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United Kingdom

TITLE: **Basslink KP199.256 Failure Examination 27th to 29th April 2016**

REPORT No: **ER 795**

CUSTOMER: **Basslink (BPL)**

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DATE: **27th May 2016**

Summary

The high voltage HVDC cable element of the Basslink Interconnector failed on the 20th December 2015.

The section of cable containing the failure site was recovered from the seabed on the 27th March 2016 and shipped to the Prysmian laboratory at CESI, Milan for an independent failure investigation to be conducted.

The independent inspection was conducted by Cable Consulting International Ltd in the presence of representatives from the following interested parties: Basslink, Keppel Infrastructure Trust, FM Global, Hydro Tasmania, and Prysmian over the period 27th to 29th April 2016. The CCI engineers conducting the inspection were Eur Ing Laurence Trim and Eur Ing Brian Gregory.

This report provides a factual account of the features found during the layer by layer visual inspection of the failed cable sample.

Distribution: BPL

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1 Introduction

The HVDC Basslink Interconnector spans approximately 300km from Victoria in Australia to George Town in Tasmania. The 400kV high voltage HVDC submarine cable element of the Interconnector failed on 20th December 2015.

The section of cable containing the failure site was recovered from the seabed on 27th March 2016 using the *C/S Ile de Re.* The section of cable containing the failure site, and several other samples including two cable sections immediately adjacent to the north and the south of the failure site, were packaged and shipped to the Prysmian laboratory at CESI, Milan, for an independent failure investigation to be conducted.

The independent inspection was conducted by Cable Consulting International Ltd (CCI) in the presence of representatives from the following interested parties: Basslink, Keppel Infrastructure Trust, FM Global, Hydro Tasmania, and Prysmian over the period 27th to 29th April 2016. The CCI engineers conducting the inspection were Eur Ing Laurence Trim and Eur Ing Brian Gregory.

This report provides a factual account of the features found during the layer by layer visual inspection of the failed cable sample.

2 Personnel Present at the Inspection

The following personnel were present at the independent inspection of the cable over the period 27th to 29th April 2016.

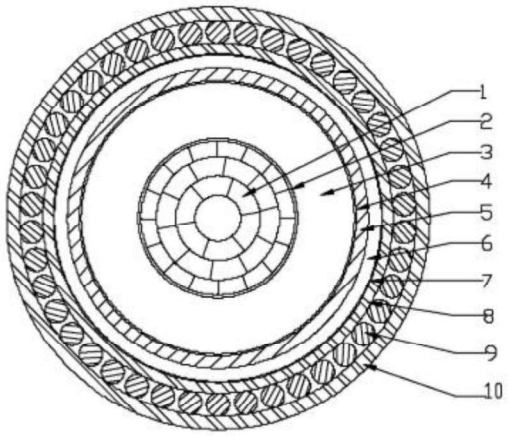
Name	Company	Representing
[redacted]	Basslink	BPL
[redacted]	Keppel Infrastructure Trust	BPL
[redacted]	March	BPL (Translation support)
Gerard Flack	Hydro Tasmania	Hydro Tasmania
Fred Steennis	DNV-GL	Hydro Tasmania
[redacted]	FM Global	FM Global
[redacted]	FM Global	FM Global
[redacted]	PowerSure Technology Ltd	FM Global
[redacted]	Prysmian (Quality)	Prysmian
[redacted]	Prysmian (Senior Technologist)	Prysmian
[redacted]	Prysmian (Head of R&D Labs)	Prysmian
[redacted]	Prysmian (Product & Process Quality Manager)	Prysmian
[redacted]	Prysmian (Installations Manager)	Prysmian

BPL engaged CCI to conduct the independent cable failure examination works. The engineers conducting the works were Eur Ing Laurence Trim and Eur Ing Brian Gregory.

3 Cable Build Description

The cable build as provided by Pirelli (now Prysmian) records[1] forwarded from Basslink is described as follows with the detailed dimensions provided in Figure 1 and Figure 2:

> *The present document describes in detail the material, dimensions and features of the HVDC 1500mm² single core 400kV submarine cable ….*
>
> *The submarine cable consists of copper conductor insulated by special paper tapes impregnated with viscous non draining compound, lead sheath protected with PE jacket, reinforced with steel tapes and armoured with external galvanised steel wires.*



2.2 Constructional details			
1 Conductor	Description: Central rode plus three layers of segmental strips Material Total nominal cross section	 mm²	 Copper 1500
	Central rod diameter	mm	12
	First strip layer, Pirelli DWG n° 468: Number of strips • Laying direction • Nominal stranding lay loss	 %	 6 Right Hand 2
	Second strip layer, Pirelli DWG n° 469: Number of strips • Laying direction • Nominal stranding lay loss	 %	 10 Left Hand 2
	Third strip layer, Pirelli DWG n° 492: Number of strips • Laying direction • Nominal stranding lay loss • Nominal diameter	 % mm	 12 Right Hand 2 43.8

Figure 1 Cable build extracted from the Detailed Cable construction document[1] (Part 1)

[1] Pirelli Project Document Number: BL_PCSE_CE003 Rev 2, titled: "Detailed Cable Construction Specification for HVDC 400kV 1500mm² submarine and 2000mm² land cables and Parameter Summary for EMTDC cable models", dated 21/05/2004

2 Conductor Screen	Description: four layers of carbon black paper tapes Nominal thickness Nominal diameter	 mm mm	 0.45 44.8
3 Insulation	Description: Non-pressure assisted, mass impregnated, wood pulp paper tapes Tape thickness range Tape width range Total number of tapes (approx.) Minimum wall thickness Construction set up thickness (informative) Nominal diameter Impregnating viscous compound	 mm mm N° mm mm mm type	 0.05 ÷ 0.105 20 ÷ 26 210 18.0 18.3 81.3 Dussek T 2015
4 Insulation Screen	Description: carbon black paper intercalated with metallised paper plus one layer of copper woven fabric tapes Approx. thickness Nominal diameter	 mm mm	 0.6 82.5
5 Lead Alloy Sheath	Description: extruded E Lead Alloy Alloy composition Tin Antimony Lead Nominal thickness Minimum thickness at any point Nominal diameter	 % % mm mm mm	 0.4 0.2 The remainder 3.15 2.9 89.1
6 PE Sheath	Description: Extruded black Linear Low density polyethylene sheath Nominal thickness Minimum thickness at any point Nominal diameter	 mm mm mm	 3.2 2.6 96
7 Reinforcement	Description: Bedding of two starts of overlapped polyester tapes; approx. thickness Two layers of two starts galvanised steel tapes laid with gap and right direction plus anticorrosion bitumen layer Thickness x width Nominal diameter	 mm mm mm	 0.3 0.3x40 97.9
8 Bedding	Description/type: Four layers of polyester tapes Thickness (approx.) Nominal diameter	 mm mm	 1.4 100.7

9 Armour	Description: Galvanised steel wires with overall anticorrosion bitumen layer Diameter of armour wire Nominal number Lay direction Nominal diameter	 mm mm	 5.5 54 ± 1 left 111.7
10 Serving:	Description/type: Polypropylene strings, ¼ yellow coloured and ¾ black Nominal thickness Approx. string number (indicative) Lay direction Nominal diameter	 mm = mm	 3.5 72 left 119
Expected overall diameter		mm	121
Weight of cable	In air	kg/m	43.0
	In water		32.3

2.3 Electrical Data		
DC resistance of conductor at 20 °C	Ohm/km	0.0121
Surge impedance	Ohm	18.0
Capacitance to neutral	μ F/km	0.39

Figure 2 Cable build extracted from the Detailed Cable construction document[1] (Part 2)

4 Investigation Procedure

On arrival at the CESI facility, the Prysmian engineers were noted to be removing the lid of the shipping crate containing the cable samples.

Once all parties had arrived at the Prysmian CESI facility in Milan, the inspection commenced on 27th April 2016 with an introductory briefing.

The Basslink representative gave a welcome to all in attendance. All parties were invited to introduce themselves and their affiliation. A sign in sheet was circulated for attendees to append a business card and to record their representation.

Prysmian gave a brief safety overview for working at the CESI facility over the next few days.

CCI read out the *Basslink Cable Fault Investigation – Communication Protocol* "rules of engagement" document to ensure that all parties had received and understood the protocol. An overview of the first day of the investigation was outlined.

An overview of the progress achieved during each day of the investigation is summarised as follows:

4.1 Investigation Day 1

The works commenced with the logging of the contents of the shipping crate containing the cable samples. Two samples were selected for inspection:

- Sample "VICT-144" was selected as a reference sample, the centre of the 9m long section being approximately 20m from the failure site.
- Sample "VICT-146" contained the failure site in the central section of the 11.5m length.

The two samples were removed from the shipping crate and transported via linear trolleys into the laboratory. The samples were carefully lifted onto supports using two forklift trucks. An aluminium half pipe was inserted underneath the centre of the sample containing the failure site to ensure that the region did not preferentially bend at the mechanical disturbance of the geometry at the failure site. Both samples were adequately supported during the removal and lifting works.

The inspection of reference cable sample commenced, sample number "VICT-144". All materials removed, with the exception of the cable end caps and the polypropylene strings, were retained and given a sample reference number commencing "VICT-144/x" where x was an incrementing number commencing at 1. A sample log was maintained by CCI and is included in Section 6 of this report.

A 2m section of the cable sample, from position 4m to 6m measured from the north end of the sample, was progressively dismantled with the following information taken:

- The cable end caps were removed and electrical insulation resistance measurements were conducted using a 1kV megger between i) the lead sheath and the armour layer, and ii) the lead sheath and the conductor.
- An arbitrary "top dead centre" mark was applied to the north end of the cable sample.
- The surface condition of the sample was inspected and logged.
- The diameter of the cable over the string serving was measured.
- The lay length of the outer polypropylene string layer was measured.
- The diameter over the armour wires was measured.
- The lay length of the armour layer was measured.
- The diameter over the fibrous bedding tape was measured.
- The diameter over the galvanised steel reinforcement tapes was measured.
- The diameter over the polyethylene sheath was measured.
- The diameter over the lead sheath was measured.
- Signed "tamper tag" seals were applied to the top opening of each sample bag.

4.2 Investigation Day 2

All "tamper tag" seals were confirmed to be intact on arrival at the CESI facility.

Continuation of the layer by layer inspection of the reference sample "VICT-144":

- A 750mm section of lead sheath was removed.
- The diameter over the copper woven fabric binder tape was measured.
- The diameter over the screening tapes was measured.
- The diameters, paper tape thicknesses, and paper tape widths were taken for the following heads of paper tapes: 1,2,3,4 & 5.

The inspection of sample "VICT-144" was halted as sufficient information had been obtained from the reference sample.

Start of inspection of sample reference "VICT-146" containing the fault position.
The sample containing the failure site was progressively dismantled layer by layer with the following information taken:

- End caps removed from the cable sample.
- Electrical measurements performed between the lead sheath and the armour wires, and lead sheath to the conductor.
- The external surface of the cable was inspected.
- The diameter over the polypropylene strings was measured.
- The dimensions of two bulge features at 4.52m and 5.0m were measured.
- The lay length of the polypropylene strings was measured.
- The diameter over the armour wires was measured.
- The armour lay length was measured to the north and to the south of the two bulge features.
- The diameter over the armour bedding tape was measured.
- The diameter over the polyethylene sheath was measured.
- The sample was cling film wrapped and signed "tamper tag" seals were applied over the wrapping. Signed "tamper tag" seals were placed onto the openings of all sample bags.

4.3 Investigation Day 3

All "tamper tag" seals were confirmed to be intact on arrival at the CESI facility.

Continuation of the layer by layer inspection of the failed sample:

- Dimensions and sketches were taken of the lead features.
- The diameter over the copper woven fabric tape was measured.
- Features over the screening tapes sketched.
- The diameter over the screening tapes was measured.
- The diameter over the outside of the first head of insulation tapes was measured.
- The diameter over each paper head was measured at both ends of the sample along with paper thickness and paper width.
- The diameter over the conductor was measured.
- Samples were packaged and dispatched for retention by CCI.

5 Investigation detail

5.1 Cable samples as received at CESI

The cable samples were received at the Prysmian CESI facility in Milan in a large wooden crate. Figure 3 is a photo showing the samples within the crate following removal of the lid and the supporting braces. Sample VICT-146 containing the fault position is on the left hand side of the image.

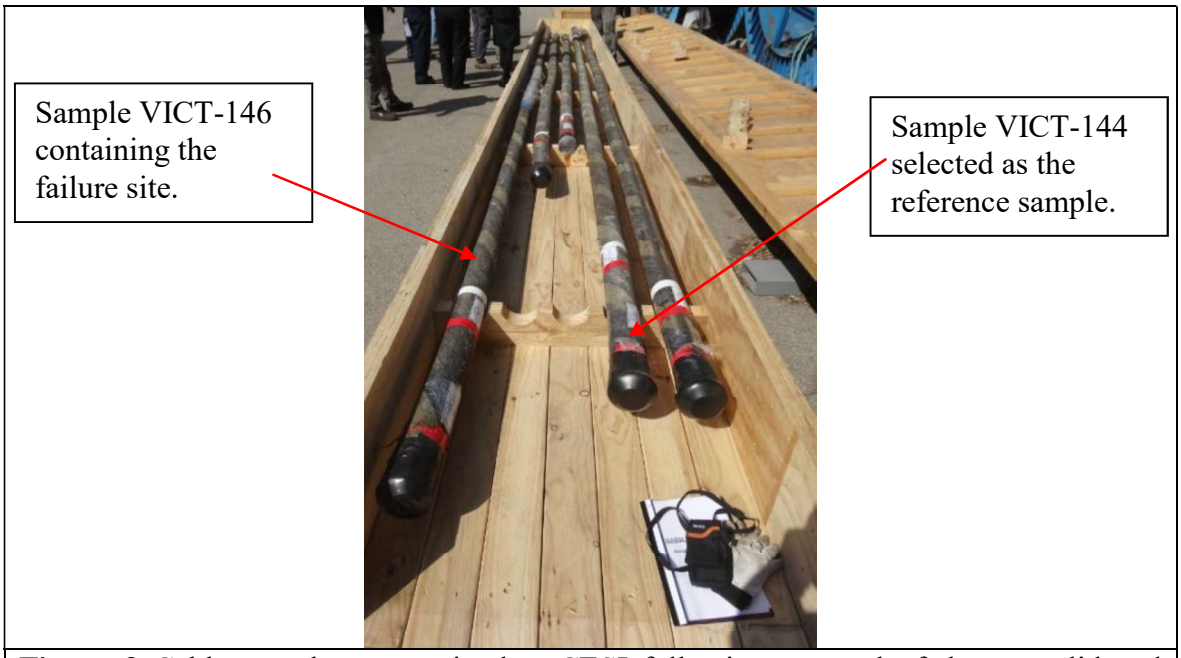


Figure 3 Cable samples as received at CESI following removal of the crate lid and supporting braces.

An oily substance was noted on the floor of the crate beneath the end caps of some of the samples, Figure 4.



Figure 4 Oily compound (ringed) beneath the northern end cap of sample reference VICT-144.

One loose roving was noted to be present on sample reference VICT-146 to the northern end of the polyethylene sheeting present around the central section of the sample, Figure 5.

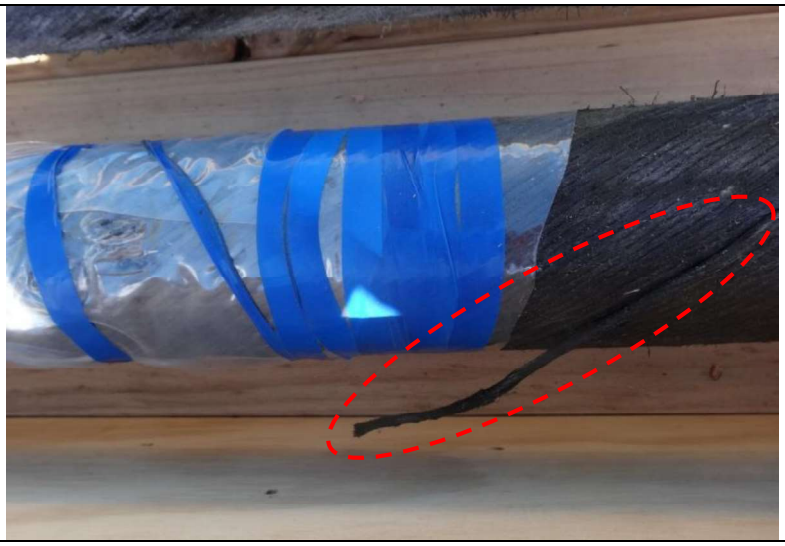


Figure 5 Loose roving (ringed) on sample reference VICT-146.

5.2 Sample removal from the crate and transportation into the laboratory

The cable samples under inspection, samples referenced VICT-144 (selected as a reference sample) and VICT-146 (containing the failure site), were individually pulled from the crate by attaching a sling to the southern end of the sample. Sample VICT-144 was pulled over a roller and strapped to a chain of cable trollies. The sample was then towed into the laboratory facility with observers pulling the tail end of the sample to ensure it remained in a straight orientation.

Sample VICT-146 was removed in a similar manner, however prior to removal a half section length of aluminium was slid under the central section of the cable to ensure that the region of the cable containing the failure site did not flex.



Figure 6 Sample VICT-144 on the linear trollies.



Figure 7 Sample VICT-146 being lifted onto the inspection stands, sample VICT-144 on the left hand side of the image already positioned onto the inspection stands.

5.3 Cable Sample Labelling

Each cable sample within the shipping crate had a label affixed to the northern end giving a unique reference number. An example of the label attached to VICT-004 is shown in Figure 8.



Figure 8 Example of a sample label attached to the northern end of Sample VICT-004.

Subsequent samples removed from the cable and retained were referenced with the cable sample number followed by an incremental sample number, e.g. VICT-144/1, VICT-146/1. The sample log is included in Section 6 of this report.

5.4 Inspection of Reference Sample, VICT-144

The 9m length cable sample reference VICT-144 was selected for inspection as a remote sample.

5.4.1 Insulation resistance Lead Sheath to Armour wires and Conductor to Lead Sheath

The end caps were removed from the north and south ends of the sample.

The heat shrink end caps had been applied over a layer of silver coloured tape that had been bound over the outside of the polypropylene string serving.

A liquid was noted to have leaked from the northern end of the sample onto the floor of the shipping crate.

Green verdigris was noted to be present in patches on the exposed ends of the conductor, Figure 9.

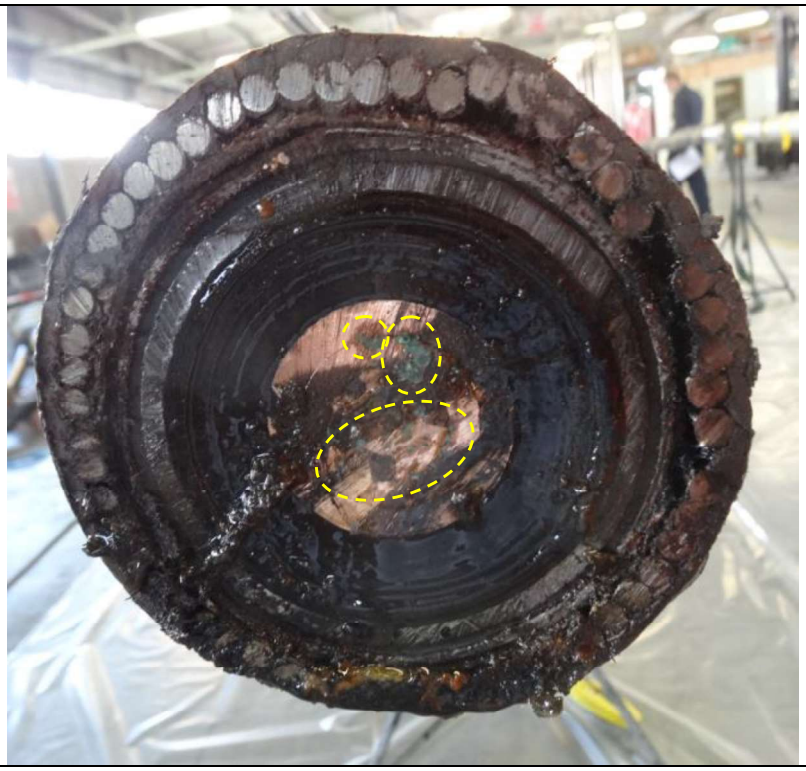


Figure 9 Sample VICT-144, north end cable cross section following removal of the end cap, green verdigris patches ringed.

The insulation resistance of the lead sheath to the armour wires was measured using a 1kV Megger. A resistance of 0.07MΩ was measured at a test voltage of 1kV.

The insulation resistance of the conductor to the lead sheath was measured as 36.5MΩ at a test voltage of 1kV.

5.4.2 External surface of the sample

A 2m section of the sample, centred approximately 21m to the south of the fault position, was selected for examination. The 2m region spanned the region 4m to 6m from the north end of the sample.

An arbitrary top dead centre (TDC) marker was painted using a white marker on the cable surface for logging circumferential orientations. All circumferential orientations are referenced looking from south to north along the sample.

Facts noted:

- The yellow and black contrasting polypropylene string serving, applied with a left hand lay, was in good condition. The colour change could be discerned between the yellow and black strings.
- A red paint marker was present on the surface of the cable at position 5.54, Figure 10.

- One string roving along the length was noted to run proud of the others, Figure 10.
- A 20mm length "tuft" of string was noted at position 5.54, Figure 10.

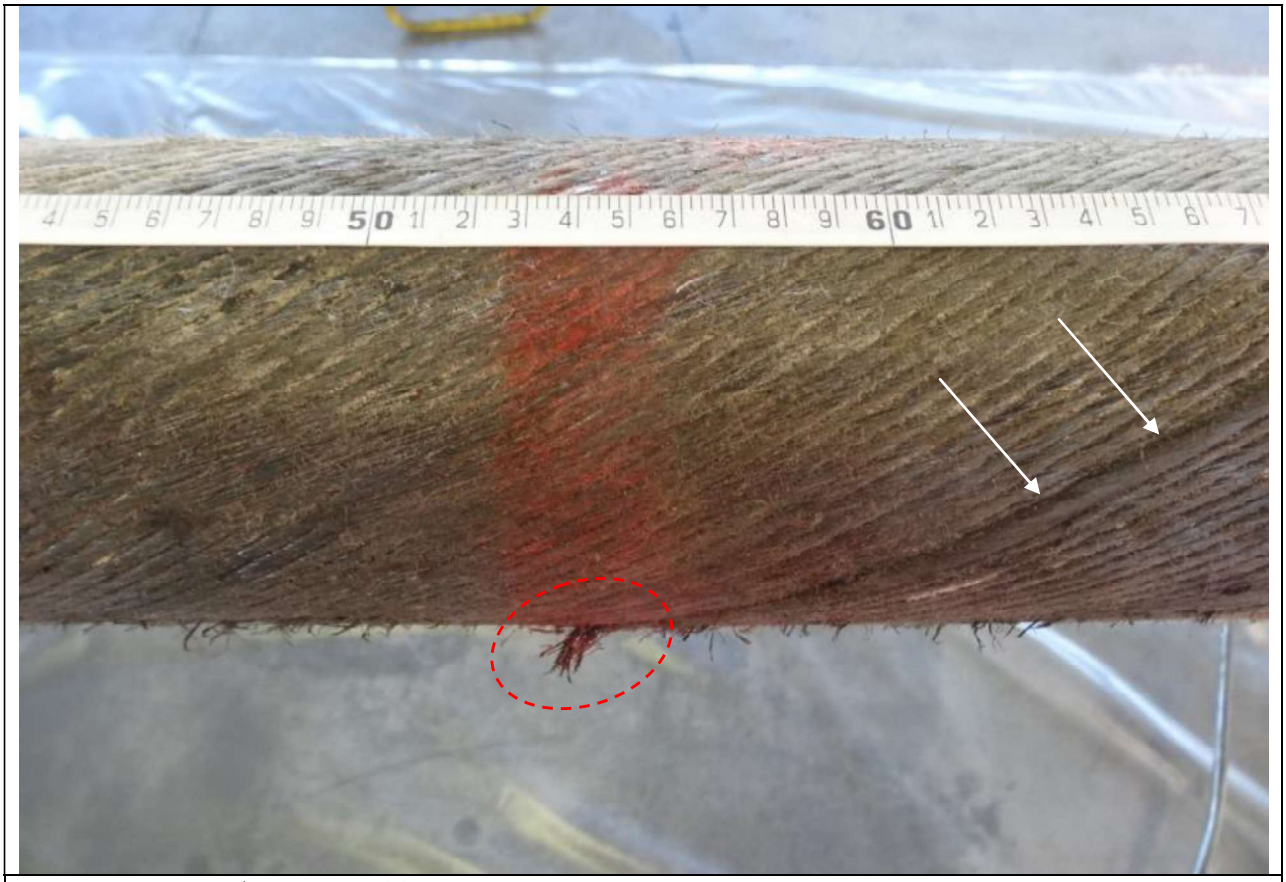


Figure 10 Sample VICT-144, red paint and a "tuft" of polypropylene string at position 5.54; proud string roving (arrowed).

- A 30mm wide "dark band" was present along the length of the sample at the 3 o'clock orientation.
- The lay length of the string serving was measured as 560mm to 580mm.
- The diameter over the polypropylene strings was measured using a diameter tape as 116.25mm.
- The diameter measured using external callipers in the 9-3 o'clock orientation was 115.0mm, and in the 6-12 o'clock orientation was 115.7mm.
- A total of 70 strings were removed from the outside of the sample.

5.4.3 Armour wire layer

Facts noted:

- The 55 armour wires had been applied with a left hand lay.
- The lay length of the armour was measured to be 1310mm.

- The average diameter of an armour wire was measured as 5.3mm.
- The diameter over all the armour wires was measured in four positions along the sample and recorded to be in the range 110.75mm to 111.00mm.
- The widest gap between armour wires was measured as 5mm, Figure 12.
- There was variability in the amount of bitumen present over each of the armour wires.



Figure 11 Sample VICT-144, armour wire layer – north end of sample.



Figure 12 Sample VICT-144, armour wire layer – widest gap between wire (left hand image) and wires touching (right hand image).

The 2m length of armour wires were removed by circumferentially cutting at the 4m and 6m positions using an angle grinder.

5.4.4 Armour Wire Bedding Layer

The layer consisted of white fibrous tapes secured in position using a 12mm width black binder tape applied with a left hand lay.

Facts noted:



Figure 13 Sample VICT-144, armour wire removal works revealing the white fibrous bedding tape held in place with a black binder.

- The tape was partially adhered to the underside of the bitumen coated armour wires and tended to tear on removal of the armour wire layer, Figure 13.



Figure 14 Sample VICT-144, fibrous bedding tape held in place with a black binder, left hand lay.

- The diameter over the bedding tape was measured as 100.5mm**.**
- The 10mm width black binder tape was applied with a left hand lay, with a lay length of 110mm.
- The bedding layer consists of four tapes applied with a double start on a left hand lay. The bedding tape width was measured as 100mm.

5.4.5 Galvanised Steel Reinforcing Tapes

The galvanised steel reinforcing tapes were applied in two layers. The outer layer comprised two tapes of width 40mm applied with a double start, on a right hand lay.

The diameter measured using external callipers in the 9-3 o'clock orientation was 97.7mm, and in the 6-12 o'clock orientation was 97.9mm.

Facts noted:

- The gap between the outer two tapes varied and measured in the range 2.5mm to 6mm.
- A witness of the armour wire layer could be seen in the outer tape layer, Figure 15.
- A dark coloured tarnishing and a white powdery material were present on the external surface of the tapes, Figure 16.



Figure 15 Sample VICT-144, galvanised steel reinforcing tapes, outer layer.



Figure 16 Sample VICT-144, galvanised steel reinforcing tapes, outer layer – 5.5mm gap measured between two tapes and dark tarnishing / white powdery deposit adhered to the surface of the tape.

The two outer reinforcement tapes were removed to reveal the inner two reinforcement tapes. The inner layer tapes were applied with a right hand lay, on a double start, with gaps between adjacent tapes measuring from 3mm to 5mm, Figure 17.

The diameter measured over the inner tape layer was measured as 98.0mm using a diameter tape. The diameter measured using external callipers in the 9-3 o'clock orientation was 96.1mm, and in the 6-12 o'clock orientation was 97.1mm.



Figure 17 Sample VICT-144, galvanised steel reinforcing tapes, inner layer – 5.5mm gap measured between two tapes and dark brown material / white powdery deposit adhered to the surface of the tape.

Facts noted:

- A fibrous bedding tape could be seen in the gap between the tapes applied over the polyethylene sheath.
- The galvanised steel tapes were a dark grey colour.
- A dark brown material was present on the surface of the inner tapes at the butt gap position where the outer tapes had been positioned.

The two inner galvanised steel tapes were removed to reveal a white fibrous cushioning layer tape that had been applied with a left hand lay over the polyethylene sheath, Figure 18.

The remnant of the tape and a white powdery deposit was wiped from the surface of the polyethylene oversheath using an alcohol based solvent.



Figure 18 Sample VICT-144, surface of the polyethylene oversheath following removal of the cushioning layer applied beneath the inner layer of galvanised steel reinforcing tapes.

5.4.6 Polyethylene Oversheath

The diameter over the polyethylene oversheath, when measured using a diameter tape, was in the range 96.0mm to 96.5mm.

The diameter measured using external callipers in the 9-3 o'clock orientation was 95.3mm, and in the 6-12 o'clock orientation 96.1mm.

A small witness mark (too small to measure) could be seen on the surface of the oversheath corresponding to the position where the inner layer of galvanised steel reinforcement tapes had been positioned, Figure 19.



Figure 19 Sample VICT-144, surface of the polyethylene oversheath following removal of the cushioning layer applied beneath the inner layer of galvanised steel reinforcing tapes after cleaning.

The oversheath was removed by making i) two circumferential cuts using a large pipe cutting tool near the 4m and 6m marks, and b) a longitudinal knife cut along the 11 o'clock orientation of the sample. The polyethylene sheath was prised off to reveal the lead sheath beneath.

5.4.7 Lead Sheath

The lead sheath was a dull light grey colour. The diameter of the layer, measured using a diameter tape, was in the range of 89.25mm to 89.5mm.

The diameter of the sheath was measured in three positions using vernier callipers in the 9-3 o'clock and the 6-12 o'clock orientations:

Sample VICT-144 Vernier Calliper measurements over the lead sheath.			
Orientation	**North end**	**Mid point**	**South end**
9-3 o'clock	88.6mm	88.7mm	88.7mm
6-12 o'clock	88.9mm	88.8mm	88.9mm

Facts noted:

- A longitudinal line of regularly spaced dark marks was present in the 9 o'clock orientation along the sample, Figure 20.
- A smooth, periodic, right hand lay witness mark could be seen on the surface of the sheath. The repetition of the mark was every 45mm, Figure 21.
- A witness mark of a perforated surface could be seen on a left hand lay, Figure 21.
- A 14mm by 7mm mark was present at the north end of the sample in the 12 o'clock orientation, Figure 21.
- A 25mm by 8mm width mark was present at the north end of the sample in the 2 o'clock orientation, Figure 21.
- Numerous straight longitudinal lines are present along the surface of the lead sheath, Figure 21.

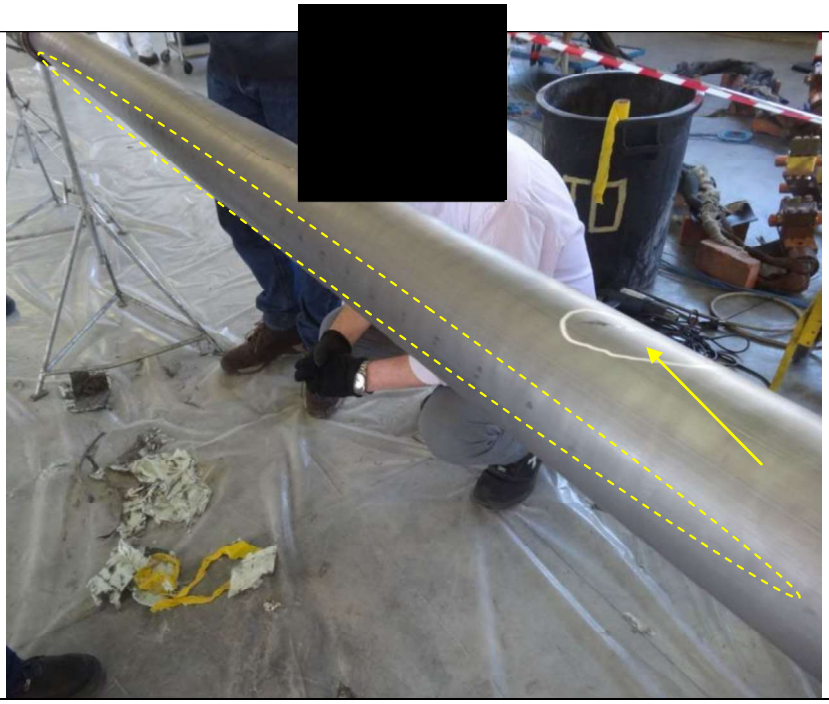


Figure 20 Sample VICT-144, surface of the lead sheath looking south to north showing a) a set of regularly spaced dark marks in the 9 o'clock orientation (yellow ring) and b) a white ringed mark made by the jointers during removal of the sheath (yellow arrow).

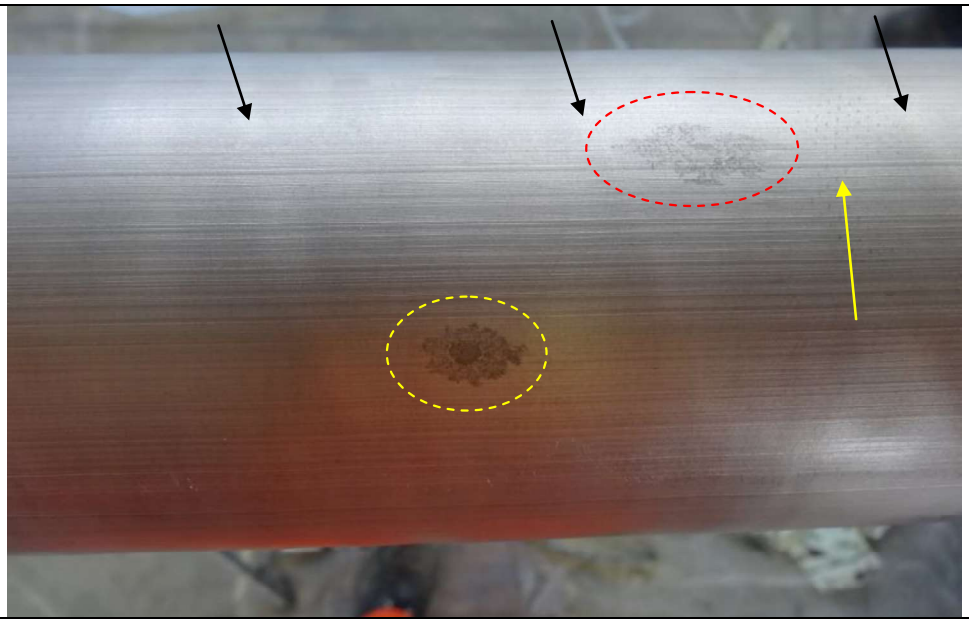


Figure 21 Sample VICT-144, surface of the lead sheath at the north end of the sample showing a) the two marks in the 12 o'clock (yellow ring) and 2 o'clock (red ring) orientations, b) the periodic witness mark on a right hand lay (black arrows), and c) the witness mark of a perforated surface with a left hand lay (yellow arrow).

A 750mm section of the lead sheath was removed from the sample between length marks 4.027m and 4.750m. The sheath was removed by scoring a tramline along the 2 o'clock orientation of the sample.



Figure 22 Sample VICT-144, Internal surface of the lead sheath and copper woven fabric tape beneath.

Facts noted:

- The inside of the lead sheath was a light grey colour, Figure 22.
- The inside surface was sticky with compound.
- A witness of the underlying copper woven fabric tape was visible on the inside of the sheath, Figure 22.

5.4.8 Copper Woven Fabric Tape

Two intercalated copper woven fabric tapes were applied with a left hand lay. The tape overlap was measured as 14mm. The tape width was measured as 47mm.

Sample VICT-144 Measurements over the copper woven fabric tapes.			
Orientation	**North end**	**Mid point**	**South end**
9-3 o'clock	81.9mm	81.4mm	81.6mm
6-12 o'clock	81.9mm	81.3mm	81.4mm
Diameter Tape	82.75mm	82.5mm	82.5mm

Facts noted:

- On removal of the tapes, mass impregnating compound was noted to "string" between the internal surface of the tape and the underlying screening tapes.

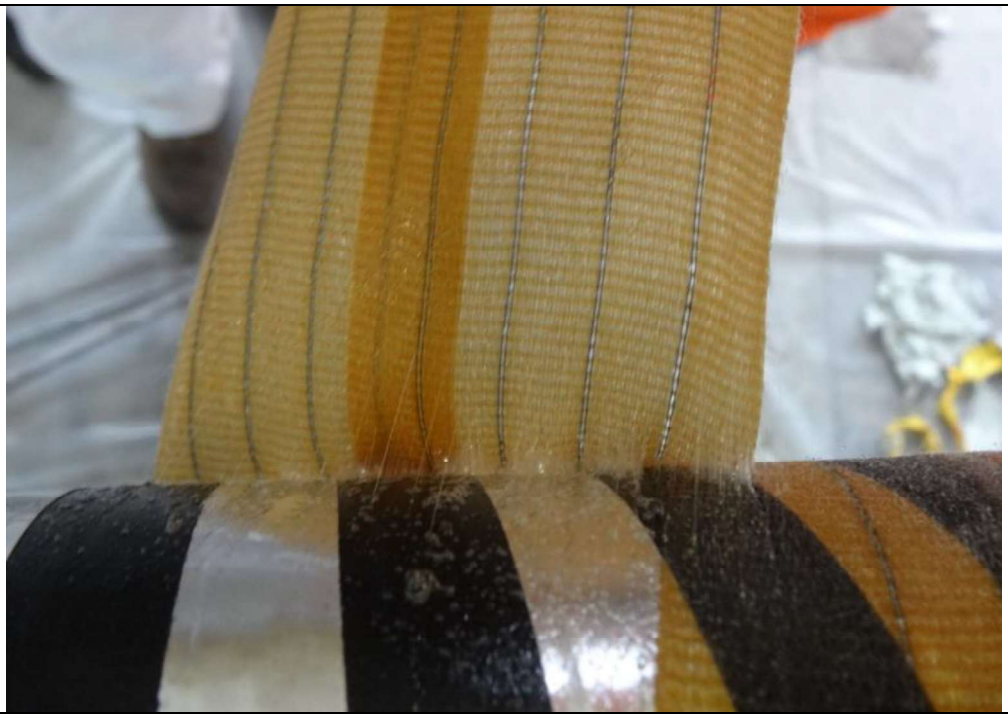


Figure 23 Sample VICT-144, Compound "stringing" on removal of the copper woven fabric tapes from over the screening tapes.

5.4.9 Insulation Screening Tapes

Two insulation screening tapes, one aluminium and carbon backed, the other plain carbon, had been applied intercalated with an overlap of 14mm using a right hand lay. The metalised carbon tape measured 26mm in width. The plain carbon paper measured 24mm in width.

The following diameter measurements were taken over the outside of the screening tapes:

Sample VICT-144 Measurements over the copper woven fabric tapes.			
Orientation	**North end**	**Mid point**	**South end**
9-3 o'clock	81.28mm	81.38mm	81.22mm
6-12 o'clock	81.50mm	81.20mm	81.0mm
Diameter Tape	82.0mm	81.8mm	82.0mm

The screening tapes were removed to reveal the insulation papers beneath, Figure 24.

Facts noted:

- There was no obvious smell to the papers.
- Compound stringing was noted between the papers on removal.

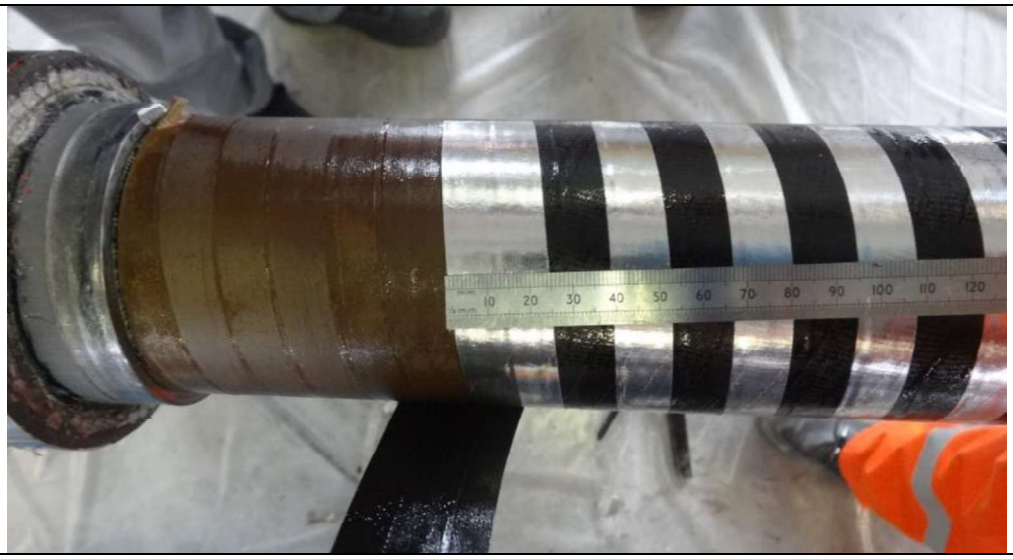


Figure 24 Sample VICT-144, Removal of the screening tapes to reveal the outer head of insulation tapes.

5.4.10 Paper Insulation - Head 1 (outer)

Inspection of the outer surface of the Head 1 paper tapes, Figure 25.

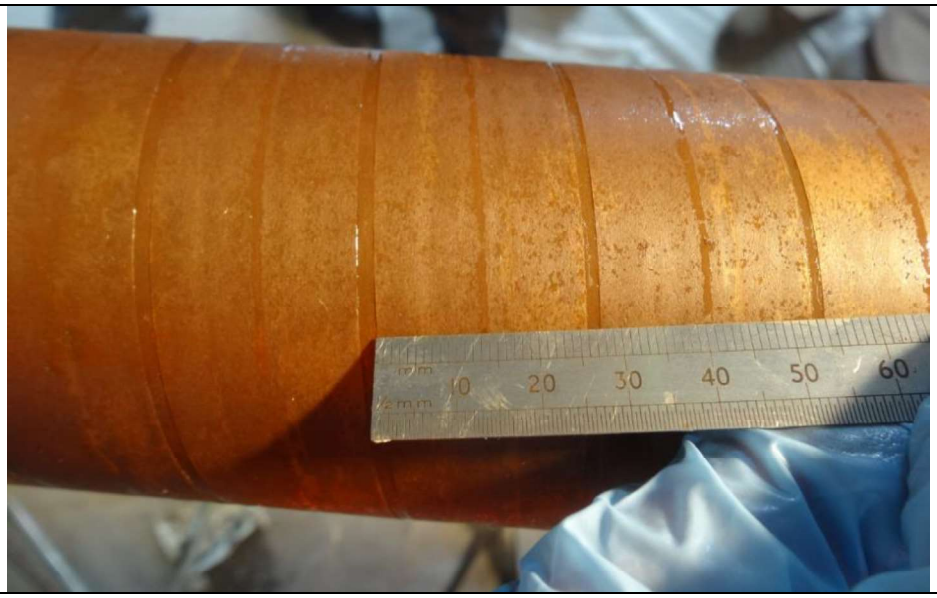


Figure 25 Sample VICT-144, Image showing the surface of Head 1of insulation tapes.

Facts noted:

- The diameter over the insulation was measured as 81.4mm at three locations (north end, mid point, south end).
- Clear and transparent insulation compound was noted to be present within the insulation surface butt gaps.

- Tape width was measured as 26mm and applied with a right hand lay.
- No brown spots or markings were noted in the outer butt gaps.
- 10 insulating papers were found in the head and removed.
- The thickness of the tapes were measured as 0.090mm, 0.091mm, 0.088mm, 0.082mm.
- The smallest and largest butt gaps between papers were measured as 1.0mm and 2.5mm respectively.
- The tapes did not snap when bent back on themselves.
- Uniform compound stringing was noted between the underside of Head 1 tapes and the surface of Head 2 tapes, Figure 26.

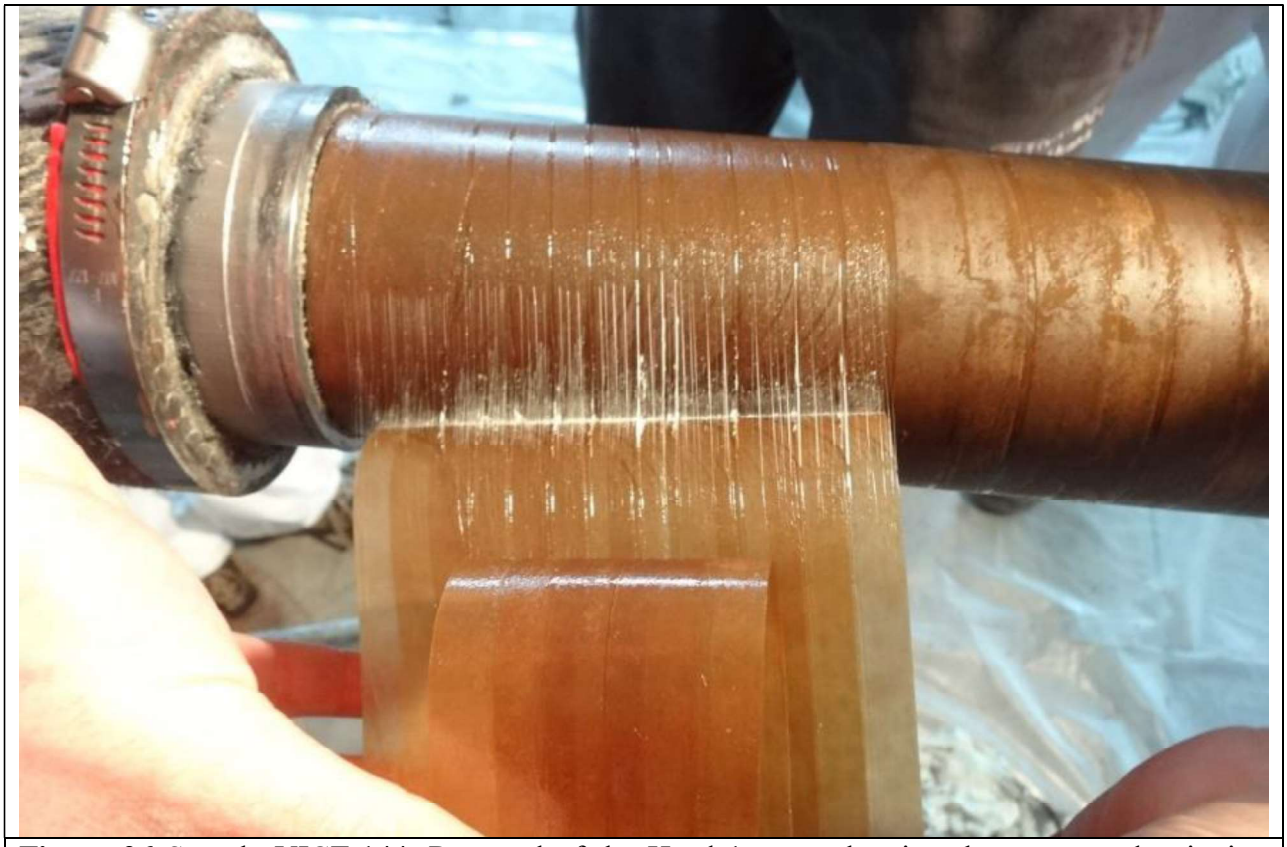


Figure 26 Sample VICT-144, Removal of the Head 1 tapes showing the compound stringing between tape head layers, right hand lay.

5.4.11 Paper Insulation - Head 2

Removal of the Head 2 paper tapes, Figure 27.



Figure 27 Sample VICT-144, Removal of Head 2 insulation tapes, left hand lay.

Facts noted:

- The diameter over the Head 2 tapes was measured as 79.5mm at three locations (north end, mid point, south end).
- Clear and transparent insulation compound was noted to be present within the insulation surface butt gaps.
- The thickness of the tapes were measured as 0.097mm, 0.096mm and 0.105mm.
- One tape had lost registration with the adjacent tape and was overlapping by 2mm.

5.4.12 Paper Insulation - Head 3

Removal of the Head 3 paper tapes, Figure 28.



Figure 28 Sample VICT-144, Removal of Head 3 insulation tapes, right hand lay.

Facts noted:

- The diameter over the Head 3 tapes was measured as 77.75mm at three locations (north end, mid point, south end).
- The head consists of 10 tapes applied with a right hand lay.
- The tape thickness was measured as 0.090mm.
- Tapes did not snap when bent back on themselves.
- Clear and transparent insulation compound was noted to be present within the insulation surface butt gaps.
- Compound bubbles, approximately 1.5mm in diameter, were noted to form on removal of the head, Figure 29.
- A 3mm diameter black feature was noted on the surface of the third tape in the head, Figure 30.
- A < 2mm diameter black feature was noted on the surface of the ninth tape, Figure 31.

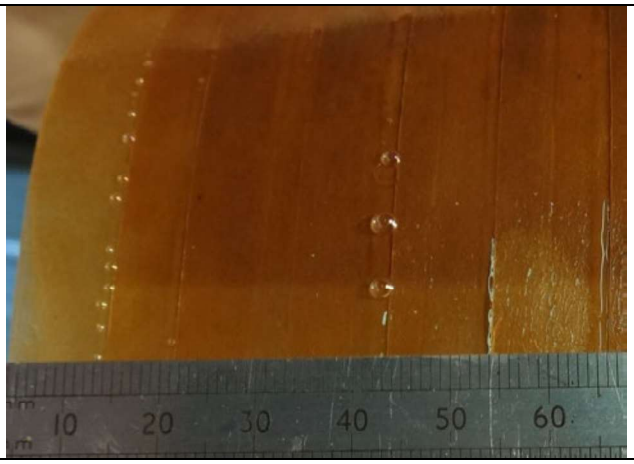


Figure 29 Sample VICT-144, Compound bubbles noted on removal.



Figure 30 Sample VICT-144, Black feature noted on the surface of the 3rd tape.

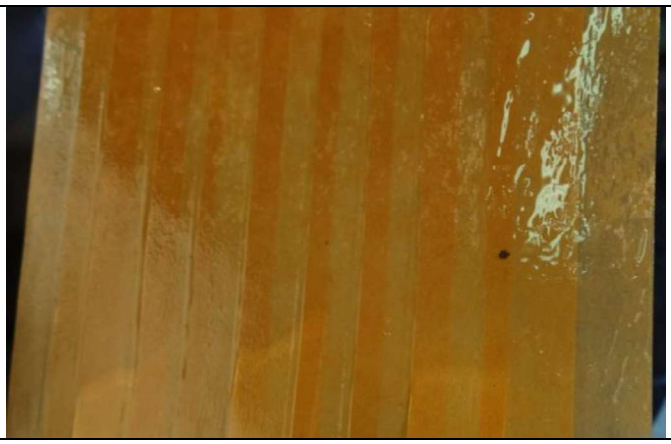


Figure 31 Sample VICT-144, Black feature noted on the surface of the 9th tape.

5.4.13 Paper Insulation - Head 4

Removal of the Head 4 paper tapes, Figure 32.

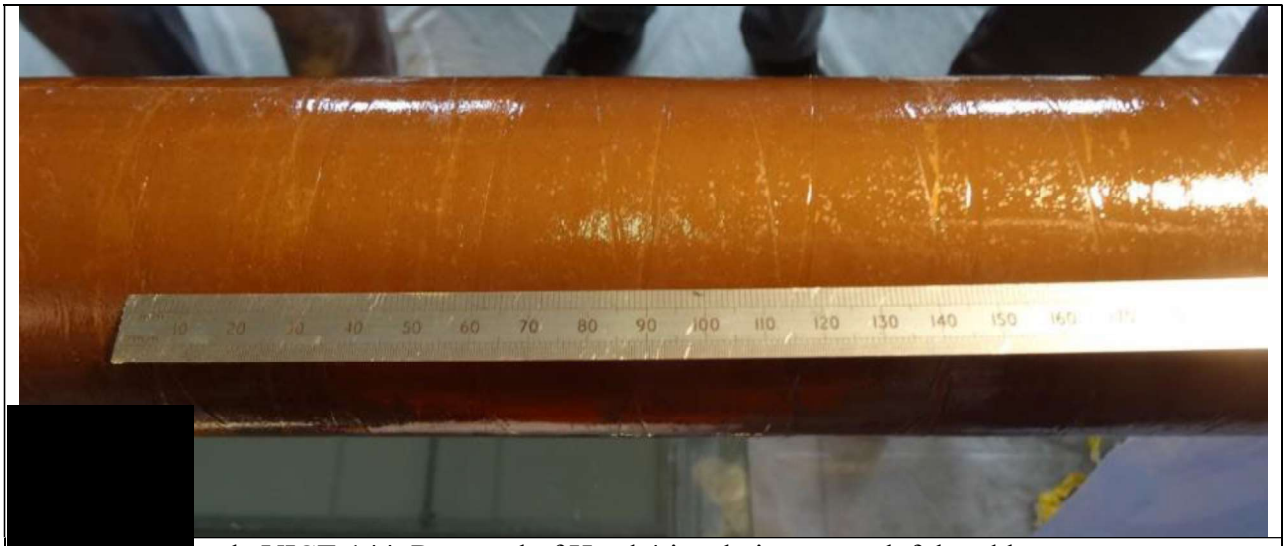


Figure 32 Sample VICT-144, Removal of Head 4 insulation tapes, left hand lay.

Facts noted:

- The diameter over the Head 4 tapes was measured as 75.8mm at three locations (north end, mid point, south end).
- The head with applied with a left hand lay.
- The tape width was measured as 26mm.
- The tape thickness was measured as 0.103mm.
- The smallest butt gap between tapes was measured as 1mm, the largest was measured as 4mm.
- Compound stringing was noted between the tapes of Head 4 and Head 5 on removal along with the presence of small bubbles.

5.4.14 Paper Insulation - Head 5

Removal of the Head 5 paper tapes, Figure 33.



Figure 33 Sample VICT-144, Removal of Head 5 insulation tapes, right hand lay.

Facts noted:

- The diameter over the Head 5 tapes was measured as 74.0mm at three locations (north end, mid point, south end).
- The head with applied with a right hand lay and consisted of 12 tapes.
- The tape width was measured as 24mm.
- The tape thickness was measured as 0.095mm.
- The largest butt gap was measured 2mm and the smallest was measured at 0.5mm.
- Tapes did not snap when bent back on themselves.

The sample was wrapped in cling film and suspended at this position to enable sample reference VICT-146 to be inspected.

5.5 Inspection of Sample VICT-146

The 11.47m HV cable sample labelled VICT-146 containing the failure site was inspected. Measurements taken during the inspection are referenced to the distance from the north end of the sample.

The aluminium half pipe positioned on the cable for manoeuvring the sample was removed, Figure 34. Additional supports were applied under the cable near to the failure site.



Figure 34 Sample VICT-146, Removal of aluminium half pipe from the sample.

The polyethylene sheeting wrapped around the cable failure site was removed.

5.5.1 Insulation Resistance Lead Sheath to Armour Wires and Conductor to Lead Sheath

The end caps were removed from the north and south ends of the sample.

The end caps had been applied over a silver tape that had been applied over the surface of the polypropylene strings, Figure 35.



Figure 35 Sample VICT-146, End cap removed from the North end of the sample (left hand image), South end (right hand image).

The insulation resistance of the layers sandwiching the lead sheath to the armour wires was measured using a 1kV Megger. The layer was an electrical short circuit and would not withstand the application of any voltage.

The insulation resistance of the conductor to the lead sheath was measured. The layer was an electrical short circuit and would not withstand the application of any voltage.

5.5.2 External Surface of the Cable

The external surface of the cable was inspected. An arbitrary top dead centre (TDC) mark was applied on the north end of the sample.



Figure 36 Sample VICT-146, General condition of the external surface of the cable, looking from south to north i.e. on the 3 o'clock side.

A very slight bend was noted in the cable sample as positioned on the stands at position 7.8m, Figure 37.



Figure 37 Sample VICT-146, Very slight bend in the sample at position 7.8m, photo from the northern end of the sample, bend position as noted by Mr Gregory's finger.

The outer layer of the cable consisted of bands of black and yellow coloured polypropylene string roving applied with a left hand lay.

Facts noted:

- The outer diameter of the cable over the rovings was measured at the following locations: 2m - 116.75mm; 4m - 116.75mm; 4.52m – 130mm; 5m – 123.0mm; 6m - 116.5m; 11.0m – 117.5m.
- One polypropylene string had been cut at position 4.04m, Figure 38, (BPL advised that the string had been cut on the vessel during recovery). The helical gap left in the roving, from the string cut position, led to the hole that was present in the cable at position 4.52m.
- All other polypropylene strings were intact along the length of the sample.
- Some longitudinal scuff marks were present along the surface of the polypropylene string serving.
- A 180mm length bulge was present centred at position 4.52m, Figure 39. The bulge was most pronounced in the 3 o'clock orientation and extended over 300mm of the circumference of the cable. The circumference over the bulge at this position was measured as 367mm. (This will be referred to as the northern bulge).
- A hole that extended into the cable construction was present centred at position 4.52m and in the 1 o'clock orientation, Figure 39 to Figure 41.
- A bulge was present in the cable at position 5.0m and centred in the 3 o'clock orientation, Figure 42. The bulge extended across a length of 200mm. The bulge extended between 120 – 150mm around the circumference of the cable at this point. The diameter of the cable measured over the bulge was 123.0mm. (This will be referred to as the southern bulge).
- At position 5.0m a region of sticky compound was noted on the polypropylene strings.



Figure 38 Sample VICT-146, Cut polypropylene string at position 4.04m.



Figure 39 Sample VICT-146, Northern bulge with hole (ringed) at location 4.52m.



Figure 40 Sample VICT-146, Close up of fault hole position at 4.52m (ringed).



Figure 41 Sample VICT-146, Further close up of fault hole position at 4.52m.



Figure 42 Sample VICT-146, Southern bulge at position 5.0m (ringed), and the Northern bulge position at 4.52m (arrowed).



Figure 43 Sample VICT-146, An image showing the surface of the roving at the Southern bulge position in the 3 o'clock orientation.

- There was no obvious disturbance of the polypropylene roving over the southern bulge region, Figure 43.
- Two longitudinal "dark bands" ran along the length of the cable sample. At the north end the bands run in the 11:30 and 00:30 o'clock orientations. At the northern bulge position the bands run in the 11:00 o'clock and TDC orientations. At the south end the bands run in the 10:00 o'clock and 11:00 o'clock orientations.
- The lay length of the polypropylene strings was measured at the north and south ends of the sample. The lengths measured 549mm and 544mm. The lay length of the strings in the vicinity of the northern and southern bulge features measured 546m and 564mm.

A worm drive clamp was applied over the polypropylene strings at positions 3.5m and 6.0m from the north end of the sample. The strings were removed between the clamps to reveal the armour wire layer beneath.

5.5.3 Armour wire layer

The armour wire layer was applied with a left hand lay.

Diameter measurements were taken over the armour wire layer using a diameter tape at the following positions:

Sample VICT-146 Diameter tape measurements over the armour wires		
Distance from North end of the sample (m)	Diameter measured (mm)	Comment
4.00	111.0	-
4.40	112.5	-
4.53	125.5	Centre line of northern bulge
4.70	111.5	-
4.90	112.5	-
5.00	118.5	Centre line of southern bulge
5.16	111.5	-
5.50	112.0	-



Figure 44 Sample VICT-146, View of the armour wire – image taken at the north end of the sample looking south.



Figure 45 Sample VICT-146, Distortion to the armour wires at the northern (left hand image) and southern (right hand image) bulge positions. Photos taken from the north looking south.



Figure 46 Sample VICT-146, northern bulge armour wire distortion around the hole (north to the right hand side of the image).

Facts noted:

- At the northern bulge, armour wires have distorted in both a clockwise and anticlockwise fashion at the position coincident with the hole in the construction at position 4.52m, Figure 45.
- The length of the distortion formed in the armour wires adjacent to the hole was 180mm.
- At the widest point, the gap between the armour wires at the hole was 10.5mm.
- The armour wire lay length to the north of the sample was measured as 1305mm.
- The armour wire lay length to the south of the sample was measured as 1320mm.

- At the southern bulge position there was no distortion of the armour wires at the 9 o'clock orientation.
- There were no broken armour wires within the section exposed.
- The wires were coated in a bitumous compound.
- There was no armour wire to lead sheath earth link present within the sample.

The armour wires were removed from the region spanning 3.5m to 6.0m from the north of the sample to reveal the armour bedding layer.

5.5.4 Armour bedding layer

The armour bedding layer was formed from two layers of white / green coloured fibrous tapes, applied with a left hand lay, held in place by a black fibrous binder tape applied with a left hand lay.

The diameters over the bedding tape were measured as follows:

Sample VICT-146 Diameter tape measurements over the armour bedding tapes		
Distance from North end of the sample (m)	Diameter measured (mm)	Comment
4.00	102.5	-
4.40	102.5	-
4.53	117.5	Centre line of northern bulge
4.70	104.5	-
4.90	104.5	-
5.00	111.1	Centre line of southern bulge
5.16	101.0	-
5.50	104.0	-

Facts noted:

- The bedding layer tapes adhered to the bitumen coated armour wires on removal, Figure 47.
- The tapes were displaced and discoloured around the hole position at 4.52m, Figure 48.
- The tapes at position 5.0m were discoloured and sticky with compound in the 6 o'clock orientation, Figure 49.



Figure 47 Sample VICT-146, Armour wire bedding tapes, view looking from north to south.



Figure 48 Sample VICT-146, Armour wire bedding tapes at position 4.52m.



Figure 49 Sample VICT-146, Armour wire bedding tapes at 5.0m, top view = TDC orientation, bottom view = 6 o'clock orientation.

The armour bedding layer tapes were removed to reveal the galvanised steel reinforcing tapes beneath.

5.5.5 Galvanised Steel Reinforcing Tapes

The galvanised steel reinforcing tapes were applied in two layers. The outer layer consisted of two tapes of width 40mm applied with a right hand lay.

Facts noted:

- The tape butt gaps at the north end of the sample ranged in width from 0.4mm to 6mm, Figure 50.
- The tape butt gaps at the south end of the sample were evenly spaced, Figure 50.
- A witness mark of the overlaying armour wires was present on the outer layer of tapes, Figure 50.
- The tapes were split across the northern bulge from position 4.46m to 4.59m in the 9 o'clock and 12 o'clock orientations. The splits aligned with the left hand lay angle of the armour wires.



Figure 50 Sample VICT-146, Galvanised steel reinforcing tapes at the north end of the sample (left hand image) and the south end of the sample (right hand image).



Figure 51 Sample VICT-146, Splits in the outer layer of galvanised steel reinforcing tapes at the northern bulge feature (9 o'clock orientation).



Figure 52 Sample VICT-146, Splits in the outer layer of galvanised steel reinforcing tapes at the northern bulge feature (9 – 12 o'clock orientation).

- A rucked tape edge was noted at position 4.42m in the 3 o'clock orientation, Figure 53.
- An exposed section of polyethylene oversheath was present spiralling anticlockwise from position 4.97m at the 12 o'clock orientation to position 5.07m at the 1 o'clock orientation, Figure 54.
- A tape was broken in the 3 o'clock orientation at position 5.0m, Figure 55.



Figure 53 Sample VICT-146, Rucked reinforcement tape (ringed) on the north side of the northern bulge at position 4.42m (1 o'clock orientation).

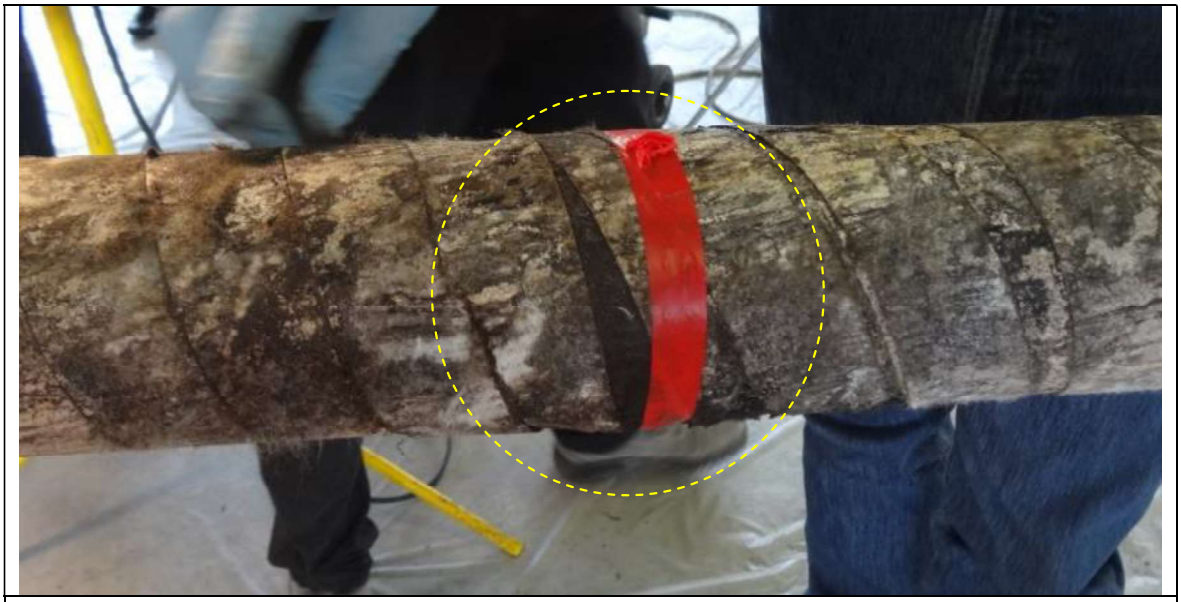


Figure 54 Sample VICT-146, Exposed section of polyethylene oversheath (ringed) spiralling from position 4.97m to 5.07m (12 o'clock anticlockwise to the 1 o'clock orientation). Broken tape end secured with red tape during the inspection.



Figure 55 Sample VICT-146, Broken reinforcing tapes at the southern bulge position.

The outer layer of reinforcing tapes was removed to reveal the inner two reinforcing tapes.

The inner reinforcement consisted of two tapes applied with a double start on a right hand lay. The surface of the tapes was a light grey colour. The lay length of the tapes was measured as 81mm at the north end of the sample.



Figure 56 Sample VICT-146, Inner reinforcing tapes at the north end of the sample.

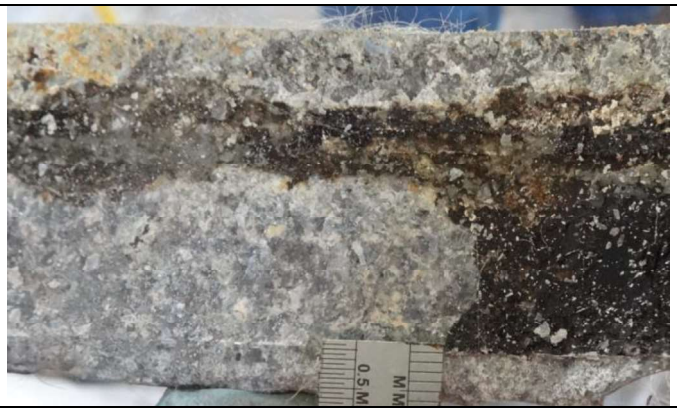


Figure 57 Sample VICT-146, Inner reinforcing tapes texture, black discolouration and a ruler measuring the adjacent tape overlap distance at position 4.32m.

Facts noted:

- A white accretion was present on the surface of the inner reinforcing tapes, along with patches of a black discolouration, Figure 56.
- At position 4.26m, the gap between the inner tapes had closed such that the tapes were touching.
- At position 4.32m, the tapes were noted to be overlapped, Figure 57.
- The polyethylene oversheath was exposed between the inner tapes at a position just to the north of the northern bulge position, Figure 58.
- Two tapes were broken (jagged edges) over the northern bulge feature, Figure 58 and Figure 59.
- Two tapes were broken over the southern bulge feature, one had a straight edge, Figure 60 and Figure 61.



Figure 58 Sample VICT-146, Inner reinforcing tapes at the northern bulge position (image taken from the 3 o'clock side).



Figure 59 Sample VICT-146, Inner reinforcing tapes at the northern bulge position (image taken from the 9 o'clock side), region of exposed polyethylene sheath (ringed).

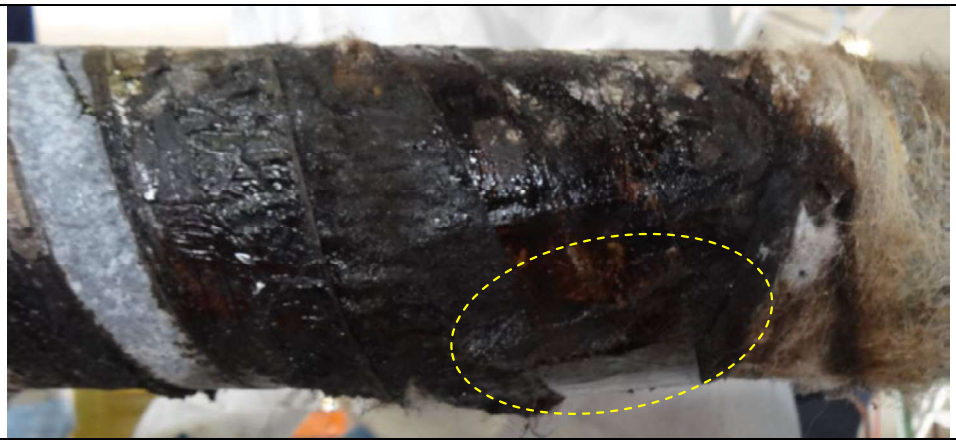


Figure 60 Sample VICT-146, Inner reinforcing tape break at the southern bulge position (image taken from the 3 o'clock side).



Figure 61 Sample VICT-146, Inner reinforcing tape break at the southern bulge position (square ended).

The tapes were removed to reveal the fibrous reinforcement tape bedding layer.



Figure 62 Sample VICT-146, Black staining on the inner surface of the reinforcement tape bedding layer at the southern bulge position.

- A black stain was noted on the inner surface of the reinforcement tapes at the southern bulge position, Figure 62.

The layer was removed to reveal the surface of the polyethylene oversheath.

5.5.6 Polyethylene Oversheath

The polyethylene oversheath was coated in a white powdery deposit, Figure 63. Compound was present on the surface of the oversheath at the northern and southern bulge features.



Figure 63 Sample VICT-146, White deposit present on the surface of the polyethylene oversheath (image taken looking north to south along the sample).

The following diameter measurements were taken over the oversheath:

Sample VICT-146 Diameter tape measurements over the Polyethylene Oversheath		
Distance from North end of the sample (m)	Diameter measured (mm)	Comment
4.00	96.25	-
4.40	96.25	-
4.54	110.0	Centre line of northern bulge
4.63	96.75	-
4.70	96.25	-
4.90	96.5	-
5.00	103.75	Centre line of southern bulge
5.10	97.0	-
5.20	96.0	-
5.50	96.0	-

The surface of the polyethylene sheath was cleaned using an alcohol based solvent.

Facts noted:

- At the northern bulge position two splits were present in the oversheath, Figure 64. The longer of the two splits at the 1 o'clock orientation measured 85mm in length and had a width of 20mm at its widest point. The shorter split measured 30mm in length and 8mm at its widest point.
- At the southern bulge position a small longitudinal split was present in the oversheath at the 5 o'clock to 6 o'clock orientation, Figure 65. Lightly squeezing the area emitted a fine jet of water from under the oversheath.



Figure 64 Sample VICT-146, Northern bulge split features (TDC image taken from the 3 o'clock side of the sample).



Figure 65 Sample VICT-146, Southern bulge feature (image taken from the 4 o'clock orientation of the sample).

The oversheath was cut longitudinally at the 9 o'clock orientation to remove it from the lead sheath beneath.

The internal surface of the oversheath was prised open to enable the internal bore of the oversheath to be viewed, Figure 66 and Figure 67.



Figure 66 Sample VICT-146, Internal view of the oversheath at the northern bulge feature.



Figure 67 Sample VICT-146, Internal view of the oversheath at the southern bulge feature.

5.5.7 Lead Sheath

The polyethylene oversheath was removed to reveal the lead sheath, Figure 68 to Figure 71.

The lead sheath was generally a dull light grey colour. Numerous straight longitudinal lines were present along the surface of the lead sheath. Two bulge features were present on the sample. A sticky compound was present on the lead sheath at the bulge positions.

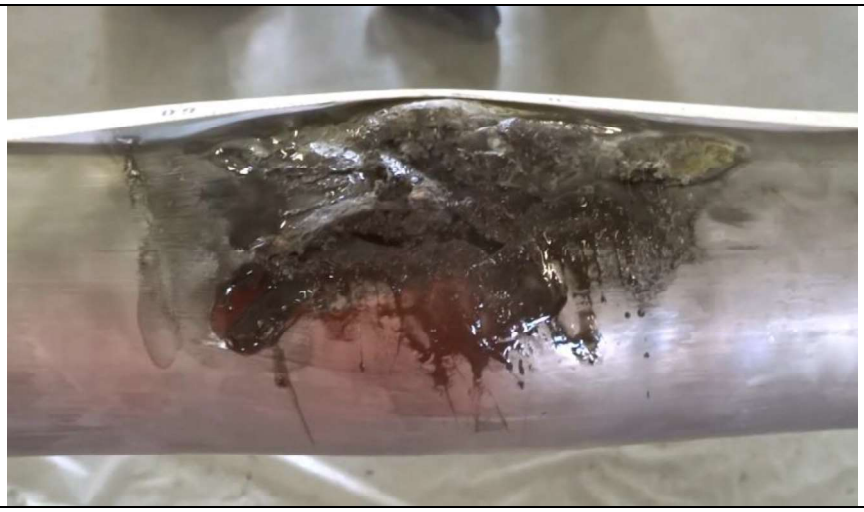


Figure 68 Sample VICT-146, Northern bulge feature following removal of the polyethylene sheath and prior to cleaning (north is to the right hand side of the image).

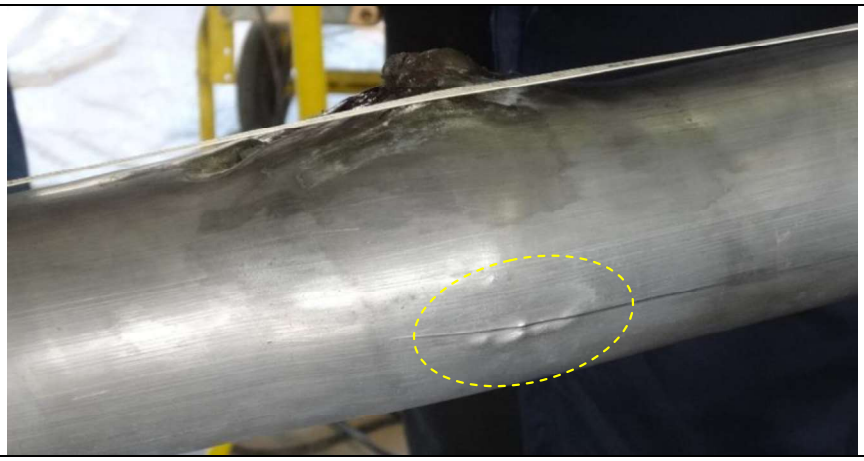


Figure 69 Sample VICT-146, Northern bulge, crease in the lead at the 9 o'clock orientation, ringed (north is to the left hand side of the image).

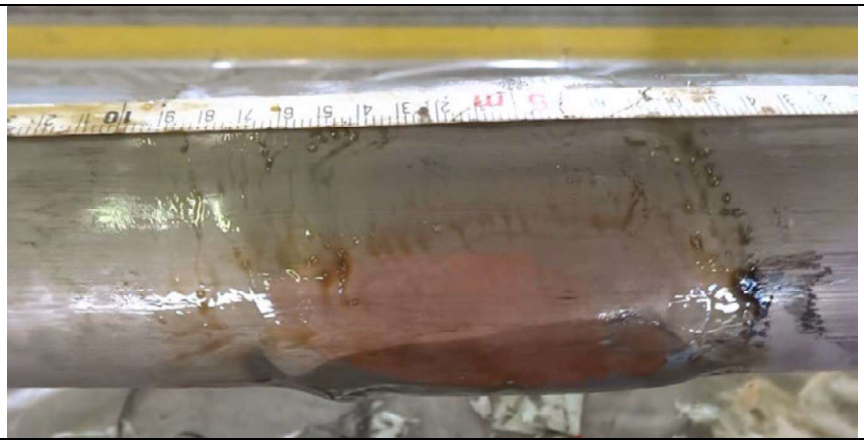


Figure 70 Sample VICT-146, Southern bulge feature following removal of the polyethylene sheath and prior to cleaning (north is to the right hand side of the image).

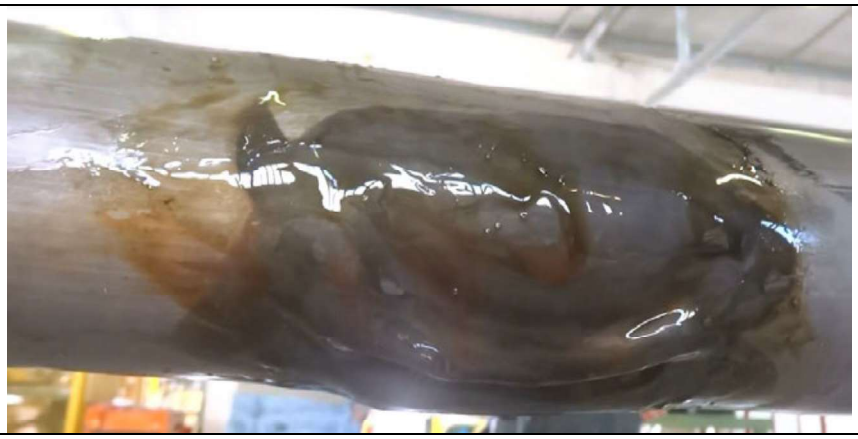


Figure 71 Sample VICT-146, Southern bulge feature at the 5 o'clock orientation prior to cleaning (north is to the right hand side of the image).

Facts noted:

- The northern raised bulge extended from position 4.45m to 4.59m, Figure 68. A hole was present in the TDC orientation, with splits and creases that followed the left hand lay angle of the armour wire layer and extended from the 11 o'clock to the 2 o'clock orientations. The lead immediately adjacent to the hole and the splits was discoloured. A small crease was present at the 9 o'clock orientation, Figure 69. A dark coloured sticky compound was present from the TDC orientation to the 3 o'clock orientation.
- The lead at the southern bulge, from position 4.94m to 5.12m, was coated in a sticky compound that had a yellow coloured tinge, Figure 70. At the 2-3 o'clock orientation the lead colour changed from a light grey to a dark grey, Figure 71. The colour change extended clockwise, across a 100mm length raised crease in the lead, to the 9 o'clock orientation.

The free compound was cleaned from the surface of the lead.

- The southern bulge (Figure 74 and Figure 75), is a raised feature including the circumference of the lead sheath spanning the clockwise orientation from 6 o'clock around to 4 o'clock. The feature followed a right hand lay helical shape with a longitudinal lay length of 115mm. Centred at the 5 o'clock orientation a smooth "m" shaped longitudinal crease was present in the lead. The two pinched together peaks of the crease were 10mm proud from the surface of the lead. The crease measured 100mm in length. The peaks of the crease were spaced 8mm apart. The two crease peaks joined at each end of the feature in a semi-circular knuckle of diameter 20mm. The edges of the bulge were smooth in shape.
- A fine split was present in the central pinch of the crease.



Figure 72 Sample VICT-146, The lead sheath after removal of the free surface compound (north to the right hand side of the image).



Figure 73 Sample VICT-146, Splits in the lead sheath at position 4.45m to 4.59m – northern bulge (north end to the left of the image)

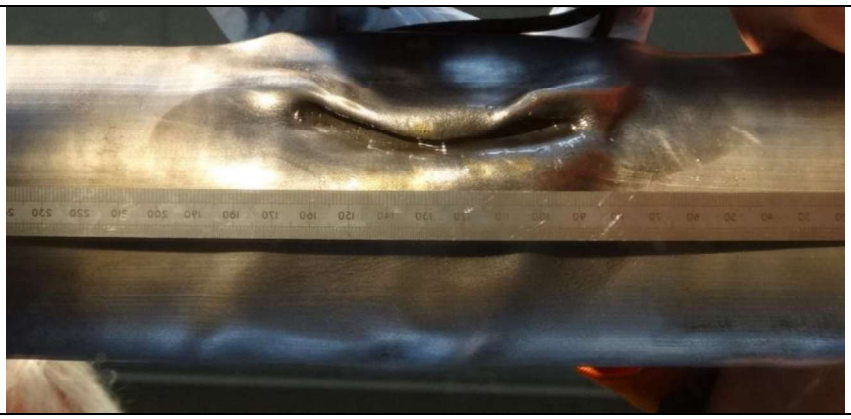


Figure 74 Sample VICT-146, Southern bulge crease (as photographed looking into a mirror placed beneath the cable sample – north to the left hand side of the image).

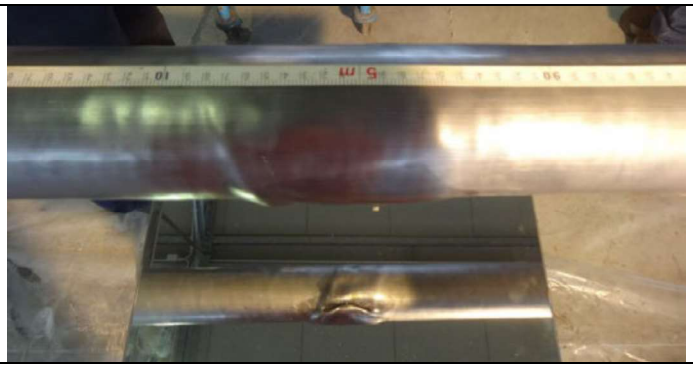


Figure 75 Sample VICT-146, Southern bulge – topside and underside viewed together (north to the right hand side of the image)

The lead sheath was removed by a) making circumferential cuts at positions 4.0m and 5.5m; and b) scoring longitudinal tramlines along the 9 o'clock and 4 o'clock orientations. A further circumferential cut was made on the top half of the sheath at position 4.40m. The top half and bottom half of the sheath were removed in stages.



Figure 76 Sample VICT-146, Tramlines cut along the lead sheath



Figure 77 Sample VICT-146, Internal discolouration of the lead sheath at the northern bulge position (north to the right hand side of the image)



Figure 78 Sample VICT-146, Removal of the lower half of the lead sheath (north to the left hand side of the image)



Figure 79 Sample VICT-146, Lower half of the lead sheath at the southern bulge position (north to the left hand side of the image)

Facts noted:

- The internal surface of the lead sheath was discoloured at the northern bulge position, Figure 77.
- No free compound was present within the sheath at the northern bulge position, Figure 78.
- Free compound was present within the sheath at the southern bulge position, Figure 79.
- A witness mark of the underlying copper woven fabric tape was present on the inside of the lead sheath, Figure 79.

5.5.8 Copper Woven Fabric Tape

The copper woven fabric tape was applied with a left hand lay. The insulation screening tapes could be seen beneath the layer applied with a right hand lay.



Figure 80 Sample VICT-146, Copper woven fabric tape layer at the north end of the sample (north to the right hand side of the image)

Facts noted:

- A crease could be seen in the screening tapes beneath the copper woven fabric tape at the north end of the sample, Figure 80.
- Clusters of dark rectangular shaped patches could be seen in the metallised screening tape beneath the weave of the fabric tape layer, Figure 81.



Figure 81 Sample VICT-146, Dark patches in the metallised papers to the north of the southern bulge – zoomed region of the upper figure is shown in the lower view (north to the right hand side of the image).

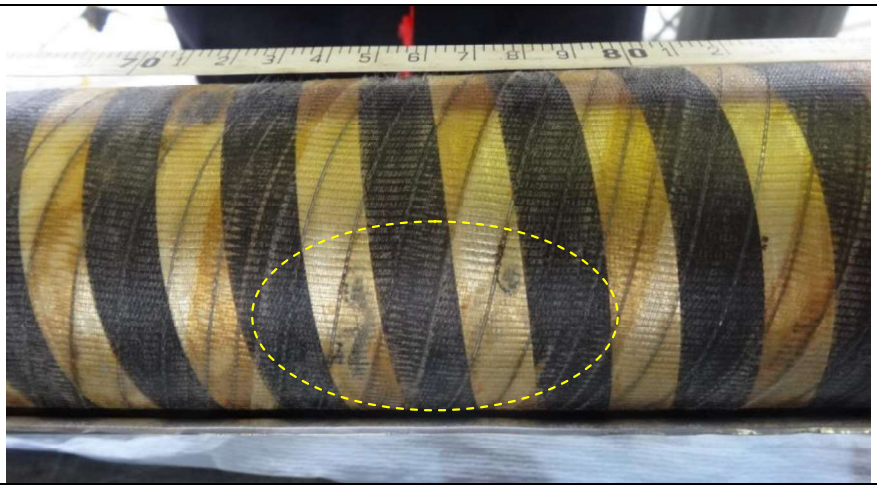


Figure 82 Sample VICT-146, Discolouration in the copper woven fabric tape layer at position 4.7 to 4.8m (ringed), 9 o'clock orientation (north to the left hand side of the image).



Figure 83 Sample VICT-146, Copper woven fabric tape layer at the south end of the sample, 3 o'clock orientation (north to the right hand side of the image)



Figure 84 Sample VICT-146, Copper woven fabric tape layer at the northern bulge, 3 o'clock orientation (north to the right hand side of the image)

- Discolouration near to the copper woven strands within the tape was noted along the sample with the discolouration generally towards the south side of the strand, Figure 82.
- The tapes were discoloured in the 3 o'clock orientation between position 5.0m and 5.4m, Figure 83.
- The tapes were discoloured and burnt at the northern bulge feature, Figure 84.
- The tapes at the position of the southern bulge feature were uniformly laid and coated with a free layer of impregnation compound, Figure 85.

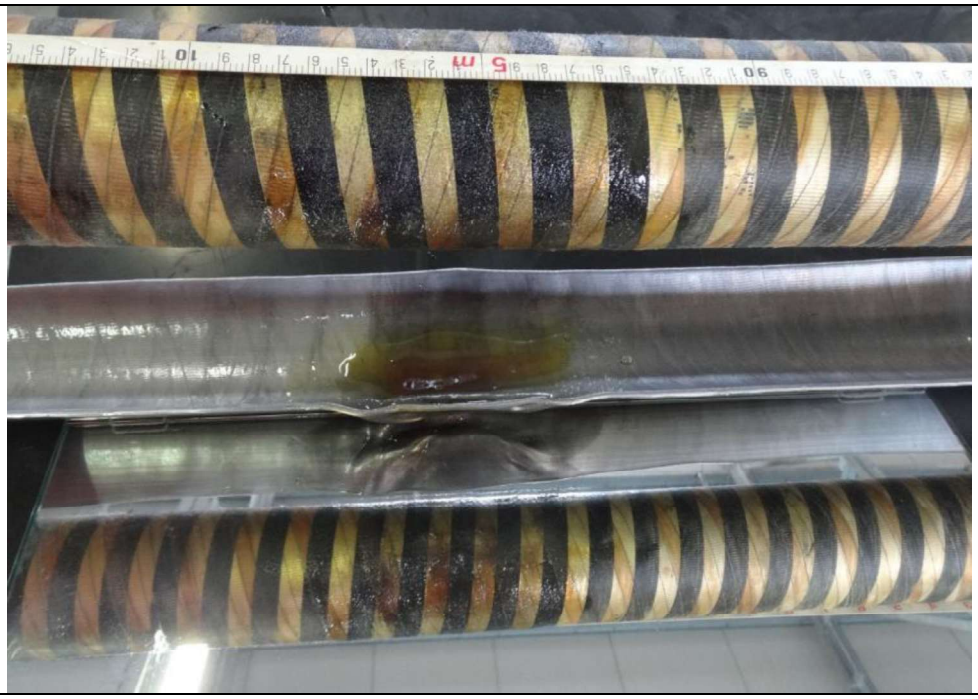


Figure 85 Sample VICT-146, Copper woven fabric tape layer at the southern bulge, 3 o'clock orientation, top side and reflected underside (north to the right hand side of the image)

The diameters measured across the copper woven fabric tape layer were as follows:

Sample VICT-146 Diameter tape measurements over the copper woven fabric tape		
Distance from North end of the sample (m)	Diameter measured (mm)	Comment
4.10	82.5	-
4.20	82.5	-
4.30	82.5	-
4.40	82.5	-

4.45	85.5	Start of northern bulge
4.50	99.5	Near centre of northern bulge
4.60	85.5	-
4.70	82.75	-
4.80	82.75	-
4.90	82.75	-
5.00	83.75	Centre of southern bulge. Bulge now hardly discernible on the CWF layer.
5.03	83.6	-
5.10	82.9	-
5.20	82.5	-
5.30	82.5	-
5.40	82.75	-

The copper woven fabric tape layer was removed to expose the insulation screening tapes. The two double start overlapping tapes were broken at the northern bulge position.

5.5.9 Insulation Screening Tapes

The screening tapes were applied with a right hand lay. The gaps between the metallised and plain carbon tapes were uniform along the insulated core.



Figure 86 Sample VICT-146, Screen tapes between the northern and southern bulge regions, TDC orientation (north to the right hand side of the image)

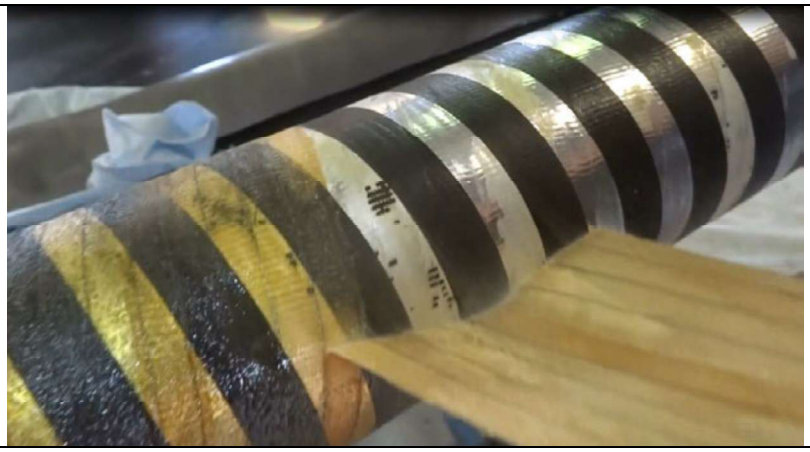


Figure 87 Sample VICT-146, Screen tapes at the southern bulge region, 3 o'clock orientation showing black marks on the surface of the metallised paper tapes (north to the right hand side of the image).



Figure 88 Sample VICT-146, Screen tapes at the southern bulge region, white tarnishing on the surface of the metallised paper tapes (north to the right hand side of the image).

Facts noted:

- The screening tapes were split at the northern bulge feature.
- The tarnishing on the metallised carbon paper appeared on the outer side of the tape rather than the section where the overlapping plain carbon tape was present.
- Whitish colour tarnish was present around the circumference of the layer between position 4.94m to 5.06m.
- The black clusters coincided with the open weave of the overlaying copper woven fabric tape.
- The insulated core was firm when squeezed with finger pressure.

The diameters measured over the insulation screen tapes were measured as follows:

Sample VICT-146 Diameter tape measurements over the insulation screen tapes		
Distance from North end of the sample (m)	Diameter measured (mm)	Comment
4.10	82.0	-
4.20	82.0	-
4.30	82.0	-
4.40	82.25	-
4.54	99.5	Centre of northern bulge
4.64	82.5	-
4.70	82.25	-
4.80	82.0	-
4.90	82.25	-
5.00	83.0	Centre of southern bulge. Bulge now hardly discernible on the insulation screen.
5.10	82.1	-
5.20	81.9	-
5.30	81.8	-
5.40	81.9	-

The insulation screening tapes were removed to reveal the outer head of paper insulating tapes.

5.5.10 Paper Insulation Heads

5.5.10.1 Head 1

The outer head of paper insulation (Head 1) was a dull brown colour. The tapes were discoloured and heavily carbonised in the region of the northern bulge position. The insulation tapes were dry of compound in the region of the northern bulge.

A 240mm long longitudinal crease was present at the TDC orientation to the north side of the northern bulge. The feature led to a 190mm long carbonised split in the tapes between position 4.44m, and 4.63m at the northern bulge.

There was no radial hole in the insulation tapes at the 5.0m position. A 190mm longitudinal crease shadow was present within the first head of tapes at the 3 o'clock orientation between the positions 5.18m to 5.37m, Figure 91.



Figure 89 Sample VICT-146, Head 1 insulation tapes, crease shadow leading to the northern bulge feature - ringed (north to the right hand side of the image)



Figure 90 Sample VICT-146, Discoloured insulation tapes at the northern bulge region, (north to the right hand side of the image)

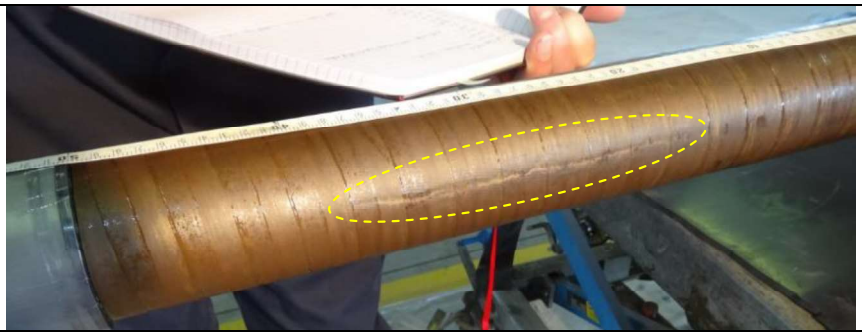


Figure 91 Sample VICT-146, Crease shadow within the insulation tape head between positions 5.18m to 5.37m, 3 o'clock orientation (north to the right hand side of the image)

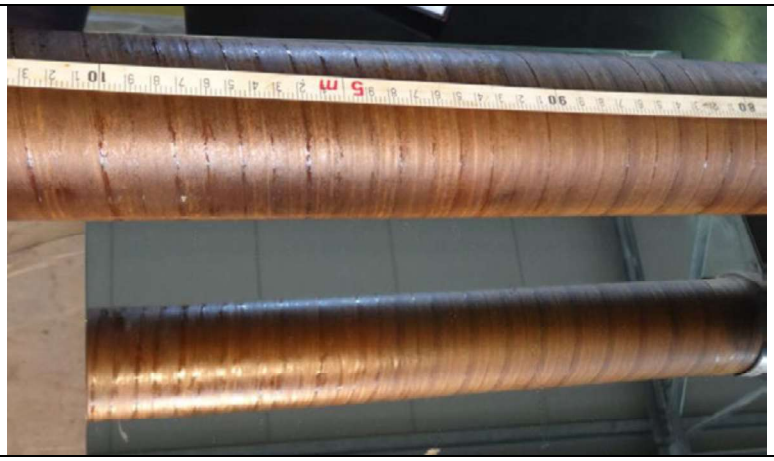


Figure 92 Sample VICT-146, Head 1 insulation tapes at the 5.0m position with the underside visible in the mirror (north to the right hand side of the image).

The diameters measured over the Head 1 insulation tapes were measured as follows:

Sample VICT-146 Diameter tape measurements over the Head 1 insulation tapes		
Distance from North end of the sample (m)	Diameter measured (mm)	Comment
4.10	81.5	-
4.20	81.6	-
4.30	81.6	-
4.40	81.8	-
4.53	99.0	Near centre line of northern bulge (screening tapes still adhered)
4.65	82..0	-
4.70	81.8	-
4.80	81.6	-
4.90	81.8	-
5.00	82.4	Centre of southern bulge. Bulge now hardly discernible on the insulation tapes.
5.10	81.75	-
5.20	81.6	-

5.30	81.5	-
5.40	81.6	-

Head 1 was applied with a right hand lay. The tape width was measured as 26mm. The largest butt gap between tapes was measured as 3.0mm and the smallest was measured 1.0mm. The head of 10 tapes was removed.

The tape width was measured as 26mm. The tape thickness was measured as 0.095mm. A tape sample when bent back on itself and pinched did not break.



Figure 93 Sample VICT-146, Head 1 insulation tapes approaching the northern bulge position (north to the top of the image).



Figure 94 Sample VICT-146, Head 1 insulation tapes at the northern bulge position (north to the right hand side of the image).

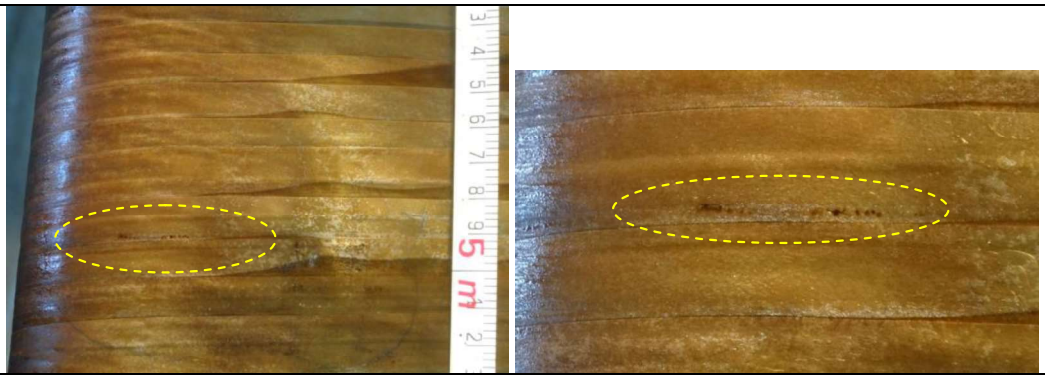


Figure 95 Sample VICT-146, Head 1 insulation tapes at the southern bulge position, row of small brown spots – ringed; zoomed image on the right (north to the top of the image).



Figure 96 Sample VICT-146, Crease contained within the Head 1 insulation tapes at position 5.18m to 5.37m, orientation 3 o'clock (north to the top of the image).

5.5.10.2 Head 2 Insulation Papers

Head 2 was applied with a left hand lay. The dimensions of the insulation over Head 2 are summarised as follows:

Sample VICT-146 Diameter tape measurements over the Head 2 insulation tapes, tape thickness and width		
Distance from North end of the	Diameter measured (mm)	Comment

sample (m)		
4.30	79.75	North end
5.20	79.5	South end
Tape thickness	0.089mm	Outer tape – did not break on bending
Tape width	26mm	-
Lay	left hand	-
Butt Gaps	2 – 3mm max	-



Figure 97 Sample VICT-146, Head 2 insulation tapes at the northern bulge position (north to the right hand side of the image).



Figure 98 Sample VICT-146, Head 2 insulation tapes at the northern bulge position, split in the 9 o'clock orientation (north to the left hand side of the image).



Figure 99 Sample VICT-146, Head 2 insulation tapes at the northern bulge position, 3 o'clock orientation view (north to the right hand side of the image).

Facts noted:

- The tapes were wet with water at the northern bulge position.
- Three carbonised slots were present at the northern bulge position, the main two form a cross shape at the TDC orientation, and the third is in the 9 o'clock orientation.
- Within the three main slots the dark material was friable, grey in colour, low density "foam" like matter. The slots were heavily carbonised.

5.5.10.3 Head 3 Insulation Papers

Head 3 was applied with a right hand lay. The dimensions of the insulation over Head 3 are summarised as follows:

Sample VICT-146 Diameter tape measurements over the Head 3 insulation tapes, tape thickness and width		
Distance from North end of the sample (m)	Diameter measured (mm)	Comment
4.10	75.7	North end
Tape thickness	0.105mm	Outer tape – did not break on bending
Tape width	26mm	-
Lay	right hand	-

5.5.10.4 Head 4 Insulation Papers

Head 4 was applied with a left hand lay. The dimensions of the insulation over Head 4 are summarised as follows:

Sample VICT-146 Diameter tape measurements over the Head 4 insulation

tapes, tape thickness and width		
Distance from North end of the sample (m)	Diameter measured (mm)	Comment
4.10	75.7	North end
Tape thickness	0.099mm	Outer tape – did not break on bending
Tape width	26mm	Stringing of compound from the north end; Stringing of compound from the south end.
Lay	left hand	-



Figure 100 Sample VICT-146, Head 4 insulation tapes at the northern bulge position, TDC view (north to the right hand side of the image).

5.5.10.5 Head 5 Insulation Papers

Head 5 was applied with a right hand lay. The dimensions of the insulation over Head 5 are summarised as follows:

Sample VICT-146 Diameter tape measurements over the Head 5 insulation tapes, tape thickness and width		
Distance from North end of the sample (m)	Diameter measured (mm)	Comment
4.20	74.0	North end
5.30	74.2	South end
Tape thickness	0.103mm	Outer tape – did not break on

		bending
Tape width	24mm	Uniform stringing of compound from the south end. On the South end the long groove / crease is now less pronounced and is a flat.
Lay	right hand	

5.5.10.6 Head 6 Insulation Papers

Head 6 was applied with a left hand lay. The dimensions of the insulation over Head 6 are summarised as follows:

Sample VICT-146 Diameter tape measurements over the Head 6 insulation tapes, tape thickness and width		
Distance from North end of the sample (m)	Diameter measured (mm)	Comment
4.20	72.0	North end
5.30	74.2	South end
Tape thickness	0.101mm	Outer tape – did not break on bending.
Tape width	24mm	Uniform stringing of compound from the south end. On the South end the long groove / crease is now less pronounced and is a flat.
Lay	left hand	

5.5.10.7 Head 7 Insulation Papers

Head 7 was applied with a right hand lay. The dimensions of the insulation over Head 7 are summarised as follows:

Sample VICT-146 Diameter tape measurements over the Head 7 insulation tapes, tape thickness and width		
Distance from North end of the sample (m)	Diameter measured (mm)	Comment

5.30	69.8	South end
Lay	right hand	Outer tape - did not break on bending.

5.5.10.8 Head 8 Insulation Papers

Head 8 was applied with a left hand lay. The dimensions of the insulation over Head 8 are summarised as follows:

Sample VICT-146 Diameter tape measurements over the Head 8 insulation tapes, tape thickness and width		
Distance from North end of the sample (m)	Diameter measured (mm)	Comment
4.20	67.8	North end
5.30	67.7	South end
Tape thickness	0.100mm	Outer tape – did not break on bending.
Tape width	24mm	Crease at 3 o'clock near south lead cut has gone.
Lay	left hand	-

5.5.10.9 Head 9 Insulation Papers

Head 9 was applied with a right hand lay. The dimensions of the insulation over Head 9 are summarised as follows:

Sample VICT-146 Diameter tape measurements over the Head 9 insulation tapes, tape thickness and width		
Distance from North end of the sample (m)	Diameter measured (mm)	Comment
4.33	65.6	North end
5.30	65.75	South end
Tape thickness	0.089mm	Outer tape – did not break on bending.
Tape width	24mm	-

Lay	right hand	Tapes to the south side of the northern bulge feature (failure site) are creased at the butt gaps until position 5.1m. Tapes to the north of the failure site are not creased. Tapes to the south of position 5.1m are not creased.

5.5.10.10 Head 10 Insulation Papers

Head 10 was applied with a left hand lay. The dimensions of the insulation over Head 10 are summarised as follows:

Sample VICT-146 Diameter tape measurements over the Head 10 insulation tapes, tape thickness and width		
Distance from North end of the sample (m)	Diameter measured (mm)	Comment
5.30	63.4	South end
Lay	left hand	Outer tape – did not break on bending.

5.5.10.11 Head 11 Insulation Papers

Head 11 was applied with a right hand lay. The dimensions of the insulation over Head 11 are summarised as follows:

Sample VICT-146 Diameter tape measurements over the Head 11 insulation tapes, tape thickness and width		
Distance from North end of the sample (m)	Diameter measured (mm)	Comment
~4.2	61.2	North end
~5.30	61.2	South end
Tape thickness	0.093mm	Outer tape – did not break on bending.
Tape width	24mm	-

Lay	right hand	Crease / flat at south end now completely gone.

5.5.10.12 Head 12 Insulation Papers

Head 12 was applied with a left hand lay. The dimensions of the insulation over Head 12 are summarised as follows:

Sample VICT-146 Diameter tape measurements over the Head 12 insulation tapes, tape thickness and width		
Distance from North end of the sample (m)	Diameter measured (mm)	Comment
~4.2	59.0	North end
~5.30	58.8	South end
Tape thickness	-	Outer tape – did not break on bending.
Lay	left hand	-

5.5.10.13 Head 13 Insulation Papers

Head 13 was applied with a right hand lay. The dimensions of the insulation over Head 13 are summarised as follows:

Sample VICT-146 Diameter tape measurements over the Head 13 insulation tapes, tape thickness and width		
Distance from North end of the sample (m)	Diameter measured (mm)	Comment
~4.2	56.5	North end
~5.30	56.5	South end
Tape thickness	-	Outer tape – did not break on bending.
Tape width	24mm	-
Lay	right hand	-

5.5.10.14 Head 14 Insulation Papers

Head 14 was applied with a left hand lay. The dimensions of the insulation over Head 14 are summarised as follows:

Sample VICT-146 Diameter tape measurements over the Head 14 insulation tapes, tape thickness and width		
Distance from North end of the sample (m)	Diameter measured (mm)	Comment
~4.2	54.25	North end
~5.30	54.25	South end
Tape thickness	-	Outer tape – did not break on bending.
Tape width	24mm	A 4mm diameter dark inclusion was noted in a tape ~200mm south of the northern bulge/failure site. Compound stringing was present between the tapes.
Lay	left hand	-

5.5.10.15 Head 15 Insulation Papers

Head 15 was applied with a right hand lay. The dimensions of the insulation over Head 15 are summarised as follows:

Sample VICT-146 Diameter tape measurements over the Head 15 insulation tapes, tape thickness and width		
Distance from North end of the sample (m)	Diameter measured (mm)	Comment
~4.2	52.0	North end
~5.30	51.9	South end
Tape thickness	0.065mm	Outer tape – did not break on bending.
Tape width	20mm	Compound stringing was present between the tapes.
Lay	right hand	-

5.5.10.16 Head 16 Insulation Papers

Head 16 was applied with a left hand lay. The dimensions of the insulation over Head 16 are summarised as follows:

Sample VICT-146 Diameter tape measurements over the Head 16 insulation tapes, tape thickness and width		
Distance from North end of the sample (m)	Diameter measured (mm)	Comment
~4.2	50.5	North end
~5.30	50.5	South end
Tape thickness	-	Outer tape – did not break on bending.
Lay	left hand	Some butt gap creases noted

5.5.10.17 Head 17 Insulation Papers

Head 17 was applied with a right hand lay. The dimensions of the insulation over Head 17 are summarised as follows:

Sample VICT-146 Diameter tape measurements over the Head 17 insulation tapes, tape thickness and width		
Distance from North end of the sample (m)	Diameter measured (mm)	Comment
~4.2	49.0	North end
~5.30	48.9	South end
Tape thickness	0.057mm	Outer tape – did not break on bending.
Tape width	20mm	Core is firm and round
Lay	right hand	No features noted on north or south side of the failure site.

5.5.10.18 Head 18 Insulation Papers

Head 18 was applied with a left hand lay. The dimensions of the insulation over Head 18 are summarised as follows:

Sample VICT-146 Diameter tape measurements over the Head 18 insulation

tapes, tape thickness and width		
Distance from North end of the sample (m)	Diameter measured (mm)	Comment
~4.2	47.5	North end
~5.30	47.3	South end
Tape thickness	-	Outer tape – did not break on bending.
Lay	left hand	-

5.5.10.19 Head 19 Insulation Papers

Head 19 was applied with a right hand lay and was the first layer of insulation papers applied of the conductor screening tapes. The dimensions of the insulation over Head 19 are summarised as follows:

Sample VICT-146 Diameter tape measurements over the Head 19 insulation tapes, tape thickness and width		
Distance from North end of the sample (m)	Diameter measured (mm)	Comment
~4.2	45.9	North end
~5.30	45.75	South end
Tape thickness	0.076mm reducing to 0.045mm over the conductor screen	Outer tape – did not break on bending. Inner tape – did not break on bending.
Tape width	20mm	Compound stringing was present between the tapes.
Lay	right hand	No pin holes could be seen when a torch was shone behind the tapes during removal.



Figure 101 Sample VICT-146, Head 19 insulation tapes at the north end of the sample, 9 o'clock view (north to the left hand side of the image).

5.5.10.20 Head 19 Conductor Screening Papers

The final two tapes in Head 19 were plain carbon screening papers applied with a right hand lay. The dimensions of the conductor screening tapes are summarised as follows:

Sample VICT-146 Diameter tape measurements over the Head 19 screening tapes, tape thickness and width		
Distance from North end of the sample (m)	Diameter measured (mm)	Comment
~4.2	44.75	North end
~5.30	44.75	South end
Tape thickness	0.110mm	Outer tape – did not break on bending. Inner tape – did not break on bending.
Tape width	20mm	Compound stringing was present between the tapes.
Lay	right hand	No pin holes could be seen when a torch was shone behind the tapes during removal.

5.5.10.21 Head 20 Conductor screening tapes

Head 20 was applied with a left hand lay and was the first layer of papers applied as the conductor screening tapes. The dimensions of the insulation over Head 20 are summarised as follows:

Sample VICT-146 Diameter tape measurements over the Head 20 insulation tapes, tape thickness and width		
Distance from North end of the sample (m)	Diameter measured (mm)	Comment
~4.2	44.25	North end
~5.30	44.25	South end
Lay	left hand	

5.5.11 Conductor

The conductor to the north and south of the failure site was exposed. The diameter over the conductor was measured as 43.9mm at the north end of the sample, and 44.0mm at the south end of the sample, using a diameter tape.

The outer strands of the conductor were laid up with a right hand lay.



Figure 102 Sample VICT-146, Failure site insulation papers prior to being cut from the conductor TDC view (north to the right hand side of the image).

The cluster of papers forming the failure site, following the application of orientation markings, Figure 102, was removed from the conductor by cutting through the papers in the 3 o'clock orientation. The papers were removed as a single piece and retained, Figure 103.



Figure 103 Sample VICT-146, Failure site insulation papers being removed from the conductor, TDC view (north to the right hand side of the image).



Figure 104 Sample VICT-146, Failure site insulation papers being removed from the conductor, TDC view (north to the right hand side of the image).



Figure 105 Sample VICT-146, Conductor erosion centred at position 4.54m, 3 o'clock orientation view (north to the right hand side of the image).



Figure 106 Sample VICT-146, View of the conductor at position 5.0m, 3 o'clock orientation view (north to the right hand side of the image).

Facts noted:

- An erosion of 4.75mm – 5.0mm in depth was present in the conductor centred at position 4.54m in the TDC orientation, Figure 104 and Figure 105.
- The erosion was estimated to have been present over 30% of the conductor circumference.
- The surface of the conductor over a region of approximately 130mm was rough to the touch with a stippled texture, Figure 105.
- Verdigris was present in patches on the conductor in the stippled region.
- The conductor at position 5.0m was smooth and clean with no features to note, Figure 106.

6 Sample Log

During the examination materials removed from the cable samples were given a unique number and logged for retention.

The list of items retained from samples VICT-144 and VICT-146 are as follows:

6.1 Samples from VICT-144:

VICT 144/1 Armour off 2m Lengths
VICT 144/2 Reinforcing tapes off 2m (2x outer layer)
VICT 144/3 Reinforcing tapes off 2m (2x Inner Layer)
VICT 144/4 Bedding tape (fibres) over black PE/ o/s
VICT 144/5 PE o/s
VICT 144/6 Lead Sheath (750–27) mm long
VICT 144/7 CWF tape
VICT 144/8 Outer 2 screening tape
VICT 144/9 Outer head 1
VICT 144/10 Head 2
VICT 144/11 Head 3A has first half of length 3mm black feature on tape 2 from head
VICT 144/12 Head 3B 2nd half of sample length small inclusions
VICT 144/13 Head 3C
VICT 144/14 Head 4
VICT 144/15 Head 5
VICT 144/16 0.5 sample Pb sheath + tapes (4.754m + 0.5m)

6.2 Samples from VICT-146

VICT 146/1 "Cut" end of PP string to north fault hole.
VICT 146/2 PP servings – cut around main bulge hole.
VICT 146/3 4 armour wires from over main bulge + hole fault on ACW side.
VICT 146/4 7 armour wires from over main bulge + hole fault on CW side + went over top of second bulge.
VICT 146/5 7 wires off ACW side 10 o'clock to 12 o'clock.
VICT 146/6 7 wires off ACW.
VICT 146/7 7 wires off ACW.
VICT 146/8 7 wires off ACW.
VICT 146/9 7 wires off ACW.
VICT 146/10 6 wires off ACW.
VICT 146/11 Bedding tape over reinforcing.
VICT 146/12 Outer steel reinforcing tape from N to first bulge / broke.
VICT 146/13 1 string broken off over fault hole – reinforcing tape.
VICT 146/14 1 reinforcing tape outer between two bulges (broke off).
VICT 146/15 Outer reinforcing tape 2nd bulge to south serving cut.
VICT146/16 2nd reinforcing tape from north end serving cut to 1st Bulge + small steel piece close to Fault (20mm long).

VICT 146/17 Steel 2nd tape from first bulge to second bulge broken at both positions. 2nd bulge end is jagged.
VICT 146/18 2nd tape from 2nd bulge south to southern serving cut.
VICT 146/19 Steel tapes last two double start from N end to 1st bulge (broken) take off together because 2nd tape overlaps 1st.
VICT 146/20 2 inner steel tapes removed from between 2 bulges – both ends were ruptured.
VICT 146/21 3rd tape in (steel) - has square end.
VICT 146/22 Small piece off inner tape over bulge.
VICT 146/23 PE oversheath.

VICT 146/24 Lead sheath – top half from 5m to 5.5m.
VICT 146/25 3 o'clock strip of lead sheath.
VICT 146/26 9 o'clock strip of lead sheath.
VICT 146/27 4 o'clock to 8 o'clock low half of lead sheath.
VICT 146/28 Top half of lead sheath 4.00m & 4.40m up to near 1st bulge at 5.400m.
VICT 146/29 Top half of lead sheath 4.700m to 5.500m (also is over 2nd bulge at 12o/c).
VICT 146/30 CWF tape from N lead cut to first bulge/hole.
VICT 146/31 CWF tape from 1st bulge centreline to south lead cut.
VICT 146/32 Carbon + M.Carbon screen tapes N cut to start of bulge.
VICT 146/33 Carbon + M.Carbon screen from south of main bulge to lead cut S at 5.500m.
VICT 146/34 Screen over N.end of main bulge/slot.
VICT 146/35 Head 1 N lead cut to bulge + over 1st ½ of bulge.
VICT 146/36 Head 1 over bulge.
VICT 146/37 Head 1 bulge to S. lead cut.
VICT 146/38 Head 2 N. lead cut to bulge
VICT 146/39 Head 2 bulge to lead cut S end.
VICT 146/40 Head 3 N cut lead to bulge.
VICT 146/41 Head 3 over bulge.
VICT 146/42 Head 3 bulge to s cut.
VICT 146/43 Head 4 N lead cut to bulge.
VICT 146/44 Head 4 bulge to S end lead cut.
VICT 146/45 Head 5 N lead cut to bulge.
VICT 146/46 Head 5 bulge to S end.
VICT 146/47 Head 6 N lead cut N end of bulge.
VICT 146/48 Head 6 bulge to South end.
VICT 146/49 Head 7 N end to bulge.
VICT 146/50 Head 7 bulge to S lead cut.
VICT 146/51 Head 8 N lead cut to cut bulge & Bulge to S lead cut – In one bag
VICT 146/52 Head 9 lead cut N to S (but not over bulge).
VICT 146/53 Head 10 North lead cut to S lead cut (but not over bulge).
VICT 146/54 Head 11 North lead cut to S lead cut (but not over bulge).
VICT 146/55 Head 12 North lead cut to S lead cut (but not over bulge).
VICT 146/56 Head 13 North lead cut to S lead cut (but not over bulge).
VICT 146/57 Head 14 North lead cut to S lead cut (but not over bulge).
VICT 146/58 Head 15 North lead cut to S lead cut (but not over bulge).
VICT 146/59 Head 16 North lead cut to S lead cut (but not over bulge).

VICT 146/60 Head 17 North to South lead cuts (but not bulge).
VICT 146/61 Head 18 North to South lead cuts (but not bulge).
VICT 146/62 Head 19 last head (10 papers + 2 Carbons).
VICT 146/63 2 inner carbon screens over conductor.
VICT 146/64 Paper insulation cut from over failure site.
VICT 146/65 Conductor.
VICT 146/66 Washings/brushings of conductor.

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

TITLE: **Basslink KP199.256 Failure Examination 7th to 9th June 2016 at CCI**

REPORT No: **ER 808**

CUSTOMER: **Basslink (BPL)**

AUTHOR: **Eur Ing Laurence Trim BEng CEng MIET**
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DATE: **27th June 2016**

Summary

The high voltage HVDC cable element of the Basslink Interconnector failed on 20th December 2015.

The section of cable containing the failure site was recovered from the seabed on 27th March 2016 and shipped to the Prysmian laboratory at CESI, Milan for an independent failure investigation to be conducted.

An independent inspection of the failed cable was conducted by Cable Consulting International Ltd in the presence of representatives from the following interested parties: Basslink, Keppel Infrastructure Trust, FM Global, Hydro Tasmania, and Prysmian over the period 27th to 29th April 2016.

Key components from the initial inspection were retained and shipped to CCI's offices in Underriver Kent for further visual examination. A further visual examination of the following components was conducted over the period 7th to 9th June 2016: Conductor sample (including removal of segments to inspect for joints), Dismantling of insulation papers from the failure site, Lead sheath from the failure site, Polyethylene oversheath inspection, Inspection of reinforcement tapes, Degreasing and staining of insulation paper tapes from the outer and inner heads of the insulation (Heads 1 & 19).

This report provides a factual account of the features found during the further visual inspection of the above components.

Distribution: BPL

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1 Introduction

The HVDC Basslink Interconnector spans approximately 300km from Victoria in Australia to George Town in Tasmania. The 400kV high voltage HVDC submarine cable element of the Interconnector failed on 20th December 2015.

The section of cable containing the failure site was recovered from the seabed on 27th March 2016 using the *C/S Ile de Re.* The section of cable containing the failure site, and several other samples including two cable sections immediately adjacent to the north and the south of the failure site, were packaged and shipped to the Prysmian laboratory at CESI, Milan, for an independent failure investigation to be conducted.

An independent inspection of the failed cable was conducted by Cable Consulting International Ltd (CCI) in the presence of representatives from the following interested parties: Basslink, Keppel Infrastructure Trust, FM Global, Hydro Tasmania, and Prysmian over the period 27th to 29th April 2016. CCI Report ER 795, dated 27th May 2016, was issued detailing the facts found during the inspection.

Components from the initial inspection that were not inspected in detail at CESI were retained and shipped to CCI's offices in Underriver, Kent. A further visual examination of the following components was conducted over the period 7th to 9th June 2016:

- Conductor sample (including removal of segments to inspect for joints),
- Dismantling of insulation papers from the failure site,
- Lead sheath from the failure site,
- Polyethylene oversheath from the failure site,
- Reinforcement tapes,
- Insulation papers from the outer and inner heads of the insulation (Heads 1 & 19).

This report provides a factual account of the features found during the further visual inspection of the above components.

The top dead centre (TDC) orientation marks referenced in the report were applied to the samples during the CESI, Milan inspection. Circumferential orientations are referenced looking from south to north along the samples with 12 o'clock being the TDC position.

2 Personnel Present at the Further Visual Inspection

The following personnel were present at the further visual inspection of the retained components over the period 7th to 9th June 2016.

Name	Company	Representing
[redacted]	Basslink	BPL
Stephen Bendeich	Hydro Tasmania	Hydro Tasmania

Fred Steennis	DNV-GL	Hydro Tasmania
[redacted]	FM Global	FM Global
[redacted]	PowerSure Technology Ltd	FM Global

BPL engaged CCI to conduct the further examination works. The engineers conducting the works were Eur Ing Laurence Trim and Eur Ing Brian Gregory.

3 Samples as received at CCI

The samples retained from the CESI inspection were received at the CCI facilities Underriver Kent on 16th May 2016, Figure 1.



Figure 1 Samples retained from the Milan inspection as received by CCI.

4 Inspection Detail

4.1 Conductor examination

The section of conductor from the fault site (sample reference VICT-146/65) was further inspected.

The sample measured 978mm in length.

The sample was noted to have a permanent set across the length, Figure 2. The knee of the set was centred at the conductor erosion site which was coincident with the northern bulge position (4.55m from the north end of the sample when inspected in Milan).

The northern end of the conductor was noted to be straight when aligned against a straight edge for a distance of 333mm, the distance from the centre of the centre of the erosion to the northern edge of the sample. When positioned with the 6 o'clock orientation of the northern end resting against a

straight edge, the set of the southern end of the conductor was measured to be a deflection of 27mm from the straight edge, Figure 2.



Figure 2 Permanent set measured in the main conductor (north to the left of the image).

A 130mm length tarnished and eroded region was present on the conductor that coincided with the position of the centre of the northern bulge position (4.55m from the northern end of the sample when inspected in Milan), Figure 3.



Figure 3 Tarnished and eroded section of the conductor at the northern bulge site, TDC view (north to the left of the image).

Either side of the eroded and tarnished region, the paper semi-conductive screening tapes had adhered to the conductor surface. Various colours were present within the eroded section of conductor: Verdigris (green), copper, russet red, red/brown and black.

The main erosion site was 45mm in length, Figure 4.

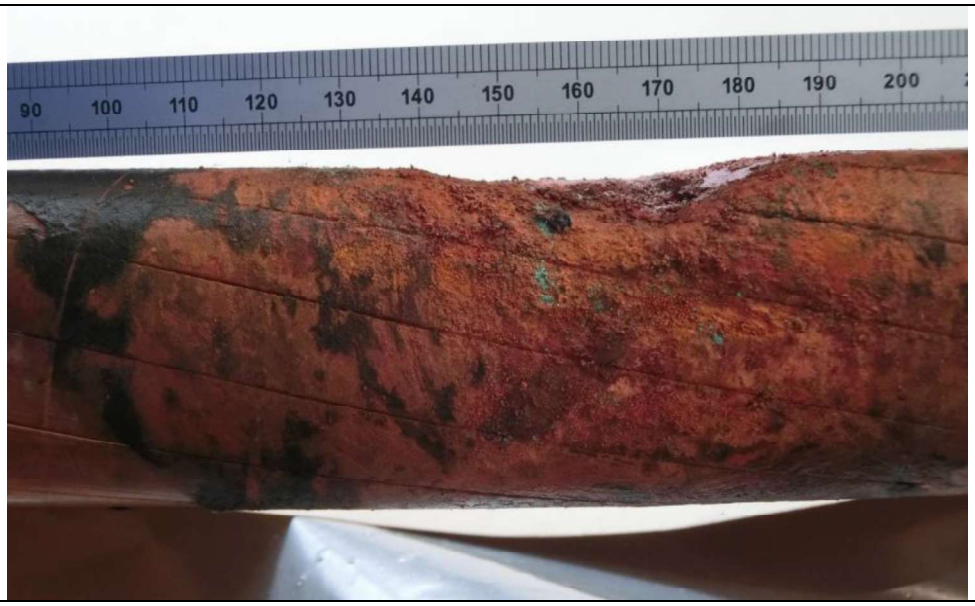


Figure 4 Tarnished and eroded section of the conductor at the northern bulge site, 9 o'clock orientation (north to the left of the image).



Figure 5 Erosions present in the 9 o'clock orientation of the conductor at the northern bulge site (north to the left of the image).

The outer diameter of the conductor was measured as 44.0 mm at locations either side of the erosion site.

The outer layer of the conductor contained 12 shaped segments applied with a right hand lay, and a lay length of 660mm.

The outer layer segments of the conductor were numbered from 1 to 12, with number 1 starting at the 12 o'clock position on the southern end of the sample and incrementing in an anticlockwise fashion (when looking from the south end to the northern end).

The conductor was progressively dismantled into individual segments, Figure 6. The segments were measured to have a radial thickness of 6mm.



Figure 6 Removing segment number 8 from the conductor (north to the left of the image).

Segment number 2 passed through the TDC of the erosion site. On removal the segment was noted to be very thin at the central position indicating that a 6mm thickness of copper had been eroded at the centre of the feature.



Figure 7 Segment number 2 prior to removal showing the depth of the erosion (north to the left of the image).

Insulation compound was noted to be present throughout the build of the conductor.

The underside face of the outer segments were inspected under a microscope. The surface die marks, the wire drawing scores present on the inside of the segments, were noted to be linear and

passed beneath the eroded area without deviating. No conductor segment joints were noted within the sample.



Figure 8 Segment number 2 following removal showing the depth of the erosion as 6mm, i.e. the radial depth of the segment (north to the left of the image).

A red/brown substance and Verdigris was found on the surface of the second layer of segments beneath the deepest section of the erosion, Figure 9. The sticky red/brown substance could be easily removed using the tip of a knife blade, Figure 10.

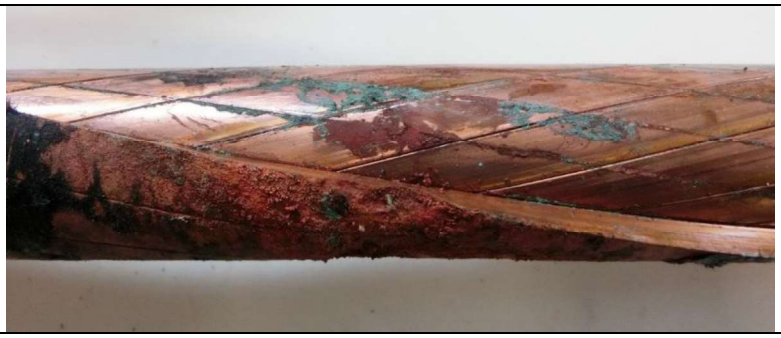


Figure 9 Red/brown substance and Verdigris beneath the eroded region on the surface of the second layer of conductor segments (north to the left of the image).



Figure 10 The sticky brown substance could be removed from the second layer of conductor segments using a knife.

The second layer of 10 off conductor segments was applied with a left hand lay and a lay length of 430mm. The diameter over the second layer of conductor segments was measured as 32.25mm at the north and south ends of the sample.

The copper segments of the second layer of the conductor were shiny and bright.

The conductor segments were numbered 1 to 10 starting at the TDC orientation at the south end of the sample and numbered in an anticlockwise direction (when looking south to north).

The segments were removed. Segment number 8 coincided with the TDC of the northern bulge fault location position. A small amount of spluttering and a 3mm by 1mm length erosion was present in the surface of the segment, Figure 11.

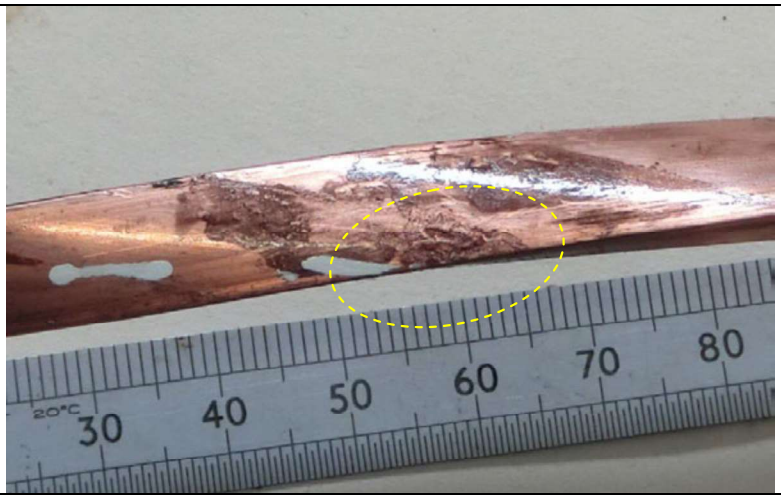


Figure 11 Spluttering on the surface of segment number 8 of the second layer of wires (ringed).

Insulation compound was noted to be present in between the conductor segments.

The third layer of 6 off conductor segments measured 22.0mm in diameter. The segments were applied with a lay length of 230mm on a right hand lay. The copper was noted to be bright and shiny. On dismantling, compound was noted to be present between the conductor segments.

The central rod of the conductor was measured to be 12mm in diameter. The central rod was noted to have a permanent set with the knee of the bend centred at a position 330mm from the north end of the sample. When the north end of the rod was positioned against a straight edge, the south end deflected 29mm from the edge.

The conductor segment sets were labelled and retained, Figure 12.

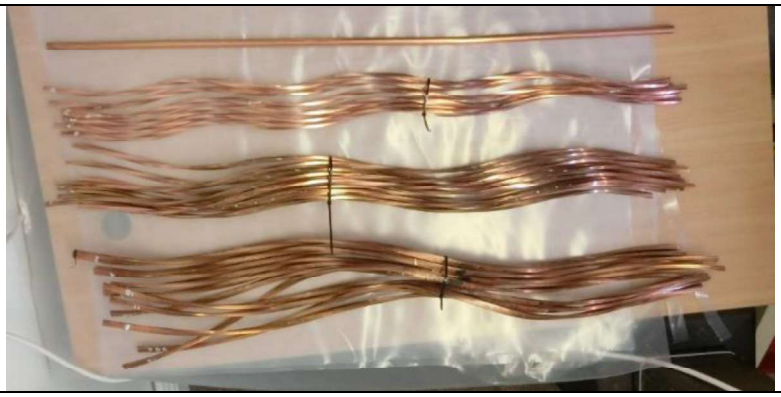


Figure 12 Conductor segments and central rod following dismantling.

4.2 Insulation Papers from the Failure Site

Sample reference: VICT-146/64 – Fault site.

At the CESI inspection the failure site papers remaining on the conductor were cut along the 3 o'clock orientation and prised from the conductor. Prior to removal, white paint marks were made on the papers to indicate the TDC orientation and the north / south end of the sample. The relative positioning of the white paint markings can be determined with reference to figure 102 in CCI Report ER795.



Figure 13 Failure site papers as packaged in Milan.



Figure 14 Failure site papers as opened at CCI's premises.

The papers as packaged following the CESI inspection are shown in Figure 13. The papers following removal of the packaging at CCI's premises are shown in Figure 14. The papers had an acrid smell.

The loose outer papers from the bundle were removed from the sample and retained on an acetate slide, Figure 15.



Figure 15 Layers of loose papers retained on acetate sheets.

During removal of the outer papers, a small amount of insulation compound stringing could be detected between tapes, Figure 16.



Figure 16 Compound stringing present in the outer papers (ringed).

The fault site contained three main split features:

- A curved split in the 9 o'clock orientation, 150mm in length.
- A sine wave shaped split across the TDC orientation, 130mm in length with a peak to peak amplitude of 30mm.
- A circumferential split that adjoined both splits at the centre of the sample.

There were no splits in the underside of the papers at the fault site.

The three main splits were heavily carbonised and extended through the complete insulation thickness to the semi-conductive screening tapes. Verdigris was present on the edges of some the splits. A red/brown compound was present within the burnt tapes, Figure 17.

The longitudinal paper cut, made at the 3 o'clock orientation in CESI, was used to access the central tapes of the fault site.

The black coloured, semi-conductive, carbon paper conductor screening tapes were internally inspected before being removed, Figure 18. The tapes had been disturbed during the removal of the sample at CESI as some tapes had adhered to the conductor. Some verdigris was present on the remaining central tapes, Figure 19. No longitudinal creases or rucks were noted in the remaining tapes.

With the internal screening tapes removed, the underside of the internal insulation tapes was inspected, Figure 20.

A central hole was present that extended through all layers of the insulation, Figure 21. The outer hole position coincided with the TDC orientation of the cable.



Figure 17 Red / brown compound present within the burnt papers (ringed).



Figure 18 Inspection of the inside of the conductor screening tapes.



Figure 19 Inspection of the inside of the conductor screening tapes.



Figure 20 Inspection of the inside of the inner insulation tapes.

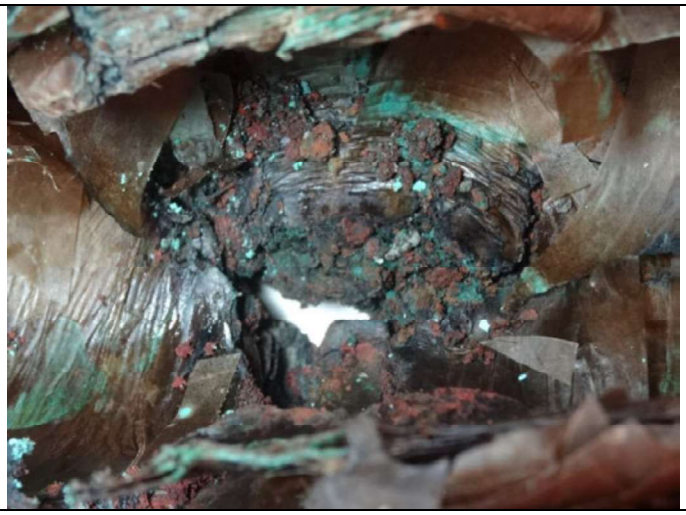


Figure 21 Fault hole through the insulation tapes.

Circumferential rucks were present within the inner insulation tapes around the fault hole position, Figure 22.



Figure 22 Circumferential paper rucks around the fault hole.

The cylinder of papers was further dismantled into three main sections to further reveal the fault path through the insulation and the condition of the papers, Figure 23 to Figure 26.



Figure 23 The 4.21mm radial thickness of papers removed from the outer cylinder.



Figure 24 The 5.25mm radial thickness of papers removed from the central section of the failure site.



Figure 25 The inner 4.20mm thickness of insulation papers.



Figure 26 The dismantled insulation paper sections from the failure site.

A small amount of insulation compound was noted between the papers. The papers were heavily burnt at the fault position. A cavity of carbonised matter was present between the inner 9.45mm thickness of papers extending into the outer split features. The fault damage site was wider on the outside of the paper insulation than at the centre.

During dismantling, some circumferential splits were found within the bulk of the insulation papers. The splits in the papers were opposite the failure site. The edges of the splits were not carbonised, Figure 27.



Figure 27 Non-carbonised torn papers on the underside of the fault site (ringed).

4.3 Lead Sheath Inspection

The lead sheath sections removed from the failure site, sample references VICT-146/27, VICT-146/28 and VICT-146/29, were inspected externally and internally.



Figure 28 The lead sheath sections laid out alongside the polyethylene oversheath (inner view – top image; outer view – bottom image; North to the left hand side of the image).

In Figure 28, the northern bulge at the failure site is towards the left hand side of the image, and the southern bulge is towards the right hand side of the image.

The following lead sheath thickness measurements were taken from the main samples:

Sample reference	Northern End measurement (mm)	Southern end measurement (mm)
VICT-146/27	3.79	3.92
	3.95	3.86
	3.79	3.72
VICT-146/29	3.62	3.60
	3.79	3.80
	3.22	4.16

4.3.1 Internal surface of lead sheath

The internal surface of the lead contains impressions of the right and left hand lay tapes of the underlying copper woven fabric tape and the metallised paper screening tapes applied over the insulation layer, Figure 29.



Figure 29 Internal view of the impressions within the lead sheath sections.

The tape impressions are also present on this inside of the northern and southern bulge features, Figure 30 and Figure 31.

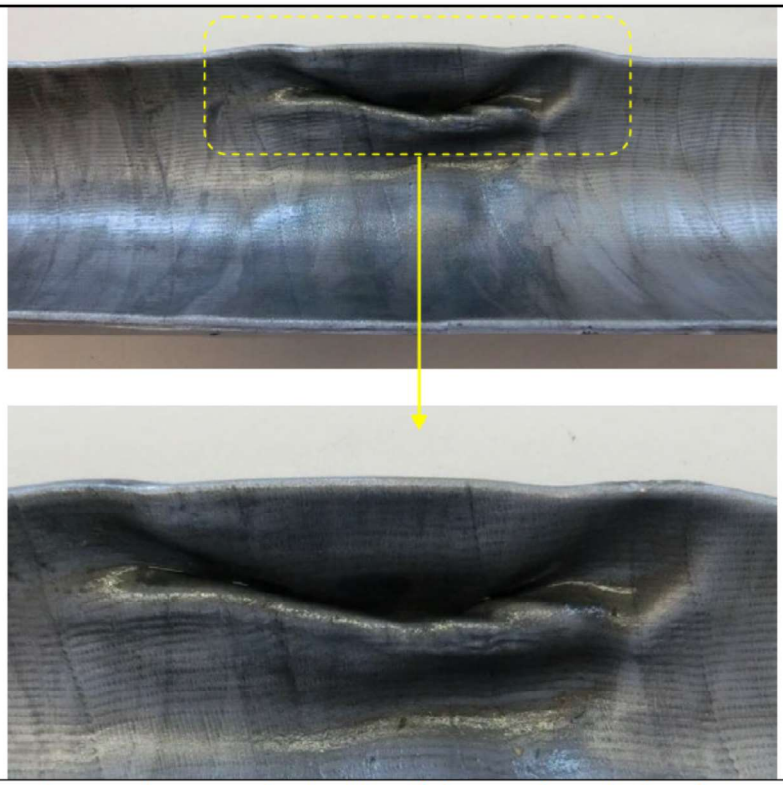


Figure 30 Tape impressions on the inside of the southern bulge feature (north to left hand side).



Figure 31 Tape impressions on the inside of the northern bulge feature (North to left hand side).

The copper woven fabric tape was fused to the internal surface of the lead sheath at the northern bulge position, Figure 31.

A line of molten lead globules was noted along the 9 o'clock edge of the lead sheath at the northern bulge position, Figure 32.



Figure 32 Lead globules at the northern bulge in the 9 o'clock orientation (ringed) (North to right hand side).

At the northern bulge position either side of the main split features (TDC orientation), numerous lead globules were present on the underside of the lead sheath, Figure 33.

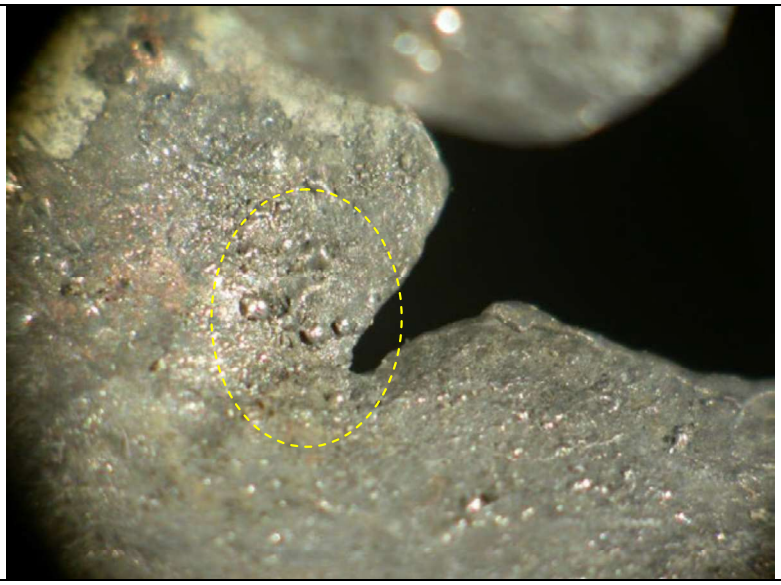


Figure 33 Lead globules under the northern bulge split at the TDC orientation (ringed).

4.3.2 External Inspection of the Lead Sheath

The two bulge features at the northern and southern positions were inspected.

The northern bulge is a bulbous distortion that spans a length of approximately 130mm, Figure 34. Crossing the TDC orientation there are two splits. The largest of these is 60mm in length and contains a square shaped notch. The extremities of the split merge into creases within the lead sheath at the north and south ends. A smaller split, approximately 35mm in length, runs parallel to the larger split separated by a parallel distance of approximately 25mm.



Figure 34 View of the northern bulge split at the TDC orientation (north to the left hand side).

The surface of the lead sheath at the northern bulge position was discoloured and tarnished. Pitting and globular deposits were present around the edges of the smaller split, Figure 35. The edges of

the notch feature within the larger split are rounded in appearance when viewed using a low power microscope, Figure 36.

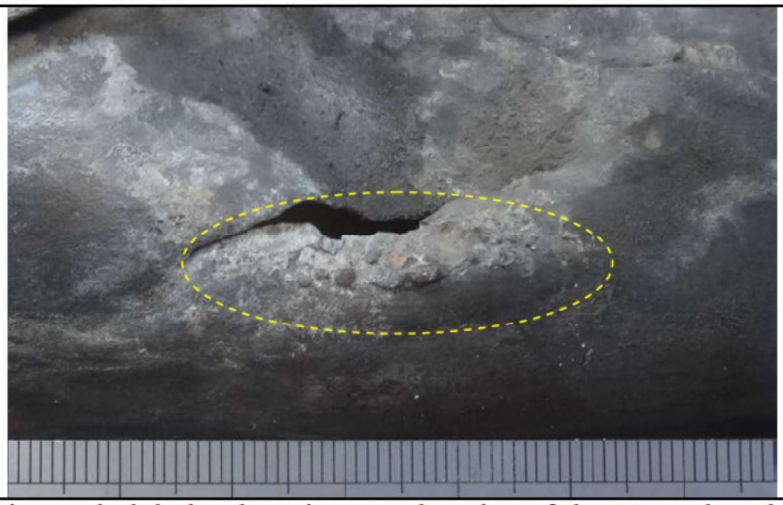


Figure 35 Pitting and globular deposits near the edge of the 35mm length split – ringed (north to the left hand side).

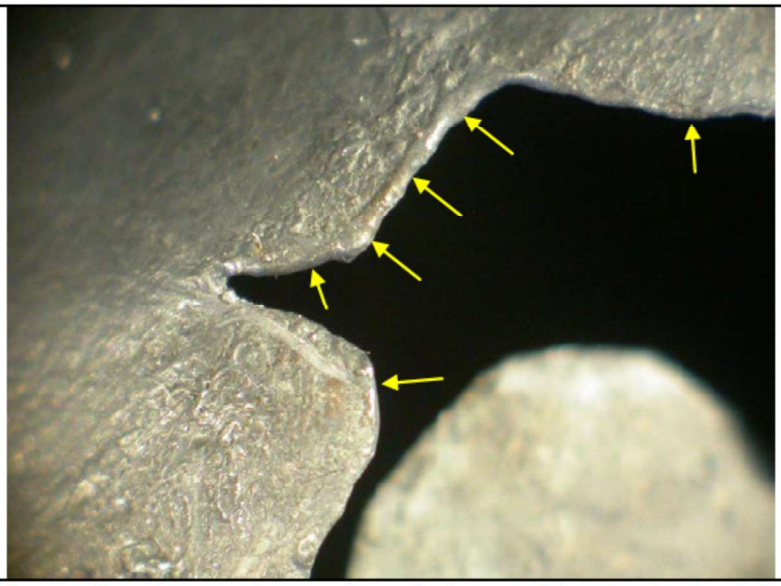


Figure 36 Molten split edges at the northern bulge position in the 9 o'clock orientation (arrows).

The southern bulge is a bulbous parallelogram form that was more pronounced at the 4 to 5 o'clock orientation, Figure 37. At this position there was a crease in the lead sheath that was approximately 90mm in length, Figure 38. The shape of the bulge followed a right hand lay form.



Figure 37 View of the top and bottom halves of the southern bulge (north to the left hand side). Underside at top of image, TDC half at bottom of image.

A fissure that penetrates through the lead sheath was present within the fold of the crease but could not be photographed.



Figure 38 Outer view of the southern bulge crease (north to the left hand side).

The light grey colour of the lead sheath was discoloured to a dark grey colour in a region clockwise from the 3 o'clock to 9 o'clock orientations in the near vicinity of the crease.

4.4 Polyethylene Oversheath Inspection

The internal and external surfaces of the polyethylene oversheath, sample reference VICT-146/23, were inspected, Figure 39.

The polyethylene oversheath retained markings of a) the northern bulge feature, b) the southern bulge feature, and c) witness lines of the overlaying reinforcement tapes.



Figure 39 Polyethylene oversheath, sample reference VICT-146/23 (north to the left hand side).

The internal surface of the component was inspected by prising opening the oversheath along the removal cut line (at the 9 o'clock orientation), Figure 40. The component was left clamped open for a 12 hour period before inspecting.



Figure 40 Polyethylene oversheath clamped open for inspection (north end to the top of the picture).

Internal views of the northern bulge feature are shown in Figure 41 and Figure 42.

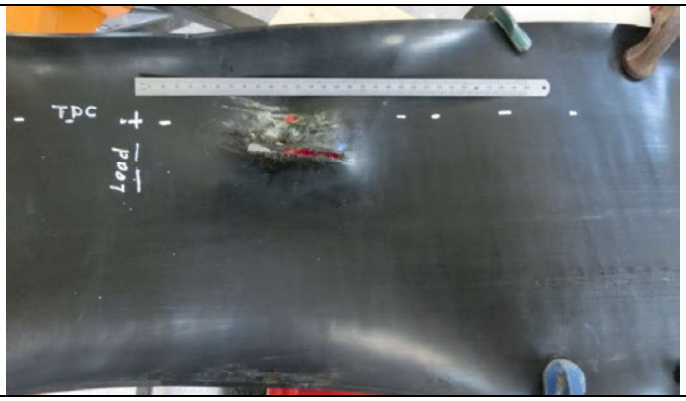


Figure 41 Northern bulge internal view (north to the left of the picture).

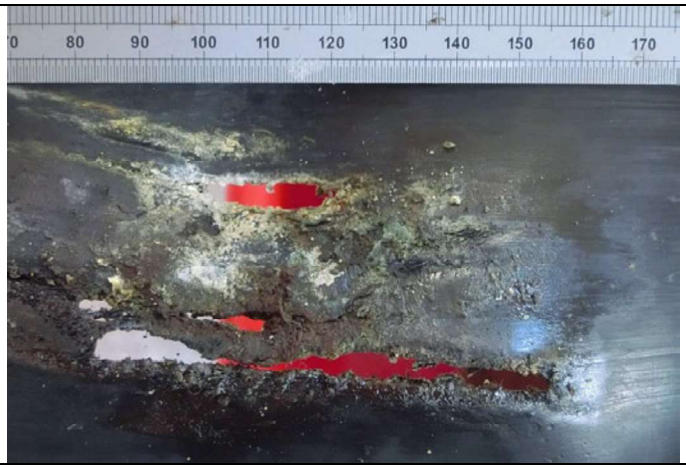


Figure 42 Northern bulge internal view of the splits (north to the left of the picture).

An internal view of the southern bulge is shown in Figure 43.



Figure 43 Southern bulge internal view (north to the left of the picture).

External views of the northern and southern bulges are shown in Figure 44 and Figure 45.

Orientation	**Figure 44** Northern bulge images
9 o'clock	
TDC	
3 o'clock	
6 o'clock	

Orientation	**Figure 45** Southern bulge images
9 o'clock	
TDC	
3 o'clock	
6 o'clock	

To record the external markings on the oversheath, the component was opened along the 9 o'clock cut line and clamped flat to a work bench, Figure 46 and Figure 47. A paper map was developed of the witness line markings present on the surface of the component (the map indicated the tape positions but excluded the detail of failure site split markings), Figure 48.

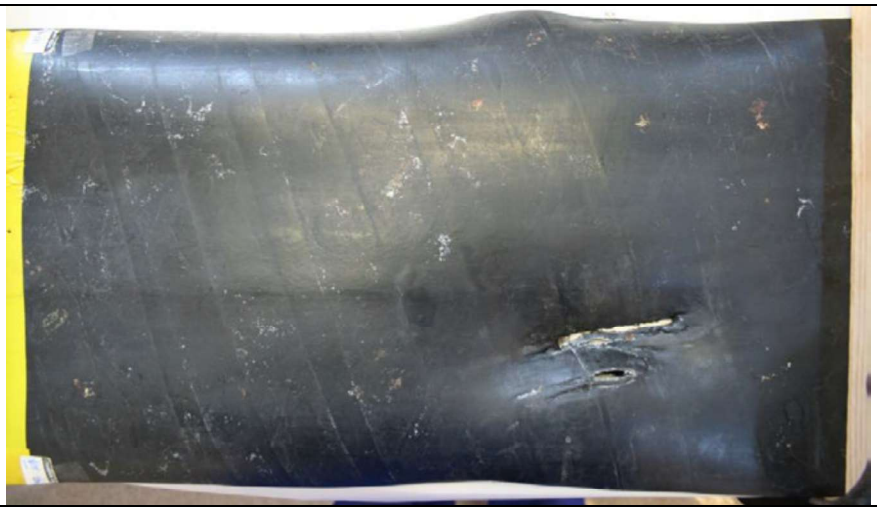


Figure 46 Northern bulge translation external view (north to the left of the picture).



Figure 47 Southern bulge translation external view (north to the left of the picture).

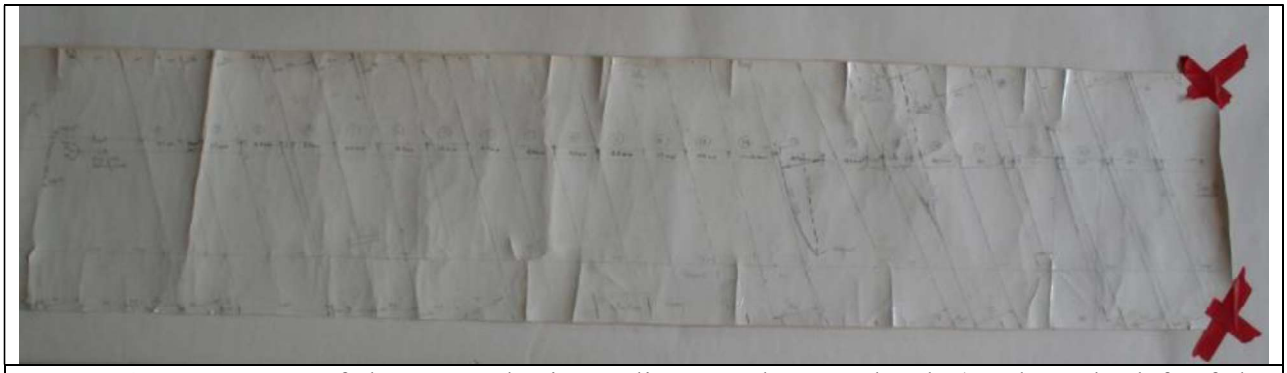


Figure 48 Paper map of the external witness lines on the oversheath (north to the left of the picture).

The perpendicular spacing measured between the witness lines (formed by the inner galvanised steel tape lines) drawn on the map was recorded via measurement of the horizontal spacing between the tapes at three horizontal lines representing the TDC, 4 o'clock and 8 o'clock orientations around the circumference of the component. The results are recorded in the following table:

	Gap perpendicular to edge of tape/mm		
Tape Number	**TDC**	**4 o'clock (120°)**	**8 o'clock (240°)**
1-2	16	18	20
2-3	-1	-2	-2
3-4	4	9	15
4-5	3	2	1
5-6	1	4	5
6-7	-2	-2	-2
7-8	-2	-2	-2
8-9	-1	0	0
9-10	-1	-1	-1
10-11	-1	-1	0
11-12	0	0	1
12-13	0	-1	-2
13-14	0	0	0
14-15	0	-2	-4
15-16	*	*	*
16-17	0	0	0
17-18	*	*	*
18-19	0	0	0
19-20	8	12	16
20-21	14	8	4
21-22	7.5	6	6
22-23	7.5	6	4

*witness lines were not visible at these positions therefore a gap could not be measured.

A 6mm length circumferential split that extended through the polyethylene oversheath was present in the 5 o'clock orientation of the southern bulge, Figure 49.

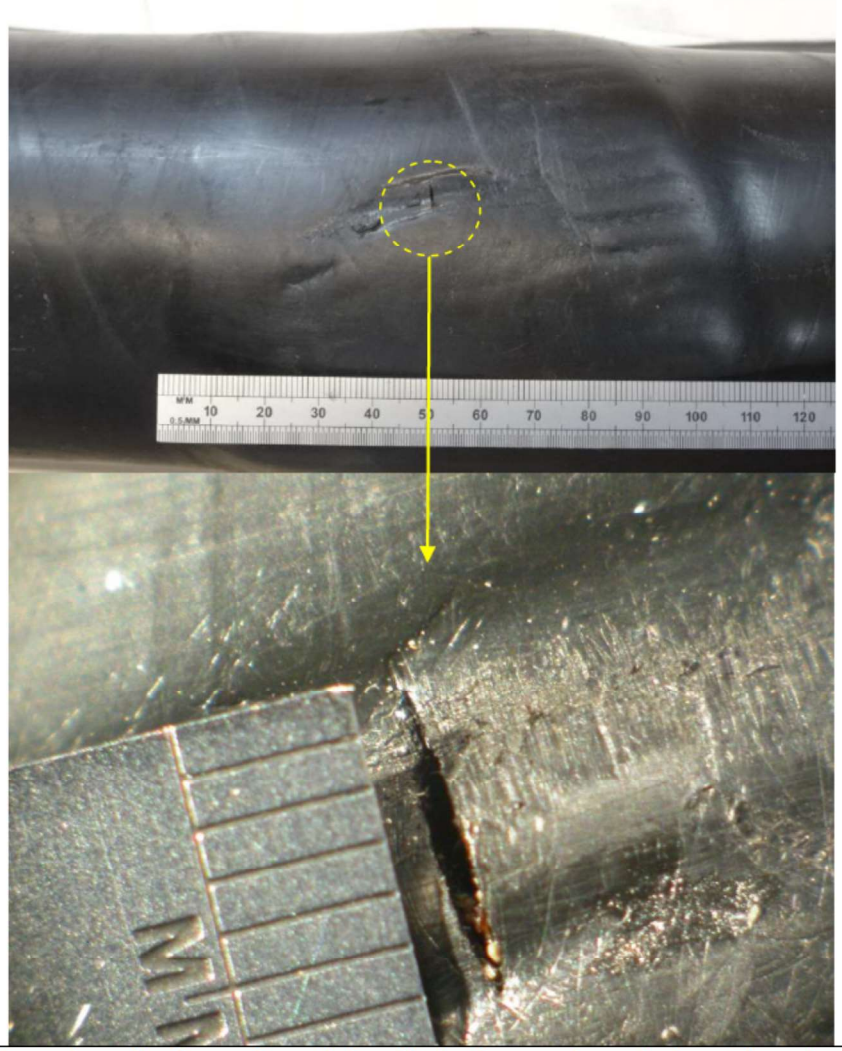


Figure 49 6mm length circumferential split in the southern bulge (ringed and enlarged under a low power microscope).

To facilitate the mapping exercise, two short sections of oversheath were removed from the north and south ends of the sample. These sections were numbered VICT-146/23 A and VICT-146/23 C. The thickness of the polyethylene was measured at the north and south ends of each sample:

Sample reference	Northern end thickness measurement (mm)	Southern end thickness measurement (mm)
VICT-146/23 A	3.70	3.61
	3.49	3.74
	3.84	3.73
VICT-146/23 C	3.65	3.66
	3.72	3.82
	3.52	3.44

4.5 Inspection of the Reinforcing Tapes

The two sets of reinforcing tapes, outer tapes and inner tapes, were inspected. The sample references of the tapes are as follows:

Outer layer tapes:

VICT-146/12, VICT-146/13, VICT-146/14, VICT-146/15, VICT-146/16, VICT-146/17, VICT-146/18.

Inner layer tapes:

VICT-146/19, VICT-146/20, VICT-146/21, VICT-146/22.

The samples as received at CCI are shown in Figure 50.



Figure 50 Reinforcement tape samples as received at CCI.

4.5.1 Outer Tape Layer Inspection

The sample bags containing the outer layer of reinforcement tapes were opened and the PVC retaining tapes applied around the samples at CESI removed.

The tapes were laid out and the fractured ends between discrete lengths compared and aligned, Figure 51 to Figure 57.



Figure 51 Outer reinforcement tape samples (north to left hand side).

Outer tape sample reference	Image of tape ends aligned
Figure 52 VICT-146/12 & 13	
Figure 53 VICT-146/13 & 14	

Figure 54 VICT-146/14 & 15	
Figure 55 VICT-146/16 (long piece to small section joint)	
Figure 56 VICT-146/16 & 17	
Figure 57 VICT-146/17 & 18	

Towards the northern end of the long section of tape, labelled as sample reference VICT-146/16, an edge crease was present, Figure 58 (See also Figure 53 of ER795).



Figure 58 Outside (left) and underside (right) images of the crease in sample VICT-146/16.

The external surfaces of the tapes were tarnished and discoloured with traces of various different coloured accretions. The internal surfaces of the tapes were tarnished with white and brown accretions.

The tapes were laid into a vertical coil on the surface of a work bench. The tape end positions that were co-incident with the north and south bulge positions were noted to protrude from the coil.

4.5.2 Inner Tape Layer Inspection

The sample bags containing the inner layer of reinforcement tapes were opened and the PVC retaining tapes applied around the samples at CESI removed.

The tapes were laid out and the fractured ends between discrete lengths compared and aligned, Figure 59 to Figure 65.

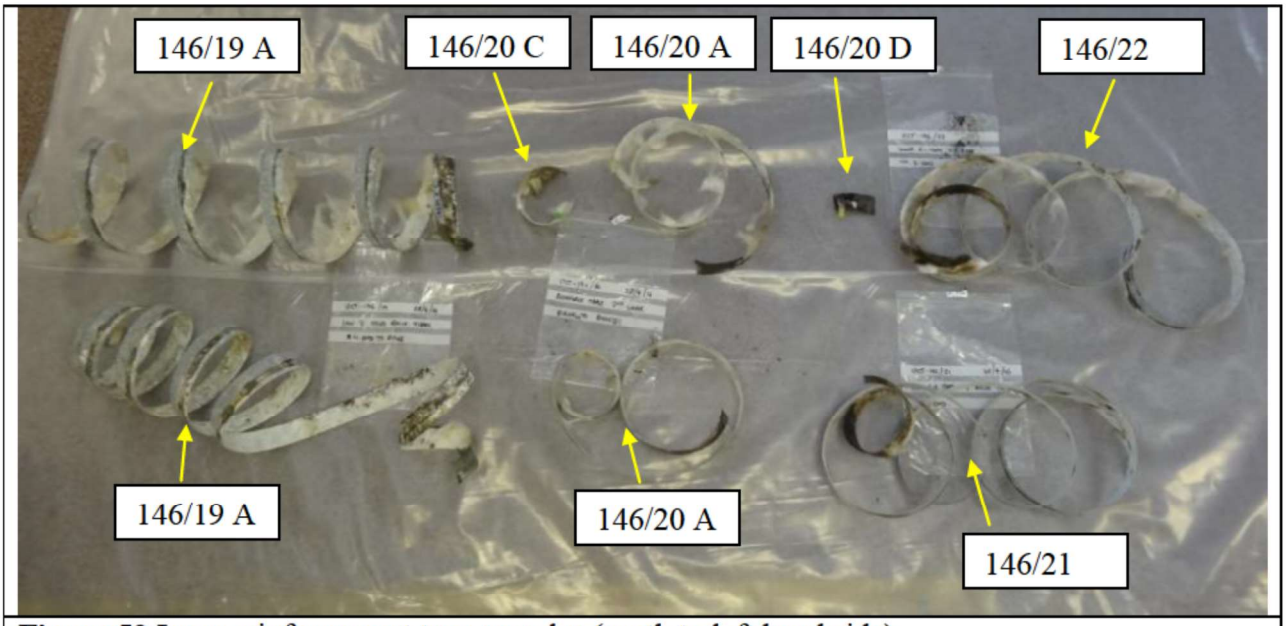


Figure 59 Inner reinforcement tape samples (north to left hand side).

Inner tape sample reference	Image of tape ends aligned
Figure 60 VICT-146/19A & 20 C	
Figure 61 VICT-146/20C & 20 A	
Figure 62 VICT-146/20 A & 20 D	
Figure 63 VICT-146/20 D & 22	

Figure 64
VICT-146/19 B & 20 B



Figure 65
VICT-146/20 B & 21





Figure 66 Surface appearance of the inner reinforcing tapes – VICT-146/22.

The external surface of the tapes were tarnished and discoloured with a dusty white accretion. A darker band was present on the tape surface co-incident with the position were the overlying tape had been positioned, Figure 66. A fibrous material was adhered to the inner surface of the tapes.

The inner tapes were laid into a vertical coil on the surface of a work bench. The tape end positions that were co-incident with the north and south bulge positions were noted to protrude from the coil, Figure 66.

4.6 Paper Tape Inspection

Samples of insulation papers were taken from the northern and southern ends of the VICT-146 cable from Head No.1 (outer insulation head) and Head No. 19 (inner insulation head), Figure 67.

1m samples lengths were cut from the following retained sample references:

VICT-146/35 – Head 1 Tapes (north end to north bulge)
VICT-146/37 – Head 1 Tapes (northern bulge to south end)
VICT-146/62 – Head 19 Tapes (north and south end tapes in one bag)*

*A 1m sample was taken from both the north and southern ends of the tapes in this bag.

The sampled tapes were numbered 1 to 10 using a pencil on the southern end of each sample. The tape sets from each head were submerged in Nusolve Degreasing Agent for a period of 2 ½ hours to dissolve the insulation compound from the papers. Once degreased and dried the papers were stained in a dye solution, containing 0.5mg of Methylene Blue diluted in 1000ml of deionised water, for 3 minutes.

The papers were inspected over a light box.



Figure 67 Paper tape sampling – VICT-146/37A northern bulge to southern end



Figure 68 Paper degreasing and staining.

4.6.1 Sample VICT-146-35 A

Stained papers from Head No.1 – Northern end to northern bulge.

No. tapes in Head: 10 papers,
Paper width: 26mm,
Paper thickness: 0.097 – 0.110mm

Pinholes recorded: None.

Visual inspection: In the outer 2 tapes periodic faint lines visible within the stain where the butt gap positions were present on the tapes.

4.6.2 Sample VICT-146-37 A

Stained papers from Head No.1 – Northern bulge to southern end.

No. tapes in Head: 10 papers,
Paper width: 26mm,
Paper thickness: 0.096 - 0.113mm

Pinholes recorded: None.

Visual inspection: In the outer 2 tapes (numbered 9 & 10), periodic faint lines were visible within the stain where the butt gap positions were present on the tapes, Figure 69. In tape number 9 two dark marks were recorded, the largest of these is shown in Figure 69. The dark marks were on one side of the tape only.

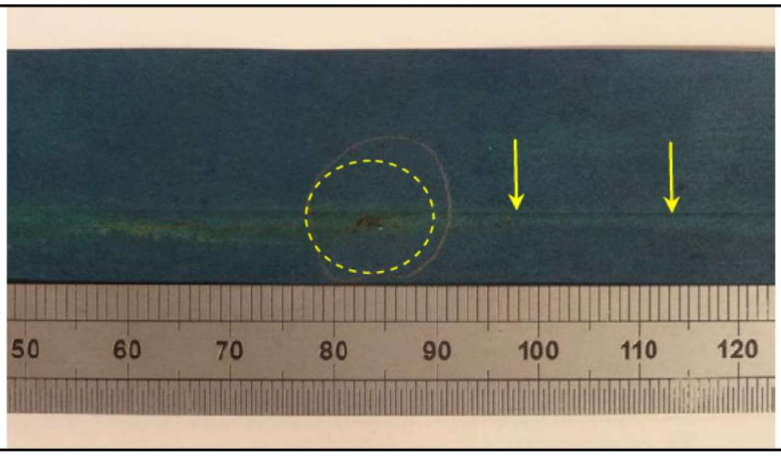


Figure 69 VIVT-146/37 A - Paper 9, Example of periodic butt gap witness mark on the tape (marked by arrows) and a 3mm dark patch (ringed) which was present on one side only.

4.6.3 Sample VICT-146-62 A

Stained papers from Head No.19 – Northern bulge to southern end.

No. tapes in Head:	10 papers,
Paper width:	20mm,
Paper thickness:	6 x 0.049 - 0.052mm (inner tapes), 4 x 0.070 - 0.083mm (outer tapes),

Pinholes recorded: None.

Visual inspection: No features noted.

4.6.4 Sample VICT-146-62 B

Stained papers from Head No.19 – Northern bulge to southern end.

No. tapes in Head:	10 papers,
Paper width:	20mm,
Paper thickness:	6 x 0.042 - 0.051mm, 4 x 0.062-0.072mm

Pinholes recorded: None.

Visual inspection: No features noted.

5 Updated Sample Log

During the first CESI examination, materials removed from the cable samples were given a unique number and logged for retention.

Items further dismantled during the second inspection at CCI were given a further unique identifier by the addition of a letter following the original sample number. These items are identified in italics in the lists below.

The updated list of items retained from samples VICT-144 and VICT-146 are as follows:

5.1 Samples from VICT-144:

VICT 144/1 Armour off 2m Lengths
VICT 144/2 Reinforcing tapes off 2m (2x outer layer)
VICT 144/3 Reinforcing tapes off 2m (2x Inner Layer)
VICT 144/4 Bedding tape (fibres) over black PE/ o/s
VICT 144/5 PE o/s
VICT 144/6 Lead Sheath (750–27) mm long
VICT 144/7 CWF tape
VICT 144/8 Outer 2 screening tape
VICT 144/9 Outer head 1
VICT 144/10 Head 2
VICT 144/11 Head 3A has first half of length 3mm black feature on tape 2 from head
VICT 144/12 Head 3B 2nd half of sample length small inclusions
VICT 144/13 Head 3C
VICT 144/14 Head 4
VICT 144/15 Head 5
VICT 144/16 0.5 sample Pb sheath + tapes (4.754m + 0.5m)

5.2 Samples from VICT-146

VICT 146/1 "Cut" end of PP string to north fault hole.
VICT 146/2 PP servings – cut around main bulge hole.
VICT 146/3 4 armour wires from over main bulge + hole fault on ACW side.
VICT 146/4 7 armour wires from over main bulge + hole fault on CW side + went over top of second bulge.
VICT 146/5 7 wires off ACW side 10 o'clock to 12 o'clock.
VICT 146/6 7 wires off ACW.
VICT 146/7 7 wires off ACW.
VICT 146/8 7 wires off ACW.
VICT 146/9 7 wires off ACW.
VICT 146/10 6 wires off ACW.
VICT 146/11 Bedding tape over reinforcing.
VICT 146/12 Outer steel reinforcing tape from N to first bulge / broke.
VICT 146/13 1 string broken off over fault hole – reinforcing tape.

VICT 146/14 1 reinforcing tape outer between two bulges (broke off).
VICT 146/15 Outer reinforcing tape 2nd bulge to south serving cut.
VICT146/16 2nd reinforcing tape from north end serving cut to 1st Bulge + small steel piece close to Fault (20mm long).
VICT 146/17 Steel 2nd tape from first bulge to second bulge broken at both positions. 2nd bulge end is jagged.
VICT 146/18 2nd tape from 2nd bulge south to southern serving cut.
VICT 146/19 Steel tapes last two double start from N end to 1st bulge (broken) take off together because 2nd tape overlaps 1st.
VICT 146/20 2 inner steel tapes removed from between 2 bulges – both ends were ruptured.
VICT 146/21 3rd tape in (steel) - has square end.
VICT 146/22 Small piece off inner tape over bulge.
VICT 146/23 PE oversheath.

- VICT 146/23 A – Short southern end section of PE oversheath
- VICT 146/23 B – Main section of PE oversheath
- VICT 146/23 C – Short northern end section of PE oversheath

VICT 146/24 Lead sheath – top half from 5m to 5.5m.
VICT 146/25 3 o'clock strip of lead sheath.
VICT 146/26 9 o'clock strip of lead sheath.
VICT 146/27 4 o'clock to 8 o'clock low half of lead sheath.
VICT 146/28 Top half of lead sheath 4.00m & 4.40m up to near 1st bulge at 5.400m.
VICT 146/29 Top half of lead sheath 4.700m to 5.500m (also is over 2nd bulge at 12o/c).
VICT 146/30 CWF tape from N lead cut to first bulge/hole.
VICT 146/31 CWF tape from 1st bulge centreline to south lead cut.
VICT 146/32 Carbon + M.Carbon screen tapes N cut to start of bulge.
VICT 146/33 Carbon + M.Carbon screen from south of main bulge to lead cut S at 5.500m.
VICT 146/34 Screen over N.end of main bulge/slot.
VICT 146/35 Head 1 N lead cut to bulge + over 1st ½ of bulge.

- VICT 146/35 A – North end papers degreased and stained.

VICT 146/36 Head 1 over bulge.
VICT 146/37 Head 1 bulge to S. lead cut.

- VICT 146/37 A – South end papers degreased and stained.

VICT 146/38 Head 2 N. lead cut to bulge
VICT 146/39 Head 2 bulge to lead cut S end.
VICT 146/40 Head 3 N cut lead to bulge.
VICT 146/41 Head 3 over bulge.
VICT 146/42 Head 3 bulge to s cut.
VICT 146/43 Head 4 N lead cut to bulge.
VICT 146/44 Head 4 bulge to S end lead cut.
VICT 146/45 Head 5 N lead cut to bulge.
VICT 146/46 Head 5 bulge to S end.
VICT 146/47 Head 6 N lead cut N end of bulge.
VICT 146/48 Head 6 bulge to South end.
VICT 146/49 Head 7 N end to bulge.

VICT 146/50 Head 7 bulge to S lead cut.
VICT 146/51 Head 8 N lead cut to cut bulge & Bulge to S lead cut – In one bag
VICT 146/52 Head 9 lead cut N to S (but not over bulge).
VICT 146/53 Head 10 North lead cut to S lead cut (but not over bulge).
VICT 146/54 Head 11 North lead cut to S lead cut (but not over bulge).
VICT 146/55 Head 12 North lead cut to S lead cut (but not over bulge).
VICT 146/56 Head 13 North lead cut to S lead cut (but not over bulge).
VICT 146/57 Head 14 North lead cut to S lead cut (but not over bulge).
VICT 146/58 Head 15 North lead cut to S lead cut (but not over bulge).
VICT 146/59 Head 16 North lead cut to S lead cut (but not over bulge).
VICT 146/60 Head 17 North to South lead cuts (but not bulge).
VICT 146/61 Head 18 North to South lead cuts (but not bulge).
VICT 146/62 Head 19 last head (10 papers + 2 Carbons).

- VICT 146/62 A – North end papers degreased and stained
- VICT 146/62 B – South end papers degreased and stained

VICT 146/63 2 inner carbon screens over conductor.

VICT 146/64 Paper insulation cut from over failure site.

- VICT 146/64 A – Fault site outer papers
- VICT 146/64 A2 – Outer papers
- VICT 146/64 B – Material sample from inside fault site
- VICT 146/64 C – Paper transferal working acetate (not retained)
- VICT 146/64 D – Failure site papers
- VICT 146/64 E – Fragments from fault site
- VICT 146/64 F - Failure site papers
- VICT 146/64 G - Failure site papers
- VICT 146/64 H - Failure site papers
- VICT 146/64 I - Failure site papers
- VICT 146/64 J - Failure site screen tapes papers
- VICT 146/64 K – Material from failure site
- VICT 146/64 L - Failure site papers
- VICT 146/64 M - Failure site papers
- VICT 146/64 N - Failure site papers

VICT 146/65 Conductor.

- VICT 146/65 A – 12 off segments from conductor outer layer
- VICT 146/65 B – 10 off segments from conductor second layer
- VICT 146/65 C – 6 off segments from conductor third layer
- VICT 146/65 D – 1 off conductor central rod

VICT 146/66 Washings/brushings of conductor.

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Report on Thermal Analysis (DSC) of Samples From 400KV Basslink Cable Fault

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Job No: G11863
Ref: Datafiles\D\DLA Piper G9748\G11863 DSC testing\G11863 Report DSC Testing.doc
Date: 29th November 2016
Prepared by: N Kenworthy

Registered in England & Wales No: 5764619

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1. Introduction

The high voltage HVDC cable element of the Basslink Interconnector failed on 20th December 2015.

The section of cable containing the failure site was recovered from the seabed on 27th March 2016 and shipped to the Prysmian laboratory at CESI, Milan for an independent failure investigation.

CCI conducted the independent failure inspections in the presence of other representatives and their findings were reported in ER795 and ER808. Various samples from the failure site were then shipped back to CCI in the UK for continued inspection work.

Materials Technology Ltd were instructed by DLA Piper Australia to carry out some further analysis on various components of this cable which was reported in G9748. Following this work some additional thermal analysis was requested on the polyethylene sheath component. This report details the additional investigations conducted by Materials Technology Ltd.

2. Samples

CCI provided the following list of samples. All samples were provided as complete cable sheaths with a longitudinal cut where they were removed from the original cable. Samples were supplied in various lengths as detailed below.

Table 2: Samples Supplied

Sample ID	Description
VIC-144/5	Black Polyethylene oversheath approx. 2m long. Sheath remote from failure zone i.e. reference section.
VIC-146/23A	Black PE sheath approx. 500mm long. Sheath from one end of failure zone.
VIC-146/23C	Black PE sheath approx. 500mm long. Sheath from opposite end of failure zone.

Small sections, measuring approximately 1cm x 3cm, were cut from the end of each specimen in table 2. Samples were then prepared from these sections by taking a cube of material approximately 3 mm square from the inner surface of the sheath and from freshly exposed material i.e. uncontaminated surfaces.

3. Methodology

Thermal analysis of the specimens was conducted using Differential Scanning Calorimetry (DSC). This was conducted using a TA Instruments DSC Q100. A triple scan was performed on each sample by heating from ambient (20°C) to 170°C at a rate of 20°C/min followed by controlled cooling from 170°C to 20°C at 20°C/min and then a final ramp from 20°C to 170°C at 20°C/min.

This technique allows the material to be analysed in the as received state and in the fully annealed state. The main purpose of this analysis was to determine any significant thermal history of the material and hence the cable.

The resulting thermograms plot scan temperature versus heat flow. Analysis was then conducted on each plot to determine any relevant features of interest.

4. Definitions

The following definitions have been used in this report

Acronym	Description
°C	Degrees Centrigrade
CCI	Cable Consulting International
DSC	Differential Scanning Calorimetry
kV	Kilo volts (1000 volts)
LDPE	Low Density Polyethylene
mm	Millimetre
MDPE	Medium Density Polyethylene
MTL, MTech	Materials Technology Ltd
PE	Polyethylene

5. Results

The resulting thermograms are shown below in figures 1 to 9. The data is summarised in table 3 below.

Table 3: Summary of DSC Analysis

Sample	1st Heating		2nd Heating		Comments
	Melting Point [°C]	% Crystallinity	Melting Point [°C]	% Crystallinity	
146/23A	115.53	26.05	118.20	23.77	Small inflection around 40°C
146/23C	116.14	25.58	118.27	23.71	Small inflection around 40°C
144/5	117.33	25.57	118.52	23.66	Small inflection around 40°C

The resulting thermograms show melting curves typical of a polyethylene type polymer. In each case the 1st scan shows a relatively broad melting envelope which peaks at around 115°C which is a typical value for LDPE/ MDPE. The crystallinity values of around 25-26% are given by the area of the melting envelope divided by the heat of fusion for the PE unit cell. Once again these values are typical of commercial LDPE/MDPE grades.

There are no obvious secondary melting peaks visible in the main melting envelope which would indicate any obvious thermal history. However, there is a very small plateau region at around 40°C in each case. This plateau region is very small but could indicate that the thermal history of the product was in the region of 40°C but it is not possible to state this with any degree of certainty. The plateau region does disappear on secondary heating which does support this.

After controlled cooling followed by secondary heating there is a small increase in the overall melting point and the appearance of a secondary melting peak due to a secondary crystal structure and reordering of the melt. This also causes a slight reduction in the overall crystallinity due to this secondary phase.

Figures 6 through 9 show an overlay comparison of each scan. As can be seen these all overlay well with no significant differences. The only difference was a small shift in the melting peak for sample 144/5 but this is deemed to be within experimental error.

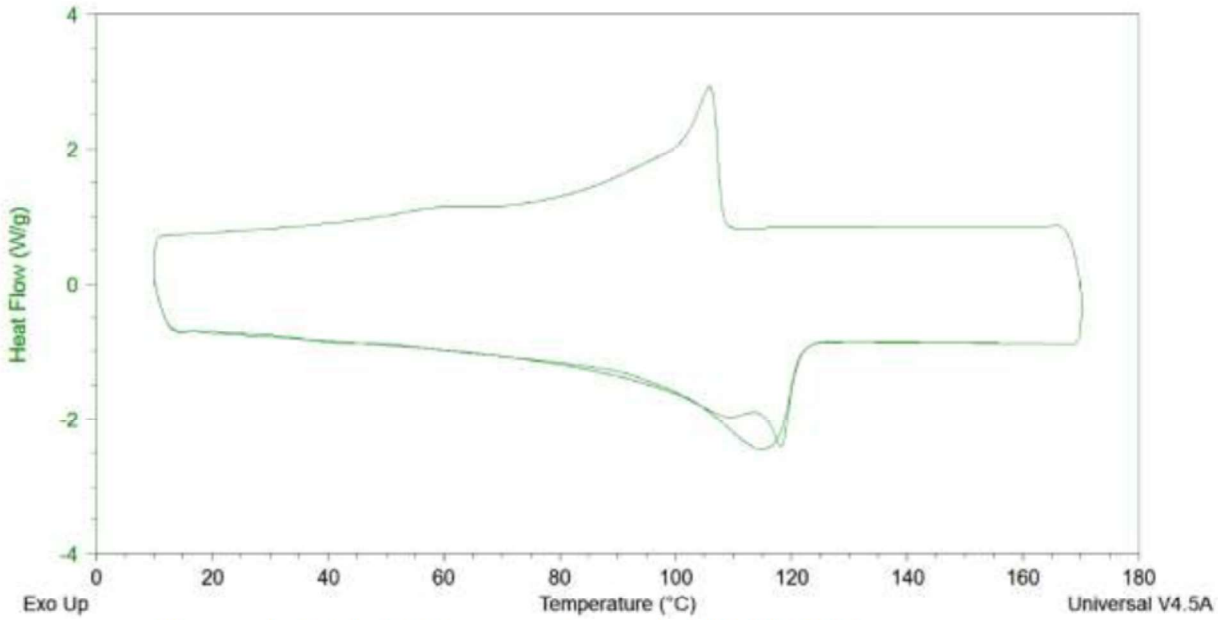


Figure 1: Triple DSC scan of sample VIC146-23A

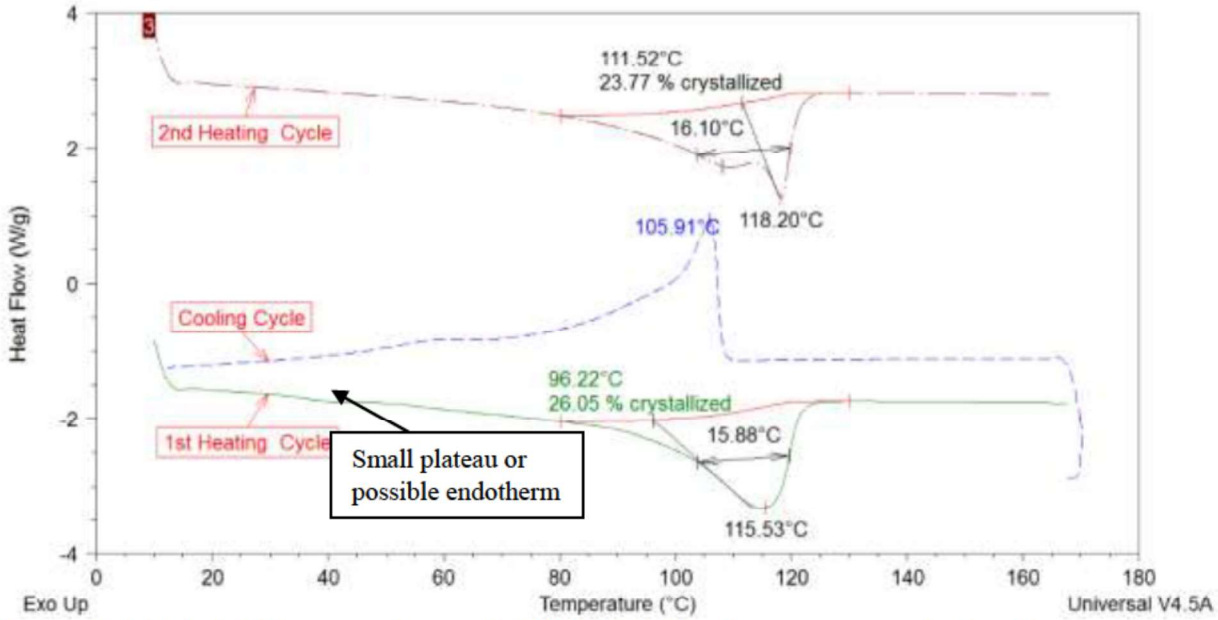


Figure 2: Triple DSC scan of sample VIC146-23A. Curves separated and analysed.

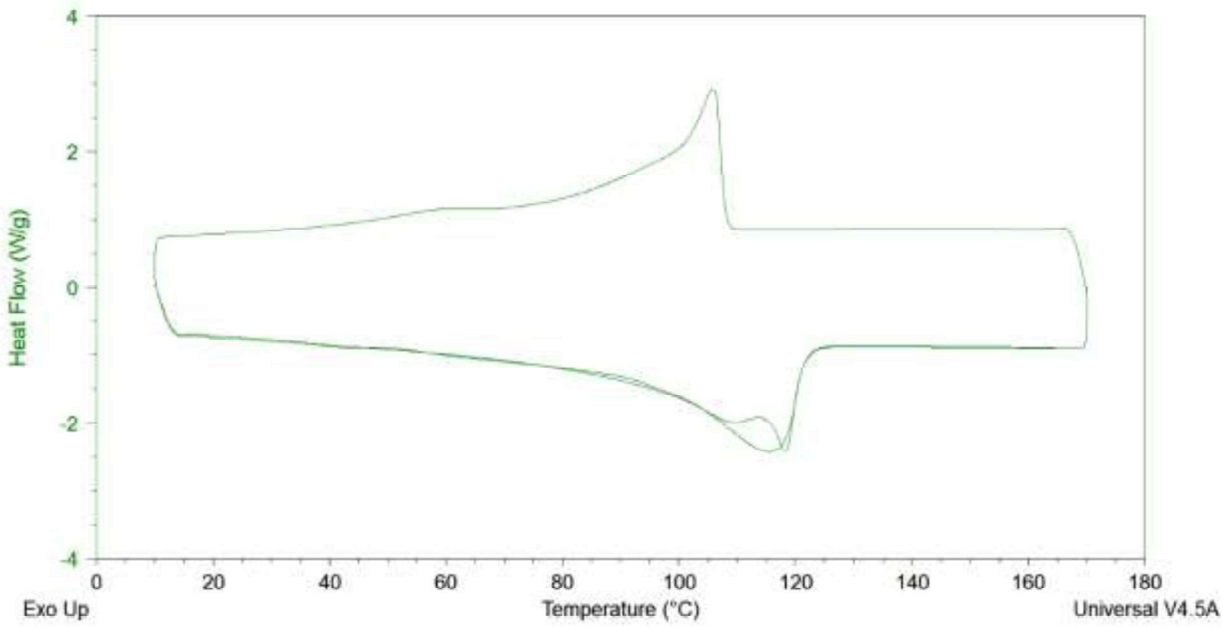


Figure 3: Triple DSC scan of sample VIC146-23C

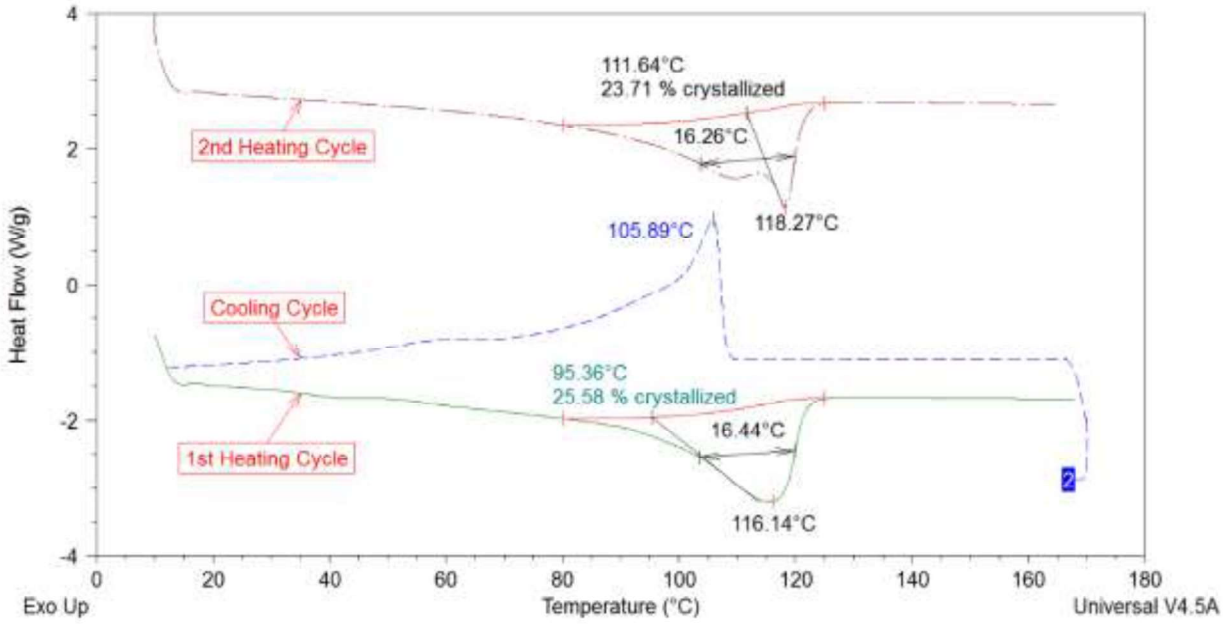


Figure 4: Triple DSC scan of sample VIC146-23C. Curves separated and analysed.

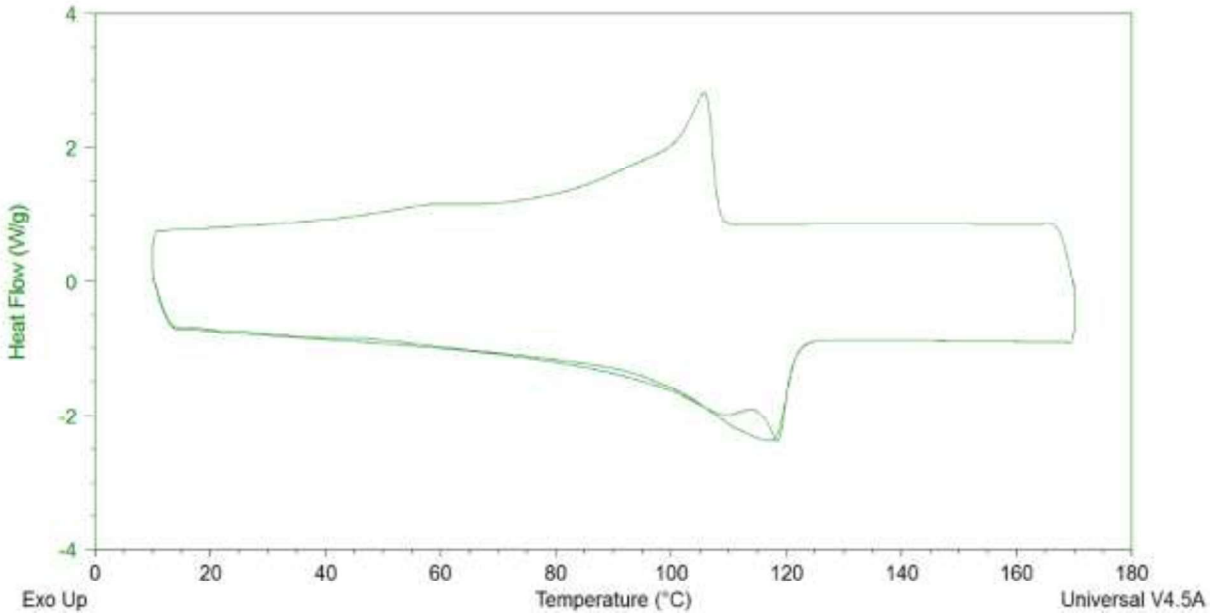


Figure 5: Triple DSC scan of sample VIC144-5

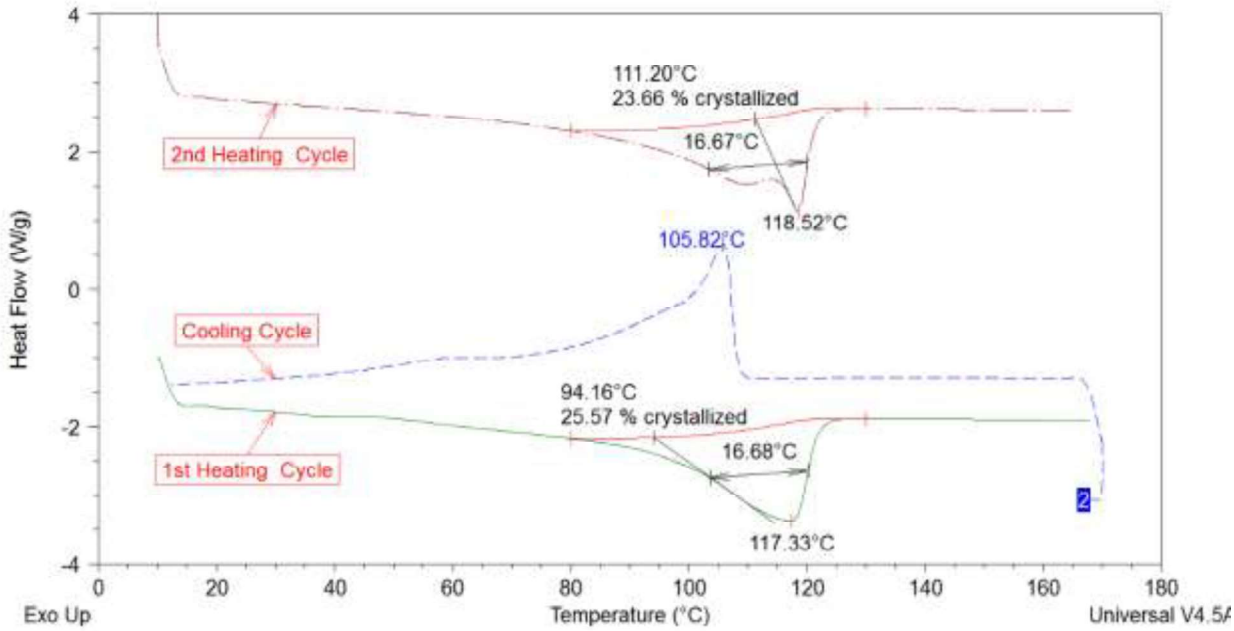


Figure 6: Triple DSC scan of sample VIC144-5. Curves separated and analysed.

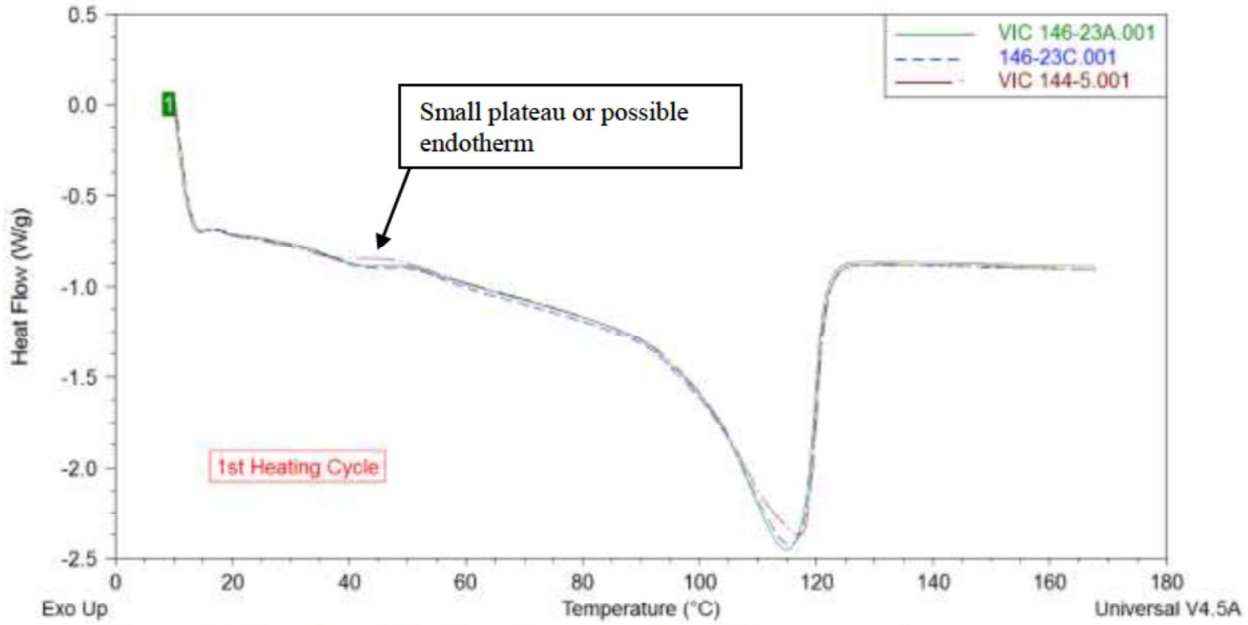


Figure 7: Overlay of first heating scan for all three samples.

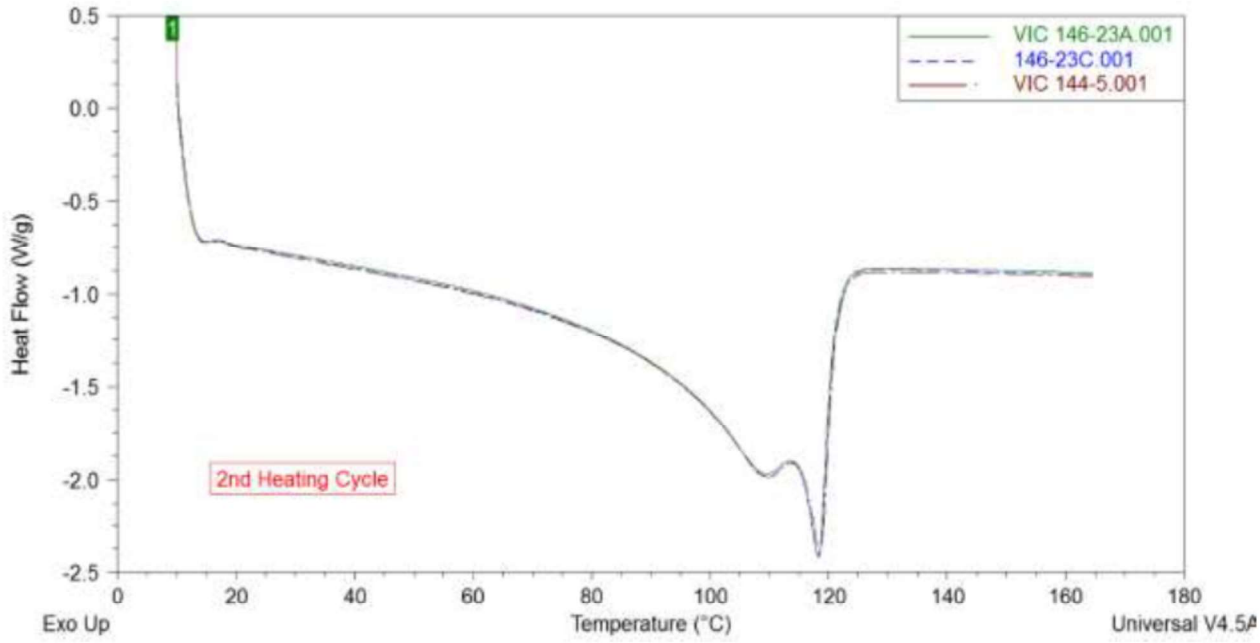


Figure 8: Overlay of second heating scan for all three samples.

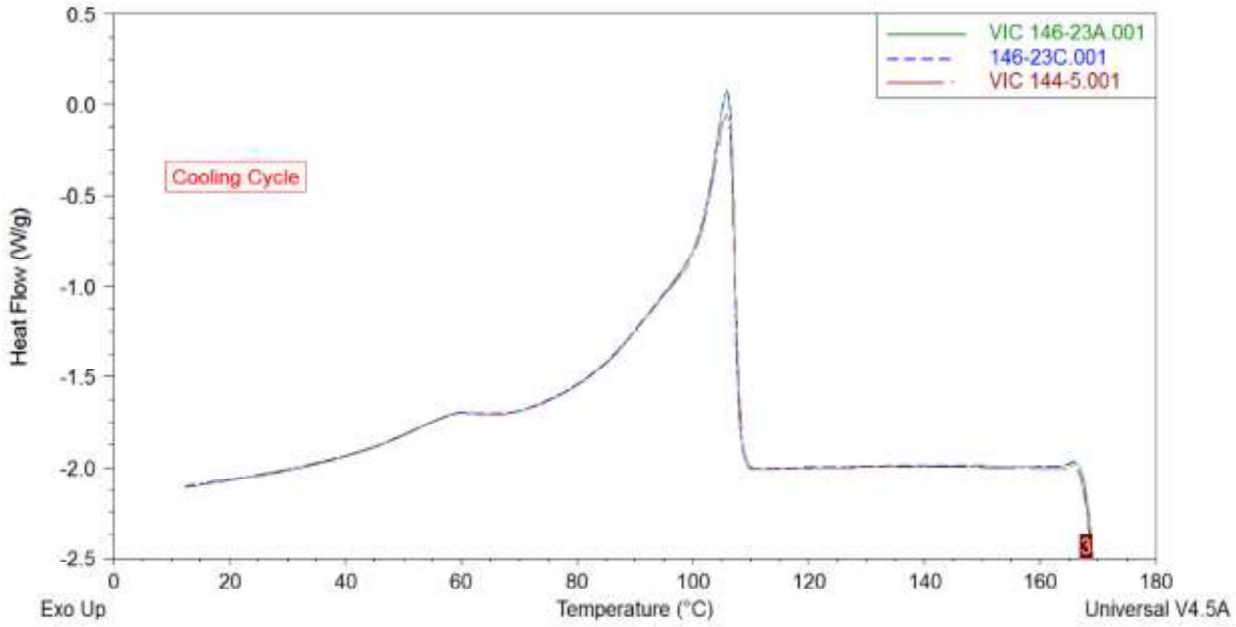


Figure 9: Overlay of controlled cooling scan for all three samples.

6. Discussion

Thermal Analysis (DSC) can be used to show the thermal history of some polymers like polyethylenes. As polyethylenes are semi-crystalline materials any thermal history i.e. exposure of the material to heat, results in a reordering of the crystalline phase resulting in a secondary melting peak. This secondary peak coincides with the actual exposure temperature. Hence any thermal history of the material should be visible in the melting envelope as a secondary peak.

The resulting scans did not show any significant secondary melting peaks and hence did not indicate any significant thermal history. However, in each curve there was a minor plateau region at around 40°C which did disappear on the second heat. This could be a very small endotherm indicative of thermal history up to around 40°C but due to the small size of this event it is not possible to state with any degree of certainty if this is a thermal history peak.

The samples analysed in this work were taken from either end of the fault region and also from a remote region. Hence they are deemed to be representative of the whole cable in these regions. The exact grade of polyethylene has not been specified so it is not possible to compare this with manufacturers data.

7. Conclusions

Three cable sheath samples have been analysed for thermal history using DSC. From this work the following conclusion can be made to date:

1. All three samples produced very similar melting curves with peak melting points around 115°C which is consistent with a LDPE or MDPE type polyethylene.
2. All three samples produced very similar initial crystallinities with values around 25-26%.
3. There was no evidence of significant secondary melting peaks which would indicate obvious thermal history.
4. There was a very small plateau region at around 40°C which could be a secondary melting event indicative of thermal history up to this temperature but due to the small nature of this transition it is not possible to state this with any degree of certainty.

Prepared by:



Signed:

Dated: 29th November 2016

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Report on Analysis of Samples From 400 kV Basslink Cable Fault

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Job No: G9748
Ref: \Datafiles\D\DLA Piper G9748\Reports\G9748 Report DLA Piper.doc
Date: 28th November 2016
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1. Excutive Summary

This report was commissioned by DLA Piper Australia to independently review various samples and components taken from a high voltage HVDC cable. The cable in question was a 400kV interconnector known as the Basslink Interconnector which failed on 20th December 2015.

Materials Technology ltd conducted a variety of inspections and further testing of selected samples taken from this cable including the lead sheath, polyethylene sheath and steel reinforcing tapes. As part of this work, Materials Technology also reviewed existing inspection reports produced by Cable Consulting International (CCI).

The key findings from this report are:

1. There is no evidence of material defects, repairs or poor quality manufacturing of the lead sheaths examined.
2. There was evidence of significant heat damage to the lead sheath. The North Bulge has significant heat damage with evidence of metal sputtering and temperatures in excess of 327°C and possibly higher.
3. There were extensive splits in the lead sheath of the North Bulge and one small split in the South Bulge.
4. There is evidence of significant thinning of the lead sheath in the North Bulge failure zone as a result of the failure.
5. The splitting of the lead sheath in this region is consistent with hot material being ejected from the inside of the cable i.e. the damage to the lead sheath is the result of the failure at the insulation layers and is not a pre-existing cause or defect in the sheath.
6. The chemical analysis of the lead sheath showed lower than expected levels of antimony and tin in the sheath.
7. Mechanical testing of steel reinforcing tapes from the reference section did not show anything unusual and the resulting break stress was in the expected region for a mild steel product but this has not been compared with any actual specification data.
8. The reinforcing tape breaks from the failed cable sample are all consistent with tensile type failures or tear failures or combinations of both. There is no evidence of fatigue related failures. There is no evidence to indicate the speed of these tape failures.
9. Some reinforcing tapes show evidence of movement caused by the failure which has resulted in both rucking and tearing of the reinforcing tapes. In the extreme cases this has resulted in the reinforcing tapes folding over .e.g. tape 16, and in other cases it has resulted in small tears e.g. reinforcing tapes 17 and 14.
10. There was no evidence of joins, welds or defects in the reinforcing tapes examined.
11. Reinforcing tapes 19b and 20b fracture faces did not match. There is evidence of a small missing section of reinforcing tape immediately over the North Bulge split. This may have been lost during dismantling as CCI photographic evidence indicates that it was present in the CESI inspection.

12. There was evidence of a 15mm wide butt gap in the steel reinforcing tapes immediately prior to the North Bulge caused by reinforcing tapes 19a and 19b being overlapped by about 10mm over a tape length of 400mm. This has also caused the damage of these tapes during dismantling. These tapes were probably in this position in service.
13. There was evidence of a 30mm wide gap in the steel reinforcing tapes over the South Bulge resulting in the armour wire indentations in the PE sheath in this region at time of failure. Evidence indicates that this was also probably like this at time of service.
14. There was significant evidence that the reinforcing tapes have seen temperatures in excess of 415°C (Zinc melting point) at the North Bulge during the fault and in isolated areas this may have been higher immediately over the splits at the North Bulge.
15. Tape witness marks on the PE sheath were more faint between the two failure zones (North and South Bulge) when compared to the remote reference section.

2. Introduction

The high voltage HVDC cable element of the Basslink Interconnector failed on 20th December 2015.

The section of cable containing the failure site was recovered from the seabed on 27th March 2016 and shipped to the Prysmian laboratory at CESI, Milan for an independent failure investigation.

CCI conducted the independent failure inspections in the presence of other representatives and their findings were reported in ER795 and ER808. Various samples from the failure site were then shipped back to CCI in the UK for continued inspection work.

Materials Technology Ltd were instructed by DLA Piper Australia to carry out some further analysis on various components of this cable (see letter of instruction appendix 1). This report details the additional investigations conducted by Materials Technology Ltd.

3. Methodology & Test Regime

At the request of the client, an initial visual inspection of the components was conducted using both naked eye and microscopy. This work was considered to be non-destructive. Following this initial inspection work, the client approved selected sampling and additional analysis work that resulted in some partial destruction of selected samples. Where possible, any sample residues were retained.

The programme of work included the following items:

1. Visual and microscopic inspection of all galvanised reinforcing tapes
2. Microscopic inspection of all tape fracture faces.
3. Visual and microscopic inspection of the lead sheath and related fractures and bulges.
4. Visual and microscopic inspection of the PE sheath.
5. Scanning Electron Microscopy (SEM) of selected lead sheath samples and tape fractures.
6. Tensile testing of reference steel reinforcing tapes from the remote sample 144.
7. Chemical analysis of lead sheath.
8. Metallurgical analysis of polished lead sheath specimens..

4. Definitions

The following definitions have been used in this report

Acronym	Description
CCI	Cable Consulting International
EDX / EDS	Energy-Dispersive X-ray Spectroscopy
Dia.	Diameter
GSW	Galvanised steel wire
HVDC	High voltage direct current
ICP-OES	Inductively coupled plasma, optical emission spectroscopy
kV	Kilo volts (1000 volts)
mm	Millimetre
MDPE	Medium Density Polyethylene
MI	Mass impregnated
MPa	Mega Pascals (N/mm^2)
MTL, MTech	Materials Technology Ltd
PE	Polyethylene
SEM	Scanning Electron Microscopy
TDC	Top dead centre
µm	Microns ($1/1000^{th}$ of mm)
UTS	Ultimate tensile strength

5. Samples

Under instruction of DLA Piper, CCI provided the following list of samples. All samples were hand delivered with a signed sample receipt sheet.

Table 2: Samples Supplied

Sample ID	Description
VIC-144/2	Two outer reinforcing tapes
VIC-144/3	Two inner reinforcing tapes
VIC-144/5	Black Polyethylene oversheath approx. 2m long
VIC-144/6	Lead sheath approx. 0.7m long
VIC-146/12	Steel reinforcing tape
VIC-146/13	Steel reinforcing tape
VIC-146/14	Steel reinforcing tape
VIC-146/15	Steel reinforcing tape
VIC-146/16	Steel reinforcing tape
VIC-146/17	Steel reinforcing tape
VIC-146/18	Steel reinforcing tape
VIC-146/19	Steel reinforcing tape
VIC-146/20	Steel reinforcing tape
VIC-146/21	Steel reinforcing tape
VIC-146/22	Steel reinforcing tape
VIC-146/23A	Black PE sheath approx. 500mm long
VIC-146/23B	Black PE sheath approx.. 1.5m long
VIC-146/23C	Black PE sheath approx. 500mm long
VIC-146/24	Lead Alloy Sheath
VIC-146/25	Lead Alloy Sheath
VIC-146/26	Lead Alloy Sheath
VIC-146/27	Lead Alloy Sheath approx. 1.5m long
VIC-146/28	Lead Alloy Sheath
VIC-146/29	Lead Alloy Sheath approx. 1m long

All reinforcing tapes were supplied in individual polyethylene bags with a unique sample reference. Each tape also had a tied label attached.

The lead sheath samples were supplied as long lengths individually wrapped in polyethylene and uniquely identified.

The PE sheath samples were supplied in boxes and sample idenfitication was written on their surface.

For the purpose of this report the CCI sample notation and orientation has been retained. Where additional sampling has taken place the CCI sample numbering has been retained and a suffix number added.

Table 3 details the additional samples taken by Materials Technology Ltd.

Table 3: Sample References of Additional Sampling by MTL

Sample ID	Description
VIC-146-12/1	2cm fracture end of tape 12 taken for SEM analysis. Cleaned with soap solution and water.
VIC-146-16/1	2cm fracture end of tape 16 taken for SEM analysis.
VIC-146-17/1	2cm fracture end of tape 17 taken for SEM analysis. Cleaned with soap solution and water
VIC-146-19B/1	2cm fracture end of tape 19 taken for SEM analysis.
VIC-146-27/1	Small section of lead sheath taken from remote region for chemical analysis
VIC-146-28/1	Small section of lead sheath taken from remote region for chemical analysis
VIC-146-29/1	Sample of lead sheath taken over split for SEM analysis of globules.
VIC-146-29/2	Sample of powdery residue recovered after removal of 146-29/1.
VIC-146-29/3	Additional sample of powdery residue recovered after removal of 146-29/1.
VIC-146-29/4	Lead sheath sample from over North Bulge away from split.
VIC-146-29/5	Lead sheath sample remote from North Bulge. Near to TDC
VIC-146-27/6	Lead sheath sample from over South Bulge.
VIC-144/2/1	Cut tape specimens for tensile testing at 10mm/min
VIC-144/2/2	Cut tape specimens for tensile testing at 200mm/min
VIC-144/3/1	Cut tape specimens for tensile testing at 10mm/min
VIC-144/3/2	Cut tape specimens for tensile testing at 200mm/min

6. Results

The results of the analysis of each component are detailed below.

Lead Sheath

Lead Sheath (North Bulge)

See Table 4, photos 1 through 23 for images relevant to this section. The North Bulge sample was identified as VIC-146/29 and consisted of a half tube section of the lead sheath removed from the cable. It was approximately 109.5cm in length and contained a large bulge with multiple splits (3), see photo 1. The approximate length of the affected region was around 12cm along the main axis of the cable. The splits had completely ruptured the lead. A score line had been applied to the lead sheath at 300mm from the North end indicating the 4.47m mark. This is post damage labelling by CCI.

The general condition of the lead remote from the failure region was considered to be good with no obvious manufacturing or material defects. The approximate thickness of the lead was in the region of 3 to 3.5mm. There was a clear impression of the woven binder tapes on the inside of the lead along its entire length. The impressions did not indicate any significant issues with the tape lay or application immediately below the lead.

The external surface of the lead showed some extrusion witness lines but it was generally considered to be smooth and of normal consistency remote from the failure region. The extrusion lines did not indicate any discontinuities or possible repairs or infills.

The failure region consisted of a large bulge and 3 large splits within the lead sheath. The splits were random splits generally aligned along the main axis of the cable which is consistent with splitting and tearing from circumferential stress (hoop stress). The split areas showed evidence of significant thinning of the lead in this region (see photo 3). Approximate measurements indicate at least down to 1.4mm but near the split edges this is probably lower. However, it is not possible to accurately measure these without further damaging the samples.

The split regions showed evidence of significant heat damage during the fault condition. There was evidence of molten lead immediately in the region of the splits with metal sputter sitting on the surfaces close to the edges (see photo 6). This indicates that localised temperatures have been in excess of 327°C (melting point of lead) and probably significantly higher to produce sputtering of the metal. The general areas around the splits also showed further heat damage with evidence of partial reflow of the metal.

The external surface of the lead showed some staining and the edge of the staining shows some porous nature to the lead (see photo 3). This is consistent with hot gases or liquids exiting the lead sheath and condensing on the surfaces immediately around the failure region and causing localised melting or attack.

There was also evidence of some reddish / rust coloured globules on the exterior surface around the splits. These were more isolated but may be the result of molten steel or copper from the subsurface layers. SEM analysis was conducted on these globules and is reported later in this report.

On the inner surface there is evidence of woven binder tape residue which appears partially degraded and stuck to the lead (see photo 16). This also indicates very high localised temperatures and probably in excess of 400°C during the fault condition to produce this sort of effect.

Within the splits these was a small textile fibre residue and what appeared to be a paper residue (see photo 5 &17). Both of these are consistent with material being ejected from within the cable.

The exterior surface of the lead showed the remains of the extrusion witness lines but there was some general “orange peel” texture to the surface of the lead within the bulge area. This has resulted from the localised heating and deformation within this region giving rise to slightly different crystal structure on the surface in these regions. A small sample was taken from this region and subjected to micro-section analysis to confirm this. The surface of the sheath in this region was also inspected with SEM. See SEM section later for results.

The edges of the splits are generally heat damaged and the edges of the lead are well rounded due to the heat from the fault condition destroying most of the fracture face evidence. However, close to the ends of the split it is possible to see some of the fracture face with a microscope. This fracture face is consistent with a tear type fracture rather than any fatigue. Sampling of the lead sheath in the split region for SEM analysis did not uncover any additional evidence in relation to the fracture faces but further debris was found under this section of lead and was retained for SEM analysis.

There is no evidence to indicate pre-existing faults in this region of the lead sheath and there is no evidence to indicate the speed with which the bulge or the cracks occurred. However, the significant evidence of localised heat damage, thinning of the lead and tear type splits indicates that this probably occurred over a relatively short period of time and probably occurred as a single explosive event. See latter section for results on metal microstructure analysis.

Lead Sheath (South Bulge)

See Table 4 for images relevant to this section. The South Bulge sample was identified as sample VIC-146/27 and was approximately 149.5cm long. At approximately 100cm from the north end of the sample there was a 7cm long bulge and a significant fold within the lead. Some oily residue was present on the inside and outside of the lead in this region and there was evidence of an amber oily residue within the folds of the lead.

At the North Bulge location on this sample there was a small area of woven binder tape adhered to the lead surface, probably due to heat damage during the fault, and there was molten lead globules on the edge of the specimen. This section of the sample aligns with the North Bulge region and is further evidence of the high temperatures around the North Bulge (see photo 9). The remaining inner surface of this specimen appeared free of other adherents and the tape indentations were clearly visible along the entire length of the lead sheath. Close to the fold there was a small zone of the binder tape impressions that showed a slightly different witness pattern with a large gap in the weave indicating a possible joint or discontinuity at this location (See photo 12).

The exterior surface of the lead in the South Bulge region also showed some “orange peel” texture to the surface and under the microscope this appeared to be a more pronounced crystal structure (see photo 22). This is probably

due to combination of heat and mechanical deformation in this region. A sample was taken from this region for micro-section analysis. See section on polished microsections later in this report.

It was not possible to measure the lead thickness in this region due to the folding of the lead but it did not appear as thinned as the North Bulge. There was evidence of a small split in the folded region of the lead sheath but this was only visible under optical microscope (see photo 11). Hence the staining of the sheath in this region could have resulted from loss of MI compound from this split and is probably the result of the collaps of this bulge.

There is no evidence to indicate the growth rate of this bulge and no evidence of any significant heating such as molten lead so temperatures were probably below 327°C in this region.

In the absence of additional evidence the fold within the lead sheath in this location is consistent with a large blister (probably resulting from internal pressure or hot vapours) that has subsequently collapsed in on itself.

Table 4: Photographic Evidence



Photo 1: North Bulge and splits in lead sheath. Note general heat damage to surrounding areas.



Photo 2: Inside surface of North Bulge Area around splits shows significant heat damage.

Table 4: Photographic Evidence

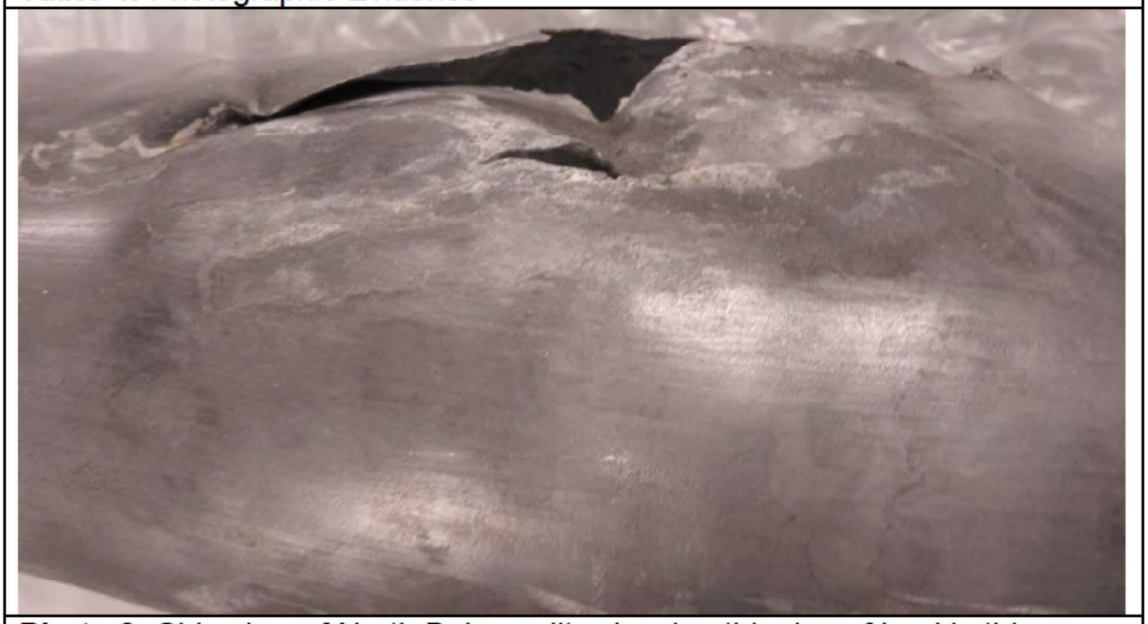


Photo 3: Side view of North Bulge splits showing thinning of lead in this region. Note also surface staining of lead around splits from residue.



Photo 4: General view of North Bulge surface showing slight orange peel texture.

Table 4: Photographic Evidence

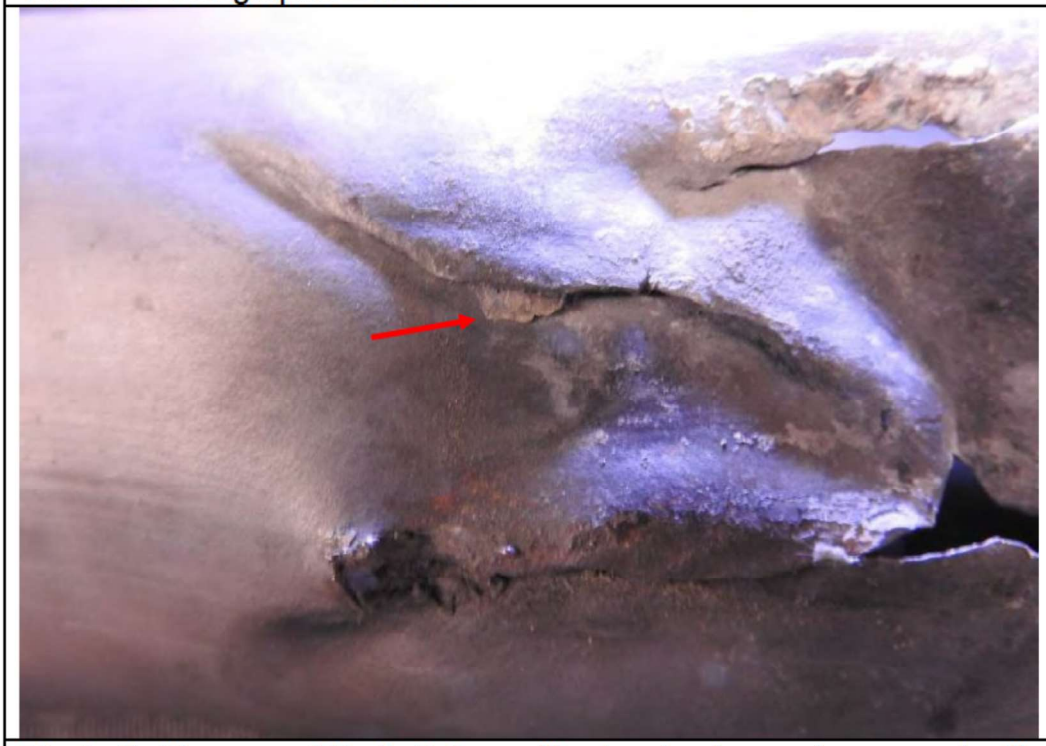


Photo 5: Close up of North Bulge splits showing trapped paper or textile within split.

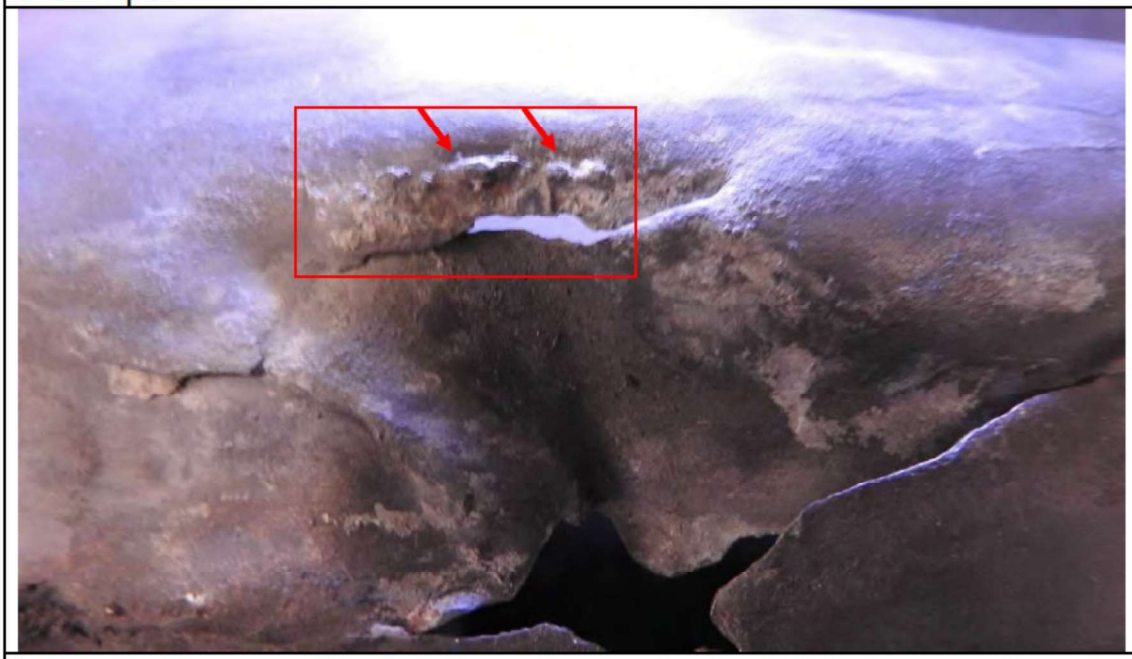


Photo 6: Close up of North Bulge splits showing lead globules on surface of sheath. Evidence of molten lead and temperatures in excess of 327°C. Red box indicates sample area taken for SEM analysis.

Table 4: Photographic Evidence

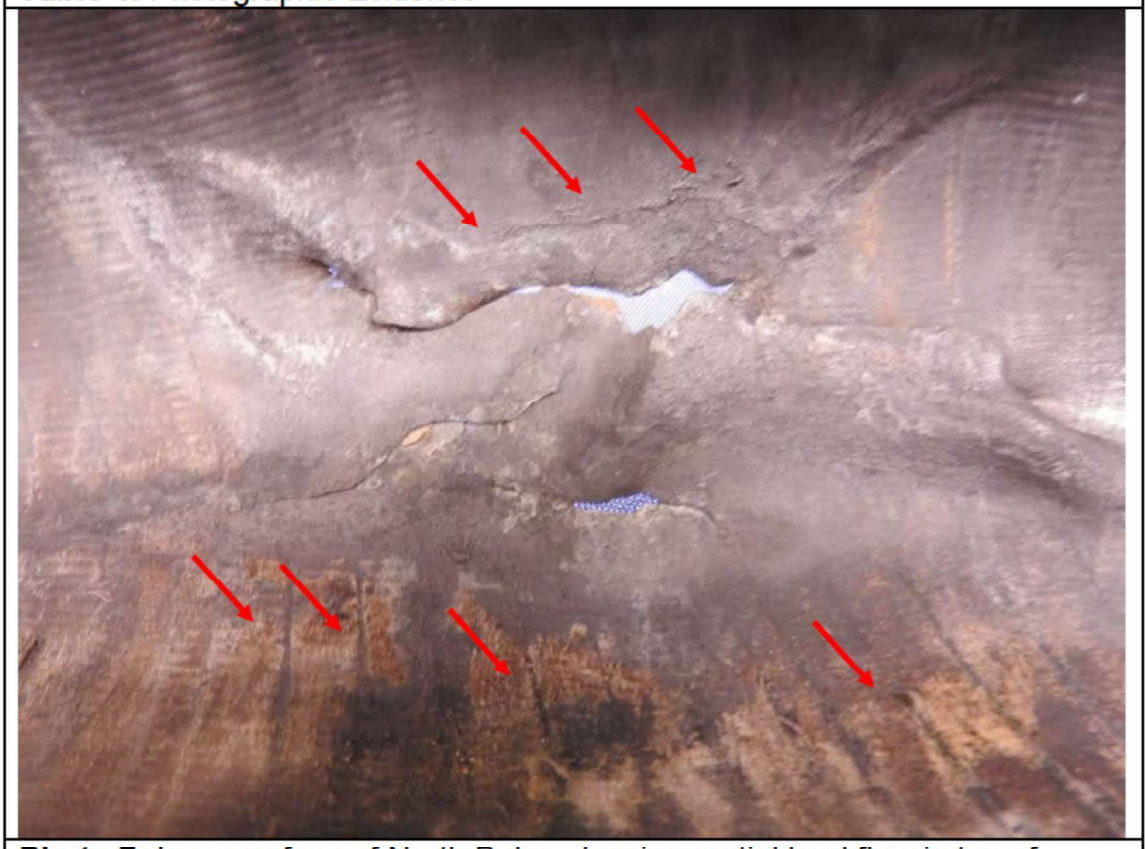


Photo 7: Inner surface of North Bulge showing partial lead flow in top of image and adhesion of woven binder tapes to lead surface in lower part of image. Woven tapes appear partially degraded indicating localised temperatures in excess of 400C for the tapes.



Photo 8: Inside surface of South Bulge showing witness patterns of woven binder tapes and folding of lead in this region. Consistent with a large blister forming.

Table 4: Photographic Evidence

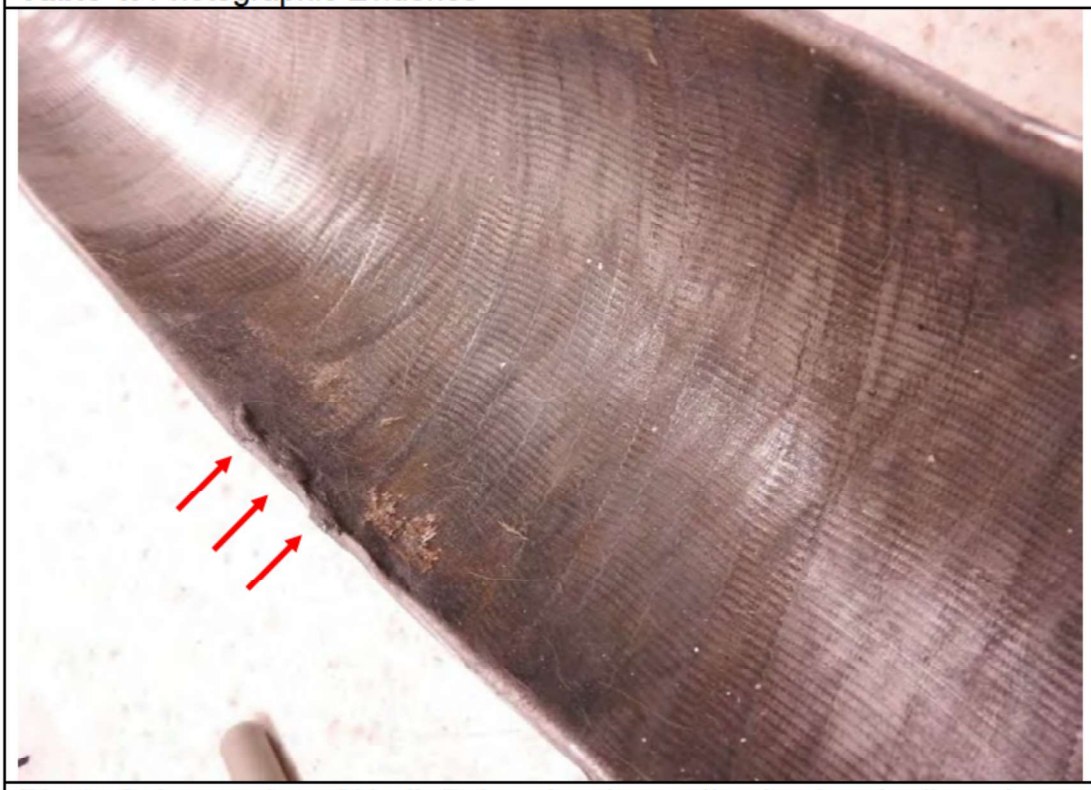


Photo 9: Inner edge of North Bulge showing molten lead and adhered woven tape indicating high temperatures in this region.

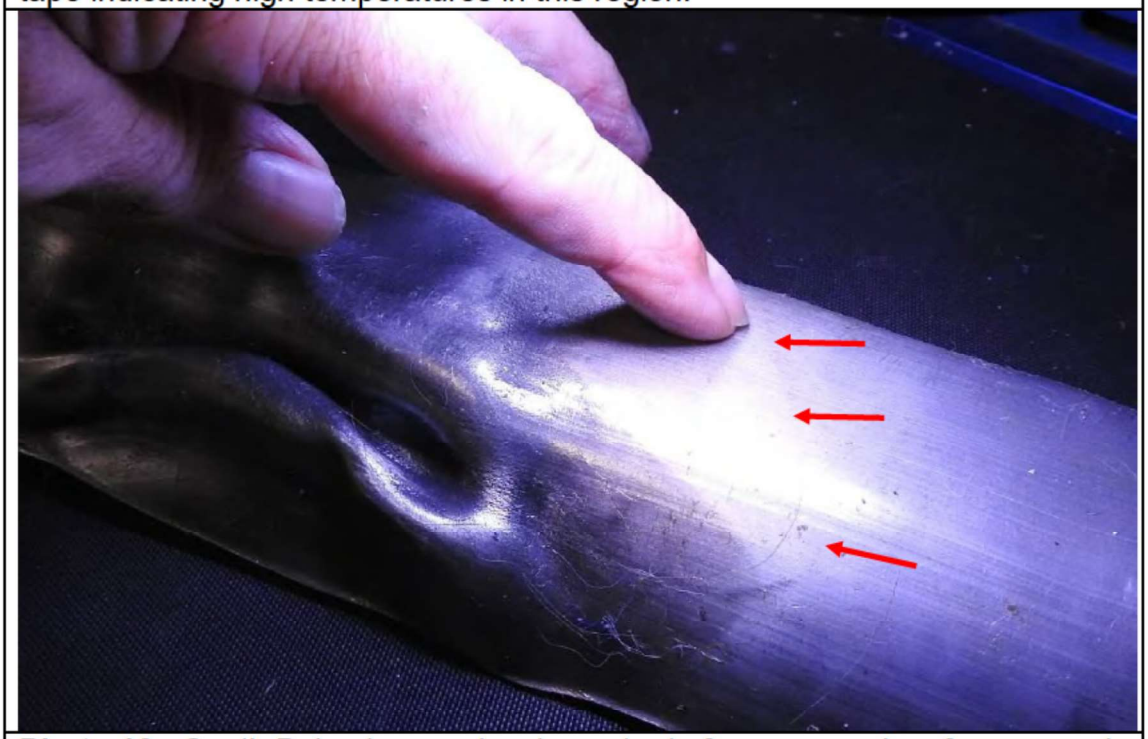


Photo 10 : South Bulge image showing extent of orange peel surface around fold.

Table 4: Photographic Evidence

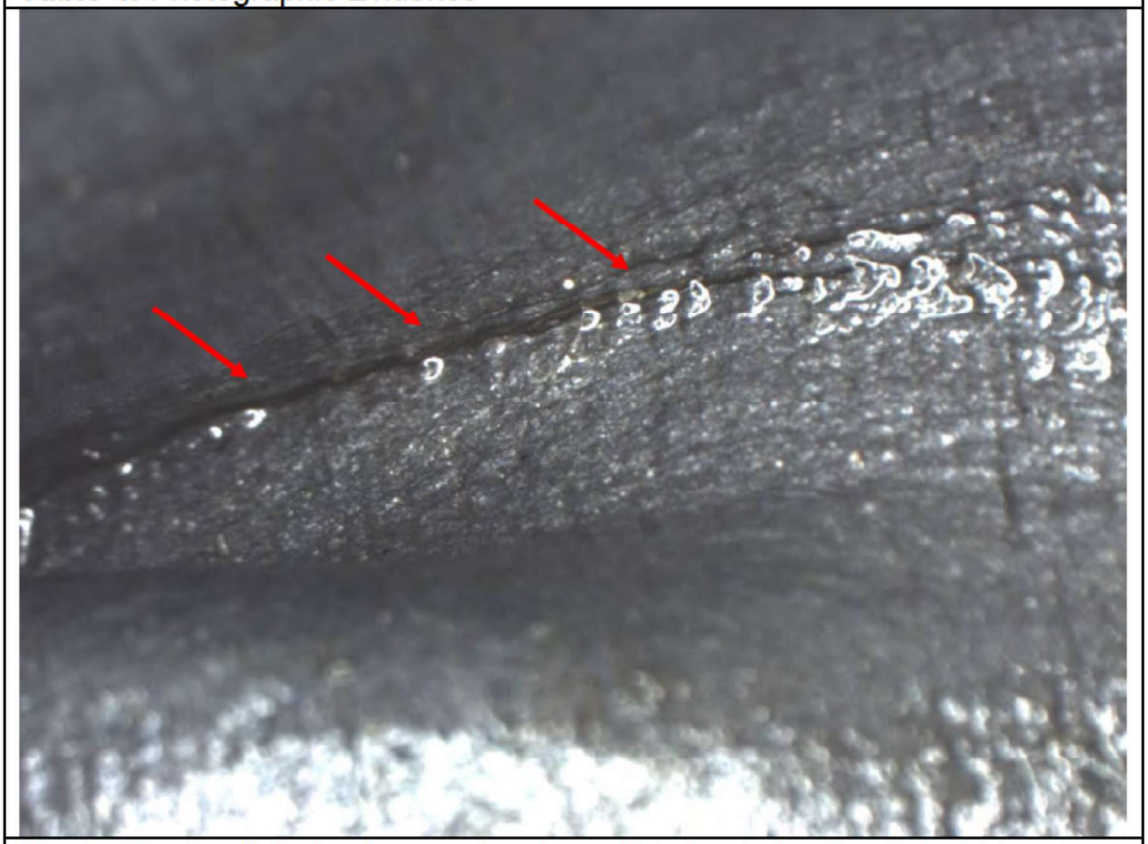


Photo 11 : South Bulge image showing split in lead sheath within fold region.

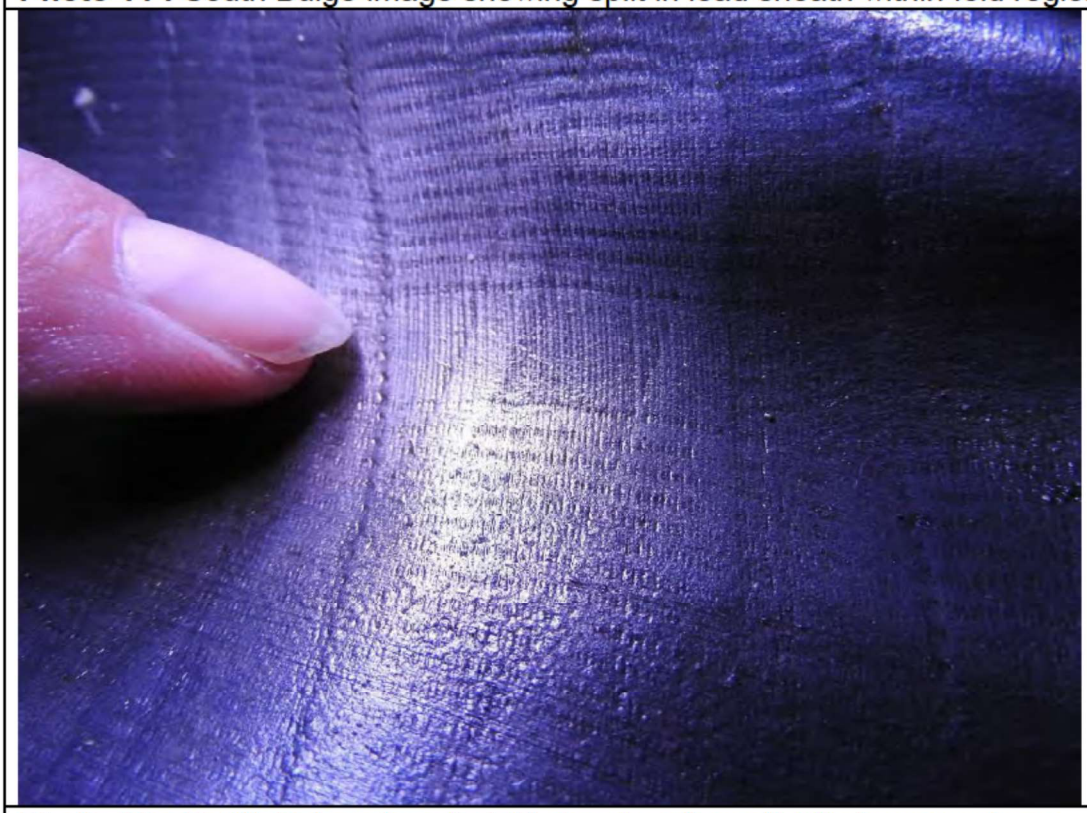


Photo 12 : South Bulge close to fold showing discontinuity in woven tape.

Table 4: Photographic Evidence

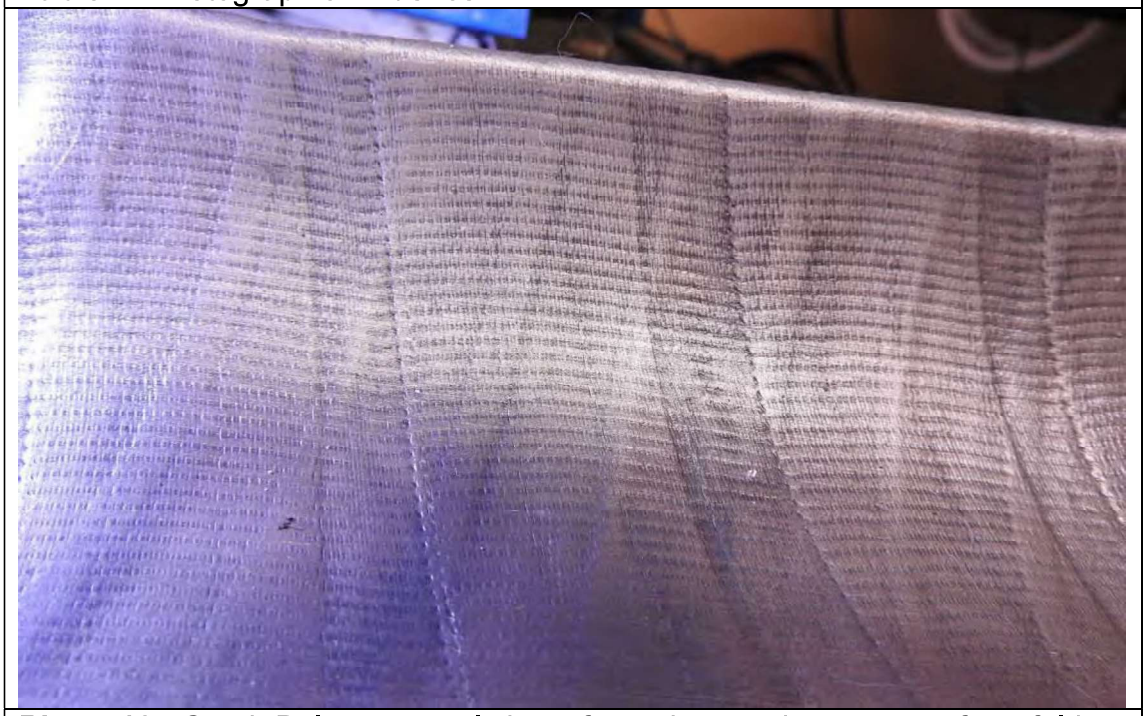


Photo 13 : South Bulge, general view of tape impressions remote from fold showing even weave to tapes.



Photo 14: North Bulge, close up view under optical microscope of inner surface of lead showing evidence of molten surface due to reflow of lead indicating high localised temperatures during fault.

Table 4: Photographic Evidence



Photo 15: North Bulge, close up view under optical microscope of inner surface of lead showing molten globules of lead.



Photo 16: North Bulge, close up view under optical microscope of inner surface of lead showing woven binder tape adhered to surface of lead and screen wire (arrows) embedded in lead due to heat from the cable fault.

Table 4: Photographic Evidence



Photo 17: North Bulge, close up view under optical microscope of inner surface of lead showing textile fibre trapped within split.

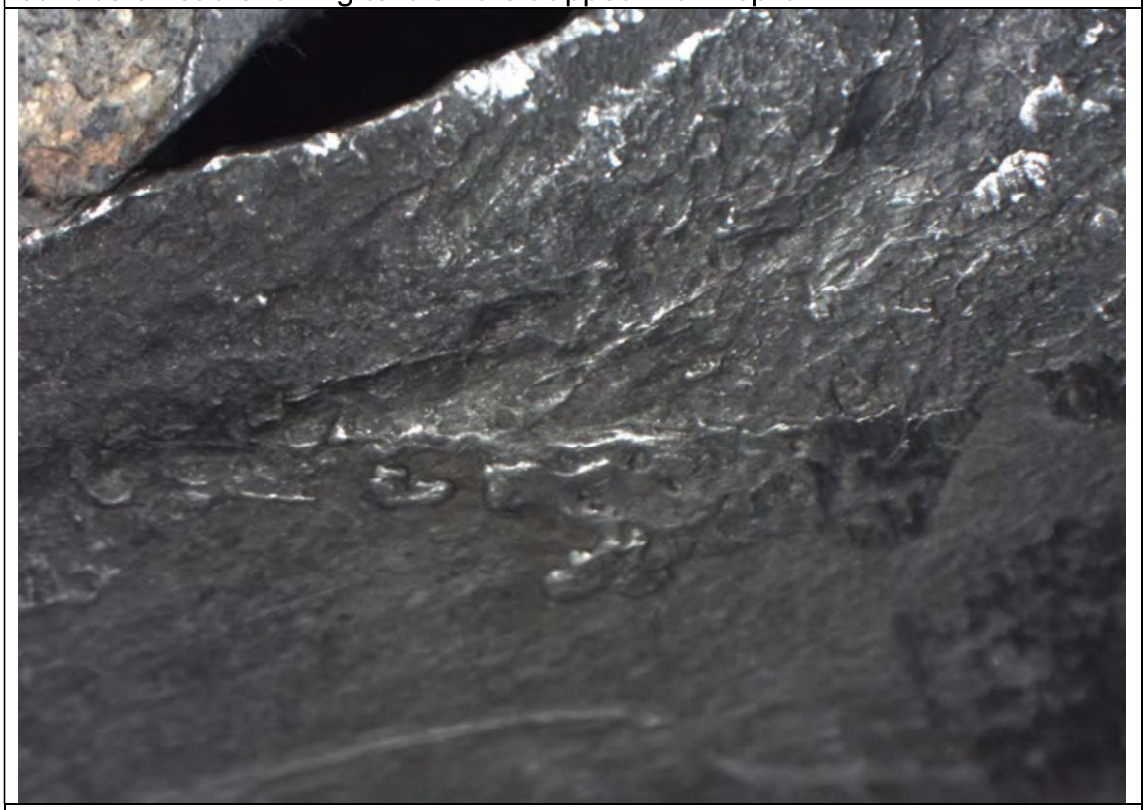


Photo 18: North Bulge, close up view under optical microscope of split surface of lead showing residue of molten surface of lead indicating high temperatures.

Table 4: Photographic Evidence



Photo 19: North Bulge, close up view under optical microscope of split surface of lead showing metal globules, lead and possible iron or copper in centre of image. Analysed further under SEM section later in this report.



Photo 20: North Bulge, close up view under optical microscope of split surface of lead showing paper inclusion within split.

Table 4: Photographic Evidence

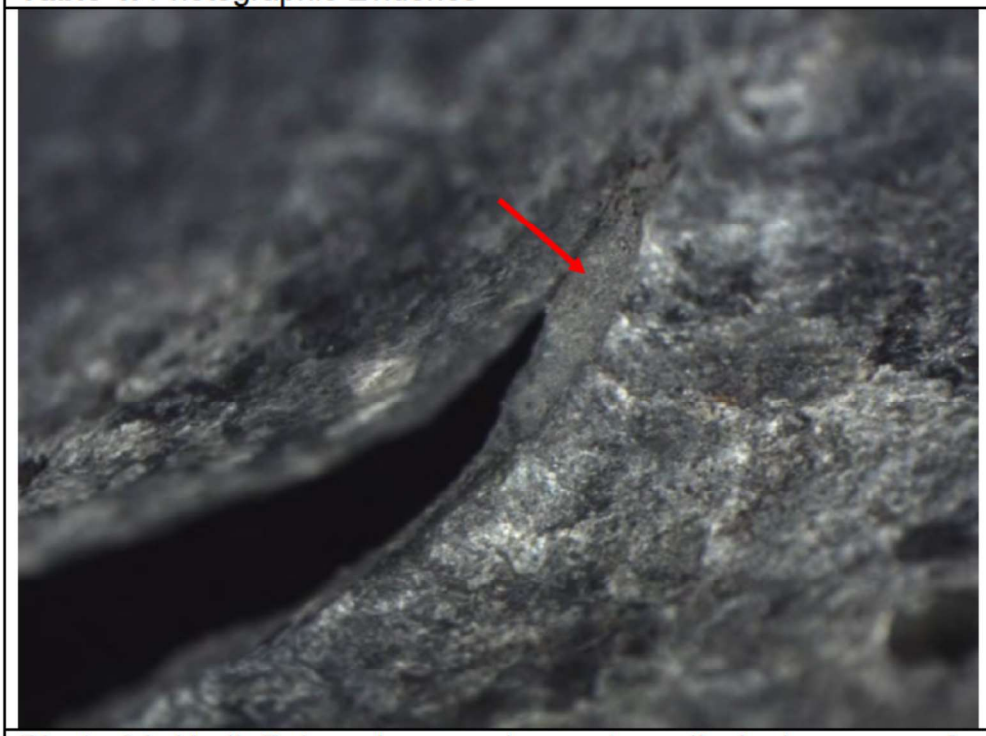


Photo 21: North Bulge, close up view under optical microscope of split fracture face at end of fracture showing fracture to be tear type fracture.

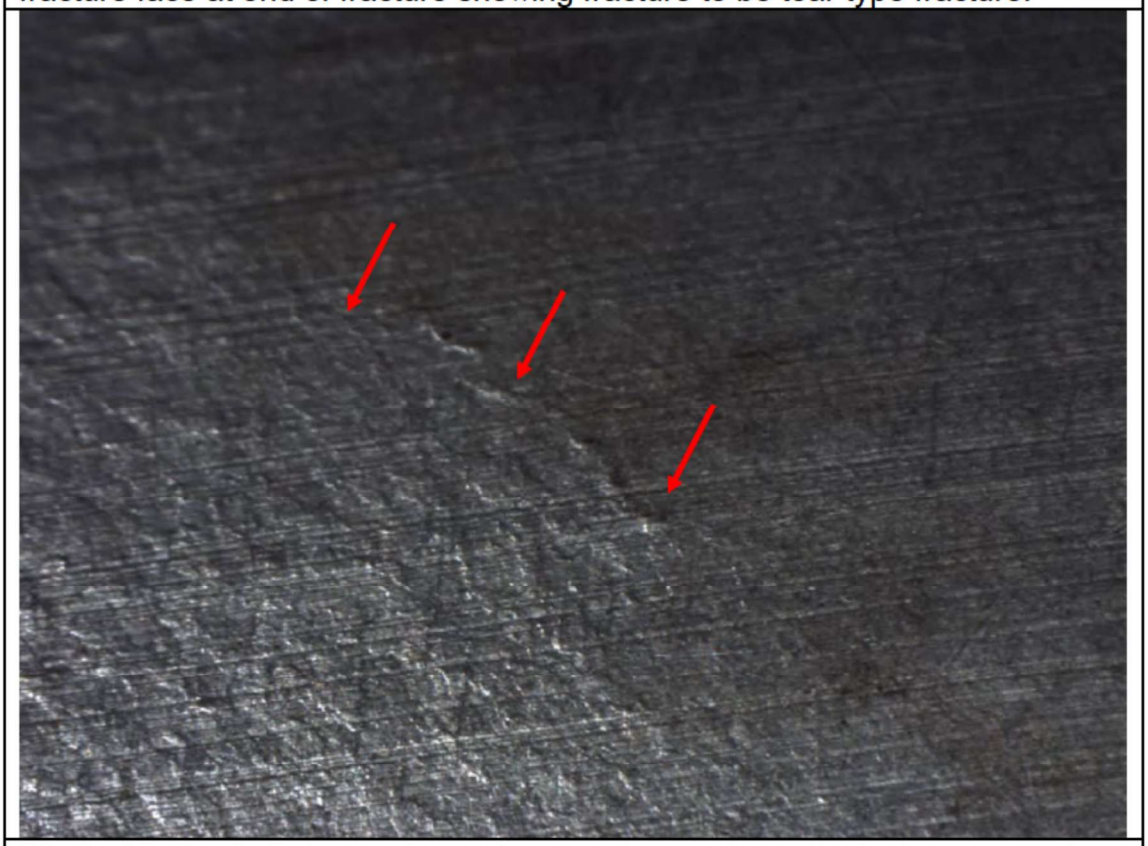


Photo 22: South Bulge surface, close up view under optical microscope of surface showing orange peel texture.

Table 4: Photographic Evidence

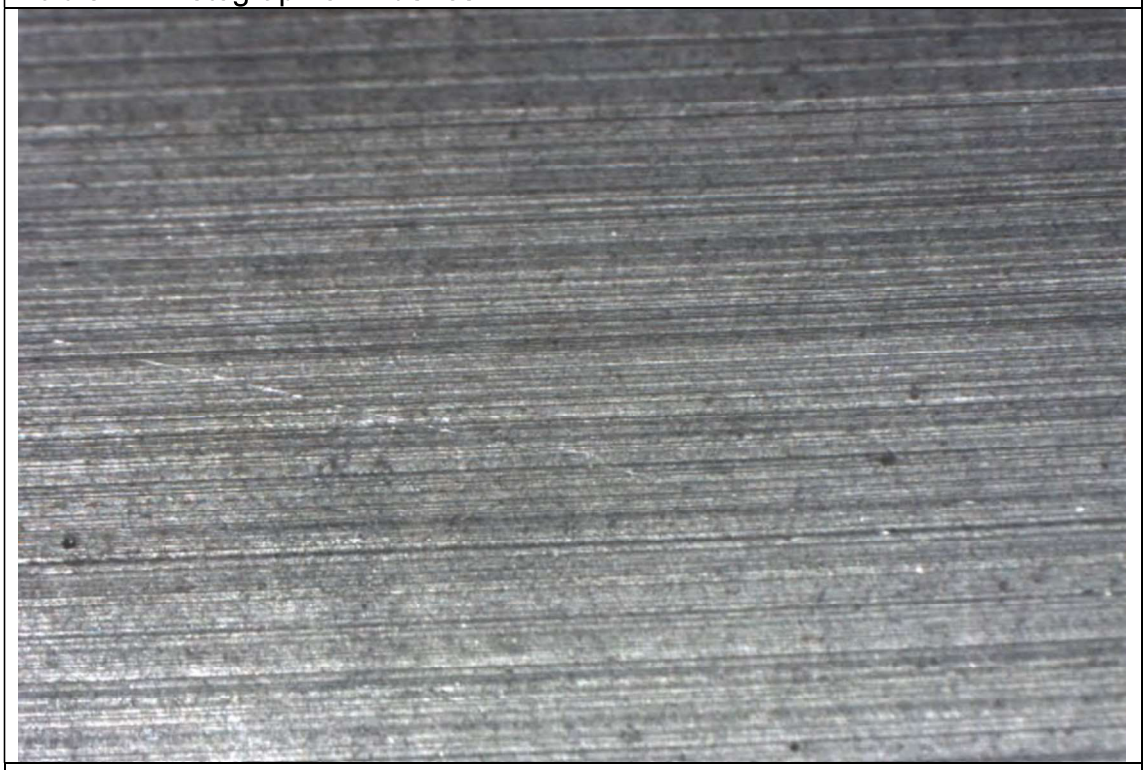


Photo 23: South Bulge, close up view under optical microscope of surface remote from bulge. Surface smooth and extrusion witness marks visible.

Steel Reinforcing tapes

The steel tapes were inspected along their entire length and particular attention was given to the fracture faces and any defects. Images were recorded digitally and observations are summarized below in Table 5. Outer tapes are shaded in grey in table 5. Tape locations are shown figures 3 & 4.

Most of the reinforcing tapes and particularly the two external tapes showed evidence of corrosion product or some white rusting consistent with corrosion due to seawater exposure. The reinforcing tapes were speckled with some red rust product but this was not considered to be gross corrosion considering their age of 10-11 years. Some localized corrosion was more extensive due to the combined effects of heat damage during the fault and removal of the zinc protective coating. Overall the reinforcement tapes were considered to be in good general condition.

Table 5: Tape Observations

Sample ID	Description
VIC-146/12	Tear type failure and some wrinkling of tape immediately next to failure region. Some edge rucking of tape and deformation consistent with rucking. Fracture matches tape 13 fracture face.
VIC-146/13	Tear type failure. Some sideways deformation of tape. One fracture matches tape 12 and the other end matches tape 14.
VIC-146/14	Tear type failure with matching face to sample 13. Small split in edge of tape. Other end of tape fracture matches tape 15. Witness marks on edge of tape match tape 17 witness marks.
VIC-146/15	Some blistering of zinc galvanising (cause not known). Two small splits in fracture edge which are possibly screwdriver damage during dismantling. Remainder of fracture is probably tensile type failure. Fracture matches other end of tape 14. Some transverse rucks in tape and some edge rucks.
VIC-146/16	Tear type failure and some wrinkling of tape. A large fold in tape edge. Some deformation of tape edges either side of fold. Some bitumen evident within folds therefore has probably occurred post cable damage. Fracture a good match to tape 17 fracture.
VIC-146/17	Tensile and Tear failure of tape that matches sample 18 and the other end matches tape 16. Some wrinkles in tape consistent with deformation of tape. Fracture is consistent with tearing. Partial split in middle of tape length i.e. partial tear.
VIC-146/18	Tear type failure. Some blistering evident to zinc galvanizing (cause not known) and some transverse wrinkles in tape. A good match to tape 17.
VIC-146/19a	Tensile failure indicated at one end. Fracture has good match to tape 20C. Tape tapers at other end i.e. cut end of tape. Edges of tape were turned up and deformed and in process of folding over. This appears to be the result of dismantling and caused by tape 19b being under 19a during removal.
VIC-146/19b	Heavy corrosion & some heat damage on fractured end of tape. Some loss of galvanizing and some evidence of molten metal, probably steel. Indicates very high temperature exposure close to fracture. Evidence of tape being underlapped with tape 19a, clear witness mark of approximately 10mm over a tape length of about 400mm. Tear on edge of tape probably caused during dismantling of tape when pulled free

Sample ID	Description
	from 19a. Some rucking of tape. Fracture does not match any samples.
VIC-146/20a	One end of tape slightly wrinkled with a tensile type failure. Tape matches 20C fracture. Other end of tape had a combination of tensile and tear type failure and matched tape 20d. Significant deformation of tape at failure.
VIC-146/20b	Localised heat damage, melting of galvanizing, tensile and tear failure. Some sideways deformation of tape. One end has a good match to tape 21 fracture but other end does not match remaining samples.
VIC-146/20c	Fracture indicates tensile failure at one end and tear at the other end. A central ruck within the tape. Fracture matches tape 20A with similar ruck. Other end has a good match to tape 19a.
VIC-146/20d	Localised blistering of galvanizing evident (cause not known). Tensile failure of tape. One end of tape has good match to tape 20A, other end matches tape 22.
VIC-146/21	Large galvanizing crystals evident at point of failure. Some buckling and wrinkling of tape edges. Generally heavy corrosion along length of tape. Fracture face indicates tensile mode failure. Heavy rucking of tape at edges. Fracture has good match to tape 20b.
VIC-146/22	Blistering of Zinc galvanising evident (cause not known). Probably tensile and tear combination failure. Fracture is a good match to tape 20d.

The majority of the tape evidence indicates that they have failed in a either a tensile or tear manner or a combination of these failure modes. There was no evidence for fatigue type failures. Tensile failures will occur if a significant hoop stress is applied to the tape taking it to its breaking point. This typically results in a straight fracture face perpendicular to the applied stress and necking of the material within the fracture region.

Tear type failures will occur if the reinforcing tapes are twisted or deformed from their original lay position or the tensile stress is applied non uniformly. This will also result in the edge rucking observed on some of the reinforcing tapes where the excess material accumulates. Hence tearing will be initiated on one side of the tape and rucking of the tape will initiate on the opposite side of the tape. Tear fracture faces tend to be less linear and have a knife edge appearance to their fracture faces. Figure 1 below shows a schematic representation of these two failure modes.

Figure 2 shows a schematic representation of the relative positions of each tape portion. The results of the initial tape analysis demonstrated two key findings:

1. The fold in tape 16 is consistent with post fault damage but this required the tape fold to be opened up to confirm this.
2. The fracture face of tape 19b did not match the fracture face of tape 20b and indicated either a tape overlap or a missing piece of tape at this location. This aspect was investigated further below.

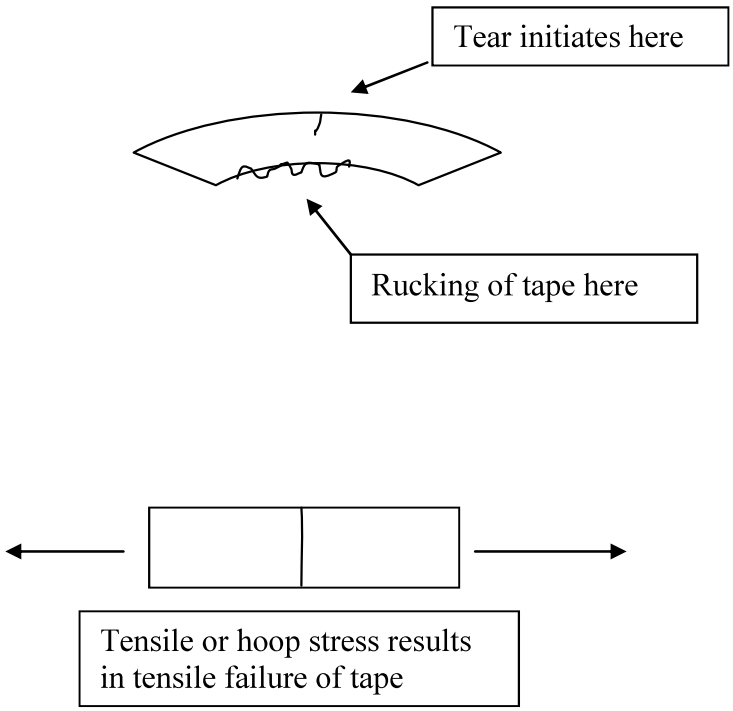


Figure 1: Schematic showing typical tape deformations and resulting tear or tensile failures.

Additional photographic evidence is shown below in Table 6.

Figure 3 below shows a schematic representation of the relative tape positions and key features of interest. The upper image shows the relative positon of the inner reinforcing tapes and the lower image shows the relative position of the outer reinforcing tapes. The images are not intended to be to scale and are for reference purposes only.

Figure 4 shows the key measurements taken from the north end of the PE sheath.

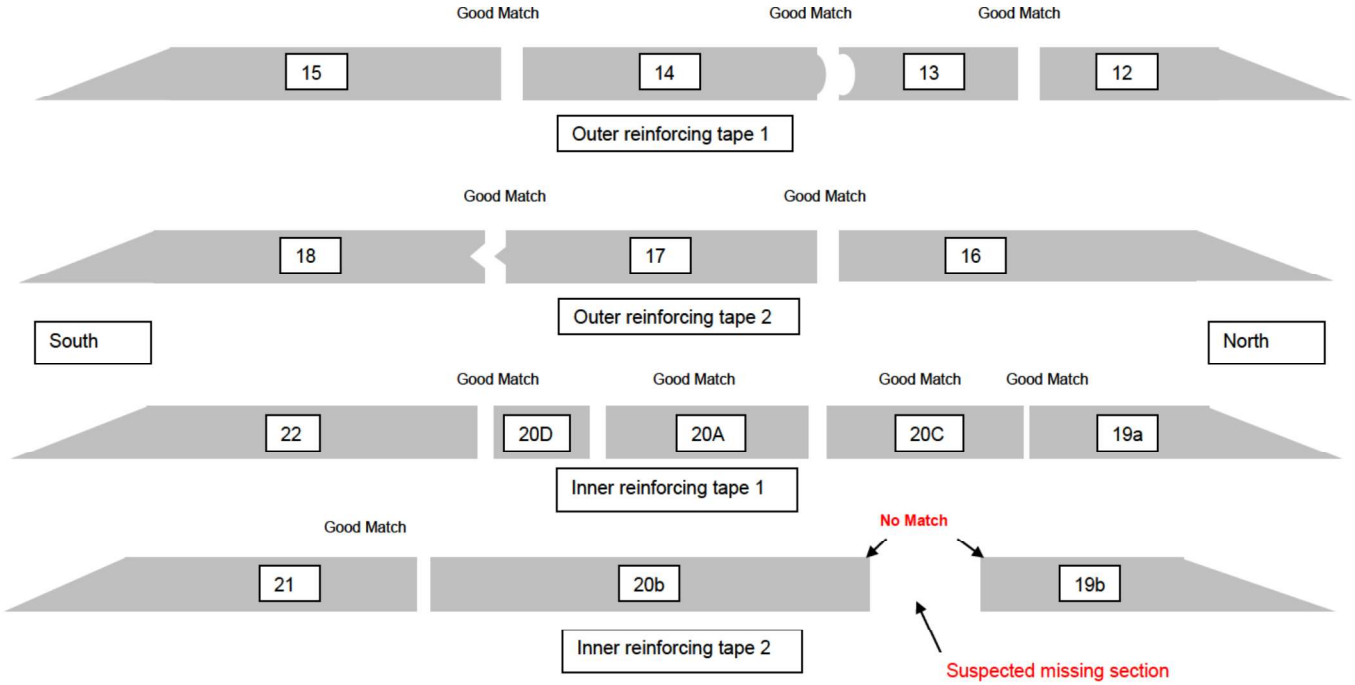


Figure 2: Schematic view showing relative position of tape fracture sections. Reinforcing tapes consist of two inner and two outer reinforcing tapes.

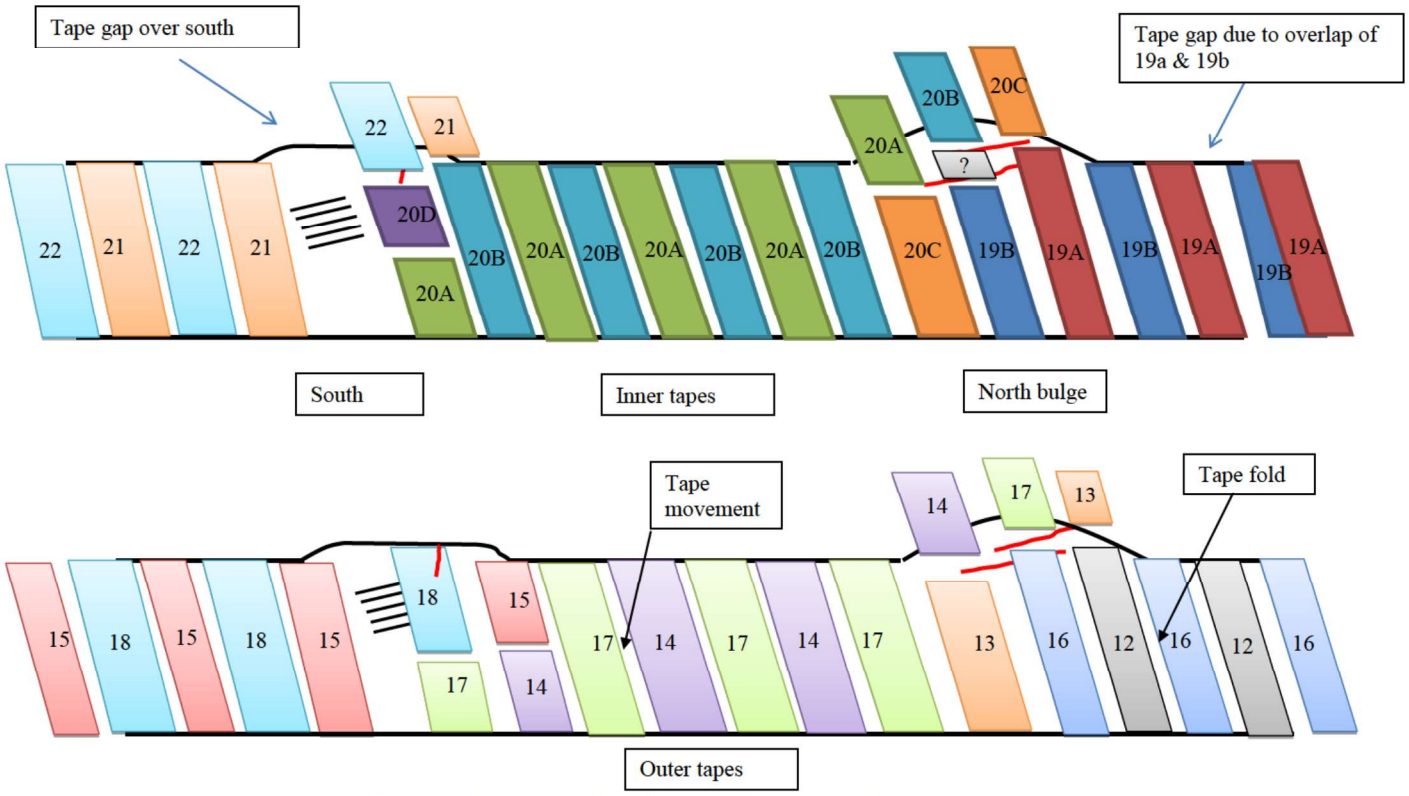


Figure 3: Schematic view of tape numbers and relative positions

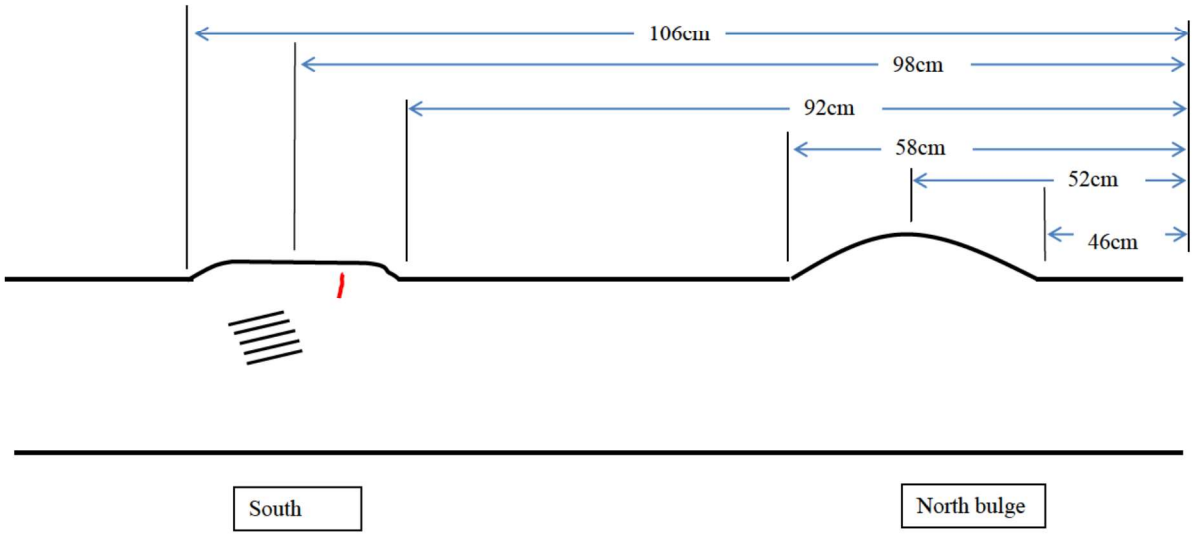


Figure 4: Schematic view of PE sheath showing key measurements

Table 6: Photographs of Tape Features



Photo 24: Tape VIC-146/20C showing typical tear type fracture. Note non linear fracture face.



Photo 25: Tape VIC-146/12 showing typical wrinkling / rucking on one edge of tape.

Table 6: Photographs of Tape Features



Photo 26: Tape VIC-146/12 showing typical transverse deformation of tape.



Photo 27: Tape VIC-146/13 and 14 showing matching tear fractures

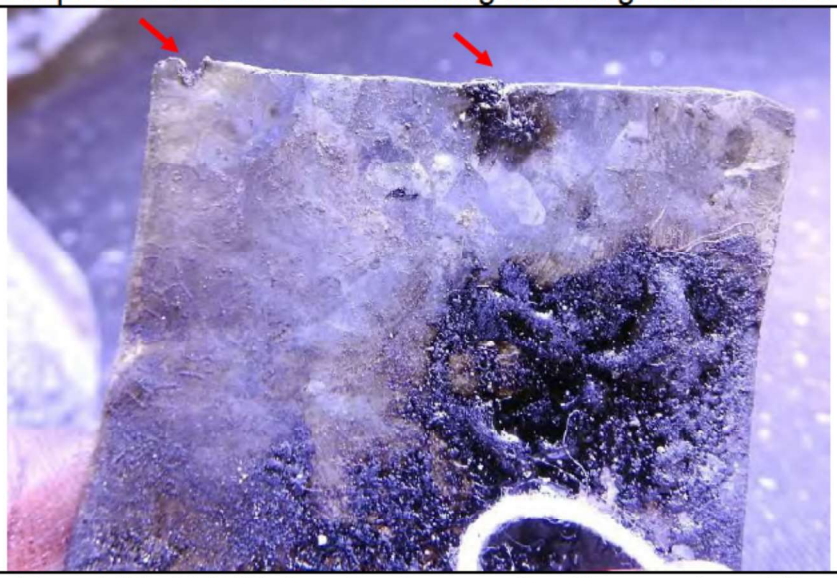


Photo 28: Tape VIC-146/15 showing two small splits on edge of fracture face. Crystal structure of zinc is also visible on surface.

Table 6: Photographs of Tape Features

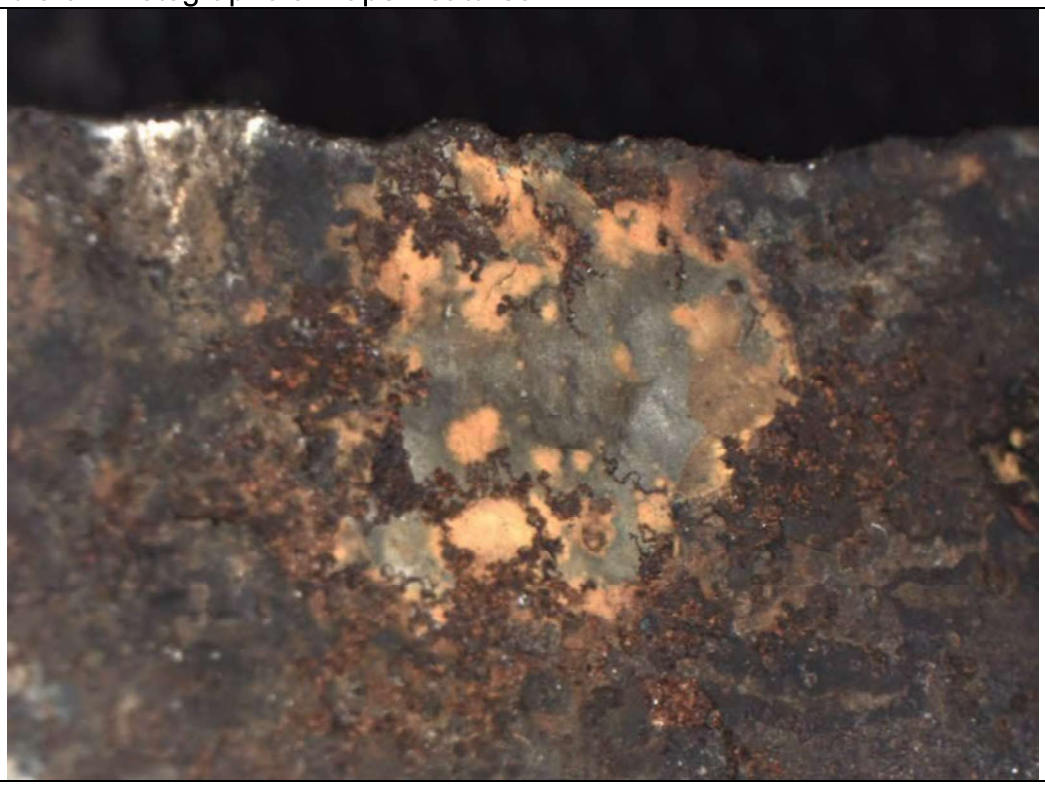


Photo 29: Tape VIC-146/19b example of extensive corrosion and loss of zinc coating in this region probably due to localised heating from the cable fault. Temperatures in excess of 415°C (Zinc melting) during the cable fault.

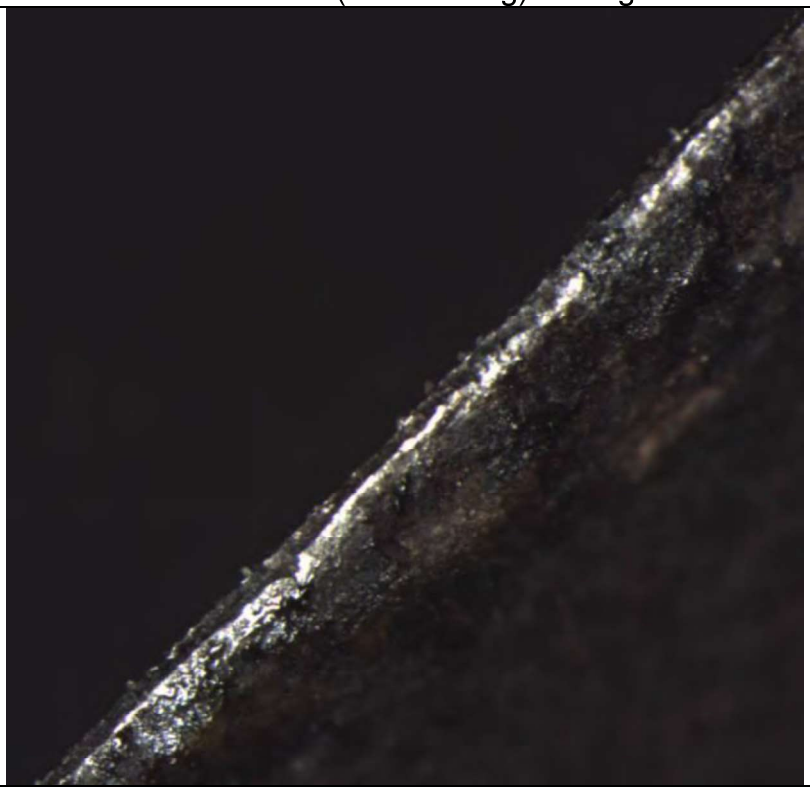


Photo 30: Tape VIC-146/20b example of close up of tape fracture face showing tensile type failure. Necked fracture face.

Table 6: Photographs of Tape Features



Photo 31: Tape VIC-146/20d fracturing of zinc coating close to fracture edge indicating tensile failure.

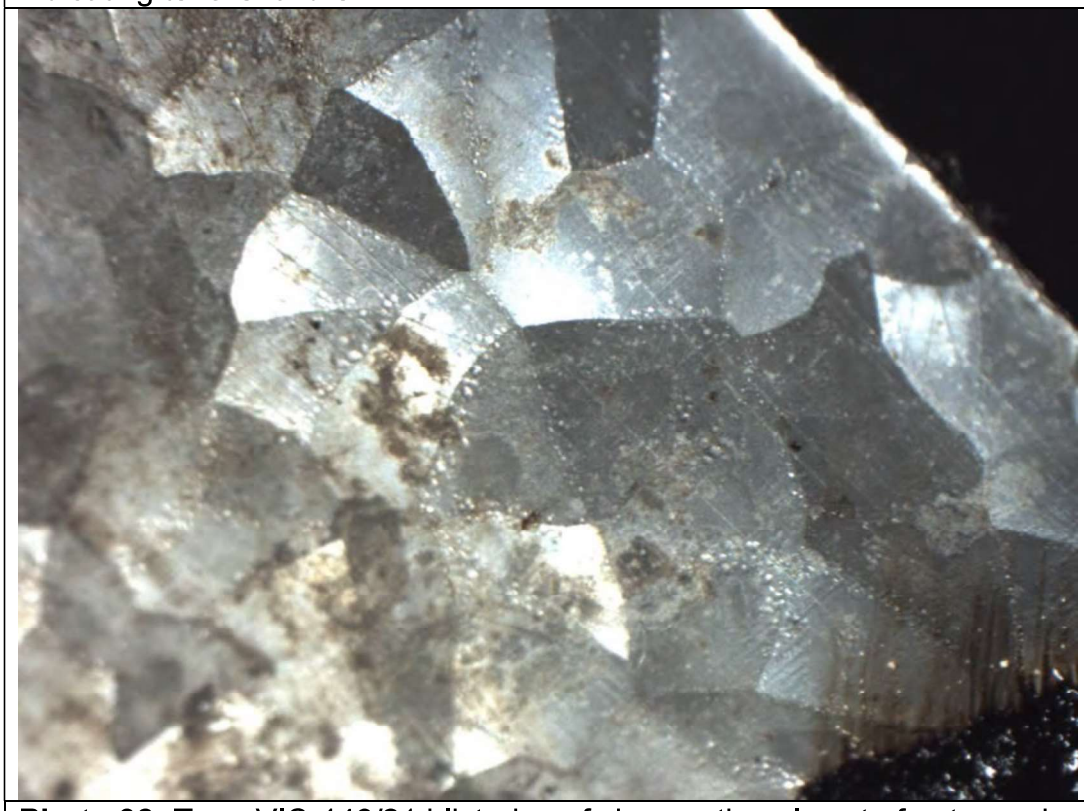


Photo 32: Tape VIC-146/21 blistering of zinc coating close to fracture edge (cause not known).

Table 6: Photographs of Tape Features



Photo 33: Tape VIC-146/19b, tear in tape edge caused by pinching of tape at overlap with 19a. 10mm witness mark evident at top of image along tape.



Photo 34: Tape 146/14 and 17 showing pattern match of reinforcing tapes, corrosion and bitumen indicating original position of reinforcing tapes.



Photo 35: Tape VIC-146/14 and 17 showing pattern match of reinforcing tapes, corrosion and bitumen indicating original position of tapes.

Table 6: Photographs of Tape Features



Photo 36: Tape VIC-146/14 and 17 showing pattern match of reinforcing tapes, corrosion and bitumen indicating original position of tapes.



Photo 37: Tape VIC-146/14 and 17 showing pattern match of tapes, corrosion and bitumen indicating original position of tapes.



Photo 38: Tape VIC-146/14 and 17 showing pattern match of reinforcing tapes. Note black regions where tapes show signs of overlapping (arrowed). Patterns indicate this is post damage movement. Note also small split in edge of tape 14 caused by movement of tape 17.

Table 6: Photographs of Tape Features



Photo 39: Tape VIC-146/14 and 17 showing position post failure. Note tapes interlock due to small tear on tape 14. Black edges overlap. Tape 17 has been pushed back during the cable fault resulting in final tear of tape and rucking of tape edges.

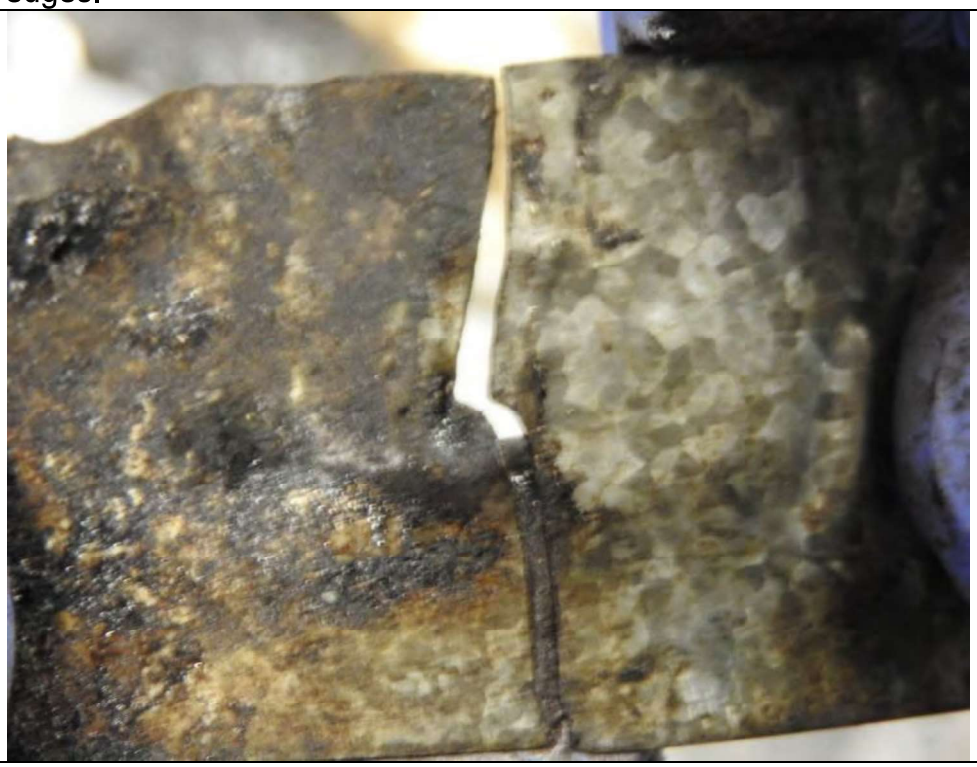


Photo 40: Tape VIC-146/17 fracture join with tape 18 showing tear which has probably initiated on bottom of image and travelled towards top of image due to movement of tape away from bulge.

Tape 16 Further Investigation

The fold in tape 16 was photographed and then gently prised open to reveal the inner surface of the tape. This demonstrated that the inner surfaces were bitumised and heavily oxidized which was consistent with the unfolded areas of the tape. This indicates that the folding of the tape occurred after the initial cable damage.

The tape immediately next to tape 16 was tape 12. This tape shows significant deformation and rucking in the immediate area of the tape 16 fold. This, together with the witness marks shows that the fold in tape 16 occurred as a result of the movement of tape 12 impinging on the edge of tape 16 and resulting in folding.

Table 7: Photographic Evidence – Tape 16



Photo 41: Tape VIC-146/16 (top surface) showing folded edge and non-linear orientation of tape. Fold contains evidence of bitumen. Evidence consistent with fold occurring after damage to cable due to sliding movement of tape causing rucking followed by folding.



Photo 42: Tape VIC-146/16 showing fold (bottom surface). Note location of tape overlap marks on edge of tape.

Table 7: Photographic Evidence – Tape 16



Photo 43: Tape VIC-146/16 showing fold opened up (top surface)



Photo 44: Tape VIC-146/16 showing fold opened up (bottom surface)

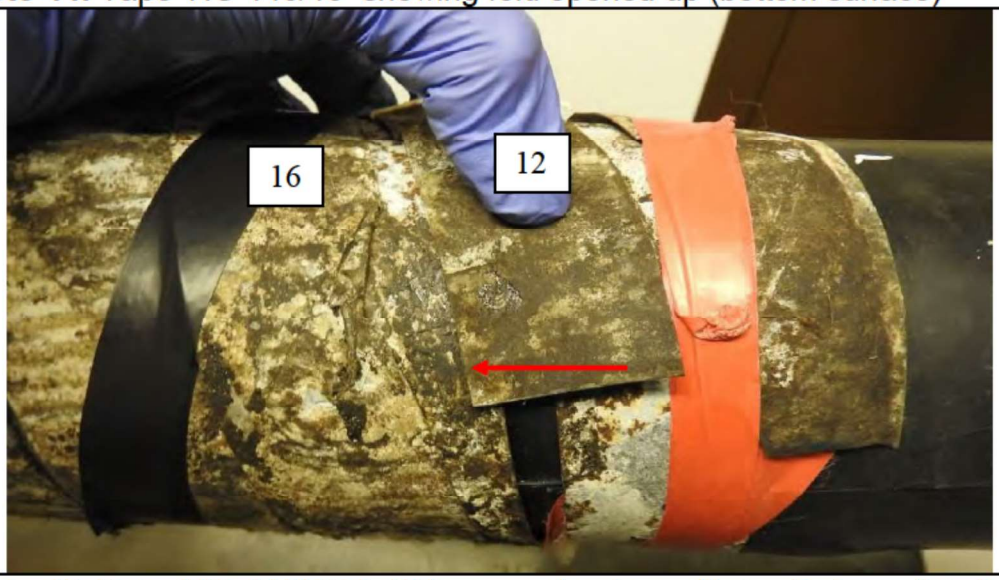


Photo 45: Tape VIC-146/16 & 12 in approximate positions. Deformation & movement of tape 12 has caused fold. Arrow indicates movement of tape 12.

Table 7: Photographic Evidence – Tape 16



Photo 46: Tape VIC-146/16 & 12 in approximate positions showing movement of tape 12 which has caused rucking of tape 12 edge and fold on tape 16.



Photo 47: Tape VIC-146/12 (left) & 16 (right) with fold opened showing similar levels of corrosion and staining.

Table 7: Photographic Evidence – Tape 16



Photo 48: Tape VIC-146/12 (right) & 16 (left) with fold opened showing inner surface witness marks and bitumised area under fold.

Tape VIC-146/17 & 14

Tape 14 showed evidence of a small split in the edge of the tape. There were also witness marks around this section of the tape which indicates that tape 17 had impinged on tape 14 causing the split. This is approximately 160mm from the fractured end of tape 14 and just prior to the South Bulge. The witness marks indicate that this is a post failure event i.e. tape 17 has moved away from the South Bulge towards tape 14.

Tape VIC-146/19b Further Investigation

The fracture evidence for tape 19b showed that it did not match tape 20b. Photographic evidence of the original CCI inspection was provided to allow comparison with actual reinforcing tapes. Table 8 shows the photographic evidence.

MTL pictures of tapes 19B and 20B were overlaid onto the CCI image for direct comparison of corrosion patterns and fracture edges. Whilst this is not as accurate as comparing actual parts it was sufficient to be able to confirm the approximate locations of tape 19B and 20B edges at the time of dismantling. The evidence in Table 8 also demonstrates that tape 19B was a good match to the edge of the suspected missing portion.

Hence, overall this evidence indicates that reinforcing tapes 20B and 19B fracture faces did not match because there was a missing portion of tape that was probably lost during dismantling. This portion was in the order of 18 to 20mm in length and was probably heavily corroded or heat damaged.

Table 8 – Photographic Evidence for Tape 19b and 20b

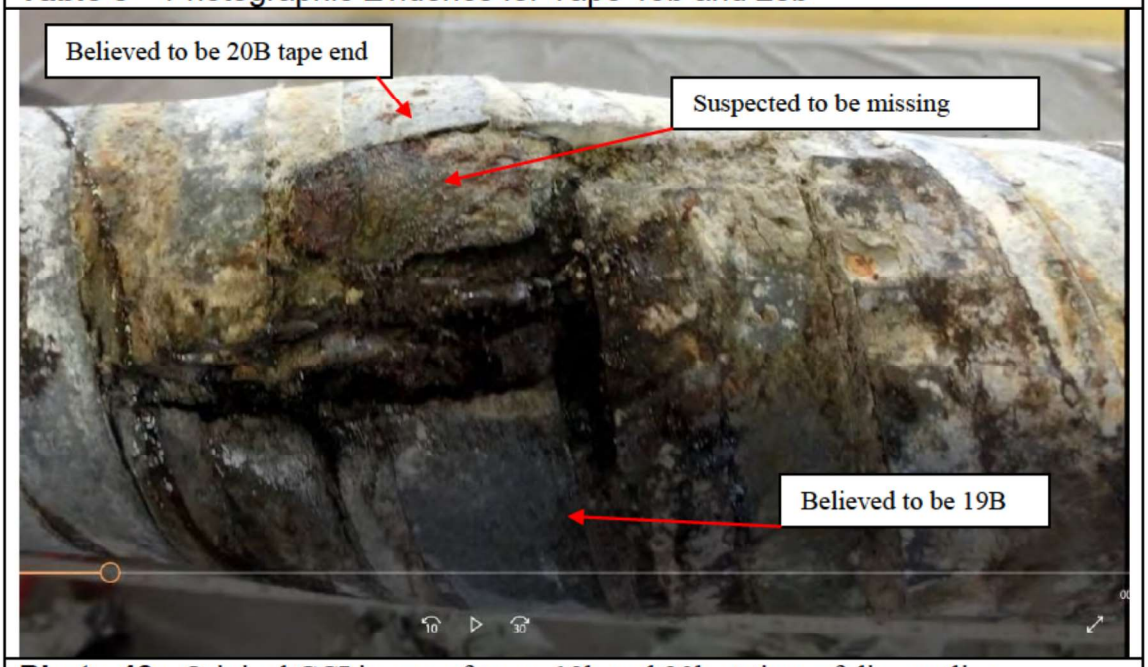


Photo 49: Original CCI image of tapes 19b and 20b at time of dismantling



Photo 50: MTL photograph of tape 19B used to match on above photo.

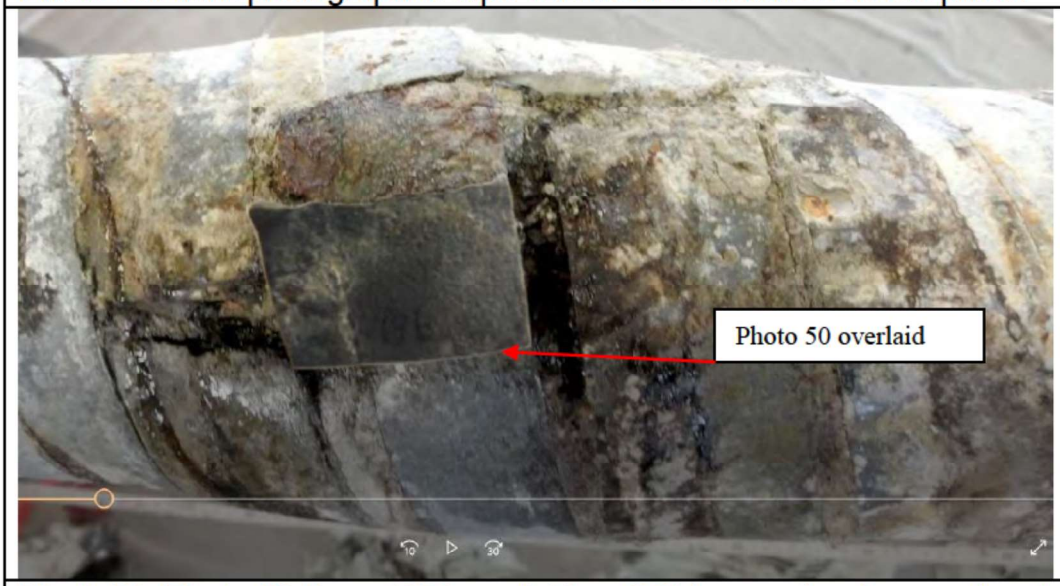


Photo51: Photo 50 (tape 19B) overlaid on CCI image showing good match with suspect region. Note left hand side of tape has a small fold.

Table 8 – Photographic Evidence for Tape 19b and 20b

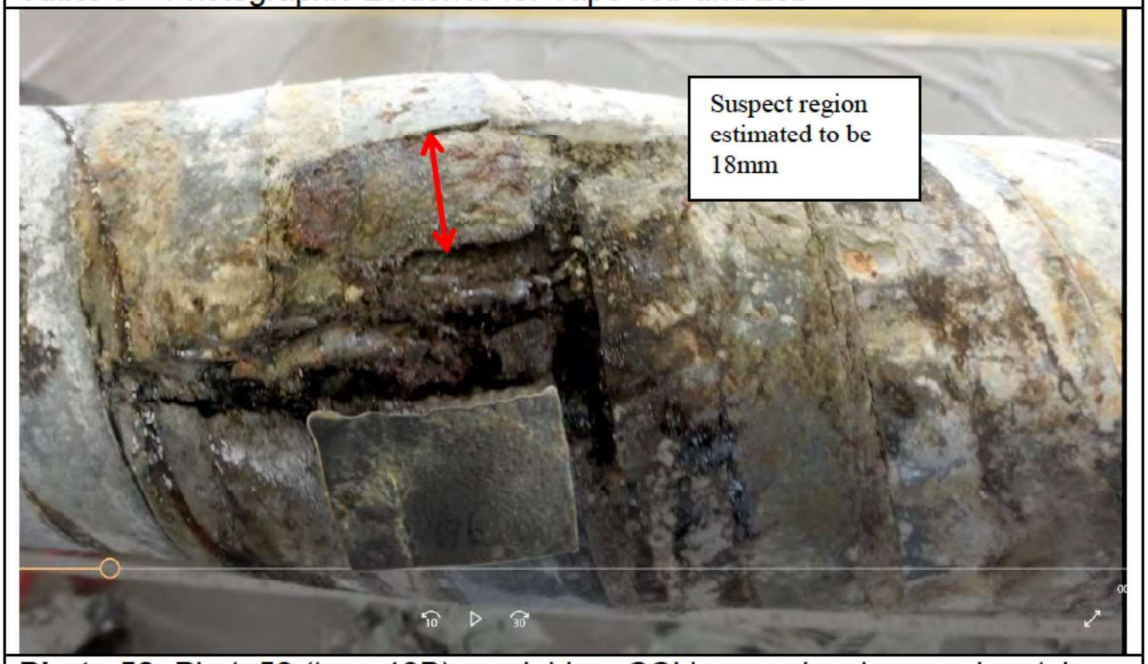


Photo 52: Photo50 (tape 19B) overlaid on CCI image showing good match with bottom part of tape confirming that this is 19B location.



Photo 53: CCI image of North Bulge showing suspected position of tape 20B and suspect region.

Table 8 – Photographic Evidence for Tape 19b and 20b

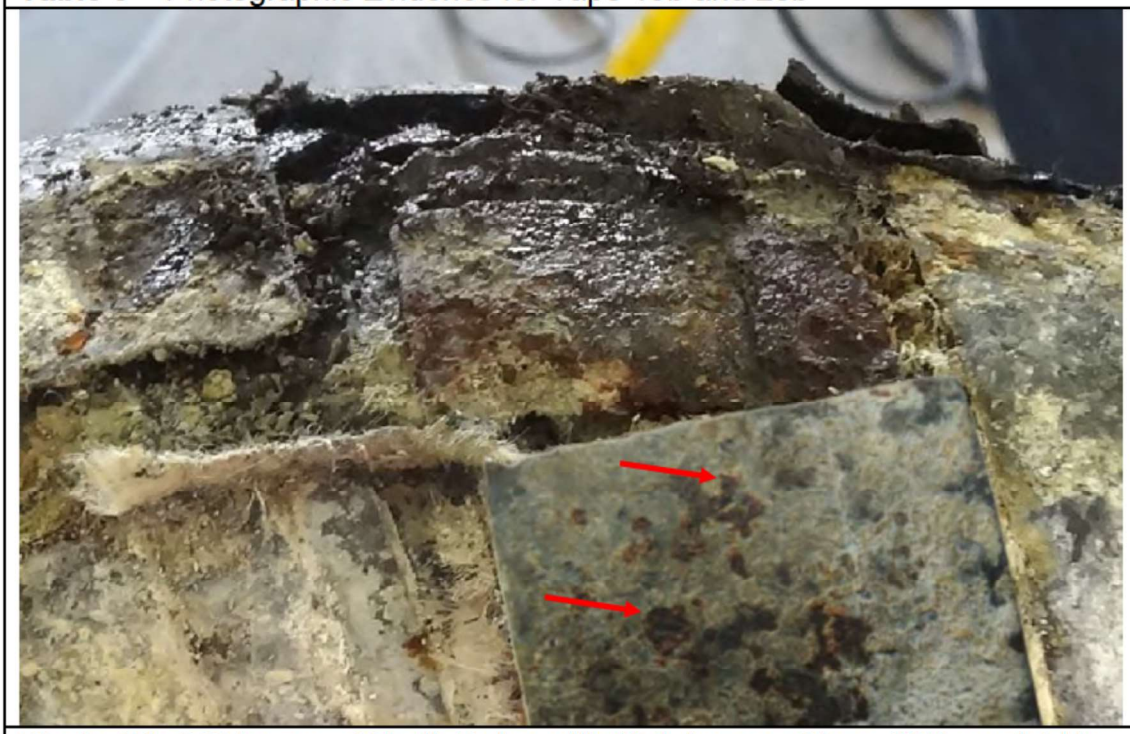


Photo 54: CCI image of North Bulge with MTL image of tape 20B overlaid in correct position. Shows good match to edge and corrosion pattern of tape in original image. Confirms that tape 20B was in this location and that suspect region is missing. Compare this image with photo 53.

Examination of Polyethylene Sheath

The PE sheath (VIC-146/23B) was examined by a combination of naked eye and low power optical microscope. The PE sheath contained two large bulges which were separated by approximately 50cm. The largest bulge had 3 splits which broke through the full thickness of the PE sheath. These splits matched those on the lead sheath in the North Bulge area. The largest of these splits was approximately 8cm long and the two smaller splits were approximately 2 to 3cm long.The second bulge in the PE sheath was more cyclindrical in shape and contained only one small circumferential split of about 6mm. There were also indentations in the sheath near to this region which are consistent with armour wire indentations. The diameter over both bulges was around 10.6cm compared to around 9.6cm remote from the bulges. The second bulge matched the location of the South Bulge in the lead sheath and the circumferential split was positioned over the fold in the lead sheath.

The edge of the splits in the PE sheath (North Bulge) showed a small amount of yielding on the fracture faces typical of PE based materials when they fail in a tensile manner i.e. due to hoop stress. The internal edges of the PE sheath showed some evidence of heat damage but the external surface did not show any significant heat damage following the cable fault other than the general deformation of the bulges. The South Bulge showed less evidence of heat damage. This is consistent with the observations on the underlying lead sheath which indicate higher temperatures in the North Bulge region.

The reinforcing tape witness marks were visible on the surface of the PE sheath and this showed the original tape positions in service. Between the bulges the tape witness marks were less discernible. Remote from the failure regions the tape spacing was typically in the region of 4 to 6mm i.e. clearance between edge of inner tape 1 and inner tape 2. However, leading up to the North Bulge there was a tape gap of around 15mm evident. Over the South Bulge of the PE sheath there was an exposed region of PE sheath with a gap of about 30mm between the reinforcing tapes. This coincided with the armour wire indentation in the sheath in this region. Hence this indicates that this region of the PE sheath was exposed inservice. During the fault the expansion of the sheath in this region resulted in pressure on the armour wires and the resulting indentations.

The witness lines on the PE sheath allowed the reinforcing tapes to be repositioned on the sheath and hence allowed the tape positions relative to the fault locations and to each other to be examined again under laboratory conditions. This has demonstrated that the witness lines on the sheath match witness lines on the reinforcing tapes and hence confirm that the reinforcing tapes were in those positions in service operation. Witness marks directly over the splits in the PE sheath also confirm the location of tape 19b and show that the missing piece of tape (18mm piece) was positioned between the two splits in the PE sheath. Hence it was located in the primary fault region.

The witness marks also confirm the location of reinforcing tapes 19a and 19b and show that they were overlapped by about 10mm over a tape length of

around 400mm causing the 15mm gap in the reinforcing tapes prior to the North Bulge. Hence this is why these reinforcing tapes were damaged on their edges during disassembly.

On the South Bulge the witness marks show that tape 22 and 20D were positioned over the circumferential split and hence this split probably occurred when the reinforcing tapes fractured in this region.

PE sheath sample 144/5 was also examined in a similar manner. This sheath sample was remote from the failure region and was for reference purposes. This also showed clear tape witness marks and they were similar along the entire length of the specimen. The tape clearances varied a little but were typically in the region of 4 to 6mm. There were no unusual gaps or joins evident.

Table 9: PE Sheath Photos

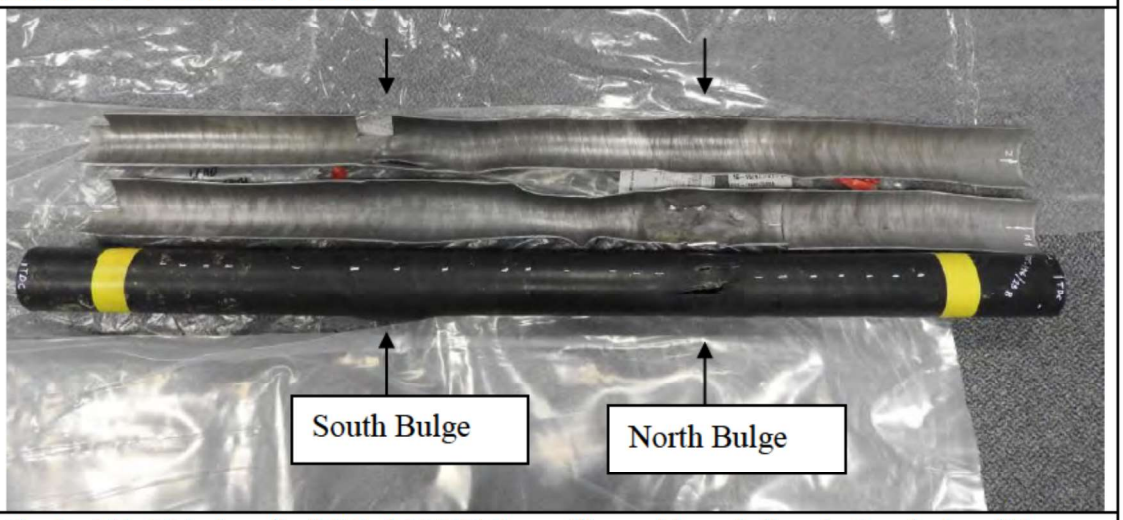


Photo 55: PE sheath (VIC-146/23B) positioned in relation to lead sheathing VIC-146-27 and VIC-146-29



Photo 56: Close up of PE sheath (VIC-146/23B) and North Bulge on lead sheath showing matching patterns in split regions.

Table 9: PE Sheath Photos



Photo 57: Close up of PE sheath (VIC-146/23B) and South Bulge on lead sheath. PE sheath has been rotated to show small split area that was located under lead sheath fold region.

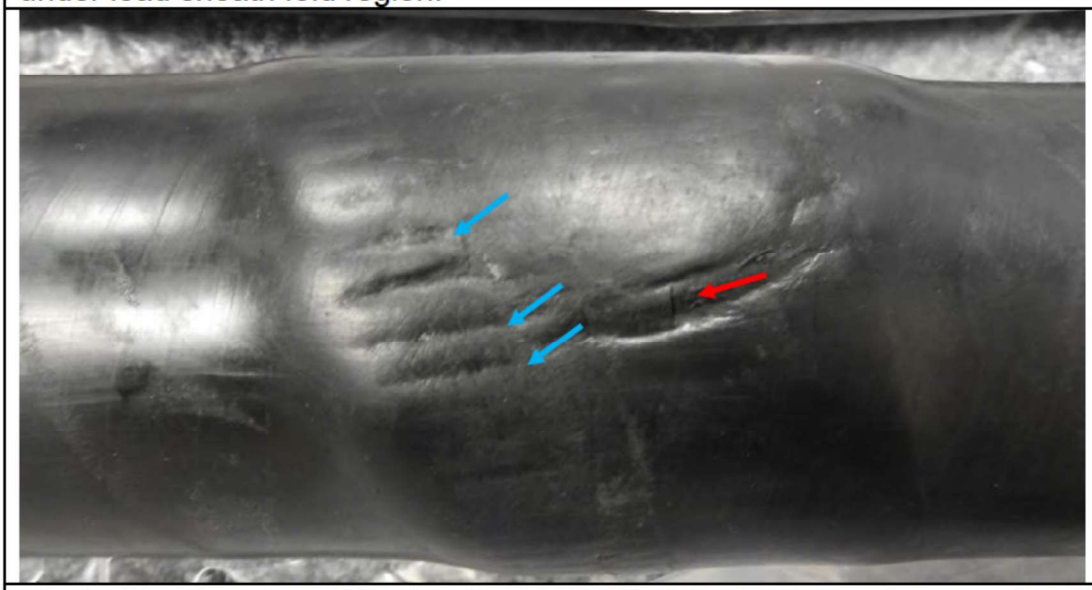


Photo 58: Close up of PE sheath (146/23B) at South Bulge show small split (red arrow) at point of tape split. Armour wire indentations on left (blue arrow). This region not covered by reinforcing tapes in service.

Table 9: PE Sheath Photos



Photo 59: Close up of PE sheath (VIC-146/23B) North Bulge inner surface showing evidence of some localized heat damage around splits.



Photo 60: Close up of PE sheath (VIC-146/23B) South Bulge inner surface showing no significant heat damage or carbonizing of material.

Table 9: PE Sheath Photos



Photo 61: PE sheath (146/23B) just prior to North Bulge showing tape gap of around 15mm due to tapes 19a and 19b being overlaid by about 10mm.



Photo 62: PE sheath (146/23B) close up of split in South Bulge. Approximately 6mm long.

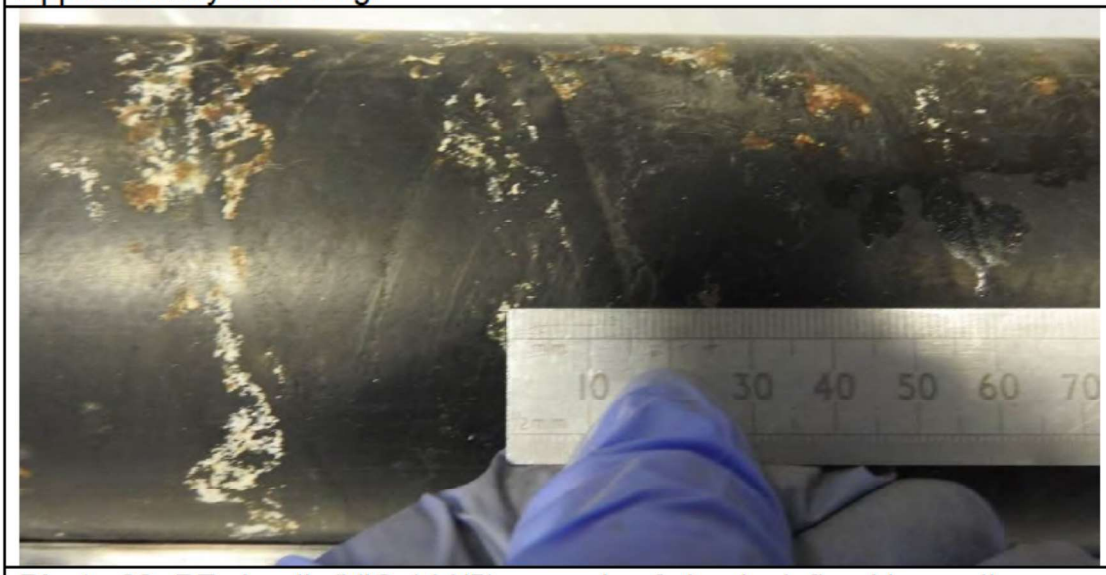


Photo 63: PE sheath (VIC-144/5) example of clearly defined tape witness marks and typical gap evident on reference sample. 5mm gap in this example.

Table 9: PE Sheath Photos

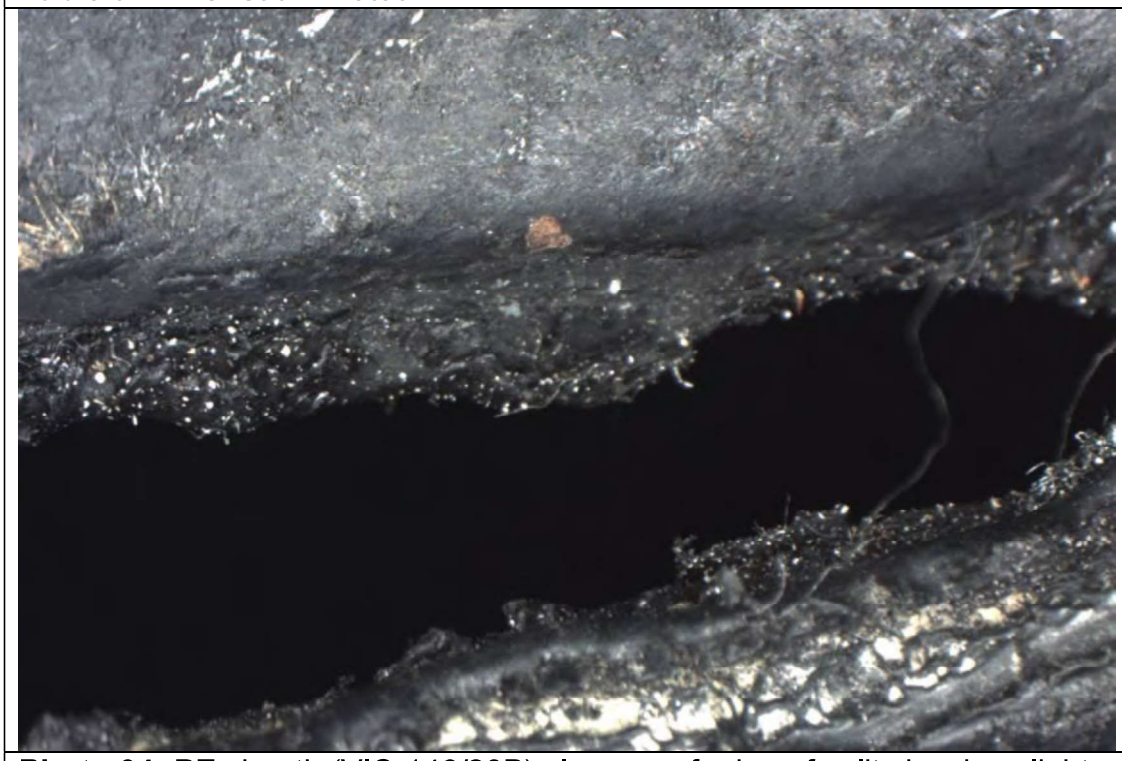


Photo 64: PE sheath (VIC-146/23B) close up of edge of split showing slight necking (yielding) of PE at point of failure. Typical of tensile type failure of PE.



Photo 65: PE sheath (VIC-146/23B) with inner reinforcing tapes in correct location. Tape missing from central part of failure.

Table 9: PE Sheath Photos



Photo 66: PE sheath (VIC146/23B) north of North Bulge showing tapes 19a and 19b overlapped by 10mm and 15mm of exposed PE.



Photo 67: PE sheath (VIC-146/23B) South Bulge with inner reinforcing tapes in correct location over circumferential split.



Photo 68: PE sheath (VIC-146/23B) general view of cable with inner reinforcing tapes over South Bulge. Note exposed PE sheath on left of bulge.

Table 9: PE Sheath Photos

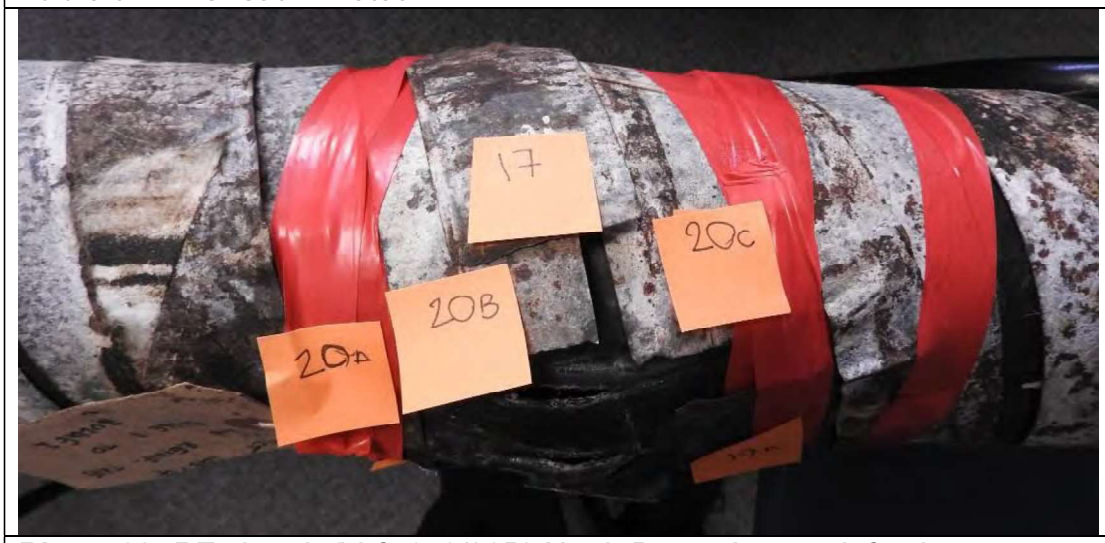


Photo 69: PE sheath (VIC-146/23B) North Bulge. Inner reinforcing tapes and part of outer reinforcing tapes in correct location over main split.



Photo 70: PE sheath (VIC-146/23B) inner and outer tapes in correct location.



Photo 71: PE sheath (VIC-146/23B) souther bulge over split showing second tape layer in correct location.

Table 9: PE Sheath Photos



Photo 72: PE sheath (VIC-146/23B) just prior to South Bulge showing tape 17 and tape 14. Tape 14 split has been caused by tape 17 moving to the right.

Scanning Electron Microscopy

SEM was conducted on a range of samples. This included a range of tape fracture faces and lead sheath samples. A small section of the lead sheath immediately above the primary split area was removed from the sheath and used for this testing (146-29/1). This sample was a section that contained metal globules on the surface and these globules were examined for composition. The general surface of the lead sheath was also examined at x100, x1000 and x3000 magnification in each of the key areas.

Some residue was also found trapped beneath this specimen when the lead was removed. This was also examined under SEM to determine chemical composition. The resulting SEM images are shown in the table below.

Table 10: SEM Images

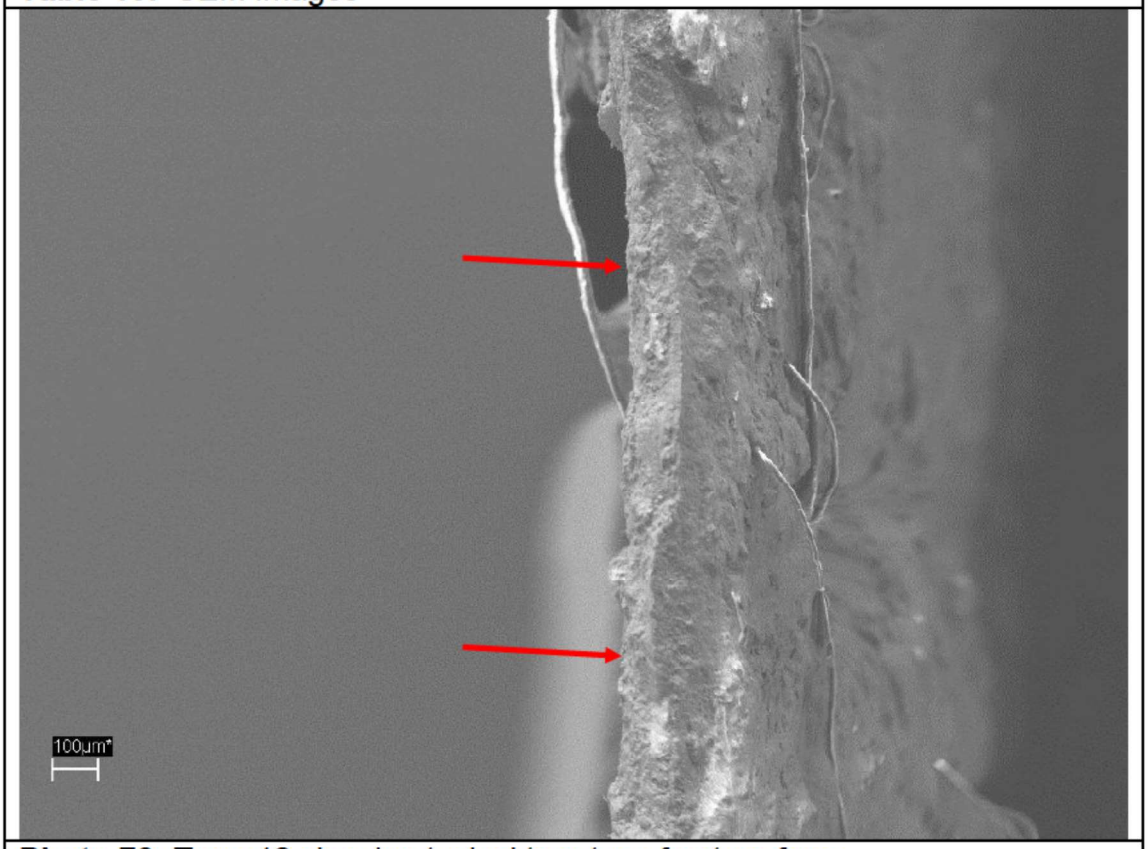


Photo 73: Tape 12 showing typical tear type fracture face.

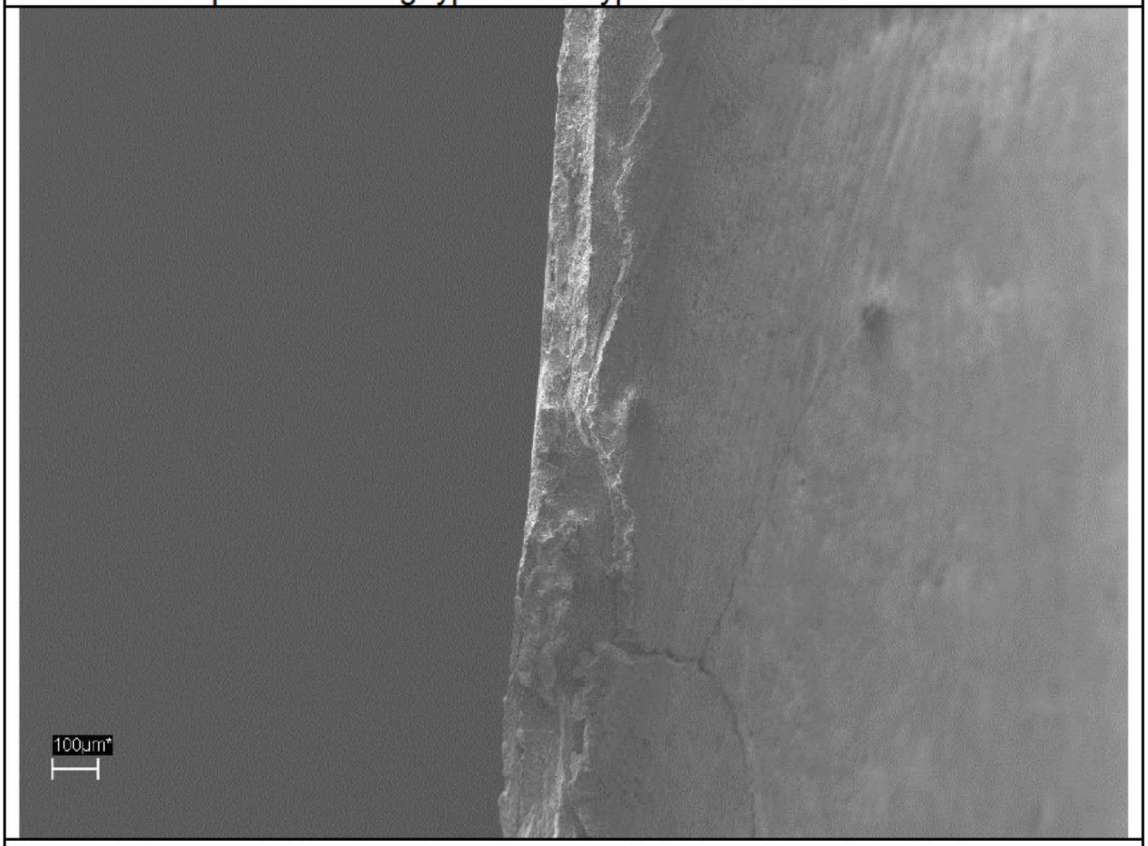


Photo 74: Tape 17 fracture face (from South Bulge, join with 18) showing typical mixed tear (lower) and tensile (upper) type fracture face. Some cracking of the zinc coating is also evident around fracture face.

Table 10: SEM Images

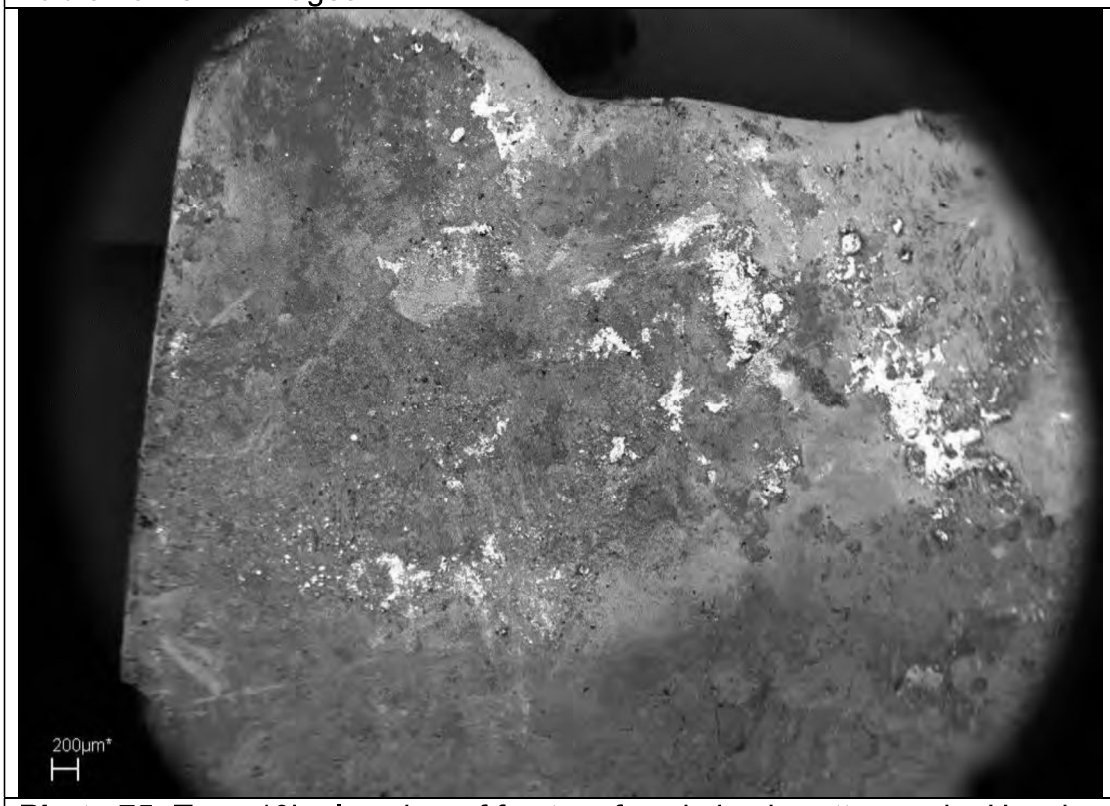


Photo 75: Tape 19b plan view of fracture face in backscatter mode. Heavier elements show as whiter regions. Shows heat damage edge.

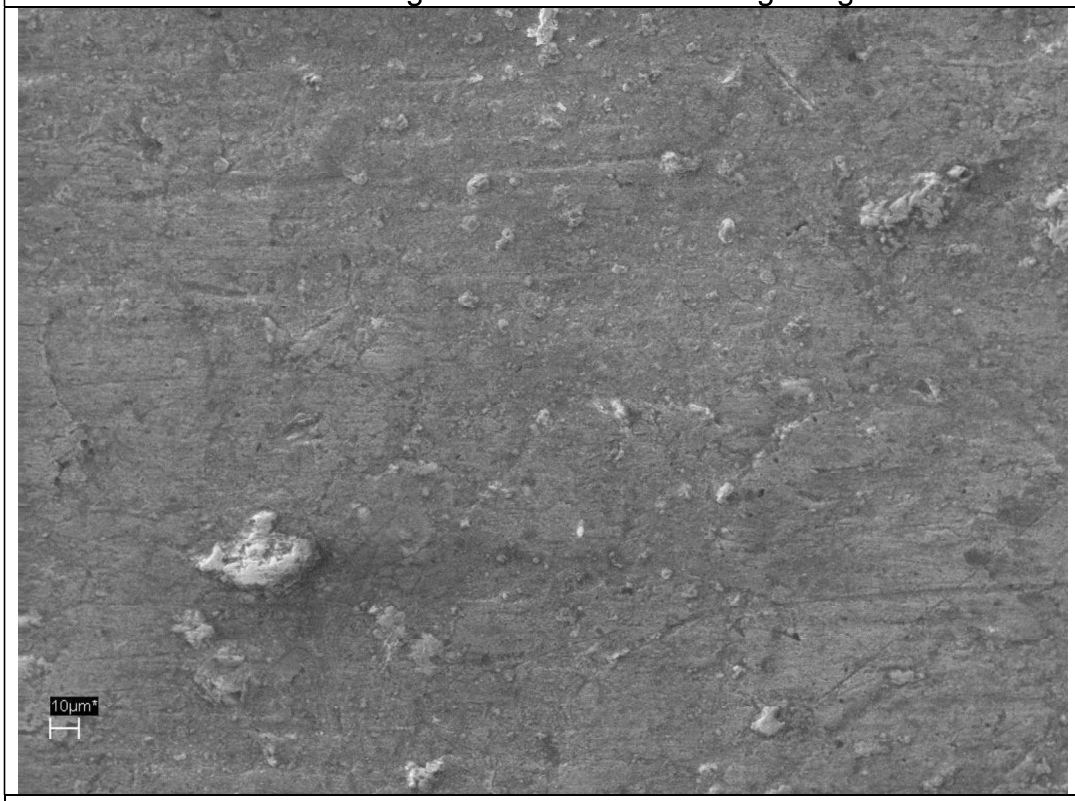


Photo 76: Sample VIC-146-29-4 plane view of lead surface over North Bulge x1000.

Table 10: SEM Images



Photo 77: Sample VIC-146-29-5 plane view lead surface over remote region x1000

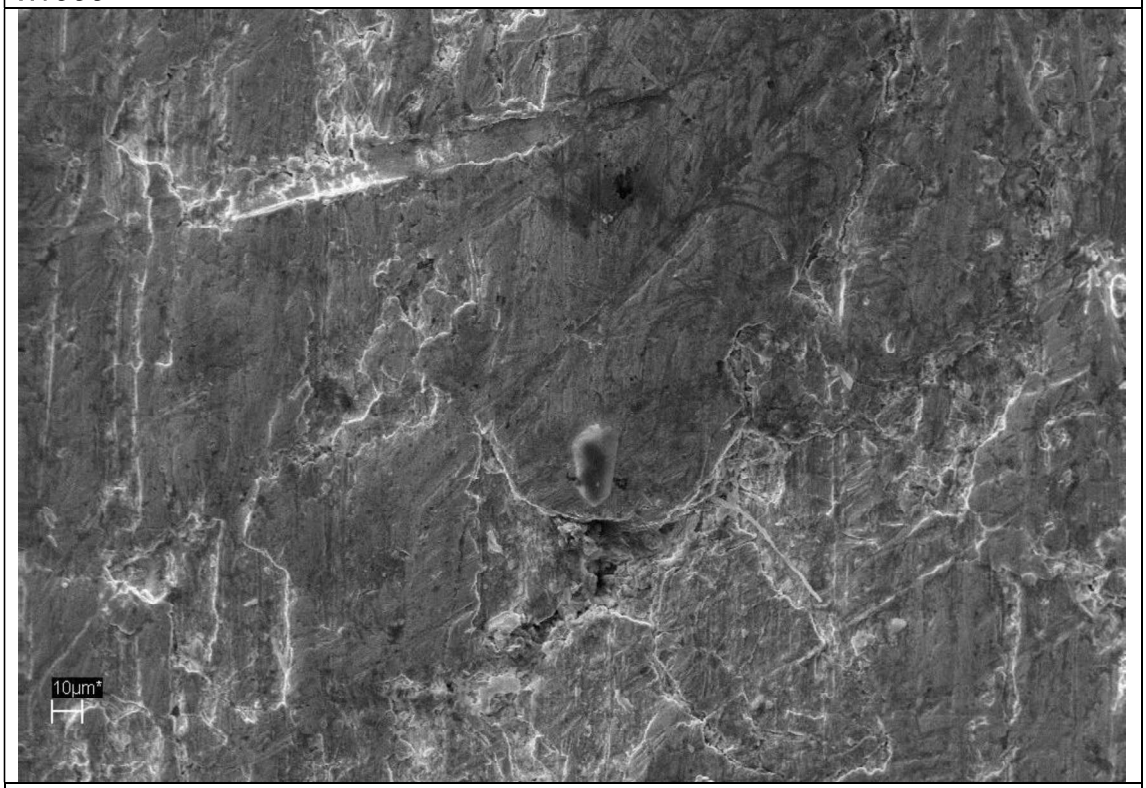


Photo 78: Sample VIC-146-29-6 plan view of lead surface over South Bulge region x1000.

Table 10: SEM Images

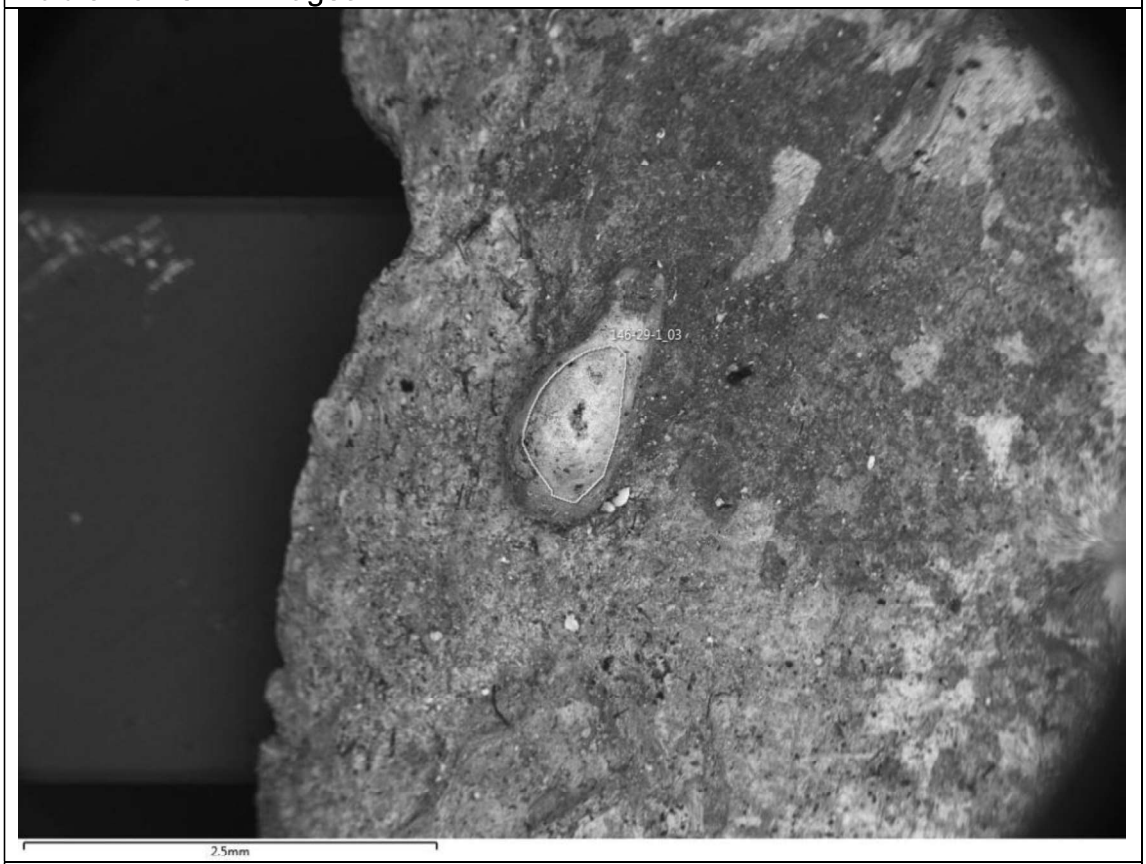


Photo 79: Sample VIC-146-29-1 lead fracture face with metal globules.

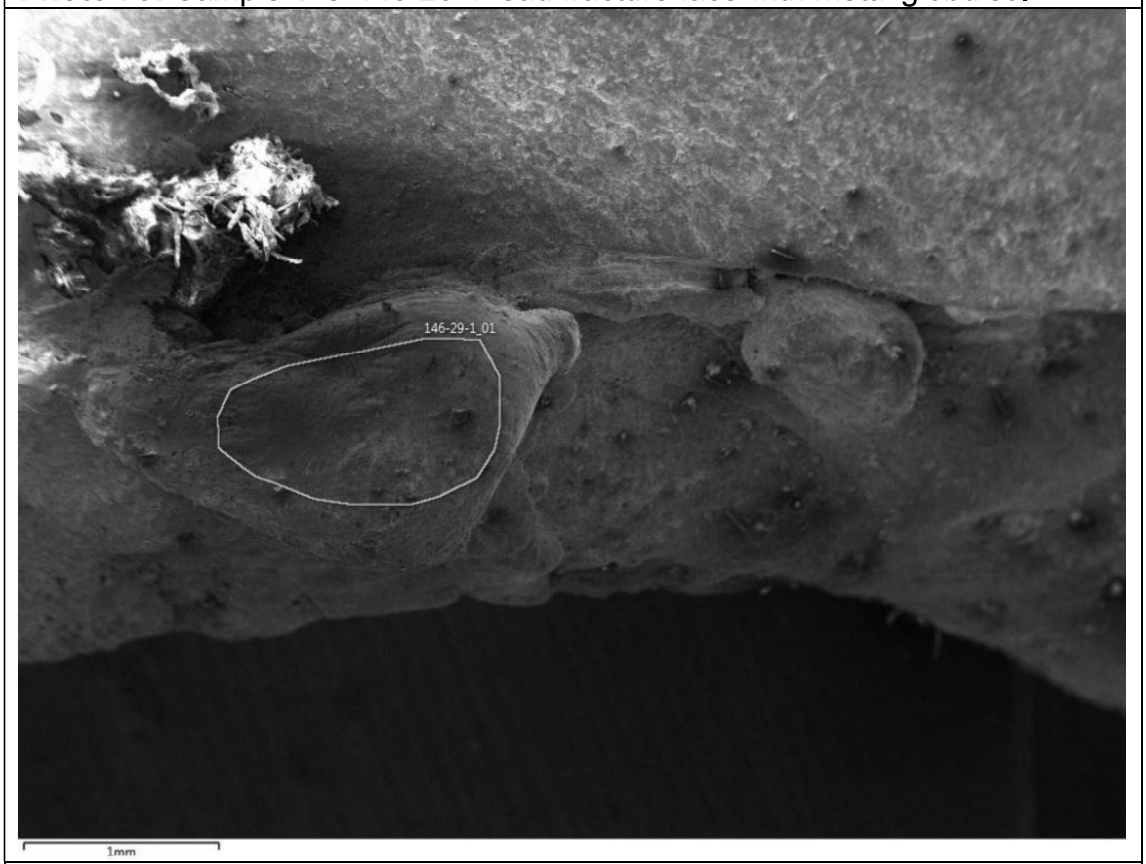


Photo 80: Sample VIC-146-29-1 lead fracture face with metal globules

The elemental analysis (EDAX) performed on the various samples is detailed in Table 11 below and shows each sample analysed in the vertical columns and the weight percent of each element detected in the rows. Generally the level of detection is around 1% accuracy but this depends on the particular element. Hence values above this limit should be considered significant. Photos 79 and 80 highlight typical areas that were analysed on the surface of the samples.

From Table 11 we see that the surface of the lead sheath (South Bulge) showed only lead and small quanitites of tin present as expected. This confirms the chemical compositional analysis conducted by ICP-OES which is more accurate.

The section of lead sheath taken from the split region (North Bulge) with the globules on the surface showed some minor levels of sodium, calcium and magnesium which is to be expected due to salt water exposure. The main metallic composition of the globules was lead with trace quantities of copper. This confirms the general visual observations that the lead sheath has melted in the region of the split and included some copper sputter from the conductor. Hence temperatures have been high in this region during the cable fault.

The powdery residue trapped beneath the lead sheath in the split region was found to have a high carbon content along with calcium, copper and lead and hence is probably a mixture of hydrocarbon based material and metal sputter. This is probably ejected material from within the cable and hence maybe woven binder tape and or paper.

The analysis of tape 19 shows the results from different areas on the surface of the tape close to the fracture region. High levels of iron and zinc are expected from the tape material. But high levels of lead and some copper were also detected and again confirm that this particular tape was exposed to significant temperature and additional metal sputter. This is consistent with this tape being positioned close to the split in the primary failure region.

The general plan view images of the lead sheath samples both over the bulges and remote from the bulges (photos 76 to 78) did not reveal any special features of interest.

	Table 11: SEM/EDAX analysis of samples							
Element	**146-27-6 Area**	**146-29-1 01**	**146-29-1 02**	**146-29-1 03**	**146-29-2 01**	**146-19b Area 1**	**146-19b Area2**	**146-19b Area3**
	South Bulge surface	Globules on lead by split			Powder from under split	Different areas on tape 19 surface		
C					58.62%			
O	7.22%	16.21%	25.11%	20.07%	19.57%	35.97%	25.19%	23.78%
Na		1.27%	2.04%	1.28%		7.36%		1.49%
Mg		0.41%	0.94%		0.53%	3.83%	0.77%	
Al		0.32%	0.85%	0.51%	0.2%	0.37%		
Ca		0.88%	1.69%	1.21%	3.06%	1.66%	0.28%	0.66%
Si					0.25%	0.37%		0.2%
S						1.08%		
Cl			1.17%		0.25%	0.46%		0.63%
Fe		0.57%	0.615	0.41%	0.51%	12.58%	1.68%	2.39%
Ni								
Cu		1.58%	6.29%		9.09%	3.08%		
Sn	1.63%			1.57%				
Sb								
Pb	91.15%	78.76%	61.29%	74.26%	5.95%	13.87%	69.19%	63.91%
Zn				0.7%	1.98%	19.38%	2.89%	6.94%
Total	100%	100%	100%	100%	100%	100%	100%	100%

Chemical Analysis

Two samples from the lead sheath (146-27/1 & 146-28/1) were subjected to full chemical analysis using ICP-OES. The results of this analysis are detailed in the table below and expressed as weight percentage of each element.

Uncertaintity data is 14.7% at 95% confidence limit for tin and 16.1% at 95% confidence limit for antimony. Detection limits are 0.0020% for both elements.

Table 12: Results of Chemical Analysis

Sample	**146-27/1**	**146-28/1**
Element		
Lead (Pb)	99.8%	99.8%
Silver (Ag)	<0.0005 %	<0.0005 %
Aluminium (Al)	<0.0005 %	<0.0005 %
Arsenic (As)	<0.0005 %	<0.0005 %
Gold (Au)	<0.0005 %	<0.0005 %
Bismuth (Bi)	0.0022	0.0020
Cadmium (Cd)	<0.0005 %	<0.0005 %
Copper (Cu)	<0.0005 %	<0.0005 %
Iron (Fe)	<0.0005 %	<0.0005 %
Indium (In)	<0.0005 %	<0.0005 %
Nickel (Ni)	<0.0005 %	<0.0005 %
Antimony (Sb)	0.11 %	0.096 %
Tin (Sn)	0.14 %	0.093%
Tellurium (Te)	<0.0005 %	<0.0005 %

The grade of lead sheath is reported to be Lead Alloy E grade with a nominal 0.4% tin and 0.2% antimony.

Tensile Testing of Reinforcing Tapes

Samples of tape were taken from the unfailed reference section of cable (tapes 144-2 & 144-3) . The reinforcing tapes were cut longitudinally to reduce the sample width to around 20mm and a test length of around 150mm was used. The reinforcing tapes were tensile tested at two test speeds of 10mm/min and 200mm/min using a Testometric tensile testing machine with wedge type jaws. A gauge length of 75mm was used and elongation at break was measured using jaw separation.

Full stress/strain curves are detailed in the appendix 2. Table 13 summarises the results.

Table 13: Summary of Tape Tensile Testing

Tape Location	**Outer**		**Inner**	
Sample	**144-2**		**144-3**	
Test Speed	**10mm/min**	**200mm/min**	**10mm/min**	**200mm/min**
Thickness [mm]	0.35	0.35	0.35	0.35
Ave. Width [mm]	20.6	19.48	19.96	20.03
Min Stress at Break [Mpa]	295.5	363.3	441.8	446.3
Average Stress at Break [MPa]	**390.5**	**463**	**512.2**	**504.9**
Maximum Stress at Break [Mpa]	513	561.4	569.4	538.2
Min Strain at Break [%]	3.4	2.25	3.2	3.6
Average Strain at Break [%]	**4.8**	**5**	**6.2**	**6.2**
Maximum Strain at Break [%]	9.6	11.13	9.9	9.2
Min force per unit width [N/mm]	103.4	127.1	154.6	156.2
Force at Break per unit width [N/mm]	**136.7**	**162**	**179.3**	**176.7**
Max force per unit width [N/mm]	179.6	196.5	199.3	188.4

Whilst no specification has been provided for these tapes at this stage, the results are considered to be fairly typical of a mild steel type product with results around the 400 to 500MPa region. The results for the outer tape are slightly lower as these showed more evidence of corrosion.

Testing at the slower test speed tended to allow the tape to tear from corrosion points whereas at the faster test speeds the tapes fractured in a more straight tensile manner. At the lower test speeds some necking of the specimen was evident in the width direction.

Overall the tensile tests do not give rise for any concern.

Polished Micro-sections

Small sections of lead sheath were taken from three separate locations. This included a sample over the North Bulge area but remote from the split (VIC-146/4), a sample over the South Bulge area but remote from the fold (VIC-146/6) and a sample remote from both fault areas near to TDC (VIC-146/5). Each sample was approximately 2cm square. The samples were further cut down to specimens of approximately 1cm long and were mounted in cold curing resin and then polished to a metallographic finish using a combination of polish and etch techniques. A final etch was then conducted to reveal the microstructure. Samples were then examined under high power optical microscope and images recorded digitally.

The polished section in each case was along the main axis of the cable. Table 14 shows the resulting images. All images are shown at the same magnification and random measurements of crystal size have been made in each case.

Table 14: Photographs of Lead Micro-sections

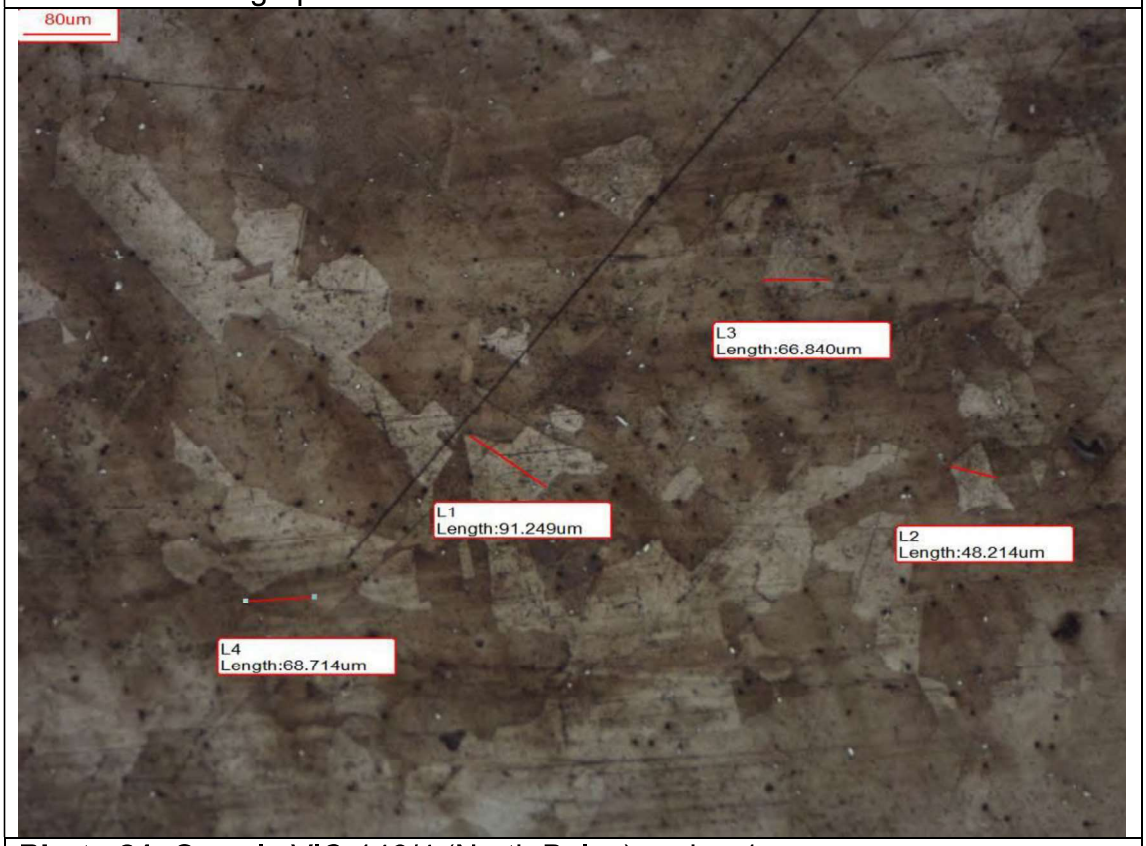


Photo 81: Sample VIC-146/4 (North Bulge) region 1.

Table 14: Photographs of Lead Micro-sections

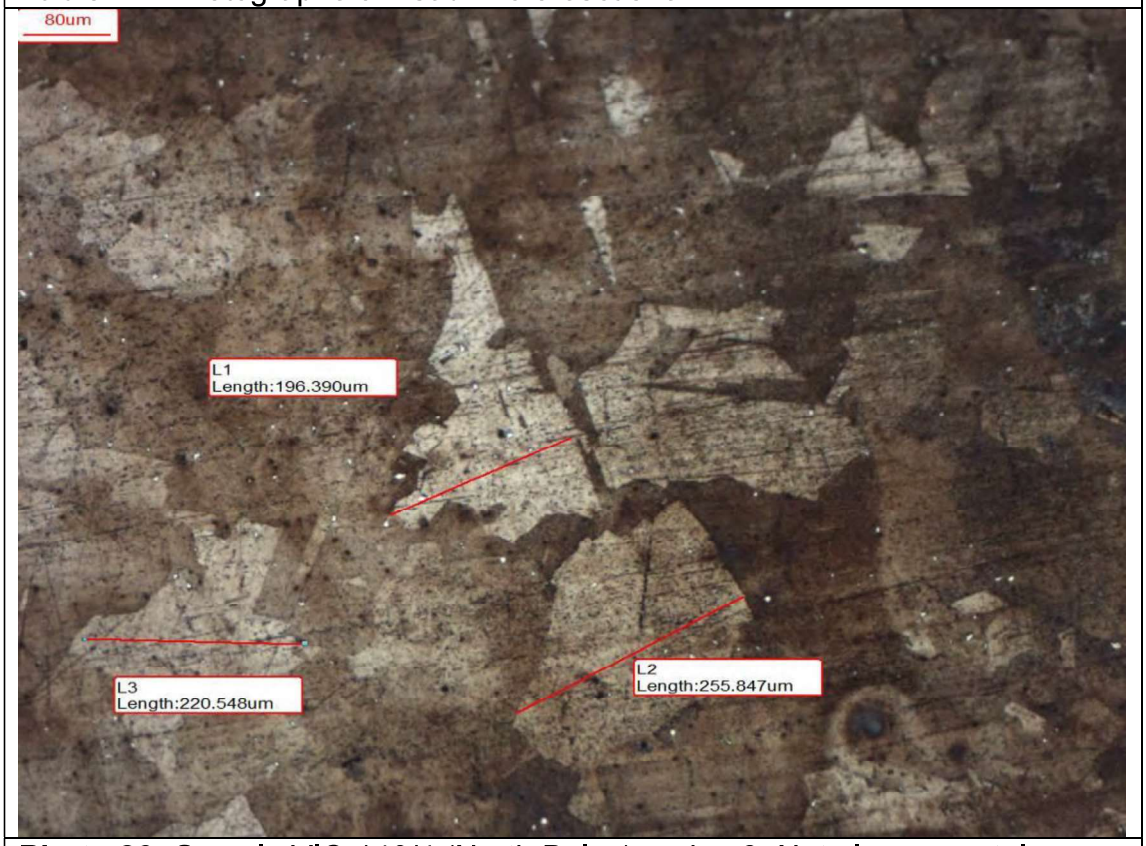


Photo 82: Sample VIC-146/4 (North Bulge) region 2. Note large crystal structure.

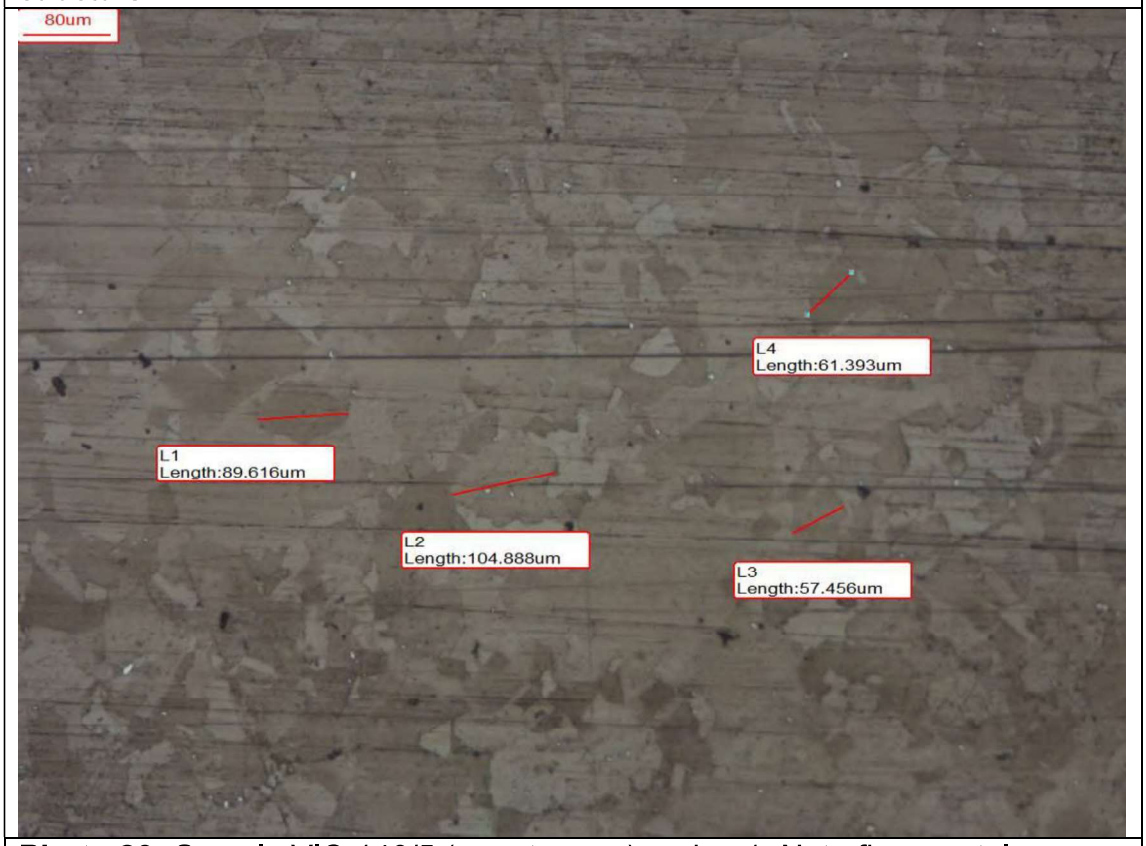


Photo 83: Sample VIC-146/5 (remote area) region 1. Note fine crystal structure.

Table 14: Photographs of Lead Micro-sections

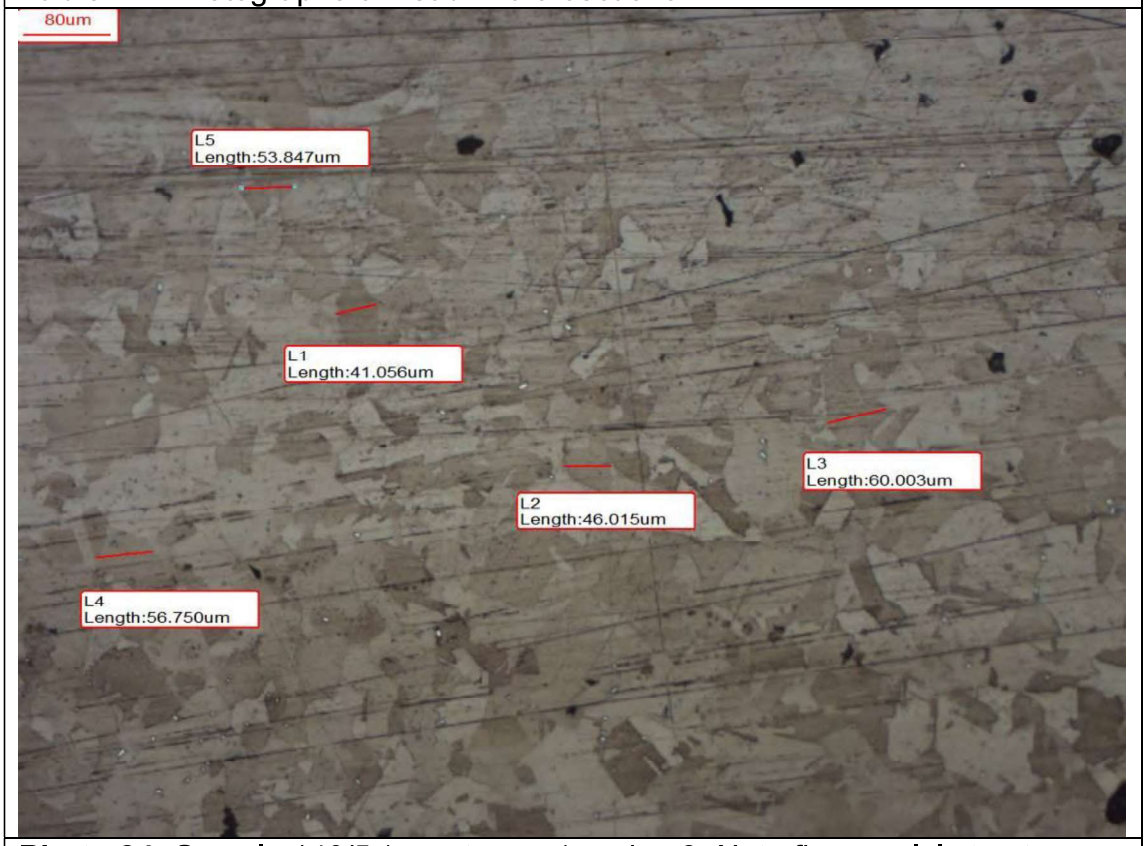


Photo 84: Sample 146/5 (remote area) region 2. Note fine cryslal structure.

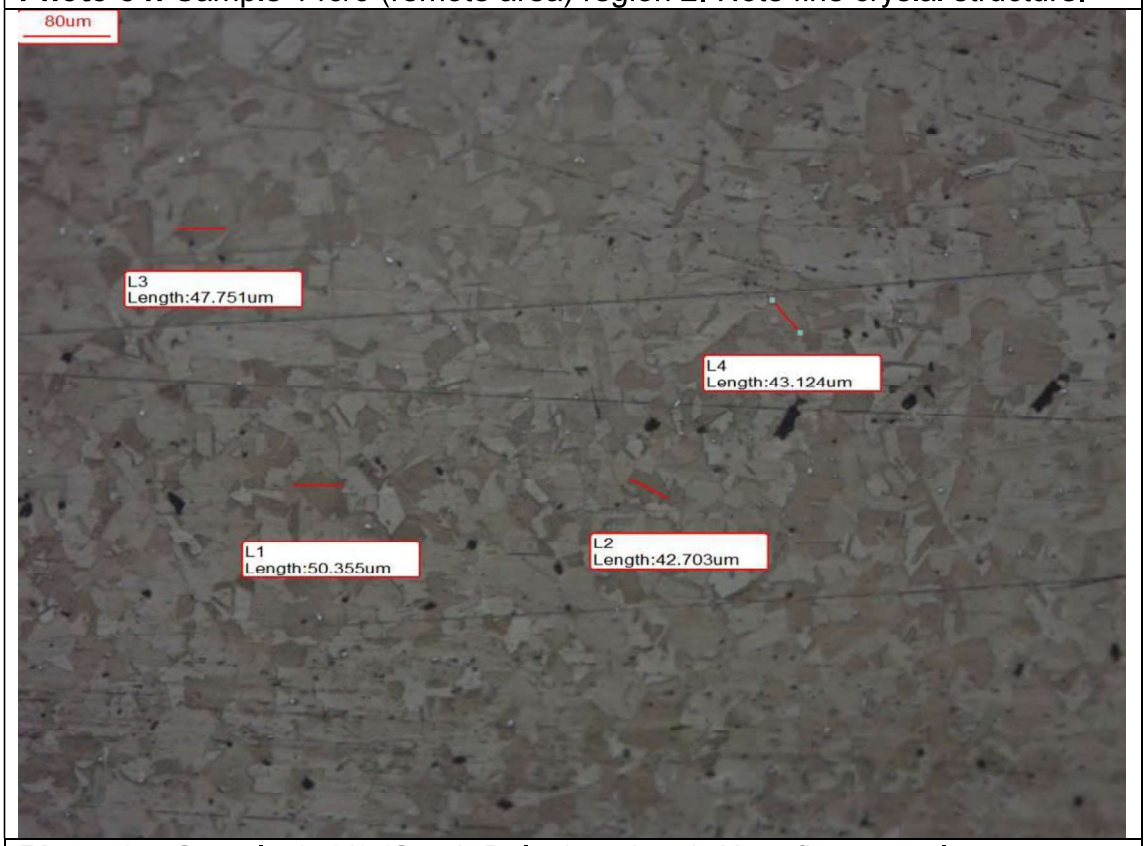


Photo 85: Sample 146/6 (South Bulge) region 1. Note fine crystal structure.

Table 14: Photographs of Lead Micro-sections



Photo 86: Sample 146/6 (South Bulge) region 1. Note fine crystal structure.

From the micro-sections it can be seen that both samples VIC-146-5 and VIC-145-6 have a fine grain crystal structure with crystal size typically around 40-60µm. Sample VIC-146-4 has a much coarser and larger overall crystal structure and more variable in size range. Typical size ranged from 48 to 255µm. This could indicate additional heat exposure during the cable fault in this region resulting in the annealing of the lead in this region and larger crystal growth as a result. This would be consistent with the other observations made throughout this report.

7. Discussion

Analysis of the lead sheath in this report indicates that there were no obvious manufacturing defects in the lead sheath and no signs of repairs. The North Bulge shows significant evidence of heat damage during the cable fault resulting in localised melting and metal sputter whereas the South Bulge does not show such signicificant evidence. For this reason the North Bulge is likely to have experienced significantly higher temperatures. The microstructure analysis appears to support this view.

There was a small split in the South Bulge which has allowed the MI/degradation products to exude from this location and hence the staining and liquid residue in this region.

The steel reinforcing tapes did not show any evidence of joins or welds but there were a number of interesting features of note. Tapes 14 and 17 showed some post damage movement which has resulted in tape 17 impinging on tape 14 and causing a small split. Tape 16 had a fold in the edge of the tape and this has been caused by tape 12 movement post failure.

Inner tapes 19a and 19b were overlapped by about 10mm along a tape length of 400mm in service, which has resulted in an exposed section of PE sheath of about 15mm. Over the Southerm Bulge there was an exposed section of PE sheath that measured about 30mm and this was in this situation in service.

Reinforcing tape 19b and 20b fracture faces did not match and indicate that there is a small section of missing tape in the order of 18mm in length from the evidence. This is shown in the CCI image photo 49. This may have been severly heat damaged.

The PE sheath in the fault region shows evidence of tape witness marks but these are not so pronounced between the fault regions. The remote sample showed clear witness marks along its entire length. The witness marks confirm the tape evidence indicating the two gaps in tapes prior to the North Bulge and immediately over the South Bulge.

The inside of the PE sheath over the North Bulge shows evidence of heat damage during the fault condition which confirms the lead sheath findings i.e. localised high temperatures over the North Bulge. There was no significant heat damage over the South Bulge during the fault condition.
The PE sheath had a small circumferential split over the South Bulge which coincided with the split in the lead sheath below. This also coincided with tape 22 and 20D fracture.

The SEM analysis confirmed that the metal globules around the split region were primarily lead with trace quantities of copper. This is consistent with the other observations indicating high localised temperatures. Tape 19b also showed evidence of lead and copper present on its surface along with

damage to the zinc coating. Hence tapes immediately in the vicinity of the splits also experienced high temperatures.

Chemical analysis of the lead shows that Antimony and Tin are present in the lead. No other unexpected elements were detected.

Mechanical testing of the tapes from the reference section, 144/6, did not show any significant results. Values of breaking stress were typically in the range of 400 to 500MPa which would be expected for a mild steel tape. These values have not been compared to any manufacturers datasheet or specification but these results do not give cause for concern.

8. Conclusions

Various components from the failed Basslink 400kV DC cable have been analysed in this report. This has included, steel tapes, lead sheath and the PE sheath. From this work the following conclusion can be made to date:

1. There is no evidence of material defects, repairs or poor quality manufacturing of the lead sheaths examined.
2. There was evidence of significant heat damage to the lead sheath. The North Bulge has significant heat damage with evidence of metal sputtering and temperatures in excess of 327°C and possibly higher.
3. There were extensive splits in the lead sheath of the North Bulge and one small split in the South Bulge.
4. There is evidence of significant thinning of the lead sheath in the North Bulge failure zone as a result of the failure.
5. The splitting of the lead sheath in this region is consistent with hot material being ejected from the inside of the cable i.e. the damage to the lead sheath is the result of the failure at the insulation layers and is not a pre-existing cause or defect in the sheath.
6. The chemical analysis of the lead sheath showed lower than expected levels of antimony and tin in the sheath.
7. Mechanical testing of steel reinforcing tapes from the reference section did not show anything unusual and the resulting break stress was in the expected region for a mild steel product but this has not been compared with any actual specification data.
8. The reinforcing tape breaks from the failed cable sample are all consistent with tensile type failures or tear failures or combinations of both. There is no evidence of fatigue related failures. There is no evidence to indicate the speed of these tape failures.
9. Some reinforcing tapes show evidence of movement caused by the failure which has resulted in both rucking and tearing of the reinforcing tapes. In the extreme cases this has resulted in the reinforcing tapes folding over .e.g. tape 16, and in other cases it has resulted in small tears e.g. reinforcing tapes 17 and 14.
10. There was no evidence of joins, welds or defects in the reinforcing tapes examined.

11. Reinforcing tapes 19b and 20b fracture faces did not match. There is evidence of a small missing section of reinforcing tape immediately over the North Bulge split. This may have been lost during dismantling as CCI photographic evidence indicates that it was present in the CESI inspection.
12. There was evidence of a 15mm wide butt gap in the steel reinforcing tapes immediately prior to the North Bulge caused by reinforcing tapes 19a and 19b being overlapped by about 10mm over a tape length of 400mm. This has also caused the damage of these tapes during dismantling. These tapes were probably in this position in service.
13. There was evidence of a 30mm wide gap in the steel reinforcing tapes over the South Bulge resulting in the armour wire indentations in the PE sheath in this region at time of failure. Evidence indicates that this was also probably like this at time of service.
14. There was significant evidence that the reinforcing tapes have seen temperatures in excess of 415°C (Zinc melting point) at the North Bulge during the fault and in isolated areas this may have been higher immediately over the splits at the North Bulge.
15. Tape witness marks on the PE sheath were more faint between the two failure zones (North and South Bulge) when compared to the remote reference section.

Prepared by:



Signed:

Dated: 28th November 2016

9. Curriculum Vitae- NICHOLAS KENWORTHY

PERSONAL DETAILS

Name:	Nicholas Kenworthy
Address:	Materials Technology Ltd, Unit 5, Rushington Court, Chapel Lane, Totton, Hampshire, UK, SO41 8GN
Nationality:	British
Position:	Technical Director Materials Technology Ltd.
Qualifications:	Post Graduate Diploma, Polymer Science & Technology (London School of Polymer Technology, University of North London)

Diploma of Associateship in Polymer Science & Technology, GPRI - London School of Polymer Technology, University of North London

Business & Technician Education Council (BTEC), Higher National Certificate (HNC) in Polymer Science & Technology

CAREER PROFILE

October 2004 – Present, Material Consultant – Materials Technology Limited. Responsible for providing a wide range of expert technical services to a range of industries. Involved in materials selection and testing, failure investigation and avoidance, compound development, inspection and quality control. Lectures to Engineers throughout industry on materials including marine surveyors, electrical approval bodies and in house training programmes. Clients include virtually all industries from multi-nationals to small enterprises. Markets include; cable, automotive, medical, marine, insurance & litigation. Expert in all aspects of polymeric materials.

2000- September 2004, Technical Manager – LV Product Development & Materials, Pirelli

Responsible for a team of 8 Engineers reporting to the Chief Engineer. Principle duties included coordination and control of R&D programmes across 4 sites to ensure timely delivery and on budget. Development of new cable products, development and implementation of new cable technology and engineering. Development of novel cable compounds for internal manufacture and use by all divisions. Implementation of cost reduction initiatives across UK sites and to take part in factory improvement teams. Member of Pirelli European teams working to rationalise materials and maximize purchasing initiatives. Technical authority for control and development of company

material approval database in line with ISO9001 & 14000. Specify and supply technical instructions and manufacturing instructions for full range of compounds.

1992 – 2000 Technical Manager – Energy & Comms. Materials, Pirelli
1990 – 1992 Section Leader, Energy Materials Group, Pirelli
1989 – 1990 Section Leader, Energy Product Development, Pirelli
1988 – 1989 Senior Technologist, Special Materials Group, Pirelli
1987 – 1988 Technologist, Special Materials Group, Pirelli
1986 – 1987 Senior Technician, Special Materials Group, Pirelli
1984 – 1985 Laboratory Assistant, Rubber & Plastics Group, Pirelli

The role of Materials Technology Ltd includes:

Investigation of markets, failure avoidance and failure investigation, selection of materials, corrosion studies, inspection, quality control, welding engineering, NDT, R.&.D. Quality assurance to assist companies to achieve ISO 9000 certification, chemical engineering, acting as expert witness.

Background covers most industries including civil engineering, defence, oil, gas, petrochemicals, marine, automotive, leisure, fashion, medical, defence, telecommunications.

TECHNICAL EXPERIENCE

Nicholas Kenworthy, has over 30 years experience in the field of materials and has been widely involved in materials selection, compounding and development of including plastics, rubbers, metals, ceramics, failure investigation and avoidance, specification writing, supervision, non-destructive testing & analysis of materials, inspection, quality assurance and quality control for industries including petrochemical, oil, offshore, marine, cable, electronics, aerospace, automotive and leisure.

He acts as a materials expert for a number of clients on a retainer basis and is routinely involved in insurance and litigation work. He has lectured to engineers throughout industry on materials and materials related aspects.

APPENDIX 1

Letter of Instruction from DLAPiper To MTL Dated 13th September 2016 Ref JZC/JZC/3127430/517258/AUM/121

Metallurgical examination of samples from the Basslink cable
To undertake a metallurgical examination of samples of lead alloy sheath and galvanised steel tapes taken from a mass impregnated single core DC cable in the vicinity of an electrical failure site. Do not destroy any samples and evidence, including any removing, scraping or causing other damage. All tests shall and must be non-destructive.

There are two bulges in the lead sheath that are accompanied by disturbance and separation of the overlying reinforcing tapes. The reinforcing layer comprises four tapes applied in two layers. Each layer comprises two double start tapes laid with a butt gap. The north lead sheath bulge is immediately over the site of the electrical failure. The south lead sheath bulge is 400 mm approximately to the south of thet this location the electrical core has not failed.

1. **Non-destructive examination of samples of lead alloy sheath**

1.1. Objectives - to examine the samples and determine:

1.1.1. whether the South bulge formed slowly or quickly;
1.1.2. whether the North Bulge formed slowly or quickly;
1.1.3. the condition of the lead alloy sheath before the failure.

1.2. Work content:

1.2.1. visual and dimensional examination of the north and South Bulge samples and orientation with the photographs in CCI report ER808;

1.2.2. examination of rupture faces and morphology. How fast were the processes that lead to deformation or fracture of the supplied samples? What tests should be undertaken to confirm this, other than the matters set out below?;

1.2.3. non-destructive examination of the rupture sites (including avoiding etching, staining and dye penetration);

1.2.3.1. lead alloy grain structure;
1.2.3.2. lead alloy composition and uniformity;
1.2.3.3. corrosion;
1.2.3.4. cracks;
1.2.3.5. possible signs of fatigue;
1.2.3.6. possible signs of a pre-existing lead alloy sheath repair;
1.2.3.7. possible signs of electrical power arc ablation.

1.3. Samples of lead alloy sheath:

1.3.1. north and South Bulges: six samples; VICT 146/24 to VICT 146/29.

2. **Non-destructive examination of the tape samples**

2.1. Objectives - to conduct a non-destructive examination of the tape samples and determine:

2.1.1. The type of fracture faces.
2.1.1.1. Slow or quick failure.
2.1.1.2. The orientation of the stresses leading to failure.

2.1.1.3. Corrosion.
2.1.1.4. Fatigue.
2.1.1.5. Tear.
2.1.1.6. Crease.

2.1.2. The possible presence of a pre-existing tape join (i.e. overlap, mechanical, welded).

2.1.3. The condition of the reinforcing tapes before the electrical failure.

2.2. Work content

2.2.1. Visual and dimensional examination of the tape samples and orientation with the photographs in CCI Report ER808.
2.2.2. Tape fracture analysis and morphology:
2.2.2.1. Were the tapes in a continuous length, i.e. whether the faces of separated tapes join. (reference ER808 figures 52–65).
2.2.2.2. Fast creep?
2.2.2.3. Hoop stress failure?
2.2.2.4. Cable axial failure?

2.2.3. Examination of the tape crease shown in ER808 figure 58:

2.2.3.1. Had the tape crease pre-existed the electrical failure or been formed by the electrical failure?

2.2.4. non-destructive examination of the tapes at the fracture sites (including avoiding etching, staining and die penetration):

2.2.4.1. structural integrity of the steel tape and galvanised layers;
2.2.4.2. corrosion;
2.2.4.3. cracks;
2.2.4.4. possible signs of fatigue;
2.2.4.5. possible signs of a pre-existing tape joint or repair;
2.2.4.6. possible signs of electrical power arc ablation.

2.3. **Samples of reinforcing tapes:**

2.3.1. north and South Bulges: 11 samples; VICT 146/12 to VICT 146/22.

APPENDIX 2

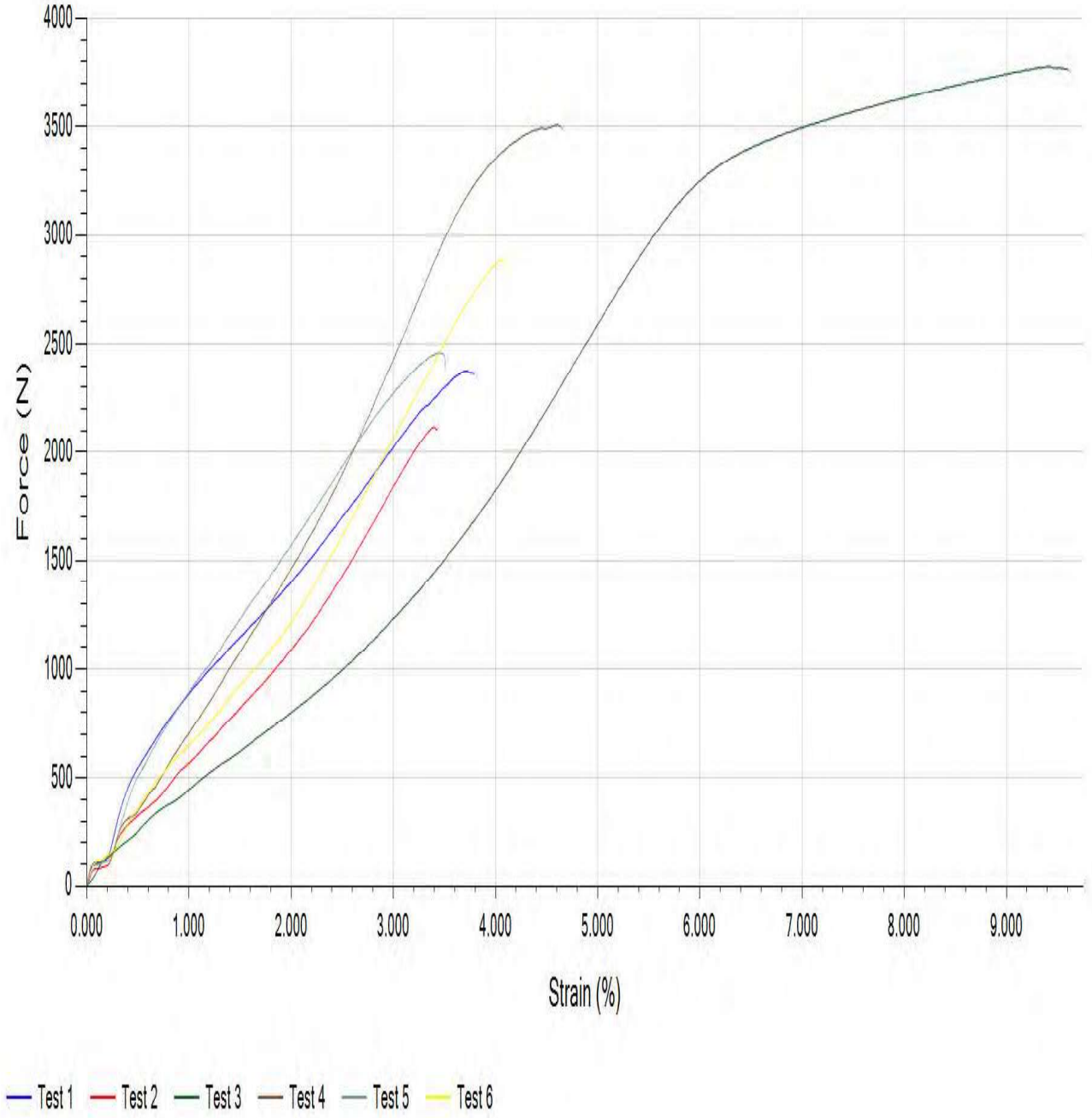
Stress / strain curves from testing of reinforcing tapes

Customer : DLA Piper	**Test Name : 17. General Method-Metal Tapes**
Material Type : Galv Steel Tape	**Test Type : Tensile**
Sample Ref : Vict 144/2 outer	**Test Date : 15/10/2016 10:46**
Operator : N Kenworthy	**Test Speed : 10.000 mm/min**
	Pretension : 2.000 N
	Width : 20.000 mm
	Thickness : 0.350 mm
	Sample Length : 75.000 mm

Comments :

Test No	Thickness (mm)	Width (mm)	Stress @ Peak (N/mm²)	Strain @ Peak (%)	Force @ Break (N)	Stress @ Break (N/mm²)	Strain @ Break (%)
1	0.350	18.890	359.525	3.721	2364.000	357.559	3.789
2	0.350	20.350	297.087	3.403	2105.000	295.542	3.429
3	0.350	20.940	515.623	9.395	3760.000	513.030	9.615
4	0.350	21.677	462.373	4.597	3483.000	459.078	4.653
5	0.350	21.240	330.912	3.441	2391.000	321.630	3.511
6	0.350	20.633	399.360	4.060	2860.000	396.037	4.083
Min	0.350	18.890	297.087	3.403	2105.000	295.542	3.429
Mean	0.350	20.622	394.147	4.769	2827.167	390.479	4.847
Max	0.350	21.677	515.623	9.395	3760.000	513.030	9.615
S.D.	0.000	0.966	82.530	2.309	667.482	83.177	2.378
C. of V.	0.000	4.687	20.939	48.412	23.610	21.301	49.059
L.C.L.	0.350	19.607	307.536	2.346	2126.682	303.189	2.351
U.C.L.	0.350	21.636	480.758	7.193	3527.651	477.769	7.342

Test No	Force @ Break (N/mm)						
1	125.146						
2	103.440						
3	179.561						
4	160.677						
5	112.571						
6	138.613						
Min	103.440						
Mean	136.668						
Max	179.561						
S.D.	29.112						
C. of V.	21.301						
L.C.L.	106.116						
U.C.L.	167.219						

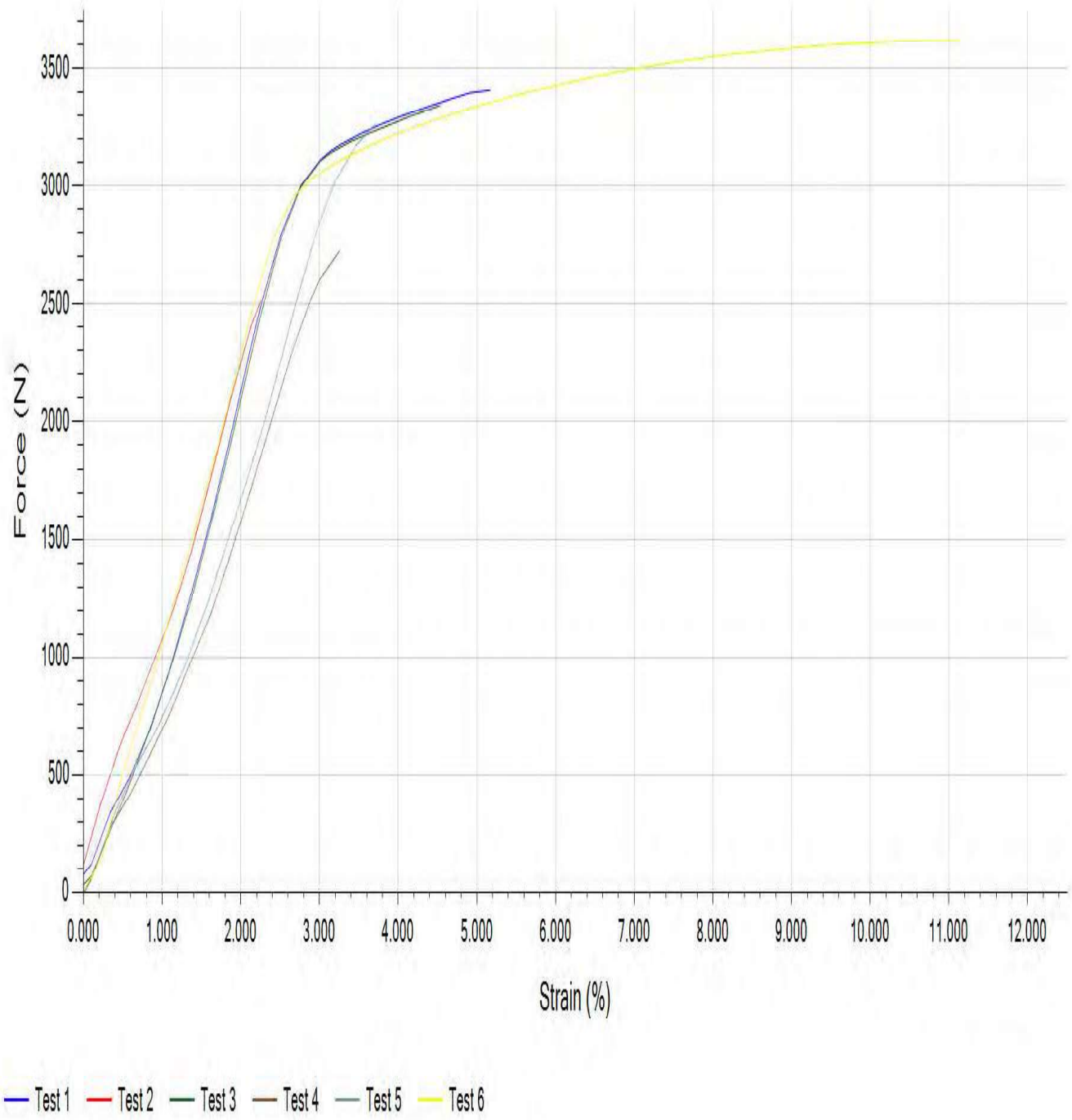

4000
3500
3000
2500
2000
1500
1000
500
0
Force (N)
0.000
1.000
2.000
3.000
4.000
5.000
6.000
7.000
8.000
9.000
Strain (%)
Test 1
Test 2
Test 3
Test 4
Test 5
Test 6

Customer : DLA Piper	**Test Name : 17. General Method-Metal Tapes**
Material Type : Galv Steel Tape	**Test Type : Tensile**
Sample Ref : Vict 144/2 outer 200	**Test Date : 15/10/2016 11:10**
Operator : N Kenworthy	**Test Speed : 200.000 mm/min**
	Pretension : 2.000 N
	Width : 20.000 mm
	Thickness : 0.350 mm
	Sample Length : 75.000 mm

Comments :

Test No	Thickness (mm)	Width (mm)	Stress @ Peak (N/mm²)	Strain @ Peak (%)	Force @ Break (N)	Stress @ Break (N/mm²)	Strain @ Break (%)
1	0.350	19.400	502.504	5.167	3412.000	502.504	5.167
2	0.350	19.800	363.348	2.253	2518.000	363.348	2.253
3	0.350	19.313	495.151	4.535	3347.000	495.151	4.535
4	0.350	19.390	401.975	3.256	2728.000	401.975	3.256
5	0.350	20.573	453.854	3.712	3268.000	453.854	3.712
6	0.350	18.423	561.410	10.880	3620.000	561.410	11.130
Min	0.350	18.423	363.348	2.253	2518.000	363.348	2.253
Mean	0.350	19.483	463.040	4.967	3148.833	463.040	5.009
Max	0.350	20.573	561.410	10.880	3620.000	561.410	11.130
S.D.	0.000	0.701	72.135	3.068	428.900	72.135	3.164
C. of V.	0.000	3.598	15.579	61.759	13.621	15.579	63.175
L.C.L.	0.350	18.748	387.339	1.748	2698.727	387.339	1.688
U.C.L.	0.350	20.219	538.742	8.187	3598.940	538.742	8.330

Test No	Force @ Break (N/mm)						
1	175.876						
2	127.172						
3	173.303						
4	140.691						
5	158.849						
6	196.494						
Min	127.172						
Mean	162.064						
Max	196.494						
S.D.	25.247						
C. of V.	15.579						
L.C.L.	135.569						
U.C.L.	188.560						

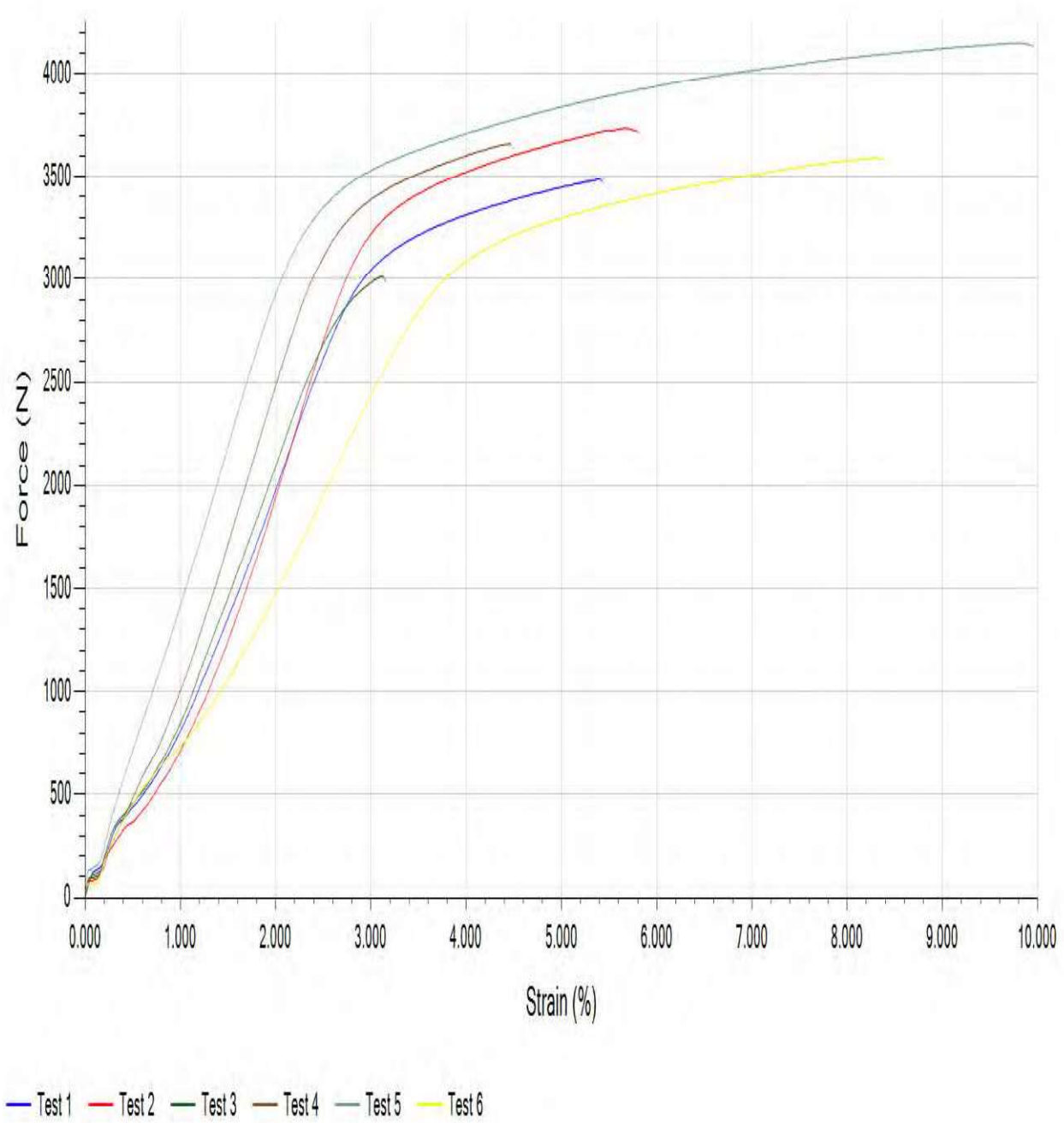

Force (N)
3500
3000
2500
2000
1500
1000
500
0
0.000
1.000
2.000
3.000
4.000
5.000
6.000
7.000
8.000
9.000
10.000
11.000
12.000
Strain (%)
Test 1
Test 2
Test 3
Test 4
Test 5
Test 6

Customer : DLA Piper	**Test Name : 17. General Method-Metal Tapes**
Material Type : Galv Steel Tape	**Test Type : Tensile**
Sample Ref : Vict 144/3	**Test Date : 15/10/2016 10:30**
Operator : N Kenworthy	**Test Speed : 10.000 mm/min**
	Pretension : 2.000 N
	Width : 20.000 mm
	Thickness : 0.350 mm
	Sample Length : 75.000 mm

Comments :

Test No	Thickness (mm)	Width (mm)	Stress @ Peak (N/mm²)	Strain @ Peak (%)	Force @ Break (N)	Stress @ Break (N/mm²)	Strain @ Break (%)
1	0.350	19.220	518.508	5.381	3465.000	515.088	5.436
2	0.350	20.597	518.106	5.661	3715.000	515.332	5.800
3	0.350	19.297	446.109	3.105	2984.000	441.816	3.156
4	0.350	20.597	507.702	4.456	3635.000	504.234	4.482
5	0.350	20.700	572.533	9.776	4125.000	569.358	9.959
6	0.350	19.337	530.589	8.252	3571.000	527.634	8.399
Min	0.350	19.220	446.109	3.105	2984.000	441.816	3.156
Mean	0.350	19.958	515.591	6.105	3582.500	512.244	6.205
Max	0.350	20.700	572.533	9.776	4125.000	569.358	9.959
S.D.	0.000	0.740	40.920	2.471	370.610	41.330	2.527
C. of V.	0.000	3.705	7.936	40.468	10.345	8.068	40.721
L.C.L.	0.350	19.182	472.648	3.513	3193.566	468.870	3.553
U.C.L.	0.350	20.734	558.534	8.698	3971.434	555.617	8.857

Test No	Force @ Break (N/mm)						
1	180.281						
2	180.366						
3	154.635						
4	176.482						
5	199.275						
6	184.672						
Min	154.635						
Mean	179.285						
Max	199.275						
S.D.	14.465						
C. of V.	8.068						
L.C.L.	164.105						
U.C.L.	194.466						

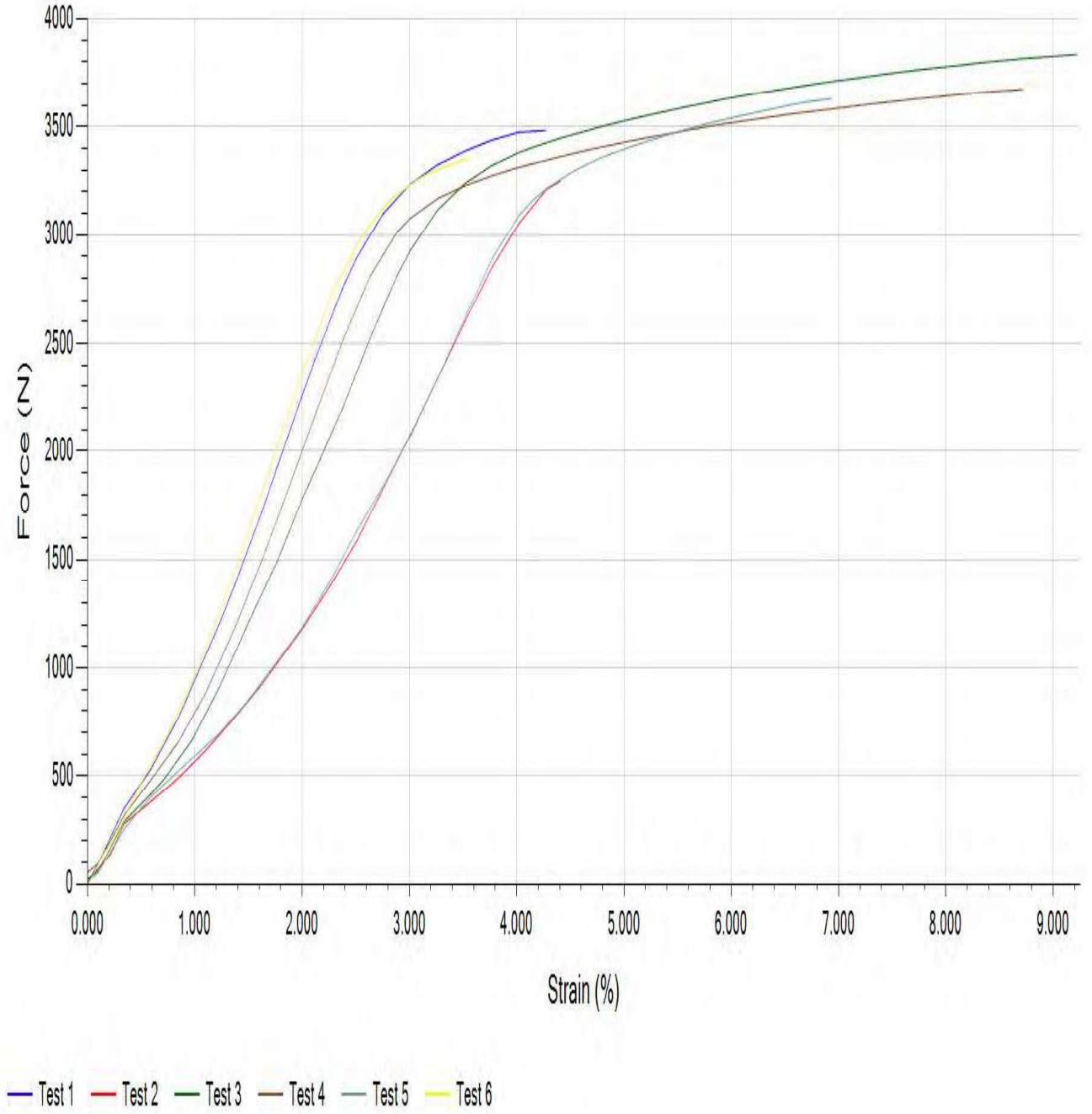

Force (N)
4000
3500
3000
2500
2000
1500
1000
500
0
0.000
1.000
2.000
3.000
4.000
5.000
6.000
7.000
8.000
9.000
10.000
Strain (%)
Test 1
Test 2
Test 3
Test 4
Test 5
Test 6

Customer : DLA Piper	**Test Name : 17. General Method-Metal Tapes**
Material Type : Galv Steel Tape	**Test Type : Tensile**
Sample Ref : Vict 144/3 inner 200	**Test Date : 15/10/2016 11:01**
Operator : N Kenworthy	**Test Speed : 200.000 mm/min**
	Pretension : 2.000 N
	Width : 20.000 mm
	Thickness : 0.350 mm
	Sample Length : 75.000 mm

Comments :

Test No	Thickness (mm)	Width (mm)	Stress @ Peak (N/mm²)	Strain @ Peak (%)	Force @ Break (N)	Stress @ Break (N/mm²)	Strain @ Break (%)
1	0.350	19.607	507.545	4.270	3483.000	507.545	4.270
2	0.350	20.793	446.304	4.404	3248.000	446.304	4.404
3	0.350	20.357	538.249	9.223	3835.000	538.249	9.223
4	0.350	19.513	537.956	8.713	3674.000	537.956	8.713
5	0.350	20.393	508.718	6.937	3631.000	508.718	6.937
6	0.350	19.520	491.218	3.565	3356.000	491.218	3.565
Min	0.350	19.513	446.304	3.565	3248.000	446.304	3.565
Mean	0.350	20.031	504.998	6.186	3537.833	504.998	6.186
Max	0.350	20.793	538.249	9.223	3835.000	538.249	9.223
S.D.	0.000	0.553	34.197	2.445	217.073	34.197	2.445
C. of V.	0.000	2.759	6.772	39.525	6.136	6.772	39.525
L.C.L.	0.350	19.451	469.111	3.620	3310.028	469.111	3.620
U.C.L.	0.350	20.610	540.886	8.751	3765.639	540.886	8.751

Test No	Force @ Break (N/mm)						
1	177.641						
2	156.206						
3	188.387						
4	188.285						
5	178.051						
6	171.926						
Min	156.206						
Mean	176.749						
Max	188.387						
S.D.	11.969						
C. of V.	6.772						
L.C.L.	164.189						
U.C.L.	189.310						


Force (N)
4000
3500
3000
2500
2000
1500
1000
500
0
0.000
1.000
2.000
3.000
4.000
5.000
6.000
7.000
8.000
9.000
Strain (%)
Test 1
Test 2
Test 3
Test 4
Test 5
Test 6

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

TITLE: **Basslink KP199.256 Failure Investigation Findings**

REPORT No: **ER 833**

CUSTOMER: **Basslink (BPL)**

AUTHOR: **Eur Ing Laurence Trim BEng CEng MIET**
Eur Ing Brian Gregory BSc CEng MIEEE FIET

DATE: **2nd December 2016**

Summary

1. Independent examinations of the failed Basslink cable were performed by CCI at the Prysmian and CCI Laboratories. Metallurgical and materials examinations were performed by Materials Technology.

2. The findings of the investigation are:

3. The fault occurred within the cable. The fault was not at a location of a joint, or a lead sheath to armour bond.

4. In the absence of surviving evidence it was not possible to determine the cause of failure of the cable as:

   - There was no evidence of any pre-existing external mechanical damage to the cable.
   - The electrical fault was a 'radial, short path' type. The path extended through the paper tape insulation between the conductor at high voltage and the lead alloy sheath at low voltage.
   - There was no evidence of any incipient electrical activity connected with the fault site or present elsewhere in the cable.
   - The point of initiation within the fault path and the direction of propagation of the electrical failure could not be determined due to the severity of the fault damage.

5. The fault position was beneath the northern bulge in the cable.

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6. The northern bulge was formed by the explosive effect of the electrical power arc within it.

7. A second bulge was present 480 mm to the south of the northern bulge. The insulation inside the southern bulge was sound and did not contain electrical distress.

8. The southern bulge was formed by the shock wave travelling to a location where the steel reinforcing tapes had a wider butt gap and experienced a force above their breaking point.

9. The operating conditions at, and preceding, the time of failure were no different to those of the year 2015. The cable was within its thermal rating.

10. The insulation adjacent to the failure site was sound and showed no evidence of thermal ageing.

11. A sample of cable remote from the fault site was in sound condition.

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1 Introduction

12. Cable Consulting International Ltd (CCI) is an independent engineering consultancy that provides expertise on supertension land and submarine cable system technology. The technology includes all types of cable systems that operate in the voltage range 11kV upwards. The technology includes the 400kV mass impregnated HVDC Basslink cable discussed in this report.

13. CCI was established in 2001 and employs a team of eight degree qualified engineering staff. Seven of the engineers, including the authors of this report, are Chartered Engineers and members of the European Federation of Associated Engineers (FEANI Registered). Six of the engineering staff, including the main authors of this report, have previous experience working for a major cable manufacturer designing, developing, manufacturing and installing supertension land and submarine cable systems. One engineer has experience working for a power transmission utility.

14. CCI provides engineering expertise on cable systems specifically including all aspects of the technology that spans from cable termination to cable termination of a cable circuit.

15. CCI has consulted on a wide range of topics including, but not limited to: cable system design, route selection, thermal design calculations, the production of cable system design and manufacturing specifications, cable system procurement support, factory manufacturing capability assessments, product prequalification and type test witnessing, product factory acceptance test witnessing, cable and accessory condition assessment monitoring, failure investigation works and the provision of expert opinion.

16. CCI has conducted numerous failure investigations on cables and cable accessories in the voltage range 11kV to 400kV, including previously examining in 2006 the 400kV HVDC mass impregnated Basslink cable featured in this report.

17. Eur Ing Laurence Trim is a Senior Consultant at CCI joining the company in 2004 (CV appended in Section 7). He has over 25 years experience working in the power industry with a focus on land and submarine power cable technology including: design, development, condition assessment, testing, and failure investigations. Prior to joining CCI Laurence worked for 11 years within a cable manufacturing facility (BICC Supertension and Subsea Cables) before moving into consultancy roles. In 2006 Laurence was engaged by insurance loss adjusters to investigate the cable failures associated with the commissioning of the 400kV Basslink.

18. Eur Ing Brian Gregory is the Technical Director and a founding Director of CCI (CV appended in Section 7). He has 53 years experience working in the power industry on all aspects of land and subsea cable systems. Between 1963 and 2001 he had experience with BICC and AEI in the manufacture of supertension land and subsea cable systems, becoming the Chief Engineer of BICC Supertension and Subsea Cables in 1992. Brian has extensive experience in the forensic

examination of cables and accessories that failed during development evaluation tests and in service operation. He has experience in the manufacture of all types of land and submarine cables.

2 Glossary

19. The following abbreviations are used within this report:

AEMO	Australian Energy Market Operator
CCI	Cable Consulting International Limited
CESI	CESI S.p.A, via Rubattino, 54, I-20134 Milan – Italy
Core	The internal build of the cable that includes the conductor, the insulation, insulation screens and binder tapes.
DSC	Differential scanning calorimetry
HE	High voltage cable earth bond
HFJ	High voltage cable factory joint
HV	High voltage
HVDC	High voltage direct current
km	Kilometre
KP	Kilometre position
kV	Kilovolt
LV	Low voltage
mm	millimetre
PE	Polyethylene
PE oversheath	Polyethylene oversheath
Reinforcing tape(s)	Galvanised steel reinforcing tape(s)
XLPE	Cross-linked polyethylene
VICT-144	Sample reference VICT-144
VICT-146	Sample reference VICT-146
Tape head	A set of individual paper tapes applied with a common lay angle and direction to form a part of the lapped paper insulation thickness.

3 Overview

20. The 400kV HVDC Basslink Interconnector cable spans 298 km from the cable to overhead line transition station near McGaurans Beach in Victoria to the transition station near Four Mile Bluff in Tasmania, Figure 1. The cable link was manufactured and installed by Pirelli (later acquired by Prysmian). The cable link was placed into commercial operation in April 2006.

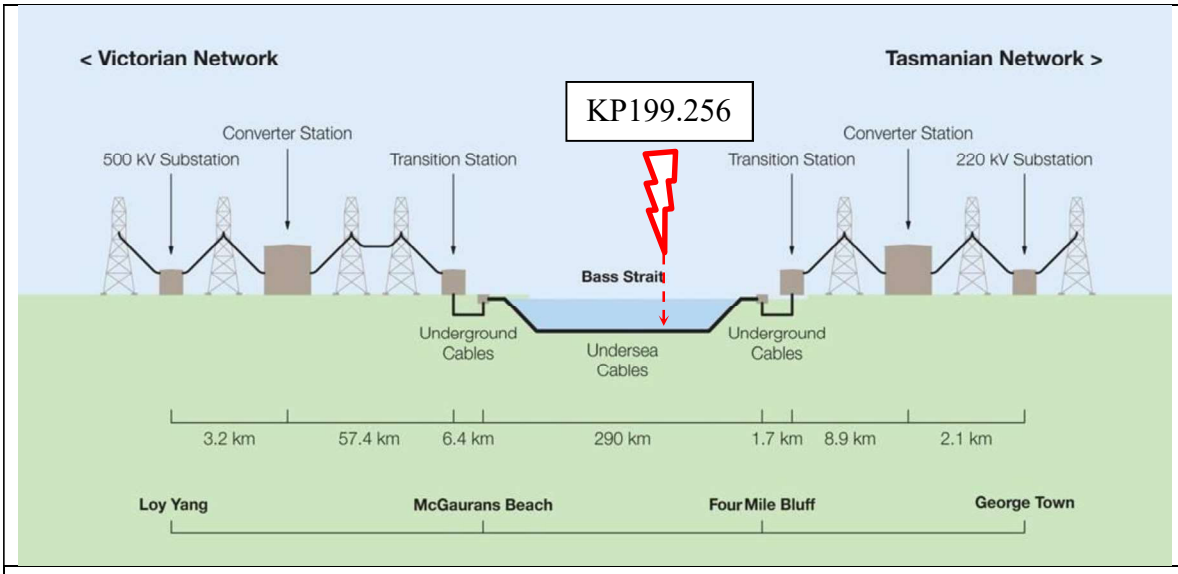


Figure 1 Basslink schematic diagram showing the failure position

21. The submarine section of the link comprises the following elements:

- A 400kV, 1500mm² copper conductor, high voltage (HV) direct current (DC) cable insulated with MI (mass impregnated) paper tapes, lead alloy sheath, anti-corrosion PE sheath, galvanised steel reinforcing tapes, galvanised armour wires and polypropylene string serving {ER 795, Section 3}.
- A 12kV, 1400mm² copper conductor, low voltage (LV) metallic return cable insulated with cross-linked polyethylene insulation (XLPE).
- A fibre optic communications cable.

22. During installation of the submarine section, the three elements were bound as a bundle and simultaneously laid onto the seabed in approximately 100km long sections. Ship and land based jointing activities connected the three subsea cable sections and two land cable sections into a continuous 298km length. The cable bundle was post-lay buried in the sea bed using a combination of remote operated subsea jetting and rock cutting machinery.

23. The cable link was designed to continuously transmit 500MW of power and to dynamically transmit 630MW for defined periods when the Basslink equipment is operating within certain parameters [1,2].

24. The 400kV HVDC submarine cable element of the Interconnector failed on the 20th December 2015 at 14:05hrs. The failure was located in the cable at position KP199.256 (measured from the McGaurans Beach transition joint that connects the submarine and land cable, Victoria), Figure 1. The failure was in the cable and was not i) at a joint, the nearest being a factory joint HFJ 3.1 at location KP 199.398[3] or ii) at a bond between the lead sheath and armour wires, the nearest being HE 3.3 at KP 199.345[4]. The water depth at this location is 72.8 m[5] and the cable burial depth 0.5m.

25. The Basslink cable had operated in service for nearly ten years prior to the failure event. During the original commissioning process some cable failures had occurred, had been made good and had satisfactorily withstood a final HV commissioning test. This is the first cable failure to have occurred after the HV commissioning test. The present failure location is remote from the locations of the commissioning test failures.

26. Following the fault a number of electrical 'burning-out' procedures were applied to the cable length to permit the fault location position to be determined. These procedures are standard industry practice commonly used as part of cable fault location. The purpose of burning-out is to reduce the electrical resistance to a low value by additional burning of the fault damaged insulation. The procedures increase the original fault damage and may destroy pre-fault evidence that had been present within the cable.

27. During the fault location and cable recovery processes there was no evidence of disturbance of the sea bed over the buried cable fault position; for example disturbance by third party intervention such as a ship's anchor or fishing gear. The cable had been correctly buried and was protected within the sea bed.

28. The 11.5m section of cable containing the fault site at KP199.256 was recovered from the seabed on the 27th March 2016 using the Cable Ship Ile de Re. This section of cable, and four other sections immediately adjacent to the north and the south of the failure site, were packaged and shipped to the Prysmian laboratory at CESI, Milan.

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[1] Siemens Report titled "Overload / Dynamic Rating Study Report", PTDH171/P-000090/ED1.011.CTV-A, dated 25.01.05
[2] Siemens Report titled "Pole Control System Information Manual", PTDH171/P-000090/EB2.341.CTV-R, dated 24.04.2006.
[3] Pirelli, Basslink Position of Cable Joints, Rev 0, November 2005.
[4] Pirelli, Basslink Position of Earth Connections, Rev 0, November 2005.
[5] Pirelli, Basslink Alignment Sheet 25 of 35, Drg No AL_3196B1-25, Rev 1, December 2005.

29. An independent Stage 1 inspection of the failed cable sample, VICT-146, and unfailed reference sample, VICT-144, was conducted by Cable Consulting International Ltd (CCI) at CESI in the presence of representatives from the following interested parties: Basslink, Keppel Infrastructure Trust, FM Global, Hydro Tasmania, and Prysmian over the period 27th to 29th April 2016. Under the direction of CCI the Stage 1 inspection dismantled the individual cable components in preparation for a future detailed Stage 2 bench top inspection. Prysmian provided the laboratory, cable jointers, technicians and tools to dismantle the cable components.

30. CCI Report ER 795, dated 27th May 2016, was issued to give a factual account of the features found during the Stage 1 inspection at CESI.

31. Cable components were selected at CESI and sent to CCI's laboratory at Underriver, Kent, UK for the Stage 2 bench top inspection.

32. Inspection of the components listed below from the failure site was conducted by CCI over the period 7th to 9th June 2016 in the presence of representatives from the following interested parties: Basslink, FM Global and Hydro Tasmania.
    - Conductor,
    - Paper tape insulation at, and immediately adjacent to, the fault site,
    - Lead alloy sheath,
    - Polyethylene (PE) oversheath,
    - Reinforcing tapes,
    - Insulation paper tapes from the outer and inner 'heads' of the insulation (Heads 1 & 19). (Note: A 'head' is the group of paper tapes, in the case of the Basslink cable being typically 12 in number, that are applied by one of the many sequential lapping heads that form the complete factory lapping machine. Each lapping head rotates in an alternate direction.)

33. CCI Report ER 808, dated 27th June 2016, was issued to give a factual account of the features found during the Stage 2 inspection.

34. During the Stage 2 examination samples were identified for further detailed metallurgical and material inspection.

35. Materials Technology Ltd, Southampton, UK performed metallurgical and materials inspections of the retained samples.

36. CCI arranged for the following samples to be delivered to the Materials Technology Laboratory:
    - Lead alloy sheath from the failed sample VICT-146.
    - PE oversheath from the failed sample VICT-146.
    - Reinforcing tapes from the failed sample VICT-146.
    - PE oversheath from the remote sample VICT-144.

- Reinforcing tapes from the remote sample VICT-144.

37. Materials Technology performed detailed metallurgical and analytical work as reported in references G9748 issued on 28th November 2016 and G11863 issued on 29th November 2016.

38. This concluding report draws together the key features reported during the three stages of work with the objectives of i) explaining the significance of their presence and ii) determining whether sufficient evidence had survived on which to base a cause of failure.

39. This concluding report should be read in conjunction with the following:

- CCI Report ER 795, titled "Basslink KP199.256 Failure Examination 27th to 29th April 2016" dated 27th May 2016.
- CCI Report ER 808, titled "Basslink KP199.256 Failure Examination 7th to 9th June 2016 at CCI", dated 27th June 2016.
- Materials Technology Report G9748, titled "Report on Analysis of Samples from 400kV Basslink Cable", dated 28th November 2016.
- Materials Technology Report G11863, titled "Report on Thermal Analysis (DSC) of Samples From 400kV Basslink Cable Fault", dated 29th November 2016.

4 Investigation Findings

40. The facts from the examinations of the cable samples containing the failure site (VICT-146) and unfailed reference sample (VICT-144), are listed in CCI Report references ER 795 and ER 808.

41. The facts from the metallurgical and analytical examination of the retained components are listed in Materials Technology Ltd reports G9748 and G11863.

42. This report makes references to the figures and section numbers in reports ER 795, ER 808, G9748 and G11863 that factually describe the features. This report does not replicate the photographs and detailed descriptions.

43. In the following sections the various key features of the failure site are summarised with respect to each component within the cable construction starting from the cable conductor and working outwards. The significance of each feature to the investigation is discussed and a conclusion given.

4.1 Conductor

44. Arc erosion of the copper conductor had formed a concave depression to a maximum radial depth of 6 mm, length of 45 mm and circumferential distance of 42 mm (30% of the circumference) {ER 795, Figure 105}. The surface had been eroded / ablated to form a shallow depression extending a length of 130 mm. Over this length the normally smooth conductor surface exhibited a uniformly roughened surface texture similar to that achieved by a grit blasting process {ER 808, Figures 4 & 5}. This finish was attributed to the erosion from both the fault arc burning and the fault location 'burning-out' processes.

45. A 20 mm diameter circular depression was present in the centre of the conductor erosion {ER 808, Figures 3 to 5}. This was identified as the HV end of the main power arc.

46. A permanent set (bend) was present in the conductor. It was centred at the fault position {ER 808, Figure 2}. Evidence of non-carbonised, torn insulating paper tapes was found on the underside of the fault position {ER 808, Figure 27}. The torn paper tapes were deduced to have been formed post-fault. The cause was attributed to the cable bending preferentially at the fault location during recovery from the seabed. The bending stiffness of the cable had been reduced at this location by the burnt paper tape insulation, by the fault damaged lead and PE sheaths and by the broken steel reinforcing tapes.

47. The conductor outside the fault area was in a sound condition i.e. it had a smooth cylindrical surface free of protrusions and it correctly contained impregnating compound in the interstices between the copper segments {ER 808, Pages 7 and 9, Section 4.1}.

48. The individual conductor segments that form the cylindrical conductor shape were inspected for the possible presence of a factory welded join by looking for continuity of colouration and of manufacturing die marks {ER 808, pages 7 and 8, Section 4.1}. No sign of a welded join was present either within the arc damaged conductor, or in the non-fault affected conductor. It is concluded that the surviving conductor geometry had been sound prior to the electrical failure.

4.2 Conductor Screen Tapes

49. The carbon paper conductor screen tapes that had been in the fault path were destroyed and the adjacent tapes severely burnt and degraded by the power arc {ER 795, Section 5.5.11, Figure 103; ER 808, Section 4.2, Figures 18 and 19}.

50. The conductor screening tapes outside this zone were in sound condition and had been well applied {ER 795, Sections 5.5.10.20 and 5.5.10.21}.

51. There was no evidence of a defect having been present within the surviving conductor screen tapes.

4.3 Insulation

52. The paper insulation tapes in the fault path had been destroyed by the power arc {ER 795, Figures 90, 94, 97 and 98; ER 808, Figures 14, 20, 21 to 25}.

53. The paper tapes adjacent to the fault zone had been swollen by the sea water that had entered through the fault puncture holes in the lead and PE sheaths after the failure event {ER 795, Section 5.5.10.2, Figures 97, 98 and 99}.

54. Making an allowance for the presence of water swollen paper tapes, the tapes were judged to have been sound and well applied, i.e. insulation that i) was firm and absent of creases and wrinkles and ii) had uniform butt gap widths and tape registration (overlaps). There were isolated cases in sample reference VICT-144 of variation in tape registration {ER 795, Section 5.4.11} i.e. variation in the typical 70/30% overlap. There was no sign of electrical distress within the butt gaps at these locations.

55. A uniform distribution of impregnating compound was present in the insulation away from the failure site. The compound was present within the butt gaps between the paper tapes and over each layer of tape i.e. the insulating tapes, screening tapes and core protective copper woven fabric tape {ER 795, Figures 26 and 27}. Immediately adjacent to the fault position the surviving insulation contained less compound and had a drier appearance. Evidence of residual compound was present within the papers at the failure site {ER 808, Figure 16}. The local reduction in impregnating compound was attributed to evaporation by heat from the fault arc.

56. Moisture tests to assess the dryness of the paper insulation were discounted as sea water had entered the sample containing the fault through the fault punctured lead and PE sheaths. Verdigris was also present at the cut ends of the conductors in cable samples VICT-144 and VICT-146 {ER 795, figure 9} and indicated that moisture was present along the sample lengths. It was concluded that moisture and electrical tests on the cable samples would not have given representative results.

57. The general condition of the paper insulating tapes was tested for the possible presence of thermal aging. A tape sample from each tape head was bent back on itself to test for the absence of any heat embrittlement {ER 795, Sections 5.5.10.1 to 5.5.10.20}. No signs of heat aging embrittlement or discolouration were found in any of the non-fault affected tapes.

58. A row of small brown spots was present in one butt gap between insulating tapes at distance 5.0 m from sample datum {ER 795, Figure 95} at a position 480 mm to the south of the fault path i.e. at the southern bulge. The spots were present in a gap on one side of the tape only. There was no evidence of electrical pinholing, waxing or deterioration to the paper tape surfaces. There was no evidence that the spots were associated with the fault, or would have led to electrical distress.

59. Samples of paper tapes were taken from Head Number 1 (outer insulation head) and Head Number 19 (inner insulation head) and were solvent extracted, dyed and examined {ER 808, Section 4.6}. The absence of waxing confirmed that electrical partial discharging sufficient to have formed micro-crystalline wax had been absent.

60. A crease in the form of a shallow furrow was present at the top dead centre positon on the north side of the fault path at the Northern Bulge {ER 795, Section 5.5.10.1, Figure 89}. The furrow did not contain soot. The furrow adjoined a split connected to the fault site, which did contain soot. It was concluded that the furrow had formed post fault and so had remained clean. There was no evidence of deterioration or damage to the paper insulation at the location of the furrow. Furrows were absent from the insulation in sample VICT-144. It was concluded that the furrow in the failed sample had formed after the fault.

61. A similar shallow furrow to the above, 190 mm long, was present at the 3 o'clock orientation in the outer 3.67 mm radial thickness of tapes below the surface of the outer insulation tapes, south of the Southern Bulge {ER 795, Figure 91}. There was no evidence of deterioration or damage to the paper insulation. There was no sign of any soot or debris within the furrow. The conclusion was reached that the furrow had been formed after the fault.

4.4 Insulation Screen Tapes

62. The insulation screening tapes immediately in the fault path had been destroyed and adjacent tapes severely burnt and degraded by the power arc {ER 795, Figures 84 and 90}. The

metallised carbon paper screening tapes outside this zone had been well applied and were in sound condition.

63. The metallised carbon screening tapes over the insulation between the northern and southern cable bulges exhibited a loss of the aluminium foil surface and a white tarnished appearance {ER 795, Figures 81, 87 and 88}. These were concluded to have been caused by: i) current flow during the fault and during subsequent fault location activities and ii) corrosion due to sea water entry after the fault.

64. Away from the fault site the screening tapes were in sound condition {ER 795, Figure 22 to 24}.

4.5 Core Binder Tape

65. The copper woven fabric binder tape had been destroyed in the immediate vicinity of the fault path {ER 795, Figure 77 and 84}. Adjacent to the fault hole, the tape had been fused to the lead sheath by the power arc {ER 808, Figure 31}. The binder tape adjacent to the fault was in sound condition. The shape of the binder tape, of its woven copper wire and of the underlying core screening tapes had been impressed as witness marks into the inner surface of the lead sheath {ER 808, Figure 29 and 30}. There was no evidence of any electrical pitting by the current flow from the insulation to the lead sheath. It was concluded that the binder tapes had been present in service operation and that the copper continuity wire, which it contained, had been in contact with both the screening tapes and the lead sheath.

4.6 Lead Alloy Sheath

66. Two areas of damage to the extruded lead alloy sheath were present. One was over the site of the electrical fault path, this disturbance being termed the ‘northern bulge’, and the second approximately 480 mm further south being termed the ‘southern bulge’. There was no definitive central position on a given component within each bulge and so the distances reported between the bulge centres had a variation of ±20mm.

67. Samples of lead sheath were mounted and polished by Materials Technology {G9748, Pages 61 to 64} from the following positions in sample VICT-146: i) the northern bulge, ii) the southern bulge and iii) remote from the bulges. The grain (crystal) sizes in the sample from the northern bulge were found to be larger than those from the southern and remote samples. It was concluded that the northern bulge had experienced a higher temperature rise, this being consistent with the heat generated by the power arc. The southern bulge and the remote sheath sample had a similar smaller grain size indicating that they had not experienced the high temperature rise. No defects were found in the grain structure of the samples or on the surfaces of the lead sheath.

68. The composition of the lead sheath from two samples of VICT-146 was analysed by Materials Technology {G9748, Page 59}. The lead alloy was determined to contain: Tin 0.093% – 0.14%,

and Antimony 0.096% – 0.11%. The measured percentages are lower than the values for 'lead alloy E' given in the Pirelli cable build document {ER 795, Figure 2} of Tin 0.4% and Antimony 0.2%, these being the nominal values for the lead alloy ingots and the sheath at the start of a lead sheathing extrusion run. The lead sheath was observed to be sound near to the southern and northern bulges {G9748, Page 65 and 66}. It was concluded that the measured composition of the lead alloy sheath had not contributed to the electrical failure.

4.6.1 Northern Bulge in the Lead Sheath

69. At the fault position the lead sheath exhibited three splits at the 2 o'clock to 11-30 o'clock orientations. The splits {ER 808, Figure 34; G9748, Photos 1 to 7} followed a similar orientation to the cross shaped electrical fault splits in the paper insulation {ER 795, Figures 90 and 94}. The inner surface of the lead sheath and the edges of the splits had been melted by arc burning {ER 808, Figures 33, 35 and 36; G9748, Pages 9 and 10}. A surviving split fracture face was consistent with a tear type of fracture rather than a fatigue fracture {G9748, Page 10}.

70. At the fault position a longitudinal mark of molten lead was present on the inner surface of the sheath at the 9 o'clock orientation {ER 795, Figure 69; ER 808, Figure 32}. The lead sheath was not punctured at this position. The mark was over the position of a longitudinal split in the paper insulation {ER 795, Figure 98} where a subsidiary power arc had connected to the main arc path.

71. The lead sheath was bulged outwards at the 2 o'clock to 11-30 o'clock orientation, resembling the shape of an oblate spheroid (a rugby ball) {ER 795, Figure 73}. It was concluded that the bulge had been formed by the pressure wave from the power arc. The growth of the bulge had been partly constrained by the outer reinforcing tapes (which broke) and by the armour wires which held. It was concluded that, at the centre part of the cross shaped electrical fault pattern, the splits in the bulged lead sheath had been formed between the constraining armour wires.

72. The inner surface of the bulged lead sheath contained markings showing that pre-fault it had been in intimate contact with the underlying core binder and screening tapes {ER 808, Figures 31 and 32; G9748, Photos 2 and 7}.

73. Globules of condensed metal were present on the inner surface of the lead sheath that, in addition to lead, contained a trace of copper {ER 808, Figure 33; G9748, Photos 79 and 80, Table page 58}. The sources were concluded to be vaporised lead from the sheath {ER 808, Figure 33} and copper from the conductor {ER 808, Figures 3 to 5}.

74. The lead sheath at the northern bulge site was concluded to be the low voltage end of the fault path.

4.6.2 Southern Bulge in the Lead Sheath

75. The shape of the southern bulge was a bulbous parallelogram that was more pronounced at the 4 o'clock to 5 o'clock orientation {ER 808, Figure 37}. A pronounced folded crease, 90 mm long, was present in the bulged lead sheath {ER 795, Figure 74; ER 808, Figure 38; G9748, Photo 8}. The crease in the lead sheath contained a small longitudinal split as evinced by leakage of the MI compound {ER 795, Figure 71; G9748, Photo 11}. It was concluded that i) the lead sheath had been expanded by the pressure wave travelling from the fault beneath the northern bulge and ii) then, under compression from the 7 bar external water pressure, had collapsed and split to form the fold. The lead sheath had been partly constrained in the radial direction by the steel reinforcing tapes (which broke) and the outer armour wires, which held. The northern and southern ends of the bulge had been constrained in the longitudinal direction by unbroken steel reinforcing tapes, as evinced by their lay angle having formed the end shapes of the bulge.

76. The internal surface of the bulge contained tape impressions of the underlying core binder and metallised paper screening tapes {ER 808, Figure 30; G9748, Photos 12 and 13}. The impressions showed that before the fault the lead sheath had been in close contact with the core tapes.

77. There was no evidence of any arc pitting or erosion sites on the inside surface of the lead sheath under the bulge region indicating that, when in service, the lead sheath had been in good electrical contact with the core binder.

78. There was no molten lead or arc burning present within the southern bulge. It was concluded that no electrical failure was present within the southern bulge.

4.7 Polyethylene Oversheath

79. During the examination at the CCI laboratory the PE sheath was pinned open for a period of 12 hours and the internal surfaces examined {ER 808, Figures 40 and 41}. The PE sheath was also examined in detail by Materials Technology {G9748}. The polyethylene sheath was observed to be sound near to the southern and northern bulges. There was no evidence of a factory repair.

80. Witness marks of the overlying reinforcing tape edges had been impressed into the outer surfaces of all the samples of PE oversheath through a 0.3 mm layer of polyester bedding tape. The diameter over the PE sheath between the bulges of VICT-146 {ER 795, Table page 45} was closely similar to the diameters of the PE sheath remote from the bulges in VICT-146 and VICT-144. It was concluded that, in service operation, the overlying reinforcing tapes had performed their normal function of uniformly constraining the PE sheath and lead sheaths.

81. Variations were present in the width of the butt gaps between the steel reinforcing tapes on, and in-between, the northern and southern bulges. The butt gap spacings varied between a

gap of 30 mm and an overlap of 6 mm. The butt gap spacings were uniform in the two 0.5 m samples of cable inspected at the remote ends of the failure sample VICT-146 and at the remote reference sample VICT-144. The evidence from the witness marks showed that the butt gap variations of the inner tapes had been present in service operation. The evidence of patterns on, and damage to, the outer tapes showed that some tapes had moved as a result of the bulge formation during the electrical fault {G9748, Photo 39 and Photos 41 to 48}.

82. It was concluded from the evidence in items 80, 81 and Section 4.8 that the butt gap variations had not caused or contributed to the electrical failure at the northern bulge.

83. A DSC analysis was performed by Materials Technology {G11863} on samples of PE sheath, two were from the failed sample VICT-146 and one was from the remote sample VICT-144. A sample of polyethylene has the property of being able to store in its crystalline structure the memory of the highest temperature (below its crystalline melting point) that it has previously experienced. Report G11863 concluded that:
    - There was no evidence of significant secondary melting peaks which would indicate obvious thermal history.
    - There was a very small plateau region at around 40°C which could be a secondary melting event indicative of thermal history up to this temperature but due to the small nature of this transition it is not possible to state this with any degree of certainty.

84. The above shows that there is a low possibility that all three samples had experienced the same temperature event of 40°C. As the samples in VICT-146, in the vicinity of the power arc, had the same thermal history as the remote sample VICT-144 it was deduced that the 40°C temperature had not been caused by local heating during the failure. It is not possible to determine if the small inflection recorded {G11863, Table 3} is indicative of a historic thermal event, for example: operation in service, solar heating in transit on the cable ship, or a factory manufacturing process. It is concluded that the PE sheath temperature did not contribute to the electrical failure.

85. The northern and southern bulges on the PE oversheath were coincident with the bulges on the underlying lead sheath {ER 795, Figures 63 to 65; ER 808, Figure 28}. They are further described below:

4.7.1 Northern Bulge on the Polyethylene Oversheath

86. The PE oversheath had been preferentially bulged in the region of the top dead centre position i.e. over the main power arc path through the paper insulation, {ER 808, Figure 44 – 9 o'clock and 3 o'clock views}.

87. The inside of the PE sheath over the northern bulge shows evidence of heat damage from the fault i.e. localised high temperatures {G9748, Page 65, Photo 59}. The temperature was greater than the melting point of the PE sheath, which was measured to be 118°C {G11863, Table 3}.

88. The PE oversheath contained three parallel splits coincident with the fault exit holes in the underlying lead sheath. The splits followed the lay of the armour wires {ER 795, Figures 46 and 64; ER 808, Figures 41, 42, 44 and 46}. It was concluded that during the fault the armour wires had constrained the formation of the bulge in the PE and underlying lead sheaths.

4.7.2 Southern Bulge on the Polyethylene Oversheath

89. The PE oversheath was bulged into a cylindrical shape that followed the helical right hand lay of the overlaying steel reinforcing tapes {ER 808, Figure 45}. This showed that the northern and southern edges of the bulge had been constrained from longitudinal movement by the steel reinforcing tapes.

90. There was no significant heat damage to the PE sheath over the southern bulge {G9748, Page 65, Photo 60}.

91. A small circumferential split was present in the PE oversheath that, when squeezed, ejected a mixture of water and MI compound {ER 795, Page 46; ER 808, Figure 49}.

92. When the PE oversheath was removed {ER 795, Figures 67 and 71} MI compound and water were found between the internal surface of the PE oversheath and the external surface of the lead sheath.

93. A rhomboid shaped witness mark had been impressed onto the outer surface of the bulged PE oversheath {ER 808, Figures 45 and 47; G9748, Photo 58}. The shape spiralled around the bulge for one circumference (a length of 326 mm with a maximum axial width of 30 mm). Impressions of the armour wires had been indented into the surface of the oversheath within the rhomboid shape, {ER 808, Figure 45; G9748, Photo 58}. These witness marks corresponded to the position in the overlying steel reinforcing tapes where, during dismantling in the Prysmian laboratory, a wide butt gap was found in both the inner and outer layers of tapes. The butt gap widened from 0 mm to 30 mm and back to 0 mm, {ER 795, Figure 54}, (see also the section on Steel Reinforcing Tapes). The surface of the PE sheath had been covered with the polyester bedding tapes. The bedding tapes continued across the rhomboid shaped witness mark. It was concluded that the gap in the reinforcing tapes had been present pre-fault and that there is no evidence that this contributed to the electrical failure.

4.8 Steel Reinforcing Tapes

94. Breaks were present in each of the four steel reinforcing tapes immediately over each bulge {ER795, Figures 51 to 54}. The breaks were in alignment with the overlying steel armour wires

that had constrained the bulges in the PE and lead sheaths. It was concluded that the tapes had been fractured by the internal pressure generated by the power arc.

95. The metallurgical examination of the fractured tape edges {G9748, Pages 23 to 40, Figure 2} and a review of the ER 795 photographs confirmed that all the tapes had been continuous with no evidence of any factory joins. During the CCI examination {ER 808} the fractured ends between discrete lengths of reinforcing tapes were compared and aligned {ER 808, Figures 52 to 57 and Figures 60 to 65}. It was found that two inner reinforcing tape ends, VICT-146/19B and VICT-146/20B, did not align {ER 808, Figure 64}. CCI reviewed the photographic records of the examination at CESI {ER 795} and found that a piece of reinforcing tape approximately 18-20 mm long had been present between the tape ends directly over the fault site. The photograph {G9748, Photo 49} was examined by Materials Technology who concluded that the edges on the photograph of the missing piece was a good match with the edges of tapes VICT-146/19B and VICT-146/20B {G9748, Photos 51 and 52}. It was concluded that all the reinforcing tapes prior to the fault had been continuous and that a tape join had not been present.

96. Inner and outer reinforcing tapes were sampled from the reference cable, VICT-144, and tensile tested and exhibited a consistent mechanical strength {G9748, Page 60}. There was no evidence that the tapes had lost their strength in service operation. It is not a design requirement that the reinforcing tapes should withstand the tensile stress generated by an electrical fault.

97. Variation was present in the spacing of the individual steel reinforcing tapes in the sample containing the failure site {ER 795, Figures 50, 53 to 57; G9748, Pages 24 to 40}:

    a. The variations in butt gap spacings were local to the short length of cable sample that contained the two bulges in sample VICT-146. The butt gap spacings varied between a gap of 30 mm {ER 795, Figure 54} and an overlap of 6-10 mm {ER 795, Figure 57; ER 808, Table page 28; G9748, Photo 33}.

    b. For comparison the butt gap spacings in the remote reference sample VICT-144 {ER 795, Figure 16 and 17} were 2.5 mm to 6 mm.

98. The inner tapes left witness marks of their edges on the underlying PE sheath. These were found to be present on the reference cable sample VICT-144 {ER 795, Figure 19}, which was 21m from the fault. It was concluded that the witness marks were generated pre-fault in normal service operation {G9748, Pages 44 and 45, Photo 63}.

99. The witness marks were present on the failed sample, VICT-146, and found to match the tape variations observed during the inspections {ER 808, Table page 28; G9748, Pages 44 to 52}.

100. Between the bulges, faint marks of the reinforcing tapes were present on the PE oversheath {G9748, Page 44}. The diameter over the PE sheath between the bulges was closely similar to the diameter remote from the bulges {ER 795, Table page 45}. There was no evidence found of factory tape joins in the reinforcing tapes {G9748, Pages 40 to 43}, or that the tapes had relaxed or broken in service before electrical failure occurred. It was concluded that in service operation the reinforcing tapes had performed their normal function of constraining the PE and lead sheaths.

101. There was evidence that some of the outer tapes had moved as a result of the formation of the bulge features during the electrical fault. For example a tape had moved and formed a rucked (folded) tape edge at a position just to the north of the northern bulge {ER 795, Figure 53; ER 808, Figure 58; G9748, Pages 37 to 40}.

102. Microscopic examination of the reinforcing tapes over the northern bulge in the vicinity of the fault exit hole {G9748, Table 5} found evidence of melted galvanising, loss of galvanising and molten metal probably steel. The melting point of zinc is 415°C and the melting range for mild steel is 1425°C – 1540°C. This is consistent with the heat generation from a power arc and its associated temperature (5000°C – 19,400°C).

103. Microscopic blisters were reported to be present on reinforcing tapes over the southern bulge {G9748, Table 5, Photos 31 and 32}. These are present around the zinc crystal boundaries. The cause of these is unknown. There is no evidence that the microscopic blisters contributed to the electrical failure at the northern bulge.

104. It was concluded that i) there had been pre-existing variation in the tape butt gap widths of the inner reinforcing tapes, ii) the outer reinforcing tape layer had been moved as a result of the formation of the bulges at the time of the fault and iii) the tapes between the two bulges had effectively constrained the underlying PE sheath and lead sheath from expansion. There is no evidence that the reinforcing tapes or the variation in the butt gap width had caused or contributed to the electrical failure.

4.9 Armour Wires and Polypropylene String Serving

105. The armour wires and polypropylene string serving in the region of the failure site at KP199.256 were in good condition {ER 795, Figures 36, 38 to 43}.

106. During recovery of the faulted cable onto the ship it was noted that one string had broken and had started to unwind {ER 795, Figure 38}. The break in the string was coincident with the fault exit hole. The string had been severed by melting. It was concluded that the string had been severed by hot gas escaping from the fault exit hole.

107. No evidence of external mechanical damage or third party intervention was found on the polypropylene string servings or on the galvanised steel armour wires.

108. Two bulges 480 mm apart were present in the armour and serving {ER 795, Figure 42}. At the northern bulge a wider gap was present between two armour wires {ER 795, Figure 46} through which the fault exit hole could be seen to pass through the steel reinforcing tapes, PE oversheath and lead sheath {ER 795, Figure 41}.

109. During the inspections at CESI {ER 795} and at CCI {ER 808} there was no evidence that the cable at the northern bulge had been externally mechanically disturbed or punctured prior to the fault. The northern bulge was coincident with the location of the electrical failure site.

110. It was concluded that external mechanical damage to the cable had not occurred and that the northern bulge had been caused by the internal electrical failure.

5 Discussion

5.1 Fault Path

111. The fault path present in sample VICT-146 is concluded to be a short path, radial failure, which extended through the insulation between the conductor and the lead sheath, as shown in Figure 2.

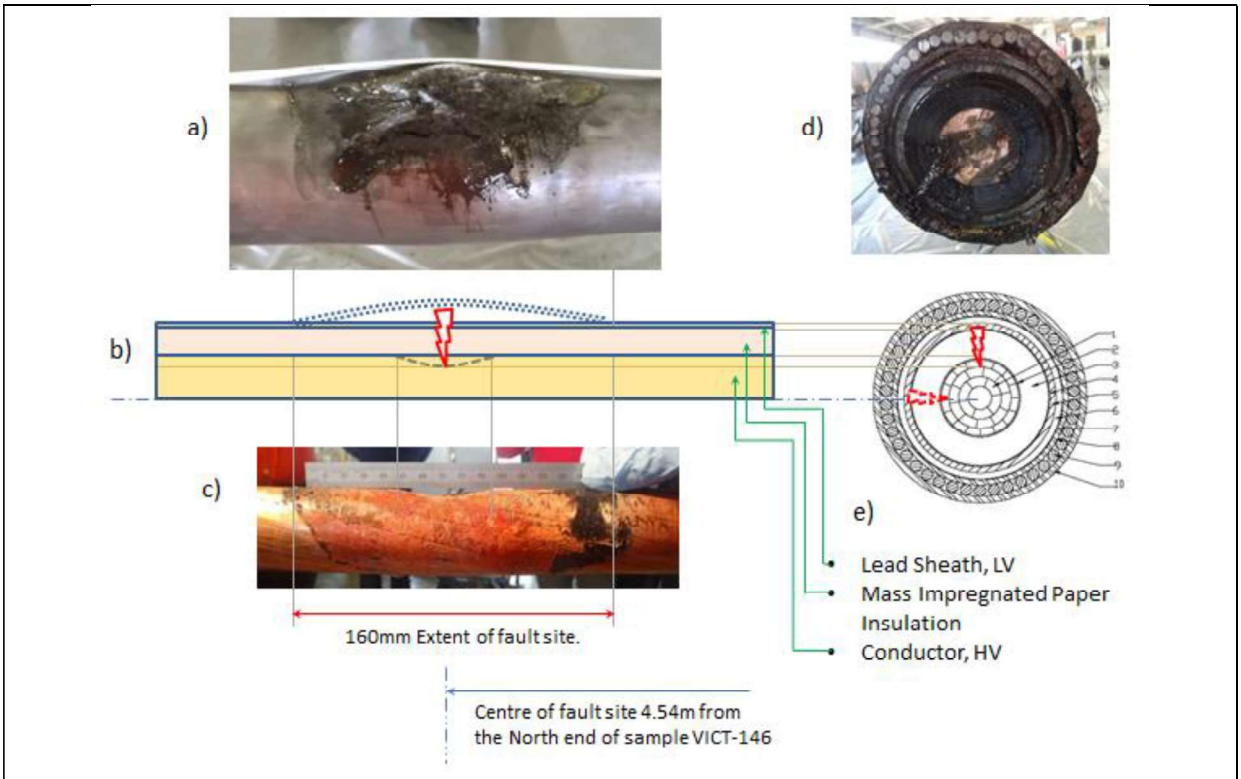


Figure 2 Basslink schematic diagram showing the fault path

- Figure 2 b) is a longitudinal sectional view of the fault arc path. The fault extended radially through the paper tape insulation between the lead sheath at LV, Figure 2 a) and the conductor at HV, Figure 2 c).
- In Figure 2 c) the centre of the HV end of the power arc can be seen to be a 20 mm diameter eroded crater in the conductor at the 12 o'clock position.
- Figure 2 a), b) and c) show that the longitudinal extent of the fault site is short i.e. 160 mm
- Figure 2 e) is a cross-sectional diagram through the cable looking from south to north. The main fault arc path is close to 12 o'clock. A subsidiary arc exit occurred at 9 o'clock. Figure 2 d) is a photograph of the cut end of the cable sample.

112. There was no pre-fault evidence found in the surviving paper tape insulation of incipient electrical treeing, abnormal cable geometry, or foreign material. Due to the extent of the paper tape burning it was not possible to determine the point of initiation of the pre-arc electrical fault, nor in which direction the fault path had propagated.

5.2 Cable Power Flow Record

113. A simple assessment was performed of the cable load and the rate of cable heating/cooling in the time before failure. The power flow verses time graph[6] is shown in Figure 3 for the 14 hour 5 minute period prior to failure. The Authors were provided with a load flow record[7] for the year 2015 before failure.

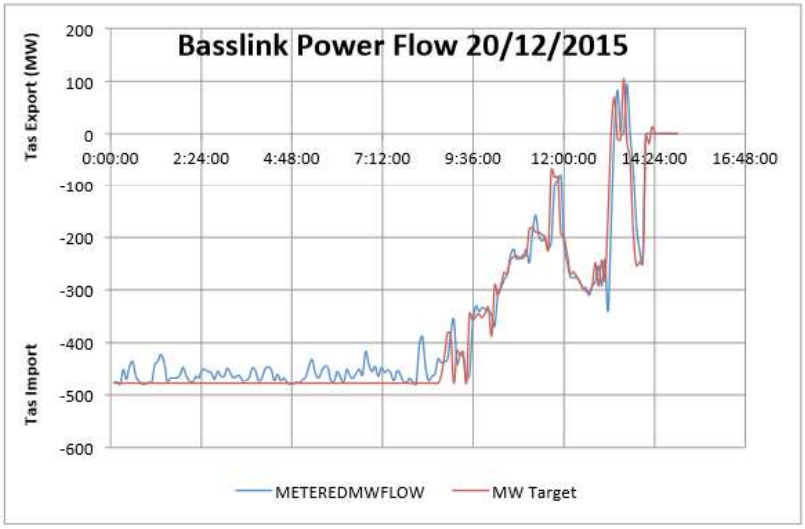


Figure 3 Basslink load flow extracted from Media Statement 10th March 2016

[6] Source: http://www.basslink.com.au/media/ Basslink Media Statement, Clarification 10th March 2016
[7] Excel spreadsheet "Basslink 2015.xls" data source AEMO.

114. The power record shows:

a. The cable had been carrying a near continuous power level of 478 MW (95% of the continuous cable rating of 500MW) for 740 minutes (importing from Victoria), this period ended 325 minutes before failure.
b. The power level then decreased and reached zero 45 mins prior to failure.
c. The power was then at near zero for 25 minutes with two five minute periods of power export.
d. The final import of power commencing 20 minutes prior to failure.
e. Failure occurred at 14:05 hours, with the cable carrying 249 MW (50% of the continuous cable rating of 500MW).

115. The cable is considered to have experienced the following thermal and voltage conditions prior to failure:

- In period b) the cable was cooling.
- At the start and end of period c) the cable experienced two voltage polarity reversals.
- In period e) the cable was heating.

116. It was concluded that the operating conditions at, and preceding, the time of failure were no different to those of the year 2015. The cable was within its thermal rating.

5.3 Sequence of Events

117. Figure 4 schematically depicts the sequence of events as determined from the investigation evidence. The cable is shown with the galvanised steel reinforcing tapes revealed. The polypropylene string serving, the galvanised steel armour wires and the polyester bedding tapes have been removed.

118. Before the failure (Figure 4a), the cable had a mechanically sound construction and did not exhibit the two bulges present during the inspection. The blue line above the cable depicts the continuity of the galvanised steel reinforcing tapes. The two layers of reinforcing tapes (two in each layer) were intact, sound and had no factory joins. Between the two bulge positions the reinforcing tapes had performed their normal function of constraining the PE and lead sheaths. The diameter over the PE sheath between the two bulges was normal. The pattern of the innermost reinforcing tapes had been imprinted on the PE sheath in normal service operation. The imprinted pattern showed that the tapes between the eventual bulge positions had variations in the width of the butt gaps, the widest being 30 mm as shown by the black symbol on the right hand side of Figure 4a.

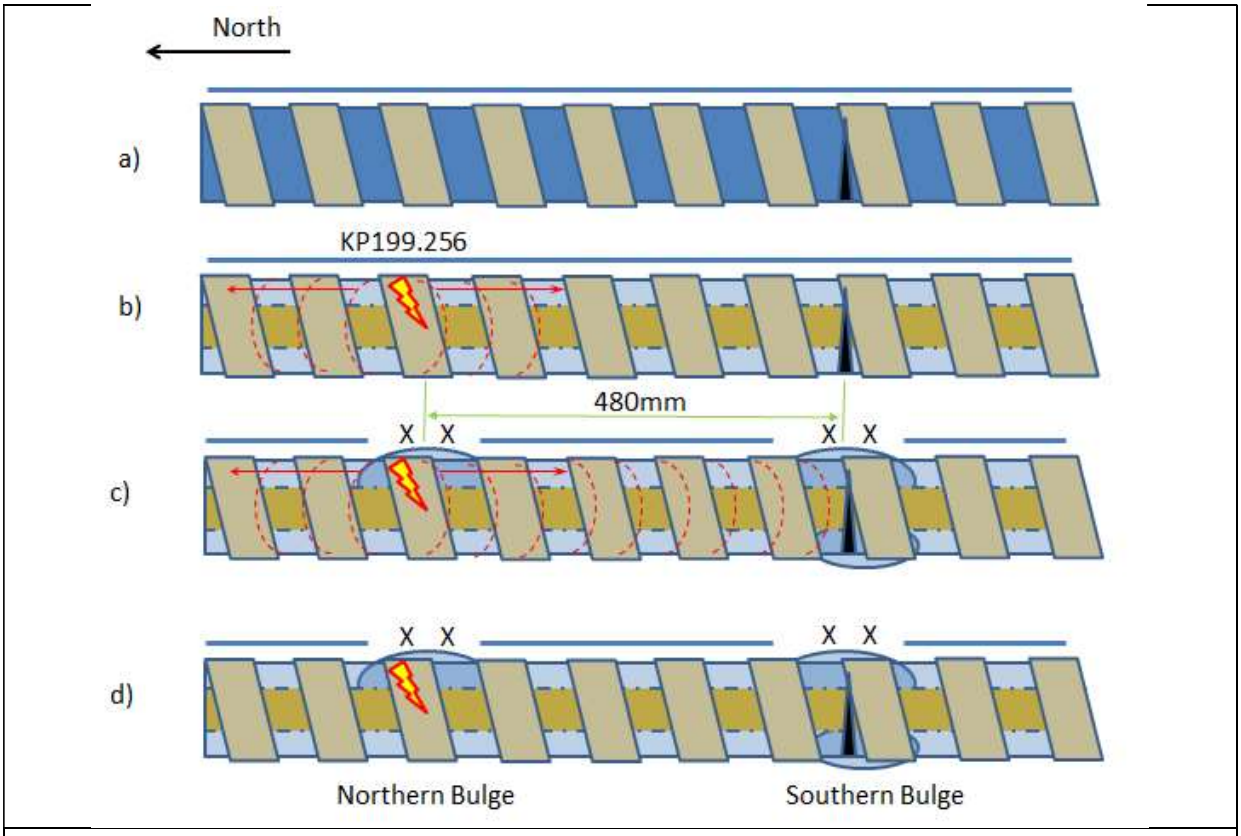


Figure 4 Diagram showing the sequence of formation of the northern and southern bulges

119. An electrical fault (Figure 4b) occurred at position KP199.256, the eventual position of the northern bulge. The fault produced a carbonised path through the paper insulation, which bridged radially between the conductor at HV and the lead sheath at LV. The inrush of current formed a power arc that was supplied partly from the converter stations and partly from the discharge energy of the 298 km length of cable. The arc path formed two cross shaped slits through the paper insulation near to the 12 o'clock position. A subsidiary arc path formed a longitudinal slit at the 9 o'clock position between the conductor and the sheath.

120. At the eventual position of the northern bulge the shock wave pressure from the power arc (Figure 4c) was transmitted radially through the lead and PE sheaths, which acted as diaphragms, and onwards to the four galvanised steel reinforcing tapes. The hoop stress in the tapes exceeded their tensile strength and they broke, this being denoted in Figure 4c by the symbol X. It is not a design requirement that the reinforcing tapes should withstand the pressure generated by an electrical fault. Simultaneously the power arc i) stretched the lead sheath to form the rounded shape of the northern bulge, ii) formed three slits in the lead sheath and iii) ablated the conductor to form a crater in its surface. The expansion of the lead and PE sheaths was constrained by individual steel armour wires which were bent and opened to form a gap. The PE sheath was part melted and part punctured by the hot gasses to form 3

slits in the interstices between the armour wires. The escaping hot gasses melted and severed one of the polypropylene strings.

121. The southern bulge was formed as a consequence of the failure event at the northern bulge. The power arc pressure wave (Figure 4c) travelled along the cable, pressurising the lead sheath, the PE sheath and the steel reinforcing tapes as it did so. At 480 mm to the south of the fault position a wider butt gap of 30 mm was present in both the inner and outer reinforcing tape layers, which had pre-existed the fault {ER 795, Figure 54}. The force acting on the steel tapes at this position was increased and the four tapes broke as denoted by the symbol X.

122. At the southern bulge the lead sheath expanded and was constrained by the armour wires. The expanded lead sheath then collapsed under compression from the 7 bar external water pressure. A longitudinal fold and split were formed in the lead sheath {ER 808, Figures 37 and 38; G9748 Photo 11} and a short circumferential split was formed in the PE sheath {ER 808, Figure 49}. MI compound from the paper insulation collected within the bulged lead sheath and leaked outwards through the split {ER 795, Figures 60, 63 and 71}. Water entered the PE sheath.

123. Figure 4d depicts the two bulges that were found when the cable was recovered from the sea bed and was examined.

6 Conclusions

124. The findings of the investigation are:

125. The fault occurred within the cable. The fault was not at a location of a joint, or a lead sheath to armour bond.

126. In the absence of surviving evidence it was not possible to determine the cause of failure of the cable as:

- There was no evidence of any pre-existing external mechanical damage to the cable.
- The electrical fault was a ‘radial, short path’ type. The path extended through the paper tape insulation between the conductor at high voltage and the lead alloy sheath at low voltage.
- There was no evidence of any incipient electrical activity connected with the fault site or present elsewhere in the cable.
- The point of initiation within the fault path and the direction of propagation of the electrical failure could not be determined due to the severity of the fault damage.

127. The fault position was beneath the northern bulge in the cable.

128. The northern bulge was formed by the explosive effect of the electrical power arc within it.

129. A second bulge was present 480 mm to the south of the northern bulge. The insulation inside the southern bulge was sound and did not contain electrical distress.

130. The southern bulge was formed by the shock wave travelling to a location where the steel reinforcing tapes had a wider butt gap and experienced a force above their breaking point.

131. The operating conditions at, and preceding, the time of failure were no different to those of the year 2015. The cable was within its thermal rating.

132. The insulation adjacent to the failure site was sound and showed no evidence of thermal ageing.

133. A sample of cable remote from the fault site was in sound condition.

134. Report Prepared by: Eur Ing L R Trim & Eur Ing B Gregory

135. Signed:



Eur Ing L R Trim



Eur Ing B Gregory

136. Dated: 2nd December 2016

7 CV's

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CONSULTANT EXPERIENCE

Eur Ing LAURENCE RICHARD TRIM *BEng, CEng, MIET*

A Chartered electrical engineer with over twenty years involvement in high voltage product development, design, manufacturing and consulting. He has:

- Detailed knowledge of high voltage engineering.
- Has conducted failure investigations on numerous items of HV & EHV plant.
- Has experience with both land and subsea cable systems 11kV to 400kV, HVAC & HVDC.
- Has conducted on-site condition assessment inspections and measurements.

CABLE CONSULTING INTERNATIONAL LTD **2004 to present**

Consulting Engineers specialising in underground and subsea power transmission cables, HVAC and HVDC.

Senior Consultant

CCI projects have included (list non-exhaustive):

UK – EAE – Design Assurance for the 400kV Medway Tunnel Uprating Project.

UK – Doble Power Test - Inspection and root cause analysis of a discharge damaged 132kV XLPE cable terminations.

UK – NGT – Power cable systems earthing and bonding study, West Coast Mainline.

UK – NGT – ACR current measurements at West Coast Mainline track feeder substations.

UK – NGT – Inspection of 66kV XLPE cable jointing works at Harker Substation.

UK – Confidential – Investigation into the failure of a 400kV GIS Termination in a NG Substation.

UK – London Array Ltd – Independent witnessing of 150kV offshore submarine cable termination construction.

UK – London Array Ltd – Engineering support during the installation of two 400kV XLPE cable circuits including GIS terminations.

UK – Steege Kingston – Technical assistance in the loss adjustment of multiple damages to a 400kV HVDC subsea cable system.

UK – Steege Kingston – Independent inspection and root cause failure analysis of a 33kV subsea cable joint recovered from the Shapinsay to Stronsay subsea cable link.

UK – Magnox – Engineering review and supervision of 132kV oil filled cable works.

UK – Scottish & Southern / Talisman – Supervision of repairs to damage caused during manufacture to the 33kV Beatrice offshore windfarm subsea cable interconnector.

UK – Faber Maunsell, Fugro, Holequest, Molem, Morrison, Quantum - onsite measurement of soil thermal resistivity and electrical resistivity values.

UK – EDF Powerlink – Independent inspection and root cause failure analysis of 11kV & 22kV cable joints and terminations.

UK – Scottish & Southern Energy Ltd – Feasibility study on the installation of power cables across a Scottish Loch.

UK – Ithaca Energy Ltd – Engineering support in the design and manufacture of a 10km submarine power link to the Beatrice (Jacky) platform.

UK – RES – Engineering support in the design and manufacture of Offshore Windfarm export and inter-array cabling.

UK – CENTRICA – Client representative responsible for overseeing cable handling and jointing activities during the repair of an offshore windfarm export cable.

UK – Eon – Thermal assessment of a proposed 30km land cable route for the connection of an off shore windfarm.

UK – SKM – Engineering support during the manufacture and installation of a 50km 132kV export cable for an offshore windfarm.

UK – SKM – Engineering support during the manufacture and installation of infield turbine array cables for an offshore windfarm.

China – Chevron Texaco – Condition assessment inspection of cable systems installed on an FPSO.

Ireland – GE Wind Energy – Engineering review, off shore supervision and testing of repairs to a 38kV offshore windfarm subsea export cable.

Northern Ireland – NIE – Condition assessment of 275kV, fluid filled, condenser cone, cable terminations.

Northern Ireland – Mutual Energy – Provision of technical support in writing contract employer's requirements for the replacement of the return conductors of a subsea HVDC interconnector.

Northern Ireland – Mutual Energy – Lead technical consultant for the replacement of return conductors for a subsea HVDC interconnector.

Nigeria – AES – Engineering support into the selection of 132kV XLPE cable accessories.

Portugal – Portugen – Independent inspection and root cause analysis of multiple failures that occurred in a 220kV XLPE cable system (cable and terminations).

Portugal – Portugen – Appointed consultant to oversee 220kV XLPE cable replacement works.

NZ – Orion – Assessment of thermo-mechanical performance of 3-core oil filled cable joint designs.

USA – EPRI – Study on the HVDC performance of solid dielectic cable systems.

USA – ConEdison – Motthaven substation design study on installation of cables in tunnels.

USA – White & Williams – Expert witness for an arbitration tribunal involving a 220kV oil immersed transformer cable termination.

UAE – Dugas – Independent inspection and root cause analysis of 11kV cable joints.

UAE – Dugas – Market review, selection and testing of a suitable 11kV XLPE cable joint design.

UAE – Crawford & Co – Independent inspection and technical assessment of 400kV XLPE cable termination failures.

UAE – DEWA – Independent inspection and assessment of 132kV cable terminations and joints following failures.

UAE – DEWA – Independent inspection and failure investigations into 400kV Oil Immersed Termination failures.

UAE – DEWA – Engineering support for the design, manufacture and installation of a 400kV XLPE cable system being installed into a tunnel.

ERA Technology Ltd, Principal Electrical Engineer **2001 - 2004**
Engineering consultancy

- Responsible for providing comprehensive advice to clients on engineering matters with particular expertise in high voltage power transmission equipment.
- Effective management of projects to ensure engineering detail, budgets and time scales are achieved.
- Listening to client's needs to enable the formulation of effective project proposals.
- Building relationships with existing clients and networking to draw in potential customers.
- Costing and setting the price of prospective projects.
- Conducting detailed measurements, investigations and analysis either on site or in the laboratory primarily, but not limited to, high voltage engineering plant.
- Writing detailed reports of work conducted giving analysis of results, conclusions and recommendations for further work.

Pirelli (formerly BICCGeneral (part of General Cable), Supertension & Subsea Systems, formerly BICC Cables Ltd) **1990 - 2001**
Manufacturers, installers and project managers of high voltage underground and undersea electric cable systems

Project Manager, Project Engineering Section, Chief Engineer's Department 1999 to 2001

- Responsible for research and development of supertension products with specific expertise in accessory technology.
- Proactive leader managing teams of up to 5 engineers; guiding, training, encouraging ideas and skills to further both themselves and the project / company.
- Formulating budget requirements and project schedules to ensure contract deadlines are achieved – typical project budgets ~ £100k.
- Broad based engineering knowledge used to verify and authorise the work of the project team.
- Pre and post sales technical support (presentations / discussions) provided for customers, factory and site installations. UK and overseas installation sites visited to provide assertive guidance.
- Directing site incident investigations – open minded, analytical approach with swift thinking and competent action under pressure.
- Notable projects included: a suite of new accessories at 230kV into the supertension product range, thus enabling two contracts into Singapore supplying 90km of cable worth in excess of £100m.

BICC Cables Ltd
Section Leader - Accessories Development, Chief Engineer's Department **1997 - 1999**

- Responsible for the timely development of supertension accessories.
- Managing a section of 5 engineers with an annual budget of £800k.
- Generation of project specifications and development programmes to meet contractual and projected market requirements.
- Allocation of projects to the engineering staff; considering current work load and areas of expertise.
- Guidance, verification and authorisation of engineering input to ensure appropriate calculations and all technical aspects are considered.
- Presenting technical information to management and customers; providing pre and post sales support.
- Preparing and conducting annual appraisals for the engineers.
- Recommending appropriate training for each engineer, to enhance their function within the team, and to aid professional career progression.
- Notable projects include: Development of one piece premoulded joint technology; Development of full range of accessories for 220kV application (SF_6 Gas Insulated Switchgear, Oil Immersed Transformer Termination, One Piece Joint, Out Door Sealing End).

BICC Cables Ltd
Senior Development Engineer **1996 - 1997**
Development Engineer **1994 - 1996**
Accessories Development Section, Chief Engineer's Department

- Responsible for detailed engineering input into a range of accessory development projects.
- Engineering all aspects of accessory design using finite element analysis tools and other computer aided techniques, considering: electrostatic; mechanical; thermal & materials issues.
- Integrating new products into the accessories factory by submitting technical reports and directing: rubber / resin mould tool design and manufacture; process development; prototyping; development of routine mechanical & electrical tests, inspection procedures.
- Evaluation of completed designs by development testing (electrical and mechanical); and type approval testing.
- Liaison with factory personnel at all levels to progress projects and hand over technical details.
- Formulating project plans using MS Project.
- Notable projects include: Accessories for 400kV XLPE CIGRE Prequalification test; Accessories for first UK 400kV XLPE installation.

BICC Cables Ltd - Sponsored Student Apprentice, Training Department. **1990 - 1994**

- IEE accredited training plan involving 6 three month project placements working in a number of departments around the Supertension Cable manufacturing site and a practical EP1 course.
- Degree course attended from 1991 to 1994 working summer placements at the factory.

Qualifications and Training

Chartered Engineer and Member Institution of Engineering and Technology (formerly the Institution of Electrical Engineers)	2001
European Federation of National Engineering Associations, FEANI, Registered. First Registration	2001
Loughborough University of Technology BEng. (Hons) Electrical and Electronic Engineering	1994

Publications and Patents

Publications: "Supertension Accessory Design to ensure Reliable Performance", IEE, June 1998;
"Electric Cables Handbook" – 3rd Edition, contributor, 1997, ISBN 0-632-04075-0.

Patent: "Electric Cable Joints and Methods of Making Them – Pinned Insulation", (GB) 9718925.2, 5th Sept 1997.

Professional Activities

Laurence is an individual member of CIGRE.

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United Kingdom

1st December 2016

Biography of Brian Gregory

Name: Eur Ing Brian Gregory BSc, CEng, MIEEE, FIET

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Work: PO Box 1, Sevenoaks, Kent, TN14 7EN, UK
Home: 62 Knole Road, Dartford, Kent, DA1 3JW, UK

Job Title:
Technical Director of Cable Consulting International Ltd (CCI), an independent consulting company of power cable experts. He is a founder member of CCI, which was incorporated in 2002.

Academic Qualifications:
He received an honours degree from the City University, London in 1968 in Electrical and Electronic Engineering following combined academic and engineering training in a five year professional sandwich course. His final year project thesis was 'Thermal Analysis and Synthesis of Temperature Distributions in Super Tension Joints'.

Professional Qualifications:
He is:

A Fellow of the IET, (over a 52 year period he has been a Student, a Member and a Fellow of the Institution of Electrical Engineers; now the Institution of Engineering Technology).
A Chartered Engineer
A FEANI registered European Engineer
A Member of the IEEE
A Member of CIGRE (International Council on Large Electric Systems)

Professional Publications
He has authored over 50 published technical papers and chapters in technical books on all aspects of power cable systems and their accessories. He is listed as an inventor in a number of patents.

Professional Activities
He is a UK observer member of CIGRE Study Committee B1 'Insulated Cables' and has been for 24 years.
He is presently a member of CIGRE WG B1-34 that is preparing to publish a technical guide: 'Mechanical Forces in Large Cross Section Cable Systems'.
He was the Secretary and member of CIGRE WG 21-06 that published TB 89, 'Accessories for HV Extruded Cables, Part 1 Compendium of Accessory Types and Part 2 Glossary of Component Names'
He was a member and team leader in CIGRE JWG 23/21/33 that published TB 218, 'Gas Insulated Transmission Lines (GIL)'

He was a member of the IEE PGP8 committee that organised the annual session programme for cables and overhead lines
He was an IEE referee for technical papers on cables submitted for publication

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Professional Experience

He received professional training as a student apprentice with AEI Supertension Cables from 1963 to 1968. In 1969 he joined BICC Supertension Cables as a Development Engineer for cables and accessories, becoming the Accessories Development Section Leader and in 1981 the Chief Development Engineer.

He was the Chief Engineer of BICC Supertension and Subsea Cable Systems from 1992 to 2000 with responsibilities for supertension cable technology worldwide. In 2000 he was the Consultative Chief Engineer of Pirelli Supertension Cable Systems UK.

From 2001 to the present date he has held the position of Technical Director of Cable Consulting International Ltd.

Professional Expertise

He has extensive expertise in his present role of independent CCI consultant in:

- Analysing and advising technical requirements for new cable applications
- Analysing the consequence of manufacturing and installation difficulties to cable system performance and giving advice on remedial measures
- Forensically analysing the cause of test and in-service failures and giving advice on remedial measures
- Advising the residual life expectancy of cable circuits
- Providing an expert witness service to public enquiries and to courts.
- Lecturing in training courses (UK, Australia and New Zealand) on extruded XLPE cables systems and self-contained fluid filled cable systems.

He is an expert in the thermo-mechanical behaviour of XLPE, HPFF and SCFF cable systems (rigid, flexible and duct-manhole systems), producing design guides and calculation methods for EPRI, CIGRE and National Grid.

He has extensive expertise from his previous role as Chief Engineer of the then world's largest supertension cable factory giving expert advice on:

Research, development, design, manufacture, testing and commercialisation of land and submarine cable systems (cable and accessories)

AC and DC cable systems from 11 kV to 800 kV,
Cable systems insulated with extruded XLPE and EPR, fluid impregnated PPL and paper tapes, mass impregnated paper tapes and LPGF and HPGF paper tapes.

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1st December 2016

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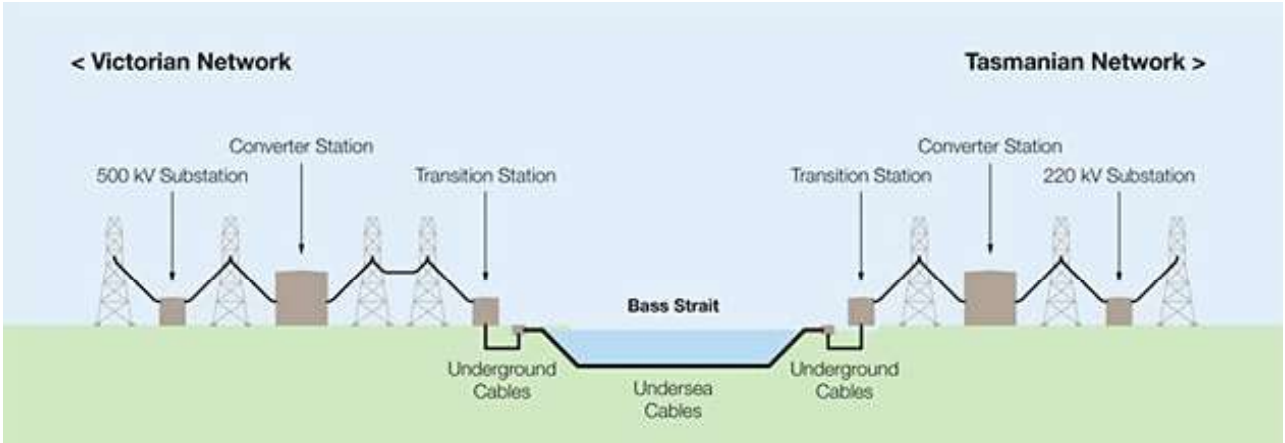
DNV·GL

EXPERT REPORT FRED STEENNIS

Basslink outage 2015 – Root cause analysis of the failed HVDC power cable

Clayton Utz

Report No.: 16-2443
Date: 2017-12-15



Project name:	Expert report Fred Steennis	DNV GL - Energy
Report title:1	Basslink outage 2015 – Root cause analysis of the failed HVDC power cable	Energy Advisory P.O. Box 9035
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Date of issue:	2017-12-15	Registered Arnhem 09006404
Project No.:	10018081	
Organisation unit:	AM	
Report No.:	16-2443	

Applicable contract(s) governing the provision of this Report:

Objective:

To investigate the root cause of the failure that happened in the Basslink cable in Australia, between Victoria and Tasmania in December 2015

Prepared by:	Verified by:	Approved by:
E.F. Steennis Sr. Principal Consultant Power cables	B. Kruizinga Consultant	R.A.M. Denissen Head of Section AM

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1 INTRODUCTION

1.1 General

In December 2015, the Basslink cable failed after ten years of service operation. Related to this failure, I performed a root cause analysis. This introducing Section explains who is my customer and the scope of this report. Also it describes the structure of the report, how references are used and gives definitions for common terms and abbreviations.

1.2 The customer

Clayton Utz acts for Hydro-Electric Corporation (Hydro Tasmania) in relation to matters arising from the outage of Basslink, the High Voltage Direct Current (HVDC) submarine cable across Bass Strait, which occurred on 20 December 2015 (Basslink Outage).

1.3 Scope of this report

This Expert Report is provided to Clayton Utz in response to their request to identify the possible causes (including their related probabilities) of the Basslink outage and any relation to the way the cable was operated by Basslink operator Basslink Pty Ltd (BPL).

1.4 Structure of this report

The report will start in Section 2 with various formalities, among which my qualifications. Part of this Section is also my approach when performing a root cause investigation in case of a cable system failure, see Section 2.4.5, called "Approach in case of a failure investigation". As a result, in investigating the root cause for the Basslink cable, I worked in line with the methodology described here. This means that:

1. I studied all stages in the cable life, i.e. design, production, installation and operation and I compared these to international common practice where applicable (see Section 5.2); and
2. I gave special attention to those weaknesses which are known from literature to be typical for a Basslink type power cable and checked whether a weakness in the Basslink cable could have been introduced during one of the before mentioned stages (See Section 5.3).

A summary of my opinion will be given in Section 3.

The material provided, being used throughout my investigation, is presented in Section 4.

Section 5 will first introduce some general electrotechnical matters to create a better understanding of what will follow (Section 5.1), followed by an introduction of the applied type of power cable, with a focus on its design and potential weaknesses (Section 5.2). This is followed in Section 5.3 by a discussion on the Basslink cable, taking into account contractual issues, power rating, construction, design, production, and so on, up to the failure that happened in December 2015 and the work done by BPL to find the root cause of this failure.

Section 6 will come back to some potential weaknesses of HVDC cable in general and how these could be linked to the Basslink cable, in the way it was operated and failed.

In Section 7, I will respond to various key questions from Clayton Utz. These key questions were mentioned in Clayton Utz's letter of instructions, see the Appendix M.

1.5 References used in this report

There are two different types of references used throughout the report:

- References which are related to material supplied by Clayton Utz are referred to as [TAB xx], and these are listed in Section 4 ("Material provided");
- The remaining references are coded as [/xx/, author, year] and are listed in Section 8 ("References").

1.6 Definitions and abbreviations

1.6.1 Definitions

- For the probability of events, the following definitions are used:

  1. Improbable: something that is possible but is unlikely to occur or prove to be true.
  2. Possible: something which may prove to be true, but that is not certain
  3. Probable: something that is likely to occur or prove to be true, having more evidence for than against.

  The applied definitions are as defined in the letter of instructions I received [dated 2017-11-03; Appendix M].

- Overstressed: the thermal, electrical, mechanical or chemical circumstances have become such that the expected life time of the component will be compromised.
- Testing:
  - Type test: a set of tests made in order to qualify the design and the manufacturing of the cable system against the conditions of the intended application. The tests do not take into account any overload conditions. The tests are of such a nature that, after they have been made, they need not be repeated unless changes are made in either the material, design or process parameters outside the nominal tolerances, such that the resultant changes in dielectric, mechanical and/or thermal properties of the cable affect the life time of the cable [/28/, Cigré, 2000];
  - Routine test: Routine tests are made to demonstrate the integrity of the manufactured cable and to verify that the product meets the design and manufacturing specifications within the specified tolerances [/28/, Cigré, 2000];
  - Factory acceptance test (FAT): tests conducted on every component to be supplied for an order in the presence of the customer or the customer's representative. Often a FAT is a routine test but it can contain other items as an overview of corrective actions in case of deviations;

- Site acceptance test (SAT), also called After laying test (ALT): tests conducted on the installed cable, including its accessories, to demonstrate the integrity of the installed cable system;

- Technical items as power, electrical voltage, electrical stress, current, partial discharges, etc, are introduced in Section 5.1.

1.6.2 Abbreviations

A	Ampère, the derived unit for the electrical current I
AC	Alternating (Electrical) Current
BPL	Basslink operator Basslink Pty Ltd
CDVC	Cable Dependent Voltage Control
Cigré	from French: Conseil International des Grands Réseaux Électriques (International Council on Large Electric Systems)
CCI	Cable Consulting International Limited
CLPS	Cable Load Prediction System
DC	Direct Current
DSC	Differential Scanning Calorimetry; DSC is a thermo-analytical technique in which the difference in the amount of heat required to increase the temperature of the investigated sample and a reference sample is measured as a function of the temperature. Certain polymers (among which polyethylene (PE) and cross-linked polyethylene (XLPE) tend to exhibit a wider range of melting points compared to other materials like metals. This characteristic makes it possible to review and extract the temperature history of the polymer because it leaves a fingerprint on its melting range. See for a further explanation on DSC reference /8/
E	Electrical stress or Electrical field
EDSO	European Distribution System Operators' Association
EHV	Extra High Voltage (above 230 kV)
HV	High Voltage (above 35 kV and not exceeding 230 kV)
HVDC	High Voltage Direct Current
Hydro Tasmania	Hydro-Electric Corporation
I	Electrical current, flow of electric charge, measured in units of Ampere (or Coulomb per second)
IEEE	Institute of Electrical and Electronics Engineers
k	kilo (thousand)
km	kilometre
KP	Kilometre Position
kV	kilovolt
LV	Low Voltage (up to 1 kV)
m	milli (1 thousandth)
m	metre
M	Mega (1 million)

- MIND — Mass Impregnated Non Draining, it is an impregnant for the paper insulation material of a HVDC power cable based on a viscous compound
- mm — millimetre
- MV — Medium Voltage (above 1 kV and not exceeding 35 kV)
- ns — nano-second
- P — Electrical power, the rate of doing work, measured in units of Watt (Joule per second)
- P_{loss} — Power loss, the rate of electrical losses (conversion to heat), measured in units of Watt (Joule per second)
- PE — Polyethylene
- PFI — Power Failure Investigation
- pu — per unit; it is he expression of system quantities as fractions of a defined base unit quantity
- R — Electrical resistance, measured in units of Ohm (Ω)
- Reinforcement tape — Galvanised steel reinforcing tape
- Smartlife — A platform of European network owners various studying aspects (among which power cable reliability). This platform is an initiative of EDSO
- t — Time
- U — Electrical voltage, electrical potential difference, measured in units of Volts (or Joule per Coulomb)
- U_o — the rated DC voltage between conductor and core screen (grounded metal sheath) for which the cable and accessories are designed
- V — Volt, the derived unit for electric potential difference U
- W — Watt, the derived unit of electrical power P
- XLPE — Cross-linked polyethylene
- Ω — Ohm, the derived unit of electrical resistance R

2 FORMALITIES

2.1 Name and address of the author of this report

The name and address of the author of this report is

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2.2 Expert witness Code of Conduct

I have been provided with the Code of Conduct (Supreme Court of Tasmania, Practice Direction, No 1 of 2016, dated January 5th, 2016), Appendix C.

2.3 Acknowledgement that the expert has read the code and is bound to it

I acknowledge that I have read the Code of Conduct as mentioned in Section 2.2 and that I am bound to this Code of Conduct.

2.4 Qualifications of the author

2.4.1 Curriculum Vitae (summary)

After my university study, I started working for DNV GL (formerly KEMA and DNV KEMA) in 1982. Meanwhile, I have many years of experience in numerous power cable projects, done for customers world-wide. My type of this work is further described below.

The background of DNV GL is given in Appendix H.

A first part of my work is related to research and development. Here, projects are defined based on customer's needs after which a proposal is made and once granted, the resulting research and development work is often done in a team of specialists. A focus point here is the development of diagnostic techniques for power cables.

In line with this research and development work, since 1999, I am also a part-time professor at the Technical University Eindhoven in the Netherlands (see also Section 2.4.4). In this role I give lectures on underground power cables and give guidance to PhD students in their underground power cable related research. Under my responsibility meanwhile eight PhD students received their doctor degree.

Another part of my work is performing and managing power cable failure analysis (see also Section 2.4.2). The knowledge on degradation processes on one hand and DNV GL's independency combined with its test facilities on the other make it logic for many network owners and cable manufacturers to ask DNV GL's support in case of a power cable failure. The main goal is always to identify the root cause, but behind this request can be a safety, an economic or a technical issue.

A further part of my work is related to ageing, asset management and remaining life issues, also for power cables.

A next part of my work is giving courses world-wide on various aspects of Underground Power Cables, like Ageing, Asset Management, Remaining Life, Factory Testing, Field Testing and Failure Analysis.

I have also several years of experience as a full-time manager within DNV GL. Especially, in recent years I have given guidance to less experienced colleagues in my role of Senior Principal Consultant.

I have published many papers (> 150), reflecting my experience with many different power cable projects, see Section 2.4.3.

I have received two awards:

- 1991 - Hidde Nijland Award, a Dutch award of the power sector, 1991; for my contribution in the field of new testing methods for cables and the applicability of superconductors in power technology.
- 2014 - DNV GL Innovation Award 2014 – for my invention of Smart Cable Guard, a unique on-line monitoring tool locating weak spots that can lead to failures and accurate locator for temporary and permanent failures for medium voltage cables.

An important patent of which I am shared patent holder is: E. F. Steennis, P. A. A. F. Wouters, P. C. J. M. van der Wielen and J. Veen, "Method and system for transmitting an information signal over a power cable", Int. Patent No. WO 2004/013642, June 2002.

My full CV is shown in Appendix G.

2.4.2 Experience with failure investigations on power cables

Since 2016, I am DNV GL Energy's coordinator of all power failure investigations around the globe. Because DNV GL is impartial, has much experience with components for electrical power and has many supporting laboratories (for material testing, high voltage testing and high power testing), DNV GL is seen by its customers as a leading organization for performing the root cause analysis in case of an electrical power failure.

Over time, and certainly in my role as (Senior) Principal Consultant for DNV GL Energy, I have performed many different power cable failure investigations. This type of work started in the late 1990-s and since then has grown (especially in the last 10 years), such that is has become a world-wide business for DNV GL where all its offices around the world are involved. A reference list of power failure investigations performed on power cables is given in Appendix A. In almost all cases I have been the lead expert, if not involved as an expert or reviewer.

The power failure investigations have been done for many different companies: utilities, cable manufacturers and insurance companies. Most of these power cable failure investigations are related to AC systems, simply because most cable systems world-wide are AC based. All failure investigations are classified. As a result, only a list of company names for which such investigations were done, can be given here, but no reference is made to the power cable investigations itself. Companies for which I was the lead expert are (among others):

- [redacted]
- [redacted]
- [redacted]
- [redacted]
- [redacted]
- [redacted]



The majority of these power cable failure investigations are related to HV and EHV systems, which is because of the importance of this voltage class.

The main object in all these investigations was to find the root cause of the failure of a cable, or a cable accessory as a joint or termination. These could have a follow up in finding the cause behind the technical root cause and / or in recommending on mitigating actions and / or support in court sessions.

Activities performed during a failure investigation are: interviews, literature study, discussions, dismantling of the failed component, material tests, electrical tests, analyses, reporting and sometimes followed by publications or court sessions. See Section 2.4.5.

Concerning the Basslink type of cable (an HVDC MIND cable), I have been involved in seven of such power cable failures investigations (with a failure investigation approach as introduced Section 2.4.5):

- one in Europe [redacted] in an expert advisor role
- one in Asia [redacted] in an expert advisor role
- five in relation to the [redacted] where I was the lead failure investigator on behalf of the [redacted] As the lead failure investigator, I was responsible for
    - the investigation of all aspects from design, production, installation and operation
    - the dismantling and inspection of the faulty cable part (and reference cable parts)
    - the decision about material tests to be performed and the arrangement of these
    - the analysis, the conclusions and the proposed mitigating actions
    - writing and discussing the report.
- Finally, I was recently consulted as an expert to formulate a remaining life program for a similar type of cable, after it had experienced various failures. Because of its nature, I am not allowed to give further details here.

2.4.3 Publications on power cable failure investigations

Because of the fact that failure investigations result in classified reports, it is not possible to disclose the information in publications reflecting actual findings for individual cases. But in a few cases, publications have been made with a more general nature, based on individual (multiple) cases and presented in a way that the phenomena leading to the failure are clarified or where investigation results have been grouped for a statistical approach.

For the first type of publication, I would like to mention the publications mentioned in my CV in Appendix G (where the /Pxx/ means that it is a publication mentioned in my CV): /P3/, /P4/, /P9/, /P10/, /P12/, /P14/, /P16/, /P18/, /P19/, /P20/, /P24/, /P25/, /P27/, /P39/, /P47/, /P48/, /P49/, /P50/, /P57/, /P59/, /P60/, /P72/, /P78/, /P80/, /P85/, /P95/, /P97/, /P102/, /P112/, /P126/, /P137/, /P144/, /P148/, /P151/, /P152/, /P155/, /P157/, /P158/, /P159/, /P162/, /P163/, /P164/, /P165/, /P166/, /P167/. Most of these

references reflect experiences with medium voltage cable systems for which laboratory test methods or diagnostic field tests are being developed.

For the second type of publication, also reflecting HV cable systems (among which HVDC cable systems), the following reference /P17/ has to be mentioned, called "Failures in underground power cables – return of experience". This was published and presented at the 9th International Conference on Insulated Power Cables (JICABLE), Versailles, France, June 21-25, 2015. This paper is also shown in Appendix B.

2.4.4 Professorship and its connection to power cable failure degradation knowledge

As a part-time professor at the Technical University Eindhoven in the Netherlands, I have a role in studying the performance and ageing of power cable networks and to develop diagnostics for these cables.

Because of this role, on a regular basis I am discussing the known and sometimes not well understood power cable problems with representatives of cable manufacturers, network owners and with colleagues from research and testing institutes. Many of these representatives and colleagues play a role in national and international working groups from for instance the IEEE, Smartlife and Cigré where similar subjects are being discussed.

This knowledge helps to understand the playing field of ageing power cable systems and where possible the background of failures.

And based on this knowledge, my students (PhD and MSc) are investigating ageing phenomena, to understand remaining life issues and to develop modelling tools and diagnostic tools. Some publications, in which I am co-author, reflect these studies, see Section 2.4.3 above (referring to the publications where the first author is (among others) Wagenaars, Wielen, Mousavi Gargari, Li, Wu, Barakou, Kruizinga, Simons).

As a professor (and before I became a professor, as an expert), another role is to be member of the doctoral committee on invitation of the promotor of another university. In this role, I read the (draft) thesis, comment on it and then discuss its content with the doctoral candidate, prior and during the public defence of the thesis. Among others, this happened for doctoral students at the Delft University of Technology in the Netherlands, where the thesis subject was the degradation of HVDC MIND cables like the Basslink cable [/25/, Jeroense, 1997] or where the thesis subject was the degradation of HVDC XLPE cables [/49/, Jonuz, 2007], [/60/, Bodega, 2006].

2.4.5 Approach in case of a failure investigation

A power failure investigation is often needed after an incident, where it is important to identify at least the technical root cause.

In many power failure cases it is not possible to get full certainty about the actual technical cause of the failure. That is normally caused by the fact that a power failure comes with considerable damage, sometimes a full explosion, if not a fire as well. Under such circumstances crucial evidence can get lost

because it is destroyed. What also can impede the power failure investigation is the fact that restoration of the power supply has often to be done quickly, losing further evidence in this way.

If a technical root cause cannot be found easily with full certainty, then there are many different (overlapping) methods to perform the root cause analysis in a structured way. Just to mention a few: Kepner Tregoe, Ishikawa, Human performance analysis, Tripod analysis, Bow-tie analysis. These methods are summarized in Appendix I. Like DNV GL, many companies dealing with failure analysis have their own approach, often with elements of the above-mentioned methods. Personally, I prefer to use a combination of:

- Kepner-Tregoe method (reason: it helps to structure the questions to be asked); and
- the Ishikawa method (reason: it helps to stay aware of all possible contributors to a failure).

The Human performance analysis might become useful once it becomes clear that human related factors play a role in the root cause of the failure. The Tripod analysis can in a later stage become powerful in graphically presenting causes and consequences, including barriers that should or did not function. Finally, the Bow-tie analysis is mainly of interest in case also mitigating actions would have to be analyzed, which is not the subject of this report.

One element of a root cause analysis is that all information must be gathered that could help to identify the cause of the failure. That is not just the result of the dismantling of the equipment that failed, hoping to see deviations from normal (and not caused by the failure). It is also important to collect information with respect to the design, the production, the installation and the operation. For instance, one can check if the design tests have been done according to a reputable testing regime and whether these design tests were passed successfully. The same counts for the manufacturing of the equipment. Of special importance is to find if there were deviations during the manufacturing, which should have been reported. A further source of information for the root cause analysis can be a literature survey. Certain studies and experiences have been made available in the public domain and are a valuable additional source of information in case of a root cause analysis.

Once all information is made available, one can check this in relation to possible causes. To do so, a list of imaginable possible root causes can be created and all information collected can be used to verify whether an imaginable root cause can be falsified or not. One falsification (in a row of required conditions) is enough to rule out a possible root cause.

In this way, a list of possible root causes can end up with these causes identified as "impossible, improbable, possible, probable, proven". Would one root cause end up as "proven", then the case is solved. But often what remains are several causes still "possible" or "probable", without having one "proven".

Next step is to check the degree of probability for each of the possible root causes. Here statistics can help, but also general knowledge or a discussion with several knowledgeable people (Delphi approach) to find the degree of probability. Would this result in a list with all possible causes "improbable", apart from one being "probable", then the actual root cause is found with a reasonable degree of certainty.

2.5 Declaration that the author has made all inquiries needed

Herewith I declare that I have been able to make all inquiries needed to identify the possible causes (including their related probabilities) and any relation to the way the cable was operated by Basslink operator Basslink Pty Ltd (BPL) of the Basslink outage.

3 SUMMARY OF OPINIONS

The Basslink cable is a 400 kV HVDC MIND cable link with 298 km (of which 283 km subsea) of power cable connecting Victoria to Tasmania. This link was commissioned in April 2006. It is owned and operated by Basslink Pty Ltd (BPL). The Basslink cable was manufactured and installed by Pirelli. After almost 10 years of failure free service operation, the cable failed in December 2015.

The cause of the failure is probably the fact that it was thermally overstressed during several periods in its service life, [redacted] Due to this, there was permanent degradation by void formation in the inner layers of the insulation material. During the cooling down prior of the failure in December 2015, the voids did enlarge and the extra electric stress from the voltage polarity reversal just before the failure caused the cable to degrade quickly and break down.

4 MATERIAL PROVIDED

I received material from Clayton Utz to support me in my investigation. These are listed in the letter of instructions, see Appendix M of this report. For easy reading and reference, all materials are listed below.

	Title	Date	Identification number	Rev
A. Expert Code				
1.	Expert Witness Code of Conduct (Supreme Court of Tasmania)	5 January 2016	Practice Direction 1 of 2016	
B. Background				
[redacted]				
C. Pirelli/Prysmian documents				
[redacted]				

	Title	Date	Identification number	Rev
[redacted]				

	Title	Date	Identification number	Rev
[redacted]				
D. Siemens documents				
[redacted]				

	Title	Date	Identification number	Rev
[redacted]				
E. Load data				
[redacted]				
F. Fault finding reports				
[redacted]				

	Title	Date	Identification number	Rev
[redacted]				
G. Photographs				
[redacted]				
H. CCI examination				
[redacted]				
56.	CCI Report, Basslink KP199.256 Failure Examination 27th to 29th April 2016	27 May 2016	ER 795	
[redacted]				
58.	CCI Report, Basslink KP199.256 Failure Examination 7th to 9th June 2016 at CCI	27 June 2016	ER 808	
I. Other documents				
[redacted]				

	Title	Date	Identification number	Rev
[redacted]				

	Title	Date	Identification number	Rev
[redacted]				

	Title	Date	Identification number	Rev
[redacted]				
J. Correspondence				
[redacted]				
K. CCI and Materials Technology Reports				
[redacted]				
68.	Materials Technology Report, Report on Analysis of Samples From 400 kV Basslink Cable Fault	28 November 2016	G9748	
69.	Materials Technology Report, Report on Thermal Analysis (DSC) of Samples From 400KV Basslink Cable Fault	29 November 2016	G11863	
[redacted]				

5 BACKGROUND INFORMATION

5.1 Voltage, electrical stress, current, power and temperature and how these are related

5.1.1 Voltage

HVDC (High Voltage Direct Current) systems for power transmission are normally operated at a certain voltage (potential difference) U, where the outside of the system like a metal sheath is at ground potential (zero Volt) and the inner side (the metal conductor) is at a high DC voltage. In case of a DC system, and thus also a HVDC system, the voltage is not changing over time, unless it is switched on or off for instance.

In between the conductor and metal sheath is an insulation material, which can be a gas or a solid material. For an overhead line, the insulation material is the air around the wire (conductor). For a power cable, the insulation material is often paper (impregnated with oil) or a plastic.

The system's potential difference U is measured in units of Volts, which is abbreviated to V or it is measured in units of kiloVolts, which is abbreviated to kV. This potential difference is present between the metal sheath at ground potential and the conductor. The potential difference is made by a surplus of plus charges in the conductor or a surplus of negative charges in the conductor, both in relation to the charges in the metal sheath. In case of a surplus of positive charges in the conductor, the system is at positive voltage. In case of a surplus of negative charges, the system is at negative voltage.

The insulation material is needed, otherwise the surplus of charges can't be kept away from the grounded metal sheath. That is because opposite charges strongly attract each other. An inability of the insulation material to do so, will lead to a breakdown at its weakest spot. The attraction forces are incredibly high. Feynman /1/ said the following about this (and read in the following sentence for the electrons the negative charges and for the protons the positive charges): "*If you were standing at arm's length from someone and each of you had one percent more electrons than protons, the repelling force would be incredible. How great? Enough to lift the Empire State Building? No! To lift Mount Everest? No! The repulsion would be enough to lift a "weight" equal to that of the entire earth*". Would we be dealing with a surplus of opposite charges for the above mentioned two persons, the word repelling can be replaced by attraction. In electrical systems the differences in numbers of charges are not that big as

mentioned in Feynman's example, but still big enough to be extremely demanding for the purity of an insulation material, in order to withstand these forces and related phenomena, certainly in the case of high voltages.

The high voltage for HVDC systems is in the range of a few hundred kV. In other words, the system is operated at a few hundred kV. The Basslink cable has a system voltage (U) of 400 kV.

The electrical voltage U is a more general expression. In the further report, sometimes U_o is used, next to U. U_o is the rated DC voltage between conductor and core screen (grounded metal sheath) for which the cable and accessories are designed. Thus, U_o of the Basslink cable is 400 kV.

5.1.2 Electrical field or Electrical stress

It is not so easy to explain the electrical field or electrical stress in simple terms. A good introduction is given in /73/. In a few words one can see an electrical stress E as a force field that attracts or repels electric charges. As such it is a relevant parameter for the occurrence of (partial) discharges.

The system's electrical stress E is measured in units of Volts per meter, which is abbreviated to V/m or it is measured in units of kiloVolts per mm, which is abbreviated to kV/mm.

In a simple approach (just for illustration) one can see it as follows. Between the plates of a flat capacitor, of which the upper plate is at a certain voltage U and the bottom plate is grounded, the electrical stress is homogeneous in the insulation material between the two plates. The electrical stress is defined as the electrical voltage U divided by the distance between the plates d. For instance, if the electrical voltage U is 400 kV and the distance d is 20 mm, then the electrical stress E is 20 kV/mm. In this flat capacitor, the magnitude of this electrical stress is everywhere the same. For instance, it is found to have this magnitude of 20 kV/mm just under the upper plate with the high voltage as well as just above the bottom plate at ground potential. In a cylindrical configuration as a power cable the electrical stress close to the conductor is higher than close to the grounded metal sheath.

In the above description, it is assumed that the insulation material has homogeneous electrical properties.

5.1.3 Electrical Current

The above-mentioned conductor is normally carrying an electrical current I. It means that the surplus of charges is moving from one side of the system to the other side. By moving charges while the system is at a certain voltage level, power can be transmitted. Power will be introduced further in the next Section.

The current is measured in units of Ampere, which is abbreviated to A. If during 1 s, 1 A is flowing, it represents a flow of about $6 \cdot 10^{18}$ electrons passing by. The 10^{18} represents a 1, followed by 18 zeros. The Basslink cable can for instance transmit a current I of 1250 A on a permanent basis.

In case of a DC system, and thus also a HVDC system, the current is only changing over time based on the wish to transmit more power or less power. In an AC (Alternating Current) system, the current is also periodically changing with a frequency of 50 Hz (for instance).

5.1.4 Power transmission

Electrical systems as the Basslink cable have the object to transmit power from one side of the system to the other side. The electrical power flow P for a HVDC connection is given by the multiplication of the system voltage U and the flowing current I. In other words, it follows the formula $P = U \cdot I$. The power is measured in units of Watt, abbreviated to W. For the Basslink cable, where the system voltage U is 400 kV and the transmitted current I is 1250 A, the transmitted power P is 500 000 kW, or P = 500 MW, where M stands for Mega. A quantity of 500 MW is in the range of power produced by a medium sized nuclear power plant. This 500 MW is the maximum continuous power that can be transmitted. If less power has to be transmitted, then this is normally done by reducing the amount of current transmitted, while the system voltage stays unchanged.

5.1.5 Power transmission and voltage polarity reversals

In order to change the power flow direction one can choose to reverse the voltage or to reverse the current (not both). But since the convertor station set-up for Basslink (and many other HVDC connections in the world) is such that the current can't be reversed, the only alternative is to reverse the voltage.

By reversing the voltage, one can choose to bring electrical power from Victoria to Tasmania or vice versa. The process comes with a so called "voltage polarity reversal".

5.1.6 Electrical current and cable temperature

Since any conductor (apart from a superconductor) has a certain electrical resistance, the electrical current flowing through the conductor will come with losses. Such losses mean heat production.

The amount of heat produced is directly related to the amount of electrical current I flowing and the electrical resistance R of the conductor. This power loss P_{loss} is related to the multiplication of the square of the current and the electrical resistance. Thus, $P_{loss} = I \cdot I \cdot R$, or in other words, $P_{loss} = I^2 \cdot R$. This power loss is expressed in Watt (W).

If there is no electrical current flowing, the conductor losses are zero. Under full electrical current load, the losses will reach their maximum. That is the most critical situation from a thermal point of view for a power cable.

Since the maximum conductor temperature for any power cable is limited to a certain temperature, the maximum current has to be limited as well. This results in the above mentioned 1250 A as the maximum continuous current for the Basslink cable, where the maximum insulation temperature (close to the heat producing conductor) is [redacted]

This heat produced in the conductor, flows from this conductor to a cooler area, being the outer world, via the insulation material, to the metal sheath and all other layers. All these layers together have a thermal resistance. Due to that, there is a temperature drop over all these layers. And thus, there is a temperature drop over the cable insulation material as well. It means, that as soon as the cable is transmitting power and thus current is flowing through the conductor, the insulation near the conductor will be warmer than the insulation near the lead sheath.

Materials not only have a certain thermal resistance, but also a thermal capacitance. It means that it takes time to heat up a cable. Roughly, it takes hours at full cable load (the maximum current flowing) to bring a cable from a certain starting temperature to its maximum temperature. This is illustrated in Figure 1, where the current is going from zero to its maximum current load at t = 0, where the cable temperature takes hours to reach its maximum. The y-axis in Figure 1 represents per unit (pu) values (see Section 1.6.2 for an explanation of per unit values).

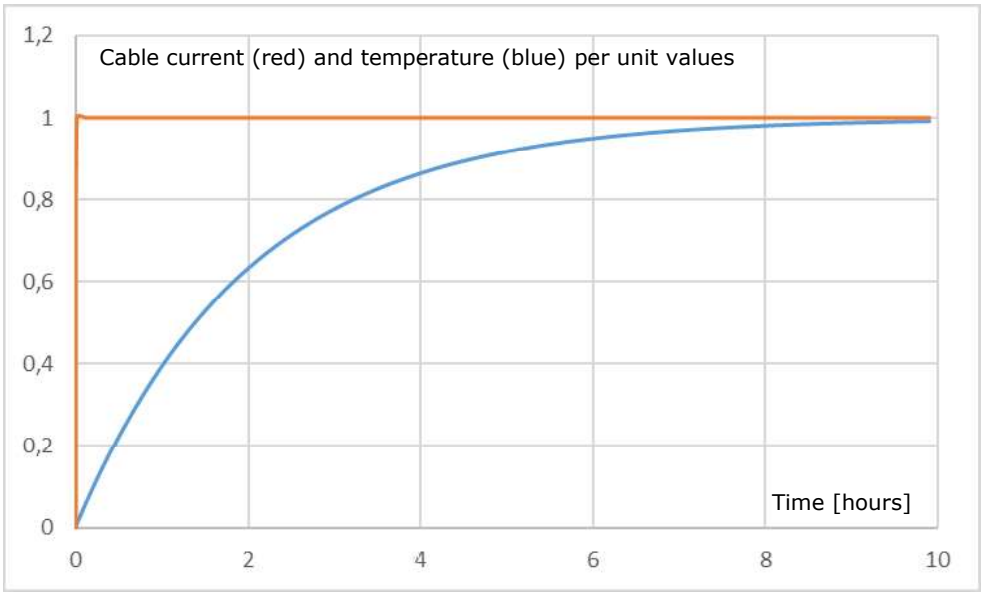


Figure 1 **Illustrative temperature response (blue line) of a cable if the current (red line) is changed stepwise. The x-axis represents hours, the y-axis represents per unit values.**

5.2 Mass impregnated power cables for HVDC, their construction and limitations

5.2.1 General

For transmission of large amounts of electric energy across long sea crossings the so-called Mass Impregnated Non Draining (MIND) HVDC subsea cable has for long been and at the time of installation of the Basslink cable was the state-of-the-art technology [/53/, Worzyk, 2009].

In [/40/, Runde, 2014], the following is said about recent installations. These "*operate at typically 450 - 500 kV and have a continuous power rating per cable of up to 800 MW. These all represent very large investments, and among them is the world's longest power cable, NorNed, connecting the Norwegian and Dutch grids. Several new projects are under way, and in a future pan-European power grid subsea cables in the North Sea and the Mediterranean are expected to play a crucial role, both for exchanging power with continental Europe and for transferring power generated in large off-shore wind farms. Even though it is generally believed that cross linked polyethylene (XLPE) insulated cables will enter this*

market in the future, it is certain that MIND cable technology will remain the dominant solution for long times. The ability of this cable technology to handle the large mechanical stresses associated with installation at large sea depths has over the years been developed substantially, and today MIND cables are in operation down to 1650 m. The majority of the failures that have occurred during service have been caused by external factors, typical trawl doors and anchors. The reliability of the cable itself is in general found to be very good, indicating that the technology is robust and that the type testing has been sufficiently demanding".

The general design set-up of a typical HVDC MIND paper insulated power cable will be introduced, with help of an illustration shown in Figure 2 (the cable shown here is not the Basslink cable, but a 350 kV HVDC MIND power cable, installed in 1991 on the New Zealand HVDC Inter-island scheme). A good summarizing introduction on HVDC MIND power cables is given in Lawson's report [TAB 61].

In the Section 5.2.2 to 5.2.9 the typical HVDC MIND power cable will be presented. More can be found among others in [/53/, Worzyk, 2009].

In Section 5.2.10 more will be said about the insulation material and its potential weaknesses. This is an important matter in the case at hand.

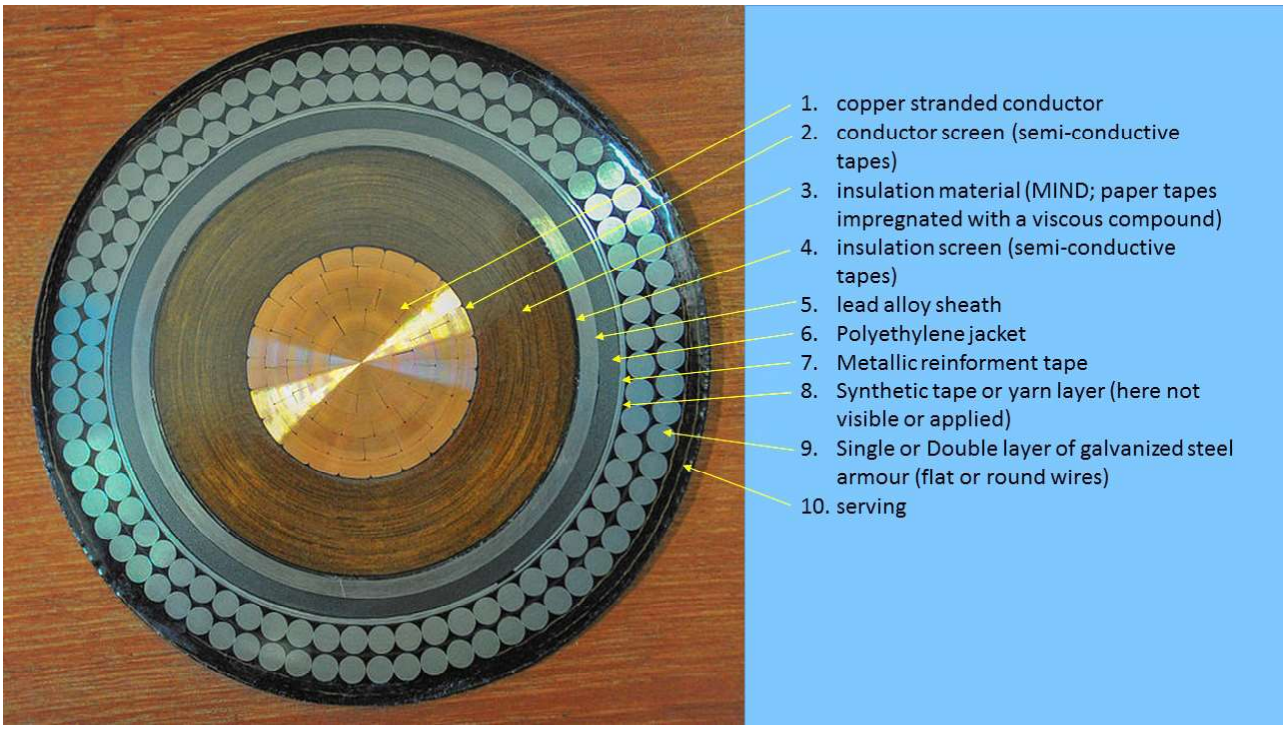


Figure 2 **Cross section of submarine cable rated 350 kV, 1430 A HVDC cable with MIND insulation, installed in 1991 on the New Zealand HVDC Inter-island scheme (reference: wikimedia.org).**

5.2.2 The conductor

To let a current flow from one side of the connection to the other side, a conductor is needed. The conductor is placed in the centre of the cable. A conductor is round and normally made of copper or aluminium wires. On transmitting power, the conductor is put on a high voltage.

Around the conductor there are semiconducting tapes, which main role is to ensure that there is a smooth conductive transition layer between the metal conductor and the insulation material.

5.2.3 The insulation material

To isolate electrically the conductor (at high voltage) an insulation material is needed. The reasons for having an insulation material are explained in Section 5.1.1.

The electrical insulation of HVDC MIND power cables consists of paper, impregnated with a viscous compound. It is this viscous compound which leads to the description "mass-impregnated". This impregnant should not flow downhill in case a cable is installed in a hilly area or a landing zone. By choosing the impregnant type correctly, i.e., with enough viscosity, it will not start to flow on an incline indeed. Such cables are called "non-draining". The combination of mass-impregnated and non-draining makes such cable so called Mass-Impregnated Non-Draining (MIND) cables.

The basis of the insulation material is paper, which comes in layers wound around each other. The paper layers are helically wound with small spaces in between, see Figure 3. These spaces are called butt gaps. These butt gaps are needed:

- to keep the cable flexible (with help of the impregnant, the paper layers can slide over each other without buckling or creasing) and
- to allow the impregnant to penetrate the cable during production.

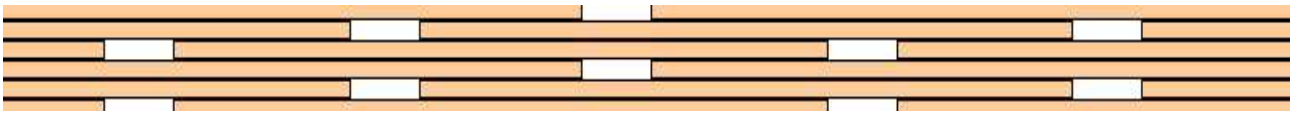


Figure 3 Artificial drawing of a few paper layers inside the insulation material of a MIND power cable. The spaces between the paper windings are called butt gaps.

Some important aspects of the insulation material will be treated in Section 5.2.10:

- void formation
- temperatures allowed
- electric field distribution

5.2.4 Lead sheath

To prevent water from entering the insulation material, this insulation is enclosed by a lead sheath.

Under the lead sheath there is a set of layers of (semi-)conducting tapes, which main role is to avoid that there is a smooth conductive transition layer between the lead sheath and the insulation material.

5.2.5 Polyethylene (PE) jacket

Lead is a soft metal and not well able to withstand pressure from the protection layers without getting damaged. Therefore, a PE jacket (an alternative word is PE sheath) is used.

5.2.6 Metallic reinforcement tapes

To keep the paper layers of the insulation material compressed during current load cycles (or heat cycles), metallic reinforcement tapes are being applied. These tapes are often embedded:

- in polyester tapes to prevent the sharp edges of the metallic tapes damaging the PE jacket and to allow sliding with respect to each other on installing the cable and the various surrounding layers,
- in bitumen to prevent the metallic tapes getting corroded by (sea) water.

5.2.7 Synthetic tape or yarn bedding

It is the object of the synthetic tape or yarn bedding to prevent that the heavy metal armour will in one or another way damage the layers underneath. Also these layers might help to allow that on installing the cable the various surrounding layers can slide with respect to each other.

5.2.8 Armour

The armour consists of one or two layers of steel (zinc coated) wires or tapes. The armour protects the submarine cable from getting damaged after it is installed, but also give the cable mechanical strength while it is being installed. A double layer (with opposite pitch) is normally used to install the cable in deeper water given the heavy weight of the cable hanging on the installation vessel during its installation. By using an opposite pitch, the armour based torsion forces are eliminated.

5.2.9 Serving

The serving holds all components of the cable together and provides additional protection from external stresses. It is often bitumen impregnated, to avoid corrosion of the metal layers underneath.

5.2.10 Insulation material – some key issues

5.2.10.1 Void formation in the insulation material

The thermal expansion and contraction of the impregnant is much greater than that of the surrounding paper. In a cable under operation, the conductor and inner part of the insulation is warmer than the outer part of the insulation.

To prevent the impregnant from migrating from the inner layers near the conductor to the outer paper windings, the paper windings are wound with a certain tension. Moreover, outside the lead sheath, steel tapes (called reinforcement tapes) can be wound during production with tension giving additional force to keep the paper windings tightly compressed, especially during the cooling stage. That is needed to

avoid that on cooling down the impregnant, contracting more than the surrounding paper, will give rise to void formation.

But if despite the above-mentioned measures, voids are created, and if their size is large enough, inside these voids sparks will appear. Sparks are also called partial discharges, which can be seen as miniature lightning strokes. These sparks are the consequence of the combination of the high electrical stress inside a void and the low breakdown voltage of this void. Once there is a spark, and if followed by more of such sparks, the surrounding insulation material will degrade such that a full breakdown of the whole insulation material will follow. It can take minutes to days (or more) in a polymer material environment, but it can take hours to years in a paper insulated environment because the impregnant tends to redistribute, forcing the spark to act on another spot. More background information is given in Appendix J.

Various authors mention that HVDC MIND cables during tests fail in the cooling down of the cable (see Appendix K). That is generally attributed to the void formation in the cable insulation during its cooling down stage, where the voids as mentioned above create a platform to ignite partial discharges and degradation. In Appendix P, the void formation according to [/40/, Runde, 2014] is visualized. In [/40/, Runde, 2014] the following is said about it: "…. *generally assumed that the breakdowns are caused by the formation of extended cavities in the insulation during a load reduction or turn-off. The cavities are thought to be a result of the thermal expansion and contraction of the impregnant being much greater than that of the paper*".

5.2.10.2 Maximum temperature of the insulation material

Because of the fact that void formation on cooling down has to be avoided, both the conductor temperature and temperature difference over the insulation material of a MIND power cable during operation are kept below a certain level. The maximum temperature of the insulation is practically the same as the maximum temperature of the conductor. For the Basslink cable these both maximum temperatures are introduced in Section 5.3.5, but are mentioned already here: the maximum conductor temperature is [redacted] and the maximum temperature difference over the insulation is [redacted]

As a consequence, thermal degradation of the insulation material (expected far beyond [redacted] causing the impregnant or paper to degrade on a molecular level (like excessive depolymerisation) is not playing a role [/18/, Hjalmarsson, 1992], [/40/, Runde, 2000] within the foreseen lifetime of a HVDC power cable (assuming this foreseen lifetime is in the range of 40 years). With that, it is not expected that paper layers become brittle, that the impregnant get solidified, etc, as one can see happening in MV MIND cables thermally overstressed, with an example given in part 3.1 of [/54/, Steennis, 2014].

5.2.10.3 Electric stress distribution in the insulation material

The electric stress distribution is obtained by a redistribution of charges inside the insulation material.

a) Normal electric stress distribution in the insulation material

The electric stress distribution in the insulation material of a HVDC cable depends on the temperature distribution inside the insulation. That has to do with the fact that the electric stress distribution is

depending on the conductivity of the insulation material and that conductivity in turn depends on the insulation material temperature. Under isothermal conditions, the electric field is highest at the conductor side. However, when the cable is carrying a high load, the insulation material on the conductor side has a higher temperature [redacted] and with that a higher conductivity than on the lead sheath side of the insulation material, where the temperature is lower (for instance 35 °C) and the conductivity is lower. These differences are such, that under this condition the electric stress gets higher at the lead sheath side of the insulation. This is illustrated in various publications, among which in [/4/, Occhini, 1967], [/2/, Hampton, 2000] and [/40/, Runde, 2014]. From [/4/, Occhini, 1967] an illustrative figure is copied below in Figure 4. The actual electrical stress in a power cable can differ from what is shown in Figure 4, and will depend on the design (material properties, dimensions) and the actual temperature. But the fact that the electric stress distribution is influenced by the temperature difference is a reason to limit this temperature difference. As said before, the temperature difference limit is related to the cable design and for the Basslink cable it is mentioned in Section 5.3.5, being [redacted]

The electric stress distribution shown here is obtained after a certain time and is therefore called "steady state electric stress".

Electric field E

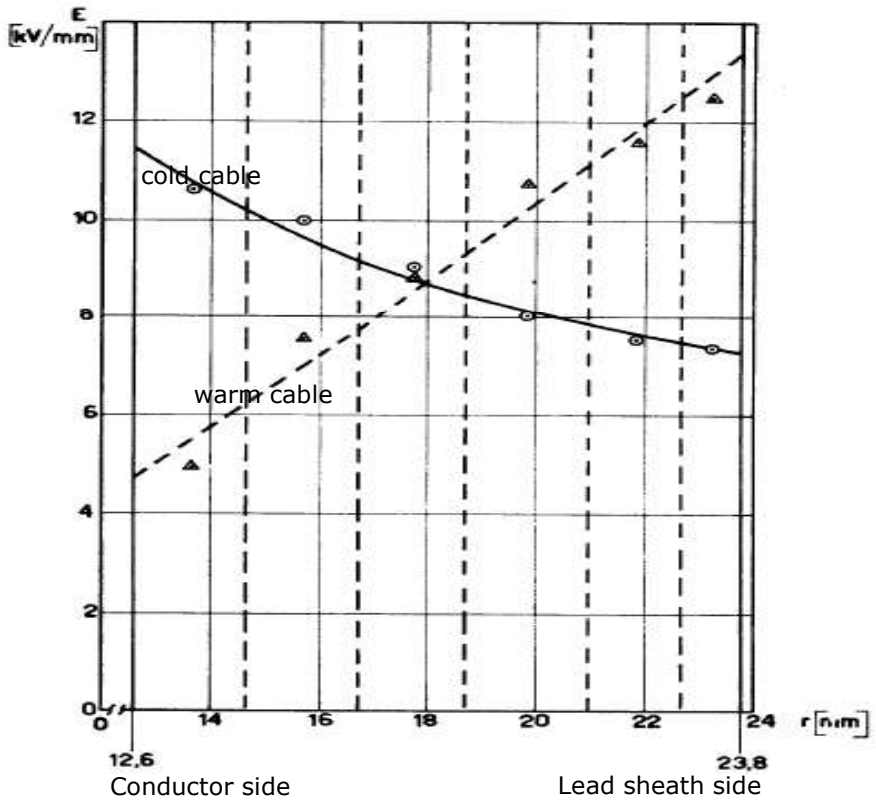


Figure 4 **The steady state electric stress over the insulation material of a typical HVDC MIND cable. At 12.6 mm is the conductor side, at 23.8 mm is the lead sheath side. The continuous line represents the electric stress distribution of the steady state condition of a cable without a temperature difference over the cable insulation. The dotted line represents the electric stress distribution as a steady state condition of a cable with a 20 °C temperature difference (with the conductor being warmer) [/4/, Occhini, 1967].**

b) Electric stress during voltage polarity reversals

The reason for a network owner to apply voltage polarity reversals is explained in Section 5.1.5.

I carried out a literature survey with a focus on voltage polarity reversals, with the purpose to get a complete picture of this phenomena and to show its relevance for the breakdown strength of HVDC MIND power cables.

The findings are summarized in Appendix Q of this report at hand. In short the following can be said about voltage polarity reversals and their impact on the HVDC MIND power cables:

1) Right after a voltage polarity reversal, the electric stress in the insulation at certain locations is much higher than the steady state electric stress. Depending on the location, it can be factors higher. This is illustrated in Figure 5 for the electric stress at for instance the conductor side of the insulation material. Only after a certain time, the steady state electric stress will be reached again, but this will take many minutes if not hours. This time is needed to redistribute (space) charges inside the insulation material. The actual electrical stresses created and redistribution speed of

charges will depend the cable design (diameters, actual insulation material applied) and the temperatures of the insulation as a function of time.

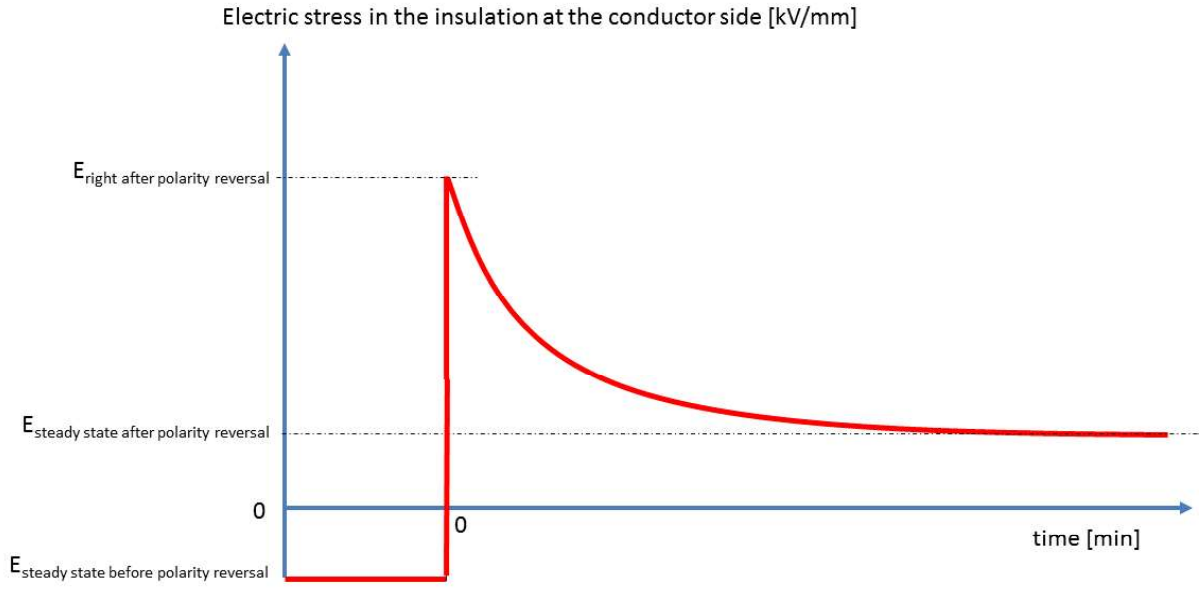


Figure 5 Artificial drawing of the electric stress at the conductor side of the insulation material of a warm cable, right after and long after a voltage polarity reversal.

2) The redistribution of space charges is called discharging or deionisation. Its speed is depending on the electrical conductivity of the insulation material and is quite reproducible. In a warm cable, this redistribution goes faster than in a cold cable.

3) Because of that, in order to avoid to electrically over-stress, degrade, age and breakdown the insulation material, voltage polarity reversals (the time to perform this reversal, but also their number per day and year) are a design issue for HVDC power cables in general, and MIND cables as well. In line with this, voltage polarity reversals are part of Cigré's Electra 189 [/28/, Cigré, 2000] recommended testing regime.

4) For the same reason, network owners often take the voltage polarity reversal time as an operational matter. By performing a slow voltage polarity reversal (with introducing a certain waiting time or deionisation time, like illustrated in Figure 6), the insulation material will be stressed less than in case of a fast one. For instance, in [/35/. Skog, 2006] said that the default voltage polarity reversal time is 1 hour, but in case of marketing constraints can be reduced to 14 minutes (assuming full power). And in [/31/, Giorgi, 2002] the voltage polarity reversal time (de-ionization time) of 10 min, with up to 1000 times/year with a min time interval of 2 hours is mentioned. It does not mean that the deionization time is always chosen as mentioned above. I talked with various HVDC MIND cable operators in Europe and learned that the deionization time nowadays in many cases is 2 minutes, and in one case it was in the second range (but in this case,

the cable was prevented from cooling down, which is an important detail).

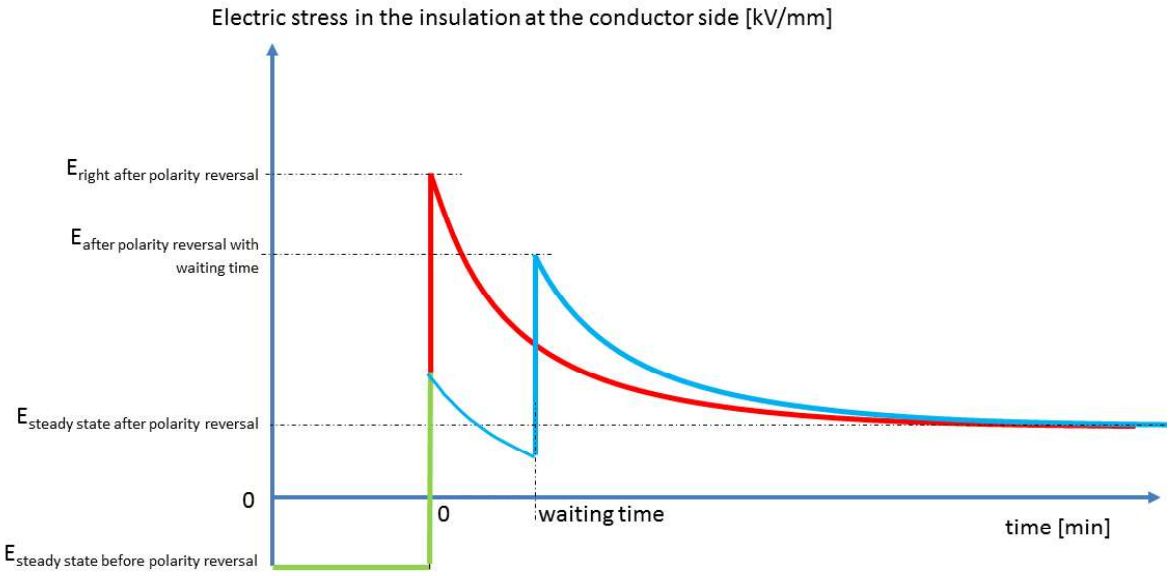


Figure 6 **Artificial drawing of the electric stress at the conductor side of the insulation material of a warm cable, right after and long after a voltage polarity reversal (green plus red line), and in case a voltage polarity reversal is done by taking some waiting time (green plus blue line) to partly deionise the insulation material and reduce the electric stress during this voltage polarity reversal operation.**

5) [redacted] Also from 2016 until now, there are no known failures reported during service operation, where clearly voltage polarity reversals caused the failures. However, it is my own experience that a failure (which I investigated) has occurred in a HVDC cable right after a voltage polarity reversal.

Project	Year	Length km	No. of Failures	Cause of Failure
[redacted]				

[redacted]

Figure 7 HVDC MIND power cable reliability as reported in [TAB 24], being dated December 6th, 2006.

5.2.10.4 Concluding remark concerning the insulation material issues

Thermal matters: In [/40/, Runde, 2014] it is said**.** "*… the cooling period after load reduction or turn-off is the most critical part of the dielectric type test and thus presumably also for the operation of a subsea mass impregnated HVDC cable. Moreover, it is assumed that dielectric breakdowns under such conditions are caused by formation of excessively large cavities or voids in the insulation".*

Running a power cable above its thermal limit of [redacted] (at the conductor side of the insulation) is an issue of concern, because it will contribute to an imbalance in the impregnant distribution, which will contribute to void formation. Above that, the cooling down regime is also important. A too quick cooling down over a too large temperature range can give rise to void formation, coming with sparks inside the voids which ultimately can lead to a local degradation and failure. Furthermore, operating a power cable above its thermal limits will also increase the electric stress at the outer side of the insulation, and most probably beyond design levels.

Voltage polarity reversals: The voltage polarity reversals (applied during a change in the direction of the power flow) can give rise to considerable additional electric stresses inside the insulation material and thus such a situation is additionally demanding for a HVDC MIND insulation material.

Degradation reversible or irreversible: I also investigated whether thermal degradation (via impregnant redistribution and void formation) and the impact of voltage polarity reversals come with reversible or irreversible degradation. Concerning thermal degradation, several authors from publications [/30/, Bossio, 2002], [/33/, Morshuis, 2005] and [/40/, Runde, 2014] mention, and also from personal interviews I found, that this degradation is irreversible. Concerning voltage polarity reversals, the situation is less clear, but one author [/27/, Isayama, 1999] found an irreversible degradation. None of the publications or interview results mentions that thermal related degradation or voltage polarity reversal related degradation is reversible.

It is possible, that a **combination** of the above-mentioned issues can be responsible for a breakdown.

Both issues will be discussed in relation to Basslink's cable operation, i.e. thermal matters in Section 6.2 and voltage polarity reversals in Section 6.3.

However, [/40/, Runde, 2014] also said that "*the behaviour of the cable insulation under different load conditions, and thus the risk of having such breakdowns, is not understood. Although mass impregnated cables is a mature technology with HVDC subsea cables in service since the 1950s, it is reason to suspect that their real capacity and operational flexibility are not fully exploited*".

5.3 The Basslink cable

5.3.1 General information

The Basslink cable is a 400 kV HVDC cable link connecting the Loy Yang Power Station in Victoria to the George Town substation in northern Tasmania.

Basslink is a monopolar HVDC link with a metallic return comprising 298 km of power cable and 65 km overhead lines (Figure 8).

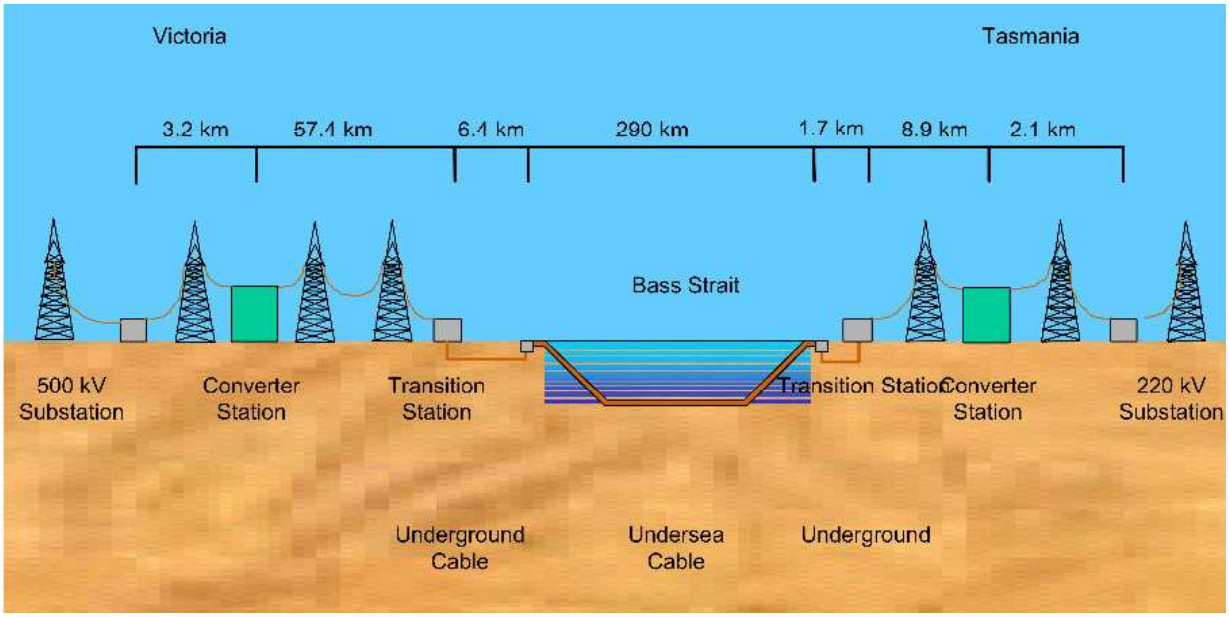


Figure 8 Basslink cable conceptual elevation map, from [/34/, Bex, 2006].

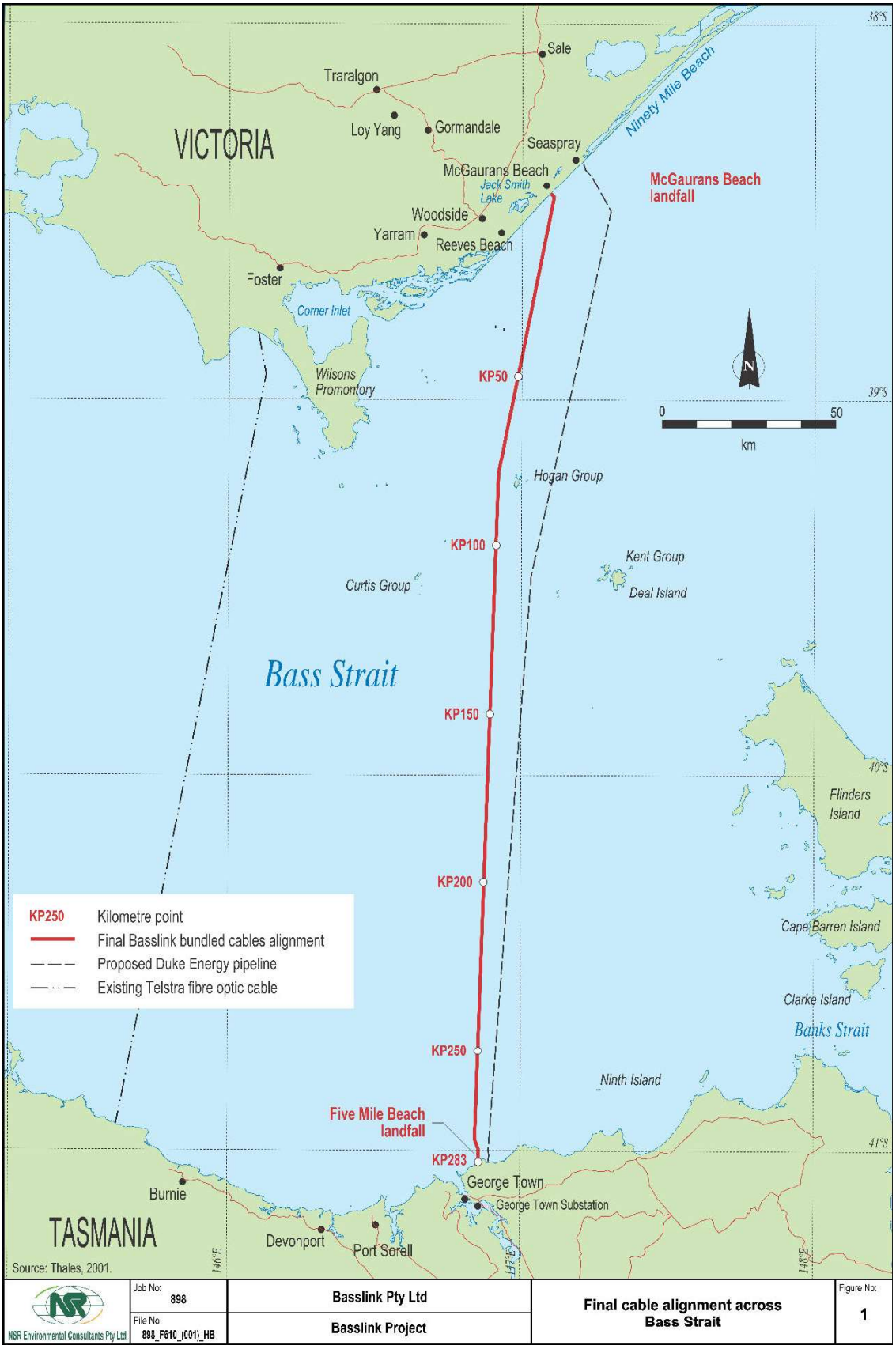


Figure 9 Basslink cable route map, from [TAB 3].

The Basslink HVDC link was commissioned in April 2006. It is owned and operated by Basslink Pty Ltd (BPL). Between October 10th, 2005 and May 10th, 2007 BPL was known as National Grid Australia Pty Ltd.

The subsea section of Basslink is 283 km long [Figure 9]. The convention for pinpointing a part of the cable is via Kilometer Points (KPs), which are measured from the Victorian end of the cable.

The Basslink cable was manufactured and installed by Prysmian Cavi e Sistemi Energia Sri (formally known as Pirelli), between 2003 and 2005. Prysmian formed a consortium with Siemens for the engineering, procurement, and construction phase of the Basslink project, with Prysmian responsible for the design, manufacture, installation and commissioning of the subsea and land cable and Siemens responsible for the converter stations, power lines and other land based work.

The design life of Basslink, and with that of the cable, is 40 years and Basslink should be capable of achieving annual availability target value of 97.5% with a minimum value of not less than 97%.

5.3.2 Basslink contractual obligations

The Basslink Services Agreement (BSA) is an agreement between BPL and Hydro Tasmania, [redacted]

The Basslink Operations Agreement (BOA) is an agreement between BPL and the State of Tasmania [redacted]

5.3.3 Power rating and dynamic power issues

The connection has a rated continuous power transfer capacity of 500 MW (normal rating, 1250 A) with a dynamic rating of 630 MW (1565 A) for a period of up to [redacted] The 630 MW rating is used for export from Tasmania and 480 MW is used for import into Tasmania.

There are various documents treating the issue of the power rating for the submarine cable. [redacted]

- [redacted]
- [redacted]
- [redacted]

[redacted]

[redacted]

[redacted]

[redacted]

There were arbitrations between Hydro Tasmania and BPL in 2013-2014, which related to the capacity and operation of Basslink following interruptions to the operation of Basslink during extreme weather conditions that occurred in January and February 2009. [redacted]

5.3.4 Basslink cable construction

The 400 kV HVDC sub-sea cable has a copper conductor with a cross-section of 1500 mm^2 and is steel armoured with mass impregnated non draining (MIND) paper insulation. [redacted] there is no further explanation of the cable design needed here.



Figure 10 Basslink submarine cable – cross-sectional view and summary of the various layers.

In addition to the 400 kV HVDC sub-sea cable, Basslink has a metallic return cable and a fibre optic cable. These are bundled together. [redacted]. The metallic return cable returns the current

from one side of the connection to the other side of the connection. [redacted]

5.3.5 Basslink cable design issues

The Basslink submarine power cable has been tested at different moments to prove the design.

- [redacted]
  - [redacted]
  - [redacted]
- [redacted]
  - [redacted]
  - [redacted]

  [redacted]
- [redacted]

[redacted]

A weakness however is, that I have been provided with no evidence that the tests were witnessed by an external knowledgeable and independent party and thus, the above conclusion comes with this related uncertainty.

[redacted]

5.3.6 Basslink cable production issues

[redacted]

[redacted]

A weakness however is, that I have been provided with no evidence that the tests were witnessed by an external knowledgeable and independent party and thus, the above conclusion comes with this related uncertainty.

5.3.7 Basslink cable installation

[redacted]

The 400 kV HVDC sub-sea cable and metallic return cable are bundled and laid together. [redacted]

[redacted]

[redacted]

[redacted]



Figure 11 Basslink submarine cable – Original Cable Lay – depth of coverage [TAB 58.3.1].

I conclude that the cable installation in the area where the fault of December 2015 happened the installation does not show reasons to assume that it might have caused a weakness in the power cable.

5.3.8 Basslink cable joint positions

5.3.8.1 Introduction



Figure 12 Joint positions as a function of the installed cable length in KP.

5.3.8.2 Factory joints

-
-

5.3.8.3 Installation joints

5.3.8.4 Repair joints

-
-

[redacted]

5.3.9 Accelerated ageing tests on recovered HVDC cable

[redacted]

5.3.10 Basslink cable operation

The Basslink cable has been in commercial operation since April 28th, 2006 until its failure on December 20th, 2015 at 2:05 pm. Apart from this failure there have been no other power cable failures during this service operation period. This was derived from the fact that there were no long duration interruptions, apart from the one in December 2015. [TAB 59.1]. The power flow during the full period is shown in Figure 13, its information being derived from [TAB 38] and [TAB 39].

[redacted]

As can be seen in Figure 13, the Basslink cable both transmitted power from Victoria to Tasmania and vice versa. In case of:

- a positive power flow in the below figures the power flow is from Tasmania to Victoria.
- a negative power flow in the below figures the power flow is from Victoria to Tasmania.

It will be clear that the positive power flow (from Tasmania to Victoria) is often larger than the maximum rating of the power cable, being 500 MW. That is possible indeed, since the maximum power rating of 500 MW is related to a permanent current load. Would a higher current load be restricted in time and preceded or followed by a lower current load, then the maximum power rating can be higher indeed. That is because the actual limitation to operate a cable (at a given voltage) doesn't come from the power, but comes from the temperature which is a result of the current load. It will take time to heat up the power cable at a given current load. As a result, even a higher current (and thus power flow) is possible for a while, as long as that temperature limit will not be surpassed. Using a cable in this way is called Dynamic Rating. [redacted]



Figure 13 **Power flow as a function of time from the start of commercial operation in April 2006 until the failure moment on December 20th, 2015 at 2:05 pm (5 minute measurements). The a-x-axis values represent sample numbers and can be ignored.**

5.3.11 The failure circumstances – power in the months, days and hours before the failure

In the period preceding the failure, the power flow was as shown in Figure 14, Figure 15 and Figure 16, its information being derived from [TAB 38] and [TAB 39].

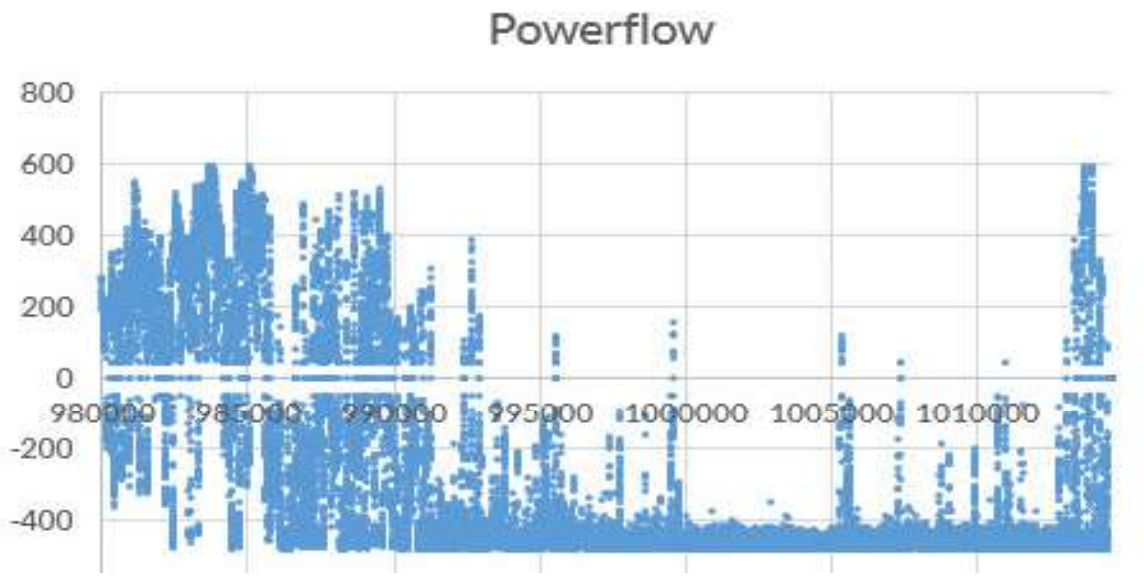


Figure 14 **Power flow as a function of time for the last 5 months before the failure, i.e. from August 22nd, 2015 until the failure moment on December 20th, 2015 at 2:05 pm (5 minute measurements). The a-x-axis values represent sample numbers and can be ignored.**

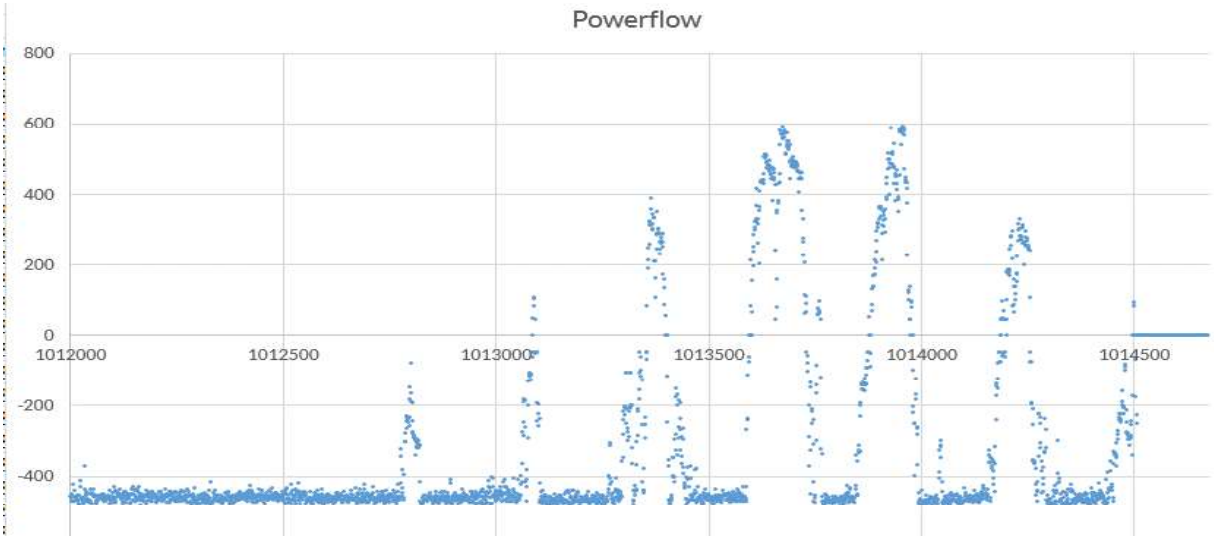


Figure 15 **Power flow as a function of time for the last 9 days before the failure, i.e. from December 11th, 2015 until the failure moment on December 20th, 2015 at 2:05 pm (5 minute measurements). The a-x-axis values represent sample numbers and can be ignored.**

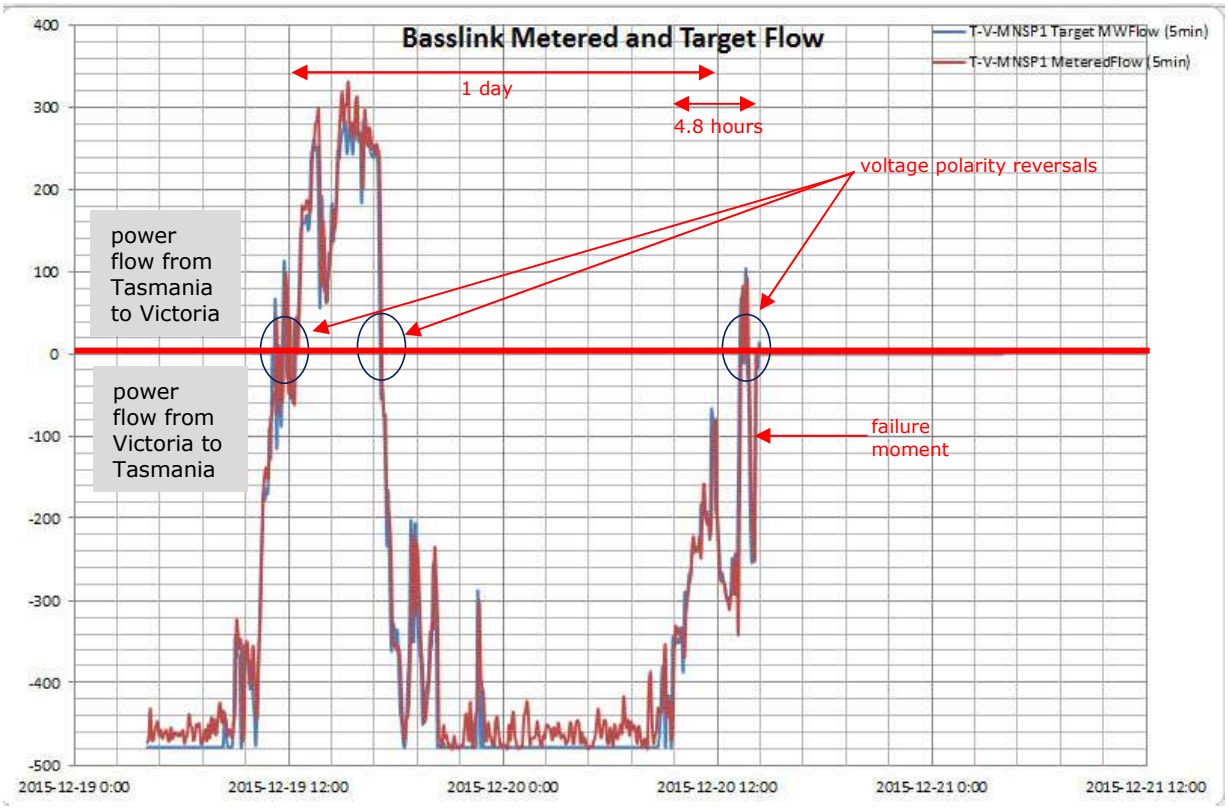


Figure 16 **Power flow as a function of time for the last 1.5 days before the failure, i.e. from December 19th, 2015 at about 5 am until the failure moment on December 20th, 2015 at 2:05 pm (5 minute measurements). The failure moment is shown and various voltage polarity reversals are visible.**

Concerning the last hours before the failure, CCI in their report [TAB 67], item 114 and item 115 summarized the power flow, current load and temperature as follows:

"*(114) The power record shows:*

a. *The cable had been carrying a near continuous power level of 478 MW (95 % of the continuous rating of 500 MW) for 740 minutes (importing from Victoria), this period ended 325 minutes before failure.*

b. *The power level then decreased and reached zero 45 minutes prior to failure.*

c. *The power was then at near zero for 25 minutes with two five minute periods of power export.*

d. *The final import of power commencing 20 minutes prior to failure.*

e. *Failure occurred at 14:05 hours, with the cable carrying 249 MW (50 % of the continuous cable rating of 500 MW).*

(115) The cable considered to have experienced the following thermal and voltage conditions prior to the failure:

- *In period b) the cable was cooling*

- *At the start and end of period c) the cable experienced two voltage polarity reversals*
- *In period e) the cable was heating"*

5.3.12 The failure circumstances – fault location and cable retrieval

On December 20th, 2015, at approximately 2.04 PM, the Basslink HVDC cable experienced a fault which caused it to cease operating.

[redacted]



Figure 17 Failure location, based on Basslink operational information, from [TAB 44].

[redacted]

[redacted]

- [redacted]
- [redacted]
- [redacted]
- [redacted]

It is my opinion that these positions are far enough from the cable breakdown spot to exclude these from this failure in a first approach.

On June 13th, 2016 the cable was returned to service, after having replaced the failure spot with spare cable and by applying also [redacted] repair joints. [redacted]

5.4 Basslink power cable failure investigation

5.4.1 CCI's investigation and CCI's conclusion (what was done, my role)

After the Basslink cable failure in 2015, BPL engaged CCI to conduct the independent cable failure examination works. [redacted]

[redacted]

The CCI reports presenting the factual findings are [TAB 56] and [TAB 58]. [redacted]

[redacted]

This was followed by a conclusive report from CCI about the cause of the failure [TAB 67]. The conclusions (in summary) are important and therefore the relevant part (starting with paragraph 3 from the summary in [TAB 67]) is repeated here:

3. *The fault occurred within the cable. The fault was not at a location of a joint, or a lead sheath to armour bond.*
4. *In the absence of surviving evidence it was not possible to determine the cause of the failure of the cable as:*
   - *There was no evidence of any pre-existing external mechanical damage to the cable.*
   - *The electrical fault was a 'radial, short path' type. The path extended through the paper tape insulation between the conductor at high voltage and the lead sheath alloy at lower voltage.*
   - *There was no evidence of any incipient electrical activity connected with the fault site or present elsewhere in the cable.*
   - *The point of initiation within the fault path and the direction of propagation of the electrical failure could not be determined due to severity of the fault damage.*
5. *The fault position was beneath the norther bulge in the cable.*
6. *The northern bulge was formed by the explosive effect of the electrical power arc within it.*
7. *A second bulge was present 480 mm to the south of the northern bulge. The insulation inside the southern bulge was sound and did not contain electrical distress.*
8. *The southern bulge was formed by the shock wave travelling to a location where the steel reinforcement tapes had a wider butt gap and experienced a force above their breaking point.*
9. *The operation conditions at, and preceding, the time of failure were no different to those of the year 2015. The cable was within its thermal rating.*
10. *The insulation adjacent to the failure site was sound and showed no evidence of thermal ageing.*
11. *A sample of cable remote from the fault site was in sound condition*".

[redacted]

5.4.2 Certain CCI findings further elaborated

5.4.2.1 [redacted]

[redacted]

[redacted]



Figure 18 **From [TAB 58, figure 2], a sharply curved spot with permanent set found in the conductor (the red lines illustrate the curve).**

[redacted]



Figure 19 **From [TAB 56, figure 15 left and figure 50 right], showing a wrinkled outer layer of the reinforcement tape (left picture: the reference cable (20 m away from the failure spot), right picture: of the failed cable part).**

[redacted]

Figure 20 **Own photos taken during the dismantling, showing the smooth inner layer of the reinforcement tape of the reference cable (20 m away from the failure spot), right picture: of the failed cable part).**

[redacted]

[redacted] But both during production and installation, a long duration temperature load of [redacted] (although not impossible) not very realistic for the following reasons:

- From production, it is not a known typical peak in a DSC curve from a PE sheath.
- From transportation and installation: the cable part with the later fault position was about 8 km away from the start of the cable length [redacted] As a result, I assume that this cable part (with later fault) was not in the upper layer on any basket during storage or transportation. And thus, the cable part with the later fault being embedded in an environment of other cables parts, the cable temperature must have been close to the daily average temperature, which is more in the range of maximum 30 °C. That does not fit with the found DSC peak temperature of [redacted]

[redacted] With a thermal gradient of [redacted] this is the [redacted] temperature fall over the insulation plus 1.2 °C temperature fall over the conductor screen and insulation screen) [redacted] this finding could indicate that the Basslink cable has been operated close to or even beyond its maximum allowed conductor temperature of [redacted] Therefore, this finding will be discussed in more detail in Section 6.2.

5.4.3 Final remark

[redacted] In [TAB 67] CCI also checked the load of the cable in the hours prior to the failure and concluded (see above, item 9) that "*The operation conditions at, and preceding, the time of failure were no different to those of the year 2015. The cable was within its thermal rating*".

It is my opinion that the failure investigation reflected by CCI's work was limited in its approach. [redacted]

[redacted] I already explained in Section 5.2.10 that in literature insulation degradation can be explained because of overheating the cable, followed by cooling and /or too rapid / many voltage polarity reversals.

[redacted]

[redacted]

6 KEY ISSUES OF THE OPERATION OF A POWER CABLE

6.1 General

According to [/34/, Bex, 2006], "*the southern and eastern Australian system operates under market conditions managed centrally by the National Electricity Market Management Company Ltd (NEMMCO). The market dispatch is managed automatically by generation offers and load bids covering pre-dispatch (unit commitment) and five minute dispatch (generator targets – energy dispatch) subject to network security constraints and management of reserves (frequency control ancillary services – FCAS market). Basslink has been developed by National Grid Australia (NGA). In its role as the project developer, NGA registered Basslink with NEMMCO as a Market Network Service Provider (MNSP). This means that Basslink can offer its capacity/price to the market and during operations will receive 5 minute flow targets*".

6.2 Cable temperature and degradation

6.2.1 How is the temperature of the power cable controlled for the Basslink cable?

There are requirements set to the Basslink power cable, [redacted] (see also Section 5.3.2 and Section 5.3.3). [redacted]

However, the actual cable load of course will differ from the load situations mentioned in these technical documents.

I learned that a Cable Load Prediction System (CLPS) for the Basslink cable [redacted]

In order to identify the actual cable temperatures that were reached, [redacted]

6.2.2 What conclusions can be drawn from this?

As was shown by [/72/, de Wild, 2017], the Basslink cable had periods during operation [redacted] that

- [redacted]
- [redacted]

In [/72/, de Wild, 2017], the following is said about this: "*the calculation results have shown that both the maximum conductor temperature limit has been exceeded as well as the maximum temperature difference over the insulation material. The maximum conductor temperature limit is found to be exceeded in 2 modelled time periods with the highest value exceeding the limit by* [redacted] *The maximum temperature difference over the insulation layer is found to be exceeded* [redacted]

It appears, the cable has been thermally overstressed during certain periods of its life time. Due to this it is probable that the impregnant will have migrated to the outer regions of the power cable insulation, leaving behind voids. The amount of impregnant doing so does not have to be much. However, some of these voids are permanent because the impregnant will not fully return in the cooling stage of the cable. Permanent voids are dangerous, because during later stages of heating up and cooling down, as happens in a dynamic cable load, these voids will shrink and expand. If voltage polarity reversals are added with high electric stress, this might lead to a cable failure. In a thermally overstressed cable, also the electric field strength on the outside of the cable insulation will reach levels beyond the design values. Both situations are dangerous and can introduce a failure (immediately or over time). Much about this degradation is said in Section 5.2.10.

6.3 Voltage polarity reversals and degradation

6.3.1 How are the voltage polarity changes controlled for the Basslink cable?

Also [/34/, Bex, 2006] says: "*As the Australian electricity market is based upon 5-minute dispatch intervals market outcomes can require Basslink to reverse power flows within 5 minutes. To achieve this a short 2-minute cable discharging time between changing voltage polarity has been achieved. As a result, the standard CIGRE cable load cycle test was altered to reflect expected power flows under market conditions*".

In my role as an expert, I went through the information made available to me [redacted]

[redacted]



Figure 21 Voltage polarity reversal interpretation Basslink.

[redacted]

6.3.2 What conclusions can be drawn from this?

6.3.2.1 voltage polarity reversal time

[redacted]

[redacted]

[redacted]

Figure 22 **Voltage polarity reversal interpretation Basslink and recommendation Pirelli, showing a conflict (red arrow) with respect to the voltage polarity reversal time.**

[redacted]

It must be mentioned, that it is known that in type tests based on Cigré Electra 189 for the electrical part [/28/, Cigré, 2000] (as being applied for the type testing of the Basslink cable), in §3.8 the following

is said about the voltage polarity reversal duration: "*the recommended time duration for a polarity reversal is 2 minutes*"**.** This expression however, does not reflect a recommended operational condition, but a recommended test regime. A test regime normally reflects worse conditions than those seen in service to accelerate ageing if any.

[redacted]

Because of their nature, after a voltage polarity reversal the discharging process inside the cable insulation is much faster in the first minutes, slowing down considerably over time. Due to this, especially the first minutes are critical in the discharging process. That is the reason, Cigré in their test protocols and often network owners during actual operation reduce the speed of the voltage polarity reversal. In other words, often network owners block the voltage polarity reversal for a certain time. The impact of a blocking time (waiting time or deionisation time) is illustrated in Figure 23. On performing a voltage polarity reversal, per definition, a long waiting time will reduce the electric stress inside the cable insulation more than a short waiting time.

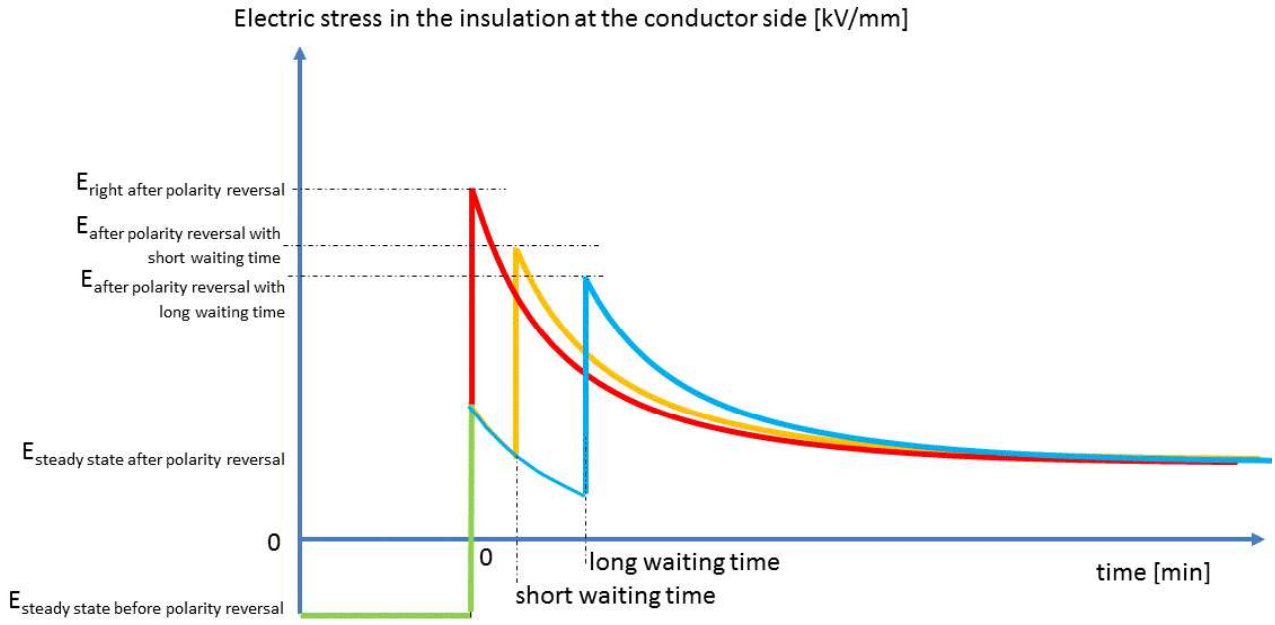


Figure 23 **Artificial drawing of the electric stress at the conductor side of the insulation material of a warm cable, right after and long after a voltage polarity reversal (green plus red line), but also in case of a voltage polarity reversal is done by taking a short waiting time (green plus orange line) or a long waiting time (green plus blue line) to partly deionise the insulation material and reduce the electric stress inside the cable insulation during this voltage polarity reversal operation.**

Thus, it is certain that a [redacted] voltage polarity reversal time [redacted] comes with a higher electric stress inside the cable insulation than in case of a 5 minutes voltage polarity reversal time.

6.3.2.2 voltage polarity reversal number per day

I also looked to the daily number of voltage polarity changes that have been performed for the Basslink cable over the years. [redacted]



Figure 24 **Number of voltage polarity reversals per day for the over the whole period that the Basslink cable was in service based on [TAB 42].** [redacted]

[redacted]

6.3.2.3 voltage polarity reversal number per year

I finally looked to the yearly number of voltage polarity changes that have been performed for the Basslink cable over the years. [redacted]



Figure 25 **Number of voltage polarity reversals per year for the over the whole period that the Basslink cable was in service based on [TAB 42].** [redacted]



Figure 26 **Number of voltage polarity reversals per quarter for the over the whole period that the Basslink cable was in service based on [TAB 42].** [redacted]

7 QUESTIONS AND ANSWERS

7.1 Question 1

What do you consider to be the possible cause or causes of the failure that occurred on 20 December 2015 and why?

Answer:

Possible causes listed below are possible in the light of being imaginable, knowing that the submarine power cable failed after 10 years of operation, without further knowledge about the precise failure location, failure circumstances, operation history, etc.. In that light, the possible causes can be related to

issues with the design, the production, the installation, external damage, the operation / ageing (see also Section 2.4.5). All these are listed below in the Sections 7.1.1 to 7.1.11.

7.1.1 Deficient power cable construction per design

Explanation: Examples of a deficient cable construction per design are the use of wrong materials, or correct materials with wrong dimensions, etc.

Reason for being a possible cause: In case of a deficient cable construction per design, from the start of operation or over time certain parts of the cable might get overstressed.

7.1.2 Deficient cable production

Explanation: Examples of a deficient cable production are an insufficient impregnation of the paper windings with an impregnant, or the application of other materials than prescribed / specified, or the wrong positioning of materials, etc.

Reason for being a possible cause: In case of a deficient cable production, from the start of operation or over time certain parts of the cable might get overstressed.

7.1.3 Deficient joint construction per design

Explanation: Examples of a deficient manufacturing joint construction per design or full scale joint design are the use of wrong materials, or correct materials with wrong dimensions, etc.

Reason for being a possible cause: In case of a deficient joint construction per design, from the start of operation or over time certain parts of the joint might get overstressed.

7.1.4 Deficient joint production

Explanation: Examples of a deficient joint production are an insufficient impregnation of the paper windings with an impregnant, or the application of other materials than prescribed / specified or the wrong positioning of materials, etc.

Reason for being a possible cause: In case of a deficient joint production, from the start or over time certain parts of the joint might get overstressed.

7.1.5 Weakness from a repair spot

Explanation: A repair spot can be the consequence of an incident during production, transportation or installation, where the cable has a repair without making a repair joint.

Reason for being a possible cause: In case of insufficient repair, from the start or over time certain parts of the repair spot might get overstressed.

7.1.6 External cable damage

Explanation: Situations where a power cable can suffer from a mechanical force resulting in an external cable damage can be found in the cable handling during production, transportation and installation. But also, such an external mechanical force can come from anchoring or fishing activities after the cable is installed.

Reason for being a possible cause: Once a power cable has been damaged by an external force, certain parts inside the cable might get overstressed which can immediately or over time result in a cable failure.

7.1.7 Voltage ripple from converter station operation

Explanation: The DC voltage will have a ripple (harmonics) originating from the 50 Hz to DC conversion and vice versa in the converter station, which comes with normal operation. The ripple means in fact that the power cable system (made for DC) is experiencing some AC voltage component. This AC voltage component might cause a different electrical stress distribution and in certain cases also a higher electrical stress / more thermal losses than would be the case with just DC. It can also have an impact on the system stability [/44/, Wood, 2012], [/45/, Wood, 2014].

Reason for being a possible cause: If this voltage ripple is relatively large, it can result in another electrical stress distribution in the insulation material of the power cable system or of a joint. For polymer cables, it is known that it can influence the partial discharge activity [/46/, Olsen, 2014].

7.1.8 Overvoltages from the connected network

Explanation: The network, connected to the Basslink cable, might be a source of over voltages, that can enter the power cable. Such over voltages might originate from the convertor station, during converter station malfunctioning for instance, or as a result of lightning that hits the DC lines between the convertor station and transition station (Figure 8). With that, so called transient over voltage might happen inside the power cable, which exists for a short time (less than a second for instance). Depending on its frequency content it will enter the power cable on one end and travel towards the other end, meanwhile increasing the voltage over the power cable system insulation.

Reason for being a possible cause: Too high or too many (or both) overvoltages can electrically overstress the insulation material of the power cable or of a joint, the moment these are present.

7.1.9 Thermally induced stress

Explanation: During normal power transmission, an electrical current is flowing through the power cable conductor. Because the conductor has an electrical resistance, this electrical current will create thermal losses in the power cable conductor. These thermal losses heat up the cable. The surroundings of the cable will absorb this heat. As a result, there is a constant flow of heat from the inside of the power cable towards its surroundings.

Some further background information is given in Section 5.1.6 ("Electrical current and cable temperature") and Section 6.2 ("Cable temperature and degradation").

Reason for being a possible cause: In case of insufficient heat flow towards or absorption by the surroundings, over time certain parts of the cable might get thermally overstressed. One example is, when the soil, surrounding the cable, has (got) thermal properties which are such that the cable can't fully release its heat (anymore).

7.1.10 Voltage polarity reversal stress

Explanation: During a change of the power flow direction, the voltage goes from plus 400 kV to minus 400 kV (or vice versa) within a short period of time. This voltage reversal is called voltage polarity reversal.

Reason for being a possible cause: Especially in the case of DC operating conditions, as is the case for the Basslink cable, voltage polarity reversals will electrically (over)stress the power cable insulation material. In a healthy cable, where the cable is prevented from cooling too much during a voltage polarity reversal, it is not an immediate problem (maybe on the long term, but that is not known), but in a compromised cable insulation, such voltage polarity reversals can be dangerous for the power cable insulation. Some further background information is given in Section 5.1.5 ("Power transmission and voltage polarity reversals") and Section 6.3 ("Voltage polarity reversals and degradation").

7.1.11 An incidental weakness

Explanation: Characteristics of an incidental weakness are that it is not foreseen by engineers and network operators and nevertheless happened, but where the scale is such that it is restricted to one location or else a very small number of locations. Some examples are

- A single irregularity got accidentally embedded in the insulation during production. The irregularity was overlooked during the Factory Acceptance Test, but found during the Commissioning Test. It is a typical example of an accidental weakness. In this case the incidental weakness could be found before it could create a failure during operation.
- Somebody from production got fired and before leaving the factory in an angry mood did stick a knife into the cable insulation material. Luckily it was deep enough to be detected by the Factory Acceptance Test (with partial discharge detection and localization). This is also the purpose of the Factory Acceptance Test, but realize that it was nevertheless an incidental weakness.

Most incidental weaknesses are very difficult or impossible to be unveiled, however the above two described incidental weaknesses come from the author's experience and could be traced concerning their background by coincidence.

The incidental weakness is different from an event out of control of people involved in the cable design, production, installation and operation, where large scale incidents take place like a war, hurricane or a terrorist attack.

Reason for being a possible cause: For now an incidental weakness can't be excluded as a possible failure cause.

7.2 Question 2

Of the possible causes of failure, what is the probability associated with each cause and why?

Answer:

For the possible causes as mentioned in Section 7.1, the following probabilities and reason for this choice are given.

7.2.1 Deficient power cable construction per design

Probability: improbable

Reason for the chosen probability:

[redacted]

[redacted]

[redacted]

[redacted]

7.2.3 Deficient joint construction per design

Probability: improbable (effectively impossible)

Reason for the chosen probability:

[redacted]

- [redacted]
- [redacted]

[redacted]

7.2.4 Deficient joint production

Probability: improbable (effectively impossible)

Reason for the chosen probability:

[redacted]

- [redacted]
- [redacted]

[redacted].

7.2.5 Weakness from a repair spot

Probability: improbable

Reason for the chosen probability:

[redacted]

- [redacted]
- [redacted]

[redacted]

Of course, the repair can have been very small, but that is normally not the case.

Altogether, it makes this possible cause quite improbable.

7.2.6 External cable damage

Probability: improbable

Reason for the chosen probability:

[redacted]

- [redacted]
- [redacted]

[redacted]

A smaller damage might have been created by a shark bite. Such a cause or potential cause for cable failures has been mentioned in industry based conferences on submarine cable. But it is my opinion that shark bites might be a failure cause for lighter submarine cables as telecom cables, not for heavily armoured power cables. [redacted] and a shark bite would quite probably also have led to scratches of other teeth, which have not been observed.

A further argument is that the cable was most probably not exposed (in terms of not having a sand cover) prior to the failure. [redacted]

7.2.7 Voltage ripple from converter station operation

Probability: improbable

Reason for the chosen probability: A voltage ripple can cause a somewhat different electrical stress distribution and maybe also influence the partial discharge activity (if any) [/46/, Olsen, 2014]. But it would be speculative to assume that a voltage ripple as such will be harmful for an HVDC cable. It has

never been mentioned in literature or by experts with whom I could speak. Therefore, I consider the probability as improbable.

7.2.8 Overvoltages from the connected network

Probability: improbable

Reason for the chosen probability: Because the cable failed far from the coastal area (about at least 100 km) where over voltages are damped, it is an improbable cause.

7.2.9 Thermally induced stress

Probability: probable

Reason for the chosen probability:

As was shown by [/72/, de Wild, 2017], the Basslink cable had periods during operation [redacted]

- [redacted]
- [redacted]

Under these circumstances, two things can happen that can lead to a reduced insulation quality.

1) In the first place, in a cable with a too high conductor temperature, there is a risk that the impregnant will migrate from the inner layers near the warm conductor to the cooler outer paper windings. Once, the cable starts cooling down, the impregnant will not fully return and voids form in the insulation layers near the conductor. In these voids electrical sparking can happen, degrading the surrounding insulation material. This can immediately or over time result in a failure. It is not known if this amount of migrated impregnant is detectable in one or another way, because it can be a very local issue, depending on local circumstances.

   About the void formation, [/40/, Runde, 2014] said the following about it: "*…. generally assumed that the breakdowns are caused by the formation of extended cavities in the insulation during a load reduction or turn-off. The cavities are thought to be a result of the thermal expansion and contraction of the impregnant being much greater than that of the paper*". See for a further treatment of this degradation mechanism Section 5.2.10.1 and Section 5.2.10.2.

2) In the second place, in a too warm cable, the electric stress at the outside of the insulation material will increase beyond the design level. See for a further treatment of this degradation mechanism Section 5.2.10.3. Would there be a small weakness in the insulation material nearby the lead sheath for instance, the too high electric stress can start up a degradation process locally which immediately or over time can result in a failure.

Because the cable failed in the cooling down stage, I assume that the first mentioned mechanism has been involved in the failure.

There is a supporting argument why the Basslink cable indeed might have reached high conductor temperatures during certain periods in the operation. [redacted]

The dismantling of the faulty cable sample and a reference sample from nearby the faulty spot (see Section 5.4) showed that the cable has not been thermally aged. [redacted] This was explained already in Section 5.2.10.2.

7.2.10 Voltage polarity reversal stress

Probability: probable (in having a contributing impact)

Reason for the chosen probability: The fact that the cable broke down shortly after having had two voltage polarity reversals (Section 5.3.11, Figure 16) indicates that there is a probable relation between the voltage polarity reversals have had an impact on the failure cause.

On purpose I wrote that the voltage polarity reversal regime probably contributed to the failure. That is, because in a healthy cable (without (large) voids), a deionisation time during voltage polarity reversals of 2 minutes as applied for the Basslink cable does not seem to be harmful for a cable. This I learned from interviews with various HVDC MIND cable operators in Europe, where a deionisation time of 2 minutes is quite common and never resulted in related cable failures. Even, the deionisation time in case of the NorNed MIND cable (commissioned in 2008, thus at present 9 years in service) is less than 1 minute (this information I was allowed to share). But in these cases, network owners tend to avoid that

during a voltage polarity reversal, the cable is cooling down too much by realizing a fast ramping up and down.

Because of the fact that the Basslink cable very probably had voids as a result of the thermal regime (explained in Section 7.2.9), the voltage polarity reversal regime is now more relevant. Now, mainly as a trigger, not as the sole root cause of the failure. [redacted]

7.2.11 An incidental weakness

Probability: improbable

Reason for the chosen probability: Because one of the above-mentioned failure causes was concluded to be probable, this "incidental weakness" becomes improbable. Would one of the above-mentioned failure causes have been found as proven, this "incidental weakness" would have become impossible.

7.3 Question 3

Which of the possible causes of failure, if any, can be attributed to the way in which the cable was operated by BPL? In answering this question, please identify the facts and assumptions on which you rely to identify the way in which the cable was operated by BPL.

Answer:

This answer will take the outcome of Question 1 in Section 7.1 as a starting point. But the answer will be restricted to the causes that have a probability "possible" or "probable" as shown for the answer on Question 2 in Section 7.2.

Both probable causes

- "thermally induced stress" and
- "voltage polarity reversal stress"

are clearly related to the way the cable has been operated by BPL.

In the Sections 7.2.9 and 7.2.10 treat the facts and assumptions on which this is based.

7.3.1 Thermally induced stress

Reason: thermally induced stress is related to the amount of power transmitted which can be influenced and if needed limited by BPL.

7.3.2 Voltage polarity reversal stress

Reason: the voltage polarity reversal induced stress is related to the number of changes in the power direction and the speed with which these occur, which can be influenced and if needed adjusted by BPL.

7.4 Question 4

Further to question 3, if any possible cause of failure is attributable to the way in which the cable was operated by BPL, is there anything that a prudent, experienced and competent person in the position of BPL should have done to prevent the failure?

Answer:

Both the possible causes "thermally induced stress" and "voltage polarity reversal stress" are clearly related to the way the cables have been operated by BPL and could have been influenced by BPL, for the reasons mentioned below.

7.4.1 Thermally induced stress

The thermally induced stress could have been avoided in two different ways.

It is related to the operation of the Basslink power cable, as was seen in [/72/, de Wild, 2017] where it was concluded that [redacted] were exceeded significantly, predominantly in the duration of the high load period. This is something that could have been avoided.

However, there is an additional issue. It is the fact that the Basslink interconnector is believed to have worse thermal properties as compared to several engineering documents. This could have been avoided by:

1. having carried out a review of the thermal engineering calculations;
2. to have performed a full cable route survey with soil samples, such to check the engineering calculations with respect to thermal properties of the soil and laying depth and to update the actual possible load based on these findings;

3. to have put an effort in setting up a Current Load Prediction System (CLPS), which has been tested and proven to predict accurate results;
4. to have created a set of operational limitations, which would protect the cable from overheating as long as such a CLPS is not available.

7.4.2 Voltage polarity reversal stress

As was said already, the voltage polarity reversal regime did contribute to the development of the failure. The amount of voltage polarity reversal induced stress can be influenced and if needed limited / adjusted by BPL. [redacted] But because the voltage polarity reversal regime (if the cable is not thermally overstressed) is not the main cause of the failure, but just a contributor, its impact for the present case is small, but can't be fully ignored.

7.5 Question 5

Is there a possible cause of failure which you consider to be the probable cause of failure and why?

Answer:

The probable cause of the failure is the "thermally induced stress" for reasons mentioned in Section 7.2.9. In short, the cable has been operated such that the conductor temperature could reach temperatures considerably above its limit of [redacted] This resulted in voids. In these voids electrical sparking took place. These sparks degraded the insulation material (read, the walls of the voids) until it became so weak that it could not withstand the enhanced electric stress during a voltage polarity reversal, after which the cable failed. The time between the first void formation until the failure is difficult to identify. It can be a process of minutes to years, depending on the actual circumstances. The fact that the cable broke down in its cooling stage supports the hypothesis that void formation played a role.

The "voltage polarity reversal induced stress" contributed to the failure. As was explained in Section 7.1.10, voltage polarity reversals come with considerable electrical stress enhancements. These electrical stress enhancements concentrate in the voids due to the difference in dielectric properties of the void and surrounding insulation material. The fact that the cable broke down shortly after two voltage polarity reversals supports the hypothesis that the related electric stress enhancement played a role.

In summary, the combination of

- thermally induced void formation during cooling (with the void formation in the insulation material close to the conductor) and

- the electrical stress enhancement in these voids due to voltage polarity reversals

are very probably the reason why the Basslink power cable failed, where the thermal part is related to the root cause of the failure and the voltage polarity reversal regime is a contributor.

Both, the thermally induced stress and voltage polarity reversal induced stress are a direct result of the way the Basslink cable is operated.

7.6 Question 6

Do you regard any of the possible causes of failure as improbable and why?

Answer:

Possible causes which to the authors opinion are improbable are the following (for reasons given in Section 7.2):

- Deficient power cable construction per design
- Deficient cable production
- Deficient joint construction per design
- Deficient joint production
- Weakness from a repair spot
- External cable damage
- Voltage ripple from converter station operation
- Overvoltages from the connected network
- Incidental weakness

7.7 Question 7

What tests (if any) are necessary to establish or would assist or be likely to assist in establishing the probable cause of failure, or narrowing the possible causes of failure?

Answer:

7.7.1 Load cycle test with voltage polarity reversals (Cigré Electra 189)

7.7.1.1 Introduction

It is probable that the Basslink cable has been exposed to too high temperatures preceding the failure in December 2015, see Section 7.5. It is also probable that this has led to an irreversible degradation of the insulation (see Section 5.2.10.4), where permanent voids were created in the butt gaps of the insulation material. It is helpful to check the above-mentioned statements by testing a piece of cable. Would there be considerable degradation indeed, the cable piece will not pass the test. In that sense, the outcome of the test can on one hand help to more firmly conclude on the root cause of the failure and the resulting void creation and it can be helpful in deciding about future operational conditions, to avoid failures as much as possible.

7.7.1.2 Proposed test

The proposed test is to repeat the test that is described in [redacted] followed by lightning impulse tests in accordance with Cigré Electra 189 [/28/, Cigré, 2000]. For this a cable piece is needed of about 50 m for reasons mentioned in Section 7.8.1.2.

7.7.2 Other tests

7.7.2.1 Introduction

There is an example of testing done on an HVDC MIND, after samples were retrieved at the end of its service life. It is the Gotland 1 cable, that has been in service for 32 years, without having had internal cable failures. It was in operation from 1954 to 1986, with the first 16 years at a power rating of 20 MW (100 kV and 200 A), and the remaining 16 years at a power rating of 30 MW (150 kV and 200 A). The last before the power rating was increased, the cable experienced an overload (in current) of 15 %. The highest field strength (which happened at the conductor side of the insulation) happened under no load conditions and was 20 kV/mm in the first 16 years and became 28 kV/mm in the remaining 16 years [/18/, Hjalmarsson, 1992]. The power flow has been mainly in one direction. There were no internal cable faults during the life time of the power cable.

At the end of its operational life, various cable parts were retrieved from the sea floor in length of 45 m to 120 m. Also spare cable lengths were available. The cable parts have been subjected to various tests, described in the following subsections (only, those related to the cable insulation material are mentioned here).

7.7.2.2 Loss-factor measurements

Loss factor measurements (both at 50 Hz up to several kV and at low voltage over a wide frequency and temperature range) have been done. Such loss-factor measurements are helpful to get insight in conduction and polarization phenomena and to determine for instance whether there is moisture in the insulation.

Result: no significant difference in the spare and service aged cable lengths.

7.7.2.3 Breakdown tests

Impulse tests and DC breakdown tests have been done. None of these came with voltage polarity reversals. The cable retrieved from operation had very low breakdown values, but these were attributed to the rough mechanical handling during retrieval. Once, these weak cable parts were removed, the remaining breakdown values were comparable to the cables from stock.

Result: It is my opinion, that because of the screening done, this result is not very reliable. For instance, the authors in [/18/, Hjalmarsson, 1992] found that the loss-factor increased at higher test voltages, indicating that there might have been voids in the cable insulation of the aged cable samples, resulting in partial discharge activity and related losses. And because there were not many voltage polarity reversals, it is possible that the cable could survive despite these voids.

7.7.2.4 Degree of polymerisation

The degree of polymerisation informs about the length of the cellulose chains of the paper insulation. Thermal ageing will make these shorter, resulting in a lower level of the degree of polymerisation.

Result: It was found that the spare and aged cable lengths gave similar results. However, the results were significantly lower than what is seen for new paper insulation. Thus, the decrease in the degree of polymerisation observed can be attributed to thermal ageing indeed, but between the spare cable and aged cable, the average temperatures over the years did not differ enough to show this in the degree of polymerisation.

7.7.2.5 Tensile properties paper insulation

The tensile properties refer to the tensile strength and elongation at break of the paper insulation.

Result: no significant difference in the spare and service aged cable lengths

7.7.3 Conclusion

The most reliable test, to see whether the thermal ageing has resulted in permanent degradation by the creation of permanent voids, is the electrical part of the type test according to Cigré Electra 189 [/28/, Cigré, 2000]. This is the load cycle test with voltage polarity reversals, followed by lighting impulse tests, performed on a cable length of about 50 m. The word 'about' is chosen in line with Cigré requirement.

7.8 Question 8

Further to question 7, if testing is appropriate, what material (including retrieved samples of cable and documents), if any, would be required to undertake any such tests? If it is necessary in your opinion to test a retrieved sample of cable, would any testing-related limitations or difficulties arise from the condition of that sample as at the time of testing? If yes, please explain the reasons for that answer, identifying the nature and scope of any such testing-related limitations or difficulties.

Answer:

7.8.1.1 Introduction

In question 7, it is proposed to perform a load cycle test with voltage polarity reversals followed by lighting impulse tests in accordance with Cigré Electra 189 [/28/, Cigré, 2000].

For this test, a cable piece is needed of about 50 m in length (also, 40 m is mentioned as the minimum length needed) for reasons mentioned in Section 7.8.1.2. This cable length should come from retrieved cable, that came from the repair of the fault.

[redacted]

There is another potential issue, once such a cable length would have been made available for testing. It is the fact that the retrieved cable length might have suffered from water ingress and/or mechanical damage. Cable retrieval therefore is a delicate process, else, the testing is useless. The retrieved cable length can reasonably well tested for water ingress.

7.8.1.2 Reasons to use a 40 m cable sample

A minimum of 40 m cable length is necessary in order to perform for the following reasons:

- the cable length must accommodate terminations at each end of the cable and still retain a sufficient test length of cable (termination points are usually 5 m to 8 m long themselves);
- the actual test length of cable (excluding the terminations) must be long enough to hold a particular temperature so that the testing can be carried out accurately (any length shorter than 40 m including terminations will provide a less accurate result);
- although two cable lengths of 20 m each could be joined together, the joint would constitute a weakness in the 40 m cable length which would likely compromise the testing (the test might fail at the joint).

7.9 Question 9

In addition to question 8 above, what other testing do you consider necessary as a matter of Good Electricity Industry Practice to inform the probable cause of failure?

Answer:

No other tests are proposed to further establish the probable root cause if the failure, apart from the one mentioned in Section 7.7.1. That is, because the assumed degradation is related to voids, making many tests other than those mentioned in Section 7.7.1 irrelevant.

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APPENDIX A

Reference list DNV GL failure investigations on power cables up to 2016

In this table PFI means Power Failure Investigation

#	PFI started	region customer	failed component	AC or DC	voltage class
1	1997	Europe	termination	AC	(E)HV
2	1998	Europe	termination	AC	(E)HV
3	2001	Europe	termination	AC	(E)HV
4	2002	Europe	termination	AC	(E)HV
5	2002	Europe	cable	AC	MV
6	2002	Europe	joint	AC	MV
7	2003	Europe	joint	AC	(E)HV
8	2003	Europe	joint	AC	(E)HV
9	2003	Europe	cable	AC	MV
10	2003	Europe	joint	AC	MV
11	2004	Europe	cable	AC	(E)HV
12	2004	Europe	termination	AC	MV
13	2004	Europe	joint	AC	MV
14	2005	Europe	termination	AC	(E)HV
15	2005	Europe	cable	AC	(E)HV
16	2005	Europe	joint	AC	(E)HV
17	2005	Europe	termination	AC	(E)HV
18	2005	Europe	termination	AC	(E)HV
19	2005	Europe	termination	AC	(E)HV
20	2005	Europe	termination	AC	MV
21	2006	Middle East	termination	AC	(E)HV
22	2006	Europe	termination	AC	(E)HV
23	2006	Europe	termination	AC	(E)HV
24	2006	Europe	termination	AC	(E)HV
25	2006	Middle East	termination	AC	(E)HV
26	2006	Europe	termination	AC	(E)HV
27	2006	Middle East	termination	AC	(E)HV
28	2006	Europe	termination	AC	(E)HV
29	2006	Middle East	termination	AC	(E)HV
30	2006	Europe	cable	AC	MV
31	2006	Europe	joint	AC	MV
32	2007	Europe	termination	AC	(E)HV
33	2007	Europe	cable	AC	(E)HV
34	2007	Europe	joint	AC	(E)HV
35	2007	Europe	cable	AC	(E)HV
36	2007	Europe	joint	AC	(E)HV
37	2007	Asia	joint	AC	MV
38	2007	Europe	joint	AC	MV
39	2007	Europe	joint	AC	MV
40	2007	Europe	termination	AC	MV
41	2008	Europe	joint	AC	(E)HV
42	2008	Europe	cable	DC	(E)HV
43	2008	Asia	joint	AC	(E)HV
44	2008	Europe	termination	AC	(E)HV
45	2008	Europe	joint	AC	MV
46	2008	Europe	cable	AC	MV
47	2009	Europe	termination	AC	(E)HV
48	2009	Europe	termination	AC	(E)HV
49	2009	Europe	joint	AC	(E)HV
50	2009	Europe	cable	AC	(E)HV

51	2009	Middle East	cable	AC	(E)HV
52	2009	Middle East	cable	AC	(E)HV
53	2009	Europe	termination	AC	(E)HV
54	2009	Europe	cable	DC	(E)HV
55	2009	Europe	joint	AC	(E)HV
56	2009	Europe	termination		(E)HV
57	2009	Europe	cable	AC	MV
58	2009	Europe	joint	AC	MV
59	2009	Europe	joint	AC	MV
60	2009	Europe	cable	AC	MV
61	2010	Europe	cable	DC	(E)HV
62	2010	Asia	termination	AC	(E)HV
63	2010	Asia	termination	AC	(E)HV
64	2010	Europe	joint	AC	(E)HV
65	2010	Asia	joint	AC	(E)HV
66	2010	Europe	cable	AC	LV
67	2010	America	cable	AC	MV
68	2010	Asia	termination	AC	MV
69	2010	Europe	termination	AC	MV
70	2010	Middle East	cable	AC	MV
71	2010	Europe	cable	AC	MV
72	2010	Europe	cable	AC	MV
73	2010	Europe	joint	AC	MV
74	2011	Middle East	cable	AC	(E)HV
75	2011	Asia	termination	AC	(E)HV
76	2011	Europe	termination	AC	(E)HV
77	2011	Europe	joint	AC	(E)HV
78	2011	Europe	termination	AC	(E)HV
79	2011	Europe	joint	AC	(E)HV
80	2011	Europe	cable	DC	(E)HV
81	2011	Asia	joint	AC	(E)HV
82	2011	Europe	cable	AC	(E)HV
83	2011	Europe	joint	AC	(E)HV
84	2011	Middle East	joint	AC	(E)HV
85	2011	Europe	cable	AC	(E)HV
86	2011	Middle East	joint	AC	MV
87	2011	Middle East	termination	AC	MV
88	2011	Europe	termination	AC	MV
89	2011	Middle East	cable	AC	MV
90	2011	Europe	cable	AC	MV
91	2011	Europe	joint	AC	MV
92	2011	Europe	cable	AC	MV
93	2011	Europe	joint	AC	MV
94	2011	Europe	cable	AC	MV
95	2011	Europe	joint	AC	MV
96	2011	Europe	termination	AC	MV
97	2012	Asia	joint	AC	(E)HV
98	2012	Europe	termination	AC	(E)HV
99	2012	Asia	termination	AC	(E)HV
100	2012	Europe	termination	AC	(E)HV

101	2012	Africa	cable	AC	(E)HV
102	2012	Europe	cable	DC	(E)HV
103	2012	Europe	joint	AC	(E)HV
104	2012	Europe	termination	AC	(E)HV
105	2012	America	termination	AC	(E)HV
106	2012	Europe	termination	AC	(E)HV
107	2012	America	joint	AC	(E)HV
108	2012	Middle East	cable	AC	(E)HV
109	2012	Europe	cable	AC	(E)HV
110	2012	Asia	joint	AC	(E)HV
111	2012	Europe	termination	AC	(E)HV
112	2012	Middle East	joint	AC	(E)HV
113	2012	Middle East	joint	AC	(E)HV
114	2012	Europe	cable	DC	(E)HV
115	2012	Europe	joint	AC	LV
116	2012	Middle East	cable	AC	MV
117	2012	Europe	joint	AC	MV
118	2012	Europe	joint	AC	MV
119	2012	Europe	joint	AC	MV
120	2012	Europe	joint	AC	MV
121	2012	Europe	cable	AC	MV
122	2012	Europe	cable	AC	MV
123	2012	Europe	joint	AC	MV
124	2013	Middle East	joint	AC	(E)HV
125	2013	Europe	cable	AC	(E)HV
126	2013	Europe	cable	AC	(E)HV
127	2013	Europe	joint	AC	(E)HV
128	2013	Europe	joint	AC	(E)HV
129	2013	Middle East	joint	AC	(E)HV
130	2013	Europe	cable	AC	(E)HV
131	2013	Asia	joint	AC	(E)HV
132	2013	Asia	termination	AC	(E)HV
133	2013	Europe	termination	AC	(E)HV
134	2013	Middle East	cable	AC	(E)HV
135	2013	Europe	joint	AC	MV
136	2013	Europe	joint	AC	MV
137	2013	Europe	joint	AC	MV
138	2013	Europe	joint	AC	MV
139	2013	Europe	joint	AC	MV
140	2013	Europe	cable	AC	MV
141	2013	Europe	joint	AC	MV
142	2014	Asia	termination	AC	(E)HV
143	2014	Asia	cable	AC	(E)HV
144	2014	Asia	joint	AC	(E)HV
145	2014	Asia	cable	AC	(E)HV
146	2014	Middle East	termination	AC	(E)HV
147	2014	America	termination	AC	(E)HV
148	2014	Asia	cable	AC	(E)HV
149	2014	Middle East	cable	AC	(E)HV
150	2014	Asia	cable	AC	(E)HV

151	2014	Middle East	joint	AC	(E)HV
152	2014	Middle East	cable	AC	(E)HV
153	2014	Europe	termination	AC	(E)HV
154	2014	Europe	joint	AC	(E)HV
155	2014	Middle East	termination	AC	(E)HV
156	2014	America	termination	AC	(E)HV
157	2014	Asia	Cable	AC	(E)HV
158	2014	Asia	cable	DC	(E)HV
159	2014	Middle East	cable	AC	LV
160	2014	Europe	joint	AC	MV
161	2014	Europe	joint	AC	MV
162	2014	Europe	joint	AC	MV
163	2014	Europe	bushing	AC	MV
164	2014	Europe	joint	AC	MV
165	2014	Europe	joint	AC	MV
166	2014	Europe	joint	AC	MV
167	2014	Asia	cable	AC	MV
168	2014	Europe	termination	AC	MV
169	2014	Europe	joint	AC	MV
170	2014	Europe	termination	AC	MV
171	2014	Europe	cable	AC	MV
172	2014	Europe	cable	AC	MV
173	2015	Europe	Joint	AC	(E)HV
174	2015	Asia	termination	AC	(E)HV
175	2015	Asia	cable	AC	(E)HV
176	2015	America	termination	AC	(E)HV
177	2015	Europe	joint	AC	(E)HV
178	2015	Europe	termination	AC	(E)HV
179	2015	Europe	joint	AC	(E)HV
180	2015	Europe	cable	AC	(E)HV
181	2015	Europe	cable	AC	(E)HV
182	2015	Europe	cable	AC	(E)HV
183	2015	Europe	cable	AC	(E)HV
184	2015	Middle East	joint	AC	(E)HV
185	2015	Middle East	termination	AC	(E)HV
186	2015	Asia	cable	AC	(E)HV
187	2015	Europe	cable	AC	(E)HV
188	2015	Europe	termination	AC	(E)HV
189	2015	Europe	termination	AC	(E)HV
190	2015	Europe	termination	AC	MV
191	2015	Europe	cable	AC	MV
192	2015	Europe	joint	AC	MV
193	2015	Europe	joint	AC	MV
194	2015	Europe	joint	AC	MV
195	2015	Europe	termination	AC	MV
196	2015	Europe	joint	AC	MV
197	2015	Europe	cable	AC	MV
198	2015	Europe	joint	AC	MV
199	2015	Europe	Joint	AC	MV
200	2015	Europe	joint	AC	MV

201	2015	Europe	cable	AC	MV
202	2015	Europe	cable	AC	MV
203	2015	Europe	joint	AC	MV
204	2015	Europe	cable	AC	MV
205	2016	Australia	cable	DC	(E)HV
206	2016	Europe	cable	AC	(E)HV
207	2016	Middle East	cable	AC	(E)HV
208	2016	Middle East	cable	AC	(E)HV
209	2016	Europe	cable	AC	(E)HV
210	2016	Australia	cable	AC	(E)HV
211	2016	Middle East	termination	AC	(E)HV
212	2016	Europe	termination	AC	(E)HV
213	2016	Asia	cable	AC	(E)HV
214	2016	Middle East	termination	AC	(E)HV
215	2016	Asia	joint	AC	(E)HV
216	2016	Middle East	joint	AC	(E)HV
217	2016	Europe	joint	AC	(E)HV
218	2016	Europe	termination	AC	(E)HV
219	2016	Europe	joint	AC	LV
220	2016	Europe	cable	AC	LV
221	2016	Europe	Joint	AC	MV
222	2016	Europe	termination	AC	MV
223	2016	Europe	joint	AC	MV
224	2016	Middle East	cable and joint	AC	MV
225	2016	Middle East	cable	AC	MV
226	2016	Middle East	joint	AC	MV
227	2016	Asia	cable	AC	MV

APPENDIX B

DNV GL paper Jicable 2015 conference on failure investigations on power cables

This paper is reference [/52/, Van Maanen, 2015]

Failures in underground power cables – return of experience

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ABSTRACT

For many years, the DNV GL Energy branch on operational excellence (formerly known as KEMA), is performing failure analyses on all types of power equipment. On a regular basis also underground power cables are being investigated. An investigation is normally focused on finding the root cause of failure. An important outcome of the root cause analysis is the identification of required actions aiming to avoid future failures, like improving design, production, installation, testing or service circumstances. The investigation also gives insight in which other components might suffer from the same problem and may have to be replaced to prevent outages, related safety problems, costs and reputation issues. Failures as mentioned above, can be a full breakdown, but can also be a defect found by a diagnostic test. In this paper, common experiences as obtained by DNV GL with failure analyses over many years will be shared with the reader.

INTRODUCTION

Due to the increasing demand for power, coupled with the geographical expansion of this need, we are more and more relying on the reliability of the grid. The amount of cable installations (both land and submarine) is growing rapidly around the world.

In case of a power failure, it is of crucial importance to know what is the root cause (or are the causes) of that failure. This is due to:

1. Technical reasons. There is a need to avoid a similar failure in the future. So where in the process from design, manufacturing, testing, installation and operation is improvement needed? Knowing the cause of failure is a crucial part in the feedback loop for improvement. Furthermore, knowing the root cause is necessary to assess the risk of failure in similar situations (e.g. same type of components).
2. Economical / political reasons. There can be major consequences for customers, as well as penalties, indirect costs, reputation damage, etc.
3. Insurance. The party responsible for the failure has to be identified.
4. Safety. Related to the chance of a similar failure in the future, what are the safety hazards in case of e.g. different circumstances?

In some cases the root cause of failure is obvious, like in case of digging activities. In many cases, however, a more extensive failure investigation is needed to find the root cause of failure.

In case of a failure investigation, there are often multiple stakeholders involved in the failure analysis, depending on the importance of the connection. Besides the owner of the cable system (network owner) there is usually involvement of the manufacturer(s), the installer(s), representatives of the users of the connection, insuring companies, et cetera. Since all these stakeholders have different interests there is a clear need for a knowledgeable, independent and impartial party to lead the investigation and that is responsible for the validity of the outcome of the investigation.

DNV GL is fulfilling the role of independent and impartial party for many years already and has therewith built up a wealth of experience in failure investigations. These failure investigations got formalized in the late nineties into an official service called 'Power Failure Investigations'. These investigations are performed on all types of power components, such as transformers, switchgear, lines, isolators, bushings, rotating equipment, all kinds of station equipment, etc. DNV GL adapted a uniform method for such failure investigations and often multiple disciplines need to be combined together for more complex investigation (where multiple components are involved, which is quite regular, and/or network studies are needed). This paper is about the failure investigations on power cables.

Over the years a significant increase in the number of failure investigations on power cables per year is observed as depicted in Fig. 1. A total of approximately 170 individual cases have been recorded over the period from 1997 until the end of 2014. Relevant information from these investigations has been collected and used to create insight in many details, statistics, degradation and failure mechanisms of power cables all over the world.

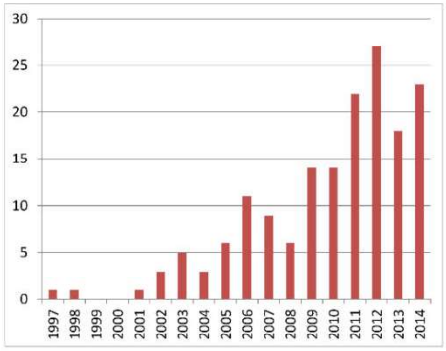


Fig. 1: the number of cable system related failure investigations per year

Due to high confidentiality of this information not everything can be shared in a paper like this. Information that can be traced back to the manufacturer, the network operator or any other involved party will obviously never

be shared. What can be shared, after being anonymized, is information like:

- What type of component failed? E.g. cable, joint or termination.
- What type of cable is involved? E.g. paper cable, XLPE, EPR, SCFF, etc.
- What is the voltage class?
- When was the cause of the failure incurred? E.g. during design, production, installation or service life.

Furthermore, where applicable, common root causes are identified and discussed in this paper. With this, despite the mentioned needed level of confidentiality of this subject, interesting results can be observed.

FAILURE STATISTICS

Governing all failure investigations

In this chapter the defining characteristics over the entire (power cable failure investigation) data population (170 cases) are highlighted. Note that the information presented here is based on the investigations performed by DNV GL only and is not be regarded as a way to determine overall statistics in general without further consideration.

In Fig. 2 the distribution of failures between the different components is shown. Roughly two thirds of the failure investigations involved cable joints and terminations, and one third involved failures of cable itself. Thus, the cable accessories (joints and terminations) seem to inherit the highest risk for failure. The following chapter will discuss the underlying causes for the cable and accessories failures separately.

In Fig. 3 the involved cable insulation types that were involved in the failure cases are shown. As the modern type of insulation material applied, XLPE is present in the vast majority of cases. Paper Insulated Lead Covered (PILC) cables are quite common in continental Europe for medium voltage networks. However, since they are mainly used on the medium voltage level, only a smaller part is being investigated with an external independent party. Combined with the fact that these cables have been in operation for many years these form the second largest group. Other types of cables have come up sporadically for several reasons. It must be noted that not all network owners order an investigation upon failure, let alone by a third party. Especially in case of very old cables and low and medium voltage cable classes, often failed components are simply discarded or internally investigated.

Fig. 4 shows the distribution of the failures over the voltage classes. The largest part is located within the range of 36 to 230 kV. Note that for voltages higher than 230 kV the currently installed cable length is still relatively small, which explains the relatively low number of investigations in that range (being 14 %). The number of cases for low voltage application is very low, likely due to the previously mentioned reasons.

Failures causes

It is not a certainty that a failure investigation yields one clear root cause. Sometimes it is a combination of several causes and sometimes only the likelihood of the various possible root causes can be evaluated, as real evidence

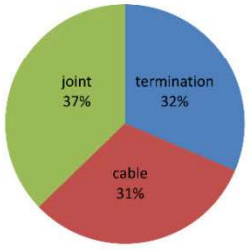


Fig. 2 the distribution of failures between components

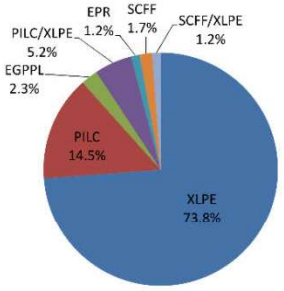


Fig. 3: the cable insulation types involved

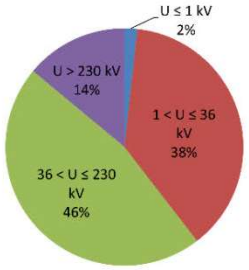


Fig. 4: the voltage classes involved

is destroyed by the breakdown. The certainty of the investigation conclusion depends on a multitude of factors, such as availability and quality of the evidence and surrounding information. This information involves all operational data such as voltages, load, network configuration, network operation, et cetera. Moreover, it is important that all relevant quality control steps in the design, qualification, fabrication, installation and operation can be checked. These steps are in place to ensure that the equipment is fulfilling all requirements put forward in the agreed quality standard. In the majority of cases the IEC standards and guidelines are used for this purpose.

There are usually several factors playing a role in the process leading to a failure, which all need to be taken into account. In some cases the investigation yields several hypotheses which may be compared on the basis of their likelihood using the available surrounding

information. In a few cases the available information is such that the investigation does not lead to a conclusion with respect to the failure cause. In the end, all failure causes have been categorized into 6 generalized groups, being

1. **ageing**: the failure occurred as a consequence of natural ageing of the component
2. **design**: the failure occurred as a consequence of an inadequate design of the component
3. **external damage**: the failure occurred as a consequence of an external foreign object damaging the component
4. **installation**: the failure occurred due to an inadequate installation (technique)
5. **production**: the failure occurred as a consequence of an error during production (handling or material)
6. **unknown**: the cause of the failure remained unclear.

In the next two paragraphs the distribution of these failure causes is treated separately for cables and accessories.

Failures in cables

The distribution of failure causes for cable failures is depicted in Fig 5.

The majority of failures in (investigated) cables have their origin in the production process itself. Some common causes that are seen include:

- mechanical damage during handling of the cable, e.g. during manufacturing, internal transport or during a factory repair
- defects in the insulation (voids, inclusions, etc.).

This is despite the fact that usually factory acceptance tests are in place, such as high voltage withstand tests and partial discharge measurements. It is not always a matter of the right test but also good interpretation of the test results. Moreover, some slight defects may not be severe enough to show up during factory testing, but may cause al failure at a later time.

An example of an error in interpretation of test results is given in Fig 6. Here a defect (void) in the insulation was created during production. This void created partial discharge activity during factory testing but this was mistaken for noise. This caused the cable to be approved for delivery. The defect was later detected during the site acceptance test.

After production related issues, the installation and external damage are the largest contributors. Installation errors, similar to external damage, often involve

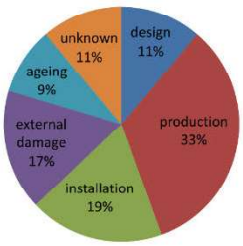


Fig. 5: the general failure causes for cables

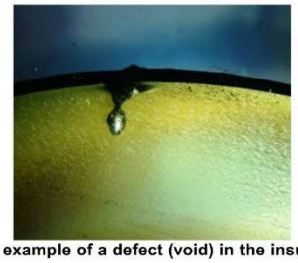


Fig. 6: example of a defect (void) in the insulation of a cable



Fig. 7: example of a cable installation technique that led to damage of the cable

mechanical damage of the cable. This can be due to a bad installation technique involving too high pulling forces or giving insufficient protection to the cable for instance. An example is given in Fig. 7.

In total 11% of the investigated cable failures were related to the design of the cable. This shows that the design qualification (pre-qualification tests and type tests), despite the extensive tests involved, are still missing a certain part of the design related defects.

In 11% of the cases no cause for the failure could be found.

The continuing process of interconnecting the grid as well as the implementation of offshore wind farms has caused a strong rise in the application of submarine cables. This is also visible is the number of investigations related to submarine cables, depicted in Fig. 8. The specific installation of these cables requires significantly stricter mechanical demands for these cables, for instance by the application of armor wires. The handling on a vessel in ocean conditions also presents quite a number of challenges with respect to the handling of the cable. In roughly 50% of the cases investigated by DNV GL, mechanical issues form the basis for the problems. An

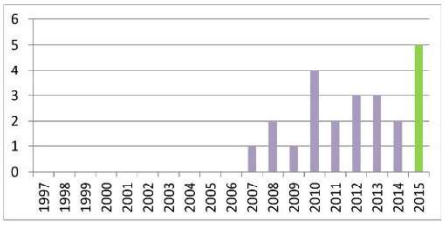


Fig. 8: The number submarine cable related investigations per year (with 2015 thus far)

example of such a case is depicted in Fig. 9.



Fig. 9: example of a submarine cable that was damaged due to wrong handling during installation (coiling)

Failures in joints and terminations

The distribution of failure causes for cable accessories (here: joints and terminations) is depicted in Fig. 10.

The majority of failures in cables accessories have their origin in installation related defects. The main underlying reason for this is the fact that all accessories for cables have to be fitted in the field where the conditions are not ideal. This is combined with the relatively high electrical fields and mechanical forces acting on the accessories, apart from extremely high demands for cleanliness, smoothness and accuracy, especially for insulation surfaces in the interface between cable and accessory insulation. The majority of the failures in accessories stem from this region. Especially for extra high voltage applications, the requirements for surface preparation are quite demanding. Moreover, the preparation of this surface remains to be predominantly a manual process. Installation failures can also originate from insufficiently experienced jointers, unclear installation manuals, language issues, etc.

The use of pre-moulded sleeves in high and extra-high voltage applications is quite common. This technology has the big advantage that it is fully assembled (fabricated) in the factory and can as such be fully tested before installation. This also seems to be verified by the relatively low percentage of failures that are related to production (8%).

Upon installation such a sleeve is stretched over the cable such that it retains sufficient interface pressure over the years. The stretching / expanding of the sleeve and positioning over the cable requires large forces. After fitting the sleeve, it must exert sufficient interfacial pressure to prevent partial discharges to occur in the interface region. This gives birth to a number of potential problems, e.g.

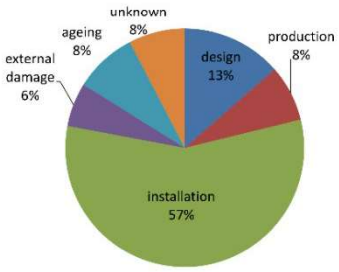


Fig. 10: the failure causes for accessories

- Any pollution or particle that gets trapped between the sleeve and the expansion tool may damage the sleeve in the most sensitive area; the interface between cable and accessory insulation. This is a challenge especially in dusty environments. Due to the large forces in such a sleeve, a tiny scratch (tenths of µm) can cause the sleeve to rupture over time.
- During expansion, large forces exist internally in the sleeve. Note that the sleeve consists out of insulating and semi-conductive materials, each with different mechanical properties. This means that all kinds of internal forces act on various surfaces inside the sleeve. The sleeve must be able to cope with these forces otherwise it may (partly) rupture.
- The mechanical properties of the sleeve have to be sufficiently stable to ascertain sufficient interfacial pressure over the years.

An added difficulty with these interface related defects is the application of grease products in the interface to reduce friction between the sleeve and the expansion tool and/or cable insulation. This grease has the ability to



Fig. 11: defect in the interface between cable insulation and sleeve (top) giving rise to partial discharges (yellow traces)

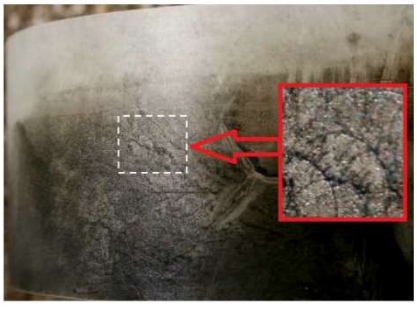


Fig. 12: example of tiny scratches in the prepared insulation surface causing a failure

temporarily reduce the effect of certain defects such as a small scratch in the insulation. As such it can prevent degradation, until the moment it is inevitably absorbed by (diffused into) the surrounding materials. This mechanism is deemed capable of delaying degradation (partial discharges, electrical treeing) for months or even years. This also means that a certain defect may stay hidden during commissioning testing (which serves as the quality control for the installation).

The percentage of accessory failures related to design is, quite similar to that for cables, 13%. This seems to show that the design qualification (pre-qualification tests and type tests) is approximately as effective for cables as it is for accessories. The number of unresolved cases (unknown) is 8%, again quite similar to that for cable failures.

CONCLUSION

DNV GL has fulfilled the role of knowledgeable, independent and impartial party for the investigation of failures in cable systems for several years and has therewith built up a wealth of experience in failure investigations.

A total of approximately 170 individual power cable investigations have been recorded over the period from 1997 until the end of 2014.

Relevant information from these investigations has been collected and used to create insight in the causes for failures to happen and, where possible, to identify common factors. This has led to improvements in design, production, testing, installation and operation of power cable systems, as knowing the root cause of failures is crucial for improvement of the complete chain.

REFERENCES

[1] E. Pultrum, He, Hong and Gruntjes, R; 2015, "Type testing cable and accessories, a must", CIRED 2015

APPENDIX C
Code of Conduct - Supreme Court of Tasmania [TAB 01]

SUPREME COURT OF TASMANIA

PRACTICE DIRECTION

No 1 of 2016 5 January 2016

The following Practice Direction is published by direction of the Chief Justice, the Honourable Justice Alan Blow OAM.

EXPERT OPINION EVIDENCE – EXPERT EVIDENCE CODE OF CONDUCT

On 6 January 2016 amendments to rules 514, 515 and 516 *Supreme Court Rules* 2000 will commence. The amended rules refer to an Expert Witness Code of Conduct which has been developed by the Harmonisation of Rules Committee, a committee established by the Council of Chief Justices.

The Council of Chief Justices has approved the Code for adoption as a uniform code. The Code contains requirements similar, but not identical, to those previously imposed by the rules.

The amended rules require every expert witness to comply with the Code unless the Court or a judge orders or directs otherwise. The Expert Witness Code of Conduct is attached.

EXPERT WITNESS CODE OF CONDUCT

Application of Code

1 This Code of Conduct applies to any expert witness engaged or appointed:

(a) to provide an expert's report for use as evidence in proceedings or proposed proceedings; or

(b) to give opinion evidence in proceedings or proposed proceedings.

General Duties to the Court

2 An expert witness is not an advocate for a party and has a paramount duty, overriding any duty to the party to the proceedings or other person retaining the expert witness, to assist the Court impartially on matters relevant to the area of expertise of the witness.

Content of Report

3 Every report prepared by an expert witness for use in Court shall clearly state the opinion or opinions of the expert and shall state, specify or provide —

(a) the name and address of the expert;

(b) an acknowledgment that the expert has read this code and agrees to be bound by it;

(c) the qualifications of the expert to prepare the report;

(d) the assumptions and material facts on which each opinion expressed in the report is based (a letter of instruction may be annexed);

(e) the reasons for and any literature or other materials utilised in support of each such opinion;

(f) (if applicable) that a particular question, issue or matter falls outside the expert's field of expertise;

(g) any examinations, tests or other investigations on which the expert has relied, identifying the person who carried them out and that person's qualifications;

(h) the extent to which any opinion which the expert has expressed involves the acceptance of another person's opinion, the identification of that other person and the opinion expressed by that other person;

(i) a declaration that the expert has made all the inquiries which the expert believes are desirable and appropriate (save for any matters identified explicitly in the report), and that no matters of significance which the expert regards as relevant have, to the knowledge of the expert, been withheld from the Court;

(j) any qualification of an opinion expressed in the report without which the report is or may be incomplete or inaccurate;

(k) whether any opinion expressed in the report is not a concluded opinion because of insufficient research or insufficient data or for any other reason; and

(l) where the report is lengthy or complex, a brief summary of the report at the beginning of the report.

Supplementary Report Following Change of Opinion

4 Where an expert witness has provided to a party (or that party's legal representative) a report for use in Court, and the expert thereafter changes his or her opinion on a material matter, the expert shall forthwith provide to the party (or that party's legal representative) a supplementary report which shall state, specify or provide the information referred to in paragraphs (a), (d), (e), (g), (h), (i), (j), (k) and (1) of clause 3 of this code and, if applicable, paragraph (f) of that clause.

5 In any subsequent report (whether prepared in accordance with clause 4 or not) the expert may refer to material contained in the earlier report without repeating it.

Duty to Comply with the Court's Directions

6 If directed to do so by t he Court, an expert witness shall —

(a) confer with any other expert witness;

(b) provide the Court with a joint report specifying (as the case requires) matters agreed and matters not agreed and the reasons for the experts not agreeing; and

(c) abide in a timely way by any direction of the Court.

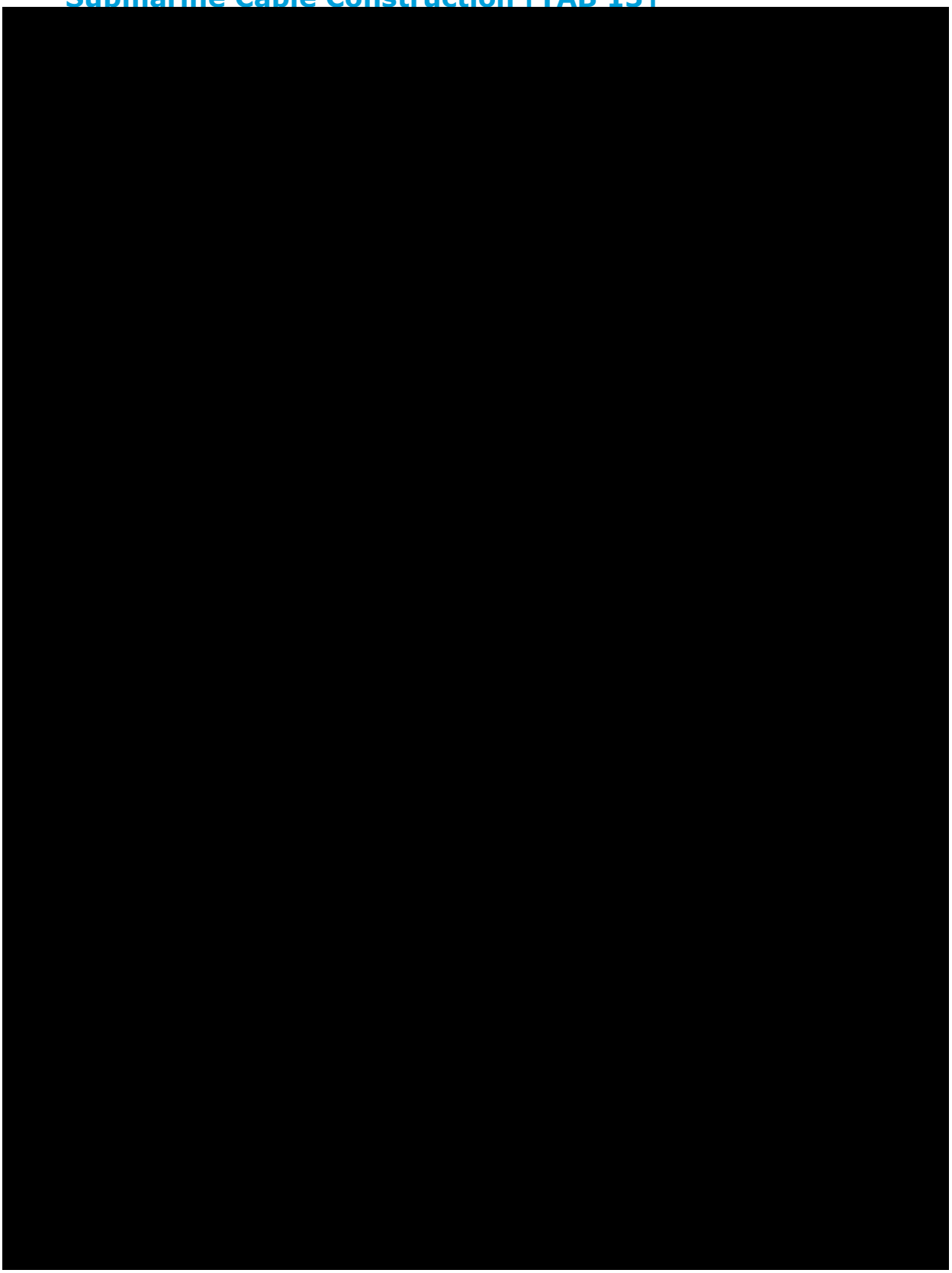
Conferences of Experts

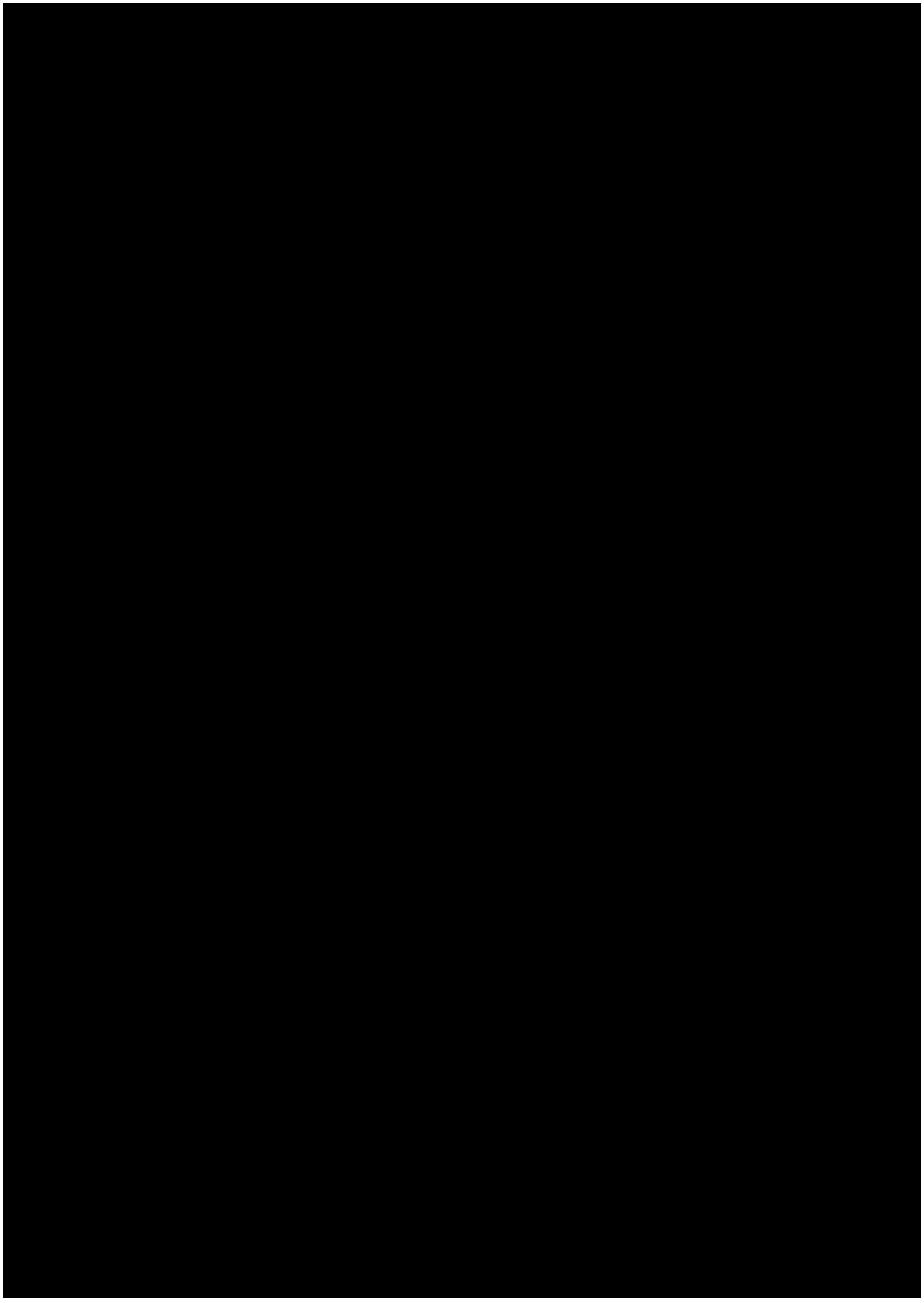
7 Each expert witness shall —

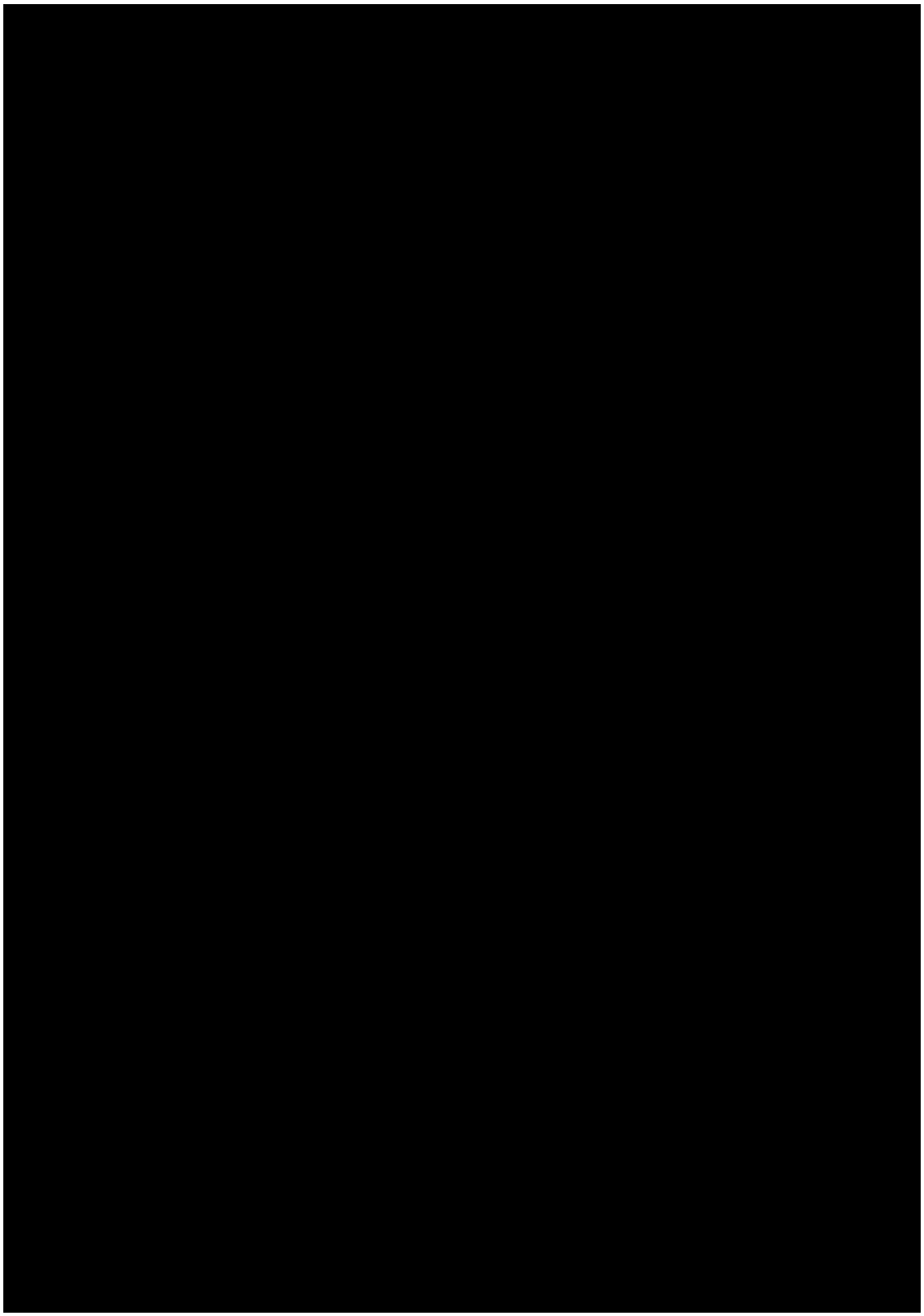
(a) exercise his or her independent judgment in relation to every conference in which the expert participates pursuant to a direction of the Court and in relation to each report thereafter provided, and shall not act on any instruction or request to withhold or avoid agreement; and

(b) endeavour to reach agreement with the other expert witness (or witnesses) on any issue in dispute between them, or failing agreement, endeavour to identify and clarify the basis of disagreement on the issues which are in dispute.

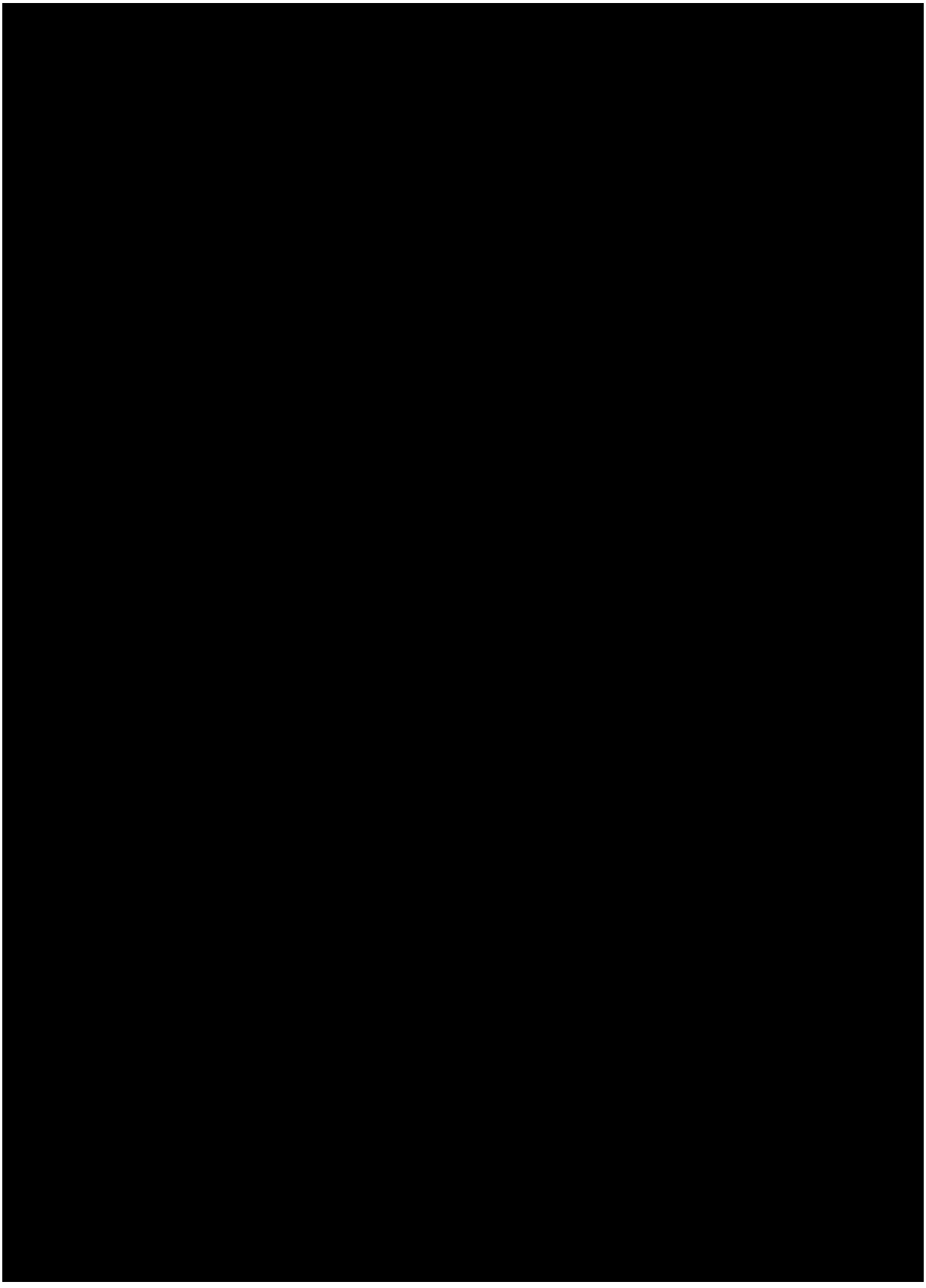
APPENDIX D
Submarine Cable Construction [TAB 13]





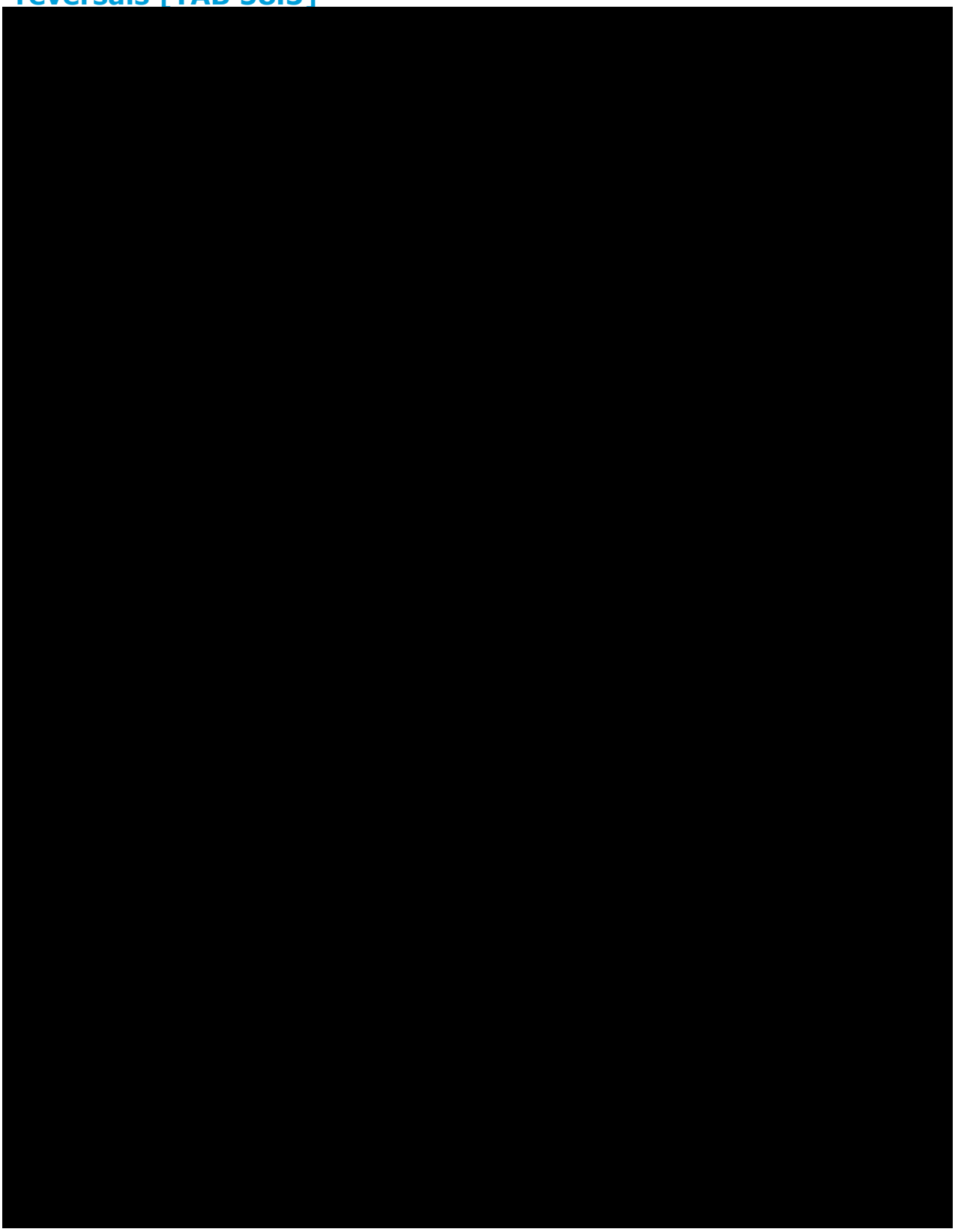


APPENDIX E
Pirelli letter to Basslink about voltage polarity reversals [TAB 18]



APPENDIX F

Letter Basslink to Hydro Tasmania about voltage polarity reversals [TAB 58.3]



APPENDIX G
CV Fred Steennis

Function

Senior Principal Consultant

Role

Coordinator Power Failure Investigations within DNV GL Energy, world-wide

Personal statistics

Citizenship: Dutch

Date of birth: Nov 16, 1954

Language capabilities

Language	Speaking	Reading	Writing
English	Good	Good	Good
German	Good	Good	Fair
French	Basic	Basic	Basic
Dutch	Excellent	Excellent	Excellent
Portuguese	None	Basic	None

Academic and professional attainment

Field of expertise	University/School	Year
PhD Electrical Engineering	Technical University Delft	Jan 1987 - Jun 1989
MSc Electrical Engineering (cum laude)	Technical University Eindhoven	Sep 1976 - Dec 1981
Master Electrical Engineering (cum laude)	Institute of Technology (HTS)	Sep 1972 - Jun 1976

Summary of professional experience

Mr. Steennis has many years of experience in numerous power cable projects. In the case of R&D management related activities, such projects start with identifying the customer's needs which come from many contacts, former projects, failure investigations, etc., after which a proposal is made and if granted the R&D work is often a team effort. In line with this, since 1999, Mr. Steennis is also a part-time professor at the technical University Eindhoven in which role he is giving lectures on underground power cables and giving guidance to PhD students in their underground power cable related research. Under his responsibility meanwhile 8 PhD students received their doctor degree.

Also, Mr. Steennis is well-known with failure analysis in power cable projects. The knowledge on degradation processes on one hand and DNV GL's independency combined with its test facilities make it logic for many network owners and cable manufacturers to ask DNV GL's support in case of a power cable failure. The main goal is always to identify the root cause, but behind this request can be a safety, economical or technical issue. Since DNV GL is involved in this type of work on a very regular basis, all this experience helps to become more and more efficient. This is clearly a very international business. Regarding consultancy services in power cable projects, the activities of Mr. Steennis are mainly related to cable ageing, asset management, cable failures and remaining life issues. These services very often are done for customers anywhere in the world.
Mr. Steennis has also several years of experience as a full-time manager within DNV GL. Especially, in recent years he gives guidance to less experienced colleagues in his role of Senior Principal Consultant.
Mr. Steennis has published many papers (> 150), reflecting his experience with many different power cable projects.

Mr. Steennis received two awards:
1) 1991 - Hidde Nijland Award, a Dutch award of the power sector, 1991; for his contribution in the field of new testing methods for cables and the applicability of superconductors in power technology
2) 2014 - DNV GL Innovation Award 2014 – for his invention of Smart Cable Guard, a unique on-line monitoring tool locating weak spots that can lead to failures and accurate locator for temporary and permanent failures for medium voltage cables

An important patent of which Mr. Steennis is shared patent holder is: E. F. Steennis, P. A. A. F. Wouters, P. C. J. M. van der Wielen and J. Veen, "Method and system for transmitting an information signal over a power cable", Int. Patent No. WO 2004/013642, June 2002

Professional training

Year	Institute	Description
March 2016	De Federatie	Trainers learn from / with trainers
Sep 2009 - Dec 2009	Huthwaite	Spin-selling
Jun 2009 - Jun 2009	Huthwaite	Winning Proposals
Jan 1996 - Dec 1997	Krauthammer	Short Commercial Courses
Jan 1993 - Dec 1994	De Baak	Management,
Jan 1990 - Dec 1992	KEMA	Short Commercial Courses
Jan 1983 - Dec 1983	Technical University Eindhoven	Post graduate course on Statistical theory for test set-ups

Other information

Awards

- Hidde Nijland Award, a Dutch award of the power sector, 1991; for his contribution in the field of new testing methods for cables and the applicability of superconductors in power technology
- DNV GL Innovation Award 2014 – for his invention of Smart Cable Guard, a unique on-line monitoring tool locating weak spots that can lead to failures and accurate locator for temporary and permanent failures for medium voltage cables

Patents

- E. F. Steennis, P. A. A. F. Wouters, P. C. J. M. van der Wielen and J. Veen, "Werkwijze en system voor het overbrengen van een informatiesignaal over een vermogenskabel", Dutch Patent No. NL 1020925, June 2002.
- E. F. Steennis, P. A. A. F. Wouters, P. C. J. M. van der Wielen and J. Veen, "Method and system for transmitting an information signal over a power cable", Int. Patent No. WO 2004/013642, June 2002

Employment record

Technical University Eindhoven **Sep 1999 - Oct 2015**

Position: Professor

- Part-time (1 day / week) professor with a special subject being "power cable diagnostics". Giving lectures on power cables, guiding students among which PhD students.

SEP (nowadays called TenneT) **Jan 1995 - Dec 1995**

Position: Engineering manager a.i.

- Engineering manager a.i. project [redacted] KEMA supports SEP with engineering management in their realization of the HVDC cable connection from Norway to the Netherlands

DNV GL (partly formerly KEMA and DNV KEMA) **Jan 1982 - Oct 2015**

Position: Service Line Principal / Senior Principal Consultant

- 2010 and onwards: Principal Consultant on Underground Powers Cables and Submarine Power Cables; active in several projects on power cables in general, asset management, tests & diagnostics and failure analysis. Project manager of several R&D projects. Lecturer of the DNV GL Power Cable Courses. Since 2013 also coordinator Power Failure Investigations for DNV GL Energy for all types of Power Equipment.

- 1995 - 2010: Consultant / Specialist on Underground Power Cables; active in several projects on power cables in general, asset management, tests & diagnostics and failure analysis. Project manager of several R&D projects. Lecturer of the KEMA Power Cable Courses.

- 1995-1999: Manager of the departments related to 1) Cables and Insulating Materials and 2) Manager of the department High-Voltage Testing and Diagnostics. The total number of employees of this department was 43 people.

- Unit 1995: Research worker in many different projects on power cables in general, asset management, tests & diagnostics and failure analysis. Project manager of several R&D projects.

Detailed professional experience

Courses on Power cables and Courses on Power Failure Investigations

Period :	about 1999 - present
Customer :	many different customers, all confidential
Position:	Trainer
Description:	- General course on Underground Power Cables - Specialiced Courses Remaining Life of MV Underground Power Cables - Course on Power Failure Investigations
Activities performed:	Making course books and Power Point presentations; giving courses; guiding students and examining their results; follow up where needed

Condition assessment and remaining life studies

Period :	about 1982 - present
Customer :	many different customers, all confidential
Position:	(Senior) Principal Consultant
Description:	Condition assessment and remaining life studies of low voltage cables, medium-voltage cables and / or high-voltage cables
Activities performed:	Interviews, literature study, discussions, analyses, reporting, starting regular meetings with network owners, arranging experiments to check the remaining life aspects; reporting and publications (Cired, JICABLE)

Root cause analyses after a failure of a component in an Underground Power Cable System, up to December 2017, [confidential / classified], for among others:

Period :	about 1986 - present
Customer :	ABB (Sweden), Alcoa (USA), Alliander, formerly Nuon (the Netherlands), Ausnet (Australia), Brookfield (UK), Brugg cables (Switzerland), CEM (Macau, China), CERN (Switzerland), China Light and Power (Hong Kong), ConEdison (USA), Delta

	Lloyd (the Netherlands), Delta NWB (the Netherlands), El Sewedy (Egypt), Energinet.dk (Denmark), Enexis, formerly Essent (the Netherlands), Exsym (Japan), Florida Light and Power Co. (USA), Hong Kong Electric (Hong Kong), IEC (Israel), ILJIN (Korea), Jeddah cables (Kingdom of Saudi Arabia), Kahramaa (Qatar), KEPCO (Korea), LS Cable (Korea), Mutual Energy (Ireland), Nalcor (Canada), Nat Grid (UK), Nexans (France), nkt cables (Germany), Pacific Electric Wire and Cable Co (Taiwan), Prysmian (the Netherlands, Italy), Reliance (India), Saudi Cable Company (Kingdom of Saudi Arabia), SPPG (Singapore), Stedin, formerly Eneco (the Netherlands), Taihan (Korea), Tata Steel (the Netherlands), TenneT Offshore GmbH (Germany), TenneT TSO B.V. (the Netherlands), TEPCO (Japan), Transco (Abu Dhabi), Westland Infra (the Netherlands), all confidential.
Position:	(Senior) Principal Consultant
Description:	Study to find the root cause of a faillure of a cable, joint or termination; guiding also in the cause behind the technical root cause; support in Court Sessions;
Activities performed:	Interviews, literature study, discussions, analyses, reporting, starting regular meetings with network owners, arranging experiments to check hypotheses on failure causes of joints; reporting and publications (Cired, JICABLE); Court sessions

Publications and papers

/P1/ Lars Herre, Peter Wouters, Fred Steennis, Roald de Graaff, On the electromagnetic coupling of AC and DC circuits on hybrid transmission towers, IEEE International Energy Conference (ENERGYCON), 2016, DOI: 10.1109/ENERGYCON.2016.7514143, pp: 1-6.

/P2/ F. Barakou, M.H.J. Bollen, S. Mousave-Gargari, O. Lennerhag, P.A.A.F. Wouters, E.F. Steennis, Impact of load modeling on the harmonic impedance seen from the transmission network, 17th International Conference on Harmonics and Quality of Power (ICHQP), 2016, DOI: 10.1109/ICHQP.2016.7783466, pp: 283-288.

/P3/ Fred Steennis, Paul Wagenaars, Peter van der Wielen, Peter Wouters, Yan Li, Tjeerd Broersma, Denny Harmsen, Pascal Bleeker, Guarding MV cables on-line: With travelling wave based temperature monitoring, fault location, PD location and PD related remaining life aspects, IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 23, Issue 3, 2016, DOI: 10.1109/TDEI.2016.005566, pp: 1562-1569.

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APPENDIX H
DNV GL

Driven by the purpose of safeguarding life, property and the environment, DNV GL enables organizations to advance the safety and sustainability of their business. DNV GL provides classification, technical assurance, software and independent expert advisory services to the maritime, oil & gas and energy industries. DNV GL also provides certification services to customers across a wide range of industries. Combining leading technical and operational expertise, risk methodology and in-depth industry knowledge, DNV GL empowers their customers' decisions and actions with trust and confidence. DNV GL continuously invests in research and collaborative innovation to provide customers and society with operational and technological foresight. Operating in more than 100 countries, DNV GL's professionals are dedicated to helping customers make the world safer, smarter and greener. Concerning the company DNV GL, see www.dnvgl.com.

Of further interest is that DNV and KEMA merged into DNV KEMA in 2012 and the company's name became DNV GL in 2013 after a further merge with GL. Thus, DNV GL unites the strengths of DNV KEMA, GL Garrad Hassan, and GL Renewables Certification. See concerning the merger activities over time www.dnvgl.com/merger.

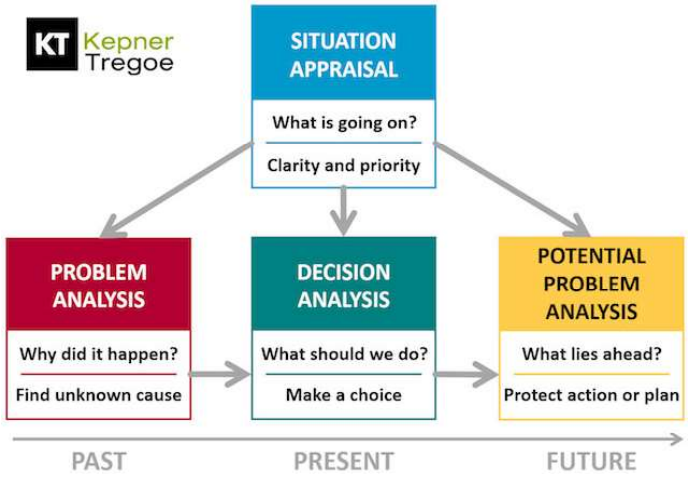
APPENDIX I

Failure analysis methods - Kepner-Tregoe, Ishikawa, Human Performance Analysis, Tripod, Bow-tie

Kepner-Tregoe:

The Kepner-Tregoe method (reference, among others /9/**)** is based on the following six steps:

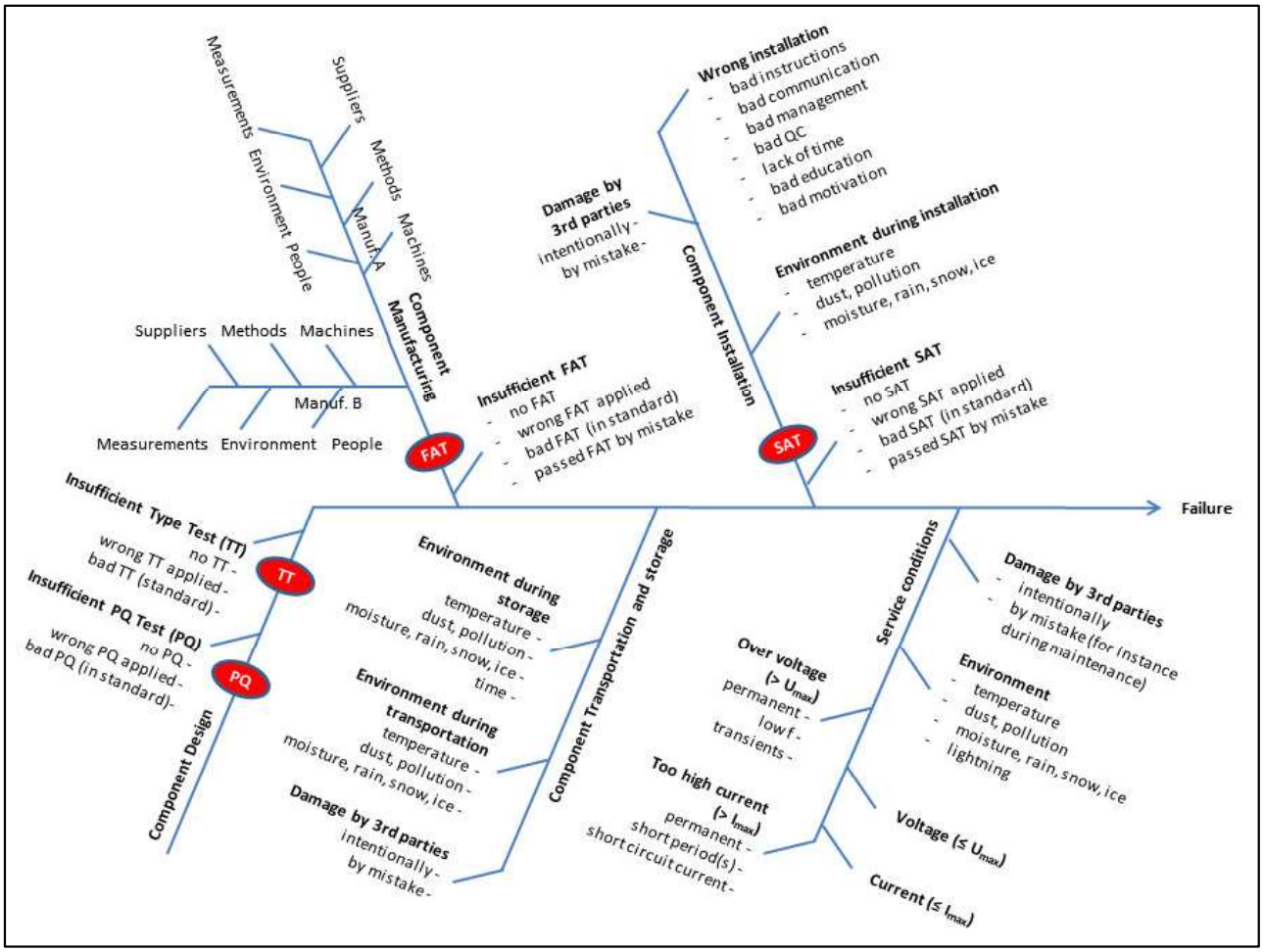
1. Situation appraisal
2. Specification of the problem:
    a. What? What not?
    b. Where? Where not?
    c. When? When not?
3. Development of possible causes
    a. Use IS and IS NOT
4. Test for probable cause
5. Decide for optimal solution(s)
6. Think beyond the fix
    a. Potential problem analysis



	IS	IS NOT
What (identify)		
Where (location)		
When (timing)		
Extent (magnitude)		

Ishikawa

Ishikawa introduced a fishbone structure, all contributors to a failure are presented, with the object to give structure and once made, to present and not to forget contributing elements (reference, among others /10/). An example is shown for a cable failure related fish-bone.



Human performance analysis

The Human performance analysis (reference, among others /11/) has its focus mainly on human based contributors to a failure. Standard questions are related to:

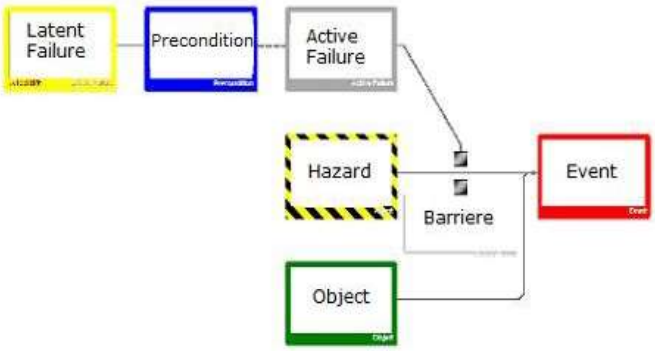
- Procedure
- Training
- Quality control
- Communication
- Management system
- Human relations
- Direct supervision

Tripod analysis

The tripod analysis (reference, among others /12/) is strong because it combines mapping technical and organisations elements contributing to a failure, graphically presented. Its graphical presentation makes

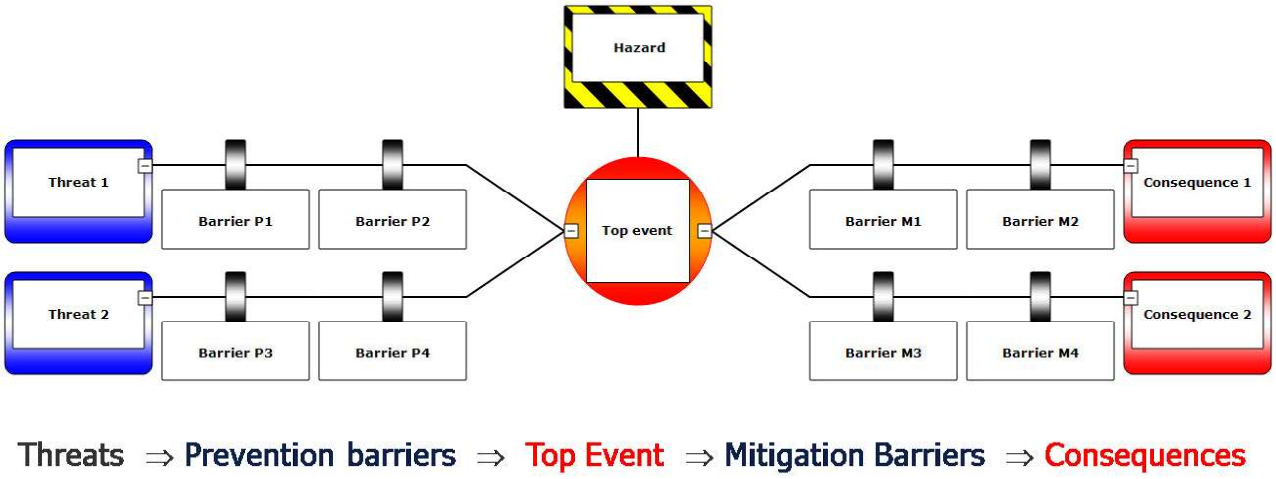
it possible to show barriers that normally should prevent a failure, but which seems not to have worked if the failure happens (like a safety system that failed). The incident facts are built into a tree, showing:

- WHAT happened? (what is the incident process?)
- HOW did it happen? (what hazard management elements failed?)
- WHY did it happen? (what caused the elements to fail?)



Bow-tie

A bow-tie method (reference, among others /13/) has the tripod part up to the failure as shown above, but from that point it develops further into a risk model where mitigating actions are defined. It is a good communication tool. It is able to illustrate much information on one page. It is simple and effective. But it doesn't have quantitative parts.



APPENDIX J
Void formation and partial discharges

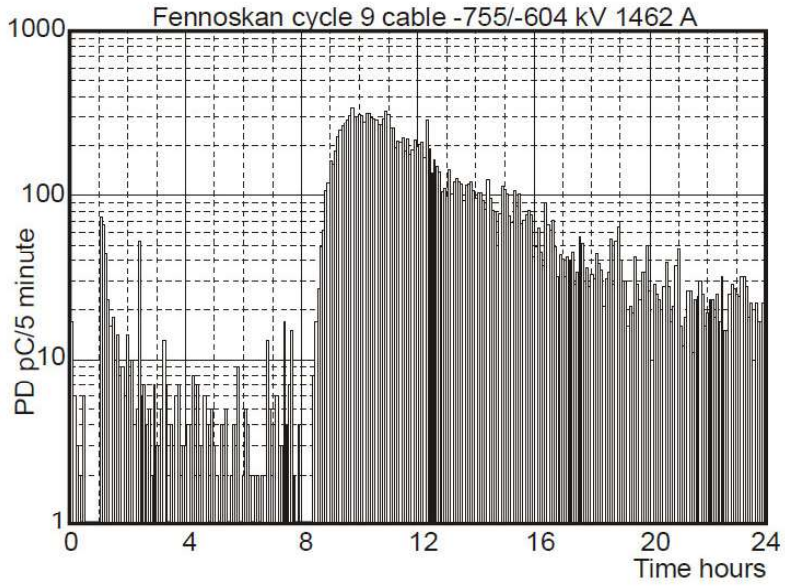
Void formation must be avoided because such voids will not be immediately filled up with the impregnant and are thus, at least for a while, gas / air filled pockets. Gas / air filled voids have a much lower breakdown strength than the surrounding paper and impregnant. Much literature deals with this subject (out of the many publications: [/56/, Kreuger, 1995], [/57/, Kreuger, 1992]).

In short, the lower breakdown strength of a void is the result of two facts.

- In the first place, because of the dielectric properties of the materials involved, the electrical stress in a void is higher than in the surrounding paper and impregnant.
- In the second place, inside the void, if one of the gas atoms gets charged (for instance by the nuclear radiation of the surrounding materials), it will start to move by the force of the electrical stress acting on a charged particle. The relatively high electrical stress will accelerate the charged particle quickly. Different from a more solid material as paper or impregnant, there is not much in a void that will stop the moving particle, gaining speed until it finally hits another gas atom. Because of the high kinetic energy gained during the "long" duration acceleration, the hit will create new charged particles, which on their turn start to get accelerated and will hit more atoms. This process is an avalanche and it will take place in a fraction of a second (out of the many publications: [/56/, Kreuger, 1995], [/55/, Chvyreva, 2016]). It can be seen as a spark, partial discharge or miniature lightning stroke inside a void. It can come with enough force to damage the surrounding material.

Once there is a spark, and if followed by more of such sparks, the insulation material will degrade such that a full breakdown of the whole insulation material will follow. It can take minutes to days (or more) in a polymer material environment, but it can take hours to years in a paper insulated environment because the impregnant tends to redistribute, forcing the spark to act on another spot. And maybe, paper is better able to withstand sparks than a polymer is doing [/71/, Qian, 2015]. It will also depend on the electrical stress in the void and thus on the voltage class of the cable. It is generally assumed that in HV cables, the degradation process goes faster than in MV cables for instance.

It is known that partial discharges are common under AC conditions, but these happen also under DC conditions. In [/74/, Elovaara, 2002] clearly illustrated this for the Fenno-Skan cable, where cable samples have been subjected to heat cycles. Especially during the cooling stage partial discharge activity was dominant, showing that this is the period of void creation. This is illustrated in the figure below from [/74/, Elovaara, 2002], where the first 8 hours represent the hearing and the remaining hours the cooling stage. The y-axis represents the partial discharge activity.


Fennoskan cycle 9 cable -755/-604 kV 1462 A
1000
100
10
1
PD pC/5 minute
0
4
8
12
16
20
24
Time hours

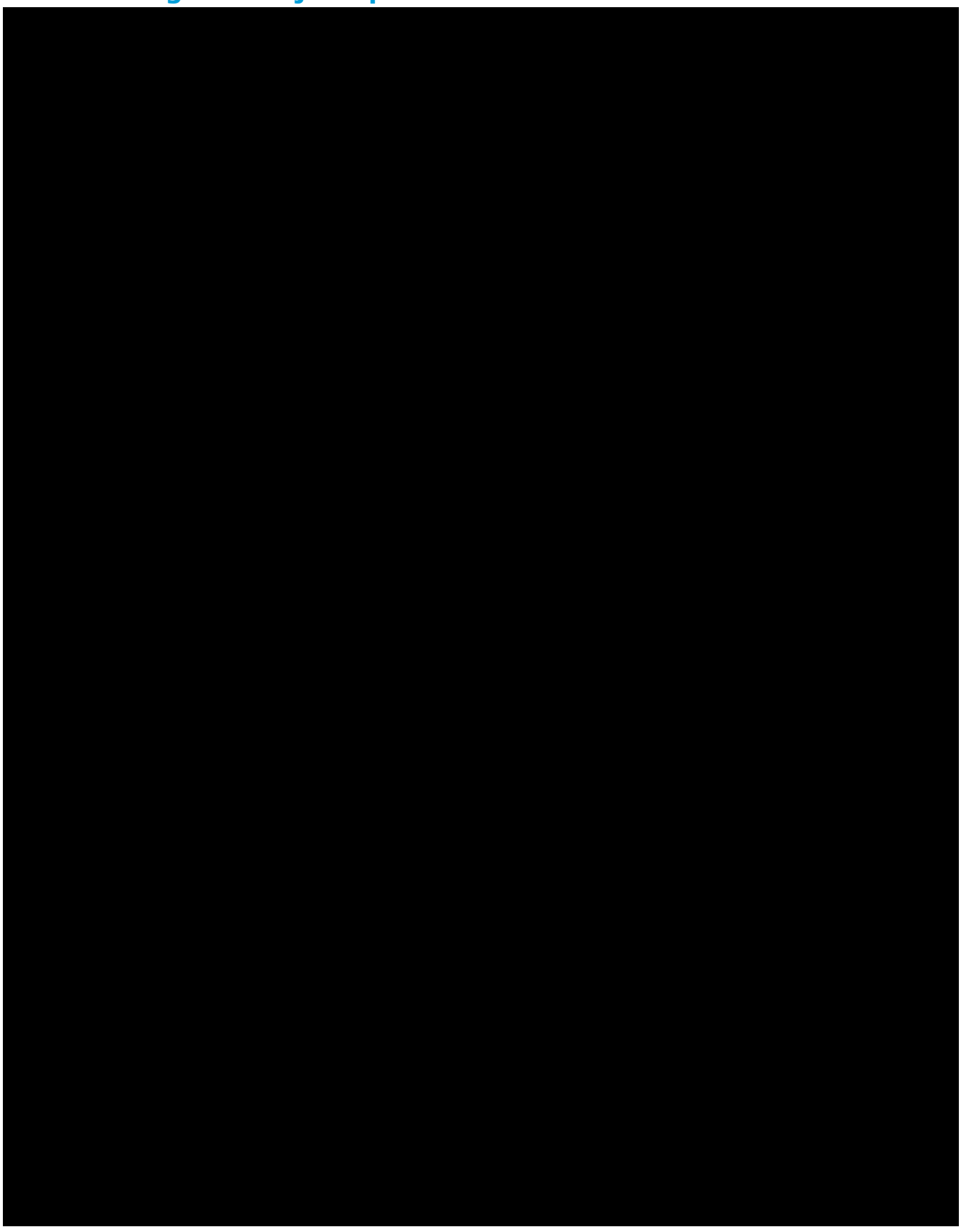
APPENDIX K
Breakdown during cooling down in HVDC MIND

Several authors [/19/, Gazzana, 1992], [/29/, Evenset, 2000] claim that a breakdown of a HVDC MIND power cable mainly happens in the cooling down stage. Also [/40/, Runde, 2014] mentions the relation between a failure and cooling down, where especially the void formation is investigated, see Appendix P.

For the initiation of a breakdown in a HVDC MIND power cable, [/19/, Gazzana, 1992] gave the following more extensive explanation: "*The critical situation which strongly affects the DC breakdown level under cooling is originated by a mechanical instability of a floating large laminar void, which can be suddenly formed and may grow to an undefined size in a soft insulation during the thermal contraction of the compound under D.C. voltage. This effect can be explained by the unbalance of the tangential electrostatic forces acting to expand an arising void against the mechanical pressure between papers, their adhesion due to the compound, their electrostatic attraction, and the mobility and viscosity of the compound. A contribution to this mechanism is also due to the presence of very high free electrostatic charges trapped at the surface of a suddenly arising void which can produce high energy discharge capability*". This explanation combines various experiences expressed in literature that a breakdown seems to happen often during the cooling stage and that there is an impact of interfacial charges (alternative words are electrostatic charges and space charges). The impact of interfacial charges is (much) more dominant, right after a voltage polarity reversal being done to switch the direction of the power flow. The reason for and the impact of voltage polarity reversals is further explained in Section 6.3. But it means, that a combination of cooling down a power cable combined with a voltage polarity reversal is a demanding moment for a HVDC MIND power cable.

On cooling down a cable, once a breakdown occurs, it can happen that the breakdown area is elongating along a certain length, but it can also be more radial under isothermal (isothermal means here that the temperature at the inside and outside of the insulation material are the same) conditions or when the paper layers are more compacted as can happen with support of reinforcement tapes. Concerning this there are two references. [/19/, Gazzana, 1992]. He wrote: "*A peculiarity of the breakdown occurring during the cooling phase is that the breakdown tracking is always elongated, from 1 to 2 m or longer, following a longitudinal path between paper layers, starting apparently from a single position, generally far from the terminals. No polarity effect is observed. No electrical trees are found in points other than the breakdown tracking. In isothermal condition the breakdown path is instead mostly radial.*". Also [/29/, Evenset, 2000] concludes the following for a breakdown of a HVDC MIND cable in the cooling down stage: "*The breakdown paths were very long, usually had an axial length of 1 m to 1.5 m, occasionally even longer. …… we developed the MI insulation by increasing the lapping tension and changing the paper insulation. …… The breakdown path for the DC breakdown changed substantially, it was short, in the order of 200 to 300 mm axially. The breakdown path for the superimposed impulse was still long, around 1 m.*"

APPENDIX L
Cable lengths and joint positions



APPENDIX M
Letter of instructions provided by Clayton Utz

CLAYTON UTZ

Confidential

Email 3 November 2017

Mr Fred Steennis
Senior Principal Consultant
DNV GL Energy
Utrechtseweg 310
6812 AR Arnhem
NETHERLANDS

Fred.Steennis@dnvgl.com

Dear Mr Steennis

Basslink Interconnector Outage

We refer to previous discussions and confirm that Clayton Utz acts for the Hydro-Electric Corporation (**Hydro Tasmania**) in relation to matters arising from the outage of Basslink, the high voltage direct current submarine cable across Bass Strait, which occurred on 20 December 2015 (**Basslink Outage**).

1. Engagement

1.1 You are engaged to prepare a report which may be used in legal action between Hydro Tasmania and Basslink Pty Limited (**BPL**).

1.2 You may be required to make yourself available to give evidence at any hearing of a dispute, should legal proceedings be commenced.

2. Background

2.1 The background for this matter is set out in **Attachment 1**.

3. Documents

3.1 You are briefed with the documents set out in **Attachment 2**.

3.2 The documents included in Attachment 2 have also been provided to your colleague, Frank de Wild. Not all the documents in Attachment 2 will be relevant to your report.

4. Questions

4.1 Terminology:

(a) *Possible* means something which may prove to be true, but that is not certain.

(b) *Probable* means something that is likely to occur or prove to be true, having more evidence for than against.

(c) *Improbable* means something that is possible but is unlikely to occur or prove to be true.

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(d) *Good Electricity Industry Practice* is:

> where the practice concerns the operation of an interconnection under conditions comparable to Basslink, the means of practice of a significant proportion of operators of OECD nations exercising that degree of skill, diligence, prudence and foresight that reasonably would be expected from an operator of an interconnection under conditions comparable to Basslink (taking into account factors such as, but not limited to, the relevant size, duty, age and technological status of the relevant interconnection and applicable legislative requirements, approvals, licences and codes).

The definition of *Good Electricity Industry Practice* is further explained in Section I of **Attachment 1.**

4.2 Please answer the following questions in your report:

1. What do you consider to be the possible cause or causes of the failure that occurred on 20 December 2015 and why?
2. Of the possible causes of failure, what is the probability associated with each cause and why?
3. Which of the possible causes of failure, if any, can be attributed to the way in which the cable was operated by BPL? In answering this question, please identify the facts and assumptions on which you rely to identify the way in which the cable was operated by BPL.
4. Further to 3, if any possible cause of failure is attributable to the way in which the cable was operated by BPL, is there anything that a prudent, experienced and competent person in the position of BPL should have done to prevent the failure?
5. Is there a possible cause of failure which you consider to be the probable cause of failure and why?
6. Do you regard any of the possible causes of failure as improbable and why?
7. What tests (if any) are necessary to establish or would assist or be likely to assist in establishing the probable cause of failure, or narrowing the possible causes of failure?
8. Further to 7, if testing is appropriate, what material (including retrieved samples of cable and documents), if any, would be required to undertake any such tests? If it is necessary in your opinion to test a retrieved sample of cable, would any testing-related limitations or difficulties arise from the condition of that sample as at the time of testing? If yes, please explain the reasons for that answer, identifying the nature and scope of any such testing-related limitations or difficulties.
9. In addition to 8 above, what other testing (if any) do you consider necessary as a matter of Good Electricity Industry Practice to inform the probable cause of failure?

4.3 In answering the above questions, please ensure you explain the concepts and terminology you have used to allow a lay person to understand your answers. Please also ensure that you identify the foundation(s) for your conclusions, and that you explain the reasoning leading to each conclusion.

5. Requirements for Report

5.1 Should a dispute between the parties lead to arbitration or litigation, the parties will agree rules for giving evidence and you will be required to comply with those rules. In the meantime

please comply with the Expert Witness Code of Conduct used by the Supreme Court of Tasmania (**Tab 1**).

5.2 The Expert Witness Code of Conduct provides guidance to independent expert witnesses in understanding their role and duties in the dispute resolution process.

5.3 The Expert Witness Code of Conduct requires an expert to include in their report:

(a) the name and address of the expert;

(b) an acknowledgment that the expert has read the Expert Witness Code of Conduct and agrees to be bound by it;

(c) the qualifications of the expert to prepare the report;

(d) the assumptions and material facts on which each opinion expressed in the report is based (this letter of instruction may be annexed);

(e) the reasons for and any literature or other materials utilised in support of each such opinion;

(f) if applicable, that a particular question, issue or matter falls outside the expert's field of expertise;

(g) any examinations, tests or other investigations on which the expert has relied, identifying the person who carried them out and that person's qualifications;

(h) the extent to which any opinion which the expert has expressed involves the acceptance of another person's opinion, the identification of that other person and the opinion expressed by that other person;

(i) a declaration that the expert has made all the inquiries which the expert believes are desirable and appropriate (save for any matters identified explicitly in the report), and that no matters of significance which the expert regards as relevant have, to the knowledge of the expert, been withheld from the Court;

(j) any qualification of an opinion expressed in the report without which the report is or may be incomplete or inaccurate;

(k) whether any opinion expressed in the report is not a concluded opinion because of insufficient research or insufficient data or for any other reason; and

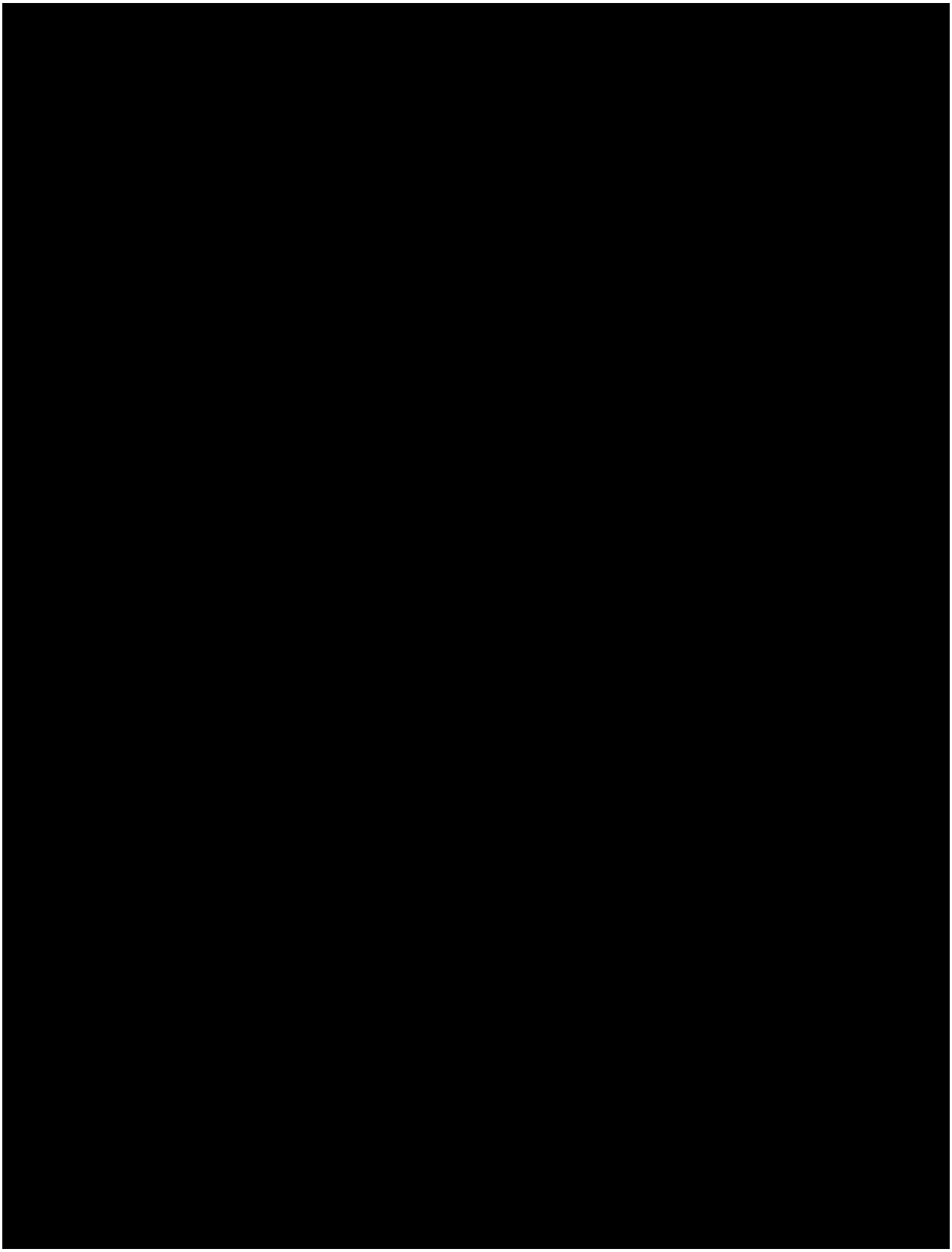
(l) where the report is lengthy or complex, a brief summary of the report at the beginning of the report.

Yours sincerely

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Claire McKenzie, Senior Associate
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Our ref 968/15760/80167367



Attachment 1 - Background

A. THE BASSLINK CABLE

1. The Basslink cable is a HVDC cable link connecting the Loy Yang Power Station in Victoria to the George Town substation in northern Tasmania. A description of the cable is under **Tab 2**. A map of the cable route prior to the 2016 repair is under **Tab 3**.

2. The Basslink cable is owned and operated by Basslink Pty Ltd (**BPL**). Between 10 October 2005 and 10 May 2007 BPL was known as National Grid Australia Pty Ltd.

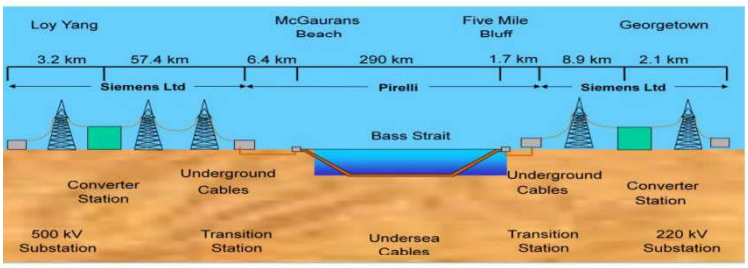
3. The subsea section of Basslink is 290 km long. The convention for pinpointing a part of the cable is via Kilometer Points (**KPs**), which are measured from the Victorian end of the cable.

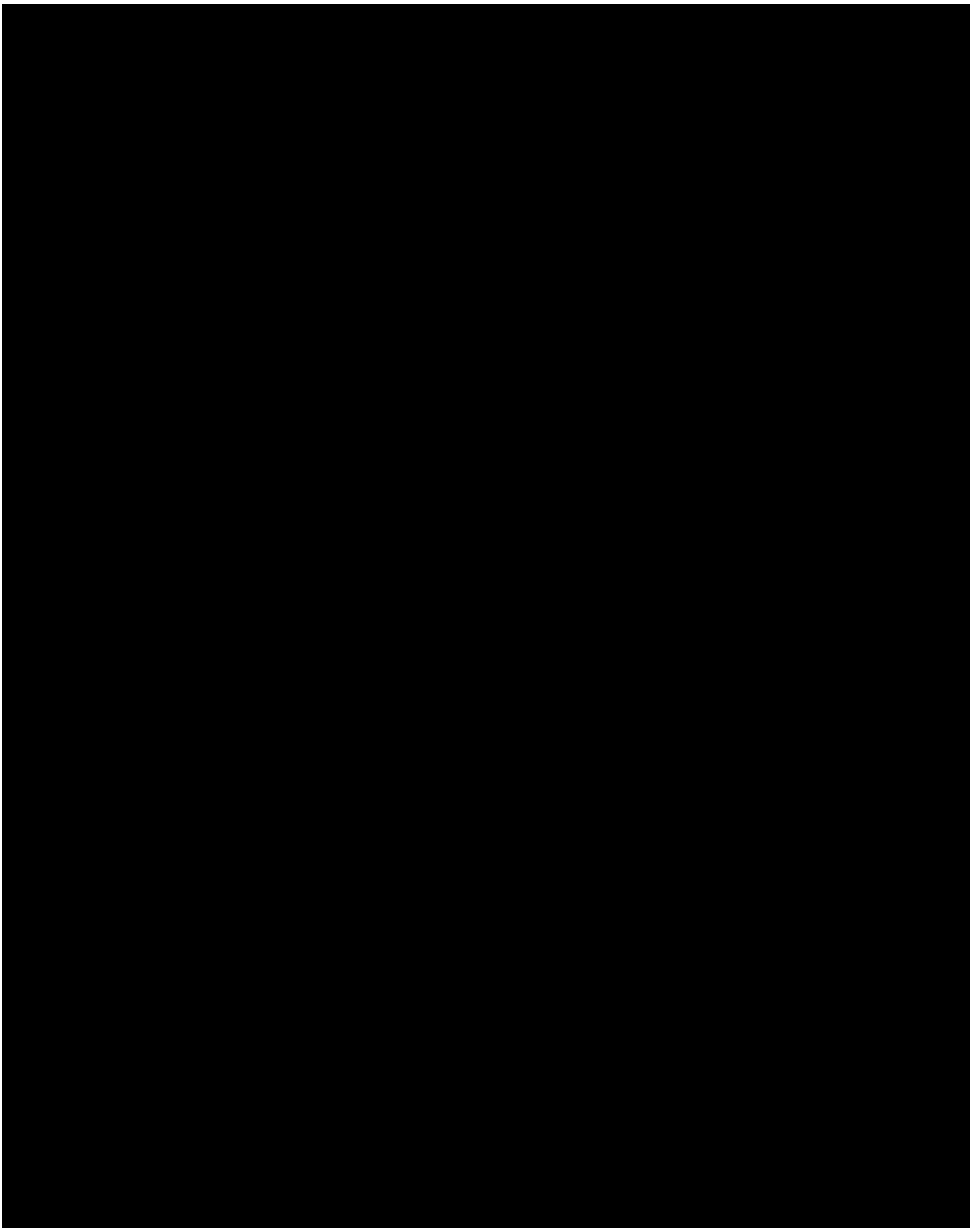
4. The subsea section has a maximum water depth of 80 meters. The HVDC cable is 1500mm^2 in cross section and has nominal voltage of 400KV.

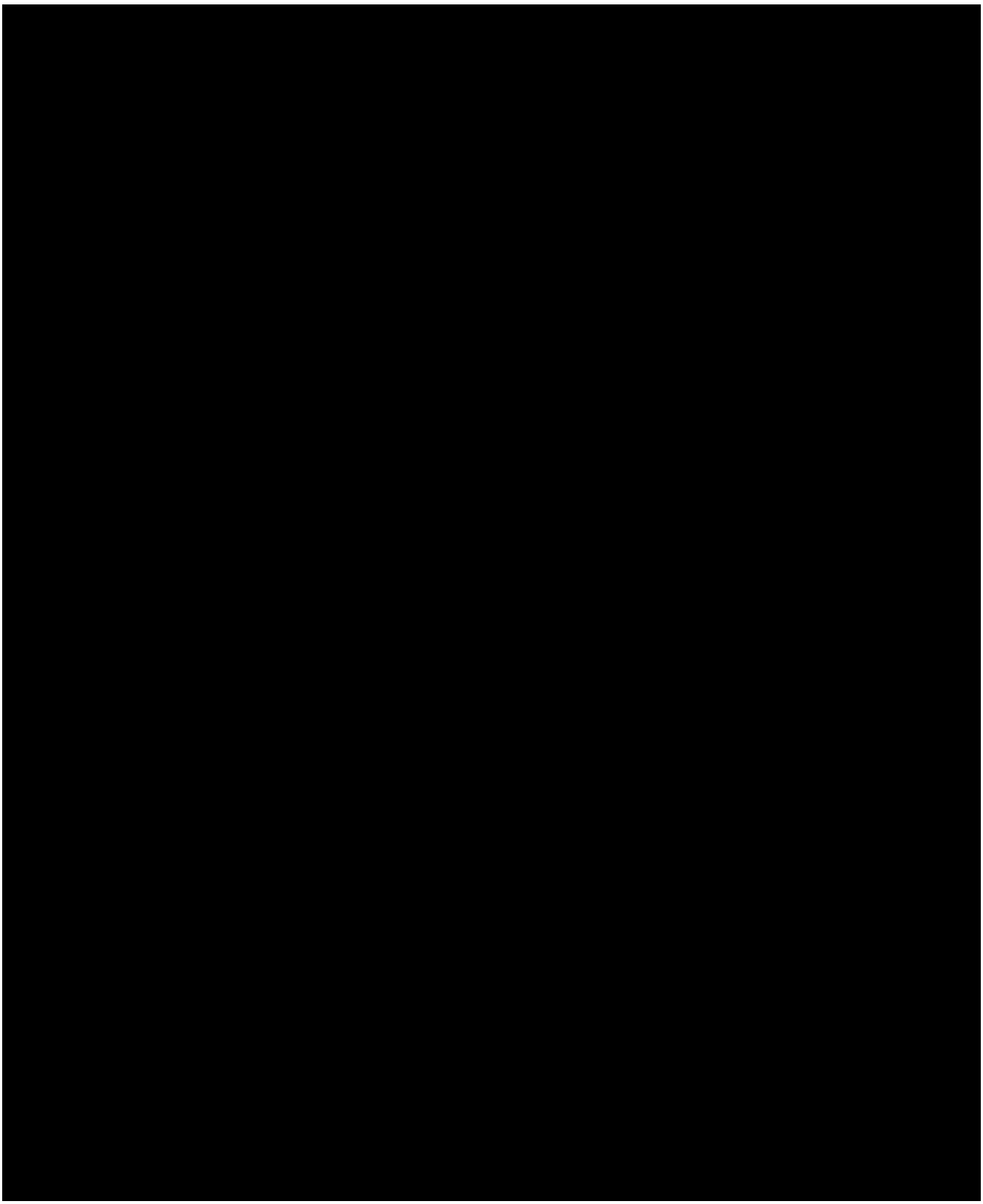
5. The HVDC cable is bundled with two other cables – the metallic return cable (**MR cable**) and a fibre optic cable (**FO cable**). The metallic return cable is 1400mm^2 in cross section whilst the FO cable is much thinner.

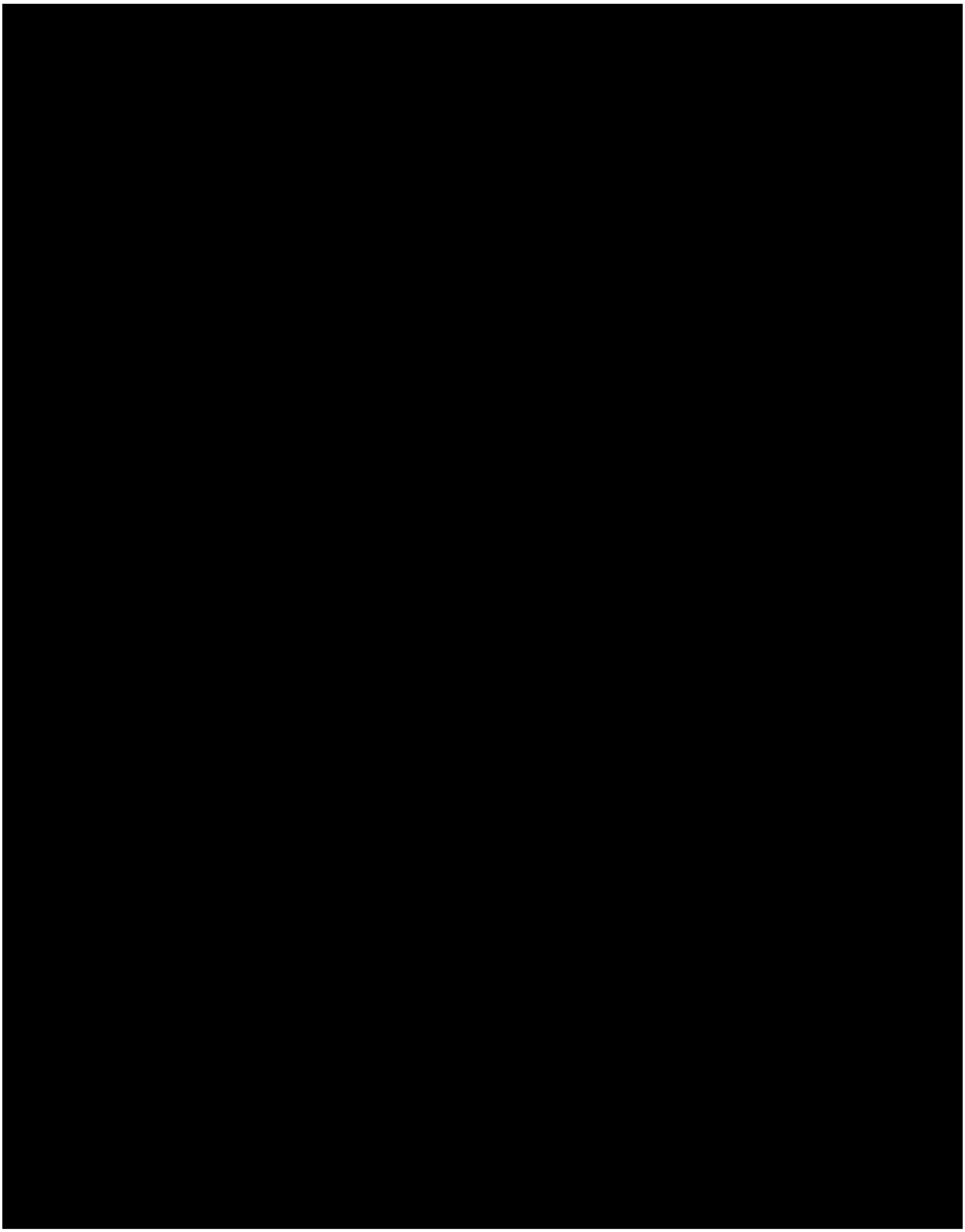
6. An image providing an overview of the Basslink system appears below.

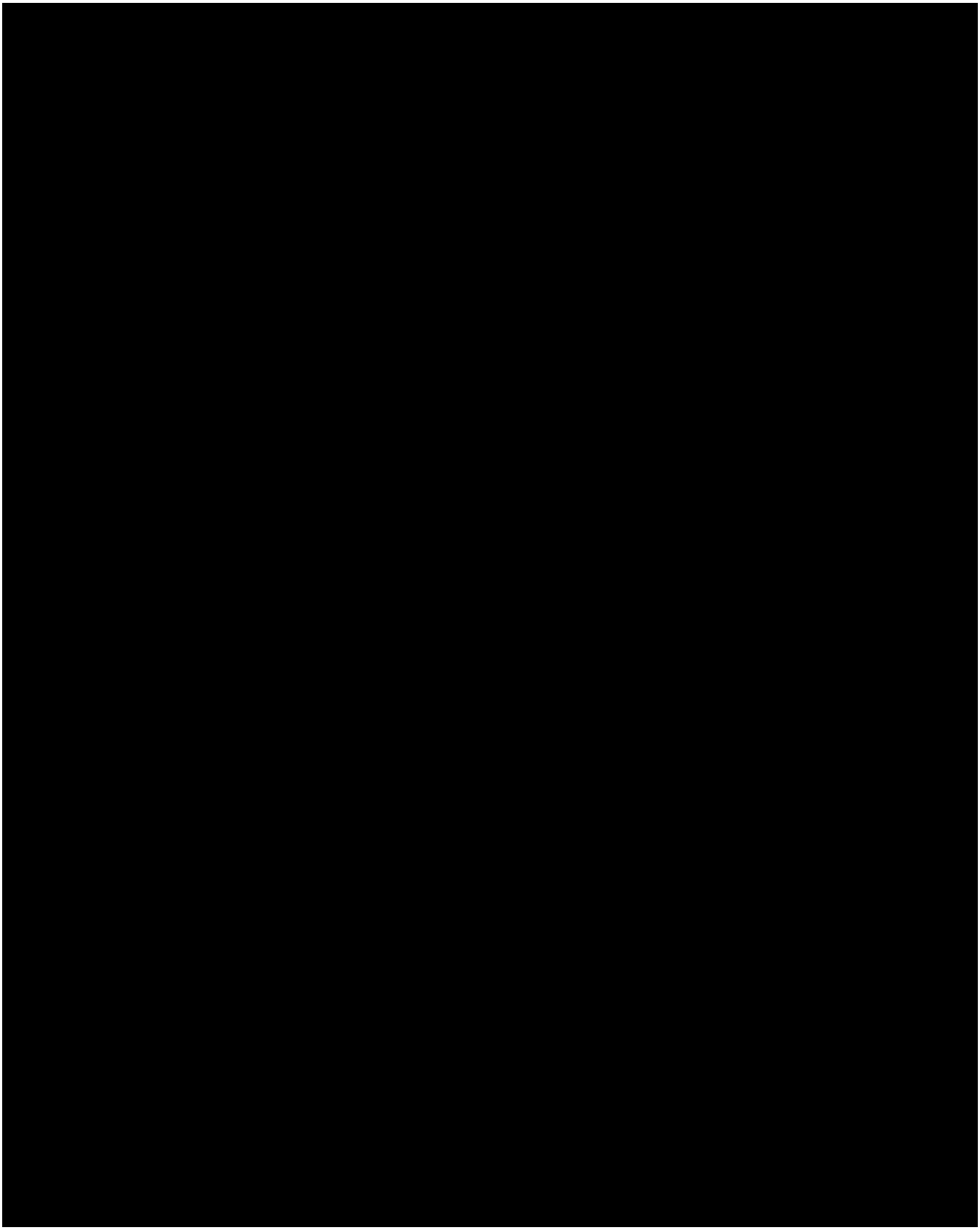
Overview of Basslink

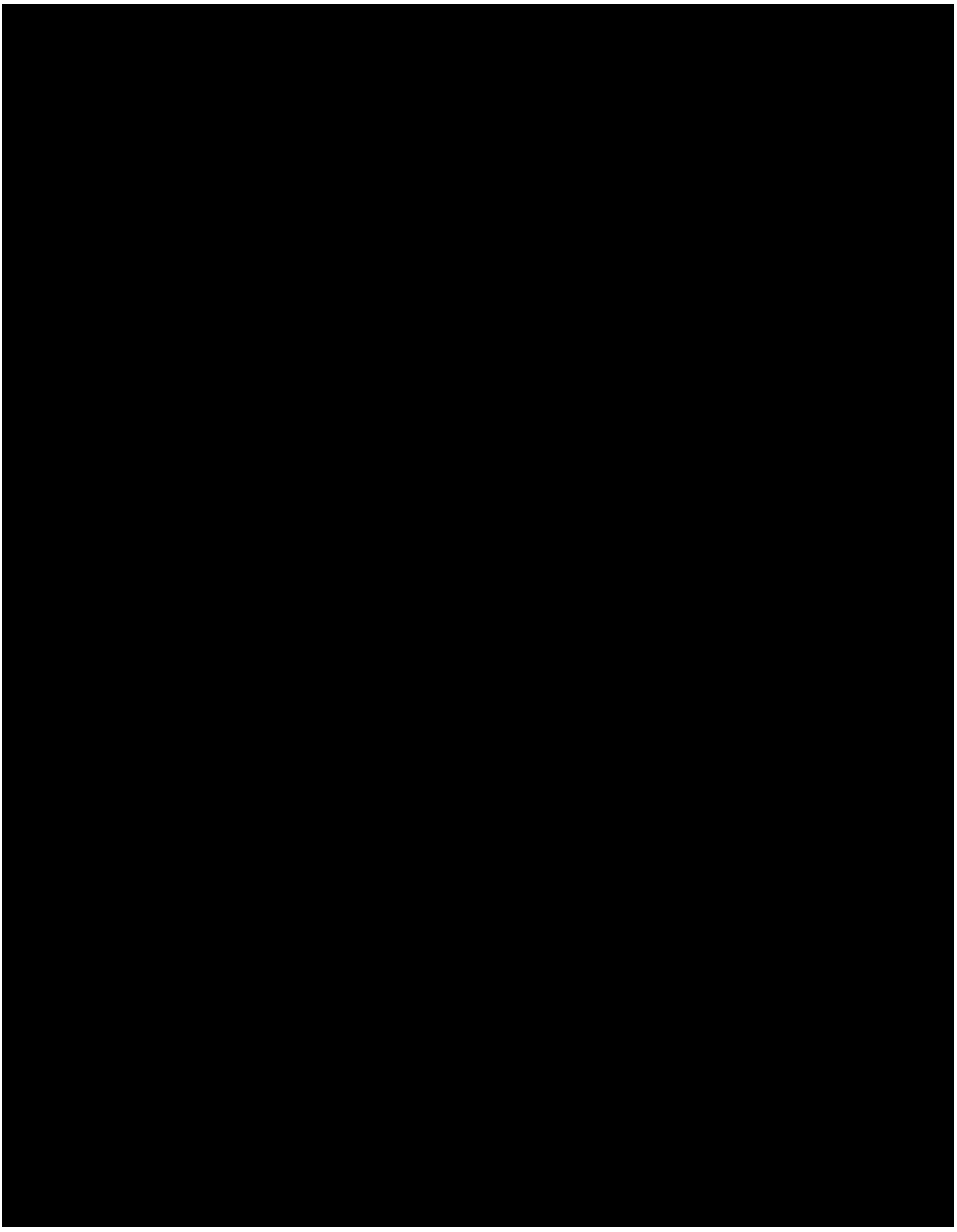


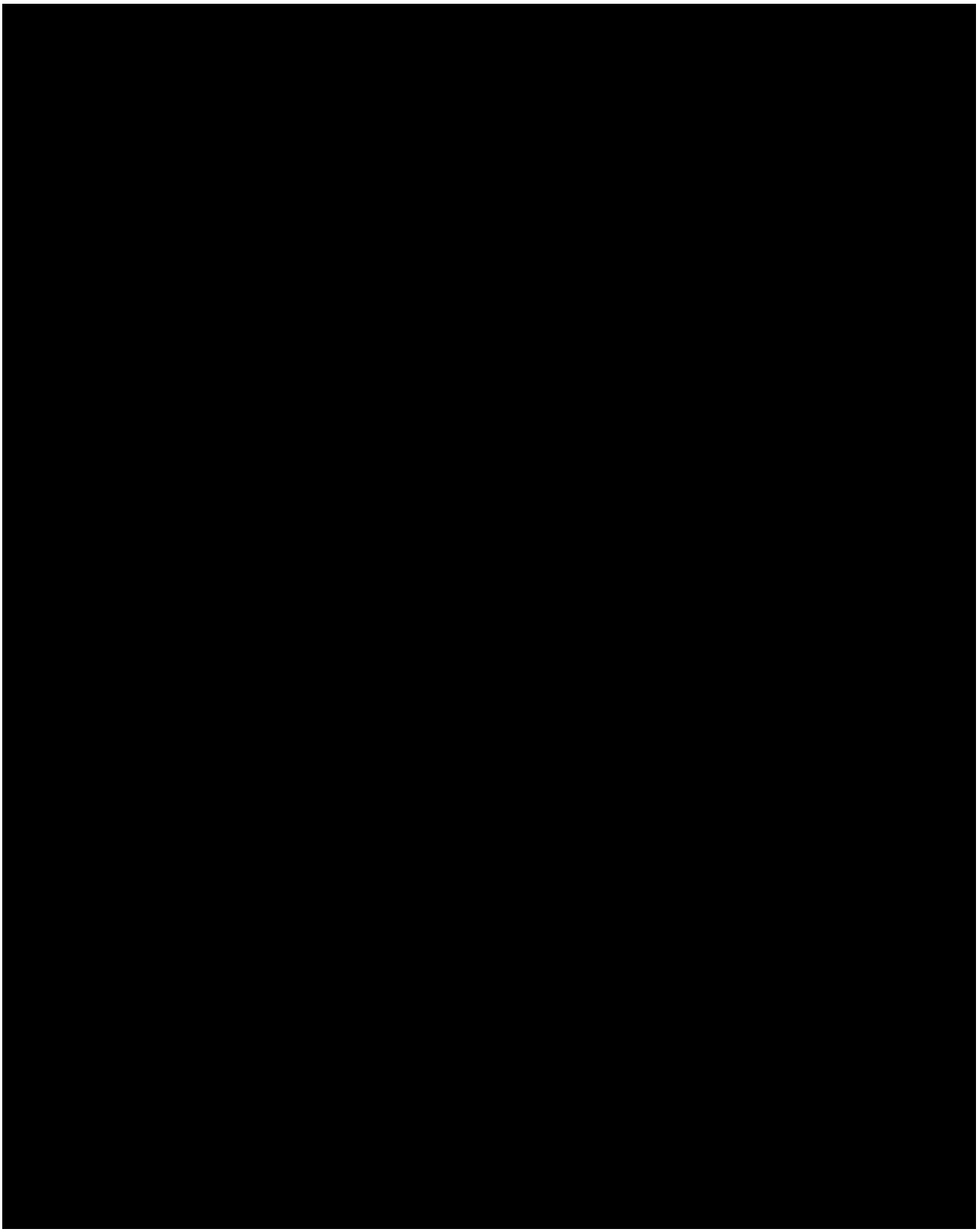


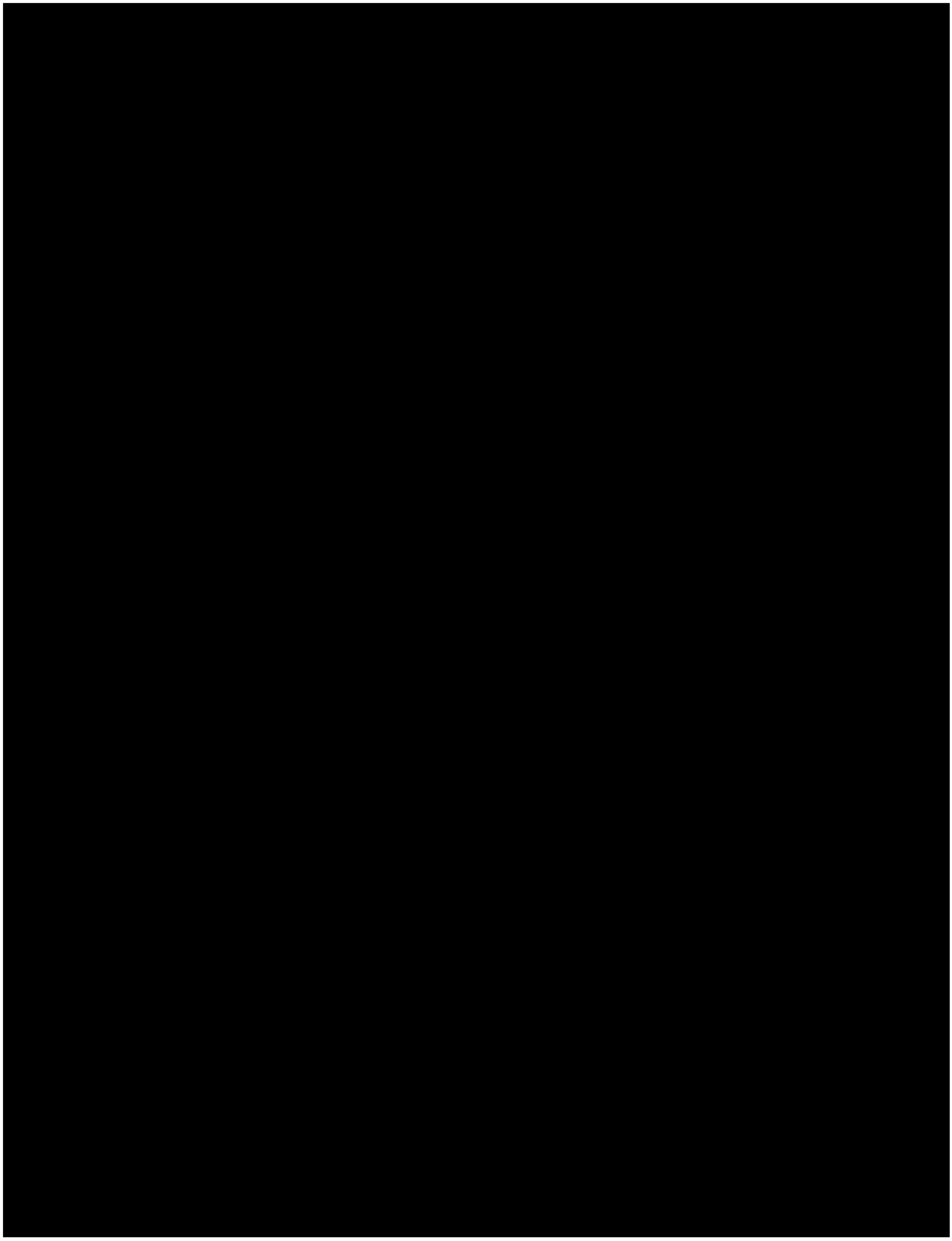


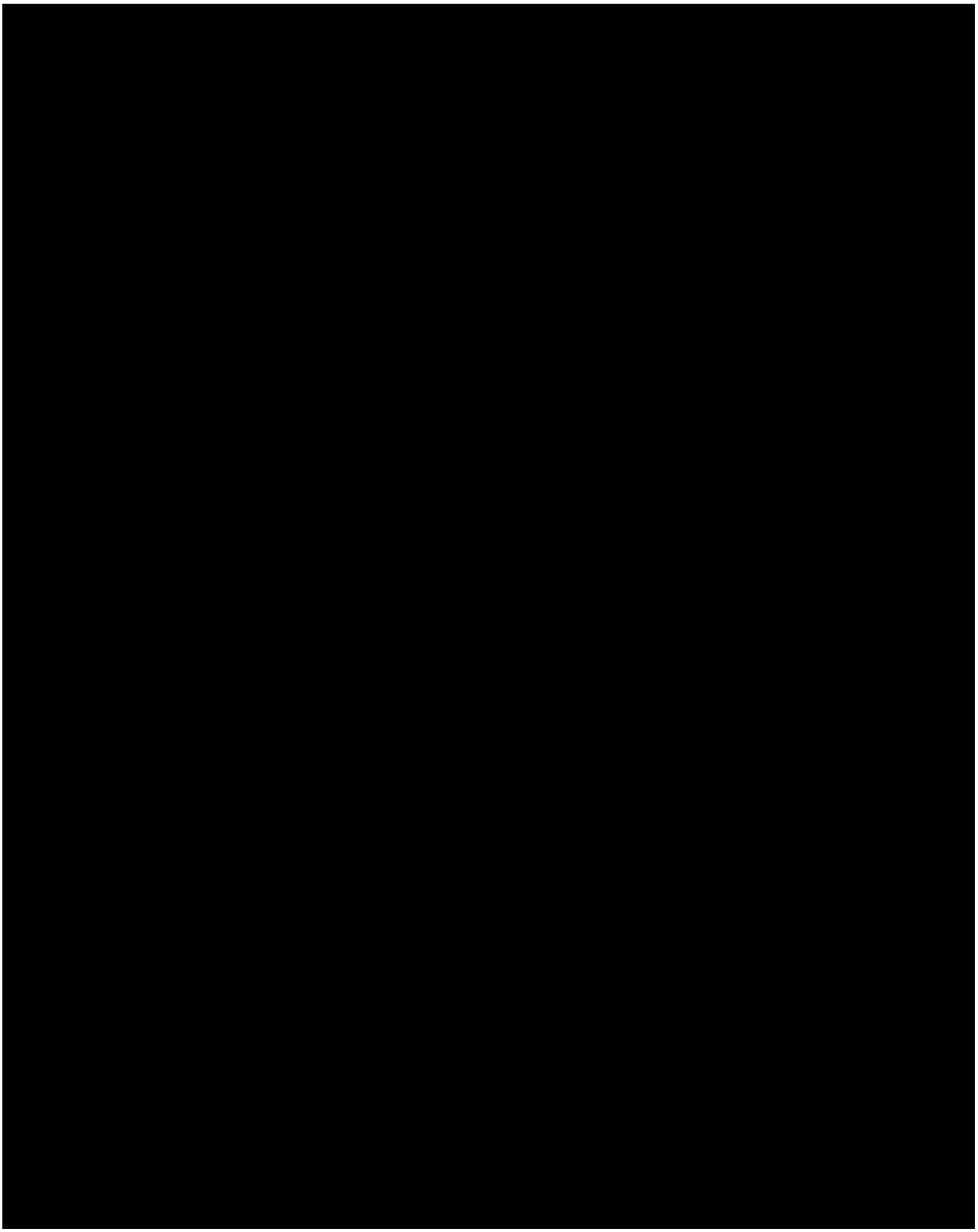


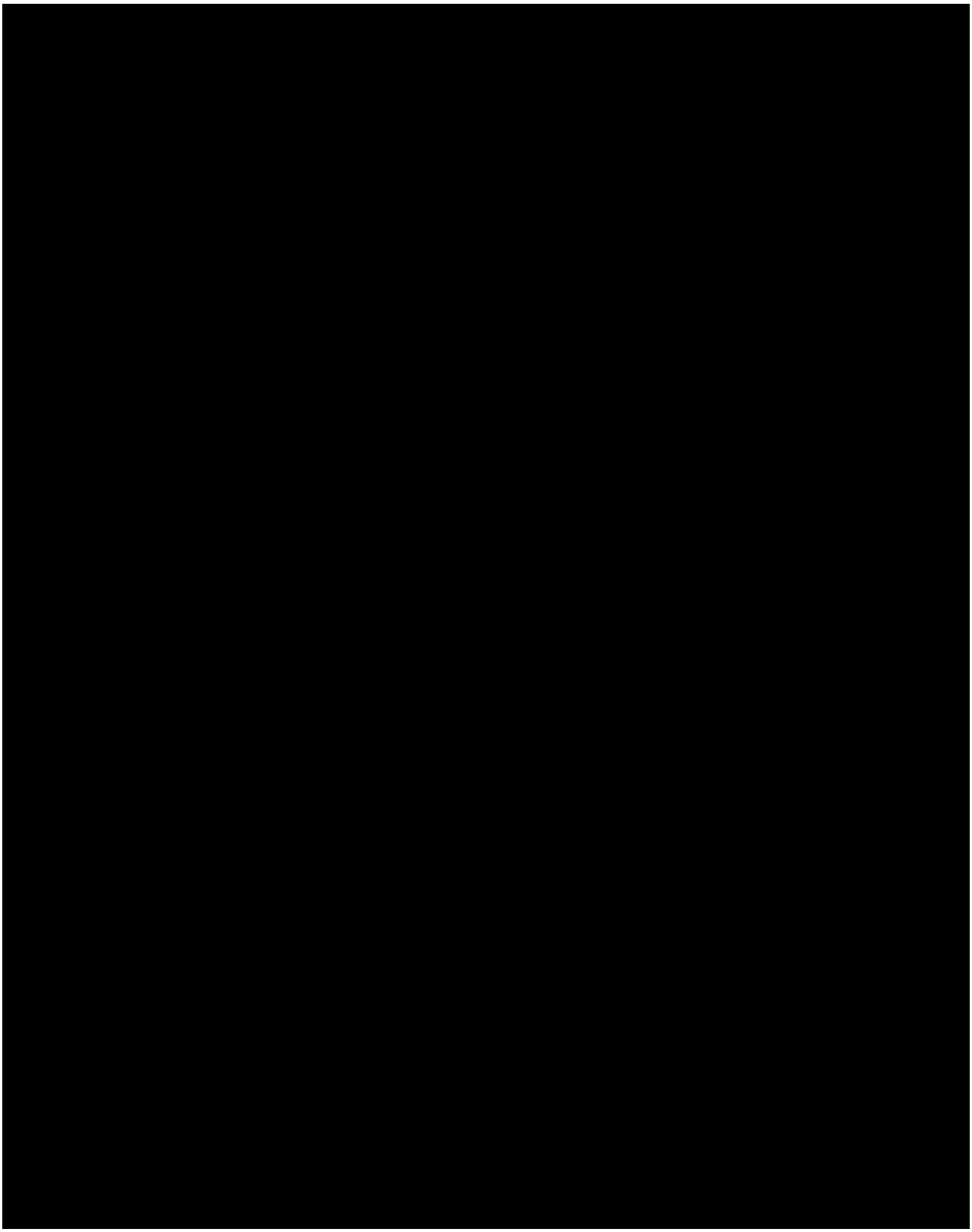


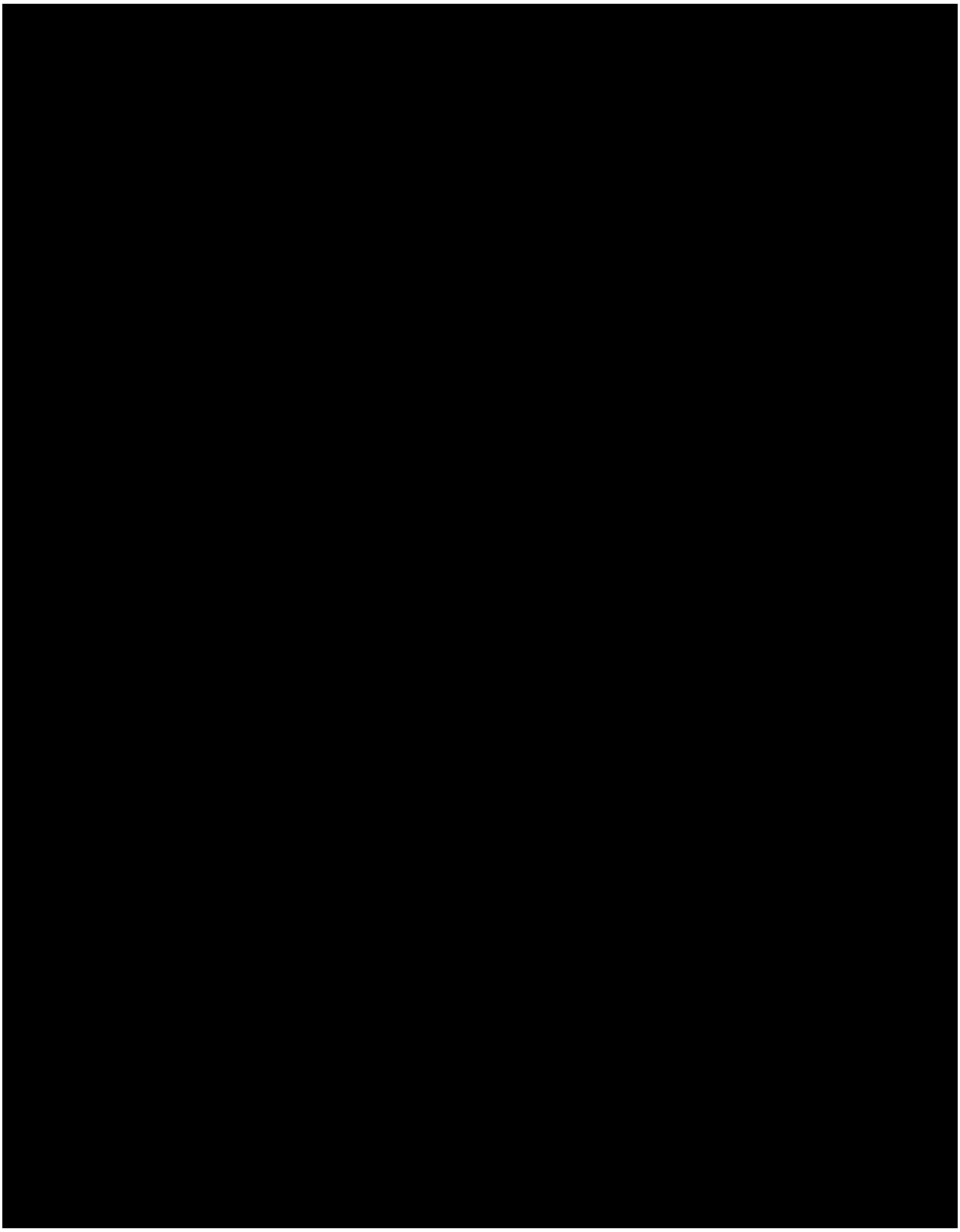


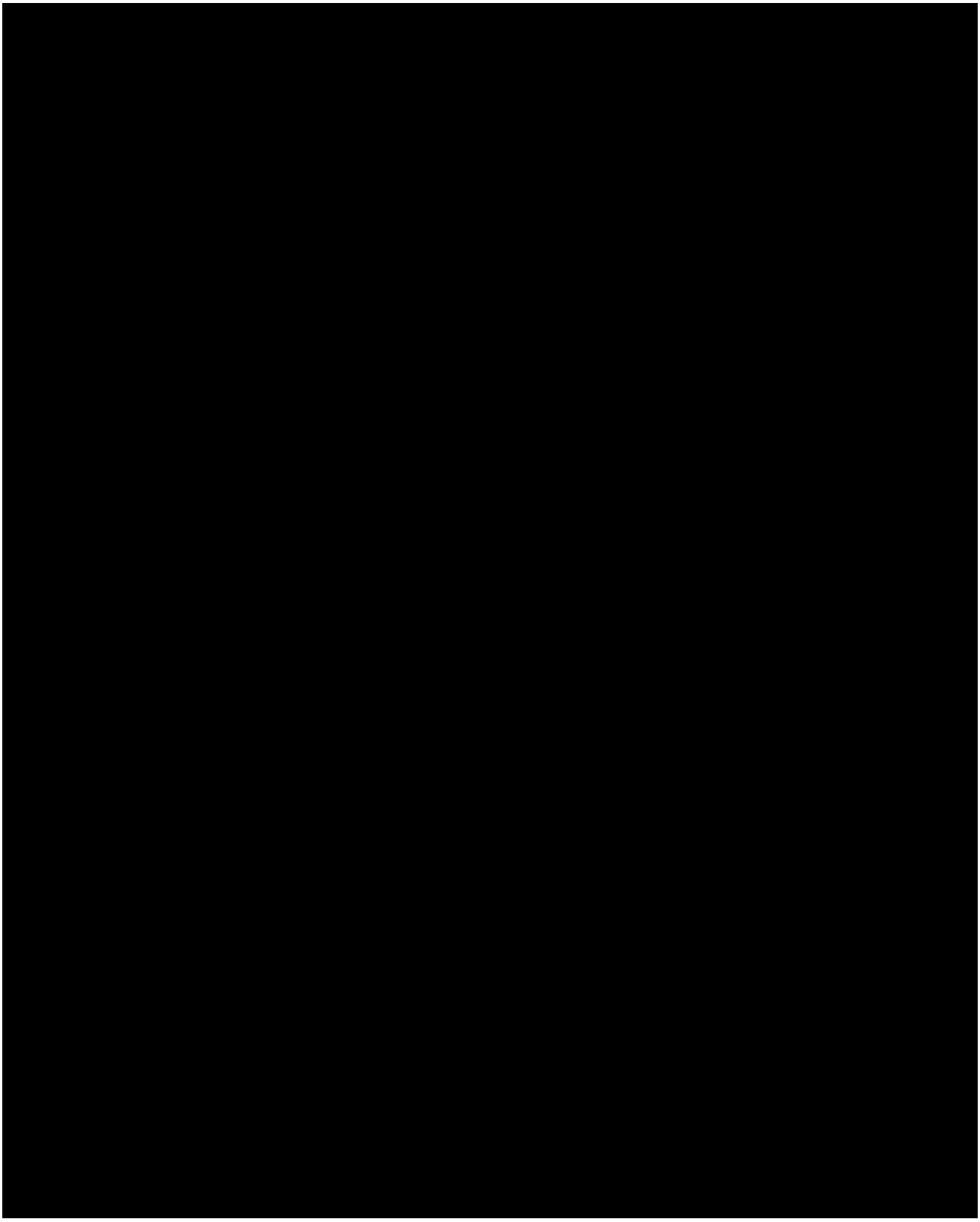


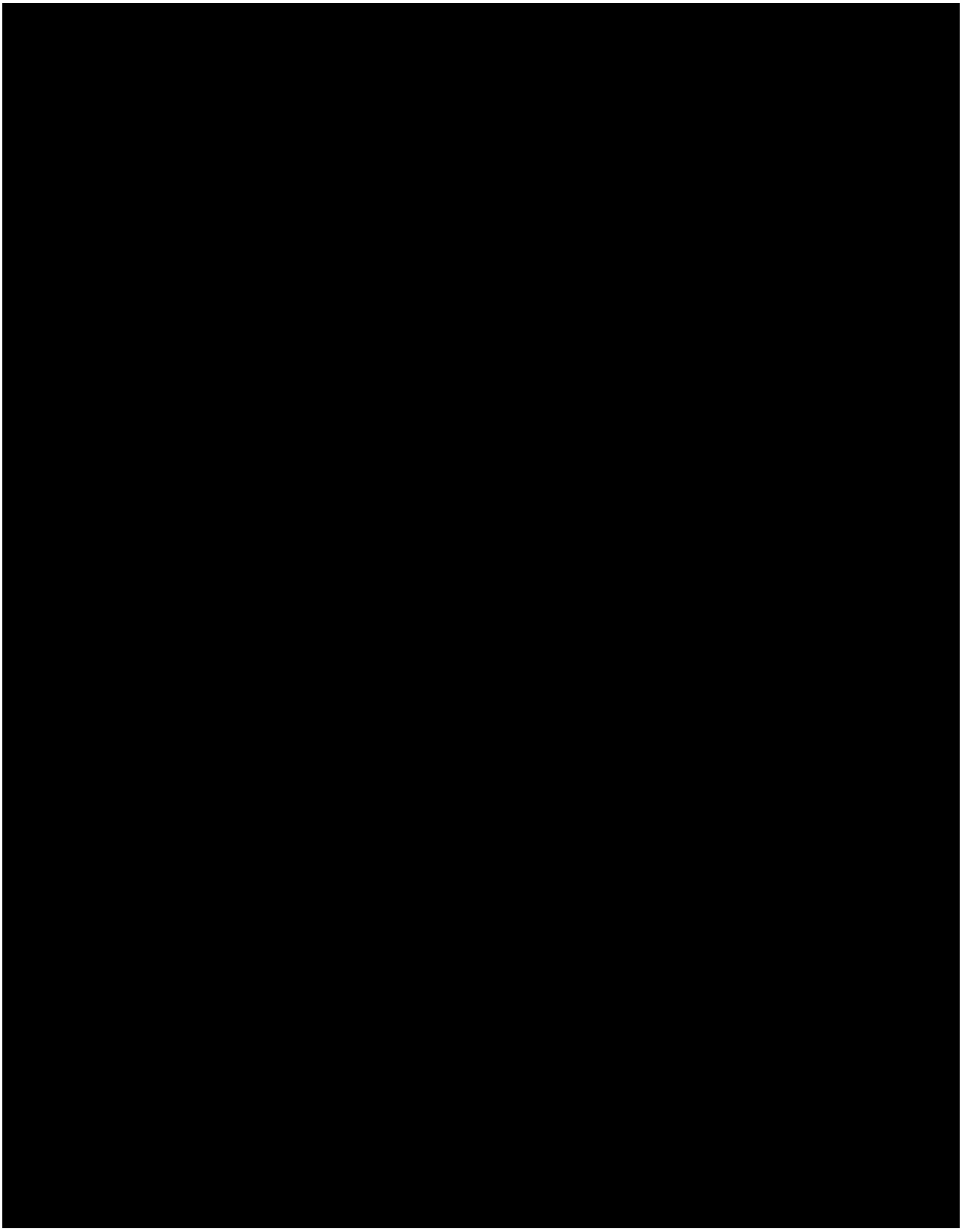


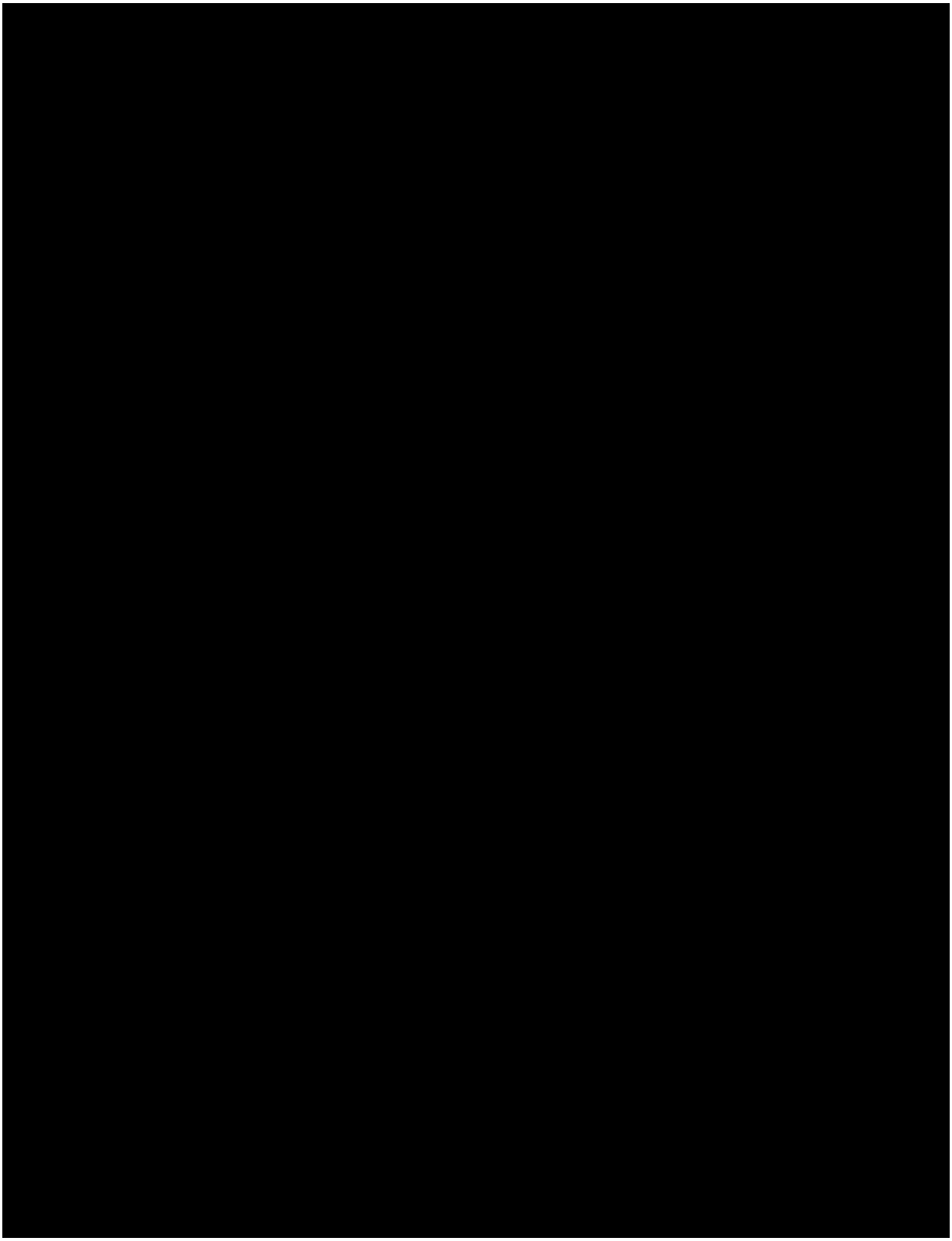


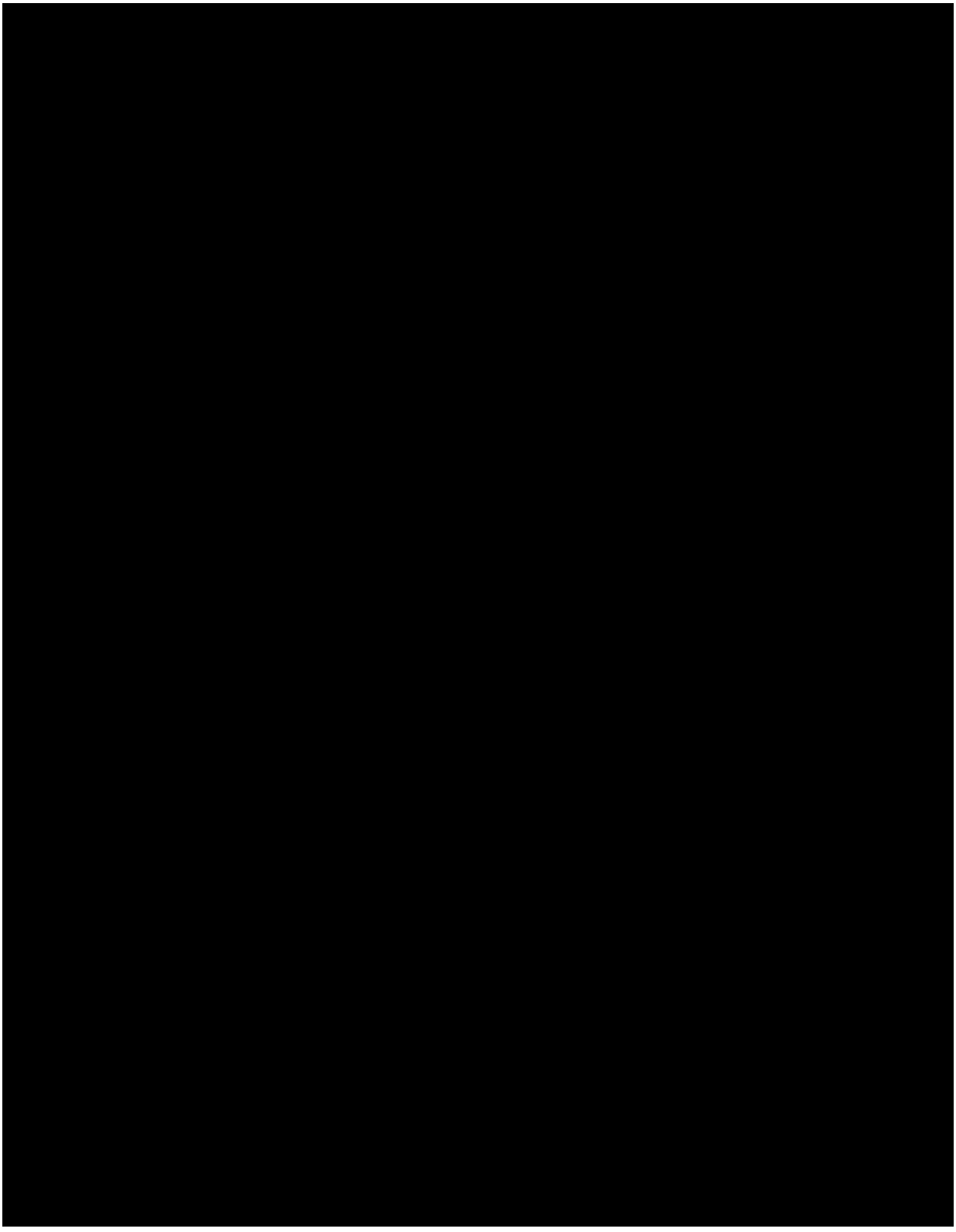


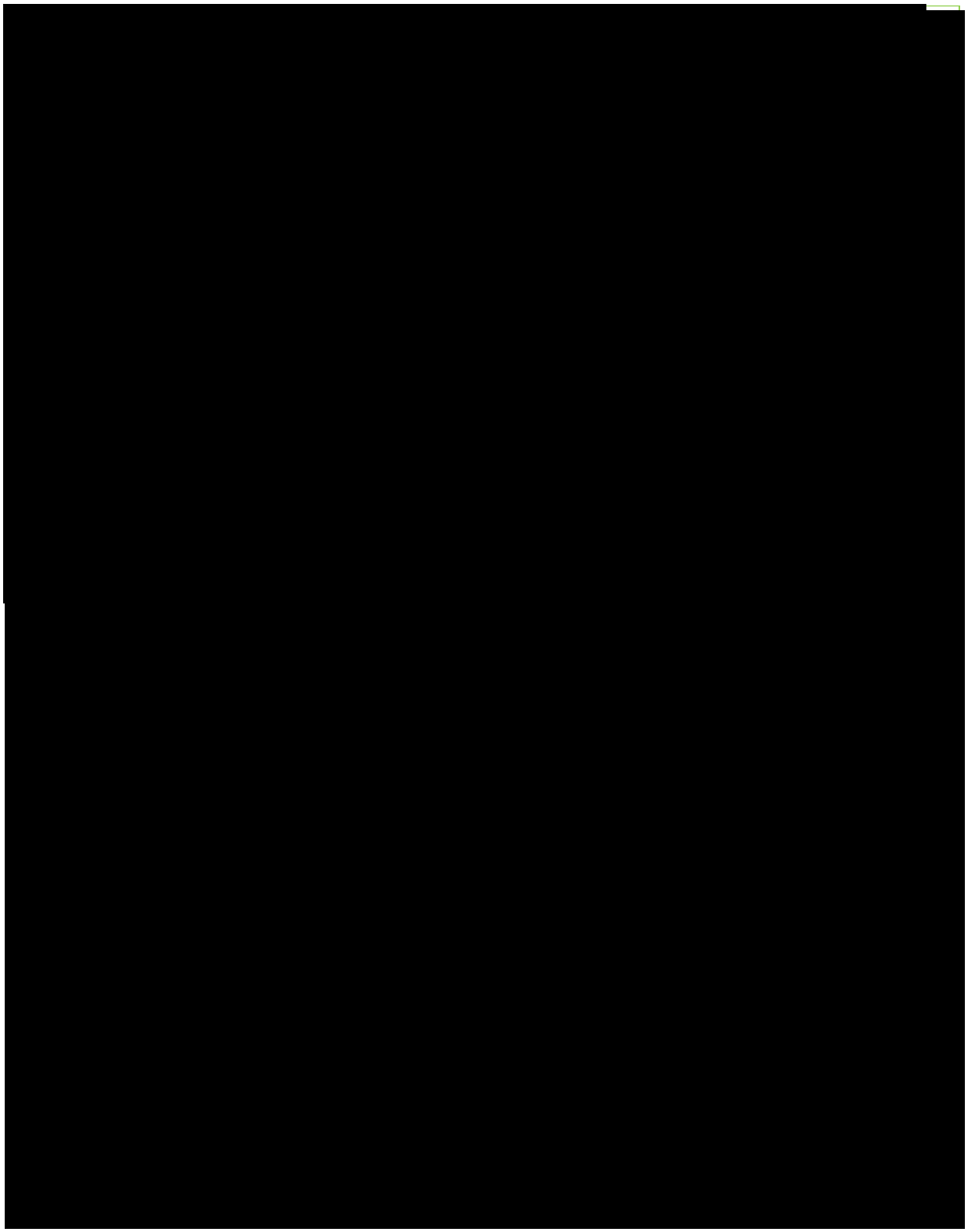


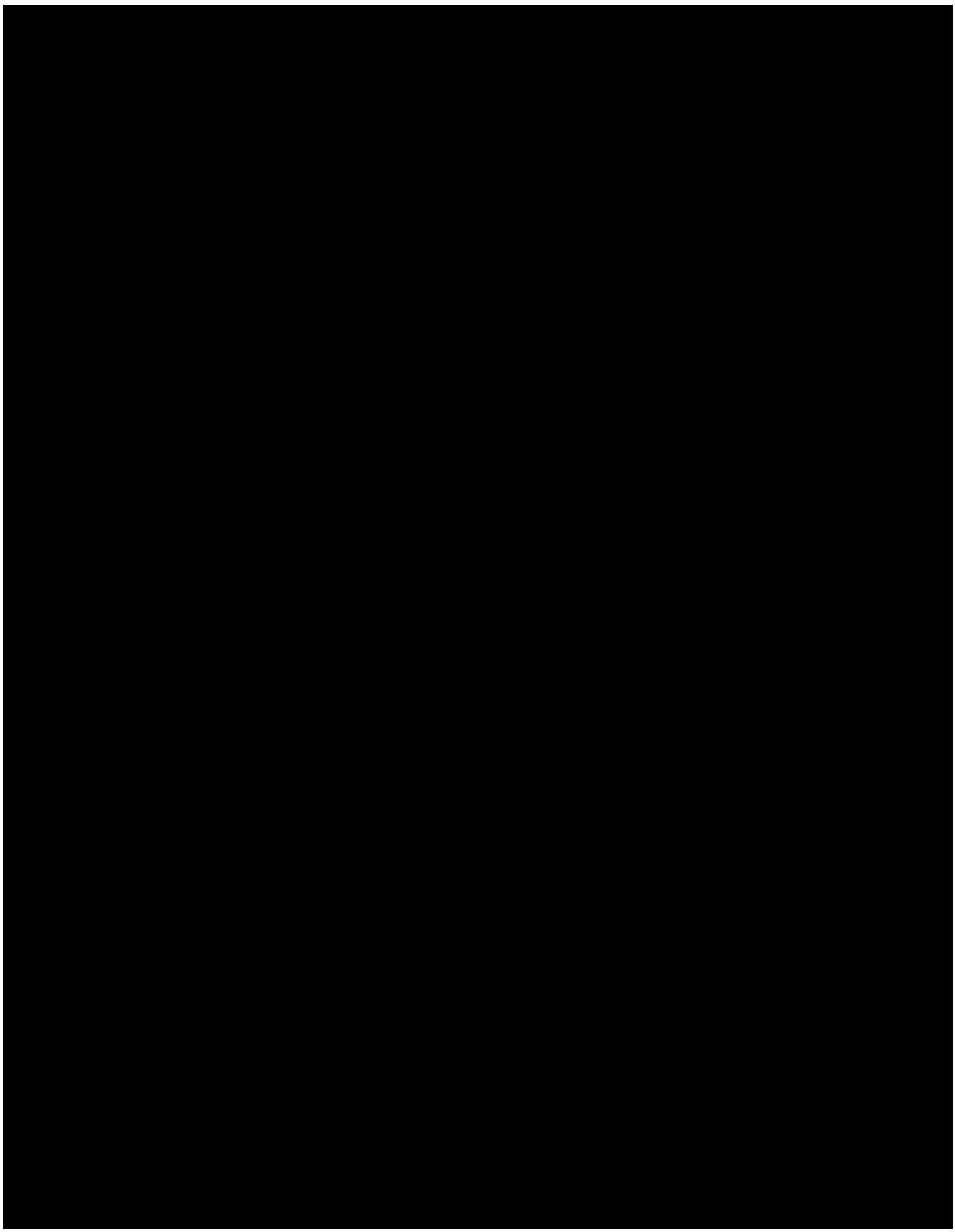


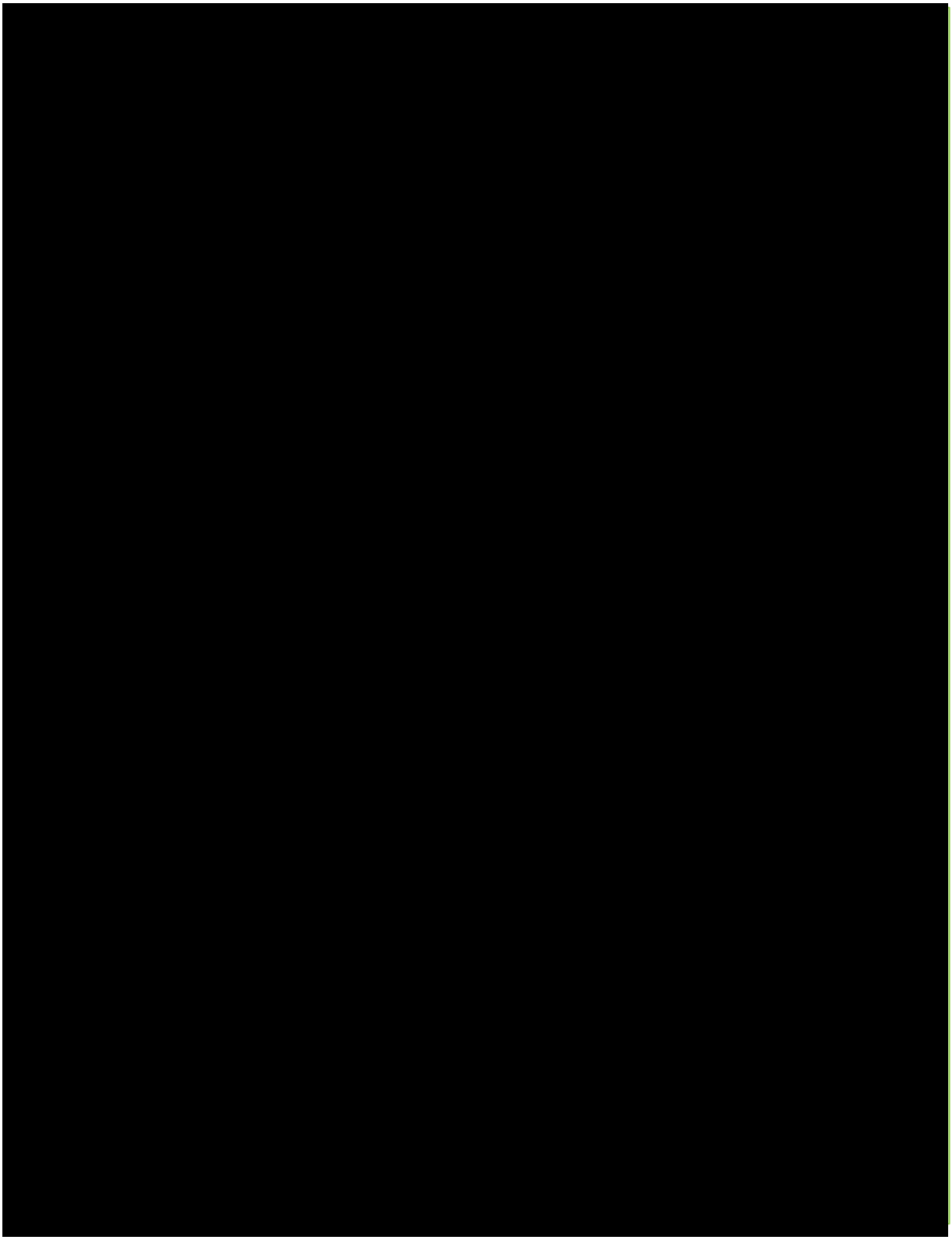


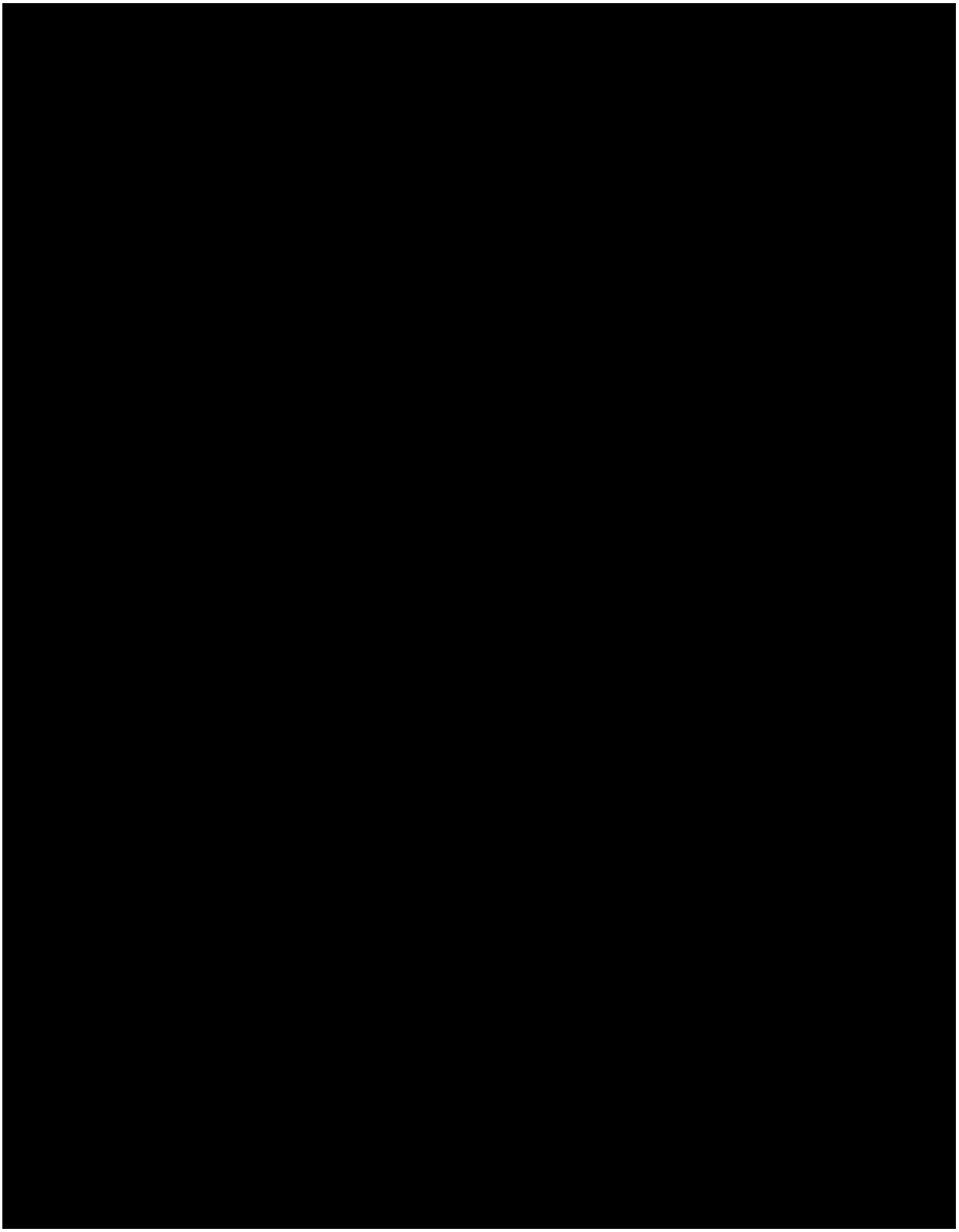












Operators in OECD nations

155. The definition of GEIP in the Interpretation Memorandum confines the meaning of "significant proportion of operators" in the NEC definition (which is now the NER definition) to mean a "significant portion of operators in OECD nations".

156. There are 35 OECD member countries which include:

(a) Australia;

(b) Canada;

(c) Chile;

(d) Denmark;

(e) Finland;

(f) France;

(g) Germany;

(h) Japan;

(i) Korea;

(j) Netherlands;

(k) Norway;

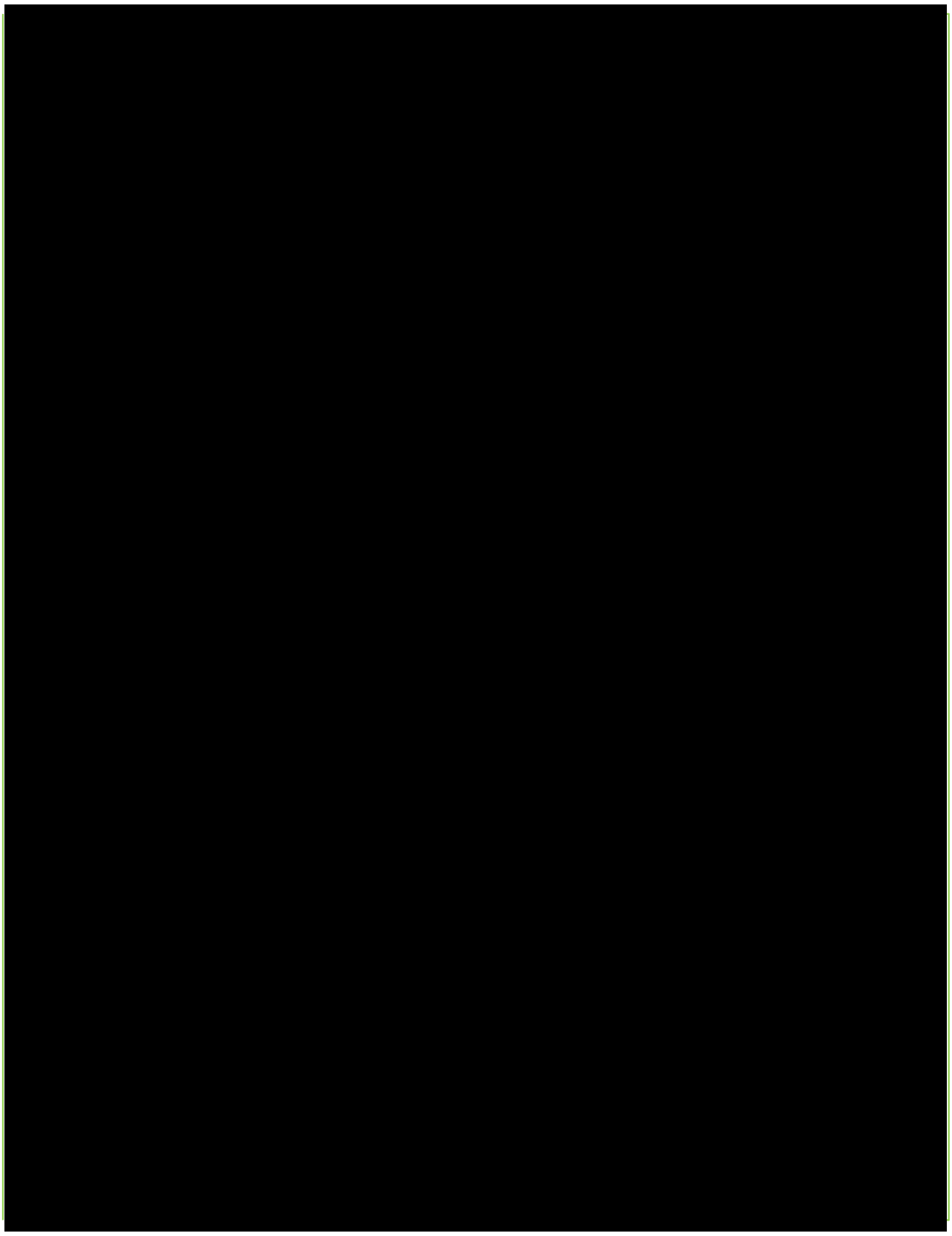
(l) Poland;

(m) Sweden;

(n) United Kingdom; and

(o) United States.

[redacted]



Attachment 2 - Documents

	Title	Date	Identification number	Rev
A. Expert Code				
1.	Expert Witness Code of Conduct (Supreme Court of Tasmania)	5 January 2016	Practice Direction 1 of 2016	
B. Background				
[redacted]				
C. Pirelli/Prysmian documents				
[redacted]				

	Title	Date	Identification number	Rev
[redacted]				

	Title	Date	Identification number	Rev
[redacted]				
D. Siemens documents				
[redacted]				

	Title	Date	Identification number	Rev
[redacted]				
E. Load data				
[redacted]				
F. Fault finding reports				
[redacted]				

	Title	Date	Identification number	Rev
[redacted]				
G. Photographs				
[redacted]				
H. CCI examination				
[redacted]				
56.	CCI Report, Basslink KP199.256 Failure Examination 27th to 29th April 2016	27 May 2016	ER 795	
[redacted]				
58.	CCI Report, Basslink KP199.256 Failure Examination 7th to 9th June 2016 at CCI	27 June 2016	ER 808	
I. Other documents				
[redacted]				

	Title	Date	Identification number	Rev
[redacted]				

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	Title	Date	Identification number	Rev
[redacted]				

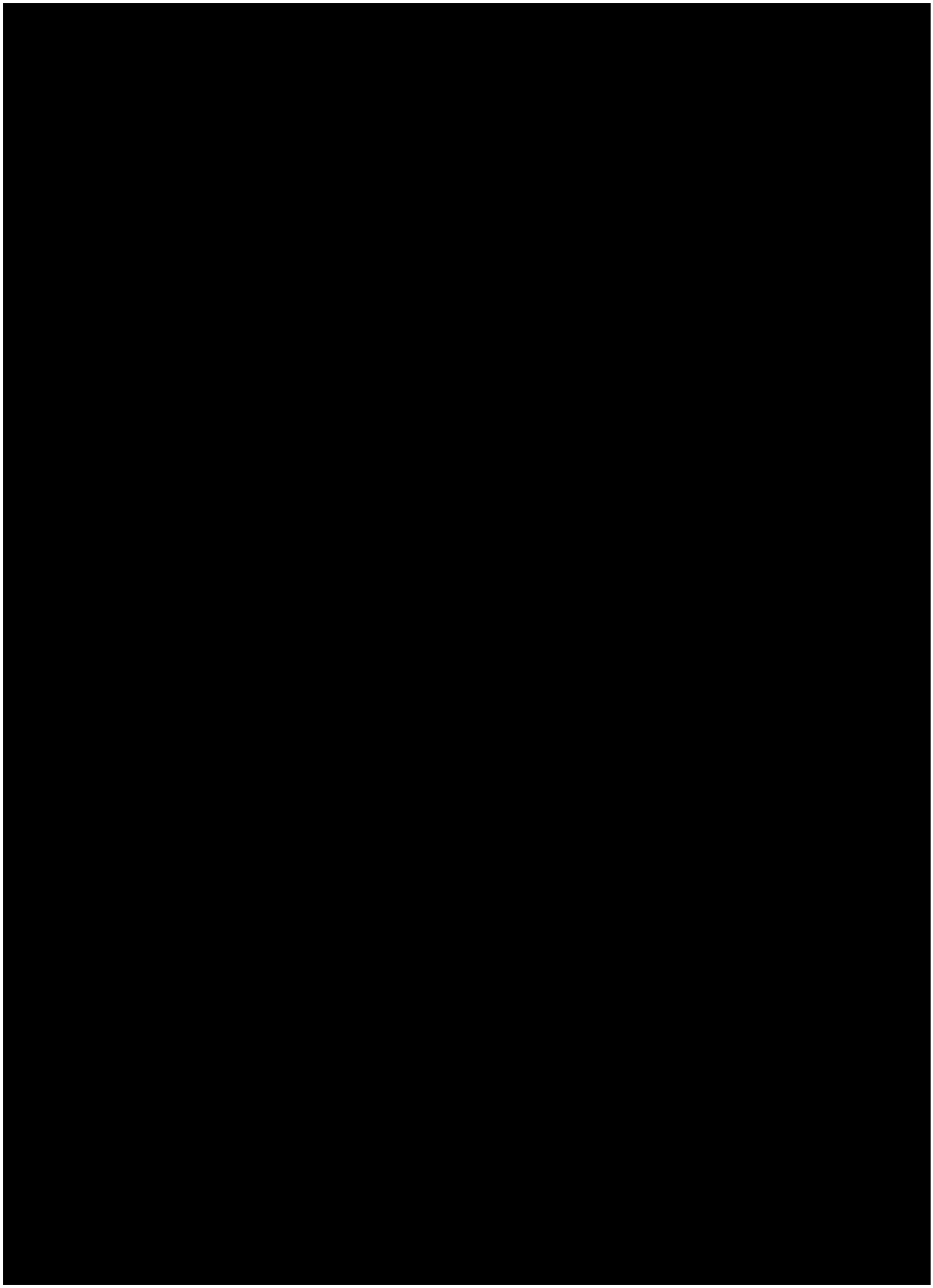
	Title	Date	Identification number	Rev
[redacted]				
J. Correspondence				
[redacted]				
K. CCI and Materials Technology Reports				
67.	CCI Report, Basslink KP199.256 Failure Investigation Findings	2 December 2016	ER 833	
68.	Materials Technology Report, Report on Analysis of Samples From 400 kV Basslink Cable Fault	28 November 2016	G9748	
69.	Materials Technology Report, Report on Thermal Analysis (DSC) of Samples From 400KV Basslink Cable Fault	29 November 2016	G11863	
[redacted]				

	Title	Date	Identification number	Rev

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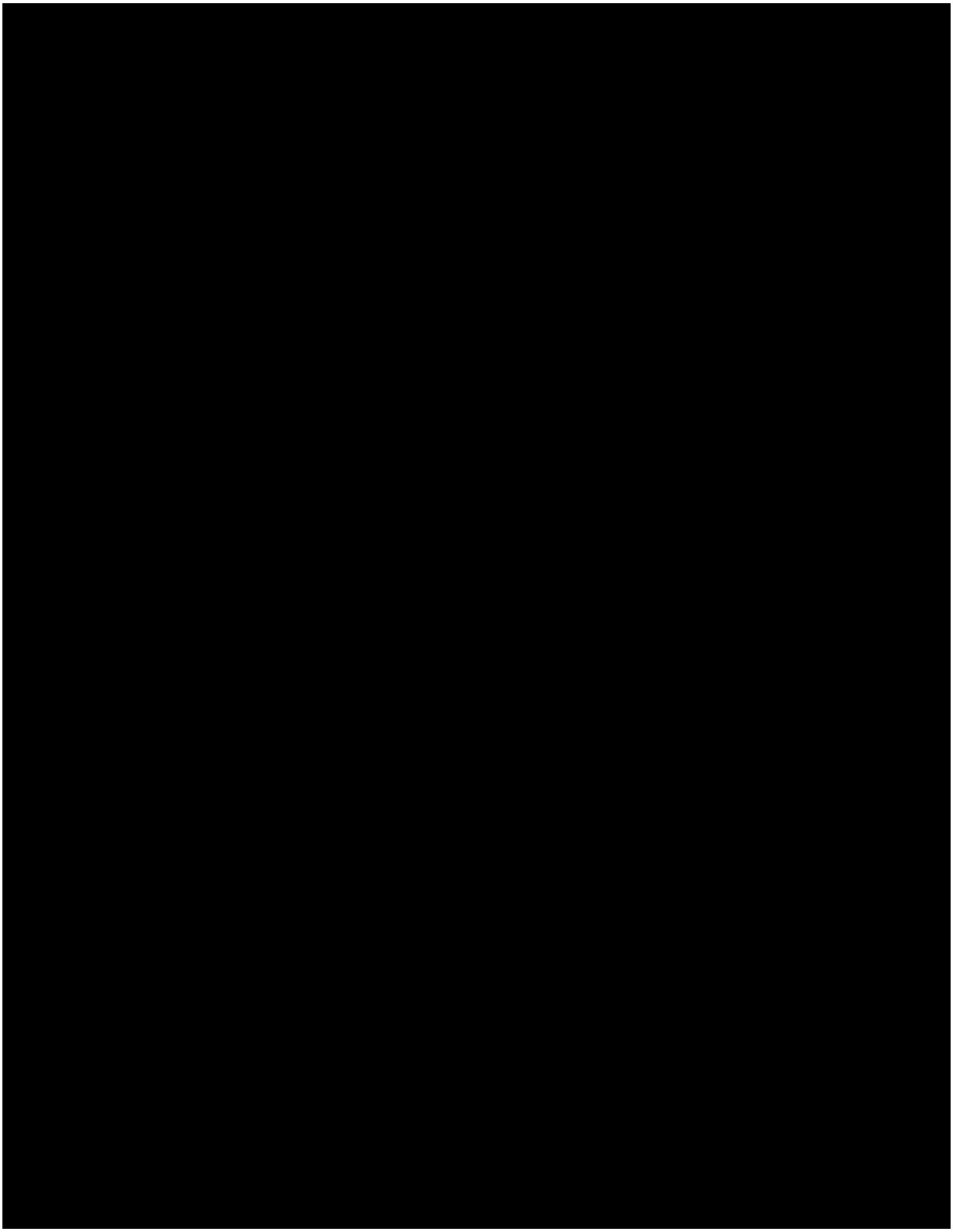
APPENDIX N

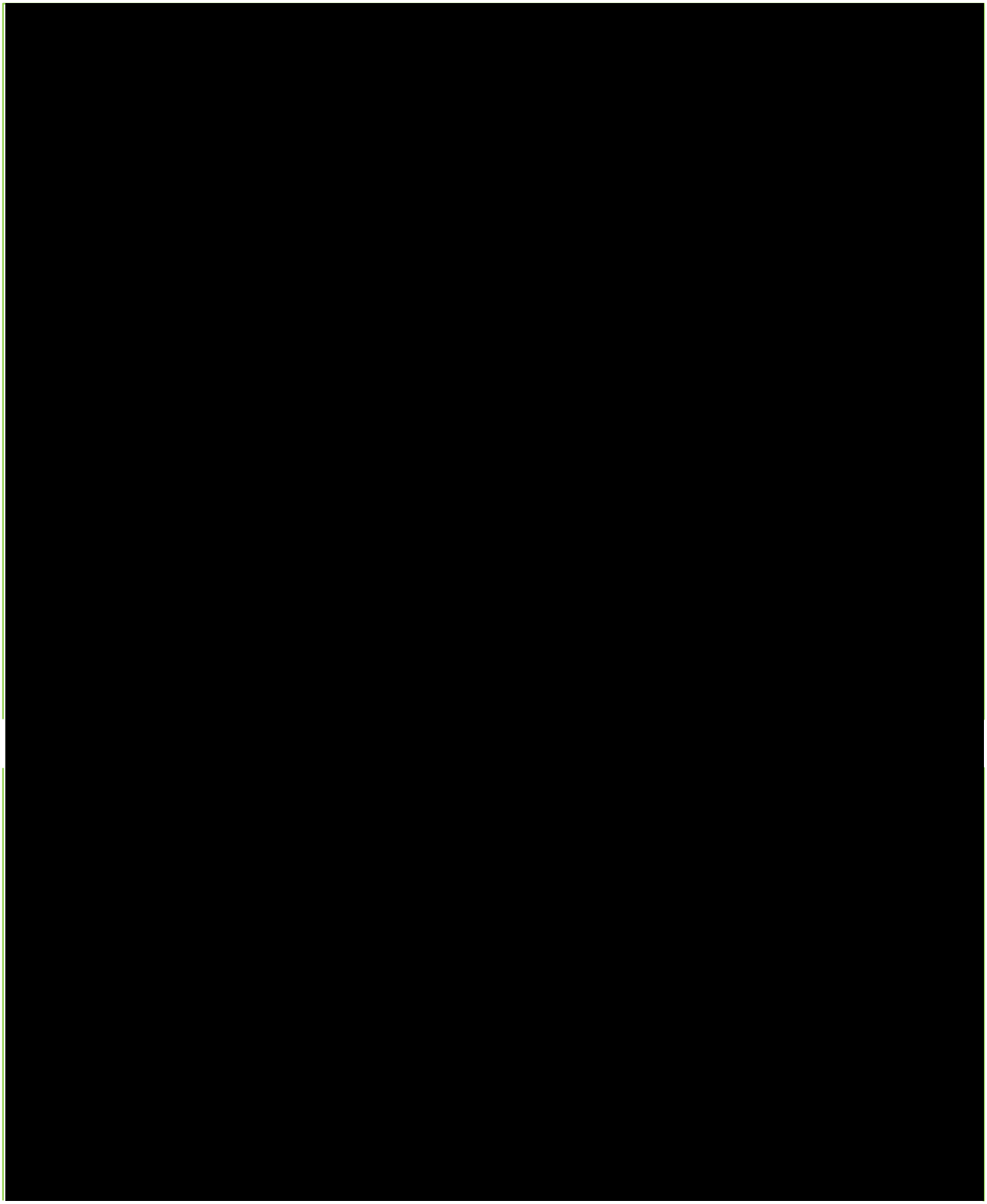
Polarity reversal question letter BPL to HT 2003-05-13 [TAB 58.2.1]



APPENDIX O

Polarity reversal BPLHT meeting report dated 2003-11-03 [TAB 58.2.2]





APPENDIX P
Void formation according to Runde, 2014

According to [/40/, Runde, 2014]

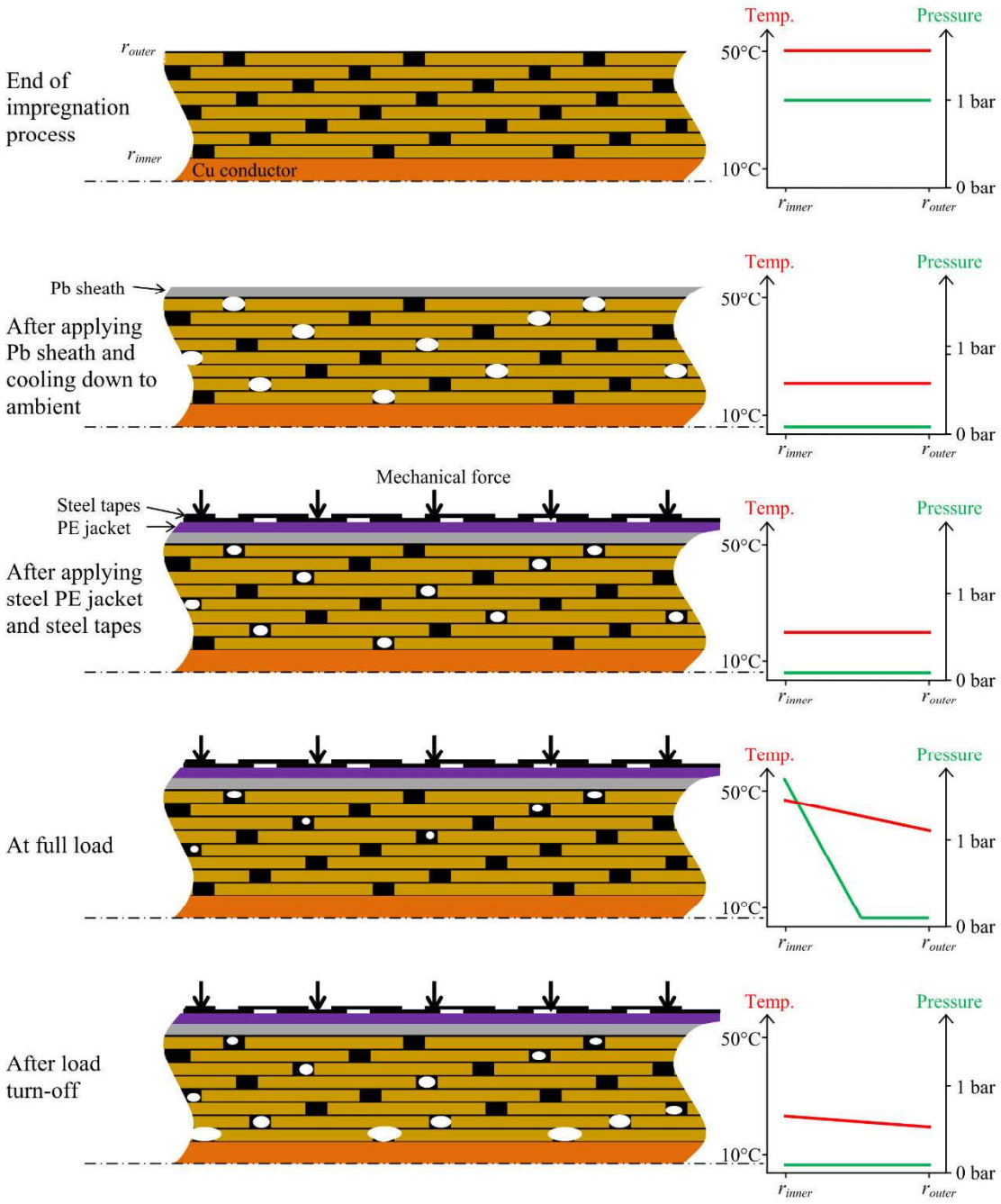


Figure. 2. Temperature and pressure profiles and the resulting cavitation in the insulation of a mass impregnated cable under different conditions (schematically). The white areas are cavities that are formed as a result of thermal contraction of the mass. Their size, number and location vary in the radial direction during the different load conditions (see text).

APPENDIX Q
Voltage polarity reversals - a literature review

The following is summarized from a literature investigation I have carried out on the relevance and impact of voltage polarity reversals for HVDC MIND power cables.

What can be seen from literature is that voltage polarity reversals in power cables lead to an extra high electrical stress inside the insulation right after the moment of such a reversal [/3/, Hall, 1956], [/4/, Occhini, 1967], [/5/, Bahder, 1969], [/24/, Morshuis, 1997], [/25/, Jeroense, 1997], [/26/, Jeroense, 1998], [/40/, Runde, 2014]. Right after a quick (within seconds) voltage polarity reversal, such an electric field can become close to double in the insulation paper layers close to the conductor (see for instance various of the above mentioned references, in particular also [/40/, Runde, 2014]). As a result, a breakdown tends to happen right after a voltage polarity reversal in case an insulation material is operated close to its breakdown voltage level [/3/, Hall, 1956], [/27/, Isayama, 1999]. This is also the experience of the author for at least one of the HVDC MIND cable failures investigated. In [/5/, Bahder, 1969] it is even suggested that due to the nonhomogeneous nature of the insulation the effective stresses appearing immediately after reversal will be higher than what is based on modelling. And thus [/5/, Bahder, 1969] concluded that this assumes that the breakdown voltage depends on the maximum change in stress and hence is limited to short times after voltage polarity reversal. In [/7/, Bahder, 1978] it is stated that voltage polarity reversal has been taken as a design issue for power cables indeed.

If no breakdown happens, in the minutes and hours after the voltage polarity reversal, the electrical (space) charges inside the insulation re-settle (polarization current) and reduce the electrical stress again to its steady state level. How fast this happens is depending on the actual properties of the insulation material (its conductivity for instance), but also on the actual temperature of the insulation material [/4/, Occhini, 1967]. In [/16/, Hauge, 1988 – discussion Smedsfelt] it is proposed to work under voltage polarity reversal conditions with reduced voltages for 10 minutes to release the insulation material (to which the author of [/16/, Hauge, 1988] replies that an alternative would be to keep the insulation material under pressure with certain means, which can be seen maybe as the reinforcement tapes as used in the Basslink cable). Also [/40/, Runde, 2014] mentions the discharging time, where is said: "*The time constant for conduction is of the order of minutes and hours ….*". Reflecting the importance of the voltage polarity reversal, [/34/, Bex, 2006], for the Basslink cable extra measures were taken to handle the quick voltage polarity reversal. This was said: "*As the Australian electricity market is based upon 5-minute dispatch intervals market outcomes can require Basslink to reverse power flows within 5 minutes. To achieve this a short 2-minute cable deionisation time between changing voltage polarity has been achieved. As a result, the standard CIGRE cable load cycle test was altered to reflect expected power flows under market conditions*". Here the deionization time has to be read as discharging time. In [/35/, Skog, 2006] informs about time to perform the voltage polarity reversal ranging from 140 minutes to 14 minutes. In [/31/, Giorgi, 2002] informs about time to perform the voltage polarity reversal being 10 minutes (with 10 faster (immediate) voltage polarity reversals per year as long as the time in between these reversals is at least 10 hours).

I made an artificial drawing, see Figure 27, of what happens with the electrical stress close to the conductor in case of a voltage polarity reversal. Values are based on information given by [/4/, Occhini, 1967]. In Figure 27, the voltage steps E_{geo} and E_{st} are on scale. Also the time 0, 2 and 5 minutes are on scale. But the time constants for deionisation are chosen to illustrate the impact. What these are in real is much depending on the actual insulation properties (among which the conductivity (as a function of the temperature). What happens if the voltage polarity reversal is done at once (-U to +U in a second for instance) is illustrated by the line A, B, C, H. In case the voltage polarity reversal is done in two steps, first from -U to 0 kV and 2 minutes later from 0 kV to +U is illustrated with the line A, B, D, E, H. And in case the voltage polarity reversal is done in two steps, first from -U to 0 kV and 5 minutes later from 0 kV to +U is illustrated with the line A, B, F, G, H. It is shown that waiting longer (applying a longer deionisation time) before the second voltage step is done helps to reduce the electric stress.

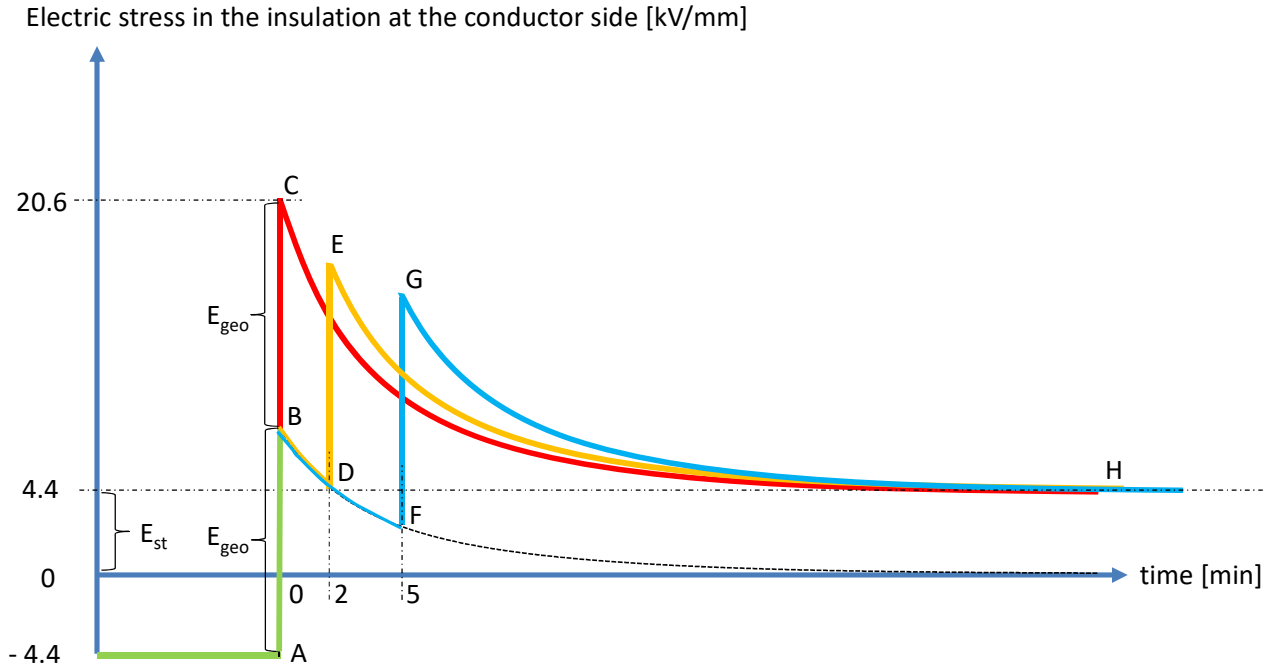


Figure 27 **Artificial drawing of the stress reduction in case a certain deionisation time is taken into account.**

Whether an insulation material is sensitive for voltage polarity reversals is depending on its nature. This is shown for instance in [/3/, Hall, 1956]. Oil-filled power cables with a paper insulation impregnated with a low viscous oil and put under a quite high oil pressure are hardly sensitive for voltage polarity reversals, while mass-impregnated non draining (MIND) power cables clearly show to be depending on this effect. Even more sensitive for voltage polarity reversals are XLPE insulated power cables, reason why this type of insulation material can't be used without specific alterations and only in the recent years such cables have become available. In [/25/, Jeroense, 1997], [/26/, Jeroense, 1998] it is stated that

the space charge distributions in MIND cables are very reproducible. In [/27/, Isayama, 1999] concluded that the breakdown voltage in samples is getting lower as a consequence of the number of voltage polarity reversals, but his reversals are done in 0.5 s or 1 s and that is very quick compared to normal MIND cable operation. In [/38/, Lennon, 2009] the following remark is made: "*Space charge is a design constraint unique to DC technology*"**.** In [TAB 61], Lawson mentions this "*The cable designer has to carry out the necessary calculations to ensure that the electric field does not exceed 30 kV/mm at all points across the insulation wall and under all operating conditions*". This remark covers also the voltage polarity reversal moment. But it is not clear from where Lawson did get this electric stress limitation.

Back to the MIND cables, like the Basslink cable. Because of the fact that in general MIND cables are sensitive for voltage polarity reversals, Cigré ([/6/, Cigré, 1974], [/15/, Cigré, 1980]) has set up test requirements for this type of power cable in which voltage polarity reversals play a role (with 10 heat cycles at 1.5 Uo with each 4 hours a voltage polarity reversal). It is recommended by Cigré to do the voltage polarity reversal in 2 minutes, although 10 minutes is allowed as a maximum, showing that in this range of minutes the voltage polarity reversal is considered to have an impact. In [/28/, Cigré, 2000] the heat cycle requirement was reduced to 1.4 Uo, probably because of the higher system voltages. Moreover, in [/28/, Cigré, 2000], it is recommended to perform the voltage polarity reversal in 2 minutes, without mentioning that 10 minutes is allowed as a maximum as well, as happened in earlier Cigré recommendations [/6/, Cigré, 1974] and [/15/, Cigré, 1980]. This shows that voltage polarity reversals not only have an impact as said above, but that it is relevant as well to consider the reversal phenomena in a lower minute range. In [/32/, Cigré, 2005] the test conditions are even more clearly described because of the voltage polarity reversal impact and to arrange fair testing for different conditions (cold, warm). In [/31/, Giorgi, 2002] and [/36/, Rendina, 2008] for MIND HVDC deep sea cables, extra voltage polarity reversal tests have been carried out, showing the attention for this item in case of quality issues.

Literature doesn't report on incidents with MIND cables that failed due to voltage polarity reversals [/20/, Cigré, 1994]. [/18/, Hjalmarsson, 1992] informed that the Gotland cable (taken out of service after 32 years of operation) never failed because of electrical ageing, only because of external impacts. Samples of the service aged cable were tested and compared with spare cable and no considerable ageing was found (however, it was operated at 'normal' electric stresses for 16 years only). Another publication [/40/, Runde, 2014] reports that MIND cables normally fail because of external damage and "*The reliability of the cable itself is in general found to be very good, indicating that the technology is robust and that the type testing has been sufficiently demanding*". Also [/41/, Mazzantim, 2015] reports that "*Mass Impregnated Non-Draining (MIND) cables are known to be able to withstand the voltage polarity reversal without particular problems*", but one has to realize that this is said in 2015 and thus in the light of developments of XLPE cable, known to be sensitive to voltage polarity reversals. But [/39/, Skog, 2010] mentioned that the NorNed MIND HVDC cable (the longest in the world) experienced three failures of which the cause was unknown and certainly not related to an external damage.

A 2015 overview of HVDC cables in the world is provided by [/42/, Ardelean, 2015]. A more specific overview of MIND cables, installed until 1996 is given in [/23/, Khalil, 1997] and a further overview including operating parameters is given in [/40/, Runde, 2014]. But not much is known about the applied or allowed number of voltage polarity reversals per day or per year for such cable being in operation. Only [/18/, Hjalmarsson, 1992] informed for the Gotland cable that there has been two voltage polarity reversals per day during three years at 'normal' electric stress (after the cable started operating at 150 kV, before that it was 100 kV). As a general logic situation one can consider two voltage polarity reversals per day, because of the fact that in case of an interconnector often on one side there is hydro power and on the other side thermal power, where hydro power is used as the main power source and only during the night at low demand the thermal power is used to feed back. And [/40/, Runde, 2014] reports concerning this issue "*Changing the direction of the power flow by reversing polarity causes temporary dielectric stresses of a considerable higher magnitude …….. It is however, quite common to impose one or more operational restrictions or special procedures during power reversal that reduce the dielectric stress. For example, setting a maximum power ramping rate, temporarily reducing the voltage level somewhat, or specifying a few minutes waiting time at zero power, will help. Thus, the large values given in Table I for field under polarity reversal are not necessary experienced under real operation of the cable, nor are the values directly comparable. But the numbers clearly illustrate that transient conditions such as polarity reversals may imply dielectric stresses greatly exceeding those seen under start-up or steady state operation*".

Based on [/16/, Hauge, 1988], where parts of the 10 years old Skagerak HVDC MIND cable have been subjected to laboratory tests, the expected future field strength of cables could become 35 kV/mm, but the author added that under more onerous conditions such as frequent load variations, voltage polarity reversals, (..etc..) , the design stress should be somewhat lower. However, a design stress of some 30 kV/mm (..etc..) would obviously be safe even under such circumstances. It shows another publication taking into account the voltage polarity reversals.

More technical information about space charges and conduction mechanisms (conduction is highly related background of the increased electric field strengths during voltage polarity reversals) in the insulation material of MIND cables is given in among others [/21/, Jeroense, 1995], [/24/, Morshuis, 1997], [/25/, Jeroense, 1997], [/26/, Jeroense, 1998], [/33/, Morshuis, 2005], [/37/, Tang, 2009]. In [/38/, Lennon, 2009] there is also more information on degradation mechanisms of MIND cables, although with a focus on a more fundamental approach and thermal issues. An interesting remark is that in MIND cables "*At elevated ambient temperatures or electrical stress levels the leakage current increases throughout the insulation due to a rise in the conductivity. In turn, the leakage current heats the insulation further and the conductivity again rises due to its temperature dependency. This behavior continues until a balance is reached or until a thermal breakdown occurs in the insulation*". Also [/40/, Runde, 2014] says more about degradation, where a known one (happening in type testing) is the cooling down stage: "*….. the ones occurring during cooling typically have breakdown channels that follow interfaces between the paper layers and may become 1 - 2 m long in the axial direction. Such breakdowns, hereafter referred to as "load cycling breakdowns", are unique to MIND cables*". This was

already said by [/19/, Gazzana, 1992], but this author added that also more radial breakdown paths can happen under isothermal conditions. Moreover, [/29/, Evenset, 2000], confirming that MIND cable is sensitive for the cooling down stage because of cavity formation, showed that a radial breakdown path is common in case the paper pressure is high, else the breakdown path is much longer, around 1 m indeed.

In [/17/, Embaie, 1988], [/22/, Nyman, 1996] and [/30/, Bosisio, 2002] voltage polarity reversals are not discussed since here the focus is on degradation and failures related to cavity formation during cooling down the cable. As a result, for operating during a cooling down regime, the voltage is studied (for the Fenno-Skan cable in [/17/, Embaie, 1988]) or already performed (for the Baltic cable in [/22/, Nyman, 1996]) to be made lower. But the Baltic cable so far was not operated beyond 50 % of its capacity. In [/19/, Gazzana, 1992] the cooling down sensitivity of a MIND cable is mentioned as well and studied in detail. But in the last line of the conclusion the following is said: "*A contribution to this mechanism is also due to the presence of very high free electrostatic charges trapped at the surface of a suddenly arising void which can produce high energy discharge capability*".

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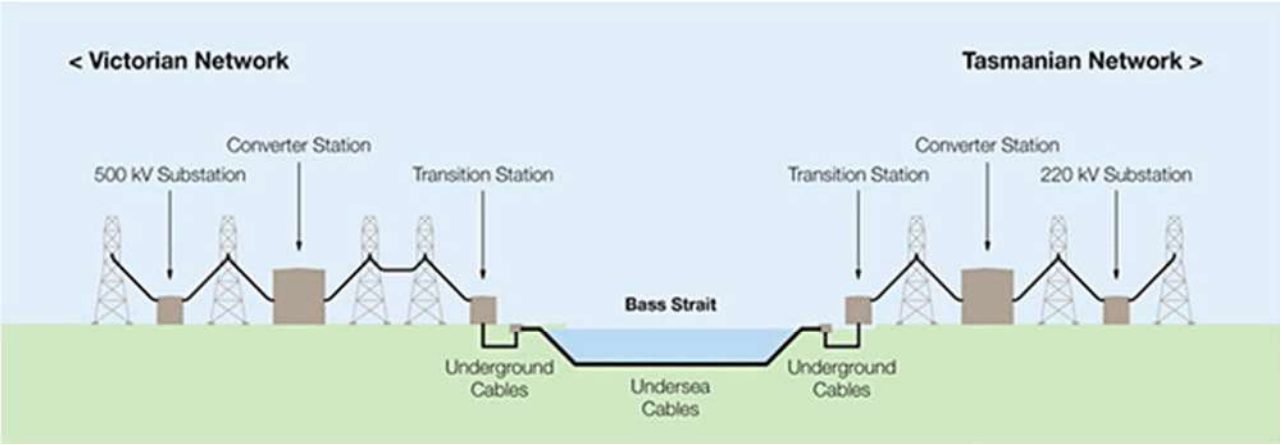
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EXPERT REPORT FRED STEENNIS

Basslink outage 2015 – Reply to CCI report ER1112

Clayton Utz and Ashurst Australia

Report no.: 20-2598
Date: 2020-07-13



Project name:	Expert report Fred Steennis	DNV GL - Energy
Report title:	Basslink outage 2015 – Reply to CCI report ER1112	DNV GL Netherlands B.V. Energy Advisory
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Date of issue:	2020-07-13	
Project No.:	10156982	
Organisation unit:	AM	
Report No.:	20-2598	

Objective:

To investigate the root cause of the failure that happened in the Basslink cable in Australia, between Victoria and Tasmania in December 2015 – Review CCI report ER1112

Prepared by:	Verified by:	Approved by:
E.F. Steennis Sr. Principal Consultant Power cables	B. Kruizinga Consultant	K.-J. van Oeveren Head of Department Asset Management

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Basslink, HVDC, failure

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1 INTRODUCTION

1.1 General

In December 2015, the Basslink cable failed after ten years of service operation. Related to this failure, I performed a root cause analysis[1].

This introductory section explains who my customer is, the scope of this report and the background of some of the reports issued for the Basslink failure case. Also, it describes the structure of the report, how references are used and gives definitions for common terms and abbreviations.

1.2 The customer

My customers Clayton Utz and Ashurst Australia (Ashurst) act for Hydro-Electric Corporation (Hydro Tasmania) and the State of Tasmania (the State) in relation to matters arising from the outage of Basslink, the High Voltage Direct Current (HVDC) submarine cable across Bass Strait, which occurred on 20 December 2015 (Basslink Outage).

1.3 Scope of this report

This expert report is provided to Clayton Utz, Ashurst, Hydro Tasmania and the State in response to their request (see 'Letter of instructions' dated 3 July 2020, Appendix A) to (and I quote here):

- *"Set out any matters raised in the reports of* [redacted] *that cause you to alter your opinion as set out in your report dated 18 June 2020 in relation to matters that might inform BPL's claim that the failure of the Basslink HVDC cable in December 2015 was a Force Majeure Event (as that term is defined in the Basslink Services Agreement)*
- *Responding to any matters raised in the reports of* [redacted] *and Mr. Balog that you consider relevant to the issue as to whether the failure was a Force Majeure Event, including any considerations relevant to the views expressed in those reports as to the manner of operation of the Basslink cable having regard to what a prudent and experienced and competent person would have done (measured by reference of the standard set out in the Basslink Services Agreement)*
- *For the purposes of preparing your report, please do not consider or take into account* [redacted] *report …… ".*

1.4 References used in this report

After I have submitted my 20-2078 report [9], I have been provided by Clayton Utz with a copy of the following reports:

[redacted]

[2] Expert report of [redacted] dated 19 June 2020 (ER 1112)

[3] SINTEF report number 2020:00318, dated 13 May 2020

[redacted]

[6] Expert report of Georg Balog, dated 19 June 2020

[redacted]

[1] [9].

Also, I make reference to two recent DNV GL reports:

[8] F. de Wild, Expert report - Thermal analysis of the Basslink interconnector, Doc no.: 19-3114 Rev. 1, dated 2020-01-31.

[9] E.F. Steennis, Expert report - Basslink outage 2015 – Root cause analysis of the failed HVDC power cable, Doc no.: 20-2078, dated 2020-06-18.

References in this report are described in footnotes. Sometimes, these footnotes can be found on preceding pages of this report, in case it is a re-used footnote. The above reports will be referenced as [1] to [9].

I may refer to other reports, papers, etc. as well:

- References which are related to material supplied by Clayton Utz are referred to as [TAB xx] or [TAB xx, year] in case the year is relevant.
  These references are listed in Appendix L (in attachment 2 of this Appendix) of [9], dated 2020-06-18
- The remaining references are coded as /xx/ and in case more information is added as [/xx/, author, year] or coded as [/xx/, year] if preceded by the author. If the same reference appears more than once in a paragraph or section, sometimes only the first time the full reference will be mentioned, followed by referring to the author only
  These references are listed in Section 7 ("References") of [9], dated 2020-06-18.
- Prysmian was formerly known as Pirelli. The change of the name happened during the Basslink project. I will only refer to Prysmian.

1.5 Definitions and abbreviations

For definitions and abbreviations, I refer to Section 1.7 of [9], dated 2020-06-18.

1.6 Structure of this report

1. The report will start in Section 2 with various formalities, among which are my qualifications.
2. Taking into account the scope of this report, I read the reports and data which are new to me [1], [2], [4], [5], [6] and [7].
3. Concerning the reports from [redacted] I might refer to certain temperatures calculated, but I leave it to [redacted] and Mr de Wild to discuss the results of their thermal models.
4. I take note of the conclusions expressed in the reports from [redacted] and Mr Balog [6] [redacted] and "*an analysis would have discovered the deficiencies of the installed Protection System*"[3]. [redacted]
5. [redacted] I found various points of agreement on facts, [redacted] In my report from June 2020 [9] I address most of the points. In Section 4 of this report, I will summarize these points in brief.

   However, there is one point which I will treat in detail in this report. It is a very important phenomenon in relation to the operation of the Basslink HVDC MIND cable, [redacted] called the 'length-effect' of a cable, which I will discuss in Section 3 of this

[redacted]

[3] Expert report of Mr Balog, Chapter 4, page 32 (under 'Answer to Question 2(c)).

report. In my opinion, by not taking this into account, [redacted] has reached incorrect conclusions. I have referred to the 'length-effect' already in my June 2020 report [9].

In short, the 'length-effect' explains that a 300 km long cable (as the Basslink cable) has natural variability reducing the ability of the cable for the entire 300 km length to perform in the same way as it did [redacted]

[redacted]. For the Basslink cable designed to operate with a maximum conductor temperature of [redacted] and a maximum temperature difference over the cable insulation plus screens of [redacted]. Meanwhile, the tested cable length should not fail. For a [redacted] such test temperatures are normally not problematic (this is the 'length-effect'), [redacted], because of the 'length-effect', the ability to withstand electrical stresses are potentially lower at the failure location [redacted]

One of the further consequences of the 'length-effect' is, that it makes plausible that the cable failed at the failure location [redacted]

[redacted]

2 FORMALITIES

2.1 Name and address of the author of this report

The name and address of the author of this report is

Prof. dr. Evert Frederik Steennis (Fred Steennis)
Senior Principal Consultant
DNV GL Energy
Utrechtseweg 310
6812 AR Arnhem
The Netherlands

2.2 Expert witness Code of Conduct

I have been provided with the Code of Conduct (Supreme Court of Tasmania, Practice Direction, No 1 of 2016, dated January 5th, 2016) [TAB 01] and the IBA expert obligations [TAB 1.1].

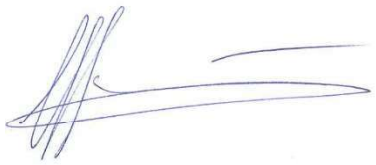
2.3 Acknowledgement that the expert has read the code and is bound to it

I acknowledge that I have read the Code of Conduct and the IBA expert obligations as mentioned in Section 2.2 and that I am bound to this Code of Conduct.

Save for my work on the December 2015 Basslink cable failure which previously led to three reports [/80/, /81/, [9]] and now has led to this report, I have no prior relationship with Hydro Tasmania, the State, Basslink Pty Ltd or their legal advisors or Mr. Robert French AC.

I affirm my genuine belief in the opinions expressed in this report.

I, Evert Frederik Steennis, confirm the above statements and acknowledgements.



2020-07-13, Arnhem, the Netherlands

2.4 Qualifications of the author

For my qualifications I refer to Section 2.4 of [9], dated 2020-06-18.

2.5 Declaration that the author has made all inquiries needed

Herewith I declare that I have been able to make all possible inquiries needed to identify the possible causes (including their related probabilities) and any relation to the way the Basslink cable was operated by (BPL) prior to the Basslink outage.

3 THE 'LENGTH-EFFECT'

[redacted]

My opinion:

1 [redacted]. One has to take into account the 'length-effect'. This 'length-effect' will certainly lower the acceptable electrical stresses for the 300 km long Basslink cable operating in the field by a considerable (but unknown) percentage [redacted]

2 The 'length-effect' is known in literature under different names, like 'size-effect', 'volume-effect' and 'enlargement-law'

3 I introduced the 'length-effect' and its impact on my conclusions in my report from June 2020 [9][7]

4 The length effect is for instance mentioned by Prysmian in Occhini's paper from 1971[8] and by Borealis in Hampton's paper from 2006[9]

5 I myself in the 1980s experienced the impact of the 'length-effect' during my PhD work when I discovered that cables samples of 6 m (that came from a cable of several km, failing in service) tested in the laboratory had surprisingly high breakdown values. The difference between the breakdown electrical stress for the laboratory test samples and the cable in the field was a factor of 4 (on average)[10]. I studied the case and I learned that this was caused by the 'length-effect'. This 'length-effect' informs us that due to variations in production (and installation) quality, there will be concentration points along a voluminous object where all 'natural' variations can coincide to create a much lower breakdown value than one found for a short sample. Simply, because in a short cable sample the chance to have this unique combination is very small. Ageing, whether thermal, electrical, mechanical or chemical, can influence the variation in quality and thus its impact

6 Mathematics to study this have been developed based on Weibull statistics, and I am only mentioning one study out of many[11]

7 For cables, with a similar insulation material and cross-section, the breakdown electrical stress for the long cable in the field in relation to the short cable tested in the laboratory is following the formula:

$$\left(\frac{\alpha_1}{\alpha_2}\right) = \left(\frac{L_2}{L_1}\right)^{1/\beta} \quad (1)$$

Where

- α_1 is the electrical breakdown stress for the short cable length
- α_2 is the electrical breakdown stress for the long cable length
- L_1 is the length of the short cable

[6] [2], Section 6.1.

[7] [9], Section 6.1.9.2, page 90 and Appendix R, page 201.

[8] E. Occhini, 1971 /84/ wrote: *"The dielectric strength of any electrical insulation system decreases with the stressed area or, in the case of a cable, with its length"*.

[9] R.N. Hampton, 2006. Effect of size on electrical performance. Conference Record of the 2006 IEEE International Symposium on Electrical Insulation. Hampton wrote in his Abstract of this paper: *"The electrical breakdown performance, either unaged or after ageing (laboratory or service), is often used as the basis for qualification of a device, design or material. Many of these features that effect these performance levels have been discussed in other documents; contaminants, propensity for water treeing, insulation and semiconducting materials. However, the size of cable tested is rarely discussed. This is somewhat surprising as it has been long recognized that electrical failure is an Extreme Value (the Weibull distribution is a member of this family) or weakest link process. In Extreme Value processes the performance of the whole cable device is determined by the single "weakest link". Thus when more "weak links" are present the chance of failure is consequently higher: the measured performance depends on weak link concentration or size of the device. Additionally at some dimensions the thickness of the dielectric can influence the breakdown mechanism itself; especially if the thermal influences are present"*.

[10] E.F. Steennis, Water treeing, the behaviour of water trees in extruded cable insulation, Ph.D. thesis Technical University Delft, (first edition) ISBN 90 353 1020 9, (second edition) ISBN 90 353 1022 5. KEMA, Arnhem, The Netherlands, 1989 (reference /P177/ in [9].

[11] G.C. Stone, et al, Parameter estimation for the Weibull distribution, IEEE Transactions on Electrical Insulation, Volume 12, No 4, August 1977, page 253-260.

- L_2 is the length of the long cable
- β is the shape factor

It is the shape factor β, that represents the variation of quality along the cable. A low β means much variation, a high β means less variation. No variation is in practice impossible

8 Laboratory tests show that the electrical breakdown stresses and the shape factor come with uncertainties. That also makes predictions subject to uncertainties. But I want to focus on the general trend and the lessons we can learn from this 'length-effect'.

Marzinotto in a paper from 2011[12] from Terna[13] used the above-mentioned formula (1) to calculate the impact of the length of an HVDC MIND power cable[14].

Marzinotto also proposed values for the shape factor β in their more recent paper from 2015, where the shape factor β for HVDC MIND cable had the values 12, 15 and 18[15].

Since Marzinotto not only changed the length, but also the cable diameter, rather than using his results, I made my own graph for a HVDC MIND cable where I only vary the length.

But taking this into account, my results presented in Figure 1 are fully in line with Marzinotto's findings. To demonstrate how the shape factor influences the 'length-effect', I used a wide range of practically possible shape factors β of 10, 20 and 30[16]. The actual value of the shape factor and related uncertainties for the Basslink cable are not known to me. But important are the conclusions that can be drawn, independent from the actual shape factor.

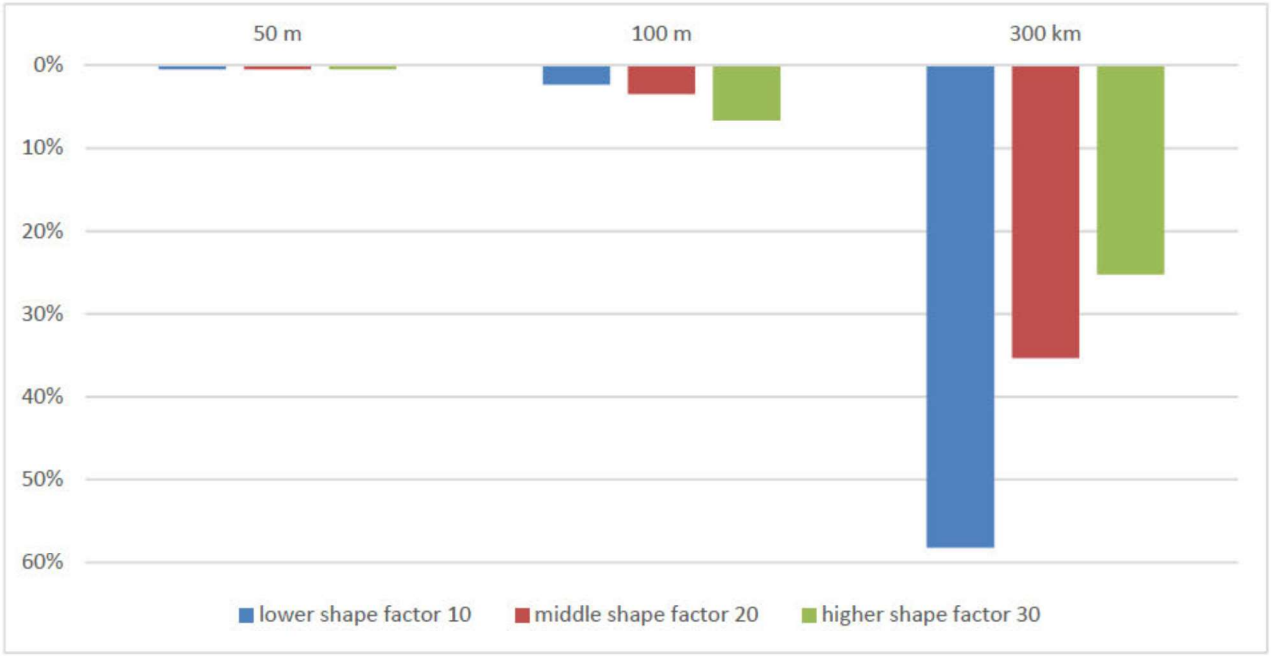


Figure 1 The reduction in the level at which breakdown occurs as a function of the cable length, shown for three different quality variation factors β

[12] M. Marzinotto. A deeper insight into the application of the enlargement law to HVDC cable lines, 2010 Annual report conference of Electrical Insulation and Dielectric Phenomena (CEIDP, 17-20 October 2010, USA).

[13] The Italian Transmission System Operator, Italy.

[14] See in Marzinotto's paper formula 3 and take the same cable (apart from the length), resulting in my formula (1).

[15] M. Marzinotto. The statistical enlargement law for HVDC cable lines part 2: application to enlargement over cable radius. IEEE Transactions on Dielectrics and Electrical Insulation, Volume 22, Issue 1, February 2015.

[16] In my work I did for my PhD thesis, I found for new XLPE insulated cables a shape factor β between 4 and 11, taking into account the 95% confidence bounds. Showing a value of 20 or 30 in the graph above is therefore probably quite optimistic for an HVDC MIND cable. Reference: E.F. Steennis, Water treeing, the behaviour of water trees in extruded cable insulation, Ph.D. thesis Technical University Delft, (first edition) ISBN 90 353 1020 9, (second edition) ISBN 90 353 1022 5. KEMA, Arnhem, The Netherlands, 1989 (reference /P177/ in [9]).

What can be concluded from this evaluation is the following:

a For any reasonable shape factor (even if significantly higher than Marzinotto's propositions), the electrical stresses that can be withstood for a 300 km long cable are considerably lower than those obtained (on average) [redacted]

b Beforehand, the position where different types of variations related to the 'length-effect' merge is unknown. But where there is a failure, without an external cause, it is likely that the failure happened at this weakest link position

c [redacted] where I assume the cable lengths being involved are less than 100 m, the expected quality of the insulation may on average be expected to be close to [redacted]

Therefore, [redacted] the expected ability to withstand the electrical stresses and high temperatures during service operation is high. In such (limited) lengths, per the 'length-effect' there is a much smaller chance for variations to coincide into a weakness.

The 'length-effect' explains also why Herstad[19] and Isayama[20] in their laboratory tests on miniature cables ([redacted]) and Hauge for the Skagerrak cable samples[22] ([redacted] found high electrical breakdown stresses or could withstand high temperatures. [redacted] I explained that a limited cable length not failing at [redacted] is fully understandable once considering the 'length-effect'.

As I wrote in my June 2020 report[25], [redacted] This is plausible, since the ability to withstand thermal overstress of the cable will depend a lot on the quality of the reinforcing tape arrangement.

[redacted]

19 Herstad, K. The influence of conductivity and permittivity on breakdown strength and testing procedure of oil-paper HVDC cable insulation, Cigré paper 15-03, 1980.

20 /27/: Isayama, Y, et al, The polarity reversal properties of Power cable, 13th ICDL, 1999, Nara, Japan.

21 [2], § 202.

22 /16/: O. Hauge. Performance of the 250 kV HVDC Skagerak Submarine Cables - further development of the HVDC paper-insulated, mass-impregnated (solid type) submarine cable, IEEE Transactions on Power Delivery, Vol. 3, NO. 1, January 1988, pages 1 – 15.

[redacted]

25 [9], Executive summary, part B, length effect, page 2.

4 SUMMARY OF OPINIONS

In Table 1 I summarize the main differences between the opinions of [redacted] and me in relation to the cause of the failure in December 2015 and the operation of the Basslink HVDC MIND power cable by BPL.

I will make reference to various reports, papers, etc. in footnotes.

Table 1 Overview opinions [redacted] and me related to the failed Basslink HVDC MIND power cable

Finding	[redacted]	**My opinion report 20-2078 plus additional information on the 'length-effect' and load since the repair in this report**
1 [redacted]	[redacted]	Dismantling did not show evidence for any degradation mechanism. This does not exclude thermal degradation as the failure cause [redacted]
2 [redacted]	[redacted]	[redacted]
3 [redacted]	[redacted]	Because the insulation is probably [redacted] enlarged void formation (and with that the risk of failure) is reduced[34]. This is a characteristic which is used by manufacturers to reach higher operating voltage levels, but not higher operating temperatures (supported by literature)[30]. If the cable is being operated outside the thermal design limits, such enlarged voids (or other thermally stimulated

[redacted]

	[redacted]	degradation processes) are a potential degradation risk for the cable insulation[35].
4 [redacted]	[redacted]	[redacted] showed that the cable design is in line with the requirements, but the precondition is that the Basslink cable is operated within, amongst others, the thermal design limitations [redacted] Going beyond that might be possible for [redacted] but is very risky to operate a long cable length of 300 km outside the design limitation because of the 'length-effect' (The 'length-effect is presented in Section 3 of this report). The 'length-effect' illustrates that the withstand electrical stress in a long cable (at certain positions) is much lower than in a short (Type Tested) cable. A lower breakdown stress at such a position involves a reduced capability to withstand ageing, including thermal ageing. It is therefore not appropriate to stretch the 300 km long Basslink [redacted]

[redacted]

	temperature drop figures over which the product can perform".[39]	[redacted]
5 [redacted]	[redacted]	DNV GL (Mr de Wild) calculated for the failure position that the maximum conductor temperature was [redacted] I leave it for Mr de Wild and [redacted] to discuss the results of their thermal models. Irrespective of the outcome of this discussion, I conclude that at the failure location the conductor temperature has been above the thermal design limit [redacted] for several days up to about one month, probably somewhere between [redacted] It means that the Basslink cable at the failure spot has been thermally overstressed for a considerable period with respect to its design limitations.
[redacted]	[redacted]	The 'length-effect' (supported by literature and discussed in Section 3 of

[redacted]

[redacted]	[redacted]	this report) shows that [redacted] the ability to withstand electrical stresses (and with that the ability to withstand thermal degradation) is likely higher ([redacted]) than at the failure location ([redacted]) [redacted][6]. [redacted].
[redacted]	[redacted][48]	In my June 2020 report I refer to [redacted] possible thermally stimulated failure mechanisms, of which two come with enlarged void formation. The [redacted] comes with a too high electrical stress because of a too high temperature difference over the cable insulation[49]. [redacted] I explained in my June 2020 report[50]: "*... it can take up to years in a paper insulated environment because the compound tends to redistribute, forcing the spark to act on another spot. And possibly, paper is better able to withstand partial discharges than a polymer [/71/, Qian,*

[redacted]

		2015]. It will also depend on the electrical stress in the void and thus on the materials surrounding the void, the distribution of charges surrounding a void, the presence of voltage polarity reversals in the case of DC cables and the voltage class of the cable. It is generally assumed that in HV cables, the degradation process goes faster than in MV cables for instance, but within its voltage class, DC cables, with fewer partial discharges, are in that respect assumed to degrade more slowly". [redacted], from which I conclude that voltage polarity reversals in the end stage of the ongoing degradation since the thermal excursion [redacted] gave a last supportive push to cause the cable to fail[52].
[redacted]	"[redacted]	I checked the power load profile since the repair of the cable and compared this with the [redacted] see Appendix B. I concluded that the load since the repair has by far not been as high as [redacted] The failure free operation of the Basslink cable since the repair in 2016 can be consequence of the lower thermal exposure since this repair. In this way, [redacted], the failure free operation since the repair in 2016 supports my conclusion that the cable in 2015 has probably failed because of the thermal overload the cable has experienced before that failure.

[redacted]

9	Cause of the failure	"*in the absence of surviving evidence, it is not possible to determine the cause of failure*"[54].	The evidence[55] that I have seen from both Mr de Wild and [redacted] leads me to conclude that the cable was thermally overstressed and with help of the polarity reversals it failed at the weakest spot[57]. The fact that the cable was thermally overstressed was caused by the manner in which the cable was operated over its design temperature limits. Other possible causes (e.g. external damage) were not found[58]. The failure, after almost 10 years of operation, fits with a thermal ageing process[58], where possible alternatives as electrical[59], mechanical, chemical or radiation related ageing processes are neither expected to have happened during operation nor at or near the failure location.

[redacted]

APPENDIX A
Letter of instructions

CLAYTON UTZ

Confidential

Email 3 July 2020

Mr Fred Steennis
Senior Principal Consultant
DNV GL Energy
Utrechtseweg 310
6812 AR Arnhem
NETHERLANDS

Fred.Steennis@dnvgl.com

Dear Mr Steennis

Basslink Interconnector Outage

As you are aware, Clayton Utz acts for the Hydro-Electric Corporation (**Hydro Tasmania**), and Ashurst acts for the State of Tasmania (**State**), in arbitrations with Basslink Pty Limited (**BPL**) in relation to the high voltage direct current submarine cable across Bass Strait (**HVDC Cable**). We understand that Ashurst has separately engaged you as an expert on behalf of the State for the purposes of these arbitrations.

[redacted]

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[redacted]

3. Requirements for Report

3.1 In preparing your report, please ensure you *explain* the concepts and terminology you have used to allow a lay person to understand your answers. Please also ensure that you identify the foundation(s) for your conclusions and that you explain the reasoning leading to each conclusion.

3.2 Where you have relied upon academic literature or information contained in documents provided to you, please identify this and provide references to such literature or documents in your report.

3.3 Please also have regard to the following requirements for expert reports under the IBA Rules on the Taking of Evidence (applicable in the arbitrations) (**Tab 1.1** of the index at Attachment 2 to our letter of instruction dated 8 June 2020). These Rules require that expert reports include:

(a) a statement regarding the expert's present and past relationship (if any) with any of the parties, their legal advisors and if necessary, the arbitral tribunal, and a description of the author's background, qualifications, training and experience;

(b) a description of the instructions pursuant to which the expert is providing opinions and conclusions;

(c) a statement of the expert's independence from the parties, their legal advisors and the arbitrator;

(d) a statement of the facts on which the expert is basing his or her expert opinions and conclusions;

(e) the expert opinions and conclusions, including a description of the methods, evidence and information used in arriving at the conclusions;

(f) an affirmation of the expert's genuine belief in the opinions expressed in the expert report; and

(g) the expert's signature, date and place.

3.4 Please provide a final copy of your reply report by no later than **6 July 2020**.

Yours sincerely

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Our ref 968/15760/80173193

APPENDIX B
Load 2014 and since the repair

[redacted]

[redacted]

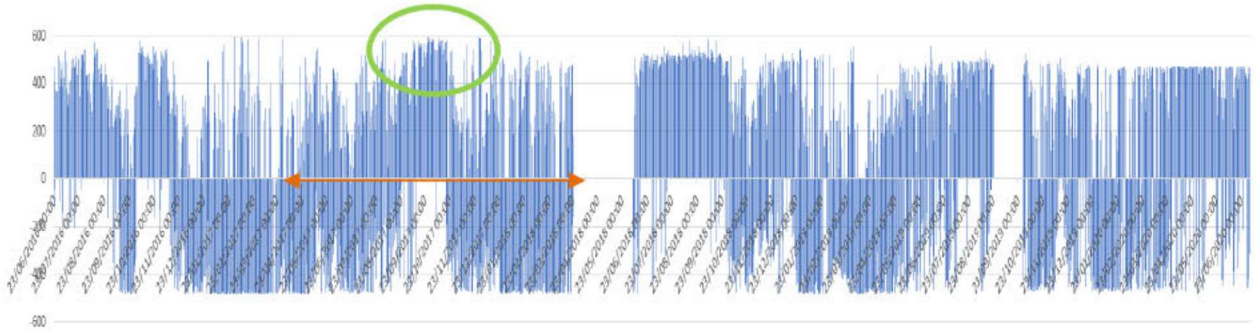
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[redacted]



[redacted]



[redacted]

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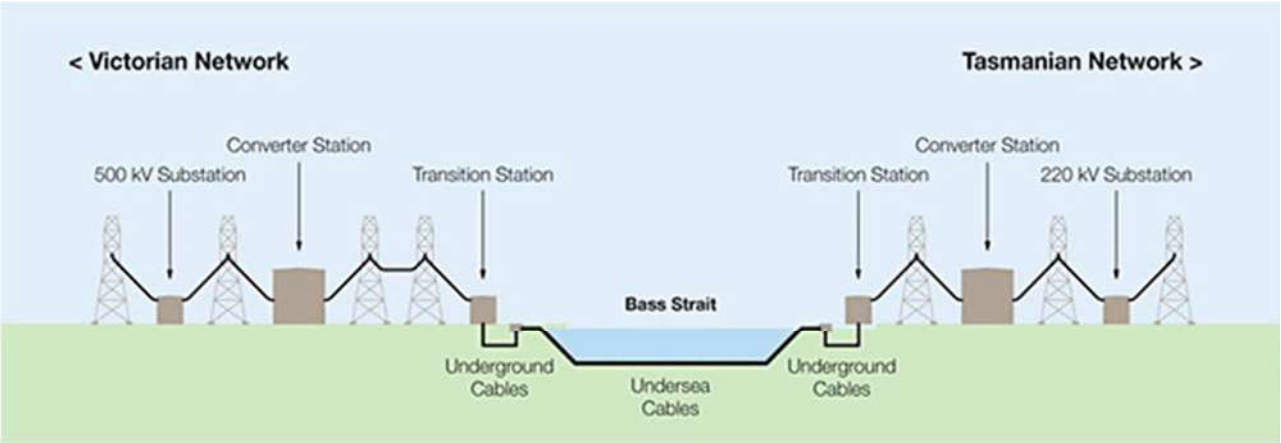
DNV·GL

EXPERT REPORT FRED STEENNIS

Basslink outage 2015 – Root cause analysis of the failed HVDC power cable

Clayton Utz and Ashurst Australia

Report No.: 20-2078
Date: 2020-06-18



Report type:	Expert report Fred Steennis	DNV GL - Energy
Report title:1	Basslink outage 2015 – Root cause analysis of the failed HVDC power cable	DNV GL Netherlands B.V. Energy Advisory
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Date of issue:	2020-06-18	
Project No.:	10156982	
Organisation unit:	AM	
Report No.:	20-2078	

Objective:

To investigate the root cause of the failure that happened in the Basslink cable in Australia, between Victoria and Tasmania in December 2015

Prepared by:	Verified by:	Approved by:
E.F. Steennis Sr. Principal Consultant Power cables	B. Kruizinga Consultant	K.-J. van Oeveren Head of Department Asset Management

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Keywords:

Basslink, HVDC, failure

Rev. No.	Date	Reason for Issue	Prepared by	Verified by	Approved by
0	2020-06-17	Draft A	E.F. Steennis	B. Kruizinga	
0	2020-06-18	Final report	E.F. Steennis	B. Kruizinga	K.-J. van Oeveren

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EXECUTIVE SUMMARY

A. Introduction

The Basslink cable is a 400 kV HVDC MIND power cable link with 298 km (of which 283 km is subsea) of power cable connecting Victoria to Tasmania. This link was commissioned in April 2006. It is owned and operated by Basslink Pty Ltd (BPL). The Basslink cable was manufactured and installed by Pirelli (now known as Prysmian). After almost ten years of failure free service operation, the cable failed in December 2015.

My opinion expressed in this report is based on the information I had at the time of submitting my report.

Already in 2017 I wrote a report on the cause of the Basslink cable failure [/80/, 2017], where I concluded that the Basslink HVDC cable had failed because of having been thermally overstressed. Since then I received new information and developed my thoughts about the failure cause (still being thermally overstressed) expressed below. For some more detailed history see Section 1.5.

B. The probable cause of the failure

Introduction

The probable cause of the failure is "thermally induced stress", where the cable has been thermally overstressed, beyond its thermal design limits.

Calculated thermal overstress

Based upon the information provided to me to date, during its operational life of almost 10 years (116 months) until the Basslink HVDC cable failed in December 2015, the cable has been thermally overstressed during several periods. This happened particularly in [redacted] months before the cable failed.

Under thermal stress exposure beyond the design limits, three different degradation processes can happen that can lead to a reduced insulation quality. These three different thermal degradation processes are presented in Section 6.4 and in Appendix V. In two of these processes enlarged void formation inside the cable insulation plays a role in the degradation processes. It is my opinion that it is probable that one or a combination of these degradation processes started during one of the periods that the cable was thermally overstressed (most probably in [redacted] where this overstress reached extreme values), after which this degradation slowly continued during the operation of the Basslink cable until the failure occurred in December 2015.

[redacted] But I want to emphasize that this development was used to reach higher voltage levels for transmitting the power, as happened to many cables installed since the 1990s, including amongst others the Basslink cable. This development was NOT used by cable manufacturers of HVDC MIND power cables with a similar design as the Basslink cable to increase the maximum design temperatures. Exceeding these temperatures is challenging the cable insulation where thermally driven degradation and a resulting failure is a probable consequence.

Length effect

De Wild [TAB 65.0.4, 2020] calculated that at certain locations the cable has been thermally overstressed to a higher degree than at the failure location. These are so-called thermal bottleneck locations. In two of these locations the maximum conductor temperature went up to [redacted] and the maximum temperature difference over the cable insulation (not including the screens) went up to [redacted]

One would initially expect a failure of the Basslink cable of being thermally overstressed to occur at one of the thermal bottlenecks. But there is also a so called 'length effect' (see Appendix R for a further explanation). The 'length effect' reflects natural variations along the cable with respect to (amongst others) the precise soil conditions and cable quality. In a properly designed, installed and operated cable, such natural variations would not be a reason for a cable to fail within its foreseen lifetime. In that sense, natural quality variations are not considered as a design or manufacturing defect. However, for a cable being thermally overstressed, the positions where local variations merge into areas with lower quality, it is the weakest link which will be the preferred location for the thermally overstressed cable to fail. Two relevant variations for the Basslink cable are mentioned here:

- Everywhere along the Basslink cable the actual thermal soil property natural variations will create slightly lower or higher temperatures than calculated by De Wild (and CCI). De Wild calculated for the failure location that the maximum conductor temperature went up to [redacted] and the maximum temperature difference over the cable insulation (not including the screens) went up to [redacted]. However, due to the actual thermal soil property variations, somewhat higher temperatures may have been reached, realistically [redacted] and [redacted] respectively. See for a further explanation Section 5.2.2.1, in particular the part "Maximum temperatures at the failure location taking into account the uncertainties". Such slightly higher temperatures at the failure location may have created extra degradation in an already thermally overstressed cable
- One can expect that everywhere along the Basslink cable the counterpressure from the reinforcing tapes will slightly vary. And indeed, at the failure location it was found that:
  - [redacted]
  - [redacted]

[redacted].

The impact of voltage polarity reversals

The cable has been subjected to many voltage polarity reversals that come with a change in the direction of the power flow. As is explained in Section 6.1.10, such voltage polarity reversals result in a temporary but considerable increase of the electrical stress inside the cable insulation which happens along the whole cable. The fact that the cable broke down shortly after two voltage polarity reversals, supports the hypothesis that the related increase of the electrical stress played a role.

Summary

The Basslink cable failed because it was thermally overstressed, where the cable has been operated beyond its thermal design limits.

By way of further explanation:

- The increase of the electrical stress due to voltage polarity reversals contributed to the development of the failure in the thermally overstressed power cable
- [redacted] explains why the cable failed at the thermally overstressed failure location rather than at other thermally overstressed locations (thermal bottleneck locations) along the Basslink cable.

Notes

Both, the thermally induced stress and voltage polarity reversal induced stress are a direct result of the way the Basslink cable is operated.

Apart from thermally induced stress, the other candidates for the cause of the failure mentioned in Section 6.1 (related to design, production and installation, including their normal variations) are considered improbable.

The fact that the Basslink HVDC power cable failed after almost 10 years of service operation supports the conclusion that an ageing mechanism such as thermally induced stress caused the failure.

C. Answers in summary to the questions raised by Clayton Utz's letter of instructions, see Appendix L

Question 1

What do you consider to be the probable cause of the failure that occurred on 20 December 2015 and why?

> The possible failure causes that have been investigated by me are: deficient design, production, weakness from a repair spot, external damage to the cable, voltage ripple from the converter station, overvoltages from the connected network, thermally induced stress, voltage polarity reversals (used to reverse the power transmission direction) and an incidental weakness
>
> Out of these, the thermally induced stress, where the cable was exposed to temperatures beyond its thermal design limits, was found to be the probable cause of the failure
>
> The voltage polarity reversals have probably contributed to the failure, but only after the thermally induced stress had weakened the cable
>
> See Section 6.1 for a full description and see this Executive summary, part B for a comprehensive summary.

Question 2a

Is there a maximum conductor operating temperature that the HVDC Cable should not exceed (**Maximum Conductor Operating Temperature**) to ensure that the HVDC Cable is operated in a manner that does not adversely impact its long term performance or service life? If your answer is yes, what is the basis for your answer and upon what source(s) do you rely in support of your answer?

> The maximum allowed operating conductor temperature for the Basslink cable is [redacted]
>
> See Section 6.2 for a full description and reasoning.

Question 2b

Is there a maximum temperature difference over the paper insulation layer of the HVDC Cable that should not be exceeded (**Maximum Temperature Difference**) to ensure that the HVDC Cable is operated in a manner that does not adversely impact its long term performance or service life? If your answer is yes, what is the basis for your answer and upon what source(s) do you rely in support of your answer?

The maximum allowed operating temperature difference over the cable insulation (without screens) for the Basslink cable is [redacted]

The maximum allowed operating temperature difference over the cable insulation with screens (between the conductor and lead sheath) for the Basslink cable is [redacted]

See Section 6.3 for a full description and reasoning.

Question 2c

What, if any, risks arise if the HVDC Cable is operated in excess of the Maximum Conductor Operating Temperature and/or the Maximum Temperature Difference?

There are three different ways the cable can thermally degrade, although a combination of these is possible as well:

1. In case only the conductor temperature is exceeded beyond its design limit, one can expect that the cable insulation will expand such that the outer cable layers will be permanently stretched which can result in a reduced counter pressure, such that enlarged voids can be developed, in particular in the outer layers of the cable insulation which can result in degradation starting at such enlarged voids and a failure over time
2. In case only the temperature difference over the cable insulation is exceeded beyond its design limit, one can expect that there will be an electrical stress beyond the design limits in the outer layers of the cable insulation, which, together with the normal voids present here, can result in degradation starting at such normal voids and a failure over time
3. In case both the conductor temperature and the temperature difference over the cable insulation are exceeded beyond their design limits, then, apart from the degradation mechanism described above, also the compound that is in between the paper windings can migrate away from the inner cable insulation, which can result in the creation of enlarged voids in the inner layers of the cable insulation which can result in degradation starting at such enlarged voids and a failure over time.

See Section 6.4 for a full description and reasoning.

Question 3

Which of the possible causes of failure, if any, can be attributed to the way in which the cable was operated by BPL? In answering this question, please identify the facts and assumptions on which you rely to identify the way in which the cable was operated by BPL.

Out of the possible causes, which appeared to be the probable causes, both the thermally induced stress (in particular, the part related to the load of the cable) and the voltage polarity reversals are related to the way the cable is operated by BPL.

See Section 6.5 for a full description and reasoning.

Question 4

Further to question 3, if any possible cause of failure is attributable to the way in which the cable was operated by BPL, is there anything that a prudent, experienced and competent person in the position of BPL should have done to prevent the failure?

Out of the possible causes, which appeared to be the probable causes "thermally induced stress" and "voltage polarity reversal stress", both are clearly related to the way the cables have been operated by BPL and could have been avoided by BPL.

Concerning the thermally induced stress, De Wild [TAB 65.0.4, 2020, Executive summary] wrote: "*The Basslink connector was operated such that the cable system was highly loaded …… This resulted in temperatures that increased over prolonged periods of time thereby exceeding thermal limits …*". But additionally, De Wild wrote: "*The soil around the submarine power cables has worse thermal properties…much worse in comparison to what was assumed during engineering of the cable system. This resulted in higher temperatures than assumed during engineering*". This could have been avoided by having carried out a review of the thermal engineering calculations and having performed a full cable route survey with soil samples, such to check the engineering calculations with respect to thermal properties of the soil and laying depth and to update the actual possible load based on these findings.

See Section 6.6 for a full description and reasoning.

Question 5

What tests (if any) do you consider are necessary as a matter of Good Electricity Industry Practice to establish or would assist or be likely to assist in establishing the probable cause of failure, or narrowing the possible causes of failure?

As a consequence of the Basslink cable having been thermally overstressed, the most reliable test to see whether the thermal ageing has resulted in permanent degradation by:

- The creation of localized enlarged voids of permanent nature or
- The creation of localized electrical degradation of permanent nature from such voids or from normal voids subjected to an electrical stress beyond the design limits,

is the electrical part of the Type Test according to Cigré Electra 189 [/28/, Cigré, 2000]. This is the load cycle test with voltage polarity reversals, followed by lightning impulse tests, performed on a cable length of at least 40 m. Preferably such a test is combined with a partial discharge test[1] during load cycling, being able to identify (and even locate) the presence of such localized degradation.

However, it is not guaranteed that the tested cable length will show the presence of this degradation (by partial discharge activity and /or a failure) during such a test, since the degradation (if any left after the failure) can be a localized issue, not per definition critically present in the cable length to be tested. And testing many more cable lengths can be considered as impractical.

See Section 6.7 for a full description and reasoning.

[1] Partial discharges or electrical sparks are localized dielectric breakdowns of a small portion of an electrical insulation system under electrical stress.

Question 6

Further to question 5, if testing is appropriate, what material (including retrieved samples of cable and documents), if any, would be required to undertake any such tests? If it is necessary in your opinion to test a retrieved sample of cable, would any testing-related limitations or difficulties arise from the condition of that sample as at the time of testing? If yes, please explain the reasons for that answer, identifying the nature and scope of any such testing-related limitations or difficulties.

Further to the answer of Question 5: the cable lengths for the tests should come from retrieved cable, that came from the repair of the fault in early 2016. But there are practical issues to be taken into account, such as the need to combine shorter cable lengths made available into a decent cable length to be tested (40 m at least) and the fact that the retrieved cable lengths might not be usable because of water ingress and / or damages from the retrieval operation.

See Section 6.8 for a full description and reasoning.

1 INTRODUCTION

1.1 General

In December 2015, the Basslink cable failed after ten years of service operation. Related to this failure, I performed a root cause analysis. This introductory section explains who my customer is, the scope of this report and the history of some of the reports issued for the Basslink failure case. Also, it describes the structure of the report, how references are used and gives definitions for common terms and abbreviations.

1.2 The customer

My customers Clayton Utz and Ashurst Australia (Ashurst) act for Hydro-Electric Corporation (Hydro Tasmania) and the State of Tasmania (the State) in relation to matters arising from the outage of Basslink, the High Voltage Direct Current (HVDC) submarine cable across Bass Strait, which occurred on 20 December 2015 (Basslink Outage).

1.3 Scope of this report

This expert report is provided to Clayton Utz, Ashurst, Hydro Tasmania and the State in response to their request to identify the possible causes (including their related probabilities) of the Basslink outage that happened in 2015 and any relation to the way the cable was operated by (BPL).

1.4 Structure of this report

The report will start in Section 2 with various formalities, among which my qualifications. Part of this section is also my general approach when performing a root cause investigation in the case of a cable system failure, see Section 2.4.5, called "Approach in case of a failure investigation". As a result, in investigating the root cause for the Basslink cable, I worked in line with the methodology described here. This means that:

1. I studied all stages in the cable life, i.e. design, production, installation and operation and I compared these to international common practice where applicable
2. I gave special attention to those weaknesses which are known from literature to be typical for a Basslink type power cable and checked whether a weakness in the Basslink cable could have been introduced during one of the before mentioned stages.

The material provided, being used throughout my investigation, is presented in Appendix L.

Section 3 will first introduce some general electrotechnical matters to create a better understanding of what will follow (Section 3.1), followed by an introduction of the applied type of power cable, with a focus on its design and potential weaknesses (Section 3.2 to Section 3.5).

This is followed in Section 4 by a discussion on the Basslink cable, taking into account contractual issues, power design rating, construction, design, production, and so on, up to the failure that happened in December 2015. The work done by BPL to find the root cause of this failure is presented in Section 4.8.

Section 5 will come back to some potential weaknesses of HVDC cable in general and how these could be linked to the Basslink cable, in the way it was operated and failed.

In Section 6, I will respond to key questions from Clayton Utz. These questions were mentioned in Clayton Utz's letter of instructions, see the Appendix L. Part of this is an answer to the question of why, in my opinion, did the Basslink cable fail, which is treated in Section 6.1.

1.5 History of the DNV GL and CCI reports issued so far

After the failure of the Basslink cable in December 2015, CCI performed an investigation[2] (based on the [redacted] and issued their failure investigation report [TAB 67, December 2, 2016]. This report summarized all of their examinations (issued in previous reports) and concluded that the failure cause was not found, but for sure was not caused by an external damage. CCI's reporting did not investigate matters such as [redacted] Concerning this last point, CCI wrote: "*The operating conditions at, and preceding, the time of failure were no different to those of the year 2015. The cable was within its thermal rating*" [TAB 67, § 131].

Following CCI's report, De Wild [/72/, December 14, 2017] developed a model to calculate the cable temperature as a result of the way the cable was operated. In his report, De Wild mentioned that there was a thermal issue, where the cable had experienced temperatures above its design limit of [redacted] for the conductor temperature and [redacted] for the temperature difference over the cable insulation plus screens, mainly in [redacted] Based on these two design limitations, De Wild calculated a maximum allowed temperature difference over the cable insulation without the screens of [redacted] [/72/, 2017]

Based on the before mentioned information from CCI and based on the result of De Wild's calculations on the cable temperature, I issued my failure investigation report [/80/, December 15, 2017]. In this report, I not only investigated the outcome of the dismantling and related material tests as presented by CCI, but I also investigated design issues and related design tests, production issues and related production tests, installation issues and related tests and operational conditions. Concerning the operational conditions and the load during operation, I referred to De Wild's findings. I concluded that the cable had probably failed because of having been thermally overstressed. I also described the probable degradation mechanism related to these thermal issues. Here I focussed on the worst-case situation found by De Wild for the period of [redacted] where both the maximum conductor temperature and temperature difference over the insulation happened to be higher than the design limits. In order to illustrate the consequence of a HVDC MIND power cable being thermally overstressed, I mentioned two different degradation mechanisms. One mechanism was based on the migration of the compound in between the cable insulation paper layers, such that permanent enlarged voids inside the cable insulation were created, which together with the electrical stress present here started the degradation followed over time by the failure. This is a degradation mechanism mentioned by Runde [/40/, 2014]. The other possible degradation mechanism was based on the increase of the electrical stress inside the cable insulation which could start a similar degradation and over time result in a failure, but now without the need for enlarged voids. Since the cable failed during cooling down, where voids are maximized in an environment where the compounds tend to shrink considerably more than the surrounding paper insulation, at that time I considered the degradation related to Runde's approach as the more probable one.

Based on the fact that I concluded that the Basslink cable had been thermally overstressed with potentially permanent degradation in certain spots along the cable, I also wrote a report proposing mitigating actions [/81/, December 2017] such to prevent as much as possible additional failures of this type.

[2] See Section 4.8, where CCI's reports, their conclusions and my role are mentioned in more detail.

In response to my report [/80/, December 15, 2017] and De Wild's report [/72/, December 14, 2017], CCI issued a report [TAB 76, November 29, 2018], see also [TAB 76.1] and [TAB 76.2], reflecting on these two DNV GL reports. [redacted]

Important for thermal calculations are the actual soil conditions surrounding the cable, which so far were only estimated based on some limited findings during the retrieval of the faulty cable and further on the engineering assumptions mentioned by Pirelli. A marine survey was done and reported in 2019, where the actual soil conditions along the whole Basslink subsea cable were measured.

This was an input for an update of the work done by De Wild and he wrote a new report [TAB 65.0.4, De Wild, January 31, 2020], where he mentioned that, based on his model and updated input values, the Basslink cable had experienced temperatures that were even higher than De Wild had calculated in 2017. De Wild kept the thermal design limits mentioned above, apart from one, where, in his updated calculations, instead of [redacted] [/72/, 2017, page 33], he found [redacted] [TAB 65.0.4, 2020, page 43] for the maximum allowed temperature difference over the cable insulation without the screens.

Based on all this additional information, I had the opportunity to deepen my knowledge and thoughts about the failure mechanisms and I wrote a new failure investigation report. That is the report at hand. I confirm that my opinion that the cable was thermally overstressed has not changed. But I did explore the related degradation mechanisms further and added one, which is based on the fact that the cable insulation material under high load conditions beyond the design limits is able to expand such that it can result in permanent deformation of the layers surrounding the cable insulation layers. Once this has happened, under normal load conditions and related shrinkage of the insulation enlarged voids can appear, and now, in a similar way as mentioned above, the cable can degrade and over time fail. This is a degradation mechanism mentioned by Huang [/87/, 2015] and recently by Runde [/91/, 2020] as well. Since identifying the actual degradation mechanism in a thermally overstressed cable is very complicated (also admitted by Runde and Huang) and even not fully understood, in this report I refrain from concluding which of the three degradation mechanisms is the more probable one that caused the failure, although I think it will have been one or a combination of these. It is also not relevant to make that choice, since what is relevant is that there are various degradation mechanisms possible and able to let a HVDC MIND cable fail after it had been thermally overstressed.

[redacted] However, the report at hand is not elaborating on this aspect.

1.6 References used in this report

There are two different types of references used throughout the report:

- References which are related to material supplied by Clayton Utz are referred to as [TAB xx] or [TAB xx, year] in case the year is relevant.

  These references are listed in Appendix L (in attachment 2 of this Appendix)

- The remaining references are coded as /xx/ and in case more information is added as [/xx/, author, year] or coded as [/xx/, year] if preceded by the author. If the same reference appears more than once in a paragraph or section, sometimes only the first time the full reference will be mentioned, followed by referring to the author only.

These references are listed in Section 7 ("References").

1.7 Definitions and abbreviations

1.7.1 Definitions

- For the probability of events, the following definitions are used:

  1. Improbable: something that is possible but is unlikely to occur or prove to be true
  2. Possible: something which may prove to be true, but that is not certain
  3. Probable: something that is more likely than not to occur or prove to be true, having more evidence for than against.

  The applied definitions are as defined in the letter of instructions I received [dated 2020-06-08; Appendix L]

- Power cable: an electrical cable, an assembly of one or more insulated electrical conductors, held together with an overall sheath. The assembly is used for the transmission of electrical power (the amount of power transmitted is related to the electrical voltage times the electrical current), where the conductor is carrying the electrical current and the insulation is preventing the conductor at high voltage to breakdown towards the overall sheath. For high voltages and extra high voltages, such power cables may be buried in the ground (at sea, they are sometimes exposed)
- Load: the amount of current flowing through the conductor of a cable. This is also called 'cable load'
- Overstressed: the thermal, electrical, mechanical or chemical circumstances have become such that the expected lifetime of the component will be compromised
- Breakdown: the failure of a cable or cable model; in laboratory circumstances the word 'breakdown' is more common, while when this happens during operation, the word 'failure' is more common.
- Testing:
  - Type Test: a set of tests made in order to qualify the design and the manufacturing of the cable system against the conditions of the intended application. The tests do not take into account any overload conditions. The tests are of such a nature that, after they have been made, they need not be repeated unless changes are made in either the material, design or process parameters outside the nominal tolerances, such that the resultant changes in dielectric, mechanical and/or thermal properties of the cable affect the lifetime of the cable [/28/, Cigré, 2000]
  - Routine Test: Routine Tests are made to demonstrate the integrity of the manufactured cable and to verify that the product meets the design and manufacturing specifications within the specified tolerances [/28/, Cigré, 2000]
  - Factory Acceptance Test: tests conducted on every component to be supplied for an order in the presence of the customer or the customer's representative. Often a Factory Acceptance Test is a Routine Test but it can contain additional items, such as an overview of corrective actions in the case of deviations

- Site Acceptance Test, also called After Laying Test or Commissioning Test: tests conducted on the installed cable, including its accessories, to demonstrate the integrity of the installed cable system.

In the report expressions are used as the activity related to a 'Type Test', being called 'Type Testing' or having been 'Type Tested'

- Technical items as power, electrical voltage, electrical stress, current, partial discharges, etc., are introduced in Section 3.1.

1.7.2 Abbreviations

A	Ampère, the derived unit for the electrical current I
AC	Alternating (Electrical) Current
Ashurst	Ashurst Australia
BPL	Basslink operator Basslink Pty Ltd
CDVC	Cable Dependent Voltage Control
Cigré	from French: Conseil International des Grands Réseaux Électriques (International Council on Large Electric Systems)
CCI	Cable Consulting International Limited
CLPS	Cable Load Prediction System
DC	Direct Current
DSC	Differential Scanning Calorimetry; DSC is a thermo-analytical technique in which the difference in the amount of heat required to increase the temperature of the investigated sample and a reference sample is measured as a function of the temperature. Certain polymers (among which polyethylene (PE) and cross-linked polyethylene (XLPE) tend to exhibit a wider range of melting points compared to other materials such as metals. This characteristic makes it possible to review and extract the temperature history of the polymer because it leaves a fingerprint on its melting range. See for a further explanation on DSC reference /8/
E	Electrical stress or Electrical field
EDSO	European Distribution System Operators' Association
EHV	Extra High Voltage (above 230 kV)
HV	High Voltage (above 35 kV and not exceeding 230 kV)
HVDC	High Voltage Direct Current
Hydro Tasmania	Hydro-Electric Corporation
I	Electrical current, flow of electric charge, measured in units of Ampere (or Coulomb per second)
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers

- k — kilo (thousand)
- km — kilometre
- KP — Kilometre Position
- kV — kilovolt
- LV — Low Voltage (up to 1 kV)
- m — milli (1 thousandth)
- m — metre
- M — Mega (1 million)
- MIND — Mass Impregnated Non Draining, it is based on an impregnant for the paper insulation material of a HVDC power cable based on a viscous compound
- mm — millimetre
- MV — Medium Voltage (above 1 kV and not exceeding 35 kV)
- ns — nano-second
- P — Electrical power, the rate of doing work, measured in units of Watt (Joule per second)
- P_{loss} — Power loss, the rate of electrical losses (conversion to heat), measured in units of Watt (Joule per second)
- PE — Polyethylene
- PFI — Power Failure Investigation
- pu — per unit; it is the expression of system quantities as fractions of a defined base unit quantity
- R — Electrical resistance, measured in units of Ohm (Ω)
- Reinforcing tape — Galvanised steel reinforcing tape
- Smartlife — A platform of European network owners various studying aspects (among which power cable reliability). This platform is an initiative of EDSO
- t — Time
- the State — the State of Tasmania
- U — Electrical voltage, electrical potential difference, measured in units of Volts (or Joule per Coulomb)
- U_o — the rated DC voltage between conductor and core screen (grounded metal sheath) for which the cable and accessories are designed
- V — Volt, the derived unit for electric potential difference U
- W — Watt, the derived unit of electrical power P
- XLPE — Cross-linked polyethylene

- Ω Ohm, the derived unit of electrical resistance R.

2 FORMALITIES

2.1 Name and address of the author of this report

The name and address of the author of this report is

Prof. dr. Evert Frederik Steennis (Fred Steennis)
Senior Principal Consultant
DNV GL Energy
Utrechtseweg 310
6812 AR Arnhem
The Netherlands

2.2 Expert witness Code of Conduct

I have been provided with the Code of Conduct (Supreme Court of Tasmania, Practice Direction, No 1 of 2016, dated January 5th, 2016) [TAB 01] and the IBA expert obligations [TAB 1.1].

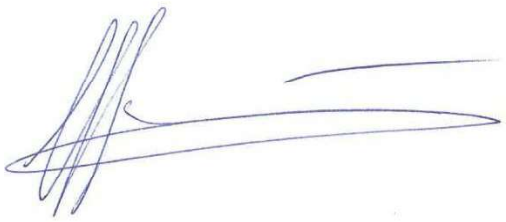
2.3 Acknowledgement that the expert has read the code and is bound to it

I acknowledge that I have read the Code of Conduct and the IBA expert obligations as mentioned in Section 2.2 and that I am bound to this Code of Conduct.

Save for my work on the December 2015 Basslink cable failure which previously led to two reports [/80/, /81/] and now has led to this report, I have no prior relationship with Hydro Tasmania, the State, Basslink Pty Ltd or their legal advisors or Mr. Robert French AC.

I affirm my genuine belief in the opinions expressed in this report.

I, Evert Frederik Steennis, confirm the above statements and acknowledgements.



2020-06-18, Arnhem, the Netherlands

2.4 Qualifications of the author

2.4.1 Curriculum Vitae (summary)

After my university study, I started working for DNV GL (formerly KEMA and DNV KEMA) in 1982. Meanwhile, I have many years of experience in numerous power cable projects, done for customers world-wide. My work of this type is further described below.

The background of DNV GL is given in Appendix H.

A first part of my work is related to research and development. Here, projects are defined based on customer's needs after which a proposal is made and once granted, the resulting research and development work is often done in a team of specialists. A focus point here is the development of diagnostic techniques for power cables.

In line with this research and development work, since 1999, I am also a part-time professor at the Eindhoven University of Technology in the Netherlands (see also Section 2.4.4). In this role I give lectures on underground power cables and give guidance to PhD students in their underground power cable related research. Under my responsibility meanwhile eight PhD students received their doctor degree.

Another part of my work is performing and managing power cable failure analysis (see also Section 2.4.2). The knowledge on degradation processes on one hand and DNV GL's independency combined with its test facilities[3] on the other make it logic for many network owners and cable manufacturers to ask DNV GL's support in the case of a power cable failure. The main goal is always to identify the root cause, but behind this request can be a safety, an economical or a technical issue.

A further part of my work is related to ageing, asset management and remaining life issues, also for power cables.

A next part of my work is giving courses world-wide on various aspects of Underground Power Cables, such as Ageing, Asset Management, Remaining Life, Factory Testing, Field Testing and Failure Analysis.

I have also several years of experience as a full-time manager within DNV GL. Especially, in recent years I have given guidance to less experienced colleagues in my role of Senior Principal Consultant.

I have (co-)published many papers (> 180), reflecting my experience with many different power cable projects, see Section 2.4.3.

I have received two awards:

- 1991 - Hidde Nijland Award, a Dutch award of the power sector, 1991; for my contribution in the field of new testing methods for cables and the applicability of superconductors in power technology
- 2014 - DNV GL Innovation Award 2014 – for my invention of Smart Cable Guard, an on-line monitoring tool locating weak spots in medium voltage power cables that can lead to failures. Smart Cable Guard can also accurately locate temporary and permanent failures.

An important patent of which I am shared patent holder is: E. F. Steennis, P. A. A. F. Wouters, P. C. J. M. van der Wielen and J. Veen, "Method and system for transmitting an information signal over a power cable", Int. Patent No. WO 2004/013642, June 2002.

My full CV is shown in Appendix G.

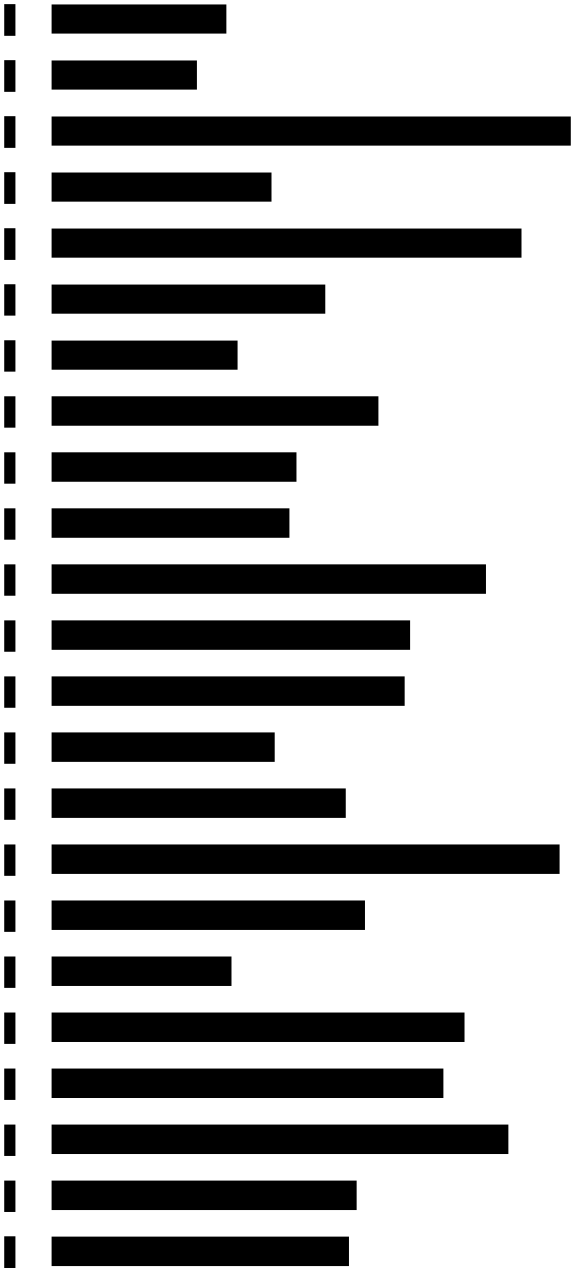
2.4.2 Experience with failure investigations on power cables

Between 2016 and 2019, I have been DNV GL Energy's coordinator of all power failure investigations around the globe. Because DNV GL is impartial, has much experience with components for electrical power and has (or has access to) many supporting laboratories (for material testing, high voltage testing and high power testing), DNV GL is seen by its customers as a leading organization for performing the root cause analysis in the case of an electrical power failure.

[3] Per January 2020, a part of the test facilities is transferred to CESI and now owned by CESI. Nevertheless, these test facilities are near our office and are being contracted for supporting power failure investigating activities where needed.

Over time, and certainly in my role as (Senior) Principal Consultant for DNV GL Energy, I have performed many different power cable failure investigations. This type of work started in the late 1990s and since then has grown (especially in the last 12 years), such that is has become a world-wide business for DNV GL where several of its offices around the world are involved. A reference list of power failure investigations performed on power cables is given in Appendix A. In many cases I have been the lead expert, if not involved as an expert or reviewer.

The power failure investigations have been done for many different companies: utilities, cable manufacturers and insurance companies. Most of these power cable failure investigations are related to AC systems, simply because most cable systems world-wide are AC based. All failure investigations are classified. As a result, only a list of company names for which such investigations were done, can be given here, but no reference is made to the power cable investigations itself. Companies for which I was the lead expert are (amongst others):





The majority of these power cable failure investigations are related to HV and EHV systems, which is because of the importance of this voltage class.

The main object in all these investigations was to find the root cause of the failure of a cable, or a cable accessory as a joint or termination. These could have a follow up in finding the cause behind the technical root cause and / or in recommending on mitigating actions and / or support in court sessions.

Activities performed during a failure investigation are: interviews, literature study, discussions, dismantling of the failed component, material tests, electrical tests, analyses, reporting and sometimes

followed by publications or court sessions. See Section 2.4.5 ("Approach in case of a failure investigation").

Concerning the Basslink type of cable (an HVDC MIND power cable), I have been involved in seven of such power cable failures investigations (with a failure investigation approach as introduced Section 2.4.5):

- One in Europe ([redacted] in an expert advisor role
- One in Asia [redacted] in an expert advisor role
- Five in relation to the [redacted]), where I was the lead failure investigator on behalf of the [redacted]. As the lead failure investigator, I was responsible for:
    - The investigation of all aspects from design, production, installation and operation
    - The dismantling and inspection of the faulty cable part (and reference cable parts)
    - The decision about material tests to be performed and the arrangement of these
    - Tthe analysis, the conclusions and the proposed mitigating actions
    - Writing and discussing the report
- Finally, I was recently consulted as an expert to formulate a remaining life program for a similar type of HVDC MIND power cable (above [redacted] operating voltage), after it had experienced various failures, most probably not caused by external damage. This cable is planned to be investigated, starting July 2020. Because of its nature, I am not allowed to give further details here.

2.4.3 Publications on power cable failure investigations

Because of the fact that failure investigations result in classified reports, it is not possible to disclose its information in publications reflecting actual findings for individual cases. But in a few cases, publications have been made with a more general nature, based on individual (multiple) cases and presented in a way that the phenomena leading to the failure are clarified (first type of publications) or where investigation results have been grouped for a statistical approach (second type of publications).

For the first type of publication, I would like to mention the publications mentioned in my CV in Appendix G (where the /Pxx/ means that it is a publication mentioned in my CV): /P16/, /P18/, /P23/, /P24/, /P26/, /P28/, /P30/, /P32/, /P33/, /P34/, /P38/, /P39/, /P41/, /P53/, /P61/, /P62/, /P63/, /P64/, /P71/, /P73/, /P74/, /P86/, /P92/, /P94/, /P99/, /P109/, /P111/, /P116/, /P126/, /P140/, /P151/, /P158/, /P162/, /P165/, /P166/, /P169/, /P171/, /P172/, /P173/, /P176/, /P177/, /P178/, /P179/, /P180/, /P181/. Most of these references reflect experiences with medium voltage cable systems for which laboratory test methods or diagnostic field tests have been or are being developed.

For the second type of publication, also reflecting HV cable systems (among which HVDC cable systems), the following papers have to be mentioned:

- "Failures in underground power cables – return of experience" /P31/. This paper was published and presented at the 9th International Conference on Insulated Power Cables (JICABLE), Versailles, France, June 21-25, 2015. This paper is also shown in Appendix B
- "Statistics, experiences and learning from failures in power cable systems during PQ and type tests, tests after installation and service operation" /P1/. This is a paper that is planned to be

published and presented at the Cigré session in Paris, France, August 2020. The paper has been submitted to Cigré but it is not yet made available for distribution.

But both papers show DNV GL's involvement in power cable failure investigations.

2.4.4 Professorship and its connection to power cable failure degradation knowledge

As a part-time professor at the Eindhoven University of Technology in the Netherlands, I have a role in studying the performance and ageing of power cable networks and to develop diagnostics for these cables.

Because of this role, on a regular basis I am discussing the known and sometimes not well understood power cable problems with representatives of cable manufacturers, network owners and with colleagues from research and testing institutes. Many of these representatives and colleagues play a role in national and international working groups from for instance the IEEE, IEC, Smartlife and Cigré where similar subjects are being discussed.

This knowledge helps to understand the playing field of ageing power cable systems and where possible the background of failures.

And based on this knowledge, my students (PhD and MSc) are investigating ageing phenomena, to understand remaining life issues and to develop modelling tools and diagnostic tools. Some publications, in which I am co-author, reflect these studies, see Section 2.4.3 above (referring to the publications where the first author is (amongst others) Wagenaars, Wielen, Mousavi Gargari, Li, Wu, Barakou, Kruizinga, Simons, Deursen).

As a professor (and before I became a professor, as an expert), another role is to be member of the doctoral committee on invitation of the promotor of another university. In this role, I read the (draft) thesis, commented on it and then discussed its content with the doctoral candidate, prior and during the public defence of the thesis. Amongst others, this happened for doctoral students at the Delft University of Technology in the Netherlands, where the thesis subject was the degradation of HVDC MIND power cables such as the Basslink cable [/25/, Jeroense, 1997] or where the thesis subject was the degradation of HVDC XLPE cables [/49/, Jonuz, 2007], [/60/, Bodega, 2006].

2.4.5 Approach in case of a failure investigation

A power failure investigation is often needed after an incident, where it is important to identify at least the technical root cause.

In many power failure cases it is not possible to get full certainty about the actual technical cause of the failure. That is normally caused by the fact that a power failure comes with considerable damage, sometimes a full explosion, if not a fire as well. Under such circumstances crucial evidence can get lost because it is destroyed. What also can impede the power failure investigation is the fact that restoration of the power supply has often to be done quickly, potentially losing further evidence in this way.

If a technical root cause cannot be found easily with full certainty, then there are many different (overlapping) methods to perform the root cause analysis in a structured way. A paper presented at Cigré by Ali Said Al-Hadabi [/89/, 2014] gave a general approach of failure investigations as part of asset management. In this general approach it is mentioned that it is important to gather at least historical data (in particular design test reports, production test reports and commission test reports), maintenance data, operational data and forensic data. For the failure investigation itself, several strategies can be used to collect, analyse and present data. Just to mention a few: Kepner Tregoe,

Ishikawa, Human performance analysis, Tripod analysis, Bow-tie analysis. These methods are summarized in Appendix I. Like DNV GL, many companies dealing with failure analysis have their own approach, often with elements of the above-mentioned methods. Personally, I prefer to use a combination of:

- Kepner-Tregoe method (reason: it helps to structure the questions to be asked)
- The Ishikawa method (reason: it helps to stay aware of all possible contributors to a failure).

The Human performance analysis might become useful once it becomes clear that human related factors play a role in the root cause of the failure. The Tripod analysis can in a later stage become powerful in graphically presenting causes and consequences, including barriers that should or did not function. Finally, the Bow-tie analysis is mainly of interest in the cases where mitigating actions would have to be analyzed, which is not the subject of this report.

One element of a root cause analysis is that all information must be gathered that could help to identify the cause of the failure. The importance of this broad approach was emphasized in the above-mentioned paper [/89/, Ali Said Al-Hadabi, 2014]. A broad approach is not just the result of the dismantling of the equipment that failed, hoping to see deviations from normal (and not caused by the failure). It is also important to collect information with respect to the design, the production, the installation and the operation. For instance, one can check if the design tests have been done according to a reputable testing regime and whether these design tests were passed successfully. The same counts for the manufacturing of the failed equipment. Of special importance is to find if there were deviations during the manufacturing, which (should) have been reported. A further source of information for the root cause analysis can be a literature survey. Certain studies and experiences have been made available in the public domain and are a valuable additional source of information in the case of a root cause analysis.

Once all information is made available, one can check this in relation to possible causes. To do so, a list of imaginable possible root causes can be created and all information collected can be used to verify whether an imaginable root cause can be falsified or not. One falsification (in a row of required conditions) is enough to rule out a possible root cause.

In this way, a list of possible root causes can end up with these causes identified as "impossible, improbable, possible, probable, proven". Would one root cause end up as "proven", then the case is solved. But often what remains are several causes still "possible" or "probable", without having one "proven".

Next step is to check the degree of probability for each of the possible root causes. Here statistics can help, but also general knowledge or a discussion with several knowledgeable people (Delphi approach) to find the degree of probability. Would this result in a list with all possible causes "improbable", apart from one being "probable", then the actual root cause is found with a reasonable degree of certainty.

2.5 Declaration that the author has made all inquiries needed

Herewith I declare that I have been able to make all possible inquiries needed to identify the possible causes (including their related probabilities) and any relation to the way the Basslink cable was operated by (BPL) prior to the Basslink outage.

3 BACKGROUND INFORMATION

3.1 Voltage, electrical stress, current, power and temperature and how these are related

3.1.1 Voltage

HVDC (High Voltage Direct Current) systems for power transmission are normally operated at a certain voltage (potential difference) U, where the outside of the system such as the metal sheath is at ground potential (zero Volt) and the inner side (the metal conductor) is at a high DC voltage. In the case of a DC system, and thus also a HVDC system, the voltage is not changing over time, unless it is switched on or off for instance.

In between the conductor and metal sheath is an insulation material, which can be a gas or a solid material. For an overhead line, the insulation material is the air around the wire (conductor). For a power cable, the insulation material is often paper (impregnated with oil) or a plastic.

The system's potential difference U is measured in units of Volts, which is abbreviated to V or it is measured in units of kiloVolts, which is abbreviated to kV. This potential difference is present between the metal sheath at ground potential and the conductor. The potential difference is made by a surplus of plus charges in the conductor or a surplus of negative charges in the conductor, both in relation to the charges in the metal sheath. In the case of a surplus of positive charges in the conductor, the system is at positive voltage. In the case of a surplus of negative charges, the system is at negative voltage.

The insulation material is needed, otherwise the surplus of charges cannot be kept away from the grounded metal sheath. That is because opposite charges strongly attract each other. An inability of the insulation material to do so, will lead to a breakdown at its weakest spot. The attraction forces are incredibly high. Feynman /1/ said the following about this (and read in the following sentence for the electrons the negative charges and for the protons the positive charges): "*If you were standing at arm's length from someone and each of you had one percent more electrons than protons, the repelling force would be incredible. How great? Enough to lift the Empire State Building? No! To lift Mount Everest? No! The repulsion would be enough to lift a "weight" equal to that of the entire earth*". Were we dealing with a surplus of opposite charges for the above mentioned two persons, the word repelling can be replaced by attraction. In electrical systems the differences in numbers of charges are not that big as mentioned in Feynman's example, but still big enough to be extremely demanding for the purity of an insulation material, especially in the case of high voltages.

The high voltage for HVDC systems is in the range of a few hundred kV. In other words, the system is operated at a few hundred kV. The Basslink cable has a system voltage (U) of 400 kV.

The electrical voltage U is a more general expression, related to the system voltage. In the report, sometimes U_o is used, next to U. U_o is the rated DC voltage between conductor and core screen (grounded metal sheath) for which the cable and accessories are designed. Thus, U_o of the Basslink cable is 400 kV. For an AC system in the power industry, the U and U_o normally differ, but for a DC system as with the Basslink connection, U and U_o are identical, but used both in documents. Mainly, U_o is used in the case of defining testing levels, for instance by mentioning that a test voltage should be 1.4 U_o.

3.1.2 Electrical field or Electrical stress

It is not so easy to explain the electrical field or electrical stress in simple terms. A good introduction is given in /73/. In a few words one can see an electrical stress E as a force field that attracts or repels

electric charges. As such it is an important factor for the occurrence of electrical sparks, also called partial discharges, being localized dielectric breakdowns of a small portion of an electrical insulation system under electrical stress.

The system's electrical stress E is measured in units of Volts per meter, which is abbreviated to V/m or it is measured in units of kiloVolts per mm, which is abbreviated to kV/mm.

In a simple approach (just for illustration) one can see it as follows. Between the plates of a flat capacitor, of which the upper plate is at a certain voltage U and the bottom plate is grounded, the electrical stress is homogeneous in the insulation material between the two plates. The electrical stress is defined as the electrical voltage U divided by the distance between the plates d. For instance, if the electrical voltage U is 400 kV and the distance d is 20 mm, then the electrical stress in between the two plates E is 20 kV/mm. In this flat capacitor, the magnitude of this electrical stress is everywhere the same. For instance, it is found to have this magnitude of 20 kV/mm just under the upper plate with the high voltage as well as just above the bottom plate at ground potential. In a cylindrical configuration as a power cable the electrical stress close to the conductor is higher than the electrical stress close to the grounded metal sheath, due to the curvature and different radii of the two surfaces.

In the above description, it is assumed that the insulation material has homogeneous electrical properties.

3.1.3 Electrical Current

The above-mentioned conductor is normally carrying an electrical current I. It means that the surplus of charges is moving from one side of the system to the other side. By moving charges while the system is at a certain voltage level, power can be transmitted. Power will be introduced further in the next section.

The current is measured in units of Ampère, which is abbreviated to A. If during 1 s, 1 A is flowing, it represents a flow of about $6 \cdot 10^{18}$ electrons passing by. The 10^{18} represents a 1, followed by 18 zeros. The Basslink cable is designed, for instance, to transmit a current I of 1250 A on a permanent basis.

In the case of a DC system, and thus also a HVDC system, the current is only changing over time based on the wish to transmit more power or less power. In an AC (Alternating Current) system, the current is also periodically changing with a frequency of 50 Hz (for instance).

3.1.4 Power transmission

Electrical systems as the Basslink cable have the object to transmit power from one side of the system to the other side. The electrical power flow P for a HVDC connection is given by the multiplication of the system voltage U and the flowing current I. In other words, it follows the formula $P = U \cdot I$. The power is measured in units of Watt, abbreviated to W. For the Basslink cable, where the system voltage U is 400 kV and the transmitted current I is 1250 A, the transmitted power P is 500 000 kW, or P = 500 MW, where M stands for Mega. A quantity of 500 MW is in the range of power produced by a medium sized nuclear power plant. This 500 MW is the maximum continuous power for which the Basslink cable is designed to be transmitted. If less power has to be transmitted, then this is normally done by reducing the amount of current transmitted, while the system voltage stays unchanged.

3.1.5 Power transmission and voltage polarity reversals

In order to change the power flow direction one can choose to reverse the voltage or to reverse the current (not both). But since the convertor station set-up for Basslink (and many other HVDC connections in the world) is such that the current cannot be reversed, the only alternative is to reverse the voltage.

By reversing the voltage, one can choose to bring electrical power from Victoria to Tasmania or vice versa. The process of reversing the voltage comes with a so called "voltage polarity reversal".

3.1.6 Electrical current and cable temperature

Since any conductor has a certain electrical resistance, the electrical current flowing through the conductor will come with losses. Such losses mean heat production.

The amount of heat produced is directly related to the amount of electrical current I, flowing through the conductor and the electrical resistance R of the conductor. This power loss P_{loss} is related to the multiplication of the square of the current and the electrical resistance of the conductor. Thus, $P_{loss} = I \cdot I \cdot R$, or in other words, $P_{loss} = I^2 \cdot R$. This power loss is expressed in Watt (W).

If there is no electrical current flowing, the conductor losses are zero. Under full electrical load (where load reflects the current flowing through the conductor), the losses will reach their maximum. That is the most critical situation from a thermal point of view for a power cable.

Since the maximum conductor temperature for any power cable per design is limited to a certain temperature, the maximum current has to be limited as well. This results in the above mentioned 1250 A as the maximum continuous current for the Basslink cable, where the maximum conductor temperature and with that the maximum insulation temperature (close to the heat producing conductor) are [redacted]

This heat produced in the conductor, flows from this conductor to a cooler area, being the outer world (the soil and sea), via the insulation material, to the metal sheath and all other layers. All these layers together have a thermal resistance. Due to that, there is a temperature drop over all these layers. And thus, there is a temperature drop over the cable insulation material as well. It means, that as soon as the cable is transmitting power (and thus current is flowing through the conductor), the insulation near the conductor will be warmer than the insulation near the lead sheath.

The cable insulation is surrounded by semiconductive screens, also called screens or semiconductive tapes (see Section 3.2.3 to Section 3.2.4). The total thickness of these screens is small compared to the total thickness of the cable insulation. In the case where a cable is transmitting power there is not only a major temperature drop over the cable insulation, but also a minor one over these screens. For that reason, there are two temperature differences that can be taken into account, one is the temperature difference over just the cable insulation and one that is including the temperature difference over the screens as well. Materials not only have a certain thermal resistance, but also a thermal capacitance. It means that it takes time to heat up a cable. Roughly, it takes hours at full load (the maximum current flowing) to bring a cable from a certain starting temperature to its maximum temperature. This is illustrated in Figure 1 for a hypothetical cable (also an HVDC cable such as the Basslink cable), where the current is going from zero to its maximum load at t = 0, where the cable temperature takes hours to reach its maximum. The y-axis in Figure 1 represents per unit (pu) values for the cable temperature and cable current (see Section 1.7.2 for an explanation of per unit values).

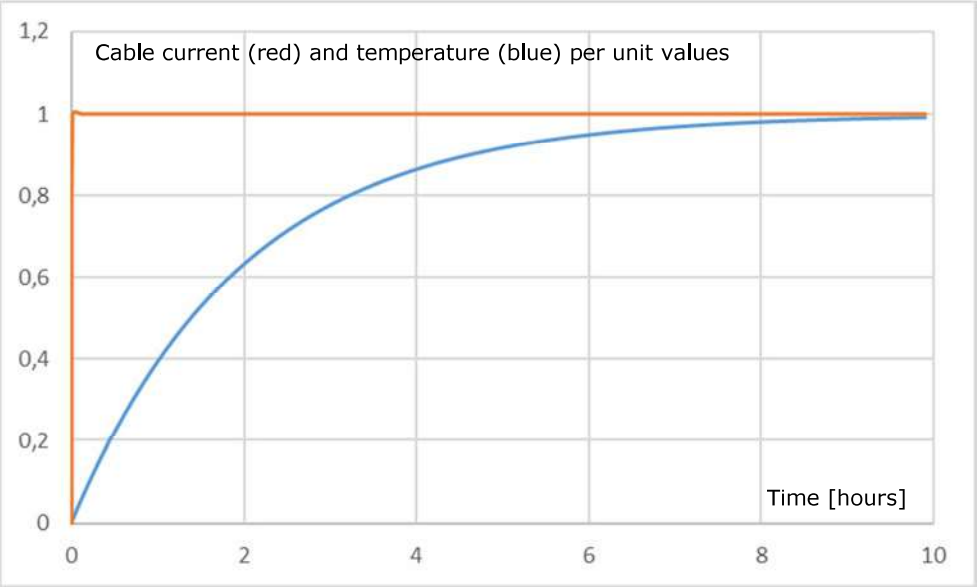


Figure 1 **Illustrative temperature response (blue line) of a hypothetical cable (also an HVDC cable) if the current (red line) is changed stepwise. The x-axis represents hours, the y-axis represents per unit values of both the cable temperature and cable current**

3.2 Mass impregnated power cables for HVDC, their construction and limitations

3.2.1 General

For the transmission of large amounts of electric energy across long sea crossings MIND HVDC subsea cables have for long been and, at the time of installation of the Basslink cable, were the state-of-the-art technology [/53/, Worzyk, 2009].

In [/40/, Runde, 2014], the following is said about recent installations. These "*operate at typically 450 - 500 kV and have a continuous power rating per cable of up to 800 MW. These all represent very large investments, and among them is the world's longest power cable,* [redacted]*, connecting the Norwegian and Dutch grids. Several new projects are under way, and in a future pan-European power grid subsea cables in the North Sea and the Mediterranean are expected to play a crucial role, both for exchanging power with continental Europe and for transferring power generated in large off-shore wind farms. Even though it is generally believed that cross linked polyethylene (XLPE) insulated cables will enter this market in the future, it is certain that MIND cable technology will remain the dominant solution for long times. The ability of this cable technology to handle the large mechanical stresses associated with installation at large sea depths has over the years been developed substantially, and today MIND cables are in operation down to 1650 m. The majority of the failures that have occurred during service have been caused by external factors, typical trawl doors and anchors. The reliability of the cable itself is in general found to be very good, indicating that the technology is robust and that the type testing has been sufficiently demanding*".

The general design set-up of a typical HVDC MIND paper insulated power cable will be introduced, with the help of an illustration shown in Figure 2 (the cable shown here is not the Basslink cable, but a 350 kV HVDC MIND power cable, installed in 1991 on the New Zealand HVDC Inter-island scheme). A good summarizing introduction on HVDC MIND power cables is given in Lawson's report [TAB 61].

In Section 3.2.2 to Section 3.2.9 the typical HVDC MIND power cable will be presented. More can be found amongst others in [/53/, Worzyk, 2009].

In Section 3.3 to Section 3.5 more will be said about the insulation material and its potential weaknesses. Potential weaknesses are important for the case at hand.

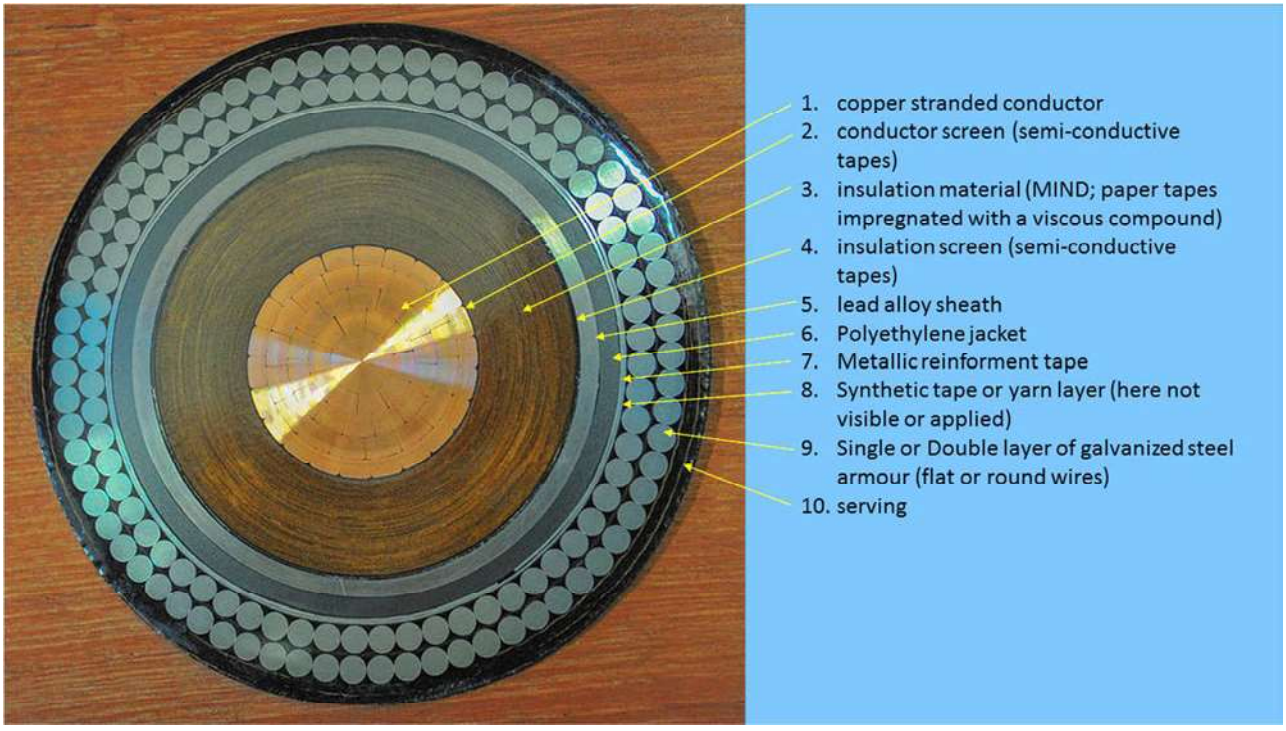


Figure 2 **Cross section of submarine cable rated 350 kV, 1430 A HVDC cable with MIND insulation, installed in 1991 on the New Zealand HVDC Inter-island scheme (reference: wikimedia.org)**

3.2.2 The conductor

To let a current flow from one side of the connection to the other side, a conductor is needed. The conductor is placed in the centre of the cable. A conductor is round and normally made of copper or aluminium wires. On transmitting power, the conductor is put on a high voltage.

Around the conductor there are semiconducting tapes, which main role is to ensure that there is a smooth conductive transition layer between the metal conductor and the insulation material.

3.2.3 The insulation material

To isolate electrically the conductor (at high voltage) an insulation material is needed. The reasons for having an insulation material are explained in Section 3.1.1.

The electrical insulation of HVDC MIND power cables consists of paper, impregnated with a viscous compound. It is this viscous compound which leads to the description "mass impregnated". This compound should not flow downhill in the case a cable is installed in a hilly area or a landing zone. By choosing the compound type correctly, i.e., with enough viscosity, it will not start to flow on an incline. Such cables are called "non-draining". This is the reason that such cables are called Mass Impregnated Non-Draining (MIND) cables.

The basis of the insulation material is paper, which comes in layers wound around each other. The paper layers are helically wound with small spaces in between, see Figure 3. These spaces are called butt gaps. These butt gaps are needed:

- To keep the cable flexible (with help of the compound, the paper layers can slide over each other without buckling or creasing)
- To allow the compound to penetrate the cable insulation during production.

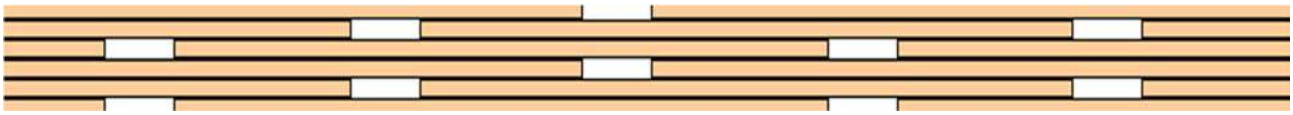


Figure 3 Artificial drawing of a few paper layers inside the insulation material of a MIND power cable. The spaces between the paper windings are called butt gaps

Some key issues of the cable insulation material, both in relation to the cable temperature, will be treated in Section 3.3 and Section 3.4. These are respectively:

- Void formation
- Electrical stresses.

3.2.4 Lead sheath

To prevent water from entering the insulation material, this insulation is enclosed by a lead sheath.

Under the lead sheath there is a set of layers of (semi-)conducting tapes, the main role of which is to provide a smooth conductive transition layer between the lead sheath and the insulation material.

3.2.5 Polyethylene (PE) jacket

Lead is a soft metal and not well able to withstand pressure from the outer protection layers without getting damaged. Therefore, a PE jacket (an alternative word is PE sheath) is used on top of the lead sheath and underneath the further outer layers.

3.2.6 Metallic reinforcing tapes

During operation, a power cable gets warm and cold, depending on the load. Such temperature variations come with expansion and contraction forces. During the contraction, the compound in between the paper layers tend to create voids during cooling down and voids exposed to an electrical stress can create partial discharges that can degrade the cable insulation (Section 3.3 elaborates on this key issue). In order to restrict the void formation, the cable insulation is put under an external counter pressure of reinforcing tapes that restrict the expansion of a warm cable.

These reinforcing tapes are often embedded:

- In polyester tapes to prevent the sharp edges of the metallic tapes damaging the PE jacket underneath and to allow sliding with respect to each other and with the various surrounding layers on installing the cable
- In bitumen to prevent the metallic tapes getting corroded by (sea) water.

3.2.7 Synthetic tape or yarn bedding

The purpose of the synthetic tape or yarn bedding is to prevent the heavy metal armour from damaging the layers underneath. During installation, these layers can assist the various surrounding layers to slide with respect to each.

3.2.8 Armour

The armour consists of one or two layers of steel (zinc coated) wires or tapes. The armour protects the submarine cable from getting damaged after it is installed, but also gives the cable mechanical strength while it is being installed. A double layer (with opposite pitch) is normally used to install the cable in deeper water given the heavy weight of the cable hanging on the installation vessel during its installation. By using an opposite pitch, the armour based torsion forces are eliminated.

3.2.9 Serving

The serving holds all components of the cable together and provides additional protection from external stresses. It is often bitumen impregnated, to avoid corrosion of the metal layers underneath.

3.3 Void formation - a key issue for the insulation material

3.3.1 Introduction

As an introduction to void formation in the cable insulation of a HVDC MIND power cable, it is relevant to understand the way the insulation material of such a cable is manufactured, as will be shown in Section 3.3.2.

Void formation in such cables is introduced in Section 3.3.3, followed by information on cable failures and their background, such to understand whether void formation has been recognized as critical for MIND HVDC cables or not, see Section 3.3.5.

The Basslink cable was produced in a period of time where the insulation material properties were changed (made more compact), such to be able to withstand the higher operating voltages (and related transmission levels). That will be introduced in Section 3.3.6, which will be followed by the expected void formation in such cables in Section 3.3.7 (discussing the formation of smaller voids) and Section 3.3.8 (discussing the formation of enlarged voids).

3.3.2 Insulation material

As mentioned in Section 3.2.3, the insulation material of a HVDC MIND power cable such as the Basslink cable consists of many paper layers and in between these layers is a compound (also called 'mass' of 'impregnant', being the reason to call such a cable 'mass impregnated').

Paper thicknesses are in the range of 100 μm. A HVDC MIND power cable such as the Basslink cable can have around 200 of such paper layers.

Adjacent paper winding turns are separated from each other by a small gap in the range of 1 mm. Such a gap is called a butt gap. On following the paper windings, butt gaps are spiralling around the cable in a helix.

On cable production larger empty spaces (large voids) inside the paper insulation (especially the butt-gaps) have to be filled up with the above-mentioned insulating compound.

Thus, during production the papers are impregnated with a compound at an elevated temperature, typically around 120 °C, for several days. Because prior to the impregnation process, the paper windings were vacuum dried, the compound (at these elevated temperatures) will penetrate the paper windings and will fully fill the butt gaps. After that, the cable is slowly cooled down (a matter of weeks) and during this period more compound will penetrate the cable as long as the compound is sufficiently fluid. This further impregnation happens, because the compound shrinks on cooling down, which requires additional compound. Once the impregnation virtually ceases, at a temperature of 50 °C to 55 °C, the lead sheath and other external layers are applied to cover the cable insulation. The lead sheath is a water barrier. Further external layers, in particular the steel reinforcing tapes, have the function to keep the insulation material under a certain pressure while the cable goes through expansion and contraction under thermal load cycles. These thermal load cycles are associated with the load cycles coming with power transmission. The pressure is there to help to prevent uncontrolled void formation, see also Section 3.2.6 and the discussion below.

The above-mentioned temperature of 50 to 55°C is quite essential. Below this temperature the diffusion of the compound through the paper insulation is not or hardly possible. Runde /40/ wrote that based on information from Alcatel (referring to a personal communication with Balog from Alcatel): "*the impregnation process virtually ceases at a temperature of about 50/55°C*".

This means also that above this temperature limit, migration of the compound is possible again. This has implications for (enlarged) void formation as will be explained later. That is also the reason, that 50 °C to 55 °C is considered to be the maximum operation temperature. Runde /40/ wrote in introducing his analysis: "*The conductor temperature is in all cases set to 50 °C, typically considered the maximum safe operating temperature for such cables*".

Also Lawson [Tab 61, 2014, page 12] wrote: "*Electrical discharge in voids created by operating HVDC MI cables at temperatures in excess of the design limit of 55 °C is, therefore, the primary technical risk associated with operating HVDC MI cables outside their design limits*".

Note:

The HVDC MIND Moyle cable, manufactured by Nexans, is designed to operate at 60 °C (Balog, 2002, /78/). [redacted] However, I have the opinion that the Moyle cable and its high design maximum conductor temperature of 60 °C cannot be used as a reference for the traditional HVDC MIND power cable (such as the Basslink cable) for the following two reasons:

- The construction of the Moyle cable is fundamentally different from the Basslink cable and most other HVDC MIND power cables used around the world. The Moyle cable has a copper return conductor surrounding the PE jacket and lead sheath on top of the main insulation, see this illustrated in Figure 4. This potentially results in a different temperature profile and other pressures inside the cable insulation. It is unclear whether this typical Moyle cable construction has an impact on the formation or suppression of the formation of enlarged voids

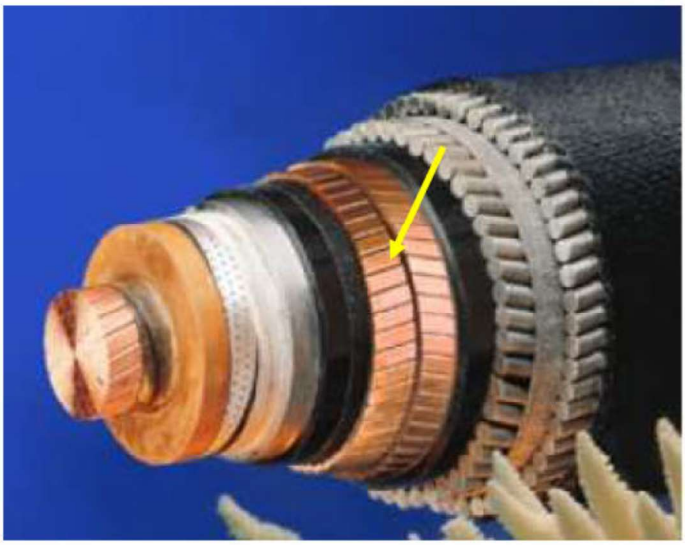


Figure 4 **Moyle cable /78/, with the copper return conductor identified with the yellow arrow. The copper return conductor in this Moyle cable replaces the reinforcing tapes (item 7) as mentioned in Figure 2**

- It is unclear whether the Moyle cable has been operated at this thermal limit of 60 °C.

3.3.3 Void formation in general

Voids in literature are sometimes referred to as cavities.

Many papers describe the insulation material of HVDC MIND power cables and their potential weaknesses related to void formation, especially appearing or enlarging during the cooling stage.

A good introduction on this subject of void (cavity) formation is given by Runde [/40/, 2014]. Runde wrote: "*... generally assumed that the breakdowns are caused by the formation of extended cavities*[4] *in the insulation during a load reduction or turn-off. The cavities are thought to be a result of the thermal expansion and contraction of the impregnant*[5] *being much more that that [sic] of the paper*".

I will often refer to Runde, though where appropriate, also other input information will be mentioned.

The following authors will be mentioned regularly in this section and their references are mentioned here:

- Evenset who published his paper in 2000 /29/
- Runde who published his paper in 2014 /40/
- Balog, being reference 13 in the above mentioned paper from Runde /40/.

Runde and his co-authors cite many different publications, among which they refer to work undertaken by Evenset from Alcatel (now Nexans, one of the major cable manufacturers) and to a personal communication with Georg Balog, also from Alcatel. The author's full name is Magne Runde and his co-authors are Rolf Hegerberg, Niklas Magnusson, Erling Ildstad and Tor Ytrehus. At the time of publishing

[4] Extended cavities are enlarged voids, which can be present in butt gaps, but can sometimes further grow in between the paper layers, which is called a wedge action.

[5] The 'impregnant' is what I call 'compound'

their paper, the authors worked for Sintef and the Norwegian University of Science and Technology (NTNU). Sintef is a highly regarded independent research organization founded in 1950 that conducts contract research and development projects. Their work was sponsored by three major power transmission utilities, Statnett, National Grid and TenneT, as well as the Research Council of Norway. I conclude that there is enough combined know-how in these companies to judge Runde's work. For these reasons, I consider Runde as a reliable reference.

In Appendix O, the void formation according to Runde is visualized. In summary it is as follows. When during production the cable is fully impregnated, at 50 °C or 55 °C and the cable has its lead sheath, the cable is further cooled to room temperature. A crucial aspect of the compound is that it is shrinking considerably more than the surrounding paper layers and other materials. According to Eriksson [/92/, 1994], the thermal contraction of the compound is around ten times more than paper. As a result, on cooling down the existing compound thermally contracts, but insufficient additional compound enters the insulation to compensate this. Consequently, multiple small (normal) voids will be created, mainly inside the butt gaps, because these butt gaps contain most of the shrinking compound and the surrounding paper layers cannot follow this shrinkage.

3.3.4 Voids and risk on failure

Small (normal) voids are not a problem during normal cable operation. But when in one or another way during testing or operation large voids are created[6], then there is a potential problem. If the cable is operating under voltage, then such large voids (enlarged voids) give rise to the risk that electrical partial discharges can occur inside or from these voids which can result in the surrounding material to degrade. Once degradation has started, further degradation is possible, such as puncturing the paper layers around the void and/or the formation of a tree like structure of burned material crossing the insulation material called electrical trees, which are normally followed by a breakdown (failure).

Because of the shrinkage of the compound, such enlarged voids can mainly be created during the cooling down period of a HVDC MIND power cable.

In [/40/, Runde, 2014] it is said: "*… the cooling period after load reduction or turn-off is the most critical part of the dielectric type test and thus presumably also for the operation of a subsea mass impregnated HVDC cable. Moreover, it is assumed that dielectric breakdowns under such conditions are caused by formation of excessively large cavities or voids in the insulation".*

In my opinion, the following papers illustrate this potential risk of enlarged void formation, because on increasing the transmission capacity and in order to protect the cable from failing, the voltage during the change of the power direction (and related cooling down) is reduced by 20 % [/22/, Nyman, 1996][/74/, Elovaara, 2002]. They mentioned that this was a regime that started with the [redacted] cable and that happened to the [redacted] after two years of operation. In this way, the voltage is reduced during the cooling down stage (with its related void formation), which reduces the risk on failure.

Appendix J gives an example of partial discharge activity under DC circumstances in a HVDC MIND power cable, [redacted] showing that void formation (in which partial discharges which could be measured occur) as expected happens during the cooling down or turn-off of a power cable. Also Runde [/90/, 2019] showed such partial discharge activity during cooling down of a HVDC MIND power cable, although Runde measured these partial discharges with an AC source.

[6] Especially this can happen in a cable operated above its thermal design limits. This subject is further elaborated on in Section 3.3.8 ("Enlarged void formation in compact insulation").

Especially, when a cable is operated beyond its thermal design limits, there is a risk on failure (in which voids or enlarged voids play a role). There are two ways to run a cable beyond its thermal design limits:

- The maximum temperature at the conductor side of the insulation is beyond its design value
- The temperature difference over the cable insulation is beyond its design value.

Both are issues of concern, because the first one or a combination of both will contribute to enlarged void formation during the cooling down. More about enlarged void creation mechanisms is written in Section 3.3.8 ("Enlarged void formation in compact insulation").

If the temperature difference is beyond the design limits there is another issue. In such a case the electrical stress in the outer layers of the cable insulation exceeds the maximum design electrical stress. In this case normal voids (not per definition enlarged) will be challenged. This is explained in Section 3.4 ("Electrical stresses inside the cable insulation - another key issue of the insulation material").

These thermally stimulated degradation processes are summarized in Appendix V.

I investigated whether thermal degradation comes with reversible or irreversible degradation. Several authors from publications [/30/, Bossio, 2002], [/33/, Morshuis, 2005], [/40/, Runde, 2014] and [/87/, Huang, 2015] mention, and also from personal interviews I found, that this degradation is irreversible. None of the publications or interview results mention that thermal related degradation is reversible.

As a result, manufacturers made and are making an effort to suppress enlarged void formation. This effort will be discussed further Section 3.3.6 ("Development of the insulation material in order to reach higher power transmission").

3.3.5 Cable failures

3.3.5.1 Introduction

Authors that mention void formation during cooling down and related cable failures in HVDC MIND power cables are Gazzana [/76/, 1968], Lawson [/14/, 1978], Gazzana, [/19/, 1992], Nymann, [/22/, 1996], Evenset and Runde.

Cable failures can happen during testing (in particular during Type Testing) or during service operation. Both will be treated below.

3.3.5.2 Cable failures during Type Testing

Part of the design test of a cable is a Type Test. And part of the Type Test is a load cycle test where a cable sample of about 50 m representing the full cable (to be) produced is selected. In the Type Test this cable sample goes through thermal load cycles (load cycles) from room temperature to a temperature in between 55 °C to 60 °C and back. During these load cycles, the cable is kept at a certain test voltage level.

The most critical stage of the Type Test is the cooling down stage that is part of each load cycle. A breakdown of the HVDC MIND power cable insulation is most likely to happen during this part of the Type Test. Authors attribute this breakdown to the fact that not just voids are created, but that some of these voids become relatively large if these voids are able to grow in between the paper layers (being called 'wedge action'), resulting in partial discharge activity that reaches levels to create degradation (puncturing paper layers and/or electrical treeing in between the paper layers) followed by a breakdown.

Gazzana [/19/, 1992] gave the following more extensive explanation of the breakdown mechanism during the cooling down stage during Type Testing: "*The critical situation which strongly affects the DC*

breakdown level under cooling is originated by a mechanical instability of a floating large laminar void, which can be suddenly formed and may grow to an undefined size in a soft insulation during the thermal contraction of the compound under D.C. voltage. This effect can be explained by the unbalance of the tangential electrostatic forces acting to expand an arising void against the mechanical pressure between papers, their adhesion due to the compound, their electrostatic attraction, and the mobility and viscosity of the compound. A contribution to this mechanism is also due to the presence of very high free electrostatic charges trapped at the surface of a suddenly arising void which can produce high energy discharge capability".

On cooling down a cable, once a breakdown occurs, it can happen that the breakdown area is elongating along a certain length, but it can also be more radial under isothermal[7] conditions or when the paper layers are more compacted as can happen with a higher lapping tension combined with the support of reinforcing tapes. Concerning this there are two references. [/19/, Gazzana, 1992]. He wrote: "*A peculiarity of the breakdown occurring during the cooling phase is that the breakdown tracking is always elongated, from 1 to 2 m or longer, following a longitudinal path between paper layers, starting apparently from a single position, generally far from the terminals. No polarity effect is observed. No electrical trees are found in points other than the breakdown tracking. In isothermal condition the breakdown path is instead mostly radial*". Also [/29/, Evenset, 2000] concludes the following for a breakdown of a HVDC MIND power cable in the cooling down stage: "*The breakdown paths were very long, usually had an axial length of 1 m to 1.5 m, occasionally even longer. …… we developed the MI insulation by increasing the lapping tension and changing the paper insulation. …… The breakdown path for the DC breakdown changed substantially, it was short, in the order of 200 to 300 mm axially. The breakdown path for the superimposed impulse was still long, around 1 m.*"

3.3.5.3 Cable failures during operation

As mentioned already in Section3.3.1 "(Introduction)", Runde in 2014 wrote: "*The majority of the failures that have occurred during service have been caused by external factors, typical trawl doors and anchors. The reliability of the cable itself is in general found to be very good, indicating that the technology is robust and that the Type Testing has been sufficiently demanding*".

It was reported by [redacted]

But occasionally there have been failures not related to external damages:

- I interviewed several European HVDC MIND power cable operators, operating twelve of these cables (see Appendix U for a summary of the outcome). Out of their twelve HVDC MIND power cables, one cable had failures after the load was increased (although keeping the maximum operating temperature below 55 °C, as I was informed by the cable operator). It is not certain whether the cable has soft or compact insulation (see for the difference between soft and compact insulation Section 3.3.6)
- Worzyk, 2009 stated in his book [/53/: section 9.2] that "*Unfortunately cable operators are somewhat reluctant about reporting failure statistics*", being in line with DNV GL's experience. Certain failures with HVDC MIND power cables are mentioned in Worzyk's book [/53/: Section

[7] Isothermal means here that the temperature at the inside and outside of the insulation material are the same

9.2.2 (table 9.2)] informing about internal faults, showing that although the majority of cable issues are caused by external damages, there are cable insulation issues as well

- DNV GL has investigated the failure of a HVDC MIND power cable failure with insulation material that can be considered as [redacted], taking into account its installation year and voltage level. The failure occurred in an area where the cable experienced relatively high temperatures due to circumstances, where these temperatures are expected to have been close to [redacted] This cable failed during cooling down, indicating that enlarged void formation has played a role. Classified information
- DNV GL is going to investigate several HVDC MIND power cable failures with insulation material that can be considered as [redacted] and taking into account my first observations most probably did not fail because of external damages.

3.3.6 Development of the insulation material in order to reach higher power transmission

In order to reach higher transmission power levels, generally system voltages are needed in the range of 400 kV or higher. For that, manufacturers wanted to improve the HVDC MIND power cable construction to prevent the cable from failing in the cooling down stage of a Type Test for such cables. In that regard they took measures to reduce the enlarged void formation in this cooling down stage.

The most promising step to achieve this was to put the paper windings around the conductor with a higher tension. In this way enlarged voids and in particular the wedge action of such voids can be reduced. In other words, manufacturers went from soft to (more) compact insulation. This development occurred during the 1990s, reported by:

- Pirelli (now Prysmian): Gazzana, 1992 /19/, Gazzana, 1993 /77/
- Alcatel (now Nexans): Evenset, 2000 /29/.

From the discussions I had, referenced in Appendix U, it would appear that since the late 1990s most if not all manufacturers started to make more compact insulation to reach the higher system voltage. [redacted]

In my first Failure Investigation Report I already made reference to measures to this development and although I did not use the word 'compact' insulation, my description (quoted next) could have made clear that my investigation included 'compact' insulation, see [Steennis, /80/, 2017, Section 5.2.10.1, § 2]: "*To prevent the impregnant from migrating from the inner layers near the conductor to the outer paper windings, the paper windings are wound with a certain tension. Moreover, outside the lead sheath, steel tapes (called reinforcement tapes) can be wound during production with tension giving additional force to keep the paper windings tightly compressed, especially during the cooling stage. That is needed to avoid that on cooling down the impregnant, contracting more than the surrounding paper, will give rise to void formation*".

In that respect, CCI's statement [TAB 76, § 830]: [redacted] is inaccurate. In Section 3.3.8 ("Enlarged void formation in compact insulation"), I will show that enlarged void formation cannot be excluded in the case of [redacted] if such insulation material is thermally overstressed.

[redacted]

3.3.7 Formation of small (normal) voids in cables with compact insulation

Because the formation of small (normal) voids is a consequence of the different shrinkage rate between the compound and the paper windings of the cable insulation during cooling down, the creation of small voids will occur in both soft and compact cable insulation. That such void formation occurs in cables even with [redacted] is also mentioned by CCI [TAB 76, § 77]. Such small voids are expected not to be related to degradation and failures, at least, not on a short-term basis and in the absence of an electrical stress beyond the relevant design electrical stress level.

3.3.8 Enlarged void formation in compact insulation

CCI wrote [TAB 76, § 932]: [redacted]

CCI [TAB 76, § 824] stated [redacted]

In summary, concerning the risk on enlarged void formation (and I quote some words from the first paragraph) CCI mentioned that [redacted]

The issue of enlarged void formation in [redacted] is treated here. [redacted]

[redacted] Enlarged void formation is still possible, in particular in the insulation of a thermally overstressed HVDC MIND power cable. There are published papers that discuss directly or indirectly breakdown and enlarged void formation in compact insulation. These will be treated below in Sections 3.3.8.1 to 3.3.8.3.

[9] Produced between 2003 and 2005, see Section 4.1.

3.3.8.1 Enlarged void formation according to Evenset

Alcatel [/29/, Evenset, 2000] reported the following about the breakdown in his experiments in the case of a more [redacted] material (with more interface pressure between the paper layers): "*The results from the development programme showed that the electrical properties of the insulation during thermal cycling are significantly improved by* [redacted]. *Although the DC breakdown occurred during cooling with both designs, the breakdown paths were mostly radial in the insulation with high interfacial pressure instead of axially along the paper interfaces. This difference in the propagation of the breakdown is probably related to the formation and growth of cavities in the insulation during cooling*".

With that, the breakdown in more [redacted] material is still taking place during the cooling down stage, although at higher voltage levels ("*properties improved*"). Evenset said in his introduction: "*… the effect of increasing the interfacial pressure in the insulation is probably to reduce the size of the cavities formed during cooling and therefore the reduction in the dielectric strength is less pronounced"*.

Note that Evenset does not write that enlarged voids are not created anymore, but that their sizes are reduced. Evenset mentioned as well that also for [redacted] the breakdown still happens in the cooling down stage ("*the DC breakdown occurred during cooling with* [redacted]*"*) and that brings me to the conclusion that most probably also in [redacted] there is potentially enlarged void formation prior to breakdown.

3.3.8.2 Enlarged void formation mentioned by Runde

It is mentioned by Runde, that in a thermally overstressed cable, the compound (which he calls 'mass') tends to migrate to the outer regions of the insulation, leaving behind larger voids near the inner side of the insulation. This is an irreversible process. Runde [/40/, 2014] wrote about this: "*…… a high load may lead to a permanent redistribution of the mass in the radial direction. When the load is turned off, this may cause excessive cavitation in the inner part of the insulation because the mass deficit here has increased*".

A similar description of this compound migration, Runde mentioned in his more recent paper [/91/, 2020, Section 4, § 4], referring to state of the art HVDC MIND power cables in excess of 500 kV.

Runde /40/ wrote also that it appeared that "*the initial cavity growth occurred along the butt gaps, provided that a sufficient compressive force was applied. Consequently, in a cable it is expected that if the plateau pressure is sufficiently high, cavitation takes place only in the butt gaps, at least in the beginning*". Runde wrote as well: "*This apparently reduces the tendency for cavities to expand between the paper layers to neighboring butt gaps, thereby establishing a discharge channel. Tests with tighter lapped paper have shown a substantially higher dielectric strength during load turn-off, although the breakdowns that eventually occur show, to a large extent, the typical features of load cycling breakdown."* (after this sentence, Runde is referring to Evenset [/29/, 2000]). Runde continues with the following words: *"Consequently, excessive cavity formation during load cycling remains a critical phenomenon that is associated with the most challenging part of the type test"]*, with my underlined emphasis.

In other words, [redacted] a similar process of enlarged void formation is still possible and is thus not fully suppressed (Runde used the wording '*reduces*', not the wording 'cancelled').

Runde wrote further "*…. the maximum temperature the insulation experiences and the temperature difference across the insulation during rated load current are assumed to be the most influential parameters when considering the risk for load cycling breakdowns*". It is my view that Runde's

expression '*risk for load cycle breakdowns*' means that there is a risk for enlarged void formation in a thermally overstressed cable.

Runde also wrote that under these circumstances there is potentially more radial mass flow under external pressure. This means that the [redacted] of the sea water above the cable is not per definition considered as an advantage preventing the formation of enlarged voids.

3.3.8.3 Enlarged void formation physics according to Huang

A possible complication of creating a [redacted] is the fact that at high load (and with that high temperatures) there is [redacted] and such can come with considerable thermo-mechanical forces during high loads [/87/, Huang, 2015]. If the [redacted] become too high, Huang /87/ writes: "*… the sheath may go through permanent plastic deformation if its yield strength is exceeded. Subsequently on cooling, the sheath cannot return to its original position, while the insulation contracts normally. As a result, the interior of the sheath is no longer completely filled and cavities occur*". This is an alternative way to create voids, potentially enlarged voids, but in the outer edges of the cable insulation.

Also Runde mentioned in his more recent paper [/91/, 2020, Section 4, § 10] the possibility of such a permanent plastic deformation of the layers outside the cable insulation.

3.3.8.4 Experimental evidence

Huang /87/ notes that it is difficult to observe what is happening in a thermally overstressed cable. He writes: "*However, the complicated mechanism is hard to examine through experiments and even advanced numerical models …. can only reflect the above process in qualitative terms*".

3.3.9 Evidence for enlarged voids after a failure in a HVDC MIND power cable with compact insulation

If an enlarged void forms in a HVDC cable with MIND paper insulation, it is expected to be highly localized, this is particularly so with [redacted]. The resulting sparking, puncturing paper layers and/or electrical treeing happen locally as well. Outside the breakdown channel, evidence for this type of failure is normally not found.

This has been mentioned by Pirelli in laboratory tests [/77/, Gazzana, 1993], where enlarged voids are expected by Gazzana to have caused the breakdown. Gazzana wrote: "*From the observation of the breakdown tracking it appears also that there is only one void in which the electrical discharge is originated, given the absolute absence of electrical treeing in the remainder of the insulation. Very likely it should be the most critical void, i.e. either the most highly stressed or the weakest one*". "*In any case if partial discharges appear in more than one void, they should have such an intensity or duration unable to leave any visible trace*".

From Gazzana's paper I read that the above-mentioned observation was valid for '[redacted]' where the chance of having enlarged voids is larger than in '[redacted]'. That reduces further the probability to find enlarged voids after a breakdown in cable with '[redacted]'.

It should be appreciated that a breakdown occurring in laboratory conditions, as reported by Gazzana, will exhibit much less damage to the cable compared to a failure occurring in service. With that, the extent of damage of a failure in service (and failed because of enlarged void formation) further limits the chance to find traces of such enlarged voids and related degradation processes near the breakdown spot in cables.

One can even question whether another enlarged void outside the destroyed breakdown area (if any would (still) be present) could be easily recognized. If it is there, it is expected to be inside or around one of the butt-gaps with a typical butt-gap depth of around 100 µm (paper thickness) and typical width around 1 mm. The length of the enlarged void might be in the range of a few millimetres along a butt gap. In the remainder of the butt-gap and in between the paper layers there is compound. On removing paper layers, the compound will partly end up in compound strings. An example of such a situation during dismantling of a HVDC MIND power cable is shown in Figure 5. On removing paper layers, enlarged voids (if (still) present) would be very difficult to observe in between the clearly visible compound strings during a dismantling operation. In short, the answer to the question whether 'another enlarged void outside the breakdown channel could be easily recognized' is that it will be (almost) impossible to recognize such an enlarged void in between the compound strings.

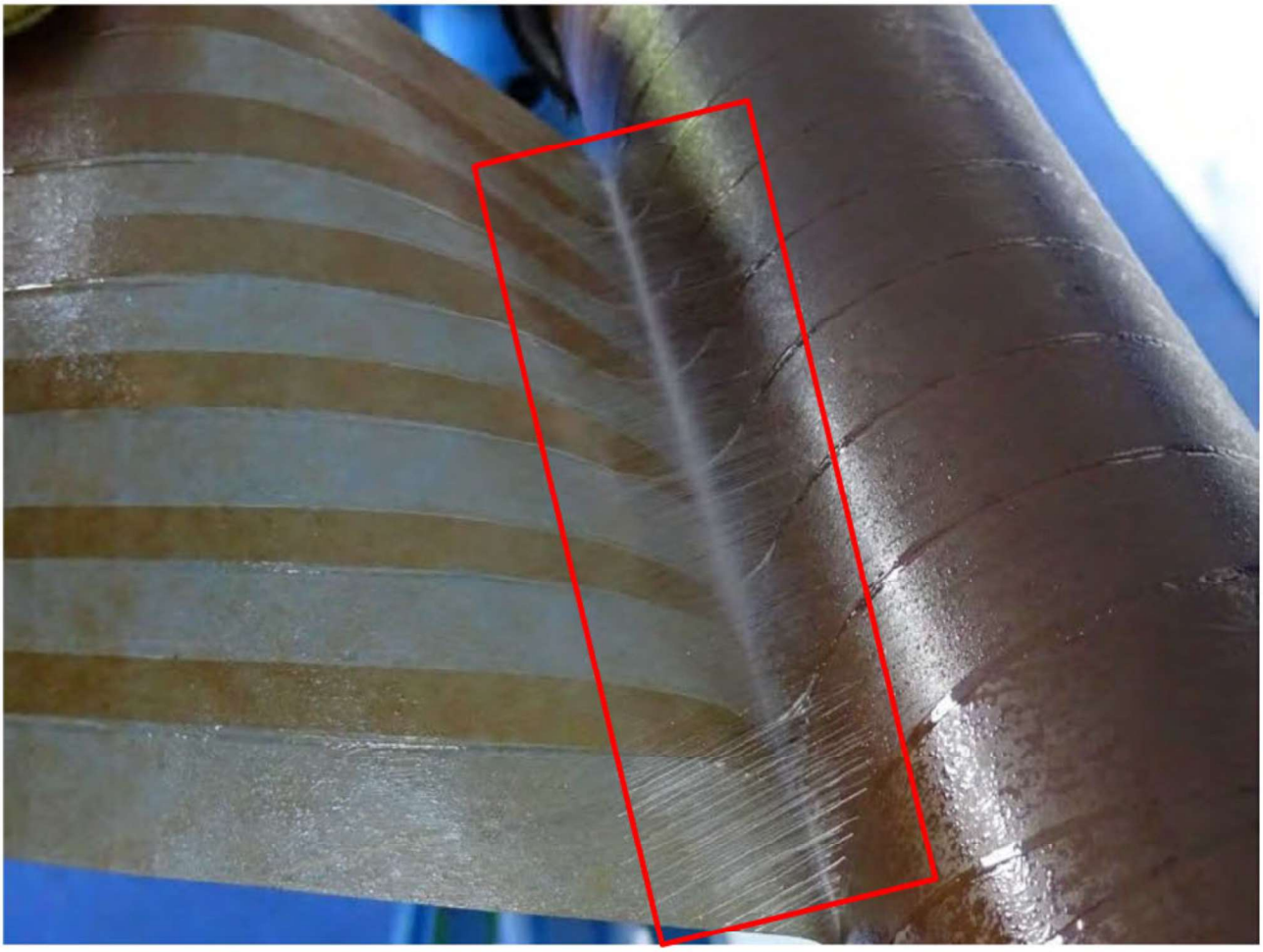


Figure 5 **Compound strings (red rectangle) as seen during dismantling a HVDC MIND power cable, obtained during one of the failure investigations on such a cable done by DNV GL**

As long as enlarged voids (if present) outside the breakdown channel are small enough, it would also not come with electrical activity able to degrade / puncture the surrounding paper layers, reducing further the chance to identify signs of degradation.

All this is resulting in a low probability that evidence for enlarged voids outside the breakdown channel can be found visually, even if the breakdown was a consequence of an enlarged void.

CCI wrote [TAB 76, § 932]: [redacted] As I made clear in this Section, such evidence is not expected to be found, and the lack of that evidence cannot exclude enlarged void formation.

3.4 Electrical stresses inside the cable insulation - another key issue of the insulation material

3.4.1 Introduction

If a cable is under voltage, there is an electrical stress everywhere in the insulation material, also near the conductor and near the lead sheath.

Electrical stresses are a main driver behind the creation of partial discharges in and around voids (whether these are normal or enlarged in size). It is therefore necessary to take into account the electrical stresses when considering the issue of cable degradation.

The increase of electrical stresses can come from two different sources:

- Firstly, it is the high electrical stress directly related to the operation temperature, which will be treated in Section 3.4.2
- Secondly it is the high electrical stress that happens during voltage polarity reversals, introduced and explained in Section 3.4.3.

3.4.2 Temperature related electrical stress distribution in the insulation material

3.4.2.1 Introduction

The electrical stress distribution in the insulation material of any HVDC cable depends on the temperature distribution inside the insulation. That has to do with the fact that the electrical stress distribution depends on the conductivity of the insulation material and that this conductivity in turn depends on the insulation material temperature. Under isothermal conditions, the electric field is highest at the conductor side. However, when the cable is carrying a load (a current is flowing through the conductor), the conductor heats up and the insulation material at the conductor side gets a higher temperature than at the lead sheath side. As a result, the electrical conductivity of the insulation material near the conductor gets lower compared to the one near the lead sheath. These differences are such, that under load conditions the electrical stress at the lead sheath side of the insulation increases compared to the no load condition.

This phenomenon, for an HVDC MIND power cable, is illustrated in various publications, among which in [/4/, Occhini, 1967], [/2/, Hampton, 2000] and [/40/, Runde, 2014].

From [/4/, Occhini, 1967] an illustrative figure is copied below in Figure 6. The electrical stress distribution shown here is obtained after a certain time and is therefore called "steady state electrical stress". For this particular HVDC MIND power cable, the steady state electrical stress under full load at the outside of the cable insulation is higher than the steady state electrical stress at no load on the inside of the cable insulation. The actual steady state electrical stresses for any other HVDC MIND power

cable will differ from this since these will depend on the design (material properties, dimensions) and the actual temperature, but the trend will be the same.

3.4.2.2 Conclusion

The steady state electrical stress is influenced by the temperature difference and is therefore a reason or one of the reasons for manufacturers to limit this temperature difference. At temperatures beyond that temperature difference design limitation, the steady state electrical stresses in the insulation near the lead sheath exceed the steady state electrical stress design levels (i.e. maximum permissible electrical stress).

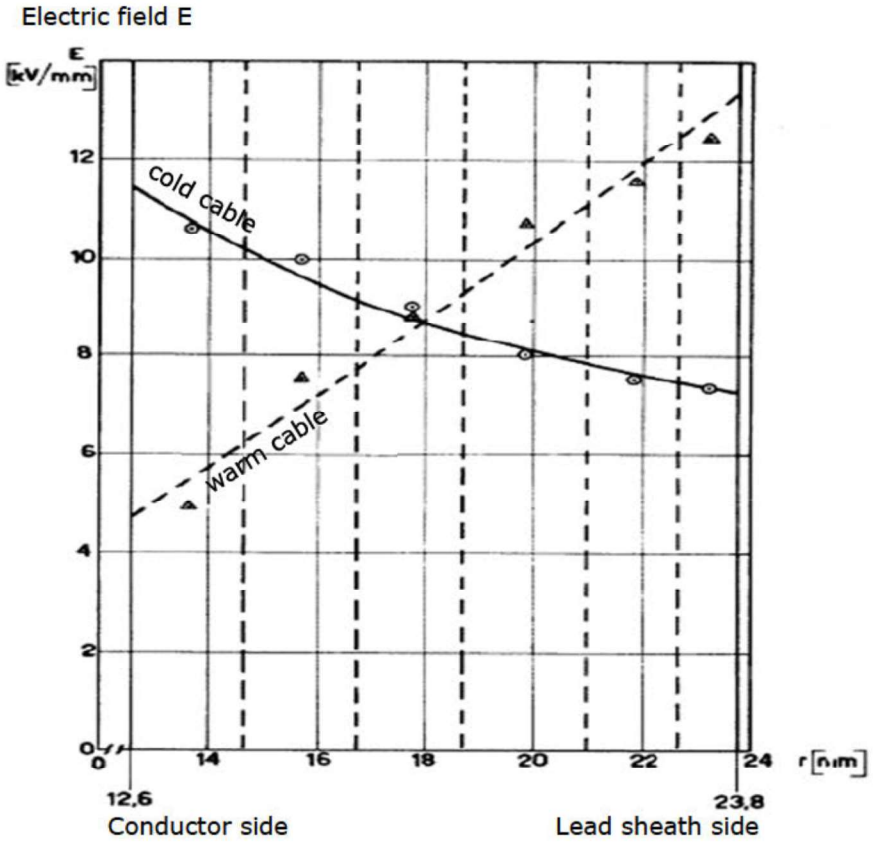


Figure 6 **The steady state electrical stress over the insulation material of a typical HVDC MIND power cable. At 12.6 mm is the conductor side, at 23.8 mm is the lead sheath side. The continuous line represents the electrical stress distribution of the steady state condition of a cable without a temperature difference over the cable insulation. The dotted line represents the electrical stress distribution as a steady state condition of a cable with a 20 °C temperature difference (with the conductor being warmer) [/4/, Occhini, 1967]**

3.4.3 Electrical stress during voltage polarity reversals

3.4.3.1 Introduction

As was introduced in Section 3.1.5, for the Basslink cable, the change in direction of the power flow involves a voltage polarity reversal. This may take place a few times per day.

Voltage polarity reversals come with a redistribution of charges. This redistribution is a slow process and as a result such voltage polarity reversals increase the electrical stress inside the cable insulation temporarily. This is further explained in Appendix P.

For that reason, these voltage polarity reversals potentially contribute to the degradation of the insulation of HVDC MIND power cables.

For that reason:

- I carried out a literature survey with a focus on voltage polarity reversals, with the purpose to get a complete picture of this phenomena and to verify its relevance for the degradation of HVDC MIND power cables. A summary is given in Appendix P
- I also interviewed various European operators of HVDC MIND power cables (together operating twelve different HVDC MIND power cables) to check their opinion on the relevance of voltage polarity reversals. The outcome is presented in Appendix U.

3.4.3.2 Findings

In short, the following can be said about voltage polarity reversals and their impact on the HVDC MIND power cables:

1) During and after a voltage polarity reversal, the electrical stress in the insulation at certain locations is much higher than the steady state electrical stress. Thus, voltage polarity reversals come with a considerable increase of the electrical stress. The combined green and red curve in Figure 7 illustrate this, where the voltage polarity reversal is done at moment 0. Only after a certain time, the steady state electrical stress will be reached again, but this will take many minutes if not hours, meanwhile redistributing electrical charges inside the insulation material. Alternative words used for this redistribution are deionisation and discharging

2) The extent of the increase of the electrical stress and speed of the deionisation in a HVDC MIND power cable depend on the cable design (diameters, actual insulation material applied), the temperatures of the insulation and the electrical stress inside the insulation, both as a function of time. In a warm cable, the process of deionisation is faster than in a cold cable

3) Because of that, in order to avoid electrically over-stress, degradation, ageing and breakdown of the insulation material, the frequency and time to perform voltage polarity reversals are design issues for HVDC power cables in general, and MIND HVDC power cables as well. In line with this, voltage polarity reversals are part of Cigré's Electra 189 [/28/, Cigré, 2000] recommended testing regime

4) For the same reason, in general cable operators often take the increase of the electrical stress during a voltage polarity reversal as an operational matter. By performing a slow voltage polarity reversal (by slowing down the ramping rate or by introducing a stepwise voltage polarity reversal with a certain dwell time, as is illustrated in Figure 7 with the combined green – blue curve), the insulation material will be less stressed electrically than in the case of a full voltage polarity reversal done instantaneously. For instance, in [/35/. Skog, 2006] said that the default voltage

polarity reversal time for the [redacted] HVDC MIND power cable link is 1 hour, but in the case of marketing constraints can be reduced to 14 minutes (assuming full power). And in [/31/, Giorgi, 2002] for the [redacted] HVDC MIND power cable link, the voltage polarity reversal time is 10 minutes, with up to 1000 voltage polarity reversals per year with a minimum time interval of 2 hours

5) It was reported by Prysmian (formerly Pirelli) in [redacted] Mostly, there were external problems causing the cables to fail, see also Appendix C. Also from 2006 until now, there are no confirmed known failures reported during service operation, where clearly voltage polarity reversals caused the failures. However, it is my own experience that a failure (which I investigated) has occurred in a HVDC MIND cable 3 minutes after a voltage polarity reversal. But here it was concluded that the voltage polarity reversal had been a trigger in an already aged cable section, while the root cause was related to something else.

   In that respect, CCI's remark [TAB 76, § 793]: "[redacted] I agree with the term [redacted]', since I expect that such a voltage polarity reversal only gets relevant in the case the cable has already been aged as I mentioned above. But I disagree with CCI [redacted]

6) I talked with various HVDC MIND power cable operators in Europe and learned that the dwell time nowadays in many cases is 2 minutes, and in one case it was in the range of seconds (but in this case, the cable was prevented from cooling down, which is an important detail, since it will prevent the creation of enlarged voids as a result of which an increase of the electrical stress coming with a voltage polarity reversal will not result in partial discharges and related degradation). Note that this way of operation has been introduced for HVDC MIND cables that (according to the cable operators) have not been operated beyond their thermal design limits.

3.4.3.3 Conclusion on the impact of voltage polarity reversals

It is my conclusion that for HVDC MIND power cables, operated within their thermal design limits, the dwell time of voltage polarity reversals are not a critical issue.

However, in case such a cable is operated beyond its thermal design limits, the dwell time (and number) of voltage polarity reversals, certainly if exceeding the recommended values, can become a factor that has to be considered as a possible contributor for degradation and a failure. This will be explained in Section 5.3 ("Voltage polarity reversals and degradation") and in Section 6.1 ("Question 1 – Probable causes of failure") and within that Section 6.1.10.

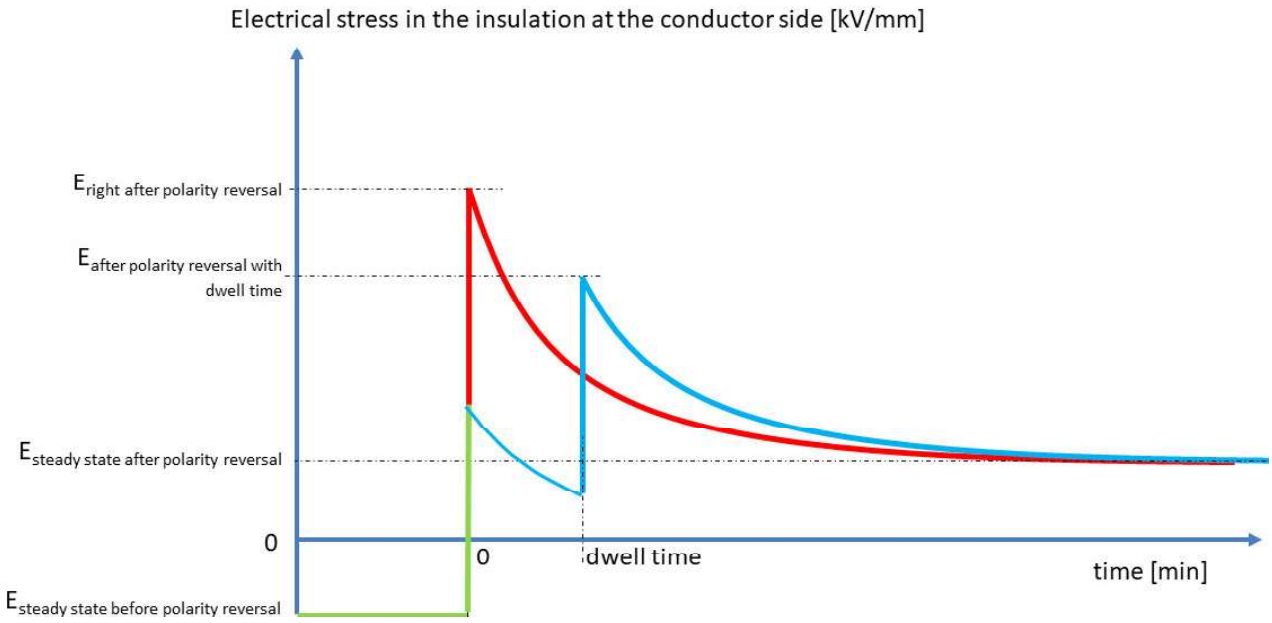


Figure 7 **Artificial drawing of the electrical stress at the conductor side of the insulation material of a warm cable, showing the impact of increasing the voltage polarity reversal time by introducing a dwell time:**

- **green-red curve: the full voltage polarity reversal is done instantaneously,**
- **green-blue curve: with a dwell time. This dwell time increases the voltage polarity reversal time in a two-step approach. This reduces the temporary electrical stress in the cable insulation**

3.5 Thermally driven chemical degradation – not a key issue of the insulation material

Thermally driven chemical degradation is known to be a relevant ageing mechanism for high voltage AC cable paper insulated oil filled cables[10], since such cables are designed to operate at high temperatures, even beyond 80 °C.

[redacted]

Also in [/18/, Hjalmarsson, 1992] and [/40/, Runde, 2000] it was mentioned that at or near the maximum operating temperature of a HVDC MIND power cable and within the foreseen lifetime of about 40 years, thermal degradation with chemical processes of the insulation material is not playing a role.

[10] With the low viscosity pressurized oil, void formation is not an issue. However, for low viscosity oils a high pressure needs to be maintained by using pressurizing equipment along the cable circuit. This is economically possible for relative short land cables but is not a practical solution for long HVDC power cables. In this case MIND cable technology is used employing a high viscosity oil or compound.

Such thermally stimulated chemical degradation, if it happens, would result in waxing of the compound and / or excessive depolymerisation of the paper making this paper brittle (as has been seen sometimes in thermally overstressed MV MIND power cables, with an example given in part 3.1 of [/54/, Steennis, 2014]). I have considered the thermal degradation with chemical processes of a HVDC MIND power cable for higher operating temperatures than the maximum operating temperature. I used a mathematical approach as mentioned in [/88/, Sumereder, page 1]. It says that the thermal based degradation speed of transformer board (being a paper – oil insulation system, comparable with MIND insulation material to a certain extent, because both are organic based) doubles at 8 degree rising over the maximum operating temperature[11], and if we assume that the life time at 55 °C of a HVDC MIND power cable is at least 40 years, then this life time is still at least 20 years at 63 °C.

Also the fact that the cable during production can pass the impregnation process for several days at 120 °C and a slow cooling down for several weeks until 55 °C [/53/, Worzyk, 2009] shows that a HVDC MIND power cable must be able to withstand temperatures around 63 °C for 20 years without noticeable thermal degradation by chemical processes of the insulation material. To calculate this, I used the thermally driven degradation speed as mentioned by Sumereder.

I therefore conclude that thermal degradation with chemical processes (as waxing and paper embrittlement) will not play a noticeable role for a HVDC MIND power cable that has been thermally overstressed permanently at temperatures up to 63 °C for a period up to 20 years. Being thermally overstressed temporarily for some weeks or months in total up to temperatures around 71 °C[12] or 72 °C will not change my conclusion since its contribution is still negligible. Note that this statement is valid only for thermally driven chemical degradation.

[11] The text is: "*Thermal aging was mathematically described generally by Arrhenius and especially for paper oil insulation systems by Montsinger … The idea of Arrhenius was that all natural processes operate on exponential functions. Montsinger found out that the degradation speed of transformer board doubles at 8 degree rising over the maximum operating temperature*"

[12] No significant thermal degradation in 20 years at 63 °C means no significant thermal degradation in 10 years at 71 °C, making a contribution of a few months only at 71 °C negligible.

4 THE BASSLINK CABLE

4.1 General information

The Basslink cable is a 400 kV HVDC cable link connecting the Loy Yang Power Station in Victoria to the George Town substation in northern Tasmania.

Basslink is a monopolar HVDC link with a metallic return comprising 298 km of power cable and 65 km overhead lines (see Figure 8).

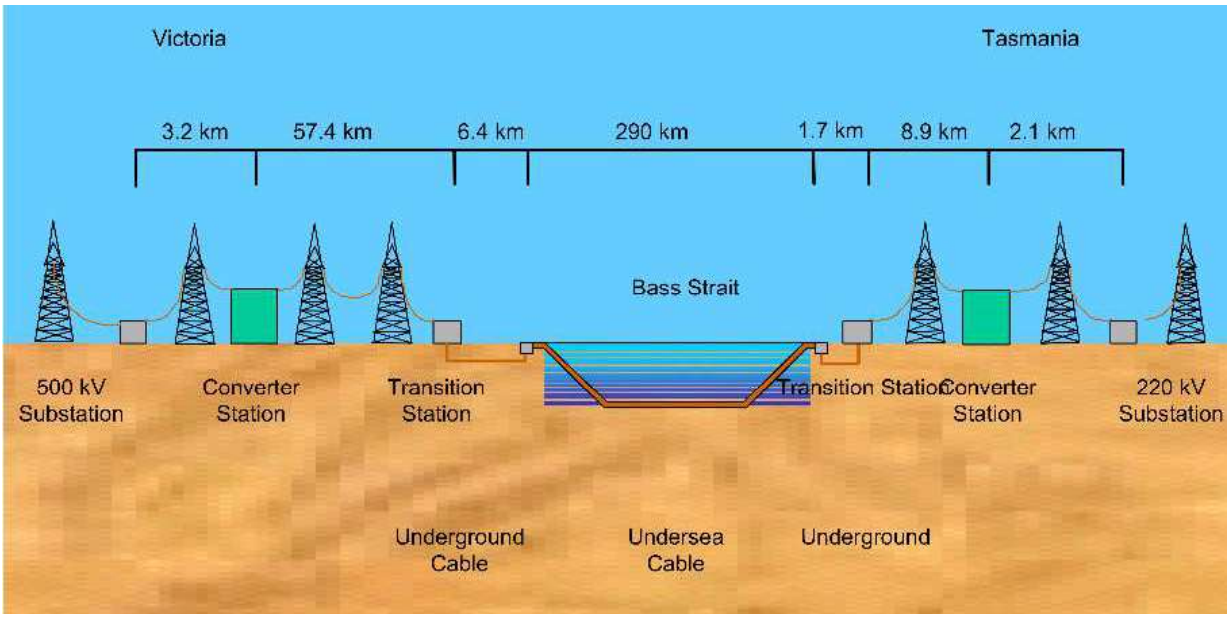


Figure 8 Basslink cable conceptual elevation map, from [/34/, Bex, 2006]

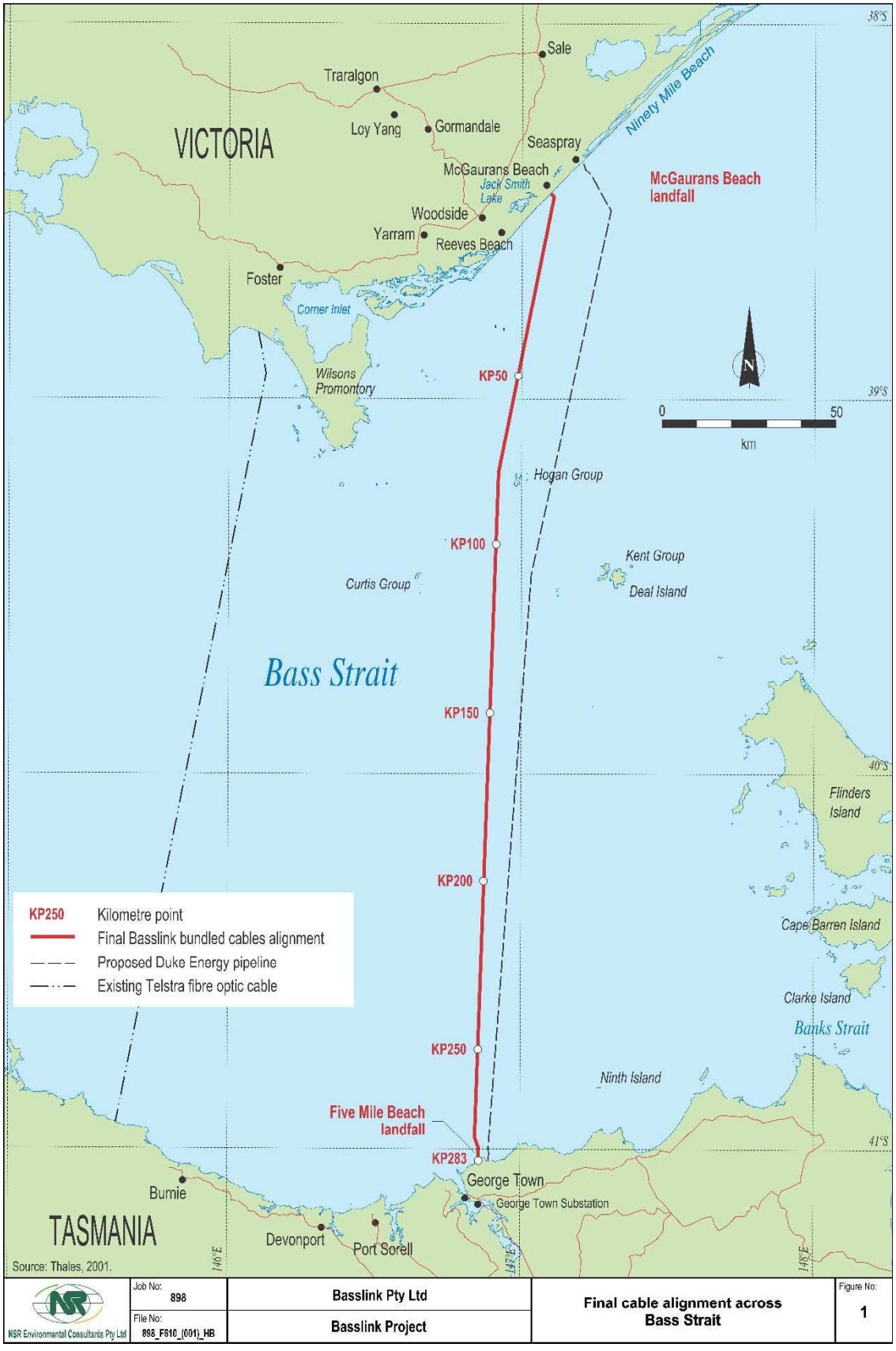


Figure 9 Basslink cable route map, from [TAB 3]

The Basslink HVDC link was commissioned in April 2006. It is owned and operated by Basslink Pty Ltd (BPL). Between October 10th, 2005 and May 10th, 2007 BPL was known as National Grid Australia Pty Ltd.

The subsea section of Basslink is 283 km long [Figure 9]. The convention for pinpointing a part of the cable is via Kilometer Points (KPs), which are measured from the Victorian end of the cable.

The Basslink cable was manufactured and installed by Pirelli (now known as Prysmian Cavi e Sistemi Energia Sri), between 2003 and 2005. Pirelli formed a consortium with Siemens for the engineering, procurement, and construction phase of the Basslink project, with Pirelli responsible for the design, manufacture, installation and commissioning of the subsea and land cable and Siemens responsible for the converter stations, power lines and other land based work.

The design life of Basslink, and with that of the cable, is 40 years and Basslink should be capable of achieving annual availability target value of 97.5% with a minimum value of not less than 97%.

4.2 Basslink contractual obligations

The Basslink Services Agreement (BSA) is an agreement between BPL and Hydro Tasmania, [redacted]

The Basslink Operations Agreement (BOA) is an agreement between BPL and the State of Tasmania [redacted]

4.3 Power design rating and dynamic power issues

The connection has a rated continuous power transfer capacity of 500 MW (normal design rating, 1250 A) with a dynamic design rating of 630 MW (1565 A) for a period of up to [redacted]

[redacted]

[redacted]

4.4 Basslink cable construction

The 400 kV HVDC sub-sea cable has a copper conductor with a cross-section of 1500 mm^2 and is steel armoured with mass impregnated non draining (MIND) paper insulation. [redacted] there is no further explanation of the cable design needed here.

[redacted]



Figure 10 Basslink submarine cable – cross-sectional view and summary of the various layers

In addition to the 400 kV HVDC sub-sea cable, Basslink has a metallic return cable and a fibre optic cable. These are bundled together. [redacted]. The metallic return cable returns the current from one side of the connection to the other side of the connection. [redacted]

[redacted]

[redacted] The fact that it was produced between 2003 and 2005 makes it probable to me that [redacted]

4.5 Basslink cable design issues

4.5.1 Introduction

The Basslink submarine power cable has been tested at different moments to prove the design.

According to Cigré, 1980 /15/, "*Type tests are tests made in order to demonstrate satisfactory characteristics to meet the intended application ….*"

A condition for such a statement is that a cable is being operated within its design limits. In the case of the Basslink cable it means with a maximum voltage of 400 kV, with a maximum operation conductor temperature of [redacted] and with a maximum temperature difference across the insulation plus screens of [redacted] (the background of these design limits is explained in Section 6.2 Section 6.3).

In my opinion, these limits, and certainly the temperature limits, are critical for a HVDC MIND power cable such as the Basslink cable. That temperatures are relevant for the Basslink cable is also underlined by CCI [TAB 76, § 268], where CCI wrote: "[redacted] Electra 171 [/58/, Cigré, 1997] and the electrical and thermal part: Electra 189 [/28/, Cigré, 2000: § 3].

4.5.2 Design tests performed

The following tests have been performed:

- [redacted]
  - [redacted]
  - [redacted]
- [redacted]
  - [redacted]
  - [redacted]
- [redacted]
- [redacted]

[15] Cigré Electra 189 [/28/, 2000] for a formal Type Test requires among others 20 heat cycles, plus 10 more for the voltage polarity reversal test.

[redacted]

4.5.3 Actual temperatures realized during the Type Test

[redacted]

A Type Test for power cables is always done at higher voltages than the operational voltage. This higher voltage compensates for the short duration of the Type Test, such that the expected electrical ageing during the cable's lifetime is covered. For the Basslink cable, the Type Test voltages are therefore [redacted] times the operational voltage, which is according to the applicable test requirements in [redacted]

[redacted] That result fits with the requirement.

16 [redacted]

[redacted] That result fits with the requirement.

[redacted] That is probably related to the practical uncertainty in reaching the prescribed temperature test limits. There are three reasons for this:

- The thermal load cycles during a Type Test are done in a laboratory at room temperature and a room temperature can vary over time. That means that a certain electrical current (used to heat up the cable) has to be adopted, depending on the starting (room) temperature
- Each new load cycle has another starting temperature because of the end temperature from the previous load cycle
- The temperature response time of a cable is slow, making that adjustments of the conductor current (used to heat up the cable) practically result in temperature undershoots or overshoots of for instance 1 to 2 °C. This is demonstrated in [TAB 76, § 160, graph 15], [redacted]

These practical limitations mentioned above result in test temperature requirements with a range. That is for the conductor temperature a range of [redacted] and for the temperature difference over the insulation plus screens where a minimum value is mentioned.

4.5.4 Interpretation of the design tests performed

Based on the Type Tests and related test performed, I conclude that the cable design with respect to its construction can be considered as being of appropriate quality in the light of known standards and related tests as performed by Pirelli.

A weakness however is, that I have been provided with no evidence that the tests were [redacted] and thus, the above conclusion comes with this related uncertainty, see [redacted] for an explanation on this uncertainty. This [redacted] also treats the uncertainties that are related to the way the temperatures are measured during [redacted]. For instance, the prescribed Type Test temperature difference over the cable insulation plus screens requires a minimum of [redacted] The minimum temperature realized was [redacted] But already with an inaccuracy of the temperature measurements of ± 0.1 °C (and often it is more, potentially ± 1 °C) one can discuss whether [redacted], leaving room for doubt. I have also not been provided with evidence that [redacted]

CCI wrote [TAB 76, § 935]: "[redacted]". This conclusive remark from CCI may be based on another conclusion of CCI [TAB 76, § 252]: [redacted]

One can question whether the cable can be operated with a maximum conductor temperature limit of [redacted] or even [redacted] since during [redacted]

It is my opinion that the [redacted] is a design limitation connected to the operational limitation, while the [redacted] to [redacted] reached during the Type Test is a test requirement, which is something else. To say it in other words, the Type Test is a verification of the design limitation and not a means to find out the maximum allowed operating temperature.

[redacted] That is, because the Type Test includes a thermal safety factor (next to an electrical safety factor) to compensate for limitations inherent in testing, such as:

- The short period of time (about [redacted]) over which tests are conducted against the very long period over time (40 years), being a factor [redacted], over which the cable must safely operate
- The short length of test cable ([redacted] against the very long cable in service (about 300 km), being a factor [redacted], over which the cable must safely operate. This length related issue is called 'length effect', see Appendix R for an explanation.

4.5.5 Conclusion on the design testing

My conclusion is that the Basslink cable is designed to operate at 400 kV with a maximum conductor temperature of [redacted] and a maximum temperature difference over the insulation (plus screens) of [redacted]

Going beyond the design voltage and temperature limits during operation is risky and must be avoided.

[redacted]

4.5.6 Remark on the superimposed voltage test as part of Type Testing

The following remark relates to design testing, but does not impact on my conclusions developed in the previous Section 4.5.1 to Section 4.5.5.

[redacted] would be expected to expose certain weaknesses that were created during the preceding loading cycles and polarity reversal tests, such as aging related to permanent void formation and electrical treeing.

However, especially enlarged voids if created in the cooling down stage of the load cycling might disappear or largely disappear during the [redacted] is done on a warm cable and in a warm cable enlarged voids can have become (much) smaller since the compound expands again on increasing the temperature, filling (partly) these enlarged voids. It means that for enlarged voids the most critical part of [redacted] is not per definition the [redacted], but the cooling down stage during load cycles, as reported by many different authors, see Section 3.3 ("Void formation - a key issue for the insulation material").

4.5.7 Remark on additional testing by Pirelli

The following remark relates to design testing, but does not impact on my conclusions developed in the previous Section 4.5.1 to Section 4.5.5.

Apart from the formal Type Test, [redacted], see the first test mentioned in Section 4.5.2 ("Design tests performed").

[redacted] Concerning the [redacted], see my previous remark.

Parts of this additional testing are [redacted]

CCI states in [TAB 76, 2018, § 242]: "[redacted]

My opinion is that because of the partly undefined set-up of this additional testing [redacted] it is not giving a firm reference to estimate the contribution of this test to establish the quality of the Basslink cable.

4.6 Basslink cable production issues

[redacted]

At this point I conclude that the Basslink cable production can be considered as being of a proven appropriate quality in the light of known standards and related tests and that there is no reason to doubt this result.

4.7 Basslink cable installation

[redacted]

The 400 kV HVDC sub-sea cable and metallic return cable are bundled and laid together. [redacted]

[redacted]

[redacted]

[redacted]

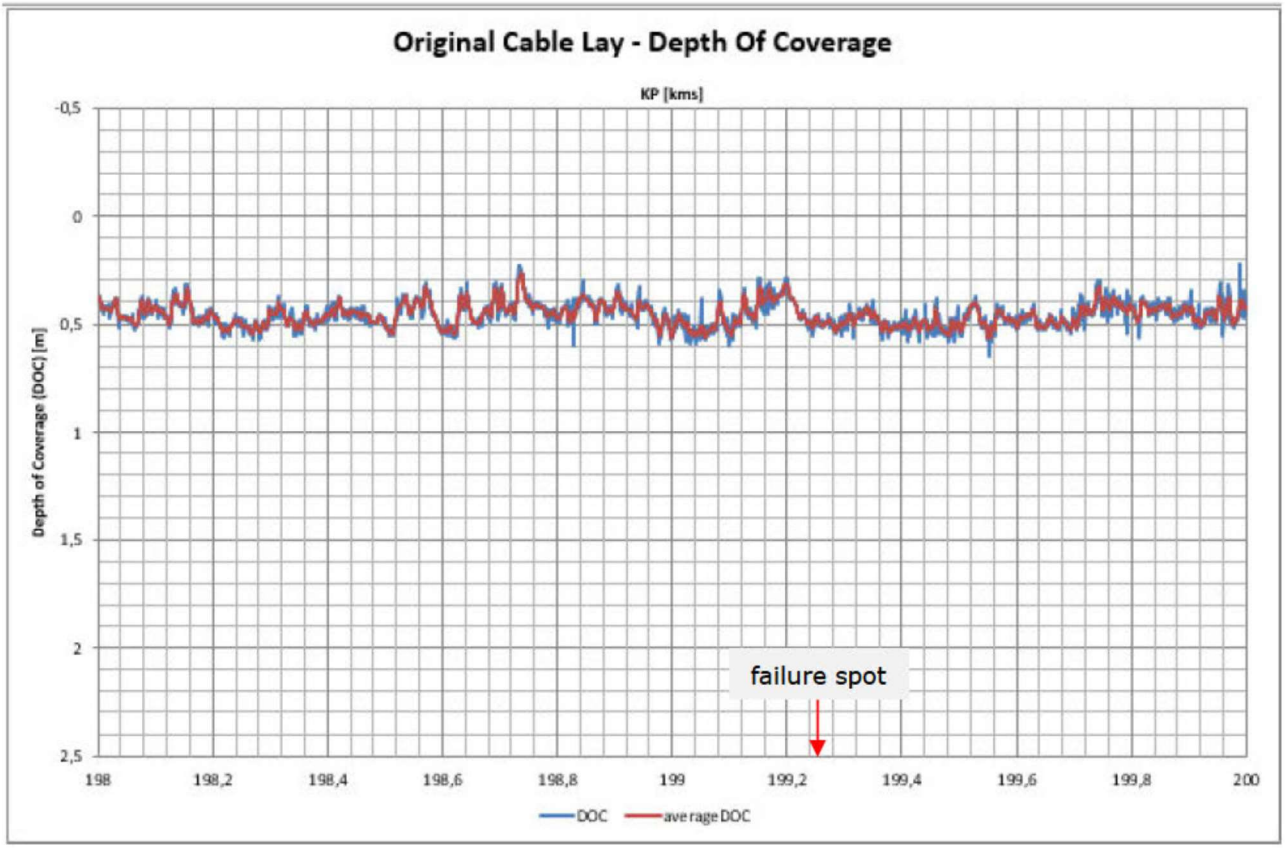


Figure 11 Basslink submarine cable – Original Cable Lay – depth of coverage [TAB 58.3.1]

[redacted]

[redacted]

I consider that the available information regarding the installation of the cable at and near the point of failure does not indicate that there was a weakness in the power cable at that point.

4.7.1 Basslink cable joint positions

4.7.1.1 Introduction

Cable lengths cannot be made infinitely long, because of the production and installation issues. For that reason, there are various joints along the cable, connecting the individual cable lengths until the full required length is obtained. [redacted]

[redacted]

[redacted]

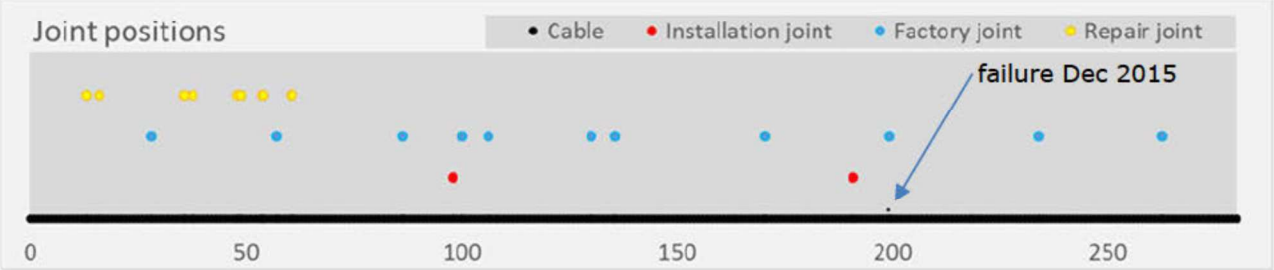


Figure 12 Joint positions as a function of the installed cable length in KP

4.7.1.2 Factory joints

[redacted]

- [redacted]
- [redacted]

[redacted]

4.7.1.3 Installation joints

[redacted]

4.7.1.4 Repair joints

[redacted]

- [redacted]
- [redacted]
- [redacted]
- [redacted]
- [redacted]

[redacted].

The failure that occurred in 2015 [redacted], making it possible to ignore these in relation to the 2015 failure being discussed in this report at hand. [redacted] invites to check whether the failure in 2015 might be related to a similar issue. This is done in Section 6.1.5 ("Weakness from a repair spot").

4.7.2 [redacted]

[redacted]

[17] Not taking into account those related to the failure in December 2015.

[18] This is an unaged cable.

[redacted]

4.7.3 Basslink cable operation

The Basslink cable has been in commercial operation since April 28th, 2006 until its failure on December 20th, 2015 at 2:05 pm. Apart from this failure there have been no other power cable failures during this service operation period. I concluded this from the fact that there were no long duration interruptions, apart from the one in December 2015 [TAB 59.1].

Below I will graphically present the power flow as derived from [TAB 38] and [TAB 39], see Figure 13, Figure 14, Figure 15 and Figure 16, where

- A positive power flow in the below figures the power flow is from Tasmania to Victoria
- A negative power flow in the below figures the power flow is from Victoria to Tasmania.

The presented power flow is measured at the receiving end and for that reason somewhat lower than those mentioned in Section 4.3.

The power flow during the full operational period is shown in Figure 13.

[redacted]

It will be clear that the positive power flow (from Tasmania to Victoria) is often larger than the maximum continuous design rating of the power cable. That is possible, since the maximum design rating is related to a continuous load. If a higher load was restricted in time and preceded or followed by a lower load, then the maximum amount of power transmitted can be increased beyond the maximum continuous design rating temporarily. That is because the actual limitation to operate a cable (at a given voltage) does not come from the power, but comes from the temperature which is a result of the load. It will take time to heat up the power cable at a given load (see Section 3.1.6). As a result, even a higher current (and thus power flow) is possible for a while, as long as that temperature design limit will not be surpassed. Using a cable in this way is called Dynamic Rating. [redacted]. But on using a Dynamic Rating approach, it is very important to keep in mind and make sure that the maximum allowed cable insulation temperatures ([redacted] a conductor temperature and [redacted] as the temperature difference over the cable insulation plus screens) are never surpassed.

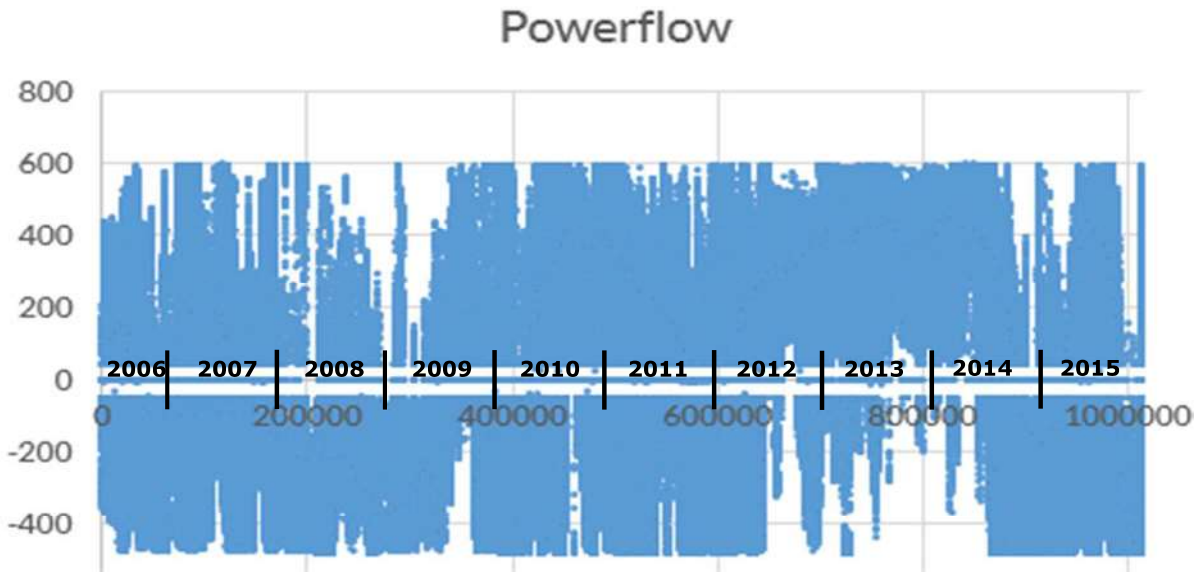


Figure 13 **Power flow as a function of time from the start of commercial operation April 28th, 2006 until the failure moment on December 20th, 2015 at 2:05 pm (5 minute measurements). The lower grey x-axis values represent sample numbers and can be ignored**

4.7.4 The failure circumstances – power in the months, days and hours before the failure

In the period of time preceding the failure, the power flow was as shown in Figure 14, Figure 15 and Figure 16, this information being derived from [TAB 38] and [TAB 39].

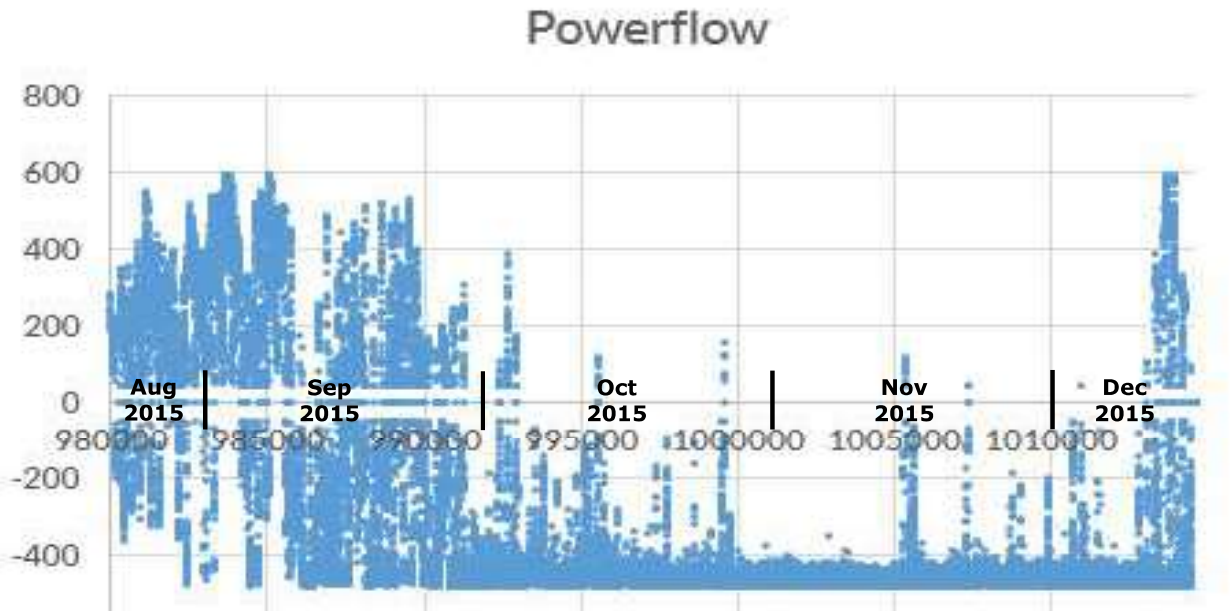


Figure 14 **Power flow as a function of time for the last 5 months before the failure, i.e. from August 22nd, 2015 until the failure moment on December 20th, 2015 at 2:05 pm (5 minute measurements). The lower grey x-axis values represent sample numbers and can be ignored**

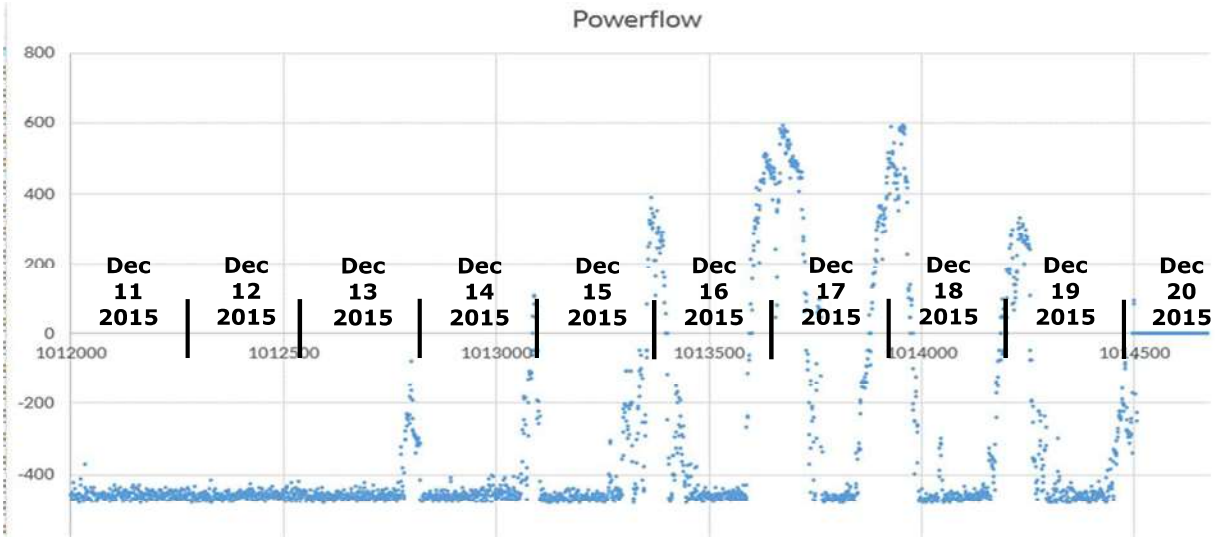


Figure 15 **Power flow as a function of time for the last 9 days before the failure, i.e. from December 11th, 2015 until the failure moment on December 20th, 2015 at 2:05 pm (5 minute measurements). The lower grey x-axis values represent sample numbers and can be ignored**

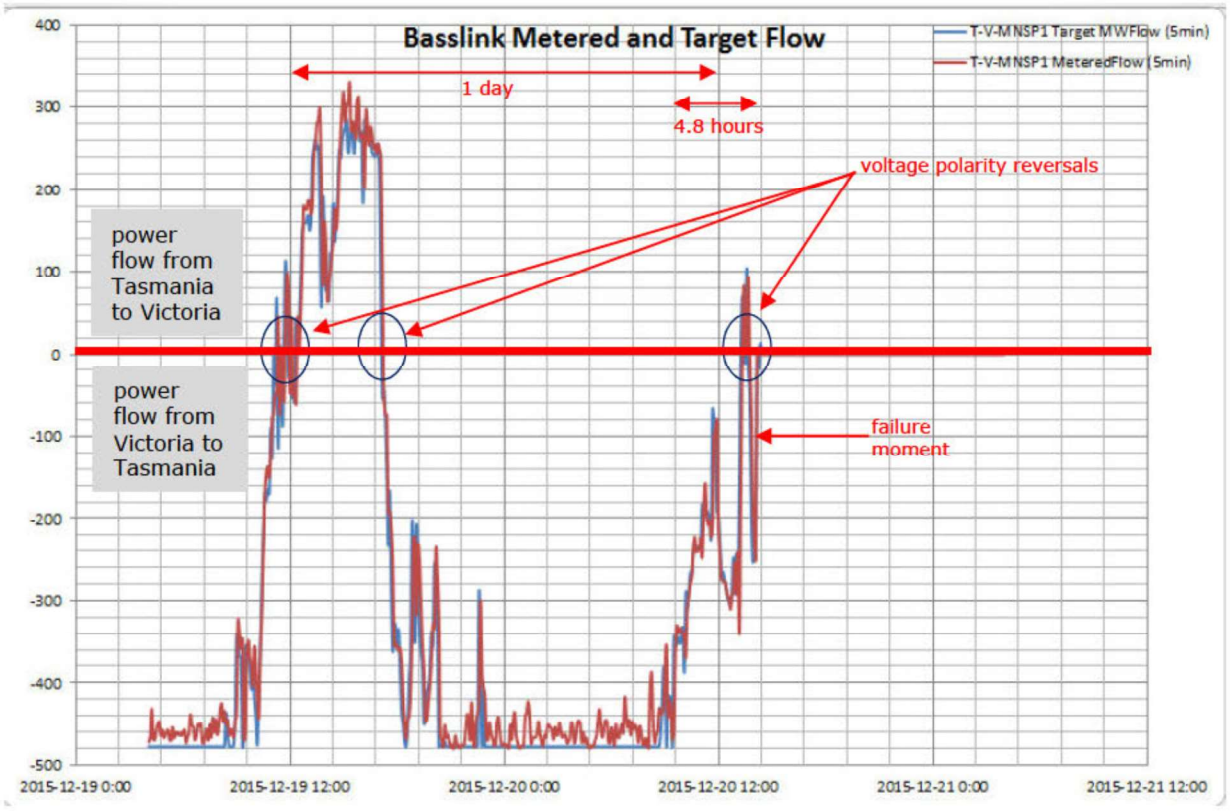


Figure 16 **Power flow as a function of time for the last 1.5 days before the failure, i.e. from December 19th, 2015 at about 5 am until the failure moment on December 20th, 2015 at 2:05 pm (5 minute measurements). The failure moment is shown and various voltage polarity reversals are visible (blue ellipses)**

Concerning the last hours before the failure, CCI in their report [TAB 67, § 114, § 115] summarized the power flow, load and temperature as follows:

"*(114) The power record shows:*

a. *The cable had been carrying a near continuous power level of 478 MW (95 % of the continuous rating of 500 MW) for 740 minutes (importing from Victoria), this period ended 325 minutes before failure*

b. *The power level then decreased and reached zero 45 minutes prior to failure*

c. *The power was then at near zero for 25 minutes with two five minute periods of power export*

d. *The final import of power commencing 20 minutes prior to failure*

e. *Failure occurred at 14:05 hours, with the cable carrying 249 MW (50 % of the continuous cable rating of 500 MW).*

(115) The cable considered to have experienced the following thermal and voltage conditions prior to the failure:

- *In period b) the cable was cooling*
- *At the start and end of period c) the cable experienced two voltage polarity reversals*
- *In period e) the cable was heating*".

4.7.5 The failure circumstances – failure location and cable retrieval

On December 20th, 2015, at approximately 2.04 PM, the Basslink HVDC cable experienced a fault which caused it to cease operating.

[redacted]



Figure 17 Failure location, based on Basslink operational information, from [TAB 44]

[redacted]

- [redacted]
- [redacted]
- [redacted]
- [redacted]
- [redacted]
- [redacted].

[redacted]

It is my opinion that these positions are far enough from the cable failure spot to exclude these as having any contribution to the failure, unless some subsequent evidence emerges which could lead me to another opinion.

On June 13th, 2016 the cable was returned to service, after having replaced the failure spot with spare cable and by applying also repair joints. [redacted]

4.8 Basslink power cable failure investigation

4.8.1 CCI's investigation and CCI's conclusion (what was done, my role)

After the Basslink cable failure in 2015, BPL engaged CCI to conduct the cable failure examination works. [redacted]

- [redacted]
  - [redacted]
  - [redacted]
- [redacted]
  - [redacted]
- [redacted]
  - [redacted]
  - [redacted]
  - [redacted]
- [redacted]
  - [redacted]
  - [redacted]
  - [redacted]
  - [redacted]

[redacted]

- [redacted]
  - [redacted]
- [redacted]
  - [redacted]
  - [redacted]
- [redacted]
  - [redacted]
  - [redacted].

The CCI reports presenting the factual findings are [TAB 56] and [TAB 58]. [redacted]

[redacted]

[redacted]

This was followed by a report from CCI about the cause of the failure [TAB 67]. The conclusions (in summary) are important and therefore the relevant part (starting with § 3 from the summary in [TAB 67]) is repeated here:

" ….

3. *The fault occurred within the cable. The fault was not at a location of a joint, or a lead sheath to armour bond.*
4. *In the absence of surviving evidence it was not possible to determine the cause of the failure of the cable as:*
   - *There was no evidence of any pre-existing external mechanical damage to the cable*
   - *The electrical fault was a 'radial, short path' type. The path extended through the paper tape insulation between the conductor at high voltage and the lead sheath alloy at lower voltage*
   - *There was no evidence of any incipient electrical activity connected with the fault site or present elsewhere in the cable*
   - *The point of initiation within the fault path and the direction of propagation of the electrical failure could not be determined due to severity of the fault damage*
5. *The fault position was beneath the norther bulge in the cable*
6. *The northern bulge was formed by the explosive effect of the electrical power arc within it*
7. *A second bulge was present 480 mm to the south of the northern bulge. The insulation inside the southern bulge was sound and did not contain electrical distress*
8. *The southern bulge was formed by the shock wave travelling to a location where the steel reinforcement tapes had a wider butt gap and experienced a force above their breaking point*
9. *The operation conditions at, and preceding, the time of failure were no different to those of the year 2015. The cable was within its thermal rating*
10. *The insulation adjacent to the failure site was sound and showed no evidence of thermal ageing*
11. *A sample of cable remote from the fault site was in sound condition*".

In summary, CCI concluded that they could not identify the root cause of the failure.

Note: Since CCI's root cause investigation was based [redacted], and CCI's conclusion was that the root cause of the failure could not be identified, DNV GL decided to widen the scope and explore additional matters related to the design, production, installation and service operation of the Basslink cable, in line with DNV GL's normal approach for such failure investigations as described in Section 2.4.5 ("Approach in case of a failure investigation"). This further exploration resulted in various DNV GL reports as mentioned in Section 1.5 ("History of the DNV GL and CCI reports issued so far").

4.8.2 Certain CCI findings further elaborated

4.8.2.1 [redacted]

[redacted]

[redacted]



Figure 18 **From [TAB 58, figure 2], a sharply curved spot with permanent set found in the conductor (the red lines illustrate the curve)**

4.8.2.2 [redacted]

[redacted]



Figure 19 **From [TAB 56, figure 15 left and figure 50 right], showing a wrinkled outer layer of the reinforcing tape (left picture: the reference cable (20 m away from the failure spot), right picture: of the failed cable part)**

[redacted]

Figure 20 [redacted])

4.8.2.3 [redacted]

In addition to CCI's examinations reported in the first half year of 2016 [TAB 56], [TAB 58], Materials Technology Ltd examined various samples from the dismantled cable and reported the results late 2016 [TAB 68].

Concerning the reinforcing tape it was mentioned: "*The reinforcing tape witness marks were visible on the surface of the PE sheath and this showed the original tape positions in service*" [TAB 68, page 44].

[redacted]

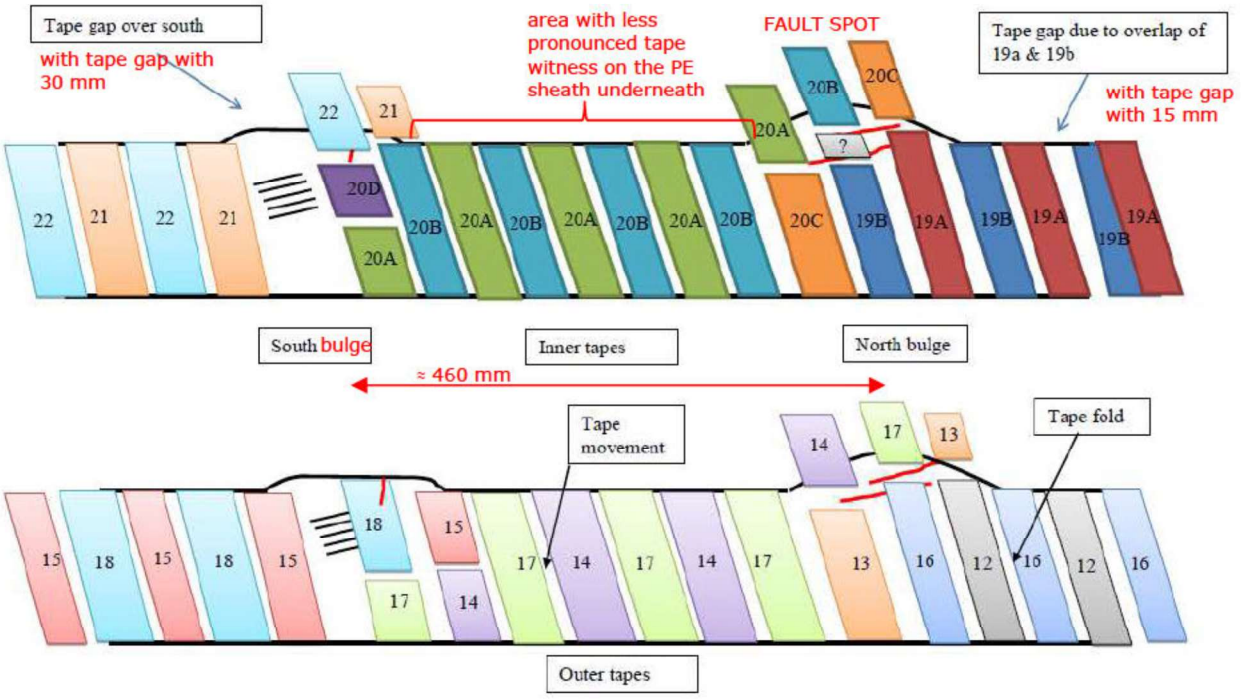


Figure 21 **Schematic view of the reinforcing tape numbers and their relative positions, copied from [TAB 68, their figure 3]. The text and other markers in red are added by the author to bring all findings mentioned in [TAB 68, their figure 3] in this one view**

4.8.2.4 Thermal history and DSC

As mentioned in Section 4.8.2.3, in addition to CCI's examinations reported in the first half year of 2016 [TAB 56], [TAB 58], Materials Technology Ltd examined various samples from the dismantled cable. Some samples were also subjected to a DSC test and the results were reported late 2016 [TAB 69].

In short, a [redacted] can be applied to verify the historical temperature exposure of a [redacted]

[redacted]

Additionally, CCI in their Failure Investigation Report from late 2016 [TAB 67] said that it is not clear whether this temperature exposure of about 40 °C was the result of cable operation, transportation on the laying vessel or production.

[redacted]. That difference between actual and measured temperature exposure might depend on the way the [redacted] is done in their laboratories. Would this be the case, it means that the measured temperature exposure can be a result of weather conditions during storage, where an average maximum temperature of [redacted] is imaginable.

Would the temperature shift mentioned in the previous paragraph not be the case, then a long duration temperature load of about [redacted] (although not impossible) from production or installation is not very realistic for the following reasons:

- From production, it is not a known typical peak in a DSC curve from a PE sheath
- From transportation and installation: the cable part with the later fault position was about 8 km away from the start of the cable length (As a result, it is my opinion that this cable part (with later fault) was not in the upper layer on any basket during storage or transportation. And thus, the cable part with the later fault being embedded in an environment of other cables parts, the cable temperature must have been close to the daily average temperature, which is more in the range of maximum .

[redacted]

[redacted] The maximum conductor temperature per design is [redacted] and the maximum temperature difference over the insulation plus screens per design is [redacted] resulting in a maximum PE sheath inner wall temperature per design of [redacted]

5 KEY ISSUES OF THE OPERATION OF THE BASSLINK POWER CABLE

5.1 General

According to [/34/, Bex, 2006], "*the southern and eastern Australian system operates under market conditions managed centrally by the National Electricity Market Management Company Ltd (NEMMCO). The market dispatch is managed automatically by generation offers and load bids covering pre-dispatch (unit commitment) and five minute dispatch (generator targets – energy dispatch) subject to network security constraints and management of reserves (frequency control ancillary services – FCAS market). Basslink has been developed by National Grid Australia (NGA). In its role as the project developer, NGA registered Basslink with NEMMCO as a Market Network Service Provider (MNSP). This means that Basslink can offer its capacity/price to the market and during operations will receive 5 minute flow targets*".

Per design, during operation the cable temperature should be limited to a maximum conductor temperature of [redacted] with a maximum temperature difference over the insulation plus screens of [redacted] which implicates a maximum temperature difference over the insulation only (thus, without screens) of [redacted] TAB 65.0.4, De Wild, 2020; Chapter 4.4.4, page 44].

5.2 Cable temperature and degradation

5.2.1 How is the temperature of the power cable controlled for the Basslink cable?

There are requirements set to the Basslink cable, [redacted] (see also Section 4.2 and Section 4.3). [redacted]

However, the actual load and cable environment differ from those mentioned in the technical documents describing the starting points.

I[redacted]

5.2.2 Calculated temperatures for the Basslink cable

In order to find the actual Basslink cable temperatures that were present in the cable until the moment of the failure, De Wild [/72/, 2017] and CCI [TAB 76, CCI, 2018] each created a thermal model. With help of known and if not known, estimated parameters and with the known load profile, both De Wild and CCI calculated the maximum temperatures that the Basslink cable experienced.

On 31st January 2020, De Wild wrote a new report [TAB 65.0.4, De Wild, 2020], where now more actual cable burial depths (De Wild refers to a reference [TAB 124] from 2019, not in my files), sea water temperatures [TAB 120] and soil characteristics could be taken into account [TAB 129.1] from 2019. Since this report from De Wild contains the latest findings, I used these for my evaluation, which will be treated in Section 5.2.2.1. De Wild calculated the cable temperatures not only as a function of time but also as a function of the location.

Concerning the temperatures calculated by CCI, I only have their report from 2018. I therefore must restrict my evaluation to CCI's 2018 findings, which will be treated in Section 5.2.2.2.

Since I am not an expert in thermal modelling, I will only refer to the final results made available by De Wild and CCI. De Wild uses an analytical model based on the international standard IEC 60853-2 [TAB 65.0.4, reference 12] and [redacted]

5.2.2.1 Cable temperatures according to De Wild

Maximum temperatures found in general

In Figure 22, De Wild's conclusion from his report is shown. He concluded that the Basslink cable had been thermally overstressed and he gave the reasons for this.

11 CONCLUSIONS

The thermal analysis showed that in various periods during the operational history, the submarine cable section of the Basslink interconnector has been thermally loaded beyond the maximum operating temperature and beyond the maximum temperature difference over the insulation material.

This is caused by the following main elements:

1. The thermal properties of the soil that is actually present around the submarine power cables are [redacted] More precisely, the cables are installed in [redacted]
2. The actual cable operation was such that the cable system was highly loaded. In various time periods, the interconnector was loaded [redacted] and [redacted] This resulted in temperatures that increased over prolonged periods of time without possibilities for the cable to cool down.

[redacted]

4. I believe that the finding that the submarine cable section of the Basslink interconnector exceeded its thermal limitations, will not change as a result of the variation in input parameters that I consider to be likely.

Figure 22 De Wild's conclusion with respect to the cable temperature overload and the causes for this [TAB 65.0.4, De Wild, 2020, Section 11, Conclusions, page 180]

Along the Basslink cable, De Wild found various spots that can be considered as thermal bottlenecks.

The worst-case temperature situations were found at two bottleneck positions 1 and 2 in [redacted]. For these two bottleneck positions, but also for the failure location, the historical maximum temperatures found are presented in Table 1, being a copy from [TAB 65.0.4, De Wild, 2020, Table 25 on page 142].

One can see in Table 1 that the maximum conductor temperatures and maximum temperature differences over the cable insulation at the bottleneck positions are close to [redacted] and [redacted] respectively.

Table 1 The maximum cable temperatures for Bottleneck location 1 and 2 and for the Failure location for [redacted] [TAB 65.0.4, De Wild, 2020, page 142]

	Bottleneck 1[26]	Bottleneck 2	Failure location
Maximum conductor temperature found [°C]	[redacted]	[redacted]	[redacted]
Maximum temperature difference over insulation material found [°C]	[redacted]	[redacted]	[redacted]
Maximum lead sheath temperature [°C]	[redacted]	[redacted]	[redacted]
Maximum metered transmitted power flow at the receiving end [MW]	599		
Maximum calculated current in the HVDC submarine cable [A]	[redacted]		

Maximum temperatures found at the failure location

Information about the temperatures at the failure location as mentioned below can be found in De Wild's report, but the relevant plots from this report I have reproduced in Appendix W of my report.

De Wild calculated, that around [redacted], both the maximum conductor temperature and maximum temperature difference over the insulation (often in combination) were for many days considerably above the design limits of [redacted] and [redacted] respectively. For this period, the calculated maximum conductor temperature and maximum temperature difference over the cable insulation are [redacted] and [redacted] respectively at the failure location. These calculations also show that during this period, it happened that at the failure location [redacted] above its design limit while at that particular moment this was not the case for the temperature difference over the insulation.

But also during other periods of time, before [redacted], these design limits were surpassed to a certain extent, as De Wild showed in [TAB 65.0.4, 2020, Section 8.4 – Section 8.7]. In total, during various hours or days the temperature difference over the insulation was beyond the design level of [redacted] and occasionally this was combined with the maximum conductor temperature being beyond the design level of [redacted]

Making an assessment from the thermal plots in De Wild's report shown in Appendix W it is seen that at a number of occasions the temperatures exceeded their thermal limits:

[redacted]

[redacted]

The contribution of uncertainties to the maximum temperatures

These calculated temperatures come per definition with uncertainties, related to the uncertainties of the values of the input parameters used in De Wild's model. These are identified by De Wild for bottleneck position 1 and are shown in Table 2, being a copy from [TAB 65.0.4, De Wild, 2020, Table 32 on page 171].

In order to estimate the possible maximum temperatures, but now including the uncertainties, that happened at the two bottleneck locations and failure location, I treat these uncertainties further below.

These uncertainties include:

1. Uncertainties which give variations in the maximum temperature along the Basslink cable. These are:

   [redacted]

   I added up these uncertainties, which become:

   - For the maximum conductor temperatures [redacted]

- For the maximum temperature differences over the insulation [redacted].

Here the first value given is found by adding up the uncertainties at the lower end and the second value given is found by adding up the uncertainties at the higher end, but it is taken into account that if the impact of the thermal resistivity of the soil comes with an opposite contribution of the thermal diffusivity of the soil.

2. Uncertainties that would reduce the temperature along the Basslink cable as a whole (not location dependent). The only uncertainty of this category is:

   - [redacted]

   These uncertainty ranges become:

   - For the maximum conductor temperatures [redacted]
   - For the maximum temperature differences over the cable insulation [redacted]

   Also here, the first value given is found by adding up the uncertainties at the lower end and the second value given is found by adding up the uncertainties at the higher end. The [redacted] counts if the cable representation and cable insulation thermal resistivity are in line with choices made by Mr. De Wild [TAB 65.0.4, 2020].

The result is presented below.

Note: I round the value of the conductor temperature to whole numbers in order to compare this with the design limitation of [redacted] which is also a whole number.

Maximum temperatures at the bottleneck location 1 taking into account the uncertainties

For bottleneck location 1, De Wild's calculated maximum conductor temperature is [redacted]

- Subtracting the low end of all the uncertainties along the cable length this maximum conductor temperature drops to [redacted] This is [redacted] above the design limit of [redacted]
- Subtracting further the low end of the uncertainty related to the whole cable, it comes down to [redacted] This is still 9[redacted] above the design limit of [redacted]

For bottleneck location 1, De Wild's calculated maximum temperature difference over the cable insulation is [redacted]

- Subtracting the low end of all the uncertainties along the cable length this maximum temperature difference would become [redacted] This is [redacted] above the design limit of [redacted]
- Subtracting further the low end of the uncertainty related to the whole cable, it comes down to [redacted] This is [redacted] above the design limit of [redacted]

Note that De Wild wrote that it is unrealistic that all uncertainties at the low end come together in one spot [TAB 65.0.4, De Wild, 2020, page 172, § 7 from the top]. Noting the fact that it is unrealistic, De Wild's calculations show that even with all uncertainties added up, the Basslink cable had experienced a thermal overstress at this location for certain amount of time[20].

[20] Despite the fact that it is unrealistic, but if I anyhow reduce the temperatures found by De Wild and as shown for bottleneck location 1 [TAB 65.0.4, De Wild, 2020, page 143, figure 89] with the combined uncertainties mentioned above, then even in this case the maximum conductor temperatures are for several days above [redacted] and many days above [redacted]

Maximum temperatures at the failure location taking into account the uncertainties

Should the Basslink cable have failed just because of being thermally overstressed, one would initially expect a failure at one of the bottlenecks. But there are two things that need to be considered in relation to this:

- First, there might be other issues that played a role in the cable degradation at the failure location
- Second, the precise temperature at the failure location might have been somewhat higher than what was calculated by De Wild (and CCI), based on local variations of the soil conditions. That last subject will be treated here.

Both items will be treated in Section 6.1.9.2. But the 2nd item will be introduced below.

De Wild has not presented temperature uncertainties for the failure location. In a first approximation, I therefore assume that the temperature uncertainties found for bottleneck location 1 are indicative for the temperature uncertainties at the failure location as well.

Under this assumption, it is interesting to see how much warmer the cable at the failure location might have been if one of the uncertainties has played a role[21]. A realistic one is the thermal resistivity of the soil. The effect of the uncertainty of this thermal resistivity is treated below.

Concerning the maximum conductor temperature, the impact of the uncertainty of a higher thermal resistivity of the soil is [redacted] but since the uncertainty of the thermal diffusivity of the soil works in the opposite direction, this is a contribution of [redacted] see Table 2, copied from [TAB 65.0.4, De Wild, 2020, page 171, Table 32].

As a result, the maximum conductor temperature at the failure spot, when only the soil parameter uncertainty is taken into account, becomes now [redacted] This is quite close to those calculated by De Wild at the two bottlenecks, which are [redacted]

Concerning the maximum temperature difference over the insulation, the impact of the uncertainty of a higher thermal resistivity of the soil is [redacted], but since the uncertainty of the thermal diffusivity of the soil works in the opposite direction, this is a contribution of [redacted] see Table 2.

As a result, the maximum temperature difference over the insulation at the failure spot, when only the soil parameter uncertainty is taken into account, becomes now [redacted] This is quite close to those calculated by De Wild at the two bottlenecks, which are [redacted]

For completeness, in the same way I calculated the minima of the maximum temperatures, taking into account the uncertainties:

- The minimum conductor temperature at the failure spot (when only the soil parameter uncertainty is taken into account). This becomes [redacted] rounded to [redacted]. This is a temperature above the design limit of [redacted]
- The minimum conductor temperature at the failure spot (when all uncertainties are taken into account). This becomes [redacted] rounded to [redacted] This is a temperature above the design limit of [redacted]

[21] The chance that all uncertainties act together to the lower end or alternatively to the higher end is not very likely [TAB 65.0.4, De Wild, 2020, page 172, 7th paragraph from the top]. But it is realistic that this happened for one of the uncertainties. A realistic one is the thermal resistivity of the soil [TAB 65.0.4, De Wild, 2020, page 172, 3rd paragraph from the top], assuming that the Basslink cable has a length of 300 km making it plausible that there are certain locations where an uncertainty as the thermal resistivity of the soil towards the higher end could be present.

- The minimum temperature difference over the insulation at the failure spot (when only the soil parameter uncertainty is taken into account). This becomes [redacted] = [redacted] This is a temperature above the design limit of [redacted]
- The minimum temperature difference over the insulation at the failure spot (when all uncertainties are taken into account). This becomes [redacted] This is a temperature above the design limit of [redacted]

Table 2 The cable temperature possible deviations for Bottleneck location 1 for May 2014 [TAB 65.0.4, De Wild, 2020, page 171], depending on actual conditions

Type and reference	Change considered	Difference in cable conductor temperature	Difference in temperature difference over insulation material
Different cable representation, section 9.3.1	Changing from realistic but large cable dimensions to cable dimensions deduced for the failure location	[redacted]	[redacted]
Different electrical resistance of the cable conductors, section 9.3.2	Reducing the electrical resistance of the HVDC and MVDC cable conductor with 2%	[redacted]	[redacted]
Different thermal resistivity of the cable insulation material, section 9.3.3	Changing the thermal resistivity of the HVDC cable insulation material from 6.0 to 5.0 Km/W	[redacted]	[redacted]
Different thermal resistivity of the soil surrounding the cable, section 9.3.4	Changing the thermal resistivity of the soil to 0.86 Km/W (A) or 1.02 Km/W (B) (refer to footnote 13)	[redacted]	[redacted]
Different thermal diffusivity of the soil surrounding the cable, section 9.3.5	Changing the thermal diffusivity of the soil to $0.30 \cdot 10^{-6}$ m²/s (A) or $0.36 \cdot 10^{-6}$ m²/s (B)	[redacted]	[redacted]
Different burial depth, section 9.3.6	Changing the burial depth to 1.80 m (A) or 2.12 m (B)	[redacted]	[redacted]
Different moving averaging length, section 9.3.7	Changing the moving averaging length from 161 m to 25 m	[redacted]	Not affected

5.2.2.2 Cable temperatures according to CCI

[redacted]

[redacted]

I disagree with this statement from CCI. Concerning this, I wrote in Section 4.5.4 ("Interpretation of the design tests performed") on page 51 the following: "*One can question whether the cable can be operated with a maximum conductor temperature limit of* [redacted] *or even* [redacted] *since during the Type Test these were the minimum and maximum temperatures realized. It is my opinion that the* [redacted] *is a design limitation connected to the operational limitation, while the* [redacted] *reached during the Type Test is a test requirement, which is something else. To say it in other words, the Type Test is a verification of the design limitation and not a means to find out the maximum allowed operating temperature".* Note: That a cable sample of 50 m in a Type Test passed a slightly higher temperature than allowed during surface operation with a length of 300 km is not surprising, taking into account the 'length effect' (see Appendix R for an explanation of the 'length effect').

What can be derived from CCI's calculation as well is that the maximum temperature difference over the cable insulation plus screens of [redacted] below the design limit of [redacted]

CCI, in their reporting of 2018, could not have taken into account the actual thermal soil properties and burial depths as made available in 2019, which are different from their assumptions. For instance, the thermal resistance as found for the soil is higher than [redacted] as used for the engineering. And this will most probably result in a higher maximum conductor temperature and maximum temperature difference over the insulation.

I therefore conclude that according to CCI's calculations done in 2018 the cable has been thermally overstressed at the failure location during the period [redacted] And I expect that even higher temperatures might be found by CCI if the actual and worse thermal properties of the soil (compared to the engineering values) as made available in 2019 are going to be used by CCI in an update of their calculations.

5.2.3 Conclusion

It appears, the cable at the failure location has been thermally overstressed, at least in [redacted], being [redacted] before the failure happened.

The background of the fact that the cable has been thermally overstressed is mainly the excessive load and (as concluded by De Wild, see Figure 22) to a less extent the [redacted]

How this is related to the cause of the failure will be treated in Section 6.1 ("Question 1 – Probable causes of failure").

5.3 Voltage polarity reversals and degradation

5.3.1 Introduction

Also [/34/, Bex, 2006] says: "*As the Australian electricity market is based upon 5-minute dispatch intervals market outcomes can require Basslink to reverse power flows within 5 minutes. To achieve this a short 2-minute cable discharging time between changing voltage polarity has been achieved. As a result, the standard CIGRE cable load cycle test was altered to reflect expected power flows under market conditions*".

In this report I am using the word 'dwell time', which means the same as deionisation time or discharging time chosen by a cable operator to discharge the cable between the first and second step in one voltage polarity reversal.

Background information on the increase of the electrical stress that comes with a voltage polarity reversal I gave in Section 3.4.3. A literature survey on this item is shown in Appendix P.

Here, I concluded that the way a voltage polarity reversal is done has had quite some impact on the Type Testing regime and the way cable operators manage such a voltage polarity reversal. A dwell time is often applied by cable operators to reduce the impact of the voltage polarity reversal. However, as was mentioned in Section 3.4.3 as well, [redacted]. But it has to be mentioned as well that these cable operators also claim that their cables are operated within the thermal design limits.

Nevertheless, since a voltage polarity reversal has a potential impact on the ageing of any HVDC MIND power cables, I studied the way voltage polarity reversals are being carried out for the Basslink cable and whether this differs from the European industrial practice.

5.3.2 How are the voltage polarity changes controlled for the Basslink cable?

I have considered the information made available to me in relation to specifically the Basslink cable. I [redacted].

[redacted]

[redacted]

[redacted]



Figure 24

It must be mentioned, that it is known that in Type Tests based on Cigré Electra 189 for the electrical part [/28/, Cigré, 2000] in §3.8 the following is said about the voltage polarity reversal duration: "*the recommended time duration for a polarity reversal is 2 minutes*". This expression, however, does not reflect a recommended operational condition, but a recommended test regime. A test regime normally reflects more demanding conditions than those seen in service to accelerate ageing if any.

Because of their nature, after a voltage polarity reversal the discharging process inside the cable insulation is much faster in the first minutes, slowing down considerably over time. Due to this, especially the first minutes are critical in the discharging process. That is the reason, Cigré in their test protocols and often network owners during actual operation reduce the speed of the voltage polarity

reversal. In other words, often network owners block the voltage polarity reversal for a certain time. The impact of a dwell time is illustrated in Figure 25. On performing a voltage polarity reversal, per definition, a long dwell time will reduce the electrical stress inside the cable insulation more than a short dwell time.

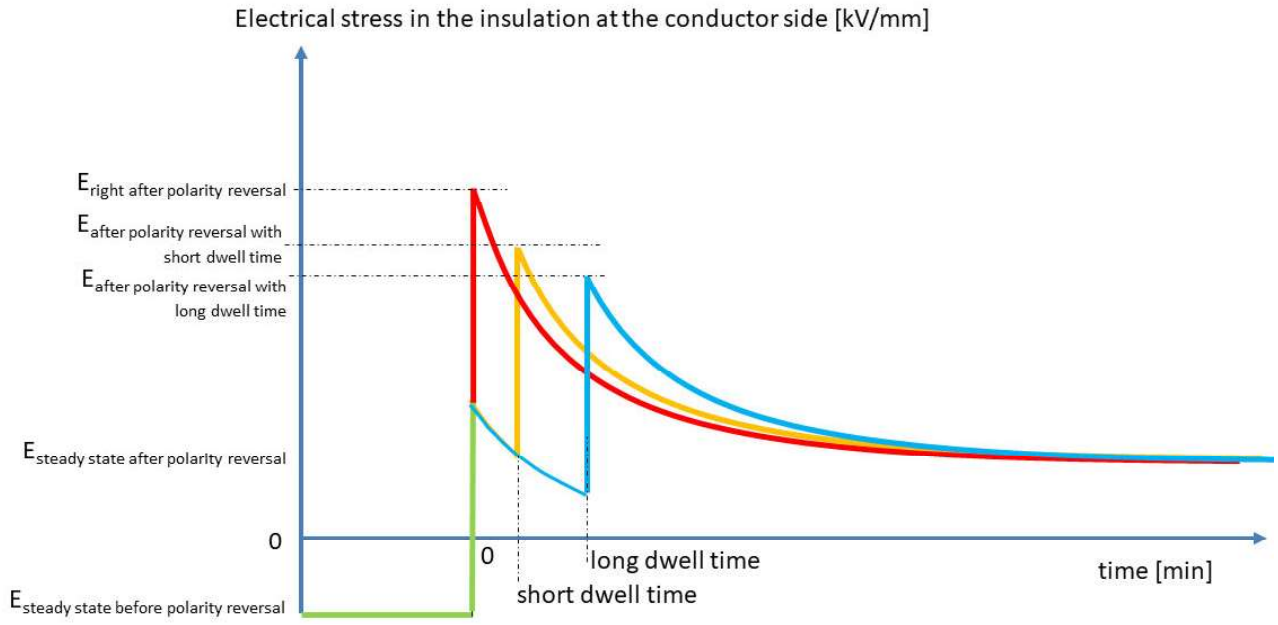


Figure 25 **Artificial drawing of the electrical stress at the conductor side of the insulation material of a warm cable, showing the impact of increasing the voltage polarity reversal time by introducing a shorter or longer dwell time:**

- **green-red curve: the full voltage polarity reversal is done instantaneously,**
- **green-orange curve: with a short dwell time,**
- **green-blue curve: with a long dwell time**

5.3.4 The voltage polarity reversal number per day and per year

I also looked to the daily number of voltage polarity changes that have been performed for the Basslink cable over the years.

The evaluation is presented in Appendix S.

[redacted]

5.3.5 Conclusion

[redacted]

In a HVDC MIND power cable, operated within its thermal design limits, I do not consider this reduced dwell time or even an overshoot of voltage polarity reversals during certain days as crucial, in line with what I summarized in Section 5.3.1. However, for a thermally overstressed HVDC MIND power cable as the Basslink cable, the choice for a shorter dwell time and more voltage polarity reversals than recommended by Pirelli means that these choices will potentially have contributed to the degradation.

How voltage polarity reversals are related to the cause of the failure will be treated in Section 6.1.10 ("Voltage polarity reversal stress").

6 QUESTIONS AND ANSWERS

6.1 Question 1 – Probable causes of failure

What do you consider to be the probable cause of the failure that occurred on 20 December 2015 and why?

In answering question 1, please identify each possible cause of failure which you considered and explain the view you formed about whether each such possible cause of failure was probable or improbable.

Answer:

The probable cause of the failure is "thermally induced stress", where the cable has been thermally overstressed, beyond its design limits.

The list below (presented in Section 6.1.1 to Section 6.1.11) shows causes which I consider as possible in the sense that these are causes which are plausible or potentially realistic and that should be considered as possibilities, given that the cable has been in operation for almost 10 years.

In that light, the possible causes can be related to issues with the design, the production, the installation, external damage, the operation / ageing (see also Section 2.4.5 ("Approach in case of a failure investigation")).

Per possible cause, I will identify whether I consider the possible cause as probable or improbable.

6.1.1 Deficient power cable construction per design

Explanation: Examples of a deficient cable construction per design are the use of wrong materials, or correct materials with wrong dimensions, etc.

Reason for being a possible cause: In the case of a deficient cable construction per design, from the start of operation or over time certain parts of the cable might get overstressed.

Probability: improbable

Reason for the chosen probability:

[redacted] Knowing this, there is not a full guarantee that the cable construction per design is such that a lifetime of 40 years will be met ([redacted], but it makes the chance of a deficient cable construction per design quite improbable.

[redacted] Another HVDC MIND power cable that I investigated had the same issue and did not fail so far because of this fact. For these reasons, there is not enough ground to assume that this [redacted]

[redacted]

6.1.2 Deficient cable production

Explanation: Examples of a deficient cable production are an insufficient impregnation of the paper windings with a compound, or the application of other materials than prescribed / specified, or the wrong positioning of materials, etc.

Reason for being a possible cause: In the case of a deficient cable production, from the start of operation or over time certain parts of the cable might get overstressed.

Probability: improbable

Reason for the chosen probability:

[redacted]

- [redacted]
- [redacted]

[redacted]

There is however one point that asks some elaboration. [redacted] According to me [redacted] this has not caused the failure. The displacement is such, that it is probably not the direct cause of the failure. I will come back to this item in discussing the failure cause in Section 6.1.9.2.

[redacted]

- [redacted]
- [redacted]

[redacted]

6.1.3 Deficient joint construction per design

Explanation: Examples of a deficient manufacturing joint construction per design or full scale joint design are the use of wrong materials, or correct materials with wrong dimensions, etc.

Reason for being a possible cause: In the case of a deficient joint construction per design, from the start of operation or over time certain parts of the joint might get overstressed.

Probability: improbable (effectively impossible)

Reason for the chosen probability:

[redacted]

- [redacted]

- [redacted]

[redacted].

6.1.4 Deficient joint production

Explanation: Examples of a deficient joint production are an insufficient impregnation of the paper windings with a compound, or the application of other materials than prescribed / specified or the wrong positioning of materials, etc.

Reason for being a possible cause: In the case of a deficient joint production, from the start or over time certain parts of the joint might get overstressed.

Probability: improbable (effectively impossible)

Reason for the chosen probability:

[redacted]

- [redacted]
- [redacted]

[redacted]

6.1.5 Weakness from a repair spot

Explanation: A repair spot can be the consequence of an incident during production, transportation or installation, where the cable has a repair without making a repair joint.

Reason for being a possible cause: In the case of insufficient repair, from the start or over time certain parts of the repair spot might get overstressed.

Probability: improbable

Reason for the chosen probability:

[redacted]

- [redacted]
- [redacted]

[redacted]

[redacted].

Altogether, it makes this possible cause quite improbable.

6.1.6 External cable damage

Explanation: Situations where a power cable can suffer from a mechanical force resulting in an external cable damage can be found in the cable handling during production, transportation and installation. But also, such an external mechanical force can come from anchoring or fishing activities after the cable is installed.

Reason for being a possible cause: Once a power cable has been damaged by an external force, certain parts inside the cable might get overstressed which can immediately or over time result in a cable failure.

Probability: improbable

Reason for the chosen probability:

[redacted]

A smaller damage might have been created by a shark bite. Such a cause or potential cause for cable failures has been mentioned in industry-based conferences on submarine cable. But it is my opinion that shark bites might be a failure cause for lighter submarine cables as telecom cables, not for heavily armoured power cables as the Basslink cable. [redacted] and a shark bite would quite probably also have led to scratches of other teeth, which have not been observed.

A further argument is that the cable was most probably not exposed (in terms of lacking a sand cover) prior to the failure. [redacted] This is giving an additional reason to expect that having an external damage from matters such as anchoring, fishing activities or shark bites is improbable.

6.1.7 Voltage ripple from converter station operation

Explanation: The DC voltage will have a ripple (harmonics) originating from the 50 Hz to DC conversion and vice versa in the converter station, which comes with normal operation. The ripple means in fact that the power cable system (made for DC) is experiencing some AC voltage component. This AC voltage component might cause a different electrical stress distribution and in certain cases also a higher electrical stress / more thermal losses than would be the case with just DC. It can also have an impact on the system stability [/44/, Wood, 2012], [/45/, Wood, 2014].

Reason for being a possible cause: If this voltage ripple is relatively large, it can result in another electrical stress distribution in the insulation material of the power cable system or of a joint. For polymer cables, it is known that it can influence the partial discharge activity [/46/, Olsen, 2014].

Probability: improbable

Reason for the chosen probability: A voltage ripple can cause a somewhat different electrical stress distribution and maybe also influence the partial discharge activity (if any) [/46/, Olsen, 2014]. But I could not find any source of information that showed that a voltage ripple as such is harmful for an HVDC cable. It has never been mentioned in literature or by experts with whom I could speak. Therefore, I consider this possible cause as improbable.

6.1.8 Overvoltages from the connected network

Explanation: The network, connected to the Basslink cable, might be a source of over voltages, that can enter the power cable. Such over voltages might originate from the convertor station, during converter station malfunctioning for instance, or as a result of lightning that hits the DC lines between the convertor station and transition station (Figure 8, page 44). With that, a so called transient over voltage might happen inside the power cable, which exists for a short time (less than a second for instance). Depending on its frequency content it will enter the power cable on one end and travel towards the other end, meanwhile increasing the voltage over the power cable system insulation.

Reason for being a possible cause: Too high or too many (or both) overvoltages can electrically overstress the insulation material of the power cable or of a joint, the moment these are present.

Probability: improbable

Reason for the chosen probability: Because the cable failed far from the coastal area (about at least 100 km) where over voltages are damped, it is an improbable cause.

6.1.9 Thermally induced stress

Explanation: During normal power transmission, an electrical current is flowing through the power cable conductor. Because the conductor has an electrical resistance, this electrical current will create thermal losses in the power cable conductor. These thermal losses heat up the cable. The surroundings of the cable will absorb this heat. As a result, there is a constant flow of heat from the inside of the power cable towards its surroundings.

Some further background information is given in Section 3.1.6 (“Electrical current and cable temperature”) and Section 5.2 (“Cable temperature and degradation”).

Reason for being a possible cause: In case of insufficient heat flow towards or absorption by the surroundings, over time certain parts of the cable might get thermally overstressed. One example is, when the soil, surrounding the cable, has (got) thermal properties which are such that the cable cannot fully release its heat (anymore). Alternatively, it is possible that the electrical current through the conductor of the cable (load) was such (more and/or longer in duration) that there was more heat generated than foreseen.

In particular a HVDC MIND cable is sensitive to being operated at a temperature level beyond its design level. It can degrade in different ways. This will be explained in Section 6.4.

Probability: probable

Reason for the chosen probability:

6.1.9.1 Temperatures at the failure location exceeded the design limits

I concluded in Section 5.2.3 that at the failure location the Basslink cable has experienced a too high thermal stress during certain moments, the main period being the [redacted] period. There are two sources for this, one from DNV GL and one from [redacted]

1. As was shown by De Wild [TAB 65.0.4, 2020] and explained in more detail in Section 5.2.2.1 ("Cable temperatures according to De Wild"), the Basslink cable had periods of time during operation (mainly in [redacted]) that the cable was thermally overstressed.

   At the failure location De Wild's calculated temperatures were:

   a. The conductor temperature reached a level of [redacted] which temperature is about [redacted] above the design limit of [redacted]

   b. The temperature difference over the cable insulation at the failure location reached a level of at least [redacted] which temperature is [redacted] above the design limit of [redacted]

   De Wild has calculated the temperatures in the cable at the failure location for various periods of time during the cable operation, not only for [redacted] [TAB 65.0.4, 2020, sections 8.4 to 8.9]. For these other periods in [redacted] and [redacted] sometimes the temperature difference over the insulation and occasionally the maximum conductor temperature to a certain extent were beyond their design levels

2. [redacted]

In summary and based upon the information provided to me to date, during its operational life of almost 10 years (116 months) until the Basslink HVDC cable failed in December 2015, the cable has been thermally overstressed during several periods. This happened particularly in the [redacted] period, being [redacted] before the cable failed.

Under thermal stress exposure beyond the design limits, three different degradation processes can happen that can lead to a reduced insulation quality. These three different thermal degradation processes are presented in Section 6.4 and in Appendix V. In two of these processes enlarged void formation inside the cable insulation plays a role in the degradation processes. It is my opinion that it is probable that one or a combination of these degradation processes started during one of the periods that the cable was thermally overstressed (most probably in [redacted] where this overstress reached extreme values), after which this degradation slowly continued during the operation of the Basslink cable until the failure occurred in December 2015.

[redacted] But I want to emphasize that this development was used to reach higher voltage levels for transmitting the power, as

happened to many cables installed since the 1990s, including amongst others the Basslink cable. This development was NOT used by cable manufacturers of HVDC MIND power cables [redacted] to increase the maximum design temperatures. Exceeding these temperatures is challenging the cable insulation where thermally driven degradation and a resulting failure is a probable consequence.

6.1.9.2 Length effect

De Wild [TAB 65.0.4, 2020] calculated that at certain locations the cable has been thermally overstressed to a higher degree than at the failure location. These are so-called thermal bottleneck locations. In two of these locations the maximum conductor temperature went up to [redacted] and the maximum temperature difference over the cable insulation (not including the screens) went up to [redacted]

One would initially expect a failure of the Basslink cable of being thermally overstressed to occur at one of the thermal bottlenecks. But there is also a so called 'length effect' (see Appendix R for a further explanation). The 'length effect' reflects natural variations along the cable with respect to (amongst others) the precise soil conditions and cable quality. In a properly designed, installed and operated cable, such natural variations would not be a reason for a cable to fail within its foreseen lifetime. In that sense, natural quality variations are not considered as a design or manufacturing defect. However, for a cable being thermally overstressed, the positions where local variations merge into areas with lower quality, it is the weakest link which will be the preferred location for the thermally overstressed cable to fail. Two relevant variations for the Basslink cable are mentioned here:

- Everywhere along the Basslink cable the actual thermal soil property natural variations will create slightly lower or higher temperatures than calculated by De Wild (and CCI). De Wild calculated for the failure location that the maximum conductor temperature went up to [redacted] and the maximum temperature difference over the cable insulation (not including the screens) went up to [redacted] However, due to the actual thermal soil property variations, somewhat higher temperatures may have been reached, realistically [redacted] and [redacted] respectively. See for a further explanation Section 5.2.2.1, in particular the part "Maximum temperatures at the failure location taking into account the uncertainties". Such slightly higher temperatures at the failure location may have created extra degradation in an already thermally overstressed cable
- One can expect that everywhere along the Basslink cable the counterpressure from the reinforcing tapes will slightly vary. And indeed, at the failure location it was found that:
  - [redacted]
  - [redacted]

[redacted].

6.1.9.3 The contribution of voltage polarity reversals

The cable has been subjected to many voltage polarity reversals that come with a change in the direction of the power flow. As is explained in Section 6.1.10, such voltage polarity reversals result in a temporary but considerable increase of the electrical stress inside the cable insulation which happens along the whole cable. The fact that the cable broke down shortly after two voltage polarity reversals, supports the hypothesis that the related increase of the electrical stress played a role.

6.1.9.4 Summary

The Basslink cable failed because it was thermally overstressed, where the cable has been operated beyond its thermal design limits.

By way of further explanation:

- The increase of the electrical stress due to voltage polarity reversals contributed to the development of the failure in the thermally overstressed power cable
- [redacted]

6.1.9.5 Notes

Both, the thermally induced stress and voltage polarity reversal induced stress are a direct result of the way the Basslink cable is operated.

Apart from thermally induced stress, the other candidates for the cause of the failure mentioned in Section 6.1 (related to design, production and installation, including their normal variations) are considered improbable.

The fact that the Basslink HVDC power cable failed after almost 10 years of service operation supports the conclusion that an ageing mechanism such as thermally induced stress caused the failure.

6.1.10 Voltage polarity reversal stress

Explanation: During a change of the power flow direction, the voltage goes from plus 400 kV to minus 400 kV (or vice versa) within a short period of time. This voltage reversal is called voltage polarity reversal.

Reason for being a possible cause: Especially in the case of DC operating conditions, as is the case for the Basslink cable, voltage polarity reversals will electrically (over)stress the power cable insulation material. In a healthy cable, where the cable is prevented from cooling down too much during a voltage polarity reversal, it is not an immediate problem (maybe on the long term, but that is not known), but in a compromised cable insulation, such voltage polarity reversals can be dangerous for the power cable insulation. Some further background information is given in Section 3.1.5 (“Power transmission and voltage polarity reversals”) and Section 5.3 (“Voltage polarity reversals and degradation”).

Probability: probable (in having a contributing impact)

Reason for the chosen probability: The fact that the cable broke down shortly after having had two voltage polarity reversals (Section 4.7.4, Figure 16) indicates that there is a probable relation between the voltage polarity reversals and the cause of failure.

I wrote that the voltage polarity reversal regime probably contributed to the failure. That is, because in a healthy cable (without (large) voids), a time for voltage polarity reversals of 2 minutes as applied for the Basslink cable does not seem to be harmful for a cable as I explained in Section 3.4.3 ("Electrical stress during voltage polarity reversals"). This I learned from interviews with various HVDC MIND power cable operators in Europe, where such a time span is quite common and never resulted in related cable failures. Even, the time for voltage polarity reversals in case of the [redacted] cable [redacted] is less than 1 minute (this information I was allowed to share). But in all these cases, the European cable operators interviewed mentioned that they operate their cables within the thermal design rating and moreover they tend to avoid that during a voltage polarity reversal, the cable is cooling down too much by realizing a fast ramping up and down.

Because of the fact that the Basslink cable very probably had enlarged voids or a higher electrical stress as a result of the thermal regime (explained in Section 6.4), the voltage polarity reversal regime is now more relevant. In this particular case it is relevant mainly as a trigger and not as the sole root cause of the failure, as I wrote in Section 5.3.5. [redacted]

- [redacted]
- [redacted]

these could have helped to postpone the failure moment, but it is not possible to quantify this.

6.1.11 An incidental weakness

Explanation: Characteristics of an incidental weakness are that it is not foreseen by engineers and cable operators and nevertheless happened, but where the scale is such that it is restricted to one location or else a very small number of locations. Some examples are:

- A single irregularity got accidentally embedded in the insulation during production. The irregularity was overlooked during the Factory Acceptance Test, but found during the Commissioning Test. It is a typical example of an accidental weakness. In this case the incidental weakness could be found before it could create a failure during operation
- Somebody from production got fired and before leaving the factory in an angry mood did stick a knife into the cable insulation material. Luckily it was deep enough to be detected by the Factory Acceptance Test (with partial discharge detection and localization). This is also the purpose of the Factory Acceptance Test, but realize that it was nevertheless an incidental weakness.

Most incidental weaknesses are very difficult or impossible to be unveiled, however the above two described incidental weaknesses come from the author's experience and could be traced concerning their background by coincidence.

The incidental weakness is different from an event out of the control of people involved in the cable design, production, installation and operation, where large scale incidents take place, for instance a war, hurricane or a terrorist attack.

Reason for being a possible cause: For now an incidental weakness cannot be excluded as a possible failure cause.

Probability: improbable

Reason for the chosen probability: Because one of the above-mentioned failure causes was concluded to be probable, this "incidental weakness" becomes improbable. Would one of the above-mentioned failure causes have been found as proven, this "incidental weakness" would have become impossible.

6.2 Question 2a – Maximum operating conductor temperature

Is there a maximum conductor operating temperature that the HVDC Cable should not exceed (**Maximum Conductor Operating Temperature**) to ensure that the HVDC Cable is operated in a manner that does not adversely impact its long term performance or service life? If your answer is yes, what is the basis for your answer and upon what source(s) do you rely in support of your answer?

Answer:

Various sources mention a maximum allowed cable conductor operating temperature for the Basslink cable of [redacted] Sometimes it is mentioned directly in reports, sometimes it is related to type test requirements, indirectly showing the same allowed cable conductor operating temperature. These sources are listed below:

- [redacted]
- [redacted]
- [redacted]
- [redacted]
- [redacted]
- [redacted]
- [redacted]

A HVDC MIND power cable should not exceed this maximum conductor operating temperature for reasons mentioned in Section 6.4.

6.3 Question 2b – Maximum operating temperature across insulation

Is there a maximum temperature difference over the paper insulation layer of the HVDC Cable that should not be exceeded (**Maximum Temperature Difference**) to ensure that the HVDC Cable is operated in a manner that does not adversely impact its long term performance or service life? If your

answer is yes, what is the basis for your answer and upon what source(s) do you rely in support of your answer?

Answer:

Various sources mention a maximum allowed temperature difference over the cable insulation plus screens for the Basslink cable of [redacted] in relation to type test requirements, indirectly showing this. These sources are listed below:

- [redacted]
- [redacted]
- [redacted]
- [redacted]

A HVDC MIND power cable should not exceed this maximum operating temperature difference over the cable insulation for reasons mentioned in Section 6.4.

6.4 Question 2c – Impact of exceeding the maximum temperatures

What, if any, risks arise if the HVDC Cable is operated in excess of the Maximum Conductor Operating Temperature and/or the Maximum Temperature Difference?

Answer:

In order to understand the potential degradation in a thermally overstressed cable, the following is important.

In the cable insulation of paper layers and a compound there are voids and electrical stresses. Normal voids combined with normal electrical stresses are expected not to introduce unforeseen degradation because these are in line with the design.

But deviations from normal can start an unwanted degradation (and eventually result in a failure), in particular:

- If caused by abnormal voids exposed to normal electrical stresses or
- If caused by normal voids exposed to abnormal electrical stresses or
- A combination of both.

Here 'normal' means, as per design and 'abnormal' means larger (for the voids) or higher (for the electrical stresses) than per design.

The fact that the cable broke down in its cooling down stage (a typical stage where voids (whether enlarged or not) have their maximum size) supports the reasoning that next to the electrical stress, voids were an actor in this degradation process.

The void sizes and the electrical stress levels are influenced by the conductor temperature and the temperature difference over the cable insulation.

The precise degradation process in a thermally overstressed cable is a complicated matter. As a guide, Table 3 and Table 4 summarize at a high level the thermally stimulated possible degradation processes as known from literature. Which of these processes take place will depend on the actual thermal overstress situation and material properties?

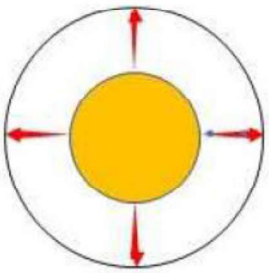
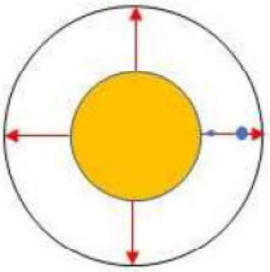
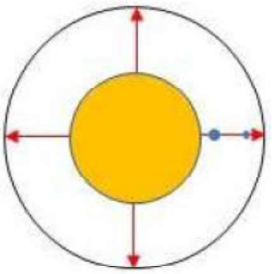
For the Basslink cable, at certain moments during the cable life, these temperatures were both together or separately beyond their design limits. Because over time the Basslink cable has been thermally overstressed in different ways it is not possible to conclude which of the thermally stimulated degradation processes mentioned in Table 3 and related Table 4 were the main contributors. Only in Table 4 the references are mentioned.

This explanation is also found (slightly more elaborated) in Appendix V.

Table 3 The thermal scenarios and resulting physical processes

Thermal scenarios	$T_{conductor} \leq$ [redacted]	$T_{conductor} >$ [redacted]
$T_{difference\ over\ the\ cable\ insulation} \leq$ [redacted]	Scenario 0	Scenario 1 • Thermal expansion of the cable insulation
$T_{difference\ over\ the\ cable\ insulation} >$ [redacted]	Scenario 2 • The electrical stress in the outer insulation layers reach values beyond the design limits	Scenario 3 • Thermal expansion of the cable insulation • Migration of the compound away from inner insulation layers • The electrical stress in the outer insulation layers reach values beyond the design limits

Table 4 The physical processes and resulting degradation

Physical process	Degradation process	Illustration (see note 3)
The electrical stress in the outer insulation layers reach values beyond the design limits Being part of thermal scenario 2 and 3 in Table 3	As a result, the electrical stress, being beyond the design limits in the **outer** cable insulation layers, can create partial discharges in and around one or more normal voids, causing degradation at this spot and a failure. According to many different authors, see Section 3.4.2.	
Thermal expansion of the cable insulation Being part of thermal scenario 1 and 3 in Table 3	1. This can create permanent deformation of outer reinforcing layers, which reduces the compression forces needed to keep voids small. 2. If this happens, one or more enlarged voids of permanent nature can be created, especially in the outer cable insulation layers (see also note 1). 3. As a result, the electrical stress (within its design limits) in the **outer** cable insulation layers can create partial discharges in and around the enlarged void(s), causing degradation at this spot and a failure. According to [Huang, /87/, 2015].	
Migration of the compound away from inner insulation layers Being part of thermal scenario 3 in Table 3	1. The lack of compound can create one or more enlarged voids of permanent nature in the inner insulation layers (see also note 2). 2. As a result, the electrical stress (within its design limits) in the **inner** cable insulation layers can create partial discharges in and around the enlarged void(s), causing degradation at this spot and a failure. According to [Runde, /40/, 2014] and [Evenset, /29/, 2000]. See also note 2.	

Notes:

1. An enlarged void of permanent nature can be (partly or fully) filled with compound or compressed when the cable is warm and reappear (in full size) once the cable is cooling down. In fact, it means that each time a cable cools down the enlarged void will reappear.
2. For migrating the compound, two processes are relevant. These are the viscosity of the compound and the 'pushing' force acting on it to move the compound away from its origin. Two examples are mentioned here, but everything in between is possible as well:
   - If the maximum conductor temperature is close to the maximum design temperature (and the viscosity of the compound is still high) but the temperature difference over the insulation considerably exceeds the design value (resulting in a high pushing force), the compound can migrate.
   - Likewise, if the maximum conductor temperature considerably exceeds to the maximum design temperature (and the viscosity of the compound is low) but the temperature difference over the insulation is close to the design value (resulting in a mild pushing force), the compound can migrate.
3. The red arrows represent the electrical stress (field) in the cable insulation. The blue dots represent the voids (in some cases enlarged) in the cable insulation. The yellow part is the cable conductor. The illustration is not on scale.

The dismantling of the faulty cable sample and a reference sample from nearby the failure spot (see Section 4.8) showed that the cable has not been thermally aged in terms of [redacted] That is also not expected because the cable at the failure location will not have

been operated beyond 72 °C for a long period of time[22] and at this temperature level thermal degradation of the insulation material causing the compound or paper to degrade on a molecular level (in particular: depolymerisation) is not playing a role. This is explained in Section 3.5 ("Thermally driven chemical degradation – not a key issue of the insulation material"). But lacking this molecular type of thermal degradation does not exclude that enlarged voids created in a thermally overstressed cable could have caused the failure.

The dismantling of the faulty cable sample showed that the cable next to the failure location does not show signs of electrical activity, such as puncture of the insulation material by high energetic electrons or electrical treeing, nor enlarged voids. This is also not expected to be found, although enlarged void formation at the failure spot could have caused the failure. As explained in Section 3.3.9 ("Evidence for enlarged voids after a failure in a HVDC MIND power cable with compact insulation") evidence of this type is not normally found with compact insulation.

6.5 Question 3 – Possible causes of failure related to operation

Which of the possible causes of failure, if any, can be attributed to the way in which the cable was operated by BPL? In answering this question, please identify the facts and assumptions on which you rely to identify the way in which the cable was operated by BPL.

Answer:

I will restrict my answer to the probable causes.

Both probable causes

- "Thermally induced stress" and
- "Voltage polarity reversal stress"

are clearly related to the way the cable has been operated by BPL.

Sections 6.1.9 and Section 6.1.10 treat the facts and assumptions on which this is based.

6.5.1 Thermally induced stress

Reason: thermally induced stress is related to the amount of power transmitted which can be influenced and if needed limited by BPL.

6.5.2 Voltage polarity reversal stress

Reason: the voltage polarity reversal induced stress is related to the number of changes in the power direction and the speed with which these occur, which can be influenced and if needed adjusted by BPL.

6.6 Question 4 – Preventing possible causes of failure

Further to question 3, if any possible cause of failure is attributable to the way in which the cable was operated by BPL, is there anything that a prudent, experienced and competent person in the position of BPL should have done to prevent the failure?

[redacted]

Answer:

I will restrict my answer to the probable causes.

Both the possible causes "thermally induced stress" and "voltage polarity reversal stress" are clearly related to the way the cables have been operated by BPL and could have been influenced by BPL, for the reasons mentioned below.

6.6.1 Thermally induced stress

The thermally induced stress could have been avoided in two different ways.

It is related to the operation of the Basslink power cable, as was concluded in [TAB 65.0.4, De Wild, 2020, Executive summary]: "*The Basslink connector was operated such that the cable system was highly loaded. In various time periods, the interconnector was loaded significantly beyond* [redacted] *and significantly beyond* [redacted]*. This resulted in temperatures that increased over prolonged periods of time thereby exceeding thermal limits, without enough possibilities for the cable to cool down.*"

This is something that could have been avoided.

However, there is an additional issue. In [TAB 65.0.4, De Wild, 2020, Executive summary] wrote as well: "*The soil around the submarine power cables has* [redacted]

This could have been avoided by:

1. Having carried out a review of the thermal engineering calculations
2. Having performed a full cable route survey with soil samples, such to check the engineering calculations with respect to thermal properties of the soil and laying depth and to update the actual possible load based on these findings.

6.6.2 Voltage polarity reversal stress

As was said already, the voltage polarity reversal regime did contribute to the development of the failure. The amount of voltage polarity reversal induced stress can be influenced and if needed limited / adjusted by BPL. This has not been done, despite the recommendations given by [redacted] This is, to the author's opinion, an omission. But because the voltage polarity reversal regime (if the cable is not thermally overstressed) is not the main cause of the failure, but just a contributor, its impact for the present case is small, but cannot be fully ignored.

6.7 Question 5 – What tests can give further information

What tests (if any) do you consider are necessary as a matter of [redacted] to establish or would assist or be likely to assist in establishing the probable cause of failure, or narrowing the possible causes of failure?

Answer:

6.7.1 Load cycle test with voltage polarity reversals (Cigré Electra 189)

6.7.1.1 Introduction

It is probable that the Basslink cable has been exposed to too high temperatures preceding the failure in December 2015, see Section 6.1.9. It is possible that this has led to irreversible degradation of the cable insulation (see Section 6.5) outside the breakdown spot, where

- One or more enlarged voids of permanent nature were created in the butt gaps of the insulation material
- One or more normal voids under the influence of the electrical stress beyond the design limit or one or more enlarged voids under the influence of the electrical stress within or beyond the design limit have created signs of electrical degradation connected to these voids (like tracking channels or puncture of paper layers).

It is helpful to confirm the above-mentioned statement by testing a piece of cable. Should there be considerable degradation as mentioned above, the cable piece will probably not pass the test. In that sense, the outcome of the test can, on one hand, help to more firmly conclude on the root cause of the failure and the resulting void creation. On the other hand, it can be helpful in deciding about future operational conditions, to avoid failures as much as possible.

6.7.1.2 Proposed test

The proposed test is to repeat the test that is described in [redacted] followed by lightning impulse tests in accordance with Cigré Electra 189 [/28/, Cigré, 2000]. It is additionally proposed to add partial discharge measurements to this test. For this, a cable piece of at least 40 m is needed for reasons mentioned in Section 6.8.2. Preferably, such a test should be done on more than one cable sample, to reduce the impact of local variations in quality. For the test description below, only one test is assumed for practical reasons.

However, the above described test proposed gives potential confirmation to increase the certainty that the cable failed because of having been thermally overstressed. It is not guaranteed that the tested cable (per definition limited in length) will show the presence of such degradation (by partial discharge activity and / or a failure) during such a test, since the degradation is expected to be a localized issue, not per definition present to enough extent in the cable length to be tested. If there is any degradation left after the failure, testing many more cable lengths (for instance ten) could help, but might be considered as not practical, especially since issues such as available cable lengths, water ingress or the impact of the retrieval can play a role.

6.7.2 Other tests

6.7.2.1 Introduction

There is an example of testing done on an HVDC MIND, after samples were retrieved at the end of its service life. It is the Gotland 1 cable, that has been in service for 32 years. It was in operation from 1954 to 1986, with the first 16 years at a power design rating of 20 MW (100 kV and 200 A), and the remaining 16 years at a power rating of 30 MW (150 kV and 200 A). The last year before the power design rating was increased, the cable experienced an overload (in current) of 15 %. The highest field strength (which happened at the conductor side of the insulation) is present under no load conditions and was 20 kV/mm in the first 16 years and became 28 kV/mm in the remaining 16 years [/18/,

Hjalmarsson, 1992]. The power flow has been mainly in one direction. There were no internal cable faults during the lifetime of the power cable.

At the end of its operational life, various cable parts were retrieved from the sea floor in length of 45 m to 120 m. Spare cable lengths were also available. The cable parts have been subjected to various tests, described in the following subsections (only, those related to the cable insulation material are mentioned here).

6.7.2.2 Loss-factor measurements as mentioned by Hjalmarsson

Loss-factor measurements (both at 50 Hz up to several kV and at low voltage over a wide frequency and temperature range) have been done. Such loss-factor measurements are helpful to get insight in conduction and polarization phenomena and to determine for instance whether there is moisture in the insulation.

Result: no significant difference in the spare and service aged cable lengths.

6.7.2.3 Breakdown tests as mentioned by Hjalmarsson

Impulse tests and DC breakdown tests have been done. None of these came with voltage polarity reversals. The cable retrieved from operation had very low breakdown values, but these were attributed to the rough mechanical handling during retrieval. Once these weak cable parts were removed, the remaining breakdown values were comparable to the cables from stock.

Result: It is my opinion, that because of the screening done, this result is not very reliable.

6.7.2.4 Degree of polymerisation as mentioned by Hjalmarsson

The degree of polymerisation informs about the length of the cellulose chains of the paper insulation. Thermal ageing will make these shorter, resulting in a lower level of the degree of polymerisation.

Result: It was found that the spare and aged cable lengths gave similar results. However, the results were significantly lower than what is seen for new paper insulation. Thus, the decrease in the degree of polymerisation observed can be attributed to thermal ageing, but between the spare cable and aged cable, the average temperatures over the years did not differ enough to show this in the degree of polymerisation.

6.7.2.5 Tensile properties paper insulation as mentioned by Hjalmarsson

The tensile properties refer to the tensile strength and elongation at break of the paper insulation.

Result: no significant difference in the spare and service aged cable lengths.

6.7.2.6 Other tests not mentioned by Hjalmarsson

One can consider other tests (apart those mentioned above), but other tests that I am aware of are not recommended by me for the following reasons:

- Bulk tests are not able to find a localized degradation (such as the loss-factor measurement mentioned above) or
- Sample tests of a smaller part of the cable insulation are not directed to find localized degradation (such as the degree of polymerisation and the tensile properties mentioned above) or

- Sample tests of a smaller part of the cable insulation (such as a visual inspection) have a limited chance to have a sample in which precisely the localized degradation is present, would it be visible.

6.7.3 Conclusion

The most reliable test, to see whether the thermal ageing has resulted in permanent degradation by the creation of enlarged voids of permanent nature, is the electrical part of the Type Test according to Cigré Electra 189 [/28/, Cigré, 2000]. This is the load cycle test with voltage polarity reversals, followed by lightning impulse tests, performed on a cable length of at least 40 m. Preferably such a test is combined with a partial discharge test during load cycling[23], being able to identify (and even locate) the presence of localized degradation.

However, it is not guaranteed that the tested cable length will show the presence of localized degradation (by partial discharge activity and / or a failure) during such a single test, since the localized degradation is not per definition critically present in the cable length to be tested. Testing many more cable lengths (for instance ten) could help, but might be considered as not practical, especially since issues like available cable length, water ingress or the impact of the retrieval can play a role.

The other tests mentioned above I consider as not useful to identify the impact of thermal degradation where a limited number of spots with degradation (if any left after the failure) are expected.

6.8 Question 6 – Materials needed for tests

Further to question 5, if testing is appropriate, what material (including retrieved samples of cable and documents), if any, would be required to undertake any such tests? If it is necessary in your opinion to test a retrieved sample of cable, would any testing-related limitations or difficulties arise from the condition of that sample as at the time of testing? If yes, please explain the reasons for that answer, identifying the nature and scope of any such testing-related limitations or difficulties.

Answer:

6.8.1 Introduction

In question 7, it is proposed to perform a [redacted] with voltage polarity reversals followed by lightning impulse tests in accordance with Cigré Electra 189 [/28/, Cigré, 2000], preferably with an additional partial discharge test during [redacted].

For this test, a cable piece is needed of at least 40 m in length for reasons mentioned in Section 6.8.2. This cable length should come from retrieved cable, that came from the repair of the fault.

[redacted]

[23] Partial discharge tests have been done on a retrieved old HVDC MIND cable, see [/74/, Elovaara, 2002], see also Appendix J. It has also been done on unused and used HVDC MIND cable [/90/, Runde, 2019].

[redacted]

There is another potential issue, once such a cable length would have been made available for testing. It is the fact that the retrieved cable length might have suffered from water ingress and/or mechanical damage. Cable retrieval is therefore a delicate process, or else, the testing is useless. The retrieved cable length can reasonably well be tested for water ingress.

6.8.2 Reasons to use a cable sample with a minimum length of 40 m

A minimum of 40 m cable length is necessary in order to perform for the following reasons:

- According to Cigré Electra 189 [/28/, Cigré, 2000], the "*assembly to be tested shall consist of at least 30 m of cable …"*. Taking into account that considerable length of the two test terminations (usually up to 8 m long each) the remaining cable test length between the terminations would be 14 m, which in my opinion is quite short. The preferred cable length between the terminations for a test is at least 24 m, resulting in minimum length of the cable made available for the test of 40 m
- the actual test length of cable (excluding the terminations) must be long enough to hold a particular temperature so that the testing can be carried out accurately (any length shorter than 40 m including terminations will provide a less accurate result)
- although two cable lengths of 20 m each could be joined together, the joint would constitute a weakness in the 40 m cable length which would likely compromise the testing (the test might fail at the joint).

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APPENDIX A

Reference list DNV GL failure investigations on power cables up to start 2019

In this table PFI means Power Failure Investigation

#	Investigation start year	Customer region	Failed component category	AC or DC	Voltage class
1	1997	Europe	termination	AC	HV
2	1998	Europe	termination	AC	HV
3	2001	Europe	termination	AC	HV
4	2002	Europe	cable	AC	MV
5	2002	Europe	termination	AC	HV
6	2002	Europe	joint	AC	MV
7	2003	Europe	joint	AC	HV
8	2003	Europe	termination	AC	HV
9	2003	Europe	cable	AC	MV
10	2003	Europe	joint	AC	MV
11	2003		joint	AC	HV
12	2004	Europe	cable	AC	HV
13	2004	Europe	termination	AC	MV
14	2004	Europe	termination	AC	MV
15	2004	Europe	joint	AC	MV
16	2005	Europe	cable	AC	HV
17	2005	Europe	termination	AC	MV
18	2005	Europe	joint	AC	HV
19	2005	Europe	termination	AC	HV
20	2005	Europe	termination	AC	HV
21	2005	Europe	termination	AC	HV
22	2006	Europe	cable	AC	MV
23	2006	Europe	joint	AC	MV
24	2006	Middle East	termination	AC	EHV
25	2006	Europe	termination	AC	HV
26	2006	Europe	termination	AC	HV
27	2006	Europe	termination	AC	HV
28	2006	Middle East	termination	AC	EHV
29	2006	Europe	termination	AC	HV
30	2006	Middle East	termination	AC	EHV
31	2006	Europe	termination	AC	HV
32	2006	Middle East	termination	AC	EHV
33	2007	Europe	termination	AC	HV
34	2007	Asia	joint	AC	MV
35	2007	Europe	joint	AC	MV
36	2007	Europe	joint	AC	MV

37	2007	Europe	cable	AC	HV
38	2007	Europe	joint	AC	HV
39	2007	Europe	cable	AC	EHV
40	2007	Europe	termination	AC	MV
41	2007	Europe	joint	AC	EHV
42	2008	Europe	joint	AC	MV
43	2008	Europe	cable	AC	MV
44	2008	Europe	joint	AC	HV
45	2008	Europe	cable	DC	EHV
46	2008	Asia	joint	AC	HV
47	2008	Europe	termination	AC	EHV
48	2009	Europe	termination	AC	HV
49	2009	Europe	termination	AC	HV
50	2009	Europe	joint	AC	EHV
51	2009	Europe	cable	AC	EHV
52	2009	Middle East	cable	AC	HV
53	2009	Europe	cable	AC	MV
54	2009	Middle East	cable	AC	HV
55	2009	Europe	termination	AC	HV
56	2009	Europe	cable	DC	EHV
57	2009	Europe	joint	AC	HV
58	2009	Europe	joint	AC	MV
59	2009	Europe	joint	AC	MV
60	2009	Europe	cable	AC	MV
61	2009	Europe	termination		EHV
62	2010	North America	cable	AC	MV
63	2010	Asia	termination	AC	MV
64	2010	Europe	termination	AC	MV
65	2010	Middle East	cable	AC	MV
66	2010	Europe	cable	DC	EHV
67	2010	Asia	termination	AC	HV
68	2010	Europe	cable	AC	LV
69	2010	Asia	termination	AC	HV
70	2010	Europe	cable	AC	MV
71	2010	Europe	cable	AC	MV
72	2010	Europe	joint	AC	MV
73	2010	Europe	joint	AC	EHV
74	2010	Asia	joint	AC	EHV
75	2010	Europe	cable	AC	MV
76	2011	Middle East	joint	AC	MV
77	2011	Middle East	termination	AC	MV
78	2011	Middle East	cable	AC	HV
79	2011	Europe	termination	AC	MV

80	2011	Middle East	cable	AC	MV
81	2011	Asia	termination	AC	EHV
82	2011	Europe	cable	AC	MV
83	2011	Europe	termination	AC	HV
84	2011	Europe	joint	AC	EHV
85	2011	Europe	termination	AC	EHV
86	2011	Europe	joint	AC	MV
87	2011	Europe	cable	AC	MV
88	2011	Europe	joint	AC	HV
89	2011	Europe	cable	DC	EHV
90	2011	Asia	joint	AC	HV
91	2011	Europe	joint	AC	MV
92	2011	Europe	cable	AC	HV
93	2011	Europe	joint	AC	HV
94	2011	Middle East	joint	AC	HV
95	2011	Europe	joint	AC	MV
96	2011	Europe	cable	AC	EHV
97	2011	Europe	busbar	AC	MV
98	2011	Europe	termination	AC	MV
99	2012	Asia	joint	AC	HV
100	2012	Europe	termination	AC	EHV
101	2012	Asia	termination	AC	HV
102	2012	Europe	termination	AC	HV
103	2012	Middle East	cable	AC	MV
104	2012	Africa	cable	AC	HV
105	2012	Europe	cable	DC	EHV
106	2012	Europe	joint	AC	EHV
107	2012	Europe	joint	AC	MV
108	2012	Europe	termination	AC	EHV
109	2012	Europe	joint	AC	MV
110	2012	Europe	joint	AC	MV
111	2012	North America	termination	AC	EHV
112	2012	Europe	termination	AC	HV
113	2012	North America	joint	AC	EHV
114	2012	Middle East	cable	AC	HV
115	2012	Europe	cable	AC	HV
116	2012	Asia	joint	AC	EHV
117	2012	Europe	joint	AC	MV
118	2012	Europe	cable	AC	MV
119	2012	Europe	termination	AC	EHV
120	2012	Middle East	joint	AC	HV
121	2012	Europe	cable	AC	MV
122	2012	Europe	cable	AC	MV

123	2012	Europe	joint	AC	LV
124	2012	Middle East	joint	AC	HV
125	2012	Europe	cable	DC	EHV
126	2012	Europe	joint	AC	MV
127	2013	Middle East	joint	AC	HV
128	2013	Europe	cable	AC	HV
129	2013	Europe	cable	AC	HV
130	2013	Europe	joint	AC	MV
131	2013	Europe	joint	AC	MV
132	2013	Europe	joint	AC	MV
133	2013	Europe	joint	AC	MV
134	2013	Europe	joint	AC	EHV
135	2013	Europe	joint	AC	MV
136	2013	Europe	joint	AC	HV
137	2013	Middle East	joint	AC	HV
138	2013	Europe	cable	AC	HV
139	2013	Asia	joint	AC	EHV
140	2013	Asia	termination	AC	EHV
141	2013	Europe	termination	AC	HV
142	2013	Middle East	cable	AC	HV
143	2013	Europe	cable	AC	MV
144	2013	Europe	joint	AC	MV
145	2013	North America	termination		
146	2014	Asia	termination	AC	EHV
147	2014	Asia	cable	AC	EHV
148	2014	Asia	joint	AC	EHV
149	2014	Asia	cable	AC	EHV
150	2014	Middle East	termination	AC	EHV
151	2014	Europe	joint	AC	MV
152	2014	Europe	joint	AC	MV
153	2014	North America	termination	AC	EHV
154	2014	Asia	cable	AC	EHV
155	2014	Middle East	cable	AC	EHV
156	2014	Europe	joint	AC	MV
157	2014	Asia	cable	AC	EHV
158	2014	Europe	bushing	AC	MV
159	2014	Europe	joint	AC	MV
160	2014	Middle East	joint	AC	HV
161	2014	Middle East	cable	AC	HV
162	2014	Europe	termination	AC	EHV
163	2014	Europe	joint	AC	HV
164	2014	Middle East	cable	AC	LV
165	2014	Europe	joint	AC	MV

166	2014	Europe	joint	AC	MV
167	2014	Asia	cable	AC	MV
168	2014	Europe	termination	AC	MV
169	2014	Middle East	termination	AC	EHV
170	2014	Europe	cable	AC	LV
171	2014	North America	termination	AC	EHV
172	2014	Asia	Cable	AC	EHV
173	2014	Europe	joint	AC	MV
174	2014	Europe	termination	AC	MV
175	2014	Europe	cable	AC	MV
176	2014	Europe	cable	AC	MV
177	2014	Asia	cable	DC	EHV
178	2014	Middle East	cable	AC	HV
179	2014	Middle East	cable	AC	LV
180	2014	Middle East	cable	AC	LV
181	2014	Asia	joint	AC	EHV
182	2014	Asia	cable	AC	EHV
183	2014	Europe	cable	AC	MV
184	2015	Europe	Joint	AC	HV
185	2015	Asia	termination	AC	EHV
186	2015	Asia	cable	AC	EHV
187	2015	Europe	termination	AC	MV
188	2015	North America	termination	AC	HV
189	2015	Russia	joint	AC	EHV
190	2015	Asia	Termination	AC	HV
191	2015	Europe	termination	AC	HV
192	2015	Europe	cable	AC	MV
193	2015	Europe	joint	AC	EHV
194	2015	Europe	cable	AC	EHV
195	2015	Europe	cable	AC	EHV
196	2015	Europe	joint	AC	MV
197	2015	Europe	joint	AC	MV
198	2015	Europe	cable	AC	HV
199	2015	Europe	joint	AC	MV
200	2015	Europe	cable	AC	EHV
201	2015	Europe	termination	AC	MV
202	2015	Europe	joint	AC	MV
203	2015	Middle East	cable	AC	
204	2015	Middle East	joint	AC	EHV
205	2015	Middle East	termination	AC	HV
206	2015	Europe	termination	AC	HV
207	2015	Asia	cable	AC	HV
208	2015	Europe	cable	AC	EHV

209	2015	Europe	cable	AC	MV
210	2015	Europe	joint	AC	MV
211	2015	Europe	Joint	AC	MV
212	2015	Europe	termination	AC	HV
213	2015	Europe	joint	AC	MV
214	2015	Europe	termination	AC	HV
215	2015	Europe	cable	AC	MV
216	2015	Europe	cable	AC	MV
217	2015	Europe	joint	AC	MV
218	2015	Europe	cable	AC	MV
219	2015	Middle East	cable	AC	HV
220	2016	Europe	Joint	AC	MV
221	2016	Europe	termination	AC	MV
222	2016	Europe	joint	AC	LV
223	2016	Europe	joint	AC	MV
224	2016	Australia	cable	DC	EHV
225	2016	Middle East	cable	AC	MV
226	2016	Middle East	joint	AC	MV
227	2016	Europe	cable	AC	HV
228	2016	Middle East	cable	AC	EHV
229	2016	Europe	cable	AC	HV
230	2016	Middle East	cable	AC	MV
231	2016	Europe	joint	AC	HV
232	2016	Middle East	joint	AC	EHV
233	2016	Asia	joint	AC	EHV
234	2016	Asia	joint	AC	EHV
235	2016	Europe	cable	DC	LV
236	2016	Europe	termination	AC	EHV
237	2016	Middle East	termination	AC	EHV
238	2016	Asia	cable	AC	MV
239	2016	Europe	termination	AC	EHV
240	2016	Middle East	cable	AC	MV
241	2016	Asia	joint	AC	EHV
242	2016	Australia	cable	DC	EHV
243	2016	Asia	cable	AC	MV
244	2016	Australia	joint	AC	EHV
245	2016	Europe	cable	AC	HV
246	2016	Europe	joint	AC	LV
247	2017	Middle East	cable	AC	HV
248	2017	Europe	cable	AC	MV
249	2017	Asia	cable	AC	MV
250	2017	Middle East	termination	AC	EHV
251	2017	Middle East	termination	AC	EHV

252	2017	Europe	termination	AC	EHV
253	2017	Europe	termination	AC	EHV
254	2017	Europe	termination	AC	HV
255	2017	South America	cable	AC	EHV
256	2017	Europe	cable	AC	HV
257	2017	Europe	joint	AC	MV
258	2017	Europe	termination	AC	HV
259	2017	Europe	cable	AC	MV
260	2017	Europe	termination	AC	MV
261	2017	Europe	termination	AC	MV
262	2017	Europe	cable	AC	MV
263	2017	Europe	termination	AC	HV
264	2017	Europe	termination	AC	HV
265	2017	Europe	cable	AC	EHV
266	2017	Europe	cable	AC	EHV
267	2017	Europe	joint	AC	MV
268	2017	Middle East	termination	AC	EHV
269	2017	Middle East	termination	AC	EHV
270	2017	Europe	cable	AC	EHV
271	2017	Asia	termination	AC	HV
272	2017	Europe	joint	DC	EHV
273	2017	Asia	cable	AC	EHV
274	2017	Europe	termination	AC	HV
275	2017	Europe	joint	DC	EHV
276	2017	Europe	cable	AC	MV
277	2018	Europe	termination	AC	HV
278	2018	Europe	joint	AC	MV
279	2018	Europe	termination	AC	MV
280	2018	Europe	termination	AC	MV
281	2018	Europe	termination	AC	MV
282	2018	Europe	cable	AC	EHV
283	2018	Europe	termination	AC	HV
284	2018	Europe	joint	AC	HV
285	2018	Europe	termination	AC	MV
286	2018	Europe	termination	AC	MV
287	2018	Europe	cable	AC	MV
288	2018	Europe	termination	AC	HV
289	2018	Europe	termination	AC	MV
290	2018	Europe	cable	AC	EHV
291	2018	Asia	joint	AC	EHV
292	2018	Europe	cable	AC	HV
293	2018	Asia	termination	AC	EHV
294	2018	Asia	termination	AC	EHV

295	2018	Europe	cable	DC	EHV
296	2018	Europe	termination	AC	HV
297	2018	Europe	cable	AC	EHV
298	2018	Europe	cable	AC	EHV
299	2018	Middle East	joint	AC	HV
300	2018	Middle East	joint	AC	HV
301	2018	Europe	termination	AC	MV
302	2018	Europe	joint	DC	EHV
303	2018	Asia	cable	AC	EHV
304	2019	Europe	termination	AC	MV
305	2019	Europe	termination	AC	MV
306	2019	Europe	joint	AC	HV
307	2019	Europe	termination	AC	HV
308	2019	Europe	joint	DC	EHV
309	2019	Europe	joint	AC	HV
310	2019	Europe	termination	AC	EHV
311	2019	Middle East	termination	AC	MV

APPENDIX B

DNV GL paper Jicable 2015 conference on failure investigations on power cables

This paper is reference [/52/, Van Maanen, 2015]

Failures in underground power cables – return of experience

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ABSTRACT

For many years, the DNV GL Energy branch on operational excellence (formerly known as KEMA), is performing failure analyses on all types of power equipment. On a regular basis also underground power cables are being investigated. An investigation is normally focused on finding the root cause of failure. An important outcome of the root cause analysis is the identification of required actions aiming to avoid future failures, like improving design, production, installation, testing or service circumstances. The investigation also gives insight in which other components might suffer from the same problem and may have to be replaced to prevent outages, related safety problems, costs and reputation issues. Failures as mentioned above, can be a full breakdown, but can also be a defect found by a diagnostic test. In this paper, common experiences as obtained by DNV GL with failure analyses over many years will be shared with the reader.

INTRODUCTION

Due to the increasing demand for power, coupled with the geographical expansion of this need, we are more and more relying on the reliability of the grid. The amount of cable installations (both land and submarine) is growing rapidly around the world.

In case of a power failure, it is of crucial importance to know what is the root cause (or are the causes) of that failure. This is due to:

1. Technical reasons. There is a need to avoid a similar failure in the future. So where in the process from design, manufacturing, testing, installation and operation is improvement needed? Knowing the cause of failure is a crucial part in the feedback loop for improvement. Furthermore, knowing the root cause is necessary to assess the risk of failure in similar situations (e.g. same type of components).
2. Economical / political reasons. There can be major consequences for customers, as well as penalties, indirect costs, reputation damage, etc.
3. Insurance. The party responsible for the failure has to be identified.
4. Safety. Related to the chance of a similar failure in the future, what are the safety hazards in case of e.g. different circumstances?

In some cases the root cause of failure is obvious, like in case of digging activities. In many cases, however, a more extensive failure investigation is needed to find the root cause of failure.

In case of a failure investigation, there are often multiple stakeholders involved in the failure analysis, depending on the importance of the connection. Besides the owner of the cable system (network owner) there is usually involvement of the manufacturer(s), the installer(s), representatives of the users of the connection, insuring companies, et cetera. Since all these stakeholders have different interests there is a clear need for a knowledgeable, independent and impartial party to lead the investigation and that is responsible for the validity of the outcome of the investigation.

DNV GL is fulfilling the role of independent and impartial party for many years already and has therewith built up a wealth of experience in failure investigations. These failure investigations got formalized in the late nineties into an official service called 'Power Failure Investigations'. These investigations are performed on all types of power components, such as transformers, switchgear, lines, isolators, bushings, rotating equipment, all kinds of station equipment, etc. DNV GL adapted a uniform method for such failure investigations and often multiple disciplines need to be combined together for more complex investigation (where multiple components are involved, which is quite regular, and/or network studies are needed). This paper is about the failure investigations on power cables.

Over the years a significant increase in the number of failure investigations on power cables per year is observed as depicted in Fig. 1. A total of approximately 170 individual cases have been recorded over the period from 1997 until the end of 2014. Relevant information from these investigations has been collected and used to create insight in many details, statistics, degradation and failure mechanisms of power cables all over the world.

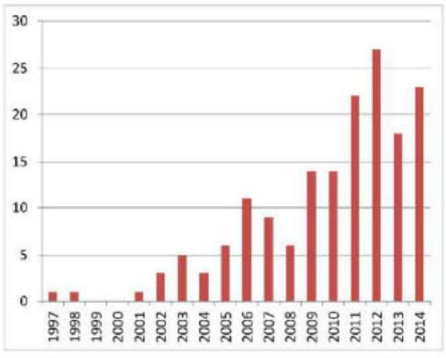


Fig. 1: the number of cable system related failure investigations per year

Due to high confidentiality of this information not everything can be shared in a paper like this. Information that can be traced back to the manufacturer, the network operator or any other involved party will obviously never

be shared. What can be shared, after being anonymized, is information like:

- What type of component failed? E.g. cable, joint or termination.
- What type of cable is involved? E.g. paper cable, XLPE, EPR, SCFF, etc.
- What is the voltage class?
- When was the cause of the failure incurred? E.g. during design, production, installation or service life.

Furthermore, where applicable, common root causes are identified and discussed in this paper. With this, despite the mentioned needed level of confidentiality of this subject, interesting results can be observed.

FAILURE STATISTICS

Governing all failure investigations

In this chapter the defining characteristics over the entire (power cable failure investigation) data population (170 cases) are highlighted. Note that the information presented here is based on the investigations performed by DNV GL only and is not be regarded as a way to determine overall statistics in general without further consideration.

In Fig. 2 the distribution of failures between the different components is shown. Roughly two thirds of the failure investigations involved cable joints and terminations, and one third involved failures of cable itself. Thus, the cable accessories (joints and terminations) seem to inherit the highest risk for failure. The following chapter will discuss the underlying causes for the cable and accessories failures separately.

In Fig. 3 the involved cable insulation types that were involved in the failure cases are shown. As the modern type of insulation material applied, XLPE is present in the vast majority of cases. Paper Insulated Lead Covered (PILC) cables are quite common in continental Europe for medium voltage networks. However, since they are mainly used on the medium voltage level, only a smaller part is being investigated with an external independent party. Combined with the fact that these cables have been in operation for many years these form the second largest group. Other types of cables have come up sporadically for several reasons. It must be noted that not all network owners order an investigation upon failure, let alone by a third party. Especially in case of very old cables and low and medium voltage cable classes, often failed components are simply discarded or internally investigated.

Fig. 4 shows the distribution of the failures over the voltage classes. The largest part is located within the range of 36 to 230 kV. Note that for voltages higher than 230 kV the currently installed cable length is still relatively small, which explains the relatively low number of investigations in that range (being 14 %). The number of cases for low voltage application is very low, likely due to the previously mentioned reasons.

Failures causes

It is not a certainty that a failure investigation yields one clear root cause. Sometimes it is a combination of several causes and sometimes only the likelihood of the various possible root causes can be evaluated, as real evidence

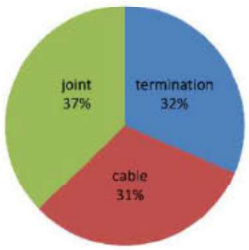


Fig. 2 the distribution of failures between components

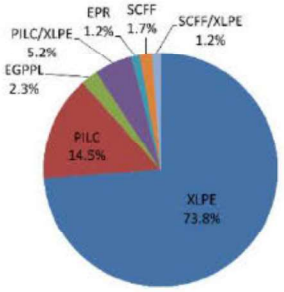


Fig. 3: the cable insulation types involved

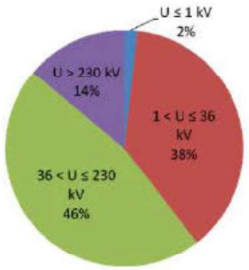


Fig. 4: the voltage classes involved

is destroyed by the breakdown. The certainty of the investigation conclusion depends on a multitude of factors, such as availability and quality of the evidence and surrounding information. This information involves all operational data such as voltages, load, network configuration, network operation, et cetera. Moreover, it is important that all relevant quality control steps in the design, qualification, fabrication, installation and operation can be checked. These steps are in place to ensure that the equipment is fulfilling all requirements put forward in the agreed quality standard. In the majority of cases the IEC standards and guidelines are used for this purpose.

There are usually several factors playing a role in the process leading to a failure, which all need to be taken into account. In some cases the investigation yields several hypotheses which may be compared on the basis of their likelihood using the available surrounding

information. In a few cases the available information is such that the investigation does not lead to a conclusion with respect to the failure cause. In the end, all failure causes have been categorized into 6 generalized groups, being

1. **ageing**: the failure occurred as a consequence of natural ageing of the component
2. **design**: the failure occurred as a consequence of an inadequate design of the component
3. **external damage**: the failure occurred as a consequence of an external foreign object damaging the component
4. **installation**: the failure occurred due to an inadequate installation (technique)
5. **production**: the failure occurred as a consequence of an error during production (handling or material)
6. **unknown**: the cause of the failure remained unclear.

In the next two paragraphs the distribution of these failure causes is treated separately for cables and accessories.

Failures in cables

The distribution of failure causes for cable failures is depicted in Fig 5.

The majority of failures in (investigated) cables have their origin in the production process itself. Some common causes that are seen include:

- mechanical damage during handling of the cable, e.g. during manufacturing, internal transport or during a factory repair
- defects in the insulation (voids, inclusions, etc.).

This is despite the fact that usually factory acceptance tests are in place, such as high voltage withstand tests and partial discharge measurements. It is not always a matter of the right test but also good interpretation of the test results. Moreover, some slight defects may not be severe enough to show up during factory testing, but may cause al failure at a later time.

An example of an error in interpretation of test results is given in Fig 6. Here a defect (void) in the insulation was created during production. This void created partial discharge activity during factory testing but this was mistaken for noise. This caused the cable to be approved for delivery. The defect was later detected during the site acceptance test.

After production related issues, the installation and external damage are the largest contributors. Installation errors, similar to external damage, often involve

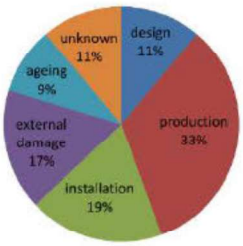


Fig. 5: the general failure causes for cables

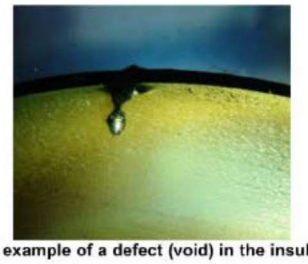


Fig. 6: example of a defect (void) in the insulation of a cable



Fig. 7: example of a cable installation technique that led to damage of the cable

mechanical damage of the cable. This can be due to a bad installation technique involving too high pulling forces or giving insufficient protection to the cable for instance. An example is given in Fig. 7.

In total 11% of the investigated cable failures were related to the design of the cable. This shows that the design qualification (pre-qualification tests and type tests), despite the extensive tests involved, are still missing a certain part of the design related defects.

In 11% of the cases no cause for the failure could be found.

The continuing process of interconnecting the grid as well as the implementation of offshore wind farms has caused a strong rise in the application of submarine cables. This is also visible is the number of investigations related to submarine cables, depicted in Fig. 8. The specific installation of these cables requires significantly stricter mechanical demands for these cables, for instance by the application of armor wires. The handling on a vessel in ocean conditions also presents quite a number of challenges with respect to the handling of the cable. In roughly 50% of the cases investigated by DNV GL, mechanical issues form the basis for the problems. An

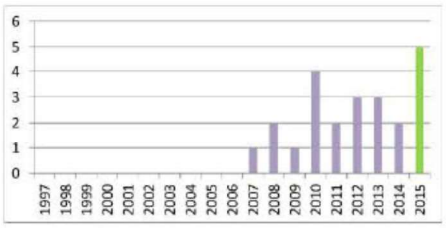


Fig. 8: The number submarine cable related investigations per year (with 2015 thus far)

example of such a case is depicted in Fig. 9.

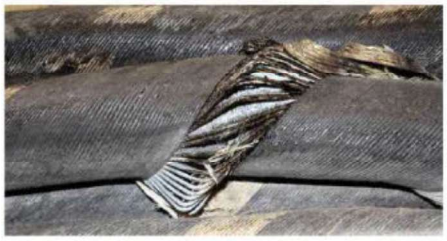


Fig. 9: example of a submarine cable that was damaged due to wrong handling during installation (coiling)

Failures in joints and terminations

The distribution of failure causes for cable accessories (here: joints and terminations) is depicted in Fig. 10.

The majority of failures in cables accessories have their origin in installation related defects. The main underlying reason for this is the fact that all accessories for cables have to be fitted in the field where the conditions are not ideal. This is combined with the relatively high electrical fields and mechanical forces acting on the accessories, apart from extremely high demands for cleanliness, smoothness and accuracy, especially for insulation surfaces in the interface between cable and accessory insulation. The majority of the failures in accessories stem from this region. Especially for extra high voltage applications, the requirements for surface preparation are quite demanding. Moreover, the preparation of this surface remains to be predominantly a manual process. Installation failures can also originate from insufficiently experienced jointers, unclear installation manuals, language issues, etc.

The use of pre-moulded sleeves in high and extra-high voltage applications is quite common. This technology has the big advantage that it is fully assembled (fabricated) in the factory and can as such be fully tested before installation. This also seems to be verified by the relatively low percentage of failures that are related to production (8%).

Upon installation such a sleeve is stretched over the cable such that it retains sufficient interface pressure over the years. The stretching / expanding of the sleeve and

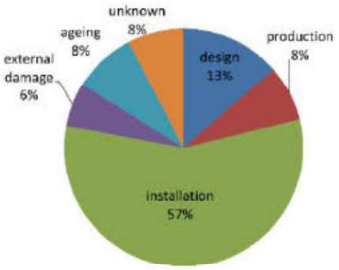


Fig. 10: the failure causes for accessories

positioning over the cable requires large forces. After fitting the sleeve, it must exert sufficient interfacial pressure to prevent partial discharges to occur in the interface region. This gives birth to a number of potential problems, e.g.

- Any pollution or particle that gets trapped between the sleeve and the expansion tool may damage the sleeve in the most sensitive area; the interface between cable and accessory insulation. This is a challenge especially in dusty environments. Due to the large forces in such a sleeve, a tiny scratch (tenths of µm) can cause the sleeve to rupture over time.
- During expansion, large forces exist internally in the sleeve. Note that the sleeve consists out of insulating and semi-conductive materials, each with different mechanical properties. This means that all kinds of internal forces act on various surfaces inside the sleeve. The sleeve must be able to cope with these forces otherwise it may (partly) rupture.
- The mechanical properties of the sleeve have to be sufficiently stable to ascertain sufficient interfacial pressure over the years.

An added difficulty with these interface related defects is the application of grease products in the interface to reduce friction between the sleeve and the expansion tool and/or cable insulation. This grease has the ability to



Fig. 11: defect in the interface between cable insulation and sleeve (top) giving rise to partial discharges (yellow traces)

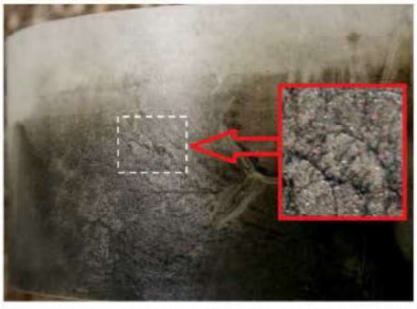


Fig. 12: example of tiny scratches in the prepared insulation surface causing a failure

temporarily reduce the effect of certain defects such as a small scratch in the insulation. As such it can prevent degradation, until the moment it is inevitably absorbed by (diffused into) the surrounding materials. This mechanism is deemed capable of delaying degradation (partial discharges, electrical treeing) for months or even years. This also means that a certain defect may stay hidden during commissioning testing (which serves as the quality control for the installation).

The percentage of accessory failures related to design is, quite similar to that for cables, 13%. This seems to show that the design qualification (pre-qualification tests and type tests) is approximately as effective for cables as it is for accessories. The number of unresolved cases (unknown) is 8%, again quite similar to that for cable failures.

CONCLUSION

DNV GL has fulfilled the role of knowledgeable, independent and impartial party for the investigation of failures in cable systems for several years and has therewith built up a wealth of experience in failure investigations.

A total of approximately 170 individual power cable investigations have been recorded over the period from 1997 until the end of 2014.

Relevant information from these investigations has been collected and used to create insight in the causes for failures to happen and, where possible, to identify common factors. This has led to improvements in design, production, testing, installation and operation of power cable systems, as knowing the root cause of failures is crucial for improvement of the complete chain.

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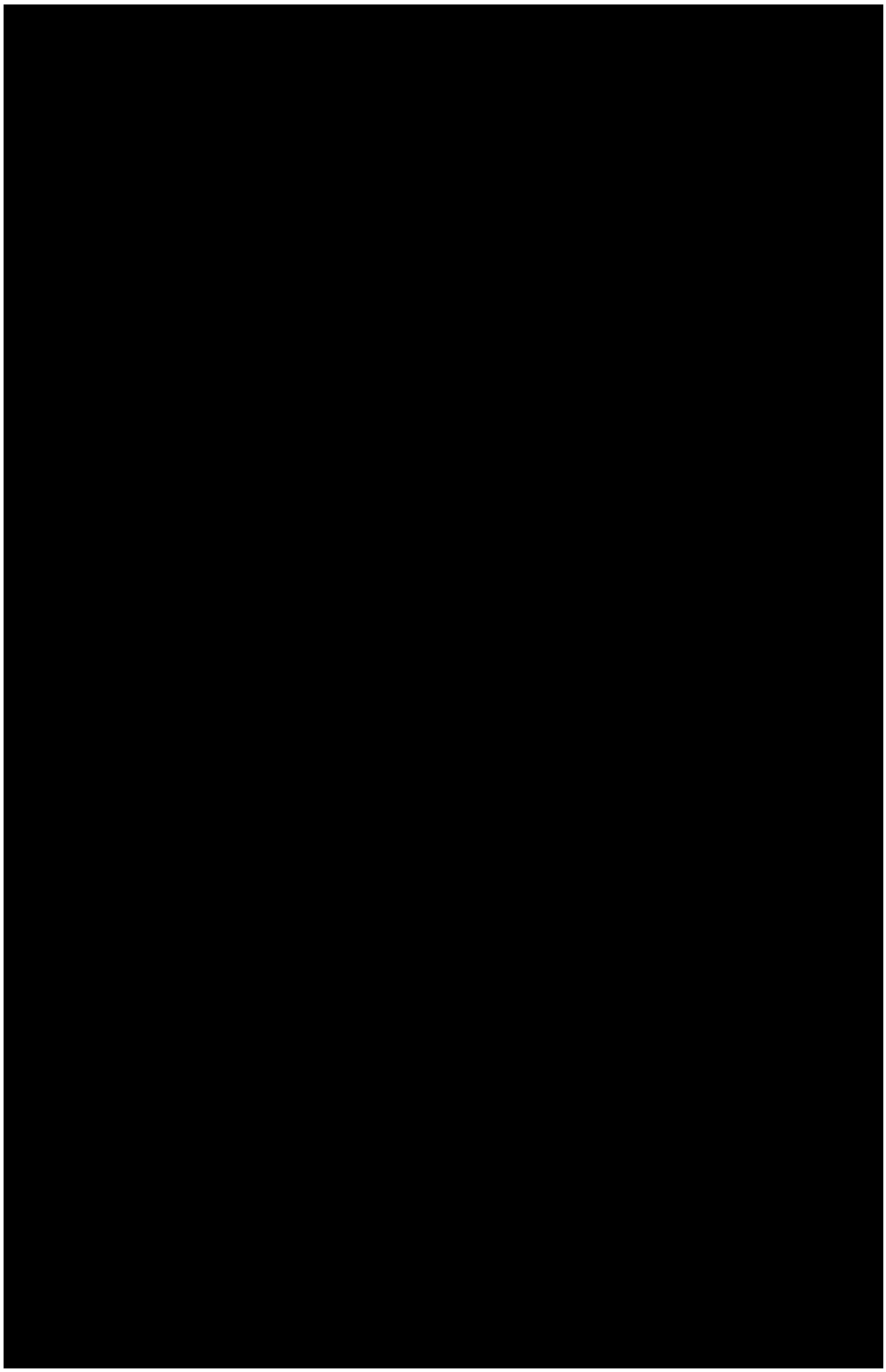
APPENDIX C

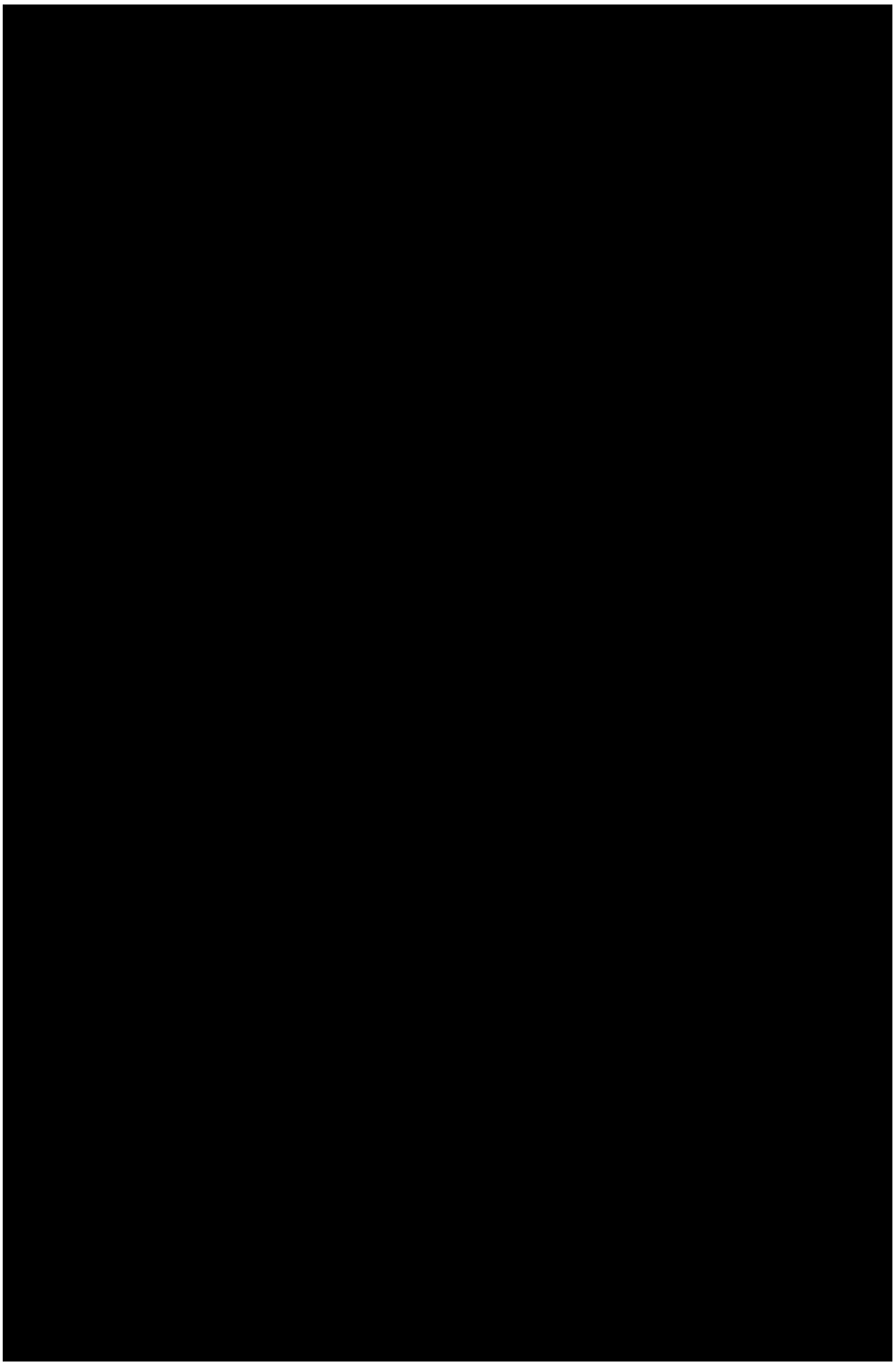
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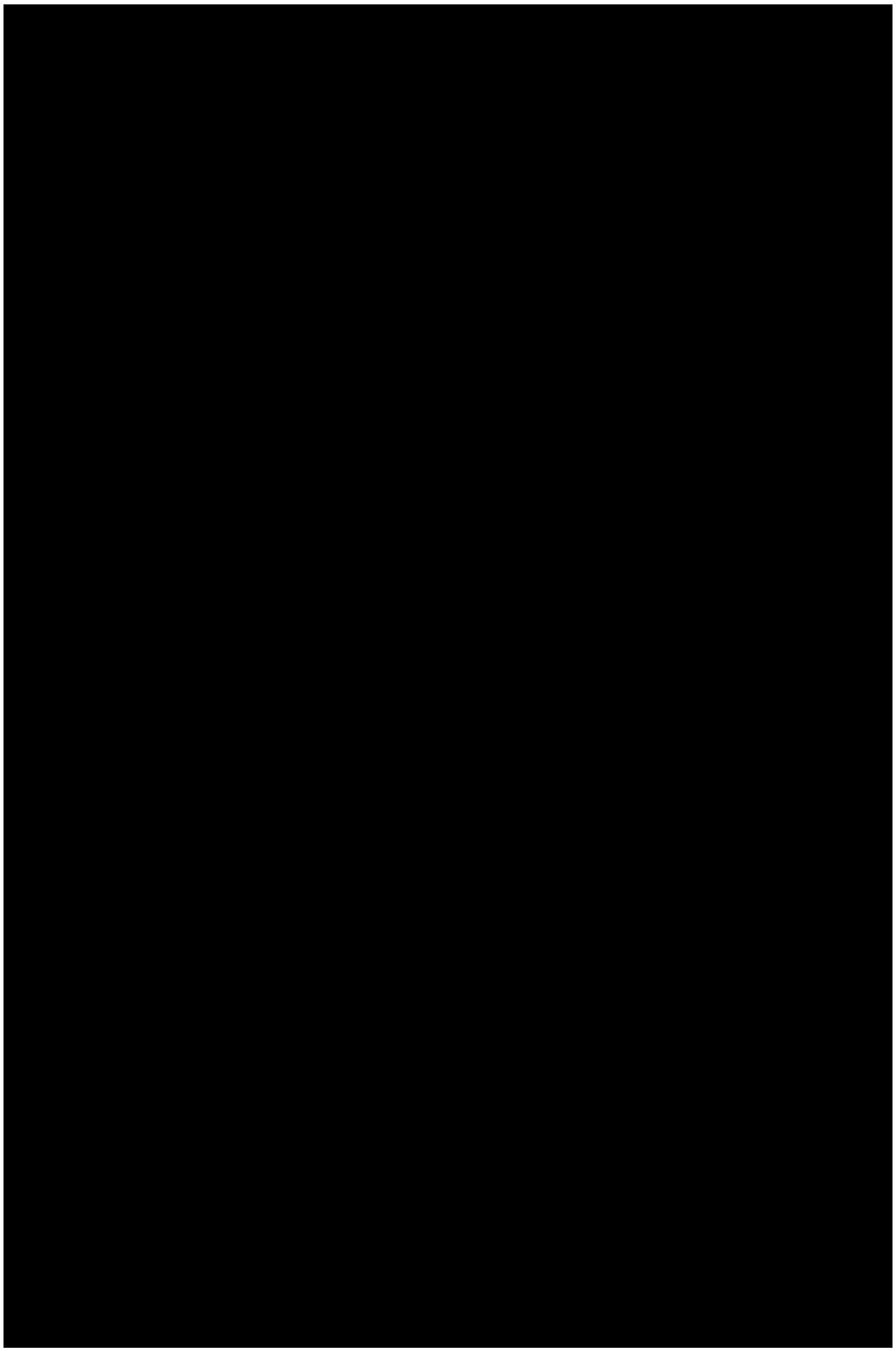


Figure 26 [redacted]

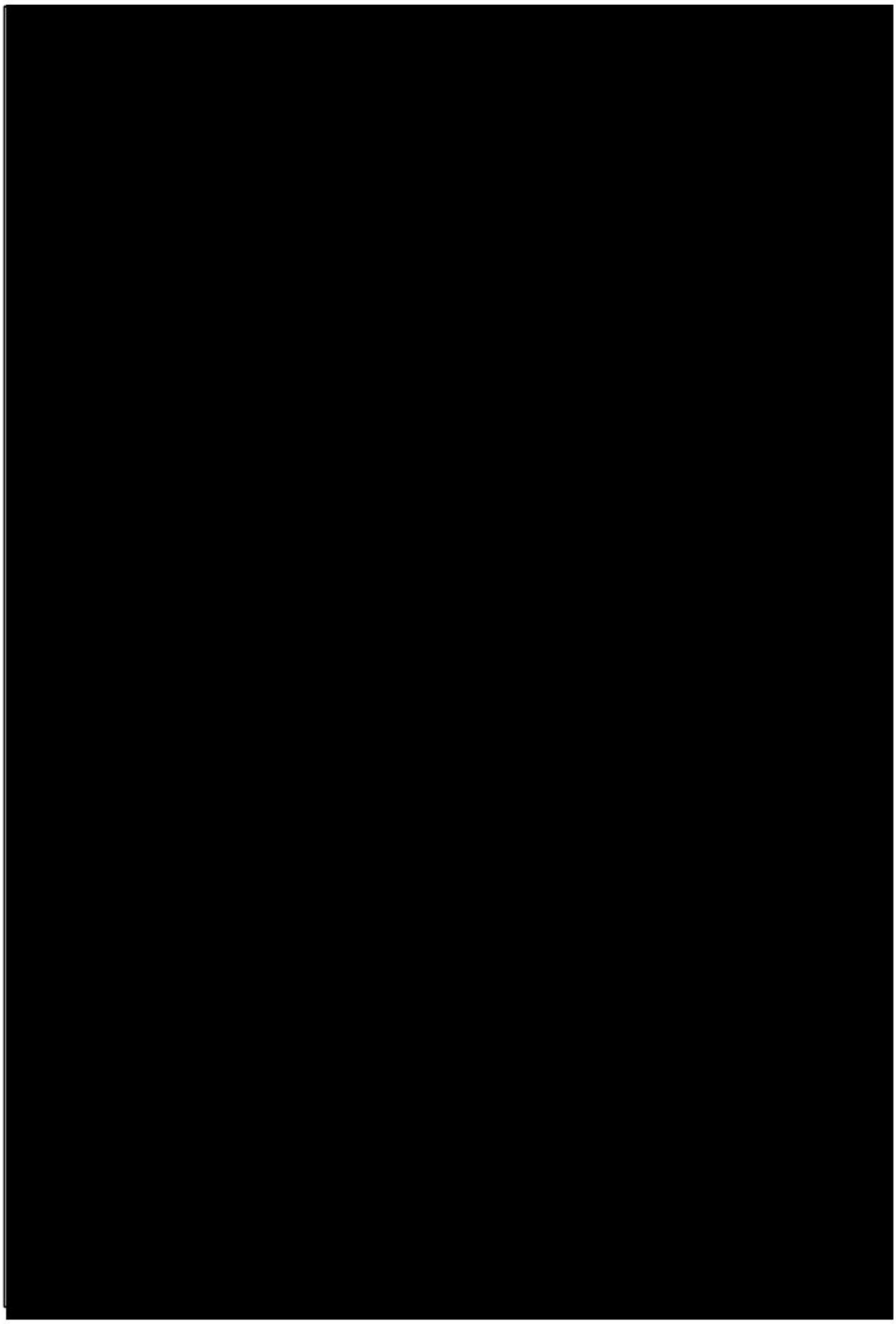
APPENDIX D
Submarine Cable Construction [TAB 13]





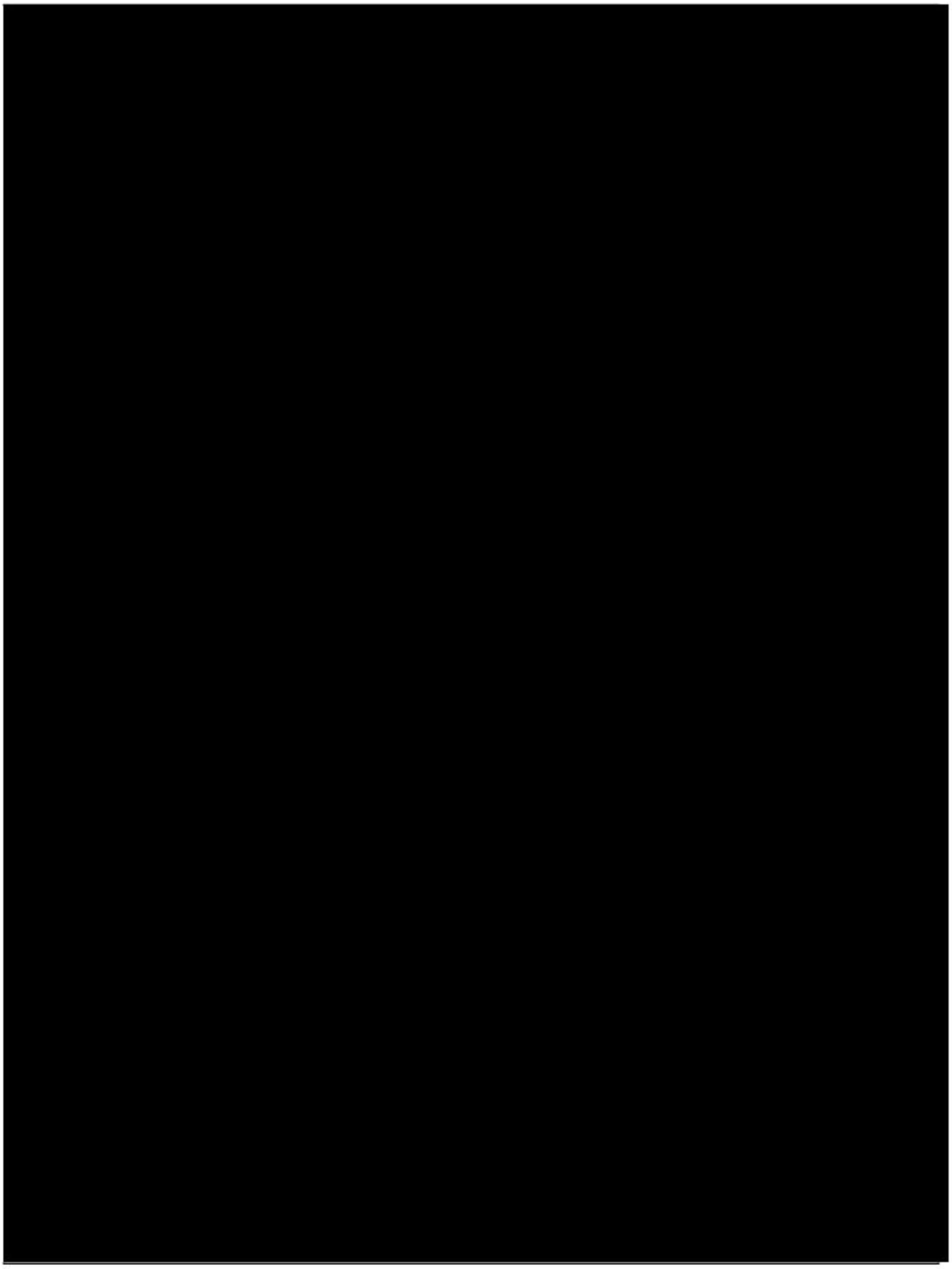


APPENDIX E
Pirelli letter to Basslink about voltage polarity reversals [TAB 18]



APPENDIX F

Letter Basslink to Hydro Tasmania about voltage polarity reversals [TAB 58.3]



APPENDIX G
CV Fred Steennis

Function
Senior Principal Consultant

Role
Coordinator Power Failure Investigations within DNV GL Energy, world-wide

Personal statistics
Citizenship: Dutch
Date of birth: Nov 16, 1954

Language capabilities

Language	Speaking	Reading	Writing
English	Good	Good	Good
German	Good	Good	Fair
French	Basic	Basic	Basic
Dutch	Excellent	Excellent	Excellent
Portuguese	None	Basic	None

Academic and professional attainment

Field of expertise	University/School	Year
PhD Electrical Engineering	University of Technology Delft	Jan 1987 - Jun 1989
MSc Electrical Engineering (cum laude)	Eindhoven University of Technology	Sep 1976 - Dec 1981
Master Electrical Engineering (cum laude)	Institute of Technology (HTS)	Sep 1972 - Jun 1976

Summary of professional experience
Mr. Steennis has many years of experience in numerous power cable projects. In the case of R&D management related activities, such projects start with identifying the customer's needs which come from many contacts, former projects, failure investigations, etc., after which a proposal is made and if granted the R&D work is often a team effort. In line with this, since 1999, Mr. Steennis is also a part-time professor at the Eindhoven University of Technology in which role he is giving lectures on underground power cables and giving guidance to PhD students in their underground power cable related research. Under his responsibility 8 PhD students received their doctor degree.
Also, Mr. Steennis is well-known with failure analysis in power cable projects. The knowledge on degradation processes on one hand and DNV GL's independency combined with its test facilities or those within reach of DNV GL inspire many network owners and cable manufacturers to ask DNV GL’s support in the case of a power cable failure. The main goal is always to identify the root cause, but behind this request can be a safety, economical or technical issue. Since DNV GL is involved in this type of work on a very regular basis, all this experience helps to become more and more efficient. This is clearly a very international business.

Regarding consultancy services in power cable projects, the activities of Mr. Steennis are mainly related to cable ageing, asset management, cable failures and remaining life issues. These services very often are done for customers anywhere in the world.

Mr. Steennis has also several years of experience as a full-time manager within DNV GL. Especially, in recent years he gives guidance to less experienced colleagues in his role of Senior Principal Consultant.

Mr. Steennis has published as an author or co-author many papers (> 180), reflecting his experience with many different power cable projects.

Mr. Steennis received two awards, see under Other information.

An important patent of which Mr. Steennis is shared patent holder is: E. F. Steennis, P. A. A. F. Wouters, P. C. J. M. van der Wielen and J. Veen, "Method and system for transmitting an information signal over a power cable", Int. Patent No. WO 2004/013642, June 2002.

Professional training

Year	Institute	Description
March 2016	De Federatie	Trainers learn from / with trainers
Sep 2009 - Dec 2009	Huthwaite	Spin-selling
Jun 2009 - Jun 2009	Huthwaite	Winning Proposals
Jan 1996 - Dec 1997	Krauthammer	Short Commercial Courses
Jan 1993 - Dec 1994	De Baak	Management
Jan 1990 - Dec 1992	KEMA	Short Commercial Courses
Jan 1983 - Dec 1983	Technical University Eindhoven	Post graduate course on Statistical theory for test set-ups

Other information

Awards

- Hidde Nijland Award, a Dutch award of the power sector, 1991; for his contribution in the field of new testing methods for cables and the applicability of superconductors in power technology
- DNV GL Innovation Award 2014 – for his invention of Smart Cable Guard, an on-line monitoring tool locating weak spots that can lead to failures and accurate locator for temporary and permanent failures for medium voltage cables

Patents

- E. F. Steennis, P. A. A. F. Wouters, P. C. J. M. van der Wielen and J. Veen, "Werkwijze en system voor het overbrengen van een informatiesignaal over een vermogenskabel", Dutch Patent No. NL 1020925, June 2002.
- E. F. Steennis, P. A. A. F. Wouters, P. C. J. M. van der Wielen and J. Veen, "Method and system for transmitting an information signal over a power cable", Int. Patent No. WO 2004/013642, June 2002

Employment record

Technical University Eindhoven **Sep 1999 - present**

Position: Professor

- Part-time (1 day / week) professor with a special subject being "power cable diagnostics". Giving lectures on power cables, guiding students among which are PhD students.

SEP (nowadays called TenneT) **Jan 1995 - Dec 1995**

Position: Engineering manager a.i.

- Engineering manager a.i. project [redacted]. KEMA supports SEP with engineering management in their realization of the HVDC cable connection from Norway to the Netherlands

DNV GL (partly formerly KEMA and DNV KEMA) **Jan 1982 - present**

Position: Service Line Principal / Senior Principal Consultant

- 2010 and onwards: Principal Consultant on Underground Powers Cables and Submarine Power Cables; active in several projects on power cables in general, asset management, tests & diagnostics and failure analysis. Project manager of several R&D projects. Lecturer of the DNV GL Power Cable Courses. Between 2016 and 2019 also coordinator of Power Failure Investigations for DNV GL Energy for all types of Power Equipment.

- 1995 - 2010: Consultant / Specialist on Underground Power Cables; active in several projects on power cables in general, asset management, tests & diagnostics and failure analysis. Project manager of several R&D projects. Lecturer of the KEMA Power Cable Courses.

- 1995-1999: Manager of the departments related to 1) Cables and Insulating Materials and 2) Manager of the department High-Voltage Testing and Diagnostics. The total number of employees of this department was 43 people.

- Until 1995: Research worker in many different projects on power cables in general, asset management, tests & diagnostics and failure analysis. Project manager of several R&D projects.

Detailed professional experience

Courses on Power cables and Courses on Power Failure Investigations

Period :	about 1999 - present
Customer :	many different customers, all confidential
Position:	Trainer
Description:	- General course on Underground Power Cables - Specialized Courses on Remaining Life of MV Underground Power Cables - Course on Power Failure Investigations
Activities performed:	Making course books and Power Point presentations; giving courses; guiding students and examining their results; follow up where needed

Condition assessment and remaining life studies

Period :	about 1982 - present
Customer :	many different customers, all confidential

Position:	(Senior) Principal Consultant
Description:	Condition assessment and remaining life studies of low voltage cables, medium-voltage cables and / or high-voltage cables
Activities performed:	Interviews, literature study, discussions, analyses, reporting, starting regular meetings with network owners, arranging experiments to check the remaining life aspects; reporting and publications (Cired, JICABLE)

Root cause analyses after a failure of a component in an Underground Power Cable System, up to December 2017, [confidential / classified], for amongst others:

Period :	about 1986 - present
Customer :	ABB (Sweden), Alcoa (USA), Alliander, formerly Nuon (the Netherlands), Ausnet (Australia), Beatrice Offshore Windfarm (Scotland), Boskalis (Netherlands), Brookfield (UK), Brugg cables (Switzerland), CEM (Macau, China), CERN (Switzerland), China Light and Power (Hong Kong), Delta Lloyd (the Netherlands), Delta NWB (the Netherlands), El Sewedy (Egypt), Energinet.dk (Denmark), Enexis, formerly Essent (the Netherlands), Enduris (the Netherlands), Exsym (Japan), Florida Light and Power Co. (USA), Hong Kong Electric (Hong Kong), Israel Electric Company (IEC) (Israel), ILJIN (Republic of Korea), JDR Cable Systems (UK), Jeddah cables (Kingdom of Saudi Arabia), Kahramaa (Qatar), KEPCO (Republic of Korea), Liander (the Netherlands), LS Cable (Republic of Korea), Mutual Energy (Ireland), Nalcor (Canada), National Grid (UK), Nexans (France), NKT (Germany), Pacific Electric Wire and Cable Co (Taiwan), Prysmian (the Netherlands, Italy), Reliance (India), Saudi Cable Company (Kingdom of Saudi Arabia), Samsung (Republic of Korea), Sedgwick (the Netherlands), SPPG (Singapore), Stedin, formerly Eneco (the Netherlands), Taihan (Republic of Korea), Tata Steel (the Netherlands), TenneT Offshore GmbH (Germany), TenneT TSO B.V. (the Netherlands), TEPCO (Japan), Transco (Abu Dhabi), VBMS (the Netherlands), Westland Infra (the Netherlands); all confidential.
Position:	(Senior) Principal Consultant
Description:	Study to find the root cause of a faillure of a cable, joint or termination; guiding also in the cause behind the technical root cause; support in Court Sessions;
Activities performed:	Interviews, literature study, discussions, analyses, reporting, starting regular meetings with network owners, arranging experiments to check hypotheses on failure causes of joints; reporting and publications (Cired, JICABLE); Court sessions

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APPENDIX H
About DNV GL

From www.dnvgl.com (dated 2020-05-07).

About DNV GL

We are the independent expert in risk management and quality assurance. Driven by our purpose, to safeguard life, property and the environment, we empower our customers and their stakeholders with facts and reliable insights so that critical decisions can be made with confidence. As a trusted voice for many of the world's most successful organizations, we use our knowledge to advance safety and performance, set industry benchmarks, and inspire and invent solutions to tackle global transformations.

We are the world's leading classification society and a recognized advisor for the maritime industry, the technical advisor to the oil and gas industry, and we deliver world-renowned testing, certification and advisory services to the energy value chain including renewables and energy management. We are one of the world's leading certification bodies, helping businesses assure the performance of their organizations, products, people, facilities and supply chains. We are also a world-leading provider of digital solutions for managing risk and improving safety and asset performance for ships, pipelines, processing plants, offshore structures, electric grids, smart cities and more.

Our Purpose, Vision and Values

Since 1864, our Purpose has been to **safeguard life, property and the environment.** Our Vision is to be **a trusted voice to tackle global transformations.** Our Values are beliefs that shape our performance; these ideals are the behaviours expected of all employees in DNV GL:

We care for each other, our customers, our planet, and we take care of ourselves.

We dare to explore, to experiment, to be different, and to be courageous, curious and creative.

We share our experience and knowledge. We collaborate with each other and our customers, and we continue to grow and develop as a result.

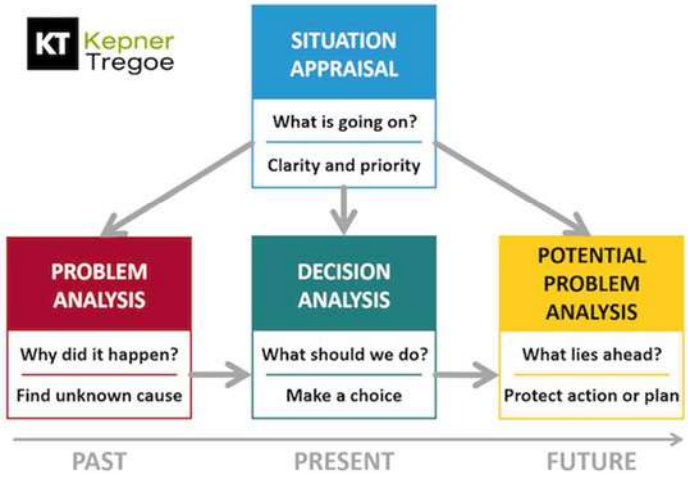
APPENDIX I

Failure analysis methods - Kepner-Tregoe, Ishikawa, HP-Analysis, Tripod, Bow-tie

Kepner-Tregoe:

The Kepner-Tregoe method (reference, amongst others /9/) is based on the following six steps:

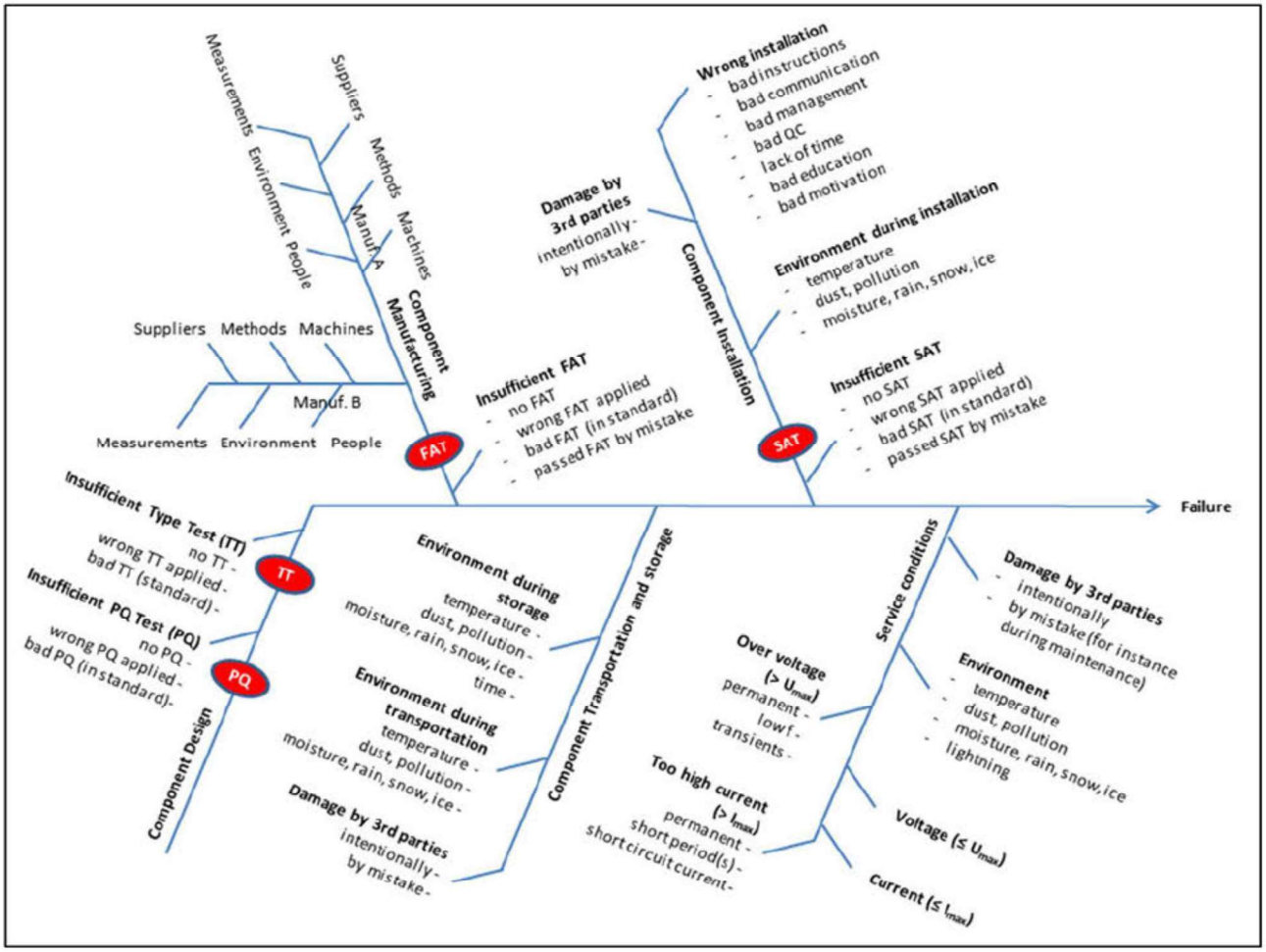
1. Situation appraisal
2. Specification of the problem:
    a. What? What not?
    b. Where? Where not?
    c. When? When not?
3. Development of possible causes
    a. Use IS and IS NOT
4. Test for probable cause
5. Decide for optimal solution(s)
6. Think beyond the fix
    a. Potential problem analysis



	IS	IS NOT
What (identify)		
Where (location)		
When (timing)		
Extent (magnitude)		

Ishikawa

Ishikawa introduced a fishbone structure, all contributors to a failure are presented, with the object to give structure and once made, to present and not to forget contributing elements (reference, amongst others /10/). An example is shown for a cable failure related fish-bone.



Human performance analysis

The Human performance analysis (reference, amongst others /11/) has its focus mainly on human based contributors to a failure. Standard questions are related to:

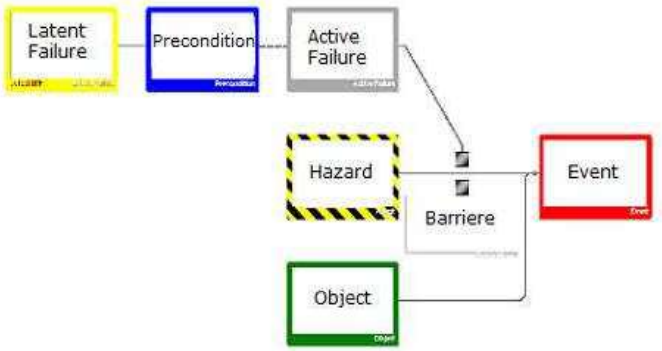
- Procedure
- Training
- Quality control
- Communication
- Management system
- Human relations
- Direct supervision

Tripod analysis

The tripod analysis (reference, amongst others /12/) is strong because it combines mapping technical and organisations elements contributing to a failure, graphically presented. Its graphical presentation

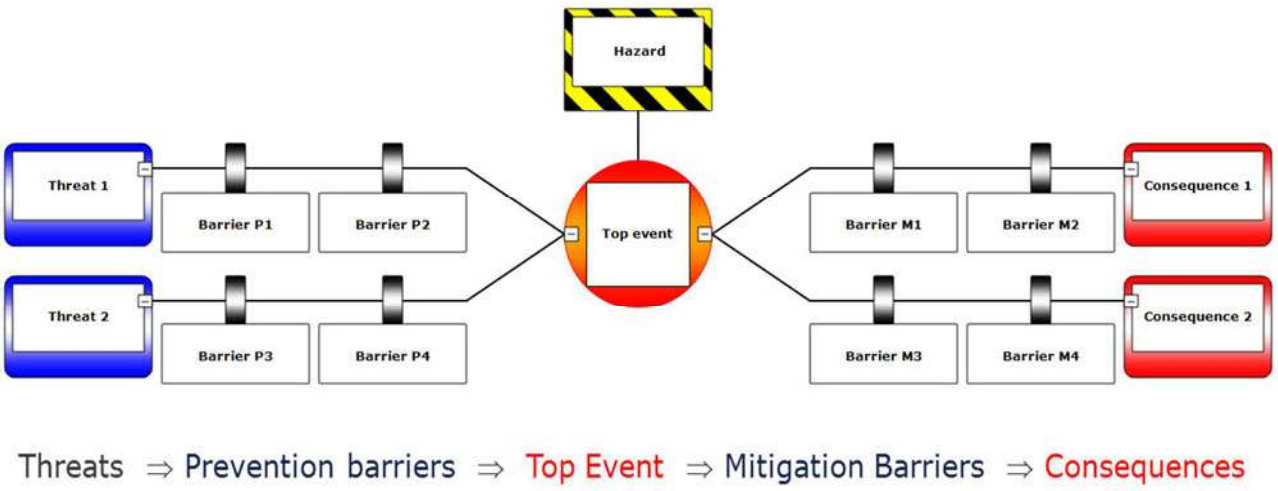
makes it possible to show barriers that normally should prevent a failure, but which seems not to have worked if the failure happens (such as a safety system that failed). The incident facts are built into a tree, showing:

- WHAT happened? (what is the incident process?)
- HOW did it happen? (what hazard management elements failed?)
- WHY did it happen? (what caused the elements to fail?)



Bow-tie

A bow-tie method (reference, amongst others /13/) has the tripod part up to the failure as shown above, but from that point it develops further into a risk model where mitigating actions are defined. It is a good communication tool. It is able to illustrate much information on one page. It is simple and effective. But it does not have quantitative parts.



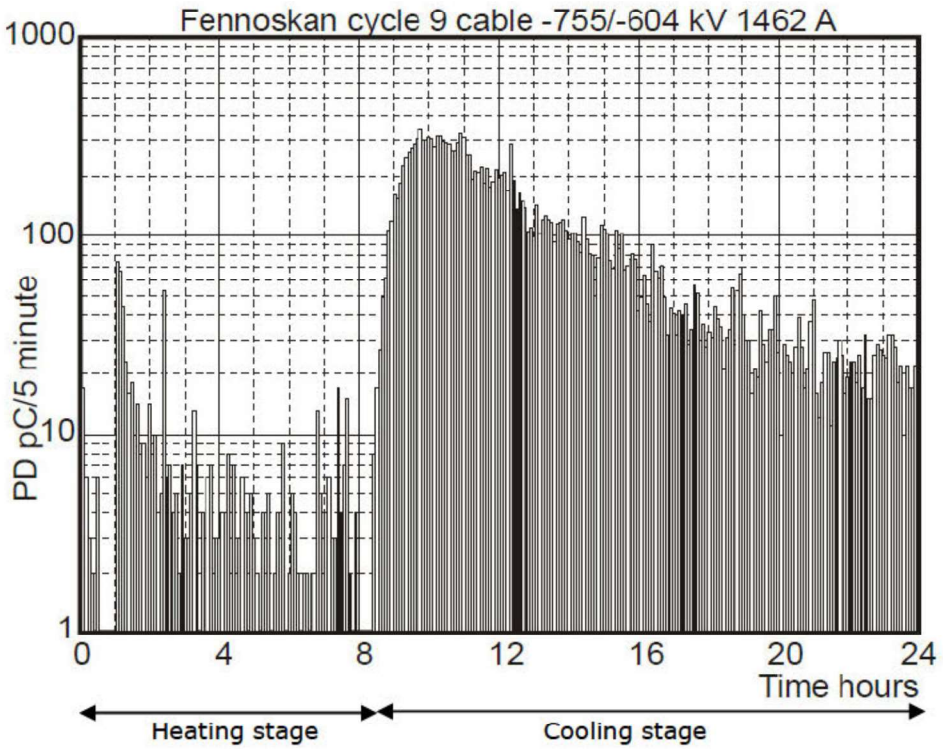
APPENDIX J
Void formation and partial discharges

Void formation must be avoided because such voids are, at least for a while, gas / air filled pockets. Gas / air filled voids have a much lower breakdown strength than the surrounding paper and compound. Much literature deals with this subject (out of the many publications: [/56/, Kreuger, 1995], [/57/, Kreuger, 1992]).

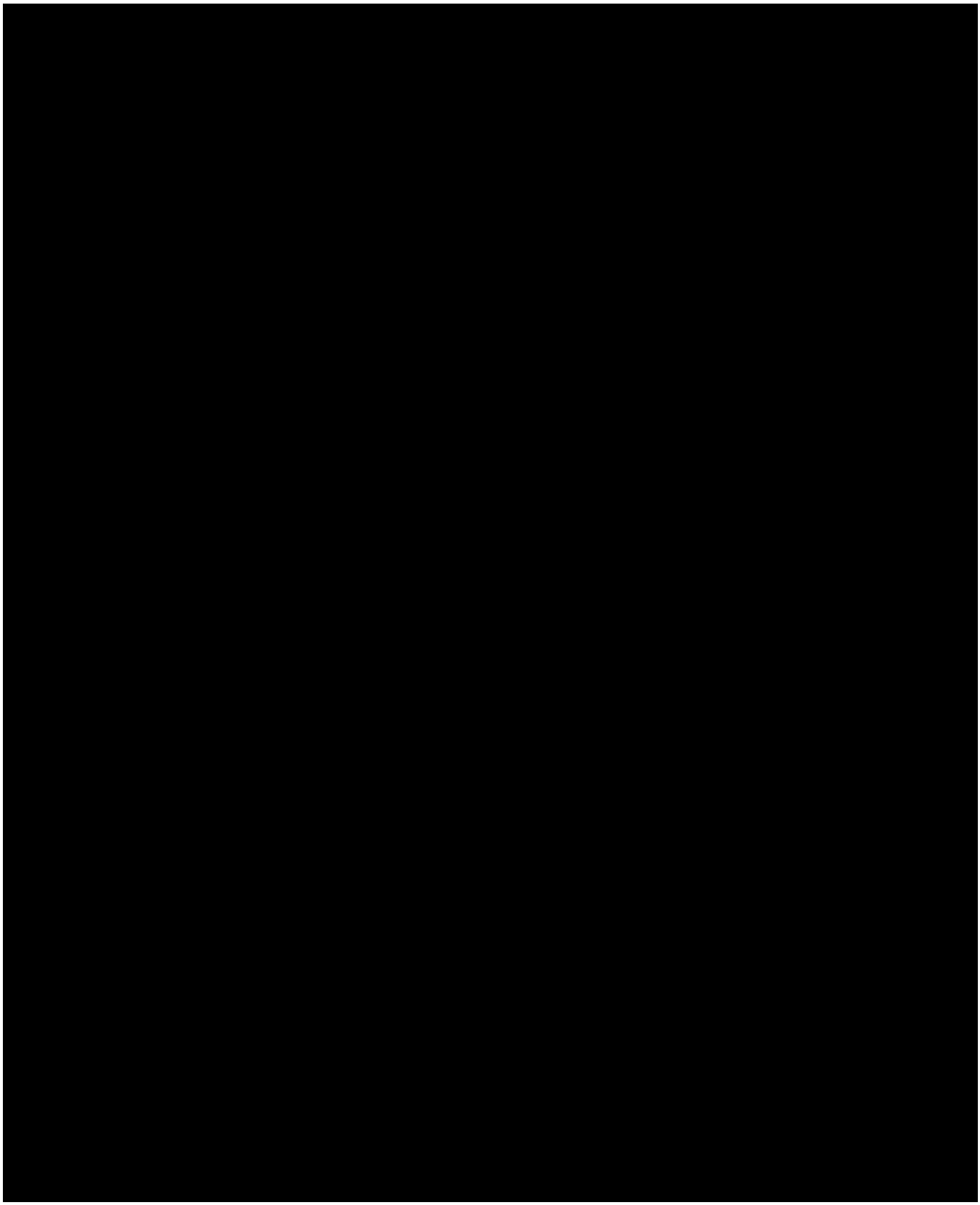
Partial discharges in voids is a known issue. And once there is a partial discharge, and if followed by more such partial discharges, the insulation material will degrade such that a full breakdown of the whole insulation material will follow.

It can take minutes to days (or more) in a polymer material environment, but it can take up to years in a paper insulated environment because the compound tends to redistribute, forcing the spark to act on another spot. And possibly, paper is better able to withstand partial discharges than a polymer [/71/, Qian, 2015]. It will also depend on the electrical stress in the void and thus on the materials surrounding the void, the distribution of charges surrounding a void, the presence of voltage polarity reversals in the case of DC cables and the voltage class of the cable. It is generally assumed that in HV cables, the degradation process goes faster than in MV cables for instance, but within its voltage class, DC cables, with fewer partial discharges, are in that respect assumed to degrade more slowly.

In case of the presence of large enough voids, it is known that partial discharges are common under AC conditions [/90/, Runde, 2019], but these happen also under DC conditions. In [/74/, Elovaara, 2002] clearly illustrated this for the [redacted] where cable samples have been subjected to heat cycles. Especially during the cooling down stage partial discharge activity was dominant, showing that this is the period of void creation. This is illustrated in the figure below from [/74/, Elovaara, 2002], where the first 8 hours represent the heating and the remaining hours the cooling down stage. The y-axis represents the partial discharge activity.



APPENDIX K
Cable lengths and joint positions



APPENDIX L
Letter of instructions provided by Clayton Utz

CLAYTON UTZ

Confidential

Email 8 June 2020

Mr Fred Steennis
Senior Principal Consultant
DNV GL Energy
Utrechtseweg 310
6812 AR Arnhem
NETHERLANDS

Fred.Steennis@dnvgl.com

Dear Mr Steennis

Basslink Interconnector Outage

As you are aware, Clayton Utz acts for the Hydro-Electric Corporation (**Hydro Tasmania**), and Ashurst acts for the State of Tasmania (**State**), in arbitrations with Basslink Pty Limited (**BPL**) in relation to the high voltage direct current submarine cable across Bass Strait (**HVDC Cable**). We understand that Ashurst has separately engaged you as an expert on behalf of the State for the purposes of these arbitrations.

1. Engagement

1.1 You are engaged on behalf of Hydro Tasmania and the State to prepare an expert report which complies with the requirements set out in paragraph 5 below, and which answers the questions set out in paragraph 4 below.

1.2 You are also likely to be required to make yourself available to confer with other experts of like discipline (most likely by telephone or videoconference) on or before 24 July 2020 and to prepare a joint report with those experts by 7 August 2020. You will also be required to give evidence at the hearing in Melbourne (again most likely by telephone or videoconference) which is currently fixed to commence on 18 August 2020 for a duration of 16 sitting days until 9 September 2020. We will let you know the likely timing, length and manner of your involvement during that 16-day period in due course, given the current circumstances.

2. Background

2.1 We refer to the background information and documents provided in our letter dated 3 November 2017.

2.2 By written report dated 15 December 2017 (17-2917), you made a series of recommendations to minimise the risk of a future failure of Basslink of the type that occurred in December 2015. You recommended updating the thermal modelling relied on by Mr de Wild in his 14 December 2017 report, which you relied on in another of your reports dated 15 December 2017 (16-2443), by replacing [redacted]

2.3 Between March and May 2019, Fugro Australia Marine Limited conducted a subsea survey of the HVDC Cable route for Hydro Tasmania. This survey, as well as work performed by CSIRO, provided the following information for the entire HVDC Cable route: geophysical, bathymetric, depth of burial, sea water temperature and laboratory analysis of sediment cores.

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2.4 You are briefed with the background information set out in **Attachment 1.** We have updated Attachment 1 since it was provided to you in our letter dated 3 November 2017 with information concerning the surveys of the HVDC Cable and to record other information provided to you since 3 November 2017.

3. Documents

3.1 You are briefed with the documents listed in **Attachment 2.**

3.2 Attachment 2 includes all of the documents you were provided with to prepare your reports dated 15 December 2017, together with new documents provided on 12 March 2020 and further documents provided with this letter (highlighted in yellow in Attachment 2).

4. Questions

4.1 Terminology:

(a) *Possible* means something which may prove to be true, but that is not certain.

(b) *Probable* means something that is more likely than not to occur or prove to be true, having more evidence for than against.

(c) *Improbable* means something that is possible but is unlikely to occur or prove to be true.

(d) [redacted]

[redacted] further explained in Section I of **Attachment 1.**

4.2 Please answer the following questions in your report:

1. What do you consider to be the probable cause of the failure that occurred on 20 December 2015 and why?

   In answering question 1, please identify each possible cause of failure which you considered and explain the view you formed about whether each such possible cause of failure was probable or improbable.

2. Please provide your opinion on the following:

   (a) is there a maximum conductor operating temperature that the HVDC Cable should not exceed (**Maximum Conductor Operating Temperature**) to ensure that the HVDC Cable is operated in a manner that does not adversely impact its long term performance or service life? If your answer is yes, what is the basis for your answer and upon what source(s) do you rely in support of your answer?

(b) is there a maximum temperature difference over the paper insulation layer of the HVDC Cable that should not be exceeded (**Maximum Temperature Difference**) to ensure that the HVDC Cable is operated in a manner that does not adversely impact its long term performance or service life? If your answer is yes, what is the basis for your answer and upon what source(s) do you rely in support of your answer?

(c) what, if any, risks arise if the HVDC Cable is operated in excess of the Maximum Conductor Operating Temperature and/or the Maximum Temperature Difference?

3. Which of the possible causes of failure, if any, can be attributed to the way in which the cable was operated by BPL? In answering this question, please identify the facts and assumptions on which you rely to identify the way in which the cable was operated by BPL.

4. Further to 3, if any possible cause of failure is attributable to the way in which the cable was operated by BPL, is there anything that a prudent, experienced and competent person in the position of BPL should have done to prevent the failure?

5. What tests (if any) do you consider are necessary as a matter [redacted] to establish or would assist or be likely to assist in establishing the probable cause of failure, or narrowing the possible causes of failure?

6. Further to 5, if testing is appropriate, what material (including retrieved samples of cable and documents), if any, would be required to undertake any such tests? If it is necessary in your opinion to test a retrieved sample of cable, would any testing-related limitations or difficulties arise from the condition of that sample as at the time of testing? If yes, please explain the reasons for that answer, identifying the nature and scope of any such testing-related limitations or difficulties.

4.3 In answering these questions, please set out your opinion on the views expressed by CCI in their report ER 990 dated 29 November 2018 insofar as those views are relevant to the above questions.

5. Requirements for Report

5.1 In preparing your report, please ensure you explain the concepts and terminology you have used to allow a lay person to understand your answers. Please also ensure that you identify the foundation(s) for your conclusions and that you explain the reasoning leading to each conclusion.

5.2 Where you have relied upon academic literature or information contained in documents provided to you, please identify this and provide references to such literature or documents in your report.

5.3 Please also have regard to the following requirements for expert reports under the IBA Rules on the Taking of Evidence (applicable in the arbitrations) (**Tab 1.1**). These Rules require that expert reports include:

(a) a statement regarding the expert's present and past relationship (if any) with any of the parties, their legal advisors and if necessary, the arbitral tribunal, and a description of the author's background, qualifications, training and experience;

(b) a description of the instructions pursuant to which the expert is providing opinions and conclusions;

(c) a statement of the expert's independence from the parties, their legal advisors and the arbitrator;

(d) a statement of the facts on which the expert is basing his or her expert opinions and conclusions;

(e) the expert opinions and conclusions, including a description of the methods, evidence and information used in arriving at the conclusions;

(f) an affirmation of the expert's genuine belief in the opinions expressed in the expert report; and

(g) the expert's signature, date and place.

Yours sincerely

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Our ref 968/15760/80173193

Attachment 1 – Background

This background document is intended to provide a general high level overview of the design, function and operation of the Basslink cable. It is not a replacement for reading the documents provided to you and you should form your own views on any matters set out in this document that are relevant to your opinion by reference to the documents provided.

A. THE BASSLINK CABLE

1. The Basslink cable is a HVDC cable link connecting the Loy Yang Power Station in Victoria to the George Town substation in northern Tasmania. A description of the cable is under **Tab 2**. A map of the cable route prior to the 2016 repair is under **Tab 3**.

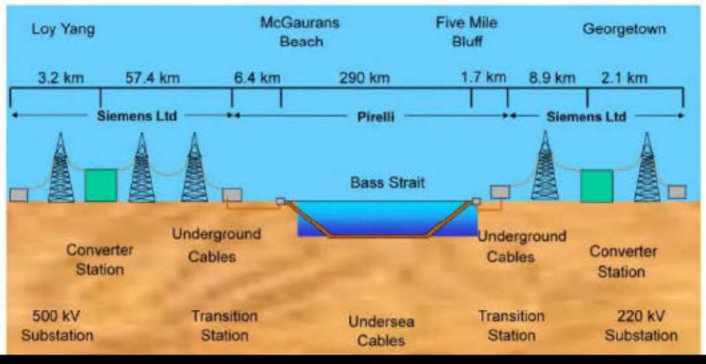
2. The Basslink cable is owned and operated by Basslink Pty Ltd (**BPL**). Between 10 October 2005 and 10 May 2007 BPL was known as National Grid Australia Pty Ltd.

3. The subsea section of Basslink is 290 km long. The convention for pinpointing a part of the cable is via *Kilometer Points* (**KPs**), which are measured from the Victorian end of the cable.

4. The subsea section has a maximum water depth of 80 meters. The HVDC cable is 1500 mm^2 in cross section and has nominal voltage of 400 kV.

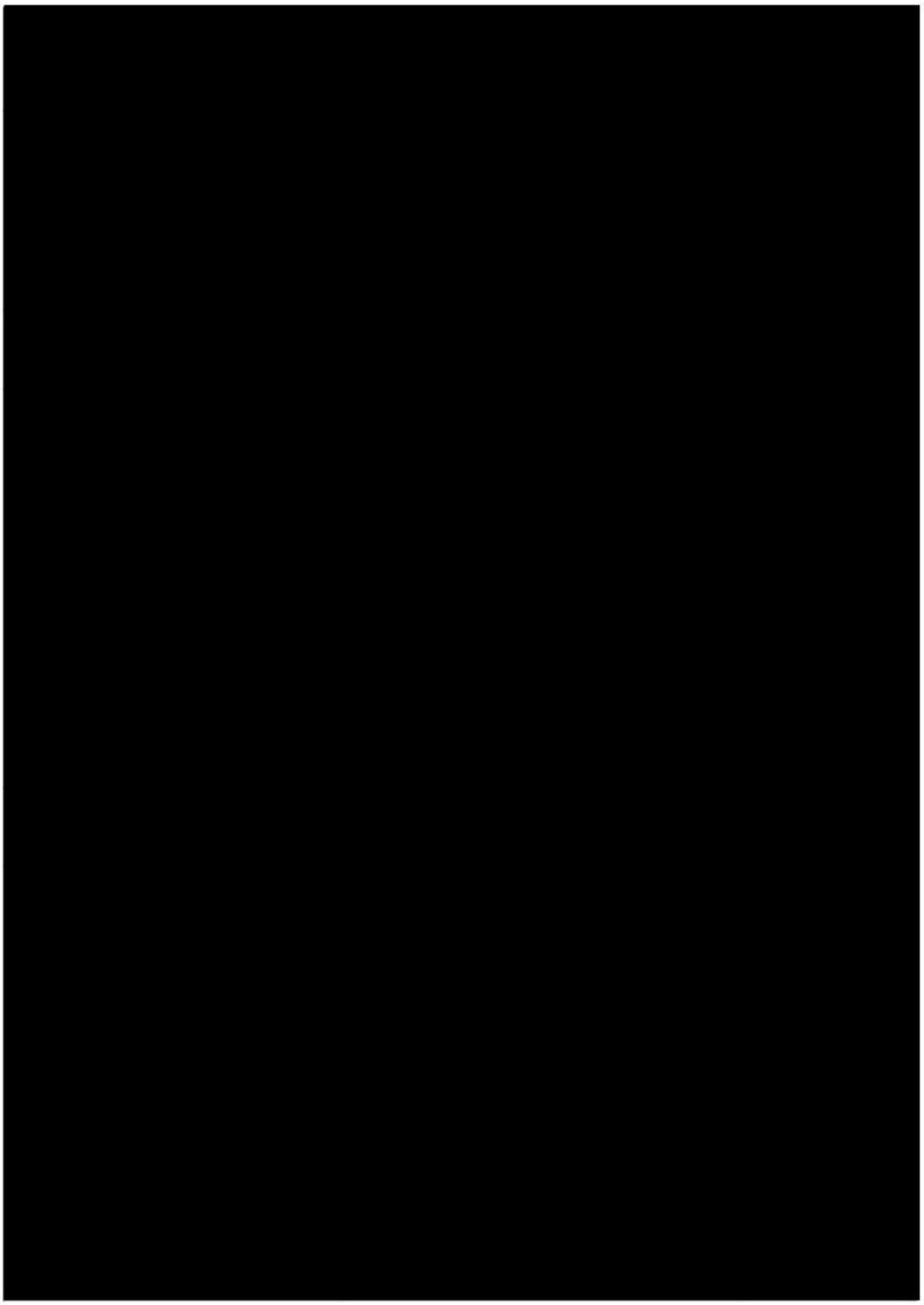
5. The HVDC cable is bundled with two other cables – the metallic return cable (**MR cable**) and a fibre optic cable (**FO cable**). The MR cable is 1400 mm^2 in cross section whilst the FO cable is much thinner.

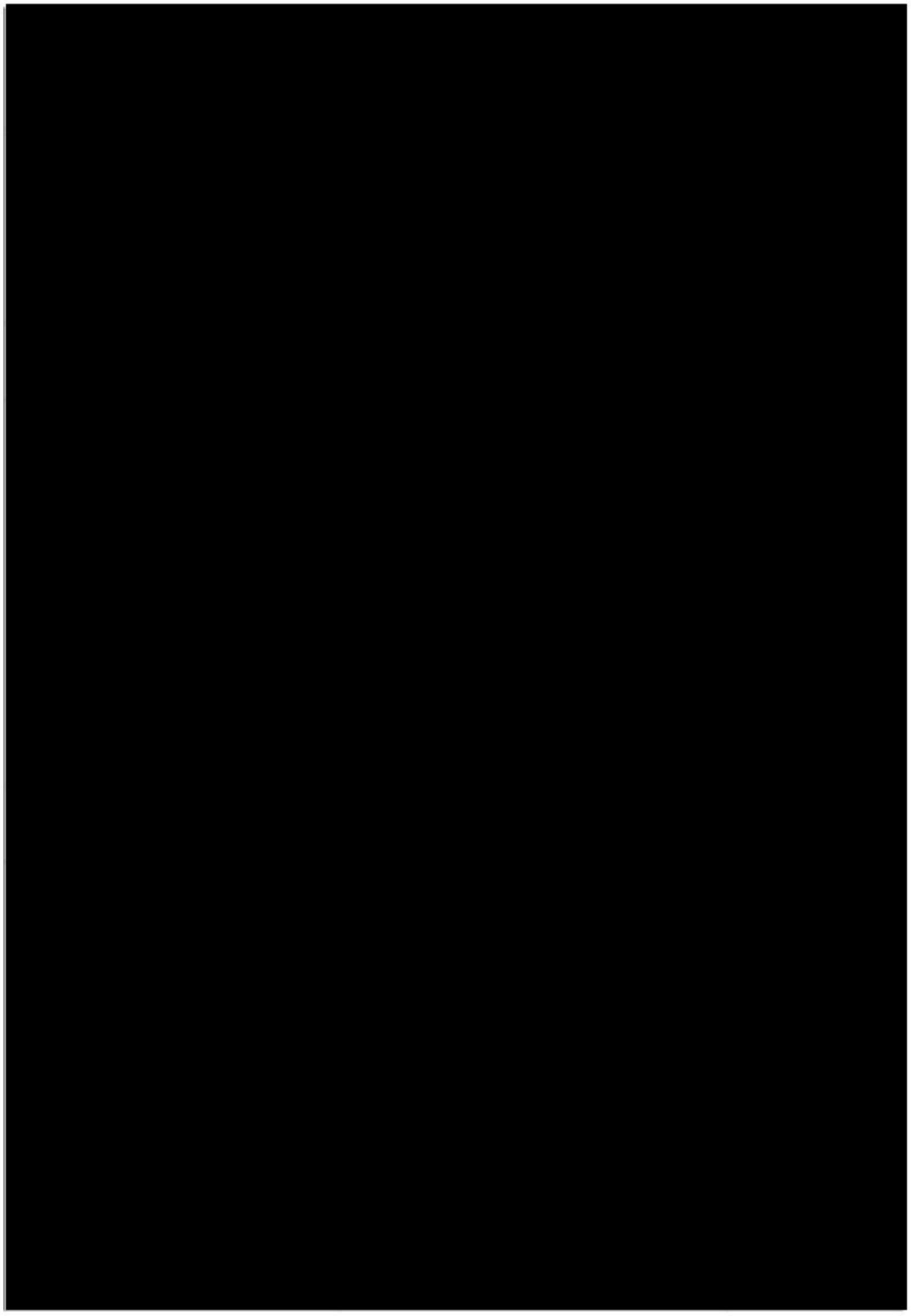
6. An image providing an overview of the Basslink system appears below.

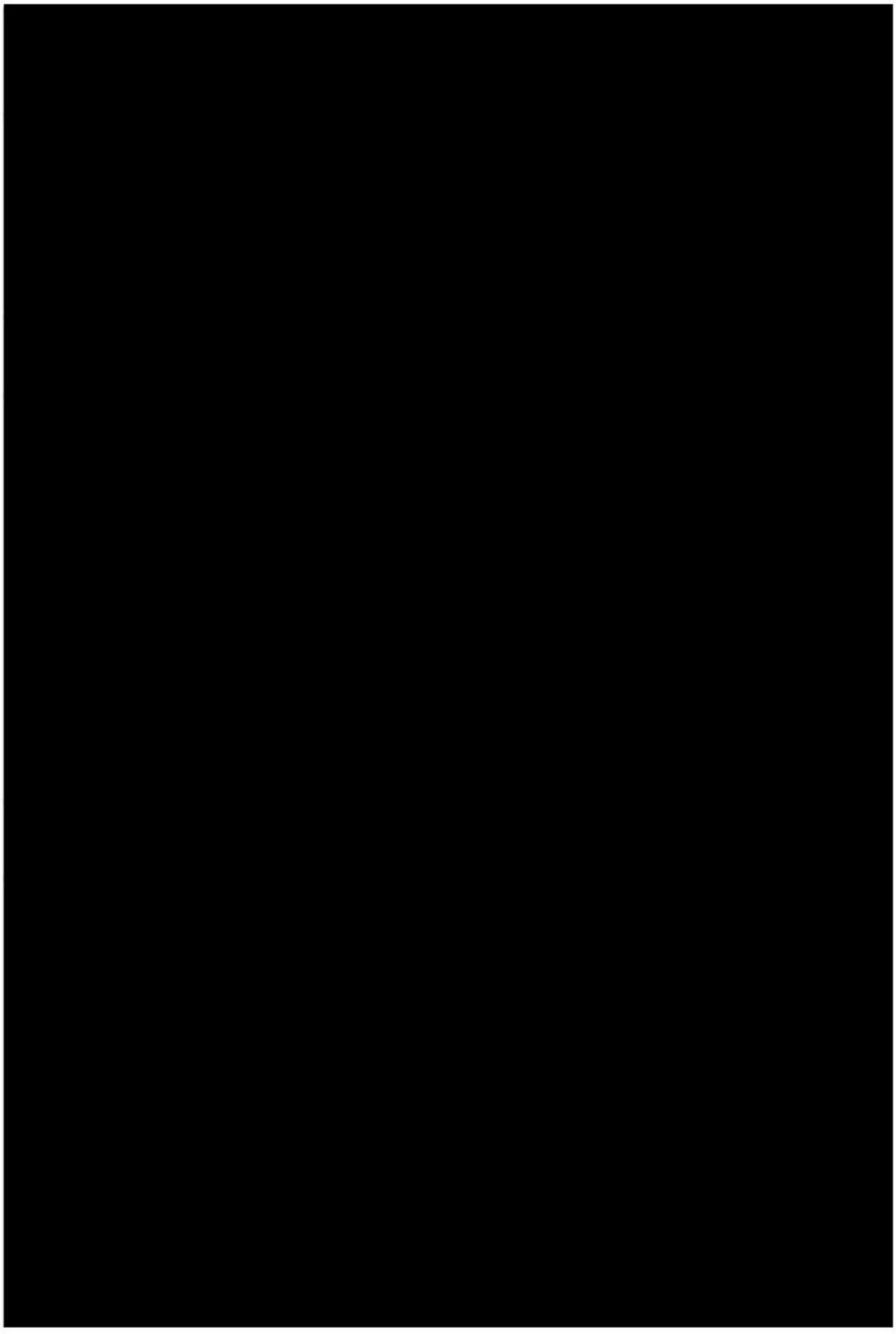


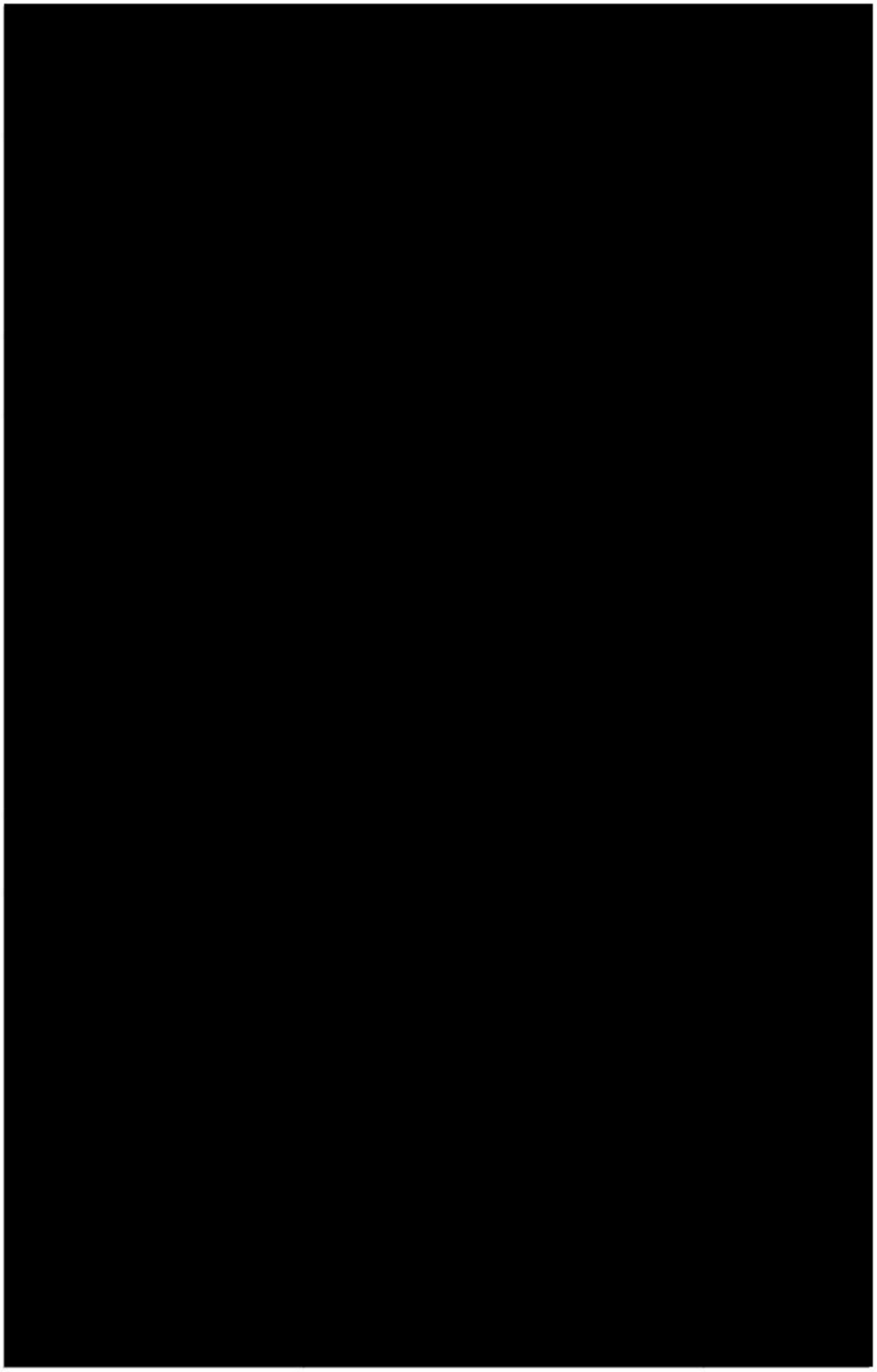
[redacted]

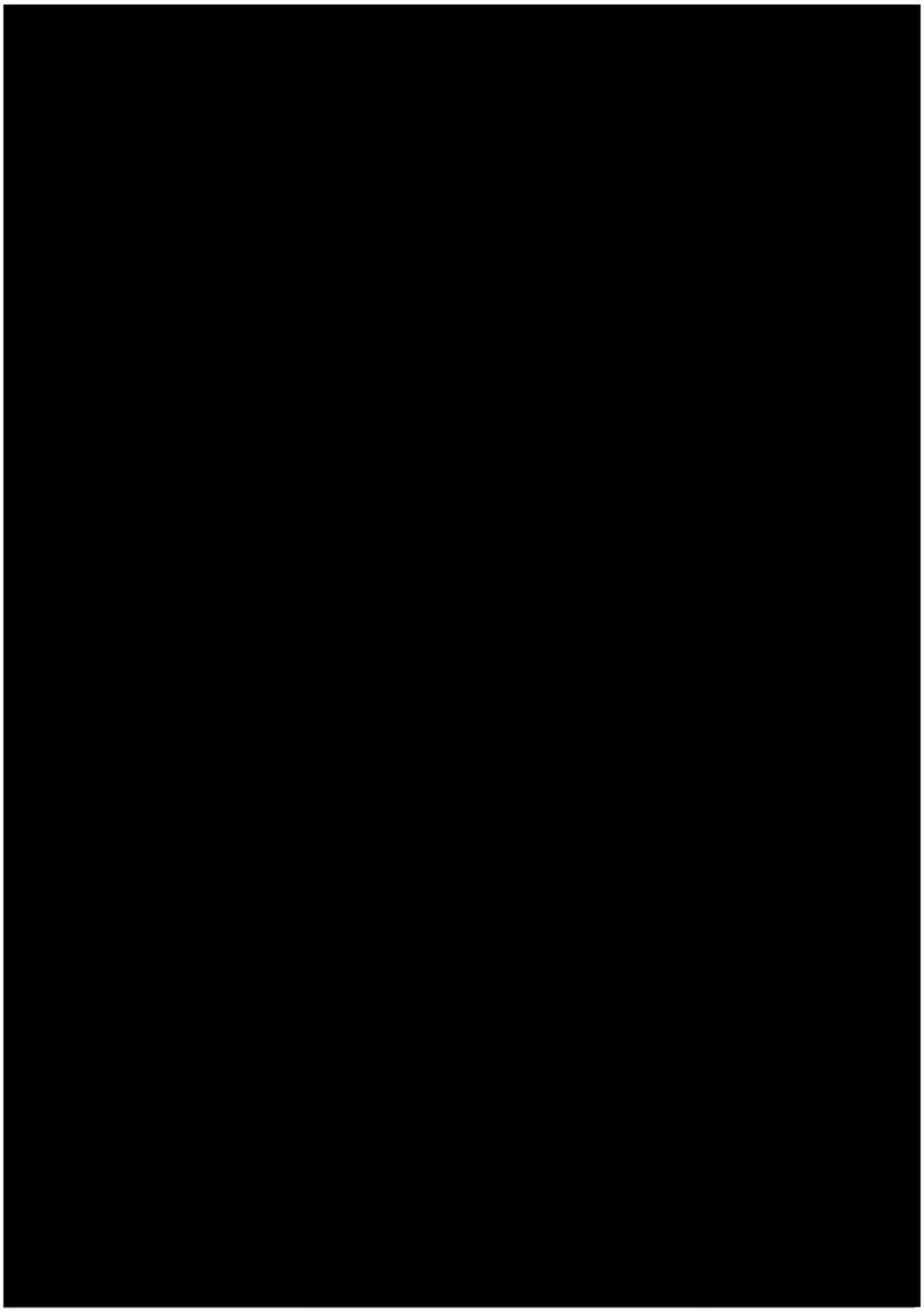
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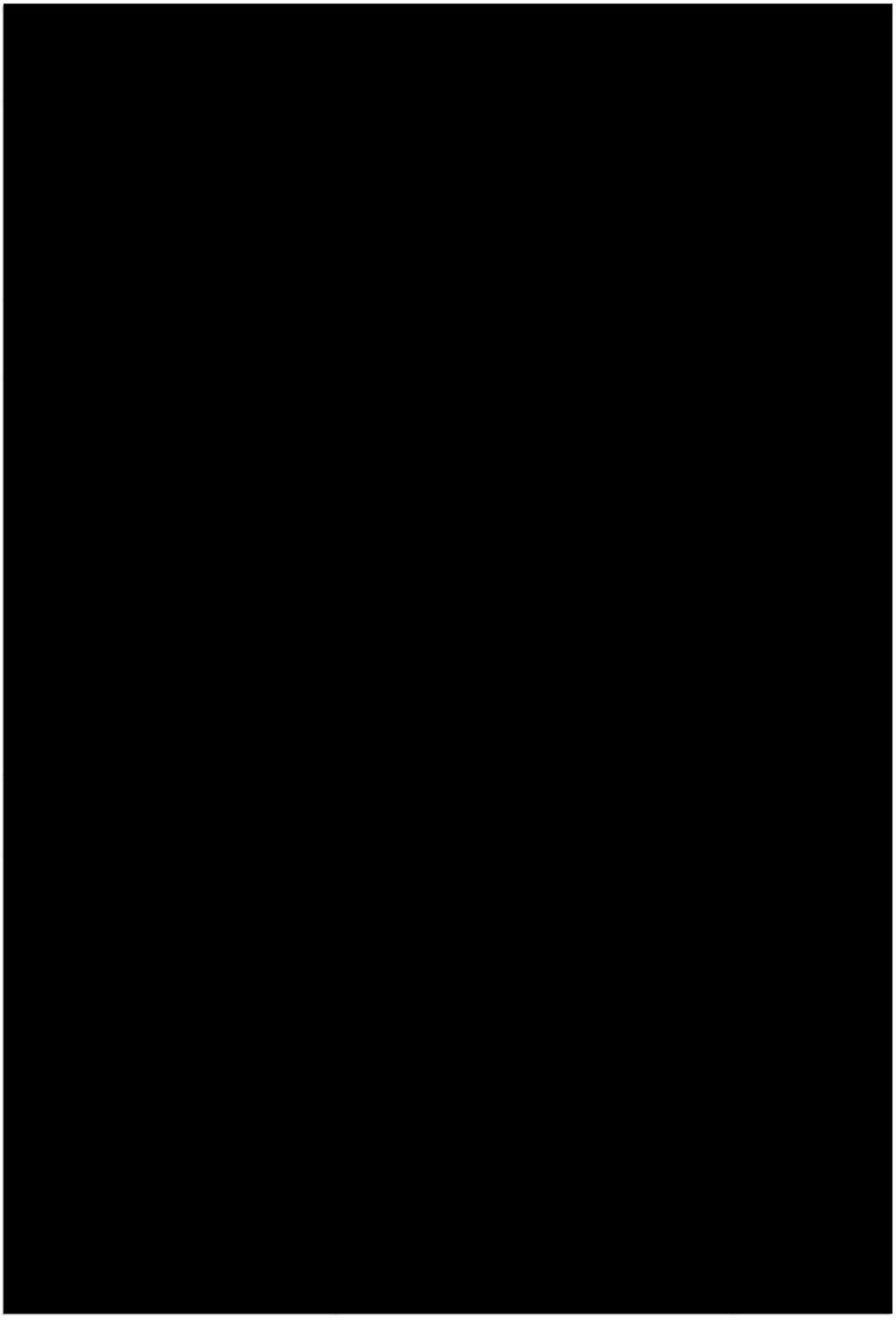


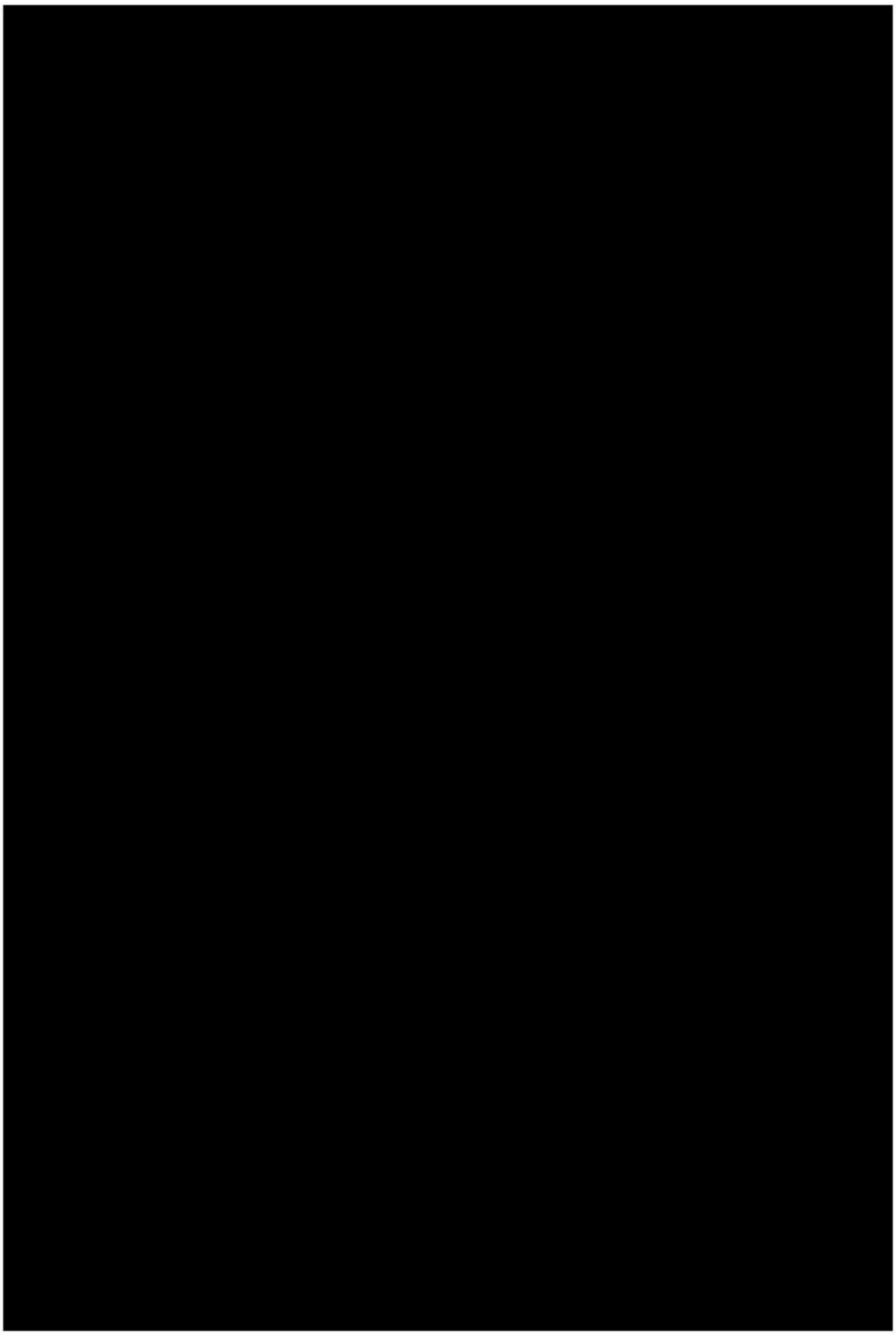


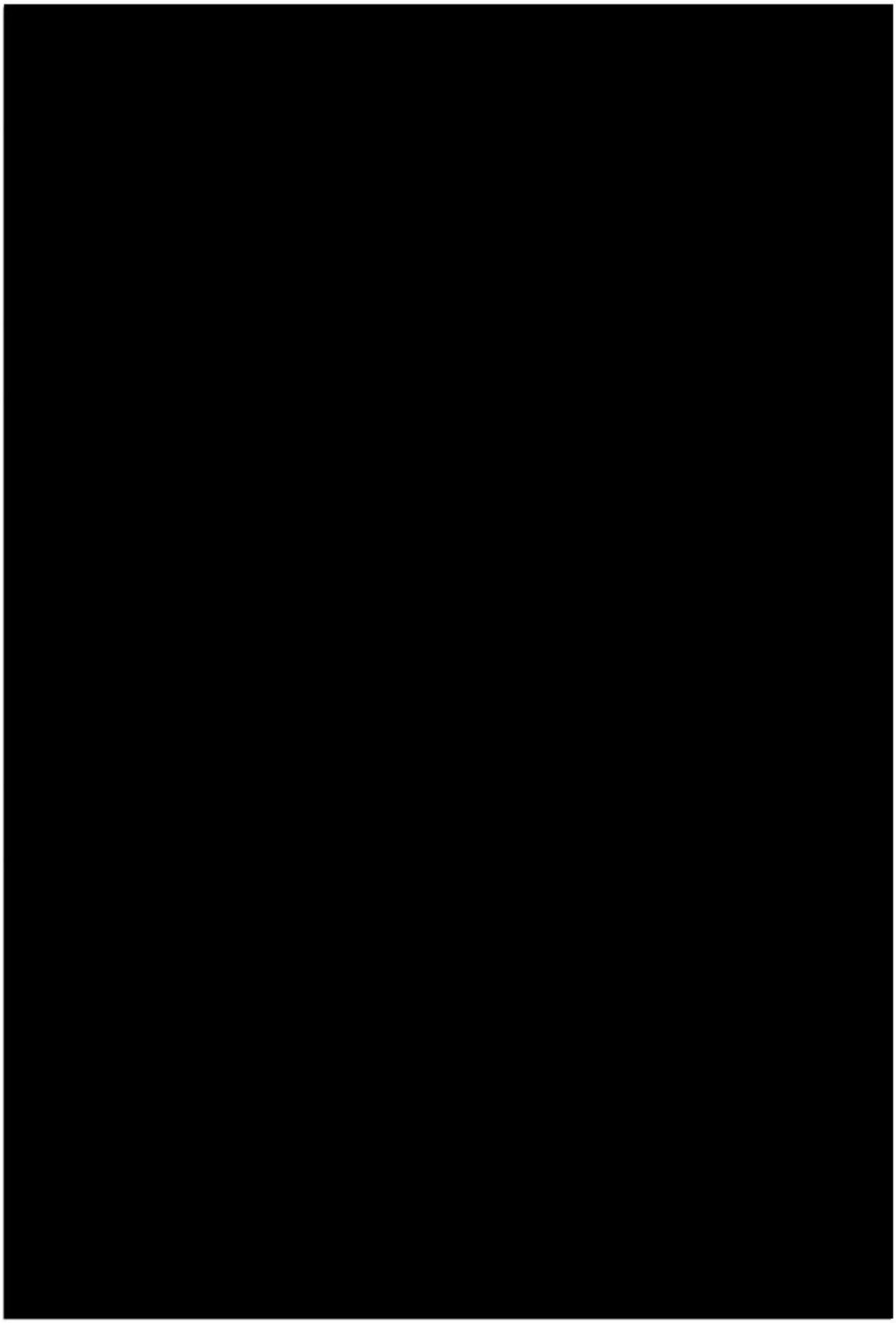


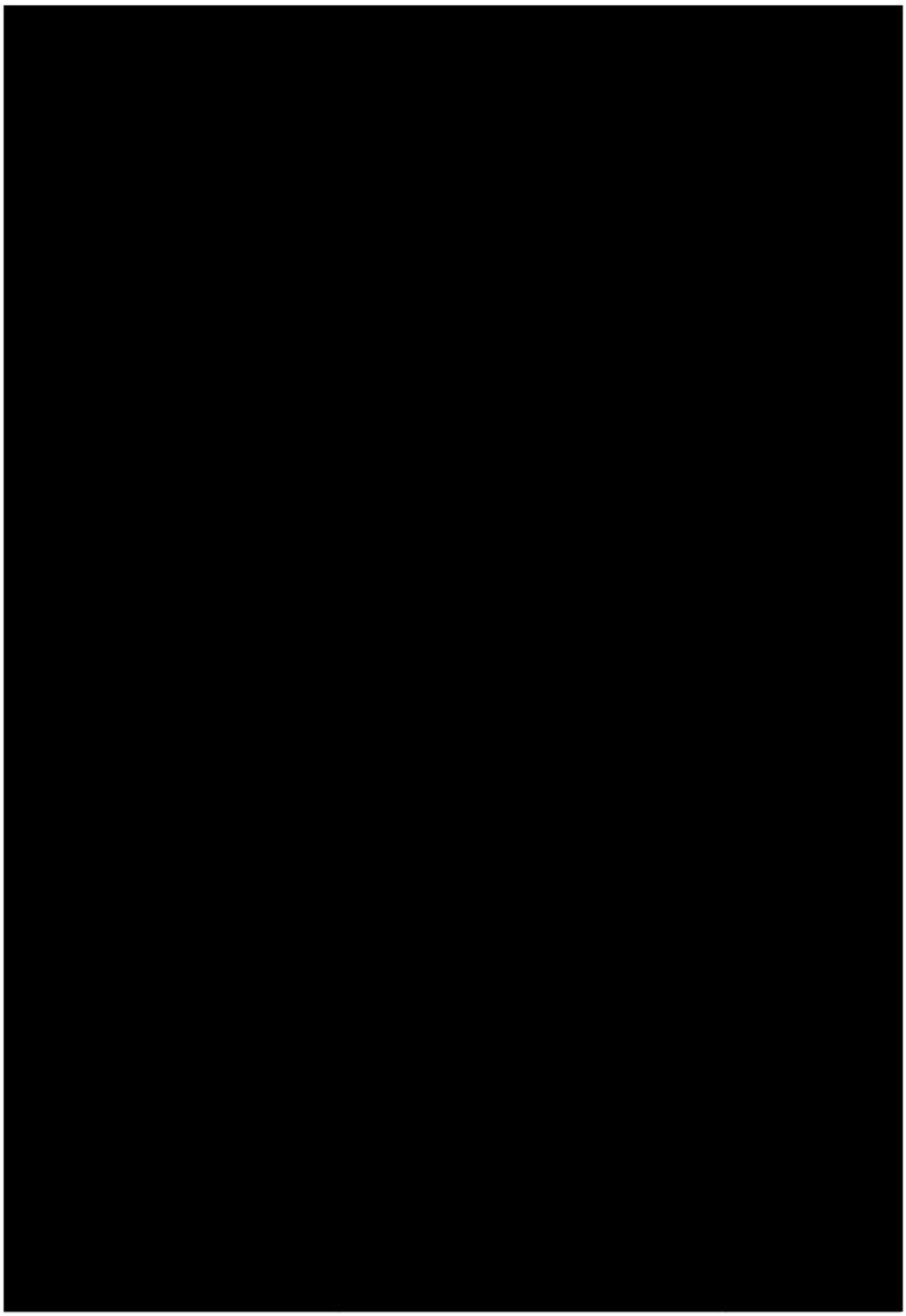


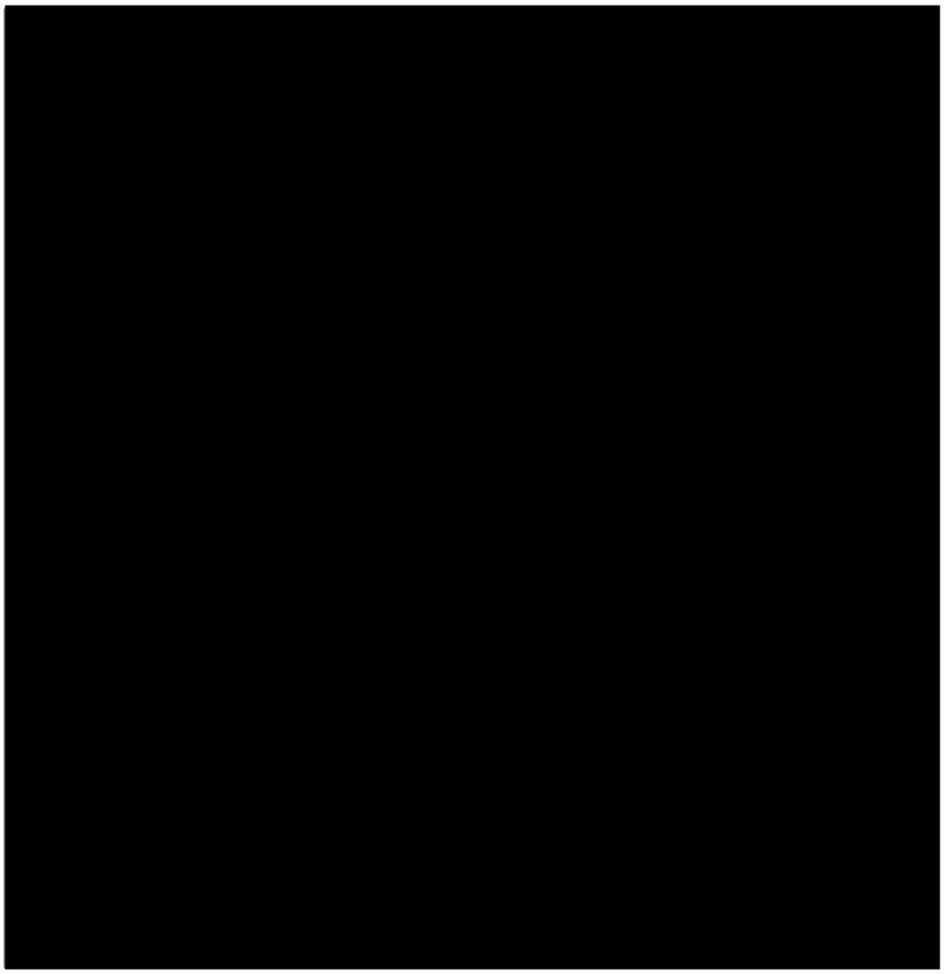




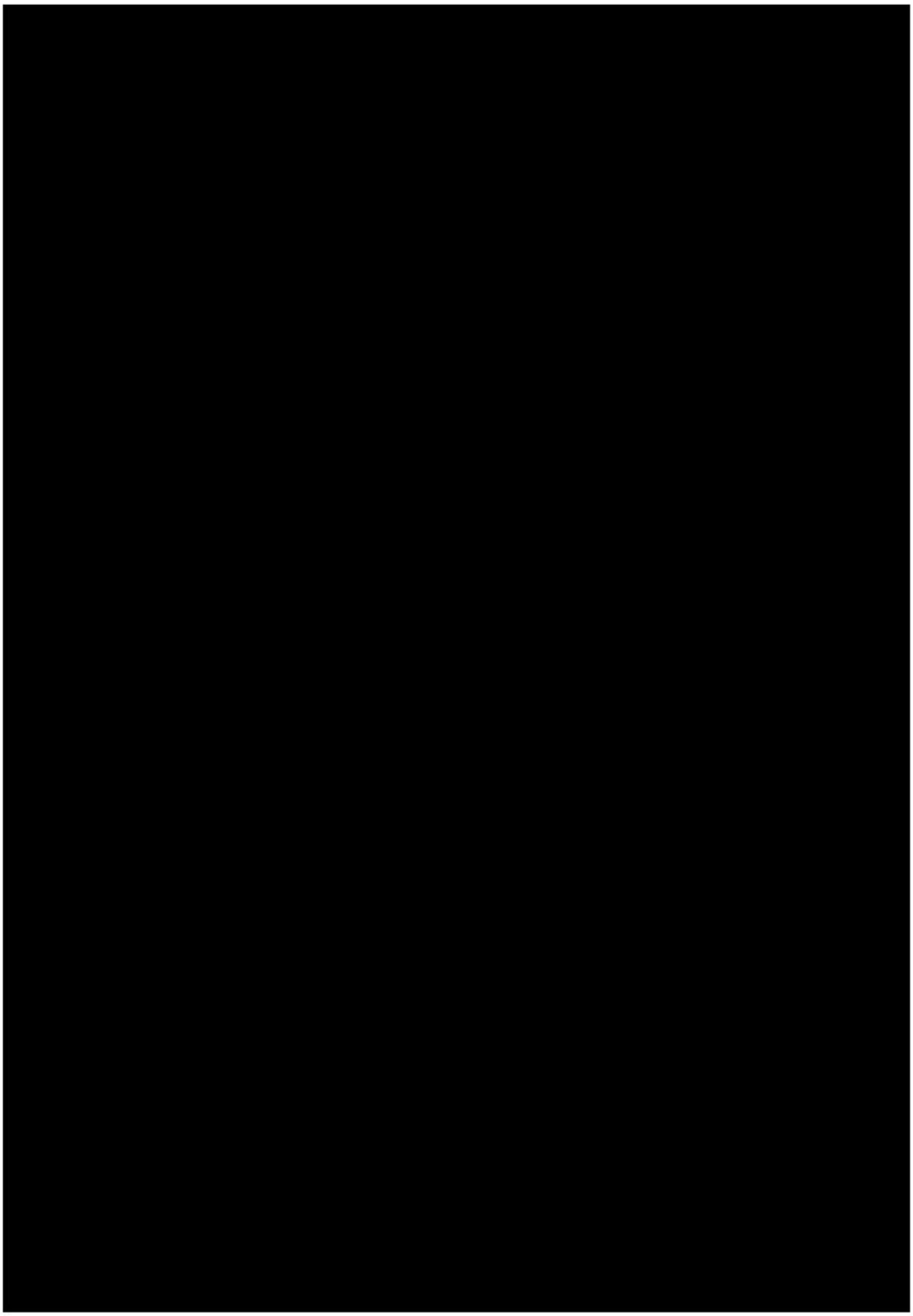


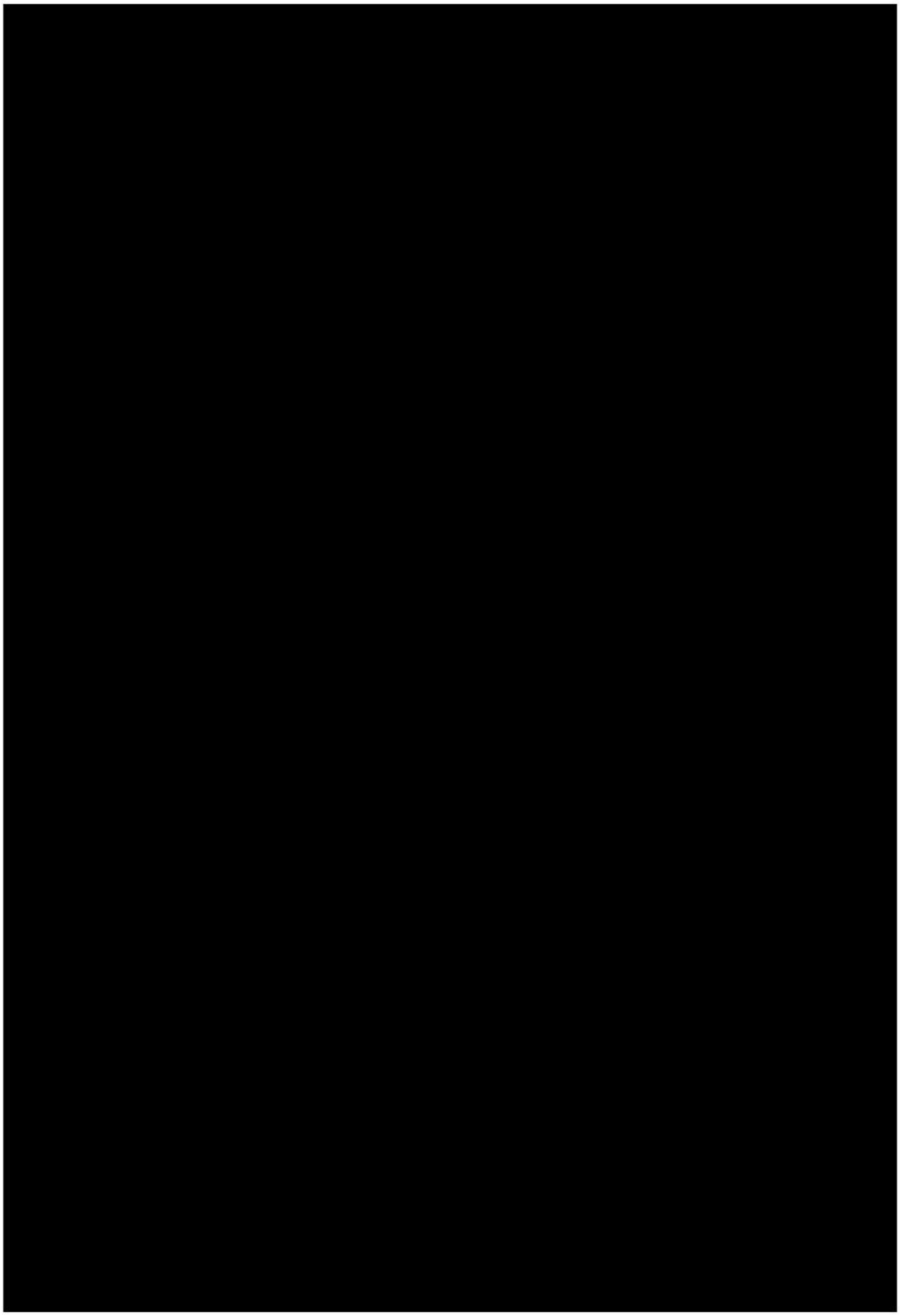


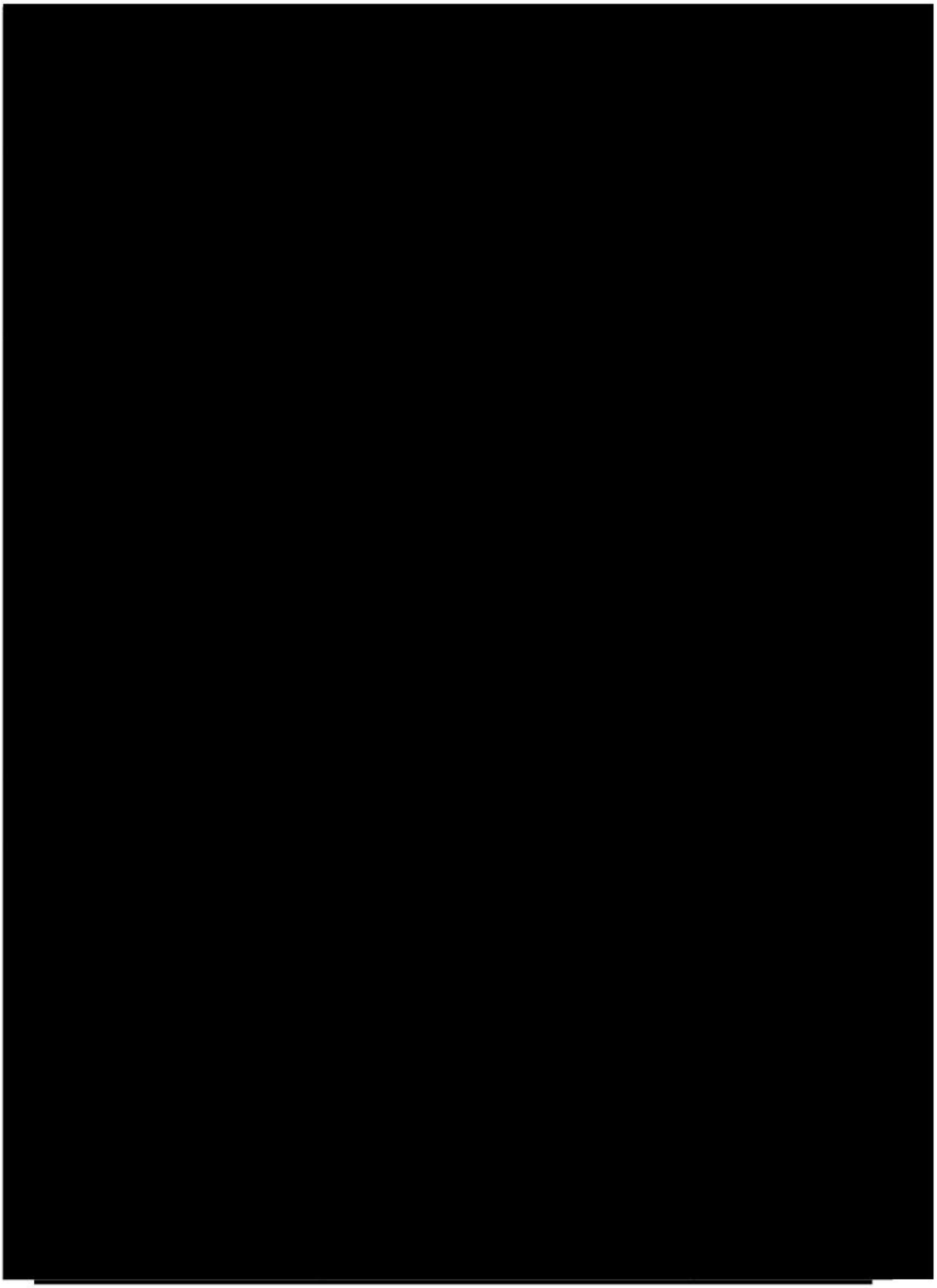


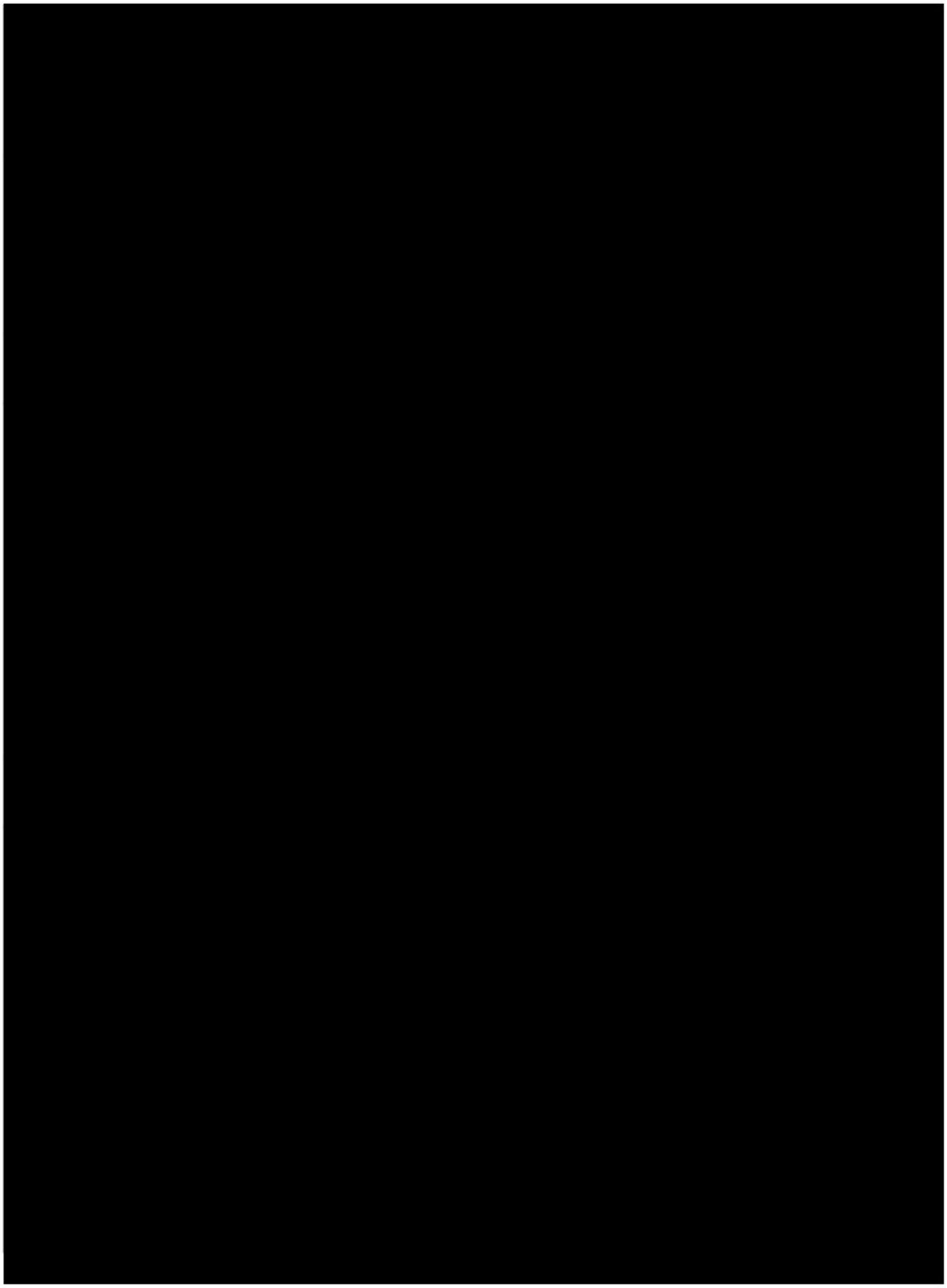


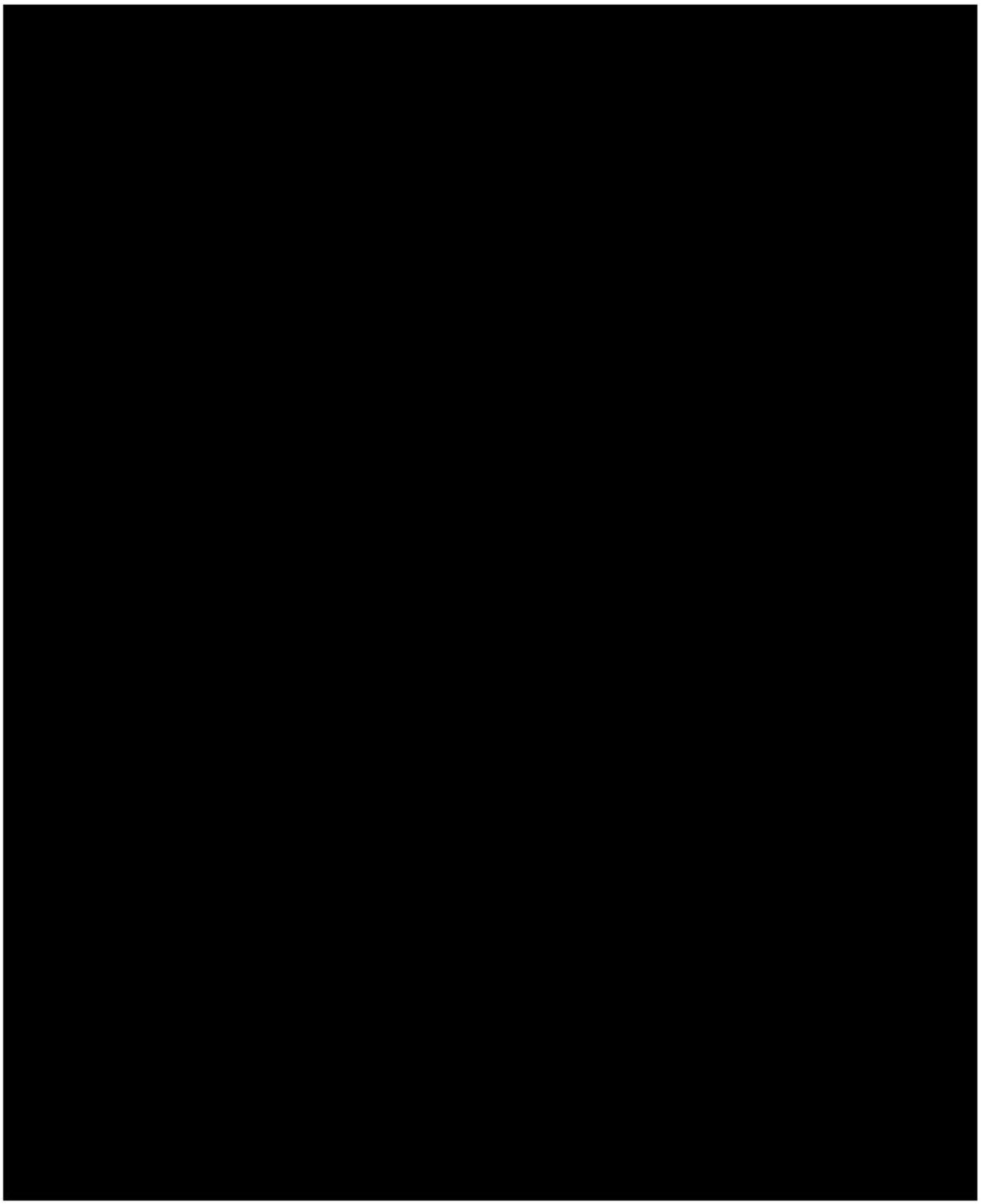
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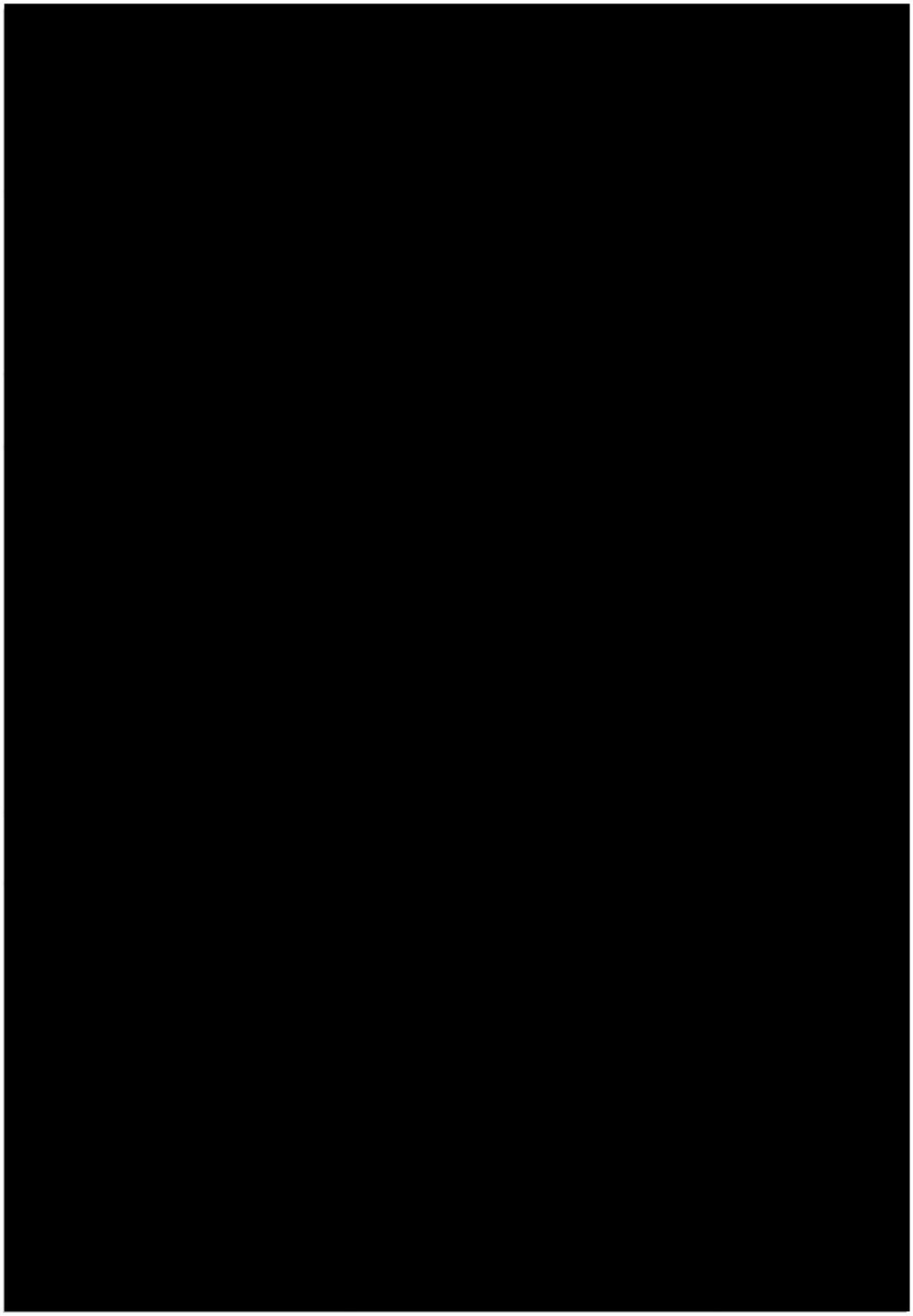


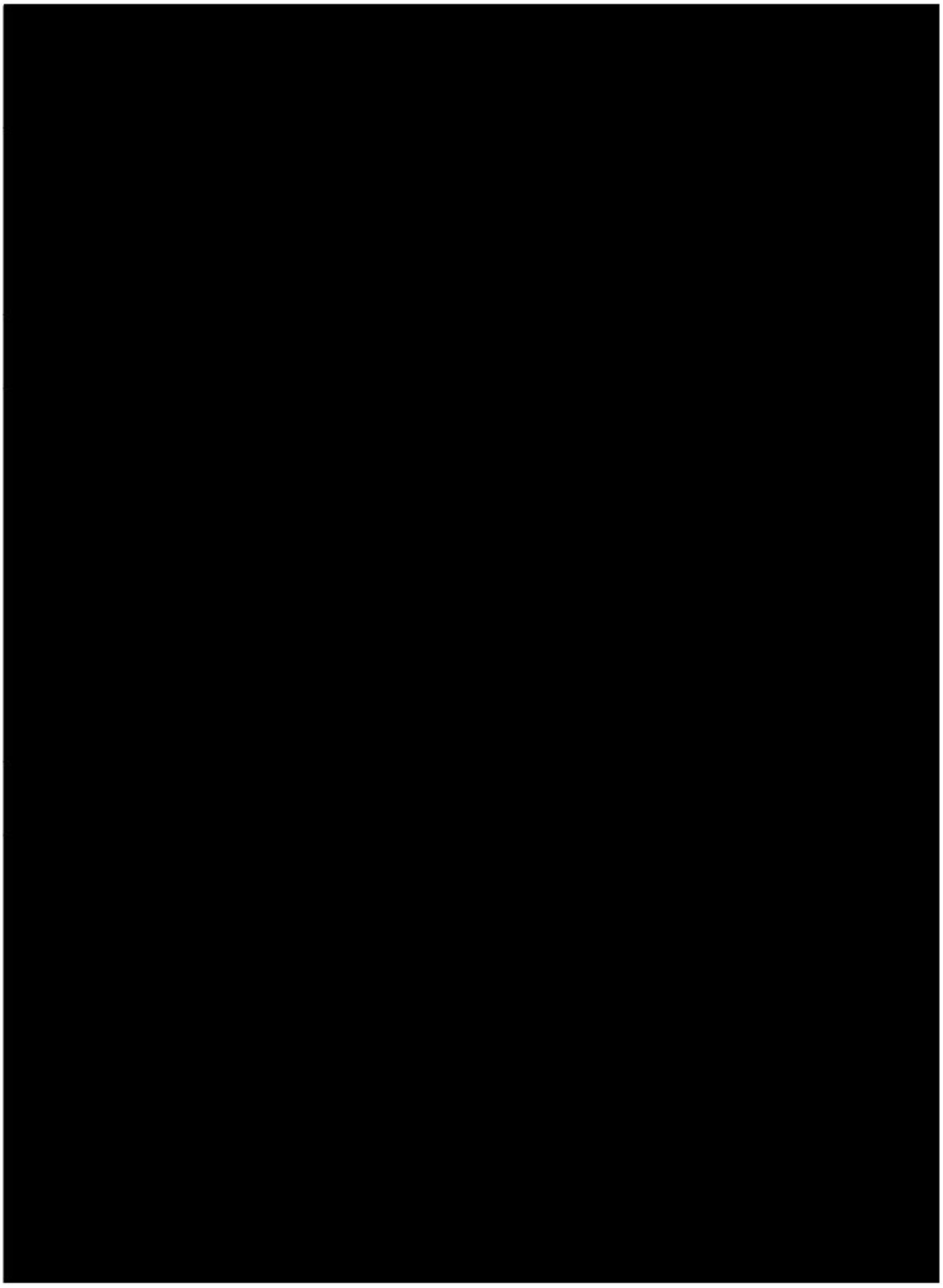


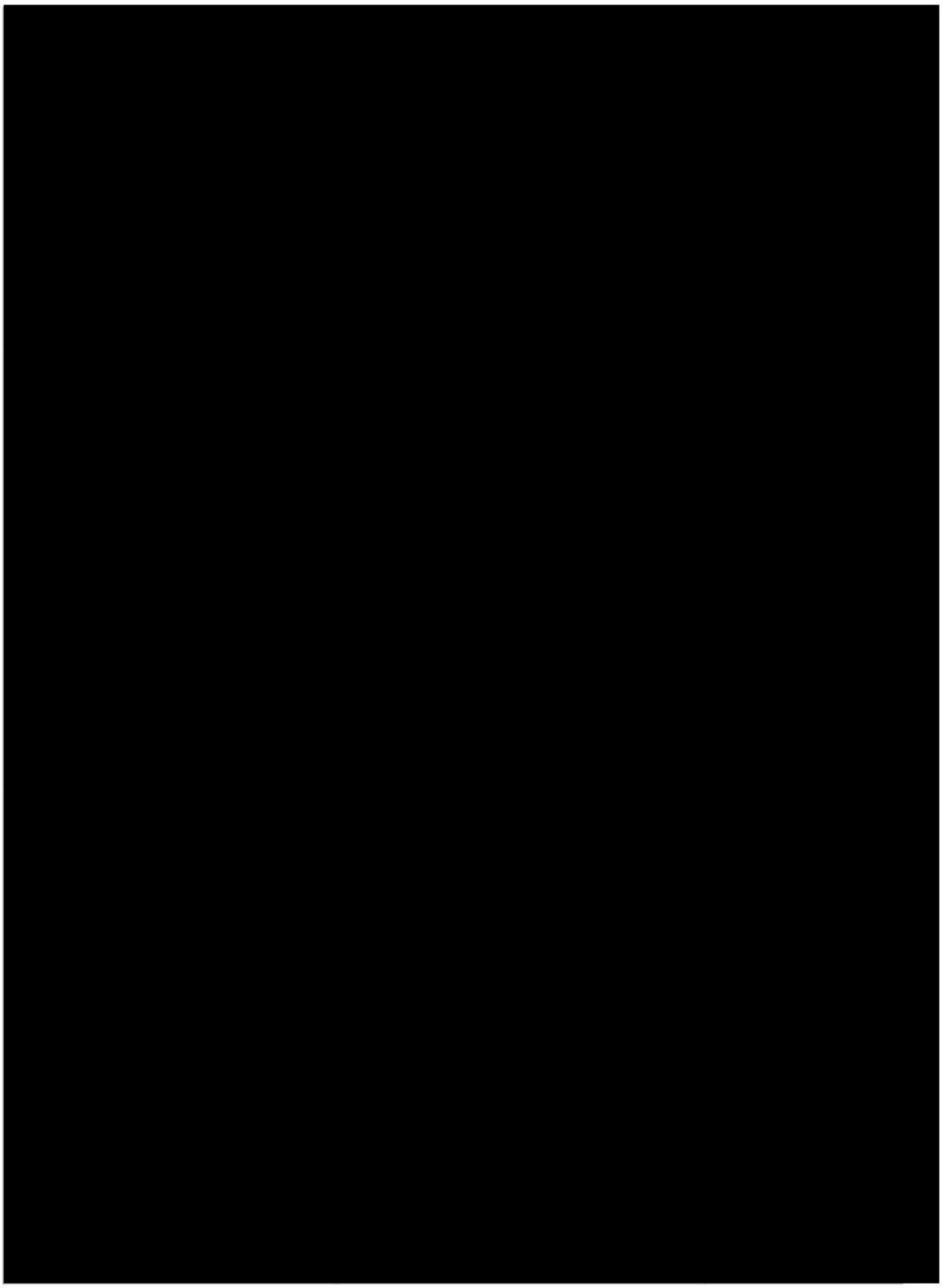


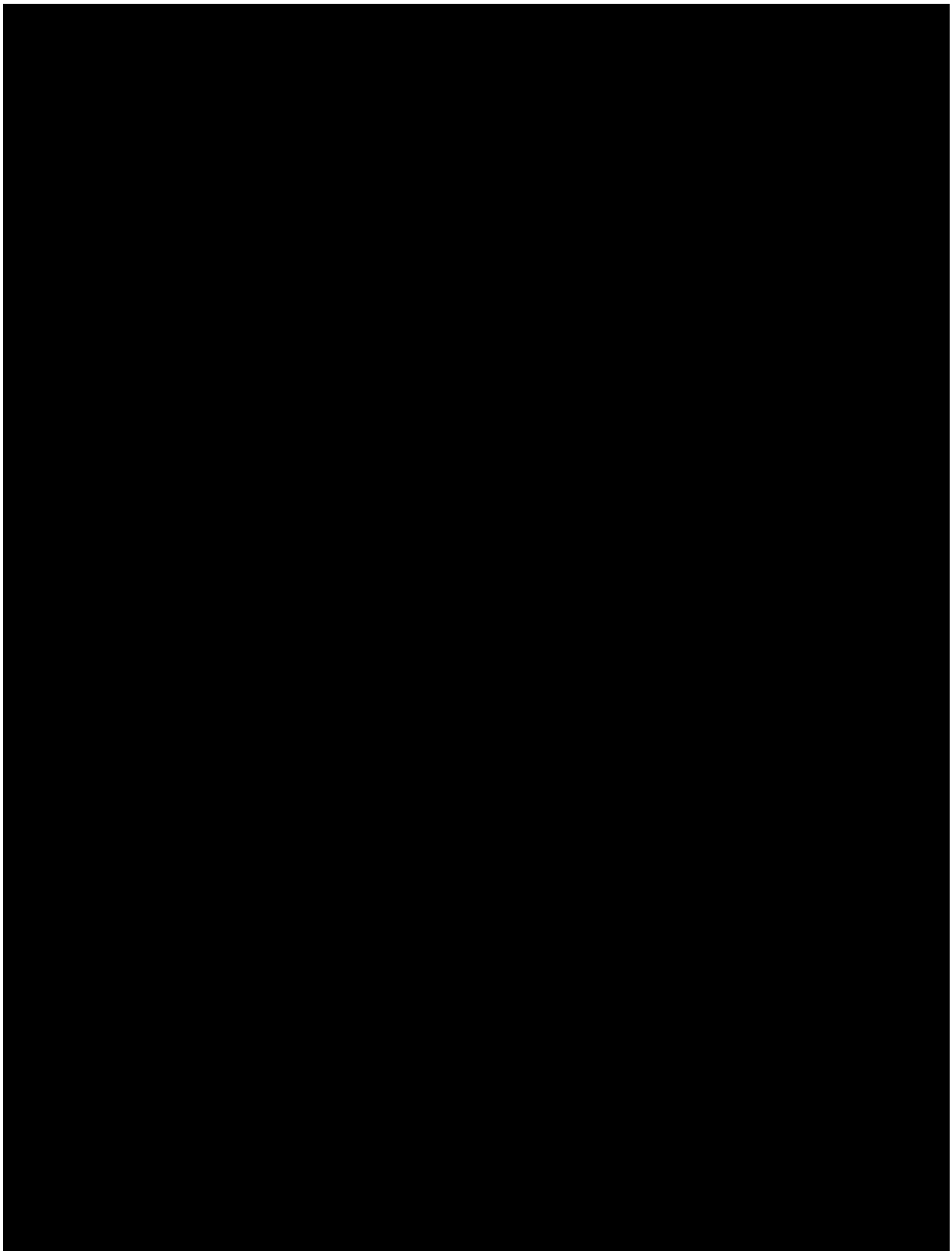


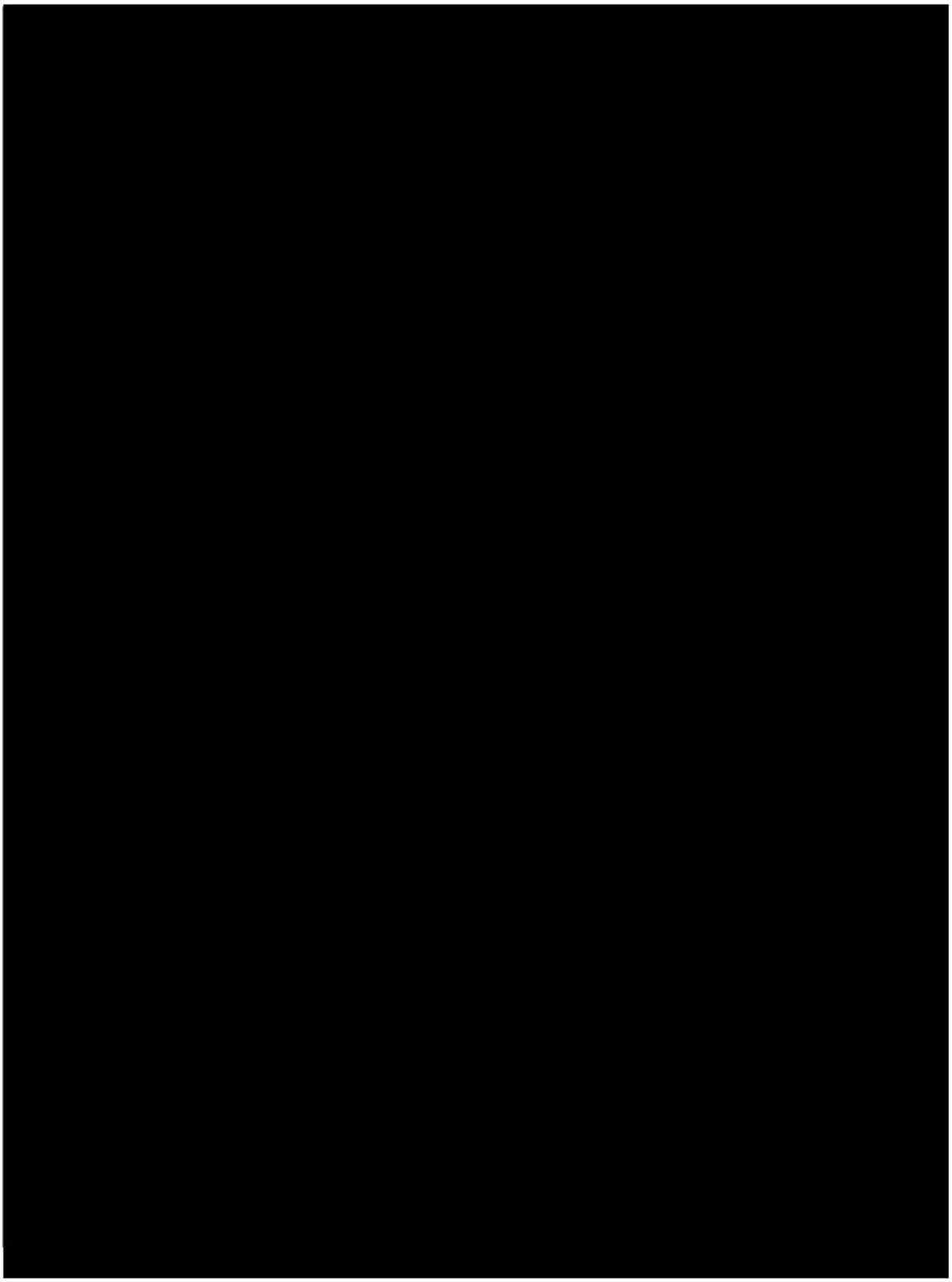














Operators in OECD nations

165. The definition of GEIP in the Interpretation Memorandum confines the meaning of "significant proportion of operators" in the NEC definition (which is now the NER definition) to mean a "significant portion of operators in OECD nations".

166. There are 35 OECD member countries which include:

(a) Australia;

(b) Canada;

(c) Chile;

(d) Denmark;

(e) Finland;

(f) France;

(g) Germany;

(h) Japan;

(i) Korea;

(j) Netherlands;

(k) Norway;

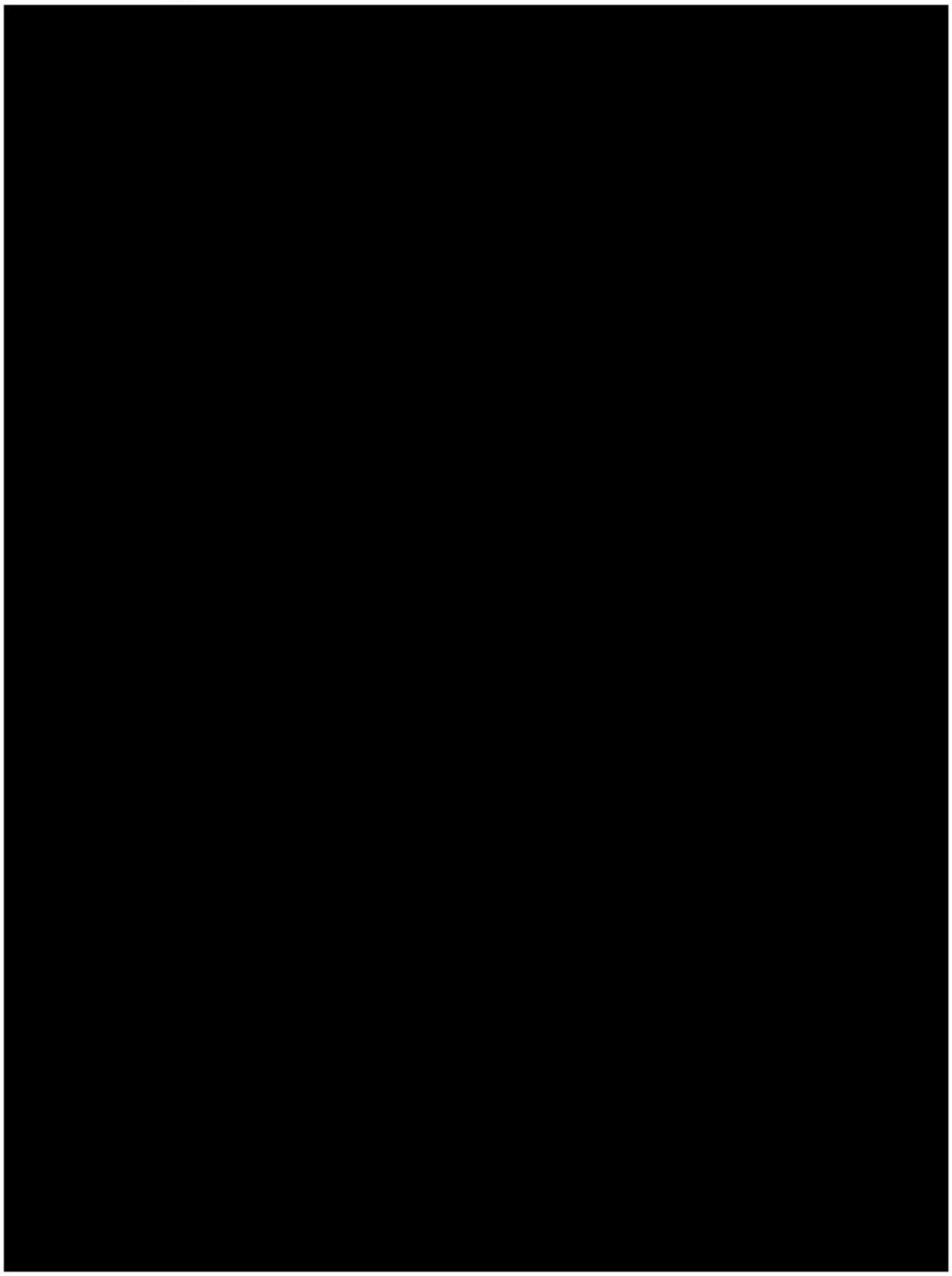
(l) Poland;

(m) Sweden;

(n) United Kingdom; and

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(o) United States.



Attachment 2 Documents

	Title	Date	Identification number	Rev
A. Expert Code				
1.	Expert Witness Code of Conduct (Supreme Court of Tasmania)	5 January 2016	Practice Direction 1 of 2016	
1.1	Article 5 of the IBA Rules on the Taking of Evidence in International Arbitration	20 May 2010		
B. Background				
[redacted]				
C. Pirelli/Prysmian documents				
[redacted]				

[redacted]

	Title	Date	Identification number	Rev
[redacted]				

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	Title	Date	Identification number	Rev
[redacted]				
D. Siemens documents				
[redacted]				

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	Title	Date	Identification number	Rev
[redacted]				
E. Load data				
[redacted]				
F. Fault finding reports				
[redacted]				

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	Title	Date	Identification number	Rev
[redacted]				
G. Photographs				
[redacted]				
H. CCI examination				
[redacted]				
56.	CCI Report, Basslink KP199.256 Failure Examination 27th to 29th April 2016	27 May 2016	ER 795	
[redacted]				
58.	CCI Report, Basslink KP199.256 Failure Examination 7th to 9th June 2016 at CCI	27 June 2016	ER 808	
I. Other documents				
[redacted]				

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	Title	Date	Identification number	Rev
[redacted]				

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	Title	Date	Identification number	Rev
[redacted]				

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	Title	Date	Identification number	Rev
[redacted]				
J. Correspondence				
[redacted]				
K. CCI and Materials Technology Reports				
67.	CCI Report, Basslink KP199.256 Failure Investigation Findings	2 December 2016	ER 833	
68.	Materials Technology Report, Report on Analysis of Samples From 400 kV Basslink Cable Fault	28 November 2016	G9748	
69.	Materials Technology Report, Report on Thermal Analysis (DSC) of Samples From 400KV Basslink Cable Fault	29 November 2016	G11863	
[redacted]				

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	Title	Date	Identification number	Rev
[redacted]				
L. Fugro Reports and Data				
[redacted]				
O. CSIRO Reports and Documents				
[redacted]				
Q. BPL Hyperlinked Witness Statements				
[redacted]				

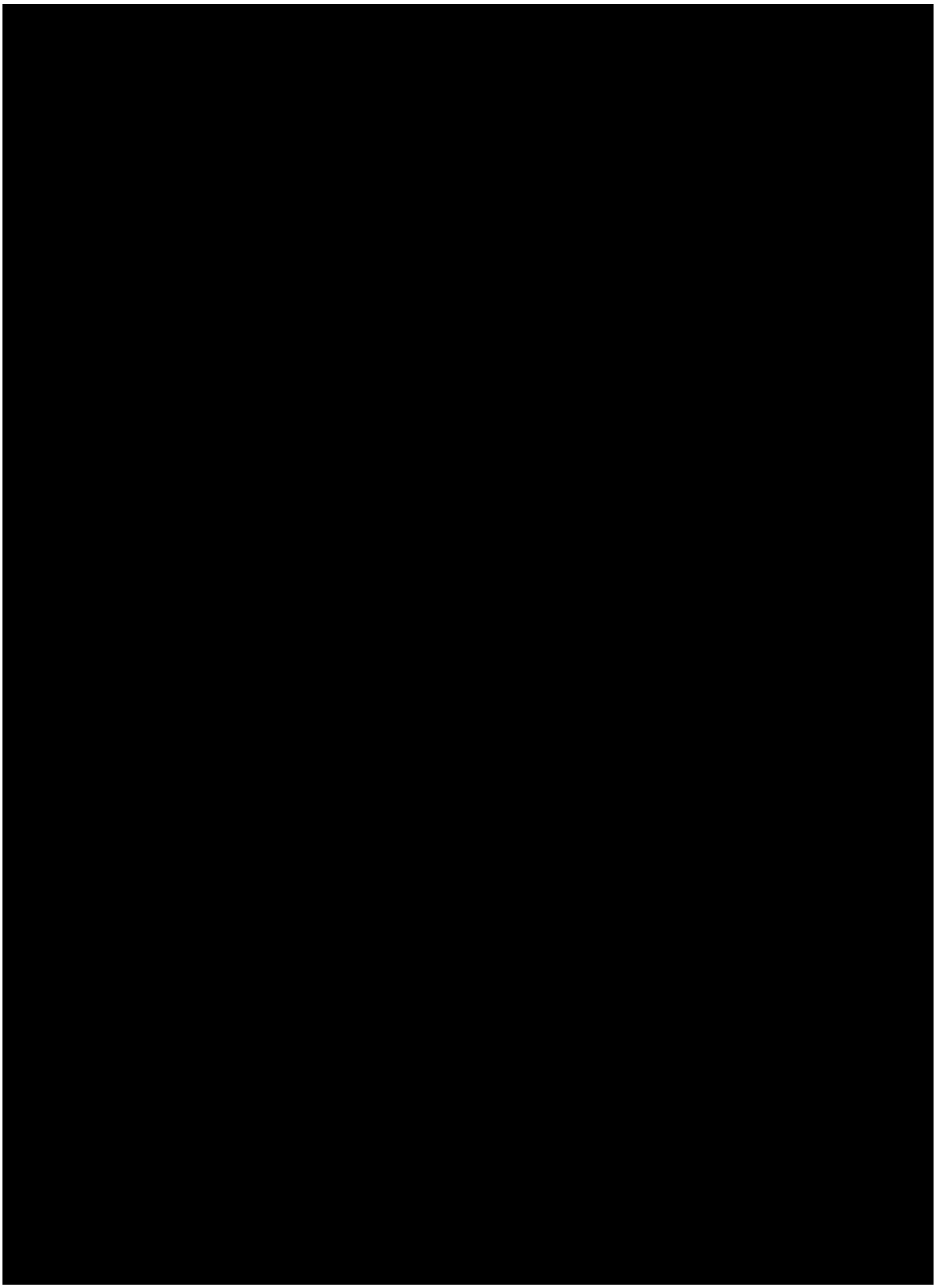
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	Title	Date	Identification number	Rev
[redacted]				

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APPENDIX M

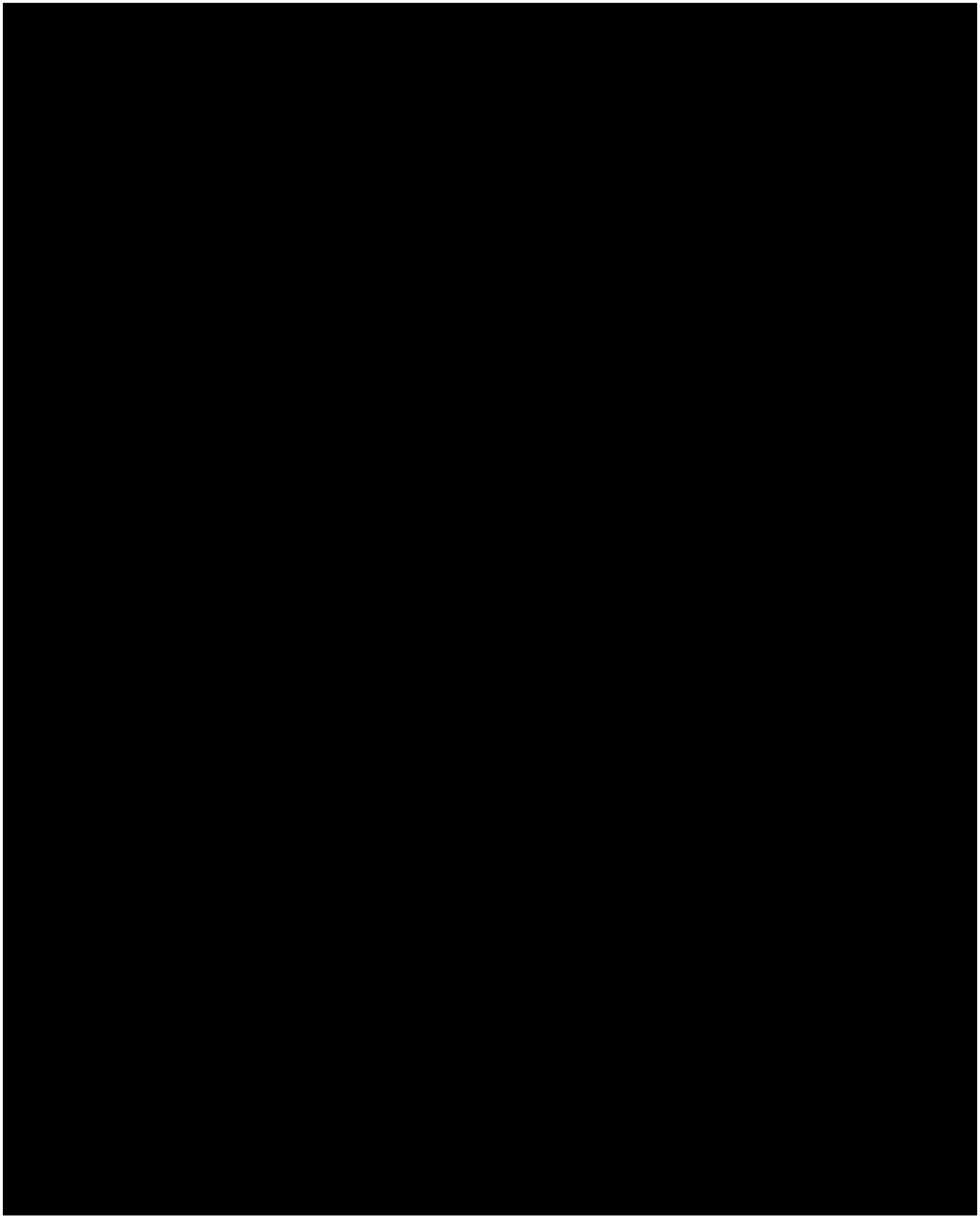
Voltage polarity reversal - Question letter BPL to HT 2003-05-13 [TAB 58.2.1]



APPENDIX N

[redacted] - BPLHT meeting report dated 2003-11-03 [TAB 58.2.2]

[redacted]



APPENDIX O
Void formation according to Runde, 2014

According to [/40/, Runde, 2014]

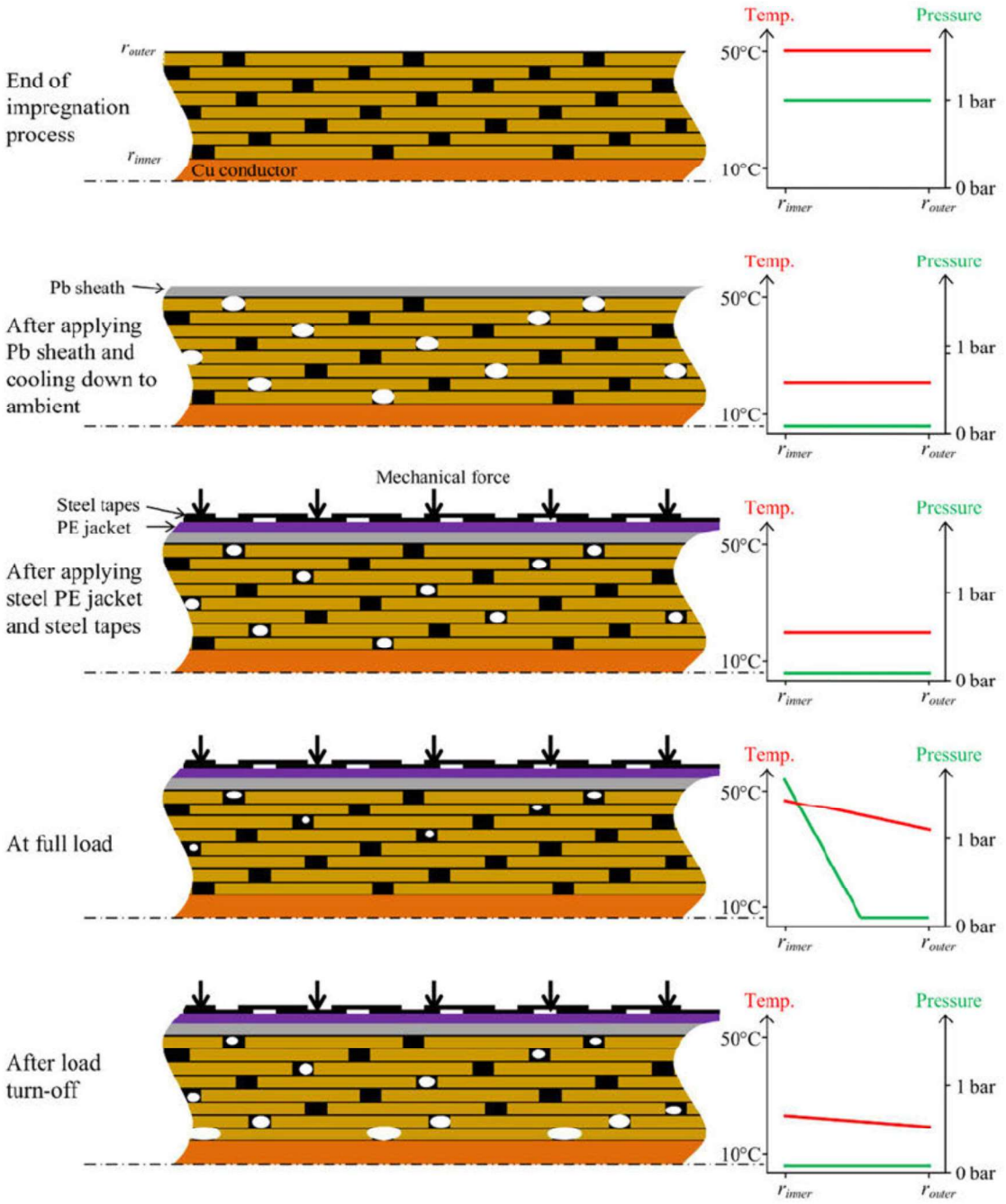


Figure. 2. Temperature and pressure profiles and the resulting cavitation in the insulation of a mass impregnated cable under different conditions (schematically). The white areas are cavities that are formed as a result of thermal contraction of the mass. Their size, number and location vary in the radial direction during the different load conditions (see text).

APPENDIX P
Voltage polarity reversals - A literature review

The following is summarized from a literature investigation I have carried out on the relevance and impact of voltage polarity reversals for HVDC MIND power cables.

Voltage polarity reversals in HVDC MIND power cables lead to an extra high electrical stress inside the insulation right after the moment of such a reversal [/3/, Hall, 1956], [/4/, Occhini, 1967], [/5/, Bahder, 1969], [/24/, Morshuis, 1997], [/25/, Jeroense, 1997], [/26/, Jeroense, 1998], [/40/, Runde, 2014]. Right after a quick (within seconds) voltage polarity reversal, such an increase of the electrical stress in the insulation paper layers close to the conductor can be considerable (see for instance various of the above mentioned references, in particular also [/40/, Runde, 2014]). This is illustrated in Figure 27.

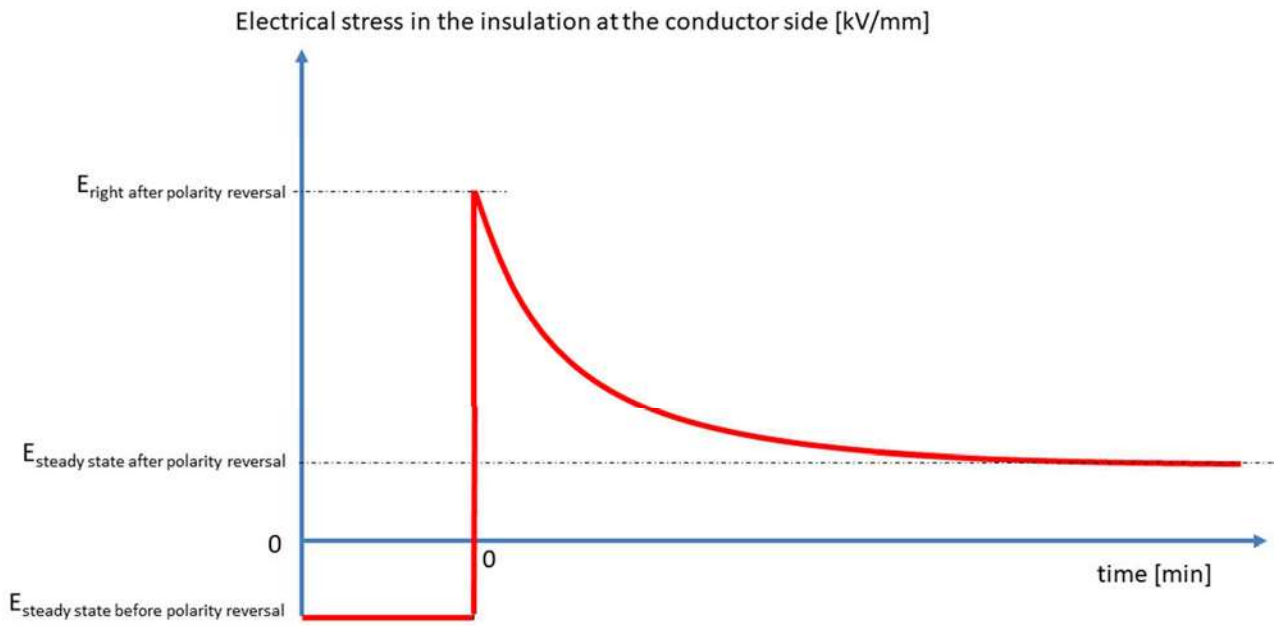


Figure 27 **Artificial drawing of the electrical stress at the conductor side of the insulation material of a warm cable, right after (at moment 0) and long after a voltage polarity reversal (on the right hand side of the curve).**

As a result, a breakdown tends to happen not long after a voltage polarity reversal in case where the insulation material is operated close to its breakdown voltage level [/3/, Hall, 1956], [/27/, Isayama, 1999]. This is also my experience for one of the HVDC MIND power cable failures investigated, where a failure happened 3 minutes after a voltage polarity reversal in a HVDC MIND power cable.

More about Isayama /27/. He carried out tests where he checked the moment of a breakdown in relation to applied voltage polarity reversals for miniature cables with three tape layers. He concluded that "...., *most breakdowns occurred immediately after the change in polarity because the change in potential of*

insulation was the largest at that point". I note that Isayama wrote 'most' and not 'all'. That means that there have been breakdowns not immediately preceded by a change in polarity. Taking into account the time between Isayama's polarity reversals, the maximum time he will have had between a polarity reversal and related breakdown is 10 minutes or less in all cases. Also, it is possible that the breakdown happened after multiple related voltage polarity reversals where earlier voltage polarity reversals pre-created the breakdown. Moreover, Isayama did his findings in miniature cables with only three tape layers, where degradation can be expected to result in a breakdown much faster than in a full sized traditional HVDC MIND power cable (for instance, the Basslink cable has 210 compacted paper layers[24]). Therefore, it is my opinion that a breakdown in the minutes after a voltage polarity reversal can be seen as potentially connected to this voltage polarity reversal. It is difficult to be more precise about the time and certainly it is impossible to identify the upper limit. The penetration of and along paper layers during a breakdown process can go extremely fast, but also very slow, depending on all types of factors such as the increase of the electrical stress created by the degradation process itself, the compactness of the paper layers, the amount of compound here and in the butt gaps, etc..[25].

Bahder [/5/, 1969] gave an extra reason to assume that the increase of the electrical stress during a voltage polarity reversal can be demanding for a HVDC MIND power cable. He suggested that due to the nonhomogeneous nature of the insulation the effective stresses appearing immediately after reversal will be higher than what is based on modelling. And thus [/5/, Bahder, 1969] concluded that this assumes that the breakdown voltage depends on the maximum change in stress and hence is limited to short times after voltage polarity reversal. In [/7/, Bahder, 1978] it is stated that voltage polarity reversal has been taken as a design issue for power cables.

In summary, failures that happen in HVDC MIND power cables, minutes and even many minutes after a polarity reversal, could very well be related to a possible impact of this polarity reversal, which is not unexpected since such a polarity reversal comes with increased electrical stresses that can start or continue the degradation until the cable will breakdown.

If no breakdown happens, in the minutes and hours after the voltage polarity reversal, via deionization the electrical (space) charges inside the insulation reduce the electrical stress again until its steady state level is reached. This is illustrated on the right-hand side of the illustrative curve shown in Figure 27. Also [/40/, Runde, 2014] mentions the discharging effect, where he wrote: "*The time constant for conduction is of the order of minutes and hours ….*". How fast this deionisation happens depends on the actual properties of the insulation material (its conductivity for instance), but also on the actual temperature of the insulation material [/4/, Occhini, 1967].

Reflecting on the importance of the voltage polarity reversal, [/34/, Bex, 2006], for the Basslink cable extra measures were taken to handle the quick voltage polarity reversal. This was said: "*As the Australian electricity market is based upon 5-minute dispatch intervals market outcomes can require Basslink to reverse power flows within 5 minutes. To achieve this a short 2-minute cable deionisation time[26] between changing voltage polarity has been achieved. As a result, the standard CIGRE cable load cycle test was altered to reflect expected power flows under market conditions*". In [/35/, Skog, 2006]

[24] See the insulation characteristics as mentioned in Appendix D [TAB 13]).

[25] DNV GL is measuring the development of degradation in medium-voltage MIND cables (with a similar construction as the HVDC MIND power cables) based on the monitoring of partial discharges (sparks) while the cables are in service under AC conditions. It was concluded that for such cables it can take for instance months before partial discharge activity develops into a breakdown (see what is written about this in Appendix J and also [/71/, Qian, 2015]. For a HV cable there is more energy to force degradation and paper puncture, but it goes slower because of the fact that there is a DC voltage and the number of partial discharges tend to increase under AC conditions.

[26] read: dwell time

informs about time to perform the voltage polarity reversal ranging from 140 minutes to 14 minutes. In [/31/, Giorgi, 2002] informs about time to perform the voltage polarity reversal being 10 minutes (with 10 faster (immediate) voltage polarity reversals per year as long as the time in between these reversals is at least 10 hours).

I made a drawing, see Figure 28, to illustrate what happens with the electrical stress close to the conductor in the case of a voltage polarity reversal. In this drawing the impact of measures to reduce the increase of the electrical stress are shown as well. Absolute values are based on information given by [/4/, Occhini, 1967] and are not per definition applicable to what happens in the Basslink cable, but the trend will be similar. Using Occhini's information, in Figure 28, the voltage steps E_{geo} and E_{st} are on scale. Also the time 0, 2 and 5 minutes are on scale. But the time constants for deionisation are chosen to illustrate the impact. What happens if the voltage polarity reversal is done at once (-U to +U in a second for instance) is illustrated by the line A, B, C, H. In case the voltage polarity reversal is done in two steps, first from -U to 0 kV and 2 minutes later (it means, a dwell time of 2 minutes) from 0 kV to +U is illustrated with the line A, B, D, E, H. And in case the voltage polarity reversal is done in two steps, first from -U to 0 kV and 5 minutes later (it means, a dwell time of 5 minutes) from 0 kV to +U is illustrated with the line A, B, F, G, H. It is shown that increasing the dwell time helps to reduce the increase of the electrical stress during a voltage polarity reversal. This statement is valid for any HVDC MIND power cable.

CCI mentioned [TAB 76, § 814, 941] that there is hardly a difference in electrical stress between a 2 and a 5 minutes dwell time. But in order to make such a statement more information is needed than, to my opinion, CCI did or could use. This is explained in Appendix T.

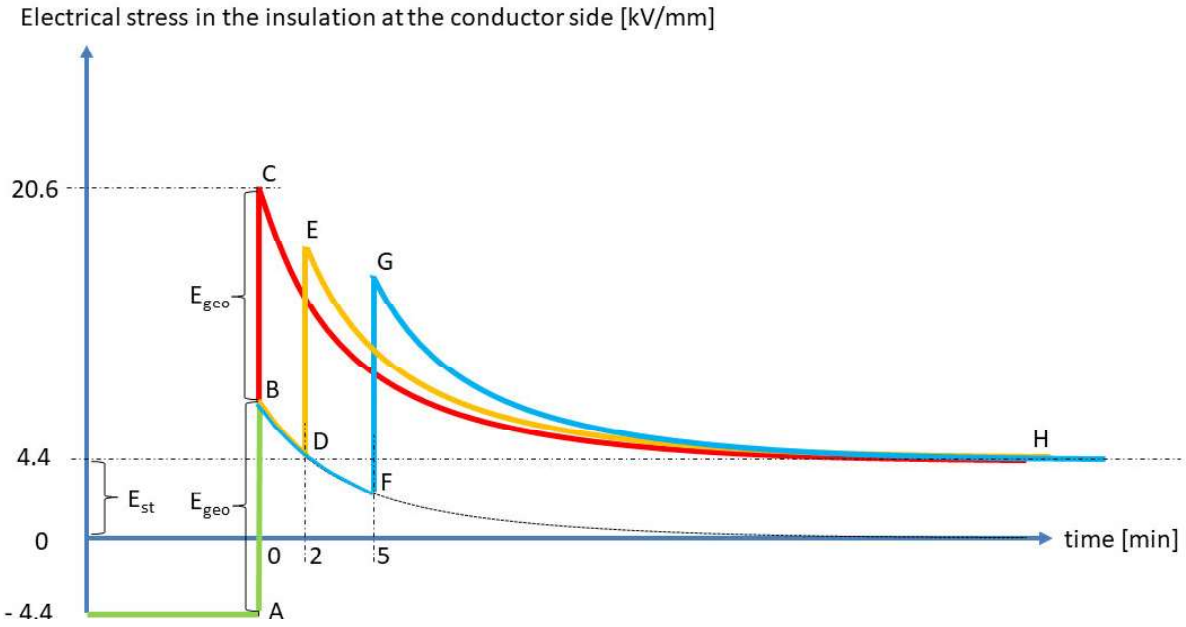


Figure 28 **Artificial drawing of the stress reduction in case a certain dwell time is taken into account.**

In [/25/, Jeroense, 1997] and [/26/, Jeroense, 1998] it is stated that the electrical charge distributions in MIND power cables are very reproducible.

In [/27/, Isayama, 1999] concluded that the breakdown voltage in samples is getting lower as a consequence of the number of voltage polarity reversals, but his reversals are done in 0.5 s or 1 s and that is very quick compared to normal HVDC MIND power cable operation.

In [/38/, Lennon, 2009] the following remark is made: "*Space charge is a design constraint unique to DC technology*".

In [TAB 61], Lawson mentions this "*The cable designer has to carry out the necessary calculations to ensure that the electric field*[27] *does not exceed 30 kV/mm at all points across the insulation wall and under all operating conditions*". This remark covers also the voltage polarity reversal moment. But it is not clear from where Lawson did get this electrical stress limitation.

Because of the fact that in general HVDC MIND power cables are sensitive for voltage polarity reversals, Cigré ([/6/, Cigré, 1974], [/15/, Cigré, 1980]) has set up test requirements for this type of power cable in which voltage polarity reversals play a role (with 10 heat cycles at 1.5 U_o with each 4 hours a voltage polarity reversal). It is recommended by Cigré to do the voltage polarity reversal in 2 minutes, although

[27] Electric field is related to electrical stress

10 minutes is allowed as a maximum, showing that in this range of minutes the voltage polarity reversal is considered to have an impact. In [/28/, Cigré, 2000] the heat cycle requirement was reduced to 1.4 U_o, probably because of the higher system voltages. Moreover, in [/28/, Cigré, 2000], it is recommended to perform the voltage polarity reversal in 2 minutes, without mentioning that 10 minutes is allowed as a maximum as well, as happened in earlier Cigré recommendations [/6/, Cigré, 1974] and [/15/, Cigré, 1980]. This shows that voltage polarity reversals not only have an impact as said above, but that it is relevant as well to consider the reversal phenomena in a lower minute range. In [/32/, Cigré, 2005] the test conditions are even more clearly described because of the voltage polarity reversal impact and to arrange fair testing for different conditions (cold, warm). In [/31/, Giorgi, 2002] and [/36/, Rendina, 2008] for HVDC MIND deep sea power cables, extra voltage polarity reversal tests have been carried out, showing the attention for this item in the case of quality issues.

Literature does not report on incidents with HVDC MIND power cables that failed due to voltage polarity reversals [/20/, Cigré, 1994]. Hjalmarsson [/18/, 1992] informed that the Gotland cable (taken out of service after 32 years of operation) never failed because of electrical ageing, only because of external impacts. Samples of the service aged cable were tested and compared with spare cable and no considerable ageing was found (however, it was operated at 'normal' electrical stresses for 16 years only). Another publication [/40/, Runde, 2014] reports that HVDC MIND power cables normally fail because of external damage and "*The reliability of the cable itself is in general found to be very good, indicating that the technology is robust and that the type testing has been sufficiently demanding*". Also [/41/, Mazzantim, 2015] reports that "*Mass Impregnated Non-Draining (MIND) cables are known to be able to withstand the voltage polarity reversal without particular problems*", but one has to realize that this is said in 2015 and thus in the light of developments of XLPE cable, known to be sensitive to voltage polarity reversals. But [/39/, Skog, 2010] mentioned that the [redacted] HVDC MIND power cable (the longest in the world) experienced three failures of which the cause was unknown and certainly not related to an external damage.

A 2015 overview of HVDC cables in the world is provided by [/42/, Ardelean, 2015]. A more specific overview of HVDC MIND power cables, installed until 1996 is given in [/23/, Khalil, 1997] and a further overview including operating parameters is given in [/40/, Runde, 2014]. But not much is known about the applied or allowed number of voltage polarity reversals per day or per year for such cable being in operation. Only [/18/, Hjalmarsson, 1992] informed for the Gotland cable that there has been two voltage polarity reversals per day during three years at 'normal' electrical stress (after the cable started operating at 150 kV, before that it was 100 kV). In general one can consider that two voltage polarity reversals per day, because of the fact that in the case of an interconnector often on one side there is hydro power and on the other side thermal power, where hydro power is used as the main power source and only during the night at low demand the thermal power is used to feed back. But deviations from this regime are common as well.

Runde [/40/, 2014] reports concerning this issue "*Changing the direction of the power flow by reversing polarity causes temporary dielectric stresses of a considerable higher magnitude …….. It is however, quite common to impose one or more operational restrictions or special procedures during power reversal that reduce the dielectric stress. For example, setting a maximum power ramping rate, temporarily reducing the voltage level somewhat, or specifying a few minutes dwell time at zero power, will help. Thus, the large values given in Table I for field under polarity reversal are not necessary experienced under real operation of the cable, nor are the values directly comparable. But the numbers clearly illustrate that transient conditions such as polarity reversals may imply dielectric stresses greatly exceeding those seen under start-up or steady state operation*".

Based on [/16/, Hauge, 1988], where parts of the 10 years old Skagerak HVDC MIND power cable have been subjected to laboratory tests, the expected future field strength of cables could become 35 kV/mm, but the author added that under more onerous conditions such as frequent load variations, voltage polarity reversals, (..etc..) , the design stress should be somewhat lower. However, a design stress of some 30 kV/mm (..etc..) would obviously be safe even under such circumstances. It shows another publication taking into account the voltage polarity reversals.

More technical information about electrical charges and conduction mechanisms (conduction is highly related background of the increased electric field strengths during voltage polarity reversals) in the insulation material of MIND power cables is given in amongst others [/21/, Jeroense, 1995], [/24/, Morshuis, 1997], [/25/, Jeroense, 1997], [/26/, Jeroense, 1998], [/33/, Morshuis, 2005], [/37/, Tang, 2009]. In [/38/, Lennon, 2009] there is also more information on degradation mechanisms of HVDC MIND power cables, although with a focus on a more fundamental approach and thermal issues. An interesting remark is that in HVDC MIND power cables "*At elevated ambient temperatures or electrical stress levels the leakage current increases throughout the insulation due to a rise in the conductivity. In turn, the leakage current heats the insulation further and the conductivity again rises due to its temperature dependency. This behavior continues until a balance is reached or until a thermal breakdown occurs in the insulation*". Also [/40/, Runde, 2014] says more about degradation, where a known one (happening in Type Testing) is the cooling down stage: "*….. the ones occurring during cooling typically have breakdown channels that follow interfaces between the paper layers and may become 1 - 2 m long in the axial direction. Such breakdowns, hereafter referred to as "load cycling breakdowns", are unique to MIND cables*". This was already said by [/19/, Gazzana, 1992], but this author added that also more radial breakdown paths can happen under isothermal conditions. Moreover, [/29/, Evenset, 2000], confirming that HVDC MIND power cable is sensitive for the cooling down stage because of cavity formation, showed that a radial breakdown path is common in case the paper pressure is high (thus, with compacted insulation), else the breakdown path is much longer, around 1 m.

In [/17/, Embaie, 1988], [/22/, Nyman, 1996] and [/30/, Bosisio, 2002] voltage polarity reversals are not discussed since here the focus is on degradation and failures related to cavity formation during cooling down of the cable. As a result, for operating during a cooling down regime, the voltage is studied (for the Fenno-Skan cable in [/17/, Embaie, 1988]) or already performed (for the Baltic cable in [/22/, Nyman, 1996]) to be made lower. But the Baltic cable so far was not operated beyond 50 % of its capacity. In [/19/, Gazzana, 1992] the cooling down sensitivity of a HVDC MIND power cable is mentioned as well and studied in detail. But in the last line of the conclusion the following is said: "*A contribution to this mechanism is also due to the presence of very high free electrostatic charges trapped at the surface of a suddenly arising void which can produce high energy discharge capability*".

APPENDIX Q
On witnessing a Type Test

APPENDIX R
Length effect

Occhini, 1971 /84/ wrote: "*The dielectric strength of any electrical insulation system decreases with the stressed area or, in the case of a cable, with its length*". Note that this 'length effect' is not related to ageing. The 'length effect' is there before ageing but it is there as well after ageing.

It means, that in a long power cable (such as the Basslink cable with a length of 300 km) there are almost for sure parts which have less quality than the 50 m of cable that passed the Type Test.

Variation of the quality of different cable samples from a full sized HVDC MIND power cable is illustrated by Hjalmarsson, 1992 /18/. He did breakdown tests on samples from spare and aged HVDC MIND power cable from the 32 year old 'Gotland 1' cable. See in this reference Table 2. One can see that the DC breakdown voltages for the three cable samples with an effective length of about 5 m range from 500 kV to 700 kV. Another cable sample with a length of about 15 m gave a breakdown voltage of 775 kV, which means that per definition a 5 m length chosen from this 15 m length would have had at least the same breakdown voltage. Thus, for the four samples of about 5 m, the breakdown DC voltages range between 500 kV to at least 775 kV.

It means that the chance that the 50 m Type Tested cable part is worse in quality than the worst one out of the other 50 m cable parts out of the 300 km full cable length is very small, about 0.02 %. One can see it also this way. The chance that under these length conditions the Type Tested cable part is of average quality at least is high. And that makes that a Type Tested cable, where the minimum test temperatures were slightly above the minimum requirements (in this case [redacted], cannot be used to declare such temperatures as realistic operational temperatures for the whole 300 km cable length.

In that respect, CCI's statement [TAB 76, § 78]: "*…. the insulation is expected to be homogeneous along its complete length.*" is fundamentally incorrect.

APPENDIX S
Voltage polarity reversal - Number per day and year at Basslink

Introduction

On deriving the number of voltage polarity reversals per day or year, it is important to define what a voltage polarity reversal is.

A voltage polarity reversal is the change in the direction of the power flow, that comes with a change in the polarity of the cable voltage. A voltage polarity reversal practically comes in two steps, as shown in Figure 7 on page 42. The first step is one where the voltage is instantaneously dropped from the full voltage to no voltage. After that there is a certain dwell time. The second step is one where the voltage is instantaneously raised from no voltage the full but opposite voltage.

For counting the number of voltage polarities per day or year, it is needed to know the duration of the dwell time beyond which one does not consider a full two step voltage polarity to have taken place. I considered this and concluded that the dwell time duration is not clearly defined in this respect, but in literature a dwell time of up two hours is still considered as being part of one voltage polarity reversal. For instance, Skog [/35/, 2006] mentioned one hour and Giorgi [/31/, 2002] mentioned two hours.

[redacted]

Based on this interpretation, I verified the daily and yearly number of voltage polarity reversals that have been performed for the Basslink cable over the period of service operation.

Voltage polarity reversal number per day

[redacted]

[28] [TAB 43] does not mention the minimum dwell time. The minimum dwell time I assumed here is 2 minutes, in line with Basslink's operation strategy [TAB 58.3], see also Appendix F.



Figure 29

[redacted]

[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]
	[redacted]

Voltage polarity reversal number per year

I finally looked to the yearly number of voltage polarity changes that have been performed for the Basslink cable over the years. [redacted]

[redacted]

[redacted]



Figure 30



Figure 31

APPENDIX T
Voltage polarity reversal - Dwell time

Introduction

Information on the electrical stresses during a polarity reversal would be helpful in order to estimate the impact of the dwell time. For that,

- an electrical model is needed but also
- the actual electrical insulation material properties for the Basslink cable as input for that model are needed.

Since the actual electrical insulation material properties for the Basslink cable are unknown, the outcome of calculations with an electrical model will come with related uncertainties. The correct electrical insulation material properties cannot be derived from literature, since the values mentioned here are conflicting. Table 6 shows the parameter values as mentioned in publications from Occhini [/4/, 1967], Bahder, [/5/, 1969], Nyberg, [/79/, 1975], Cigré, [/32/, 2005] and Jeroense [/26/, 1998].

To go one step further it is relevant to know that for the calculation of the electrical stresses, and with this the impact on the dwell time, the steady state conductivity σ is important. This conductivity is much depending on σ_o, being the insulation material conductivity at 0 °C and zero electrical stress. And the σ_o values differ with a factor 3. As a result, should one for instance calculate a marginal positive impact between the dwell times of 2 and 5 minutes using Nyberg's parameter values, this might be completely different to using Jeroense's parameter values. Using Nyberg's values is not recommended by Nyberg himself. He wrote a warning in the conclusions of his paper: "*Careful considerations must be taken when determining the relaxation times. ….*". Note that the relaxation time is the same as the deionisation time, relevant for the choice of the dwell time.

Additional uncertainty is created by Bykov, who mentioned in discussing Occhini's paper (Bykov's contribution can be found in the end of Occhini's paper) that the self-discharging time (related to the deionization times and thus the effectiveness of dwell times) depends considerably on the charging times. He wrote: "*It was found that the time of self-discharging considerably depends on the time of charging, Fig 24. Voltage reduction due to self-discharge by 10 percent takes place as follows:*

at the charge during 1 min – 2 min
at the charge during 1 hour – 15 min
at the charge during 17 h – 1 h 10 min
at the charge during 90 h – 2 h".

Since reliable input for calculating the impact of having a dwell time of 2 or 5 minutes for the Basslink cable is not available, I consider it safer to use the longest dwell time of 5 minutes (which per definition comes with lower electrical stresses than with a dwell time of 2 minutes).

Table 6 Parameter values influencing the dwell time, according to different authors

	steady state parameter values		
	α [°C^{-1}]	y [mm/kV]	σ_o (Ωm)$^{-1}\cdot10^{-16}$
Nyberg [1)]	0.113	0.03	0.3
Occhini [2)]	0.105	0.034	0.57
Bahder [3)]	0.1	0.03	0.07
Cigré [4)]	0.1	0.033	0.57
Jeroense [5)]	≈ 0.1	≈ 0.03	1
Gazzana [6)], new insulation material	0.082	0.03 (from [1)] to [5)])	0.065
Gazzana [6)], cycled insulation material	0.082	0.03 (from [1)] to [5)])	1.22
The steady state conductivity $\sigma = \sigma_o \cdot e^{(\alpha \cdot \Theta + y \cdot E)}$ with • σ_o being the insulation material conductivity at 0 °C and zero electrical stress • Θ the temperature in °C • E the electrical stress in kV/mm			
[1)] the values in Nyberg's paper [/79/, 1975] are based on flat capacitor models but it is not clear whether Nyberg measured these values or that he is referring to another source without mentioning this.			
[2)] the values in Occhini's paper [/4/, 1967] are obtained with flat capacitor models and verified with an experimental cable. In their experimental cable, the warm cable showed a 34% reduction of the electrical stress in the first hour, resulting in about 0.8 kV/mm in 3 minutes (in a linear approach, so this will be probably more in an exponential approach)			
[3)] values in Bahder's paper from [/5/, 1969] are based on flat capacitor models with three layers of impregnated paper between electrodes.			
[4)] the values in Cigré paper from [/32/, 2005] mention that the values of the parameters are to be adopted for non-pressurized mass impregnated cables i.e. for the temperature dependency α and for the electric field dependency y may be defined by the manufacturer, or in absence of this information are defined by the Cigré values mentioned in the table.			
[5)] the values in Jeroense's paper from [/26/, 1998] are derived from literature, but the source is not mentioned. The dielectric constant value $\varepsilon_r = 3.5$.			
[6)] the values in Gazzana paper from [/77/, 1993] are derived from the information given in his § 6.6, where for new insulation the average values at 50 kV/mm of $\sigma = 1.5\cdot10^{-16}$ (Ωm)$^{-1}$ at 20 °C and $\sigma = 40\cdot10^{-16}$ (Ωm)$^{-1}$ at 60 °C are taken, resulting in $\alpha = 0.02$ °C^{-1}. The y could not be derived from the information given, but a value of 0.03 mm/kV is a realistic value to assume, considering the spread in results of other researchers. That results in a σ_o of $0.065\cdot10^{-16}$ (Ωm)$^{-1}$ for new insulation material. For cycled insulation the average value of σ at 50 kV/mm is $0.75\cdot10^{-13}$ (Ωm)$^{-1}$ at 60 °C, thus, 18.75 times higher than for new insulation material. That would result in σ_o of $1.22\cdot10^{-16}$ (Ωm)$^{-1}$ for cycled insulation material (assuming the same α and y as being applicable to new insulation material).			

About CCI's calculations on the impact of the dwell time and my response to that

[redacted]

I have considered the following:

- The values from Occhini [/4/, 1967], Bahder [/5/, 1969], Nyberg [/79/, 1975], Cigré, [/32/, 2005], Jeroense [/26/, 1998] and Gazzana [/77/, 1993] differ especially with respect to their conductivity σ_0, see Table 6. Gazzana also shows that it is relevant to take into account that 'old' (cycled) insulation material can have a much higher conductivity σ_0 than 'new' insulation material, see Table 6

- Simply using Nyberg's values is not recommended by Nyberg himself. He wrote a warning in the conclusions of his paper: "*Careful considerations must be taken when determining the relaxation times. ….*". Note that the relaxation time is the same as the deionisation time, relevant for the choice of the dwell time

- Another source of information about the deionization time is found in Jeroense's publications on HVDC MIND cable /25/, /26/, respectively from 1997 and 1998.

    - Jeroense [/26/, 1998, figure 8] shows the deionization time that comes with a reduction of about 63 % of the electrical stress for a model cable. The calculated deionization time is given as a function of the conductor temperature, assuming a temperature difference

over the insulation of 15 °C, [redacted]

- [redacted]
    - Taking Jeroense's information the following can be derived. In percentage of the full electrical stress with no dwell of 42.2 kV/mm at 55 °C or 40.7 kV/mm at 40 °C would mean that an increase of the dwell time from 2 to 5 minutes has a significant and positive impact on a reduction of the electrical stress (rounded to a reduction of respectively 9 % and 4 %) and thus on the reduction on creating a further failure in a thermally overstressed insulation material.

- Of course, it is not certain whether Jeroense's information reflects the Basslink cable insulation situation. But neither this can be said from Nyberg's parameter values used by CCI

- It is not fully clear whether it is just the material properties that makes the difference shown between Jeroense and CCI's (Nyberg) calculations, or that also the modelling itself has caused this partly

- Also Bykov's information mentioned in the introduction of this Appendix shows that the self-discharging time (related to the deionization times and thus the effectiveness of dwell times) depends considerably on the charging times. That is another factor that has to be taken into account.

My opinion

[redacted]

It is my opinion that in order to make detailed electrical analysis, not only a model is needed but also reliable input data reflecting the Basslink cable insulation. This reliable input data is not available.

That was the reason to write in my report [/80/, 2017, Appendix Q]: "*I made an artificial drawing, see Figure 27, of what happens with the electric stress close to the conductor in case of a polarity reversal.*

Values are based on information given by [/4/, Occhini, 1967]. In Figure 27, the voltage steps Egeo and Est are on scale. Also the time 0, 2 and 5 minutes are on scale. But the time constants for deionisation are chosen to illustrate the impact. What these are in real is much depending on the actual insulation properties (among which the conductivity (as a function of the temperature)".

[redacted]

I agree that the first moments of a dwell time are the most effective ones. Importantly however is whether an increase of the dwell time from 2 to 5 minutes is effective or not. And that is discussed in the previous paragraph.

If needed, the impact of the dwell time can be quantified reliably under the following conditions:

- [redacted]
- [redacted].

Both are not very easy to arrange.

APPENDIX U
European cable operators interviewed about their HVDC MIND experience

In order to learn how various European cable operators operate their HVDC MIND power cable, such to avoid failures, I contacted in 2017 [redacted] did not reply to my request to discuss their cable operation, but reference [/22/, Nyman, 1996] offers some interesting operational information. The other cable operators listed above cover the following cables, where the cable connection name is followed by the commission year and operating voltage level:

- [redacted]

Including the [redacted]) the total cable length involved is 2823 km, with voltage classes of [redacted] and power transmission design rating from [redacted]

The following can be learned from these thirteen HVDC MIND power cables:

- The four cable systems commissioned until 1988 have a maximum voltage of 250 kV - 285 kV. The nine cables commissioned since 1989 are operated at voltage levels at 350 kV – 500 kV. This is illustrated in Figure 32
- For eight cables, the maximum operating temperature is (much) below [redacted] For the remaining five cables this item was not discussed
- For ten cables, the ramping is normally done such that the full change of power direction is happening within one hour (apart from one case, where it is three hours). This ramping is done to prevent that the cable would cool down too much (such to avoid shrinking voids). For three cables the ramping does not come with a certain restricting regime
- For all cables, the dwell time is in the range of zero minutes to two minutes
- For twelve cables, the number of voltage polarity reversals is market driven, but in many cases it is limited to a few per day or less. In one out of thirteen cables, this item was not discussed
- For eleven cables, there were no cable failures attributed to just the operational conditions

- For one cable, after nine years of failure free service operation, the maximum allowed power and related load during winter was increased by 14 % (the cable operator informed me that this new maximum was not applied and that the practical upper limit was 10 %), meanwhile keeping the maximum cable temperature below [redacted] But after two failures, it was decided in 2014 to return to the original load. Moreover, the system voltage was permanently reduced by 20 % to avoid further failures, reducing the maximum allowed power by 20 % compared to the original design situation.

Since I have not been able to discuss the [redacted], I retrieved information from a paper [/22/, Nyman, 1996] describing the Baltic cable after two years of operation. It was said here that in order to reduce the risk on failure during cooling down (one can read here: risk on enlarged void formation), the voltage during the change of the power direction is reduced by 20 %. The system applied to realize this is called Cable Dependent Voltage Control (CDVC) and it is still mentioned on [redacted], suggesting that it is still being used (situation December 2017).



Figure 32 **Operating voltage level as a function of the commissioning date for HVDC MIND power cables.** [redacted]

APPENDIX V
Thermal degradation processes

In order to understand the potential degradation in a thermally overstressed cable, the following is important.

In the cable insulation of paper layers and a compound there are voids and electrical stresses. Normal voids combined with normal electrical stresses are expected not to introduce unforeseen degradation because these are in line with the design.

But deviations from normal can start an unwanted degradation (and eventually result in a failure), in particular:

- If caused by abnormal voids exposed to normal electrical stresses or
- If caused by normal voids exposed to abnormal electrical stresses or
- A combination of both.

  Here 'normal' means, as per design and 'abnormal' means larger (for the voids) or higher (for the electrical stresses) than per design.

The fact that the cable broke down in its cooling down stage (a typical stage where voids (whether enlarged or not) have their maximum size) supports the reasoning that next to the electrical stress, voids were an actor in this degradation process.

The void sizes and the electrical stress levels are influenced by the conductor temperature and the temperature difference over the cable insulation.

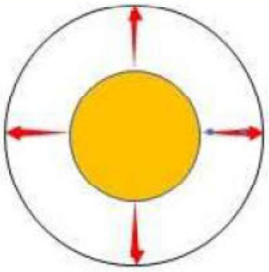
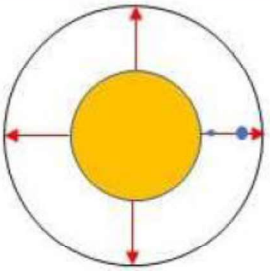
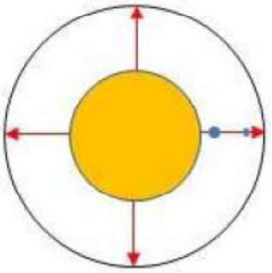
The precise degradation process in a thermally overstressed cable is a complicated matter. As a guide, Table 7 and Table 8 summarize at a high level the thermally stimulated possible degradation processes as known from literature. Which of these processes take place will depend on the actual thermal overstress situation and material properties. For very high temperatures of the lead sheath (around 70 °C) Jeroense [/26/, 1998] mentioned another possible thermal degradation mechanism, being thermal instability. [redacted] (see De Wild's calculations presented in Table 1 on page 72, the calculated lead sheath temperature at the thermal bottleneck locations had a maximum of [redacted] this thermal degradation mechanism is not further taken into account.

For the Basslink cable, at certain moments during the cable life, these temperatures were both or separately beyond their design limits. Because over time the Basslink cable has been thermally overstressed in different ways it is not possible to conclude which of the thermally stimulated degradation processes mentioned in Table 7 and Table 8 were the main contributors.

Table 7 The thermal scenarios and resulting physical processes

Thermal scenarios	$T_{conductor} \leq$ [redacted]	$T_{conductor} >$ [redacted]
$T_{difference\ over\ the\ cable\ insulation} \leq$ [redacted]	Scenario 0	Scenario 1 • Thermal expansion of the cable insulation
$T_{difference\ over\ the\ cable\ insulation} >$ [redacted]	Scenario 2 • The electrical stress in the outer insulation layers reach values beyond the design limits	Scenario 3 • Thermal expansion of the cable insulation • Migration of the compound away from inner insulation layers • The electrical stress in the outer insulation layers reach values beyond the design limits

Table 8 The physical processes and resulting degradation.

Physical process	Degradation process	Illustration (see note 3)
The electrical stress in the outer insulation layers reach values beyond the design limits Being part of thermal scenario 2 and 3 in Table 7	As a result, the electrical stress, being beyond the design limits in the **outer** cable insulation layers, can create partial discharges in and around one or more normal voids, causing degradation at this spot and a failure. According to many different authors, see Section 3.4.2.	
Thermal expansion of the cable insulation Being part of thermal scenario 1 and 3 in Table 7	1. This can create permanent deformation of outer reinforcing layers, which reduces the compression forces needed to keep voids small. 2. If this happens, one or more enlarged voids of permanent nature can be created, especially in the outer cable insulation layers (see also note 1). 3. As a result, the electrical stress (within its design limits) in the **outer** cable insulation layers can create partial discharges in and around the enlarged void(s), causing degradation at this spot and a failure. According to [Huang, /87/, 2015]. See Section 3.3.8.3 ("Enlarged void formation physics according to **Huang**").	
Migration of the compound away from inner insulation layers Being part of thermal scenario 3 in Table 7	1. The lack of compound can create one or more enlarged voids of permanent nature in the inner insulation layers (see also note 2). 2. As a result, the electrical stress (within its design limits) in the **inner** cable insulation layers can create partial discharges in and around the enlarged void(s), causing degradation at this spot and a failure. According to [Runde, /40/, 2014] and [Evenset, /29/, 2000], See Section 3.3.8.1 ("Enlarged void formation according to Evenset") and Section 3.3.8.2 ("Enlarged void formation mentioned by Runde"). See also note 2.	

Notes:

1. An enlarged void of permanent nature can be (partly or fully) filled with compound or compressed when the cable is warm and reappear (in full size) once the cable is cooling down. In fact, it means that each time a cable cools down the enlarged void will reappear.
2. For migrating the compound, two processes are relevant. These are the viscosity of the compound and the 'pushing' force acting on it to move the compound away from its origin. Two examples are mentioned here, but everything in between is possible as well:
   - If the maximum conductor temperature is close to the maximum design temperature (and the viscosity of the compound is still high) but the temperature difference over the insulation considerably exceeds the design value (resulting in a high pushing force), the compound can migrate.
   - Likewise, if the maximum conductor temperature considerably exceeds to the maximum design temperature (and the viscosity of the compound is low) but the temperature difference over the insulation is close to the design value (resulting in a mild pushing force), the compound can migrate.
3. The red arrows represent the electrical stress (field) in the cable insulation. The blue dots represent the voids (in some cases enlarged) in the cable insulation. The yellow part is the cable conductor. The illustration is not on scale.

APPENDIX W
Thermal plots De Wild [2020] - at the failure location

T_c = conductor temperature (dark green curve); ΔT = temperature difference over the insulation (light green curve); page numbers refer to [TAB 65.0.4]; '>' = larger then; '<'= smaller then; '≥' = at least.





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EXPERT REPORT FRANK DE WILD

Second supplementary report regarding the Basslink interconnector

Clayton Utz

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0	2020-08-17	First Issue	F.H. de Wild	T. du Plessis	K.-J. van Oeveren

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1 INTRODUCTION

The Basslink interconnector is a 300 km long HVDC submarine- and land-based cable system that is designed to transmit up to 630 MW of electrical energy between Tasmania and Victoria in Australia. The interconnector plays a crucial role in the transmission grid. The Basslink interconnector between the substations Loy Yang in Victoria and George Town in Tasmania failed during service on 20 December 2015 after roughly 10 years of service life.

In 2016, DNV GL was engaged by Clayton Utz to evaluate the possible technical failure cause of the Basslink interconnector outage. Clayton Utz is a law firm acting on behalf of Hydro Tasmania in relation to matters arising from the outage of the Basslink interconnector. At a later moment, I was also engaged by Ashurst Australia, the solicitors of the State of Tasmania.

During the analysis towards the technical failure cause of the Basslink interconnector outage under performance by Mr. E.F. Steennis of DNV GL, the possibility of high thermal loading and related thermal degradation was raised. This led to various requests and reports, as follows:

- An investigation into the thermal situation of the Basslink interconnector leading to my first expert report in 2017 [1]
- A further thermal analysis of the Basslink interconnector along the submarine section of the interconnector on the basis of an extended set of information. This led to a second expert report in 2020 [2]
- [redacted]

With a recent letter [5] copied in Appendix C, Clayton Utz instructed me to react to the [redacted]

Throughout this report, reference will be made to information provided to me. This will be done by referring to either a certain 'tab number' with a number between forward slashes (/tab x/). The number references information provided in [6] (Appendix H). This reference list is repeated in Appendix B of this report for ease of use. Other information sources are also referred to (e.g. reports), which are referenced with a number in between brackets ([x]). These references are provided at the end of this document.

1.1 Statements

The letter of instructions [5] requested me to comply to IBA rules. I can confirm that this report complies to these rules and can make the following statements:

The expert witness who conducted the analysis and authored this report is:

Name:	Mr. Franciscus Hendrikus De Wild (M.Sc.)
Function:	Principal consultant underground and submarine power cables
Employer:	DNV GL Netherlands B.V.
Address:	Utrechtseweg 310-B50
Postal code:	6812 AR
City:	Arnhem
Country:	The Netherlands
Email:	frank.dewild@dnvgl.com
Telephone:	+31 6 150 63 565

My CV can be found in Appendix A.

Statement on the contents of this report

This report is fully authored by me. I am employed by DNV GL Netherlands B.V., whose internal quality control procedures are followed within the reporting. This explains the functions of reviewer and approver of this report[1].

My opinions and conclusions can be found in this report, including a description of the methods and the information I used.

I have based myself on the documentation I have received previously, which is referenced throughout this report.

I declare that all inquiries which are desirable for the conduction of the work reported in this document have been made. Remaining issues which I regard as relevant are discussed in this report.

Statement on the instructions received

The instructions received by me that led to this report can be found in [5] which is repeated in Appendix C.

Statement on independency

Save for my work on the December 2015 Basslink cable failure which previously led to earlier reports and various letters, I have no prior relationship with Hydro Tasmania, the State of Tasmania, Basslink Pty Ltd or their legal advisors or Mr. Robert French AC.

I declare that I am independent from all parties named above.

Statement on my belief in this report

I affirm my genuine belief in the opinions expressed in this report.

Acknowledgements

I have read Article 5 (Party-Appointed Experts) from the document titled "IBA Rules on the Taking of Evidence in International Arbitration". In preparing this report and answering the questions put to me, I acknowledge that I have acted in accordance with the requirements of Article 5.

Agreement

I, Franciscus Hendrikus de Wild, confirm the above statements and acknowledgements.



17 August 2020, Arnhem, The Netherlands

[1] Mr. Thinus du Plessis is a senior consultant and direct colleague of Mr. De Wild yet was not involved in the Basslink analysis. He was asked to review the report for agreement to DNV GL's internal guidelines for reports. Mr. Kees-Jan van Oeveren is Mr. De Wild's direct line manager, and in that capability approves external reports.

2 THE THERMAL RESISTIVIITY MEASUREMENT OF SINTEF

[redacted] I have now analysed that information and have formed my opinion on the matter. [redacted]

I will answer the questions posed in the letter of instructions [5] (repeated in Appendix C) throughout this chapter, in a different order than as they appear in the letter of instructions.

2.1 Testing methodology

[redacted]

Question 1: [redacted]

Answer:

[redacted]

[redacted]

This ends my answer on question 1.

2.2 Error propagation

[redacted]

Question 3 (b): [redacted]

Answer:

[redacted]

[redacted]

2.3 Sources of error

[redacted]

- [redacted]
- [redacted]

[redacted]

- [redacted]

[redacted]

- [redacted]

[redacted]

- [redacted]

[redacted]

The above enables me to answer question 4 of [5].

Question 4: [redacted]

Answer:

[redacted]

This ends my answer on question 4.

2.4 Thermocouple accuracy

[redacted]

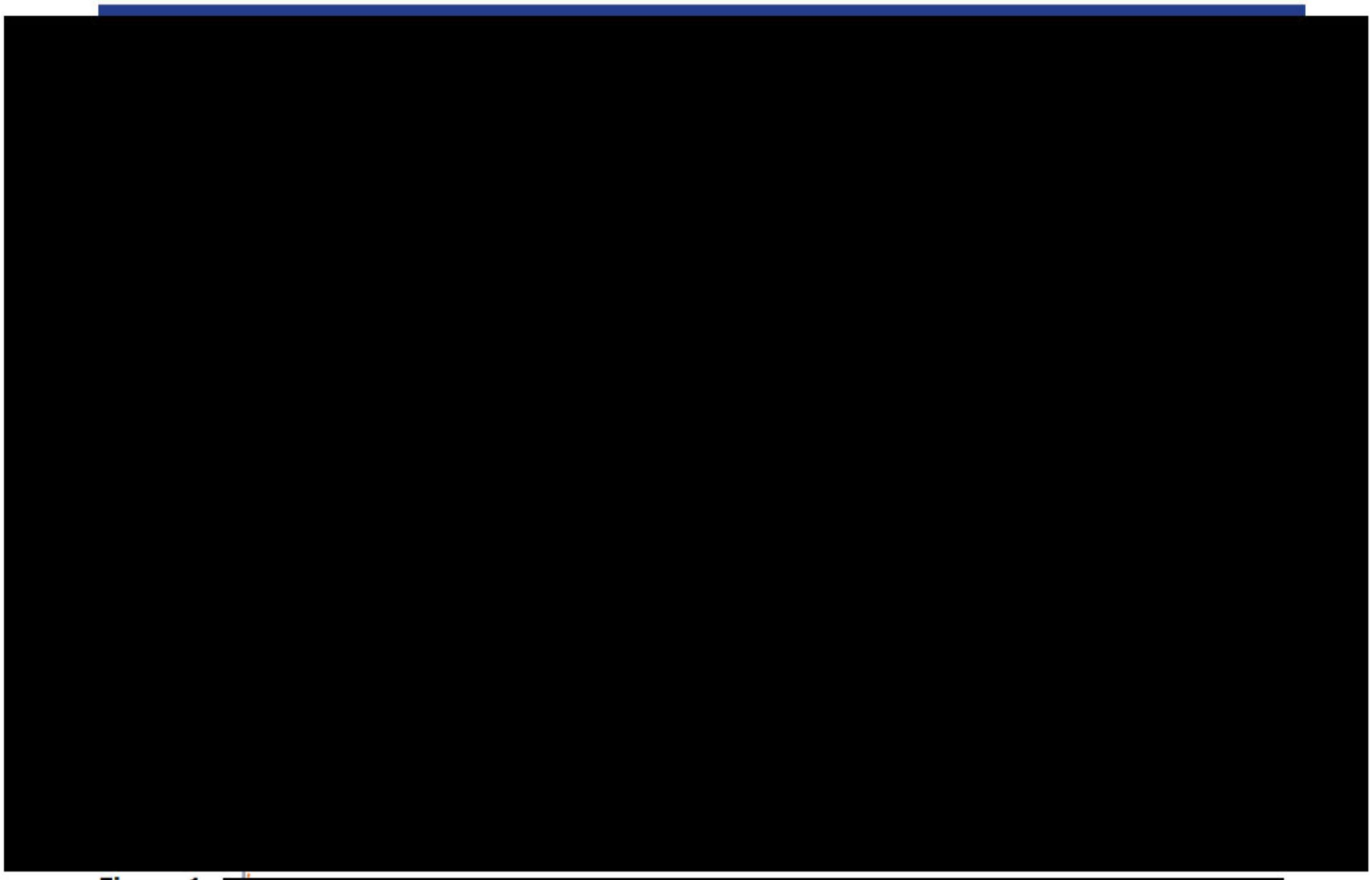


Figure 1

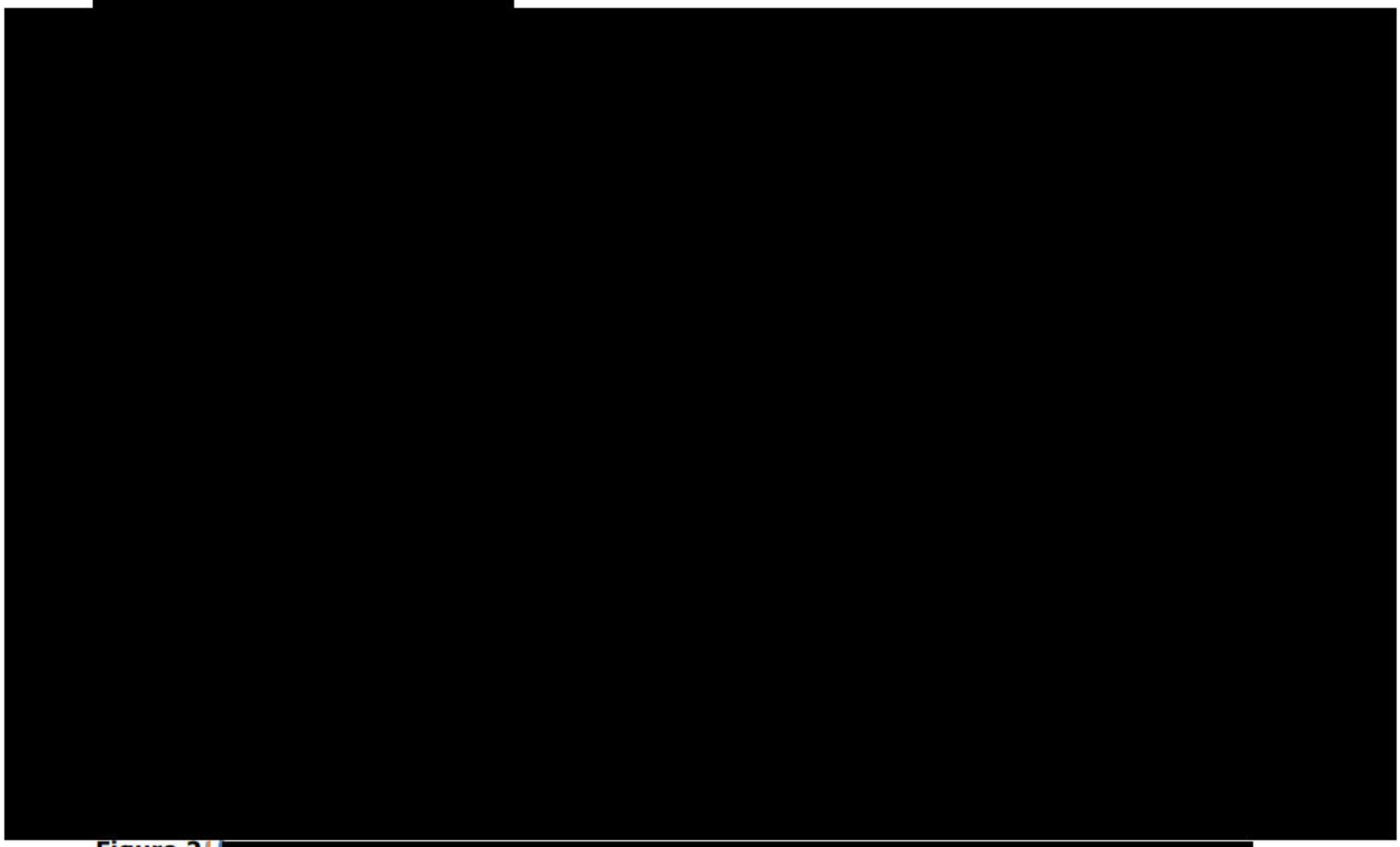


Figure 2



Figure 3

Table 1 My deductions from the heat run measurement information

[redacted]

2.5 Accuracy of the measured voltage drop along the conductor

[redacted]



Figure 4

2.6 Accuracy of the measured current flowing through the conductor

[redacted]

2.7 Accuracy of the cable sample dimensions

[redacted]

[redacted]

2.8 The thermal resistivity values

[redacted]

Table 2 [redacted]

Table 3 [redacted]

[redacted]

[redacted]

This finding also allows me to answer questions 2 and 3a of [5].

Question 2: [redacted]

Answer:

[redacted]

I note that these values must still be interpreted, refer to section 2.9.

Question 3(a): [redacted]

Answer:

[redacted]

2.9 My interpretation of the measurement result

[redacted]



Figure 5



Figure 6



Figure 7



Figure 8

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

Conclusion

[redacted]

- [redacted]
- [redacted]
- [redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

This enables me to answer question 5 in [5].

Question 5: [redacted]

[redacted]

Answer:

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

3 REFERENCES

[1] F. H. de Wild, "Thermal analysis of the Basslink interconnector near the 2015 cable failure location," reference 17-1957, 14-12-2017.

[2] F. H. de Wild, "Thermal analysis of the Basslink interconnector, reference 19-3114 Rev. 1," 2020-1-31.

[3] F. H. de Wild, "Supplementary report regarding the Basslink interconnector", reference 20-2527," 2020-06-10.

[4] F. H. de Wild, "Reply report regarding the Basslink interconnector, reference 20-2651," DNV GL, 2020-07-17.

[5] S. O'Reilly and A. Close, *Letter of instruction from Steve O'Reilly (Clayton Utz) to Frank de Wild (DNV GL),* 11-8-2020.

[6] S. O'Reilly, *Letter of instruction from Steve O'Reilly (Clayton Utz) to Frank de Wild (DNV GL).,* 20-11-2019.

[7] S. O'Reilly and A. Close, *Letter 'Basslink Interconnector outage' with reference L\336179906.1,* 14 July 2020.

[8] [redacted]

[9] [redacted]

[10] [redacted]

[11] [redacted]

[12] [redacted]

[13] [redacted]

[14] [redacted]

[15] [redacted]

APPENDIX A
CV of Mr. F.H. de Wild
CURRICULUM VITAE

(CV generation date: 2019-11-04)

Frank de Wild

Principal Consultant on Underground and Submarine Power Cables



Personal statistics

Nationality: Dutch

Date of Birth: Dec 09, 1970

Current position

Principal Consultant

Languages

Language	Speaking	Reading	Writing
Dutch	High	High	High
English	High	High	High

Education

Field of expertise	University/School	Year
Msc in Applied Physics	University of Twente	Aug 1990 - Aug 1997
Nuclear radiation hygiene and dosimetry, expertise level 3	IRI (Interfacultair Reactor Institute)	Jan 1995 - Dec 1995

Summary of professional experience

Mr. De Wild is DNV GL's principal consultant on underground and submarine power cable feasibility, design, manufacturing and realisation projects worldwide.

Mr. De Wild is an international recognised expert on underground and submarine power cable systems having over 20 years of experience. He has been involved in projects dealing with all life phases of power cable systems, ranging from conceptual designs to remaining life management and reinvestment decision making. He has worked with many companies worldwide to deal with power cables ranging to the highest voltages. HVDC cable technology, interconnectors, cables to wind farms, dynamic rating systems and failure investigations are key areas of competence of Mr. De Wild.

Mr. De Wild is an experienced project manager of large projects. He has shown strong capabilities in coping with the organisational, technical and human challenges posed. He has the ability to cope with different cultures and to work with multinational project teams and international clients. He both has experience working as a consultant and working as an independent third party expert.

Mr. De Wild has been involved as technical lead in DNV GL's largest third party certification project on submarine cables. Another example is a project in which new qualification requirements are delivered for a country stepping to a backbone of 500/525 kV HVDC cables for power transmission, which are higher than currently standardized.

Recent projects also include feasibility and design & engineering studies. A recent study on this terrain includes the full design and engineering of several 400 kV AC cable systems in the backbone of a country, and the development of technical specifications and related bid evaluation information.

On the special topic of current rating / ampacity, Mr. De Wild is an internationally recognized expert, which may be can best be illustrated by his role as convenor of all current related work groups in CIGRE which has already led to various international guidelines on the topic, but which can also be illustrated by the development of DNV GL's dynamic rating systems.

Papers and publications

- F.H. de Wild, G.J. Anders, E.C. Bascom III, S. Cray, J. Joo, W. Kamara, T. Kvarts, F. Lesur, A. Lofti, W. Moutassem, K. Pinkert, J. Pilgrim, V. Rizou, J. v. Rossum, O. Thyrvin, Overview of CIGRE WG B1.56 regarding the verification of cable current ratings, Jicable, Jun 2019
- F.H. de Wild, C.A. Plet, T. Du Plessis, Fibre Optical related failure modes of submarine power cables, Jicable, Jun 2019
- F.H. de Wild, R. de Graaff, S. Meijer (DNV GL), S. Hemphill, M. McGuckin (Mutual Energy), Impact of HVDC cable configuration on compass deviation, Jicable, Jun 2015
- De Wild (DNV GL) et al, A guide for rating calculations of insulated power cables, Jicable, Jun 2015
- S. Meijer, F.H. de Wild (DNV GL), A. Al Aghbari, M. Al Neami, M. Ashaar, M, Jaber (DEWA), Enhanced medium voltage cable ratings by improving cable trench design and thermal conditions, Jicable, Jun 2015
- S. Meijer, F.H. de Wild, G.R. Kuik,J. ter Haar, R. Ross, V. Waschk, Impact of QA/QC on the successful commissioning of long 380 kV XLPE cable systems, Cigre, Sep 2014
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- J. Jeyapalan; R. Awad; K. Barber; C. Peacock; R. Benato; I. Butt; F.H. de Wild; G. Takeshi; S. Susumi; T. Yoshihisa; K. Jeong-tae; J. Monteys; C. Moreau; K. Oberger; R. Woschitz; K.T. Yoom, Cable systems in multi-purpose or shared structures, Jicable, Jun 2011
- H. Faremo; F.H. de Wild; E. Dorison, Ageing UG systems: The Smartlife initiative, Jicable, Jun 2011
- W. Boone; F.H. de Wild; G. Sebrechts; N. Steentjes; J. v. Rossum; Q. Zhuang, Investigations towards the upgrading of existing 10 kV cables and accessories to an operating voltage of 20 kV, CIRED, Jan 2011
- J.G. Slootweg; A. Postma (Essent Netwerk BV), F.H. de Wild (KEMA), A practical approach towards optimising the utilization of MV cables in routine network planning (paper 64), Cired, Jan 2007
- F.H. de Wild; W. Boone (KEMA), HV power cables operating in a dynamic regime, a beneficial option! (paper 224), Cigre Osaka conference, Osaka, Japan, Jan 2007
- F.H. de Wild; W. Boone (KEMA), H. v.d. Geest; J. Smit (Nuon), Dynamic rating systems in general and in a hybrid 150 kV transmission system (paper 64), Jicable, Versailles, France, Jan 2007
- W. Boone; F.H. de Wild (KEMA), HV power cables installed in multi-purpose tunnels, a challengeable option! (paper 66), Jicable, Versailles, France, Jan 2007
- J.C. Smit; R. Trekop (Continuon), F.H. de Wild (KEMA), A dynamic rating system for an existing 150 kV power connection consisting of an overhead line and an underground power cable (paper B1-305), Cigre conference article, Paris, France, Jan 2006
- C.G.A. Koreman; G.L.P. Aanhaanen (TenneT), J.C.M. van Rossum; R.F.F. Koning (Prysmian), W.Boone; F.H. de Wild (KEMA), Development of a new 380 kV double circuit XLPE insulated cable system in The Netherlands (paper B1-107), Cigre conference article, Paris, France, Jan 2006

- F.H. de Wild; G.J. Meijer (KEMA), G.Geerts (ELIA), Extracting more value with intelligent cable systems, T&D World magazine, Aug 2004
- F.H. de Wild; G.J. Meijer; R.Ross (KEMA), Effect of power cable installation on current rating, magnetic fields and reliability, Jicable Conference article, Versailles, France, Jan 2003
- H.L.M. Boot (TZH), F.H. de Wild; A.H. van der Wey (KEMA), G. Biedenbach (RIBE Elektroarmaturen), Overhead line local and distributed conductor temperature measurement techniques, models and experience at TZH, CIGRE conference article, Paris, France, Jan 2002
- J.E. Jaspers; A.H. van der Wey; F.H. de Wild (KEMA), B.J. Grotenhuis (REMU), Increasing the capacity of cable systems using cable asset management based on thermal and mechanical properties, CIRED conference article, Amsterdam, The Netherlands, Jan 2001
- F.H. de Wild; P. Schmetz, The application of optical sensors for temperature, mechanical stress and moisture in energy cables in The Netherlands, Optical Fibre Conference article, Venice, Italy, Jan 2000
- E.F. Steennis; S.M. Berlijn; F.H. de Wild (KEMA), F. van den Boogaard (NKF), C.G.N. de Jong; M.J.M. van Riet (NUON), G.P.T. van der Wijk (TZH), Learning from high-voltage XLPE cable system testing and monitoring, CIGRE conference article, Paris, France, Jan 2000

Training

Year	Description
Feb 2017	Energy Academy Train the Trainer
Apr 2015	TopTech education program – University of Berkeley, California (on business innovation, technical innovation)
Feb 2015	Project Management the Energy way
Feb 2015	Essential Project Management
Jul 2014	Safety course VCA on NEN-EN 50110, NEN 3140/3840
Feb 2011	Leadership training - Leading Change and Managing People
Dec 2010	Various trainings as PATO contentwise trainings on asset management, high voltage engineering, heat transfer and optical communication networks, managerial trainings and commercial trainings

Employment

DNV GL	**Apr 2011 - Present**
Position:	Principal Consultant
Description:	Principal Consultant on Underground and Submarine Power Cables. Independent international subject matter expert on underground and submarine power cables.

KEMA	**Mar 2008 - Apr 2011**
Position:	Senior Consultant
Description:	Senior Consultant on Transmission and Distribution Systems. A focus on underground power Cables, from a technical, economic and strategic viewpoint. Highly analytical but focused on achieving practical solutions.

Developer of innovative approaches. Internationally experienced and member of multiple international organisations.

KEMA	**Mar 2003 - Mar 2008**
Position:	Consultant

KEMA	**Mar 1998 - Mar 2003**
Position:	Engineer

Projects

Ashurst Australia and Clayton Utz – Basslink failure arbitration case - Independent expert	**2016 - ongoing**
Position:	Independent expert
Description:	Independent expert on the 2015 failure of the Basslink HVDC interconnector acting on behalf of Hydro Tasmania and the State of Tasmania.
Activities performed:	Confidential

JIP CALM	**2019 - ongoing**
Position:	Principal consultant, lead expert
Description:	The JIP Cable Lifetime Monitoring will evaluate why submarine cables for offshore windfarms fail much more than other cable systems, and will mitigate main causes of failures. Furthermore, fibre optic measurement techniques will be evaluated for their use throughout the cable lifetime. Currently 30+ industry partners joined the JIP.
Activities performed:	Developed the JIP, created and developed the plan for the JIP, supported the subsidy grant and interested the industry partners to join.

KEPRI/KEPCO – 500 kV cable qualification requirements	**2017-ongoing**
Position:	Principal consultant
Description:	Development of a qualification plan comprising all tests, inspections and other quality control means to ensure new to be manufactured 500 kV HVDC systems for land based applications and submarine applications will meet their required level of quality. In this process, the 'bar will be raised' regarding the level of quality when compared to existing CIGRE guidelines and standards, given the importance of the 500 kV cable systems in the grid of the customer.

Activities performed:	Qualification plan developed comprising all tests

Third party certification of (>90 km) submarine AC transmission cable system (confidential) **Mar 2013 - 2019**

Position:	Senior inspector and Principal consultant
Description:	100% Quality control of a long and important submarine power cable project. Details are confidential.
Activities performed:	Full verification and certification of a submarine power cable. Complete manufacturing and testing phase are considered, part of the installation phase is considered.

Note: more specific project references can be supplied on request.

International courses power cable **2004 - ongoing**

Position:	Lecturer and developer
Description:	Mr. F.H. de Wild is the developer, editor and main lecturer on various DNV GL courses on power cables named below. These courses have been given 30+ times to 1000+ engineers in the cable industry. The courses have been given in multiple countries spread over three continents. Typically, twice a year the 'standard course' is given in house at DNV GL, while there are also many instances where a tailor-made course is given.
Activities performed:	Courses on power cable engineering Courses onSUbmarine power cables Courses on HVDC power cables Courses on Maintenance of HV cable systems

General - Stationary and dynamic ampacity calculations

Position:	Consultant / engineer / -project manager
Description:	Development of stationary and dynamic ampacity calculations and temperature measurements, both in existing and in new infrastructures in very many different cases, situations and countries. For example: - Current rating engineering guidelines for DNO's in different countries - Rating calculations (stationary or dynamic) for utilities, manufacturers, industries and others - Development of current rating calculation tools - Evaluation / calculation and laboratory measurements of soil thermal parameters - Governmental studies towards optimal usage of power cables, dealing with thermal bottlenecks, glass fibre usage and other aspects.

Activities performed:	All activities required

General - Dynamic rating system

Position:	project manager, consultant, developer
Description:	Range of projects involving the DNV GL dynamic rating system Dynamic rating system definition, installation and realisation for >5 different projects for multiple underground power cables, overhead lines and transformers for international utilities. Countries include: Netherlands, Spain, Denmark, Belgium, South Africa.
Activities performed:	- developer of DNV GL's DRS system - key advisor - DRS application

General - Quality management, Specifications, bid evaluations

Position:	Project manager, consultant
Description:	Consultancy and support during the (pre-) design, engineering, manufacturing installation and realisation of power cables. Many projects were performed for many companies worldwide. Topics regard: - Pre-design studies for cable connections - Design reviews - Drafting of specifications - Technical bid evaluations - Solving complex design problems - Factory audits - Quality assessment and control during manufacturing - Quality management during installation Experience was gained regarding power cables from Medium Voltage AC class up to 500 kV HVDC class, both regarding submarine and land applications.
Activities performed:	All activities necessary

General - Remaining life estimation / condition assessments

Position:	consultant
Description:	Condition assessment / Reliability / Remaining life estimations for various network owners for cables and cable networks (MV to EHV) in various projects: - Condition assessment (Dutch utilities and power producers, factories, railways) - Failure investigations and mitigation 1500 V - 380 kV (a.o. Air products, Alstom, Flagship Energy, others)

- Remaining lifetime assessment of cables and networks (E.On, DEWA)

Activities performed:	- Condition assessment - root cause analysis - remaining life assessments

General - Due diligence studies

Position:	Team member
Description:	Performed 3 due diligence studies (condition assessment and technical valuation of a complete power grid) with a strong focus on underground power cables (condition assessment of underground power cable grid, estimation of remaining life and economic value, etc.).
Activities performed:	Condition assessment of grids, valuation of grids

Memberships

Present

Cigre Workgroup B1.72 on verification of current rating calculations **Sep 2018 - Present**

Role:	Convener
Description:	Convener of an international workgroup considering the verification of current rating calculations in complex situations.

Strategic Advisory Group of study committee B1 on Power Cables **Sep 2016 - Present**

Role:	Member
Description:	Active member of the Strategic Advisory Group of CIGRE study committee B1 on power cables

Cigre workgroup B1.56 on current Rating Verification **Sep 2016 - Oct 2019**

Role:	Convener
Description:	Convener of an international workgroup considering the verification of current rating calculation tools. This leads to the publication of a CIGRE TB named "Power cable rating examples for calculation tool verification"

Cigre workgroup B1-55 on additional testing of submarine cables from 6 kV (Um=7.2 kV) up to 60 kV (Um=72.5 kV) **Sep 2016 - Apr 2018**

Role:	Secretary
Description:	Secretary of an international workgroup considering additional tests for submarine power cables including 'wet design' cables. This led to the

	publication of CIGRE TB 722, "Recommendations for additional testing for submarine cables from 6kV (Um=7.2 kV) up to 60 kV (Um=72 kV)"

Cigre national study committee B1 on Power Cables **Sep 2008 - Sep 2016**

Role:	Chairman
Description:	Chairman of the Dutch national Cigre committee on Power cables, representing the Netherlands in CIGRE SC B1

Cigre workgroup B1-35 on power cable current rating **Sep 2010 - Dec 2015**

Role:	Convener
Description:	Convener of an international workgroup considering the current rating of power cables. This led to the publication of CIGRE TB 640, "A guide for rating calculations of insulated cables"

Cigre taskforce B1-53 on installation related cable damages **Sep 2013 - Sep 2014**

Role:	Convener
Description:	Convener of an international taskforce considering installation related cable damages worldwide

Underground power cables user group of Smartlife consortium **Jan 2008 - Nov 2012**

Role:	Task leader of user group
Description:	Task leader in the Smartlife consortium responsible for work on best practices for the end-of-life transition phase and best practices for new component specifications.

Cigre workgroup B1-08 on multi-purpose structures **Sep 2007 - Sep 2008**

Role:	Member
Description:	Member of an international workgroup considering power cables installed in multi-purpose structures. This led to the publication of CIGRE TB 403, "Cable systems in Multi-purpose or shared structures"

Cigre national study committee B1 on Power Cables **Sep 2006 - Sep 2008**

Role:	Secretary
Description:	Secretary of the Dutch national Cigre committee on power cables

Cigre workgroup B1-09 on remaining life of HV cable systems **Sep 2004 - Sep 2007**

Role:	Secretary
Description:	Secretary of an international workgroup considering remaining life estimations of power cables. This led to the publication of CIGRE TB 358, "Remaining life management of existing AC underground lines"

Other information

Organized events in Netherlands to spread knowledge on power cables as a conference on power cables called 'Kabeldag', and as tutorial sessions for Dutch engineers.

Lecturer and developer of power cable training courses on engineering aspects, current rating, HVDC cable systems and submarine cable systems. These trainings were provided by Mr. De Wild to 1000+ course participants over many courses given worldwide

Active contributions to conferences as presenter of papers or posters, or convening / organizing a conference session. Conferences include: CIRED, CIGRE, JICABLE, BIS, ICEMPE and smaller conferences on submarine or land power cables (AC and DC). Part of the scientific technical committee of the conferences JICABLE HVDC 2017, ICEMPE 2017, ICEMPE 2019.

Received the CIGRE Technical Committee Award for his outstanding contribution to SC B1 in 2016

APPENDIX B
Documents received with letter of instruction dated 20 November 2019

I have used various documents that I received with the letter of instructions dated 20 November 2019, which lead to my expert report of January 2020 [2]. The documents are listed below and are referred to by the wording "/tab A-xx/" where xx is the number in the list below.

	Title	Date	Identification number	Rev
A. Expert Code				
1.	Expert Witness Code of Conduct (Supreme Court of Tasmania)	5 January 2016	Practice Direction 1 of 2016	
B. Background				
[redacted]				
C. Pirelli/Prysmian documents				
[redacted]				

Title	Date	Identification number	Rev
[redacted]			

Title	Date	Identification number	Rev

Title	Date	Identification number	Rev
[redacted]			

Title	Date	Identification number	Rev
[redacted]			

Title	Date	Identification number	Rev
[redacted]			

D. Siemens documents

[redacted]

Title	Date	Identification number	Rev
[redacted]			

E. Load data

[redacted]

F. Fault finding reports

[redacted]

G. Photographs

Title	Date	Identification number	Rev
[redacted]			

H. CCI examination

[redacted]

I. Other documents

[redacted]

Title	Date	Identification number	Rev
[redacted]			

Title	Date	Identification number	Rev
[redacted]			

Title	Date	Identification number	Rev
[redacted]			

Title	Date	Identification number	Rev
[redacted]			
J. Correspondence			
65.1	Not used		
[redacted]			

	Title	Date	Identification number	Rev
66.1	Letter from Hydro Tasmania to BPL re engineering issues and requests for information	29 October 2018		
66.2	Letter from Hydro Tasmania to BPL re engineering issues and requests for information	19 November 2018		
66.3	Letter from BPL to Hydro Tasmania re engineering issues and requests for information	19 November 2018		
66.4	Letter from DLA Piper to Clatyon Utz and Ashurst re CCI ER990	7 December 2018		
66.6	Letter from Clayton Utz to DLA Piper re Thermal and Electrical Modelling Evidence	8 May 2019		
66.7	Letter from DLA Piper to Ashurst and Clayton Utz re BOA Arbitration and BSA Arbitrations	6 June 2019		
66.8	Letter from CCI to DLA Piper re Response to DNV Letter dated 24 July 2019	10 October 2019		
66.9	Letter from Clayton Utz to DLA Piper re Thermal and Electrical Modelling Evidence	1 March 2019		
K. CCI and Materials Technology Reports				

[redacted]

	Title	Date	Identification number	Rev
[redacted]				
82.	CCI Thermal Model User Guide	20 December 2018		
L. Fugro Reports and Data				
83.	Preliminary Geotechnical Investigation	19 May 2019	GeODin/3m_Geotech Log	
84.	MGP131577_Scope B Operations and Survey Field Report_	18 April 2019	MGP131577-FLD-002	1
85.	MGP131577 CTD ASCII Listing_Final	Undated		
86.	MGP131577 DOB ASCII Listing_Final	Undated		
87.	MGP131577_ITRF2014_UTM55s_Centreline_Rev0_20190305_KP	Undated		
87.1	Thermal Conductivity Summary Table	Undated		
88.	Draft Volume 1 Integrated Report	16 July 2019		A
89.	MGP131577 Scope B Operations and Survey Field Report	16 July 2019		1
90.	Integrated Report Volume 2 - Survey Operations	31 July 2019	MGP131577-REP-002	0
91.	MGP131577 Volume 1A_Integrated Report (Rev 0)	9 August 2019	MGP131577-REP-002	0
92.	MGP131577 Volume 1B_Drawings (Rev 0)	9 August 2019		0
93.	MGP131577 Volume 1C_Drawings (Rev 0)	9 August 2019		0
94.	Appendix F - Route Position Listing MGP131577_ITRF2014_UTM55s_Centreline	9 August 2019		0
95.	Appendix G - Depth of Burial Results - MGP131577_As-Found Cable Bights DOB Listing	12 July 2019		1
96.	Appendix H - CTD Results - MGP131577 CTD ASCII Listing Final	Undated		
97.	A.1 - Preliminary Results: Particle Size Distribution (**PSD**)	Undated	FAM-18201	6
98.	B - Preliminary Results: Thermal Conductivity	Undated	FAM-18208	9
99.	B.1 - Preliminary Results: TX Permeability	Undated	FAM-18194	6
100.	B.2 - Preliminary Results: CH Permeability	Undated	FAM-18204	6
101.	C.1 - Preliminary Results: Permeability	Undated	FAM-18194	6
102.	Fugro Integrated Report Volume 1A: Results - Microscopy	9 August 2019	MPG131577-REP-002	0
103.	Excel spreadsheet: MGP 131577 DOB ASCII Listing Final (Rev 1)	29 October 2019		1
103.1	Pangeo Technical Note - Measurements and Images of the Basslink Interconnector	15 January 2019	RPT-08411-1	1
103.2	Pangeo, Analysis of 6 Basslink Overlapping Data Sets	14 January 2019	RPT-08408-1	

	Title	Date	Identification number	Rev
103.4	Pangeo, Extracted BassLink Acceptance Test Data	Undated	RPT-08412-1	
M. Subsea Survey Methods Background				
104.	Fugro, Geotechnical Laboratory Tests	Undated	FNL/GEO/APP/007	2
105.	Fugro, Sampling from Seafloor	Undated	FNL/GEO/APP/026	
106.	CSIRO, Basslink Interconnector: Subsea Cable Route Fieldwork Scoping Document	14 September 2018	OD-210637-C	
107.	Vardon et al., Interpreting and Validating the Thermal Cone Penetration Test (T-CPT)	30 July 2018		1
108.	Vardon et al., Thermal Cone Penetration Test (T-CPT)	June 2018		
N. Subsea Survey Scope				
109.	Hydro Tasmania Documentation			
109.1	Seabed Sampling and Cable Survey RFT FINAL	7 November 2018	3012001042	
109.2	Basslink-Fieldwork-Scoping-Document	6 October 2018		
110.	MGP131577 - Schedule 2 - Technical Proposal	15 January 2019		
111.	MGP131577 Addendum 01 - Combined Schedule	Undated		
112.	Seabed Sampling and HVDC Cable Survey Agreement for signing	23 January 2019		
113.	Appendix B - Experience Statements			
113.1	Pipeline Route Survey & Seismic Refraction ES	July 2018		
113.2	Site Survey Investigations	July 2018		
113.3	FAM Track Record	October 2018		
114.	Appendix C - Equipment Specifications			
114.1	Silver Star Specification	Undated		
114.2	Bhagwan Dryden Specification	Undated		
114.3	Fugro Starfix	Undated		
114.4	Fugro Starfix G2+	Undated		
114.5	Meridian Surveyor Gyrocompass	Undated		
114.6	StarfixNG Software	Undated		
114.7	Sonardyne Scout Pro USBL	Undated		
114.8	Sonardyne Ranger 2 USBL	Undated		
114.9	R2Sonic MBES	Undated		
114.10	Applanix POS-MV MRU	Undated		

	Title	Date	Identification number	Rev
114.11	Valeport MIDAS SVX2	May 2016		
114.12	Edgetech 4200 SSS	Undated		
114.13	SeaQuest Gradiometer	Undated		
114.14	Dual Van Veen Grab	Undated		
114.15	SEAS VC-450 Vibrocorer	Undated		
114.16	KD2 PRO Thermal Analyser	Undated		
114.17	Seabed Operations	Undated		
114.18	Temperature Cone	Undated		
114.19	Fugro FCV 600	Undated		
114.20	Valeport MIDAS BathyPack	May 2016		
114.21	SeaBotix LBV300-5	Undated		
114.22	Pangeo Subsea SBI	Undated		
115.	Appendix D - T-CPT Procedure			
115.1	Fugro's Electric Cone Penetration Test	Undated		
115.2	In Situ Thermal Testing Procedure	Undated		
116.	Appendix E - Management System Certification			
116.1	Fugro Australa Marine DNV 9001 2015	9 July 2018		
116.2	Fugro Australia Marine DNV 18001 2007	9 July 2018		
116.3	Fugro Australia Marine DNV 4801 2001	9 July 2018		
116.4	Fugro Australia Marine DNV 14001 2015	9 July 2018		
117.	Appendix F - QHSE Management Documentation			
117.1	Policy - APAC Quality	1 July 2017		
117.2	Quality Manual (APAC-M-23076)	7 December 2017	APAC-M-23076	
117.3	PEP - Quality Plan Template		XXXXX-PEP-Q Plan (02)	
117.4	Health and Safety Manual	7 December 2019	APAC-M-22440	
117.5	PEP - HSSE Plan Template	Undated	XXXXX-PEP-HSSE Plan (01)	
117.6	Risk Management Procedure	26 October 2017	APAC-M-22351	
117.7	Risk Management Process	28 May 2018		1
117.8	Environmental Manual	7 December 2017	APAC-M-22441	
118.	Appendix G - Contract Management Documentation			
118.1	DOR Template	Undated		2

	Title	Date	Identification number	Rev
118.2	Contract Management Plan - Example	Undated	01797-00-PLA-002	0
119.	Technical Clarification Rev 1			
119.1	BM-WI-002_86 Personnel Transfer Procedure Rev 0	7 July 2014	BM-WI-002/86	0
119.2	BM-WI-004_86 Workboat Launch & Recovery Operations Rev 1	7 December 2017	BM-WI-004/86	1
119.3	BM-WI-030_86 Daughter-Craft Operations Rev 0	30 May 2017	BM-WI-030/86	0
119.4	FNLM-GEO-APP-007 Geot Lab Test	Undated	FNLM/GEO/APP/007	
119.5	FNLM-GEO-APP-026 Sampling Seafloor	Undated	FNLM/GEO/APP/026	
119.6	Fugro Djinda - Certificate of Operation	Undated	COO-40417-001	
119.7	Fugro Djinda - Specification	Undated		
119.8	Fugro Djinda SMS (Rev 0)	Undated		0
119.9	Little Dryden - Certificate of Survey	Undated		
119.10	Little Dryden - Specification	Undated		2
119.11	MGP131577 Technical Clarifications (Rev 1)	3 January 2019	MGP131577	1
119.12	SMS Project Training Matrix	Undated		
119.13	Sonardyne Scout USBL System Installation How to Guide (SD-HT-301.4)	Undated	SD-HT-301.4	
119.14	TRA-OE-03 - Djinda Launch & Recovery	Undated	TRA-OE-003	
119.15	TRA-OE-04 - Small Boat Surveys	Undated		
119.16	TRA-OE-05 - Shallow Water Operations	Undated	TRA-HY-11	1
119.17	TRA-OE-06 - Shore Landing	Undated	TRA-HY-30	1
O. CSIRO Reports and Documents				
[redacted]				
120.1	Blackwell & Steele, Thermal conductivity of sedimentary rocks: measurement and significance.	1989		
120.2	Farouki, Thermal properties of soils	1981		
120.3	Robie et al., Thermodynamic properties of minerals and related substances at 298.15 K and 1 bar (105 Pascal) pressure and at higher temperatures	1978		
120.4	Goto & Masubayahi, Relations between the thermal properties and porosity of sediments in the eastern flank of the Juan de Fuca Ridge	2009		

	Title	Date	Identification number	Rev
120.5	Lovell, Thermal conductivity and permeability assessment by electrical resistivity measurements in marine sediments	1985		
120.6	Brigaud & Vasseur, Mineralogy, prosity and fluid control on thermal conductivity of sedimentary rocks	1989		
120.7	Horai & Simmons, Thermal conductivity of rock-forming minerals	1969		
120.8	Barry-Macauley et al., Thermal conductivity of soils and rocks from the Melbourne (Australia) region	2013		
120.9	Newson & Bunning, Thermal conductivity of deepwater offshore sediments	2004		

[redacted]

P. Land Section/BPL Easement				
129.5	Land Cable Route	19 May 2003		
129.6	Cover page summary of thermal resistivity testing from Geotherm Australasia	10 December 2019		2
129.7	Material test report from Douglas Partners	12 November 2019	667731.00-1	

	Title	Date	Identification number	Rev
129.8	Geotherm Australasia - Test Report 145201	9 December 2019		
129.9	Geotherm Australasia - Test Report 145202	9 December 2019		
129.11	Geotherm Australasia - Test Report 145203	10 December 2019		
129.12	Geotherm Australasia - Test Report 145204	9 December 2019		
129.13	Geotherm Australasia - Test Report 145205	4 December 2019		
129.14	Geotherm Australasia - Test Report 145206	4 December 2019		
129.15	Geotherm Australasia - Test Report 145207	9 December 2019		
129.16	Geotherm Australasia - Test Report 145208	10 December 2019		
129.17	Geotherm Australasia - Test Report 145209	9 December 2019		
129.18	Geotherm Australasia - Test Report 145210	9 December 2019		
129.19	Geotherm Australasia - Test Report 145211	9 December 2019		
129.20	Geotherm Australasia - Test Report 145212	9 December 2019		
129.21	Geotherm Australasia - Test Report 145213	4 December 2019		
129.22	Geotherm Australasia - Test Report 145214	4 December 2019		
129.23	Geotherm Australasia - Test Report 145215	4 December 2019		
129.24	Geotherm Australasia - Test Report 145216	9 December 2019		
129.25	Geotherm Australasia - Test Report 145217	9 December 2019		
129.26	Geotherm Australasia - Test Report 145218	9 December 2019		
129.27	Geotherm Australasia - Test Report 145219	10 December 2019		
129.28	Geotherm Australasia - Test Report 145220	10 December 2019		
129.29	Geotherm Australasia - Test Report 145221	9 December 2019		
129.30	Geotherm Australasia - Test Report 145222	8 November 2019		
129.31	Geotherm Australasia - Test Report 145223	8 November 2019		
129.32	Geotherm Australasia - Test Report 145224	4 December 2019		
129.33	Geotherm Australasia - Test Report 145225	6 December 2019		
129.34	Geotherm Australasia - Test Report 145226	6 December 2019		
129.35	Geotherm Australasia - Test Report 145227	6 December 2019		
129.36	Associated photographs provided by Geotherm Australasia	Undated		

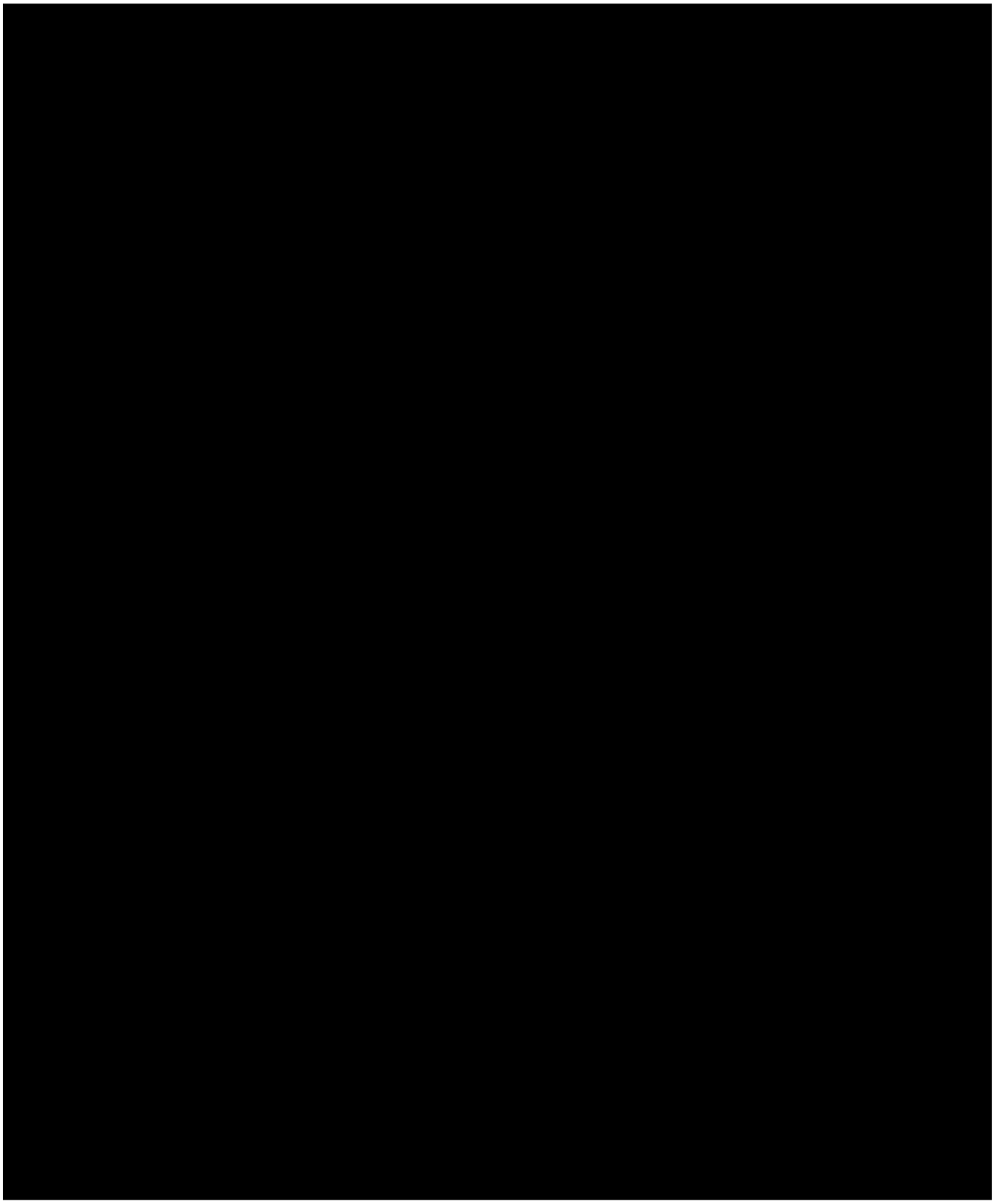
	Title	Date	Identification number	Rev
129.37	Bass Link Actual Test Points	Undated		
130.	Title Plan 198926-1	2 July 2019		
131.	Parcels of land burdened by powerline easements	28 June 2019		
132.	Allotment 16 (Title Plan 78590C)	27 June 2019		
133.	Allotment 13 - Copy of Dealing A	9 April 2018		
134.	Allotment 14 (Title Plan 68654F)	27 June 2019		
135.	Allotment 5 and 5A (Title Plan 68654F)	27 June 2019		
136.	Allotment 4 (Title Plan 68244B)	27 June 2019		
137.	Allotment 2 (Title Plan 778694H)	27 June 2019		
138.	Allotment 33 (Title Plan 778695F)	27 June 2019		
139.	Denholm photos (1)	27 June 2019		
140.	Denholm photos (2)	27 June 2019		
141.	Denholm photos (3)	27 June 2019		
142.	Denholm photos (4)	27 June 2019		
143.	Denholm photos (5)	27 June 2019		
144.	Denholm photos (6)	27 June 2019		
145.	Denholm photos (7)	27 June 2019		
146.	Denholm photos (8)	27 June 2019		
147.	Denholm photos (9)	27 June 2019		
148.	Denholm photos (10)	27 June 2019		
149.	Denholm photos (11)	27 June 2019		
150.	P4200010	27 June 2019		
151.	P4200011	27 June 2019		
152.	P4200012	27 June 2019		
153.	P4200013	27 June 2019		
154.	P4200014	27 June 2019		
155.	P4200015	27 June 2019		
156.	P4200016	27 June 2019		
157.	P4200017	27 June 2019		
158.	P4200018	27 June 2019		
159.	P4200019	27 June 2019		
160.	P4200020	27 June 2019		

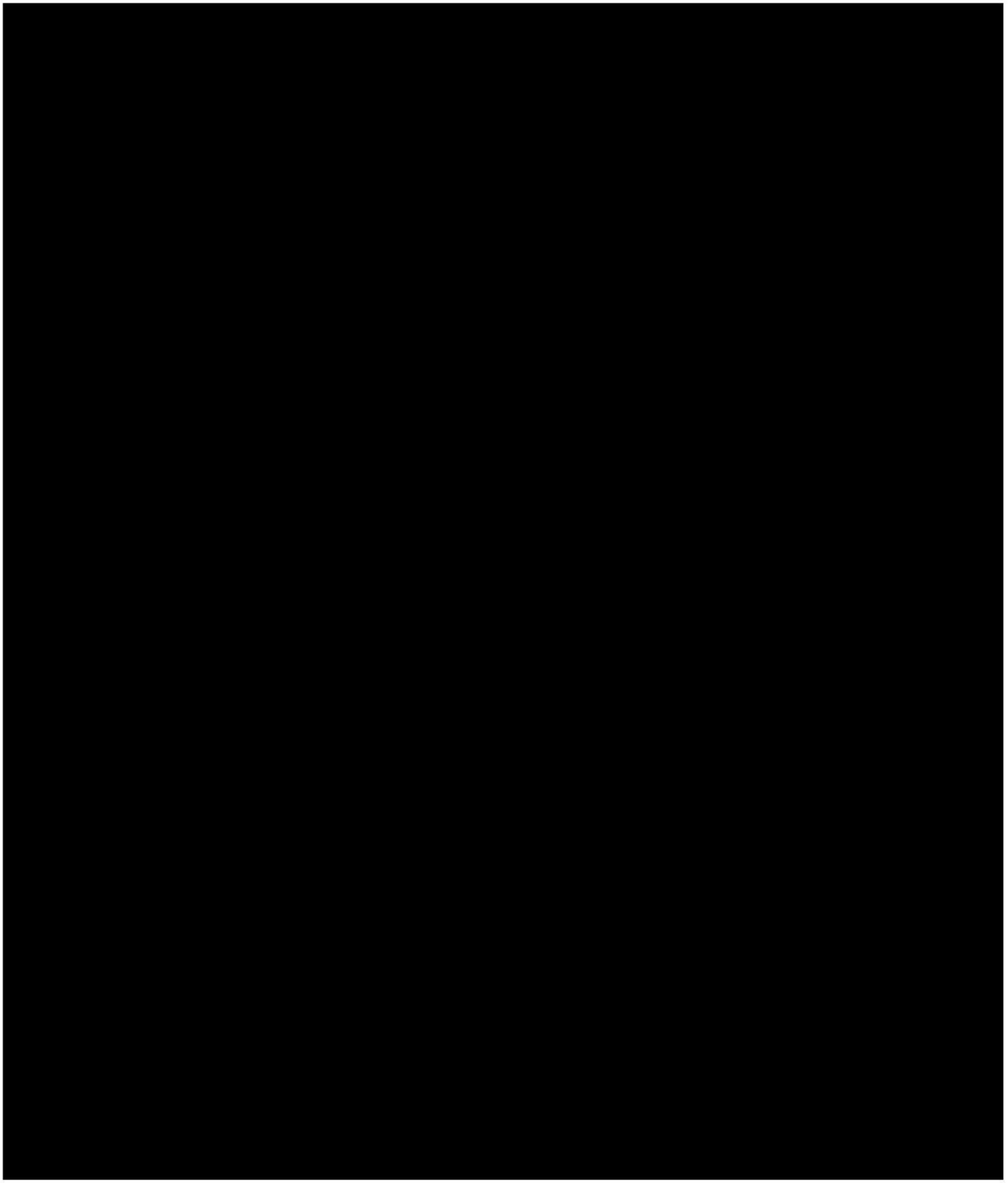
	Title	Date	Identification number	Rev
161.	P4200021	27 June 2019		
162.	P4200022	27 June 2019		
163.	P4200023	27 June 2019		
164.	P4200024	27 June 2019		
165.	P4200025	27 June 2019		
166.	P4200026	27 June 2019		
Q. BPL Hyperlinked Witness Statements				
[redacted]				
R. [redacted]				
[redacted]				

(9)

APPENDIX C
Letter of Instructions

The below letter of instructions was received on 11 August 2020. This report answers this letter.





CLAYTON UTZ

[redacted]

About DNV GL

DNV GL is a global quality assurance and risk management company. Driven by our purpose of safeguarding life, property and the environment, we enable our customers to advance the safety and sustainability of their business. We provide classification, technical assurance, software and independent expert advisory services to the maritime, oil & gas, power and renewables industries. We also provide certification, supply chain and data management services to customers across a wide range of industries. Operating in more than 100 countries, our experts are dedicated to helping customers make the world safer, smarter and greener.