Network Asset Health - Overview and Approach

Summary

This document outlines the framework adopted in the development of an effective asset health system for electricity network assets.

Revision no:	0	**HP TRIM No:**		**Approval/ Review Date:**	23 December 2016
Business function:	Strategic Asset Management			**Document type:**	Framework
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Contents

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. Position of this document

This document provides an overview of the Network Asset Health Framework (NAHF) and its application.

3. Scope

The scope of the Network Asset Health is:

Asset Health for the following asset classes:

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

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.

4. Definitions

Table 4.1: Definitions

Term	Definition
ALARP	As Low As Reasonably Practicable (ALARP). For further details refer to Australian Standard 5577 – Electricity Network Safety Management System.
Failure Mode	The specific manner in which a failure can occur.
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.
Probability of Failure (PoF)	The chance of a hazardous event occurring.
Conditional Failure	Conditional failure is the inability of an asset to meet the condition specifications and limitations placed on it.
Functional Failure	Functional failure is the inability of an asset to meet its specified function.
Natural Age	Commonly known as "age". Year elapsed since an asset's first install date
Effective Age	Apparent age of an asset based on its condition
Life Ending Failure	Type of failure that destroys an asset beyond repair. Also known as "catastrophic failure"
Non-Failure Replacement	Replacement of an asset before it is allowed to fail
Weibull Distribution	A continuous probability distribution.
SFAIRP	So Far As Is Reasonably Practicable (SFAIRP). For further details refer to Australian Standard 5577 – Electricity Network Safety Management System.
SME	Subject Matter Expert

5. Framework Principles

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 5.1.

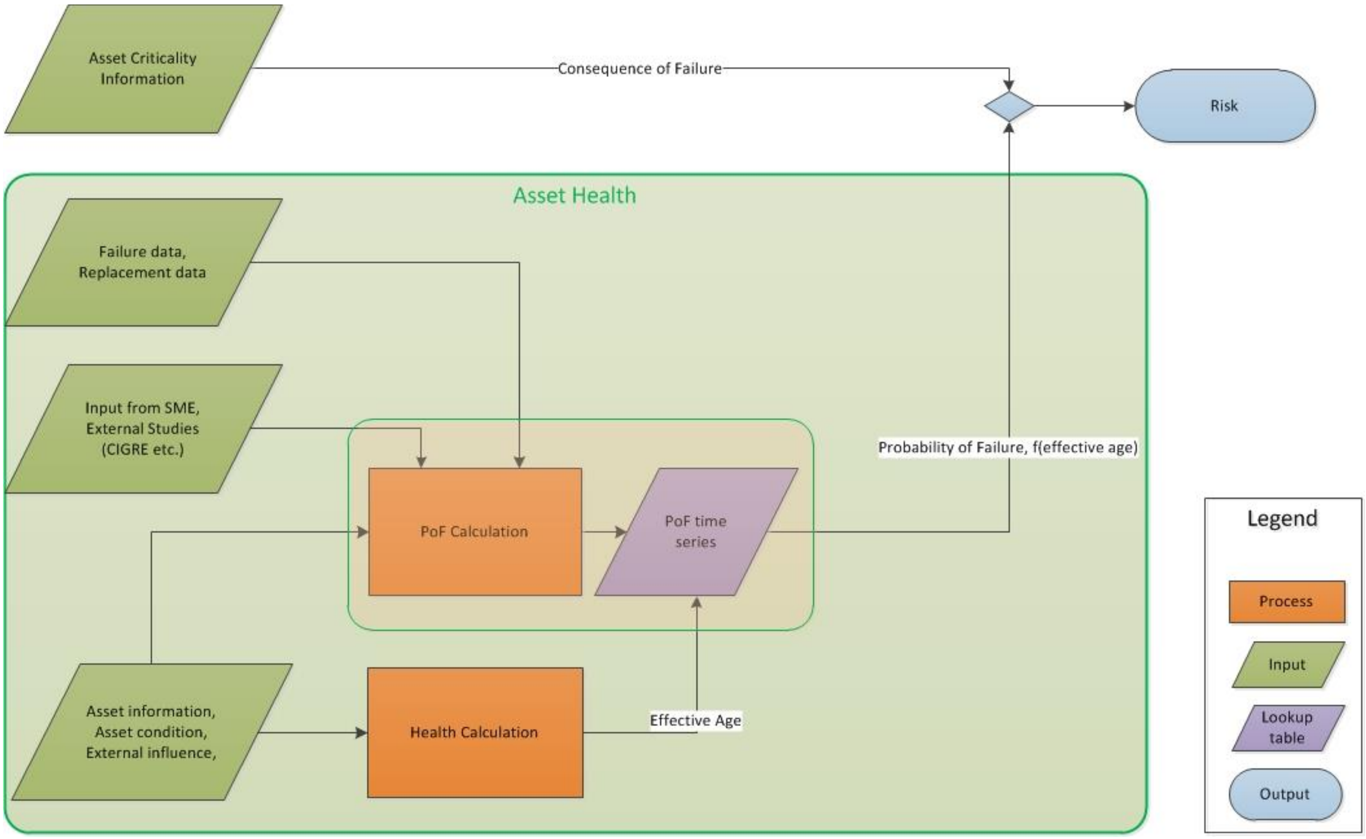

Figure 5.1: Generic high level view of risk quantification process

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 will be 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

6. Framework

The key principles on which the methodology and processes of the NAHF are based 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 aging factors can provide valuable information in forecasting asset health.
- 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 aging, 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 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).

6.1 Health Calculation

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

Figure 6.1 illustrates a generic high level view of the Health Calculation.

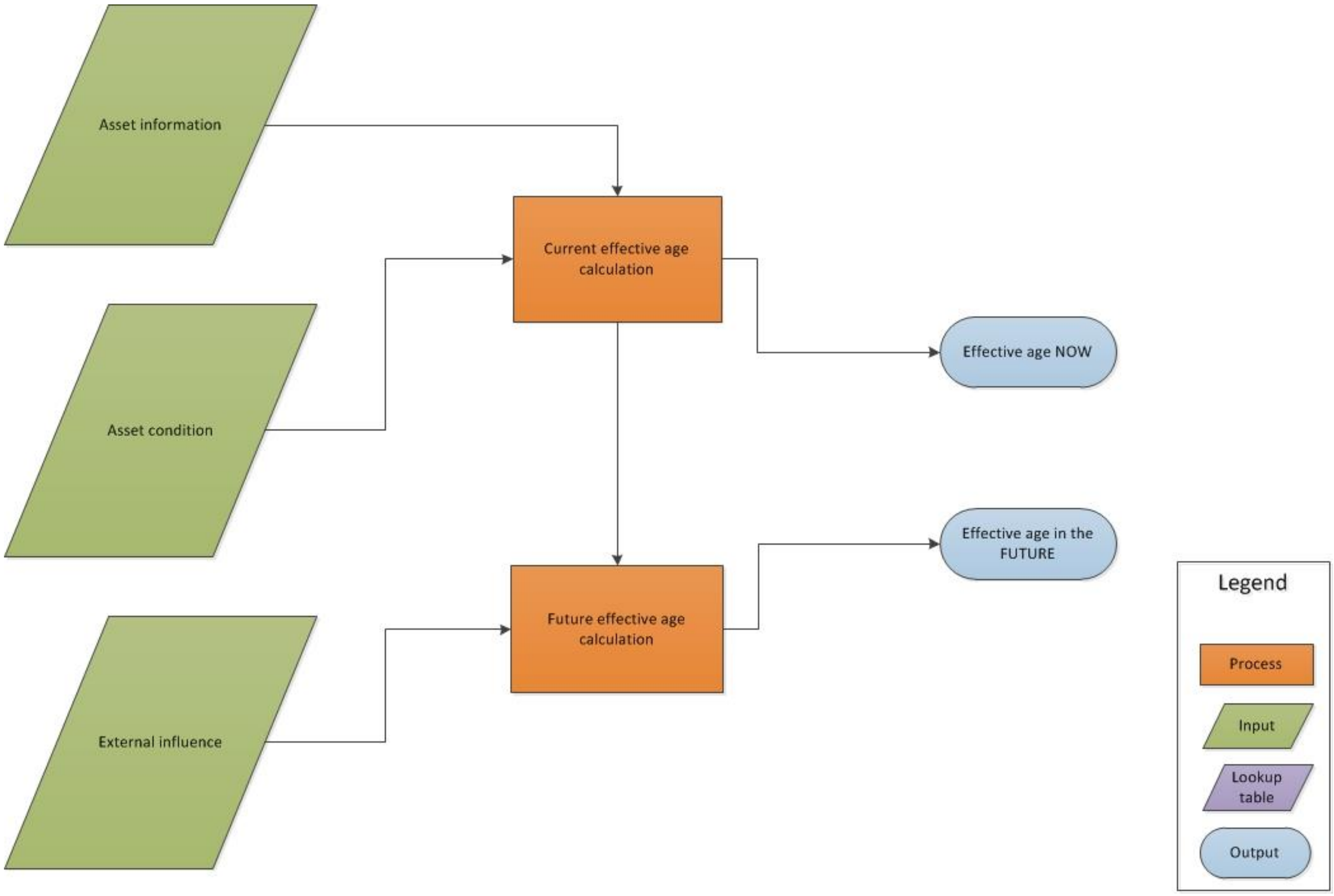

Figure 6.1: Generic high level view of Health Calculation

6.2 Probability of Failure Calculation

The outputs of the Probability of Failure (PoF) Calculation are one of more probability or failure time series which provide a mapping between the effective age and the yearly probability of failure value for a given asset class. 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.

Figure 6.2 illustrates a generic high level view of the PoF Calculation.

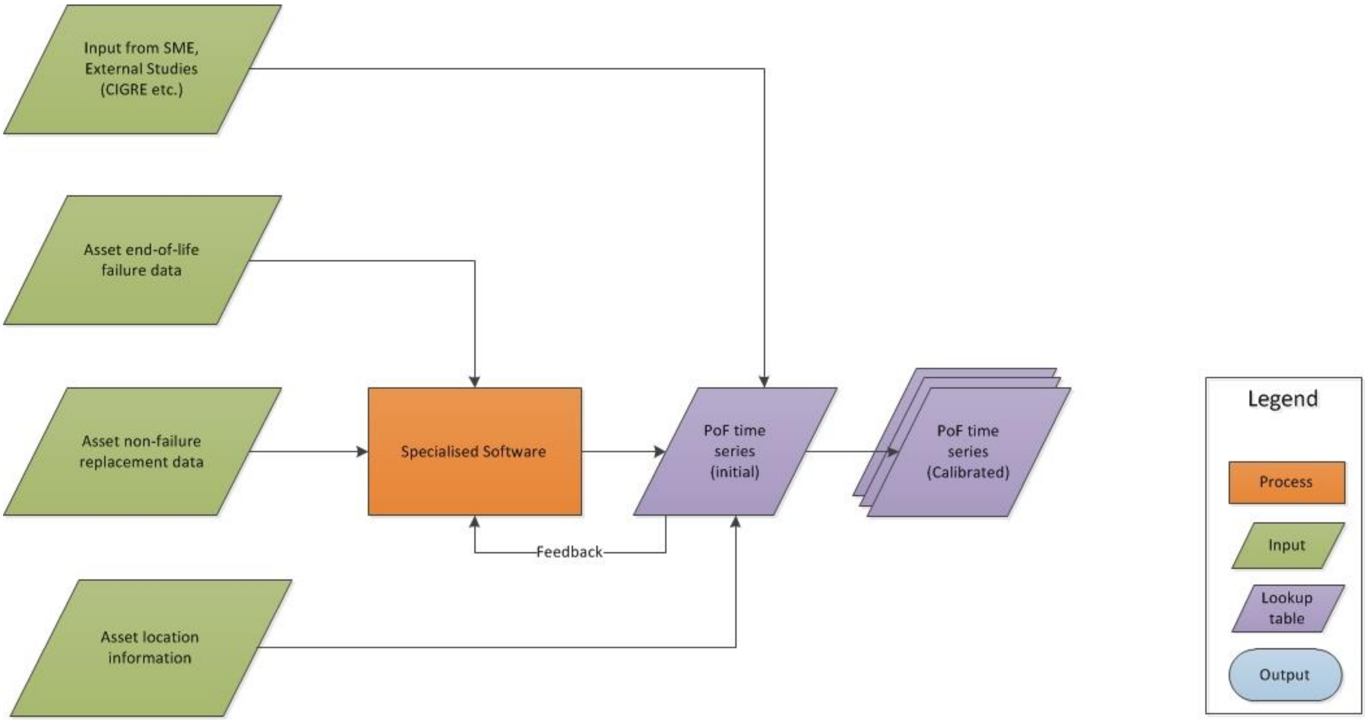

Figure 6.2: Generic high level view of PoF Calculation

6.3 Inputs

Various information inputs are required for the Health and PoF Calculations. The information input categories and use are outlined in Table 6.1.

Table 6.1: Health and PoF Calculation Inputs

Information Category	Usage	Calculation
Asset information	> Current effective age > Probability of failure	> Health Calculation > PoF Calculation
Asset condition	> Current effective age	> Health Calculation
External influence	> Future effective age moderation > Probability of failure moderation	> Health Calculation > PoF Calculation
Subject Matter Expert input, Study	> Current/future effective age moderation > Probability of failure moderation	> Health Calculation > PoF Calculation
Asset failure information	> Probability of failure	> PoF Calculation

In each Information Category, multiple input or data points are required. The data points and their relationship to the individual asset class are defined in the subsequent sections of this document.

7. Accountability

Role	Responsibilities and Accountabilities
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.
Executive Asset Strategy Committee	> Review and endorse the Network Asset Health Framework
Manager/Asset Planning	> Endorse 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 Performance and Systems Manager	> Develop and refine the Network Asset Health Framework
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.

8.1 Monitoring and review

The NAHF is reviewed by the Executive Asset Strategy Committee annually.

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.

Probability of failure study is monitored jointly by the relevant Asset Managers and Asset Performance and Systems Manager at least yearly or due to introduction of a new technology.

9. Change history

Revision no	Approved by	Amendment
0	T. Gray, A/ M/Asset Strategy	None. 1st issue

10. References

> Network Asset Risk Assessment Methodology
> Network Asset Health Framework
> Network Asset Criticality Framework
> NACA-SSAP – Protection Assets
> All relevant CIGRE Papers

11. Table of Attachments

Table 11.1 contains reference to the appropriate attachments which describe in detail the working of asset health, effective age and the associated probability of failure calculations.

Table 11.1: Detailed Calculation Reference

Asset Class	Health Reference	PoF Reference
Power Transformer	Attachment section A.2	Attachment section B.5
Oil filled Reactor	Attachment section A.2	Attachment section B.6
Circuit Breaker	Attachment section A.3	Attachment section B.7
Instrument Transformer – oil CT	Attachment section A.4.2	Attachment section B.8
Instrument Transformer – MVT	Attachment section A.4.4	Attachment section B.9
Instrument Transformer – CVT	Attachment section A.4.5	Attachment section B.10
Disconnector	*None*	Attachment section B.11
Surge Arrester	*None*	Attachment section B.12
Transmission Line	Attachment section A.5	Attachment section B.13
Protection Relay	Attachment section A.6	Attachment section B.14

Attachment A : Health

A.1 Overview

This section describes the methodology and detailed calculation of health, remaining life and effective age of the asset classes.

Key input to this process is 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 (for example, corrosion, pollution, stress events, loading, and operation) as applicable.

Input data points are selected based on their relative importance, currency, relevance, availability and practicality. Assumptions are made where required throughout the process and a specific statistical model is adopted based on existing knowledge of and suitability to a particular asset class.

The output of this process, the effective age, is used as an input to obtain a probability of failure value.

A.2 Power Transformer & Oil filled Reactor

The population under this assessment exclude the following assets/types:

> SF6 type large power transformers and reactors,

> Auxiliary transformers,

> Regulators,

> System spares.

Although an integral part of a transformer, bushings are significantly unique in terms of their reliability, failure behaviour and service lives in comparison with the rest of the transformer. Therefore, health contribution from the bushings is excluded from the transformer health calculation. Bushings are to be treated separately.

A.2.1 Health Index

This section describes the data points and factors which are applied in determining the overall power transformer and oil reactor health index (HI).

A.2.1.1 Natural Age

Transformer natural age information provided as part of the annual Regulatory Information Notification (RIN) is used. End of life threshold in terms of natural age is set to 45 years. This is recommended by major international bodies, such as CIGRE and industry practice, and is consistent with TransGrid's Substation Renewal and Maintenance Strategy (D2014/18645).

The magnitude of influence of natural age to the health index calculation is generally linear with one or more 'way points'. The relationship is positively correlated.

A.2.1.2 Defects

The previous 15 years of defect data sourced from Ellipse are analysed. The total number of defects are recorded against each plant item and used as an input for the HI calculation.

Defects which relate to a transformer's peripheral components, such as conservator sight glass, third party online condition monitoring devices such as optical winding temperature indicator, or Doble bushing monitor, are excluded. The failure of these devices does not have a major impact on a transformer's operating capability or overall health and are hence not included.

A total of 170 transformers (75% of the total population) have been found to have recorded defects. Defects are classified into five categories each with appropriate weightings assigned to them. The defect categories are:

> Oil leak from main tank

- Cooling System (Pump, Fan & Buchholz)
- Secondary (LV wiring, AVR, protection, control cabinet)
- Internal Insulation of the main tank
- Tap Changer

Based on the defect counts and the applicable weighting, a defect score is calculated and normalised. The magnitude of contribution of defects to the health index calculation is linear and they are positively correlated.

A.2.1.3 Cost of Defects

The sum of all recorded actual defect costs is used. A threshold value of $100,000 (non-escalated) incurred defect cost is used. Additional weighting factor is not applied for any transformers with cumulative defect cost above this threshold at this stage but can be added in the future if deemed necessary. Cost of defects is not used as a financial measure but to indicate severity of defects.

The influence of cost of defects to the health index is linear and acts positively.

A.2.1.4 Average load

Daily average load for each transformer for the past two years are obtained from the Supervisory Control and Data Acquisition (SCADA) system. Zero values due to transformers remaining out of service are excluded. The daily average load in MVA is then divided by the transformer's rating and is presented as a ratio.

This contribution being the ratio of transformer average load and capacity signifies usage related wear and tear and therefore is positively correlated to the health index value.

A.2.1.5 Tap Changer Operation Count (Cyclometer)

Operating statistics for the past 5 years are sourced from Ellipse. If the required data is not available in the Ellipse data extraction, SCADA event history data is used. The operating statistics data are used 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 tap changer is forecasted.

End of life threshold in terms of total number of operations is set to one million operations. This figure is in line with most manufacturers' recommendations.

Tap changer operation count contribution is linear and positively correlated to the health index calculation.

A.2.1.6 Tap Changer Type

Transformers installed with specific types of tap changers which are known to have issues are flagged and considered to have detrimental impact on transformer overall health.

Throughout this, one specific type of tap changer is considered problematic and therefore its influence is added to the overall health index calculation.

A.2.1.7 Dissolved Gas Analysis (DGA)

For each gas, caution and danger limits stipulated in Substation Condition Monitoring Manual are applied to the historic average, the maximum and the latest measurement. Zero is nominated if the value is in normal range, one if the value is in caution zone and two if the value is in danger zone.

Appropriate weightings of the gasses are applied to each gas score and a total DGA score is then calculated by summating all weighted gas scores. The below gasses are included in the calculation:

- C_2H_2
- C_2H_4
- C_2H_6
- CH_4
- CO
- CO_2
- H_2

- TCG

A.2.1.8 Oil Quality (OQ)

A wide range of factors are assessed routinely as part of oil quality assessment in TransGrid. Similar to the DGA score described in Section A.2.1.7, caution and danger limits are applied to the historic average, the maximum and the latest measurement for each of the OQ factors. OQ factors are listed below:

- % H20 per dry weighted paper
- Dielectric Breakdown Strength
- Interfacial Tension
- Furan
- Acidity
- DDF
- Resistivity
- Corrosivity

The weighting factor and threshold value for each input are discussed in the framework document.

A.2.1.9 Other inputs not in use

The following inputs are not presently in use due to the difficulty in obtaining accurate data or the complexity in calculations. Consideration will be given to include the following factors in the future:

- Rate of change, trend and ratios in dissolved gases and oil quality analysis
- Number and details of through faults
- Long term effect of natural surrounding environment (such as high ambient temperatures, corrosion)
- Impact of changing operating environment and network characteristic changes
- Severity and type of past defects
- effective age estimation using long term thermal modelling, furan and acidity data

A.2.1.10 Formulae for health index

The contributions and consolidation from each category towards the final health index score can be expressed as a function of these as outlined below:

HI = ƒ (Natural Age, Average load as % of rating, Defects, Cost of defects, DGA, Furan, Moisture, DBS, IFT, Acidity, Resistivity, Oil DDF, Oil leak, Oil corrosivity, Tap changer type)

Higher scores indicate worse condition. If the threshold limits are exceeded, either an alternate HI calculation method or a fixed value is adopted.

Applying this to each of the transformers in service, the Maximum health index score is 16.87 and the average health index score across the population is 3.09.

A.2.2 Effective age estimation

Effective age of a transformer is described to be the apparent age of a transformer based on its health index score. The steps are described in the below section.

A.2.2.1 Estimation of selected sample points

Five transformers were carefully selected such that each represented a unique point in time of a transformer life cycle. These points were arrived at based on the conditions of the transformers and were expressed in their respective ‘effective ages’. Health indices for these transformers were also calculated.

A.2.2.2 Statistical model

The effective ages were fed into a third party curve fitting tool. A non-linear exponential regression model is used to model the relationship between health index and effective age for the transformer asset class. The resultant curve represented a transformer health index and effective age mapping.

The 'goodness of fit' of the curve were checked and found to be reasonable.

A.2.2.3 Comparison of effective and natural ages

The effective ages of the transformers are based on their health indices. A side-by-side age profile comparison using the effective age and natural age indicates that the average effective age is lower than the average natural age of the transformer fleet. This is in-line with TransGrid's expectation. With strategic changes to the transformer maintenance and operation regime, this relationship is expected to change.

A.3 Circuit Breaker

A.3.1 Health Index

This section describes the data points and inputs which are applied in determining the overall circuit breaker health index. Detailed calculations and associated variables are discussed in the framework.

A.3.1.1 Natural Age

Circuit Breaker natural age is calculated from its first installed date. End of life threshold 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).

The magnitude of influence of natural age to the health index calculation is generally linear with one or more 'way points'. The relationship is positively correlated. Therefore, the health index value increases with an increase in natural age.

A.3.1.2 Defects

The previous 15 years of defect data sourced from Ellipse are analysed. The total number of recorded defects are recorded against each plant item and used as an input for the HI calculation.

Defects which relate to a circuit breaker's peripheral components, such as cyclometer counter, and third party online condition monitoring devices, such as Alstom's CB watch or Elcon's BCM/OLM, are excluded. The failure of these devices does not have a major impact on a circuit breaker's operating capability and overall health and hence are not included.

A total of 695 circuit breakers (46% of the total population of 1518) have recorded defects. Based on the defect counts and the applicable weighting, a defect score is calculated and normalised. The magnitude of contribution of defects to the health index calculation is linear and they are positively correlated.

A.3.1.3 Cost of Defects

The sum of all recorded actual defect costs is used. A threshold value of $30,000 (non-escalated) in incurred defect cost is deemed unacceptable. Only 14 circuit breakers have a cumulative total defect cost greater than $30,000. Cost of defects is not used as a financial measure but to indicate severity of defects.

The influence of cost of defects to the health index is linear and acts positively. This implies that with an increase of defect costs, the health index value increases.

A.3.1.4 Insulation type

Circuit breaker's insulation/breaking medium type is also used as an indication of the age and overall life cycle maintenance cost. It is noted that oil type (small oil) breakers are much older and more difficult to maintain due to the lack of manufacturer's support and obsolescence.

A.3.1.5 Mechanism type

Failure data and maintenance experiences prove that circuit breakers with hydraulic type mechanism are much more likely to fail and are expensive to maintain.

A.3.1.6 Operation Count (Cyclometer)

Circuit breaker operating statistics for the past 5 years are obtained from Ellipse and 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 is forecasted.

The end of life threshold in terms of total number of operations is set to 7000 operations. This is slightly conservative compared to most of the manufacturer's recommendations which normally ranges from 8000 to 10,000. The conservativeness is put in place due to having a degree of uncertainties around the key failure modes under normal operation and is justified in 'Substation Renewal and Maintenance Strategy'. The failure modes are:

> Slow operations
> Over travel
> Trip/closing spring failure
> Drive mechanism failure resulted from mechanical wear
> Motor failure
> Motor limit switch failure

This is supported by the failures of Kemps Creek 33kV circuit breakers in 2004 and 2005 and past operational experiences. Additionally, a number of circuit breakers installed in the Snowy Mountains area failed at 3,000 operations. The failed units have broken drive gear teeth and chain which is an indication of usage and load related metal fatigue/fracture.

It should also be noted that circuit breaker acceptance testing (to 10,000 operations) is based on a circuit breaker in ideal condition, in an ideal environment and with no electrical load applied.

A.3.1.7 Circuit Breaker test results

Results of High Voltage (HV) tests (time difference between contact travel, travel duration and contact resistance) from major maintenance in the last six years are sourced from the circuit breaker exception analysis tool. There are a number of well-established criteria for each type of breaker detailed in Substation Condition Monitoring Manual GM AS S1 008. The number of 'out of limit' results are counted and used as inputs.

A.3.1.8 Characteristic of normal duties

The type of duties are categorised into reactive and non-reactive switching. Circuit breakers installed in a reactive plant (capacitor banks and reactors) are flagged and used as part of the health assessment. Note, circuit breakers installed on long transmission lines or near generation sources are not distinguished at this stage as these conditions will only have some impact on the fault clearing capabilities and not the normal switching duties.

A.3.1.9 Type issues

Several type issues were identified from failure analysis by the Asset Manager and reports/observations from maintenance staff. Examples of type issues include deficiency of older technologies, spare parts availability, lack of manufacturer's support, high defect rate and high maintenance cost. The majority of the type issues are identified through specific mechanism type and insulation type and are given a higher weighting.

A separate weighting factor is applied to Sprecher and Schuh HGF215 type breakers since it is neither oil nor a hydraulic type breaker. The HGF215 type breaker has a very large spring mechanism and is prone to failure. Its main arc quenching technology is not the more advanced self-assisted puffer type, and higher forces are required to be developed by the operating mechanism to operate the circuit breaker.

A.3.1.10 Other input not in use

The following inputs are not presently in use due to the difficulty in obtaining accurate data. Therefore, the following inputs have not been included in the analysis at this stage: Further improvement can be made in the future.

> A circuit breaker's designed number of operation and X/R ratio of both the circuit breaker and the installed location
> The number and details of fault operation each circuit breaker has had in the past
> The long term effect of natural surrounding environment (such as corrosion)
> The impact of changing operating environment such as changing switching duties (for example, due to the decommissioning of services or generators) and network characteristic changes (for example, due to newly connected wind farms)

- Breaking contacts travel curve and dynamic contact resistance data

It may be possible to incorporate these inputs into the modelling in the future.

A.3.1.11 Formulae for health index

The contributions and consolidation from each category towards the final health index score is as per the below:

HI = *ƒ* (Natural Age, Projected operations in 2024, Defects, Cost of defects, Reactive Plant Circuit Breakers, No of above limit test results, Insulation Type, Mechanism Type)

Higher scores indicate worse condition.

The highest HI score calculated from these formulae is 8.55. The average health index score across the population is 1.46.

A.3.2 Effective age estimation

Effective age of a circuit breaker is described to be the apparent age of a circuit breaker based on its health index score. The steps are described in the below section.

A.3.2.1 Estimation of selected sample points

Five circuit breakers were carefully selected such that each represented a unique point in time of a circuit breaker life cycle. These points were arrived at based on the conditions of the circuit breakers and were expressed in their respective 'effective ages'. Health indices for these circuit breakers were also calculated.

A.3.2.2 Statistical model

The effective ages were fed into a third party curve fitting tool. A four parameter logistic (4PL) non-linear regression model, a symmetrical sigmoidal function which is a specific form of log function, is used to model the relationship between health index and effective age for the circuit breaker asset class. The resultant curve represented a typical circuit breaker health index and effective age mapping.

The 'goodness of fit' of the curve were checked and found to be reasonable.

A.3.2.3 Comparison of the calculated effective age with natural age

The effective ages of the circuit breakers are based on their health indices. A side-by-side age profile comparison using the effective age and natural age indicates that:

- The majority of HV transmission circuit breakers have a relatively low usage rate and are well maintained. A large proportion of the circuit breakers appear to be 'younger' than their natural age. This phenomenon appears to be more pronounced for the newer generation of circuit breakers (0 – 25 years: commissioned post 2000) where technology has improved reliability and maintenance cost.
- Circuit breakers that have a large number of defects, type issues or perform much higher normal operations (circuit switching or reactive plant switching, rather than fault switching) have much lower remaining life with respect to the fleet average.

A.4 Instrument Transformer

A.4.1 Overview

A.4.1.1 Health Index Method Summary

Table 11.2 provides a summary of the methodology adopted for each type of equipment. (Gas insulated switchgear (GIS) substations are excluded from this process.

Table 11.2: Summary of health index methodology for each equipment type

Equipment	Health index methodology	Effective age
Oil CTs	Derived from DGA, age and type issues	Effective age estimated
SF6 or epoxy CTs and VTs	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 MVTs	Derived from DGA and age	Effective age estimated
CVTs	Not used	Natural age is used.

A.4.2 Oil Current Transformers

The inputs used to determine the health index and effective age are described in this section. The relative weightings and the specific formulae are left in the framework document.

A.4.2.1 Health Index

The health index for oil filled CTs is based on available data and can be descried to be a function of its natural age, DGA result and the type issues.

The details of each of the categories are outlined below.

A4.2.1.1 Dissolved Gas Analysis

The Dissolved Gas Analysis (DGA) component of the health index is determined from the limits defined in the 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 acceptable or cautionary region, the corresponding score is used. If the gas level is in the danger region the score is multiplied by the gas level to provide the score.

A4.2.1.2 Age

The age factor for CT's over 32 is included such that a 40 year old CT will be modelled with accelerated aging. While 40 years is the nominal technical life, as outlined in the renewal and maintenance strategy, a unit may have a remaining life of up to 50 years. However, 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.

A4.2.1.3 Type Issues

TransGrid has experienced a number of failures of hairpin CTs. In particular Tyree and ABB CTs have been identified as having reduced life based on the failure of similar type CTs at Ingleburn in November 2015 and multiple failures at Bayswater (particularly in 2004 and 2009). The investigation after the explosive failure of the Ingleburn CT concluded that at least one part of the cause of the failure was due to poor manufacturing processes and the inclusion of foreign materials in the primary insulation. A recommendation included in the draft Ingleburn CT failure report requires a review of the replacement strategy for all hairpin type CTs with particular focus on the population of Tyree/ABB CTs.

A4.2.1.4 Inputs not in use

The following inputs are not presently in use due to the difficulty in obtaining accurate data. Therefore, the following inputs have not been included in the analysis at this stage:

- The long term effect of natural surrounding environment (such as corrosion)
- Defects. A significant portion of the defects are typically associated with aspects of the CT, which do not provide an indication of the life of the plant. Examples include additional sampling, repairing or replacing of gauges. A small number of oil CT's may have relevant defects but the timely and accurate extraction of this information is not feasible.
- Measurements of H_2O, CO, CO_2, N_2, O_2, DDF, Capacitance and IR. These are often associated with inaccurate readings and therefore require closer review and interpretation.

A.4.2.2 Effective Age Estimation

This section describes how the 'effective age' is estimated from the health index of each unit. The natural age of the CT population can then be compared with the effective age.

A4.2.2.1 Estimation of Selected Sample Points

Seven CTs which have been removed from service recently were selected as sample point inputs to the curve fitting methodology. The effective age of these CTs was determined by a combination of judgement, typical replacement timeframes and the level of urgency which the DGA scoring would typically address. Two additional points were included to reflect a new CT with no DGA levels detected and a mid-life CT with some DGA issues starting to develop.

A4.2.2.2 Statistical Model

A polynomial model was determined to fit the sample points. The formula for this curve was then used to calculate an effective age for the CT population.

A.4.3 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 aging 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).

A.4.4 Oil Magnetic Voltage Transformers

The inputs used to determine the HI are described in this section, excluding the relevant weighting and the formulae.

A.4.4.1 Health Index

The health index for oil filled MVTs is based on available data and can be described to be a function of its natural age and DGA results. How the asset data is converted and combined into the final health index score – is discussed in the framework document. But in general, a higher score indicates a worse asset condition. Details of each of these categories are outlined below.

A4.4.1.1 DGA

The DGA limits and scoring are as per the process for oil filled CTs described in Section A.4.2.1.1. The DGA scoring is excluded from the effective age calculations of units without any DGA results (for example types without sampling valves fitted).

A4.4.1.2 Age

TransGrid

The age factor for MVT's over 37 is included such that a 45 year old MVT will be modelled with accelerated aging. 40 years is the nominal technical life, as outlined in the renewal and maintenance strategy (nominal life of 45 years to be used in the future).

A4.4.1.3 Inputs not in use

The following inputs are not presently in use due to the difficulty in obtaining accurate data. Therefore, the following inputs have not been included in the analysis at this stage:

- The long term effect of natural surrounding environment (such as corrosion)
- Defect rates for units
- Measurements of H_2O, CO, CO_2, N_2, O_2, DDF, Capacitance and IR. These are often associated with inaccurate readings and therefore require closer review and interpretation.

A.4.4.2 Effective Age Estimation

This section describes how the effective age is estimated from the health index of each unit. The MVT natural age of the MVT population can then be compared with the effective age calculated from the health index.

A4.4.2.1 Estimation of Selected Sample Points

Three MVTs which have been removed from service recently were selected as sample point inputs to the curve fitting methodology. The remaining life of these MVTs was determined by a combination of judgement, typical replacement timeframes and the level of urgency which the DGA scoring would typically address. An additional point was included to reflect a new MVT with no DGA levels detected with a corresponding life of 45 years. A mid-life VT sample point was also selected.

A4.4.2.2 Statistical Model

A polynomial model was determined based on the sample points. The formula for this curve was then used to calculate an effective age for the VT population.

A.4.5 Capacitor Voltage Transformers

Unbalance monitors are fitted to all CVTs and are effective in identifying faults developing in CVTs just prior 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.

Medium to long term, effective age calculation is considered to be required. Therefore, until further analysis is performed, natural age should be used. Defects arising from routine inspections or alarms received along with known type issues (such as, those associated with Trench and Haefely types) are to be used as moderators of the natural age as the Asset Manager sees fit.

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).

A.5 Transmission Line

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 together to provide a service.
- A single failure of a key component makes the transmission line service unavailable.

A.5.1 Current health

Condition information, 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.

A.5.1.1 Condition data

Condition data for 200 transmission lines are available at sub-component level. One set of data is available for each transmission line, rather than at a level for each span of the transmission line. Data collection for each transmission line spans in currently underway and is prioritised on a risk basis.

"Attachment 1 – Condition Assessment Coding Guideline" as part of "Transmission Line Condition Assessment Requirements" document contains the detailed description of the available condition ratings per component.

For a given transmission line component, conditions are expressed between 1 and 10. Each condition score is mapped to a percentage health for that specific component. This relationship is presently assumed to be linear. As our understanding improves, non-linear relationships will be introduced.

A.5.1.2 Life expectancy

A5.1.2.1 Ideal nominal life – Component level

The ideal nominal life expectancy is based on the assumption that the transmission line asset is located in an ideal environment where accelerated aging factors are minimal. The ideal nominal life expectancy values at the component level are obtained from internal subject matter experts. These are cross verified with our internal service provider to ensure correctness.

A5.1.2.2 Ideal nominal life – Asset level

The ideal nominal life expectancy of transmission line structures are also obtained from the subject matter experts which are verified against several external publications. Table 11.3 lists the asset level ideal nominal life expectancy of different transmission line structures.

Table 11.3: Transmission line structure asset level ideal nominal life expectancy

Line structure type	Ideal nominal life (years)	Assumed environment
Steel tower	94	Inland, salt free
Steel pole	94	Inland, salt free
Concrete pole	94	Any
Wood pole	63	Termite free, rot free

A5.1.2.3 Location based life – Asset level

Location based life expectancy values are derived from advice provided by the subject matter expert based on corrosion zones, rot zone and termite zones. Table 11.4 lists the transmission line structure life expectancy based on the environment of its location.

Table 11.4: Transmission line structure life expectancy based on environment

Line structure type	Environment	Life expectancy
Steel tower, steel poles	Inland, low corrosion	94
Steel tower, steel poles	Mixed, moderate corrosion	75
Steel tower, steel poles	Coastal, severe corrosion	57
Wood pole	Termite free, rot free	63
Wood pole	Termite zone	63 x LRF_T
Wood pole	Rot zone	63 x LRF_R

Where, LRF = ‘Life Reduction Factor’, a multiplier value below unity. LRF represents the reduced life due to a specific environmental action.

A.5.1.3 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.

A.5.1.4 Scaled natural age

‘Natural age’ is scaled based on the installation environment of the transmission line. This scaling factor is the ratio of ‘Ideal nominal life expectancy’ and ‘Location based life expectancy’. The purpose of scaling the natural age is to represent age on an ideal age scale.

A.5.1.5 Location

The location of transmission lines is based on the right of way it traverses and is divided into the categories listed in Table 11.5.

Table 11.5: Transmission line location categories

Location
Inland
Mixed
Coastal

A.5.1.6 Ideal effective health

Ideal effective health is based on a weighted average of ‘ideal age based health’ and the ‘condition based health’.

A.5.1.7 Worst case ideal effective health

Where multiple condition ratings for a given component along the line are present, the worst case condition is selected. This is based on the understanding that components with the worst condition are likely to fail first, causing an interruption to the service subject to the component’s mission criticality within the system. Therefore, it is the worst condition that dictates the risk magnitude.

A.5.1.8 Determination of transmission line health from Sub-component health

A5.1.8.1 Weighting

In order to integrate the individual health contribution from the sub-component level to the transmission line level, a set of contribution percentages is developed. The percentage contributions are discussed in the framework document.

A5.1.8.2 Worst case ideal effective transmission line health (ideal transmission line health)

The worst case ideal effective transmission line health is also referred to in the framework as ‘ideal transmission line health’.

The aggregated percentage weighting is used to convert the sub-component level health to the transmission line level health. It is noted that all calculations are performed on an “ideal” scale, aimed at removing dissimilarity between various transmission lines in terms of their locations.

Some transmission lines consist of more than one type of structure in its construction (for example, part steel tower, and part wood pole). To accommodate this characteristic in determination of the transmission line health, weighted sums of the mutually inclusive sub-components are used.

A.5.2 Current ideal effective age

Current ideal effective age is derived from the ideal transmission line health and the ideal nominal life at the asset level. The current ideal effective age indicates the apparent age of a transmission line on its ideal scale, taking into consideration its condition and natural age.

A.5.3 Future ideal effective age

The future ideal effective age is derived by moderating its current ideal effective age by 'Age Shift Modifier'. 'Age Shift Modifier' is a multiplier that represents age acceleration or deceleration due to various factors. The factors are outlined in Table 11.6

Table 11.6: Inputs to age modifier

Age accelerating/decelerating factors
Lightning impulse overvoltage
Switching impulse overvoltage
In-zone/close-up faults
Wind event
Conductor annealing
Type fault
Design issue
Refurbishment

A.5.4 Interfacing with Transmission Line Probability of Failure

Several PoF time series are presented in Section 0, Transmission Line Probability of Failure. Currently, the following PoF time series are used to 'look up' the probability of failure values:

> Steel tower/poles, inland – represents low corrosion action
> Steel tower/poles, mixed – represents medium corrosion action
> Steel tower/poles, coastal – represents severe corrosion action
> Wood poles, low – represents normal wood poles
> Wood poles, medium – represents pressure impregnated wood poles

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

In the process of 'looking up' the PoF value, a "percentage common root cause" factor is applied. This takes into consideration the percentage ratio of the dominant root cause to all other root causes. Presently, steel corrosion is used as the dominant root cause.

A.6 Protection Relay

There are predominantly three types of protection relays 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 capability.

Similar to other assets, health of a protection relay can be determined from observing the conditions of the relays and their key sub-components. Determining health this way would be deterministic but cost prohibitive as these will 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 preference of a relay to remain in the network.

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

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

> Age factor
> Relay type
> Obsolescence/Support availability
> Forecast defects

A.6.1 Age Factor

Age factor is determined by taking the ratio of relay's natural age and its 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. Each Age factor range is assigned a score to represent service life.

A.6.2 Relay Type

Life expectancy, failure modes, accuracy, reliability etc. of protection relays are different across different relay types. Microprocessor based relays offer additional benefit such as, the ability to implement multiple schemes within the same unit, to self-monitor and alarm etc. Solid state relays tend to be problematic due to the uncertainly of their sub-components failing randomly.

Based on the above, various scores are assigned to the different relay types. Higher values indicate higher contribution to the overall deterioration of health.

A.6.3 Obsolescence/Support Availability

Manufacturers' support and technological obsolescence play a big role 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. Higher values indicate higher contribution to the overall deterioration of health.

A.6.4 Forecast Defect Rates

The historical performance of the asset group is analysed and the defect rates are forecast into the future. Currently, forecasting is only one year forward and is very basic in its calculation. The forecast is used to determine the risk the associated with assets failing and resulting in primary plant suffering from inadequate protection.

To represent the contributions from a range of defect rates, various scores are assigned to the different forecast defect rate scenarios.

A.6.5 Health Index

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

Health Index = ƒ (Age Factor Score, Relay Type, Support Availability/Obsolescence, Forecast Defect Rates)

Protection relay health index currently ranges from 0 to 100% with the ability to exceed this value in extreme circumstances.

Health index is currently used as a prioritisation indicator within the various relays to provide a view of their relative conditions.

A.6.6 Effective age

Currently no direct relationship is drawn between the effective age and the probability of failure for a protection relay. Consequently, the effective age is not worked out from the health index.

Attachment B : Probability of failure

B.1 Overview

As time passes, 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 aging, 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.

B.2 Approach

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

- Obtain all failure data for the past ten years, where possible.
- 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 and which were irreversible.
- Obtain the individual natural ages at which these failures occurred (time to fail).
- Obtain all non-failure asset replacement data for the past ten years including their natural ages at which they were replaced (time to fail).
- Input the 'time to fail' data set for life-ending failures to AWB
- Input the 'time to fail' data set for non-failure asset replacement data to AWB. Mark these data points as 'suspended'.
- Run simulation and observe the resultant Weibull parameters and the failure curve.
- Verify the outcome with the relevant CIGRE or other international study. Calibrate as required.
- Consult the Asset Manager if there is significant departure.
- Model additional failure behaviour if necessary and aggregate it to the failure curve
- Apply the failure curve to the fleet and observe the resultant number of failures it predicts for the fleet. This should generally be sufficiently close to the observed number of yearly failures. Analyse any significant departure and either accept or re-calibrate. Acceptance should be supported appropriately.

B.3 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 significantly low.

B.4 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.5 Power Transformer

The approach outlined in Section B.2 is applied to obtain the probability of failure for transformers.

B.5.1 Failure 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.

B.5.2 Non-failure replacement data

A total of 71 transformer non-failure replacement events since year 2000 were obtained from Ellipse. The data was verified to ensure that none of these replacements were as a direct result of a transformer failure.

B.5.3 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:

$\eta = 59.74$

$\beta = 4.196$

B.5.4 Verification

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

- 'CIGRE Transformer Failure Survey ELT 088 1' which is based on 400 failures across 2300 transformers over a period of 10 years (1968-1978)
- Transformer Reliability Survey: Interim Report (WG A2.37 report) which is based on failure data of 340 failures at 8900 substation transformers (100kV – 500kV) between years 2000 and 2010

TransGrid's transformer failure rate calculation using a conventional approach (as used in the external studies) suggests a failure rate of **0.57%** using the same set of failure data as obtained in Section B.5.1.

If the failure data obtained in Section B.5.1 is force fitted to an exponential distribution, a constant failure rate of **0.56%** is observed.

The comparison provides confidence in the failure dataset and its use in the modelling of a probability of failure time series.

B.6 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.

B.6.1 Failure 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.

B.6.2 Non-failure replacement data

A total of 25 oil filled reactor non-failure replacement events since the year 2000 were obtained from Ellipse. The data was verified to ensure that none of these replacements were as a direct result of a reactor failure.

B.6.3 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:

$\eta = 57.58$

$\beta = 4.484$

B.6.4 Verification

The model was verified with the SMEs. Some level of calibration was identified to be necessary.

B.6.5 Calibration

The following advice was received from the SME:

- Oil reactors are not built as robust as transformers and therefore have a generally lower service life expectancy.
- Oil reactors experience a much higher number of switching operations than a transformer. This implies that their bushings and insulation experience a significant amount of switching surges and the windings are exposed to mechanical forces due to inrush current. Additionally, the effect of daily hot and cold cycles is detrimental to their health.
- While switched in, oil reactors always run on full load.
- Oil reactors are brought online during light load condition. Hence the duty cycle of oil reactors is lower.
- Oil reactors rarely experience through faults compared to power transformers.

Based on the above, an oil filled reactor model was developed by modifying the Weibull distribution parameters. The resultant parameters are:

$\eta = 50.17$

$\beta = 4.945$

B.7 Circuit breaker

The approach outlined in Section B.2 is applied to obtain the probability of failure for circuit breakers.

B.7.1 Failure data

Circuit breaker failure data since the year 2005 was collected and verified. 'Infant mortality' type failures (that is, circuit breakers which have failed within 5 years from their first installation date) were also excluded from the modelling. A total of 21 life ending failures were obtained and used in the modelling.

B.7.2 Non-failure replacement data

A total of 81 circuit breaker non-failure replacements since the year 2005 were obtained from Ellipse. The data was verified to ensure that none of these replacements were as a direct result of a circuit breaker failure.

B.7.3 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 96%. The resultant Weibull distribution parameters are:

$\eta = 48.94$

$\beta = 3.067$

B.7.4 Verification

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

- A CIGRE study on SF_6 circuit breaker failures indicates that the SF_6 mean failure rate of TransGrid is reasonably close to that of the study.
- A Canadian Electricity Association study, examining forced outage rates of SF_6 and Small Oil circuit breakers, indicated that SF_6 circuit breakers tend to exhibit between two to three times more failures than the Small Oil circuit breakers. TransGrid's combined failure rate of **0.5%** per annum for SF_6 and Small Oil circuit breakers indicate a ratio similar to the Canadian study.

The results of the TransGrid study appeared in agreement with the results of the CIGRE and Canadian Electricity Association studies. This provides confidence in use of the computed circuit breaker failure rate in determining a probability of failure time series.

B.7.5 Calibration

No calibration is considered necessary.

B.8 Oil CT

The approach outlined in Section B.2 is applied to obtain the probability of failure for oil CTs.

B.8.1 Failure data

Oil CT failure data since the year 2005 was collected and verified. 'Infant mortality' type failures (that is, oil CTs which have failed within 5 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.

B.8.2 Non-failure replacement data

A total of 986 oil CT non-failure replacements since the year 2005 were obtained from Ellipse. The data were verified to ensure that none of these replacements were as a direct result of an oil CT failure.

B.8.3 Simulation

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

A 3-parameter Weibull distribution appeared to be the best fit with a R^2 value of 97%. The resultant Weibull distribution parameters are:

η = 253.1

β = 26.38

γ = -189

B.8.4 Verification

A recent CIGRE study on oil CT failure rates produced a range of mean failure rates. Using an identical methodology to the CIGRE study, an equivalent failure rate produced using TransGrid's failure dataset is found to be reasonably close to that of the CIGRE study.

B.8.5 Calibration

No calibration is considered necessary.

B.9 MVT

The approach outlined in Section B.2 is applied to obtain the probability of failure for MVTs.

B.9.1 Failure data

MVT failure data since the year 2005 was collected and verified. There were no 'infant mortality' type failures present in the dataset. A total of 4 life ending failures were obtained and used in the modelling.

B.9.2 Non-failure replacement data

A total of 197 MVT non-failure replacements since the year 2005 were obtained from Ellipse. The data was verified to ensure that none of these replacements were as a direct result of a MVT failure.

B.9.3 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 98%. The resultant Weibull distribution parameters are:

η = 61.52

β = 3.748

B.9.4 Verification

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

> The latest CIGRE study on MVT.

Fitting the TransGrid time to failure data into an exponential distribution yielded an equivalent failure rate of 0.1626% per annum, a result close to the CIGRE study result.

B.9.5 Calibration

No calibration is considered necessary.

B.10 CVT

The approach outlined in Section B.2 is applied to obtain the probability of failure for CVTs.

B.10.1 Failure data

CVT failure data since the year 2005 are collected and verified. There were no 'infant mortality' type failures present in the dataset. A total of 4 life ending failures were obtained and used in the modelling.

B.10.2 Non-failure replacement data

A total of 357 CVT non-failure replacements since the year 2005 were obtained from Ellipse. The data was verified to ensure that none of these replacements were as a direct result of a CVT failure.

B.10.3 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 appears to be the best fit with a R^2 value of 95%. The resultant Weibull distribution parameters are:

$\eta = 305.5$

$\beta = 1.367$

B.10.4 Verification

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

- A CIGRE study on CVT failure rates

Fitting the TransGrid time to failure data to an exponential distribution yielded an equivalent failure rate of 0.1202% per annum, a result close to the CIGRE study result.

B.10.5 Calibration

The following advice was received from the SME:

- For a given voltage level, the magnetic unit of a CVT is expected to follow a deterioration pattern similar to that of a MVT unit. Note, however, at lower voltage levels, such deterioration will begin to manifest itself at a later stage of its life.

This additional factor is modelled by "time shifting" a MVT probability of failure time series and then adding to it the existing CVT probability of failure time series. Onset of the change in behaviour is modelled to initiate at the fortieth year of the CVT's natural age, by exhibiting additional behaviour of a 20 year old MVT.

The probability of failure time series is expressed by use of a bi-Weibull distribution. The resultant bi-Weibull distribution parameters are:

$\eta_1 = 305.5$

$\beta_1 = 1.367$

$\gamma_1 = 0$

$\eta_2 = 61.52$

$\beta_2 = 3.748$

$\gamma_2 = 20$

B.11 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.

B.11.1 Failure data

Nil.

B.11.2 Non-failure replacement data

Nil.

B.11.3 Simulation

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

$\eta = 107$

$\beta = 2.2$

B.11.4 Verification

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

B.11.5 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:

$\eta = 67$

$\beta = 4.8$

B.12 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.

B.12.1 Failure data

Nil.

B.12.2 Non-failure replacement data

Nil.

B.12.3 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 aging 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:

$\eta = 55$

$\beta = 3.2$

B.12.4 Verification

Verification was performed internally by the SME.

B.12.5 Calibration

No calibration is considered necessary at present.

B.13 Transmission Line

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.

B.13.1 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
    - Wood Poles
    - Steel Grillage Foundations
- Structure Earthing
- Insulators
- Conductor and Earthwire Fittings
- Conductor and Earthwire

The probabilities of failure of the fundamental components of transmission lines are represented in the graphs throughout this section.

The probability of failure calculations have been based on deterioration of asset condition only. No allowance for events beyond the design capability of the assets has been made. Additionally, the methodology used in the calculation of these values is limited by the extent of relevant available data.

B.13.2 Condition Assessments

Condition assessments were undertaken for each asset by Field Services and in some instances, expert reports were commissioned. Each component of the asset was assigned a current condition code ranging from 1 to 6, proportioned by section or number accordingly. These formed the basis in the overall understanding of the current condition of the line.

A probability of failure was assigned to each individual component in accordance with their various assessed conditions. The weighted average of probabilities was calculated to determine the overall probability of failure of the total number of the each individual component across the line.

B.13.3 Probability of Failure calculation

B.13.3.1 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.

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 have been used in the calculation of the probability of failure tables and curves for each condition, as shown below.

B13.3.1.1 Initial Condition 6

All galvanising intact

No metal loss

0.00% probability of failure associated.

B13.3.1.2 Initial Condition 5

All galvanising lost

No metal loss

Probability of failure curve under the most aggressive corrosion shows a 6% probability of failure 50 years from now.

B13.3.1.3 Initial Condition 4

All galvanising lost

1% metal loss

Probability of failure curve under the most aggressive corrosion shows a 6.8% probability of failure 50 years from now.

B13.3.1.4 Initial Condition 3

All galvanising lost

3% metal loss

Probability of failure curve under the most aggressive corrosion shows an 8% probability of failure 50 years from now.

B13.3.1.5 Initial Condition 2

All galvanising lost

10% metal loss

Probability of failure curve under the most aggressive corrosion shows a 16% probability of failure 50 years from now.

B13.3.1.6 Initial Condition 1

All galvanising lost

20% metal lost

Probability of failure curve under the most aggressive corrosion shows a 40% probability of failure 50 years from now.

From the calculated probability curves, the probabilities of failure associated with a tower weakened by corrosion were selected at every 5 years to align with the mid points of regulatory control periods. Table 11.7 outlines the probability of failure values associated with a tower weakened by corrosion as at year 2022 (middle of regulatory control period 2):

Table 11.7: Average Probabilities of Failure on Towers as at 2022

Corrosion Level	Condition 1	Condition 2	Condition 3	Condition 4	Condition 5	Condition 6
Low	2.19%	0.56%	0.12%	0.05%	0.02%	0.00%
Medium	2.60%	0.70%	0.19%	0.10%	0.07%	0.00%
Medium/High	2.84%	0.78%	0.22%	0.13%	0.09%	0.00%

B.13.3.2 Structures – Grillage Foundations

The methodology used in the calculation of the probability of failure for tower grillage foundations is similar to that applied for the transmission line towers described above. In this instance, the points of difference are:

> The size of the steel member used in the grillage foundation

> The rate of corrosion being related to the soil characteristics of the footing

Again, it was presumed the design wind pressure of 1300Pa, with a selected RP of 2,500 years.

Corrosion of buried steelwork is coupled to the soil exposure classification, as described in AS 2159 – Piling Design and Installation, which determines the rate at which buried steel is expected to corrode in various ground and environmental conditions. Each structure with grillage foundations in the network was assessed by a Subject Matter Expert using the following inputs to estimate soil aggressiveness:

> Australian Soil Classification
> Acid Sulphate Soils
> Proximity of Estuary/Watercourse
> Salinity

These were calibrated from a sample of structures which were tested for their soil properties and subsequently had their grillages exposed to measure steel loss.

As with the towers, in the calculation of the probability of failure for tower grillage foundations, members are premised on an initial loss of section and further loss over the years is based on the corrosion environment. The initial section loss on the foundation was estimated based on the age of the tower, an expected life of a sacrificial anode of 10 years, and its soil corrosion environment.

For simplicity, the soil classification was grouped into two categories, namely, non-aggressive and aggressive (moderate). The grillage foundation probabilities of failure were selected at every 5 years to align with the mid points of regulatory control periods. Table 11.8 outlines the probability of failure values as at year 2022 (middle of regulatory control period 2):

Table 11.8: Average Probabilities of Failure on Tower Grillage Foundations as at 2022

Soil Aggressiveness Level	PoF
Non-Aggressive	0.085%
Aggressive (moderate)	0.940%

B.13.3.3 Structures – Wood Poles

The methodology used in the probability of failure calculation for wood poles is similar to that applied for the transmission line towers. Unlike condition assessment information on the towers, relevant data on the current condition of the wood poles, including the extent of decay, was unavailable. As such, the extent of decay on the pole was estimated based its age (from date of construction), and expected rates of decay. Two different calculations have been undertaken for the different types of wood poles on the network:

> Natural round wood poles
> Pressure impregnated wood poles

An expected decay rate of 1.05% per annum was used on natural round wood poles based on TransGrid's experience. The decay rate of pressure impregnated poles is typically approximately 1.5 times those of natural round wood poles.

The design basis for wood pole lines has historically been a 500Pa wind on conductors and 750Pa on the pole or a design wind pressure of 1000Pa depending on the line. A Safety (or Load) Factor of 4 was used for wood poles under maximum wind conditions as a conservative measure to allow for variation/imperfections in strength between individual poles.

In the calculation of the probabilities of failure, the pole was premised on the expected loss of section, based on its age and expected decay rate. In accounting for decay and subsequent piping of the pole, the loss of resistive strength was calculated. As with the steel towers, it has been assumed the load capacity has a linear relationship with the applied wind pressure on the structure as a simplification.

Historical failure data (for failure events only, not defects) of wood poles was unavailable; therefore, the above return period could not be moderated against any actual records. As with towers, it is recognised that for reasons such as structure utilisation, Safety (Load) Factors on wood poles, terrain effects and span lengths, an RP of 88 corresponding to the 1000Pa design wind can be considered conservative. With the expectation that the above factors would require an increase in wind speed of 10% to meet the design limits of the poles (additional increase compared to towers due to Safety Factors for wood poles), a 500 year RP, equivalent to a wind pressure of approximately 1200Pa, has been considered.

The probability of failure time series' for wood poles are obtained. In the non-aggressive environment they suggest a 5.6% probability of failure for natural round pole and a 8.2% probability of failure for pressure impregnated pole 60 years from now.

The wood pole probability of failure values were selected at every 5 years to align with the mid points of regulatory control periods. An average age of 50 years is assumed as at year 2022. Table 11.9 outlines the probability of failure values as at year 2022 (middle of regulatory control period 2):

Table 11.9: Average Probability of Failure for Wood Poles

Pole Type	Probability of Failure
Natural Round	0.271%
Pressure Impregnated	0.406%

B.13.3.4 Structure Earthing

Probability of failure for structure earthing was based on defect rates. A sample test was conducted on the structure earthing of a number of randomly selected "high safety risk" towers and the defects were noted. The "higher safety risk" towers are located in urban and semi-urban areas where the likelihood of public exposure is high. The resultant probability of failure of structure earthing is 15.4%.

The other moderators such as, likelihood of someone being in the vicinity and the level of their time exposure, are excluded from here. These are to be covered in the criticality calculation as likelihood of consequence (LOC).

B.13.3.5 Insulators

The probability of failure for insulators was comprised of the following two components:

> Base probability of failure of insulators

> Probability of failure of corroded disc insulators

Defect rates were analysed in order to calculate the base probability of failure. Across TransGrid's entire network of 37,438 structures, defect data indicates that there has been an average of 2.5 insulator failures per year over the last 10 years, typically associated with flashovers. Based on these results, the base rate probability of failure for insulators was approximated to be 1 in 100,000, or 0.001%.

For disc insulators identified with, or expected to have due to their locality, corrosion related issues, analysis has been performed on a sample of disc insulators taken from the Central Coast region in order to determine their expected remaining life. The investigation measured the remaining pin diameter on individual disc insulators in order to determine its expected remaining strength. Analysis on the first sample of 3120 insulator discs recovered from 52 suspension structures on 330kV Vales Point to Sydney North Line Number 22 since 2011, indicated that 95% of pins had a diameter of 15mm or greater. The remaining 5% of pins had diameters as low as 5mm. On the second sample, analysis of 318 insulator discs sampled from Central Coast 330kV transmission lines, it was found that 2.5% of pins had diameters of 8mm or less, down to even as low as 4mm. Based on previous experience and an assessment of typical load scenarios on the insulators at nominal span length 400m, failure of an insulator pin is expected to occur at an average diameter of 8mm. Analysis on the 318 discs was undertaken to estimate their expected life based on their atmospheric corrosion rates as per AS 4312. The probability of failure curve at different insulator condition/ages was calculated based on this data and is outlined in the framework document.

It can be seen that the probability of failure for disc insulators at 50 and 60 years of age are approximately 0.09% and 0.14% respectively. As the failure mode for insulators with an assessed Condition Code of 1 to 3 is more likely to be a pin failure resulting in conductor drop, probabilities for these insulators have been estimated using the above curve. In medium/high corrosion zones, as per AS 4312, insulators identified in the condition assessment as having Condition Codes of 1 or 2 have been assigned the probability of the theoretical worst condition age of 60 years. Insulators identified with Condition Code 3 and those installed before 1974 have been assigned the probability of the theoretical condition age of 50 years. A reduction by a factor of 3 has been applied for low corrosion zones in accordance with the different atmospheric corrosion rates specified in AS 4312.

As with the steel towers, each transmission line was assessed in accordance with its geographic corrosion zone and probability for insulators averaged across the line. The probabilities for insulators identified with Condition Codes of 4 to 6 have been estimated from the base failure rate across the network. The insulator probabilities of failure for the low and medium/high corrosion levels as at year 2022 are listed in Table 11.10

Table 11.10: Average Probability of Failure for Insulators

Corrosion Level	Cond 1-2	Cond 3	Cond 4-6
Low	0.047%	0.030%	0.001%
Medium/High	0.140%	0.089%	0.001%

B.13.3.6 Conductor and Earthwire Fittings

The probability of failure for fittings was comprised of the following two components:

> Base probability of failure of fittings

> Probability of failure of corroded fittings

Defect rates were analysed in order to calculate the base probability of failure. TransGrid defect data on conductor fittings have indicated only five urgent P1 defects requiring immediate replacement since 2006 on 2664 coastal structures. On earthwires, there have been two urgent defects in relation to fittings requiring immediate replacement since 2009 on 5328 coastal spans, only two of which were related to defective fittings. The small sample sizes mean that the ability to predict the failure rate with any degree of certainty is limited. Based on these results, and in alignment with the insulators, the base rate probability of failure for both conductor and earthwire fittings was approximated to be 1 in 100,000, or 0.001%.

The methodology used in the prediction of failure probabilities for corroded fittings have been treated slightly differently when compared to tower members, since in their non-corroded state, their strength far exceeds the forces that cause their failure. Relevant data on the existing condition of the fittings was unavailable, mostly for accessibility reasons, it is more difficult to access corroded fittings and to quantify their loss of strength. The design breaking load values for fittings on TransGrid's system have been 70kN, 120kN or 160kN. Fittings were typically designed with a significant load factor, to be more than or equal to 2 for the design wind load for tension strings and for suspension strings, 6 (or more) in still-air conditions, reducing to 3 in ultimate load conditions. The methodology used to assess the increased probability of failure is based on the calculation of component forces of a 1300Pa wind pressure applied to a typical 400m wind and weight span. Due to the access difficulties in assessing the remaining steel cross section, and the uneven appearance of rust on the surface of some components, condition data has not been used to determine the initial steel loss values of the fitting. Instead, this was assessed in accordance with the age of the transmission line, corresponding with its year of construction, and its geographic corrosion zone. Since the area loss is the critical component in determining whether the fitting has reached its failure threshold, an additional "condition age" on the fittings was applied as follows:

> 20 years for Condition 2 as per assessment

> 5 years for Condition 3 as per assessment

New fittings assessed with Condition Code 6 were assumed to have a zero probability of failure.

In accounting for corrosion and associated steel loss, it has been assumed that the load carrying capacity of fitting bolts is related linearly to the loss of steel area and that the forces on the bolt have a linear relationship with the design wind pressure.

It is noted that the methodology described above has considered failure associated with load bearing fitting bolts only and is limited accordingly. No actual failure data has been used to modulate the predicted probabilities since a relevant set of sufficient data was unavailable.

The conductor and earthwire probabilities of failure for the low, medium and medium/high corrosion levels as at year 2022 are described below.

B13.3.6.1 Conductor Fittings: Lines 45+ Years of Age

Table 11.11: Average Probability of Failure for Conductor Fittings: Lines 45+ Years of Age

Corrosion Level	Cond 1	Cond 2	Cond 3	Cond 4	Cond 5	Cond 6
Low	N/A	N/A	0.001%	0.001%	0.001%	0.000%
Medium	N/A	0.223%	0.001%	0.001%	0.001%	0.000%
Medium/High	N/A	6.458%	0.504%	0.001%	0.001%	0.000%

B13.3.6.2 Conductor Fittings: Lines Between 35-45 Years of Age

Table 11.12: Average Probability of Failure for Conductor Fittings: Lines 35-45 Years of Age

Corrosion Level	Cond 1	Cond 2	Cond 3	Cond 4	Cond 5	Cond 6
Low	N/A	N/A	0.001%	0.001%	0.001%	0.000%
Medium	N/A	0.001%	0.001%	0.001%	0.001%	0.000%
Medium/High	N/A	0.095%	0.001%	0.001%	0.001%	0.000%

B13.3.6.3 Earthwire Fittings: Lines 45+ Years of Age

Table 11.13: Average Probability of Failure for Earthwire Fittings: Lines 45+ Years of Age

Corrosion Level	Cond 1	Cond 2	Cond 3	Cond 4	Cond 5	Cond 6
Low	N/A	N/A	0.001%	0.001%	0.001%	0.000%
Medium	N/A	N/A	0.223%	0.001%	0.001%	0.000%
Medium/High	N/A	N/A	4.658%	2.314%	0.001%	0.000%

B13.3.6.4 Earthwire Fittings: Lines Between 35-45 Years of Age

Table 11.14: Average Probability of Failure for Earthwire Fittings: Lines 35-45 Years of Age

Corrosion Level	Cond 1	Cond 2	Cond 3	Cond 4	Cond 5	Cond 6
Low	N/A	N/A	0.001%	0.001%	0.001%	0.000%
Medium	N/A	N/A	0.001%	0.001%	0.001%	0.000%
Medium/High	N/A	N/A	0.223%	0.039%	0.001%	0.000%

As with the steel towers, each transmission line was assessed in accordance with its geographic corrosion zone and probability for conductor and earthwire fittings averaged across the line.

B.13.3.7 Conductor

All condition assessments undertaken have indicated that conductor assets are in good condition. No probability of failure due to corrosion has been associated with conductors.

B.13.3.8 Earthwire

Defect data on earthwires have indicated five urgent defects since 2009 on 5328 coastal spans; that is, a probability of failure of 0.02% per annum. However, of these, three were associated with aluminium earthwire failures as a result of lightning strikes, only two were related with issues with steel earthwire. As a result, the probability of failure values for earthwire in the low, medium and medium/high corrosion levels are listed in Table 11.15.

Table 11.15: Average Probability of Failure for Earthwire

Corrosion Level	Cond 1-3	Cond 4-6
Low	0.004%	0.000%
Medium/High	0.008%	0.000%

Due to the uncertainty surrounding how corrosion affects the earthwire, an additional reduction factor of two was included for lines in low corrosion areas.

B.14 Protection Relay

Protection relays have a wide range of failure modes contributed by the underlying failure modes of their internal components.

Failures of electronic components can arise from excess temperature, excess current or voltage, ionizing radiation, mechanical shock, stress or impact. In semiconductor devices, problems in the device package may cause failures due to contamination, mechanical stress of the device, or open or short circuits. Electromechanical components of a relay such as the contacts, wear with operations. During making/braking, arcing causes contact welding, hot contacts due to carbonisation and cone/crater formation etc. All of these contribute to the failure of protection relays.

Obtaining conditions of each of the internal components within each protection relay is effort intensive and cost prohibitive. Nevertheless, there is still a significant degree of uncertainly in predicting failures in this manner.

Throughout this section, probability of failure of a protection relay is determined from the past failures and observations.

Protection relay condition assessment document (NACA-SSAP) contains relay failure rates for the past ten years. Probability of failure for protection relays for a given year is determined by taking a linear trend forecast for that relay model with a zero intercept set at its earliest year of available defect data.