those that were removed from the cable trench. In published literature, variations are seen in each manufacturer's design of straight joints. This is particularly so for the internal insulation and core spacers applied over the conductor connectors. In this section the joint insulation design that was present in the cable trench is illustrated by photographs taken during the dismantling of the joints. The photographs are shown reversed; i.e. they are in the order the jointer would have assembled the joint.

At the start of jointing the lead sheath is removed by being scored and torn outwards.

The common belt paper insulation is continued for a short distance and is then removed by being torn at the 'belt insulation termination'. A binding of pre-impregnated woven cotton insulating tape is applied over the belt insulation, Figure 67. The jointer sets the insulated cable cores outwards to form the offset shape necessary to provide clearance for the application of the paper roll insulation over each conductor connector. A temporary core spacer is inserted.

The binder i) protects the paper tape core insulation from being damaged during jointing and in service, and ii) provides consistent insulation strength at the position where the electrical field diverges at the end of the insulation screen; i.e. the lead sheath cut. (The binder tape and insulation in Figure 67 would have abutted or overlapped the lead sheath, but were disturbed during dismantling).

Figure 67 Belt insulation binder at lead sheath cut: Impregnated cotton tape

The paper tape core insulation is removed to expose the ends of the conductors, Figure 68. The paper termination cut is covered with a temporary protection tape. The sector shaped conductors are circularised by a hand tool. The conductors and ferrules are pre-fluxed and the cylindrical copper ferrules are fitted. The ferrule and conductors are then basted and sweated through the filling holes with molten tin-alloy solder until it is seen to have run between the copper wires under capillary action. The conductor and ferrules are cleaned and the temporary protection removed from the insulation. (In Figure 67 and Figure 68 the dark colour of the paper insulation has resulted from the hot, black, bituminous joint filling compound having beneficially mixed with the lighter coloured factory impregnating compound and so penetrated the joint and cable insulation).

Figure 68 Conductor connectors: Copper ferrule sweated with tin-lead alloy

An infill of pre-impregnated cotton woven tape is applied between the core insulation and the end of the ferrule, Figure 69. In the photograph two ferrules have been cleaned of bituminous insulating compound and one has been left uncleaned as found after removal of the paper roll.

Figure 69 Connector infill insulation: Impregnated cotton tape

Pre-shaped paper rolls, Figure 70, are then wrapped around each individual ferrule. The paper rolls are supplied pre-impregnated with compound. They are heated before application, and during application are basted with hot compound. The paper rolls provide a more consistent insulation electrical strength and prevent the three connectors from touching each other.

Figure 70 Connector insulation: Pre-shaped paper rolls

A paper roll is applied over the three insulated cores, Figure 71, and is bound by a pre-impregnated woven cotton insulating tape. The paper roll forms a spacer to centralise the insulated cores within the lead sleeve and thus ensure the presence of an annular layer of insulating bituminous compound. The bound paper roll and lead sheath provides mechanical rigidity to prevent buckling of the cores by the axial thrust of the cable thermo-mechanical forces, which are generated during in-service heating.

Figure 71 Binder and spacer: Cotton fabric tape over common paper roll

The lead sleeve that the jointer had passed back over one of the cable ends at the start of jointing is now pulled over the insulated cores. Its ends are dressed down onto the lead sheaths of both cables and wiped seals are made with plumbing metal. Hot bituminous insulating compound is poured through one of the two holes provided in the top of the sleeve. The sleeve is topped up and is sealed by two lead caps that are plumbed onto the lead sleeve. The upper photograph in Figure 72 shows the lead sleeve peeled back during dismantling to reveal that the bituminous insulating compound has fully encapsulated the insulated cores. The lower photograph shows the insulated cores after the bitumen had been softened and drained by the application of heat. The bituminous insulating compound provides the continuation of the cable's paper tape belt insulation. The lead sleeve provides the continuation of the cable sheath's common insulation screen and of the water-tight covering.

Figure 72 Bitumen filled lead sleeve and encapsulated core insulation

The upper and lower halves of the cast iron joint shell are fitted around the joint, Figure 73 and Figure 74.

Figure 73 Inner watertight barrier: Wiped lead sleeve encapsulated within bituminous anti-corrosion protection

Figure 74 Joint shell halves: Cast iron filled with bituminous compound

A strip of lead packing is applied to each cable and a clamp integral with the cast iron joint shell is tightened to form a watertight end seal, which grips the cable and makes electrical contact with the lead sheath.

Figure 75 Cable clamp: Cast iron on lead tape packing

The cast iron joint shell is filled with hot bituminous compound, topped up and sealed. The cast iron shell and bitumen filling i) protect the joint insulation and screen from mechanical disturbance and ii) the lead sleeve from water entry and corrosion.

18.1.3 11 KV PILC to XLPE Transition Joint Design

The transition joint design is described in detail in Section 20, Appendix E.

18.2 22 kV and 33 kV Self-contained Oil-filled Cable System

18.2.1 22 kV and 33 kV Self-contained Oil-filled Cable

The historical designations for this cable type are SCOF, (self-contained oil-filled) and LPOF (low pressure oil-filled). Prior to approximately 1980 cables were impregnated with low viscosity mineral oils blended to give gas absorbency in the event of an electrical partial discharge occurring in service. After 1980 the UK cable manufacturers had changed to dodecyl-benzene (DDB) insulating fluid, which is synthetic and has a higher inherent gas absorbency and, in particular, a higher biodegradability should the fluid leak into the ground. At that time the generic name of the cable type was changed from OF to FF (fluid-filled). Both mineral and DDB cable impregnants are flammable. DDB has the advantage of a higher autogenous temperature (self-ignition in the absence of a spark), which has benefits during the factory application of a hot, extruded aluminium sheath to the impregnated cable core.

The minimum insulation thickness given in ESI 09/3[16] for a 33 kV OF cable is 3.3 mm.

In the cable trench both 22 kV and 33 kV three core cable designs, Figure 76, were installed, which although not identical, were closely similar to each other. The shaped conductors were of the oval type. Unlike the 11 kV PILC cable each core was independent, having its own separate paper taped insulation and earth screen tapes.

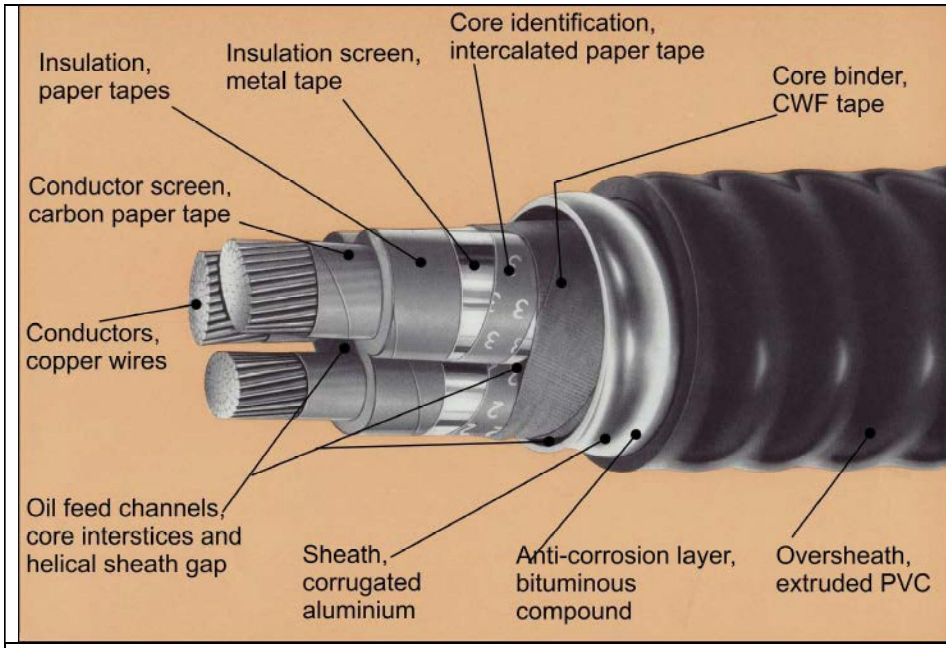


Figure 76 33 kV oil-filled three core cable

The conductor is stranded in an oval shape. This shape i) contributes to a more compact cable than possible with circular conductors and ii) has lower electrical stress raisers than present in the 11 kV PILC sector shaped conductor.

The three cores are laid up together and are bound with a CWF (copper woven fabric) tape. The tape provides thermal protection to the cores when the hot aluminium sheath is extruded onto it. The aluminium sheath is then corrugated to increase its bending flexibility for winding onto despatch cable drums and navigating bends during installation.

The core is evacuated and heated in the drying vessel. It is either:

i) Impregnated by admitting degasified oil into the vessel and then directly sheathed under oil in an aluminium press connected to the vessel, or
ii) Filled with dried air, aluminium sheathed and then re-evacuated and impregnated with oil.

Upon emerging from the aluminium press the sheath is cylindrical. It is then immediately formed into helical corrugations.

The aluminium sheath is mechanically robust and so can maintain its shape without the need to include fillers to make the laid-up core shape cylindrical. The absence of fillers forms large interstitial spaces between the cores, which, in the 33 kV cable, are designed to act as oil ducts. The helical space under the corrugated aluminium sheath also acts as an oil duct. The oil ducts are necessary during in-service operation to permit the thermally expanded oil volume to flow longitudinally and be stored in 'oil tanks' located at, for example, the cable terminations, or at certain feed/stop joint positions.

The oil tanks contain flexible sealed elements filled with pre-pressurised CO_2 gas. The gas filled elements are compressed by the inwards flow of oil into the tank. When the cable cools off-load, the gas pressure pushes the cable oil back into the cable to occupy the volume of the thermally contracted cable oil. The viscosity of the cable oil is sufficiently low to prevent gas voids from forming during expansion and contraction, as occurs in the non-pressurised PILC cable design. The absence of electrically weak voids permits i) the insulation thickness to be reduced and ii) the operating temperature of the OF cable to be increased from 65°C to 85-90°C. This gave the OF cable a significant advantage in load carrying capacity, smaller size and increased cost effectiveness. The disadvantage is that, in the event of serious damage to the metallic sheath, the low viscosity cable oil can drain from both the cable and the oil tanks. In the event of an electrical failure of an in-air installation, leaking oil can prospectively flow along the ground and so spread fire damage to adjacent circuits.

The aluminium sheath is provided with anti-corrosion protection in the form of i) a bituminous compound and ii) an extruded polymeric sheath. The OF cables in the trench were provided with a PVC sheath. As described in Section 23 Appendix H, PVC was initially considered to be a fire retardant material compared to PE and XLPE, however later experience showed that at elevated temperatures i) the plasticiser additive is flammable and ii) the plasticised PVC sheath does burn.

18.2.2 22 kV and 33 kV Self-contained Oil-filled Cable Joint

There were no OF straight joints found in the cable trench so this type is not described.

18.3 33 kV XLPE Single-core Cable System

18.3.1 33 kV XLPE Cable

The 33 kV XLPE (cross-linked polyethylene) cables, Figure 77, are of single core, triple extruded design complete with their own insulation and an inner and outer semiconducting screen, a wire screen earth return conductor, inner sheath of extruded PVC and outer sheath of PE.

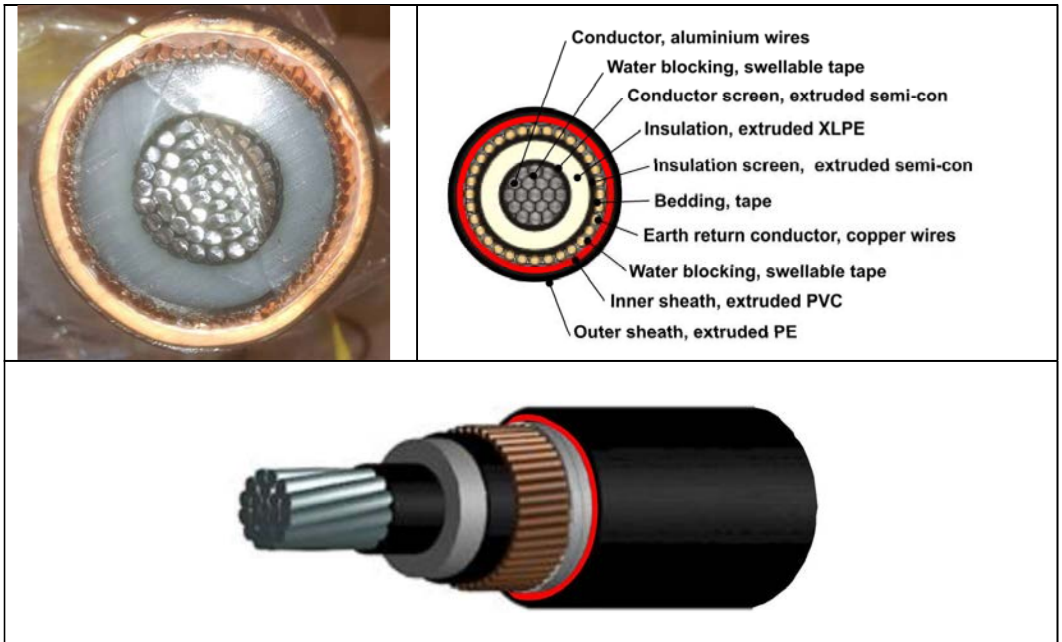


Figure 77 33 kV XLPE single core cable

In the cable trench three phase circuits were formed by laying three single core cables in trefoil-touching formations. At 33 kV it is generally preferred by utilities to select single core rather than three core cables as the XLPE insulation thickness is sufficient to make installation of a three core cable less flexible and the three core construction to make the joint larger and jointing more complex.

The cables were supplied to AS/NZS Standard 1429.1:2000; the current issue is 2006[9]. The requirements for insulation and sheathing materials are given in AS/NZS 3808:2000[17]. The nominal thickness of the XLPE insulation is given as 8.0 mm and the minimum point thickness as 7.1 mm.

The conductor shape is circular. Two semi-conducting screen layers and the PE insulation are extruded onto the conductor in one operation using a triple head die. At this stage the insulation is low density polyethylene (LDPE).

Immediately after the extrusion die the LDPE core is subjected to a vulcanising process to chemically form XLPE (cross-linked polyethylene). The purpose of cross-linking is to raise the operating temperature of the insulation from 70°C to 90°C and thus achieve a competitive performance with an OF cable. The conventional method for a 33 kV cable is to pass the extruded core through a CCV (catenary continuous vulcanisation) line comprising a metallic tube heated to approximately 200°C, which contains nitrogen gas at 10 bar pressure. The temperature activates a peroxide crosslinking additive in the PE compound. The pressure ensures that gaseous by-products of the reaction are kept in solution within the XLPE thereby preventing the formation of voids.

The 33 kV cables in the trench were supplied with an ‘easy strip’ type of insulation screen that permits the jointer to pull the screen off the XLPE insulation, thus significantly simplifying and reducing assembly time. At higher voltages a fully bonded screen is applied that requires higher skilled and more labour intensive screen stripping and polishing processes to be used.

A bedding tape is applied over the outer semi-conducting (semi-con) insulation screen onto which is laid an annular earth return conductor (alternatively named a ‘screen’, or ‘neutral’ conductor). The purpose of the ERC is i) in normal service operation to carry the insulation capacitive charging current and ii) during a system through-fault to carry fault current. The required cross-sectional area of the ERC conductor is sufficiently small that it can be formed of a single layer of individual wires that may be spaced apart. The ERC wires are then wrapped with a cushioning layer usually formed of a water blocking tape. Upon contact with water, for example following puncture of the oversheath by mechanical damage, the tape swells and prevents the flow of water along the complete cable section length.

A waterproof anti-corrosion oversheath is extruded over the ERC. The 33 kV XLPE cables in the trench were supplied to AS/NZS specification 3908[19] that requires a composite sheath comprising an inner red PVC sheath and an outer black PE sheath. This combination i) shows by a streak of red colour if the outer black layer has suffered mechanical damage during installation and ii) reduces the risk of ‘stress cracking’ of the PE outer sheath by providing a smoother intermediate PVC bedding layer in contact with any sharp edged components that may be present, thereby eliminating the ‘notch’ effect.

Some designs of higher stressed XLPE cables are vulnerable to accelerated ageing by the growth of water trees, which may occur in the insulation if i) the electrical stress is greater than 2 kV/mm, ii) the moisture content is greater than 80% of saturation and iii) large stress raisers are present in the form of inclusions in the XLPE insulation or protrusions at the semi-con screen to XLPE interface.

The 33 kV cables installed in the cable trench were of the ‘wet’ design i.e. they did not have a water-tight metallic sheath. The electrical stress in a 33 kV cable is marginal for the initiation of water trees and so the designs of cable had not been supplied with a water-tight metallic layer for installation in the cable trench. Some of the cables supplied by Olex also contained a water tree retardant grade of XLPE insulation, which interferes with the mechanism in which water molecules collect at electrical stress raisers that may be present in the insulation.

The cables in the trench had a water blocked construction to prevent water permeating inside the cable along its complete length following mechanical damage, or electrical failure. Layers of water swellable tape were placed:

- In the conductor between each annular layer of wires.
- Over the earth return conductor and under the polymeric oversheath.

18.3.2 33 kV XLPE Straight Joint

The design of a heat shrink sleeve straight joint is shown in Figure 78. This is the generic type that was present in the cable trench.

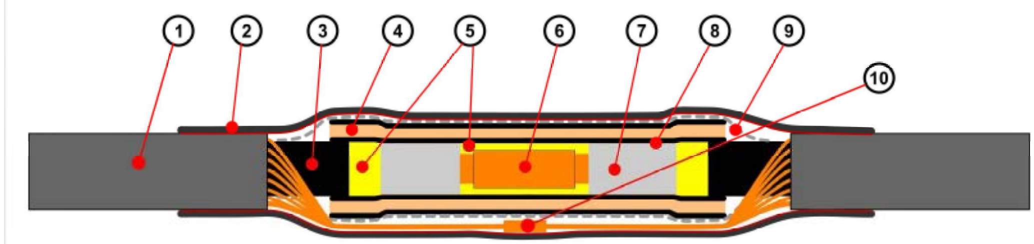


Figure 78 33 kV XLPE single core straight joint: Heat shrink type

During jointing the heat shrink sleeves are first passed back over the cable and parked, so that they can be moved into position after the connectors are joined.

The oversheaths are removed and the ERC wires folded back over the cable.

The required length of conductor is exposed using an ‘end-stripper tool’ to remove the XLPE insulation.

The outer ‘easy strip’ semi-con insulation screen is scored near to its termination position and is then pulled off the XLPE insulation. The screen termination is chamfered at the specified angle.

The compression ferrule is fitted and hydraulically compressed onto the copper conductors.

Yellow void-filling adhesive compound is used to i) fill the gaps at the ends of the ferrule, ii) circularise the deformed shape of the compression ferrule and iii) cover the insulation screen terminations such that air voids are absent. The compound is insulating and has a high permittivity stress control property that reduces the magnitude of electrical stress in the component that it covers. The corollary is that it increases the stress in the adjacent XLPE insulation.

The stress control heat shrink sleeve is slid over from the parked positions to overlap the termination of both cable semi-con insulation screens. It is shrunk down by the application of heat.

The insulation package, comprising a composite tube of outer semi-con screen and inner elastomeric insulation, is slid over and is shrunk down.

A copper mesh earth screen is wrapped over the jointed cores. This:
1) Connects to earth (i.e. to the ERC) the outer semi-con screen of the insulation package.
2) Conducts the capacitive charging current away from the insulation package to prevent it from electrically floating.
3) Reconstitutes the metallic screening role in combination with the ERC cable wires to ensure that the circuit protection operates efficiently in the event that the joint is punctured by third party, dig-in damage.

The ERC copper wires on each cable are formed into two bunches that are joined to the opposite cable at the mid-point of the joint using crimped ferrules. The ERC conductor is required to carry across the joint:

- The cable length's capacitive charging current in normal operation.
- The cable's induced screen circulating current in normal operation.
- The cable system's through-fault current.

The outer PE sheath surface of each cable is prepared as specified by the joint supplier. The outer protective heat shrink sleeve is slid over and shrunk down. The sleeve is lined with hot melt adhesive. The heat shrink process softens the adhesive such that it forms a longitudinal water seal onto the cable oversheaths.

18.3.3 33 kV XLPE Conductor Transition Joint

Conductor transition joints were present in the cable trench. The conductor transition joint is closely similar to the straight joint design but with the addition of:

1. A compression ferrule that has two different bore diameters to suit the conductor sizes to be connected. None of the XLPE straight joints in the cable trench required bi-metallic ferrules.
2. One or more adaptor sleeves. These are short heat shrink sleeves that are applied over the smaller diameter XLPE insulated core to make its diameter up to that of the cable core on the opposite, larger side.

18.4 11 kV XLPE Three Core Cable System

18.4.1 11 kV XLPE Three Core Cable

The design of the 11 kV XLPE 35 mm^2 Tunnel auxiliary supply cable is shown in Figure 79.

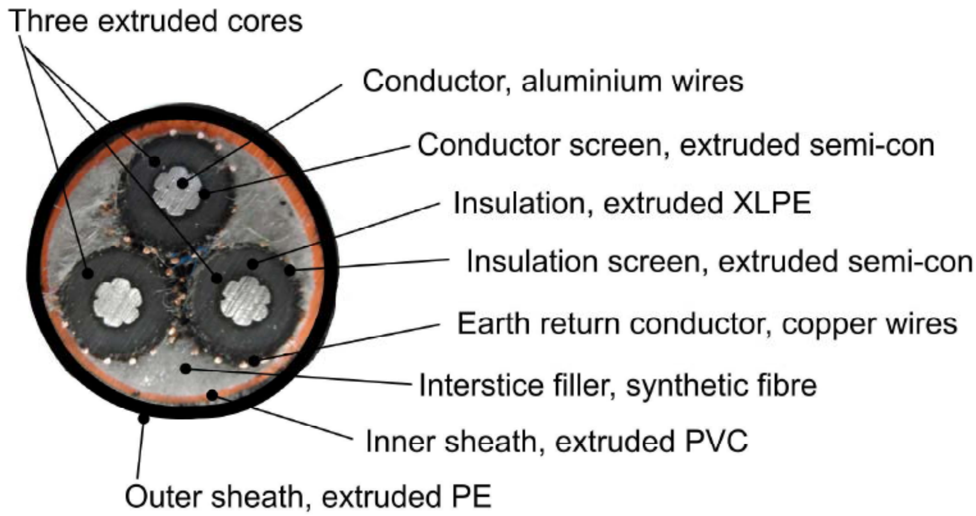


Figure 79 11 kV three core XLPE cable

The cables had been supplied to AS/NZS Standard 1429.1:2000; the current edition issue is 2006[9]. The requirements for insulation and sheathing materials are given in AS/NZS 3808[19]. The nominal insulation thickness requirement is 3.4 mm and the minimum point thickness is 2.96 mm.

In the cable factory each core is separately extruded and a concentric ERC conductor copper wire conductor is applied. The three cores are then laid up together with a fibre filler to form a cylindrical shape. A binder tape is applied overall. A composite sheath is then applied comprising an extruded inner red PVC sheath and an outer black PE sheath.

18.4.1 11 kV XLPE Three Core Cable Joint

There were no 11 kV three core XLPE straight joints found in the cable trench, so this type is not described.

19 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 electrical failure, not the passage of fire.

- **X:** XLPE Insulation with PE Serving (power cable)
- **OF:** Oil Filled Paper Insulation with PVC Serving (power cable)
- **PC:** PILC with Steel Tape Armour, Hessian served (power cable)
- **P:** Pilot Cable, PVC served
- **D:** Duct, PVC, Data Cables

De – energised

Trefoil cable designation

Cable Position	PN	Circuit Name	Cable Description
1A	8/9/10	Remuera No 3	3 x 1c 400mm² Al XLPE 33kV
1B	4/5/6/7	Newmarket No 3	3 x 1c 400mm² AL XLPE 33kV
1C	-	Duct (Communication Cables)	-
1D	1/2/3	Remuera No 2	3 x 1c 400mm² AL XLPE 33kV
2A	17	Carbine	25c 9+16 pilot
2B	14	Not in use	3c 300mm² AL PILC STA 11kV
2C	15	McNab K19	3c 300mm² AL PILC STA 11kV
2D	16	Carbine No 1	3c 300mm² AL OF PVC 33kV
2E	19/20/21	Carbine No 2	3 x 1c 630mm² Cu XLPE 33kV
2F	18	CBD Tunnel Aux	3c 35mm² AL XLPE 11kV
3A	22	McNab K02	3c 0.25 sq in Cu PILC STA 11kV
3B	23	Remuera K10	3c 0.25 sq in Cu PILC STA 11 kV
3C	24	Westfield No 2	3c 0.37 sq in Cu OF PVC 22 kV
3D	49	Westfield	32c pilot
3E	44	Westfield No 3	3c 0.37 sq in Cu OF PVC 22 kV
3F	50/51/52	St John No 3	3 x 1c 630mm² Cu XLPE 33kV
4A	41	St John No 1	3c 0.45 sq in Cu OF PVC 33 kV
4B	45	St John	11 + 8 pilot
4C	42	St John No 2	3c 0.45 sq in Cu OF PVC 33 kV
4D	43	Mt Wellington K05	3c 0.25 sq in Cu PILC STA 11kV
4E	46/47/48	Mt Wellington No 2	3 x 1c 400mm² AL XLPE 33Kv
5A	34	Mt Wellington	11 + 8 pilot
5B	35/36/37	Mt Wellington No 1	3 x 1c 400mm² Al XLPE 33kV
5C	38/39/40	Sylvia Park No 1	3 x 1c 400mm² Al XLPE 33kV
5D	11/12/13	Sylvia Park No 2	3 x 1c 400mm² AL XLPE 33kV

Figure 80 Layout of circuits in the trench

Circuit Name	Cable	Outer Sheath	Chainage (m)	Elapsed Time (mins)
Remuera K10	11 kV PILC	Hessian STA	73.00	0.00

Figure 81 1st incident: 11 kV PILC, Remuera K10 fault, 3B0, 73 m

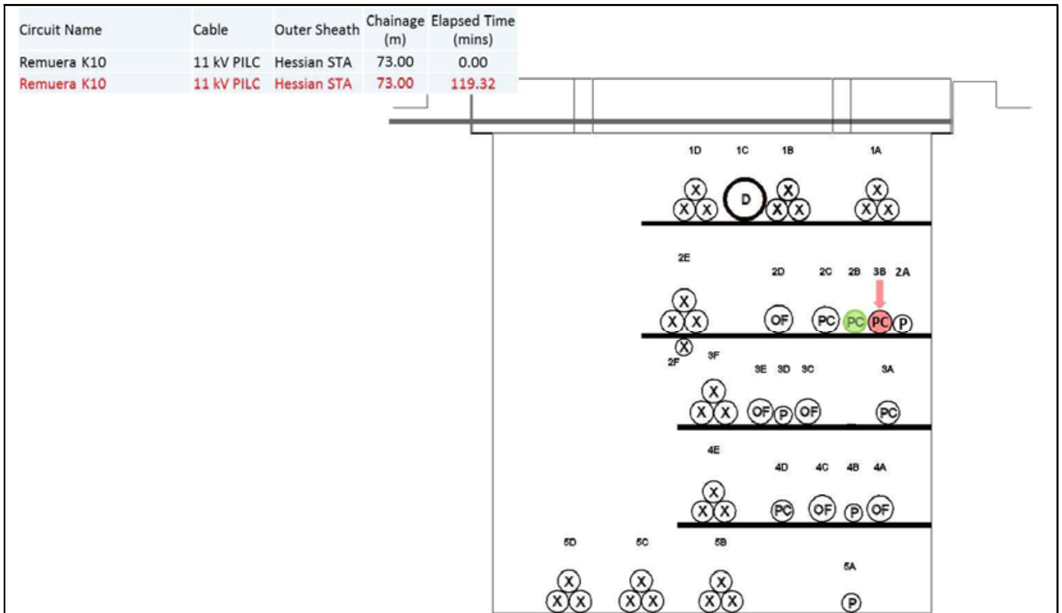
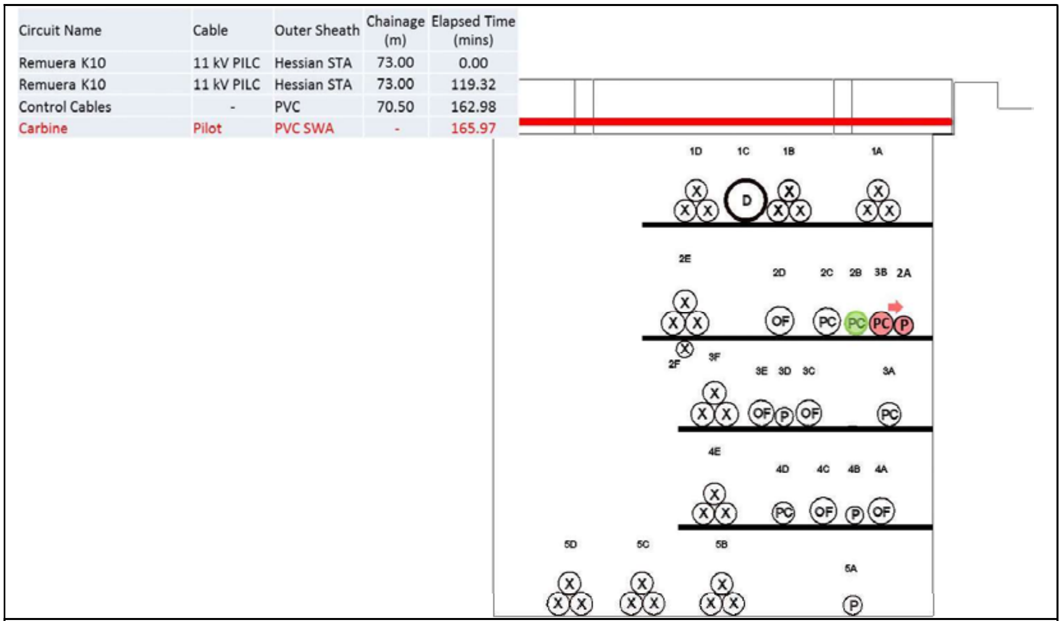


Figure 82 2nd incident: 11 V PILC, Remuera K10 reclosed and faulted, 3B0, 73 m

Figure 83 Arc crater: 11 kV PILC, Remuera K10, 3B0, 73 m

Circuit Name	Cable	Outer Sheath	Chainage (m)	Elapsed Time (mins)
Remuera K10	11 kV PILC	Hessian STA	73.00	0.00
Remuera K10	11 kV PILC	Hessian STA	73.00	119.32
Control Cables	-	PVC	70.50	162.98

Figure 84 3rd incident: T 11 control cable signal, across the cable bridge, 70.5 m



Circuit Name	Cable	Outer Sheath	Chainage (m)	Elapsed Time (mins)
Remuera K10	11 kV PILC	Hessian STA	73.00	0.00
Remuera K10	11 kV PILC	Hessian STA	73.00	119.32
Control Cables	-	PVC	70.50	162.98
Carbine	Pilot	PVC SWA	-	165.97

Figure 85 4th incident: Carbine pilot signal, 2A

Circuit Name	Cable	Outer Sheath	Chainage (m)	Elapsed Time (mins)
Remuera K10	11 kV PILC	Hessian STA	73.00	0.00
Remuera K10	11 kV PILC	Hessian STA	73.00	119.32
Control Cables	-	PVC	70.50	162.98
Carbine	Pilot	PVC SWA	-	165.97
Control Cables	-	PVC	70.50	169.20

Figure 86 5th incident: Control cable signal across the cable bridge, 70.5 m

Circuit Name	Cable	Outer Sheath	Chainage (m)	Elapsed Time (mins)
Remuera K10	11 kV PILC	Hessian STA	73.00	0.00
Remuera K10	11 kV PILC	Hessian STA	73.00	119.32
Control Cables	-	PVC	70.50	162.98
Carbine	Pilot	PVC SWA	-	165.97
Control Cables	-	PVC	70.50	169.20
Remuera No 3	33 kV XLPE	PE	72.50	170.15

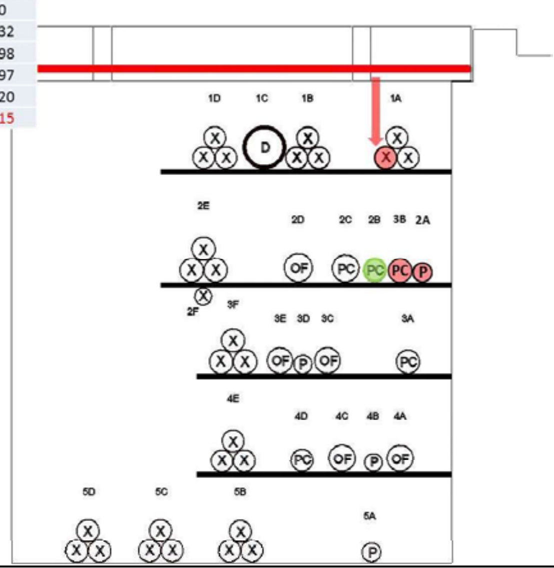


Figure 87 6th incident: 33 kV XLPE, Remuera 3 fault, 1AZ, 72.5 m

Figure 88 Arc crater: 33 kV XLPE, Remuera 3, 1AZ, at 72.5 m

Circuit Name	Cable	Outer Sheath	Chainage (m)	Elapsed Time (mins)
Remuera K10	11 kV PILC	Hessian STA	73.00	0.00
Remuera K10	11 kV PILC	Hessian STA	73.00	119.32
Control Cables	-	PVC	70.50	162.98
Carbine	Pilot	PVC SWA	-	165.97
Control Cables	-	PVC	70.50	169.20
Remuera No 3	33 kV XLPE	PE	72.50	170.15
Newmarket No 3	33 kV XLPE	PE	73.00	171.02

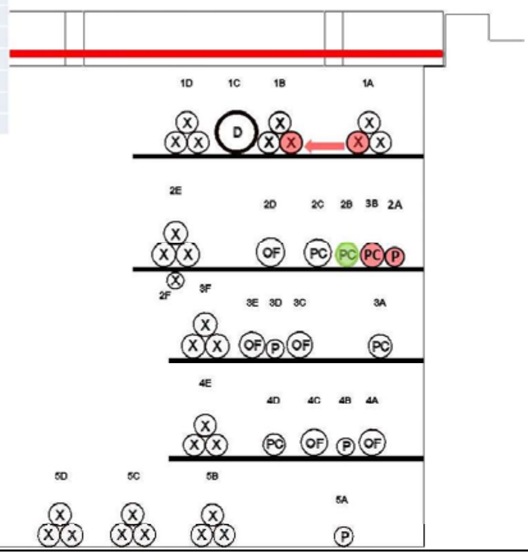
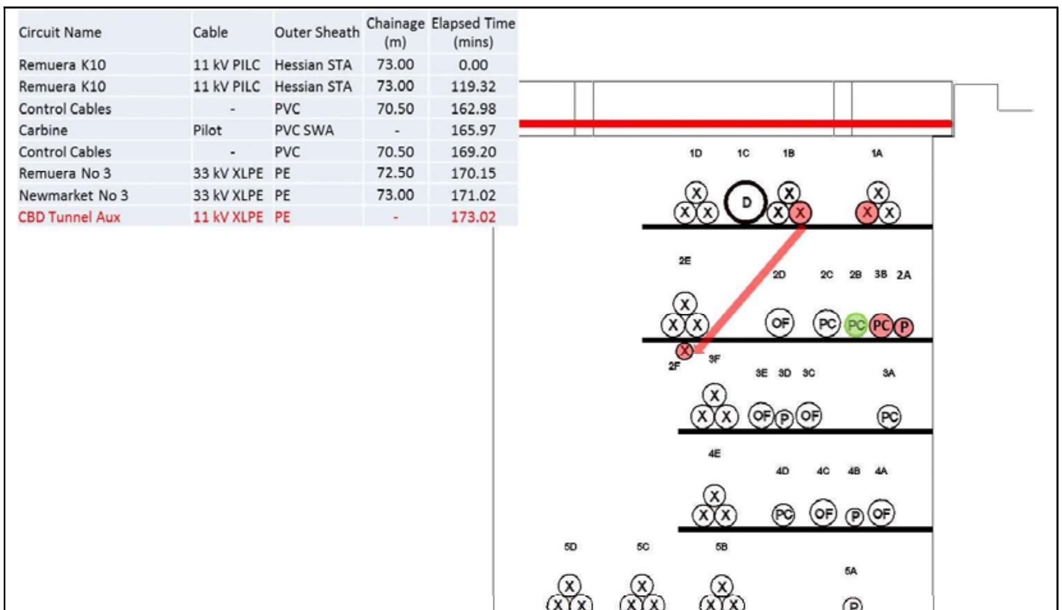


Figure 89 7th incident 33 kV XLPE, Newmarket 3 fault, 1BY, at 73 m

Figure 90 Arc crater: 33 kV XLPE, Newmarket 3, 1B-, 73 m, Y Phase



Circuit Name	Cable	Outer Sheath	Chainage (m)	Elapsed Time (mins)
Remuera K10	11 kV PILC	Hessian STA	73.00	0.00
Remuera K10	11 kV PILC	Hessian STA	73.00	119.32
Control Cables	-	PVC	70.50	162.98
Carbine	Pilot	PVC SWA	-	165.97
Control Cables	-	PVC	70.50	169.20
Remuera No 3	33 kV XLPE	PE	72.50	170.15
Newmarket No 3	33 kV XLPE	PE	73.00	171.02
CBD Tunnel Aux	11 kV XLPE	PE	-	173.02

Figure 91 8th incident 11 kV XLPE, Tunnel Auxiliary fault, 2F0, length unknown

Circuit Name	Cable	Outer Sheath	Chainage (m)	Elapsed Time (mins)
Remuera K10	11 kV PILC	Hessian STA	73.00	0.00
Remuera K10	11 kV PILC	Hessian STA	73.00	119.32
Control Cables	-	PVC	70.50	162.98
Carbine	Pilot	PVC SWA	-	165.97
Control Cables	-	PVC	70.50	169.20
Remuera No 3	33 kV XLPE	PE	72.50	170.15
Newmarket No 3	33 kV XLPE	PE	73.00	171.02
CBD Tunnel Aux	11 kV XLPE	PE	-	173.02
Carbine Road No 2	33 kV XLPE	PE	72.80	173.28

Figure 92 9th incident: 33 kV XLPE, Carbine Road 2 fault, 2EY, 72.8 m

Figure 93 Arc crater: 33 kV XLPE, Carbine Road 2, 2EY, 72.8 m

Circuit Name	Cable	Outer Sheath	Chainage (m)	Elapsed Time (mins)
Remuera K10	11 kV PILC	Hessian STA	73.00	0.00
Remuera K10	11 kV PILC	Hessian STA	73.00	119.32
Control Cables	-	PVC	70.50	162.98
Carbine	Pilot	PVC SWA	-	165.97
Control Cables	-	PVC	70.50	169.20
Remuera No 3	33 kV XLPE	PE	72.50	170.15
Newmarket No 3	33 kV XLPE	PE	73.00	171.02
CBD Tunnel Aux	11 kV XLPE	PE	-	173.02
Carbine Road No 2	33 kV XLPE	PE	72.80	173.28
Remuera No 2	33 kV XLPE	PE	72.60	175.25

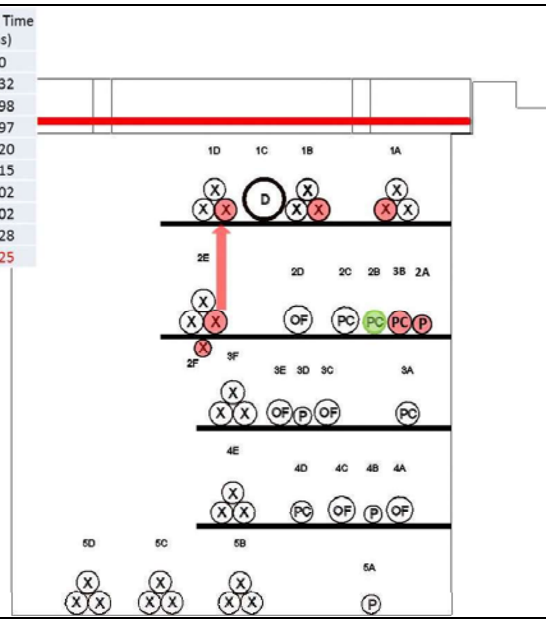


Figure 94 10th incident: 33 kV XLPE, Remuera 2 fault, 1DY, 72.6 m

Figure 95 Arc crater: 33 kV XLPE, Remuera 2, 1DY, 72.6 m

Circuit Name	Cable	Outer Sheath	Chainage (m)	Elapsed Time (mins)
Remuera K10	11 kV PILC	Hessian STA	73.00	0.00
Remuera K10	11 kV PILC	Hessian STA	73.00	119.32
Control Cables	-	PVC	70.50	162.98
Carbine	Pilot	PVC SWA	-	165.97
Control Cables	-	PVC	70.50	169.20
Remuera No 3	33 kV XLPE	PE	72.50	170.15
Newmarket No 3	33 kV XLPE	PE	73.00	171.02
CBD Tunnel Aux	11 kV PILC	PE	-	173.02
Carbine Road No 2	33 kV XLPE	PE	72.80	173.28
Remuera No 2	33 kV XLPE	PE	72.60	175.25
St John	Pilot	PVC SWA		180.10

Figure 96 11th incident: St John pilot signal, 4B, length unknown

Circuit Name	Cable	Outer Sheath	Chainage (m)	Elapsed Time (mins)
Remuera K10	11 kV PILC	Hessian STA	73.00	0.00
Remuera K10	11 kV PILC	Hessian STA	73.00	119.32
Control Cables	-	PVC	70.50	162.98
Carbine	Pilot	PVC SWA	-	165.97
Control Cables	-	PVC	70.50	169.20
Remuera No 3	33 kV XLPE	PE	72.50	170.15
Newmarket No 3	33 kV XLPE	PE	73.00	171.02
CBD Tunnel Aux	11 kV PILC	PE	-	173.02
Carbine Road No 2	33 kV XLPE	PE	72.80	173.28
Remuera No 2	33 kV XLPE	PE	72.60	175.25
St John	Pilot	PVC SWA		180.10
St John No 3	33 kV XLPE	PE	72.30	181.27
St John No 3	33 kV XLPE	PE	72.30	181.27

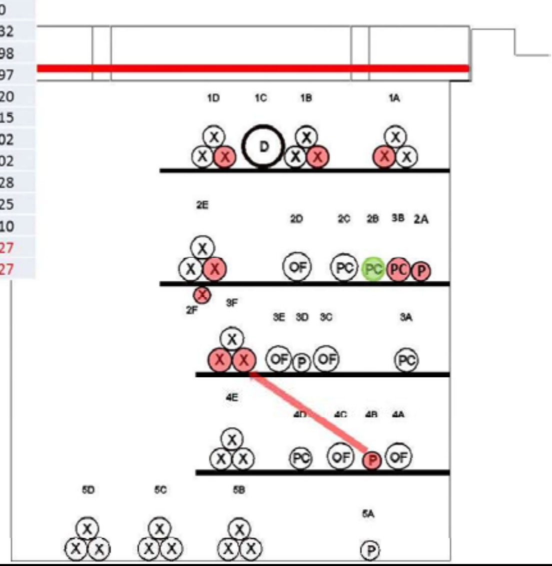


Figure 97 12th incident: 33 kV XLPE, St John 3 fault, 3FY and 3FZ, 72.3 m

Figure 98 Arc crater: 33 kV XLPE, St John 3, 3FY, 72.3 m

Circuit Name	Cable	Outer Sheath	Chainage (m)	Elapsed Time (mins)
Remuera K10	11 kV PILC	Hessian STA	73.00	0.00
Remuera K10	11 kV PILC	Hessian STA	73.00	119.32
Control Cables	-	PVC	70.50	162.98
Carbine	Pilot	PVC SWA	-	165.97
Control Cables	-	PVC	70.50	169.20
Remuera No 3	33 kV XLPE	PE	72.50	170.15
Newmarket No 3	33 kV XLPE	PE	73.00	171.02
CBD Tunnel Aux	11 kV XLPE	PE	-	173.02
Carbine Road No 2	33 kV XLPE	PE	72.80	173.28
Remuera No 2	33 kV XLPE	PE	72.60	175.25
St John	Pilot	PVC SWA	-	180.10
St John No 3	33 kV XLPE	PE	72.30	181.27
St John No 3	33 kV XLPE	PE	72.30	181.27
Westfield No 2	22 kV OFC	PVC	-	181.27
Westfield No 3	22 kV OFC	PVC	-	181.27

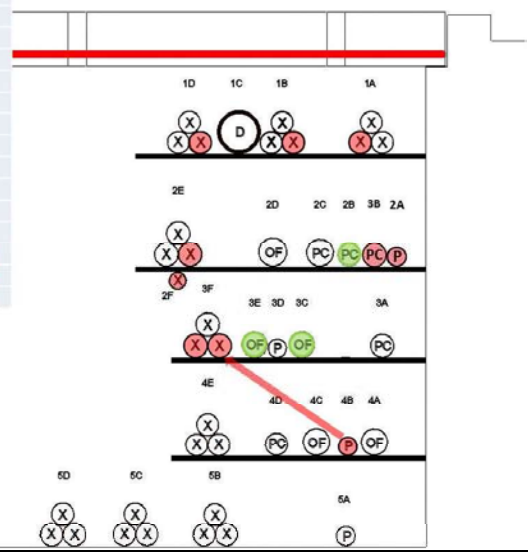


Figure 99 13th incident: 22 kV OF, Westfield 2 and 3 are opened unfailed, 3C0 and 3E0

Circuit Name	Cable	Outer Sheath	Chainage (m)	Elapsed Time (mins)
Remuera K10	11 kV PILC	Hessian STA	73.00	0.00
Remuera K10	11 kV PILC	Hessian STA	73.00	119.32
Control Cables	-	PVC	70.50	162.98
Carbine	Pilot	PVC SWA	-	165.97
Control Cables	-	PVC	70.50	169.20
Remuera No 3	33 kV XLPE	PE	72.50	170.15
Newmarket No 3	33 kV XLPE	PE	73.00	171.02
CBD Tunnel Aux	11 kV XLPE	PE	-	173.02
Carbine Road No 2	33 kV XLPE	PE	72.80	173.28
Remuera No 2	33 kV XLPE	PE	72.60	175.25
St John	Pilot	PVC SWA	-	180.10
St John No 3	33 kV XLPE	PE	72.30	181.27
St John No 3	33 kV XLPE	PE	72.30	181.27
Westfield No 2	22 kV OFC	PVC	-	181.27
Westfield No 3	22 kV OFC	PVC	-	181.27
McNab K02	11 kV PILC	Hessian STA	67.60	203.20

Figure 100 14th incident: 11 kV PILC, McNab K02 fault, 3A0, 67.6 m

Circuit Name	Cable	Outer Sheath	Chainage (m)	Elapsed Time (mins)
Remuera K10	11 kV PILC	Hessian STA	73.00	0.00
Remuera K10	11 kV PILC	Hessian STA	73.00	119.32
Control Cables	-	PVC	70.50	162.98
Carbine	Pilot	PVC SWA	-	165.97
Control Cables	-	PVC	70.50	169.20
Remuera No 3	33 kV XLPE	PE	72.50	170.15
Newmarket No 3	33 kV XLPE	PE	73.00	171.02
CBD Tunnel Aux	11 kV XLPE	PE	-	173.02
Carbine Road No 2	33 kV XLPE	PE	72.80	173.28
Remuera No 2	33 kV XLPE	PE	72.60	175.25
St John	Pilot	PVC SWA	-	180.10
St John No 3	33 kV XLPE	PE	72.30	181.27
St John No 3	33 kV XLPE	PE	72.30	181.27
Westfield No 2	22 kV OFC	PVC	-	181.27
Westfield No 3	22 kV OFC	PVC	-	181.27
McNab K02	11 kV PILC	Hessian STA	67.60	203.20
Carbine No 1	33 kV OFC	PVC CAS	68.90	207.20


1D 1C 1B 1A
D
2E 2D 2C 2B 2A
OF PC PC P
2F 3F 3E 3D 3C 3B 3A
OF P OF PC PC
4E 4D 4C 4B 4A
PC OF P OF
5D 5C 5B 5A
P

Figure 101 15th incident: 33 kV OF, Carbine No1 fault, 2D0, 68.9 m

Figure 102 Arc crater: 33 kV OF, Carbine No1, 2D0, 68.9 m

Circuit Name	Cable	Outer Sheath	Chainage (m)	Elapsed Time (mins)
Remuera K10	11 kV PILC	Hessian STA	73.00	0.00
Remuera K10	11 kV PILC	Hessian STA	73.00	119.32
Control Cables	-	PVC	70.50	162.98
Carbine	Pilot	PVC SWA	-	165.97
Control Cables	-	PVC	70.50	169.20
Remuera No 3	33 kV XLPE	PE	72.50	170.15
Newmarket No 3	33 kV XLPE	PE	73.00	171.02
CBD Tunnel Aux	11 kV XLPE	PE	-	173.02
Carbine Road No 2	33 kV XLPE	PE	72.80	173.28
Remuera No 2	33 kV XLPE	PE	72.60	175.25
St John	Pilot	PVC SWA	-	180.10
St John No 3	33 kV XLPE	PE	72.30	181.27
St John No 3	33 kV XLPE	PE	72.30	181.27
Westfield No 2	22 kV OFC	PVC	-	181.27
Westfield No 3	22 kV OFC	PVC	-	181.27
McNab K02	11 kV PILC	Hessian STA	67.60	203.20
Carbine No 1	33 kV OFC	PVC CAS	68.90	207.20
Mt Wellington No 2	33 kV XLPE	PE	66.90	207.27

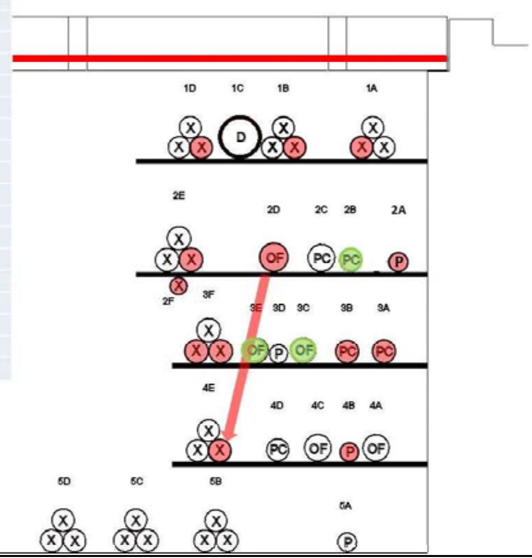


Figure 103 16th incident: 33 kV XLPE, Mt Wellington No2 fault, 4EY, 66.9 m

Figure 104 Arc crater: 33 kV XLPE, Mt Wellington No2, 4EY, 66.9 m

Circuit Name	Cable	Outer Sheath	Chainage (m)	Elapsed Time (mins)
Remuera K10	11 kV PILC	Hessian STA	73.00	0.00
Remuera K10	11 kV PILC	Hessian STA	73.00	119.32
Control Cables	-	PVC	70.50	162.98
Carbine	Pilot	PVC SWA	-	165.97
Control Cables	-	PVC	70.50	169.20
Remuera No 3	33 kV XLPE	PE	72.50	170.15
Newmarket No 3	33 kV XLPE	PE	73.00	171.02
CBD Tunnel Aux	11 kV XLPE	PE	-	173.02
Carbine Road No 2	33 kV XLPE	PE	72.80	173.28
Remuera No 2	33 kV XLPE	PE	72.60	175.25
St John	Pilot	PVC SWA	-	180.10
St John No 3	33 kV XLPE	PE	72.30	181.27
St John No 3	33 kV XLPE	PE	72.30	181.27
Westfield No 2	22 kV OFC	PVC	-	181.27
Westfield No 3	22 kV OFC	PVC	-	181.27
McNab K02	11 kV PILC	Hessian STA	67.60	203.20
Carbine No 1	33 kV OFC	PVC CAS	68.90	207.20
Mt Wellington No 2	33 kV XLPE	PE	66.90	207.27
Mt Wellington No 1	33 kV XLPE	PE	-	207.40

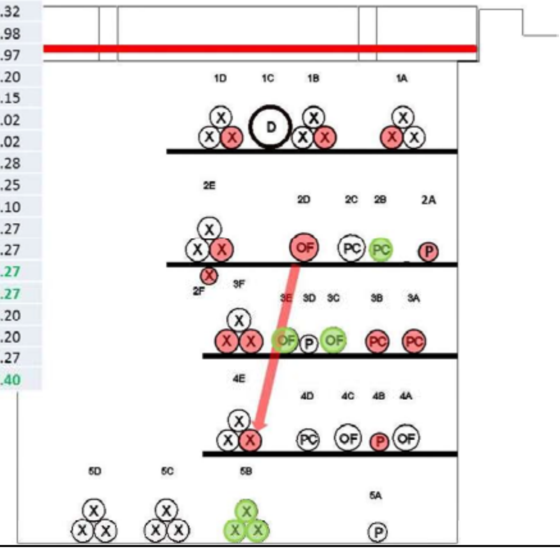


Figure 105 17th incident: 33 kV XLPE Mt Wellington No1 tripped, 5B

Circuit Name	Cable	Outer Sheath	Chainage (m)	Elapsed Time (mins)
Remuera K10	11 kV PILC	Hessian STA	73.00	0.00
Remuera K10	11 kV PILC	Hessian STA	73.00	119.32
Control Cables	-	PVC	70.50	162.98
Carbine	Pilot	PVC SWA	-	165.97
Control Cables	-	PVC	70.50	169.20
Remuera No 3	33 kV XLPE	PE	72.50	170.15
Newmarket No 3	33 kV XLPE	PE	73.00	171.02
CBD Tunnel Aux	11 kV XLPE	PE	-	173.02
Carbine Road No 2	33 kV XLPE	PE	72.80	173.28
Remuera No 2	33 kV XLPE	PE	72.60	175.25
St John	Pilot	PVC SWA	-	180.10
St John No 3	33 kV XLPE	PE	72.30	181.27
St John No 3	33 kV XLPE	PE	72.30	181.27
Westfield No 2	22 kV OFC	PVC	-	181.27
Westfield No 3	22 kV OFC	PVC	-	181.27
McNab K02	11 kV PILC	Hessian STA	67.60	203.20
Carbine No 1	33 kV OFC	PVC CAS	68.90	207.20
Mt Wellington No 2	33 kV XLPE	PE	66.90	207.27
Mt Wellington No 1	33 kV XLPE	PE	-	207.40
Mt Wellington K05	11 kV PILC	Hessian STA	50.00	207.40

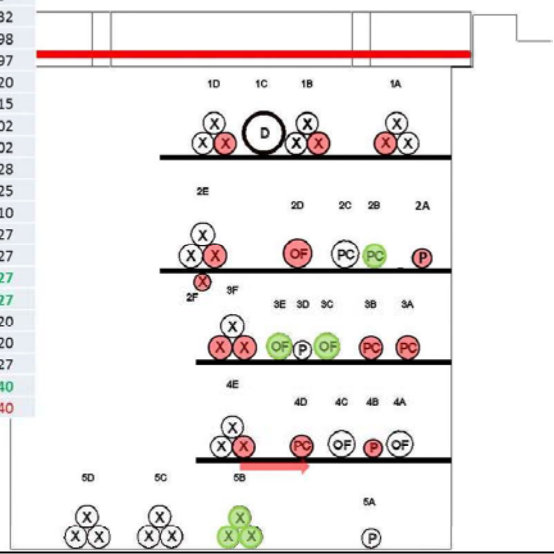


Figure 106 18th incident: 11 kV PILC, Mt Wellington K05 fault: 4D0, 50 m

Figure 107 Arc crater: 11 kV PILC, Mt Wellington K05, 4D0, 50 m

Circuit Name	Cable	Outer Sheath	Chainage (m)	Elapsed Time (mins)
Remuera K10	11 kV PILC	Hessian STA	73.00	0.00
Remuera K10	11 kV PILC	Hessian STA	73.00	119.32
Control Cables	-	PVC	70.50	162.98
Carbine	Pilot	PVC SWA	-	165.97
Control Cables	-	PVC	70.50	169.20
Remuera No 3	33 kV XLPE	PE	72.50	170.15
Newmarket No 3	33 kV XLPE	PE	73.00	171.02
CBD Tunnel Aux	11 kV XLPE	PE	-	173.02
Carbine Road No 2	33 kV XLPE	PE	72.80	173.28
Remuera No 2	33 kV XLPE	PE	72.60	175.25
St John	Pilot	PVC SWA	-	180.10
St John No 3	33 kV XLPE	PE	72.30	181.27
St John No 3	33 kV XLPE	PE	72.30	181.27
Westfield No 2	22 kV OFC	PVC	-	181.27
Westfield No 3	22 kV OFC	PVC	-	181.27
McNab K02	11 kV PILC	Hessian STA	67.60	203.20
Carbine No 1	33 kV OFC	PVC CAS	68.90	207.20
Mt Wellington No 2	33 kV XLPE	PE	66.90	207.27
Mt Wellington No 1	33 kV XLPE	PE	-	207.40
Mt Wellington K05	11 kV PILC	Hessian STA	50.00	207.40
Sylvia Park No 2	33 kV XLPE	PE	71.80	215.72

Figure 108 19th incident: 33 kV XLPE, Sylvia Park No 2 faults: 5DX

Figure 109 Arc crater: 33 kV XLPE, Sylvia Park No 2, 5DX, 71.8 m

Circuit Name	Cable	Outer Sheath	Chainage (m)	Elapsed Time (mins)
Remuera K10	11 kV PILC	Hessian STA	73.00	0.00
Remuera K10	11 kV PILC	Hessian STA	73.00	119.32
Control Cables	-	PVC	70.50	162.98
Carbine	Pilot	PVC SWA	-	165.97
Control Cables	-	PVC	70.50	169.20
Remuera No 3	33 kV XLPE	PE	72.50	170.15
Newmarket No 3	33 kV XLPE	PE	73.00	171.02
CBD Tunnel Aux	11 kV XLPE	PE	-	173.02
Carbine Road No 2	33 kV XLPE	PE	72.80	173.28
Remuera No 2	33 kV XLPE	PE	72.60	175.25
St John	Pilot	PVC SWA	-	180.10
St John No 3	33 kV XLPE	PE	72.30	181.27
St John No 3	33 kV XLPE	PE	72.30	181.27
Westfield No 2	22 kV OFC	PVC	-	181.27
Westfield No 3	22 kV OFC	PVC	-	181.27
McNab K02	11 kV PILC	Hessian STA	67.60	203.20
Carbine No 1	33 kV OFC	PVC CAS	68.90	207.20
Mt Wellington No 2	33 kV XLPE	PE	66.90	207.27
Mt Wellington No 1	33 kV XLPE	PE	-	207.40
Mt Wellington K05	11 kV PILC	Hessian STA	50.00	207.40
Sylvia Park No 2	33 kV XLPE	PE	71.80	215.72
McNab K19	11 kV PILC	Hessian STA	67.40	223.48
McNab K19	11 kV PILC	Hessian STA	67.90	223.48

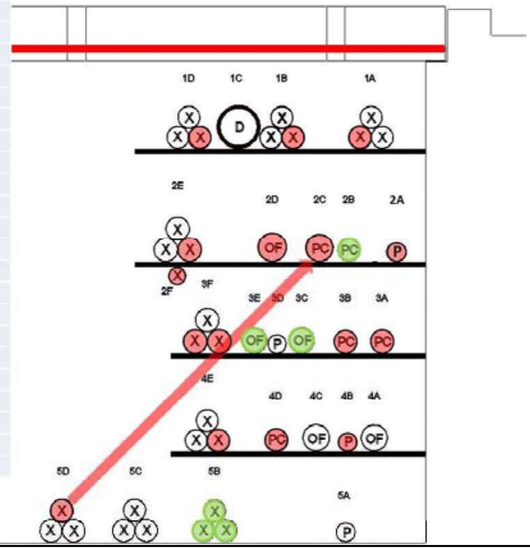


Figure 110 20th incident: 11 kV XLPE, McNab K19 fault, 2C0, 67.4 to 67.9 m

Figure 111 Arc hole in armour: 11 kV PILC, McNab K19, 2C0, 67.4 to 67.9 m

Figure 112 Arc crater in conductor: 11 kV PILC, McNab K19, 2C0, 67.4 to 67.9 m

Position	Circuit Name	Cable	Outer Sheath
2B	Not in Use	11 kV PILC	Hessian STA
4A	St John No 1	33 kV OFC	PVC CAS
3D	Westfield	Pilot	PVC SWA
4C	St John No 2	33 kV OFC	PVC CAS
5A	Mt Wellington	Pilot	PVC SWA
5C	Sylvia Park No 1	33 kV XLPE	PE

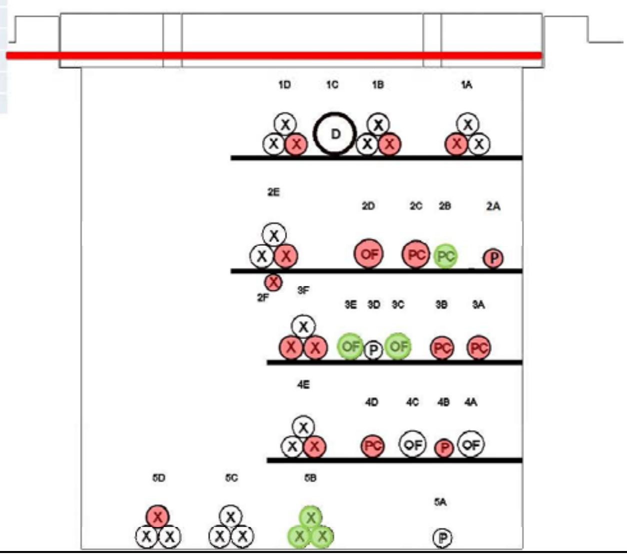


Figure 113 List of circuits that did not fail or trip

20 Appendix E, Design of 11 kV PILC to XLPE Transition Joint

20.1 General Layout of the Transition Joint

A diagram of the PILC cable side of the transition joint installed in the cable trench is shown in Figure 114. A magnified view of the crutch showing the fault location is shown in Figure 33.

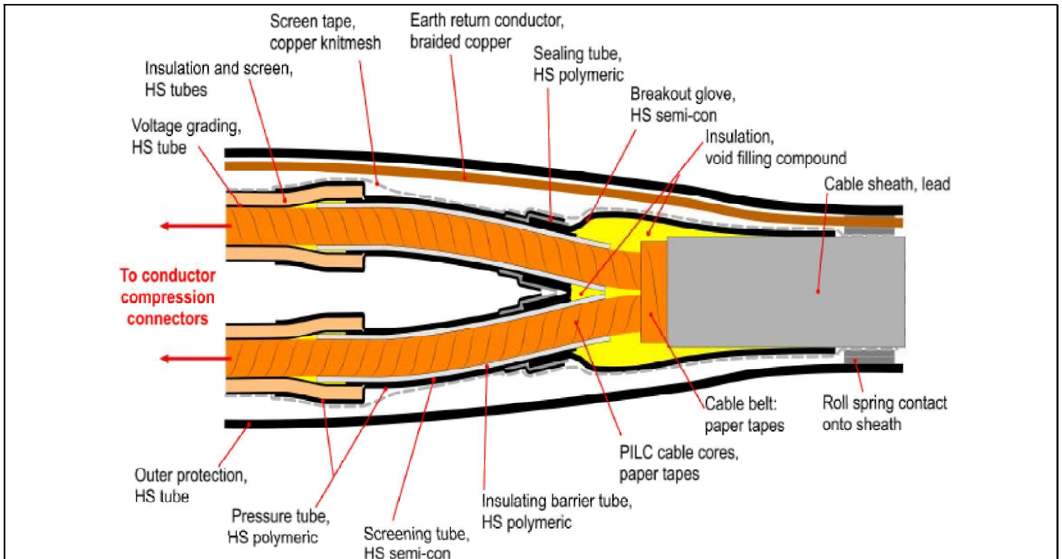


Figure 114 11 kV three core heatshrink sleeve transition joint PILC to XLPE
[HS: heat shrink]

The designs of the electrical connections to the metallic sheath and the heat shrink longitudinal water barrier seals depend upon the particular design of PILC cable with respect to the types of sheath, armour and serving. The joint design present in the cable trench is shown diagrammatically with measurements in Figure 115 and photographically in Figure 116. The component measurements referenced to the joint centre-line are shown in Figure 32.

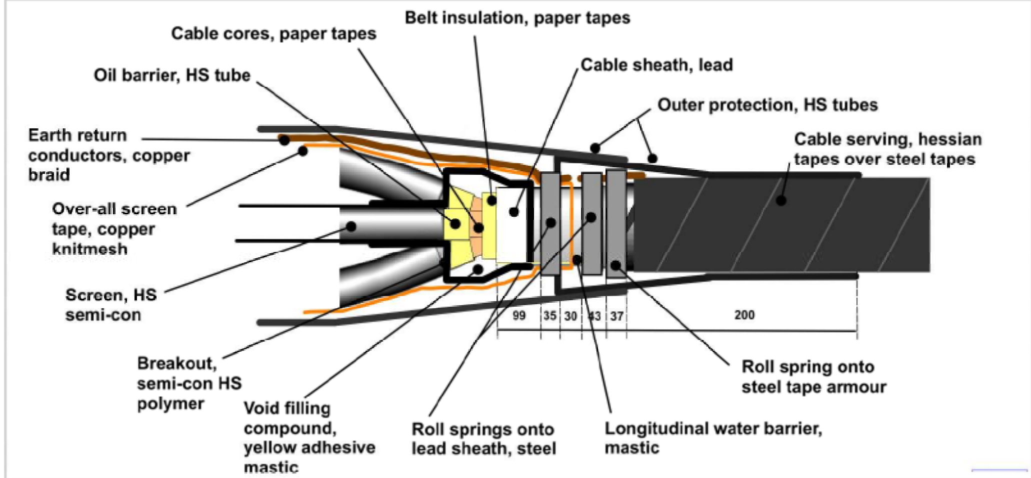


Figure 115 Unfailed11 kV transition joint: PILC end of joint

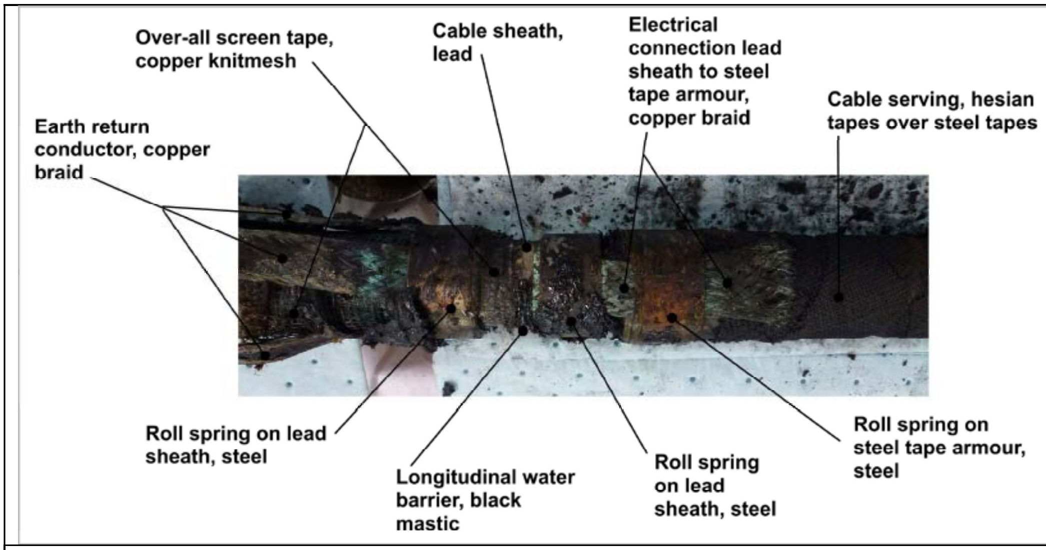


Figure 116 Electrical connections to PILC lead sheath and armour tapes

20.2 Transition Joint Assembly Sequence

Measured dimensions were taken from the unfailed transition joint at location 3B0, 79 m, and were recorded in units of millimetres on the jointing sequence diagrams, Figure 117 to Figure 128. The diagrams are based on the assembly stages given in the manufacturer's installation instruction that had the most representative design and which were found to have the closest issue date, 2003[3], to the 2001 date of installation.

The measured length of 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.

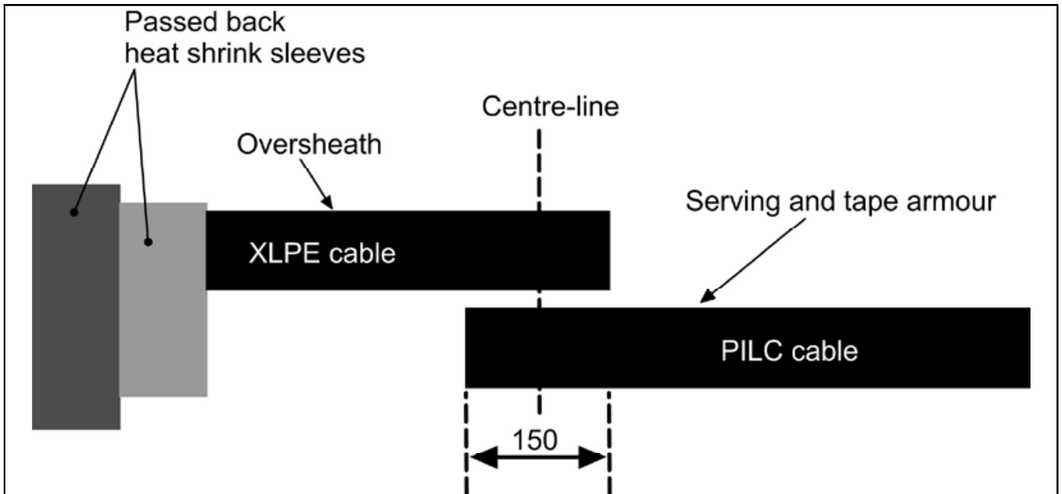


Figure 117 Outer protective heat shrink sleeves are passed-back

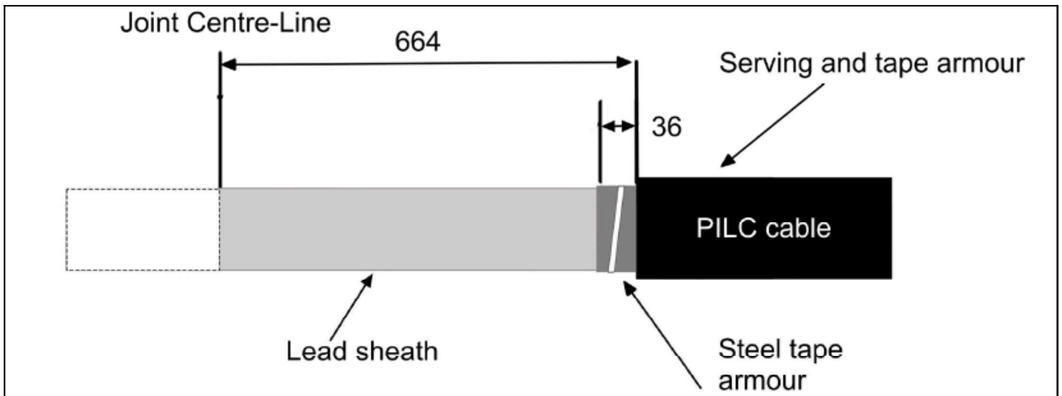


Figure 118 Serving and armour are stripped off the PILC lead sheath

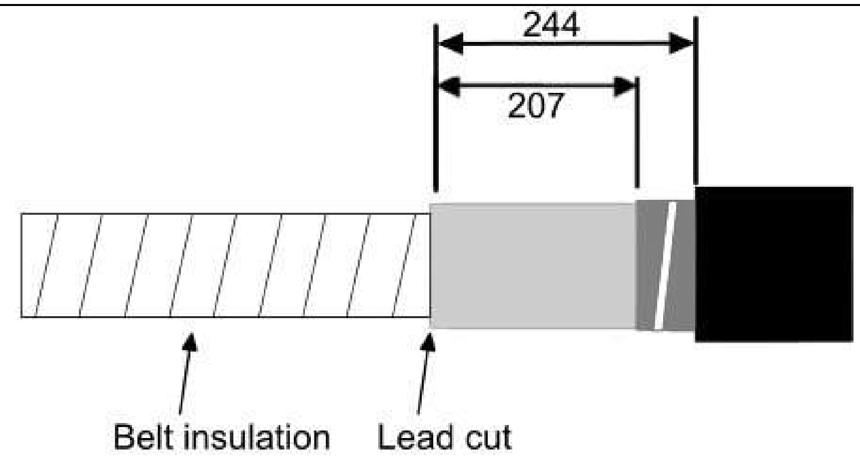


Figure 119 Lead sheath is removed from PILC cable to the lead cut position

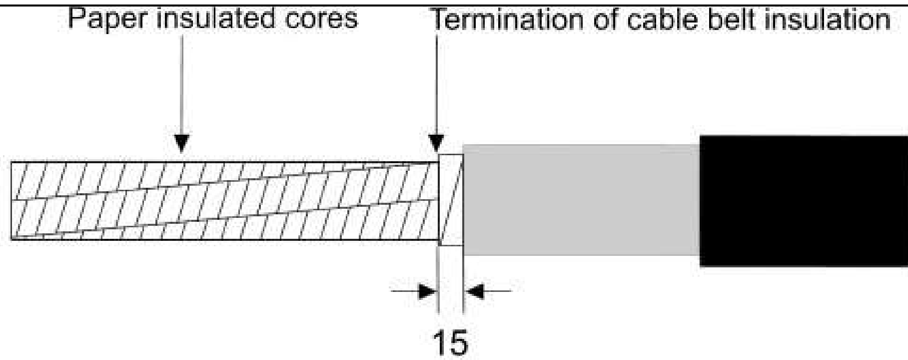


Figure 120 PILC belt tapes are torn off to form the belt insulation step

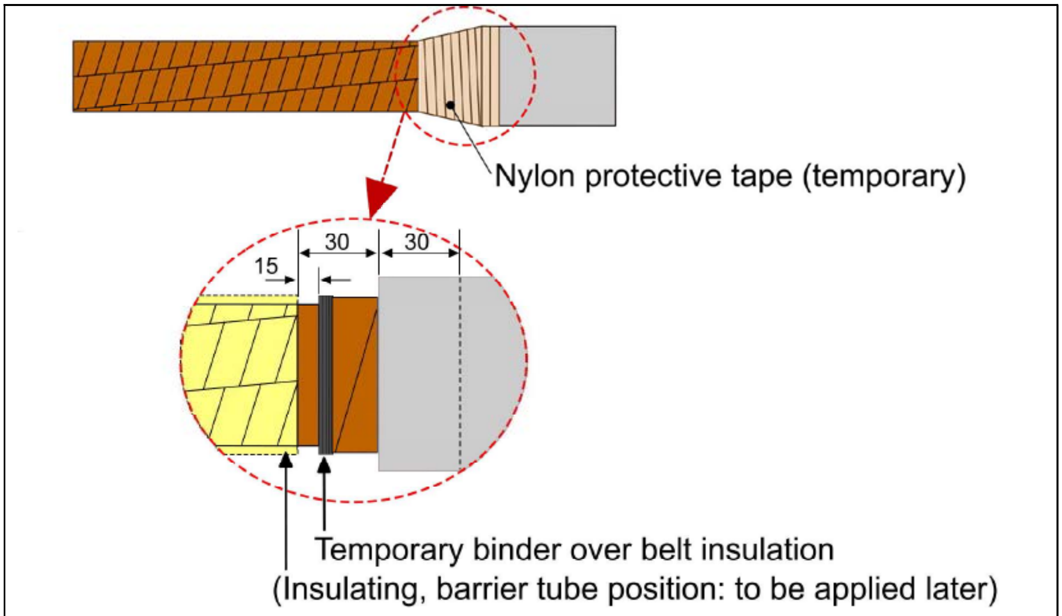


Figure 121 Nylon tapes are applied to protect the core insulation in the crutch

It is required, before fitting the insulation tubes, shown in Figure 122, to set them into offset bends similar to those shown in Figure 114 such that conductor connectors and adjacent cores will be parallel to the axis of the cable. This facilitates the penultimate stages of jointing in which the three insulated cores are bound together and wrapped with screening tape. The three cores in Figure 122 to Figure 128 are depicted for diagrammatic purposes as being straight.

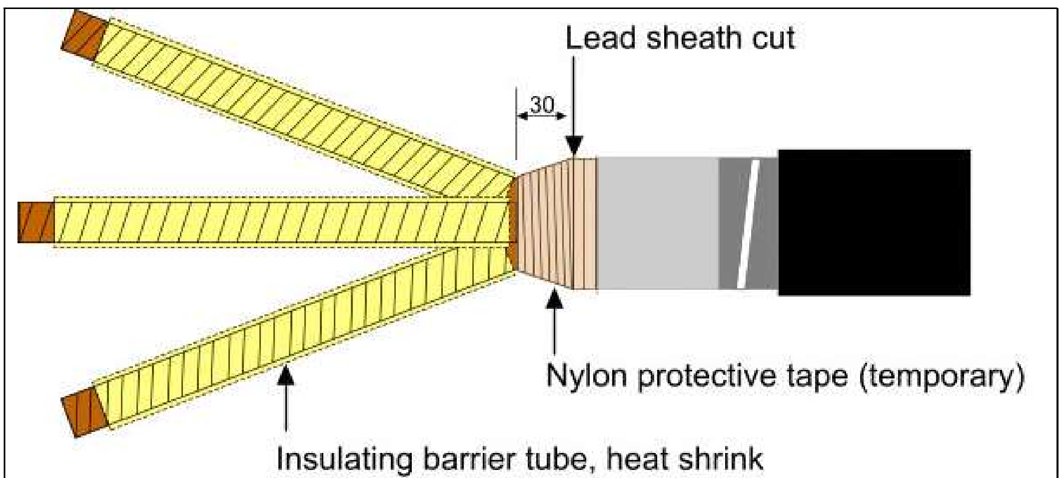


Figure 122 Insulation/barrier tubes are shrunk down over the PILC cores

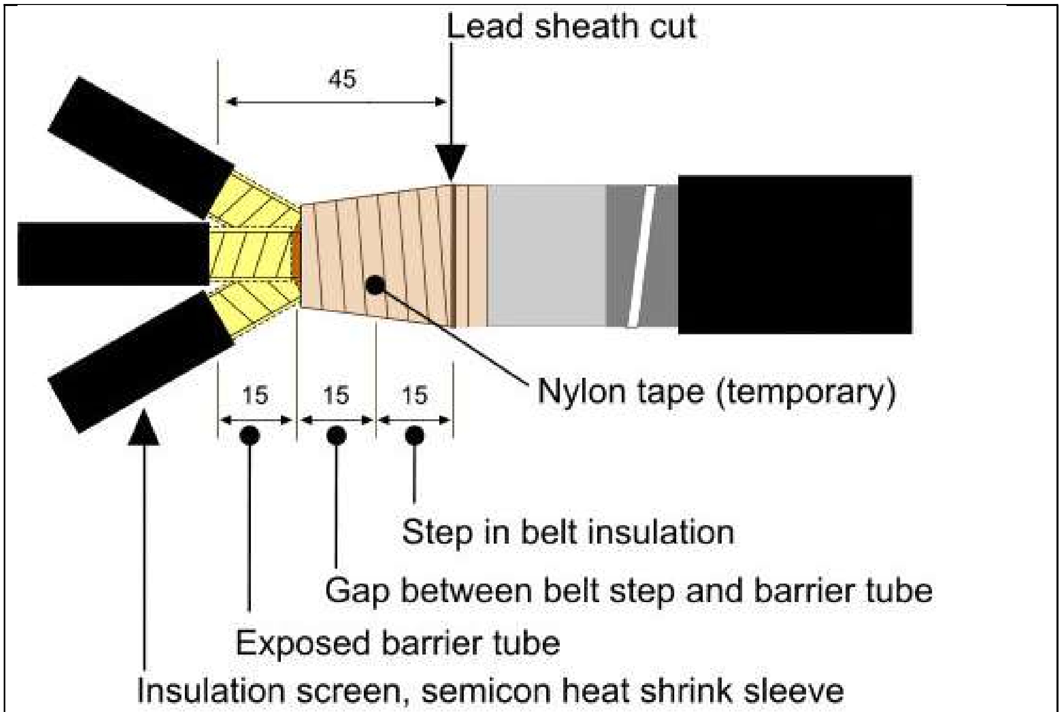


Figure 123 Conductive sleeves (earth screen) are heat shrunk onto the insulation/barrier tubes

Figure 124 shows a pre-shaped wedge of adhesive, yellow compound being inserted into the crutch of the unscreened PILC cable cores to fill and insulate the air void. It is understood that at the time of installation of the 3B0 failed transition joint in 2001 an insertion tool was not supplied as part of the jointing kit. It is understood that a suitably shaped implement was selected from the jointer's tool kit for this purpose. The supplier added a plastic tool to the joint kit at a later date. A diagram in an earlier Installation Instruction shows the wedge being inserted by a jointer's finger.

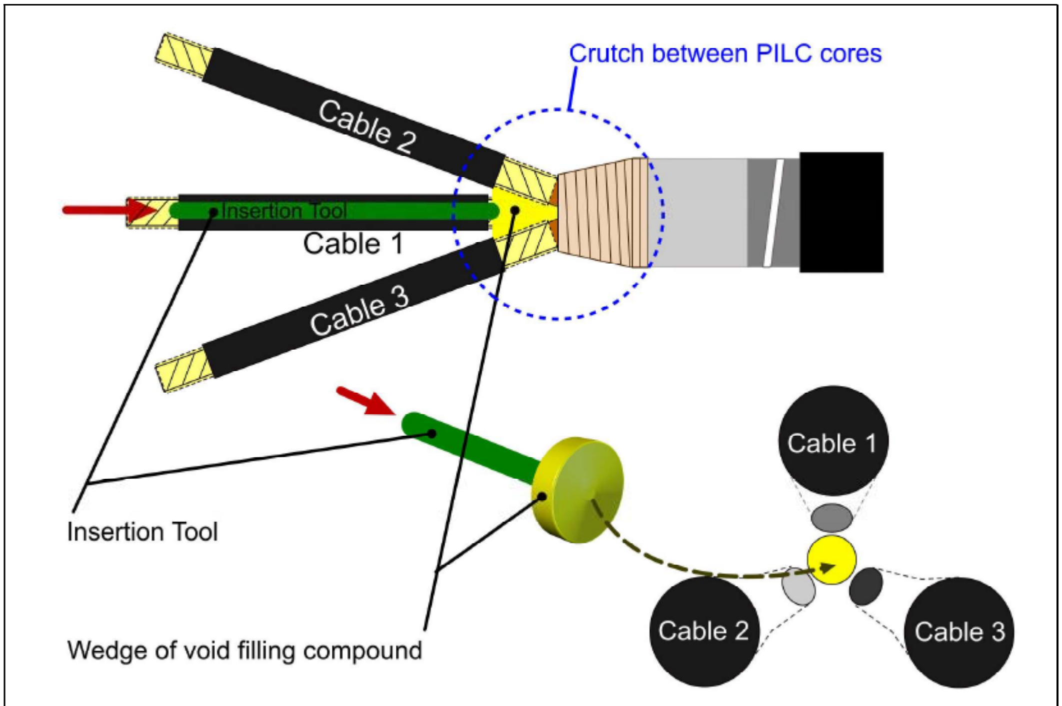


Figure 124 Wedge of insulating void-filling compound (yellow) is inserted into PILC crutch

Having inserted the wedge of compound into the crutch between the three PILC paper insulated cores the protective nylon tape is removed. Yellow void filling compound is then applied to form an insulating layer over and between the paper insulated cores. The adhesive compound is supplied in tape form interleaved between layers of disposable separating tape to prevent it from adhering to itself prior to use. Figure 125 records the overall length of the compound that was measured when the unfailed transition joint was dismantled. The yellow compound overlapped the lead sheath by 25 mm as shown by a stained area on the lead. The yellow compound was also present in the region from 25 mm up to the end of the breakout glove. In this region the compound had adhered to the lead sheath in some places and to the inside of the breakout sleeve in others. The surfaces of the compound had discoloured from yellow to a dark brown colour and gave the impression that this surface had deteriorated with age.

Similar discolouration was seen on the surfaces of the yellow void filling compound present in the XLPE to XLPE cable straight joints when they were dismantled.

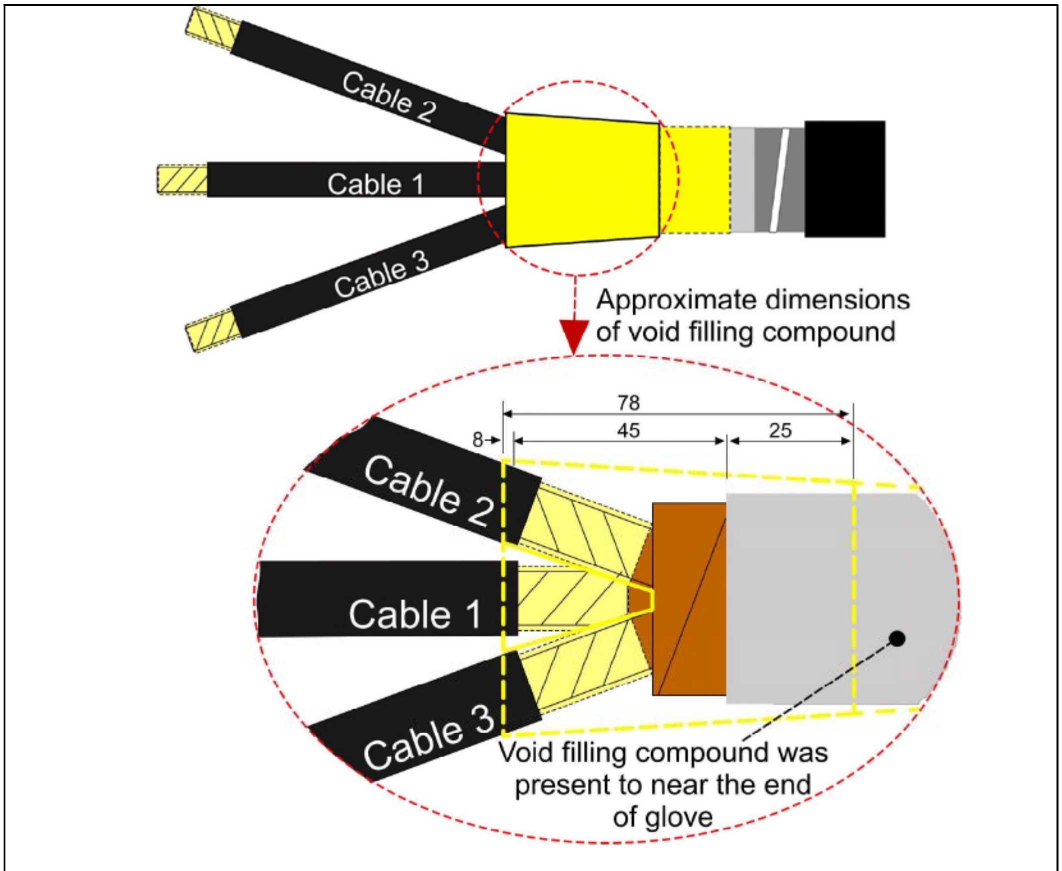


Figure 125 Protective nylon crutch tape is removed and insulating void-filling compound tape (yellow) is applied overall

A heat shrink breakout glove had been fitted over the heat shrink semi-con sleeves present over each of the three screened cores and then shrunk down onto the lead sheath, the taped yellow compound insulation and the semi-con conductive sleeves. The overlap onto the lead sheath was 93 mm as shown diagrammatically in Figure 126 of which the first 23 mm appeared to have adhered and formed a possible water seal. The overlap onto each of the semi-con core sleeves was approximately 50 mm, as shown in Figure 128. This overlap did not appear to be sealed to prevent water entry.

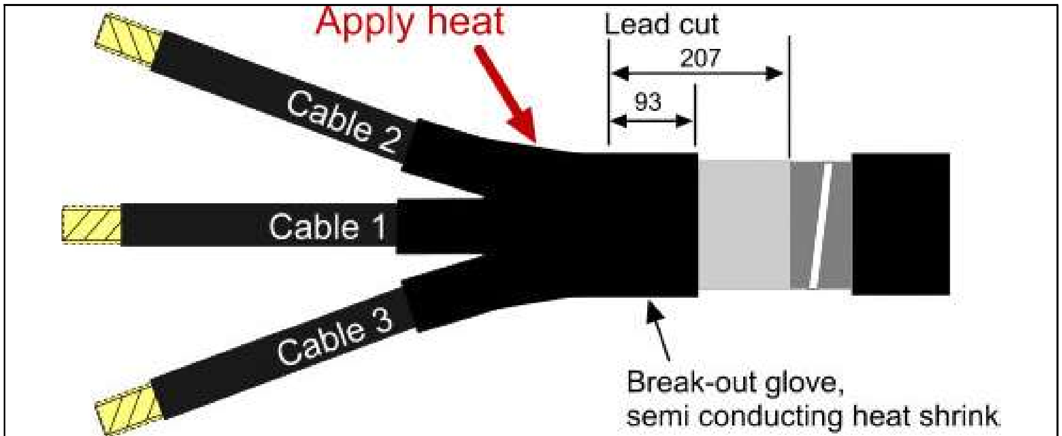


Figure 126 The break-out glove (conducting earth screen) is fitted and shrunk-down

Adhesive lined sealing sleeves of approximately 60 mm length had been heat shrunk down over the ends of the spouts on the breakout glove as shown in Figure 127. The length of the overlaps were typically 23 to 25 mm. White adhesive appeared to have been applied inside the sleeves in the factory in thin longitudinal lines. The adhesive had not been uniform spaced around the circumference and had not spread to form an annular sealing layer. The impression was given that this would not have formed an effective water seal.

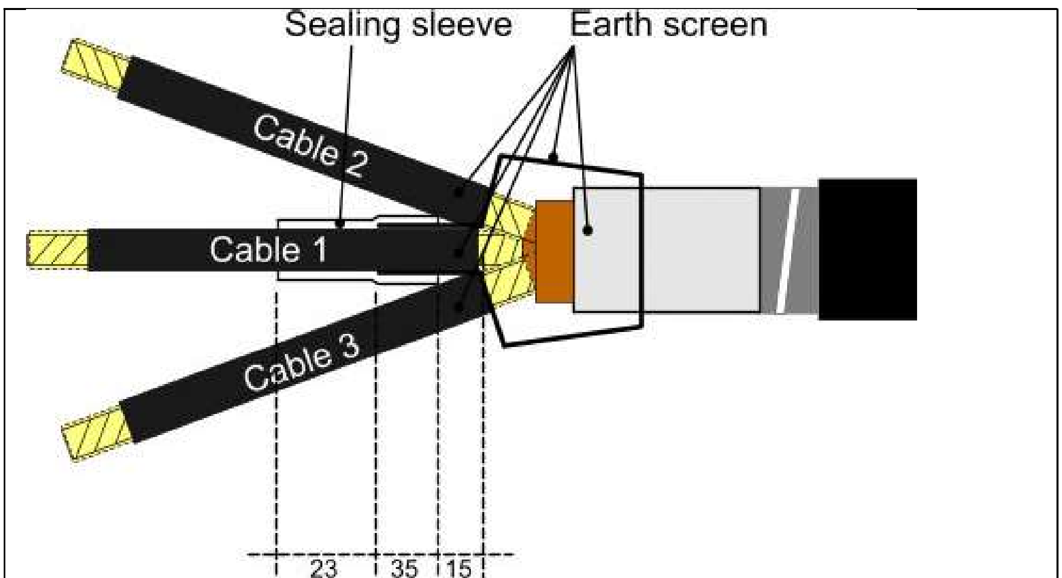


Figure 127 Sealing sleeves are fitted over the break-out glove spouts and shrunk down

The measured dimensions of the unfailed transition joint components are given in Figure 128.

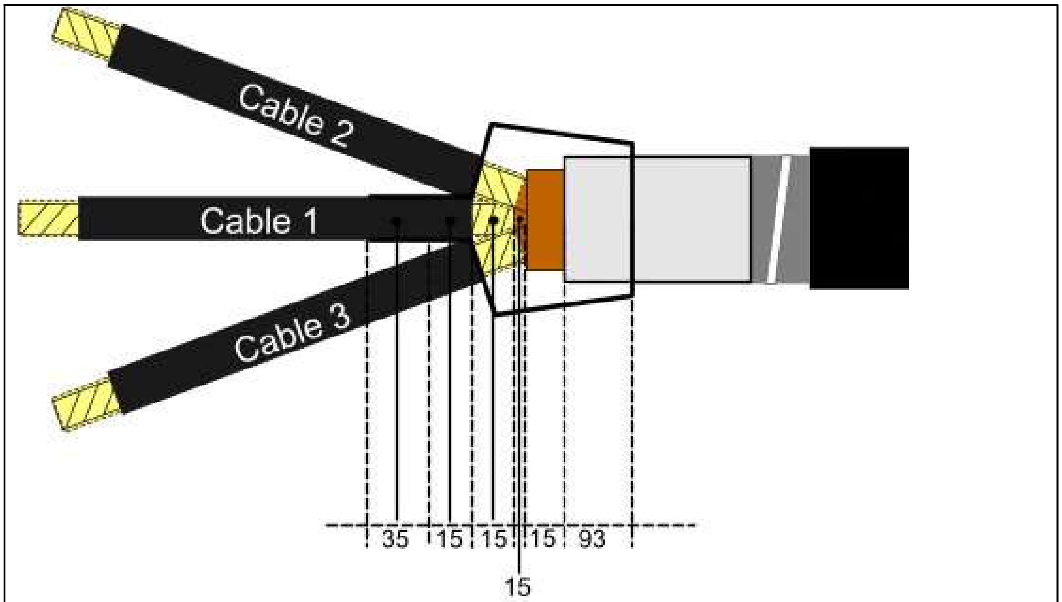


Figure 128 Dimensions of components associated with the break-out glove

Having converted the unscreened paper insulated PILC cores into semi-polymeric insulated and screened cores, they are next electrically connected to the XLPE cable cores. This stage of the jointing sequence is closely similar to that for the 33 kV XLPE straight joint as described in Section 18.3.2, Figure 78:

- The conductors are connected by a bimetallic compression ferrule. The copper half of the ferrule is compressed onto the PILC copper conductor. The aluminium half is compressed onto the XLPE aluminium conductor.
- The connectors are insulated with a combination of stress control, insulating and semi-conducting screen heat shrink sleeves and void-filling compound.

A polymeric pressure/protective tube, as shown in Figure 114, is then shrunk over the semi-con screening tube on each individual PILC core. At the breakout glove end it overlaps the short sealing sleeve. Towards the centre of the joint it overlaps the insulation and screen package present over the conductor connector. Each PILC paper insulated core is thus covered in three heat shrink tubes i) an insulating/barrier tube that is hydrocarbon oil resistant and which replaces the removed belt paper tape insulation, ii) a semi-con tube that screens the core and iii) a polymeric insulating tube that applies pressure to the two inner tubes to keep intimate contact between them and between the inner barrier tube and the paper tape insulation.

The three cores are then bound together by a copper mesh tape, which forms an overall earth screen and performs a similar electrical function to the lead sheath of the PILC cable and screen wires of the XLPE cable. (It is a requirement in UK supply regulations to provide cable systems above 600V with an earthed metallic covering.) On the PILC cable side the mesh was electrically connected to the lead sheath by contact pressure from a helical steel roll spring, as shown in Figure 115 and Figure 116.

The continuity for the return of i) AC charging current in normal operation and ii) high current during a through fault is provided by the connection of three, flexible, braided copper conductors. These are electrically connected:

- To the PILC lead sheath by pressure from a steel roll spring, Figure 115 and Figure 116.
- To the copper screen wires on the 11 kV three core XLPE cable, Figure 79, by a compression ferrule located at the midpoint of the joint.

The lead sheath is electrically connected to the steel tape armour by a short length of copper braid conductor interleaved between a second and a third steel roll spring, Figure 115 and Figure 116.

Layers of copper mesh screening tape are applied over the earth continuity conductors to bind them to the cores as shown in Figure 114.

A barrier to prevent the longitudinal entry of water is applied between the lead sheath and the inside of a protective heat shrink tube, which is applied later in the jointing process. The barrier is formed by inserting black compound into the annular gap present between the first and second steel roll springs as shown diagrammatically in Figure 115 and in the photograph of the unfailed joint, Figure 116. The spacing between the roll springs is approximately 30 mm. The width of the water barrier in the unfailed joint had been reduced to approximately 15 mm by the uneven ends of the roll springs and by the protruding presence of the ends of the copper knitmesh screen and copper braid conductors. It was considered that the design geometry of the mastic filled gap would have been inherently unpredictable and would not have been conducive to forming a consistent and reliable water barrier.

A water protective mastic/adhesive lined ‘adaptor’ heat shrink tube had been applied over the roll springs and over the hessian tape served PILC cable for a distance of 200 mm, Figure 115. It was observed that the length of the overlap of the heat shrink tube onto the cable serving could not form a watertight seal as the hessian tape serving had a water permeable open weave and the armour tapes below it had been factory applied with a gap between turns that provided a water permeable helical channel.

A larger diameter, adhesive lined, outer, heat shrink tube had been slid over the joint, as shown diagrammatically in Figure 114, and shrunk down onto the PILC cable 'adaptor' tube with an overlap of approximately 110mm. At its opposite end the protective tube is also shrunk down to seal onto the PE oversheath of the 11 kV three core XLPE cable.

21 Appendix F, 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."

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.

21.1 Conductor Temperature Calculation Method

The calculation of the conductor temperatures in the trench is complex and non-standard for the following reasons:

- The number of cable circuits (19) in the air filled trench.
- The variety of cable types: three core, single core, PILC, OF and XLPE.
- The variety of heat transfer types:
  - Conduction through the cable layers and ground.
  - Convection from the cable surfaces to the trench lining
  - Convection through the holes in the roof to ambient air
  - Radiation between each cable and the trench lining.
  - Conduction through the trench lining through the ground to ambient.
- The trench is buried at shallow depth with its concrete roof slabs level with the ground surface.
- The load current varies:
  - Each hour of the day.
  - Cyclically: being similar from one day to the next.
  - Seasonal: with differences between summer and winter.

Doubt existed that the current rating equations given in IEC 60287 were applicable to the particular cable trench and thus whether the calculated operating temperature would be sufficiently accurate.

An FEA (finite element analysis) simulation method was selected for the study based on i) 'Abaqus-Standard' FEA software for conduction and for cavity radiation and ii) Abaqus-CFD (computational fluid dynamics) for convection in air.

The method to solve the transient heating case for the cables in the trench was to:

- Model the geometry and materials of the cables, the trench and the surrounding ground.
- Model convection in air using Abaqus-Standard FEA software together with an algorithm for heat transfer between air and different surfaces based on published experimental measurements.
- Apply a step function current loading to each cable.
- Use the Abaqus Standard software to calculate the rise of conductor temperatures with heating time and abstract the conductor equilibrium plateau temperatures.
- Submit the plateau temperatures into a co-simulation comprising Abaqus-Standard together with Abaqus-CFD and compute the convective air flow patterns and heat transfer with time until the temperatures attain equilibrium.

An FEA model was constructed comprising the cables, the air filled trench and the ground surrounding the trench. The trench geometry is shown in Figure 4. The cable identification references are shown in Figure 6 with the exception that the failed 3B0 cable circuit was modelled as being in its normal position on Level 3 and not in the location on Level 2 in which the failed transition joint had been inserted.

The trench cross-section was modelled in two dimensions based on the assumption that the trench has longitudinal symmetry and negligible longitudinal heat flow. The two discrete cylindrical holes in each concrete roof slab and the air gaps between the slabs were modelled by two rectangular longitudinal slots that had the same air flow impedance and which were located at the same position as the cylindrical holes.

The trench is horizontally level and longitudinally symmetric westwards from the Gavin Street end to the 79 m chainage position. To the west of 79 m chainage the elevation of the ground surface and the trench descends to pass below steel tracks set into the switchyard surface for the purpose of transformer transportation. The trench then ascends to its original level before reaching the cable exit in the vicinity of the 33 kV Switchroom. It is considered that this local drop in level will have resulted in a chimney effect in which a limited volume of air will rise and flow both eastwards and westwards into the main run of trench. The complexity of modelling this local effect in three dimensions over the full length of the cable trench was beyond the scope and need of this temperature study. It was considered to be wise to check the results of the study to ensure that a suitable margin existed below the maximum operating temperatures for each type of cable to allow for the possibility that variations existed in the dimensions of the trench and its contents.

21.2 Current Loading Cases

Four current loading cases were studied:

1. Continuous steady state load in summer (ambient ground temperature of 23°C).
2. Continuous steady state load in winter (ambient ground temperature of 15°C).
3. Cyclic daily load in summer (ambient ground temperature of 23°C).
4. Cyclic daily load in winter (ambient ground temperature of 15°C).

In the continuous steady state load case the magnitude of the load current was taken to be equal to the peak hourly load current recorded on each circuit. The continuous steady state load FEA computation outputs conductor temperatures that are higher than those calculated by the cyclic rating method and are thus taken to be ‘engineering safe’.

In the cyclic load case an allowance is made for i) the heat output from the cables averaged over the twenty four hour cycle being lower than the continuous steady state load case and ii) the beneficial smoothing of the peak temperature by the thermal capacity of the cable and ground.

An examination of the circuit daily load patterns showed that there was a pronounced peak load in each 24 hour period. This permitted the Neher McGrath cyclic rating method[18] 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 two highest consecutive one hour peak currents were selected from a daily load curve. The two hour period is compatible with the thermal time constant of the cables of typically 0.9-1.5 hours. The application of a two hour step load is capable of raising the conductor temperature to nearly 90% of its steady state plateau value.

The value of continuous load current that generates the same heat output from the conductor as the two consecutive hourly currents was calculated. This is referred to as the two hour RMS (root mean square) current.

The twenty four hour RMS load current was also calculated for each cable circuit.

The currents for the two cases, 'continuous steady state load' and 'cyclic daily load' currents were separately applied to the model of the trench for computation of the temperatures. The calculated conductor temperatures for each load case are given in the following four sections.

21.3 Summer Continuous Steady State Loading at Peak One Hour Current Value

The increase of conductor temperatures with time calculated for the continuous steady state load case based on the magnitude of the one hour peak load are shown in Figure 129 to Figure 132. The temperatures of all the 19 cables were calculated by the Abaqus-Standard algorithm method. Figure 129 plots the temperature rise with time for the five hottest cables, these being listed in the legend on the bottom right hand side.

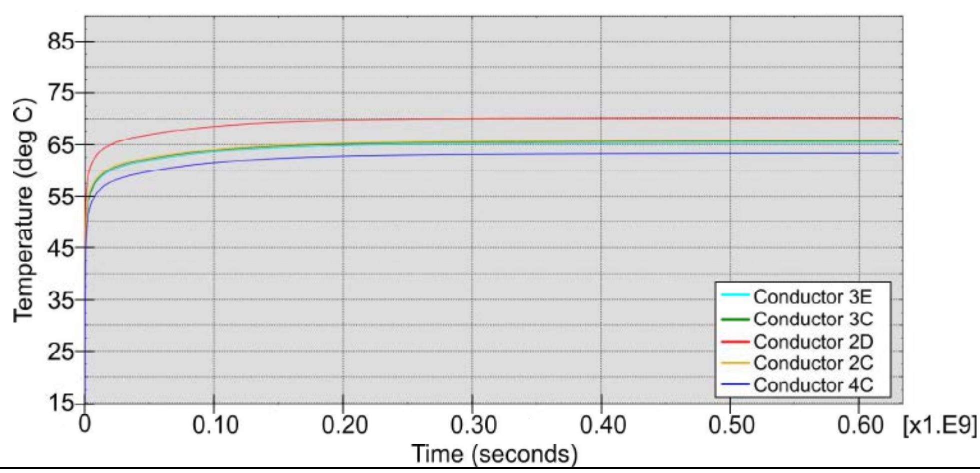


Figure 129 Temperature rise with time; continuous steady state loading at summer peak currents. Abaqus-Standard using convection algorithm equation:

The plateau conductor temperatures from Figure 129 were used as the starting temperatures for the Abaqus CFD convection model transient load case. The resulting plots of conductor temperatures with time to reach equilibrium are shown in Figure 130 to Figure 132.

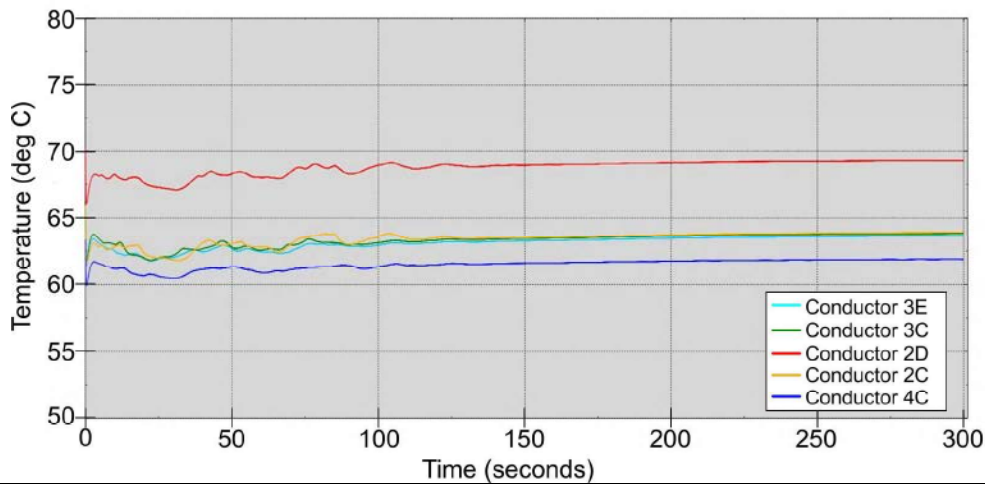


Figure 130 Temperature rise with time: continuous steady state loading at summer peak currents. Abaqus-CFD convection method

Table 11 lists the conductor temperatures of the five hottest cables. Table 11 compares the temperatures calculated by the CFD convection method with the algorithm convection method. The CFD and algorithm methods gave conductor temperatures in close agreement (within 3-4°C). The temperatures computed from the CFD simulation of convection were considered to be the most accurate.

Table 11 for continuous steady state loading shows that:

1) The maximum conductor temperature of 69°C occurred in the 33 kV OF cable 2D0. The temperature was satisfactory, being 16°C below the 85°C OF cable design limit.
2) The highest temperature of 64°C in an 11 kV PILC cable occurred in cable 2C0. This temperature was satisfactory, being 1°C below the 65°C PILC cable design limit for continuous steady state operation. No temperature margin exists to allow for possible variations in trench geometry and thermal properties along its length.

Table 11 Summer: Highest Conductor Temperatures under Continuous Steady State Loading at the Peak Current Values

Cable			Conductor Temperature [°C]		
Position	Type	Circuit	CFD	Algorithm	Design limit
2D0	33 kV OF	Carbine N° 1	69	70	85
2C0	11 kV PILC	McNab K19	64	66	65
3E0	22 kV OF	Westfield N° 3	63.5	66	85
3C0	22 kV OF	Westfield N° 2	63	66	85
4C0	33 kV OF	St John N° 2	62	63	85

Figure 131 is a velocity vector plot of the convective air flow in the trench. The arrows give flow direction. The length of the arrow is indicative of air speed. The magnitude of the air speed in metres per second may be read from the colour coded legend.

Figure 131 shows that warm air rises from the cables on the support arms on the north side (right hand) of the trench and moves upwards through the spaces between the cables. The air flow under the roof divides; the larger flow moves southwards across the trench roof with a small portion of the hot air venting out through one hole in the roof and drawing in cold air through the second hole (shown as vertical blue rectangles) and then descends on the south wall (left hand side) to flow northwards across the cables on the floor (Level 5). The minority air flow under the roof flows northwards and descends between the north wall and the adjacent cables. The highest air velocity of 0.26 m/s occurs adjacent to the south wall (on the left hand side).

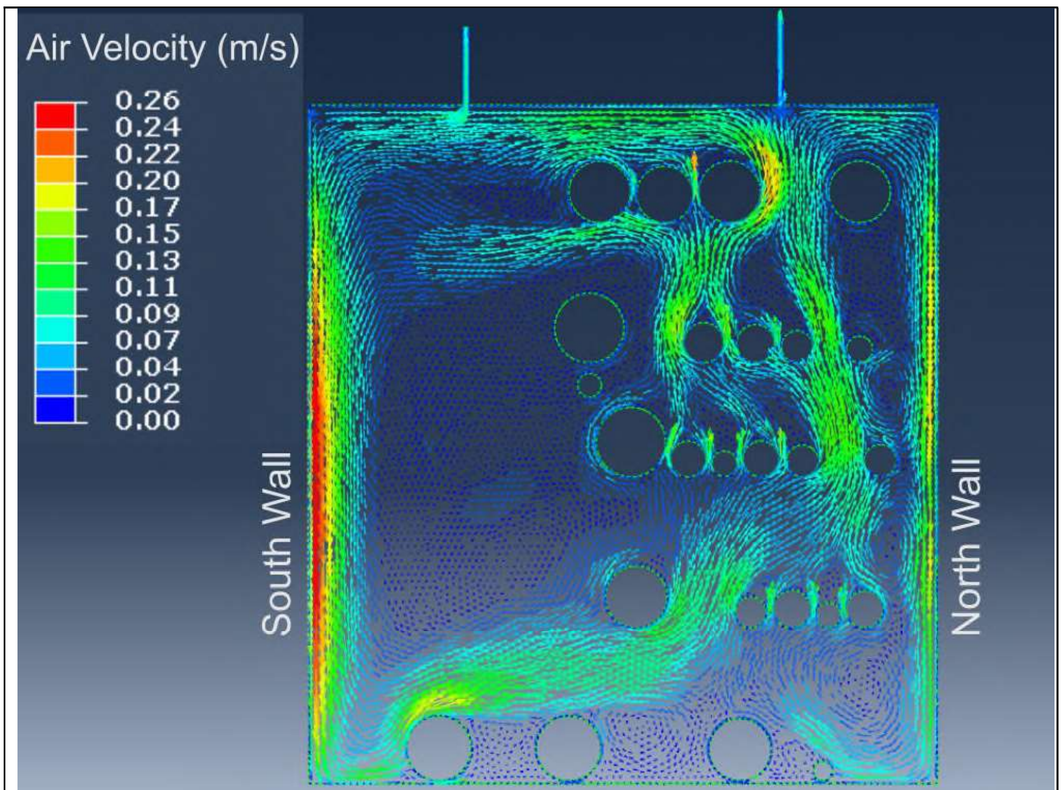


Figure 131 Velocity vector plot of air convection: continuous steady state loading at the summer peak current. Abaqus-CFD convection method

Figure 132 is a convection contour plot that shows the distribution of air temperatures in the cable trench.

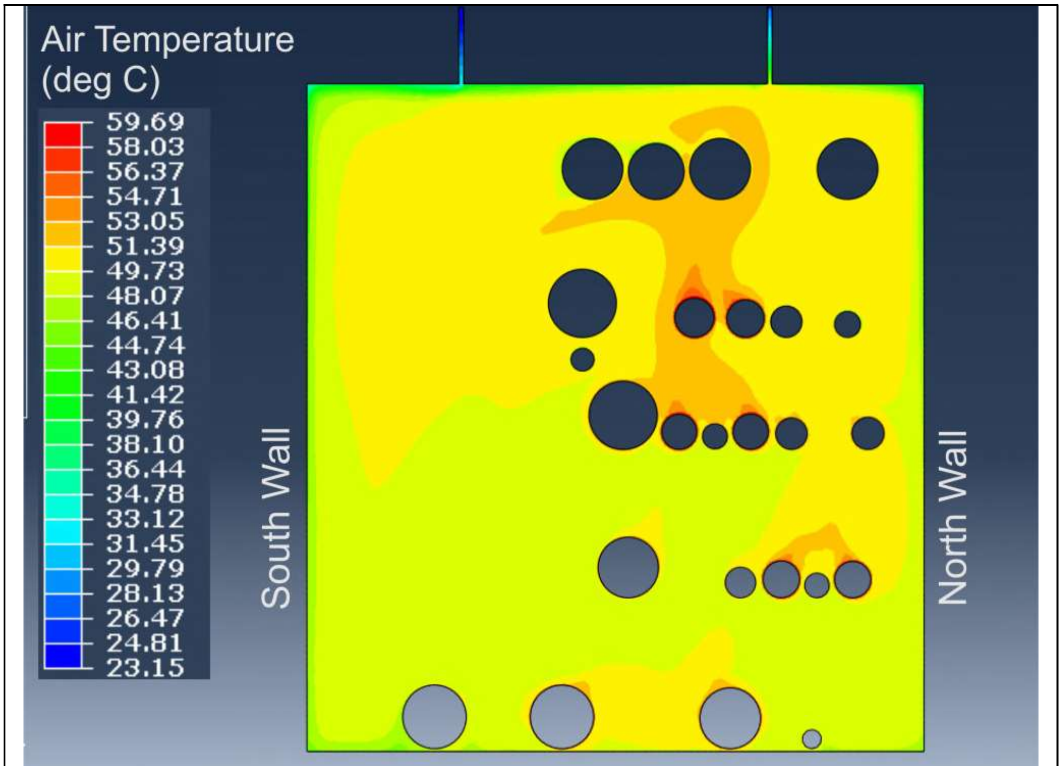


Figure 132 Air temperature contour plot: continuous steady state loading at the summer peak current values. Abaqus-CFD convection method

Figure 132 shows:

i) The highest air temperatures occur above six cables:
   - Level 2: 2C0, 11 kV PILC and 2D0, 33 kV OF
   - Level 3: 3C0, 22 kV OF and 3E0, 22 kV OF
   - Level 4: 4A0, 33 kV OF and 4C0, 33 kV OF

ii) The hot air rising from the two cables on Level 3 and Level 2 and joins to form a plume that rises to heat the 33 kV XLPE cables 1B- and 1D- on Layer 1. Hot air rising from 4A0 and 4C0 on Level 4 also forms a plume that heats 1A0.

iii) The air above the 33 kV XLPE cables 4E-, 5B-, 5C- and 5D- on Levels 4 and 5 is at a lower temperature, this being indicative of their low current loading compared to their capacity.

iv) The air rising above 3B0, the Remuera K10 circuit in which the first failure occurred, is at a comparatively low temperature (i.e. when it carried load in the years prior to 2014). The lower air temperature is dependent on both i) the average temperature of the trench air heated by the other cables and ii) the ratio of 3B0's comparative low current loading compared to its rated current carrying capacity. Arithmetically the temperature drop between the conductor and the outer cable surface is proportional to the ratio* of the 3B0 cable actual heat output to its rated heat output, (* i.e. proportional to the ratio of the square of the currents).

v) The air temperature in the trench is in the range of 43°C to 59.6°C. The average air temperature in the upper half of the trench is greater than 46°C. Cold air is drawn into the trench at 23°C from external ambient air. Thus, between day and night, the cables could prospectively experience a variation in air temperature between load and off-load (e.g. in an outage), for the high current carrying cables of 37°C (59.6°C to 23°C ambient) and for non-load carrying cables, such as the failed circuit 3B0, of 23°C (46°C to 23°C ambient).

Figure 131 and Figure 132 show the effect that actual cable spacings have on air flow and temperature. Uniform cable spacings would ideally give a distributed convective heat dissipation. Where the spacings between cables are closed, the rising air flows horizontally underneath them, so increasing the local air and cable temperatures. Where one large gap exists, the rising air is funnelled through it and forms a plume of warm air. The data cable duct, 1C0, is seen to have almost prevented the flow of air between it and 33 kV XLPE cables 1B- and 1D-.

21.4 Winter Loading: Modelling of Continuous Steady State Loading at Peak One Hour Current Value

The simulation is based on a continuous steady state current load at the winter peak one hour value for each cable.

The cable and the ground temperatures were calculated using the Abaqus-Standard Algorithm method. The colour coded legend in Figure 133 shows that the maximum winter conductor temperature was 77.02°C this being greater than the maximum summer temperature of 70.0°C.

Figure 133 shows the geometry of the ground isothermal temperatures to be smooth and uniform. This confirms that the boundaries* of the model are sufficiently remote to give an accurate temperature distribution in the trench and adjacent ground. (*The width of the model is ±50 m and its depth is 50 m).

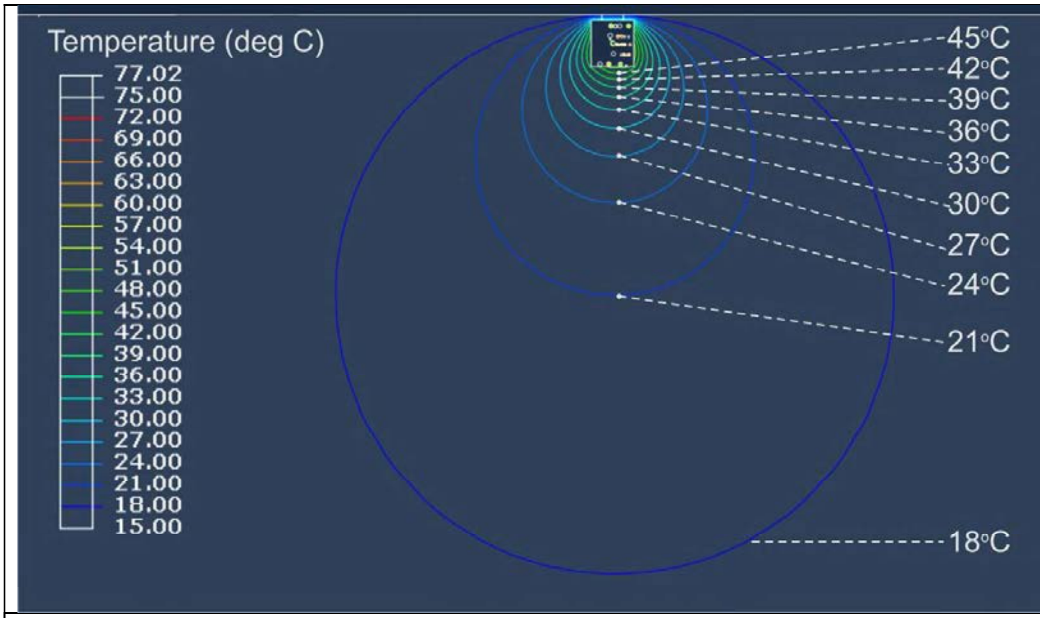


Figure 133 Abaqus-Standard Algorithm model of the cable trench showing ground isothermal lines for winter continuous loading

21.5 Winter Loading: Modelling of 24 h Cyclic Load

The calculation of the conductor temperatures when heated by a simulated 24 h cyclic load was performed in two stages using the full FEA model, the Abaqus-Standard software with algorithm convection equation and then the Abaqus CFD co-simulation software:

1. Stage 1 represented the thermal resistivity of the ground (basalt rock) as having its full value of 1.0 Km/W. A continuous load current of magnitude equal to the 24 hour RMS current was applied. The steady state temperature distribution around the walls of the trench was calculated. This temperature was thereafter taken to remain constant throughout the 24 hour period in consequence of the smoothing effect of the high thermal capacity of the surrounding ground.

2. In Stage 2 the application of the two hour peak current is taken to have a significant effect on increasing the temperature drop across the cable layers, but a negligible effect on raising the temperature of the trench walls and floor above the 24h RMS continuous loading case (from Stage 1). The peak RMS load currents (for the two hour period) were then applied as a continuous load to the 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 134, from the normal

value of 1.0 Km/W through 0.5 Km/W, 0.33 Km/W, to 0.25 Km/W. The optimum value of thermal resistivity was found to be 0.3125 Km/W. At this value the temperature of the trench lining became closely similar to that in the Stage 1 solution for the 24h RMS current (red dotted line). The thermal resistivity of the concrete roof of 1.0 Km/W was not changed during the iterations as i) the roof layer is thin and so has a lower value of thermal resistance and thermal capacitance than the mass of ground, thus permitting the transient 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.

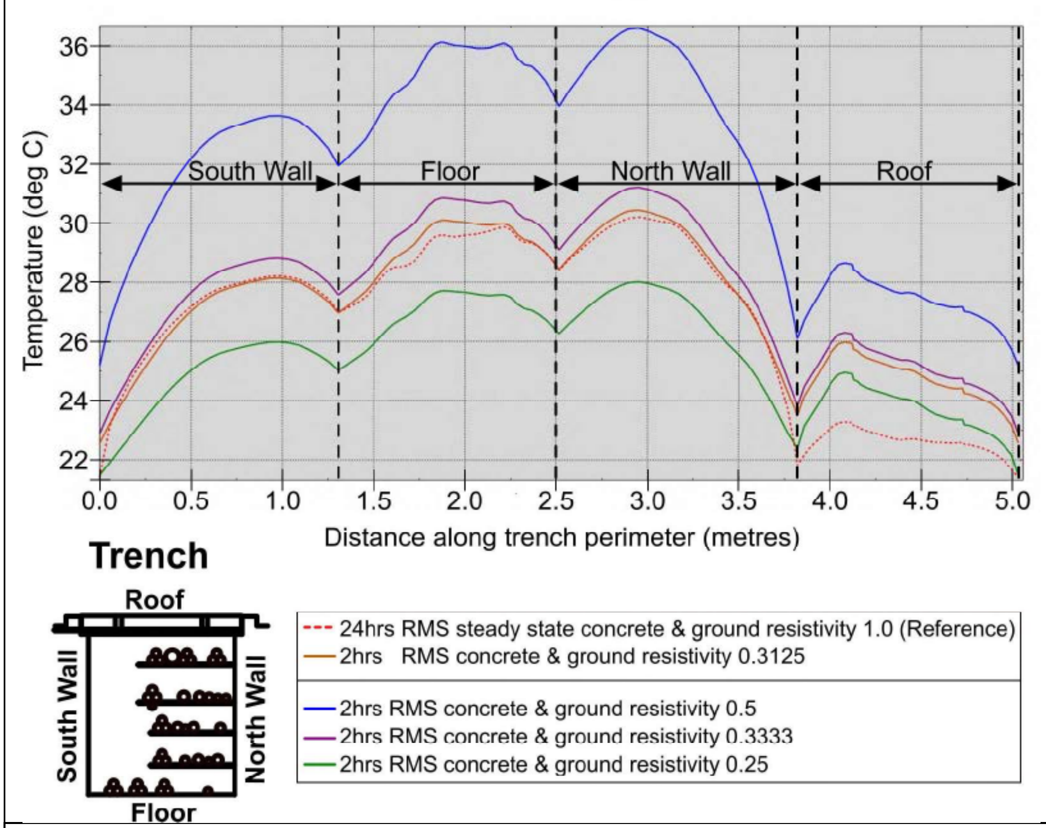


Figure 134 Winter 2 h peak 24 h cyclic rating: Iteration process to determine the effective thermal resistivity of the ground for the cyclic rating case

Having achieved the same wall and floor temperatures with a ground and wall thermal resistivity of 0.3125 Km/W, the conductor temperatures under cyclic loading were abstracted. Table 12 compares the conductor temperatures under winter cyclic loading calculated using the Abaqus-CFD co-simulation with the Abaqus-Algorithm simulation methods.

Table 12 Winter: Conductor and Sheath Temperatures under 2 h Peak 24 h Cyclic Loading

Cable Position	Cable Type	Circuit	Conductor Temperature [°C]		Max. Cable Sheath Temperature [°C]	
			CFD Co-Simulation	Algorithm	CFD Co-Simulation	Algorithm
1A-	33 kV XLPE	Remuera N°3	44.32	41.59	41.72	38.97
1B-	33 kV XLPE	Newmarket N°3	40.41	37.23	39.45	36.21
1D-	33 kV XLPE	Remuera N°2	43.71	41.18	41.49	38.93
2C0	11 kV PILC	McNab K19	57.82	56.74	49.44	48.30
2D0	33 kV OF	Carbine N°1	53.80	52.17	47.12	45.62
2E-	33 kV XLPE	Carbine N°2	38.13	35.54	37.94	35.30
3A0	11 kV PILC	McNab K02	58.24	57.97	49.32	48.60
3B0	11 kV PILC	Remuera K10	45.96	44.48	42.98	41.38
3C0	22 kV OF	Westfield N°2	48.09	46.78	44.02	42.53
3E0	22 kV OF	Westfield N°3	47.23	46.27	44.22	42.52
3F-	33 kV XLPE	St John N°3	41.88	39.93	40.76	38.81
4A0	33 kV OF	St John N°1	56.99	57.32	49.53	48.86
4C0	33 kV OF	St John N°2	59.17	59.29	50.26	49.24
4D0	11 kV PILC	Mt Wellington K05	42.19	37.54	40.51	36.15
4E-	33 kV XLPE	Mt Wellington N°2	38.66	37.30	37.84	36.42
5B-	33 kV XLPE	Mt Wellington N°1	36.77	37.30	36.15	36.49
5C-	33 kV XLPE	Sylvia Park N°1	40.60	41.18	38.37	38.69
5D-	33 kV XLPE	Sylvia Park N°2	34.00	33.94	33.56	33.53

Figure 135 shows that i) the maximum conductor temperature, cable 4C0, is 59.29°C and ii) the 1.5°C isotherms in the ground surrounding the trench are smooth and uniform.

Figure 136 is an expanded view of the temperature contour plot for the cable, the trench lining and the surrounding ground.

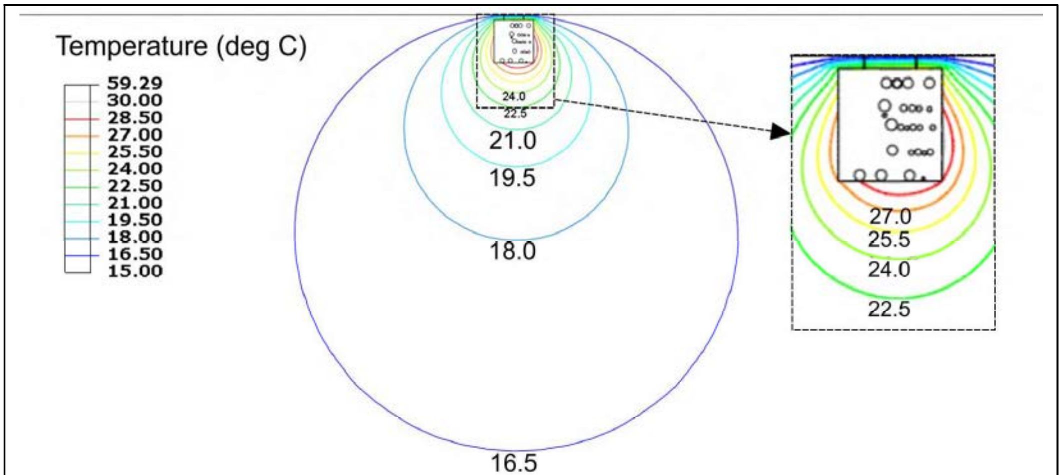


Figure 135 Winter 2 hour peak 24 hour cyclic rating (Abaqus-Standard): Ground isotherms

Figure 136 (Abaqus Standard-algorithm) shows that the highest rate of temperature drop external to the inner lining of the trench occurs through the concrete roof and indicates a higher heat dissipation through the roof. The temperature of the roof's inner surface (from Figure 134 and Figure 136) is 24°C, giving a temperature drop of 9°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 possible trench air temperature variation between day and night, assuming a night ambient of 15°C, will be less than 18°C i.e. (33°C – 15°C).

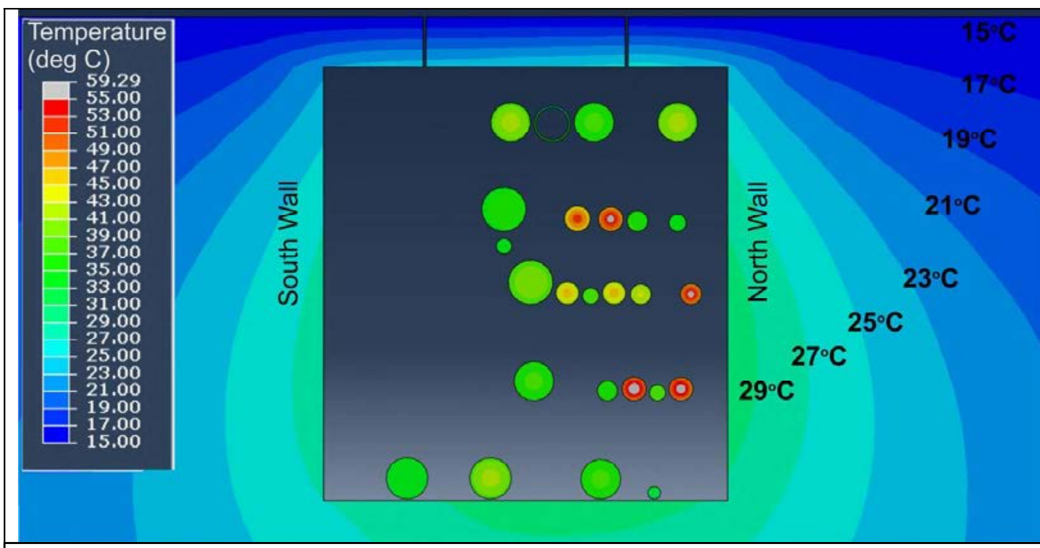


Figure 136 Winter 2 h peak 24 h cyclic rating (Abaqus-Standard): Cable and ground temperatures

Figure 137 shows the conductor temperatures reached by the five hottest conductors for winter cyclic loading using the Abaqus-Algorithm heat transfer method.

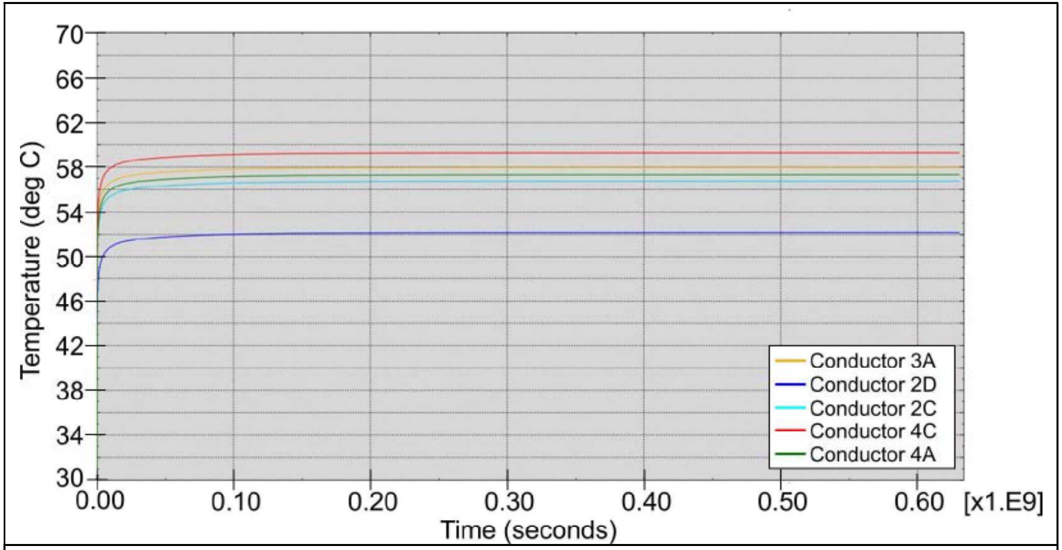


Figure 137 Winter 2 h peak 24 hour cyclic rating (Abaqus-Standard): Cable temperatures

Figure 138, Figure 140 and Figure 139 show the temperature distributions and air flows for winter loading using the full CFD co-simulation solution of the 24 h cyclic loading case based on the 2 h peak RMS current values applied to each circuit.

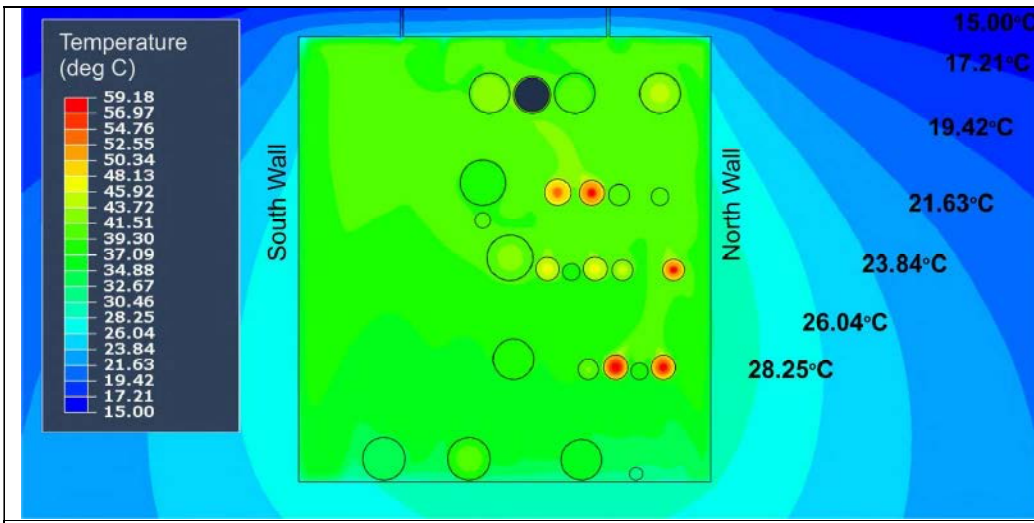


Figure 138 Winter 2 h peak 24 h cyclic rating (Abaqus CFD): Conductor, cable, air and ground temperatures

Figure 138, Figure 140 and Figure 139 show:

- The maximum conductor temperature is 59.18°C and occurs in 4C0. The highest conductor temperatures occur in cables 4C0, 3A0, 2C0, 4A0, 2D0 and 3C0.
- The maximum air temperature is 49.77°C. The highest air temperatures are next to the outer surfaces of cables 4C0, 4A0, 2C0, 3A0, 2D0 and 3E0.
- The maximum air velocity is 0.25 m/s and is adjacent to the south wall.

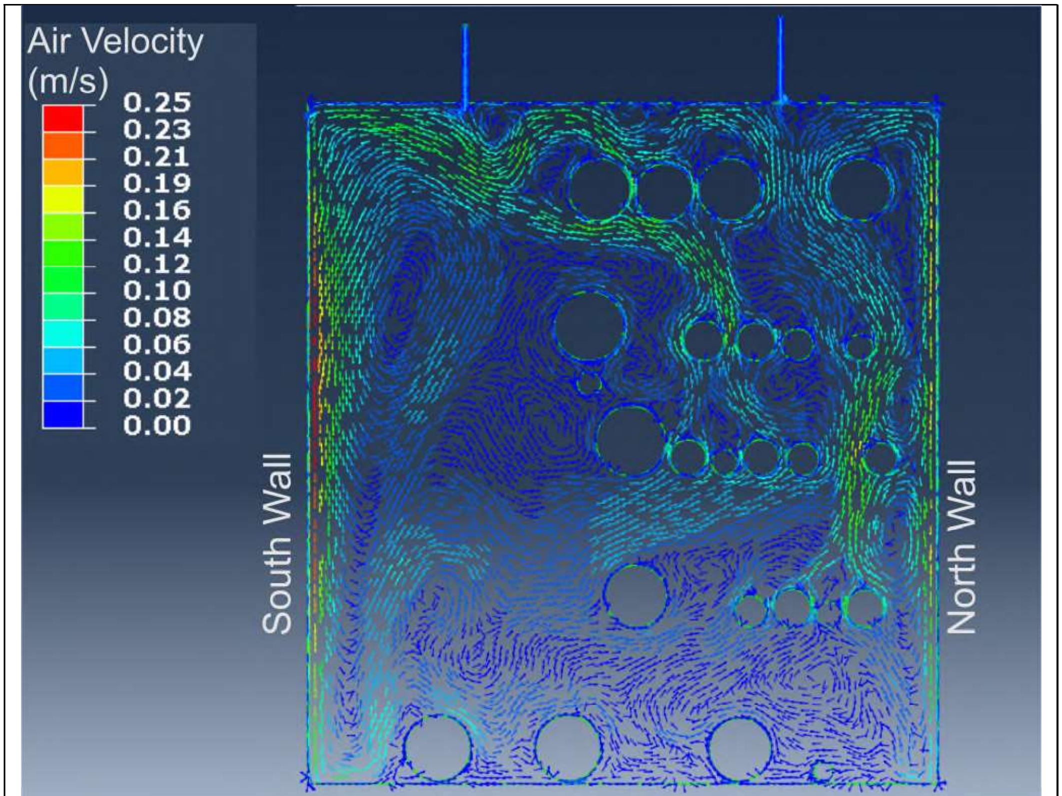


Figure 139 Winter 2 h peak 24 h cyclic rating (Abaqus: CFD): Velocity vector plot of air convection

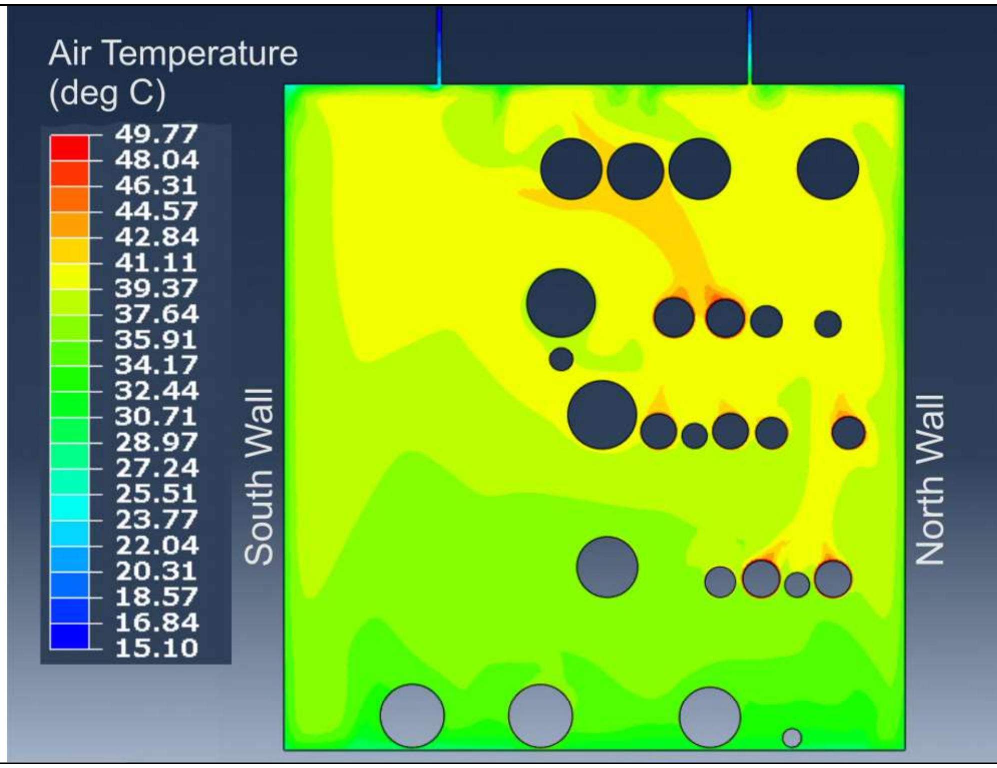


Figure 140 Winter 2 h peak 24 h cyclic rating (Abaqus CFD): Trench air temperature contour plot

The Abaqus CFD co-simulation results showed that:

- Radiation was found to be the most efficient means of heat transfer within the trench:
  - Radiation: 73.8%
  - Convection: 22.0%
  - Air vents: 4.2%

- The roof and left hand wall (southern wall) 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 for the winter 24 h cyclic loading, 2 hour peak load case, are shown in Table 13 for the five cables having the highest temperatures. The temperatures in Table 12 and Table 13 confirm that the cables are all within their design limits:

- 11 kV PILC cables were 7°C to 23°C below their design limit of 65°C i.e. an operating margin of 7°C existed.
- The circuit that was the first to fail, 3B0, 11kV PILC Remuera K10, in the years that it had carried load had a conductor temperature of 46°C i.e. 19°C below its design limit.
- 33 kV oil-filled cables were 26°C to 38°C below their design limit of 85°C.
- The 33 kV XLPE cables were 46°C to 56°C below their design limit of 90°C.

Table 13 Winter: Highest Conductor Temperatures under 2 h Peak 24 h Cyclic Loading

Cable			Conductor Temperatures [°C]	
Position	Type	Circuit	Algorithm	Design
4C0	33 kV OF	St John N° 2	59.29	85
3A0	11 kV PILC	McNab K02	57.97	65
4A0	33 kV OF	St John No 1	57.32	85
2C0	11 kV PILC	McNab K19	56.74	65
2D0	33 kV OF	Carbine N° 1	52.17	85

21.6 Summer Loading: Modelling of a 2 h Peak 24 h Cyclic Load

Table 14 gives the summer cyclic loading temperatures for the five hottest cables for comparison with the winter loadings in Table 13.

Table 14 Summer: Highest Conductor Temperatures under 2 h Peak 24 h Cyclic Loading

Cable			Conductor Temperatures [°C]	
Position	Type	Circuit	Algorithm	Design
2D0	33 kV OF	Carbine N° 1	59.5	85
2C0	11 kV PILC	McNab K19	55.0	65
3C0	22 kV OF	Westfield No 2	54.5	85
3E0	22 kV OF	Westfield No 3	54.0	85
4A0	33 kV OF	St John No 1	51.0	85

The summer and winter temperatures for the hottest cables present in both tables for summer and winter are compared in Table 15.

Table 15 Comparison of Winter and Summer Cyclic Temperatures under 2h Peak 24 h Cyclic Loading

Cable			Conductor Temperatures [°C]		
Position	Type	Circuit	Winter	Summer	Design
2D0	33 kV OF	Carbine N° 1	52	59.5	85
2C0	11 kV PILC	McNab K19	56.7	55.0	65

Summarising both winter and summer temperatures under 2 h peak 24 h cyclic loading:

- The conductor operating temperatures for winter and summer 2 h peak 24 h loading are of closely similar magnitudes.
- All of the cable temperatures were shown to be satisfactory having operating temperatures below their design limits.
- Of all the cable types, the 11 kV PILC cables were operating closest to their design limit of 65°C. The PILC cables with the highest operating temperature was 3A0 and 2C0 and operated at a margin of 7°C below their design limit. Of the PILC cable types, cable 2C0 was present in the lists of the five highest temperature cables for both summer and winter loading.
- The circuit that was the first to fail, 3B0, 11V PILC Remuera K10, had a lower conductor temperature of 46°C (i.e. in winter 19°C below its design limit of 65°C).
- The 22 kV and 33 kV oil-filled cables were more than 25°C below their design limit of 85°C.
- The 33 kV XLPE cables were more than 45°C below their design limit of 90°C.
- The temperature of the inner surface of the trench roof in summer was 31°C (8°C above ambient) and in winter 24°C (9°C above ambient).

21.7 Conclusions on Cable Operating Temperatures

The CCI Author concludes that:

i) The operating temperatures of all the cable circuits and all the types of cables within the cable trench under cyclic loading in both the summer and winter seasons are satisfactory, being below their design limit temperatures:

   a. The operating temperatures of all the 11 kV PILC cables are satisfactory, being more than 7°C below their design limit of 65°C.

      i. The cables closest to their design limiting temperature are the 11 kV PILC cables 3A0 (7°C) and 2C0 (7°C).
      ii. The 11 kV PILC circuit that was the first to fail, 3B0, Remuera K10, had a satisfactory conductor temperature 19°C below its design limit of 65°C when it was last on continuous load in 2013.

   b. The operating temperatures of all the 22 kV and 33 kV OF cables are satisfactory, being more than 25°C below their design limit of 85°C.

   c. The 33 kV XLPE cables are satisfactory having the lowest conductor temperatures of all the different types of cable, being more than 45°C below their design limit of 90°C.

ii) The temperature calculations confirmed the reason that samples of XLPE cable insulation were found by Edif ERA to have experienced temperatures above their design limit of 90°C was not by overheating in normal service operation. The CCI Author thus concludes that the cause is overheating by hot air during the fire.

22 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) Confirm that the 11 kV Remuera K10 joint experienced high arc energy.
ii) Estimate the temperature of the arc eroded conductor metal.

It is noted that calculating the behaviour of a power arc is a complex, multi-parameter, non-linear problem for which few of the parameters in the case of an 11 kV transition joint are known. Hence a rigorous academic solution is beyond the reach of this investigation.

This section uses simple engineering approximations. For the sake of simple engineering calculations it is usual to take an arc to have a near constant, low voltage drop in consequence of its highly non-linear electrical resistance.

Figure 141 Clay volumes from the conductor arc cavities

22.1 Volume of Arc Eroded Cavities

The conductor volumes eroded by the power arcs, the fault currents and the fault times are compared, Table 16. The volumes were obtained by measuring the clay and Plasticine impressions of the fault cavities. The impression 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 20 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 records:

- The measured arc erosion volume in the failed 11 kV PILC transition joint 3B0 to be 27.3 mL, this being produced by the passage of 4,200 A fault current on two occasions both of two 0.55 s duration.
- The 3B0 transition joint crater volume to have been very significantly larger than those in the other 11 kV PILC faults; i.e. 3A0 has 4.9 mL and 2C0 has 1.6 mL and 3 mL.
- The failed 3B0 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 confirmed 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	Circuit	Fault Position in Trench		Fault Type	Fault Duration	Fault Current	Arc Crater Volume
		Cross Section	Chainage				
hr min sec			m		s	A	mL
23:21:30	Remuera K10, 11 kV PILC	3B0	73	Two phase Three phase	0.053 0.508	4,200	27.3
01:20:49	Remuera K10, 11 kV PILC	3B0	73	Three phase	0.55	4,200	
02:11:39	Remuera 03, 33 kV XLPE	1AZ	72.5	Single phase-earth	0.215	16,000	25.8
02:12:31	Newmarket 3, 33 kV XLPE	1BY	73	Single phase-earth	0.131	13,962	-
02:14:31	Tunnel Aux 11 kV XLPE	2F0	-	-	-	-	-
02:14:47	Carbine Rd 2, 33 kV XLPE	2EY	72.8	Single phase-earth	0.364	16,744	16.9
02:16:45	Remuera 02, 33 kV XLPE	1DY	72.6	Single phase-earth	0.175	16,500	-
02:22:46	St John 03, 33 kV XLPE	3FX-Y	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	3A0	67.7	Two phase - earth	0.199	10,370 - 11,190	4.9
02:48:42	Carbine 01, 33 kV OF	2D0	68.9	Two phase - earth	0.412	16,000	-
02:48:46	Mt Wellington 02, 33 kV XLPE	4EY	66.9	Single phase - earth	0.196	14,500	-
02:48:54	Mt Wellington 01, 33 kV XLPE	5BY	-	-	-	-	-
02:48:54	Mt Wellington K05, 11 kV PILC	4D0	-	-	-	-	-
02:57:13	Sylvia Park 02, 33 kV XLPE	5DX	71.8	Single phase - earth	0.093	14,546	-
03:04:59	McNab K19, 11 kV PILC	2C0	67.4 – 67.9	Two phase - earth	0.319	3,980- 4,280	1.6 3

22.2 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 Stanback[19] to experimental results and later used for engineering investigations by Gammon and Matthews[25].

$$V = k.I^{1.5}t$$

Where:

Symbol		Unit or value
V	volume of metal lost for one electrode	m^3
k	constant for copper electrode	$1.185.\ 10^{-5}$
I	fault current	Amp
t	duration of fault	s

The curves in the graph in Figure 142, Figure 143 and Figure 144 were drawn to illustrate the dependence of lost copper volume on fault time and current according to the Stanback relationship. For the purpose of the illustration each line represents a constant fault duration together with a multiplying factor to represent i) the number of power arcs present during the fault between the phase conductors and ii) 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 142 for four faults that had copper conductors and in Figure 143 for three faults that had aluminium conductors.

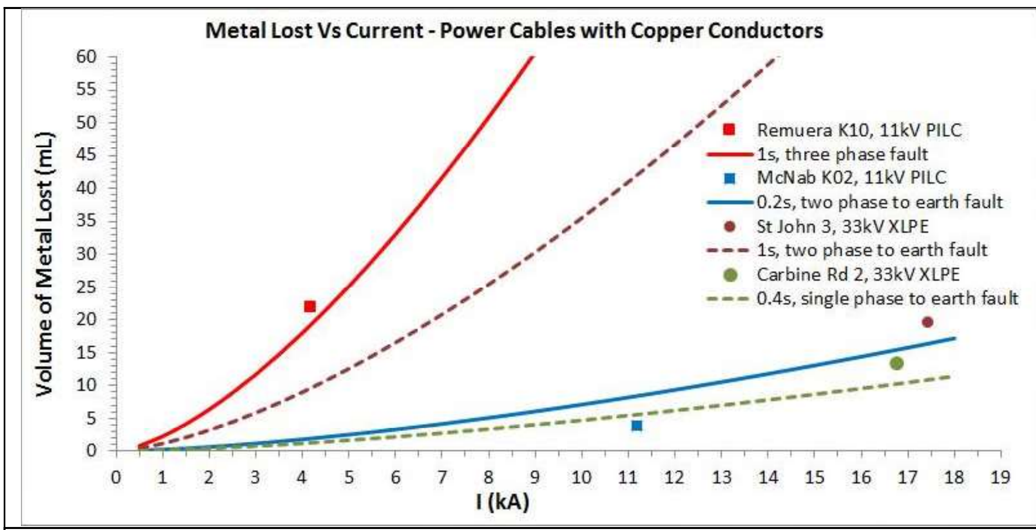


Figure 142 Volume of copper lost vs fault current

The CCI Author concludes that the fault coordinates were sufficiently close to the empirical '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.

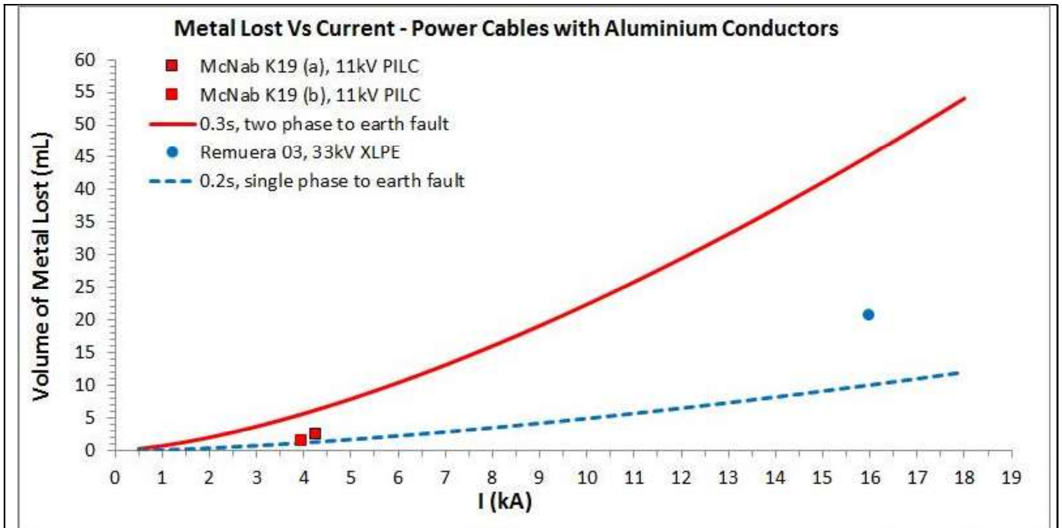


Figure 143 Volume of aluminium lost vs fault current

22.3 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°C and 20,000°C, 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 initial 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:

$$\theta = \eta . \frac{k\, V\, I\, t}{m\, C}$$

Where:

Symbol		Unit
Θ	Temperature rise	^oC
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. $Kg^{-1}.^oC^{-1}$

Figure 144 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 144 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 of 1,085^{o}C 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 approximately 3,000^{o}C is still greater than the melting point of copper and the ignition temperature of the materials.

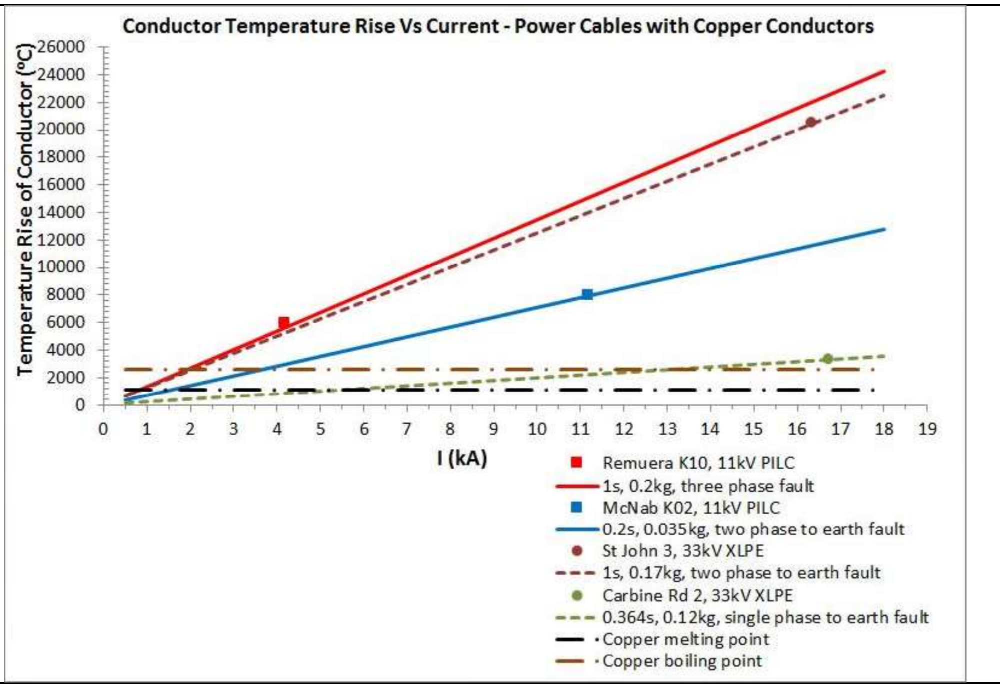


Figure 144 Temperature rise vs fault current for set fault durations

22.4 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'[20], 1955

The paper gives loss of metal by evaporation of the electrode to be 0.62 ml/K.Coulomb; i.e. 5.5 g/K.Coulomb for copper.

'Temperature Measurements in a Free Burning Arc'[21], 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 Faults'[19], 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 Air'[22], 1991

A comprehensive paper giving relationships between:

- Arc voltage with current for 100 mm arc gaps in air with copper electrodes.
- 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's[23] model

The paper has photographs 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 Arc'[24], 2000.

Measurements are given of arc parameters for electrode gaps of up to 10 mm. *[CCI Author: this is a similar dimension to the 11 kV and 33 kV cable insulation thicknesses].*

For short arc gaps and lower currents (0.2 kA to 1 kA)

The arc voltage can be calculated from: $V = (Vi + k * D)$
Where:

Symbol		Unit or value
V	Voltage drop across the arc	V
Vi	Interface voltage (the sum of the two electrode to air voltage drops)	20 V (for a copper electrode in air)
D	Distance between electrodes	mm
k	Constant	4 V/mm (for air)

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. *[CCI Author: this appears to be only approximately 30% of the mass of the arc craters in the conductors from the cable trench.]*

'Conventional and Recommended Arc Power and Energy Calculations and Arc Damage Assessment'[25], 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 Stanback[19] paper.

'Small Scale Arc Fault Testing in Air'[26], 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 20-60 V/cm length.

'Internal Arc Simulation in MV/LV Substations'[27], 2009

The paper refers to the requirement for medium voltage (generally 1,000 V to 33,000 V) switchgear to withstand severe arc faults and to be tested in accordance with IEC 62271-200 and -202. *[CCI 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 (computational fluid dynamics) 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 approximately 2 bars in a wave 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.

22.5 Conclusions: Arc Temperature and Conductor Erosion

The CCI Author concludes 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 faults in the Remuera K10 transition joint injected sufficient cumulative 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 times of the two fault events and to 1,500°C for an arbitrary 50% energy conversion. The latter is greater than the melting point of copper and three times greater than the ignition temperatures, Table 7, of the surrounding hydrocarbon materials within the transition joint.

23 Appendix H, Cable Fires, Cable Fire Performance

A review is given with reference to selected publications and to the CCI 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:

- 23.1: Cable fires and fire performance.
- 23.2: 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.

23.1 Cable Fires, Fire Performance and History.

'Development of Power Cables'[4], 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 c.1885-89. These cables were installed as part of the 7 mile long Deptford to Grosvenor Gallery feeder in London and laid along the railway embankment, they were ignited by sparks from steam locomotives[4]. 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 that was 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 in1933.

Cables and Fire Hazards, CIRED 1974

The paper[28] 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 i) a serious fire had broken out in a US subway system and ii) this would be addressed by the development of a 'smokeless' cable, which would begin shortly.

'Cable Fires in Power Stations'[29], 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. *[CCI 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, commissioned in 1965. Sometime in the late 1960's to early 1970's an oil leak from a turbine gauge-board caught fire. The fire spread to PVC cables and propagated. 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. *[CCI Author: joints are not mentioned. However joints and terminations are discontinuities in the system and fall into the same category of cable accessories.]*

The CEGB took the ENEL/CESI specification for fire retardant cable systems and undertook significant research. They funded 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 ignited and at a temperature of approximately 450°C, PVC cable propagates flame both vertically and horizontally.
- Flame propagation speeds of the order of 20 m/min have been recorded. *[CCI Author: 1.2 km/hour i.e. slow walking speed].*
- PVC starting between 150 and 275°C, before the PVC ignites, it emits large quantities of black smoke containing quantities of hydrochloric acid. 10 kg/m of flammable PVC will, when burnt, produce 1,500 m^3 of smoke.

The test adopted by ENEL and the CEGB consists of burning a section of cable 'installation' in a vertical position. A cable 'installation' is one in which cables are spaced at between 40 mm and touching. After I hour of burning, the damage must not exceed a predetermined distance; for the CEGB this was 1.5 m.

The article also describes:

- The review of existing fire precaution measures such as fire barriers.
- The successful development of fire retardant PVC cable.
- The ongoing development of low smoke and fume cable. At that time it was not clear that low smoke and fume cables could be developed to be economically viable.
- Fire detection sensing cables. It was noted that, from experience the fire risk was highest when cables were 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 of fighting cable fires by such measures as water spray equipment.

'Modern Power Station Practice[30], 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 in the late1960s 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 30332[1,2] tests. [*CCI 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 CCI 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 informative, publically available industry guide, such as produced by CIGRE.]

Tsing Yi Island, Kowloon, Joint Chamber Fire, c.1974

The CCI 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 buried adjacent to the joint chamber. The concrete walls of the chamber had been severely fire ablated and the steel reinforcing bars exposed.

'The Cables Handbook'[10], 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 CCI Author of this Penrose cable investigation report. BICC was one of the companies that developed cable sheathing materials having low fire propagation and low smoke and fume performances.

It is recorded that in the 1960s and 1970s there were several fires involving cables at power stations, where the fire propagated along ducts and tunnels at high speeds of up to 10 m/min.

Additives, such as antimony trioxide, were developed for inclusion in halogen containing compounds such as PVC and CSP (Chlorosulphonated Polyethylene) to improve their flame retardancy. However, to comply with specifications 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°C and 300°C respectively. The steam dilutes the flammable gases emitted by the base polymer and cools the surrounding area. The residue of the combustion is 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 performed well and 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. *[CCI Author: the cable components of interest to the Penrose fire investigation that increase fire resistance time are thick wall, tubular metallic layers that in combination exclude oxygen and have high melting points, high thermal conductivity and high thermal capacity, for example:*

- *Two layers of steel tape armour as used in a lead sheathed 11 kV three core PILC cable.*
- *A layer of steel wire armour, as used in 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 comparatively small and 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 Substations'[31], 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 1960s. 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 selected 400 kV 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 1990s the CCI Author was involved in a National Grid funded evaluation test at Hackney in the UK to assess the relative fire performance of prospective replacement designs of 275 kV and 400 kV cables for installation in the air space below the road surface in existing road tunnels. The test enclosure[32] shown in Figure 145 simulated a section of the cable chamber in a tunnel. Trays of diesel fuel were positioned directly underneath cable samples, or alongside cable troughs, as shown in Figure 145, to burn for a calibrated period to simulate the possible consequence of fuel leaking from the tunnel roadway into the cable chamber.

Figure 145 275 kV OF cables in troughs with diesel oil fire source in test enclosure at Hackney

Gas-filled cable types (gas compression cable at 275 kV and pre-impregnated gas-filled cable at 132 kV) had previously been installed in road tunnels and were under consideration for replacement due to ageing, corrosion and gas leaks. A 132 kV gas-filled cable sample, having an aluminium pressure sheath and insulated with paper tapes pre-impregnated with petroleum jelly was positioned above the fire source. The cable was filled with Nitrogen gas at the normal operating pressure of 14 bar. This cable type exhibited excellent fire performance as i) the aluminium sheath increased the fire survivability time, ii) when the aluminium sheath ruptured, the escaping Nitrogen gas inhibited combustion by excluding air, iii) the charred paper tape insulation around the rupture in the aluminium sheath acted as an intumescent layer that inhibited internal fire spread and iv) the absence of liquid impregnant also minimised external fire spread. However, the two different designs of gas filled cable were becoming obsolescent and were not considered further.

275 kV oil-filled, paper insulated cable with a corrugated aluminium sheath and impregnated with normal hydrocarbon cable oil exhibited a good survivability performance for short fire exposure times (i.e. less than 10 to 20 minutes) as demonstrated by reductions in fire propagation and enclosure temperature. This performance was attributed to the higher melting point and higher thermal capacity of the aluminium sheath. However, the aluminium sheath ruptured before the end of the one hour test period and the cable oil, leaking under pressure and sustained by the feed capacity of an external oil reservoir tank

spread the fire such that it burnt fiercely and flames emerged from the ends of the test enclosure.

A second oil-filled cable was tested that had been impregnated with a high flash-point silicone fluid, which prospectively should have exhibited improved fire performance. However, once the aluminium sheath had ruptured, the hot silicone fluid was found to burn as fiercely as the standard hydrocarbon cable oil and no advantage was apparent.

Three conventional 275 kV single core oil-filled cables were then laid in CBS (cement bound sand) filled concrete troughs, as shown in Figure 145. The protected cables satisfactorily withstood the fire test without damage or oil leakage. This installation method had previously been used by the CEGB for oil-filled cables installed in the Wimbledon tunnel, Figure 146. 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 oversheaths as the method increased the risk of damage to the cable oversheath during installation, occupied too much of the usable space in the tunnel and significantly reduced the current rating compared to in-air cables.

Two fire tests were performed on samples of the then new design of 275 kV cable with extruded XLPE insulation, lead sheath and polymeric oversheath. In the first test the oversheath burnt, the lead sheath melted, the XLPE burnt and fire propagated along the cables, burning fiercely and emerged from the ends of the test enclosure. It was deduced that the height of the cables compared to that of the ceiling and the magnitude of the fire temperature and heat release from the burning cable were key parameters in the cable's fire performance. This was verified by a second test in which the XLPE cable was positioned at a lower height. A significant improvement in fire performance was demonstrated.

Figure 146 Wimbledon tunnel containing a cable trough

Cable Fire Evaluation Tests by BEWAG at IPH Test Centre Berlin, c.1995

Berlin Electricity (BEWAG) undertook fire tests to i) evaluate the performance of existing and future 110 kV cable in-air installations and ii) prepare for two planned 380 kV cable tunnels underneath Berlin[33]. The CCI Author participated in i) technical discussions with BEWAG concerning prequalification tests performed in 1995 to 1996 on a 380 kV XLPE cable system, ii) discussions on the BEWAG fire test results for XLPE and OF cables and iii) an IEE seminar[32] in London, October 2000, entitled 'Cables for Installation in Tunnels' in which cable fire performance was discussed.

Berlin Electricity had changed at 110 kV from OF to XLPE cables with aluminium foil sheaths and laminated PE oversheaths. XLPE cables had been chosen because of the environmental risk of leaking cable oil polluting the ground from which drinking water is drawn. Berlin Electricity was evaluating the installation of XLPE cables at 380 kV as an alternative to OF cables in two new tunnels. A PE oversheath was selected as being the only non-halogen sheathing material available at that time that had service experience with heavy EHV (extra high voltage, greater than 200 kV) cables, however it was known to be flammable and non-fire retarding. The tunnel circuits were required to have fire retardancy (i.e. non-longitudinal flame propagation). After installation the PE oversheath was required to be coated with an approved fire retardant paint. It was reported[33]:

'Fire risks are eliminated by a special flame resistant coat that was tested under real service conditions. The test proved that, in case of a cable breakdown, the

fire will neither propagate further on the faulty cable nor extend to adjacent healthy cables due to hot gas of the short-circuit arc.'

Short circuit fire ignition and propagation tests were performed at the IPH laboratory in East Berlin. Samples of cables with different types of oversheath were tested: PE, PE coated with fire retardant paint and PVC. Each sample was first subjected to a through-fault to evaluate the mechanical strength of the support system in withstanding the electromagnetic forces. A short circuit was then simulated by inserting a spike comprising a steel nail through the insulation in different circumferential orientations to evaluate the containment of the fault within the cable, collateral damage to other cables and the tunnel, fire ignition and fire spread/retardancy.

Different durations of phase to earth short circuits were applied to simulate the circuit breaker clearance times of 3 to 8 cycles and the secondary clearance time of up to 1 second, should the primary circuit breaker fail.

Samples of 110 kV cable were tested in-air in a section of simulated rectangular tunnel. Samples of 380 kV cable were tested in a section of circular tunnel. XLPE and oil-filled cables were separately installed in different configurations. Tests were performed on 110 kV and 380 kV XLPE cables.

One 6.3 km tunnel containing two circuits of 390 kV 1600 mm^2 XLPE cable was put into operation in December 1998 and the second 5.2 km tunnel also containing two circuits was put into operation in December 2000. Two operational incidents occurred in a nine year period one at a coupling sleeve and one at a GIS termination[34]. In neither case was a fire reported to have occurred.

From the CCI Author's recollections it was concluded from the results of the tests that:

- Cable mechanical short circuit risks and fire risks can be adequately controlled to permit cable circuits to be installed with confidence in tunnels 'in-air' in both flat spaced and trefoil configurations providing the following measures are taken:
    - All PE oversheathed cables be provided with an approved flame retardant coating applied after installation. Small flames will be localised to the fault hole and, with circuit breaker times normal to new 110 kV and 380 kV systems, the small flames ignited local to the puncture hole will self-extinguish. The joints should also be coated.
    - The cable cleats and supports should be electrically insulating to prevent the arc striking and heating metal components.

  - The cable circuits should be spaced laterally and vertically both from the wall and from each other to minimise risk of collateral mechanical damage and fire spread. This is to mitigate the effect of energy emitted from the power arc. The energy is propagated by a disruptive pressure wave, hot gasses and radiant heat. It is desirable, but not essential, to stagger cable circuits such that they are not in vertical alignment and so reduce the risk of fire spread by drops of burning PE or cable oil.

  - The fault clearance times should be minimised for both primary and particularly secondary clearance operations.

- Methods of containing the energy waves by installing the cable in filled ducts and troughs or between baffle sheets were found to be ineffective (at the particular short-circuit test levels and durations applied). The methods contributed to an increase in collateral damage and in some cases to an increase in the volume of materials capable of sustaining combustion.

- For a particular application the combination of cable type, cable configuration, cable fire performance, fault current and fault clearance time, should be evaluated by fault current mechanical withstand tests and short circuit ‘spiking’ and fire tests.

- In each case the fault energy caused the outer sheaths to be punctured in addition to the cable insulation. The power arc normally extended outside the cable. In some circumstances the arc extended to strike adjacent metallic cleats, cable supports and adjacent cable ERCs. These components will be locally heated, risking spread of fire to other cables.

- At normal circuit breaker opening times for 110 kV and 380 kV (i.e. normally 3-5 cycles and less than 8 cycles) PE sheathed and coated XLPE cables and PVC sheathed OF cables had a similar acceptable self-extinguishing fire performance. Small, non-propagating flames occurred around the puncture hole in both cable types, but self-extinguished and so demonstrated the effectiveness of the protective coating. The oil leaking from the OF cable did not ignite.

- For longer circuit breaker opening times (i.e. 20 to 30 cycles) the flames around the fault hole in the PE sheathed and coated XLPE cable did not self-extinguish, but neither did they propagate. Drips of burning PE fell onto the coated PE oversheath of the cable below, but did not propagate flame along it. Oil leaking from the PVC sheathed OF cable ignited and spread the fire along the floor to other cables. It was recommended that during maintenance the floor should be kept clean and free of combustible materials.

- At 110 kV, a PVC oversheathed OF cable had a better fire retarding performance during a spiking test than a PE sheathed XLPE cable having a fire protective coating. This had been attributed to the design of OF cable in use at that date having a thinner insulation, lower arc voltage and hence lower arc energy compared to that experienced by the XLPE cable design.

- During the spiking test the fault current had normally been returned along the faulted cable's ERC (earth return conductor). The current may also be distributed and returned along the ERC of other cables when i) the arc strikes an adjacent cable or metallic support and ii) the fault clearance time is increased.

'FIPEC Report, 'Fire Performance of Electric Cables – New Test Methods and Measurement Techniques'[11], 2000

This is the final report of the European Commission SMT (Standards, Measurements and Testing) 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'[35], 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 the 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 33 kV to 110 kV cables are interpreted to have been XLPE insulated.

'Cable Systems in Multi-purpose or Shared Structures[36], CIGRE, 2010

The 2010 CIGRE Technical Brochure 403 recorded the factors and world-wide experience that would 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.

[CCI Author: although headings for fire risk considerations are given, lessons learnt from specific experiences of cable thermo-mechanical disturbance and cable fires are not considered. CIGRE initiated Working Group B1-51 in 2015 to study the fire performance of cables].

'HFFR Materials with Improved Mechanical Characteristics for MV Cable Sheathing'[37] 2003

The paper was presented at the CIRED Barcelona conference in 2003 by authors from a cable manufacturing company.

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: 0.05 m/min.
- 350°C horizontal route: 1.1 m/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/m^2.
- PVC peaks at 200 kW/m^2. *[CCI Author: it is taken that this is without plasticer].*
- Two different fire retardant filled polyolefin sheathing compounds peaked at 400 and 200 kW/m^2.

It was 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 Tepco'[38], 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. *[CCI Author: 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 with the bag installed in an aircraft* *fuselage, which demonstrated that the bag contained the disruptive effect of a simulated terrorist bomb hidden in the luggage. The shock wave produced by the rapid heating of a power arc is similar to that produced by an explosive.]*

'Fire Hazard of MV/HV Cables Installed in Tunnels'[39], 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, 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 XLPE 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:

- 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.

- In the second step the heat output is increased to 100 kW and held for a further 10 minute period. The test is stopped if the fire spread is > 2m and the heat release rate is > 250 kW.

- In the third step the heat output is increased to 300 kW and held for a further 10 minute period.

The non-fire performance EHV XLPE cable withstood the first step, but not the second step. 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 the 3.5 m length of the test rig. 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 steps, 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 (high density polyethylene) and LLDPE (linear low density polyethylene) oversheaths. At the end of the test the flame had propagated beyond the 2 m length to 2.6 m to 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 had to be 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 PE sheathed and XLPE insulated cable without a flame 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 firefighter access would have be 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'[40] 2009 and
'Fire Accident of High Voltage Cable Lines in Tunnel'[41]

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 1.16 s the line breaker reclosed onto the faulted circuit and a fault current of 17,760 A was recorded. The investigators had 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 had 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. 660°C for aluminium and 1,085°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.

The paper described that 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’.

The paper concluded 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 2009’[42].

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 found on site. It was concluded that damage to the cable had resulted from ‘persons unknown’ setting light to flammable 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 Directive'[43], 2011

This paper is 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 the 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'[44].

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:

- 29 disruptive failures (i.e. violently displaced pit lids) had occurred in a 2 year period out of 3,500 pits in the EPN region. *[CCI Author this appears to be a rate of 0.83%].* 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 as follows:
  - Very high risk pits: 149 4.2%
  - High risk pits: 228 6.5%
  - Medium risk pits: 2,685 76.7%
  - Low risk pits: 438 12.5%

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 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 147 shows the area affected by the blackout on the night of 1st April.

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 13.3 km 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.

Figure 147 Area of Kingsway in London affected by blackout

23.2 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, Edition1.1 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 cable 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 of the cable oversheath 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[1]: 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 mm^2 are tested in a spaced configuration.
- Cables of conductor cross-sectional area of 35 mm^2 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[45] 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 5.1: Fire Tests–Test for Vertical Flame Spread of Vertically-Mounted Bunched Wires or Cables'

It is stated that this Standard[46] '…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[1] in one Australian/New Zealand Standard. This has been necessary due to the fact that AS/NZS 1660.5.1 is referenced as such in a number of other Standards.'

AS/NZS 1660.5.6.2005, 'Test Methods for Electric Cables, Cords and Conductors', Method 5.6: Fire Tests-Test for Vertical Flame Propagation for a Single Insulated Wire or Cable',

It is stated that this Standard[47] '…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[1] in one Australian/New Zealand Standard. This has been necessary due to the fact that AS/NZS 1660.5.6 is referenced as such in a number of other Standards.'

24 References

[1] IEC 60332-3-10, Edition 1.1, 2009-02, 'Tests on electric and optical fibre cables under fire conditions – Part 3-10: Test for vertical flame spread of vertically-mounted bunched wires or cables – Apparatus', International Electrotechnical Commission, Switzerland.
[2] IEC 60332-3-24, Edition 1.1, 2009-02, 'Tests on electric and optical fibre cables under fire conditions – Part 3-24: Test for vertical flame spread of vertically-mounted bunched wires or cables – Category C', International Electrotechnical Commission, Switzerland.
[3] Raychem Installation Instruction ESD 0289-9/03-NZ, Transition Joints for Screened 3 – Core Plastic Insulated Cables with Wire Screen to Screened or Belted 3 – Core Paper Insulated 12 kV', 3XU-3SB, Tyco Electronics NZ Ltd, 2003.
[4] Hunter PV, Temple Hazell J, 'Development of Power Cables', George Newness ltd, London, 1956.
[5] Edif ERA report 2015-0027, 'Analysis of Samples Taken from Cable Trench at Penrose Substation', September 2015.
[6] Edif ERA report 2015-0356, 'Examination of Cable Joints from Penrose', September 2015.
[7] CIGRE Technical Brochure 194, 'Construction Laying and Installation Techniques for Extruded and Self Contained Fluid Filled Cable Systems', Chapter 4, Cable Installation Design and Laying Techniques', October 2001.
[8] EPRI Report 1001849, 'Mechanical Effects on Extruded Dielectric Cables and Joints Installed in Underground Transmission Systems in North America), Chapter 9, 'Effects of Vibration', March 2004.
[9] AS/NZS 1429.1:2006, 'Electric Cables – Polymeric Insulated, Part 1: for Working Voltages 1.9/3.3 (3.6) kV up to and including 19/33 (36) kV', Standards Australia and Standards New Zealand.
[10] Moore GF, 'Electric Cables Handbook', Third Edition, 1997, ISBN 0-632 04075-0.
[11] Grayson S.J, Van Hees P, Vercellotti U, Breulet H and Green A, The FIPEC Report, 'Fire Performance of Electric Cables – new test methods and measurement techniques', Final Report of the European Commission SMT Programme Sponsored Research Project SMT-CT96-2059', Interscience Communications Limited 2000, ISBN 0 9532312 5 9.
[12] Ford A, Gregory B, King SM, Svoma R, 'Technological Advances in Reliable XLPE Foil Laminate Cable Systems', Paper A 2.6, Jicable 99, Versailles.
[13] CIGRE WG B1.10, 'Update of Service Experience of HV Underground and Submarine Cable Systems', CIGRE Technical Brochure 379, April 2009.

---

[14] Hansen JZ, 'Service Experiences in Denmark with Mixed Medium Voltage (MV) Cable Systems Consisting of Both XLPE and PILC Cable Technologies, CIRED 2011, Paper 0767, Frankfurt, June 2011'

[15] BS 480:1966, 'Paper-Insulated Cables, For Electricity Supply for Working Voltages up to and including 33 kV', British Standards Institution.

[16] ESI 09-3, '33 kV Impregnated Paper Insulated Oil-filled and Gas Pressure Type Power Cable Systems', Electricity Supply Industry Standard, February 1982.

[17] AS/NZS 3808:2000, 'Insulating and Sheathing Materials for Electric Cables', Standards Australia and Standards New Zealand.

[18] Neher J.H. and McGrath M.H, 'The Calculation of Temperature Rise and Load Capability of Cable Systems', PAS Transactions, AIEE vol. 76, October 1957.

[19] Stanback H.I, 'Predicting Damage from 277-V Single Phase to Ground Arcing Faults', IEEE Trans Industry Applications, Vol IA-1-3, No 4, July/August 1977.

[20] Wilson W.R, 'Current Arc Erosion of Electric Contact Materials', AIEE Winter General Meeting NY, pp 657-663, August 1955.

[21] Glickstein S.G, 'Temperature Measurements in a Free Burning Arc', Welding Research Supplement', pp 222-229,1976

[22] Stokes AD and Oppenlander WT, 'Electric Arcs in Open Air', J. Phys. D: Appl. Phys. 24 26, 1991.

[23] Lowke J.J, 'Simple Theory of Free-burning Arcs', 1979 J. Phys. D: Appl. Phys. Vol 12 No 11 1873.

[24] Gouga A.M, Teste P, Andlauer, R, Leblanc T and Chabrerie J-P, 'Study of the Electrode Gap Influence on Erosion under the Action of an Electric Arc', European Physical Journal, Applied Physics, AP 11 111-122, 2000.

[25] Gammon T and Matthews J, 'Conventional and Recommended Arc Power and Energy Calculations and Arc Damage Assessment', IEEE Transactions on Industry applications, Vol 39, Nº3, May/June 2003.

[26] Fjeld E and Hage S.V, 'Small Scale Arc Fault Testing in Air', CIRED 2009, Paper 0688, June 2009.

[27] Besnard C, 'Internal Arc Simulation in MV/LV Substations', CIRED 2009, Paper 0536, June 2009.

[28] Zanelli C, Philbrick S and Beretta G, 'Cables and Fire Hazards', CIRED, pp 361-365, London, 1974.

[29] White T.M and Sutton A.R, 'Cable Fires in Power Stations'. IEE, Electronics and Power, Feb 1977.

[30] British Electricity International, 'Modern Power Station Practice, Volume D, Electrical Systems and Equipment', Third Edition 1992, Pergamon Press, ISBN 0-08-042244-6.

[31] CIGRE WG SC 23-04, 'Fire Protection Systems and Measures in Substations', CIGRE paper 23-01, 1984

[32] Gregory B, 'Choices and Considerations for the Selection of Power Cables in Tunnel Applications', IEE Symposium 'Cables in Tunnels, London, 2000.

[33] Henningsen C. H, Polster K, Muller K.B and Schroth R.G, 'New 400 kV XLPE Long Distance Cable Systems, their First Application for the Power Supply of Berlin', Paper 21-109, CIGRE Conference 1998.

---

[34] Henningsen C.G, Fischer W, 'Long Term Operational Experience with 400 kV XLPE Power Cable Systems in Berlin', Paper A.5.5, 8th International conference on Insulated Power Cables, Jicable 2011, Versailles.
[35] Deverell E, 'The 2001 Kista Blackout: Corporate Crisis and Urban Contingency', Swedish National Defence College, 2003, ISBN 91-89683-06-4.
[36] WG B1.08, 'Cable systems in multi-purpose or shared structures', CIGRE Technical Brochure, TB 403, Feb 2010.
[37] Rovira J and Martinez J, 'HFFR Materials with Improved Mechanical Characteristics for MV Cable Sheathing', CIRED 2003, Paper 59, Barcelona
[38] Toya A, Nasukawa S, 'Fire Prevention Method for 275 kV Oil-Filled Cable in TEPCO'. Paper C52, Jicable 2007, Versailles.
[39] Philippczyk C, Veno-Poulsen K, Jouneaux T, Gracias D, Loyens W, Robinson J, 'Fire Hazard of MV/HV Cables Installed in Tunnels', paper A.6.4. Jicable, 2007, Versailles.
[40] Zhang L, Zhou Z, Luo M, 'Fire Accidents of the Power Cable Line in Tunnel and Preventative Methods', 978-1-4244-3917, 2009 IEEE EIC Conf, Montreal, May 2009.
[41] Luo J, 'Fire Accident of High Voltage Cable Lines in Tunnel', Presentation to CIGRE.
[42] British Power International Ltd, 'Exceptional Events Report – EDF Energy – Fire Damage to 132 kV and Pilot Cables at Dartford Creek Cable Bridge on 20th July 2009', report 2009/10 – EDFE (LPN), Issue 2,18th May 2010.
[43] Journeaux T, 'Assessment of the Reaction to Fire Performance of Electric Cables under the EU Construction Products Directive', Jicable 11, Paper B.3.7, 2011, Versailles.
[44] UK Power Networks Ltd, "Asset Stewardship Report", entitled "Document 16 Asset Category - Cable Pits, EPN", 7th March 2014.
[45] AS/NZS 4507:2006, 'Cables-Classification of Characteristics when Exposed to Fire', Standards Australia/Standards New Zealand.
[46] AS/NZS 1660.5.1.2005, 'Test Methods for Electric Cables, Cords and Conductors', Method 5.1: Fire Tests–Test for Vertical Flame Spread of Vertically-Mounted Bunched Wires or Cables', Standards Australia/Standards New Zealand.
[47] AS/NZS 1660.5.6.2005, 'Test Methods for Electric Cables, Cords and Conductors', Method 5.6: Fire Tests-Test for Vertical Flame Propagation for a Single Insulated Wire or Cable', Standards Australia/Standards New Zealand.