Network Asset Health Framework

CONTROLLED DOCUMENT

Summary					
This document outlines the framework adopted in the development of an effective asset health system for electricity network assets.					
Revision no:	3	**TRIM No:**	D2017/02681	**Approval/ Review Date:**	25 November 2021
Business function:	Strategic Asset Management			**Document type:**	Management Framework
Process owner:	Head of Asset Management				
Author:	Stephen Renshaw, Asset Strategy Specialist Peter Gaudron, Asset Management System Specialist Deepika Parihar , Substation Asset Strategist Timothy Blair, Substation Asset Strategist Sam Murali, Substation Asset Strategist Jeremy Culberg, Substation Asset Strategist Edward Luk, Asset Works Program Strategy Manager Hazem Khamis, Digital Infrastructure Asset Strategist				
Reviewers:	Adam Hoare, Digital Infrastructure Asset Manager Charles Kurniawan, Transmission Lines and Cables Asset Manager Evan Lamplough, Substations Asset Manager Debashis Dutta, Asset Analytics and Insights Manager				
Approver:	Andrew McAlpine, Acting Head of Asset Management				

A printed copy of this document may not be the current version. Please refer to the Wire to verify the current version.

Contents

List of Tables

List of Figures

List of Appendices

1. Purpose

The purpose of this document is to outline the methodologies and processes applied to calculate the current and future effective age of individual network assets, and the effective age and probability of failure mappings for each network asset class. This document supports:

- Effective and efficient risk based investment decision making.
- Achievement of the asset management objectives and ultimately the corporate objectives.

2. Scope

The scope of the Network Asset Health Framework (NAHF) is:

Asset Health for the following asset classes:

- Power transformers and oil filled reactors
- Circuit breakers
- Instrument transformers
- Transmission lines
- Protection relays
- Disconnectors and surge arresters

Probability of Failure for the following assets classes:

- Power transformers
- Oil filled reactors
- Circuit breakers
- Instrument transformers
- Disconnectors/Earth switches
- Surge arresters
- Transmission lines
- Protection relays

The NAHF provides more detail to support the principles set out in the Network Asset Risk Assessment Methodology.

3. Definitions

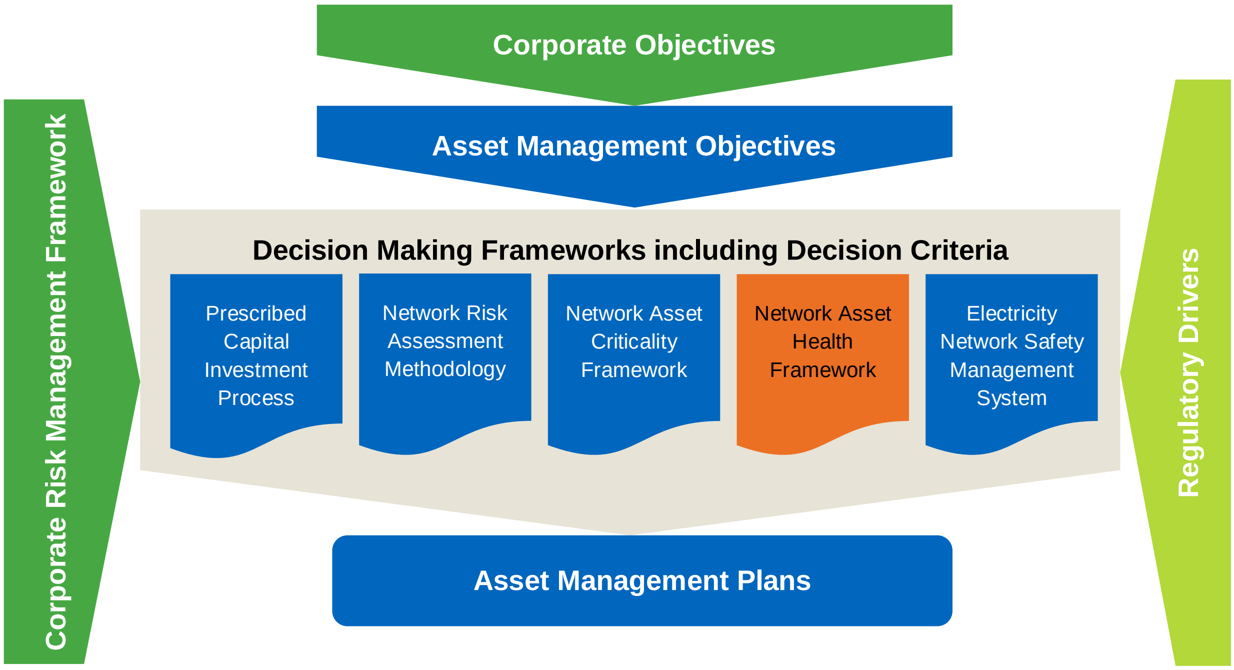
Key terms and definitions relating to the management framework or management system

Term	Definition
ALARP / SFAIRP	As Low As Reasonably Practicable (ALARP). For further details refer to Network Asset Risk Assessment Methodology.
Catastrophic failure	Catastrophic failure is when asset fails beyond repair, some of them could be explosive failure.
Conditional Failure	The inability of an asset to satisfy the operational/conditional limitations placed on it.
Effective Age	Apparent age of an asset based on its condition
Failure Mode	The way in which an asset failure occurs. e.g. conductor drop, tap changer failure, protection relay failure.
Functional Failure	The inability of an asset to perform its required function.
Life Ending Failure	Type of failure that destroys an asset beyond repair or when repair is uneconomical. Life ending failures can be catastrophic or non-catastrophic.
NACA	Network Asset Condition Assessment
Natural Age	Commonly known as “age”. Year elapsed since an asset’s first install date
Non-Failure Replacement	Replacement of an asset before it is allowed to fail
Probability of Failure (PoF)	Annual probability of a Life Ending Failure occurring.
Risk	The effect of uncertainty on achieving Transgrid’s objectives. Uncertainty can have positive and negative effects on objectives. Risk is the harm or damage (i.e. outcomes) that may occur from the occurrence of a hazardous event. Risk is measured in terms of consequence and likelihood.
Risk Assessment	A systematic process of risk analysis and evaluation.
Risk Consequence	The outcome of an event expressed qualitatively or quantitatively, affecting Transgrid’s objectives. There may be a range of possible outcomes associated with an event; these could have a positive or negative impact on objectives. The outcomes are categorised as financial, environmental (Inc. bushfire), reputational, safety (worker and public), compliance, and/or financial.
SME	Subject Matter Expert

4. Background

This document (Network Asset Health Framework) along with Network Asset Criticality Framework and Network Asset Risk Assessment Methodology forms the core network risk and investment analysis decision making framework at Transgrid. Figure 1 shows the overall framework of documents related to risk based decision making and the position of the NAHF.

Figure 1 – Decision Framework and Criteria



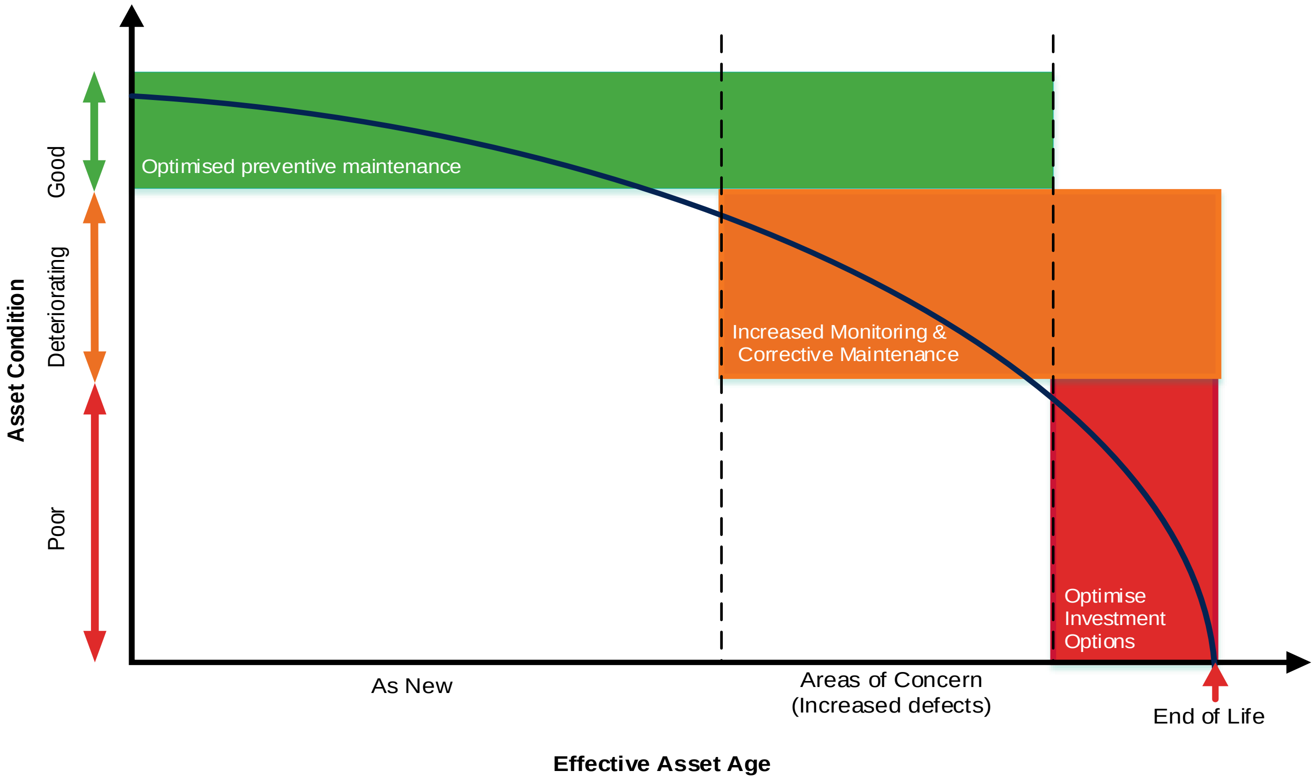
5. Framework

Asset Health is used to estimate the effective age of an asset and forecast the associated likelihood of failure of the asset now and into the future. The modelling takes input from current and historical asset information including failure, defect, maintenance, condition data, and operational/performance information. The inputs to the Asset Health model are given weightings according to their significance to overall longevity of the asset. The failure behaviour of these assets is modelled by using a statistical distribution and parameters that best fit the time to failure (or any other indicator of failure) determined by analysis of historical failure data. Asset Health is used as an input to the likelihood input to the risk assessment.

Asset Health supports the risk assessment by calculating a current health state for every major asset by comparing its health information (such as nameplate information, condition information, inspection/test results, defect/corrective maintenance data, and advice from maintenance staff) to the end-of-life criteria and thresholds for the asset type. These criteria and thresholds have been established from past experience with assets that have reached end-of-serviceable-life, expert advice and global best practice. The conditional health states map to an age (termed the Effective Age), and probability of failure, based on an understanding of the expected health of the asset at these ages, in respect of the end-of-life criteria and thresholds.

As the asset moves through its lifecycle (and Asset Health categories), the type of investment required (i.e. preventative maintenance, defect maintenance, replacement) to optimise the cost of investment against the performance and risk associated with the asset changes. Furthermore, the forecasted likelihood of failure of an asset is a conditional probability based on its remaining life (and Asset Health category). A typical asset lifecycle health (and investment) profile is shown in Figure 2.

Figure 2 – Network asset lifecycle health management profile



A number of techniques are used to gather this information about the health of the assets, including:

- Inspection and test results
- Condition assessment reports
- Historical failure data
- Historical and planned defect work data
- On-line Condition Monitoring data
- Operational and performance history information
- Equipment nameplate information (such as year of manufacture)
- Contextual information, such as location of the asset, and asset criticality
- Tacit knowledge including:
    - ‘Unstructured information’, for example anecdotal information such as irregularity reports, and advice from maintenance staff.
    - Feedback from the various asset management committees and working groups.
    - Subject matter expertise of experienced asset professionals and other staff.

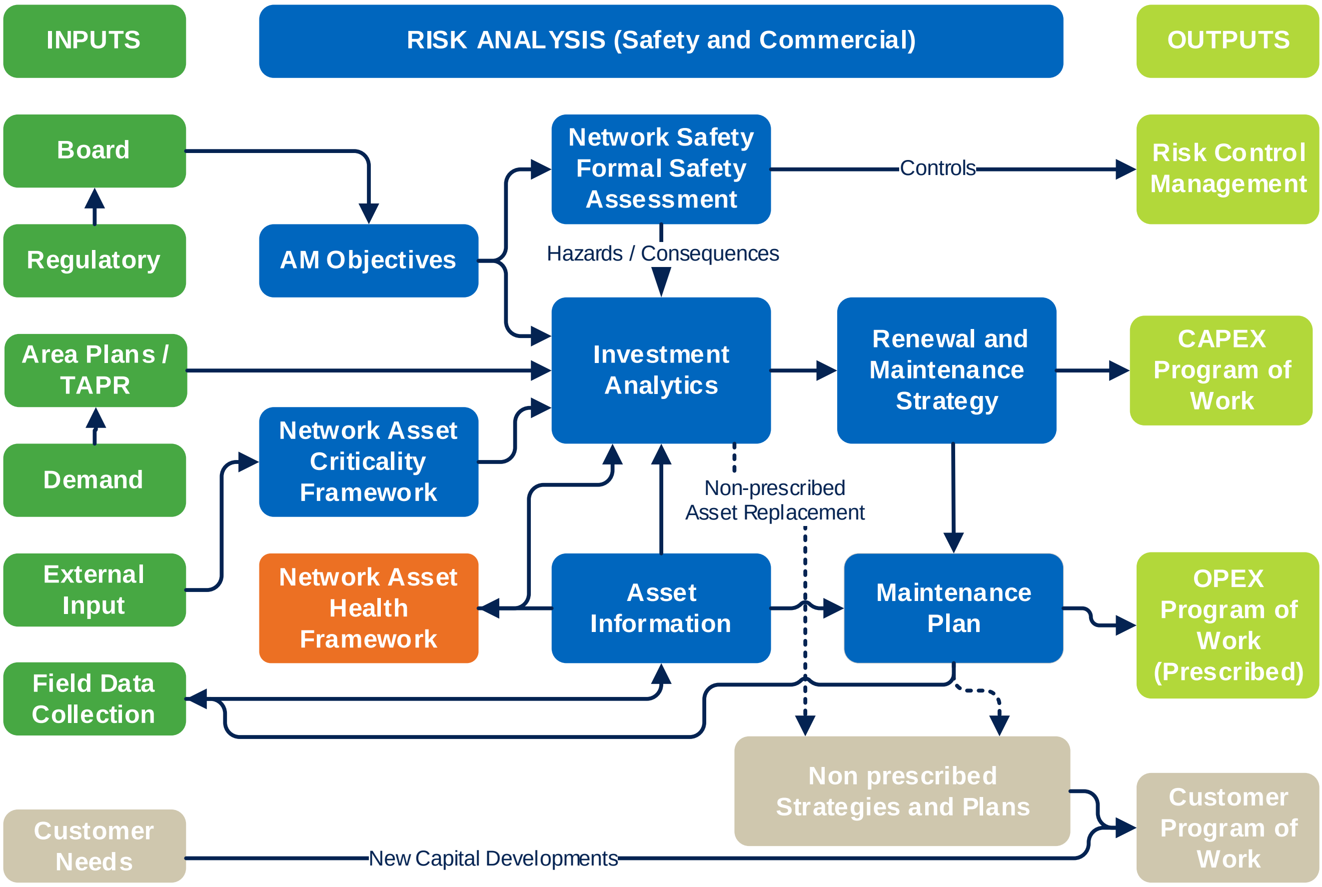
Furthermore, Asset Health leverages the component, failure mode and root cause analysis for the high potential incidents, as these are vital to determining the longevity of the asset.

Asset Health is used to identify which assets require detailed risk assessment and analysis.

6. Process / Calculation

The NAHF combines information on network assets, including their condition, surrounding environment, use, and failure modes, with engineering knowledge and practical experience of the performance of the assets to enable calculation of a probability of failure time series. This probability of failure time series, in conjunction with the asset criticality (refer to Network Asset Criticality Framework) provides the basis for quantification of asset failure risk in monetary terms, as illustrated in Figure 3.

Figure 3 – Risk Quantification Process



The outcomes from the NAHF are used to support risk assessments at all stages of the asset lifecycle.

The asset probability of failure and criticality information are used to:

- Quantify current and future risk for an individual asset for its class, thereby facilitating:
  - Risk based replacement versus refurbishment decision
  - Risk based maintenance optimisation
- Predict the number of failures, thereby facilitating:
  - Spares optimisation
  - Model network level risk for different expenditure scenarios

The key principles on which the methodology and processes of the NAHF are based upon are:

- An asset consists of different components each with a particular function, mission criticality, underlying reliability, life expectancy, and remaining life. The overall health of an asset is therefore a compound function of all of these component level attributes.

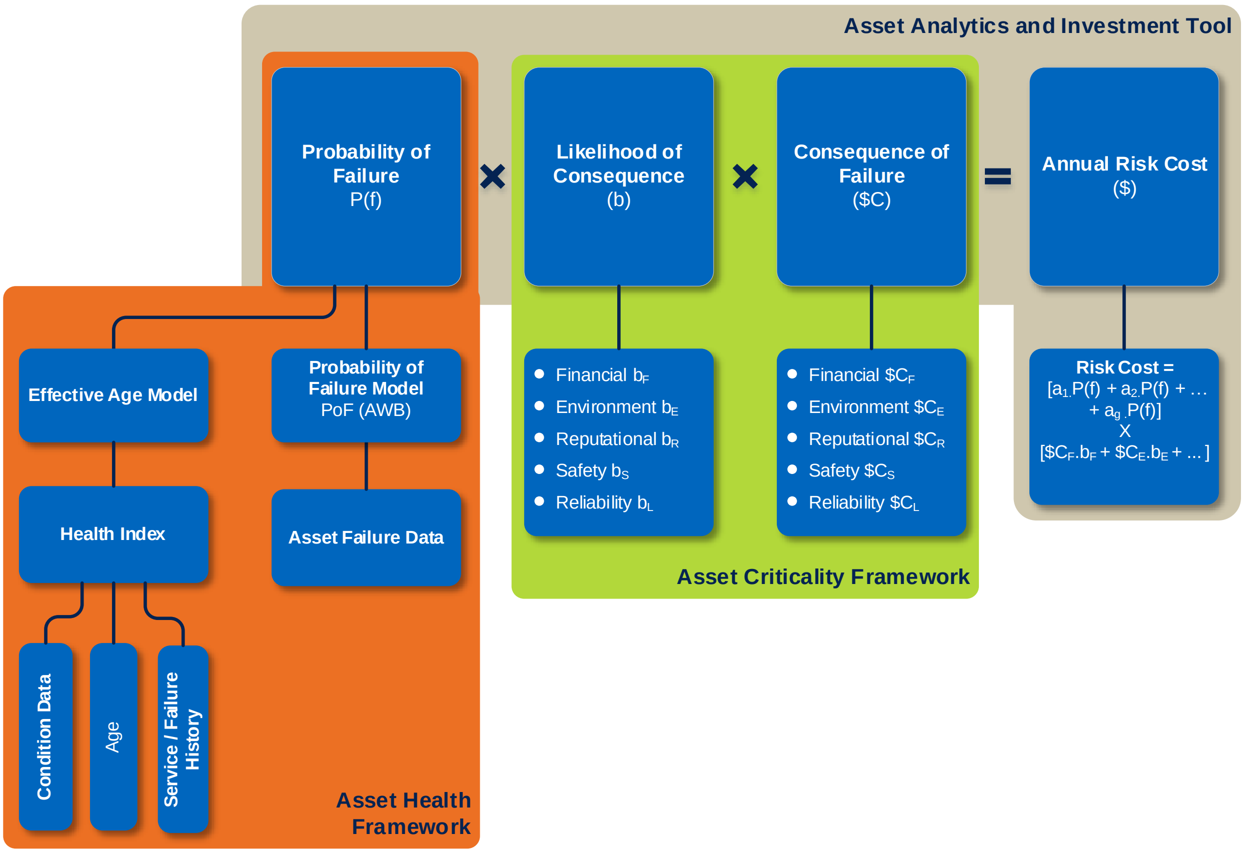
- Asset baseline information in addition to selected key asset condition measures and failure data can supply vital information on the current health of an asset.
- The future health of an asset (health forecasting) is a function of its current health and any factors causing accelerated (or decelerated) degradation or ‘age shifting’ of one or more of its components. Such moderating factors can represent the cumulative effects arising from continual or discrete exposure to unusual internal, external stresses, overloads and faults. Such ageing factors can provide valuable information in forecasting asset health for asset classes where information on degradation rates is available.
- Probability of failure of an asset can be modelled as a function of time (age), which generally follows one or more failure curves (for example, infant mortality, random, slow ageing, wear out) and can be modelled using the parameters of a Weibull distribution. Asset failure and replacement data can be used as inputs to specialised software (AWB) to identify failure behaviour and to obtain an appropriate failure curve.

The NAHF facilitates development of a comprehensive asset health system which produces the following data for each asset:

- ‘Current effective age’ is derived from asset information and condition data.
- ‘Future effective age’ (considering age acceleration/deceleration) is derived by ‘ageing’ and moderating ‘current effective age’ based on factors such as, external environment/influence, expected stress events and operating/loading condition.
- One or more mappings of effective age and probability of failure, derived from information on past failure events and replacement data.

The NAHF comprises two parts – Health and Probability of Failure (PoF) that lead to the calculation of the Conditional Probability of Failure as shown in Figure 4.

Figure 4 – Illustrates a Generic High Level View of the Health Module



6.1. Health Calculation

The outputs of the Health Module are the current and/or the future effective ages of an asset.

Table 1 – Inputs to Asset Health Calculation

Input	Description
Condition Data	Condition information from the field is used to input the actual degradation of assets.
Actual Age	Provides the actual age that is modified by condition and Service / Failure history to provide an Effective Age.
Service / Failure History.	Provides a loading on the asset that accounts for usage based and type issue failure modes, and in turn may adjust the expected calendar life of the asset. For example, if a circuit breaker is expected to be operated frequently, the cumulative effect of this will be accounted for in its forecasted effective age.

The list of factors to be considered for different types of assets is provided in Appendix A.

6.2. Probability of Failure Calculation

The outputs of the Probability of Failure (PoF) calculation are one or more probability of failure time series which provide a mapping between the effective age and the yearly probability of failure value for a given asset class. This analysis is performed by generating statistical failure curves, normally using Weibull analysis, to determine a PoF time series set for each asset that gives a probability of failure for each further year of asset life.

Figure 5 shows the high level view of the PoF calculation.

Figure 5 – High Level View of PoF Calculation

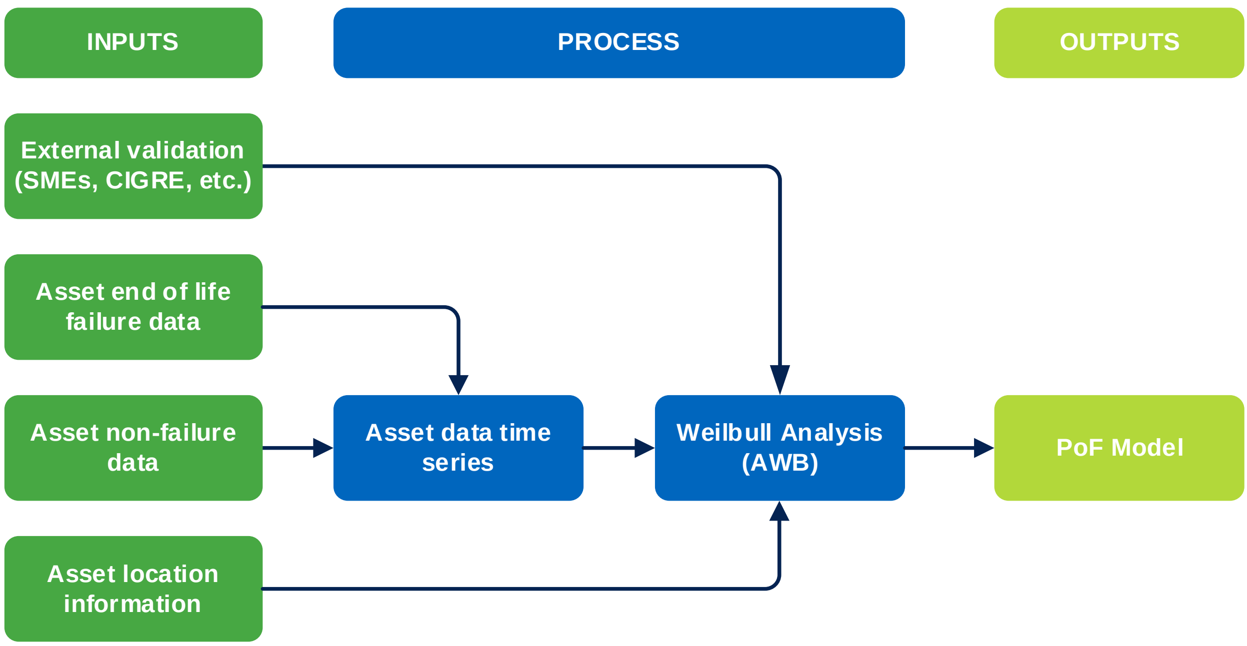


Table 2 – Input Factors to probability of failure information

Input	Description
External validation	Inputs are obtained from external sources including: • Subject matter experts (Tacit knowledge) • External forums such as CIGRE, ENA, etc. • Technical papers. This data provides sources of industry standard reliability performance for assets.
Asset end of life failure data	Provides actual in-service failure information where assets have reached end of life due to failure.
Asset non-failure data	Provides information on in-service and suspension data on assets that have not reached failure that assists the analysis software in producing accurate statistical failure probability curves.
Asset location information	For Transmission Lines, since steel corrosion is a dominant cause of failure for transmission towers, multiple probability of failure time series are produced to cater for different rates of steel degradation being situated in different corrosion zones. The forecasted probability of failure is obtained from its mapping to the forecasted effective age.

7. Accountability

Title	Responsibilities
EM / Network Planning and Operations	• Implement the controls to manage asset risks in accordance with the corporate Risk Management Framework and Network Risk Assessment Methodology • Oversight of the processes for the identification and management of asset risks, including the Network Asset Risk Management Framework and the Network Investment Process.
Asset Management Committee	• Review and endorse the Network Asset Health Framework
Head of Asset Management	• Approve and ensure the Network Asset Health Framework is fit for purpose. • Ensure consistent, effective, and efficient implementation of the Network Asset Health Framework. • Monitor the development of Need Statements and investment options.
Asset Systems and Compliance Manager	• Maintain currency the Network Asset Health Framework and compliance with management system requirements.
Asset Analytics and Insights Manager	• Review, endorse, and ensure consistency of Asset Health modelling information.
Asset Managers	• Identify key life ending failure modes, develop detailed health calculations for the assets in scope

	• Apply the Network Asset Risk Management Framework to assess and evaluate asset risk. • Develop Need Statements. • Develop investment options to address the asset risks.

8. Implementation

The NAHF will be implemented through:

- Discussions with business managers during the various asset management committee and working group meetings.
- Development of Needs Statements and Options Evaluation Reports including risk assessments consistent with this framework.
- Consideration, analysis, and evaluation of investment options through the Prescribed Capital Investment Process.
- Development of the asset management strategies and plans.
- Prioritisation and optimisation of capital expenditure at a portfolio level.

9. Monitoring and review

The NAHF is reviewed by stakeholders and endorsed by the Asset Management Committee regularly.

Asset Health is monitored and reviewed by the relevant Asset Manager at least annually or in response to an emerging issue, incident, or improved methodology.

10. Change from previous version

Revision no.	Approved by	Amendment
0	M. Jones, A/M/Asset Strategy	None. 1st issue
1	L. Wee, M/Asset Planning	• Proof reading • Health Indexing introduced in A.8 • Rearrangement within B.13
2	L. Wee, M/Asset Planning	Sections added for Transmission lines to include Concrete Poles, Electrical Induction Hazards, Underground Cables, and Easements.
3	A. McAlpine, Acting Head of Asset Management	All sections and appendices updated to processes being used in the 2021 Revenue Reset.

11. References

- Network Asset Risk Assessment Methodology
- Network Asset Criticality Framework
- NACA-SSAP – Protection Assets
- Relevant CIGRE Papers

Appendix A Health Indices

This section describes the methodology and detailed calculation of health and effective age of the asset classes (for Substation, Transmission Lines and Digital Infrastructure assets).

A.1 Substations

The Substation asset health index models have been developed based on analysis of Transgrid's in service asset population to identify how in service assets typically age and the change of their associated health indicators. Further detailed information is included in the substations asset health methodology.

The key inputs to this process are relevant asset information (nameplate data), condition data (for example, age, inspection results, and electrical/mechanical/oil test), design/type faults, historical defects, and external influences (e.g. corrosion, pollution, stress events, loading, and operation) as applicable. Input data points are selected based on availability and suitability for given assets and sub populations. The data points are combined to form an asset Health Index score (HI Score) with weightings based on their condition relevance, significance, currency. Health scores limits and weightings are typically derived from statistical observations for the asset population and/or tolerable condition monitoring parameters.

The health index score then provides relative condition adjusted health score which is used to estimate effective age.

Effective Age Estimation

The effective age of an asset is defined to be the condition adjusted age based utilising its health index score. The process of determining the effective age is described in the sections below.

The output of this process is the effective age which is used to determine the probability of failure for each asset.

Typical Ageing Model

The typical ageing model describes how an asset is expected to perform throughout its life (e.g. condition deterioration, diagnostic test results, emerging defects, reduced performance measurements) and provides a basis for evaluating each asset in comparison. The result is that assets will appear as older, younger, or equal to the expected ageing of that population.

A set of assets are established that represent the typical expected ageing throughout the service life of the asset, and should also include scenarios where assets are affected by dominant health index condition factors.

The typical ageing model provides feedback to support refinement of the HI index input weightings and once established sets the typical ageing correlation of 'average' assets to the evaluated ages.

Statistical model

The typical ageing model health index scores and evaluated effective ages form the input for the health index to effective age relationship model.

A review of the result of applying the Health Index score equation, typical ageing model, and the statistical model to current asset population is necessary to review effectiveness of the health index weightings and thresholds. A number of iterations of the process is necessary to achieve an outcome which provides consistently expected results across the population.

Power Transformer and Oil filled Reactor

This section outlines the health index methodology for oil filled power transformers reactors. It excludes the following asset types:

- SF6 type power transformers and reactors,
- Auxiliary transformers,
- Regulators,
- System spares,

Health Index Inputs

The health index is primarily based on the assessment methodology outlined in

- Cigre - 761 Condition Assessment of Power Transformers.
- IEEE - An Approach to Determine the Health Index of Power Transformers
- Transgrid - Substations Condition Monitoring Manual (D2014/09504)

Natural Age

The transformer's natural age is calculated from the year of manufacture which is typically on the transformer's nameplate or from manuals and drawings. The useful life of a transformer and oil filled reactor is 45 and 30 years as defined in Transgrid's Substation Renewal and Maintenance Strategy.

Dissolved Gas Analysis (DGA)

DGA is a key indicator of any abnormal thermal and electrical stresses that have occurred while the transformer is in service. Gases are produced due to the decomposition of the insulating mineral oil and paper. Various gases have different limits depending on the severity of the deterioration and typically indicate the temperature of the fault. The following gases are scored and weighted to determine the overall DGA score:

- Hydrogen
- Methane
- Ethane
- Ethylene
- Acetylene
- Carbon Monoxide
- Carbon Dioxide

Oil Quality (OQ)

OQ provides an indication of the transformer's thermal failure risk and any oil contamination that affects the transformer's life. The oil quality parameters listed below are scored and weighted, depending on the transformer's operating voltage.

- Breakdown Voltage (BDV)
- Moisture in Oil (PPM)

- Resistivity (RES)
- Dielectric Dissipation Factor (DDF)
- Interfacial Tension (IFT)
- Degree of Polymerisation (DP)

Bushing DDF

Dielectric dissipation factor (DDF) assesses the integrity of the insulation of the bushing. The assessment can detect excessive moisture or contamination in the bushing insulation system which can generate heating and/or dielectric breakdown. Bushings are scored based on the voltage level, bushing insulation and DDF measurements. The final score is dependent on the average and maximum DDF scores of the bushings installed on the transformer or reactor.

Quantity of Defects

Historic defect quantities and costs indicate the deterioration of key components of the transformer and reactor. They have been categorised in order to assess severity and impact on the effective age of the assets – tap changer, cooling and low voltage systems, main tank leaks and corrosion, condition drivers including insulation issues and other minor defects. The defect quantity and cost score is annualised based on the transformer's natural age or the review period of 20 years. The final score is weighted based on the category of the defect.

Load Score

The electrical power loading of the transformer affects the degradation of the transformer by increasing the temperature of insulating components which accelerates degradation. The load score is based on the average load of the transformer and excludes periods when the transformer is not in service. The number of phases and the rated capacity of the transformer are used to calculate the final load score.

Corrosive Score

Corrosive sulphur can form conductive compounds on insulating paper, disrupting the integrity of the paper leading to thermal insulation failure or electrical breakdown between adjacent conductors. Sulphur compounds coat selector switching contacts, creating loose sections of conductive silver sulphide. A score is determined based on whether the oil has corrosive sulphur, passivated or non-corrosive oil. This is confirmed by previous oil samples.

The transformer and oil filled reactor Health Index Score (HI Score) is calculated as a function of the health index inputs and corresponding weightings as outlined below:

Equation 1

$$HI\ Score = f(Natural\ Age, DGA, OQ, Bushing\ DDF, Defect, \ldots$$

$$\ldots\ Defect\ Cost, Load\ Score, Corrosive\ Score)$$

Effective Age Estimation

Assets with typical age and condition values are selected and have their health index calculated and an assessed effective age is applied. The relationship between health index and effective age is then derived from these data points. The modelled assets include a range of scenarios covering various aged assets and exhibiting good and poor condition.

Circuit Breaker

This section describes the data points, scaling factors and weightings which are applied in determining the overall circuit breaker health index score.

Health Index Inputs

Age Factors

The two factors that dominate the age and life consumption consideration for circuit breakers are natural age and operation count as recorded on the asset cyclometer. The health index utilises the leading age factor and an attenuated contribution from the lagging factor, this score sets the base score for effective age evaluation of the circuit breaker.

Natural Age

Circuit Breaker natural age is calculated from its first installed date. The threshold value in terms of natural age is set to 40 years. This is recommended by the major international bodies, such as CIGRE and industry practice and is also consistent with Transgrid's Substation Renewal and Maintenance Strategy (D2014/18645).

Operation Count (Cyclometer)

Circuit breaker cyclometer reading is obtained from AIM inspection results.

Circuit breaker operating statistics for the past 3 years are obtained from SCADA event logs to calculate the average number of operations (usage rate) per year. From the existing statistics and calculated annual usage rate, the number of operations for each circuit breaker can also be forecast to allow future evaluation effective age in future years.

The threshold value in terms of total number of operations is set to 7,000 operations. This figure represents the nominal operations based life expectancy of a circuit breaker and is based on various factors including:

- Nominal operation count limits specified by the manufacturer; these are typically electrical switching operations at or below nominal load current ratings.
- Mechanical endurance testing performed by the manufacturer to Australian Standards requirements to determine a technical classification of mechanical endurance.
- This is a type test which is performed in a factory environment, with continuous close-open operations performed over a short duration.
  This test is indicative of a durable design, however the object under test is not subject to electrical load and age & environmental deterioration.
- Variability of production line quality compared to the test object.
- Transgrid experience of asset performance supports increased risk of high cost, severe and life ending failures for circuit breakers with high operation counts and rates.

Reactive Switching

The type of switching duties are categorised into reactive and non-reactive switching. Circuit breakers performing reactive switching have increased contact wear rates and reduced switching service life. The reactive switching factor is also scaled by the operating duty and so will affect the effective age score progressively with operations (cyclometer).

This approach to shortened operating life expectancy for reactive switching is consistent with manufacturer recommendations.

Performance Factors

Performance factors are based on available asset performance data which includes defect count, defect cost, and condition monitoring (CM) result exceptions against identified limits.

The assets performance factors are evaluated against performance thresholds and can reduce or increase the effective age compared to the natural age.

The combination of these factors in the Health Index equation is designed to take the leading factor as the dominant score which impacts the health index, while the lagging factors have an attenuated contribution. This method reduces a moderate accumulation of multiple factors from having an excessive effect and adjusting effective age.

Defect Count

The historical defect data is sourced from Ellipse defect work orders and available data. The total number of recorded defect instances are identified against each asset and used as an input for the HI calculation.

Defect counts provides an indication of past issue frequency and in the context of the health index is indicative of an ongoing trend for each asset. Assets with high statistical defect count are considered to have an increased risk of presenting future defects with increased risk of a defect resulting in a life ending scenario.

Defect Cost

The historical defect data is sourced from Ellipse defect work orders and available data. The sum of all recorded actual defect costs are identified against each asset and used as an input for the HI calculation.

Defect cost provides an indication of past issue severity and in the context of the health index, is indicative of an ongoing trend for each asset. Assets with high statistical defect cost are considered to have an increased risk of presenting high cost and severe future defects with increased risk of a defect resulting in a life ending scenario.

Condition Monitoring Results

The historical condition monitoring result data is sourced from AIM as obtained through maintenance activities. The results are from non-intrusive diagnostic testing with exceptions identified where the results exceed limits established in the Condition Monitoring Manual.

Test parameters include open and close timing, contact resistance and insulation quality with only the latest test result for each parameter evaluated.

Condition monitoring result exceptions provide an indication asset condition trends based on non-intrusive test methods. Assets with high statistical condition monitoring result exceptions are considered have an increased risk of presenting operationally urgent defects increased risk of a resulting in a life ending scenario.

Type issues

The type issues factor is applied to circuit breaker asset sub populations and requires a strategy to have been identified and approved; these affected sub populations are included in the Substations Renewal and Maintenance Strategy.

Type issues that have been identified are typically associated with historical circuit breaker designs and technologies where there is an inherent vulnerability in the design, frequent and severe failures are observed, manufacturer technical and parts support has been withdrawn. A type issue is identified where such factors credibly impact on the expected service life of circuit breaker sub population which increases the risk of a defect resulting in a life ending failure.

Health Index Formula

The circuit breaker Health Index Score (HI Score) is calculated as a function of the health index inputs as outlined below:

Equation 2

$$HI\ Score = f(Natural\ Age, Cyclometer, Reactive\ Switching, Defect\ Count, \ldots$$

$$\ldots\ Defect\ Cost, CM\ Results, Type\ Issues)$$

Effective Age Estimation

Assets with typical age and condition values are selected and have their health index calculated and an assessed effective age is applied. The relationship between health index and effective age is then derived from these data points. The modelled assets include a range of scenarios covering various aged assets and exhibiting good and poor condition.

Instrument Transformer

Overview

The instrument transformers (ITs) in Transgrid's network are mainly of two types – oil insulated IT and SF6 gas insulated IT. Epoxy resin ITs are also installed at lower voltage levels but their population is much smaller than SF6 and oil insulated ITs. As the population of SF6 and resin insulated ITs is relatively small and they are young, a health index has not been developed for them.

Oil insulated ITs have risk of explosive failure and are part of aged units on the network. Therefore this document is primarily reviewing health index of oil insulated ITs. Instrument Transformers can experience failures in service either due to:

1. Design and manufacturing defects,
2. System stresses that are over the design limit, for e.g. lightning strike; and
3. Ageing or degradation due to system stresses over time.

The first type of failures are usually infant mortality or classified as type issues when proven to be found with particular batch of equipment. These type of failures are also detectable via DGA analysis to some extent, usually in forms of partial discharge or low temperature faults. Monitoring rate of rise of gases after detection of abnormal gases is another efficient methods in pre-detection of failure. Current HI accounts for type issues in assessment.

The knowledge of system stresses is often considered during the procurement stages, in rare few occasions either system stresses increase over time or were underestimated during acquisition process. This types of failures cannot be predicted and dealt operationally as incident happens. In some cases these types of failures could be detected or identified via DGA analysis after the fault has occurred.

The third type of failures as identified in CIGRE TB 725 are caused by environmental, thermal, and electrical stresses on the network. Environmental stresses include moisture ingress, which accelerates ageing as seals deteriorate and ITs start to leak while in service. Moisture ingress in paper-oil insulation degrades its insulating properties and subsequently increases the risk of failure.

The key diagnostic methods for condition assessment of instrument transformers as per research are PD (partial discharge) and DGA including oil quality along with information of leak and corrosion to validate the cause of moisture ingress. Transgrid has well established oil database and current used DGA analysis has proven to be a useful tool in condition assessment of oil filled ITs.

In regards to DGA analysis, Transgrid has periodic condition assessment review of ITs via review of DGA results. Based on this review, the rise of gases like C_2H_2 above the acceptable limit will warrant immediate action and are therefore not useful for long term replacement planning based on a slow but steadily increasing risk of failure. These actions are listed in Transgrid's substation condition monitoring manual.

Therefore the following parameters are included in the Health Index scoring:

- Age
- H_2O measurement in ppm (indication of moisture ingress in paper) and;
- DGA analysis.

Health Index Method Summary

Table 3 provides a summary of the methodology adopted for each type of equipment. Gas insulated switchgear (GIS) substations are excluded from this process.

Table 3 – Summary of health index methodology for each equipment type

Equipment	Health index methodology	Effective age
Oil CTs	Derived from natural age, DGA score, moisture and type issues	Effective age calculated from health index model
Oil-Sand-Paper insulated CTs	As per Oil CTs	Effective age calculated from health index model
SF6 or epoxy CTs	Not used	SF6 CTs have been installed more recently, are generally in mid-life and leaks are the most significant issue being experienced. Natural age is used.

Oil Current Transformers

The inputs used to determine the health index are described in this section, including the relative weighting and the formulae.

In Transgrid's network, there are some oil insulated CTs which have sand or quartz filled in along with oil. Filling of sand provides mechanical strength to the conductor and also reduces quantity of oil in these CTs. The design was aimed at reducing the consequences of oil CT failure such as large oil spill.

Health Index Formulae

The oil current transformer Health Index Score (HI Score) is calculated as a function of the health index inputs as outlined below:

Equation 3

$$HI\ Score = f(Natural\ Age, DGA, Moisture\ Scoring, Type\ Issues)$$

Health Index Inputs

Dissolved Gas Analysis (DGA)

The limits for the DGA component of the health index is determined from analysing actual DGA results of last 10 years and determined lower and upper limits for each age group using percentile method along with consideration of Transgrid's substation condition monitoring manual.

A weighting has then been applied to reflect the relative importance of detection of each gas. If the level is in the lower or upper limits the corresponding weighting is used to get the DGA score.

Moisture

Similar to DGA analysis, moisture limits and scores are determined for each group using statistical analysis of existing moisture results from last 10 years and multiplied by a weighting to derive moisture score.

Age

The age factor for CTs over the age of 40 is included such that a CT with age of 40 years or more will be modelled with accelerated ageing. While 40 years is the nominal technical life, as outlined in the Substations renewal and maintenance strategy, a unit may still survive past this point but will be subject to accelerated but the risk of a life ending failure during this period increases and is typically not acceptable beyond 50 years old for these types of CT.

Type Issues

Transgrid has experienced a number of failures of hairpin CTs of particular manufacturers based on Transgrid's asset failure history.

Effective Age Calculation

Assets with typical age and condition values are selected and have their health index calculated and an assessed effective age is applied. The relationship between health index and effective age is then derived from these data points. The modelled assets include a range of scenarios covering various aged assets and exhibiting good and poor condition.

SF6 Current and Voltage Transformers

The determination of HI for gas CTs and VTs is considered impractical at present since there are insufficient measurements available which can be used to determine the progress of ageing of individual units.

Until further analysis is performed, natural age should be used. Defects arising from routine inspections or alarms received are to be used as moderators of the natural age as the Asset Managers see fit.

Natural ages for gas CT or VT are calculated from their first installed date. Nominal life expectancy in terms of natural age is approximately 40 years, beyond which health is assumed to be deteriorating at a faster rate. This is consistent with Transgrid's *Substation Renewal and Maintenance Strategy* (D2014/18645).

Oil Magnetic Voltage Transformers

Health Index Formulae

The instrument transformer Health Index Score (HI Score) is calculated as a function of the health index inputs as outlined below:

Equation 4

$$HI\ Score = f(Natural\ Age, DGA, Moisture\ Scoring, Type\ Issues)$$

Health Index Inputs

DGA

The DGA limits and scoring are as per the process for oil filled CTs. The DGA scoring is excluded from the effective age calculations of units without any DGA results (for example types without sampling valves fitted).

Natural Age

The age factor for MVTs over 40 is included such that a MVT aged >=40 years will be modelled with accelerated ageing. 40 years is the nominal technical life, as outlined in the Substations renewal and maintenance strategy.

Effective Age Estimation

Assets with typical age and condition values are selected and have their health index calculated and an assessed effective age is applied. The relationship between health index and effective age is then derived from these data points. The modelled assets include a range of scenarios covering various aged assets and exhibiting good and poor condition.

Capacitive Voltage Transformers

Unbalance monitors are fitted to all CVTs and are effective in identifying the majority of faults developing in CVTs likely to lead to failure. When alarms are received the CVTs will be taken out of service and investigated. The reason for the alarm will then determine the appropriate action to be taken (return to service, repair, or replace). This is effective as an emergency / short term strategy which necessitates a high quantity of spares in hand.

An effective age calculation may be developed in the future. Therefore, until further analysis is performed, natural age should be used. Defects arising from routine inspections or alarms received along with known type issues.

CVT natural age is calculated from its first installed date. Nominal life expectancy in terms of natural age is approximately 40 years, beyond which health is assumed to be deteriorating at a faster rate. This is consistent with Transgrid's Substation Renewal and Maintenance Strategy (D2014/18645).

Disconnector

There are about 5,180 disconnectors and earth switches installed in Transgrid's network. Out of which 20% of the population is aged over 40 years, which is the typical expected nominal life of a disconnector. There is currently no health index and effective age calculation undertaken for disconnectors. However the inputs below are considered to confirm disconnector health and are included in the decision criteria for end of life renewal:

- Age profile
- Condition assessments (IWR N2314)
- Site location – corrosive vs non-corrosive
- Known type issues and site issues
- Defect data with consideration of accuracy and cost of defects
- Engineering judgement and field staff's experience of working with these disconnectors

Surge Arrester

Post completion of the gapped surge arrester replacement program, the majority of the surge arresters in the network would be of gapless type.

At present, there is no condition data on surge arresters. A few of them have base current monitoring installed which can indicate rapid deterioration of health. For longer term strategic management of the surge arresters, the natural age should be used. Defects arising from ad-hoc inspections and estimated number of expected operations (that is, for example, due to switching surge, direct strike) are to be used as moderators of the natural age as the Asset Manager sees fit.

Surge arrester natural age is calculated from its first installed date. Nominal life expectancy in terms of natural age is approximately 40 years, beyond which health is assumed to be deteriorating at a faster rate. This is consistent with Transgrid's Substation Renewal and Maintenance Strategy (D2014/18645).

Auxiliary Transformer

Auxiliary transformers within the Transgrid network are lightly loaded, and have no moving parts. Due to inherent design simplicity, reduced operating temperatures and sealed oil insulation systems, the auxiliary transformers have a longer expected asset life than power transformers. Key health indicators are:

- DGA measurements (primary condition indicator)
- Defects, particularly leaks
- Electrical measurements taken during maintenance

For dry type auxiliary transformers only rely on visual inspections and some electrical measurements taken during maintenance. Natural age is calculated from its first installed date. Nominal life expectancy in terms of natural age is approximately 50 years, beyond which health is assumed to be deteriorating at a faster rate. This is consistent with Transgrid's Substation Renewal and Maintenance Strategy.

Capacitor banks and air cored reactors

There is limited condition data available on capacitor banks and air cored reactors. These include:

- Visual inspection

- Defects, particularly hot joints and failure of individual capacitor cans
- External reactor insulation deterioration (visually identified)

These considerations are given when considering individual asset health along with the natural age which is the primary indicator of health. The availability of spares, particularly spare capacitor cans, also provides an input in the asset's viability for continued service.

Capacitor and air core reactor natural age is calculated from its first installed date. Nominal life expectancy in terms of natural age is approximately 35 years, beyond which health is assumed to be deteriorating at a faster rate. This is consistent with Transgrid's Substation Renewal and Maintenance Strategy.

Capacitor cans will lose capacitance over their life, and can fail through leaks. Both visual inspection and thermography can inform the condition of the capacitor bank.

Similarly, for air core reactors, visual and thermographic inspection can provide information with respect to the condition of the reactor.

The supporting steelwork degrades over time, and will require renewal.

Substation gantry steelwork

A population wide health index has not been developed for substation gantry steelwork. Routine inspections have identified those substations which are approaching the end of their life and detailed inspection, condition assessment and modelling is then undertaken. This results in identification of the steelwork's end of life through comparison of the time to reach the allowable loss of steelwork to the structural loads on the steelwork. The overall process is:

- Measure existing loss of galvanic protection and structural steelwork
- Develop structural model
  - determine existing loading on members
  - calculate expected future member loads based on current condition and expected corrosion rate
- Determine end of life and increasing annual probability of failure for critical components

A.2 Transmission Lines

The approach taken to calculate transmission line health is based on the following factors:

- A transmission line is a compound group of many asset components.
- Transmission lines are geotropically distributed and all of its components function together to provide a service.
- A single failure of a key component makes the transmission line service unavailable.

The key principles upon which the transmission line asset health methodology is based upon are:

- The transmission line asset consists of a number of structures/spans, each of which contributes to the health of the overall line.
- The individual structure/span consists of a compound group of components, each with a particular function, underlying life expectancy, reliability, and as a result, at any particular point in time, the remaining life.
- The overall health of an individual structure/span is a function of the health of each component.
- The components selected for asset health calculation are those where a failure can result in a conductor drop or loss of electricity supply. Failures of these components are primarily

managed by the implementation of preventative controls, which Transgrid is primarily responsible for as the network service provider. These are considered to be the main components of risk exposure on a transmission line.

- The components identified are:
  - Structures (~STR), encompassing the four constructions:
    - Steel towers
    - Steel poles
    - Concrete poles
    - Wood poles
  - Foundations (~FND)
  - Conductors (~CON)
  - Insulators (~INS)
  - Conductor fittings (~CFI)
  - Overhead earthwire (~OHEW)
  - Earthwire fittings (~OFI)
- A single failure of a key component can make the transmission line service unavailable.

Current Health

Asset condition information is the primary source of information on the current health of the transmission line and its components. Condition information obtained through routine inspections of transmission lines, such as condition rating of each component, and asset information, such as natural age, location, and ideal life expectancy, form the basis for deriving current health. Other asset baseline information, such as the natural age of the asset, can supplement inspection condition data to inform asset health. The effectiveness of the inspection in assessing the condition of the relevant transmission line component will influence the level of reliance on other asset baseline information.

The health assessment of a component is a calibration of its length of effective service and remaining service potential. It is based on the aforementioned factors, and assessed through application of experienced engineering judgement in line with industry practices.

The health assessment is typically represented as a percentage of its expected life, and is known as the effective age. Factors causing accelerated or decelerated degradation of the component may result in a difference between its effective age and its natural age, referred to also as “age shifting”.

A health score or effective age of 100% is representative of the end of functional life of an asset/ component. Where an asset/component has functionally failed, it is deemed to be beyond the end of functional life and is assigned a health score of greater than 100%.

The health assessment is a calculation taken at a point in time. The future health of the asset/component is a forecast based on the last available health assessment.

The outcomes from the transmission line health calculation are used to support risk assessments at all stages of the asset lifecycle. The component effective age calculations are used in the Asset Analytics and Investment Tool (AAIT)

Condition Data

Condition data is the primary input into the asset health calculation and is obtained through the following routine inspections:

- Climbing inspections: Applicable for all components on all transmission line constructions
- Underground inspections (UGIs): Applicable to the structure component on wood pole constructions only

Transgrid undertakes inspections on all its transmission lines structures/spans, in accordance with the frequencies specified in the *Transmission Line Maintenance Plan*. It is expected that condition data is available at every structure/span in Transgrid's network for input into the health assessment. The inspection data attributes are specified in the *Transmission Line and Easement Condition Data Collection* specification document.

Inspection data is collected through the Asset Inspection Manager (AIM) platform. Condition data from the relevant data attributes in AIM applicable to the selected component is used as input into the health assessment.

Life Expectancy

The expected life of a transmission line varies depending upon its individual components. The individual components can be broadly categorised as electrical conductors, supporting structures and fittings.

The nominated expected lives of the transmission line components are obtained from subject matter experts, which are verified against industry practice and knowledge. This includes assessment of the impact of location geography and baseline asset information on the expected life.

The expected lives listed in the following sections align the values in the Transmission Lines Renewal and Maintenance Strategy.

Structures

Steel Structures

The expected life of steel tower and steel pole structures is dependent on the atmospheric corrosion zone in which it is located. Corrosion of the steelwork, leading to loss of steel and associated structural capacity occurs at a faster rate in locations exposed to a higher level of atmospheric corrosion.

Asset baseline information which specifies the corrosion zone and construction type at a structure/span location is used to determine the applicable expected life. The expected life values for steel structures are listed in Table 4.

Table 4Table 4 – Expected life (years) for transmission line steel structures by corrosion zone

Component	Expected life C1	Expected life C2	Expected life C3	Expected life C4
Steel Tower Structure	94	94	75	57
Steel Pole Structure	85	85	75	55

Concrete Pole Structures

The expected life for all concrete pole structures is 85 years. This expected life applies across all geographical locations. Asset baseline information which specifies the construction type is used to determine the applicable expected life.

Wood Pole Structures

The expected life for all wood pole structures is 63 years. This expected life applies across all geographical locations, including both moderate and high termite hazard zones. Asset baseline information which specifies the construction type is used to determine the applicable expected life.

Foundations

Steel Tower Foundations

The expected life for foundations on steel tower structures is 90 years. This expected life applies across all geographical locations. Note steel tower grillage foundations are not considered as part of this health framework, and their expected life is beyond the scope of this assessment.

Steel Pole Foundations

The expected life for all foundations on steel pole structures is 85 years, which aligns with the expected life of the steel pole structures. This expected life applies across all geographical locations. Asset baseline information which specifies the construction type is used to determine the applicable expected life.

Concrete and Wood Pole Foundations

No expected life values have been assigned for concrete and wood pole foundations. This is due to the availability of AIM condition information relating to the foundations of both construction types.

Conductors

The expected life for all conductors is 90 years. This expected life applies across all geographical locations.

Conductor Fittings

The expected life of conductor fittings is dependent on the atmospheric corrosion zone in which it is located. The steelwork on these items generally has a significantly thinner layer of galvanising at the time of manufacture compared with other tower steelwork due to fabrication processes. These reach end of life when the zinc galvanising layer has been sacrificed, which occurs more quickly in locations exposed to a higher level of atmospheric corrosion. The expected life values for conductor fittings are listed in Table 5.

Table 5 – Expected life (years) for transmission line conductor fittings by corrosion zone

Component	Expected life C1	Expected life C2	Expected life C3	Expected life C4
Conductor Fittings	80	70	55	45

Insulators

The expected life for insulators is dependent on the type of insulator installed and is shown in Table 6. AIM condition data which specifies the type of insulator installed at any particular transmission line structure is used to determine the applicable expected life of that component.

Table 6 – Expected life (years) for transmission line Insulators

Component	Expected life
Porcelain and Glass Disc Insulators	50
Composite (both Long rod and Post) Insulators	25

Overhead Earthwire

The expected life for overhead earthwire is 90 years.

Note this expected life applies across all geographical locations. No differentiation has been made for the type of earthwire on the transmission line i.e. SC/GZ earthwire. This is due to the availability of both transmission line nameplate data and AIM condition information for overhead earthwires.

Overhead Earthwire Fittings

As with conductor fittings, the expected life of overhead earthwire fittings is dependent on the atmospheric corrosion zone in which it is located, due to the level of galvanising on these items at the time of manufacture. As typically smaller components compared to conductor fittings, overhead earthwire fittings are expected to have even lower levels of sacrificial galvanising and accordingly, shorter expected lives. The expected life values for conductor fittings are listed in Table 7.

Table 7 – Expected life (years) for transmission line overhead earthwire fittings by corrosion zone

Component	Expected life C1	Expected life C2	Expected life C3	Expected life C4
Overhead Earthwire Fittings	65	60	45	40

Natural Age

Transmission line natural age information provided as part of the annual Regulatory Information Notification (RIN) is used. In general, this is derived from the relevant year of construction information as follows:

Equation 5

Natural age = (Current year – Year of construction)

Location

Transmission lines are geographically distributed and each structure/span can be subject to different environmental effects specific to its location. These environmental effects impact the ideal life expectancy of the asset and its components. The expected life of a component in an operating environment is based from Transgrid's experience in operating the transmission network, technical knowledge, as well as industry guidelines and research. Transmission line structures/spans are assigned a geographical classification, based on their location. These are:

- Atmospheric corrosion zone, based on AS 4312-2008: Applicable to steel components
  - C1: Very Low
  - C2: Low
  - C3: Medium
  - C4: High
  - C5: Very High (no Transgrid transmission line assets are considered to be in a very high category)
- Termite zone, based on the CSIRO Termite Hazard Map: Applicable to wood poles
  - Low (no Transgrid transmission line assets are considered to be in a low category)
  - Moderate
  - High

Wood rot zoning has not been applied to structure/span locations.

These location based geographical classifications may be used to influence the respective life expectancies of the various transmission line components, and health scores of various AIM condition assessment ratings

Determination of Transmission Line Health from Sub-component Health

A health score is calculated for each component at every transmission line structure/span location. It is a combination of two elements:

- Natural Age
- Condition Score

The health score calculation is a weighted sum of the abovementioned elements, as shown in the equation below:

Equation 6

$$Health\ Score = \alpha_1(Natural\ Age) + \alpha_2(Condition\ Score)$$

Where α denotes the weightings applied to the respective elements. These weightings vary with each component type accordingly.

Natural Age

Transmission line natural age information provided as part of the annual Regulatory Information Notification (RIN) is used. Each structure/span is assigned a relevant year of construction. The natural age is calculated as follows:

Equation 7

$$Natural\ Age = Current\ Year - Year\ of\ Construction$$

Condition Score

Condition score is essentially the ‘Life Expiry’ of each component and is defined as the percentage functional life of the component which has expired or already been used. The life expiry is an empirically estimated percentage value which denotes used life of each component based on the condition ratings of each of its relevant attribute codes. In mathematical terms, (1 – Life Expiry) is the percentage remaining life of the component.

The life expiry data is unique to each attribute of every component and also varies by construction type, structure type, and corrosion zone and termite category. This life expiry data is used to create a 'Scaling Index' table unique to each component of the span. For components FND and STR, the scaling index table is unique for each component and construction type combination.

The overall condition score of each component is the weighted sum of all life expiry values for each of the component's relevant attributes based on the recorded condition ratings.

Effective Age Calculation

The health assessment of a component is typically represented as a percentage of its expected life and is known as the effective age. Factors causing accelerated or decelerated degradation of the component may result in a difference between its effective age and its natural age, referred to also as "age shifting".

As with the health score, an effective age is calculated for each component at every transmission line structure/span location, and is represented by the following equation:

Equation 8

$$Effective\ Age = Health\ Score \times Expected\ Life$$

A.3 Transmission Line Health Framework

Details of the health score and effective age calculations for each of the relevant transmission line components, including the relevant applied weightings, condition scoring, and life expiry mapping to condition data associated with inspection records, can be found in the Transmission Line Health Framework document.

Interfacing with Transmission Line Probability of Failure

Several PoF time series are presented in Section B.16, Transmission Line Probability of Failure. Currently, the following PoF time series are used to 'look up' the probability of failure values, in consideration of:

- Component: e.g. type of structure (steel tower, wood pole, concrete pole) and insulator etc.
- Component type: e.g. ACSR/GZ vs AAAC conductor, or porcelain vs composite insulators etc.
- Exposure to condition deterioration factors: e.g. atmospheric corrosion action for steel, heating events for conductor etc.

Given the current or future ideal effective age, as well as the structure types and locations, an appropriate PoF value is 'looked up'.

A.4 Digital Infrastructure

There are predominantly three types of protection, control, metering and telecommunications assets that are currently in-service in the network: electromechanical, solid state and microprocessor based. They differ from each other in terms of life expectancy, modes of failure and capabilities.

Similar to other assets, the health of a digital infrastructure asset can be determined from observing the conditions of the equipment and key sub-components. Determining health this way would be deterministic but cost prohibitive as these would require a substantial amount of effort for the value it will return. Even then, there can be a degree of uncertainly that inspections will identify conditions sufficiently enough to contribute into the health calculation in a useful way.

Moreover, although not directly related to health as such, manufacturers' support and availability of spares have a significant influence on the overall feasibility of a relay to remain in the network.

Throughout this section, digital infrastructure asset health is therefore from a combination its natural age, life expectancy, relay type, manufacturers' support and spares availability and the historical defect rates for the asset.

In scope of this section, protection relay health is determined based on the following factors:

- Age factor
- Relay type
- Obsolescence/Support availability
- Historical defects

Age Factor

Age factor is determined from the relay's natural age and its life expectancy. This is outlined as follows:

Equation 9

$$Age\ factor\ =\ natural\ age\ /\ life\ expectancy$$

For this calculation, natural age is currently calculated as age since commissioning of the relay. This ratio is not capped at unity and therefore if the natural age is greater than nominal life expectancy, the value can be greater than unity.

Age factor is assigned a score. This is outlined in the following table:

Table 8 – Age Factors

Age Factor	Score
>100%	10
<=100% and >80%	8
<= 80% and > 50%	6
<= 50%	3

Asset Type

Life expectancy, failure modes, accuracy, reliability etc. of protection relays are different across different asset types. Microprocessor based assets have a shorter life, although they offer additional benefits such as, the ability to implement multiple functions within the same unit, to self-monitor and alarm, minimise risk of dormant failures, offset additional operating expenditure through increased testing etc. Solid state and electromechanical assets tend to provide only minimal functionality often requiring increased numbers of devices, lack self-monitoring requiring additional maintenance, and testing to ensure availability.

Based on the above, various scores are assigned to the different relay types. This is outlined in the following table:

Table 9 – Asset Type factors

Type	Score
Solid State	9
Electromechanical	6
Microprocessor	3

Higher values indicate higher contribution to the overall deterioration of health.

Obsolescence/Support Availability

Manufacturers' support and technological obsolescence are a major contributor in determining if a particular make/model of relay is strategically suitable in the longer term. The risk associated with lack of support and obsolescence is due to an exposure of not being able to operate the assets to their full capability and to return assets to service within the required timeframe.

Based on the above, various scores are assigned to the different support availability/obsolescence scenario. This is outlined in the table below:

Table 10 – Obsolescence/Support factors

Support Availability/Obsolescence	Score
Obsolete - No Support - Cannibalised spares	10
Obsolete >10% of population - No Support	8
Obsolete <10% of population - No Support	6
No Obsolescence, Limited Support	5
Limited support - Manufacturer may repair failed units (min 1 spare available)	3
Full support - spares can be purchased	1

Higher values indicate higher contribution to the overall deterioration of health.

Historical Defect Rates

The historical performance of the asset group is analysed and the defect rates are summarised into a three year average. A three year historical view of defects rates provides a reasonable measure of the performance of the asset model and is an assisting lead indicator of future performance.

To represent the contributions from a range of defect rates, various scores are assigned to the different forecast defect rate scenarios. This is outlined in the table below:

Table 11 – Forecast defect rates

Forecast Defect Rates	Score
> 7.5%	10
<= 7.5% and > 5%	8
<= 5% and > 3%	6
<= 3% and > 1%	3
<= 1%	1

Higher values indicate higher contribution to the overall deterioration of health.

Health Index

The overall health of a protection relay is determined from the above three factors and can be expressed as per the following equation:

Equation 10

$$Health\ Index\ =\ (Age\ Factor\ +\ Asset\ Type\ +\ Spares\ and\ Support\ +\ Historical\ Defects)/32$$

The divisor equates to the sum of all sub scores with relay type set to 2. This has been set in such a way to allow for assets to exceed their nominal health of "100%" whereby all critical scores are 10.

Digital Infrastructure asset health index currently ranges from 0% to 120%.

The Health index is currently used as a multiplier against nominal life of an asset to establish its effective age.

A.5 Appendix A - Summary

Table 12 – Summary reference and data sources

Section no.	Equipment	Sub-section Description	Parameter	Reference	Data Source
A.1	Power Transformer and Oil filled Reactor	Natural Age	Natural Age	**Equation 1**	Ellipse, Asset Register
		Dissolved Gas Analysis (DGA) Score	Dissolved Gas Analysis (DGA) Score		Ellipse, Asset Condition
		Oil Quality (OQ)	Degree of Polymerisation (DP)		Ellipse, Oil sample result
			Breakdown Voltage (BDV)		Ellipse, Oil sample result
			Moisture in Oil (PPM)		Ellipse, Oil sample result
			Resistivity (RES)		Ellipse, Oil sample result
			Dielectric Dissipation Factor (DDF)		Ellipse, Oil sample result
			Interfacial Tension (IFT)		Ellipse, Oil sample result
			Oil Quality (OQ)		Ellipse, Oil sample result
		Bushing DDF	Bushing DDF Score		Ellipse, Field inspection
			Insulation Type Score		Ellipse, Field inspection
		Defects	Defect Group		AIM, Issue and Defect WO
		Cost of Defects	Cost of Defects Score		Ellipse, Defect WO
		Load Score	Load Score		SCADA/AMIP
			Temp Score		Calculation
		Corrosive Score	Corrosive Score		Oil sample analysis
	Circuit Breaker	Age Factors	Natural Age	**Equation 2**	Ellipse, Asset Register
			Operation Count (Cyclometer)		AIM & SCADA Event Log
			Reactive Switching		Ellipse, defect inspection
		Performance Factor	Defect Count		AIM, Issue and Defect WO
			Defect Cost		Ellipse, Defect WO
			Conditioning Monitoring Results		Measurement, AIM via PowerBI

Section no.	Equipment	Sub-section Description	Parameter	Reference	Data Source
			Type Issues		Renewal & Maintenance Strategy
	Instrument Transformers	Instrument Transformers Oil Current Transformers	Natural Age HI and threshold and HI at threshold	**Equation 3**	Calculation
			Dissolved Gas Analysis (DGA) limits in ppm		Ellipse, Oil sample result
			Moisturising Score		Calculation
			Age		Ellipse, Asset Register
			Type Issues		Renewal & Maintenance Strategy
		SF6 Current and Voltage Transformers	Natural age, nominal life expectancy		Calculation
		Oil magnetic Voltage Transformers	Health Index Formulae for Oil Filled MVTs	**Equation 4**	Calculation
		Capacitive Voltage Transformers	Natural age		Ellipse, Asset Register
	Disconnector	Disconnector	Health Index/Effective Age calculations	N/A, consider other factors	
	Surge Arrester	Surge Arrester	Natural age, nominal life expectancy		Ellipse, Asset Register
	Auxiliary Transformers	Auxiliary Transformers	Natural age, nominal life expectancy		Ellipse, Asset Register
	Capacitor banks and air cored reactors	Capacitor banks and air cored reactors	Natural age, nominal life expectancy, availability of spares		Ellipse, Asset Register Condition assessments
	Substation gantry steelwork	Substation gantry steelwork	Health index	N/A, routine inspections	AIM, external modelling
A.2	Transmission Line	Transmission Line	Health index	N/A, consider other factors	
			Current health		AIM Inspection Data, Experience engineering judgement and industry practice

Section no.	Equipment	Sub-section Description	Parameter	Reference	Data Source
			Condition Data		AIM Inspection Data, Routine Inspection (example climbing, underground inspection)
		Life expectancy	Life expectancy of structures	Table 4	Renewal and Maintenance Strategy Document subject matter experts and verified against industry practice and knowledge
			Life expectancy of foundations		Renewal and Maintenance Strategy Document subject matter experts and verified against industry practice and knowledge
			Life expectancy of conductors		Renewal and Maintenance Strategy Document subject matter experts and verified against industry practice and knowledge
			Life expectancy of conductor fittings	Table 5	Renewal and Maintenance Strategy Document subject matter experts and verified against industry practice and knowledge
			Life expectancy of conductor insulators	Table 6	Renewal and Maintenance Strategy Document subject matter experts and verified against industry practice and knowledge
			Life expectancy of conductor earthwire		Renewal and Maintenance Strategy Document subject matter experts and verified against industry practice and knowledge
			Life expectancy of conductor fittings	Table 7	Renewal and Maintenance Strategy Document subject matter experts and verified against industry practice and knowledge
		Natural Age	Natural Age	**Equation 5**	Ellipse, Asset Register
		Location	Qualitative description		Ellipse, TSS, CSIRO Termite Hazard Map, Australian Standard AS 4312-2008

Section no.	Equipment	Sub-section Description	Parameter	Reference	Data Source
		Determination of transmission line health from Sub-component health	Health Score	**Equation 6**	Transmission Line Health Framework in line with industry practice and knowledge
			Natural Age	**Equation 7**	Ellipse, Asset Register
			Condition Score	1-Life Expiry	Ellipse, industry practice and knowledge, AIM Inspection Data, Routine Inspection
			Effective Age Calculation	**Equation 8**	Ellipse, AIM Inspection Data, Industry practice and knowledge
			Probability of Failure	Transmission Line Health Framework, looked up value, B.3	Availability Work Bench
A.3	Digital Infrastructure	Age Factor	Age Factor	**Equation 9**	Ellipse, Asset Register
			Age Factor score	Table 8	Ellipse, Asset Register
		Asset Type	Asset type factor	Table 9	Ellipse, Asset Register
		Obsolescence/Support Availability	Obsolescence/Support factor		Ellipse, Asset Register, Asset Inventory, Manufacturer notices
		Historical Defect Rates	Historical Defect Rates	Table 11	AIM: Issue, Condition Data, Ellipse: Defect WO
		Health Index	Health Index	**Equation 10**	SSA Tool Excel, AWB, Ellipse: Asset Inventory

Appendix B Probability of failure

B.1 Overview

As time passes, installed assets deteriorate, their reliability decreases and their chance of failure increases. The rate at which their chance of failure increases depends on their capability to withstand the aggregated influence of factors arising from a multitude of simultaneously applied forces, actions, and reactions. Predicting failure behaviour this way is deterministic but very complex in nature.

Another method of predicting the chance of a failure is via observation of past failures of an asset/component. In this process, asset specific past failures are assessed in terms of their 'time to fail' information. Together with some prior knowledge of that specific failure behaviour, "time to fail" information is able to provide a relationship between an asset's age and its probability of failure at that age.

Throughout this section, past failure data is used to model the probability of failure of an asset as a function of time (its age). Based on the root causes of the dominant failure modes, the function generally follows one or a combination of multiple standard curves (that is infant mortality, random, slow ageing, wear out and worst when old). Fitting the 'time to fail' data to an appropriate statistical distribution is fundamental in this process.

Using the parameters of a Weibull distribution, all the standard failure curves can be expressed. The adopted approach expresses a probability of failure time series for each asset in terms of a set of Weibull parameters.

Availability Workbench 2 (AWB) by Isograph is the specialised software used to perform distribution fitting.

Approach

The below approach is taken to obtain probability of failure for a given asset class or subclass:

- Obtain all available failure data.
- Analyse and exclude failure events that did not result in an asset replacement. Exclude early childhood failures, failures due to incorrect design/install or maintenance. This gives a list of asset replacements resulting from life-ending failures at the 'wear out' stages of their lives.
- Obtain the individual natural ages at which these failures occurred (time to fail).
- Obtain all non-failure asset data including their natural ages (time to fail).
- Input the 'time to fail' data set for life-ending failures to AWB
- Input the 'time to fail' data set for in service population data to AWB and mark as 'suspended'.
- Run simulation and observe the resultant Weibull parameters and the failure curve.
- Verify the outcome based on Transgrid experience and available external sources (utilities, CIGRE, other international study) and calibrate as required.

PoF Distribution

As evident from the approach above, resultant PoF values are rather probabilistic than deterministic in nature. Therefore, it is necessary that the PoF values are expressed not only in terms of their 'the most likely values' but also with a level of errors around them in order to indicate the confidence level.

It is also evident from the approach that resultant PoF values are checked for correctness and are verified and validated against multiple sources. This indicates that the level of errors in the output is significantly low.

Assumptions

Throughout this exercise, only end of life probability of failure is modelled. This implies that the failure curves will not exhibit any infant mortality or early childhood behaviour.

B.2 Substations

Transformer

The approach outlined in B.1 is applied to obtain the probability of failure for transformers.

Modelled Data

A total of 43 life-ending failure events since 1979 were collected, and verified. The earlier failure events were excluded from this modelling due to a low level of confidence on data accuracy. In addition, given the current transformer fleet in the network, certain historic failures do not apply to the analysis since the current design and technology of transformers are significantly different to that of older transformers. Any ’infant mortality’ type failures were also excluded from the modelling. Based on this data, a total of 23 transformer failures since the year 2000 were considered.

The current in-service population was used as suspended data points.

Simulation

The above data were collated in a spreadsheet and imported into AWB. Multiple simulations were run to fit a distribution.

A 2-parameter Weibull distribution appeared to be the best fit with a R^2 ‘goodness of fit’ value of 99%. The resultant Weibull distribution parameters are:

- η = 54.21
- β = 3.61

Oil Reactor

Oil filled reactors are very similar to transformers in terms of their design, build, components and failure modes. Therefore, the transformer probability of failure model is used as the baseline, with inapplicable failure data points excluded and certain parameters altered to model oil filled reactors.

Modelled data

The following changes to the transformer failure data set were made to prepare the oil filled reactor failure rate data set:

- Failure data related to tap changer removed.
- Failure data related to bushings halved.

The oil filled reactor failure data set consisted of 15 life-ending failures.

The current in-service population was used as suspended data points.

Simulation

The above data were collated in a spreadsheet and imported into AWB. Multiple simulations were run to fit a distribution.

A 2-parameter Weibull distribution appeared to be the best fit with a R^2 value of 97%. The resultant Weibull distribution parameters are:

- η = 38.84
- β = 2.95

Circuit breaker

The approach outlined in B.1 is applied to obtain the probability of failure for circuit breakers.

Modelled data

Circuit breaker failure data since the year 2005 was collected and verified. 'Infant mortality' type failures were also excluded from the modelling. A total of 32 life ending failures were obtained and used in the modelling`.

The current in-service population was used as suspended data points.

Simulation

The above data were collated in a spreadsheet and imported into AWB.

A 2-parameter Weibull distribution appeared to be the best fit with a R^2 value of 96.8%. The resultant Weibull distribution parameters are:

- η = 47.76
- β = 4.3

Oil CT

The approach outlined in B.1 is applied to obtain the probability of failure for oil CTs.

Modelled data

Oil CT failure data since the year 2005 was collected and verified. 'Infant mortality' type failures (that is, oil CTs which have failed in early years from their first installation date) were excluded from the modelling. A total of 35 life ending failures were obtained and used in the modelling.

The current in-service population was used as suspended data points.

Simulation

The above data was collated in a spreadsheet and imported into AWB. Multiple simulations were run to fit a distribution.

A 2-parameter Weibull distribution appeared to be the best fit with a R^2 value of 98.5%. The resultant Weibull distribution parameters are:

- η = 85.95
- β = 3.08

The result of the modelling was reviewed in line with expected performance of the CTs and it was identified that the available data was not sufficient to provide a realistic representation of the failure performance of CTs. The key limitations in the available data which have led to an erroneously high η are:

- Unavailability of data points from installation through to end of life
- Expectation of a significantly higher number of asset failures experienced which have not been recorded

The manufacturing design life is usually only 40 years and other industry standards also calls for design life of current transformers to be in range of 35-50 years. This was further validated by in-service population data of current transformer at Transgrid and less than 3% of current transformers in network are above 50 years indicating that aged assets beyond this point is generally not accepted.

Therefore the following Weibull parameters have been selected based on a reasonable estimate of the true probability of failure:

- η = 50
- β = 3.08

With η = 50, the probability that 90% of assets would fail by 65.7 years of age and 99% of assets will fail by 82 years of age reflects an upper end of the expected performance for CTs.

MVT

The approach outlined in B.1 is applied to obtain the probability of failure for MVTs.

Failure data

Oil MVT failure data since the year 2001 was collected and verified. 'Infant mortality' type failures were excluded from the modelling. A total of 29 life ending failures were obtained and used in the modelling.

Simulation

The above data were collated in a spreadsheet along with in-service MVTs and imported into AWB. Multiple simulations were run to fit a distribution.

A 2-parameter Weibull distribution appeared to be the best fit with a R^2 value of 97.7%. The resultant Weibull distribution parameters are:

- η = 65
- β = 2.9

The value of β being 2.9, indicates ageing failure modes, given infant mortality is excluded from modelling. This is consistent with expectation for ageing with oil-paper insulated CTs. However the η value of 65 is too high for MVTs. The manufacturing design life is usually only 40 years and other industry standards also calls for design life of MVTs to be in range of 35-50 years. This was further validated by in-service population data of MVTs at Transgrid and less than 1.5% of MVTs in the network are above 50 years of age.

Therefore the following Weibull parameters have been selected based on a reasonable estimate of the true probability of failure:

- η = 50
- β = 3.8

CVT

The approach outlined in B.1 is applied to obtain the probability of failure for CVTs.

Modelled data

CVT failure data since the year 1996 are collected and verified. 'Infant mortality' type failures were excluded from the modelling. A total of 33 life ending failures were obtained and used in the modelling.

The above data was collated in a spreadsheet and imported into AWB along with in-service assets as suspended failures. Multiple simulations were run to fit a distribution.

A 2-parameter Weibull distribution appears to be the best fit with a R^2 value of 99%. The resultant Weibull distribution parameters are:

- η = 78
- β = 3.5

The value of β being 3.5, indicates ageing failure modes, given infant mortality is excluded from modelling. This is consistent with expectation for ageing with CVTs with capacitive elements and oil insulation. However the η value of 78 is too high for CVTs. The manufacturing design life is usually only 40 years and other industry standards also calls for design life of CVTs to be in range of 35-50 years.

This was further validated by in-service population data of CVTs at Transgrid and less than 1.5% of CVTs in the network are above 50 years of age and only 0.7% CVTs are greater than 55 years of age with oldest CVT being 62 years of age.

Therefore the following Weibull parameters have been selected based on a reasonable estimate of the true probability of failure:

- η = 50
- β = 3.8

With η = 50, the probability that 90% of assets would fail by 63 years of age and 99% of assets will fail by 77 years of age reflects the expected performance for CVTs based on their design and use in the network.

Disconnector

Due to a lack of life ending failure data on disconnectors, modelling based on failure data is not possible at present. However, there is sufficient information available in a CIGRE study that can be leveraged off in order to arrive at a probability of failure time series for the disconnectors.

However, a CIGRE study provides sufficient information to enable development of a probability of failure time series for disconnectors.

Failure data

Nil.

Simulation

The CIGRE failure rates were replicated in AWB by adjusting the Weibull parameters. The resultant parameters for a 2-parameter Weibull distribution are:

- η = 107
- β = 2.2

Verification

The CIGRE study provided the source data. No further verification was performed.

Calibration

The following advice was received from the SME:

- The probability of failure time series, solely based on the CIGRE study, fails to demonstrate the influence of age-related failure behaviour on disconnectors that are significantly old. The oldest disconnector group used in the study were 40 years of age, whereas Transgrid has in-service disconnectors that are up to 58 years old.

To model this age-related behaviour, the Weibull distribution parameters were adjusted to exhibit 'worst when old' failure behaviour. The resulting probability of failure time series was subsequently added to the CIGRE originated probability of failure time series.

The outcome of the process was verified in consultation with the SMEs and is considered to be acceptable. The probability of failure time series for disconnectors is expressed by use of a 2-parameter Weibull distribution. The resultant parameters of the Weibull distribution are:

- $\eta = 67$
- $\beta = 4.8$

Surge arrester

Due to a lack of life ending failure data on surge arresters, modelling based on failure data is not possible at present. A probability of failure time series for surge arrestors was developed by studying their key life ending failure modes, technical life expectancy, and average service life. The aggregated influence of these factors was then modelled in terms of Weibull distribution parameters.

Simulation

Investigation of available data on surge arrestors indicated the following:

- Technical life expectancy of 40 years
- Average service life of 35 years
- Dominant failure mode being seal deterioration due to ageing resulting in moisture ingress (high base current running the apparatus hotter)

A 'wear out' type behaviour calibrated with the technical life expectancy of surge arrestors appears suitable. The resultant parameters for a 2-parameter Weibull distribution are:

- $\eta = 55$
- $\beta = 3.2$

Auxiliary Transformers

The following parameters have been selected based on:

- the lack of available failure data for auxiliary transformers (they are usually replaced when the associated main transformer is replaced to achieve replacement efficiencies)
- they are usually long lasting, reflecting a high eta
- an expected wear out characteristic similar to other assets based on similar construction and degradation mechanisms.

- η = 70
- β = 4.5

Capacitor Banks

The following parameters have been selected based on:

- the lack of available failure data for capacitor banks
- an expected wear out characteristic similar to other assets based on similar construction and degradation mechanisms.

  - η = 50
  - β = 4.5

Substation gantry steelwork

The probability of failure has been determined based on development of the specific structural modelling of the relevant gantry and the expected load cases that will be applied to that gantry.

B.3 Transmission Lines

A slightly different approach is taken to calculate transmission line health as opposed to the substation assets due to the following factors:

- A transmission line is a compound group of many asset components.
- Transmission lines are geotropically distributed and all of its components function collaboratively to provide a service.
- A single failure of a key component makes the transmission line service unavailable.

Background

A key input into the quantification of asset risk is the probability of failure of the asset. For the transmission line asset class, the approach taken was to identify the key components and their functions, different failure modes of those components and relevant causes. The key components of transmission line systems are:

- Structures
  - Towers
  - Concrete Poles
  - Wood Poles
- Insulators
- Conductor and Earthwire Fittings
- Conductor and Earthwire
- Easements

Condition Assessments

Condition assessments were undertaken for each asset by Works Delivery and in some instances, expert reports were commissioned.

Inspection data is collected through the Asset Inspection Manager (AIM) platform. Condition data from the relevant data attributes in AIM and defect data available in Ellipse applicable to the selected component are used as input into the development of probability of failure curve.

A probability of failure was assigned to each individual component in accordance with their various assessed conditions.

Probability of Failure calculation

Structures – Towers

Results taken from the condition assessments, based on the assigned condition code ranging from 1 to 6, were used to estimate the existing amount of steel loss on the towers. The estimates were based on section loss measurements and galvanising readings taken from specialised condition assessments and the opinion of Subject Matter Experts. The estimates are shown in Table 13.

Table 13 – Expected Existing Steel Loss on Towers

AIM Condition Rating	NACA Asset Rating Condition	Description	Suggested Thickness Loss µm 8 x 8 x 11/16	Suggested Thickness Loss µm 1 ¾ x 1 ¾ x3/16	% Loss
1	1	> 20% Metal Loss	1.691	0.310	20
2	2	Flake Rust	0.843	0.155	3-10
3-4	3	Rust	0.210	0.039	1-2
5-6	4	50% Rust	0.084	0.015	0.5
7-8	5	First Rust	0.042	0.008	0
9-10	6	No Rust	0.000	0.000	Galv

In order to account for ongoing corrosion, the atmospheric level of corrosion (taken from AS 4312) was considered to determine the estimated rate of metal loss, following the depletion of the zinc galvanising. This varied by region, and each line section was assessed in accordance with its geographic corrosion zone to calculate the expected steel loss and hence probability of failure. Generally, the regions could be defined as follow:

- Low: Greater than 20km from the coast.
- Medium: Between 10km and 20km from the coast
- Medium/High: Within 10km from the coast

The calculation of probabilities for steel tower structures has been based on historical design wind loads on Transgrid towers. At this stage, the probability estimates are limited to the 330kV class of towers only (but can be adopted for 500kV). The 1300Pa wind pressure adopted for the 330kV towers corresponds to a return period (RP) of 1,000 years (refer to AS1170.2). Based on this, the probability of failure from exceedance of the 1,000 year RP event is 0.1% per tower year, or 5% in 50 tower years, the typical design life of the tower.

In the calculation of the probabilities of failure, each member is premised on an initial loss of section, and subsequent further loss over the years based on the corrosion environment. In accounting for corrosion and associated steel loss, the load carrying capacity of tower members is related linearly to the loss of steel area in any part of the section. As a simplification, it has been assumed the load capacity has a linear relationship with the applied wind pressure on the structure.

The actual failure data of towers in Transgrid's system has been used to moderate the predicted probability of failure calculation described above. Since 1959, there have only been seven failure events (total of 18 towers) in 330kV single circuit towers (none for double circuit) with a total sum of years in service of

413,562. Thus, from the incidence of failures of 330kV single circuit towers per year of 0.000017, the equivalent RP would be approximately 50,000 years. Whilst there is no suggestion that the design RP is actually 50,000 years, it is recognised that for a number of reasons such as tower utilisation, terrain effects, span lengths, prevailing wind direction and line orientation, a RP of 1,000 can be considered conservative. Based on a tower utilisation of 90%, typical within Transgrid's network, an increase in wind speed of 5% would be required to exceed the tower design force. This would require the RP to increase to approximately 2,500 years, and in consideration of these factors, a 2,500 year RP is considered a conservative but not inappropriate figure on which to base the probability calculations.

The following estimated values from Table 12 have been used in the calculation of the probability of failure tables and curves for each condition, as shown below.

Initial NACA Condition 6

- All galvanising intact
- No metal loss
- 0.00% probability of failure associated, therefore no probability curve.

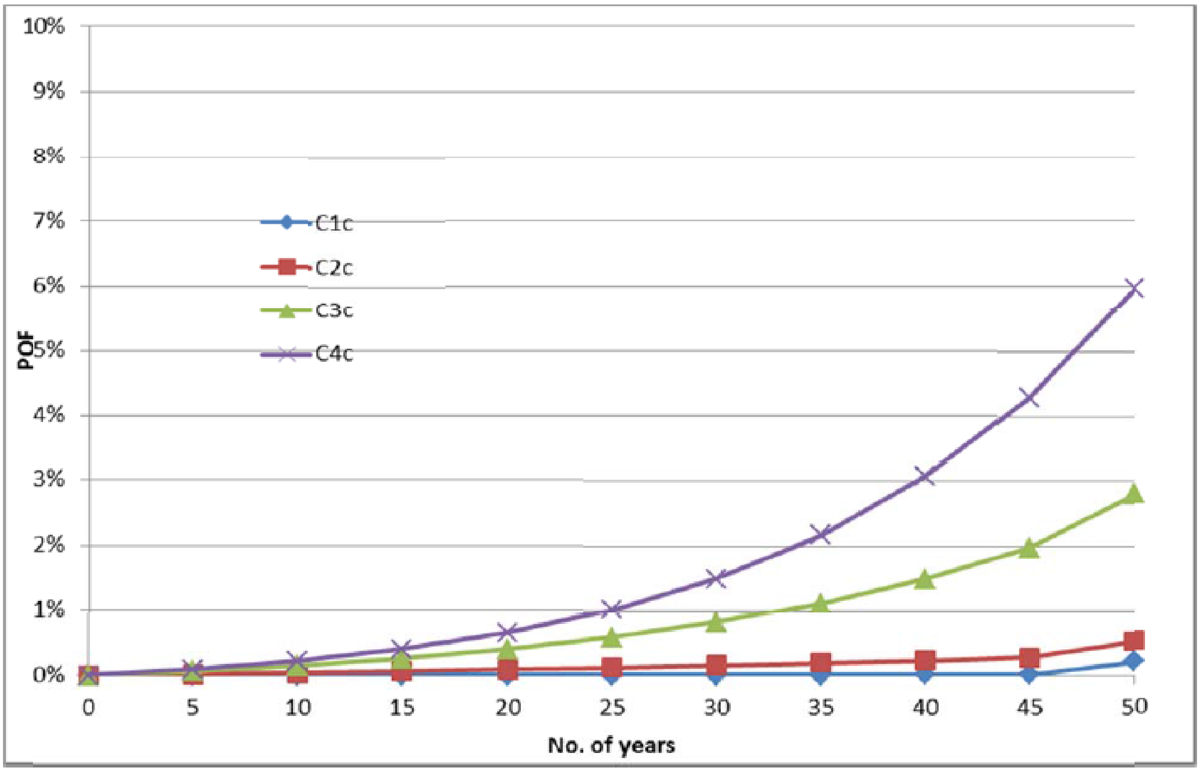
Initial NACA Condition 5

- All galvanising lost
- No metal loss
- Probability curve shown in Figure 6.

Table 14 – Steel Tower Probability Curve: Initial Condition 5

Tower member		8 x 8 x 11/16				initial loss (μm)		0.000	0%
Corrosion zone		C1	C2	C3	C4	$C1_c$	$C2_c$	$C3_c$	$C4_c$
loss μm/year		0.65	13	37.5	50				
	PoF just to wind 5 yearly	Probability (%) of failure due to wind event with corrosion of steel.				Increased probability (%) of failure only due to corrosion of steel (see assumptons).			
0	0.20%	0.040%	0.040%	0.040%	0.040%	0.000%	0.000%	0.000%	0.000%
5	0.20%	0.201%	0.221%	0.266%	0.292%	0.001%	0.021%	0.066%	0.092%
10	0.20%	0.202%	0.244%	0.351%	0.422%	0.002%	0.044%	0.151%	0.222%
15	0.20%	0.203%	0.269%	0.462%	0.605%	0.003%	0.069%	0.262%	0.405%
20	0.20%	0.204%	0.296%	0.605%	0.861%	0.004%	0.096%	0.405%	0.661%
25	0.20%	0.205%	0.326%	0.789%	1.215%	0.005%	0.126%	0.589%	1.015%
30	0.20%	0.206%	0.359%	1.024%	1.704%	0.006%	0.159%	0.824%	1.504%
35	0.20%	0.207%	0.395%	1.323%	2.370%	0.007%	0.195%	1.123%	2.170%
40	0.20%	0.208%	0.434%	1.704%	3.278%	0.008%	0.234%	1.504%	3.078%
45	0.20%	0.209%	0.478%	2.183%	4.504%	0.009%	0.278%	1.983%	4.304%
50	0.20%	0.210%	0.524%	2.793%	6.171%	0.210%	0.524%	2.793%	5.971%

Figure 6 – Steel Tower Probability Curve: Initial Condition 5



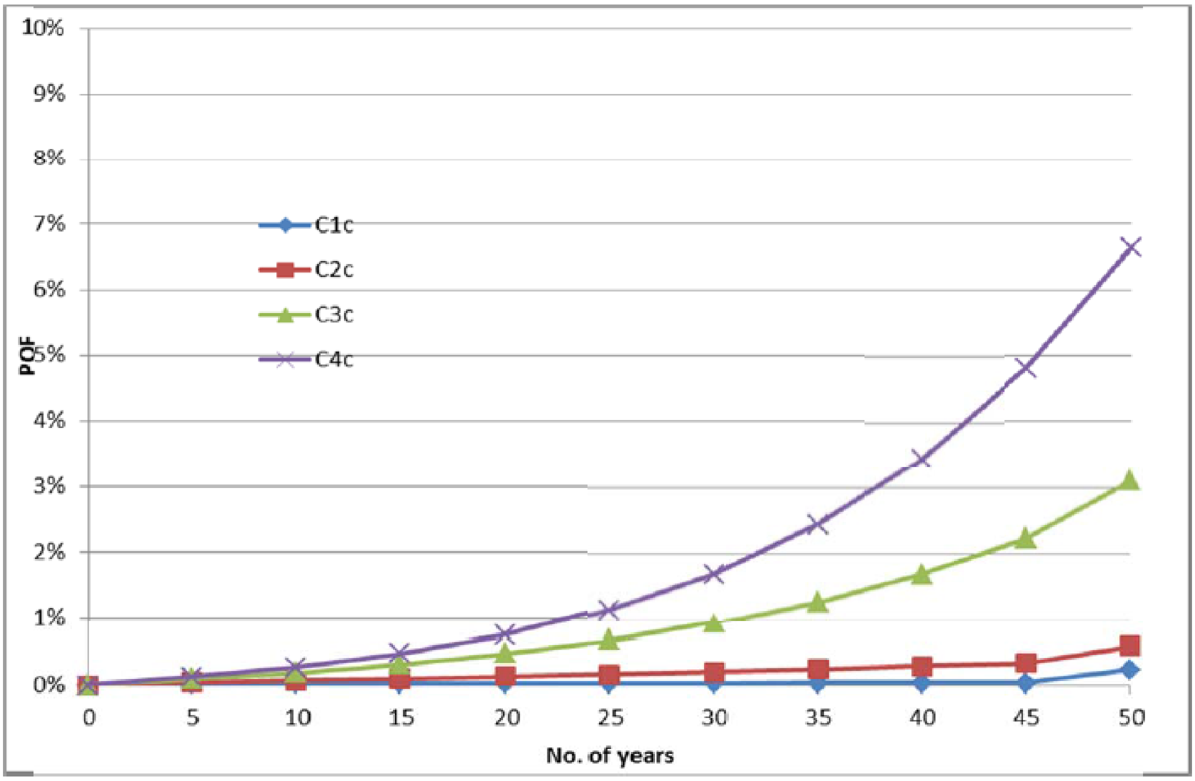
Initial NACA Condition 4

- All galvanising lost
- 1% metal loss
- Probability curve shown in Figure 7

Table 15 – Steel Tower Probability Curve: Initial Condition 4

Tower member		8 x 8 x 11/16				initial loss (µm)		0.084	1%
Corrosion zone		C1	C2	C3	C4	$C1_c$	$C2_c$	$C3_c$	$C4_c$
loss µm/year		0.65	13	37.5	50				
	PoF just to wind 5 yearly	Probability (%) of failure due to wind event with corrosion of steel.				Increased probability (%) of failure only due to corrosion of steel (see assumptons).			
0	0.20%	0.045%	0.045%	0.045%	0.045%	0.000%	0.000%	0.000%	0.000%
5	0.20%	0.228%	0.251%	0.301%	0.331%	0.028%	0.051%	0.101%	0.131%
10	0.20%	0.230%	0.277%	0.397%	0.477%	0.030%	0.077%	0.197%	0.277%
15	0.20%	0.231%	0.305%	0.522%	0.682%	0.031%	0.105%	0.322%	0.482%
20	0.20%	0.232%	0.336%	0.682%	0.967%	0.032%	0.136%	0.482%	0.767%
25	0.20%	0.233%	0.369%	0.887%	1.362%	0.033%	0.169%	0.687%	1.162%
30	0.20%	0.234%	0.406%	1.148%	1.905%	0.034%	0.206%	0.948%	1.705%
35	0.20%	0.235%	0.447%	1.481%	2.645%	0.035%	0.247%	1.281%	2.445%
40	0.20%	0.236%	0.491%	1.905%	3.649%	0.036%	0.291%	1.705%	3.449%
45	0.20%	0.238%	0.539%	2.439%	4.999%	0.038%	0.339%	2.239%	4.799%
50	0.20%	0.239%	0.591%	3.105%	6.847%	0.239%	0.591%	3.105%	6.647%

Figure 7 – Steel Tower Probability Curve: Initial Condition 4



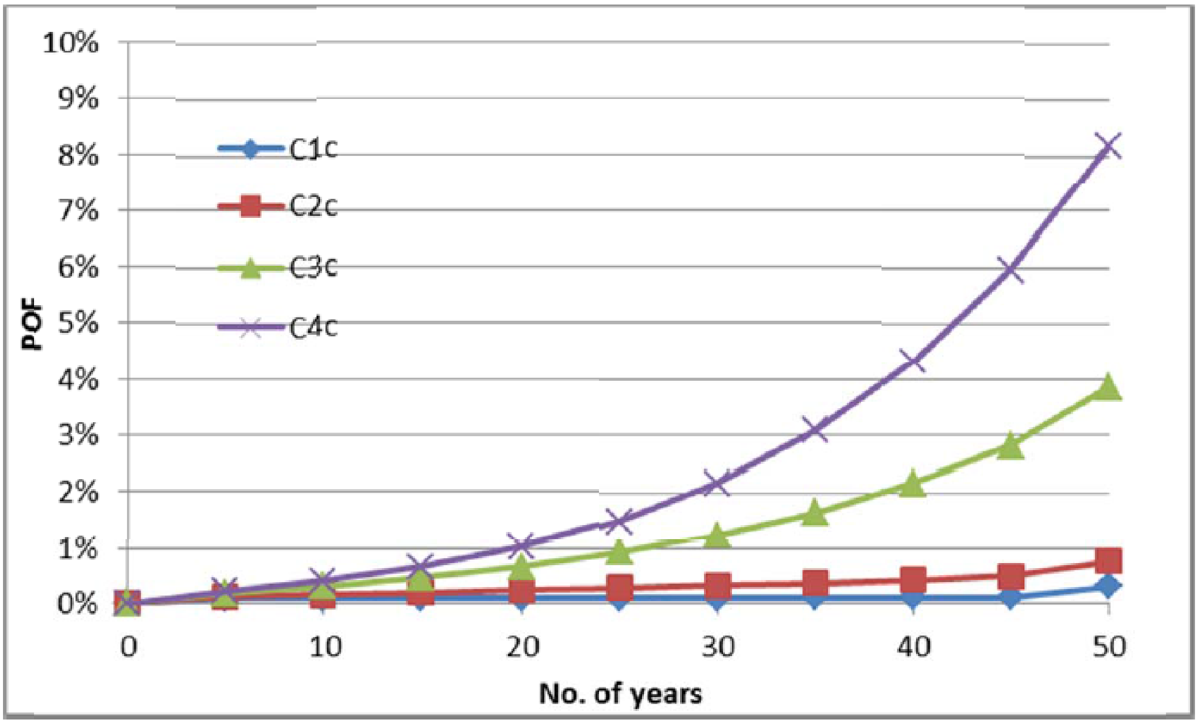
Initial NACA Condition 3

- All galvanising lost
- 3% metal loss
- Probability curve shown in Figure 8

Table 16 – Steel Tower Probability Curve: Initial Condition 3

Tower member		8 x 8 x 11/16				initial loss (µm)		0.252	3%
Corrosion zone		C1	C2	C3	C4	$C1_c$	$C2_c$	$C3_c$	$C4_c$
loss µm/year		0.65	13	37.5	50				
	PoF just to wind 5 yearly	Probability (%) of failure due to wind event with corrosion of steel.				Increased probability (%) of failure only due to corrosion of steel (see assumptons).			
0	0.20%	0.059%	0.059%	0.059%	0.059%	0.000%	0.000%	0.000%	0.000%
5	0.20%	0.294%	0.322%	0.386%	0.423%	0.094%	0.123%	0.186%	0.223%
10	0.20%	0.296%	0.355%	0.507%	0.607%	0.096%	0.155%	0.307%	0.407%
15	0.20%	0.297%	0.391%	0.663%	0.863%	0.097%	0.191%	0.463%	0.663%
20	0.20%	0.299%	0.430%	0.863%	1.218%	0.099%	0.230%	0.663%	1.018%
25	0.20%	0.300%	0.472%	1.119%	1.706%	0.100%	0.272%	0.919%	1.506%
30	0.20%	0.301%	0.518%	1.443%	2.375%	0.101%	0.318%	1.243%	2.175%
35	0.20%	0.303%	0.569%	1.855%	3.289%	0.103%	0.369%	1.655%	3.089%
40	0.20%	0.304%	0.624%	2.375%	4.524%	0.104%	0.424%	2.175%	4.324%
45	0.20%	0.306%	0.684%	3.030%	6.171%	0.106%	0.485%	2.830%	5.971%
50	0.20%	0.307%	0.750%	3.861%	8.398%	0.307%	0.750%	3.861%	8.198%

Figure 8 – Steel Tower Probability Curve: Initial Condition 3



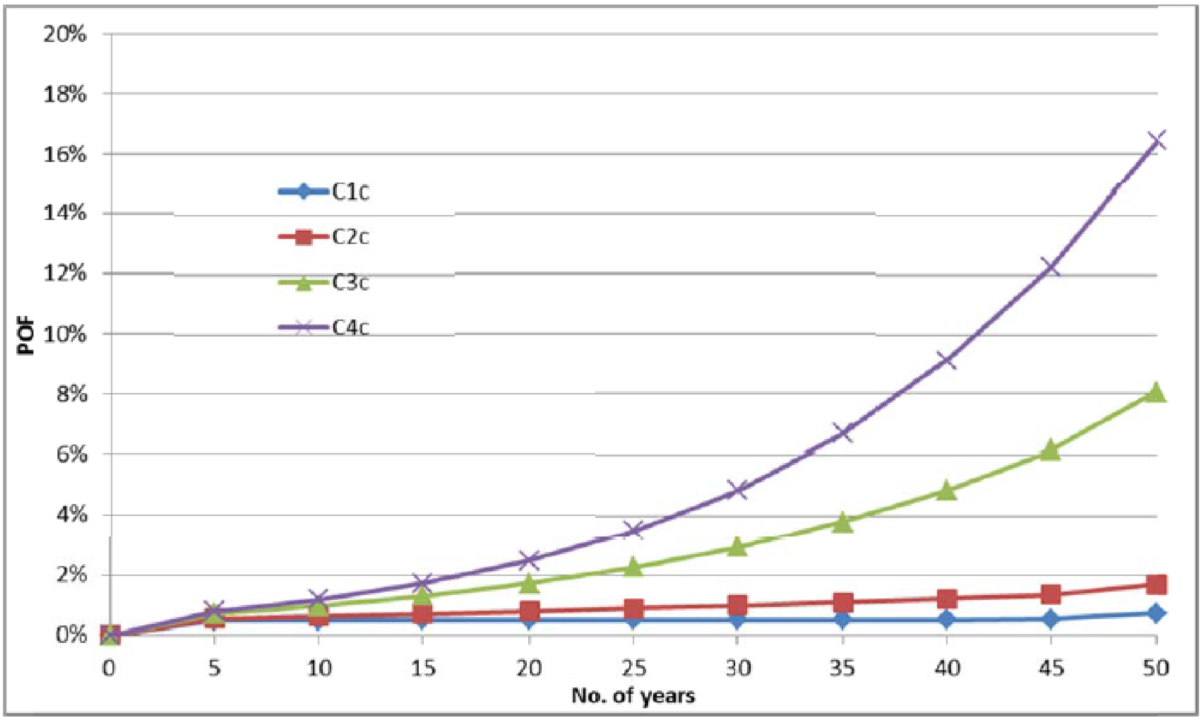
Initial NACA Condition 2

- All galvanising lost
- 10% metal loss
- Probability curve shown in Figure 9

Table 17 – Steel Tower Probability Curve: Initial Condition 2

Tower member		8 x 8 x 11/16				initial loss (µm)		0.843	10%
Corrosion zone		C1	C2	C3	C4	$C1_c$	$C2_c$	$C3_c$	$C4_c$
loss µm/year		0.65	13	37.5	50				
	PoF just to wind 5 yearly	Probability (%) of failure due to wind event with corrosion of steel.				Increased probability (%) of failure only due to corrosion of steel (see assumptons).			
0	0.20%	0.138%	0.138%	0.138%	0.138%	0.000%	0.000%	0.000%	0.000%
5	0.20%	0.693%	0.756%	0.898%	0.978%	0.493%	0.556%	0.698%	0.779%
10	0.20%	0.696%	0.828%	1.161%	1.377%	0.496%	0.629%	0.961%	1.177%
15	0.20%	0.699%	0.907%	1.499%	1.927%	0.499%	0.707%	1.299%	1.727%
20	0.20%	0.703%	0.992%	1.927%	2.674%	0.503%	0.792%	1.727%	2.474%
25	0.20%	0.706%	1.085%	2.463%	3.690%	0.506%	0.885%	2.263%	3.490%
30	0.20%	0.709%	1.186%	3.144%	5.049%	0.509%	0.986%	2.944%	4.849%
35	0.20%	0.712%	1.295%	3.999%	6.894%	0.512%	1.095%	3.800%	6.694%
40	0.20%	0.716%	1.414%	5.049%	9.339%	0.516%	1.214%	4.849%	9.139%
45	0.20%	0.719%	1.546%	6.367%	12.483%	0.519%	1.346%	6.167%	12.283%
50	0.20%	0.723%	1.686%	8.060%	16.626%	0.723%	1.686%	8.060%	16.426%

Figure 9 – Steel Tower Probability Curve: Initial Condition 2



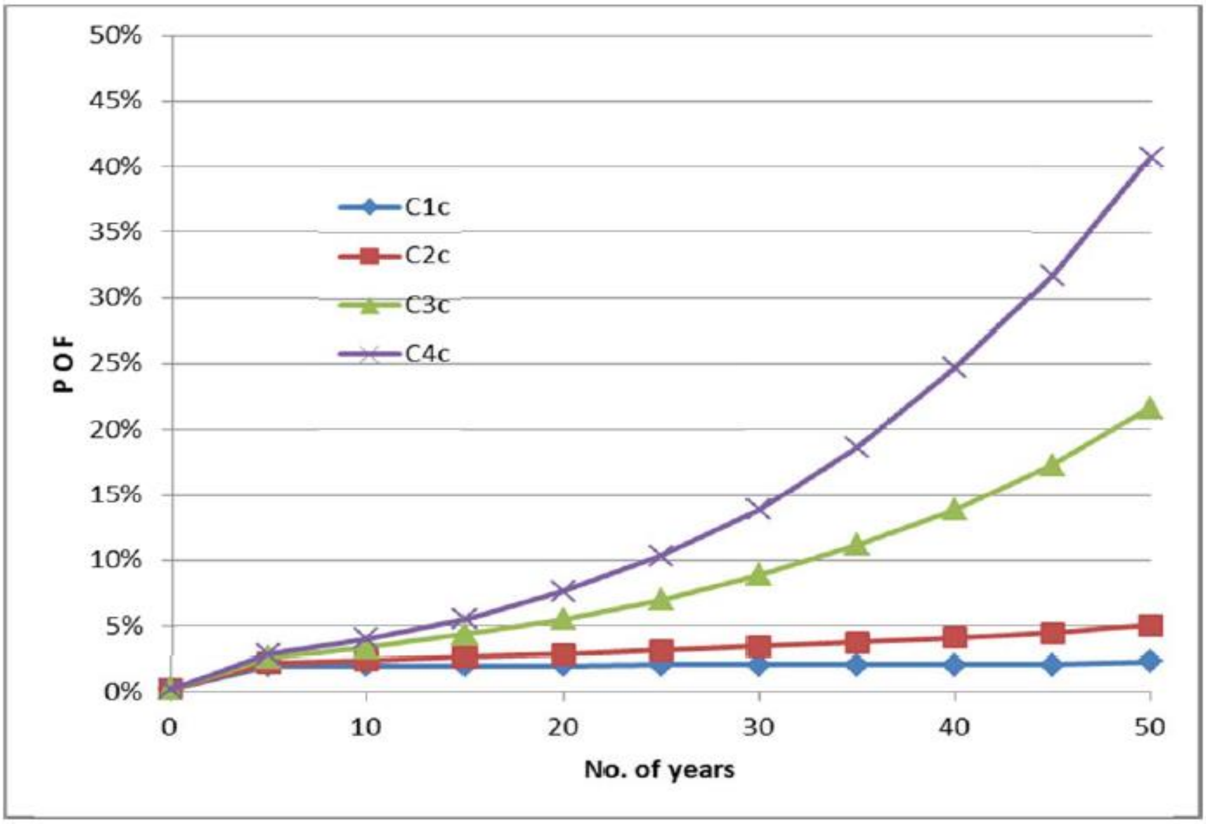
Initial NACA Condition 1

- All galvanising lost
- 20% metal lost
- Probability curve shown in Figure 10

Table 18 – Steel Tower Probability Curve: Initial Condition 1

Tower member		8 x 8 x 11/16				initial loss (µm)		1.691	20%
Corrosion zone		C1	C2	C3	C4	$C1_c$	$C2_c$	$C3_c$	$C4_c$
loss µm/year		0.65	13	37.5	50				
	PoF just to wind 5 yearly	Probability (%) of failure due to wind event with corrosion of steel.				Increased probability (%) of failure only due to corrosion of steel (see assumptons).			
0	0.20%	0.442%	0.442%	0.442%	0.442%	0.243%	0.243%	0.243%	0.243%
5	0.20%	2.203%	2.387%	2.801%	3.039%	2.003%	2.187%	2.601%	2.839%
10	0.20%	2.212%	2.604%	3.571%	4.184%	2.012%	2.404%	3.371%	3.984%
15	0.20%	2.222%	2.833%	4.524%	5.713%	2.022%	2.633%	4.324%	5.513%
20	0.20%	2.232%	3.077%	5.713%	7.809%	2.032%	2.877%	5.513%	7.609%
25	0.20%	2.242%	3.344%	7.191%	10.516%	2.042%	3.144%	6.991%	10.317%
30	0.20%	2.252%	3.636%	9.085%	14.061%	2.052%	3.436%	8.885%	13.861%
35	0.20%	2.262%	3.952%	11.351%	18.809%	2.062%	3.752%	11.151%	18.609%
40	0.20%	2.273%	4.291%	14.061%	24.858%	2.073%	4.091%	13.861%	24.658%
45	0.20%	2.278%	4.650%	17.497%	31.942%	2.078%	4.450%	17.297%	31.742%
50	0.20%	2.288%	5.049%	21.647%	40.951%	2.288%	5.049%	21.647%	40.751%

Figure 10 – Steel Tower Probability Curve: Initial Condition 1



From the calculated curves, catastrophic probability of failure curves were then constructed for steel towers in each atmospheric corrosion zone were estimated in consideration of:

- The typical level of deterioration for the service life of a tower
- Expected level of failure at these calculated deterioration levels

These were then fitted to a 2 parameter Weibull equation to obtain an estimate of the hazard rate by effective service year. The results of the modelling are given in Table 19.

Table 19 outlines the probability of failure values associated with a tower weakened by corrosion as at year 2022 (middle of regulatory control period 2):

Table 19 – Probabilities of Failure on Towers by Corrosion Zone

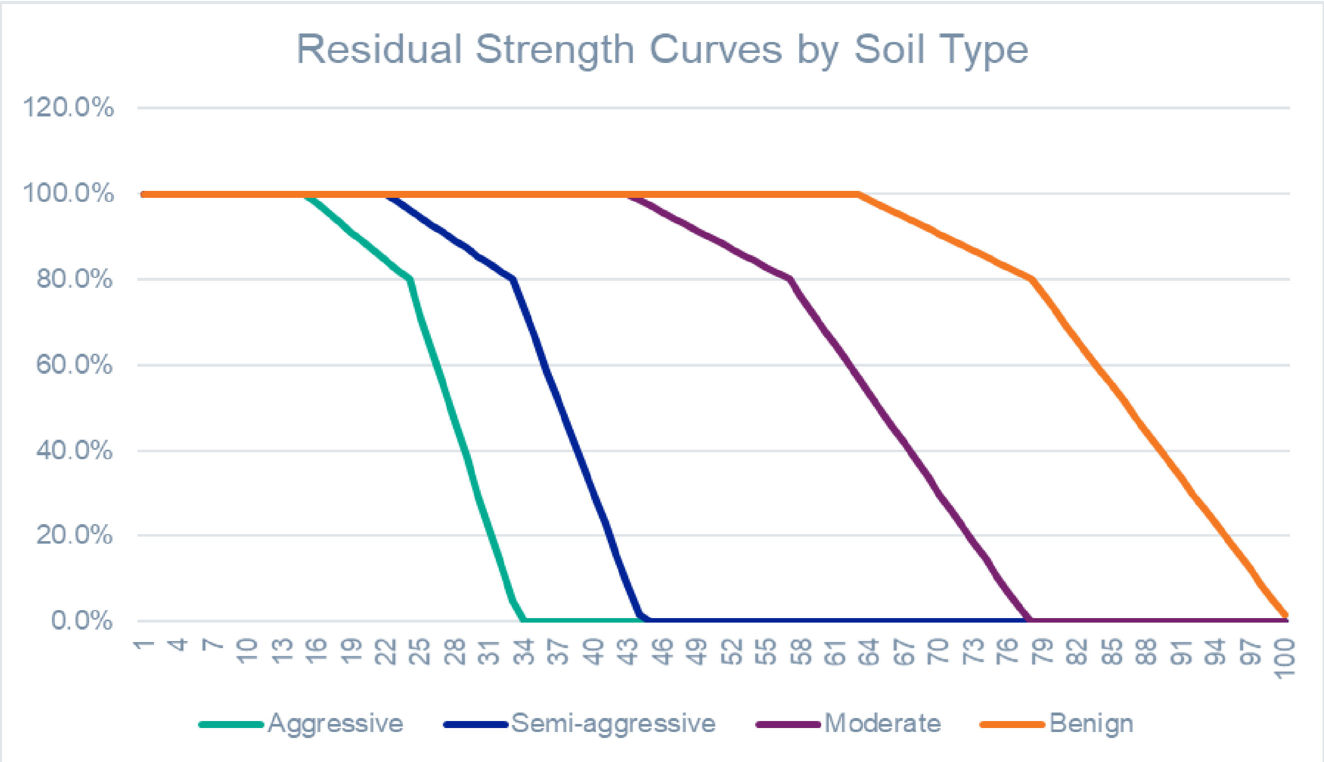
Weibull Parameters by Soil Type	C1	C2	C3	C4
η	3901.0	879.4	270.9	141.2
β	1.32	3.10	2.17	2.71

Concrete Poles

Results taken from the normalisation of the assigned condition codes, ranging from 1 to 10, against a subset of structures assessed by a Subject Matter Expert (SME), were used to estimate the level of chloride attack due to local soil conditions. The estimated level of chloride attack were then correlated to soil test results from site.

The SME then constructed degradation curves, based on destructive testing on previously recovered poles, to align with the four (4) soil classifications; Aggressive, Semi-aggressive, Moderate and Benign, are given in Figure 11.

Figure 11 – Modelled Residual Pole Strength by Soil Type



Catastrophic probability of failure curves were then constructed for each soil type by calculating the probability of the applied wind pressure exceeding the residual strength at discrete points in time. The resulting overlap of the applied stress and residual strength curves give the probability density of a catastrophic failure occurring. The probability of failure densities were then fitted to a 2 parameter Weibull equation to obtain an estimate of the hazard rate by service year for each soil type. The results of the modelling are given in Table 20.

Table 20 – Concrete Pole Weibull Parameters by Soil Type

Weibull Parameters by Soil Type	Aggressive	Semi-aggressive	Moderate	Benign
η	25	38.5	68	93
β	18.5	18.5	18.5	15.0

Electrical Induction Hazards

Electrical Induction Hazards refers to structures in urban areas which are expected to have a fence or metallic asset nearby a Transgrid asset. The probability of failure due these hazards has been calculated using the PoF values from Input 1 and 2:

Input 1	
Relevant Hazards	792[1]
Total Spans	37,646
PoF.1	0.021038092

The total amount of relevant hazards (i.e. fences or other metallic objects nearby) have been divided by the total number of spans in the network to provide the PoF.1 of 0.021

Input 2	
Avg. Outages / yr.	90.8[2]
Total Spans	37,646
PoF.2	0.002411943

The average outages per year have been divided by the total number of spans in the network to provide PoF.2 of 0.002.

The overall PoF has been calculated using a multiplication of the PoF.1 x PoF.2 to return an overall PoF for Electrical Induction Hazards of 0.0051%.

Underground Cables

The greatest risk to underground cables is external interference by members of the public. The probability of circuit strike with traditional control measures (patrols) in place is determined to be 0.02. With Cable 41, soon to be Cable 26F operated at 132 kV, the unforced failure rates would be negligible due lower electrical stresses on 132 kV operation and the relatively young age of the remaining fleet.

[1] TL Earthing – Phase 2, Transmission Line and Cable Design Report
[2] Network Performance Report – (base data – 375 faults over 4.13 years)

The probability that spares will not be available for the Self-Contained Fluid Filled (SCFF) spares during the 2020's is 99% as the manufacturer has formally advised of their plans to cease manufacture. With regards to Transgrid's XLPE spare accessory holdings, the probability that they will be not fit for purpose past 2025 is 100%, due to the shelf life of components.

Cable bridges, like other bridges with a 100 year nominal life are not maintenance free for that period. Condition of the bridges is not expected to lead to failure for the foreseeable future. Minor remedial measures are required to ensure the 100 year design life is realised. Delaying these measures would increase the required scope.

Cable monitoring systems, such as oil pressure monitoring and distributed temperature and acoustic sensing have similar failure characteristics to semiconductor based protection relays. Failures of electronic components can arise from excess temperature, excess current or voltage, ionizing radiation, mechanical shock, stress or impact. Determining the condition of these internal component would be cost prohibitive and would involve a high degree of uncertainty. Failure rate greatly increases after units' nominal life, usually around 10 years.

Structures – Wood Poles

The methodology used in the probability of failure calculation for wood poles is similar to that applied for the concrete poles. Three different calculations have been undertaken for the different types of wood poles on the network:

- Natural round wood poles
- Pressure impregnated wood poles
- Composite wood poles which are joined by a steel sleeve, such as those installed on 330kV Line 86

Defect and condition information for each type of pole taken from pole inspections were analysed to assess the level of degradation expected by effective service life. 2-parameter Weibull curves were then constructed to predict the level of functional failures of these pole types, shown in Table 21.

Table 21 – Wood Pole Function Failure Weibull Parameters by Type

Weibull Parameters by Pole Type	Natural Round	Pressure Impregnated	Composite
η	73.33	58.46	60.8
β	9.10	6.34	6.0

These functional failure statistics were then used by a SME to estimate the rate of decay, in accordance with the relevant decay models from AS 1720 for the pole type with service life. Catastrophic probability of failure curves were then constructed for each pole type by calculating the probability of the applied wind pressure exceeding the residual strength at discrete points in time, as per the design basis of the structures. As with the concrete poles, the resulting overlap of the applied stress and residual strength curves give the probability density of a catastrophic failure occurring, represented as a 2 parameter Weibull equation. The results of the modelling are given in Table 22.

Table 22 – Wood Pole Catastrophic Failure Weibull Parameters by Type

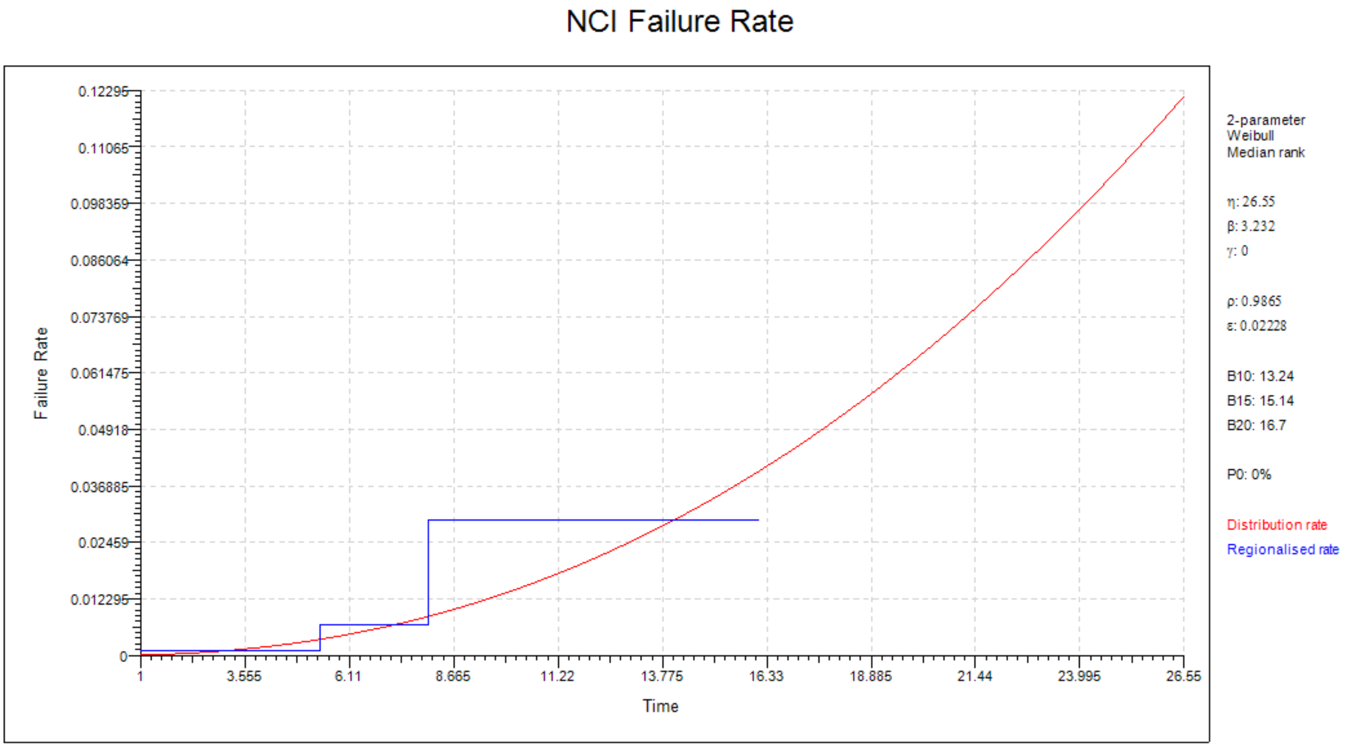
Weibull Parameters by Pole Type	Natural Round	Pressure Impregnated	Composite
η	89.0	68.0	86.0
β	12.0	18.5	12.5

Insulators – Non Ceramic Insulators

The approach outlined in B.1 is applied to obtain the probability of failure for NCIs with the period of observation extended to back to 1998 to include the entire population of Transgrid NCIs within the study.

All functional failure modes are considered, while catastrophic failures were limited to; failure of the insulating medium due to puncture, flashover or flash-under, and loss of mechanical integrity of the fibreglass rod. Insulators removed due to corrosion of the end fittings and loss of hydrophobicity were classified as functional failures, as no catastrophic failures have been observed for these failure mechanisms. Figure 12 gives the resultant failure probability curve.

Figure 12 – Non Ceramic Insulator Failure Probability Curve



The resultant Weibull distribution parameters are:

- η = 26.55
- β = 3.232

The above Weibull distribution is generated using all failures, to derive the catastrophic failure rate a conversion factor is applied to the above probability of failure. The conversion is historical ratio of function failures to catastrophic failures.

The resultant conversion factor is:

FF-CF conversion = 0.021

Verification

Verification of the modelling has been performed by comparing its results to that of the following external studies:

A recent CEATI study[3] of NCI service history within a number of North American utilities.

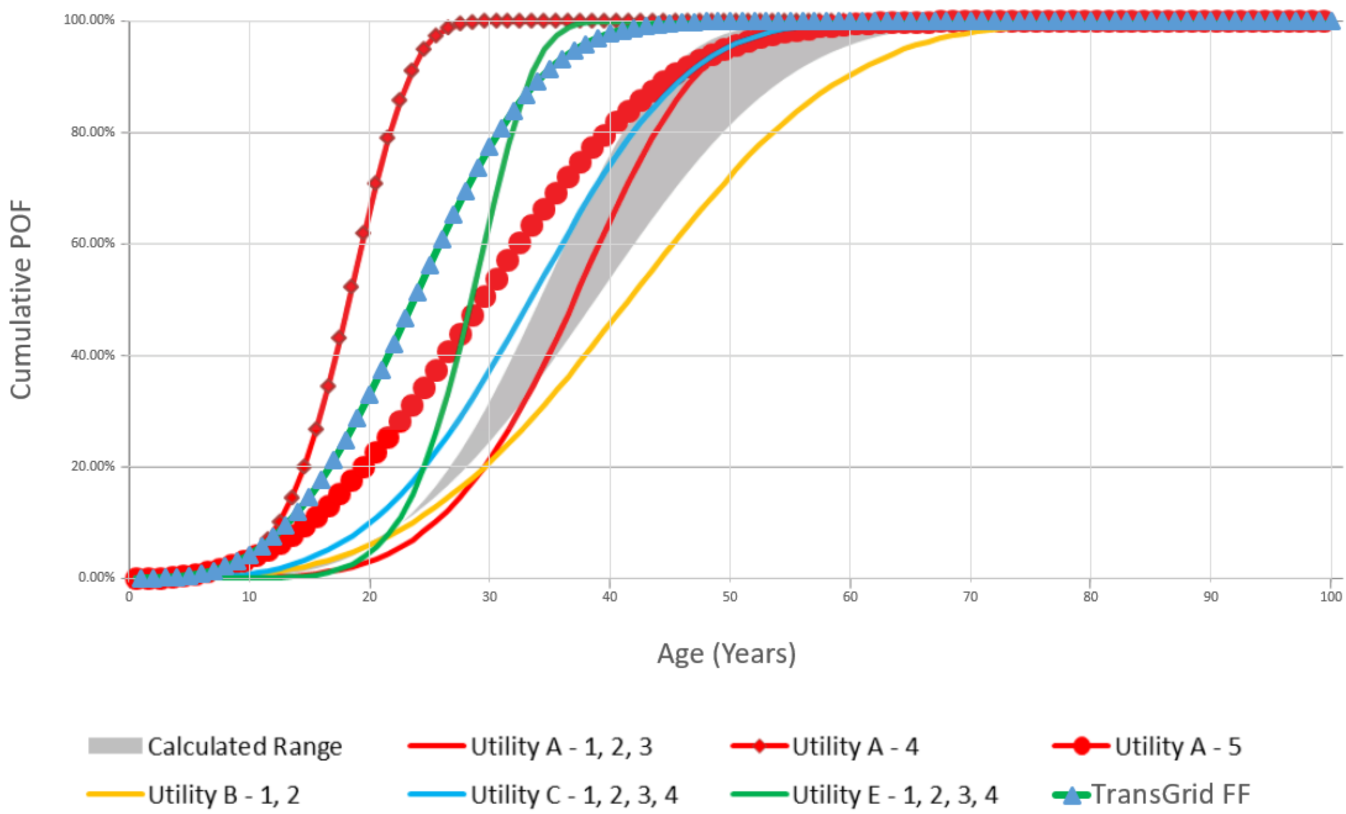
EPRI also completed a study[4] of NCI service history of 83 utilities across North America.

The CEATI study showed cumulative probability of failure for the 20th percentile ranged between 15 and 30 years, and the 95th percentile ranging from 20 to 60 years. Transgrid's results for the 20th and 95th percentiles are as follows:

- 20th = 16.7 years
- 95th = 37.2 years

Overlaying the Transgrid cumulative POF curve onto those produced in the CEATI report, as shown in Figure 13 demonstrates alignment between Transgrid's results and those observed in the CEATI study.

Figure 13 – Overlay of Transgrid's Non Ceramic Insulator Cumulative POF onto CEATI Study Results

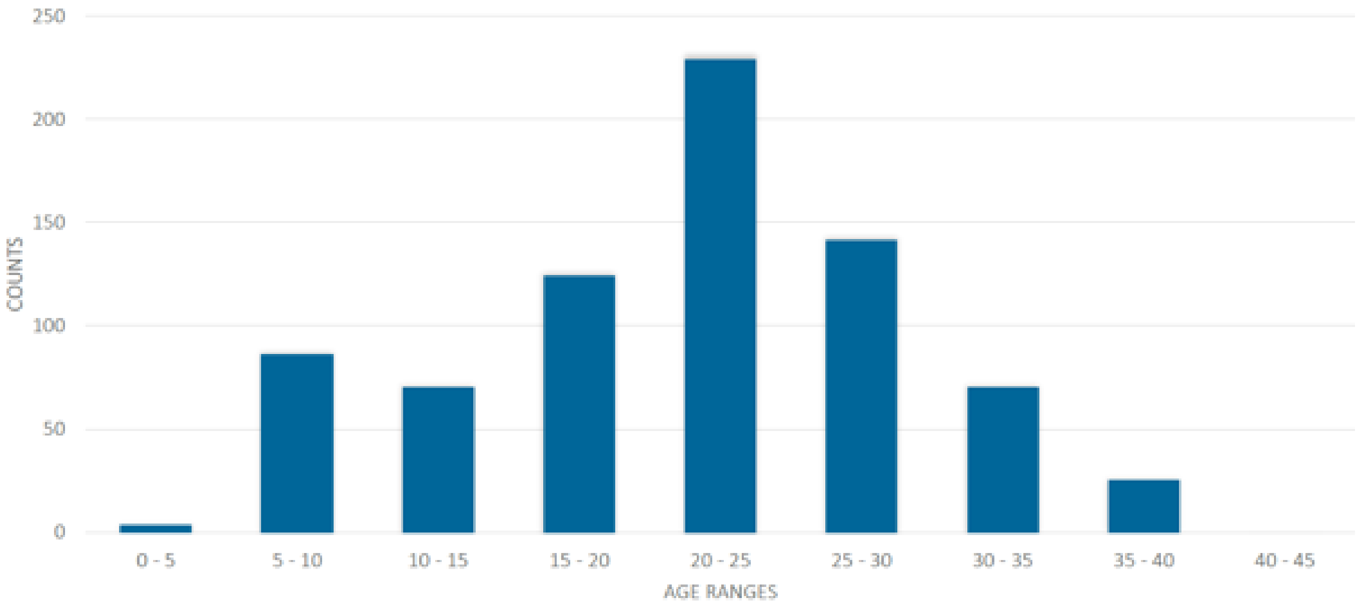


The EPRI study gave results in histogram form, as shown in Figure 14, the age of NCIs being removed from service was centred in the 20 – 25 year range. These results also align with those found in the Transgrid study.

[3] "Statistical Data and Methodology for Estimating the Expected Life of Transmission Line Components", CEATI Report: T144700-3257, September 2017, Appendix A.

[4] *"Industry-Wide Failure and Performance Database: Overhead Transmission Asset Results*", EPRI Report: 3002012699, December 2018, pp 38

Figure 14 – Non Ceramic Insulator Removed from Service by Age – EPRI Study Results



Calibration

The CEATI study is focused on in-service performance of NCIs within North America, to calibrate Transgrid's approach within the Australian context reference has been made to a paper presented by Powerlink Queensland to the INMR World Congress in October 2019[5]. The paper details the in-service performance and estimated life of insulators within Powerlink's network, for the operating conditions aligning with those expected within Transgrid network the estimated lifetimes are as follows:

- Dry Inland = 25–30 years
- Coastal & Sub-Tropical = <25 years
- Once again there is close alignment between Transgrid's results and those of the Powerlink study.

Insulators – Porcelain Disc

The approach outlined in B.1 is applied to obtain the probability of failure for porcelain disc insulators.

The failure modes of porcelain disc insulators considered were failure of pins due to corrosion and internal flash-through due to material porosity. Other failure modes such as pin-cement and cap-disc connection failures have not been observed so have not been modelled.

Insulator vintage data is collected during each climbing inspection. Validated data from all available inspection records and project replacements were used to provide additional data points to the failures in the bi-Weibull distributions. Two distributions were created, based on AS 4312 corrosion zone low corrosion zones, C1/C2 for low corrosion and C3/C4 for high corrosion.

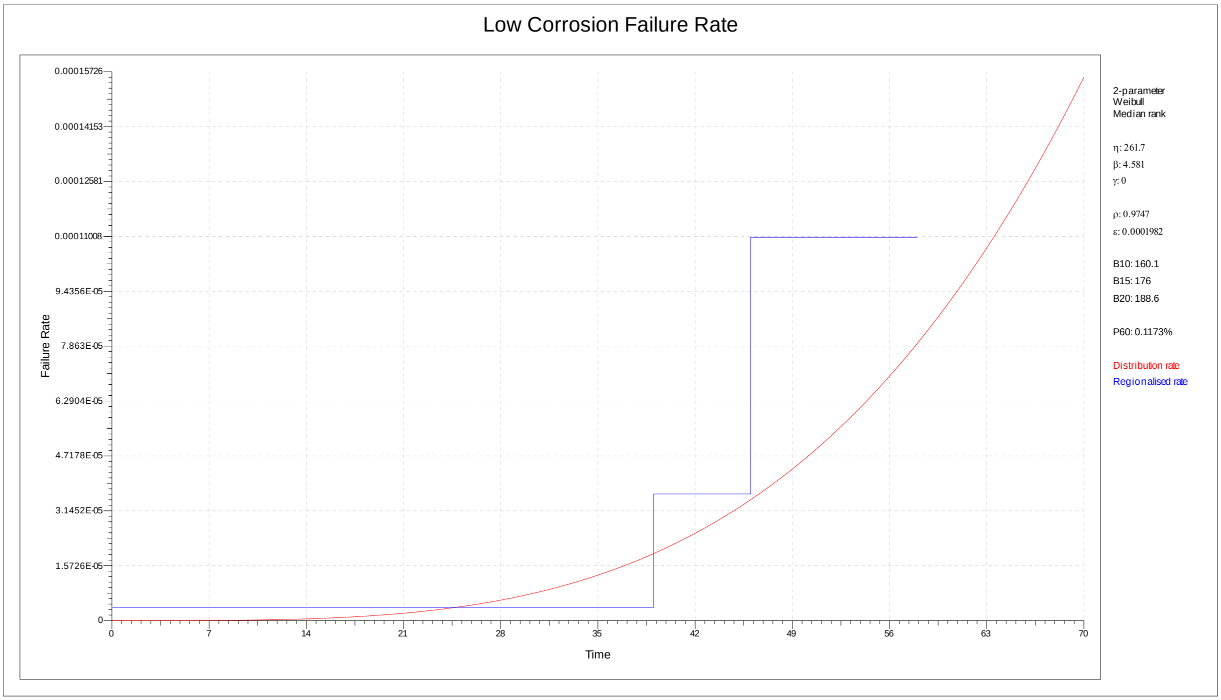
As part of an investigation into the pre-1960 insulators, ten discs were tested, with five showing unacceptable levels of porosity. The manufacturer has advised that based on the material mixes used at the time and service life, these insulators cannot be relied upon for safe operation. Due to the nature of this failure mode, a deteriorated insulator cannot be identified visually. Transients, such as back-flash due to

[5] "*Observations and Lessons from 20 Years' Experience with Non Ceramic Insulators on Transmission Lines in Queensland, Australia*", INMR World Congress, October 2019, pp 14

lightning strike can cause a degraded insulator to fail catastrophically, dropping the conductor to the ground.

The low corrosion failure curve is shown in Figure 15.

Figure 15 – Low Corrosion Area Insulator Failure Probability Curve



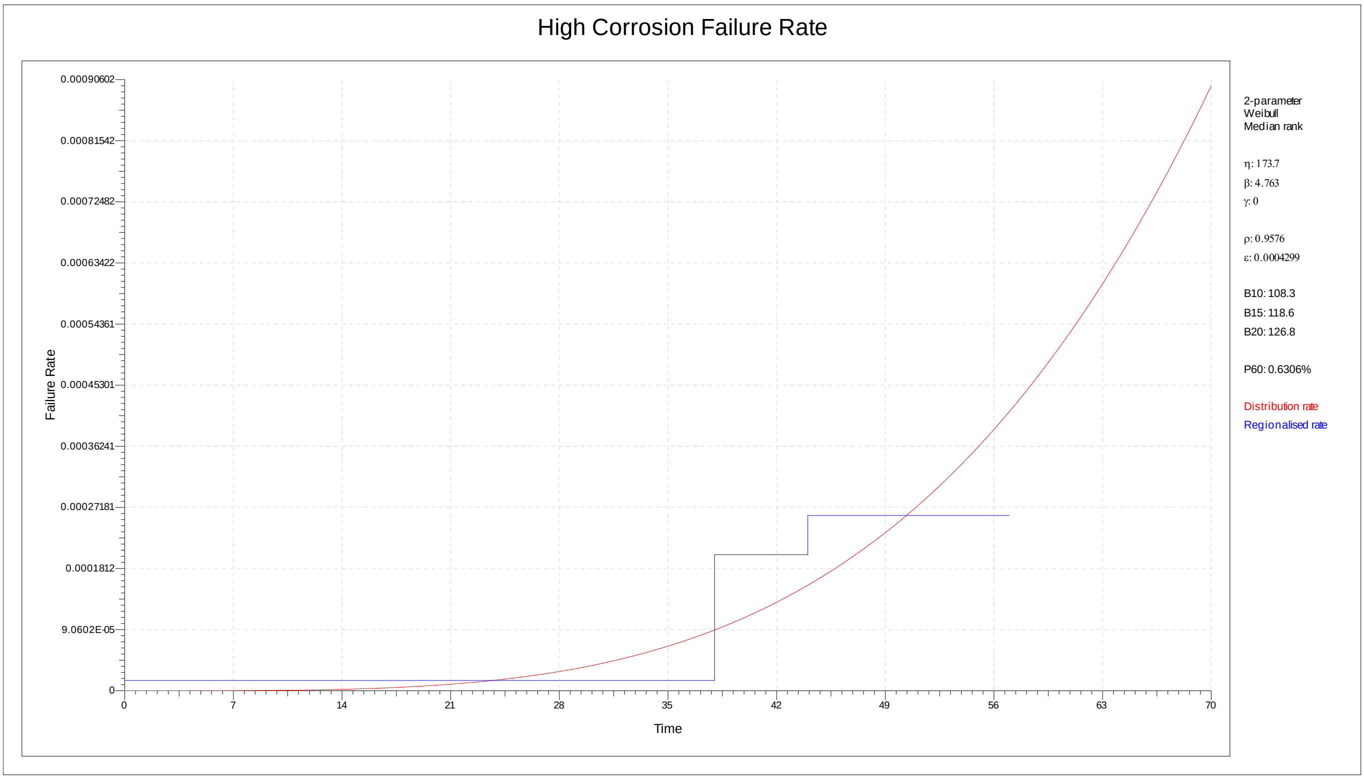
The resultant Weibull distribution parameters are:

- $\eta = 261.7$
- $\beta = 4.581$

For insulators in high corrosion areas, failures of due to pin corrosion along with validated data from all available inspection records and project replacements were used to provide additional data points in the bi-Weibull distribution.

The low corrosion failure curve is shown in Figure 16.

Figure 16 – High Corrosion Area Insulator Failure Probability Curve



The resultant Weibull distribution parameters are:

- η = 173.7
- β = 4.763

Insulators – Glass Disc Insulators

The installed location of glass disc insulators (low corrosion zones) general means that pin corrosion is not an issue. By design, glass discs do not suffer the porosity issues of porcelain disc insulators. Failures generally result in the whole disc shattering, which is easily identifiable in visual inspections, without dropping the conductor. Probability of high potential incidents for these insulators was determined as inconsequential/low.

Conductor and Earthwire Fittings

The approach to obtain the probability of failure for both conductor and earthwire fittings involved the review of fitting condition data and defect records available from climbing inspections. All functional failure modes are considered, and are primarily related to deterioration due to corrosion of steel, and wear of fitting nuts and bolts.

Since atmospheric corrosion exposure levels are a factor in the extent of steel loss on these fittings, fittings are expected to have shorter technical lives as the steel galvanising and subsequent metal loss accelerates at a greater rate in the coastal higher corrosion regions. When assessed against the corrosion zone this was confirmed in the data, and accordingly, the probability of failure curves were assessed were the following grouped corrosion zones:

- C1 and C2: Very low and low
- C3 and C4: Medium and high

2-parameter Weibull curves were then constructed to predict the level of function of failures for conductor and earthwire fittings, shown in Table 23.

Table 23 – Fitting Functional Failure Weibull Parameters by Type and Corrosion Zone

Weibull Parameters	Conductor Fitting C1/C2	Conductor Fitting C3/C4	Earthwire Fitting C1/C2	Earthwire Fitting C3/C4
η	127.4	64.24	116.5	66.61
β	4.376	10.13	5.198	10.98

The hazard functions of the above curves are shown in the figures below.

Figure 17 – Conductor Fittings Failure Probability Curve: Corrosion Zones C1 and C2

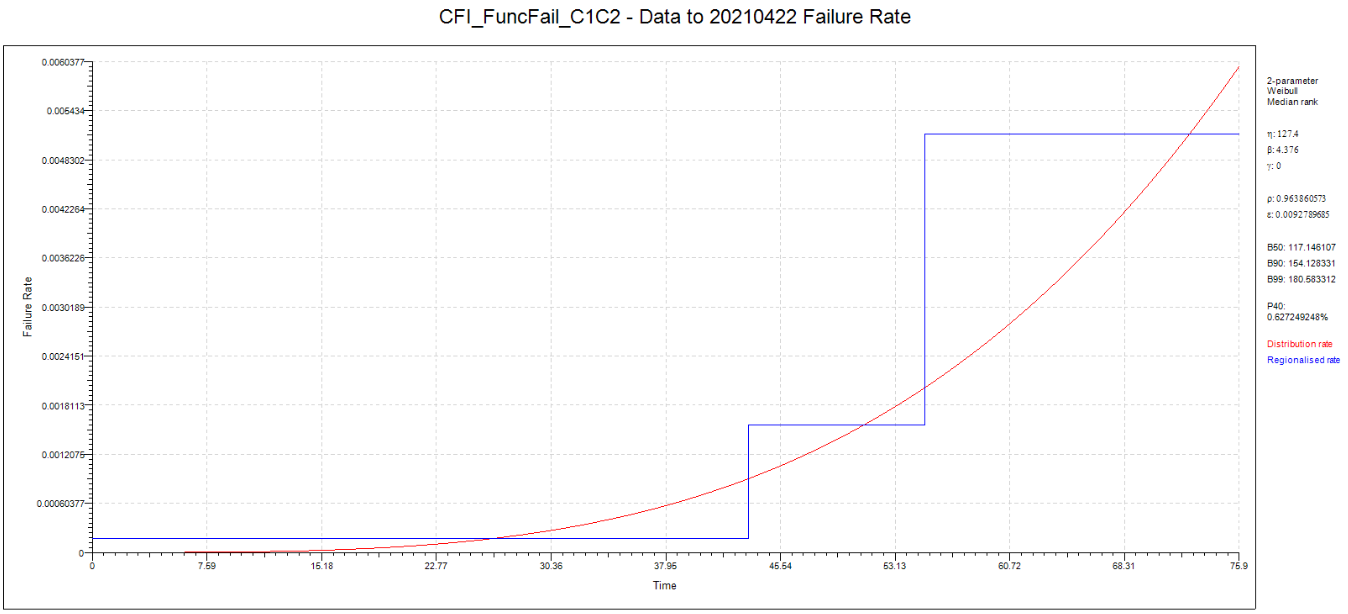


Figure 18 – Conductor Fittings Failure Probability Curve: Corrosion Zones C3 and C4

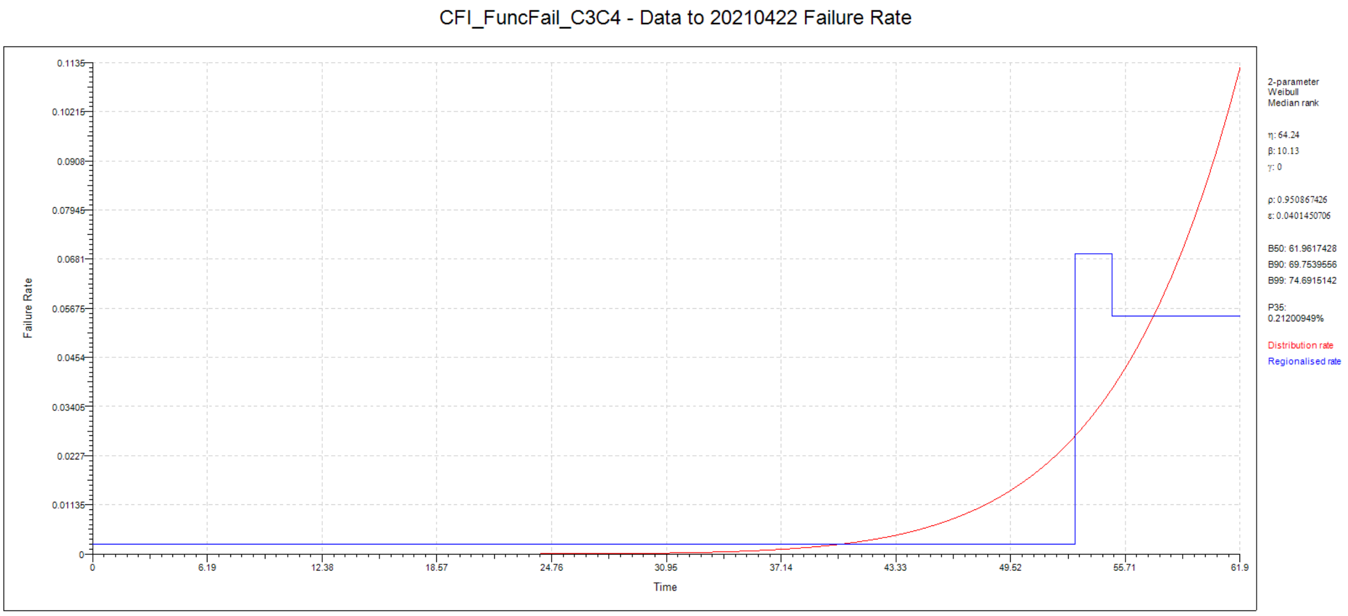


Figure 19 – Earthwire Fittings Failure Probability Curve: Corrosion Zones C1 and C2

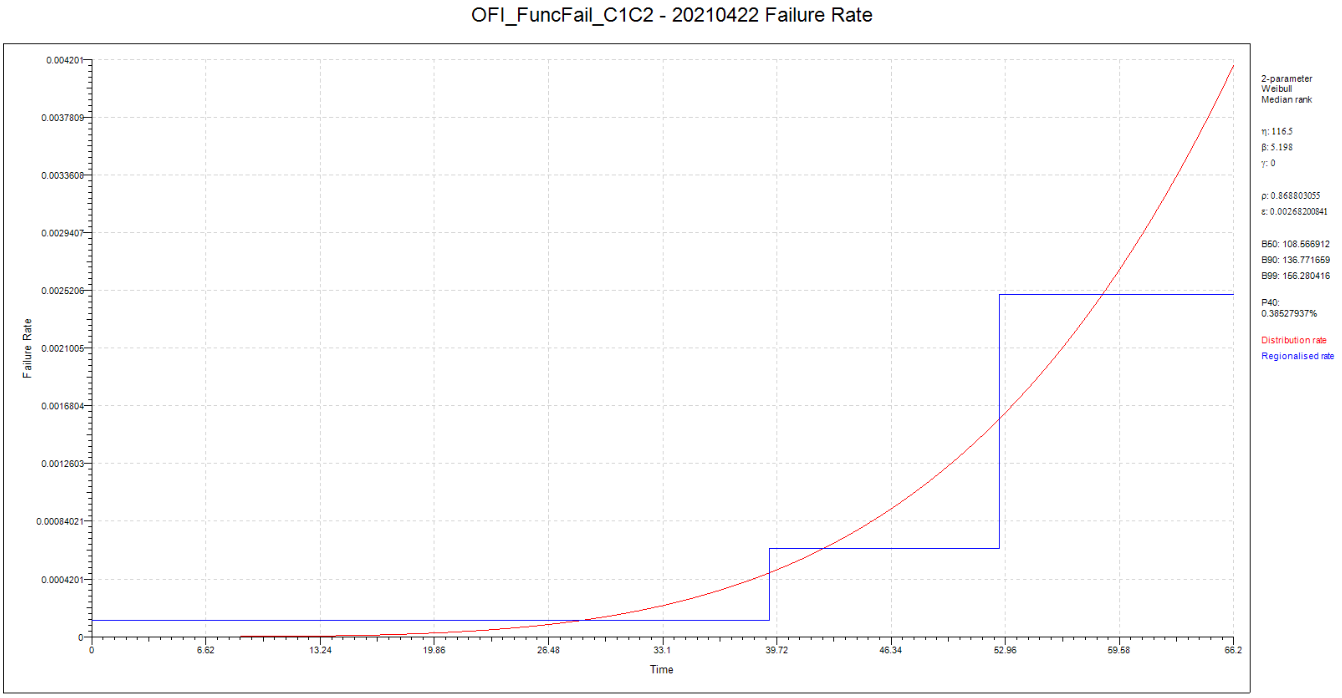
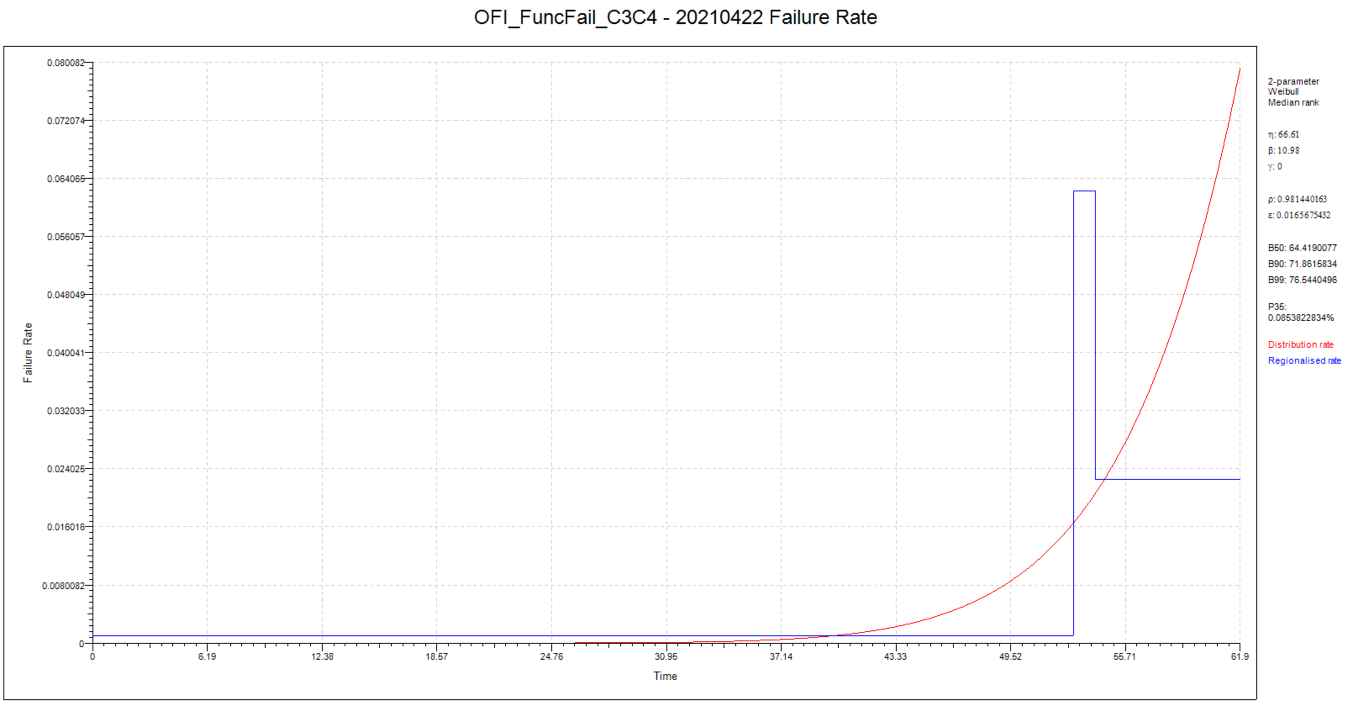


Figure 20 – Earthwire Fittings Failure Probability Curve: Corrosion Zones C3 and C4



To derive the catastrophic failure rate a conversion factor is applied to the above probability of failure, based on the historical ratio of function failures to catastrophic failures for all fitting types.

The resultant conversion factor is:

- FF-CF conversion = 0.008

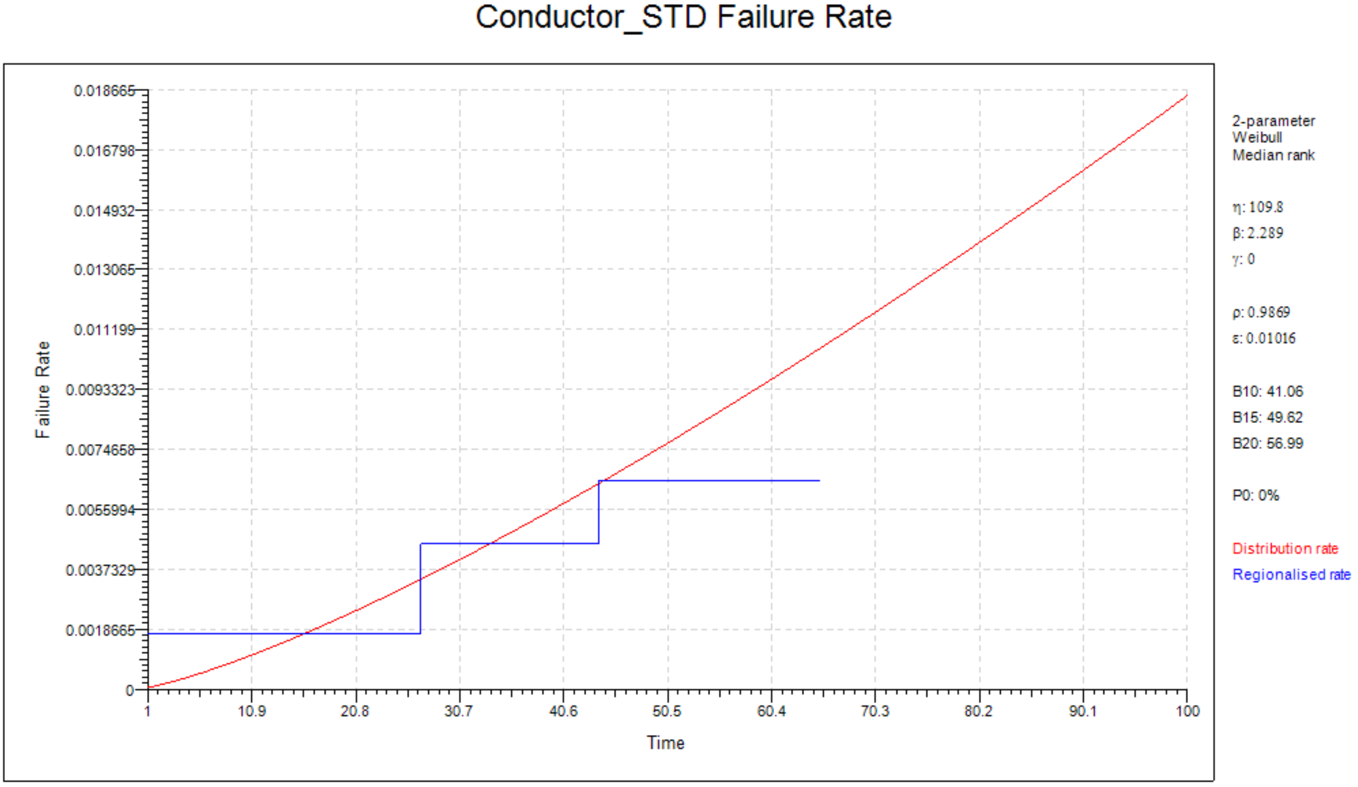
Conductor

A hybrid approach of that outlined in B.1 and the application of empirical models, which estimate the impact of bushfires and atmospheric corrosiveness on conductor service life, is used to obtain conditional probability of failure curves. The period of observation has been extended to include the service lives of the entire population of Transgrid conductors.

All conductor failure modes are considered within the study, mid-span joints have also been included as once installed they become part of the conductor and are integral to maintaining its function. Once installed, mid-span joints also materially impact the in-service performance of the conductor.

The results of the statistical analysis are given in Figure 21, this is the basic POF applied to conductors not impacted by conditional modifiers.

Figure 21 – Basic Conductor Failure Probability Curve



The resultant Weibull distribution parameters are:

- η = 109.8
- β = 2.289

Conditional Modifiers

As described above, the inclusion of mid-span joints and the impacts of bushfire accelerate the processes of degradation depending upon the type of conductor and operating environment.

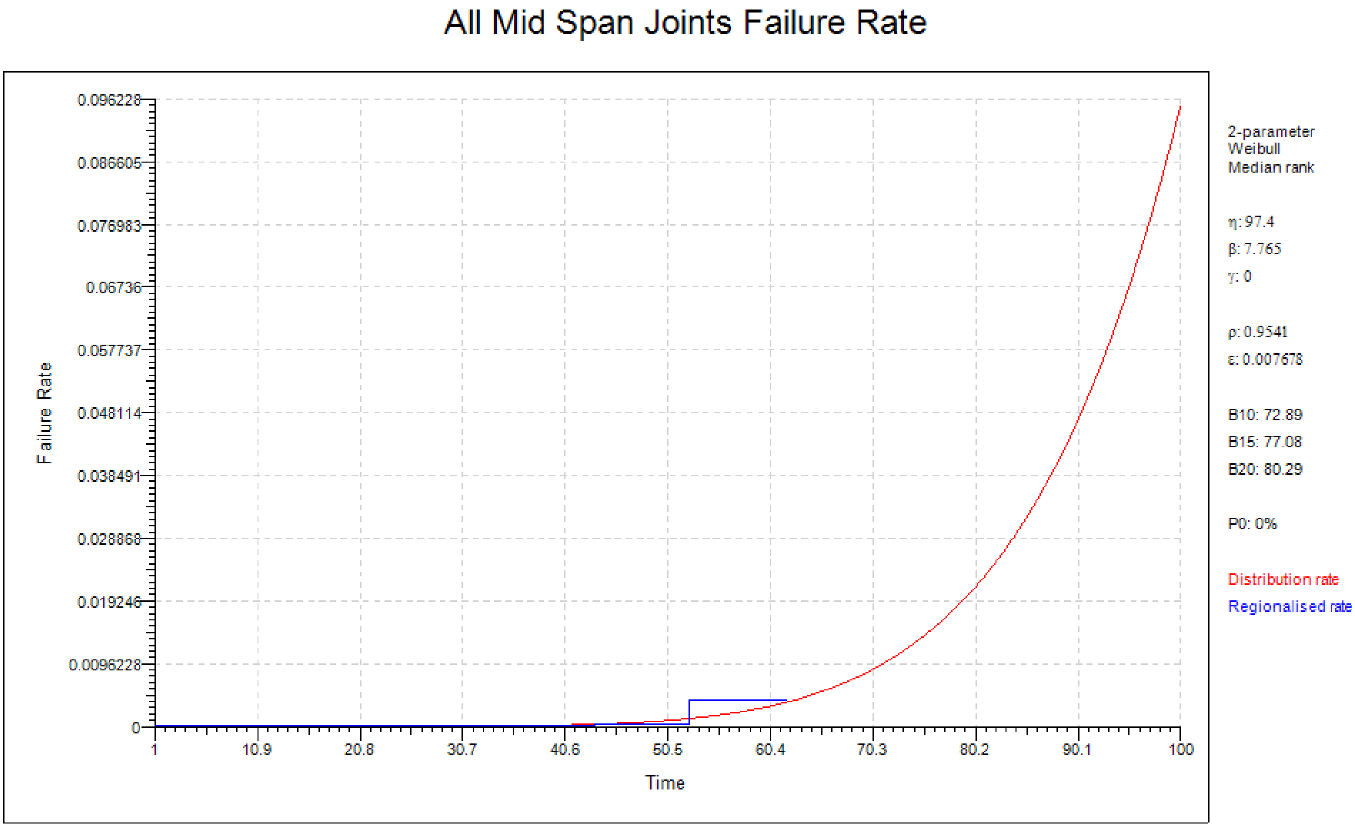
Mid-Span Joints

Mid-span joints (MSJ) are used to connect segments of conductor within span and are installed during the initial construction of a line or to repair a conductor following a failure. The role of the MSJ is to maintain or restore the mechanical and electrical continuity of the conductor.

The installation of MSJ introduces a discontinuity in the material properties and performance of the conductor and can become a focal point for stress and the collection of organic and inorganic materials from the remainder of the span. The step change in material properties where the conductor enters the MSJ creates a stress focal point which can result is fatigue, while the collection of contaminants can accelerate corrosion.

The results of the statistical analysis of spans containing MSJ are given in Figure 22.

Figure 22 – Mid-Span Joint Failure Probability Curve



Bushfire Impacts and Corrosion

Heat from bushfires can impact conductors through various mechanisms including; annealing of the aluminium strands on All Aluminium Conductors (AAC), All Aluminium Alloy Conductors (AAAC) and Aluminium Conductor Steel Reinforced/Galvanised (ACSR/GZ) type conductors, and reduction in the corrosion performance due to loss of grease and/or the galvanizing layer from the inner steel strands of ACSR type conductors.

ACSR/GZ Type Conductors

Melting of zinc galvanising occurs at temperatures exceeding 420°C, while grease will drop[6] at temperatures between 70°C and 180°C, depending upon the type of grease applied. Loss of conductor grease or the galvanizing layer results in reduced corrosion performance over the conductor's life.

For the purposes of deriving the POF, annealing of the aluminium strands has been excluded as it has a negligible impact upon the overall mechanical integrity of the conductor.

Testing results from samples of bushfire impacted conductor have confirmed the above mechanisms, with the analysis of surface deposits identifying corrosion products at the locations where loss of grease and galvanising was observed.

A SME was consulted to derive material loss rates of the steel strands, due to corrosion, for the zones covering Transgrid assets. These were used to determine the remaining time to functional failure following exposure to a bushfire, which is the trigger event that moves the ACSR conductor from the basic conductor POF to the relevant conductor corrosion POF. For those assets located further inland, C1 and C2, the POF reverts to the basic conductor parameters.

The resultant Weibull distribution parameters for the regions are:

- C4 Corrosion Zone:
- $\eta = 63.3$
- $\beta = 25.19$
- C3 Corrosion Zone:
- $\eta = 68.46$
- $\beta = 7.272$

AAAC Type Conductors

Annealing of the aluminium alloy is dependent upon the exposure temperature and duration, alloy type, method of forming the strands and any final treatments. Different aluminium alloys anneal at varying rates at lower temperatures, but all anneal rapidly at temperatures exceeding 340°C until reaching the melting point at approx. 645°C[7]. It is generally accepted that temperatures exceeding 300°C will result in a permanent reduction of tensile strength[8] for the aluminium alloys commonly used in conductors.

Using this information a SME produced a deterministic model[9] to estimate the impacts of bushfires on conductors. This model describes the expected loss of tensile strength per incident due to exposure time and temperature. Historical bushfire data and network records were utilised to determine the number of exposures and observed return period by span.

The observed return period for each span were ordered and allocated to one of the five categories based upon which 20th percentile the span fell into. The deterministic model was then applied to estimate the remaining time to functional failure for each span, based upon exposures and return period category, and

---

[6] Grease drop is the process whereby the grease from the inner strands of the conductor migrates to the surface and ceases to perform its intended function

[7] AS/NZS 7000:2016, Appendix AA

[8] "*Effect of Elevated Temperature Operation on the Tensile Strength of Overhead Conductors*", IEEE Transactions on Power Delivery, Vol. 11, No. 1, January 1996, pp 345-352

[9] "*Overhead Line Conductor Damage from Bushfires – An Assessment Methodology*", Gary Brennan, March 2020.

POFs calculated for the exposure and return period combinations. The resultant Weibull distribution parameters are given in Table 24.

Table 24 – AAAC Weibull Distribution Parameters by Bushfire Exposures and Return Period

Bushfire Count	Bushfire Return Period Category	η	β
1	1	56.19	8.952
1	2	63.64	20
1	3	68.57	70
1	4 and greater	109.8	2.289
2	1	55.1	6.858
2	2	56.96	13.01
2	3 and greater	62.85	28.24
3 and greater	1 and greater	56.1	7.622

Conductor POF Selection Logic

Weibull distributions have been generated for the various combinations of conductor type, bushfire impact, presence of MSJ and corrosion zones, the table below gives the logic applied in order to allocate the using all failures, to derive the catastrophic failure rate a conversion factor is applied to the above probabilities of failure. The conversion is the historical ratio of function failures to catastrophic failures.

Table 25 – Weibull Distribution Parameters Selection Logic

Conductor Type	Corrosion Zone	Mid-Span Joint Present	Bushfire Count	Bushfire Return Period Category	η	β
ACSR	All	NO	0	All	109.8	2.289
ACSR	C1	NO	1 and greater	All	109.8	2.289
ACSR	C2	NO	1 and greater	All	109.8	2.289
ACSR	C3	NO	1 and greater	All	68.46	7.272
ACSR	C4	NO	1 and greater	All	63.3	25.19
ACSR	C1 & C2	YES	ALL	All	97.4	7.765
ACSR	C3	YES	1 =/<	All	68.46	7.272
ACSR	C4	YES	1 =/<	All	63.3	25.19
AAAC	All	NO	0	All	109.8	2.289
AAAC	All	NO	1	1	56.19	8.952
AAAC	All	NO	1	2	63.64	20
AAAC	All	NO	1	3	68.57	70
AAAC	All	NO	1	4 and greater	109.8	2.289

Conductor Type	Corrosion Zone	Mid-Span Joint Present	Bushfire Count	Bushfire Return Period Category	η	β
AAAC	All	NO	2	1	55.1	6.858
AAAC	All	NO	2	2	56.96	13.01
AAAC	All	NO	2	3 and greater	62.85	28.24
AAAC	All	NO	3 and greater	1	56.1	7.622
AAAC	All	NO	4 and greater	All	56.19	8.952
AAAC	All	YES	1	1	56.19	8.952
AAAC	All	YES	1	2	63.64	20
AAAC	All	YES	1	3	68.57	70
AAAC	All	YES	1	4 and greater	97.4	7.765
AAAC	All	YES	2	1	55.1	6.858
AAAC	All	YES	2	2	56.96	13.01
AAAC	All	YES	2	3 =/<	62.85	28.24
AAAC	All	YES	3 and greater	1 and greater	56.1	7.622
AAAC	All	YES	4 and greater	All	56.19	8.952

Conversion Factor

The above Weibull distributions is generated using all failures, to derive the catastrophic failure rate a conversion factor is applied to the above probabilities of failure. The conversion is the historical ratio of function failures to catastrophic failures.

The resultant conversion factor is:

- FF-CF conversion = 0.024

Verification

Verification of the modelling has been performed by comparing its results to that of the following external studies:

A recent CEATI study[10] of conductor service history within a number of North American utilities.

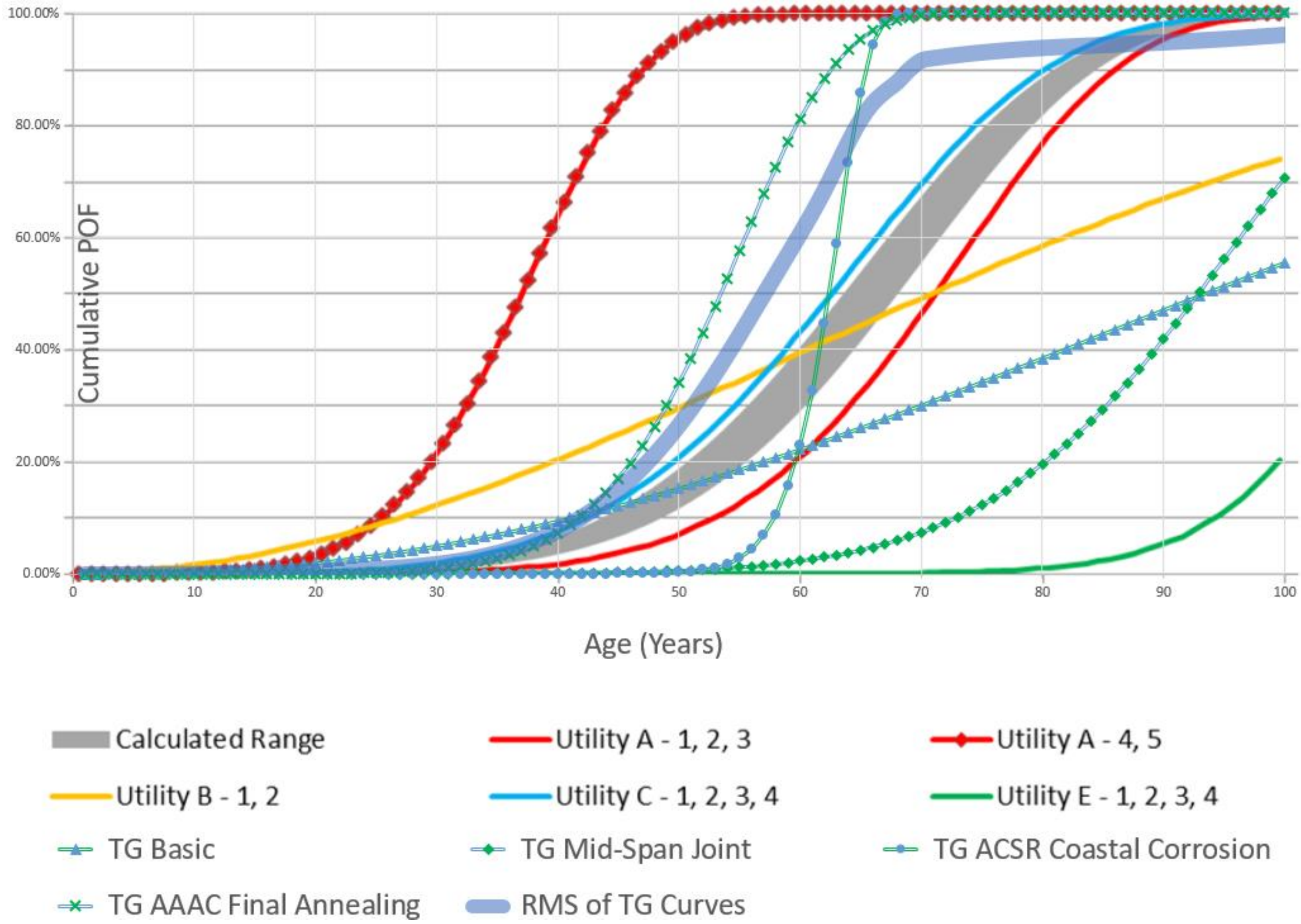
The CEATI study showed cumulative probability of failure for the 20th percentile ranged between 30 and 90 years, and the 95th percentile ranging from 50 to 150 years. Transgrid's results for the 20th and 95th percentiles of the average of the cumulative POFs are as follows:

- 20th = 50.5 years
- 95th = 92 years

[10] CEATI Report: T144700-3257 – Statistical Data and Methodology for Estimating the Expected Life of Transmission Line Components, 2017

Overlaying the Transgrid cumulative POF curves onto those produced in the CEATI report, as shown in Figure 23, demonstrates alignment between Transgrid's results and those observed in the CEATI study.

Figure 23 – Overlay of Transgrid's Conductor Cumulative POFs onto CEATI Study Results



Earthwire

The main mode of failure associated with SC/GZ earthwire is corrosion and section loss, leading to a reduction in tensile strength. Examination of assessed earthwire samples removed from service identified that particularly in the outer strands are susceptible to corrosion, and there was some loss of cross sectional area. Over 240° of the circumference of each outer strand is exposed to the external environment in the standard 7 strand arrangement.

2-parameter Weibull curves were then estimated to predict the level of function of failures for the steel earthwire in consideration of expected galvanising protection, and corrosiveness levels in AS 4312. These are shown in Table 26.

Table 26 – Fitting Functional Failure Weibull Parameters by Type and Corrosion Zone

Weibull Parameters	Earthwire Fitting C1/C2	Earthwire Fitting C3/C4
η	110	85
β	8.0	14.0

Vegetation Clearance

Given the geotropically distributed nature of transmission lines, the reliability and probability of failure (PoF) of these assets are heavily influenced by the vegetation that surrounds them.

To effectively manage the probability of failure and the overall risk easements pose to the network a detailed risk model was developed using the following parameters:

- Growth Rates
- Tree Species
- Soil Type
- Rainfall
- Span Height
- Temperature (summer mean)
- Slope

Using the above parameters an algorithm was developed to populate the span risk model and determine a PoF ranking (Low, Medium, or High) for each span / structure on the network. Table 27 shows the parameters and weightings used.

Table 27 – Easement Maintenance Strategy development based on risk

Tier	Data	Low threshold	Medium threshold	High threshold	Weighting (Overall)	Weighting (Growth rate)
1	**G:** Growth Rate				W1.1: 40%	
2	**TS:** Tree Species – max height	Slow growing (1)	Moderate growing (2)	Fast growing (3)		W2.1: 55%
2	**ST**: Soil Type - fertility	Low (1)	Moderate (1)	High (1)		W2.2: 10%
2	**RF:** Rainfall[1]	<= 33% percentile	33% - 66% percentile	>= 66% percentile		W2.3: 35%
1	**L**: Low Spans + Height ("z" value) clearances	>= 9m	7.5 – 9.0 m	<= 7.5 m	W1.2: 20%	
1	**T**: Temperature[1] – Summer average	<= 33% percentile	33% - 66% percentile	>= 66% percentile	W1.3: 35%	
1	S: Slope[1] - degrees	<= 33% percentile	33% - 66% percentile	>= 66% percentile	W1.4: 5%	
Totals					**100%**	**100%**

1: Percentiles based on sample size from each region

Filters were applied where:

- Filter A means that if the maximum tree height is less than "z" then probability of failure is Low
- Filter B – apply weighted average formula : (G. W1.1 + L. W1.2 + T. W1.3 + S. W1.4) / (W1.1 + W1.2 + W1.3 + W1.4)
- Where G – weighted average: (TS. W2.1 + ST. W2.2 + RF. W2.3) / (W2.1 + W2.2 + W2.3)

Table 28 outlines the total number of spans identified as Low, Medium or High using the above algorithm, it also shows the total number of P1's that have been recorded in those spans, over the most recent 5 year period, giving an overall PoF value for each.

Table 28 – Vegetation POF by Risk Category

	Spans (#)	Recorded P1's	PoF (%)
Low	21,658	7	0.03232%
Medium	5,517	5	0.09063%
High	10,104	14	0.13856%

The PoF values will be validated / updated based on field inspections through AIM and / or LiDAR results to identify changes in key parameters in the risk model.

B.4 Digital Infrastructure

The approach outlined in Section B.1 is applied to obtain the probability of failure for all Digital Infrastructure assets.

Digital Infrastructure Assets have built 2-parameter Weibull Models from historical defect data being modelled in Availability Workbench. The models have been applied to each technology type and are continuously refined as more asset failure and conditional data is obtained.

This methodology has been utilised to provide an overarching summary of a technology's parameters with the health index leveraged to allow for movement along the time axis for model specific issues and conditional performance.

B.5 Appendix B – Summary

The tables below summarise the 2-parameter Weibull Models for each of the asset classes.

Table 29 – Substation Assets

B.2 Substations		
Equipment	**η**	**β**
Transformer	54.21	3.61
Oil Reactors	38.84	2.95
Circuit breaker	47.76	4.3
Oil CT	50	3.08
MVT	50	3.8
CVT	50	3.8
Disconnector	67	4.8
Surge Arrester	55	3.2
Auxiliary Transformer	70	4.5
Capacitor Banks	50	4.5
Substation Gantry Steelwork	Structural modelling based on Condition Assessments from AIM.	

Table 30 –Transmission Line Assets – Structures, Poles, Insulators and Conductor Fittings

B.3 Transmission Lines		
Sub-Component	**η**	**β**
Structure - Towers C1	3901	1.32
Structure - Towers C2	879.4	3.1
Structure - Towers C3	270.9	2.17
Structure - Towers C4	141.2	2.71
Concrete Poles - Aggressive	25	18.5
Concrete Poles - Semi Aggressive	38.5	18.5
Concrete Poles - Moderate	68	18.5
Concrete Poles - Benign	93	15
Electrical Induction Hazards		
Underground Cables	Subject matter expert and industry practice and knowledge	
Structures - Wood Poles - Natural Round	73.33	9.1
Structures - Wood Poles - Pressure Impregnated	58.46	6.34
Structures - Wood Poles - Composite	60.8	6
Wood Pole Catastrophic failure - Natural Round	89	12
Wood Pole Catastrophic failure - Pressure Impregnated	68	18.5
Wood Pole Catastrophic failure - Composite	86	12.5
Insulators - Non Ceramic Insulators	26.55	3.232
Insulators - Porcelain Disc - Low corrosion	261.7	4.581
Insulators - Porcelain Disc - High corrosion	173.7	4.763
Insulators - Glass Disc Insulators	Subject matter expert and industry practice and knowledge	
Conductor Fittings - C1/C2	127.4	4.376
Conductor Fittings - C3/C4	64.24	10.13
Earthwire Fittings - C1/C2	116.5	5.198
Earthwire Fittings - C3/C4	66.61	10.98

Table 31 – Transmission Lines Assets - Conductor Type

Sub-Component	Corrosion Zone	Mid-Span Joint Present	Bushfire Count	Bushfire Return Period Category	η	β
Conductor - ACSR Type	All	NO	0	All	109.8	2.289
	C1	NO	1 and greater	All	109.8	2.289
	C2	NO	1 and greater	All	109.8	2.289
	C3	NO	1 and greater	All	68.46	7.272
	C4	NO	1 and greater	All	63.3	25.19
	C1 / C2	YES	ALL	All	97.4	7.765
	C3	YES	1 =/<	All	68.46	7.272
	C4	YES	1 =/<	All	63.3	25.19
Conductor - AAAC Type	All	NO	0	All	109.8	2.289
	All	NO	1	1	56.19	8.952
	All	NO	1	2	63.64	20
	All	NO	1	3	68.57	70
	All	NO	1	4 and greater	109.8	2.289
	All	NO	2	1	55.1	6.858
	All	NO	2	2	56.96	13.01
	All	NO	2	3 and greater	62.85	28.24
	All	NO	3 and greater	1	56.1	7.622
	All	NO	4 and greater	All	56.19	8.952
	All	YES	1	1	56.19	8.952
	All	YES	1	2	63.64	20
	All	YES	1	3	68.57	70
	All	YES	1	4 and greater	97.4	7.765
	All	YES	2	1	55.1	6.858
	All	YES	2	2	56.96	13.01
	All	YES	2	3 =/<	62.85	28.24
	All	YES	3 and greater	1 and greater	56.1	7.622
	All	YES	4 and greater	All	56.19	8.952
Conductor - ACSR/GZ Type	C4				63.3	25.19
	C3				68.46	7.272
Earthwire Fittings	C1 / C2				110	8
	C3 / C4				85	14
Vegetation Clearance - Low					Asset Inspection Manager (AIM), LIDAR Results, Ellipse	
Vegetation Clearance - Med						

Table 32 - Digital Infrastructure Assets

B.4 – Digital Infrastructure		
Equipment	**η**	**β**
Multifunction Intelligent Electronic Device: - Protection - Controller - Telecommunication	14.3	1.78
Protection Relay - Solid State	32.7	1.24
Protection Relay - Electromechanical	92.9	1.57
Protection Relay - Intertrip	26.2	1.54
Remote Terminal Unit	22.5	1.77
PC	12.7	2.09
Meter - Microprocessor	15.5	1.74
DC Battery	16.5	1.49
DC Charger	19.8	1.24
Telecommunications Terminal Equipment	47.0	1.79
Power Line Carrier Equipment	26.2	1.54