BOMBAY OTAHUHU REGIONAL MAJOR CAPEX PROJECT

ATTACHMENT B: CONDUCTOR CONDITION REPORT

Transpower New Zealand Limited

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1 Executive Summary

The Bombay – Otahuhu A transmission line is strung predominantly with Wolf ACSR/GZ conductor (with galvanised steel core wires) for 90% of the line, and the remainder is strung with Goat ACSR/GZ. This report discusses the condition of the conductor on this transmission line.

The line is 29km long and was commissioned in 1960. The Wolf ACSR/GZ conductor was installed at this time, giving a service life to date of 59 years. The Goat ACSR/GZ spans were installed 10 years later in 1970 at the substation ends, with most spans installed at the Bombay end. The conductor has performed as expected during its life. The Wolf ACSR conductor has now been in service for 15 years longer than its expected life of 44 years and we have found it to now have numerous corrosion defects that are beyond replacement criteria.

The line is located in a 'Severe' corrosion environment, with over 80% of spans within 5km of the coast, and all spans on the line are within 10km of the coast.

For the purposes of this report, the BOB-OTA A line is considered in three main sections (see table below).

Line section	Structure from / to	Description	Distance from coast (km)
OTA-WIR	T117A & B to OTA	Otahuhu – Wiri section (Wolf)	0 – 4
BOB-WIR	T53 to T117A & B	Bombay – Wiri section (Wolf)	0 – 7
	BOB to T53	Bombay – Wiri section (Goat)	8 – 11

Condition assessment and analysis undertaken has shown that the Wolf ACSR conductor on this line requires intervention. Corrosion defects have been identified on the Wolf ACSR conductor (in both sections of the line) through testing and aerial surveys, which are now beyond replacement criteria.

Until the conductor is replaced or removed, a programme of inspections and repairs is required on the BOB-OTA A line to manage the risk of failure. This is likely to be in the form of regular close aerial inspections and conductor repairs, as required. The difficulty with detecting defects on the conductor combined with the public safety implications, land use under the line and increasing demand on the transmission system is such that continuing to manage issues with inspection and corrective maintenance will be expensive. It will also not adequately address the risk of conductor failure in the medium to long-term.

2 Introduction

This document is the Condition Assessment report for the Bombay-Otahuhu A line.

2.1 Purpose

The purpose of this report is to outline condition assessment information which has led to the need to replace or remove the conductor on the BOB-OTA-A line (Bombay to Otahuhu).

2.2 Document structure

This report forms part of the Bombay Otahuhu Regional Major Capex Proposal application.

3 Why does the conductor need to be replaced?

Replacement or removal of the degraded conductors is prudent considering:

- the corrosion observed on the Wolf ACSR conductor is widespread, with numerous defects on both the OTA-WIR and BOB-WIR line sections which are at or beyond Transpower's replacement criteria
- the relatively high circuit loads on the BOB-OTA-1 and 2 circuits, compared to other circuits nationally
- public safety considerations – this line crosses numerous residential properties, urban amenities such as the Auckland Regional Botanic Gardens (10 spans), and other infrastructure including State Highway 1 (13 spans), the main trunk railway line (3 spans), city roads and regional highways (17 spans), and distribution power lines (1 span)
- the difficulties repairing conductor in an urban or suburban environment, and the increasing risk of failure over time as corrosion defects continue to degrade.

4 Background

The Bombay – Otahuhu A line is strung predominantly with Wolf ACSR/GZ conductor (with galvanised steel core wires) for 90% of the line, and the remainder is strung with Goat ACSR/GZ.

The line was commissioned in 1960 and the Wolf ACSR/GZ conductor was installed at this time, giving a service life to date of 59 years. The Goat spans were installed 10 years later in 1970 at the substation ends, with most spans installed at the Bombay end.

The line is in a 'severe' corrosion environment, with over 80% of spans within 5km of the coast, and all spans on the line are within 10km of the coast.

This line is considered in three main sections for the purposes of this conductor condition summary (see Table 1 below).

Table 1: BOB-OTA-A line sections

Line section	Structure from / to	Description	Distance from coast (km)
OTA-WIR	T117A & B to OTA	Otahuhu – Wiri section (Wolf)	0 – 4
BOB-WIR	T53 to T117A & B	Bombay – Wiri section (Wolf)	0 – 7
	BOB to T53	Bombay – Wiri section (Goat)	8 – 11

4.1 ACSR conductor

Aluminium conductor steel-reinforced conductor (ACSR) is a specific type of high-capacity, high-strength stranded type of conductor. The outer strands are aluminium, chosen for its excellent conductivity, low weight, and low cost. The central core consists of seven steel strands, providing the strength required to support the weight of the conductor, and limit the aluminium stretching due to its ductility and higher thermal expansion. This combination gives the conductor an overall high tensile strength.

The tensile capacity of ACSR conductor is calculated by combining the relative strengths of the aluminium strands and the steel core wires. In the case of Wolf ASCR/GZ conductor the aluminium strands contribute approximately 38% of the strength (~1.3% per strand) and the steel the remaining 62%.

Predicting the end-of-life and degradation of ACSR conductors is very difficult as they are prone to accelerated aluminium corrosion near end-of-life – particularly in corrosive environments. Galvanic cells (due to dissimilar metals – steel and aluminium) are formed where the zinc coating on the steel core wires has been depleted or perforated. Once the galvanising on the steel core has corroded or abraded, the aluminium strands 'sacrifice' themselves to protect the steel – increasing the rate of aluminium corrosion and loss of strength. Galvanic corrosion between aluminium and steel results in much higher corrosion rates than atmospheric corrosion.

As the conductor loses aluminium due to corrosion, we start to see aluminium oxide build up on the outside of the conductor and, in the worst cases, bulging of the conductor.

A failure mode exists where reduced conductive area increases the temperature in the steel core causing overheating. Significant corrosion of the aluminium strands leads to a loss of the conductive cross-sectional area as well as pitting of the steel core wires. Under electrical load this leads to an increase in current flowing in the steel core wires causing overheating, annealing and ultimately tensile failure. The likelihood of 'burn down' once area loss is advanced is also higher for these lines compared to lines in equivalent condition with lower electrical loads, particularly given that the circuits on the OTA-WIR section of this line are operated with variable line ratings (VLR) to increase their transmission capacity. This is the highest risk mode of failure for this line.

Failure due to mechanical overload alone is less likely for these lines. As the conductor loses aluminium cross-section and bulges, it also loses strength. From previous conductor bulge analysis on ACSR conductor we can estimate the loss of aluminium from the bulge diameter. Under high mechanical loading, the loss of strength due to corrosion can result in tensile failure of the conductor. However, the maximum design loads for conductors in both sections of these lines do not exceed 40% of the specified tensile strength of Wolf ACSR/GZ conductor, and the steel core wires alone contribute 62% of the tensile strength of the conductor when new.

Degradation of conductor condition depends primarily on the corrosiveness of the local atmosphere, but also on vibration, the conductor construction (such as greasing) and the conductor material.

The expected life of ACSR/GZ conductors has been influenced by manufacturing deficiencies known as 'Grease Holidays' where grease has not been applied, or missed, during the manufacturing process". The expected lives of Wolf and Goat conductors with 'Grease Holidays' in severe corrosion environments are 44 and 66 years respectively. The following extracts from the conductor fleet strategy TP.FL 03.01 give more detail on these corrosion mechanisms.

> **Grease holiday corrosion:** …grease applied to the core wire during manufacture provides a barrier to galvanic corrosion and can significantly extend conductor life. However, if it is applied poorly it is of little or even negative benefit. Experience has shown that grease application was poorly managed for conductors on many lines throughout the country, resulting in sections of core wire where no grease was applied at all ('grease holidays'). Grease holidays expose small localised areas of the core wire to the environment that results in higher than normal corrosion rates. In 2005, a span on the BPE-HAY A line failed due to corrosion after only 25 years in service. Subsequent close aerial inspections revealed widespread instances of bulging of the conductor on the A and B lines, all due to grease holidays.

However, modern manufacturing techniques and monitored grease application have helped address concerns over grease holidays in modern conductors.

4.2 Replacement criteria

The replacement criteria for ACSR conductors applies to the BOB-OTA A line. The applicable Transpower replacement criteria is 20% loss of tensile strength or 15% section loss.

When assessing the condition of in-service conductors all assessment is undertaken in accordance with the condition assessment service specification TP.SS 02.17 - Part C[1]. This service specification ensures that all conductors throughout the country are assessed against a common standard giving comparable and repeatable results. Figure 1 shows the coding system used for ACSR/GZ conductor.

The replacement criteria for tensile strength is chosen to ensure there is sufficient residual strength in the conductor to meet the maximum allowable design loads. The Transpower loading code TP.DL 12.01[2] gives the maximum allowable design loads for the conductor. The actual maximum utilisation of a span of conductor is highly dependent on many factors

[1] TP.SS 02.17 Transmission line condition assessment, Part C: Insulators and conductors

[2] TP.DL 12.01 Transmission line loadings code

such as span length, elevation and location and as such this is also considered when determining the appropriate time to replace the conductor.

A3.1.1 ACSR/GZ conductor (Aluminium Conductor Steel Reinforced, galvanised core wire)
Conductor types: BRHGZ, CHKGZ, CHKMODGZ COYGZ, DOGGZ, GOTGZ, HARGZ, HYNGZ, MNKGZ, MOAGZ, PGNG, PHTGZ, PRTGZ, SKKGZ, WLFGZ, ZEBGZ.

Condition code	Guidelines
100	New conductor, bright outer finish.
90	Outer strands dulled to light grey colour, brightness gone.
80	Outer strands roughened. Grease hardening.
70	Grease hard and becoming ineffective.
60	Grease now ineffective. Start of core wire zinc loss.
50	First signs of white powder between outer strands. Outer strands have roughened considerably. Grease, drying up. Core wire zinc still intact, but getting depleted.
40	Zinc on core wire depleted in isolated spots. No rusting started. First white powder visible near core.
30	White powder increasing between inner strands, some minor pitting of aluminium strands, zinc coating on core wire depleted in patches, specks of rust appearing on wire.
20 (R/C)	The conductor meets the replacement criteria defined in clause A3.1.3 below. Grease gone, lots of white powder between layers, bulging starting in larger diameter conductors. Occasional breaks to outer aluminium strands. Steel core wire rusting in patches.
10	Visible intermittent bulging, many broken aluminium strands, patchy surface rusting on core wire.
1	Severe loss of aluminium strand cross section, tensile strength effectively reduced to that of the core wire only. Burn down risk high.

A3.1.3 ACSR conductor replacement criteria
Replacement criteria for ACSR/GZ and ACSR/AC is a 20 % reduction in UTS (ultimate tensile strength), or a 15 % reduction in cross-sectional area of the aluminium. With ACSR, this will inevitably be driven by internal corrosion of the aluminium strands of conductor.

Figure 1: Extract from TP.SS 02.17 Part C

4.3 Condition assessment types

We carry out regular condition assessments on transmission lines. Conductor condition is assessed based on a combination of loss of section and loss of tensile strength. The assessments produce a condition assessment (CA) score for various components on a scale from 100 (new) to 20 (replacement or decommissioning criteria).

Line assets are generally assessed every eight years and pole lines every six years.

When the CA score of any component is less than 50, the assessment frequency is generally increased. The aim is to ensure no component can deteriorate by more than 50% between assessments (such as from CA score 60 to 30). Sites with very high degradation rates or criticality may be assessed more frequently.

Ground-based and structure-based visual assessments yield valuable results for steel earthwire because any rusting can be more readily observed. For ACSR and AAAC conductors, such assessments are of very limited use in predicting end-of-life. This is because degradation (corrosion, fatigue, fretting) generally begins on the inside of the conductor, so is invisible until well advanced. Even detecting white corrosion product or small bulges is extremely difficult from the ground when looking up into the sky.

The condition assessment (CA) approach for conductors is based on the assessed and forecast condition. Due to the limitations of ground-based and structure-based CA, we use more intensive inspection methods as the condition of the conductor gets closer to the replacement criteria. These inspection methods include close visual inspection from an aircraft (traditionally helicopters, increasingly drones), and the use of a line-crawling robot (Cormon testing) that provides a reliable assessment of the condition of the coating on the inner steel core wires. Samples may be also taken for analysis.

5 Condition of the BOB-OTA A conductor

5.1 Conductor condition assessment completed

For BOB-OTA A line, conductor CA has been undertaken using several different methods. The condition information available is summarised in Table 2 below with a further high-level discussion of results given below.

The BOB-OTA A line CA methods used have been:

- Cormon (Eddy Current) testing
- close aerial surveys
- destructive metallurgical testing.

Table 2: Summary of conductor inspection and testing

	Pre 2013	2013	2014	2015	2016	2017	2018	2019
Cormon Eddy Current Testing		X					**X**	
Close Aerial Survey	X					X	**X**	**X**
Destructive metallurgical testing	X					X		**X**

**Results and analysis associated with the reports shown in bold & grey to the right were not available for the RCP3 submission.*

At the time of preparing the RCP3 proposal there was a clear indication that the conductor was going to require condition-based intervention during the RCP3 period. However, a preferred solution had not yet been confirmed.

Additional CA undertaken since the RCP3 proposal continues to verify the need for condition-based intervention during the RCP3 period. Conductor bulging has been identified in many areas along the line. Bulging indicates that replacement criteria has been exceeded – and other corrosion observations also indicates that further bulging in other areas is likely to soon follow.

5.1.1 Cormon testing summary

The cormon detector is a non-destructive test device that uses eddy current technology to estimate the remaining thickness of zinc or aluminium coating on the steel core wires of ACSR conductors. The condition of the coating on the inner steel core wires contributes to knowledge of conductor condition and gives prior warning of where conductor budging will occur.

The cormon detector is placed on the conductor by linemen span-by-span. The device then self-propels to the other end of the span, taking measurements every 5mm to 10mm. Results from this device have proven to be remarkably accurate, providing an excellent indication of conductor condition without the need for destructive sample testing.

We have carried out a cormon test programme annually since 2006. Approximately 1,900 subconductor spans have been tested to date. Our RCP2 strategy was to begin cormon testing 10 years before predicted end-of-life, and then establish appropriate times for repeat inspections to ensure end-of-life predictions are refined as they approach. Our new strategy is to start this detailed inspection earlier, to provide a sufficient forward forecast and to meet current planning timeframes.

It is important to note that the cormon test programme is a sample-based programme, with only a small proportion of wires and spans typically tested with this equipment.

The output of the cormon analysis is a classification of the conductor into five class categories for conductor condition as shown in Table 3 below. A new conductor would be expected to have 0% coating loss (indicated Green) and the condition of conductors deteriorate from that point over time toward 100% coating loss (Black).

Table 3: Cormon testing categories

Class	Coating loss	Colour Code
1	0-5%	Green
2	5-20%	Yellow
3	20-50%	Orange
4	50-80%	Red
5	80-100%	Black

An example of the results from two Wolf ACSR spans on this transmission line are shown in Figure 2 and Figure 3, and from one Goat ACSR span in Figure 4.

Condition Over Distance:

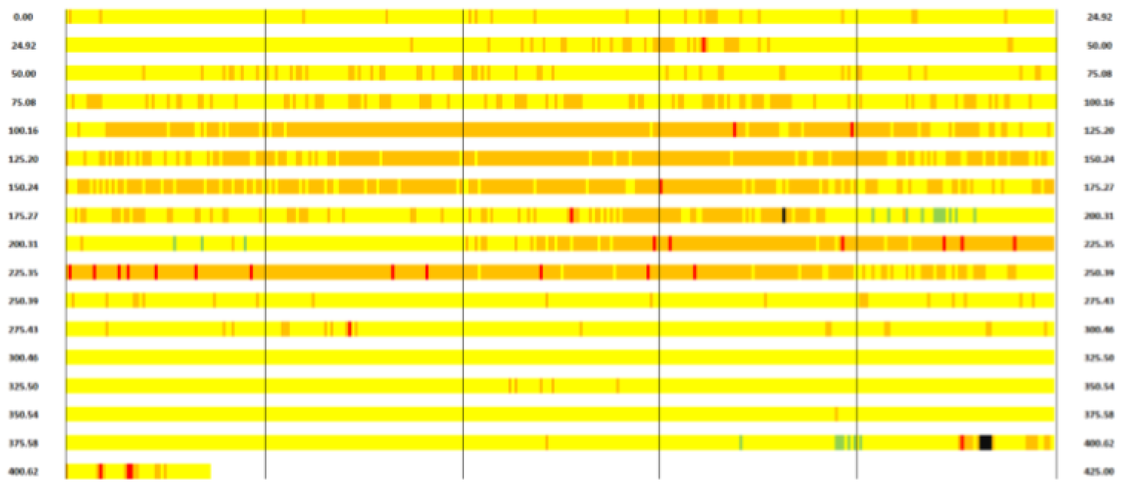

Figure 2: Example of cormon results for a single wire span of Wolf ACSR conductor from BOB-OTA-A (T89-T90)

The cormon results for this line show deterioration of the zinc coating on the steel strands for both the Wolf ACSR and Goat ACSR conductors, with many localised defects where advanced or complete coating loss is detected. Deterioration of the zinc coating exposes the steel, resulting in galvanic corrosion between the steel and aluminium strands, which leads to decreased strength, reduced conductive area, and potential overheating should enough aluminium cross section be lost. Figure 2 shows numerous localised sections reporting advanced loss of zinc coating on the steel core wires (Class 4 & Class 5). These areas of advanced coating loss are likely to have some exposed steel, and are where the aluminium conductor strands will begin to sacrifice themselves and accelerated loss of cross-sectional will be occurring.

Figure 3 and Figure 4 also illustrate that that these areas of coating loss can vary in length and are distributed along the wire, which can make localised repairs difficult, ineffective and expensive.

Condition Over Distance:

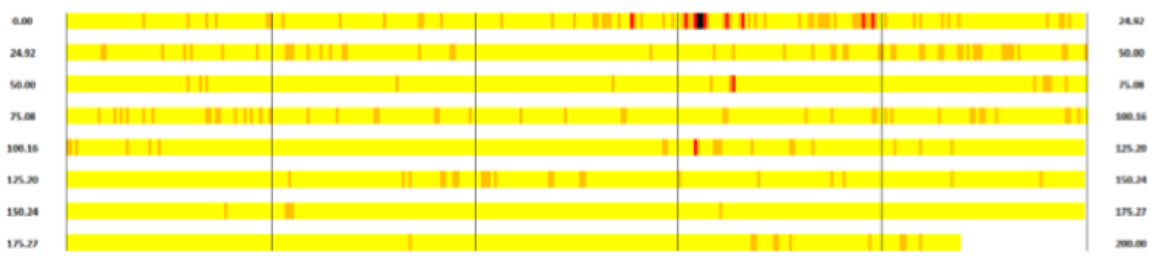

Figure 3: Cormon results for a single wire span of Wolf ACSR conductor from BOB-OTA-A (T77-T78)

Condition Over Distance:

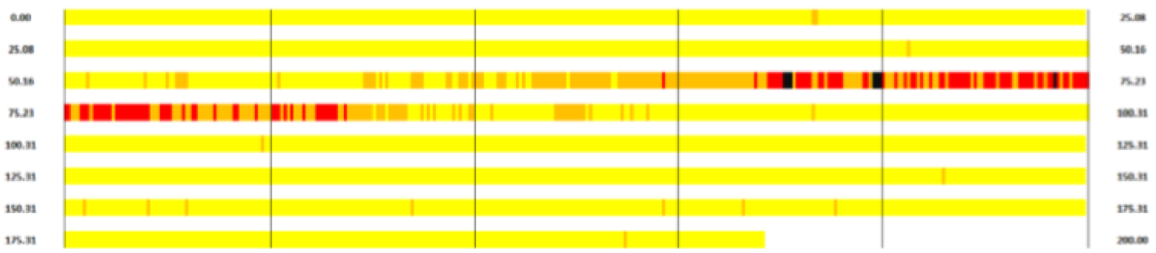

Figure 4: Cormon results for a single wire span of Goat ACSR conductor from BOB-OTA-A (T47-T47A)

Based on the cormon results we can reasonably expect that undetected internal corrosion is also occurring within the conductor, in addition to what can already be observed in close aerial surveys at this time.

5.1.2 Close aerial survey summary

Using an aircraft to undertake a close aerial survey is considered the best method of identifying conductor bulges/defects or areas requiring further monitoring known as “markers”. The BOB-OTA A line has been inspected using remotely piloted aircraft systems (RPAS, or drones) since 2017, which provides higher-quality visual condition assessment information, compared to the traditional maned--helicopter inspections.

A conductor bulge or defect is characterised by a noticeable bulge or significant corrosion product on the conductor and these correspond to a CA score of 20 or less depending on the diameter of the bulge. A marker is an area of conductor that is showing some discolouration, but visible bulging or significant build-up of corrosion product is not occurring yet. These markers can be re-evaluated during subsequent inspections and are generally good indicators that conductor bulging will occur soon. Since 2017, we have been collecting condition information for spans along this line, and these inspections are continuing as access permits. An overall summary of close aerial survey results is provided below in Table 4.

Table 4: Close aerial survey results – number of defects & number of defects per km inspected

Line	Description	Detailed aerial survey complete	Defect count		Defects per conductor (km)	
			All corrosion	*< CA20*	*All corrosion*	*< CA20*
BOB-OTA-A	OTA-WIR Wolf	48%	122	113	9.5	8.8
	BOB-WIR Wolf	66%	446	344	5.0	3.9
	BOB-WIR Goat	33%	3	0	0.3	0.0

108 out of 186 circuit spans have been inspected. 60% of the spans inspected show signs of deterioration.

The photographs in Figure 5 below show corrosion of the Bombay – Otahuhu A line conductor and the ACSR conductor degradation mechanism described above.

Figure 5: Examples of conductor defects showing corrosion bulging (span T78 – T79 and T129 – T130)

5.1.3 Destructive metallurgical testing

Lab tests on the Wolf conductor in 2019 quantified the remaining strength and cross-sectional area of bulges removed from the line. The largest bulge tested, at 117% of the original diameter, had a calculated reduction in breaking strength of ~19% of the specified rating based on tensile tests of individual strands. Considering the loss of aluminium strength measured during tensile tests, these results may represent a loss of up to 60% of effective cross-sectional area, exceeding Transpower's replacement criteria. Three internal strands were completely severed due to corrosion. Other bulges on the line may have more advanced corrosion than the bulges tested, with a number of defects expected to have similar or larger changes in diameter based on inspection images. Figure 6 shows the condition of the conductor samples during testing.

Sample A as received Layer 4 | Sample A as received Layer 3

Figure 6: Dismantling of conductor bulge, showing broken aluminium strands within conductor

Lab tests on the Goat conductor in 2017 confirmed that confirmed that galvanic corrosion is occurring in localised areas, with exposed steel and localised corrosion of aluminium. Pitting depths were 2.5% on average, and up to 8% of the strand diameter at most. The grease was tacky and losing adhesion to the strands in sections resulting in decreased corrosion protection.

Accelerated corrosion tests on ex-service ACSR conductor from other lines have shown that the galvanic corrosion rates within the conductor are many factors higher than atmospheric corrosion rates and overall corrosion rates for ‘as new’ conductors.

6 Ongoing maintenance

Ongoing inspections and maintenance will be required to ensure the risk of a conductor failure is appropriately managed until the Wolf conductor is replaced or removed. This is likely to be in the form of regular close aerial surveys, and conductor repairs as required. The numerous defects identified to date, and the public safety and access implications of the land use under the line is such that continuing to manage issues with inspection and corrective maintenance will be expensive and will not adequately address the risk of conductor failure in the medium term.

Inspections are still ongoing to capture detailed condition information for difficult-to-access spans.

The consequence and overall risk associated with conductor failure is considered high due to the public safety considerations and land use under the line, and relatively high circuit loads compared to other circuits nationally. This line crosses numerous residential properties, urban amenities such as the Auckland Regional Botanic Gardens (10 spans), and other infrastructure including State Highway 1 (13 spans), the main trunk railway line (3 spans), city roads and regional highways (17 spans), and distribution power lines (1 span).

Outages for repairs are relatively difficult to obtain, as outages on these circuits reduce the security of supply to Wiri (to N-security). This increases planning lead times and further limits our ability and desire to implement a ‘patch repairs’ approach on this line.

7 Condition assessment conclusion

The Wolf ACSR/GZ conductor on the BOB-OTA-A line is recommended for replacement or removal in RCP3 by 2024.

Replacement criteria for ACSR conductors are 15% loss of cross-sectional area, or 20% loss of tensile strength. The widespread corrosion and conductor bulging observed to date confirms that this replacement criteria has been met, and Cormon testing confirms that there is further corrosion occurring that is not yet detectable in close aerial surveys.

In summary, replacement is supported based on the defect observations below:

1. Close aerial surveys have identified widespread corrosion including significant conductor bulging – indicating aluminium losses have reached Transpower’s replacement criteria at many points along the line
2. Conductor sample testing has confirmed that galvanic corrosion is occurring, and strength and cross-sectional area losses meet Transpower replacement criteria
3. Cormon testing has identified numerous locations of advanced galvanising loss, in addition to the corrosion that is visible in close aerial surveys
4. These corrosion defects are widespread and will continue to degrade. Accelerated corrosion testing has confirmed that aluminium corrosion rates accelerate significantly once galvanic corrosion is occurring.

While additional inspection and repairs are required to manage the conductors, additional cormon testing or sample testing to further quantify degradation is not planned as it will not allow a material change in our strategy for maintaining or replacing this conductor.

