SPT.SHET_Network Asset Risk Annex (NARA)

ISSUE 18

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1.   INTRODUCTION

Risk is part of our everyday lives. In our everyday activities, such as crossing the road and driving our cars, we take risks. For these everyday activities, we often do not consciously evaluate the risks but we do take actions to reduce the chance of the risk materialising and/or the impact if it does.

Organisations are focussed on the effect risk can have on achieving their objectives e.g. keeping their staff, contractors and the public safe, providing an agreed level of service to their customers at an agreed price, protecting the environment, making a profit for shareholders.

Organisations manage risk by identifying it, analysing it and then evaluating whether the risk should and can be modified.

To help organisations to manage risks, the International Standards Organisation has produced ISO 31000:2009 Risk management - Principles and guidelines which includes several definitions, principles and guidelines associated with risk management which provide a basis for identifying risk, analysing risk and modifying risk. In addition, BS EN 60812:2006 (Analysis Techniques for System Reliability) provides useful guidance on analysis techniques for system reliability. In this methodology, we have utilised relevant content from ISO 55001, ISO 31000 and BS EN 60812.

Risk is often expressed in terms of a combination of the associated likelihood of an event (including changes in circumstances) and the consequences of the occurrence.

Likelihood can be defined, measured or determined objectively or subjectively, qualitatively or quantitatively, and described either using general terms or mathematically (such as a probability or a frequency over a given time-period).

Similarly, consequences can be certain or uncertain, can have positive and negative effects on objectives and can be expressed qualitatively or quantitatively.

A single event can lead to a range of consequences and initial consequences can escalate through knock-on effects.

The combination of likelihood and consequence is often expressed in a risk matrix where likelihood is placed on one axis and consequence on the other.

This combination is not necessarily mathematical as the matrix is often divided into categories on the rows and the columns and can be categorised in whatever form is applicable to the risks under consideration.

Sometimes this combination of likelihood and consequence is expressed mathematically as:

Equation 1

$$Risk \; = \; Likelihood \; x \; Consequence$$

In this mathematical form whilst it is necessary for the likelihood and consequence to be expressed numerically for such an equation to work, the likelihood does not necessarily have to be a probability and the consequence can be expressed in any numeric form.

When using, likelihood expressed as a probability and consequence expressed as a cost, using the risk equation provides a risk cost. This risk cost enables ranking of the risk compared with others risks calculated in the same manner. This is true for any risk expressed numerically on the same basis.

When considering the risk of a non-recurring single event over a defined time-period, the event has two expected outcomes, either it will occur resulting in up to the full consequence cost or it will not occur, resulting in a zero-consequence cost.

For this reason, the use of summated risk costs for financial provision over a defined time-period works best when there is a large collection of risks. This is because if only a small number of risks are being considered, a financial provision based on summated risk cost will either be larger or smaller than is required.

This is particularly the case for high-impact, low-probability (HILP) risks. It is generally unusual to have a large collection of HILP risks and so the summated risk cost does not give a good estimate of what financial provision is required. There are also particular considerations with respect to these risks when using risk cost to rank subsequent actions.

1.1. METHODOLOGY OVERVIEW

To ascertain the overall level of risk for each TO, the NOMs methodology will calculate Asset Risk for lead assets only, namely:

1. Circuit Breakers
2. Transformers
3. Reactors
4. Underground Cable
5. Overhead Lines
   - Conductor
   - Fittings
   - Towers (Scottish Power Transmission (SPT), Scottish Hydro Transmission (SHE-T) only)

As shown in Equation 2, the Asset Risk is the sum of the expected values of each consequence associated with that asset and a function of the probability of each failure mode occurring.

For a given asset, a measure of the risk associated with it is the Asset Risk (AR), given by:

Equation 2

$$AR = \sum_{j=1}^{n} PoF_j \times CoF_j$$

where:

PoF$_j$ = Probability of Failure *j* occurring during a given time
CoF$_j$ = the monetised Consequence of Failure *j*
n = the number of Failures associated with Asset

For the network, a measure of the risk associated with it is the Network Risk (NR), given by:

Equation 3

$$NR = \sum_{k=1}^{n} AR_k$$

where:

AR$_k$ = the Asset Risk associated with Asset, k.
n=the number of Assets on the Network

Consequence is the monetised value for each of the underlying Financial, Safety, System and Environmental components of a consequence e.g. Transformer Fire. A consequence can be caused by more than one Failure Mode, but a Consequence itself can only occur once during the next time-period. For example, an Asset or a component is only irreparably damaged once.

1.1.1. ASSET (A)

An asset is defined as a unique instance of one of the above five types of lead assets. Overhead Line and Cable routes will be broken down into appropriate segments of the route. Each Asset belongs to an Asset Family, each Asset Family has one or more Failure Modes and a Failure Mode can lead to one or more Consequences.

1.1.2. MATERIAL FAILURE MODE (F)

For reasons of economic efficiency, TOs do not consider every possible failure mode and consequence, only those which are materially significant. TOs' assessment of material significance is based upon their experience and consequential information set. TOs have different information sets and therefore have made different decisions, within the same overall methodology, about what should be measured or calculated from first principles and what must be estimated.

The material failure mode is a distinct way in which an asset or a component may fail. Fail means it no longer does what is designed to do and has a significant probability of causing a material consequence. Each failure mode needs to be mapped to one or more failure mode effects.

1.1.2.1. FAILURE MODE EFFECTS

There are many ways in which an Asset (A) can fail so to model the likelihood of an asset failure it is often more effective to consider the effect of the failure. Thus, historic data and the impact of observed conditional data can be used to determine the probability of a Failure Mode's Effect.

This Failure Mode Effect is often based on a measurable consequence of the failure; for example, the asset may be impaired functionally by a measurable level or no longer operates for a measurable period.

Failure Mode Effect	Definition
Defect	Failure requires a repair; however, it does not require an outage
Minor	Failure causes an unplanned outage, but the asset can be returned to service within 24 hours
Significant	Failure causes an unplanned outage; the asset can be repaired but remains out of service for more than 24 hours but less than 10 days
Major	Failure causes an unplanned outage which causes extensive damage. Where repairs are possible, the duration of the works will exceed 10 days, or the failure will result in the asset being replaced.

Table 1 Definition of Failure Mode Effects

Each failure mode (F_i) needs to be mapped to one or more consequences (CoF_j) and the conditional probability the consequence will manifest should the failure occur $PoF(CoF_j|F_i)$.

However, where failure modes and consequences have a one-to-one mapping, this function is not required and the Probability of Failure is equal to the Probability of Consequence.

1.1.3.   PROBABILITY OF FAILURE MODE

Probability of failure ($P(F_i)$) represents the probability that a Failure Mode Effect will occur in the next time-period. It is generated from an underlying parametric probability distribution or failure curve. The nature of this curve and its parameters are informed by a combination of TO's asset data, Industry wide data from ITOMS and EPRI and mathematical models judged appropriate by experts in this field.

Each Asset has an 'End of Life Modifier' EoL_{Y0} score assigned to it based on several parameters detailed later in this document. This EoL_{Y0} score is then used to calculate the Probability of Failure for each Failure Mode Effect $P(F)$.

In addition, a combined probability of failure for all potential Failure Mode Effects can be calculated. Detailed calculation steps are provided in the following sections and the individual TO's Licensee Specific appendix where necessary.

1.1.4.   CONSEQUENCE (C)

The monetised value for each of the underlying Financial, Safety, System and Environmental components of a Failure Mode (e.g. unplanned outage for 4 days). Each C_j has one or more F_j mapped to it.

These consequences are related to the characteristics of the Asset and its location, so the same Failure Mode for similar assets at different locations are likely to have different monetised values.

2.   PROBABILITY OF FAILURE

The determination of Probability of Failure (PoF) can be especially challenging for highly reliable assets. BS EN 60812 provides useful guidance on how to develop an estimate for PoF.

Section 5.2.9 of BS EN 60812 recognises that it is very important to consider the operational profile (environmental, mechanical, and/or electrical stresses applied) of each component that contributes to its probability of occurrence. This is because the component failure rates, and consequently failure rate of the failure mode under consideration, in most cases increase proportionally with the increase of applied stresses with the power law relationship or exponentially. Probability of occurrence of the failure modes for the design can be estimated from:

•   Data from the component life testing

•   Available databases of failure rates

•   Field failure data

•   Failure data for similar items or for the component class

When probability of occurrence is estimated, the FMEA must specify the period over which the estimations are valid (such as the expected service life).

Section 5.3.4 of BS EN 60812 provides further guidance on the estimation of failure rates where measured data is not available for every asset and specific operation condition (as is generally the case for transmission assets). In this case, environmental, loading and maintenance conditions different from those relating to the "reference" failure rate data are accounted for by a modifying factor. Special care needs to be exercised to ensure that the chosen modifiers are correct and applicable for the specific system and its operating conditions.

It is recognised that each TO will have different asset profiles in different operating environments. Different operating regimes and historic maintenance practises will therefore result in different PoF outcomes. Furthermore, differences in recording and classification of historic performance data may mean that PoF rates are not directly comparable, and different methodologies may need to be employed to determine the asset PoF.

The failure modes and effects analysis defines an end of life curve for each asset. It is recognised that some of these predicted deterioration mechanisms have yet to present themselves and were based on knowledge of asset design and specific R&D into deterioration mechanisms. In summary, the following sources of data were utilised:

•   Results of forensic evidence

•   Results of condition assessment tests

•   Results of continuous monitoring

•   Historical and projected environmental performance (e.g. oil loss)

•   Historical and projected unreliability

•   Defect history for that circuit breaker family.

This process uses asset-specific information; from both intrusive and non-intrusive inspections to derive a series of differentiators and modifiers which are then used to produce an overall End of Life Modifier. From that, the asset's failure mode frequency or Probability of Failure (PoF) is derived.

Asset management information is fed into the Process to produce a EoL Modifier for each asset, which is referred to as $EoL_{(Y0)}$. It is from this EoL Modifier that a probability of failure, (PoF), is calculated for several defined failure modes.

2.1.1.   END OF LIFE MODIFIER

The present year EoL Modifier (EoL_{Y0}) of an asset is scored on a continuous scale between 0.5 and 10. The minimum value (EoL_{lim}) of 0.5 represents the point at which there starts to be a direct relationship between the End of Life modifier and an increasing PoF. Failures associated with modifiers below this limit relate to manufacturing/installation issues or random events. With the sharply rising EoL/PoF relationship it would be expected that End of Life will be when the EoL value reaches somewhere between 6 and 10. Typically, end of life is defined as EoL of 7 or greater.
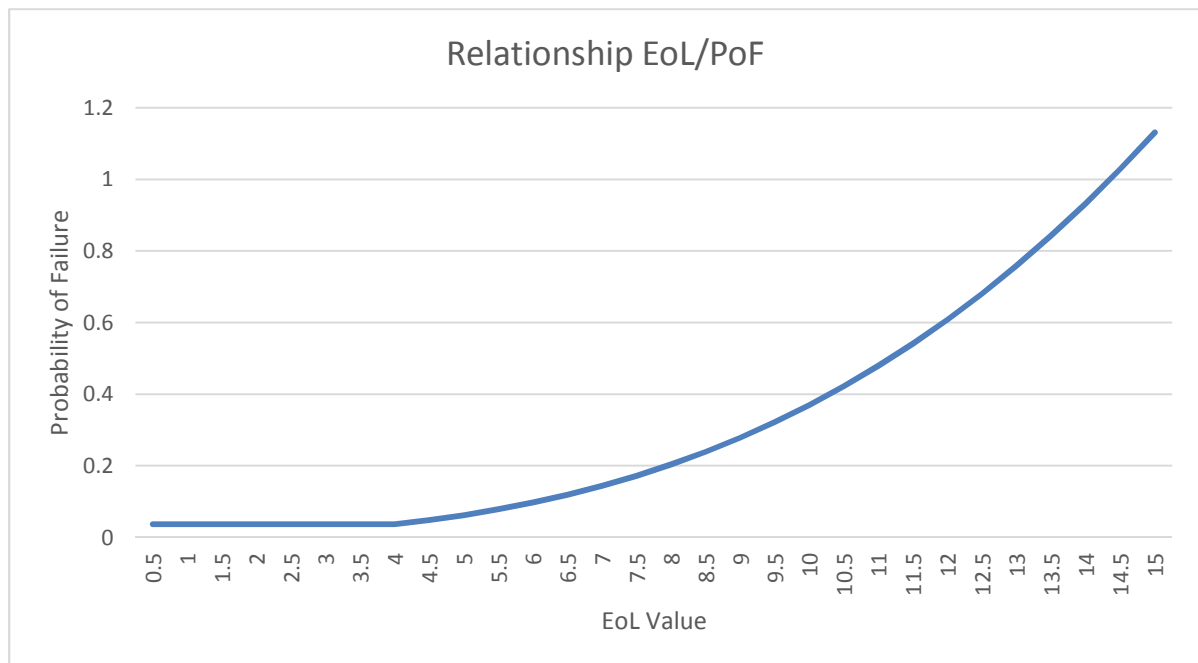
Figure 1 Relationship Between PoF and EoL

The future EoL modifier (EoL_{yn}) can produce forecast scores up to 15. This is to help with the decision-making process for asset replacement strategies. When an asset needs direct replacement, the project is likely to include a development period of several years. With the End of Life value calculated past 10, it allows for the prediction of probability of failure in the future and differentiation between assets which may fail sooner than others.

Used by EoL Calculation														
Actual Asset Lifecycle										Theoretical Life for Decision Purposes				
Normal Operation					Material Deterioration			End of Life			Projected End of Life				
1	2	3	4	5	5.5	6	6.5	7	8	9	10	11	12	13	14	15

Table 2 Showing End of Life Values

The concept of the End of Life Modifier is used to embody all variables that may influence the probability of each failure mode both at the time of calculation and in the future. The detail of the End of Life Modifier calculation is different for each asset class, reflecting the different information and the different types of degradation processes. This calculation is described in Sections 3 to 6. There is, however, an underlying structure for all asset groups as outlined in Figure 2.
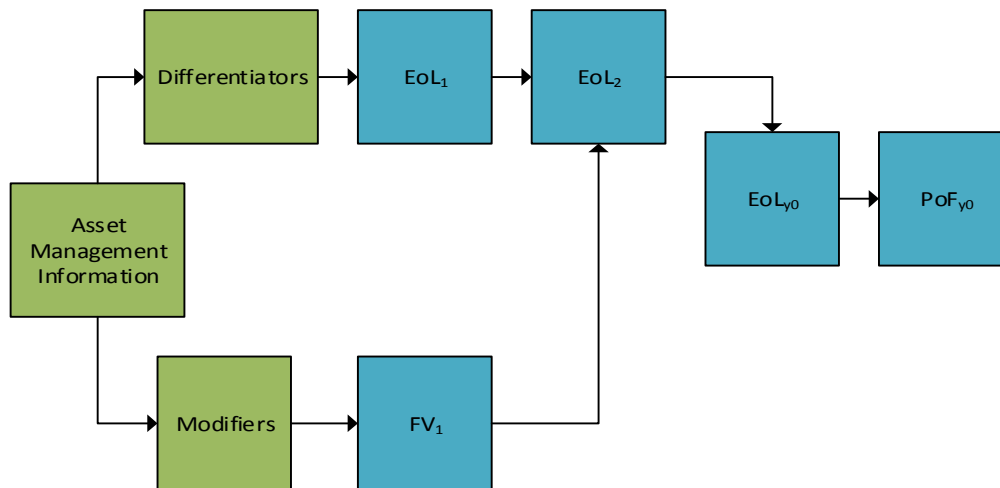
Figure 2 Process Overview

Where:

EoL_1 =   Initial End of Life Modifier

EoL_2 =   Intermediate End of Life Modifier

EoL_{y0} =   Final End of Life Value

PoF_{y0} =   Probability of failure for that year

FV_1 =   Conditional Factor Values for that asset.

2.1.2. DIFFERENTIATORS AND MODIFIERS

2.1.2.1. DIFFERENTIATORS

For a specific asset, an initial End of Life Modifier (EoL_1) is calculated using knowledge and experience of its performance and expected lifetime, taking account of differentiating factors such as original specification, manufacturer data, operational experience and operating conditions (duty, proximity to coast, etc.).

Differentiators are used to account for the different asset lifetimes that can be reasonably anticipated because of external differentiating factors. Examples of these differentiators may include:

- Duty (individually described within each asset section)
- Location specific reasons, such as proximity to coastal areas or heavily polluted industrial areas

2.1.2.2.   MODIFIERS

Information that is indicative of condition is used to create additional 'factors' that modify the initial End of Life Modifier and form the Intermediate End of Life Modifier EoL_2. This includes information that cannot be directly related to specific degradation processes, such as factors relating to fault / defect history and reliability issues associated with specific equipment types (e.g. different manufacturers). It also includes information related to specific degradation processes that identify potential end of life conditions (e.g. corrosion), but is not generally considered sufficient to provide a definitive indication of asset condition independently of other information. Whilst this information is not used to provide a specific End of Life value, it can be used to define a minimum value for the asset and a boundary value for the modifiers (See Section Intermediate EoL Modifier (EoL_2)Intermediate EoL Modifier (EoL_2)2.1.5)

Where condition information related to specific degradation process can be used to identify end of life conditions with a high degree of confidence (e.g. dissolved gas analysis of transformer oil provides a definitive indication of the health of the transformer regardless of other information available), this is used to directly derive an End of Life Value for the asset via the Specific Degradation Process Modifier. This could include condition information derived from specific tests or very detailed visual condition information obtained from helicopter inspections of overhead lines. Where appropriate, the values derived from such tests can be used in preference to the Intermediate based End of Life Modifier described above.

Within this Process, these modifiers include:

- Visual Condition
- Defects
- Asset Family Reliability
- Test Results
- Operational restrictions

Each asset will have its own suite of modifiers; these are described in more detail in the asset specific sections. Additionally, any modifiers which are Company Specific will also be described within the Licensee Specific Appendices.

Visual External Condition Factors

The observed external condition of the asset is evaluated through visual assessment by operational staff. Several components are assessed individually and assigned a condition. Each component's condition is weighted differently based on the significance of the component. These components are combined to produce an overall scale and a Condition factor is produced.

Defects

A defect is a fault on an asset which does not cause the asset to be removed from service and can be repaired. The defect module searches the input data defect list to identify any defects associated with each asset. The defects, in the form of stock phrases, automatically populate a defects calibration table against which users assign a defect severity score.

Asset Family Reliability

Asset Family Reliability is determined using the TO's own experience of assets in operation and external information where applicable. Each asset family is assigned a reliability rating (e.g. from 1-4, with 1 being Very Reliable and 4 being Very Unreliable) which then generates a reliability factor.

Test Results

Where tests have been undertaken, the results (e.g. pass, suspect or fail) for each test type are used to derive individual test factors (and if desired minimum EoL Modifier) and are then combined to produce an overall test factor.

Operational Restrictions

When a significant issue is identified regarding an asset family, an Operator can issue a NEDeR which notifies all other operators. This is called an Operational Restriction, or "OR". Each OR is assigned a severity, which then generates an Operational Restriction factor.

For assets, which have more than one OR assigned to them, it is the largest factor (or most serious OR) which is passed through to form the overall OR factor.

2.1.3. INITIAL EOL MODIFIER (EOL_1)

The Initial EoL Modifier EoL_1 is based around the age of an asset in relation to the estimated average expected service life which could be reasonably anticipated. This calculation stage does consider the expected life of the asset, coupled with its workload in operation, its situation (indoor / outdoor), location (proximity to coast, elevation, corrosion factor) and the environment. It does not however at this point consider condition, testing or defect intervention. The first stage of the derivation is described below in Figure 3.
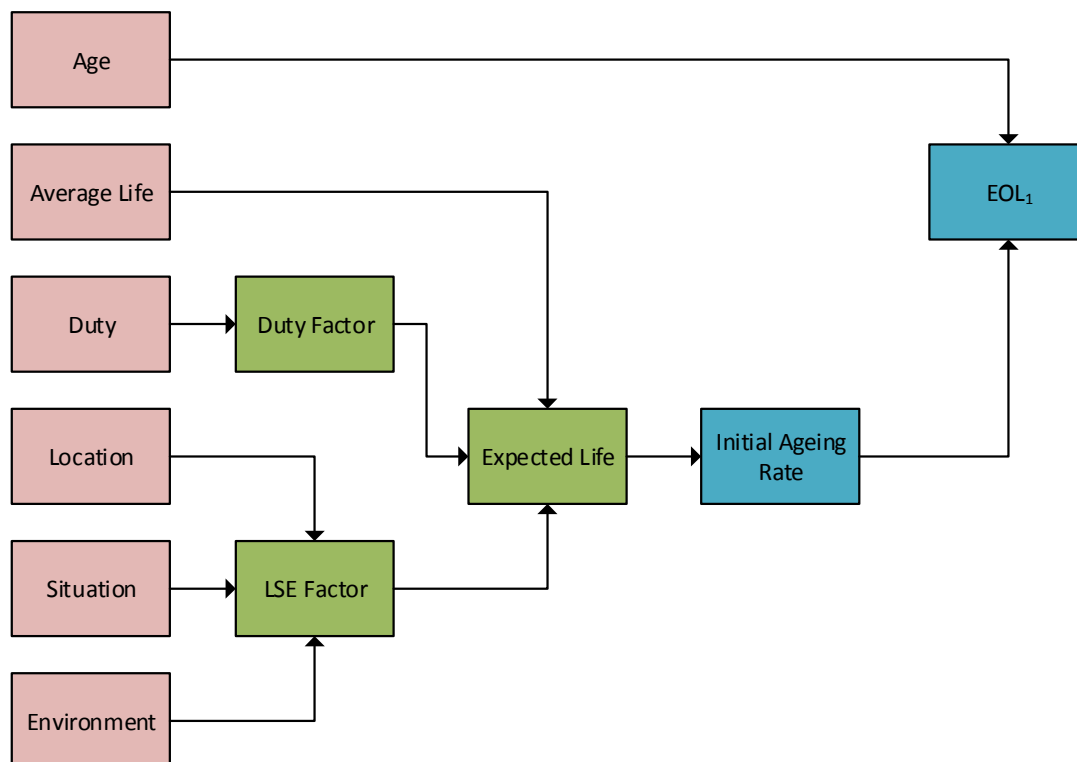
Figure 3 Derivation of Initial End of Life Modifier

Using a logarithmic function, an initial ageing rate (initial because conditional information is not considered) can be mapped out.

Finally, the Initial Ageing rate combined with the assets age and the EoL of a new asset in an exponential function determines the Initial End of Life value of that asset.

The Initial Indicator is capped at a value of 5.5 to reflect the fact that age alone should not be sufficient to indicate that an asset has reached end of life; EoL can only be achieved when there is condition related information indicating significant degradation.

It should be noted that the derivation of all factors is TO Specific and subject to calibration, testing and validation during the implementation of the methodology within the individual TOs.

2.1.3.1.   DUTY FACTOR

One of the variables required when calculating the Expected Life of an asset is its applied duty. The Duty Factor is asset specific in its determination and TO specific to the variables used to find the overall Duty Factor. It should be noted that neutral default Duty Factor values are applied to asset categories where no duty factors have been identified. This is also the case where the relevant data/information is not available to calculate the Duty Factor. More information on the Duty Factor can be discerned in the Asset Specific Sections, starting at Section 3.

2.1.3.2.   LSE FACTOR

The Expected Life of an asset is affected by the environment in which the asset is installed. The LSE factor is generally calculated from the following variables:

- Distance to coast
- Altitude
- Corrosion rating
- Situation (indoor/outdoor)
- Environment

Cables and tower foundations use additional variables which are described in more detail in the relevant sections

Equation 4

$$Location\ Factor = Max(Distance\ to\ Coast\ Factor, Altitude\ Factor, Corrosion\ Zone\ Factor)$$

The LSE Factor is then calculated as

Equation 5

$$LSE\ Factor = (((Location\ Factor - Minimum\ Location\ Factor) \times Situation\ Factor) \\ + Minimum\ Location\ Factor) \times Environment\ Factor$$

Where the Situation Factor indicates whether the asset is situated indoors or outdoors, the Environment Factor represents the severity of the local environment and the Minimum Location Factor is a constant.

Details on the possible values assigned to these variables can be found in the Licensee Specific Appendices.

2.1.3.3. EXPECTED LIFE

Starting with the Expected Average Life (L_A) for that asset class, the Duty and LSE factors are used to set an expected life (L_E) for each asset.

Equation 6

$$L_E = \frac{L_A}{F_{LSE} \times F_{DY}}$$

Where;

F_{LSE} =   LSE Factor
F_{DY} =   Duty Factor

This expected life is then used to determine the Initial end of life Modifier EoL_1.

The Expected Asset Life is the time (in years) in an asset's life when it would be expected to reach deterioration that it is likely to exhibit functional failure. The determination of the L_A considers factors such as original specification and manufacturer data. This corresponds to a EoL Modifier of 7.

2.1.4. THE AGEING MECHANISM

The model contains an ageing mechanism, which attempts to estimate the likely future EoL Modifier for each asset, referred to as EoL_{yn}, which is used to project the future PoF of each asset being considered. The rate of change of the EoL Modifier is non-linear. The degradation processes involved (e.g., corrosion) are accelerated by the products of the process, hence the rate of deterioration increases as the processes proceed.

Section 5.2.9 of BS EN 60812-2006 provides some guidance on the determination of this relationship:

"…besides published information regarding the failure rate, it is very important to consider the operational profile (environmental, mechanical, and/or electrical stresses applied) of each component that contribute to its probability of occurrence. This is because the component failure rates, and consequently failure rate of the failure mode under consideration, in most cases increase proportionally with the increase of applied stresses with the power law relationship or exponentially."

Although the standard recommends that failure rates should be derived from field failure data, there is little useful published data on electrical asset failure rates, especially at transmission level.

Nevertheless, most network owners have many years of experience of asset operation and so it is this experience and historical data that is used primarily to determine this relationship. Through the electricity industry's Strategic Technology Programme, it was observed that electrical asset failure rates correlated with asset health according to a semi-Markov relationship[1], leading to an exponential function that for a given asset, explained in Equation 7:.

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[1] "Using Modelling to Understand and Improve CBRM" STP project reference 4167 , AT Brint, JR Brailsford and D Hughes (2006).

Equation 7

$$\text{EoL}_{t2} = EoL_{t1} \cdot \exp\{\beta \cdot (t_2 - t_1)\}$$

where:

EoL_{t2}	=	EoL Modifier at time t_2
EoL_{t1}	=	EoL Modifier at time t_1
β	=	Ageing rate (see Section 7.1 for details)
$(t_2 - t_1)$	=	Time taken for the asset to move from EoL_{t1} to EoL_{t2}

The Initial Indicator of each asset is derived using its Initial Ageing Rate (Section 2.1.4.1 for further details) and its current age (this corresponds to the time taken for the asset to move from the Indicator of a new asset to its Initial Indicator) by the making the following substitutions into Equation 8:

Equation 8

$$\text{EoL}_{1,i} = \text{EoL}_{\text{New}} \cdot \exp\{\beta_{1,i} \cdot \text{Age}_i\}$$

where:

$\text{EoL}_{1,i}$	=	Initial Indicator of asset i
EOL_{New}	=	Indicator of a new asset (normally set to 0.5)
$\beta_{1,i}$	=	Initial Ageing Rate of asset i (Section 2.1.4.1)

The Initial Indicator is capped at a value of 5.5 to reflect the fact that age alone should not be sufficient to indicate that an asset has reached end of life; EoL can only be achieved when there is condition related information indicating significant degradation[2].

The methodology also calculates an 'initial ageing rate', 'b', for each asset which is used as an input to the ageing mechanism outlined below which is employed for any future asset EoL Modifier estimation. The standard EoL$_{(y0)}$ module also calculates the number of years it will take each asset to reach a EoL of 10, the EoL Modifier which is defined as the "end of life".

2.1.4.1.   INITIAL AGEING RATE

The Initial Ageing Rate is needed to determine the rate of change of the EoL Modifier. The standard approach adopted is to estimate the time for the EoL Modifier to move from 0.5 (i.e. a new asset) to 5.5 (the end of an asset's anticipated life and the point at which the probability of failure starts to rise significantly (see Section 2.1.1 for further details). The time $(t_2 - t_1)$ in Equation 7 is the Expected Life of the asset as defined in Section 2.1.3.3

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[2] This only applies in year 0; EoL can be achieved in future years when there is no condition information.

The Modified Expected Life of an asset varies depending both on the asset type and its operating conditions. Therefore, a different value must be calculated for each individual asset based on its Modified Anticipated Life, using Equation 9:

Equation 9

$$B_i = \ln\left(\frac{\text{EoL}_{MAL}}{EOL_{New}}\right) \cdot \frac{1}{L_E}$$

where:

EoL_{MAL} =   EoL Modifier of the asset when it reaches its Modified Anticipated Life (set to 5.5)

EOL_{New} =   EoL Modifier of a new asset (normally set to 0.5)

L_E =   Expected Asset Life, i (as determined using Section 2.1.3.3)

2.1.5.   INTERMEDIATE EOL MODIFIER (EOL$_2$)

The second calculation stage, i.e. to find EoL$_2$, introduces more specific asset information pertaining to observed condition, inspection surveys, maintenance test results and operator's experience of each asset. Some typical modifiers, including EoL$_1$ from the previous stage, are shown in Figure 4 Intermediate End of Life modifier derivation below.
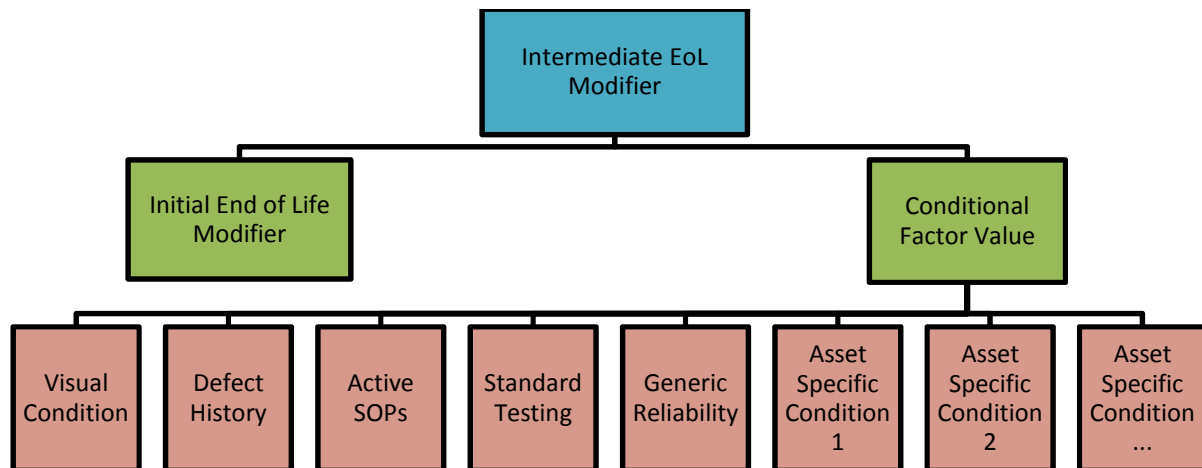
Figure 4 Intermediate End of Life modifier derivation

Condition factors are determined by specific asset information pertaining to;

•   Observed condition
•   Inspection surveys
•   Maintenance test results
•   Operator's experience of each asset
•   Reliability inputs

These are combined with respect to their individual weightings in a function known as Maximum and Multiple Increment Methodology.

Modifiers specific to each asset type are identified in asset specific modifiers Section 3 onwards.

The initial based end of life modifier does not take into consideration any of the measured assets conditional factors. To calculate an Intermediate End of Life modifier, the initial end of life modifier is simply multiplied by a conditional factor value.

Equation 10

$$EoL_2 = EoL_1 \times FV_1$$

Where condition information related to specific degradation process can be used to identify end of life conditions with a high degree of confidence (e.g. dissolved gas analysis of transformer oil provides a definitive indication of the health of the transformer regardless of other information available), this is used to directly derive an End of Life Indicator for the asset. This could include condition information derived from specific tests or very detailed visual condition information obtained from helicopter inspections of overhead lines. Where appropriate, the values derived from such tests can be used in preference to the modified age based End of Life Indicator described above. Modifiers specific to each asset type are identified in Sections 3 to 6.

2.1.5.1. MAXIMUM AND MULTIPLE INCREMENT METHODOLOGY

This MMI methodology is used to combine multiple factors into a single value that ensures the Intermediate End of Life Modifier is primarily driven by the strongest observed factor.

Whilst multiple factors may be considered in the derivation of a single combined factor using the MMI Technique there will be instances where not all the multiple factors affect the resulting factor. These conditions are expanded further below.

FV_1 is calculated in one of two ways, depending on the value of the factors being combined.

If any of the factors is greater than one:

Equation 11

$$FV_1 = Largest\ Factor + \frac{(Sum\ of\ the\ remaining\ factors) - 1}{2}$$

And, if none of the factors is greater than one:

Equation 12

$$FV_1 = Smallest\ Factor + \frac{Second\ Smallest\ Factor - 1}{2}$$

2.1.6. END OF LIFE VALUE (EOL$_{Y0}$)

The end of life value EoL_{y0}, is asset class specific and explained in the relevant sections.

In general, the EoL_{y0} is taken as the maximum of the Intermediate End of Life Modifier (EoL_2), any asset specific modifiers and the largest of the calibratable minimum forced End of Life modifiers.

2.1.6.1. MINIMUM END OF LIFE MODIFIERS

A series of calibratable minimum forced End of Modifiers are employed. These overrides serve to force the End of Life Modifier to a calibrated minimum value which is consistent with its observed or measured levels of deterioration. Minimum End of Life Modifiers are applied to each of the factors utilised in the derivation of the Intermediate End of Life Modifier. The maximum of these minimum End of Life Modifiers (known as the maximum of the minimums) is taken forward to derive an assets final End of Life Value. Details of the minimum End of Life Modifiers can be found in the Licensee Specific Appendices for each lead asset.

3. EOL CALCULATION FOR CIRCUIT BREAKERS

The following sections of this document provide an overview of the Circuit Breaker model design.

For each stage in the EoL Value derivation, the overview will identify and name all the component parts of each derivation and provide a high-level explanation of what the component parts represent.

3.1. INITIAL END OF LIFE MODIFIER

The Circuit Breaker Initial End of Life Modifier is calculated per Section 2.1.3. Variables to consider with Circuit Breakers are described below.

3.1.1. DUTY FACTOR

For each circuit breaker, the duty factor is calculated per the data available to the TO to make the best analysis of an assets utilisation.

- Presence of feeder protection (Prot), as the duty factor will be higher where this is present.
- Presence of Auto-Reclose (R_A), as the duty factor will be higher where this is present.
- Operational experience in the form of a 'high duty' exception report (D_H).
- Fault Level compared to Fault Rating, as the duty factor should be higher where the fault level exceeds the rating (D_{FAULT}).
- Latest record of the total number of Fault Clearances undertaken by the circuit breaker. (D_{CLEAR}).

The combination of these three variables determines an overall duty factor using the following equation:

Equation 13 Duty Factor Calculation for circuit Breakers SHE-T

$$F_{DY} = max(Prot, R_A, D_H)$$

Equation 14 Duty Factor Calculation for Circuit Breakers SPT

$$F_{DY} = D_{Fault} \cdot D_{Clear}$$

3.1.2. LSE FACTOR

The circuit breaker Initial End of Life Modifier is calculated per Section 2.1.3.2 where the LSE Factor is calculated as:

Equation 15

$$LSE\ Factor = (((Location\ Factor - Minimum\ Location\ Factor) \times Situation\ Factor) + Minimum\ Location\ Factor) \times Environment\ Factor$$

The Licensee Specific Appendix further explores the calibration tables.

3.1.3. EXPECTED LIFE

Starting with the Expected Average Life (L_A), the Duty and LSE factors are used to set an expected life (L_E) for each asset.

Equation 16

$$L_E = \frac{L_A}{F_{LSE} \times F_{DY}}$$

This expected life is then used to determine EoL_1.

The Expected Asset Life is the time (in years) in an asset's life when it would be expected to such deterioration that it is likely to exhibit functional failure. The determination of the L_A considers factors such as original specification and manufacturer data. This corresponds to an EoL Modifier of 7.

3.2. INTERMEDIATE EOL MODIFIER (EOL$_2$)

The circuit breaker intermediate end of life modifier is calculated in accordance with Sections 2.1.2.2 & 2.1.5 for Factors:

- Visual Condition
- Defects
- Asset Family Reliability
- Test Results
- Operational restrictions

Additional Factors that can be included in the calculation of FV_1 are:

- Oil Condition
- AFM Score
- SF_6 Condition and
- SF_6 Leak factors, as shown in the Figure 5 below.
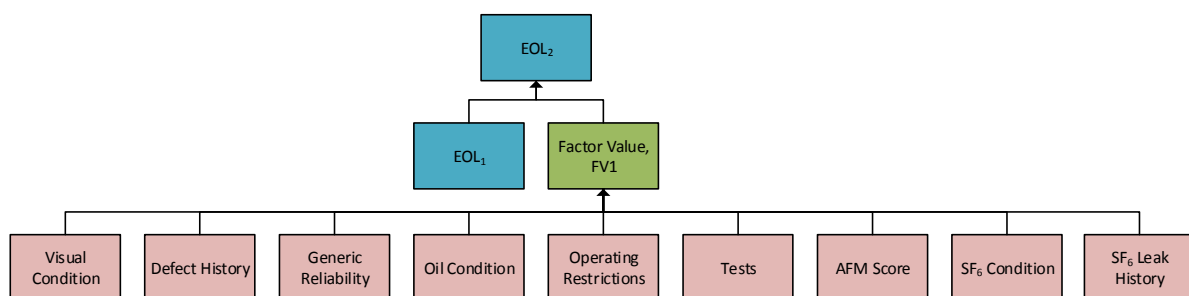
Figure 5 EoL Calculation for Circuit Breakers

After Fault Maintenance (AFM)

For assets which have after fault maintenance (AFM) scores, (i.e. assets whose arc extinguishing medium is either vacuum or SF_6), the AFM Score module considers the rate of change of each assets AFM score to estimate an "extrapolated life". This estimation is used to determine an AFM factor which is used within the "FV_1" derivation. The Licensee Specific Appendices expands further each TO's own implementation of AFM.

SF$_6$ Condition

SF$_6$ condition results (e.g. moisture, purity, dew point etc) use a series of defined multipliers to derive separate gas condition scores. The sum of the gas condition scores is then used to determine an overall SF$_6$ condition factor (SF$_{6COND}$) used in the creation of modifying factor "FV$_1$", and an optional minimum EoL Modifier can be set where poor gas condition is detected, which is set aside for later in the process.

The Licensee Specific Appendices expands further each TO's own implementation of SF$_6$ Condition.

SF$_6$ Leaks

Leakage of gas from a circuit breaker is indicative of reduced integrity of the breaker itself. The leakage history is used to create two different factors:

- SF6$_{NO}$, determined by the number of times an asset has been topped up with SF$_6$,
- SF6$_{LOST}$ a second factor which considers the volume of gas replaced in relation to the weight of SF$_6$ held by each asset by design.

A third factor, SF6$_{HIST}$, can be derived from poor leakage history exception report information which reflects the TO's experience of loss of SF$_6$ containment. The maximum of these factors is carried forward to be included in the EoL$_2$ calculation in Equation 17 .

Equation 17

$$SF6_{LEAK} = \max(SF6_{NO}, SF6_{LOST}, SF6_{HIST})$$

The Licensee Specific Appendices expands further each TO's own implementation of SF$_6$ Leakage.

3.3.   END OF LIFE MODIFIER

The circuit breaker end of life modifier is calculated as shown below:

Equation 18

$$EoL_{y0} = Max(EoL_2, Maximum\ of\ the\ Minimums)$$

4. EOL CALCULATION FOR TRANSFORMERS & REACTORS

Transformers and reactors are assigned an EoL Value (EoL) per their known condition and the service history of other similar transformers. Within this process, transmission transformers are considered as 'systems' which are made up of two components; a main tank (T_X), and a tapchanger (T_C). Each component is an individual asset, with a clearly defined linkage.

Failures involving multi-component systems such as the transformer system under consideration may be regarded as completely interdependent, and therefore links in a 'system chain'. This is the underlying principle behind the derivation of the final present day transformer system EoL Value EoL_{y0} (See Equation 19, which is generated from the larger of the transformer EoL_{y0} and its associated tapchanger EoL_{y0}..
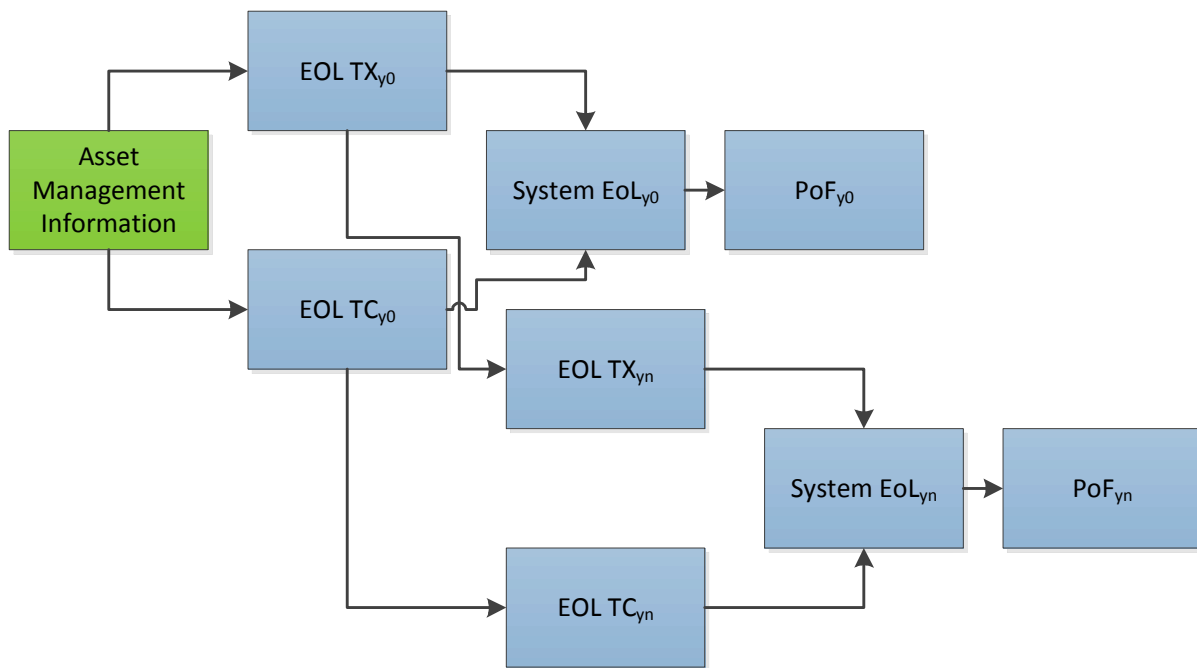
Figure 6 PoF Calculation for Transformers and Reactors

The Transformer System EoL indicator is defined as follows:

Equation 19

$$TxSystemEoL_{(y0)} = max\left(TxEoL_{(y0)}, TcEoL_{(y0)}\right)$$

Derivation of $TxEoL_{Y0}$ and $TcEoL_{Y0}$ is described in the following sections.

4.1. MAIN TANK (TX)

4.1.1. INITIAL END OF LIFE MODIFIER

The Transformer Initial End of Life Modifier is calculated per Section 2.1.3. Factors specific to Transformers are described below:

4.1.1.1. DUTY FACTOR

Duty Factor for each Transformer, the duty factor is calculated according to the data available to the TO to make the best analysis of an assets utilisation.

- Maximum operating temperature recorded against each transformer, T_{max}. SHE Transmission use this variable instead of average demand.
- Maximum demand placed upon the transformer as a percentage of its stated rating, $D_{max,}$
- Average demand placed upon the transformer as a percentage of its stated rating, D_{max}
- Severity or Frequency of Through Faults, T_F

The combination of these variables determines an overall duty factor using either Equation 20 Duty Factor Calculation for Transformers SHE-T OR Equation 21 Duty Factor Calculation for Transformers SPT depending on the TO.

Equation 20 Duty Factor Calculation for Transformers SHE-T

$$F_{DY} = max(T_{max}, D_{max}) * T_F$$

Equation 21 Duty Factor Calculation for Transformers SPT

$$F_{DY} = max(D_{max}, D_{ave})$$

4.1.1.2. LSE FACTOR

The Transformer Initial End of Life Modifier is calculated per Section 2.1.3.2 where the LSE Factor is calculated as:

Equation 22

$$LSE\ Factor = (((Location\ Factor - Minimum\ Location\ Factor) \times Situation\ Factor) + Minimum\ Location\ Factor) \times Environment\ Factor$$

The Licensee Specific Appendix further explores the calibration tables used in the LSE calculation.

4.1.2. INTERMEDIATE END OF LIFE MODIFIER

The Transformer Intermediate End of Life Modifier is calculated per Sections 2.1.2.2. & 2.1.5. for Factors:

- Visual Condition
- Defects
- Asset Family Reliability
- Test Results
- Operational restrictions

Additional Factors that can be included in the calculation of FV_1 are shown below:
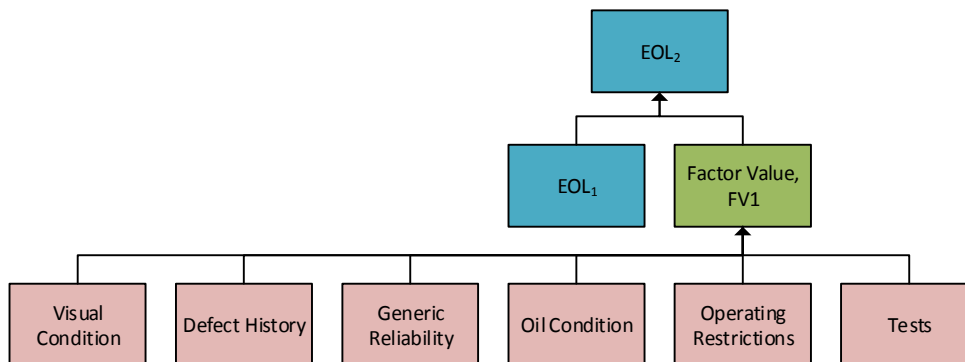
Figure 7 Transformer Intermediate EoL

Oil Condition Factor:

Established techniques such as oil analysis provide an effective means of identifying and quantifying degradation of the insulation system (oil and paper) within transformers. Oil results can also be used to identify incipient faults. The oil condition factors can consider the latest oil condition tests, (moisture (O_M), acidity(O_A), breakdown strength(O_B) or tan delta(O_T)) each of which can be used to create a test score. Each of these scores can be given a multiplier which accounts for the significance of the result. The summation of these multiplied individual oil condition test scores, O_{TOTAL}, is then used to determine an overall oil condition factor, F_{OIL}. (See Licensee Specific Appendix for specific factor values.)

Equation 23

$$O_{TOTAL} = \sum 80.(O_M, O_B, O_T), 125.O_A$$

Where the oil test is not considered to be valid it is excluded and the next available set of results are used. Oil condition is not included if the latest sample is beyond the cut-off date.

The Oil Condition Factor is further expanded upon in the Transformer section of the Licensee Specific Appendices.

4.1.3.   FINAL END OF LIFE MODIFIER

The following Modifiers are used to determine the Transformer End of Life Modifier ($TxEoL_{Y0}$):

- EoL_2
- EoL_{DGA}
- EoL_{FFA}
- Maximum of the Minimums

It can be calculated in one of two ways, based on the value of EoL_2:

If EoL_2 is the largest of the modifiers, then

Equation 24

$$TxEoL_{y0} = Max\left(EoL_2 - \left[\left(\frac{EoL_2 - Max(EoL_{DGA}, EoL_{FFA})}{2}\right)\right]\right), Maximum\ of\ the\ Minimums$$

Otherwise,

Equation 25

$$TxEoL_{y0} = Max(EoL_{DGA}, EoL_{FFA}, Maximum\ of\ the\ Minimums)$$

4.1.3.1.   DGA MODIFIER EOL_{DGA}

EoL_{DGA} is derived from the dissolved gas analysis (DGA) oil test results. This is a very well established process that enables abnormal electrical or thermal activity to be detected by measurement of hydrogen and hydrocarbon gases that are breakdown products of the oil. The levels and combination of gases enable detection of developing faults and identification of 'life threatening' conditions.

The calculation of EoL_{DGA} can be split into two parts. In the Part 1 EoL_{DGA} is calculated for each oil sample held against an asset in the company's oil database. Each oil sample is analysed for levels of Hydrogen, Acetylene, Ethane, Ethylene, Methane, Oxygen and Nitrogen which provide indications of the internal condition of the transformer. Each gas result is then combined with weighted multipliers and then summed together to form a DGA Score. Finally, the DGA Score is compared with a calibration table to generate EoL_{DGA} for each sample.

In Part 2 a Principal Result is selected from the valid oil samples of each asset. The Principal Result is selected as the sample that provides the largest EoL_{DGA} within a calibrated time period of the latest sample (usually 90 days). The Principal Result is taken forward and modified in Part 2 by considering the rate of change of DGA values from each transformer's historical test results. The boundaries for assessment of DGA levels are taken from the Cigre Working Group 15.01 paper, "New guidelines for interpretation of dissolved gas analysis in oil-filled transformers". These boundaries can provide useful information relating to incipient faults within transformers or contamination of the main tank oil from the tapchanger.

Where the oil test is not considered to be valid it is excluded and the next available set of results are used.

In line with Section 2.1.6 EoLDGA is capped at a maximum value of 10 and collared at a minimum value of 0.5. The step-by-step process is as follows:

Part 1

1. Convert each gas result (in ppm) to a Condition State via a calibration table
2. Calculate the DGA Score by multiplying each gas Condition State by a multiplier and summing

Equation 26

$$DGA\ Score = \sum 50 \times Hydrogen\ Score + 30 \times Methane\ Score + 30 \times Ethylene\ Score + 30 \times Ethane\ Score + 120 \times Acetylene\ Scores$$

3. Calculate EoL_{DGAi}

Equation 27

$$EoL_{DGAi} = min\left(\frac{DGA\ Score}{DGA\ Divider}, EoL_{DGA\ Max}\right)$$

Part 2:
1. Calculate DGA % Change

Equation 28

$$DGA\ \%\ Change = \left(\frac{max(EoL_{DGAi})}{average(EoL_{DGA})}\right) \times 100$$

2. Convert DGA % Change to a Change Description via a calibration table
3. Generate a DGA History Factor from the Change Description via a calibration table
4. Calculate the final EoL_{DGA} for each asset using the Principal Result

Equation 29

$$Principal\ Result = max(EoL_{DGAi})\ in\ the\ calibarted\ time\ period\ before\ the\ last\ sample$$

$$IF\ (Principal\ Result > DGA\ History\ Threshold)$$

$$\{$$
$$EoL_{DGA} = Principal\ Result\ \times DGA\ History\ Factor$$
$$\}$$

$$ELSE$$

$$\{$$
$$EoL_{DGA} = Principal\ Result$$
$$\}$$
$$EoL_{DGA} = max(min(EoL_{DGA}, 10), 0.5)$$

4.1.3.2. FFA MODIFIER EOL$_{FFA}$

EoL$_{FFA}$ is derived from the oil test results furfuraldehyde (FFA) value. Furfuraldehyde is one of a family of compounds (furans) produced when the cellulose (paper) within the transformer degrades. As the paper ages, the cellulose chains progressively break, reducing the mechanical strength.

The average length of the cellulose chains is defined by the degree of polymerisation (DP) which is a measure of the length of chains making up the paper fibres. In a new transformer, the DP value is approximately 1000. When this is reduced to approximately 250 the paper has very little remaining strength and is at risk of failure during operation.

Equation 30

$$EoL_{FFA} = Min(FFA_{Multiplier}FFA_{MAX}{}^{FFAPV}, EoL_{FFAMAX})$$

Where:

FFA Multiplier   =   TO Specific calibrated values included in Licensee Specific Appendices

FFA Power Value   =   TO Specific calibrated values included in Licensee Specific Appendices

Max FFA   =   FFA measurement for an asset

Where the oil test is not considered to be valid it is excluded and the next available set of results are used.

The Calibration tables used for the FFA Modifier can be found in the Transformer section of the Licensee, Specific Appendix.

4.2.   TAPCHANGER (TC)

The variables involved in the EoL calculations for Tap changers are the same as for the main tank, except for EoL$_{FFA}$. As there are no windings within a tap changer, this variable does not exist. Similarly, the DGA results are not as material within a tap changer and, as such, are incorporated into the calculation of EoL$_2$

4.2.1.   INITIAL END OF LIFE MODIFIER

The Tapchanger Initial End of Life Modifier is calculated per Section 2.1.3. Factors specific to Transformers are described below:

4.2.1.1. DUTY FACTOR

For each tapchanger, the duty factor is calculated from the following variables:

- Tapcount factor, T_F
- High Wear Rate Factor, H_F, where there is a history of high contact wear within the tapchanger

The combination of these variables determines an overall duty factor using Equation 31.

Equation 31

$$F_{DY} = max(T_F, H_F)$$

4.2.1.2. LSE FACTOR

The Transformer Initial End of Life Modifier is calculated per Section 2.1.3.2 where the LSE Factor is calculated as:

Equation 32

$$LSE\ Factor = (((Location\ Factor - Minimum\ Location\ Factor) \times Situation\ Factor) + Minimum\ Location\ Factor) \times Environment\ Factor$$

The Licensee Specific Appendix further explores the calibration tables used in the LSE calculation.

4.2.2. INTERMEDIATE END OF LIFE MODIFIER

The Tapchanger Intermediate End of Life Modifier is calculated per Section 2.1.5 for Factors:

- Visual Condition
- Defects
- Asset Family Reliability
- Oil Condition
- Test Results
- Operational restrictions
- DGA Results

Additional Factors that can be included in the calculation of FV_1 are shown below:
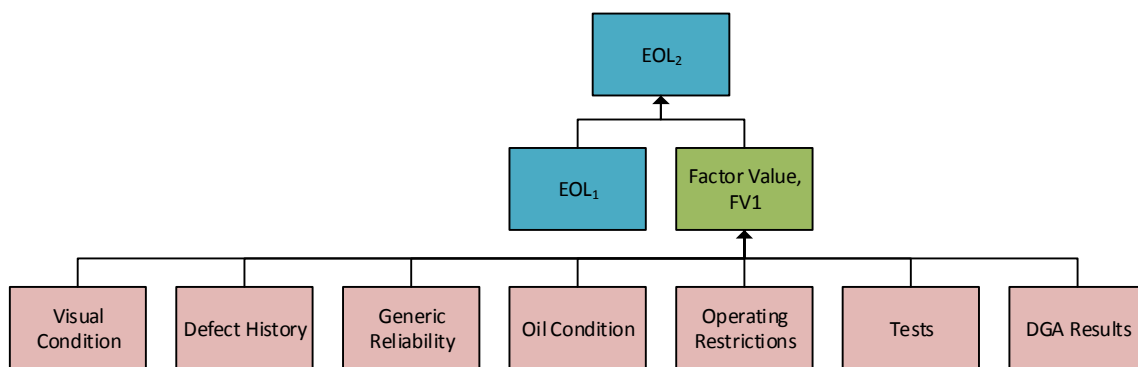
Figure 8 Tapchanger Intermediate EoL Modifier

Oil Condition and DGA Factors are calculated as for the Main Tank.

4.2.3. FINAL END OF LIFE MODIFIER

The following Modifiers are used to determine the Transformer End of Life Modifier (TxEoL$_{Y0}$):

- EoL$_2$
- Maximum of the Minimums

Equation 33

$$TcEoL_{y0} = Max(EoL_2, Maximum\ of\ the\ Minimums)$$

5. EOL CALCULATION FOR CABLES

Cables are assigned an Asset EoL Value (EoL) per their known condition and the service history of other similar cables.

Within this methodology, transmission cables are considered as number of discrete cable lengths (or 'component') which together form a distinct circuit.

For each component of cable circuit asset management information is fed into the model to produce a component EoL Modifier, referred to as EoL_{Y0}, before an overall system EoL Value is created. This system EoL Value is then used to calculate a probability of failure, PoF for several defined failure modes.

There are three separate models within the main underground cable model reflecting the following types of construction;

- Pressurised
- Non-pressurised
- Submarine cable

Each model uses a similar format, though certain condition points are 'construction' dependent and only used within that model as a factor.

5.1. INITIAL END OF LIFE MODIFIER

5.1.1. DUTY FACTOR

5.1.1.1. SHE-T IMPLEMENTATION OF DUTY FACTOR

The duty factor is calculated based upon the maximum demand placed on the cable as a percentage of its rating. It uses the following criteria to develop a duty factor for its SOLID cables;

- Maximum Demand as a percentage
- A reactive earthing presence factor

In the case for fluid filled cables

- Duty exception report is used instead of a reactive earthing presence factor

As the effects of utilisation vary between cable types, separate duty factors will be established for each cable type. This classification will be based upon insulation type.

5.1.1.2. SPT IMPLEMENTATION OF DUTY FACTOR

Similarly, to SHE-T, the duty factor is calculated based upon the maximum demand placed on the cable as a percentage of its rating. It uses the following criteria to develop a duty factor for all of its cables;

- Maximum load placed on the cable as a percentage of its rating;
- Average load placed on the cable as a percentage of its rating; and
- Operating voltage compared to design voltage.

Again, as the effects of utilisation vary between cable types, separate duty factors will be established for each cable type. This classification can also be based upon insulation type.

$$F_{DY} = D_{max} \cdot D_{ave} \cdot D_v$$

5.1.2.   LSE FACTOR FOR UNDERGROUND CABLES

For underground Pressurised and Non-Pressurised Underground Cables, the installation factor can be based upon the following variables:

- As laid depth (F_D)
- Backfill Material (F_{back})
- Laying Configuration (F_{config})
- Duct Type (F_{duct})
- Ploughed installation factor (F_C)

The combination of these variables determines an overall LSE factor (F_{LSE}) using a TO specific equation, and is further expanded upon with relevant calibration tables in the Cables section of the Licensee Specific Appendices.

5.1.3.   LSE FACTOR FOR SUBMARINE CABLES

For submarine cables the LSE is determined using the following variables:

- Cable route topology
- Cable situation factor
- Wind/wave factor
- Combined wave and current energy factor

The combination of these variables determines an overall LSE factor (F_{LSE}) using the following equation.

$$F_{LSE} = max(F_T, F_S, F_W, F_E)$$

5.1.4.   EXPECTED LIFE

Starting with the Expected Average Life (L_A), the Duty and LSE factors are used to set an expected life (L_E) for each asset.

$$L_E = \frac{L_A}{F_{LSE} \times F_{DY}}$$

This expected life is then used to determine EoL_1.

The Expected Asset Life is the time (in years) in an asset's life when it would be expected to such deterioration that it is likely to exhibit functional failure. The determination of the L_A considers factors such as original specification and manufacturer data. This corresponds to an EoL Modifier of 7.

5.2.   INTERMEDIATE END OF LIFE MODIFIER

The cable intermediate end of life modifier is calculated in accordance with Sections 2.1.2.2. & 2.1.5. for Factors:

- Visual Condition
- Defects
- Asset Family Reliability
- Test Results
- Operational restrictions

Additional Factors that can be included in the calculation of FV_1 are:

- Fault History (for non-pressurised cables)
- Leak History (for pressurised cables), as shown in Figure 9 below.
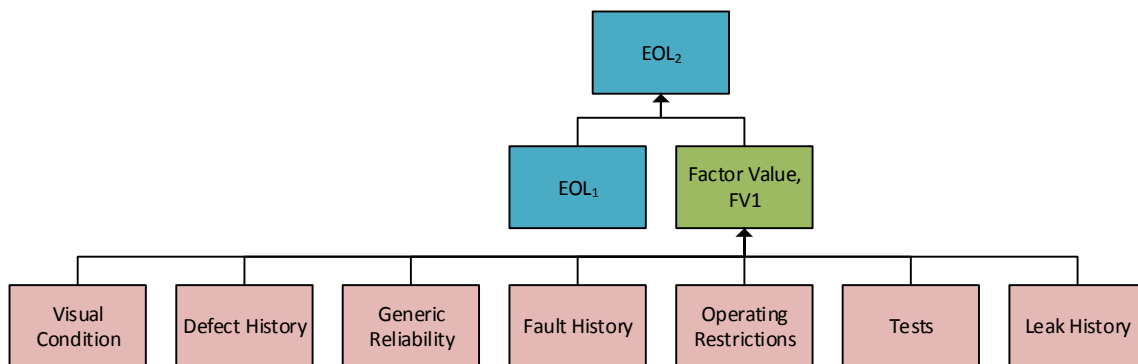
Figure 9 EoL$_2$ Calculation for Cables

Fault History

The severity of faults across the cable section is considered.

Fault history is determined by assigning severity scores to the cables the terminations and the joints themselves. These scores are then summed together to give an overall fault history score, this is then converted to a factor based on a calibration table available in the cables section of the Licensee Specific Appendices.

Leak History

The sum of the weighted top up volume divided by square root of the length provides an accurate leak history score. This is subsequently turned into a factor via a calibration table value, also available of the Licensee Specific Appendices.

5.3.   FINAL END OF LIFE MODIFIER

The end of life modifier is calculated as shown below

Equation 37

$$TcEoL_{y0} = Max(EoL_2, Maximum\ of\ the\ Minimums)$$

6. EOL CALCULATION FOR OVERHEAD LINES

OHL assets are assigned an asset EoL Value (EoL_{y0}) per their known condition, the known condition of associated components and the service history of other similar conductors, fittings and towers.

Within this methodology, three Lead Asset types are considered separately however they are, in combination, representative of an entire circuit.

- Conductors
- Fittings
- Towers
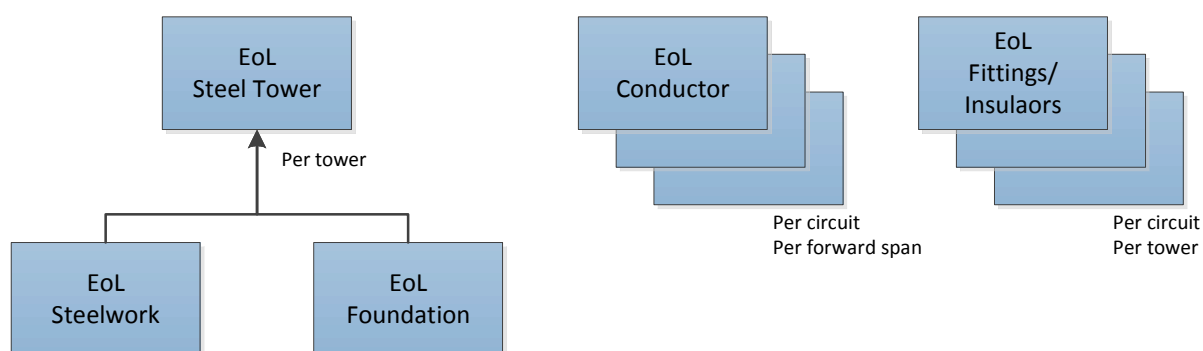
Figure 10 OHL System Overview

OHL System Overview

In addition to the 'per asset' EoL indices described above, the models will be able to include summary information by route for towers, and circuit name for spans.

In addition, the Lead Asset type of Steel Tower can be shared by multiple circuits.

6.1. CONDUCTORS

6.1.1. INITIAL END OF LIFE MODIFIER

The initial EoL indicator is based around the age of an asset in relation to the estimated average expected service life which could be reasonably anticipated. This calculation stage does not consider any condition, defect, inspection or testing information, and simply provides an impression of the likely EoL of an asset given its age, where it is located and its approximate work load.

The asset's age is taken as the date at which the conductor was replaced; if no replacement date is available, it is assumed that the original conductor is still in place and the date of tower construction is used to determine the age of the conductor.

An average life is assigned to the conductor based on the conductor type and the cross-sectional area.

6.1.1.1.   LOCATION, SITUATION AND ENVIRONMENT (LSE)

For each asset, the LSE factor is calculated from the following variables.

- Distance from the Coast
- Altitude
- Corrosion rating e.g. based on proximity to Industrial Pollution

The combination of these three variables determines an overall LSE factor (FL) using the following equation:

Equation 38

$$F_L = \max(F_D, F_A, F_C)$$

Environment

Environment also is a degrading factor for example if the conductor is in an area known to experience severe weather.

Further expansion of the calibration tables used to calculate the LSE can be found in the Licensee Specific Appendices in "Factors Common to All Lead Assets".

Duty is excluded as a factor within the conductor calculation

6.1.1.2.   SHE-T IMPLEMENTATION OF LSE FACTOR

The overall LSE factor is derived using the following equation:

Equation 39

$$LSE\ Factor = (((Location\ Factor - Minimum\ Location\ Factor) \times Situation\ Factor) \\ + Minimum\ Location\ Factor) \times Environment\ Factor$$

6.1.1.3.   SPT IMPLEMENTATION OF LSE FACTOR

The overall LSE factor is derived using the following equation:

Equation 40

$$F_{LSE} = F_{loc} \cdot F_{env}$$

6.1.1.4.   EXPECTED LIFE

Starting with the Expected Average Life (L_A), the Duty and LSE factors are used to set an expected life (L_E) for each asset.

Equation 41

$$L_E = L_A \times F_{LSE}$$

This expected life is then used to determine EoL_1.

The Expected Asset Life is the time (in years) in an asset's life when it would be expected to such deterioration that it is likely to exhibit functional failure. The determination of the L_A considers factors such as original specification and manufacturer data. This corresponds to an EoL Modifier of 7.

6.1.2.   INTERMEDIATE END OF LIFE MODIFIER

The conductor intermediate end of life modifier is calculated in accordance with Sections 2.1.2.2 & 2.1.5. for Factors:

- Visual Condition
- Defects
- Generic Reliability
- Test Results
- Operational restrictions

Additional Factors that can be included in the calculation of FV_1 are:

- Cormon Testing
- Conductor Hot Joints
- Flashover Marks, as shown in Figure 11 below
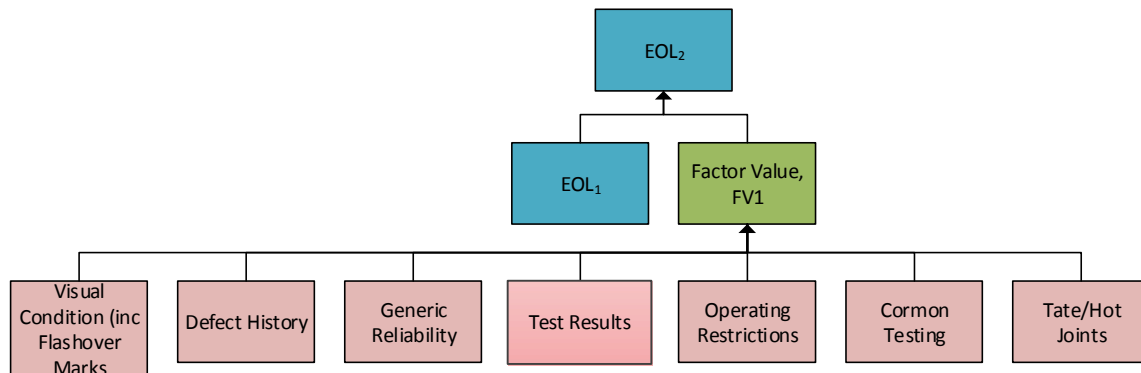
Figure 11 SHE-T's Calculation for EoL$_2$

Conductor Sampling/Cormon Testing

Conductor sampling determines the extent of corrosion a sample of the overhead conductor, which is considered to provide a representative indication of the EoL of the circuit. The results can be used to derive an EoL Modifier independently of any other information on condition or age.

The test results are used to derive a Conductor Sampling EoL Modifier via a calibration table of the form shown below. The tests results are conducted on a span or number of spans and then applied to the whole circuit.

Conductor Hot Joints

Infrared detection is used to check the thermal radiation given off by a conductor during operation. If a hot joint is detected (with a thermal value greater than a calibrated normal result) then it is assigned a factor value, Expanded further in Section 5.1.1.4 in the Licensee Specific Appendix. Once the factor is assigned a Maximum Multiple increment function is used (with tate joints condition factor) to determine and overall factor value.

Flash Over Marks

The voltage problems that cause flash over rarely produce heat and are often undetected with typical infrared inspection. Therefore, if residual marks left over from flash over are detected then we can assume those fittings are incurring voltage problems which are causing visible damage to the system. A Boolean statement is used to determine if the flash over score is added to the overall score for determining fitting end of life which is then converted into a factor using a calibration table.

6.1.3.   FINAL END OF LIFE MODIFIER

Test results provided by the Cormon testing or conductor sampling are the most robust indicator of end of life and, as such, if these results are present, the Test Factor is taken as a proxy for end of life. If these results are not present, EoL_2 (SHE-T) is taken as the final EoL modifier.

6.2. FITTINGS

To attach, insulate and join conductor spans various fittings and insulators are used. Over the course of the lifetime of these assets an EoL indicator needs to be calculated (on a per circuit and a per tower basis) as summarised in Figure 13.

6.2.1. INITIAL END OF LIFE MODIFIER – (EOL_C)

The initial EoL indicator is based around the age of an asset in relation to the estimated average expected service life which could be reasonably anticipated. This calculation stage does not consider any condition, defect, inspection or testing information, and simply provides an impression of the likely EoL of an asset given its age, where it is located and its approximate work load.

The initial End of life modifier is denoted by EoL_C instead of EoL_1. This is due to the way the Final end of life value is calculated. In previous equations, Initial end of life modifier (EoL_1) is *converted* into the Intermediate end of life modifier (EoL_2) by multiplication of a factor value. It should be noted that in this instance and the following instances in steel work and foundations (Section 6.3) calculating in this way is not comparable.

The initial End of Life value (EoL_C) is instead *compared* with the condition factors that would ordinarily constitute the Intermediate end of life modifier (for this case produced by EoL_A and EoL_B).

Comparing the values of EoL_A and EoL_B with EoL_C and taking the maximum value of these creates the Final End of life value as per 6.2.3 and is thus why they are denoted differently.
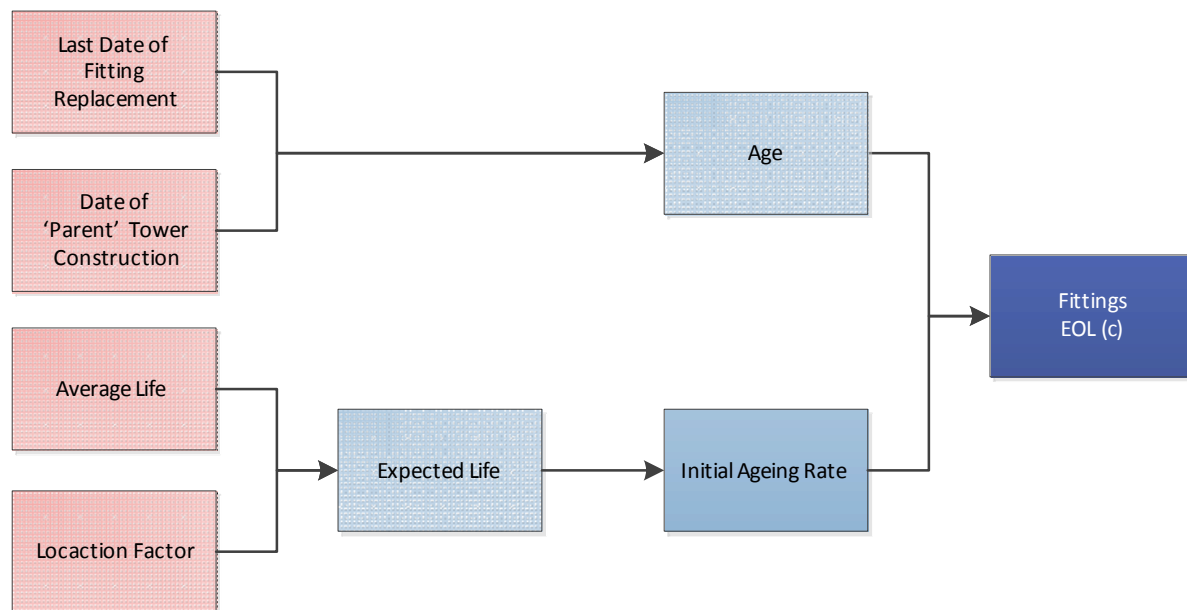
Figure 12 Initial End of Life Modifier for Fittings

The asset's age is taken as the date at which the fittings were replaced; if no replacement date is available, it is assumed that the original fittings are still in place and the date of tower construction is used to determine the age of the fittings.

An average life is assigned to the fittings based on the type of insulators (i.e. glass, polymeric or porcelain), whether they are tension/suspension fittings and the operating voltage.

6.2.1.1.   LOCATION, SITUATION AND ENVIRONMENT (LSE)

For each asset, the location factor is calculated from the following variables.

- Distance from the Coast, F_D
- Altitude, F_A
- Corrosion rating e.g. based on proximity to Industrial Pollution, F_C

The combination of these three variables determines an overall LSE factor (F_L) using the following equation:

Equation 42

$$F_L = \max(F_D, F_A, F_C)$$

The overall LSE factor is derived using the following equation:

Equation 43

$$F_{LSE} = F_{loc} \cdot F_{env}$$

The average life for that asset class and the LSE factor are used to set an expected life (L_E) for each asset.

6.2.1.2.   DUTY FACTOR

For Steel Tower fittings, SHE-T includes a duty factor in its calculation, high damper replacement can indicate too much vibration is being introduced into the system and therefore negatively affects the life expectancy of the tower.

Therefore, there is a calibration table used that modifies the value used calculate the Initial End of life modifier

Equation 44 Duty Factor for Overhead lines

$$Overall\ Duty\ Factor\ =\ High\ Damper\ Replacement\ Rate$$

It is to be noted that SPT do not include a duty factor in their calculation of the initial end of life modifier.

6.2.2. INTERMEDIATE END OF LIFE MODIFIERS

6.2.2.1. CONDITION

Where reliable and robust information provides definitive information on asset condition, the information is used to directly derive a condition based EoL indicator. This is depicted in the schematic diagram shown in Figure 13 below. Several individual condition points are assessed or rated using a pre-defined scale (typically 1 to 4 or 1 to 5). Each condition rating is then assigned a condition score via a calibration table. Each condition point has its own specific calibration table for defining the condition score.
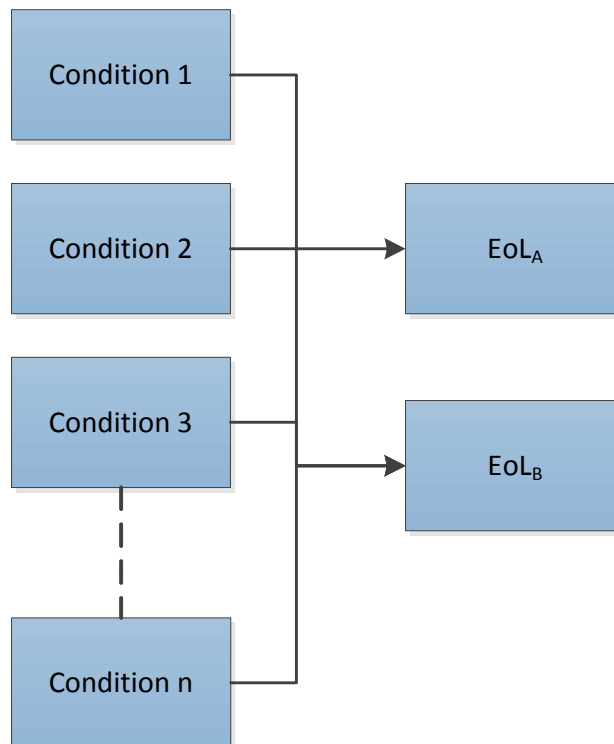
Figure 13 Derivation of condition based EoL Indices for fittings

Condition Score Calibration

EoL_a and EoL_b are two possible values for the condition based EoL indicator derived by combining the individual condition scores in two different ways. This ensures that a 'worst case' EoL indicator is derived regardless of whether the fittings have only one element in very poor condition or several elements in moderately poor condition.

6.2.3. FINAL END OF LIFE MODIFIER

The end of life modifier is calculated as shown below:

Equation 45

$$EoL_{y0} = Max(EoL_A, EoL_B, EoL_C)$$

The steel tower EoL Value is formed from a combination of a steelwork EoL and a tower foundation EoL Values.

Equation 46

$$EoL_{(T)} = weighted\ average\big(Tower\ Steelwork\ EoL_{(y0)}, Tower\ Foundations\ EoL_{(y0)}\big)$$

The Steel Tower EoL value is formed from the combination of the Tower Steelwork EoL value and the Foundation EoL value, as shown in Figure 14 below.
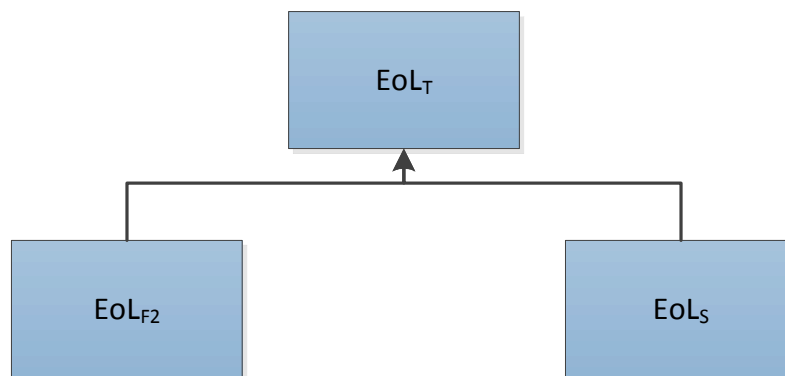
Figure 14 Steel Tower EoL Value

Once both the foundation and steelwork EoL modifiers have been calculated, the Steel Tower EoL value is formed by taking a weighted average of both the tower steelwork and the foundation EoL indices. This weighted average is subject to a minimum EoL value override which is determined by calibration values. Traditionally the weighting applied to the tower steelwork to foundation is in the region of 1:3, however this ratio can be changed as part of a calibration review.

6.3.1.   STEELWORK

6.3.1.1.   INITIAL END OF LIFE MODIFIER

An 'age based' EoL indicator, EoL_C, is derived from the asset age, last painting date and the expected service life of the tower as shown in Figure 15 below. This is only used

  i.   if no inspection data is available to derive EoL_A and EoL_B, or
  ii.   to provide boundaries for the EoL derived from inspection data.
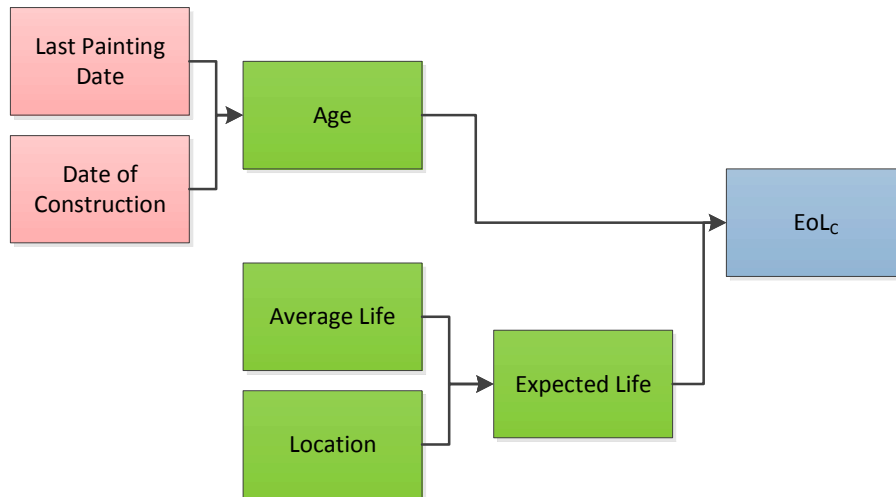
Figure 15 Steelwork EoL indicator EoL(c)

The assets age is taken from the date of tower construction and where it exists, the date at which the tower was last painted. If a tower has been painted then the expected life of the tower will be set via calibration to an expected life associated with the paint system, typically in the region of 15 years. If the tower has not been painted the year of construction is used against an expected life which is associated with the original tower steelwork galvanising, a calibration value typically set at around 30 years.

6.3.1.2. INTERMEDIATE END OF LIFE MODIFIERS

The first stage of the steel work EoL indicator is derived using the observed condition information collated from surveys and inspections, as shown in Figure 16 below.
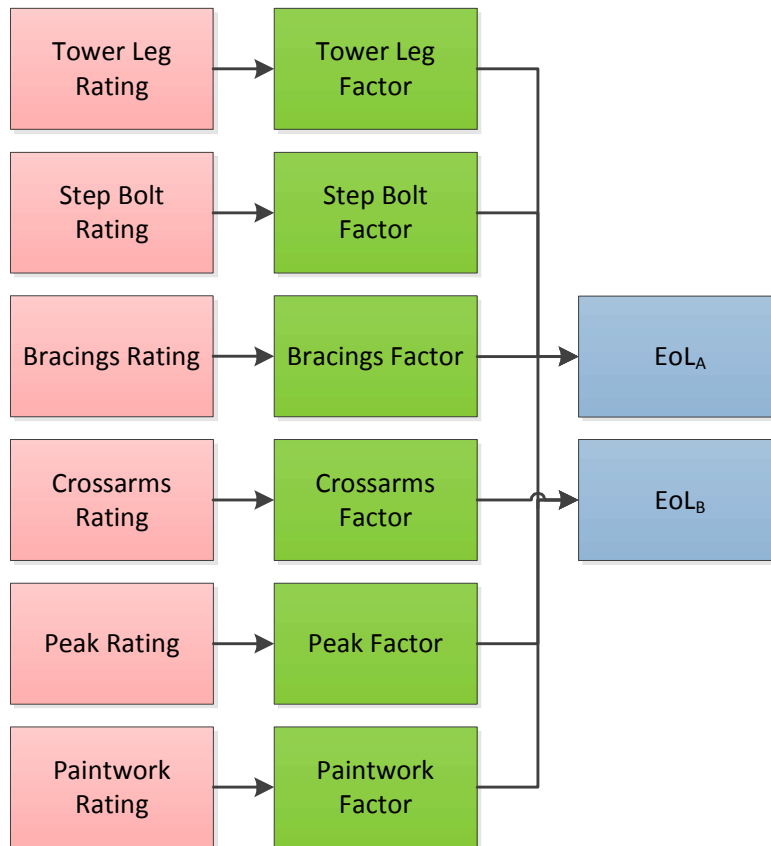
Figure 16 Derivation of initial steelwork indicators

Observed condition scores taken from inspection or condition assessments and the year in which the condition assessments took place are entered the model. Each condition point is assigned a condition score via a series of calibration lookup tables. Condition points include scores for the tower legs, step bolts, bracings, crossarms, peak, paintwork. Calibration table is available in of the Licensee Specific Appendices.

EoL_A is derived from the worst of the condition points found, while EoL_B is derived using the sum of the condition points scores divided by a calibration 'divider'. This creates two EoL indices which represent the condition of the tower steelwork in the year of condition assessment; the Implementation will then age these EoL indices to the present year.

6.3.1.3. FINAL END OF LIFE MODIFIER

The final tower steelwork EoL indicator, EoL_S, which represents the present day overall condition of the tower steelwork is determined from EoL_A, EoL_B and EoL_C as depicted below.
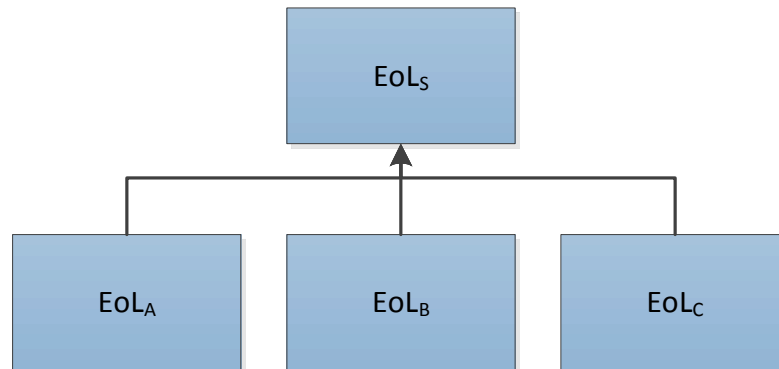
Figure 17 Tower Steelwork EoL$_S$

Where detailed condition assessment information is not available, the model will not be able to calculate EoL_A or EoL_B, and therefore EoL_S will equal EoL_C.

Where detailed condition information is available the final tower steelwork EoL indicator, EoL_S, will be the maximum of EoL_A and EoL_B. If the condition assessment identifies that the tower steel work in an as new condition, then the model will use EoL_C to modify the EoL indicator depending upon the age of the tower up to a calibratable limits which is typically set at an EoL of around 1.5.

6.3.2. FOUNDATIONS

The Implementation calculates an EoL indicator for each set of tower foundations for each tower position. The model uses information relating to the type of foundation, the environment in which the foundation is situated, along with more specific foundation test results and inspection information.

6.3.2.1. INITIAL END OF LIFE MODIFIER

The first stage of EoL indicator calculation determines the foundation initial EoL indicator, which is shown in Figure 18 below.
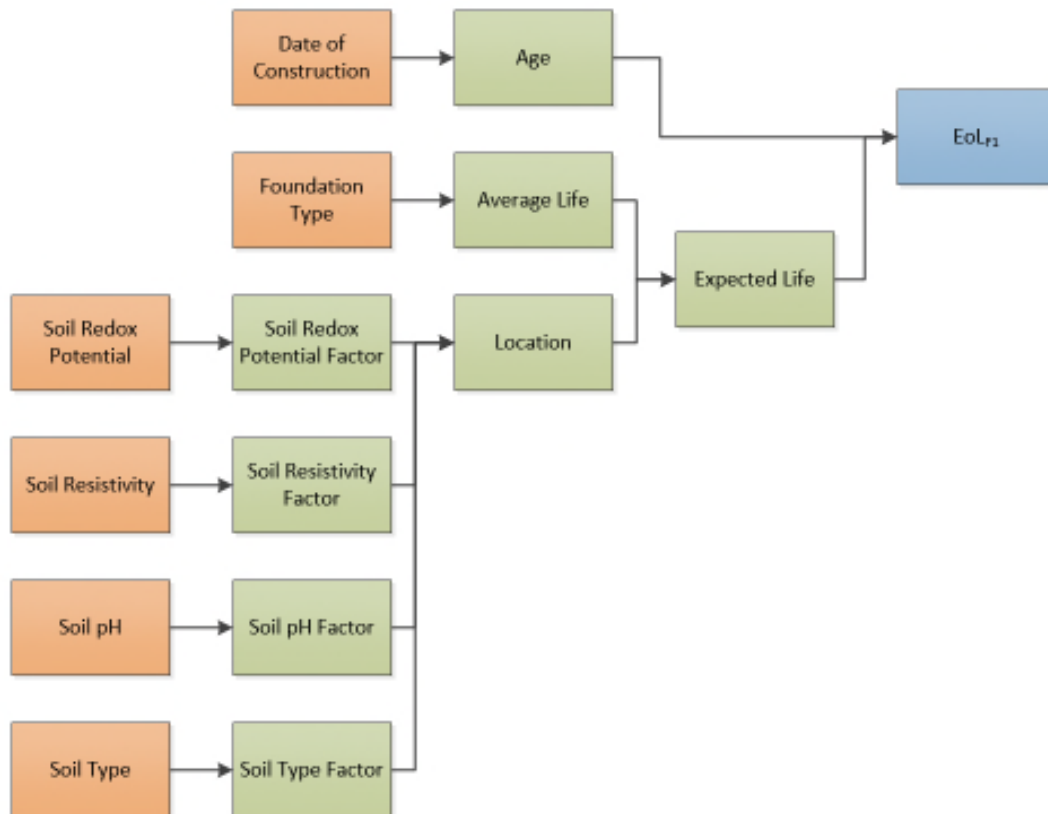
Figure 18 Initial Foundation EoL indicator, EoL_{F1}

Soil Resistivity

The resistivity value is simply converted into a score via a calibration table which is then combined with the scores for soil chemistry and redox potential. The combination of these produces a score which is converted into an overall factor when checked with a calibration table.

Soil Chemistry

The soil pH value is simply converted into a score via a calibration table which is then combined with the scores for soil resistivity and redox potential. The combination of these produces a score which is converted into an overall factor when checked with a calibration table.

Redox Potential

Redox is the process where an oxidisation and reduction reaction occur between 2 different materials that can end up altering some of the key characteristics of that material. When steel rusts the structural integrity of the steel becomes compromised; It expands, becomes more brittle and loses all ductility. These this means the properties useful for steel structures such as a tower are altered which could inevitably lead to failure. The redox value is simply converted into a score via a calibration table which is then combined with the scores for soil resistivity and chemistry. The combination of these produces a score which is converted into an overall factor when checked with a calibration table.

The overall location factor for foundations is either derived from the specific soil test results indicated in Figure 18 or from an overall soil type factor. If neither are available, the factor defaults to a neutral value of 1.
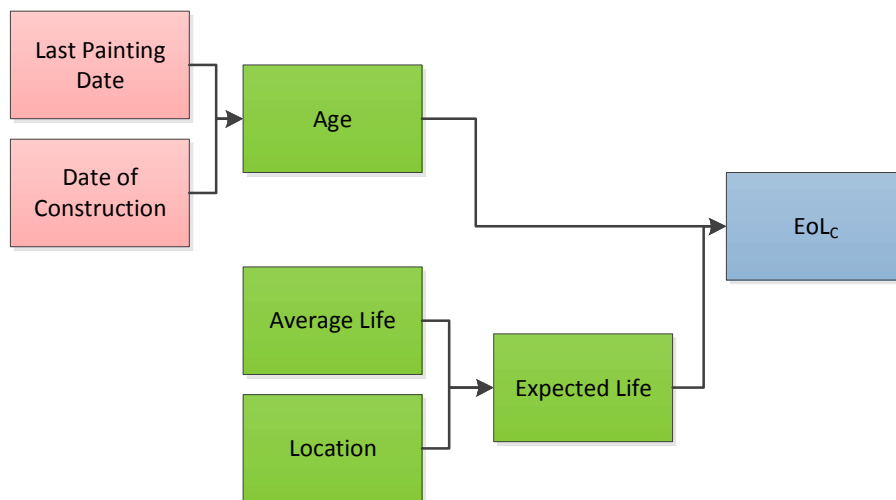
Figure 19 Steelwork EoL Indicator EoL$_C$

6.3.2.2.   INTERMEDIATE END OF LIFE MODIFIER

The second calculation stage, i.e. to find EoL_2, introduces more specific asset information pertaining to observed condition, inspection surveys, maintenance test results and operators experience. The possible inputs that can be considered, including the Foundation EoL_1 from the previous calculation stage, are shown below.
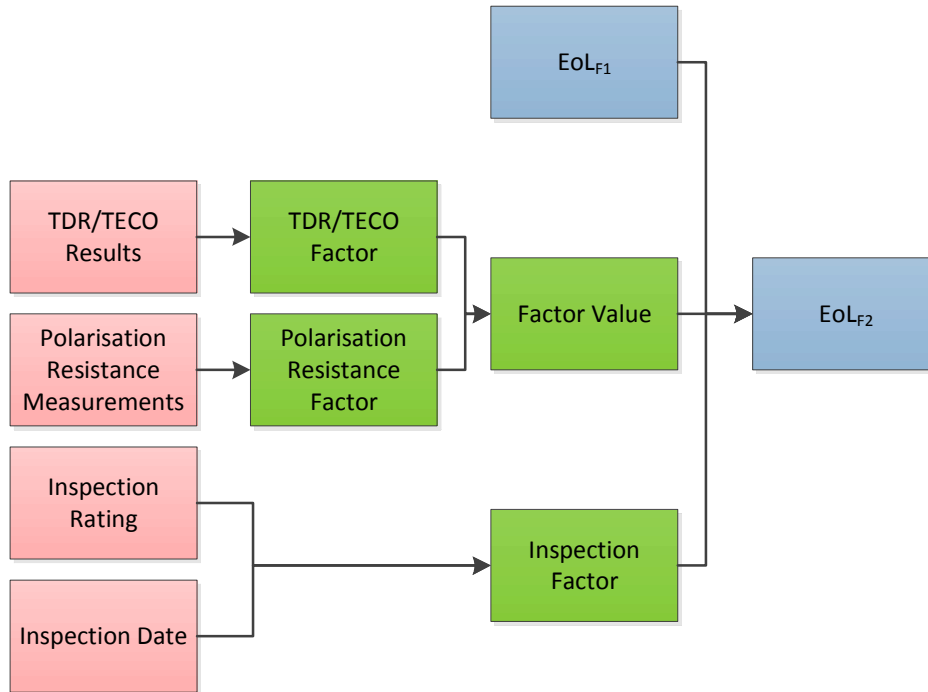
Figure 20 Interim Foundation EoL indicator EoL$_{F2}$

Within this stage of the foundation EoL indicator derivation, the results of asset specific tests carried out on tower foundations are used to modify the initial foundation EoL indicator.

This interim foundation EoL can be overridden by foundation ratings assigned to foundations which have been excavated and inspected (within defined calibration limits). The override will only take place on the condition that the date at which the excavated rating has been assigned is after the date when the foundation was last routinely inspected/tested. The EoL indicator which results from this mechanism is assigned for the year in which the excavation took place.

Where excavations and repairs have been undertaken, and the date of the completed works is later than the latest date of any condition assessment, then the test data will not be used in the creation of the foundation EoL indicator. Instead the EoL indicator will be based upon a calibration value which reflects the EoL of the asset once the repairs have been completed (at the time of completion) and aged to the present year as before.

The Test Data Calibration tables can be found on the Licensee Specific Appendices in the Steel Tower Foundations section.

6.3.2.3. STEEL TOWER EOL MODIFIER

The Steel Tower EoL indicator is formed from the combination of the Tower Steelwork EoL indicator and the Foundation EoL Indicator, as shown below.
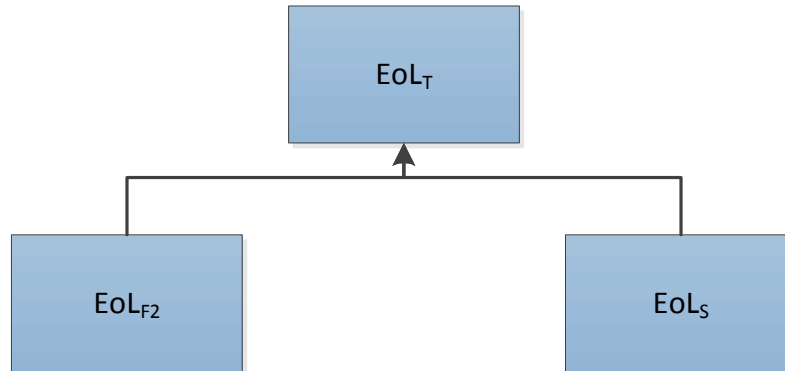
Figure 21 Steel Tower EoL indicator

Once each of the input heath indices have been created, the Steel Tower EoL indicator is formed by taking a weighted average of both the tower steelwork and the foundation EoL indices. This weighted average is subject to a minimum EoL indicator override which is determined by calibration values. Traditionally the weighting applied to the tower steelwork to foundation is in the region of 1:3, however this ratio can be changed as part of a calibration review.

7.   FORECASTING END OF LIFE

We determine the EoL Modifier in future years using the following

Equation 47

$$EoL_{y(n)} = EoL_{y(0)}e^{b\Delta T}$$

where

ΔT = time between years 0 and n.

This is initially determined using the expected life of the asset as ΔT, and the maximum and minimum EoL_S as $EoL_{(yn)}$ and $EoL_{(y0)}$ respectively. With all other variables known, b can then be calculated.

On an individual asset basis, the methodology firstly considers each asset's age to determine whether an ageing rate reduction factor should be included in the future EoL Modifier estimation calculation. For example, where an asset has reached near to end-of-life with no indications of problems, it is more likely to live longer than initially expected and so the ageing rate reduction factor should be included.

Once this has been determined, all the information is available to produce a future EoL Modifier. Having made this estimation for each of the subcomponent parts of the larger system, the Process re-combines the EoL Modifier to produce an estimated future system EoL Modifier for each asset.

The information above can also be used to determine an approximate rate of deterioration and, therefore, to estimate future asset EoL Modifier, which can be seen in Figure 22 below.
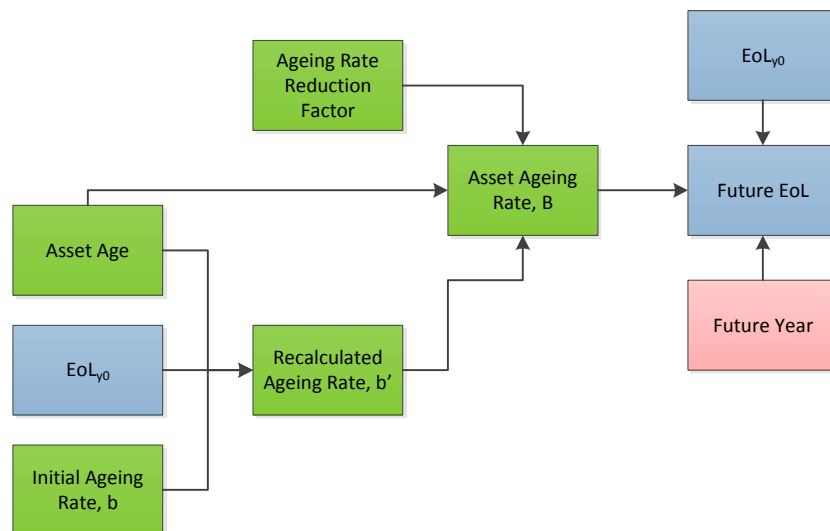
Figure 22 Forecasting Probability of Failure

The current EoL Modifier profile of a group of assets provides a 'snapshot' of the current condition of those assets. It is also possible through the application of Equation 48 to predict how these assets will behave in the future; i.e. how the EoL Modifier will change going forwards. To do so, it is first necessary to determine the Final Ageing Rate and the Ageing Reduction Factor for the asset. Once these are known, EoL Modifier for any asset in any future year t_{YN}, can be calculated as follows:

Equation 48

$$\text{EoL}_{Yn,1} = \text{maximum}\left(\text{EoL}_{Y0,i} \cdot \exp\left\{\frac{\beta_{final,i} \cdot (t_{YN} - t_{Y0})}{F_{age,i}}\right\}, EOL_{YN,max}\right)$$

where:

$\text{EoL}_{YN,i}$ =   EoL Modifier of asset i in future year Y_N

$\beta_{final,i}$ =   Final Ageing Rate of asset i (see Section 7.1 for details)

$F_{age,i}$ =   Ageing Reduction Factor for asset i (see Section 7.2 for details)

$(t_{YN} - t_{Y0})$ =   Number of years over which the asset moves from $\text{EoL}_{Y0,i}$ to $\text{EoL}_{YN,i}$

$\text{EoL}_{YN,max}$ =   Maximum allowable value for the Future Indicator; typically set to 15.

Where an Indicator is derived for multiple sub-components, the Future Indicator is derived by ageing each component to derive the EoL Modifier of the individual sub-components in the future year; these are then re-combined to produce the future overall EoL Modifier.

7.1. FINAL AGEING RATE

For assets that are new and/or in good condition, the EoL Modifier is determined using the Initial Ageing Rate. This prevents very slow ageing of an asset due to very good condition results, which would otherwise result in an unrealistic time for the asset to reach its end of life.

These assets are identified as those with a EoL Modifier below a defined threshold or those younger than a defined age limit. Equation 49. is used to calculate final ageing rate, as below:

Equation 49.

Thus, when $Age_i < Age_{recalc}$ or $EoL_{Y0,i} \leq EoL_{recalc}$

$$\beta_{final,i} = \beta_{1,i}$$

where:

$\beta_{1,I}$	=	Initial Aging Rate
Age_i	=	Current age of asset i
Age_{recalc}	=	Age limit for recalculating the ageing rate
EoL_{recalc}	=	Maximum EoL Modifier for using the Initial Ageing Rate

For other assets, the Final Ageing Rate is determined using the asset's EoL Modifier, as shown in Equation 50 :

Equation 50

$$\beta_{final,i} = maximum \left[\frac{\ln\left(\frac{HI_{Y0}}{HI_{New}}\right)}{Age_i}, \beta_{1,i}.\beta_{ratio} \right]$$

where:

β_{ratio} =   Maximum ratio between the Final Ageing Rate and the Initial Ageing Rate.

The ratio between the Initial Ageing Rate and the Final Ageing Rate is limited to prevent very rapid ageing of an asset due to very poor condition results or reliability issues that would otherwise result in an unrealistic time for the asset to reach its end of life. The maximum ratio is a calibration value and is typically set to a value of 2.

7.2. AGEING REDUCTION FACTOR

The Ageing Reduction Factor accounts for the increased life expectancy of an asset as it grows older; i.e. it slows the ageing process for assets that have started to age. This is necessary to model the effect of scheduling increasingly intensive or frequent maintenance as an asset approaches the end of its life. The relationship between EoL Modifier and the Ageing Reduction Factor is shown in Figure 23 Ageing Rate Reduction Factor.
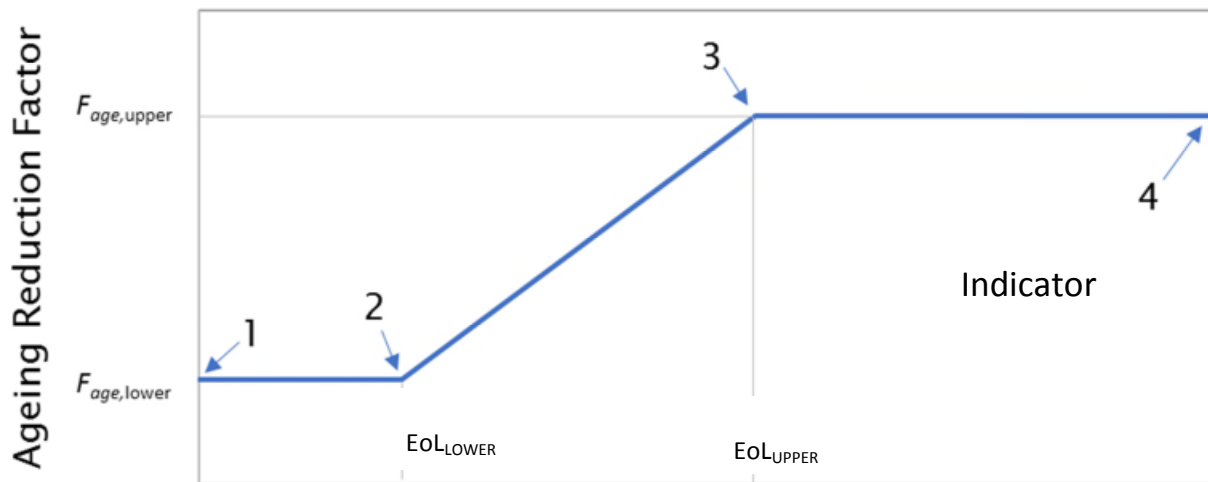
Figure 23 Ageing Rate Reduction Factor

where:

$F_{age,lower}$ =   Lower threshold for the Aging Reduction Factor
$F_{age,upper}$ =   Upper threshold for the Ageing Reduction Factor
EoL_{lower} =   Value of Indicator below which the lower threshold for the Ageing Reduction Factor is used
EoL_{upper} =   Value of Indicator above which the upper threshold for the Ageing Reduction Factor is used

If the EoL Modifier of the asset is between EoL_{lower} and EoL_{upper}, the Ageing Reduction Factor varies linearly as described by Equation 51

$$F_{age} = F_{age,lower} + \left(\frac{EoL_{Y0} - EoL_{lower}}{EoL_{upper} - EoL_{lower}} \right) \cdot \left(F_{age,upper} - F_{age,lower} \right)$$

The relationship between EoL Modifier and Ageing Reduction Factor is set via a calibration table which defines points 1 to 4 shown in Figure 23. The values used to define the Ageing Reduction Factor in all the models were determined empirically from historical records and are shown below.

Point	EoL Modifier	Aging Rate Reduction Factor
1	0.5	1.0
2	2.0	1.0
3	5.5	1.5
4	15	1.5

Table 3 Ageing Reduction Factor Calibration Values

The failure effect frequency directly maps to the failure mode frequency, due to the way that the failure effects and failure modes have been categorised.

7.3. PROBABILITY OF FAILURE CALCULATION

The relationship between the condition related probability of failure and time is not linear. An asset can accommodate significant degradation with very little effect on the risk of failure. Conversely, once the degradation becomes significant or widespread, the risk of failure rapidly increases. The use of a standard relationship between PoF and asset health means that End of Life Modifiers for all different types of assets (transformers, cables, switchgear, OHLs) have a consistent meaning. The significance of any individual End of Life Modifier value or the distribution of values for a population can be immediately appreciated. Comparisons between different assets and different asset groups can be made directly.

The method for translating the EoL Value into a probability depends on the asset type. Asset types may need their EoL Modifier translated into an Equivalent Age. The Equivalent Age can then be used to determine probability of failure for a specific end of life failure mode.

The method described here generates an expected end of life modifier function, which is used to map between the EoL modifier and an Equivalent Age. The following paragraph describes how this mapping function can be produced.

The mapping function cannot be generated using historical data points, because the data is right censored since many assets have not completed a whole lifecycle. Judgement needs to be applied about how the health of an asset is expected to deteriorate through its life. The end of life modifier is then mapped to an equivalent age, which is used by FMEA to determine the conditional probability of failure for the corresponding end of life failure mode.

The approach adopted recognises that deterioration and failure results not just from the ageing process but is influenced by events external to the item, e.g. environmental condition or poor installation.

The following two functions were considered as a means of expressing the probability of failure distribution curve mathematically:

- An exponential function, which gives a rapid rise in the probability of failure as the EoL Modifier value increases, i.e. as the deterioration approaches the point of failure.
- A cubic expression (i.e. the first three terms of a Taylor series for an exponential function).

Mathematical modelling[3] using simulated data indicates that the use of an exponential function provides a predicted failure rate that generally falls in the range of the simulated predictions up to about year 15. After this time, the function starts to give predicted failure rates that are too high. A better approach is a hybrid form of the cubic function as shown in Equation 52 [4.] This allows for the probability of failure to be constant for low value End of Life Modifiers (i.e. for assets in good condition) before increasing rapidly as the End of Life Modifier increases (i.e. as the item begins to significantly degrade). The cubic function is considered to model asset behaviour more closely than the exponential.

A threshold level (EoL_{lim}, a calibration value) determines the point at which probability of failure is derived using the cubic expression. Up to the limit defined by EoL_{lim}, the probability of failure is set at a constant value; above EoL_{lim} the cubic relationship applies.

Equation 52

$$PoF = k \cdot \left(1 + (EoL \cdot c) + \frac{(EoL \cdot c)^2}{2!} + \frac{(EoL \cdot c)^3}{3!}\right) \text{ where } EoL > EoL_{lim}$$

and

Equation 53

$$PoF = k \cdot \left(1 + (EOL_{lim} \cdot c) + \frac{(EoL_{lim} \cdot c)^2}{2!} + \frac{(EoLI_{lim} \cdot c)^3}{3!}\right) \text{ where } EoL \leq EOL_{lim}$$

where:

PoF	=	probability of failure
EOL	=	End of Life Modifiers
k & c	=	constants
EoL_{lim}	=	EoL Modifier limit below which the probability of failure is constant.

The value of c fixes the relative values of the probability of failure for different modifiers (i.e. the slope of the curve) and k determines the absolute value; both constants are calibration values which are set for each asset class and for each failure mode. Further information on determining the values for c and k is found in Sections 7.4 and 7.5 respectively.

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[3] "Applying Markov Decision Processes in Asset Management" (M Black) - PhD Thesis, (2003)
[4] "Comparing probabilistic methods for the asset management of distributed items" (M Black, AT Brint and JR Brailsford) - ASCE J. Infrastructure Systems (2005)

This Process has the benefit of being able to describe a situation where the PoF rises more rapidly as asset condition degrades, but at a more controlled rate than a full exponential function would describe. The End of Life modifier limit (EoL$_{lim}$) represents the point at which there starts to be a direct relationship between the End of Life modifier and an increasing PoF. The PoF associated with modifiers below this limit relate to installation issues or random events.

7.4. DETERMINATION OF C

The value of c is the same for all Asset Categories and has been selected such that the PoF for an asset in the worst condition is ten times higher than the PoF of a new asset.

The value of c can be determined by assigning the relative probability of failure values for two EoL Modifier values (generally $EoL = 10$ and $EoL = EoL_{lim}$). Development of the modelling system and experience (gained over twelve years of deployment) with the use of the hybrid EoL / PoF relationship has shown that an appropriate value of c is 1.086; this equates to a ratio of $EoL = 10$ to $EoL = 4$ of approximately 10.

7.5. DETERMINATION OF K

The values for k (i.e. by failure mode and asset class) are determined using data on historic failure rate data.

The value of k in Equation 54 is derived by consideration of:

- the expected number of functional failures per annum (i.e. across all the failure modes);
- the Indicator distribution for the asset category; and
- the volume of assets in the asset category.

For linear assets, the number of functional failures per kilometre per annum is used in the derivation of k; ie PoF is determined on a per length basis. The calibration process ensures that for each Asset Class, the total expected number of failures of the current asset population matches the number of expected functional failures resulting from the above analysis. Typically, the observed failure rate provides the lower bound for the number of expected functional failures and the number of replaced assets in a given year plus the observed failure rate provides the upper bound.

An estimate of the actual value can be derived from the Process itself, by taking the sum of the observed failure rate and the estimated PoF of all replaced assets. The actual value chosen may be derived from expert judgement, preferably supported by analysis of the condition of replaced assets. Where Process-produced failure rates are not supported by direct field evidence, such data should be used as the basis of review and benchmarking wherever possible.

Thus, the value of k is calculated as follows

Equation 54

$$k \cdot \sum_{i=1}^{n} \left(1 + EoL_i \cdot c + \frac{(EoL_i \cdot c)^2}{2!} + \frac{(EoL_i \cdot c)^3}{3!} \right) = \text{(Expected no. of failures per annum)}_I$$

where:

n = the number of assets in asset group I

A calibration table for all of the Values of K used across all failure modes and Lead assets by Scottish TO's are included in their Licensee Specific Appendix.

7.6.   CALIBRATION AGAINST VERY LOW OBSERVED FAILURE RATES

The electricity industry recognises that one of the most challenging aspects in modelling the performance of transmission assets is their very high reliability[5]. While there may be numerous records of "defects" or "minor failures", evidence of "major failures" may not exist and the observed failure rate for a particular asset category by particular network operators may tend towards zero. This potentially leads to an inaccurate determination of asset condition risk.

Given this widely-recognised problem (and the resulting lack of data available to each network operator), the IEC White Paper on "Strategic asset management of power networks"[6] recommends that "a standardized set of functions to which to fit historical data could be specified, together with a method for determining which particular function to use for a given data set, considering environment and load conditions. This would dramatically improve the accuracy of service life estimation across businesses and allow benchmarking and comparison of various approaches". This is the approach taken by in this Process, but it is of course dependent on the effective exchange of industry-wide data to enable effective calibration and benchmarking.

Fortunately, such exchanges do exist, including industry-wide reliability assessments, such as EPRI's Industry-Wide Substation Equipment Performance and Failure Database[7] or UMS's International Transmission Operations & Maintenance Study[8]. Where failure rates are not supported by direct field evidence, such data should be used as the basis of review and benchmarking wherever possible.

The values of k by asset class and failure mode are presented in Licensee Specific Appendices. These values have been calculated using historic failure rates (where available). Where no failures have occurred over this time-period, it is necessary to estimate the "expected" failure rate as described above.

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[5] Section 5.1.3 of CIGRE TB 422 Transmission Asset Risk Management (August 2010)
[6] http://www.iec.ch/whitepaper/pdf/iecWP-assetmanagement-LR-en.pdf
[7] http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000000001020010
[8] http://www.umsgroup.com/Americas/What-we-do/Learning-Consortia/ITOMS

8. CONSEQUENCE OF FAILURE

The consequences of the failure may fall into four categories:

Consequence	Description
System	The impact on the network of the failure and any subsequent intervention required
Safety	Impact of direct harm to public/personnel as a result of failure mode
Environment	Impact of failure mode taking into account the sensitivity of the geographical area local to the asset
Financial	Cost of the intervention needed to address and resolve the failure

Table 4 Types of Consequence of failure

These categories reflect the impact of the various failure modes which are specific to the asset and the consequences are consistent for each class of failure mode. The impact of the various failure modes will vary depending on the type of failure. For example, for less disruptive failure modes there may be no impact from a safety perspective.

Safety and environmental consequence are specific to the asset and to its physical location.

In considering the safety and environment consequences, the concept of exposure is needed. Exposure is based upon the asset's location, i.e. its proximity to a location where it has the potential to cause harm (whether to people or the environment).

Each consequence will be monetised and the price base for consequence of failure will be agreed with Ofgem although TO's should be able flex around around the agreed position where it is reasonably justified to do so.

Each TO states clearly which failure modes have been included in the analysis and explains why the chosen failure modes are considered appropriate for the analysis, as detailed in the technical appendices to this methodology. The appendices also detail how the Probability of Failure (PoF) has been determined and how modifiers have been applied to determine the asset PoF.

BS EN60812 disaggregates systems into their component parts and assesses the probability of functional failures of each component and the consequences of such functional failures, then aggregates these quantities to obtain an estimate of the overall risk of the system. A failure mode is clearly immaterial if the cost of the analysis of the functional failure of a component is much greater than value of the risk represented by the functional failure of that component, because either the probability of functional failure of a component or the consequence of failure of a component is insufficiently large.

Evidential and supporting data, suitable for FMECA analysis is usually imperfect. Some possible effects and consequences might be material, but have not yet occurred. Similarly, accurate data may not have been captured for failures, even though the effects and consequences have occurred. Effective application of FMECA therefore requires engineering judgement, both to envision material consequences that have not yet occurred and to estimate values which have not been measured and / or recorded and which cannot be reliably calculated from first principles.

There is a further requirement in the Direction to enable the identification of all material factors contributing to real or apparent performance against targets.

A non-exhaustive list of these factors is identified in Paragraph 32 of the Direction. In practice, the effect of any of these factors will be a modification to one or more inputs to the methodology. By definition, any factor

which does not result in a modification to one or more of the inputs does not contribute to real or apparent performance against targets as measured by this methodology.

For factors that do modify one or more inputs to the methodology, the methodology can be re-run incorporating these input changes and the outcomes compared with the outcomes produced before the changes are applied. Hence not only can factors be identified but also their relative materiality can be determined.

Therefore, if a TO (or Ofgem) suspects that a factor (e.g. data revisions) or change in external environment (business, legal, site or situation) will contribute to real or apparent performance against targets, then the following tests can be made:

1. Check what impact the factor has on existing inputs to the methodology – if the impact is zero then the factor has been positively classified as non-material

2. If impact is non-zero, then re-run the methodology with changed inputs and compare outputs with equivalent outputs with the un-changed inputs – The variation of output can be compared with the variations produced by other factors and ranked in terms of relative materiality

It is the aim of this section to provide quantified view in the terms of a monetised consequence.

In taking the below detailed approach it is intended that the quantification forms an approximation to how this may play out in the real world. In this case an approximation is of much greater value, due to its simplified nature and the ease of comparison and benchmark.

The monetisation does not correspond to the actual costs that will be incurred. The data used in the models attempts to approach the correct orders of magnitude to avoid confusion it does not however, guarantee this and can only be treated as abstract.

8.1.   SYSTEM CONSEQUENCE

The system consequence of a Failure or Failure Mode Effect of an asset is an indication of the asset's importance in terms of its function to the transmission system as given by the disruption to that function caused by the failure. It is measured in terms of certain system related costs incurred by the industry electricity sector if that asset were to experience a failure. These system costs can be divided into two categories, customer costs and System Operator costs. Regardless of who initially pays these costs they are ultimately born by electricity consumers. Customer costs are incurred as a result of the disconnection of customers supplied directly or indirectly (via a distribution network) by the transmission system. The cost for demand disconnections are expressed as the economic value that the user assigns to that lost load. In the case of generators being disconnected from the network there is a mechanism of direct compensation payments from the System Operator. The second category of costs are those that the System Operator incurs in undertaking corrective and preventative measures to secure the system after asset failures have occurred. These include generator constraint payments, response and reserve costs and auxiliary services costs.

Unlike the environmental, financial and safety consequences of asset failures, the existence and scale of network risk due to asset failures is dependent on the functional role that the failed asset plays in the transmission system. The transmission system is designed with a degree of resilience that seeks to ensure the impact of asset faults is contained within acceptable limits. The National Electricity Transmission System Security and Quality of Supply Standard (NETS SQSS) mandates a certain level of resilience that the design and operation of the transmission system must meet when faced with a range of scenarios and events. It is a License obligation of TO's that their networks comply with the NETS SQSS.

A range of negative system consequences (unacceptable overloading of primary transmission equipment, unacceptable voltage conditions or system instability) must be avoided for 'defined secured events' under certain network conditions. The required resilience is not absolute nor is it uniform across the network. The philosophy behind the NETS SQSS is that lower severity consequences are acceptable for relatively high probability (and therefore high frequency) faults while more severe consequences are only to be accepted for lower probability events. Figure 24 illustrates this philosophy.

This approach is further influenced by other considerations such as the geographical location of the assets in question, i.e. which TO License Area they're in, and for what timescales the network is being assessed (near term operational timescales vs. Long term planning timescales). The level of resilience required also varies depending on the function of the part of the network in question. Parts of the network which connect demand, generation or make up part of the Main Interconnected Transmission System (MITS) all have distinct design requirements dependent upon their importance to the Transmission System and the total economic value of all the customers they supply.
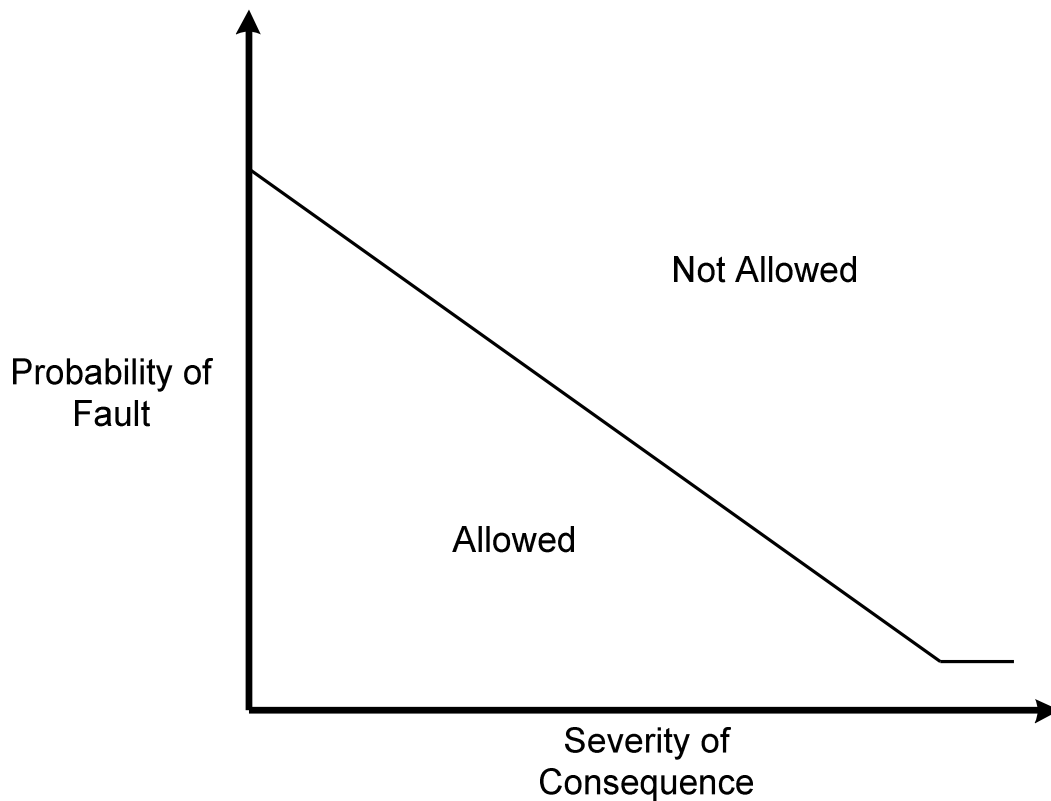
Events that the NETS SQSS requires a degree of resilience against are described as 'secured events'. These are events that occur with sufficient frequency that it is economic to invest in transmission infrastructure to prevent certain consequences when such events occur on the system. Secured events include faults on equipment and these events range from single transmission circuit faults (highest frequency) to circuit breaker faults (lowest frequency). When an asset fault occurs that results in the loss of only a single transmission circuit in an otherwise intact network, almost no customer losses are permitted and all system parameters must stay within limits without the SO taking immediate post-fault actions. While in the case of circuit breaker faults the NETS SQSS only requires that the system is planned such that customer losses are contained to the level necessary to ensure the system frequency stays within statutory limits to avoid total system collapse.

The key assumption that underpins this variation in permitted consequences of faults is that most faults are weather related and that faults caused by the condition of the asset are rare. This can be seen in that faults on overhead lines (often affected by wind and lightning) are relatively frequent events (≈20% probability per 100 km 400 kV circuit per annum) while switchgear faults are relatively less frequent (≈2% probability per 2-ended 400 kV circuit per annum). Another key assumption in the design of the SQSS is that faults are relatively short. A clear majority of circuits have a post-fault rating that is time limited to 24 hours, it is expected that faults will be resolved within this time so that this rating will not be exceeded.

Asset failures driven by asset condition do not conform to these key assumptions, they occur in assets regardless of their exposure to the elements and they can significantly exceed 24 hours in duration. The system therefore cannot be assumed to be designed to be resilient against even a single asset failure. Even if system resilience is sufficient to avoid an immediate customer or operator cost, no asset fault or failure that requires offline intervention can be said to be free from a risk cost. At the very least, the unavailability of the asset reduces system resilience to further events and therefore increases exposure to future costs.

8.1.1.   QUANTIFYING THE SYSTEM RISK DUE TO ASSET FAULTS AND FAILURES

Fundamentally the transmission system performs three functions. It receives power from generators, transports power where it is needed and delivers it to consumers. The system risk cost of a fault or failure can be quantified by combining the following costs:

1. The economic value assigned to load not supplied to consumers. Commonly described as Value of Lost Load (VOLL) in units of £/MWh

2. The cost of compensating generators disconnected from the transmission system, based on the market cost of generation (£/MWh), the size of the generator (MW) and the expected duration of disconnection (hours)

3. The cost of paying for other generators to replace the power lost from disconnected generation based on the market cost of replacement generation (£/MWh) and number of megawatt hours that require replacement

4. The increased cost in transporting power across the wider transmission network. This is comprised of:

    a. Constraint payments to generators due to insufficient capacity in part of the transmission system. This comprises the costs to constrain off generation affected by the insufficient capacity and the cost to constrain on generation to replace it. If there is insufficient replacement generation capacity, costs will include demand reduction.

    b. Payments to generators to provide auxiliary services which ensure system security and quality of supply e.g. the provision of reactive power.

The applicability and size of these cost sources are dependent upon the role of the failed asset in the system. Some assets are solely for the connection of generation or demand, while others will provide multiple functions.

The methodology for calculating these potential costs is split into three parts:

A. A customer disconnection methodology, incorporating the cost of disconnecting generation, total consumer demand and vital infrastructure sites (1, 2 and 3 above)

B. A boundary transfer methodology that estimates potential generator constraint payments (4a)

C. A reactive compensation methodology that estimates the cost of procuring reactive power to replace that provided by faulted assets (4b)

Each of these methodologies will be described in turn in the following sections. All three share a common structure that can be expressed by Equation 55;

Equation 55

$$Cost\ of\ System\ Impact\ = probability\ x\ duration\ x\ size\ x\ cost\ per\ unit$$

The total cost of system impact of a Failure Mode of an asset will be the sum of the consequence costs that come from the following three costs.

8.1.2. CUSTOMER DISCONNECTION – CUSTOMER SITES AT RISK

With exception for radial spurs, assets on the system will usually contribute towards the security of more than one substation that connects customers to the network. However, the fewer other circuits that supply a substation, the more important that asset is for the security of the site. In order to identify which sites are most at risk of disconnection because of the failure of a specific asset, the number of circuits left supplying a customer connection site after a failure of an asset, X, is defined;

Equation 56

$$X = number\ of\ parallel\ circuits\ supplying\ customer\ site(s)$$
$$- number\ of\ circuits\ tripped\ as\ a\ result\ of\ the\ Failure\ Mode\ Effect\ of\ the\ asset$$

Circuit availability statistics indicate that the importance of a circuit decreases by around two orders of magnitude for each extra parallel circuit available. Given that the uncertainty of other inputs into these calculations will be greater than 1% it is a reasonable simplification to neglect all customer sites with values of X greater than the minimum value of X; $X_{min}=min(X)$.

Once there are four or more circuits in parallel supplying a site additional circuits do not necessarily decrease the probability of losing customers as the capacity of the remaining circuits will not be sufficient to meet the import/export of the customers at risk. In parts of the network where the number and rating of circuits connecting a substation are determined solely by the need to meet local demand, there is a significant risk that once two or three circuits have been lost cascade tripping of remaining circuits due to overloading will result.

Therefore:

For assets on circuits containing transformers down to 132 kV or below if $X_{min} > 3$ it will be treated as $X_{min} = 3$ for the purposes of calculating the Probability of Disconnection (P_{oc}) and Duration (D).

Otherwise for assets on circuits at 275 kV or below if $X_{min} = 4$ it will be treated as $X_{min} = 3$ for the purposes of calculating the Probability of Disconnection (P_{oc}) and Duration (D).

Otherwise if $X_{min} > 3$ then the risk of customer disconnection will be neglected as negligible.

As there will often be multiple customer connection sites with $X=X_{min}$, to ensure that the methodology is efficient and operable a variable Z, is introduced which is equal to the number of customer sites with $X=X_{min}$ for a given asset. Only the largest group of customer sites that would be disconnected by the loss of a further X_{min} circuits is considered explicitly while the extra risk of customer disconnection due to other combinations of circuit losses is approximated using the risk multiplier coefficient M_Z:

Equation 57

$$M_Z = \frac{\sum Z + (Z-1) + (Z-2) + \dots}{Z}$$

Intuitively $M_1 = 1$, and M_Z scales with Z. Figure 25 Mz Calculation with respect to 3 customer sitesillustrates an example of how MZ is calculated with three customer Sites (M_3):
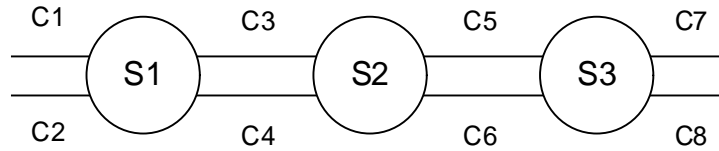
Figure 25 Mz Calculation with respect to 3 customer sites

Three substations labelled S1, S2 and S3 are part of a double circuit ring with eight circuits labelled C1-C8. Each substation is immediately connected to the rest of the system by four circuits and could be disconnected from the system if these four immediate circuits were lost. However, each substation could also be disconnected by other combinations of four circuit losses also. For example, S2 could be disconnected by the loss of C3, C4, C5 and C6, but also by losing C3, C4, C7 and C8 or C1, C2, C5 and C6 etc. More than one substation would be lost for these other combinations and all three substations would be lost for a loss of C1, C2, C7 and C8.

In order to calculate the total system consequence of a failure mode of an asset that is part of C1 we assume that the volume and cost per unit of customer connections are approximately evenly distributed among the substations (L for each substation) and that the probability (P) and duration (D) of each four-circuit combination being lost is approximately equal. The relative consequence of a loss event is then determined only by the number of customers lost. So, a loss of S1 and S2 is twice the consequence of losing only S1. There is one combination of four circuit losses involving C1 that disconnected a single substation, one combination that disconnects two substations and one that disconnects all three. Therefore, the risk cost is:

Equation 58

$$Risk\ cost = (1 \times PDL) + (1 \times 2PDL) + (1 \times 3PDL) = 6\ PDL$$

Given the risk cost of losing all three sites at once is 3PDL so the risk cost can be expressed as a function of the risk cost of losing all three sites at once:

Equation 59

$$Risk\ cost = 6\ PDL = 2 \times 3PDL = 3PDLM_3$$

Therefore, M_3 is equal to 2.

8.1.3.   CUSTOMER DISCONNECTION – PROBABILITY

The probability of a generator or consumer being disconnected because of an asset failure is a function of a wide range of variables including the physical outcome of the failure, the local network topology, asset composition of circuits, asset loading, physical proximity of assets, protection configuration and operation options for restoration. The probability of consequence is calculated as a function of five probabilities, shown in Table 5.

Probability	Symbol	Determination of Value
Coincident outage	P_o	TO statistics on planned unavailability of circuits
Damage to another circuit	P_d	TOhistorical experience of explosive/incendiary failure modes
Maloperation of another circuit	P_m	TO statistics on protection maloperation
Coincident fault to another circuit	P_f	TO fault statistics
Overloading of remaining circuit	P_l	TO specific network design

Table 5 Functions of Probability of Consequence

The probabilities P_o, P_d, P_m and P_f are determined separately by each TO according to their own methodology outlined in Licensee Specific Appendices.

The probabilities in Table 5 can be combined to create a probability tree for each value of X_{min} between 0 and 3. Below are the resulting equations for P_{oc}, the probability of disconnection.

Equation 60

$$\text{For } X_{min} = 0, P_{oc} = 1$$

Equation 61

$$\text{For } X_{min} = 1, P_{oc} = 1 - N_o N_d N_m N_f$$

Equation 62

For $X_{min} = 2$, $P_{oc} = P_d^2 + 2P_d N_d P_o + 2P_d N_d N_o P_m + 2P_d N_d N_o N_m P_f + N_d^2 P_o P_m + N_d^2 P_o N_m P_f + N_d^2 N_o P_m P_f + N_d^2 N_o N_m P_f^2$

Equation 63

For $X_{min} = 3$, $P_{oc} = P_d^2 P_o + P_d^2 N_o P_m + P_d^2 N_o N_m P_f + P_d^2 N_o N_m N_f P_l + 2P_d N_d P_o P_m + 2P_d N_d P_o N_m P_f + 2P_d N_d P_o N_m N_f P_l + 2P_d N_d N_o P_m P_f + 2P_d N_d N_o P_m N_f P_l + 2P_d N_d N_o N_m P_f^2 + 4P_d N_d N_o N_m P_f N_f P_l + N_d^2 P_o P_m P_f + N_d^2 P_o P_m N_f P_l + N_d^2 P_o N_m P_f^2 + 2N_d^2 P_o N_m P_f N_f P_l + N_d^2 N_o P_m P_f^2 + 2N_d^2 N_o P_m P_f N_f P_l + N_d^2 N_o N_m P_f^3 + 3N_d^2 N_o N_m P_f^2 N_f P_l$

Where N_o, N_d, N_m, N_f and N_l are the probabilities of no outage, no damage, no maloperation, no coincident faults and no overloading respectively.

The derivation method of the above probability equations can be followed in Figure 26, the probability tree diagram for the most complex of the four cases, $X_{min} = 3$.

Initial pre-failure network state

Asset Experience Failure Mode

3 circuits remaining

Asset Failure damages asset on two parallel circuits (P_d^2)

1 circuit remaining

Probability of parallel outage (P_o)

0 circuits remaining ($P_d^2 P_o$)

Probability of no parallel outage (N_o)

1 circuit remaining

Probability of Maloperation (P_m)

0 circuits remaining ($P_d^2 N_o P_m$)

Probability of no Maloperation (N_m)

1 circuit remaining

Probability of unrelated fault (P_f)

0 circuits remaining ($P_d^2 N_o N_m P_f$)

Probability of no unrelated fault (N_f)

1 circuit remaining

Probability of overloading circuit (P_l)

0 circuits remaining ($P_d^2 N_o N_m N_f P_l$)

Asset Failure damages asset on one parallel circuit ($2PdN_d$)

2 circuits remaining

Probability of parallel outage (P_o)

1 circuit remaining

Probability of Maloperation (P_m)

0 circuits remaining ($2P_d N_d P_o P_m$)

Probability of no Maloperation (N_m)

1 circuit remaining

Probability of unrelated fault (P_f)

0 circuits remaining ($2P_d N_d P_o N_m P_f$)

Probability of no unrelated fault (N_f)

1 circuit remaining

Probability of overloading circuit (P_l)

0 circuits remaining ($2P_d N_d P_o N_m N_f P_l$)

Probability of no parallel outage (N_o)

2 circuits remaining

Probability of Maloperation (P_m)

1 circuit remaining

Probability of unrelated fault (P_f)

0 circuits remaining ($2P_d N_d N_o P_m P_f$)

Probability of no unrelated fault (N_f)

1 circuit remaining

Probability of overloading circuit (P_l)

0 circuits remaining ($2P_d N_d N_o P_m N_f P_l$)

Probability of no Maloperation (N_m)

2 circuits remaining

Probability of two unrelated faults (P_f^2)

0 circuits remaining ($2P_d N_d N_o N_m P_f^2$)

Probability of no second unrelated fault ($2P_f N_f$)

1 circuit remaining

Probability of overloading circuit (P_l)

0 circuits remaining ($4P_d N_d N_o N_m P_f N_f P_l$)

Asset Failure damages no assets on parallel circuits (N_d^2)

Continued Below

Figure 26 Probability Tree Diagram for Xmin = 3

- Continued

- 3 circuits remaining — Probability of parallel outage (P_o) → 2 circuits remaining — Probability of Maloperation (P_m) → 1 circuit remaining — Probability of unrelated fault (P_f) → 0 circuits remaining $(N_d{}^2 P_o P_m P_f)$

- Probability of no unrelated fault (N_f) → 1 circuit remaining — Probability of overloading circuit (P_l) → 0 circuits remaining $(N_d{}^2 P_o P_m N_f P_l)$

- Probability of no maloperation (N_m) → 2 circuits remaining — Probability of two unrelated faults $(P_f{}^2)$ → 0 circuits remaining $(N_d{}^2 P_o N_m P_f{}^2)$

- Probability of no second unrelated fault $(2P_f N_f)$ → 1 circuit remaining — Probability of overloading circuit (P_l) → 0 circuits remaining $(2N_d{}^2 P_o N_m P_f N_f P_l)$

- Probability of no parallel outage (N_o) → 3 circuits remaining — Probability of Maloperation (P_m) → 2 circuits remaining — Probability of two unrelated faults $(P_f{}^2)$ → 0 circuits remaining $(N_d{}^2 N_o P_m P_f{}^2)$

- Probability of no second unrelated fault $(2P_f N_f)$ → 1 circuit remaining — Probability of overloading circuit (P_l) → 0 circuits remaining $(2N_d{}^2 N_o P_m P_f N_f P_l)$

- Probability of no maloperation (N_m) → 3 circuits remaining — Probability of three unrelated faults $(P_f{}^2)$ → 0 circuits remaining $(N_d{}^2 N_o N_m P_f{}^3)$

- Probability of two unrelated faults $(3P_f P_f N_f)$ → 1 circuit remaining — Probability of overloading circuit (P_l) → 0 circuits remaining $(3N_d{}^2 N_o N_m P_f{}^2 N_f P_l)$

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8.1.4. CUSTOMER DISCONNECTION – DURATION

A similar approach is taken with the expected duration of such a disconnection event. This is dictated by the failure mode of the asset in question, and both operational and asset interventions available to restore supply to the customers. To calculate the duration of disconnection, six separate durations are introduced in Table 6.

Duration	Symbol	Determination of Value
Duration of failure mode unavailability	D_{fm}	TO experience of failure durations
Outage restoration time	D_o	TO statistics on planned unavailability of circuits
Circuit damage restoration time	D_d	TO historical experience of explosive/incendiary failures of failure mode
Protection mal-operation restoration time	D_m	TO statistics on protection maloperation
Unrelated fault restoration time	D_f	TO fault statistics
Circuit overload restoration time	D_l	TO historical experience of overload trips

Table 6 Duration of Consequence

The durations D_{fm}, D_o, D_d, D_m and D_f are determined separately by each TO per their own methodology outlined in Licensee Specific Appendices.

The duration of customer loss is calculated by weighting the probabilities of the event combinations outlined in the formulae for P_{oc} and multiplying by the shortest of the above durations that apply to that event combination. For example, if a failure mode with X_{min} = 2 and disconnection is due to a combination of the failure mode, a parallel outage and protection mal-operation then the minimum of D_{fm}, D_o and D_m is weighted with the other minimum durations of other disconnection combinations. Below are the equations for D for different values of X_{min}.

Equation 64

$$\text{For } X_{min} = 0, \; D = D_{fm}$$

Equation 65

$$\text{For } X_{min} = 1, \; D = [min(D_{fm},D_o)P_o + min(D_{fm},D_d)P_d + min(D_{fm},D_f)P_f + min(D_{fm}, D_m)P_m] / P_{oc}$$

Equation 66

$$\text{For } X_{min} = 2, \; D = [min(D_{fm},D_d)P_d^2 + min(D_{fm}, D_d, D_o)2P_dN_dP_o + min(D_{fm},D_d,D_m)2P_dN_dN_oP_m + min(D_{fm},D_d,D_f)2P_dN_dN_oN_mP_f + min(D_{fm},D_o,D_m)N_d^2P_oP_m + min(D_{fm},D_o,D_f)N_d^2P_oN_mP_f + min(D_{fm},D_m,D_f)N_d^2N_oP_mP_f + min(D_{fm},D_f)N_d^2N_oN_mP_f^2] / P_{oc}$$

Equation 67

$$\text{For } X_{min} = 3, \; D = [min(D_{fm},D_d,D_o)P_d^2P_o + min(D_{fm},D_d,D_m)P_d^2N_oP_m + min(D_{fm},D_d,D_f)P_d^2N_oN_mP_f + min(D_{fm},D_d,D_l)P_d^2N_oN_mN_fP_l + min(D_{fm},D_d,D_o,D_m)2P_dN_dP_oP_m + min(D_{fm},D_d,D_o,D_f)2P_dN_dP_oN_mP_f + min(D_{fm},D_d,D_o,D_l)2P_dN_dP_oN_mN_fP_l + min(D_{fm},D_d,D_m,D_f)2P_dN_dN_oP_mP_f + min(D_{fm},D_d,D_m,D_l)2P_dN_dN_oP_mN_fP_l + min(D_{fm},D_d,D_f)2P_dN_dN_oN_mP_f^2 + min(D_{fm},D_d,D_f,D_l)4P_dN_dN_oN_mP_fN_fP_l + min(D_{fm},D_o,D_m,D_f)N_d^2P_oP_mP_f + min(D_{fm},D_o,D_m,D_l)N_d^2P_oP_mN_fP_l + min(D_{fm},D_o,D_f)N_d^2P_oN_mP_f^2 + min(D_{fm},D_o,D_f,D_l)2N_d^2P_oN_mP_fN_fP_l + min(D_{fm},D_m,D_f)N_d^2N_oP_mP_f^2 + min(D_{fm},D_m,D_f,D_l)2N_d^2N_oP_mP_fN_fP_l + min(D_{fm},D_f)N_d^2N_oN_mP_f^3 + min(D_{fm},D_f,D_l)3N_d^2N_oN_mP_f^2N_fP_l] / P_{oc}$$

8.1.5.   CUSTOMER DISCONNECTION – SIZE AND UNIT COST

Once the largest group of customer sites with $X = X_{min}$ for a given failure mode of an asset has been identified the size of consequence of disconnection of this group must be fully quantified. The weighted quantity of generation disconnected, MW_W is given by:

Equation 68

$$MW_W = \sum \varphi MW_{GTEC}$$

Where:

MW_{GTEC} = Transmission Entry Capacity (TEC) of each disconnected generator
φ = the design variation weighting factor.

This factor equals 1 for generators who are connected with standard SQSS levels of security. Its value for generators with lower than standard levels of security will be determined by each TO. TEC is used without any reference to load factor as this is how generator disconnection compensation is calculated as laid out in the Connection and Use of System Code (CUSC). Secondly the annual average true demand of customers disconnected, MW_D, is calculated by summing the peak demand and the embedded generation contribution during peak of all sites at risk. Both the peak demand and contribution of embedded generation is taken directly from DNO week 24 data submissions. The final inputs are the number of vital infrastructure sites of three different types supplied by sites at risk as shown in Table 7. These are demand sites of importance in terms of economic or public safety impact.

The lists of sites that belong to the categories outlined in Table 7 are deemed sensitive and thus are not included here. The selection criteria and sources for the lists of sites can be found in the individual Licensee Specific Appendices. The costs of disconnection per site, per hour were calculated by collecting as much publicly available information as possible on the costs of historic disconnection events of comparable infrastructure sites across the developed world. These costs per minute or per event were converted into current sterling prices through exchange rate and price indexation conversion. An average for each category was then taken.

Vital Infrastructure Category	Symbol and Cost		
	Number of Sites	Cost per site per hour (£/hr)	Cost per site per disconnection event (£)
Transport Hubs	S_T	$V_T = 1860000$	-
Economic Key Point	S_E	$V_E = 1440000$	-
Particularly sensitive COMAH sites	S_C	-	$V_C = 16970000$

Table 7 Size and Costs associate with Disconnection

The final component of the risk cost, the per unit cost, is separately defined for the three above quantities of customer loss. Value of Lost Load (*VOLL*) in £/MWh is the same RPI indexed value as that used in the RIIO-T1 energy not supplied incentive, £16000/MWh based on 09/10 prices.

The cost of disconnection of generation is in two parts, firstly the generation compensation payment cost, G_C, in £/MWh varies with outage duration is based upon the CUSC methodology and uses cost information from System Operator.

Equation 69

$$\text{For D} \leq 1.5\text{h, } G_c = MW_W D C_{SBP}$$

Equation 70

$$\text{For } 1.5 \text{ h} < \text{D} \leq 24\text{h}, \; G_c = MW_W(1.5C_{SBP} + \{D - 1.5\}C_{SMP})$$

Equation 71

$$\text{For } \text{D} > 24\text{h}, \; G_c = MW_W(1.5C_{SBP} + 22.5C_{SMP} + \{D - 24\}C_{TNUoS})$$

Where C_{SBP} is, the annual average system buy price in £MWh^{-1}, C_{SMP} is the annual average system marginal price in £MWh^{-1} and C_{TNUoS} is the average TNUoS refund cost per MW per hour. C_{TNUoS} is calculated by dividing the annual TNUoS charge for all generators by the total of TEC of all generators and again by 8760.

Secondly, the cost of generation replacement, G_{R*}, again dependent on D is defined as below.

Equation 72

$$\text{For } \text{D} \leq 2\text{h}, \; G_R = DC_{SMP}(0.42MW_W - 0.62MW_D)$$

Equation 73

$$\text{For } \text{D} > 2\text{h}, \; G_R = 2C_{SMP}(0.42MW_W - 0.62MW_D)$$

Equation 74

$$\text{For } G_R \geq 0, \; G_{R*} = G_R$$

$$\text{For } G_R < 0, \; G_{R*} = 0$$

This cost reflects the expense of the System Operator constraining on generation to replace that lost by the disconnection of generation. The equation multiples the duration of the disconnection and the annual average price to constrain on plant by the mismatch between the expected mismatch between generation and demand disconnected by the event. This mismatch is calculated by first taking the total TEC of generation connected to the customer sites in the group at risk, MW_w, and multiplying it by the system wide average generation load factor 0.42 (calculated by dividing the total energy generated in a year in MWh across the whole system by 8760 and then by the total TEC of all generation on the system). Secondly the peak adjusted demand, MW_D, of all customer sites in the group is multiplied by the average demand factor 0.62 (calculated by dividing the total annual transmission demand in MWh by 8760 and dividing again by the winter peak demand in MW). The difference between these two numbers is the mismatch, multiplied by the System Marginal Price in £MWh^{-1} and the duration up to a maximum of 2 hours. After 2 hours, it would be expected that the market would have self-corrected for the generation mismatch.

The vital infrastructure site disconnection cost, V, is the numbers of different types of vital infrastructure sites multiplied by the cost per site and in the case of transport and economic key point sites multiplied by D.

Equation 75

$$V = (D(V_T S_T + V_E S_E) + V_C S_C)$$

With all elements of the equation defined, the customer disconnection risk cost, $R_{customer}$, of a given asset failure mode of any asset can be described by Equation 76.

Equation 76

$$R_{customer} = P_{oc}[G_C + G_R + 0.62DMW_D VOLL + V]M_z$$

A vast majority of lead assets will return a non-zero value for customer disconnection risk, the exceptions being shunt reactors and circuits which connect nodes with more than 4 circuits. These assets will have material risks for one of the next two elements of system consequence.

Note that In the future, it may be possible to vary VOLL with the type of load lost but this is not included in the current methodology.

8.1.6.   BOUNDARY TRANSFER

This methodology estimates the cost impact of having to pay generation constraint payments in order to restrict flows across a system boundary. Unlike in the customer disconnection methodology, there is not a discrete disconnection event that either occurs or doesn't (within a given probability) but instead there is a year-round average cost per hour at which the boundary must be constrained which implicitly includes the probability of a constraint existing. The constraint cost per hour is dependent upon the number of circuits unavailable by the asset failure, Y. In the vast majority of cases this will be 1, but tower failures would usually result in two circuits being lost until the asset can be restored. Additionally, the extra constraint cost that would result from unrelated unavailability on another circuit on the same boundary must be considered.

The derivation of average constraint costs will be based on flow and price information provided by the System Operator on an annual basis. The System Operator will run simulations of a full year of operation with each boundary in with intact, N-1 depletion, N-2 depletion and N-3 depletion capabilities resulting in four annual cost of operation for the boundary, B_y, which is then calculated as follows:

Equation 77

$$B_1 = \frac{[(annual\ n-1\ cost) - (annual\ intact\ cost)]}{8760}$$

Equation 78

$$B_2 = \frac{[(annual\ n-2\ cost) - (annual\ intact\ cost)]}{8760}$$

Equation 79

$$B_3 = \frac{[(annual\ n-3\ cost) - (annual\ intact\ cost)]}{8760}$$

While a failure mode that renders Y circuits unavailable will incur costs at least the B_Y level, on average a proportion of the duration of the failure mode will be spent with Y+1 circuits unavailable, defined as P_{Y+1}. The proportion used is derived from historic fault and outage probabilities and durations. The probability of sustained boundary depletion beyond Y+1 circuits is assumed to be negligible.

These costs are multiplied by the duration of the unavailability of the asset until it is returned to service, D_{fm}, dependent upon historic precedent for the asset type and failure mode in question.

With the variables defined the methodology for determining the boundary transfer risk cost, $R_{Boundary}$, of an Asset failure mode of any asset can be described by Equation 80 Boundary transfer risk cost calculation.

Equation 80

$$R_{boundary} = D_{fm}[B_Y(1 - P_{Y+1}) + B_{Y+1}P_{Y+1}]$$

This methodology will return non-zero risk costs for all assets that belong to or affect circuits critical to the capability of one or more system boundaries with significant constraint implications.

Equation 80 can be illustrated with the example of B6, the boundary between the SPT and NGET areas. There are currently four circuits that make up this boundary. If a failure of a tower carrying two of these circuits occurs then both circuits will be unavailable until the failure has been rectified, Y = 2 for this failure. The boundary will be N-2 depletion until the failure is rectified and on average will spend some proportion, P_{Y+1}, of

the duration of failure at a N-3 depletion level due to unrelated prior outages or other unrelated faults. The weighted average boundary constraint cost per hour is calculated by first multiplying B_2 by $(1- P_{Y+1})$, the proportion of time that the boundary is at N-2 depletion. Then B_3 is multiplied by the proportion of time that the boundary will spend at N-3 depletion, P_{Y+1}. These two products are added together. This average boundary cost per hour is then simply multiplied by the average time taken to restore the circuits to service by repairing the failed tower, D_{fm}. This gives us the total expected boundary constraint for the failure mode of the tower.

8.1.7.   REACTIVE COMPENSATION

The third methodology calculates the cost impact of having reactive compensation unavailable due to a fault or failure of any asset that would render the reactive compensation unusable. This could include circuit breakers, transformers and cables as well as the compensation itself. The purpose of reactive compensation is to produce or consume reactive power to aid control of system voltage. When compensation equipment is unavailable this reactive power control is either procured from generators instead or elements of the transmission system are de-energised, reducing system resilience. As a simplification, the cost impact of a fault or failure can be quantified as the volume of reactive power not supplied multiplied by the cost per MVArh the SO must pay to buy the same service from generators. Therefore Equation 81 Is used to calculate the reactive compensation system risk cost, RRC, of an asset failure mode:

Equation 81

$$R_{RC} = R_F D_{fm} Q C_{MVArh}$$

R_F is the requirement factor of the compensation equipment made unavailable or the proportion of the year that the compensation in question is required on a scale of 0 to 1. D_{fm} is the duration of unavailability due to the asset failure mode. Q is the capacity of the asset in MVAr and C_{MVArh} is the average cost of procuring of MVAr from generation sources.

C_{MVArh} will be calculated by taking an annual sum of all costs of generators to absorb MVArs including BM actions to bring plant into service and constrain others as well as the cost of providing the reactive absorption itself. This sum is divided by the total number of MVArhs that were absorbed by generators over the year.

8.2. SAFETY CONSEQUENCE

When assets fail, they have the potential to cause harm to both the public and personnel who work on or near to the assets. In circumstances where this does happen society there is an incurred cost. The aim of this part of the methodology is to therefore capture the safety risks that deteriorating assets present to individuals who are exposed to their effects and the associated cost. In general, the safety risk for an individual asset can be expressed as shown below:

Equation 82

$$Safety\ Risk = Probability\ of\ Failure\ Mode\ Effect\ \times\ Safety\ Cost$$

Where:

- **Probability of Failure Mode Effect** – represents the likelihood of different effects occurring because of assets failing

- **Safety Cost** – represents the safety related costs associated with asset failure

For an individual asset, the general expression for 'Safety Cost' is:

Equation 83

$$Safety\ Cost = Probability\ of\ Injury\ \times\ Cost\ of\ Injury\ \times\ Exposure$$

The terms in the expression hold the following meanings:

- **Probability of Injury** – the likelihood that an individual is injured when exposed to the effects of an asset failure

- **Cost of Injury** – the cost associated with an individual sustaining an injury

- **Exposure** – modifier to reflect the number of people who are exposed to the effects of an asset failure

Individuals exposed to asset failures can potentially sustain injuries of varying severity and the likelihood of these injuries occurring will depend on the asset under consideration, the type of failure that occurs and the effects associated with that failure. Moreover, the cost associated with different types of injury will vary. Considering these variables, the 'Safety Cost' can be more formally expressed as shown below:

Equation 84

$$Safety\ Cost_i = \sum_j Probability\ of\ Injury_{j,i}\ \times\ Cost\ of\ injury_j\ \times\ Exposure_j$$

Where:

       i   =   Failure Mode Effect

       j   =   Injury Type

The total 'Safety Risk' associated with the asset can therefore be expressed as shown in the below equation.

Equation 85

$$Safety\ Risk = \sum_i PoE_i \times Safety\ Cost_i$$

Where:

       PoE   =   Probability of Failure Mode Effect

8.2.1. FAILURE MODE EFFECT & PROBABILITY OF FAILURE MODE EFFECT

The failure mode effect represents the possible effects that TOs consider because of failure and the probability of failure mode effect represents its likelihood of occurrence. The effects that are considered by the TOs and the calculation of their likelihood is described in the Licensee Specific Appendices, please refer to "Values of K" to understand the different failure modes.

8.2.2. INJURY TYPE & PROBABILITY OF INJURY

The 'Probability of Injury' represents the likelihood that an individual is injured when exposed to the effects of an asset failure. Probabilities will be assigned to each 'Injury Type' considered. The probability assigned to each category will vary depending on the failure mode that occurs and the effects that occur because of the failure mode effect materialising. For less disruptive failures there may be no impact from a safety perspective and the probability of injury will be zero. In addition, because it is assumed that the probability of injury applies to an individual, the sum of probabilities across all injury types categories for a failure effect is less than or equal to unity (i.e. an individual's injuries can only be classified under a single category of injury).

8.2.3. COST OF INJURY

Fixed costs will be assigned to the different injury types recognised by the HSE as per their website.

Whilst the appraisal values reflect a broad range of cost categories, for simplicity of presentation the appraisal values can be divided into two main component costs:

- Human costs - representing a monetary estimate of the loss of quality of life, and loss of life in the case of fatal injuries
- Financial costs, which are the sum of the following:
  - Productivity costs including:
    - net lost income, considering of loss of output and earnings due to absence from work, and offsetting transfers from one party to another, e.g. benefits payments are a cost to Government, but an equal and opposite offsetting benefit to individuals
    - production costs, such as cost of recruitment and work reorganisation

- o The cost of Employer's Liability Compulsory Insurance, less compensation pay-outs to individuals
- o Health and rehabilitation costs, such as NHS costs
- o Administrative and legal costs, such as costs of administering benefits claims

Each of these factors is discussed in the proceeding sections. The Licensee Specific Appendix consists of a table relating to the cost of certain types of injuries and this information is utilised through-out the rest of the calculations.

The 'Cost of Injury' will be calculated as below:

Equation 86

$$Cost\ of\ Injury_j = \sum Cost\ of\ Injury \times Disproportion\ Factor$$

A disproportion factor recognising the high-risk nature of the Transmission Industry is applied. Such disproportion factors are described by the HSE guidance when identifying reasonably practicable costs of mitigation. This value is not mandated by the HSE but they state that they believe that "the greater the risk, the more should be spent in reducing it, and the greater the bias should be on the side of safety".

The disproportion factor is included in each Licensee Specific Appendix under "Injury and Probability of Failure".

8.2.4.   EXPOSURE

Safety consequences are specific to individual assets and their physical location. Some assets will expose a greater number of people to their failure effects than others depending on the levels of activity near to the asset. The 'Probability of Injury' only considers whether an individual will be injured assuming they are exposed to the effects of an asset failure and does not consider whether it is likely that one or more individuals will be within the vicinity of an asset when it fails. To take into account the likely number of people exposed to the effects of an asset failure an 'Exposure' modifier is incorporated into the 'Safety Cost' calculation.

Equation 87

$$Exposure = Location\ Risk\ Rating \times Type\ Risk\ Rating$$

Under the Electricity Safety Quality and Continuity Regulations 2002 (ESQCR), risk assessments must be carried out on substation sites and overhead lines to assess the risk of interference, vandalism or unauthorised access to the asset by the public.

The Licensee Specific Appendix consists of 2 calibration tables which are used to describe the location risk and the type risk associate with exposure. Refer to "Exposure" section of the Licensee Specific Appendices for further information.

8.3. ENVIRONMENTAL CONSEQUENCE

When assets fail, they have the potential to impact on the geographical local area to the asset. The aim of this part of the methodology is to capture the environmental risks that deteriorating assets present to the environment and the associated cost. In general, the environmental risk for an individual asset can be expressed as shown below:

Equation 88

$$Environmental\ Risk_i = \sum_i (Probability\ of\ Failure\ Mode\ Effect\ \times Consequence\ of\ Environmental\ Impact)_{jk}$$

Where:

j	=	Probability of Failure Mode Effect
k	=	Consequence of Environmental Impact

- **Probability of Failure Mode Effect** – represents the likelihood of different effects occurring because of assets failing

- **Consequence of Environmental Impact** – represents the environment related costs associated with asset failure

8.3.1. FAILURE MODE EFFECT & PROBABILITY OF FAILURE MODE EFFECT

The 'Probability of Failure Mode Effect' represents the likelihood that an environmental impact occurs when an asset fails. Probabilities will be assigned to each 'Failure Mode' considered. The probability assigned to each category will vary depending on the failure mode that occurs and the effects that occur because of the failure mode effect materialising. For less disruptive failures there may be no impact from an environmental perspective, and the probability of environmental impact would be zero. In addition, because it is assumed that the probability of impact applies to an individual site, the sum of probabilities across all impact type categories for a failure effect is less than or equal to unity (i.e. the environmental impact that occurs at a site can only be classified under a single severity category).

The failure mode effect represents the possible effects that TOs consider because of failure and the probability of failure mode effect represents its likelihood of occurrence.

8.3.2. CONSEQUENCE OF ENVIRONMENTAL IMPACT

The consequence of Environmental Impact will be made up of the factors below:

Equation 89

$$Consequence\ of\ Environmental\ Impact_i = \sum_i (Environmental\ Impact\ Costs\ \times\ Impact\ Volume\ \times\ Exposure)_{jk}$$

Where:

i	=	Environmental Impact Costs
k	=	Impact Volume
l	=	Exposure

- **Environmental Impact Costs** – Represents the average cost of each environmental impact

- **Impact Volume** – Represents the average volume of environmental impact per failure mode effect

- **Exposure –** Determined by the location and size of the asset

8.3.2.1.   ENVIRONMENTAL IMPACT TYPE & COSTS

Varying types of environmental damage can occur because of asset failure. The types of environmental impacts are categorised below:

Table 8 Environmental impact by type

Impact Type	Environmental Impact Measure
Oil	Average volume of oil lost per failure (litres)
SF_6	Average volume of SF_6 lost per failure (kg)
Fire	Average probability that failure results in a fire
Waste	Average quantity of waste per failure (t)

Details of the costs and calculations are specified in the Licensee Specific Appendices.

8.3.2.2.   IMPACT VOLUME

This value is specific to each TO and represents the average chance of a fire, as well as the average volume of oil, SF_6 and waste generated by each Failure Mode Effect per voltage per asset type.

8.3.2.3.   EXPOSURE

Due to the distributed nature of the transmission assets it is important that exposure is considered. Environmental consequences are specific to individual asset size and their physical location. Some assets pose a greater risk to the environment than others. To account for this, an 'Exposure' modifier is incorporated into the 'Environmental Cost' calculation;

Equation 90

$$Exposure = Proximity\ to\ Water\ Course\ Factor\ \times\ Asset\ Located\ within\ SSSI$$

8.3.2.3.1   PROXIMITY TO WATER COURSE FACTOR

This factor allows for an adjustment to be made based on an assessment of the based on the proximity of an asset to a water course. A calibration table with these values is included in the Licensee Specific Appendices.

The default value for Location Factor is 1. The default value shall be applied to all those Asset Categories that are not shown in the Licensee Specific Appendices.

8.3.2.3.2   ASSET LOCATED WITHIN SSSI

This section is used to indicate whether an asset is located within a Site of Special Scientific Interest and will apply a multiplying factor accordingly. This is due to the recognition that any environmental impact within an SSSI is likely to have a more devastating effect.

The default value for Location Factor is 1. The default value shall be applied to all those Asset Categories that are not shown in the Licensee Specific Appendices.

8.4. FINANCIAL CONSEQUENCE

The Financial Cost of Failure is derived from an assessment of the typical replacement and repair costs incurred by the failure of the asset in each of its applicable Failure Modes and is multiplied by the probability of each Failure Mode

Equation 91

$$Financial\ Risk = \sum_i (Probability\ of\ Failure\ Mode\ Effect_i \\ \times\ Financial\ Consequence\ of\ Failure\ Mode\ Effect_i)$$

Where:

      i   =   Failure Mode Effect

- **Probability of Failure Mode Effect** – Represents the likelihood of different effects occurring as a result of assets failing

- **Financial Consequence of Failure Mode Effect** – Represents the financial costs associated with asset failure

8.4.1. FINANCIAL CONSEQUENCE OF FAILURE MODE EFFECT

Equation 92

$$Financial\ Consequence\ of\ Failure\ Mode\ Effect \\ = \sum_i (Financial\ Consequence\ of\ Failure\ (£)_i\ \times\ Location\ Factor_i)$$

Where:

- **Financial Consequence of Failure (£)** – Represents the cost of asset repair/replacement

- **Location Factor** – Represents the financial impact of an assets location in the event of a repair or replacement

The Financial Consequence of Failure Mode Effect is the cost to return the asset to service (which may extend to full replacement of the asset). This is determined based on the failure modes of the relevant asset considered: -

- **Defect:** The costs associated with addressing a Defect Failure would not usually necessitate full asset replacement. Unless otherwise stated, a value equivalent to 5% of the Asset Replacement Costs has been adopted

- **Minor:** The costs associated with addressing a Minor Failure would not usually necessitate full asset replacement; however, the works would normally be over and above those associated with addressing a Defect Failure. Unless otherwise stated, a value equivalent to 15% of the Asset Replacement Costs has been adopted

- **Significant:** The costs associated with addressing a Significant Failure would not usually necessitate full asset replacement; however, the works would normally be over and above those associated with addressing a Minor Failure. Unless otherwise stated, a value equivalent to 40% of the Asset Replacement Costs has been adopted

- **Major:** A failure of this type would necessitate full asset replacement. Asset Replacement Costs have therefore been adopted, unless otherwise stated

8.4.2.   LOCATION FACTOR

The resulting Financial Cost of Failure value can then be modified for individual assets within a Lead Asset Category based on the application of a Location Factor to result in a Financial CoF that reflects the characteristics of an individual assets location.

Location Factors other than 1, may be applied to Assets that meet the "Non-Standard" Criteria, which is defined below:

- Major Crossings (e.g. railway lines, major road, waterways)

- Rural Locations & Islands (difficult to reach with machinery/support vehicles)

- Built up Location (City centres causing disruption)

- AONBs/NSA/NP (extra costs incurred due to scenic areas)

A calibration table for these location Factor values is included in the Licensee Specific Appendices under "Location Factor"

9.   NETWORK RISK

As shown previously in Equation 58 and Equation 59 the Asset Risk is a function of the probability of each failure mode occurring and the impact of each of the consequences.

The Network Risk for each TO can be calculated by summing the Asset Risk associated with each lead asset as shown in Equation 93.The Risk Trading Model will calculate the monetised risk for each asset and aggregate to give the total Network Risk. It will reflect the processes and calculations described within this methodology and associated appendices.

The Risk Trading Model (RTM) has been developed with the aim that it will be used to assist in planning and prioritising non-load related interventions to be undertaken on assets within the transmission network between a start year (Yo) and an end year (Yn). The RTM will also fulfil NOMs Objective B, and enable the assessment of historical and forecast network expenditure in this area on the licensee's Transmission System.

The RTM is based upon a catalogue of the assets in each TOs transmission network. Included within this catalogue are specific details of the assets, along with the associated Probability of Failure in the start year (PoF_{Y0}), the monetised Consequence of Failure (CoF) and a forecast Probability of Failure in the end year (PoF_{Yn}). The RTM investigates the impact that different investment plans have upon the monetised risk of the individual asset, asset category and the whole network at Yn. Figure 30 Risk due to failure mode against time outlines the data used and steps applied within the RTM.

Figure 29 The Risk Trading Model (Highlighted in Red)

Equation 93

$$Network\ Risk = \sum_{k=1}^{n} A_k$$

9.1. RISK TRADING MODEL

The Risk Trading Model will calculate the monetised risk for each asset and aggregate to give the total Network Risk. It will reflect the processes and calculations described within this methodology and associated appendices.

The Risk Trading Model (RTM) has been developed with the aim that it will be used to assist in planning and prioritising non-load related interventions to be undertaken on assets within the transmission network between a start year (Y_o) and an end year (Y_n). The RTM will also fulfil NOMs Objective B, and enable the assessment of historical and forecast network expenditure in this area on the licensee's Transmission System.

The RTM is based upon a catalogue of the assets in each TOs transmission network. Included within this catalogue are specific details of the assets, along with the associated Probability of Failure in the start year (PoF_{Y0}), the monetised Consequence of Failure (CoF) and a forecast Probability of Failure in the end year (PoF_{Yn}). The RTM investigates the impact that different investment plans have upon the monetised risk of the individual asset, asset category and the whole network at Y_n. Figure 30 Risk due to failure mode against time outlines the data used and steps applied within the RTM.

Figure 29 The Risk Trading Model (Highlighted in Red)

10. NETWORK REPLACEMENT OUTPUTS

10.1. INTERVENTIONS

Certain types of intervention will address failure modes. These may be routine interventions, such as maintenance, or specific, such as planned replacements.

The available interventions for managing the performance of assets range from routine maintenance to full replacement.

These activities are undertaken to ensure the longevity and performance of the TOs' networks. Without effective management of these activities, and understanding the related interactions between them, the TOs would, in time, experience deterioration of network outputs which would have a significant detrimental impact on the capability of the network.

Intervention plans are optimised to deliver an efficient level of Network Risk in line with customer, consumer and stakeholder expectation. In determining this efficient level, the TOs evaluate the cost of interventions against the benefits these interventions deliver.

In determining an intervention plan in any period, the TOs need to assess the Asset Risks and decide exactly which interventions to undertake. This requires the TOs to make a binary decision (e.g. to replace, or not to replace) where every asset has an Asset Risk contribution to the Network Risk. This process involves assessing all available interventions to decide the combination which most efficiently manages Network Risk.

The cost of these interventions is not equal to the reduction in Network Risk achieved by undertaking that intervention plan.

Figure 30 Risk due to failure mode against time illustrates different types of intervention that would address failure modes in Table 9 (not to scale).

Figure 30 Risk due to failure mode against time

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88
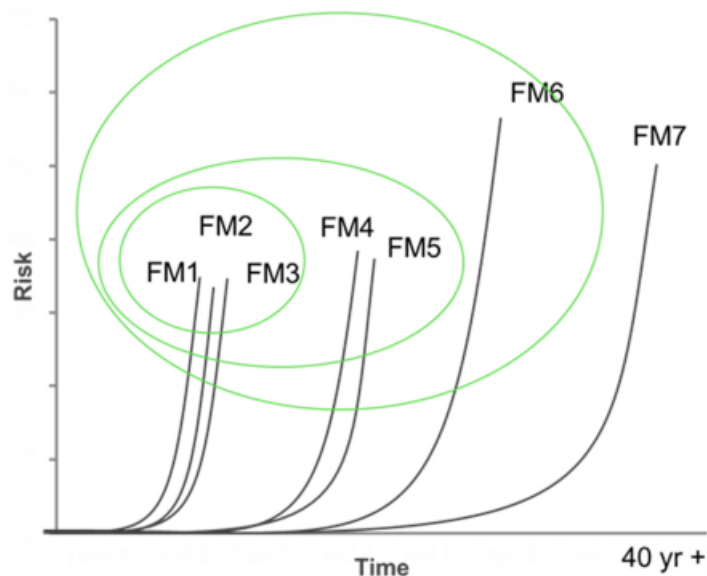
Failure Mode	1	2	3	4	5	6	7
Basic Maintenance	✔	✔	✔	✗	✗	✗	✗
Major Maintenance	✔	✔	✔	✔	✔	✗	✗
Repair	✔	✔	✔	✔	✔	✔	✗
Refurbishment	✔	✔	✔	✔	✔	✔	✗
Replacement	✔	✔	✔	✔	✔	✔	✔

Table 9 Intervention strategies that for failure modes described in Figure

Several failure modes can happen within a similar time frame/ duty cycle, so the work to be carried out needs to be selected carefully to:

- Ensure that the relevant failure modes are adequately addressed
- Reduce the whole life cost
- Limit the impact of constraints such as outages and resources.

Interventions are determined by understanding how to prevent failure modes and the collection of data to predict failures. Knowing the asset's position on each failure mode curve enables the Transmission Operator to make a targeted intervention specifically addressing those failure modes most contributing to the risk. Following the intervention, the asset risk on the asset is reduced for that failure mode.

Asset replacements are taken into consideration by removing the Asset Risk of the existing asset and adding in the Asset Risk of the new asset. In contrast, the effect of repair and refurbishment activities are taken into consideration by revaluating the appropriate condition points once the intervention has been completed, refreshing the relevant data points and recalculating End of Life Modifiers to confirm the improved condition of the asset. These changes result in a reduced current and future End of Life Value, Probability of Failure and Asset Risk.

10.1.1.   MAINTENANCE

The purpose of asset maintenance is to ensure that relevant statutory and legal requirements are met, such as those relating to safety and environmental performance, as well as allowing the TOs to gather condition information so that performance risks are better understood and mitigated.

Maintenance is a fundamental tool in the TOs' management of network reliability, safety and environmental performance (and hence customer satisfaction). Reducing maintenance to zero, or reducing levels without undertaking impact assessments, would lead to a decline in the condition of assets (this effect is seen more rapidly than for under-investment in replacement), leading to increased unplanned events and in some cases bringing forward the need for asset replacement or increasing refurbishment activities.

Maintenance policy evolves as processes and practice are periodically reviewed. The TOs reassess maintenance policy and interval decisions on an ongoing basis using the latest information available to ensure assets can achieve their anticipated asset lives and reduce the potential for unplanned disruption. Maintenance activity can uncover developing trends for defects, ensure rectification of unforeseen functional failure modes and can enable innovation.

When developing maintenance content and undertaking frequency reviews, the TOs have a systematic, structured method for cost/benefit evaluation. This includes understanding the asset's reliability for known failure modes, taking account of how the operating costs would be expected to increase during the time between maintenance tasks, identifying potential changes in performance and consideration of the impact

that a change to the maintenance task frequency might have on the life of the asset. As part of the planning process, maintenance is bundled into efficient packages to optimise access to the network and the assets.

Through maintenance activities the TOs can manage the natural deterioration of asset condition so that the assets remain operable throughout their anticipated technical life, reducing unplanned outages on the network as well as monitoring the condition of assets to improve understand of their performance. This then feeds into future asset intervention plans.

Maintenance activities are pro-active interventions which take place at regular intervals per policy. Undertaking maintenance activities ensures that the assets function correctly and can identify issues with the assets which can be addressed prior to a failure mode occurring.

A basic maintenance will involve basic checks for function of components as well as activities such as visual inspections, checks for fluid/gas levels where appropriate.

An intermediate maintenance takes place at longer intervals than a basic and will include all activities undertaken for a basic maintenance but will include additional checks on specific components of the equipment.

A major maintenance will include all the activities undertaken for a basic and intermediate maintenance but will also include comprehensive and possibly intrusive work as well as more exhaustive checks. These take place less regularly than basic and intermediate levels and generally require a significantly longer outage to carry out the work.

The intervals for the maintenance activities are determined through maintenance policy for each asset type, per the specific requirements for that asset and manufacturer data recommendations are also considered.

10.1.2.   REPAIR

Repair is generally a reactive activity responding to a failure mode when it has occurred or, in some cases, to prevent a failure mode if it can be detected before failure occurs. For some failure modes, which cannot be detected on a routine basis such as by maintenance or inspection, repair is the only available intervention once the failure mode has occurred. That is not to say that detection of the failure mode is not available and assets are monitored for known failure modes. For example, cable oil pressure is monitored and an alarm triggered if the pressure falls below a certain level. The failure mode is detected as the oil leak initiates but there are no routine interventions available to detect the occurrence of a leak before it occurs.

The only available option is to repair the cable when the oil leak is detected. Some failure modes, which lead to another failure mode, can be detected prior to failure, for example, sheath testing of cables will reveal defects in the over-sheath which, if left unrepaired, will eventually lead to the corrosion of the sheath and subsequently an oil leak. A repair intervention can then be planned to mitigate this risk.

10.1.3.   REFURBISHMENT

The decision to refurbish instead of replace an asset follows careful consideration of several criteria. For refurbishment to be technically feasible and cost-effective, the asset population size must be sufficiently large because the costs associated with developing the technical content of a refurbishment procedure, and the set-up costs to undertake the work, mean that it is difficult to make refurbishment of small populations cost-effective.

The ongoing lifetime cost of supporting a refurbished asset family must also be considered. It may be more cost-effective to replace highly complex units that require frequent intervention.

Continuing spares support must be considered. Whilst some spares can be re-engineered without significant risk, this is not appropriate for performance critical components. If such components are unavailable (or not available cost-effectively), refurbishment is unlikely to be a realistic option.

Additionally, the condition and deterioration mechanisms of the asset class must be well understood. If these criteria are met, and it is considered that refurbishment is a viable option, it would be expected that refurbishment activities would change the asset's condition and/or extend asset life.

10.1.4. REPLACEMENT

Individual assets or families which are deemed to be a priority given their risk trigger the need for replacement and capital investment. There may also be instances where the frequency of repair (and associated cost) is such that replacement is considered economic. To facilitate the development of an optimised replacement plan, priority ranked lists for replacement are created for each asset type.

10.1.5. HIGH IMPACT, LOW PROBABILITY EVENTS

A significant amount of work has been undertaken by the TOs with respect to High Impact, Low Probability events. However, given the difficulties involved in quantifying Risk in this area, it has been agreed that these assets shall not undergo any separate treatment within this methodology. The onus is on the individual TO and the business' risk appetite to determine how these assets should be managed.

11. APPENDIX I - LEAD ASSETS DETERIORATION MECHANISMS

The following sections provide background and high level deterioration mechanisms for the lead assets.

11.1. CIRCUIT BREAKERS

11.1.1. BACKGROUND

Circuit breakers are different to other lead assets as they generally have limited condition information on an individual asset basis. To gather additional condition information on sub components which has the potential to affect the end of life modifier, would require invasive work to assess the actual condition of a sub component. It is undesirable to do so in most situations as it would require a system outage.

Technically effective or cost justified diagnostic techniques, including continuous monitoring, are limited for use on large populations and are not applicable for deterioration modes determining the end of life of most types of existing circuit breaker. In addition, the deterioration age range is related to the equipment's environment, electrical and mechanical duty, maintenance regime and application.

In this methodology, a family specific deterioration component to the end of life modifier formula is introduced to account for missing condition information. Assignment to family groupings is through identification of similar life limiting factors. Family groupings are broadly split into interrupter mechanism type.

Known deterioration modes have been determined by carrying out forensic analysis of materials and components during replacement, refurbishment, maintenance and failure investigation activities or following failures. The output of the forensic analysis reports has been used to both inform and update the relevant deterioration models. Anticipated technical asset lives are based on the accumulated Engineering knowledge of TO's Defect, Failure statistics and manufacturer information. The method for mapping this knowledge to the end of life curve was presented in the functional modes and affects analysis section.

11.1.2. DETERIORATION

Circuit breakers are made up of several sub-components. These sub-components deteriorate at different rates, are different in relation to their criticality to the circuit breaker function and finally have different options regarding intervention

Although there is a correlation between age and condition, it has been observed that there is a very wide range of deterioration rates for individual units. The effect of this is to increase the range of circuit breaker condition with age, some circuit breakers becoming unreliable before the anticipated life and some showing very little deterioration well after that time.

11.1.3. AIR-BLAST CIRCUIT BREAKER TECHNOLOGY

As Air-Blast Circuit Breaker (ABCB) families approach their end of life an assessment is made regarding the relative economic impact of replacement or refurbishment considering factors such as technological complexity, population size and ongoing asset management capability for the design. Since most ABCB families are no longer supported by their original equipment manufacturer, the cost and feasibility of providing parts, skilled labour and ongoing technical support must be factored into the total cost of refurbishment. For this reason, refurbishment may only be cost-effective for certain, large family types. For small families, the cost of

establishing a refurbishment programme and maintaining appropriate knowledge and support will most often favour replacement.

Using the above approach refurbishment has, in selected cases, proven to be an effective way to extend the Anticipated Asset Life (AAL) for Conventional Air-Blast (CAB) and Pressurised head (PAB) ABCBs.

The replacement of ABCBs is considered alongside the remaining lifetime of the associated site air system. If removal of the last ABCBs at a site allows the site air system to be decommissioned, early switchgear replacement may be cost beneficial when weighed against further expenditure for air system replacement and/or on-going maintenance.

11.1.4.   OIL CIRCUIT BREAKER TECHNOLOGY

The life-limiting factor of principal concern is moisture ingress and the subsequent risk of destructive failure associated with the BL-type barrier bushing in bulk Oil Circuit Breakers (OCBs). A suitable replacement bushing has been developed that can be exchanged when moisture levels reach defined criteria, but at a high cost to the extent that is not economical to replace many bushings using this technology. Risk management of bushings has been achieved by routine oil sampling during maintenance, subsequent oil analysis and replacement of bushings where required. On this basis, the AAL for this technology has been extended and detailed plans for replacement or refurbishment remain to be developed.

11.1.5.   SF6 GAS CIRCUIT BREAKER TECHNOLOGY

The bulk of the Gas Circuit Breaker population (GCB) is relatively young compared to its AAL, and therefore many have not required replacement. A similar process to that followed for the ABCB families is being undertaken to identify refurbishment (i.e. life extension) opportunities. Where this is not technically-feasible or cost-effective, replacement is planned.

The GCB population includes many small families, with variants and differing operating regimes, and so the identification of large-scale refurbishment strategies may not be cost-effective. Technical and economic evaluation as well as further development of refurbishment strategies will take place.

A significant number of SF6 circuit-breakers which are installed on shunt reactive compensation are subject to very high numbers of operations (typically several hundred per year). The "end of life" of these circuit-breakers is likely to be defined by number of operations ("wear out") rather than age related deterioration. To assist with asset replacement planning, these circuit-breakers have been assigned a reduced asset life in this document based on a prediction of their operating regime. Different asset lives have been assigned depending on the circuit breaker mechanism type and/or if the circuit breaker has been reconditioned; in each case the asset life is based on an operating duty of 300 operations per year. It is currently proposed to recondition most types of high duty reactive switching circuit breaker when they have reached their anticipated asset life based on the number of operations they have performed. A more detailed asset specific strategy for replacement or refurbishment of these categories of circuit-breakers is being developed in terms of the actual number of operations and their forecast operating regime.

11.2. TRANSFORMERS AND REACTORS

11.2.1. BACKGROUND

Transformers and reactors share similar end of life mechanisms since they are both based on similar technologies. The same scoring method is therefore applied to calculate the End of Life modifier. For simplicity within this section the term transformer is used to mean both transformer and reactor.

Transformers are assigned an end of life modifier per the condition inferred from diagnostic results, the service history, and post mortem analysis of other similar transformers.

The health of the overall transformer population is monitored to ensure that replacement/refurbishment volumes are sufficient to maintain sustainable levels of reliability performance, to manage site operational issues associated with safety risks and to maintain or improve environmental performance in terms of oil leakage.

The process by which transformers are assigned an end of life modifier relies firstly on service history and failure rates specific to designs of transformers and secondly on routine test results such as those obtained from Dissolved Gas Analysis (DGA) of oil samples. When either of these considerations gives rise to concern, then where practicable, special condition assessment tests (which usually require an outage) are performed to determine the appropriate end of life modifier. Special condition assessment may include the fitting of a continuous monitoring system and the analysis of the data to determine the nature of the fault and the deterioration rate.

The elements to be considered when assigning an end of life modifier are:

1. Results of routine condition testing
2. Results of special condition assessment tests
3. Service experience of transformers of the same design, and forensic examination of decommissioned transformers
4. Results of continuous monitoring where available

The following additional condition indications shall be considered when deciding the repair/replacement/refurbishment strategy for a transformer:

1. Condition of oil
2. Condition of bushings
3. Condition of coolers
4. Rate of oil loss due to leaks
5. Condition of other ancillary parts and control equipment
6. *Availability of spare parts particularly for tap-changers*

11.2.2. TRANSFORMER AND REACTOR DETERIORATION

Thermal ageing of paper is the principal life limiting mechanism for transformers which will increase the failure rate with age. This failure mechanism is very dependent on design and evidence from scrapped transformers indicates a very wide range of deterioration rates. Knowledge of the thermal ageing mechanism, other ageing mechanisms and the wide range of deterioration rates are used to define the technical asset lives for transformers.

In addition to the above fundamental limit on transformer service life, experience has shown that several transformer design groups have inherent design weaknesses which reduce useful service life

The condition of Transformers can be monitored through routine analysis of dissolved gases in oil, moisture and furfural content together with routine maintenance checks. Where individual test results, trends in test results or family history give cause for concern, specialist diagnostics are scheduled as part of a detailed condition assessment. Where appropriate, continuous monitoring will also be used to determine or manage the condition of the transformer.

Methods exist to condition assess transformers and indicate deterioration before failure, however the time between the first indications of deterioration and the transformer reaching a state requiring replacement is varied and can depend on factors such as the failure mechanism, the accuracy of the detection method, and the relationship between system stress and failure. For this reason, the transformer models periodically require updating (supported by evidence from forensic analysis) as further understanding of deterioration mechanisms is acquired during the transformer life cycle.

11.2.3.   INSULATING PAPER AGEING

The thermal ageing of paper insulation is the primary life-limiting process affecting transformers and reactors. The paper becomes brittle, and susceptible to mechanical failure from any kind of shock or disturbance. Ultimately the paper will also carbonise and cause turn to turn failure, both mechanisms leading to dielectric failure of the transformer. The rate of ageing is mainly dependent upon the temperature and moisture content of the insulation. Ageing rates can be increased significantly if the insulating oil can deteriorate to the point where it becomes acidic.

The thermal ageing of paper insulation is a chemical process that liberates water. Any atmospheric moisture that enters the transformer during its operation and maintenance will also tend to become trapped in the paper insulation. Increased moisture levels may cause dielectric failures directly or indirectly due to formation of gas bubbles during overload conditions.

The paper and pressboard used in the construction of the transformer may shrink with age which can lead to the windings becoming slack. This compromises the ability of the transformer windings to withstand the electromagnetic forces generated by through fault currents. Transformer mechanical strength may be compromised if it has experienced several high currents through faults during its lifetime and the internal supporting structure has been damaged or become loose.

End of life because of thermal ageing will normally be supported by evidence from one or more of the following categories:

1. Forensic evidence (including degree of polymerisation test results) from units of similar design and load history
2. High and rising furfural levels in the oil
3. High moisture content within the paper insulation
4. Evidence of slack or displaced windings (frequency response tests or dissolved gas results)

11.2.4.   CORE INSULATION

Deterioration of core bolt and core-to-frame insulation can result in undesirable induced currents flowing in the core bolts and core steel under certain load conditions. This results in localised overheating and risk of Buchholz alarm/trip or transformer failure as free gas is generated from the localised fault. It is not normally possible to repair this type of fault without returning the transformer to the factory. Evidence of this end of

life condition would normally be supported by dissolved gas results together with forensic evidence from decommissioned transformers of similar design. Insertion of a resistor into the core earth circuit can reduce or eliminate the induced current for a period.

11.2.5. THERMAL FAULT

Transformers can develop localised over-heating faults associated with the main winding because of poor joints within winding conductors, poor oil-flow or degradation of the insulation system resulting in restrictions to oil flow. This is potentially a very severe fault condition. There is not normally a repair for this type of fault other than returning the transformer to the factory. Evidence of this end of life condition would normally be supported by dissolved gas results together with forensic evidence from decommissioned transformers of similar design.

11.2.6. WINDING MOVEMENT

Transformer windings may move because of vibration associated with normal operation or, more commonly, because of the extreme forces within the winding during through fault conditions. The likelihood of winding movement is increased with aged insulation as outlined above. Where evidence of winding movement exists, the ability of the transformer to resist subsequent through faults is questionable and therefore the unit must be assumed not to have the strength and capability to withstand design duty and replacement is warranted. There is no on-site repair option available for this condition. Winding movement can be detected using frequency response test techniques and susceptibility to winding movement is determined through failure evidence and evidence of slack windings through dissolved gas results.

11.2.7. DIELECTRIC FAULT

In some circumstances transformers develop dielectric faults, where the insulation degrades giving concern over the ability of the transformer to withstand normal operating voltages or transient overvoltage. Where an internal dielectric fault is considered to affect the main winding insulation, irreparable damage is likely to ensue. This type of condition can be expected to worsen with time. High moisture levels may heighten the risk of failure. Evidence of a dielectric problem will generally be based on operational history and forensic investigations from units of similar design, supported by dissolved gas results. Various techniques are available to assist with the location of such faults, including partial discharge location techniques. If evidence of an existing insulation fault exists and location techniques cannot determine that it is benign, then it should be considered that the transformer is at risk of failure.

11.2.8. CORROSIVE OIL

In certain cases, high operating temperatures combined with oil containing corrosive compounds can lead to deposition of copper sulphide in the paper insulation, which can in turn lead to dielectric failure. This phenomenon may be controlled by the addition of metal passivator to the oil, however experience with this technique is limited and so a cautious approach to oil passivation has been adopted. Regeneration or replacement of the transformer oil may be considered for critical transformers or where passivator content is consumed quickly due to higher operating temperatures.

11.3. UNDERGROUND CABLES

11.3.1. BACKGROUND

Cable system replacements are programmed so that elements of the cable systems are replaced when the safety, operational or environmental risks of continued operation meet defined criteria.

Replacement of cable systems are based on several metrics including age. These metrics only include a few condition related components since there is limited information that can be obtained on how deteriorated a cable is. Further condition information could be obtained by digging up and taking samples of a cable, but this is not practical, would be costly and could also cause further failures. Metrics such as the cost of repairs is considered when determining if a cable has reached the end of its life. While this isn't the most desirable metric from an analytical perspective, it does reflect historical practice and is justifiable from a consumer value perspective.

The factors to be considered when determining an end of life modifier are:

1. Historical environmental performance
2. Historical unreliability
3. Risk of tape corrosion or sheath failure
4. Results of condition assessment and other forensic evidence
5. Service experience of cable systems of similar design
6. Number of defect repairs
7. Number of cable faults
8. Duty in terms of how much time annually a cable is running at or above its designed rating
9. Bespoke nature and issues associated with specific cable systems

11.3.2.   DETERIORATION

End of technical life will generally be due to the deterioration of the main cable system; this may be associated with either mechanical or electrical integrity or withstand capability.

With the exception of cables vulnerable to reinforcing tape corrosion and cables where a known manufacturing defect has occurred (e.g. lead sheath deterioration), cable systems have generally given reliable operation and there is limited experience of long term deterioration mechanisms.

Cables can be split broadly into two classes for the purposes of understanding the end of life of this asset class, these are fluid filled cables and solid dielectric cables. In general, the cable circuit will only meet the criteria for replacement where refurbishment as described above will not address condition and performance issues and guarantee compliance with statutory requirements.

11.3.3.   END OF LIFE MECHANISMS AFFECTING BOTH TYPES OF CABLES

11.3.3.1.   LEAD AND ALUMINIUM SHEATH DETERIORATION

Fatigue and inter-crystalline cracking, and defects introduced during manufacture can cause oil leaks to develop. It is not generally possible to predict when a given cable section will fail because of this failure mode. Local repairs are not generally effective as sheath deterioration is usually distributed along the cable. End-of-life is reached where sheath deterioration is resulting in significant and widespread oil-loss (relative to duties in respect of recognised code of practice) along the cable length.

11.3.3.2.   BONDING SYSTEM

Water ingress to link boxes causes deterioration of cross-bonding systems and leaves the link box and its Sheath Voltage Limiters (SVLs) vulnerable to explosive failure under fault conditions. Specific evidence shall be gathered through condition assessment to support end-of-life determination. This issue will in general be addressed by replacement of specific components during circuit refurbishment activity or enhanced routine maintenance.

11.3.3.3.   COOLING SYSTEM

The life of a cable's cooling system is much shorter than the lifetime of the overall cable asset. Therefore, mid-life intervention maybe required to replace the cable cooling system components. While this is not the end of the life of the cable it is an important consideration as the cable is not able to do what, it was designed to do with a failed cooling system. Cooling systems tend to be unique to each cable route. Loss of the cooling capacity can typically reduce circuit rating by 40%. Most problems are experienced with the original control systems which are now obsolete. Aluminium cooling pipes are vulnerable to corrosion and plastic pipes are vulnerable to splitting, which can result in water leaks. Cooling control system and pumping equipment will also require replacement prior to the main cable system in line with circuit specific assessment. In general cooling pipework, should be managed through maintenance to achieve the asset life of the main cable system.

11.3.4.   FLUID FILLED CABLE END OF LIFE MECHANISMS

11.3.4.1.   REINFORCING TAPE CORROSION

Reinforcing tapes are used to retain the oil pressure for cables with lead sheaths. Corrosion of the tapes in certain early BICC cables and AEI cables results in the tapes breaking, the sheath splitting and consequential oil leaks. Methods are being developed for predicting failure using corrosion rates determined through sampling in combination with known operating pressures, and using degradation mechanism models. Local repairs are not considered effective mitigation as corrosion is usually distributed along the cable. End-of-life of the cable system is in advance of widespread predicted tape failure. The lead times for cable replacement schemes are considerably greater than the time to deteriorate from broadly acceptable to unacceptable cable system performance for this failure mode. This implies that pre-emptive action is required to minimise the likelihood of failure occurring. Acceptable performance is where the cable can be repaired on an ad-hoc basis; unacceptable performance is where the corrosion is distributed along a significant number of sections of the route.

11.3.4.2.   STOP JOINT DETERIORATION

Stop-joint failure presents significant safety, reliability and environmental risk. End-of-life for stop joints will be justified based upon oil-analysis data or forensic evidence from similar designs removed from service. Stop joint deterioration can be addressed via refurbishment and would not alone drive replacement of the cable system.

11.3.4.3.   CABLE JOINT DETERIORATION

In general, cable joint deterioration can be addressed via refurbishment and would not alone drive replacement of the joint or cable system.

11.3.4.4. OIL-ANCILLARIES

Corrosion of oil tanks, pipework and connections, and pressure gauges can result in oil leaks and incorrect operation of the ancillaries. Specific evidence shall be gathered through condition assessment to support end-of-life determination. This issue will in general be addressed by replacement of specific components during circuit refurbishment activity or enhanced routine maintenance.

11.3.4.5. ENVIRONMENTAL CONSIDERATIONS

TOs have a statutory obligation to comply with the Water Resources Act 1991/Water Resources (Scotland) Act 2013 and to fulfil their commitments with respect to its Environmental Statement. Utilities demonstrate compliance with the requirement of the Act through adherence to the guidance provided.

A factor to consider in determining end of technical life is when it is no longer reasonably practicable to comply with the requirements of the above legislation and guidance, and maintain a sustainable level of circuit availability.

11.3.4.6. SOLID XLPE FILLED CABLE END OF LIFE MECHANISMS:

These cables have been installed at 132kV and 275kV for some years. There is limited service experience at 400kV. Provided high standards of manufacture and installation are available, the risk of early-life failures will be avoided. No end of life mechanism has yet been identified. The long-term deterioration mechanisms would benefit from further research and development.

11.4. OVERHEAD LINES

11.4.1. GENERAL APPROACH

Routes are fully refurbished, or have critical components replaced, to maintain reliability (including a level of resilience to extreme weather conditions), operational risk and safety performance. In addition, conductors should retain sufficient residual mechanical strength to facilitate safe replacement by tension stringing methods at end of life.

Technical asset lives for OHL components in various environments have been predicted using historical condition information from previous OHL replacement schemes, condition samples taken on existing assets, and an understanding of deterioration mechanisms.

Scoring assessments are made on sections of circuit that are typically homogenous in conductor type, installation date and environment.

11.4.2. DETERIORATION

11.4.2.1. CONDUCTORS

Conductor end of life condition is a state where the conductor no longer has the mechanical strength (both tensile and ductility) required to support the combination of induced static and environmental loads.

Two main deterioration mechanisms exist:

1. Corrosion, primary cause pollution either saline or industrial

2. Wind induced fatigue, common types
    a. Aeolian vibration (low amplitude high frequency oscillation 5 to 150 Hz)
    b. sub-conductor oscillation (bundles conductors only) produced by forces from the shielding effect of windward sub-conductors on their leeward counterparts
    c. galloping (high-amplitude, low-frequency oscillation)
    d. wind sway

Conductor fatigue is usually found at clamp positions where the clamp allows more inter-strand motion within the conductor, leading to fretting of the internal layers. Loss of strand cross-section follows, then fatigue cracking, and finally strand breakage. This form of degradation is generally the life-limiting factor for quad bundles, clamping positions on twin bundles can also be affected

Conductor corrosion is also usually found at clamp positions. Interwoven conductor strands open at these points allowing for easier ingress of corroding chlorides, sulphates and moisture etc. The zinc galvanising of the core wires is corroded, eventually exposing the underlying steel. A galvanic corrosion cell is then created where the aluminium wire is sacrificial. The loss of cross-section of aluminium leads to greater heat transfer to the steel core increasing the risk of core failure. Additionally, some spacer clamps with elastomer bushings that contain carbon and have a low resistance also lead to galvanic corrosion of aluminium strands, reducing thickness, strength and ductility.

In addition, end of life may be advanced, in rare instances, due to an unexpected load or events such as extreme wind ice or heat which overload (stress) the conductor beyond its design capability. Quality of the original manufacturing could also be an issue (galvanising defects) but there is not much evidence for this in conductor condition assessment data.

11.4.2.2. INSULATORS

The end of life occurs when the increased risk of flashover (loss of dielectric strength) reaches an unacceptable level due to condition, which may or may not result in mechanical failure of the string, or a decrease in mechanical strength due to corrosion of the steel pin.

11.4.2.3. FITTINGS - SPACERS, SPACER DAMPERS AND VIBRATION DAMPERS

The functional end of life of spacers, spacer dampers and vibration dampers occurs at the point at which the conductor system is no longer protected, and conductor damage starts to occur.

These items are utilised to protect the conductor system from damage. The main deterioration mechanism is wear or fatigue induced through conductor motion. Corrosion in polluted environments can also be an issue particularly inside clamps

Wear damage to trunnions and straps of suspension clamps occurs due to conductor movement. The wear has been greatest in areas of constant wind, i.e. higher ground, flat open land and near coasts. For quad lines, at wind exposed sites, wear can be extensive and rapid failures of straps, links, shackles and ball-ended eye links can occur. This is one of the best indicators of line sections subject to sustained levels of wind induced oscillation and hence where future conductor damage is likely to become a problem.

Most conductor joints for ACSR have been of the compression type, although bolted joints are used in jumpers. Overheating joints can arise from inadequate compression along the length of the joint, mainly due to either poor design or installation problems. These allow moisture penetration and oxidation of the internal aluminium surfaces between the joint and conductor. The resistive aluminium oxide reduces the paths for current flow and may cause micro-arcing within the joint. The consequence of this deterioration is that the

joint becomes warm which further increases the rate of oxidation. Over a period, the resistive paths can result in excess current flowing in the steel core of the conductor, which can then overheat and rupture.

11.4.2.4. SEMI-FLEXIBLE SPACERS

These are fitted in the span and the semi-flexibility comes from either elastomer liners, hinges or stranded steel wire depending on the manufacturer. End of life is defined by perishing of the elastomer lining or broken/loose spacer arms. These allow for excessive movement of the conductor within the clamp leading to severe conductor damage in small periods of time (days to months, depending on the environmental input). The elastomer lining of the Andre spacer type also causes corrosion of conductor aluminium wires due to its carbon content and subsequent galvanic corrosion. A common finding of conductor samples at these positions is strands with significantly poorer tensile and torsional test results. This is a hidden condition state unless it manifests in broken conductor strands that are visible on inspection.

Replacement of these spacers has been necessary on routes that are heavily wind exposed at approximately 25 years. There are many examples still in service beyond their anticipated life of 40 years where visual end of life characteristics have not yet been met. As the condition of the associated conductor within or near the clamp can remain hidden, certain families of this type of spacer such as the 'Andre' are identified for the increased risk they pose to conductor health.

11.4.2.5. SPACER DAMPERS

As the service history of spacer dampers is limited, extensive data on their long-term performance and end of life is not yet available. The spacer arms are mounted in the spacer body and held by elastomer bushes. This increased flexibility should provide the associated conductor system with more damping and greater resilience to wind induced energy. End of life criteria will be defined by broken/loose spacer arms that allow for excessive movement of the conductor/clamp interface.

11.4.2.6. VIBRATION DAMPERS

Stockbridge dampers have always been used for the control of Aeolian vibration, a minimum of one damper being installed at each end of every span on each sub-conductor. For long spans (where specified by the manufacture) two or more may be used. End of life is defined by loss of damping capability which is visually assessed in the amount of 'droop' in and wear of the messenger cable between damper bells. The useful life of a damper is constrained by wind energy input and corrosion of the messenger wire connection with the damper bells. In areas of high wind exposure there is evidence that dampers have required replacement after 10 to 15 years. There are however many more examples of dampers operating beyond their anticipated life with no visual signs of end of life.

11.4.2.7. TOWERS

Corrosion and environmental stress are life-limiting factors for towers. The end of life of a whole tower is the point at which so many bars require changing that it is more economical to replace the whole tower. Degradation of foundations is another life-limiting factor for towers.

12. APPENDIX II – TRANSFORMER ASSET EXAMPLE CALCULATION

12.1. INTRODUCTION

This document is to be used to give a breakdown of each equation used in the methodology to calculate End of Life and Probability of Failure.

There are multiple examples each showing a unique aspect of how the change in factors affect the overall Probability of Failure.

The first example includes;

- An overview of the asset
- The main tank EoL calculation
- The tap changers EoL calculation
- The End of Life Value outputted by the system
- The nominal years to end of life
- The final Probability of Failure value of the system

The four examples cover:

- A control asset calculation where no failures or interventions having taken place in that assets life cycle. (Transformer)
- An asset which has failed due to Dissolved Gas presence and then a follow up showing a refurbishment Intervention
- A 3rd to cover the methodology on a different type of asset (Circuit Breaker)

This should provide readers with extensive understanding of the main process and how the methodology operates.

12.2. LOOKUP TABLES

The following section compiles an entire extensive list of the look up tables that are involved with calculating the End of life modifier for the main tanks, tap changers and circuit breakers. When the look up table is referred to in the calculation its Section and page number will be included so that it is easy to follow where the data is provided from.

When the look up table is referred to in the calculation, its section number will be included so that it is easy to follow where the data is provided from. These tables are indicative to help with the current example, subject to changes with the CTV work post April Submission.

12.3. MAIN TANK - LOOK-UP TABLES

12.3.1. LSE TABLES

12.3.1.1. LOCATION

> Distance to Coast Minimum	< Distance to coast Maximum	Distance to Coast Factor
0	5	**1.35**
5	10	**1.2**
10	15	**1.1**
15	20	**1.0**
20	25	**0.9**
25	5000	**0.85**
> Altitude Minimum	< Altitude Maximum	Altitude Factor
0	50	**0.9**
50	100	**1.0**
100	250	**1.1**
250	5000	**1.2**

Corrosion Zone		Corrosion Zone Factor
1		**0.85**
2		**1.00**
0		**1.00**
3		**1.05**
4		**1.15**
5		**1.35**

12.3.1.2. ENVIRONMENT

Environment	Environment Factor
Normal	**1.00**
Poor	**1.06**
Bad	**1.11**

12.3.1.3. SITUATION

Situation	Situation Factor
Indoor	**0.5**
Outdoor	**1.0**

12.3.1.4. CONSTANTS

Minimum Possible Location Factor
0.8

12.3.2. DUTY FACTOR TABLES

12.3.2.1. MAXIMUM DEMAND DUTY FACTOR

> Max. Demand / Rating Minimum	< Max. Demand / Rating Maximum	Maximum Demand Factor
0	0.70	**0.75**
0.70	0.90	**0.90**
0.90	1.00	**1.00**
1.00	1.15	**1.25**
1.15	2.00	**1.50**

12.3.2.2. MAXIMUM OPERATING TEMPERATURE DUTY FACTOR

> Max. Demand / Rating Minimum	< Max. Demand / Rating Maximum	Operating Temp. Factor
0	80	**0.75**
80	95	**1.00**
95	105	**1.25**
105	150	**1.50**

12.3.2.3. THROUGH FAULTS DUTY FACTOR

Severity / Frequency Through Faults	Through Faults Duty Factor
Normal	**1.00 (Default)**
High	**1.15**
Very High	**1.50**

12.3.2.4. CONSTANTS

Demand / Temperature Default Factor
1

12.3.3. OIL CONDITION FACTOR

12.3.3.1. MOISTURE SCORE

> Relative Humidity Minimum	< Relative Humidity Maximum	Moisture Factor
-1	15	0
15	30	2
30	50	4
50	65	8
65	500	20

Moisture Condition Index Multiplier
80

12.3.3.2. BREAKDOWN STRENGTH SCORE

> Breakdown kV Minimum	< Breakdown kV Maximum	Breakdown Factor
-1	30	20
30	40	6
40	50	2
50	10000	0

Breakdown Condition Index Multiplier
80

12.3.3.3. ACIDITY SCORE

> Acidity – mg KOH/g Minimum	< Acidity – mg KOH/g Maximum	Acidity Factor
-1	0.03	0
0.03	0.075	2
0.075	0.15	4
0.15	0.25	8
0.25	2.00	20

Acidity Condition Index Multiplier
125

12.3.3.4. TAN DELTA SCORE

> Tan Delta @ 90°c Minimum	< Tan Delta @ 90°c Maximum	Tan Delta Factor
-1	0.02	0
0.02	0.06	2
0.06	0.12	4
0.12	0.2	8
0.2	1	20

Tan Delta Condition Index Multiplier
80

12.3.3.5. OIL CONDITION FACTOR

> Combined Score Minimum	< Combined Score Maximum	Oil Condition Factor
-1	200	0.75
200	500	1.00
500	950	1.10
950	1500	1.25
1500	100000	1.50

12.3.4. DEFECT HISTORY FACTOR

12.3.4.1. DEFECT CONSTANTS

Max Age of Defects	10
Max Overall Asset Score	50
Default Initial Defect His. Fac.	1.0
Default Initial Min EoL	0.5

12.3.4.2. DEFECT TYPES

Defect Description	Defect Score
Motor Drive	1-5
Cooling System	1-5
HV Connections	1-5
LV Connections	1-5
Ancillary	1-5

12.3.4.3. DEFECT HISTORY FACTOR

> Asset Defect Score Minimum	< Asset Defect Maximum	Defect Factor
0	5	1.00
5	10	1.05
10	20	1.1
20	35	1.25
35	50	1.5

12.3.5. ACTIVE SOP FACTOR

12.3.5.1. MAXIMUM ACTIVE SOP

Max Active SOP Severity	Active SOP Factor
1	1.00
2	1.10
3	1.20
4	1.35

12.3.6. STANDARD TEST RESULTS FACTOR

12.3.6.1. PD TEST FACTOR

Latest Test Result	Latest Test Result Factor
1	0
2	4
3	10

Classification	Classification Score
1	0
2	1
3	2
4	4
5	6

Generic Rating	Rating Score
1	0
2	1
3	2
4	4

Overall Score Min.	Overall Score Max.	PD Test Factor
-1	0	0.950
0	2	1.000
2	4	1.075
4	5	1.150
5	8	1.225
8	100	1.300

12.3.6.2. DUCTOR TEST FACTOR

Latest Test Result	Latest Test Result Factor
1	0
2	4
3	10

Classification	Classification Score
1	0
2	1
3	2
4	4
5	6

Generic Rating	Rating Score
1	0
2	1
3	2
4	4

Overall Score Min.	Overall Score Max.	PD Test Factor
-1	0	0.950
0	2	1.000
2	4	1.075
4	5	1.150
5	8	1.225
8	100	1.300

12.3.6.3.   IR TEST FACTOR

Latest Test Result	Latest Test Result Factor
1	0
2	4
3	10

Classification	Classification Score
1	0
2	1
3	2
4	4
5	6

Generic Rating	Rating Score
1	0
2	1
3	2
4	4

Overall Score Min.	Overall Score Max.	PD Test Factor
-1	0	0.950
0	2	1.000
2	4	1.075
4	5	1.150
5	8	1.225
8	100	1.300

12.3.7.   GENERIC RELIABILITY

12.3.7.1.   GENERIC RELIABILITY

Reliability Score	Reliability Factor
1	0.85
2	1.00
3	1.15
4	1.35

12.3.8.   VISUAL ASSESSMENT

12.3.8.1.   MAIN TANK, GASKETS AND SEALS CONDITION FACTOR

Condition	Condition Factor
1	0.75
2	1
3	1.1
4	1.25
5	1.5

12.3.8.2.   HV CONNECTIONS CONDITION FACTOR

Condition	Condition Factor
1	0.85
2	1
3	1.05
4	1.15
5	1.35

12.3.8.3.   LV CONNECTIONS CONDITION FACTOR

Condition	Condition Factor
1	0.85
2	1
3	1.05
4	1.15
5	1.35

12.3.8.4.   ANCILLARY CONDITION FACTOR

Condition	Condition Factor
1	0.85
2	1
3	1.05
4	1.15
5	1.35

12.3.8.5.   COOLING SYSTEM CONDITION FACTOR

Condition	Condition Factor
1	0.75
2	1
3	1.1
4	1.25
5	1.5

12.3.9. DISSOLVED GAS ANALYSIS

12.3.9.1. HYDROGEN (H$_2$) CONDITION STATE

Hydrogen (H$_2$) ppm	Condition Factor
0 – 20	0
20 – 40	2
40 – 100	4
100 – 200	10
200 +	16

12.3.9.2. ACETYLENE (C$_2$H$_2$) CONDITION FACTOR

Acetylene (C$_2$H$_2$) ppm	Condition Factor
0 – 1	0
1 – 5	2
5 – 20	4
20 – 100	8
100+	10

12.3.9.3. OTHER HYDROCARBONS CONDITION FACTOR

Hydrocarbon ppm	Condition Factor
0 – 10	0
10 – 20	2
20 – 50	4
50 – 150	10
150+	16

12.3.9.4. GAS MULTIPLIER SCORE

Gas	Gas Multiplier
H2	50
C2H2	120
C2H4	30
CH4	30
C2H6	30

12.3.9.5. CONSTANTS

Condition	Value
DGA Divider	220

EoL$_{DGA}$ Max	10

12.3.9.6. GAS MULTIPLIER SCORE

> Δ DGA% Min.	< Δ DGA% Max.	Δ Description
-1000000	80	Negative
80	120	Neutral
120	150	Small
150	200	Significant
200	1000000	Large

12.3.9.7. GAS MULTIPLIER SCORE

Δ Description	DGA History Factor
Negative	0.75
Neutral	0.90
Small	1.00
Significant	1.10
Large	1.25

12.3.10. FURFURALDEHYDE ANALYSIS

12.3.10.1. CONSTANTS

Constant	Value
EoLFFA Max	10
FFA Multiplier	0.02125
FFA Power Value	0.7056
DP Multiplier	-121
DP Addition	1294

12.4. TAP CHANGERS – LOOK-UP TABLES

12.4.1. LSE TABLES

12.4.1.1. LOCATION

> Distance to Coast Minimum	< Distance to coast Maximum	Distance to Coast Factor
0	5	**1.35**
5	10	**1.15**
10	15	**1.05**
15	20	**1.0 (Default)**
20	25	**0.9**
25	5000	**0.85**
> Altitude Minimum	< Altitude Maximum	Altitude Factor
0	50	**0.9**
50	100	**1.0 (Default)**
100	250	**1.1**
250	5000	**1.2**
Corrosion Zone		Corrosion Zone Factor
1		**0.85**
2		**1.00**
0		**1.00 (Default)**
3		**1.05**
4		**1.15**
5		**1.35**

12.4.1.2. ENVIRONMENT

Environment	Environment Factor
Normal	**1.00 (Default)**
Poor	**1.06**
Bad	**1.11**

12.4.1.3. SITUATION

Situation	Situation Factor
Indoor	**0.5**
Outdoor	**1.0 (Default**

12.4.1.4. CONSTANTS

Minimum Possible Location Factor
0.8

12.4.2. DUTY FACTOR TABLES

12.4.2.1. TAP COUNT DUTY FACTOR

> Mod. Annual Tap-count Min.	< Mod. Annual Tap-count Max.	Tap Count Factor
-1	1000	**0.85**
1000	2000	**0.95**
2000	3500	**1.00**
35000	10000	**1.15**
100000	10000000	**1.35**

12.4.2.2. COUNT SCALING DUTY FACTOR

Tap-Changer Type	Through Faults Duty Factor
Vacutap	**0.25**
OCTC/OLTC Slow	**2.00**
Other	**1.00**

12.4.2.3. HIGH WEAR RATE DUTY FACTOR

Exception Report	High Wear Rate Factor
Very High	**1.35**
High	**1.00**
Normal	**1.00**

12.4.2.4. CONSTANTS

Count Scaling / Tap-count / High Wear Rate Default Factor
1

12.4.3.   OIL CONDITION FACTOR

12.4.3.1.   MOISTURE SCORE

> Relative Humidity Minimum	< Relative Humidity Maximum	Moisture Factor
-1	15	0
15	30	2
30	50	4
50	65	8
65	500	20

Moisture Condition Index Multiplier
80

12.4.3.2.   BREAKDOWN STRENGTH SCORE

> Breakdown kV Minimum	< Breakdown kV Maximum	Breakdown Factor
-1	30	20
30	40	6
40	50	2
50	10000	0

Breakdown Condition Index Multiplier
80

12.4.3.3.   ACIDITY SCORE

> Acidity – mg KOH/g Minimum	< Acidity – mg KOH/g Maximum	Acidity Factor
-1	0.03	0
0.03	0.075	2
0.075	0.15	4
0.15	0.25	8
0.25	2.00	20

Acidity Condition Index Multiplier
125

12.4.3.4.   TAN DELTA SCORE

> Tan Delta @ 90°c Minimum	< Tan Delta @ 90°c Maximum	Tan Delta Factor
-1	0.02	0
0.02	0.06	2
0.06	0.12	4
0.12	0.2	10
0.2	1	20

Tan Delta Condition Index Multiplier
80

12.4.3.5.   OIL CONDITION FACTOR

> Combined Score Minimum	< Combined Score Maximum	Oil Condition Factor
-1	200	0.9
200	500	0.95
500	950	1.00
950	1500	1.05
1500	100000	1.20

12.4.4.   DEFECT HISTORY FACTOR

12.4.4.1.   DEFECT CONSTANTS

Max Age of Defects	5
Max Overall Asset Score	50
Default Initial Defect His. Fac.	1.0
Default Initial Min EoL	0.5

12.4.4.2.   DEFECT TYPES

Defect Description	Defect Score
Gas in Buchholz	1-5
Faulty Heaters (Mechanism)	1-5
HV Bushings Oil Level Low	1-5
Tertiary Bush. Oil level Low	1-5
Explosion Vent Damaged	1-5
Bushings Damaged	1-5

12.4.4.3. DEFECT HISTORY FACTOR

Range	Defect Factor
0 - 5	**1.00**
5 - 10	**1.00**
10 - 25	**1.10**
25 – 35	**1.25**
35 - 50	**1.50**

12.4.5. ACTIVE SOP FACTOR

12.4.5.1. MAXIMUM ACTIVE SOP

Max Active SOP Severity	Active SOP Factor
1	**1.00**
2	**1.05**
3	**1.15**
4	**1.35**

12.4.6. STANDARD TEST RESULTS FACTOR

12.4.6.1. PD TEST FACTOR

Latest Test Result		Latest Test Result Factor
1		**0**
2		**4**
3		**10**
Classification		Classification Score
1		**0**
2		**1**
3		**2**
4		**4**
5		**6**
Generic Rating		Rating Score
1		**0**
2		**1**
3		**2**
4		**4**
Overall Score Min.	Overall Score Max.	PD Test Factor
-1	0	0.950
0	2	1.000
2	4	1.075
4	5	1.150
5	8	1.225
8	100	1.300

12.4.6.2. DUCTOR TEST FACTOR

Latest Test Result		Latest Test Result Factor
1		**0**
2		**4**
3		**10**
Classification		Classification Score
1		**0**
2		**1**
3		**2**
4		**4**
5		**6**
Generic Rating		Rating Score
1		**0**
2		**1**
3		**2**
4		**4**
Overall Score Min.	Overall Score Max.	PD Test Factor
-1	0	0.950
0	2	1.000
2	4	1.075
4	5	1.150
5	8	1.225
8	100	1.300

12.4.6.3. IR TEST FACTOR

Latest Test Result		Latest Test Result Factor
1		**0**
2		**4**
3		**10**
Classification		Classification Score
1		**0**
2		**1**
3		**2**
4		**4**

5	6
Generic Rating	Rating Score
1	0
2	1
3	2
4	4

Overall Score Min.	Overall Score Max.	PD Test Factor
-1	0	0.950
0	2	1.000
2	4	1.075
4	5	1.150
5	8	1.225
8	100	1.300

12.4.7. GENERIC RELIABILITY

12.4.7.1. GENERIC RELIABILITY

Reliability Score	Reliability Factor
1	0.85
2	1.00
3	1.15
4	1.35

12.4.8. VISUAL ASSESSMENT

12.4.8.1. MOTOR DRIVE CONDITION FACTOR

Condition	Condition Factor
1	0.75
2	1
3	1.1
4	1.25
5	1.5

12.4.8.2. HV CONNECTIONS CONDITION FACTOR

Condition	Condition Factor
1	0.85
2	1
3	1.05
4	1.15
5	1.35

12.4.8.3. LV CONNECTIONS CONDITION FACTOR

Condition	Condition Factor
1	0.85
2	1
3	1.05
4	1.15
5	1.35

12.4.8.4. ANCILLARY CONDITION FACTOR

Condition	Condition Factor
1	0.85
2	1
3	1.05
4	1.15
5	1.35

12.4.8.5. COOLING SYSTEM CONDITION FACTOR

Condition	Condition Factor
1	0.75
2	1
3	1.1
4	1.25
5	1.5

12.4.9. DISSOLVED GAS ANALYSIS

12.4.9.1. HYDROGEN (H$_2$) CONDITION STATE

Hydrogen (H$_2$) ppm	Condition Factor
0 – 20	0
20 – 40	2
40 – 100	4
100 – 200	10
200 +	16

12.4.9.2. ACETYLENE (C$_2$H$_2$) CONDITION FACTOR

Acetylene (C$_2$H$_2$) ppm	Condition Factor
0 – 1	0
1 – 5	2
5 – 20	4
20 – 100	8
100+	10

12.4.9.3. OTHER HYDROCARBONS CONDITION FACTOR

Hydrocarbon ppm	Condition Factor
0 – 10	0
10 – 20	2
20 – 50	4
50 – 150	10
150+	16

12.4.9.4. GAS MULTIPLIER SCORE

Gas	Gas Multiplier
H2	50
C2H2	120
C2H4	30
CH4	30
C2H6	30

12.4.9.5. CONSTANTS

Condition	Value
DGA Divider	220
EoLDGA Max	10

12.4.9.6. GAS MULTIPLIER SCORE

> Δ DGA% Min.	< Δ DGA% Max.	DGA Cond. Factor
-1	250	1.00
250	500	1.05
500	1000	1.10
1000	1500	1.15
1500	1000000	1.20

12.5. EXAMPLE 1 – FULL ASSET AUTOPSY

12.5.1. ASSET INFORMATION:

Distance to Coast:	23 Miles
Altitude:	22m
Corrosion Zone:	2
Environment:	Normal
Installation Year:	1982
Asset Age:	36
Average Life:	50
Sub-Assets:	1x Transformer
	1x Tap-changer

Last Gas Test: January 15 2018

Chemical	TxQuantity - ppm	TcQuantity - ppm
Hydrogen (H2)	5	27
Acetylene (C2H2)	1	17
Ethylene (C2H4)	3	34
Methane (CH4)	8	36
Ethane (C2H6)	2	8
Furfuraldehyde	240	-

Last Oil Test: January 15 2018

Tests	Tx Result	Tc Result
Moisture - ppm	3	14
Acidity – mg KOH/g	0.01	0.01
Breakdown kVoltage	80	65
Tan Delta @ 90°C	0.009	0.023

Last Visual Condition Test: December 29 2015

TxCondition	Score	TcCondition	Score
Main tank	2	1	2
Cooling	2	2	2
HV Connec.	1	3	1
LV Connec.	1	4	1
Ancillary	1	5	1

No Standard Test Factor Values.
No Active SOP Factor Values.
No Defect Factor Values.
No Generic Reliability Factor Values.

12.5.2. EXPECTED RESULTS:

	Y0	B_{final}	Yn	Years$_{fail}$
TxEoL	1.56	0.03597	1.74	41.70
TcEoL	3.09	0.04378	3.53	18.67

Failure Mode	Condition	Non-Condition
Defect	0.03833	0.001
Minor	0.00374	0.0015
Significant	0.00144	0.0007
Major	0.00057	0.0002

Totals	0.04409	0.00340
Asset PoF	0.04749	

12.6. MAIN TANK

12.6.1. INITIAL END OF LIFE MODIFIER - EOL_1

DC_F	23 miles from the coast	= 0.9
A_F	22 m above sea level	= 0.9
C_F	In corrosion zone 2	= 1
E_F	Environment – Normal	= 1
S_F	Located - Outside	= 1
O_F	Operating Temperature Factor	= 1
D_F	Maximum Demand Factor	= 1
T_F	Through Faults Factor	= 1
L_{FMin}	Minimum location factor	= 0.8
L_A	Average life of the Main Tank	= 50
EoL_{END}	End of Life value of an aging asset	= 5.5
EoL_{NEW}	End of Life value of a new asset	= 0.5
Age	Age of asset	= 36
DEFAULT	Default Factor Value	= 1

12.6.1.1. FIND LSE – (F_{LSE}) – [TABLE 12.3.1]

L_F $\qquad = Max (DC_F, A_F, C_F)$

$\qquad = Max (0.9, 0.9, 1.0)$

$\qquad \underline{= 1.0}$

E_F $\qquad \underline{= 1.0}$

S_F $\qquad \underline{= 1.0}$

F_{LSE} $\qquad = ((L_F - L_{FMin}) * S_F) + (L_{FMin} * E_F)$

$\qquad = ((1 - 0.8) * 1) + (0.8 * 1.0)$

$\qquad \underline{= 1.0}$

12.6.1.2. FIND DUTY – (F_D) – [TABLE 12.3.2]

The Duty data is turned into factors using a look up table.

F_D $\qquad = Max (O_F, D_F) * T_F$

$\qquad = Max (1, 1) * Normal$

$\qquad = 1 * 1$

$\qquad \underline{= 1}$

12.6.1.3. FIND EXPECTED LIFE – (L_E)

L_E $\qquad = L_A / (F_{LSE} * F_D)$

$\qquad = 50 / (1 * 1)$

$\qquad \underline{= 50 \text{ Years}}$

12.6.1.4. FIND INITIAL AGING RATE – (B_I)

B_i $\qquad = ln (EoL_{END} / EoL_{NEW}) / L_E$

$\qquad = ln (5.5 / 0.5) / 50$

$\qquad \underline{= 0.04795}$

12.6.1.5. FIND INITIAL END OF LIFE MODIFIER – (EOL_1)

EoL_1 $\qquad = EoL_{NEW} * Exp (B_i * Age)$

$\qquad = 0.5 * e^\wedge (0.04795 * 36)$

$\qquad \underline{= 2.80}$

$\underline{EoL_1 = 2.8}$

Initial EoL Modifier is always capped at 5.5 even if EoL_1 > 5.5.

12.6.2. INTERMEDIATE END OF LIFE MODIFIER – EOL$_2$

EoL$_1$	Initial End of Life Modifier	= 2.8
F$_O$	Oil Condition Factor	= 0.75
F$_S$	Standard Testing Factor	= 1.00
F$_A$	Active SOP Factor	= 1.00
F$_G$	Generic Reliability Factor	= 1.00
F$_D$	Defect Factor	= 1.00
F$_V$	Visual Condition Factor	= 1.00
FV$_1$	Factor Value	= 0.75
FMAX$_{Div}$	Max Divider for MaxMI Calculation	= 3.0
FMIN$_{Div}$	Min Divider for MinMI Calculation	= 1.5

12.6.2.1. FIND OIL CONDITION FACTOR – (F$_O$) – [TABLE 12.3.3]

TAKING THE RESULTS FROM EACH OIL CONDITION TEST A SCORE CAN BE ASSIGNED TO EACH RESULT BASED ON A LOOK-UP TABLE AND AN INDEXING VALUE.

S_M Moisture Final Score   = Score * Index

$$= 0 * 80$$

$$= 0$$

S_B Breakdown Final Score   = 0 * 80

$$= 0$$

S_T Tan Delta Final Score   = 0 * 80

$$= 0$$

S_A Acidity Final Score   = 0 * 125

$$= 0$$

F_O Oil Condition Factor   = Sum (S_M, S_B, S_T, S_A)

$$= 0$$

On a look-up table this score equates to a factor value of 0.75

12.6.2.2. FIND STANDARD TEST FACTOR – (F$_S$) – [TABLE 12.3.6]

PD TEST FACTOR – [TABLE 12.3.6.1]

Check for the PD highest result in the last 5 Years. If the results are the same over that period of 5 years use the absolute latest result.

SPDR – That result (between 1 and 3) will be converted into a score, Using a look up table. In this case, SPDR = **1**

S_{PDC} – That result should also have a numerical classification (between 1-5) which can also be converted into its own score using a look up table. **In this case, S$_{PDC}$ = 0**

S_{PDG} – The result should finally have a generic rating based on Manufacture data and the transformers Voltage Ratio between 1 and 4, which then can be converted into a 3rd and final score. In this case, **S$_{PDG}$ = 1**

The individual factor for PD can then be found as:

PD_S PD Test Score   = Sum (S_{PDR}, S_{PDC}, S_{PDG})

$$= 1 + 0 + 1$$

$$= 2$$

Which equates to a Factor of 1 on the look up table.

IR TEST FACTOR – [TABLE 12.3.6.2]

Check for the IR highest result in the last 5 Years. If the results are the same over that period of 5 years use the absolute latest result.

S_{IRR} – That result (between 1 and 3) will be converted into a score, Using a look up table. **In this case, S_{IRR} = 1**

S_{IRC} – That result should also have a numerical classification (between 1-5) which can also be converted into its own score using a look up table. **In this case, S_{IRC} = 0**

S_{IRG} – The result should finally have a generic rating based on Manufacture data and the transformers Voltage Ratio between 1 and 4, which then can be converted into a 3rd and final score. **In this case, S_{PDG} = 1**

The individual factor for IR can then be found as:

IR_S 　　 IR Test Score 　　　　 $= Sum (S_{IRR}, S_{IRC}, S_{IRG})$

$$= 1 + 0 + 1$$

$$= 2$$

Which equates to a Factor of 1 on the look up table.

DUCTOR TEST FACTOR – [TABLE 12.3.6.3]

Check for the PD highest result in the last 5 Years. If the results are the same over that period of 5 years use the absolute latest result.

S_{DR} – That result (between 1 and 3) will be converted into a score, Using a look up table. **In this case, S_{DR} = 1**

S_{DC} – That result should also have a numerical classification (between 1-5) which can also be converted into its own score using a look up table. **In this case, S_{DC} = 0**

S_{DG} – The result should finally have a generic rating based on Manufacture data and the transformers Voltage Ratio between 1 and 4, which then can be converted into a 3rd and final score. **In this case, S_{DG} = 1**

The individual factor for Ductor can then be found as:

D_S 　　 Ductor Test Score= $Sum (S_{DR}, S_{DC}, S_{DG})$

$$= 1 + 0 + 1$$

$$= 2$$

Which equates to a Factor of 1 on the look up table

Overall Standard Test Factor – Maximum Multiple Increment Method.

IF Any Factors ≤ 1, THEN MinMI Cals, ELSE MaxMI Calcs

Factors 　　　　　　　 $(PD_F = 1, IR_F = 1, D_F = 1)$ 　　　　　　 $FMin_{DIV}$ = 1.5

V_1 　　 (Minimum) 　　　　 = 1

V_2 　　 (2nd Minimum) 　　 = 1

V_3 　　　　　　　　　　 $= (V_2 - 1) / FMin_{DIV}$

$$= (1 - 1) / 1.5$$

$$= 0$$

F_S 　　　　　　　　　 $= V_3 + V_1$

$$= 0 + 1$$

$$\underline{= 1}$$

12.6.2.3. FIND ACTIVE SOP FACTOR – (F_A) – [TABLE 12.3.5]

Each Active SOP an asset has is given a severity rating (between 1 and 4), the factor is determined by a look-up table based on this rating.

SEVERITY SCORE = RANGE BASED FACTOR ON LOOK-UP TABLE

E.G.

3 (Do not operate live) = Active SOP factor of 1.2

If there are multiple SOP's, then the Maximum factor is taken.

We do not have Active SOP data for any asset and therefore the default is set to 1.

12.6.2.4. FIND GENERIC RELIABILITY FACTOR – (F_G) – [TABLE 12.3.7]

This factor is determined by a look-up table based on Manufacture data and the voltage ratio of the transformer.

Manufacturer data & Voltage Ratio = Generic Reliability Score

Generic Reliability Score = 2

Which equates to a Factor of 1 ON THE LOOK UP TABLE.

12.6.2.5. FIND DEFECT FACTOR – (F_D) – [TABLE 12.3.4]

Looking only at defect scores from the last 5 years. Each defect is assigned a severity rating between 1 and 4. Each component can have multiple defects.

E.G.

$DS_1 = 1$, $DS_2 = 3$, $DS_3 = 4$, …

The defect factor is determined by a look-up table and then summing the individual scores which is then confirmed on another look up table.

F_D Defect Factor   = Sum (DS_1, DS_2, $DS_{3, …}$)

$$= 1 + 3 + 4 + …$$

$$= 8 + …$$

On a Look-Up table this would equate to a Defect factor of 1.05

We do not have defect data for any asset and therefore the default is set to 1.

12.6.2.6. FIND VISUAL CONDITION FACTOR – (F_V) – [TABLE 12.3.8]

Using a look up table you can change the visual condition results in to individual factor values which are then combined in a Maximum Multiple Increment function to determine in an overall factor value

IF Any Factors ≤ 1, THEN MinMI Calcs, ELSE MaxMI Calcs

Factors   (1, 1, 1, 1, 1) $FMin_{DIV} = 1.5$

V_1 (Minimum)   = 1

V_2 (2nd Minimum)   = 1

V_3 $= (V_2 - 1) / FMin_{DIV}$

                                        $= (1 - 1) / 1.5$

                                        $= 0$

F_V $= V_3 + V_1$

                                        $= 0 + 1$

                                        = 1

12.6.2.7. FIND OVERALL FACTOR VALUE – (FV$_1$)

With all the previous factor values, another MMI function can determine an overall factor value.

IF Any Factors ≤ 1, THEN MinMI Calcs, ELSE MaxMI Calcs

Factors (0.75, 1, 1, 1, 1, 1)   FMin$_{DIV}$ = 3

V_1 (Minimum)   = 1

V_2 (2nd Minimum)   = 1

V_3 = $(V_2 - 1) / FMin_{DIV}$

                                          = (1 – 1) / 1.5

                                          = 0

FV$_1$ = $V_3 + V_1$

                                          = 0 + 0.75

                                          = 0.75

12.6.2.8. FIND INTERMEDIATE END OF LIFE MODIFIER – (EOL$_2$)

Multiply the Overall Factor Value with the Initial End of Life modifier to generate the Intermediate End of Life modifier.

EoL$_2$ = $EoL_1 * FV_1$

                                          = 2.8 * 0.75

                                          = 2.11

EoL$_2$ = 2.11

12.6.3. END OF LIFE VALUE FINAL – TXEOL$_{Y0}$

DGA$_{DIV}$	**DGA Analysis Divider Constant**	**= 220**
DGA$_{HIS}$	**DGA Analysis History Constant**	**= 0.75**
EoL$_{DGAMAX}$	**Maximum Allowable EoL for DGA**	**= 10**
DP$_M$	**DP Multiplier**	**= -121**
DP$_A$	**DP Addition**	**= 1294**
EoL$_{FFAMAX}$	**Maximum allowable EoL$_{FFA}$**	**= 10**
FFA$_{Multi}$	**FFA Multiplier**	**= 0.02125**
FFA$_{PV}$	**FFA Power Value**	**= 0.7056**
FFA$_{MAX}$	**Maximum FFA History Presence**	**= 240**

12.6.3.1. FIND DGA OVERALL SCORE – (S$_{DGA}$) – [TABLE 12.3.9]

S$_{DGA}$ = SUM (Chemical PPM * Calibrated Multiplier)

                            = (0*50) + (0*120) + (0*30) + (0*30) + (0*30)

                            = 0

12.6.3.2. FIND END OF LIFE MODIFIER DUE TO DGA – (EOL$_{DGA}$)

EoL$_{DGA}$ = $Min ((S_{DGA} / DGA_{DIV}), EoL_{DGAMAX})$

                            = Min (0 / 220), 10)

                            = Min (0, 10)

                            = 0

Take and average EoL$_{DGA}$ for all data that you have on that asset. (= 2.58) and divide it against your principal EoL$_{DGA}$ Result (Worst case result)

0.0 / 2.58 = 0.0

This is considered as a NEGATIVE percentage change and therefore on the Look-up table this equates to a DGA History factor of 0.75

12.6.3.3.   MULTIPLY BY THE HISTORY CONSTANT OF 0.75

$$= 0 * DGA_{HIS}$$

$$= 0 * 0.75$$

$$\underline{\mathbf{= 0}}$$

$\underline{\textbf{EoL}_{\textbf{DGA}}} = 0$

12.6.3.4.   FIND END OF LIFE MODIFIER DUE TO FFA – (EOL_{FFA}) -[TABLE 12.3.10]

Find the Maximum FFA, ppm across history - 240ppm (2018)

Est DP $\qquad = DP_M * \ln(FFA_{MAX}) + DP_A$

$\qquad\qquad = -121 * 240 + 1294$

$\qquad\qquad \underline{\mathbf{= 630.84}}$

$EoL_{FFA} = Min [FFA_{Multi} * (FFA_{MAX} \wedge FFA_{PV}), Eol_{FFAMAX}]$

$EoL_{FFA} \qquad = Min [(0.02125 * (240^{0.7056})), 10]$

$\qquad\qquad = Min [(0.02125 * 47.80), 10]$

$\qquad\qquad \underline{\mathbf{= Min [1.01, 10]}}$

$\underline{\textbf{EoL}_{\textbf{FFA}}} = 1.01$

12.6.3.5.   FIND END OF LIFE VALUE – (EOL_{Y0})

If either chemical modifier is larger than our previous EoL_2 calculated value, then the largest one becomes the final EoL_{y0}

In this case however,

$\qquad EoL_2 \qquad > \qquad Max (EoL_{DGA}, EoL_{FFA})$

$\qquad 2.11 \qquad > \qquad Max (0, 1.01)$

Because EoL_2 modifier is greater than both the modifiers for DGA and FFA, then we can determine a EoL_{y0} as below

$TxEoL_{y0} \qquad\qquad = EoL_2 - ((EoL_2 - Max [EoL_{DGA}, EoL_{FFA}]) / 2)$

$\qquad\qquad = 2.11 - ((2.11 - Max [0, 1.01]) / 2$

$\qquad\qquad = 2.11 - ((2.11 - 1.01) / 2)$

$\qquad\qquad = 2.11 - (1.1 / 2)$

$\qquad\qquad = 2.11 - 0.55$

$\qquad\qquad \underline{\mathbf{= 1.56}}$

$\underline{\textbf{TxEoL}_{\textbf{y0}}} = 1.56$

12.6.4. FORECASTING FUTURE EOL - TXEOL$_{YN}$

EoL$_{y0}$	Current EoL Value of Main Tank	= 1.56
EoL$_{New}$	EoL value of a new asset	= 0.5
EoL$_{Max}$	EoL value of an asset at end of life	= 7
L$_E$	Expected Life	= 50
Age	Age of an asset	= 36
Age$_{Thres}$	Threshold age of a new asset	= 10
B$_I$	Initial aging rate	= 0.04796
B$_{y0Cap}$	Recalculation Cap	= 1.5
B$_{y0Col}$	Recalculation Collar	= 0.75
F$_{age,lo}$	Lower increasing age threshold	= 1.0
F$_{age,up}$	Highest increasing age threshold	= 1.5
EoL$_{lo}$	Lower value where age increases	= 2.0
EoL$_{up}$	Upper value where age increases	= 5.5
Δt	Years to age (Future Year – Present)	= 3

12.6.4.1. CHECK TO SEE IF AGE LIES BELOW THRESHOLD AGE

If asset age is less than the threshold age of a new asset, then find Initial aging rate. *Else recalculate a new aging rate. Then jump to Step 6.*

If   Age <   Age$_{Thres}$ **Then**   B$_{final}$ = B$_i$

                                Else   B$_{final}$ = B$_{y0}$

      36 <≠ 10   ∴   B$_{final}$ = B$_{y0}$

12.6.4.2. FIND INITIAL AGING RATE – (B$_I$)

B$_i$ = ln (EoL$_{END}$/EoL$_{NEW}$) / L$_E$

                        = ln (5.5 / 0.5) / 50

                        = 0.04796

Jump immediately to Step 6.

12.6.4.3. FIND RECALCULATED AGING RATE – (B$_{Y0}$)

B$_{y0}$ = ln (EoL$_{y0}$ / EoL$_{NEW}$) / Age

                  = ln (1.56 / 0.5) / 36

                  = 0.0316

12.6.4.4. FIND THE AGING RATIO – (B$_{RATIO}$)

B$_{ratio}$ = B$_{y0}$ / B$_i$

                  = 0.0316 / 0.04796

                  = 0.6590

Check if (B$_{ratio}$) is near to Cap (B$_{y0Cap}$) or Collar (B$_{y0Col}$)

If	B$_{ratio}$ > B$_{y0Cap}$	*Then*	B$_{final}$ = B$_i$ * B$_{y0Cap}$
Else	B$_{ratio}$ < B$_{y0Col}$	*Then*	B$_{final}$ = B$_i$ * B$_{y0Col}$
Else	B$_{y0Col}$ < B$_{ratio}$ < B$_{y0Cap}$	*Then*	B$_{y0}$ = B$_{Final}$

0.66 < 0.75 < 1.5   ∴   B$_{final}$ = B$_i$ * B$_{y0Col}$

                         = 0.04796 * 0.75

                         = 0.03597

12.6.4.5. FIND AGING REDUCTION FACTOR – (F$_{AGE}$)

F$_{age}$ = F$_{AGE, LO}$ + ((EoL$_{y0}$ - EoL$_{lo}$)/ (EoL$_{up}$ - EoL$_{lo}$)) * (F$_{age,up}$ - F$_{age,up}$)

              = 1.0 + ((1.56 − 2.0) / (5.5 − 2.0)) * (1.5 - 1)

              = 0.937

              = 1 (as Fage = 1 is the lower limit)

12.6.4.6.   FIND AGEING CONSTANT FOR FUTURE YEARS – (B_{YN})

B_{yn} $= B_{final} / F_{age}$

                                   $= 0.03597 / 1$

                                   $= 0.03597$

12.6.4.7.   FIND END OF LIFE VALUE FOR YEAR N – (EOL_{Y3})

TxEoLy3 $= EoLy0 * EXP (Byn * 3)$

                                   $= 1.56 * e \char`^ (0.03597 * 3)$

                                   $= 1.737$

TxEoLy3 = 1.74

12.6.4.8.   CALCULATE YEARS TO REACH NOMINAL END OF LIFE.

Years to EoL $= \ln (EoLMax / EoLy0) / Byn$

                                   $= \ln (7 / 1.56) / 0.03597$

                                   $= 41.94$ years

Years to nominal End of Life = 41.94 Years

12.7. TAP CHANGER

12.7.1. INITIAL END OF LIFE MODIFIER - EOL_1

DC_F	23 miles from the coast	= 0.9
A_F	22 m above sea level	= 0.9
C_F	In corrosion zone 2	= 1.00
E_F	Environment – Normal	= 1.00
S_F	Located - Outside	= 1.00
O_F	Operating Temperature Factor	= 1
D_F	Maximum Demand Factor	= 1
T_F	Through Faults Factor	= 1
L_{FMin}	Minimum location factor	= 0.8
L_A	Average life of the Tap Changer	= 50
EoL_{END}	End of Life value of an aging asset	= 5.5
EoL_{NEW}	End of Life value of a new asset	= 0.5
Age	Age of asset	= 36
DEFAULT	Default Factor Value	= 1

12.7.1.1. FIND LSE – (FLSE) – [TABLE 12.4.1]

L_F

$= Max (DC_F, A_F, C_F)$

$= Max (0.9, 0.9, 1.0)$

$\underline{= 1.0}$

E_F

$\underline{= 1.0}$

S_F

$\underline{= 1.0}$

F_{LSE}

$= ((L_F - L_{FMin}) * S_F) + (L_{FMin} * E_F)$

$= ((1 - 0.8) * 1) + (0.8 * 1.0)$

$\underline{= 1.0}$

12.7.1.2. FIND DUTY – (F_D) – [TABLE 12.4.2]

The Duty data is turned into factors using a look up table.

F_D

$= Max (O_F, D_F) * T_F$

$= Max (1, 1) * 1$

$= 1 * 1$

$\underline{= 1}$

12.7.1.3. FIND EXPECTED LIFE – (L_E)

L_E

$= L_A / (F_{LSE} * F_D)$

$= 50 / (1 * 1)$

$\underline{= 50 \text{ Years}}$

12.7.1.4. FIND INITIAL AGING RATE – (B_I)

B_i

$= \ln (EoL_{END} / EoL_{NEW}) / L_E$

$= \ln (5.5 / 0.5) / 50$

$\underline{= 0.04795}$

12.7.1.5. FIND INITIAL END OF LIFE MODIFIER – (EOL_1)

EoL_1

$= EoL_{NEW} * Exp (B_i * Age)$

$= 0.5 * e\char`^ (0.04795 * 36)$

$\underline{= 2.80}$

$\underline{EoL_1 = 2.8}$

Initial EoL Modifier is always capped at 5.5 even if $EoL_1 > 5.5$.

12.7.2. INTERMEDIATE END OF LIFE MODIFIER – EOL$_2$

EoL$_1$	**Initial End of Life Modifier**	**= 2.8**
F$_O$	**Oil Condition Factor**	**= 0.9**
F$_S$	**Standard Testing Factor**	**= 1.00**
F$_A$	**Active SOP Factor**	**= 1.00**
F$_G$	**Generic Reliability Factor**	**= 1.00**
F$_D$	**Defect Factor**	**= 1.00**
F$_V$	**Visual Condition Factor**	**= 1.00**
FV$_1$	**Factor Value**	**= 0.75**
FMAX$_{Div}$	**Max Divider for MaxMI Calculation**	**= 3.0**
FMIN$_{Div}$	**Min Divider for MinMI Calculation**	**= 1.5**

FIND OIL CONDITION FACTOR – (F$_O$) – [TABLE 12.4.3]

TAKING THE RESULTS FROM EACH OIL CONDITION TEST A SCORE CAN BE ASSIGNED TO EACH RESULT BASED ON A LOOK-UP TABLE AND AN INDEXING VALUE.

S$_M$ Moisture Final Score = Score * Index

$$= 0 * 80$$

$$= 0$$

S$_B$ Breakdown Final Score = 0 * 80

$$= 0$$

S$_T$ Tan Delta Final Score = 2 * 80

$$= 160$$

S$_A$ Acidity Final Score = 0 * 125

$$= 0$$

F$_O$ Oil Condition Factor = Sum (S$_M$, S$_B$, S$_T$, S$_A$)

$$= 160$$

Which equates to a factor value of 0.9 on the look up table.

FIND STANDARD TEST FACTOR – (F$_S$) – [TABLE 12.4.6]

PD TEST FACTOR – [TABLE 12.4.6.1]

Check for the PD highest result in the last 5 Years. If the results are the same over that period of 5 years use the absolute latest result.

S$_{PDR}$ – That result (between 1 and 3) will be converted into a score, Using a look up table. **In this case, S$_{PDR}$ = 1**

S$_{PDC}$ – That result should also have a numerical classification (between 1-5) which can also be converted into its own score using a look up table. **In this case, S$_{PDC}$ = 0**

S$_{PDG}$ – The result should finally have a generic rating based on Manufacture data and the transformers Voltage Ratio between 1 and 4, which then can be converted into a 3rd and final score. In this case, **S$_{PDG}$ = 1**

The individual factor for PD can then be found as:

PD Test Score = Sum (S$_{PDR}$, S$_{PDC}$, S$_{PDG}$)

$$= 1 + 0 + 1$$

$$= 2$$

Which equates to a Factor of 1 on the look up table.

IR TEST FACTOR – [TABLE 12.4.6.2]

Check for the IR highest result in the last 5 Years. If the results are the same over that period of 5 years use the absolute latest result.

S_{IRR} – That result (between 1 and 3) will be converted into a score, Using a look up table. **In this case, S_{IRR} = 1**

S_{IRC} – That result should also have a numerical classification (between 1-5) which can also be converted into its own score using a look up table. **In this case, S_{IRC} = 0**

S_{IRG} – The result should finally have a generic rating based on Manufacture data and the transformers Voltage Ratio between 1 and 4, which then can be converted into a 3rd and final score. **In this case, S_{IRG} = 1**

The individual factor for PD can then be found as:

IR_S IR Test Factor   = Sum (S_{IRR}, S_{IRC}, S_{IRG})

$$= 1 + 0 + 1$$

$$= 2$$

Which equates to a Factor of 1 on the look up table.

DUCTOR TEST FACTOR – [TABLE 12.4.6.3]

Check for the Ductor highest result in the last 5 Years. If the results are the same over that period of 5 years use the absolute latest result.

S_{DR} – That result (between 1 and 3) will be converted into a score, Using a look up table. **In this case, S_{DR} = 1**

S_{DC} – That result should also have a numerical classification (between 1-5) which can also be converted into its own score using a look up table. **In this case, S_{DC} = 0**

S_{DG} – The result should finally have a generic rating based on Manufacture data and the transformers Voltage Ratio between 1 and 4, which then can be converted into a 3rd and final score. **In this case, S_{DG} = 1**

The individual factor for PD can then be found as:

D_S Ductor Test Score= Sum (S_{DR}, S_{DC}, S_{DG})

$$= 1 + 0 + 1$$

$$= 2$$

Which equates to a Factor of 1 on the look up table

OVERALL STANDARD TEST FACTOR – MAXIMUM MULTIPLE INCREMENT METHOD.

IF Any Factors ≤ 1, THEN MinMICals, ELSE MaxMI Calcs

Factors (PD_F = 1, IR_F = 1, D_F = 1) $FMin_{DIV}$ = 1.5

V_1 (Minimum)   = 1

V_2 (2nd Minimum)   = 1

V_3 = (V_2 – 1) / $FMin_{DIV}$

$$= (1 - 1) / 1.5$$

$$= 0$$

F_S = V_3 + V_1

$$= 0 + 1$$

$$\underline{= 1}$$

FIND ACTIVE SOP FACTOR – (F_A) – [TABLE 12.4.5]

Each Active SOP an asset has is given a severity rating (between 1 and 4), the factor is determined by a look-up table based on this rating.

SEVERITY SCORE = RANGE BASED FACTOR ON LOOK-UP TABLE

E.G.

We do not have Active SOP data for any asset and therefore the default is set to 1.

FIND GENERIC RELIABILITY FACTOR – (F_G) – [TABLE 2.7]

This factor is determined by a look-up table based on Manufacture data and the voltage ratio of the transformer.

Manufacterer and Voltage Ratio = Generic reliability

Generic Reliability Score: 2

Which when converted on the Look up table equates to a Factor of 1.

FIND DEFECT FACTOR – (F_D) – [TABLE 12.4.4]

Looking only at defect scores from the last 5 years. Each defect is assigned a severity rating between 1 and 4. Each component can have multiple defects.

E.G.

$DS_1 = 1$, $DS_2 = 3$, $DS_3 = 4$, …

The defect factor is determined by a look-up table and then summing the individual scores which is then confirmed on another look up table.

F_D Defect Factor   = Sum (DS_1, DS_2, $DS_{3, …}$)

$$= 1 + 3 + 4 + …$$

$$= 8 + …$$

On a Look-Up table this would equate to a Defect factor of 1.05

We do not have defect data for any asset and therefore the default is set to 1.

FIND VISUAL CONDITION FACTOR – (F_V) – [TABLE 12.4.8]

Using a look up table you can change the visual condition results in to individual factor values which are then combined in a Maximum Multiple Increment function to determine in an overall factor value

IF Any Factors ≤ 1, THEN MinMI Calcs, ELSE MaxMI Calcs

Factors (1, 1, 1, 1, 1) $FMin_{DIV}$ = 1.5

V_1 (Minimum)   = 1

V_2 (2nd Minimum)   = 1

V_3 = (V_2 – 1) / $FMin_{DIV}$

$$= (1 – 1) / 1.5$$

$$= 0$$

F_V = V_3 + V_1

$$= 0 + 1$$

$$\underline{\mathbf{= 1}}$$

FIND DGA FACTOR – (F_{DGA}) – [TABLE 12.4.9]

S_{DGA} = SUM (Chemical PPM * Calibrated Multiplier)

$$= (2*50) + (4*120) + (4*30) + (4*30) + (0*30)$$

$$= 820$$

Which Equates to a factor of 1.10 on a look up table

Unlike with transformers as there are no FFA present in the tap changer we include the DGA factor as part of our EoL_2 Calculation and not as a separate stage used to calculate EoL_{y0} as in a Main Tank.

FIND OVERALL CONDITION FACTOR – (FV_1)

With all the previous factor values using a Maximal Minimum function can determine an overall factor value.

IF Any Factors ≤ 1, THEN MinMI Calcs, ELSE MaxMI Calcs

Factors (0.9, 1, 1, 1, 1, 1, 1.10) $FMAX_{DIV}$ = 3

V_1	(Maximum)	= 1.10
V_2		= Sum where other factors - 1 > 0 (0)
		= 0
V_3		= (V_2) / $FMAX_{DIV}$
		= (0) / 2
		= 0 / 2
		= 0
FV_1		= V_3 + V
		= 0 + 1.1
		= 1.1

FIND INTERMEDIATE END OF LIFE VALUE – (EOL_2)

Multiply the Overall Factor Value with the Initial End of Life modifier to generate the Intermediate End of Life modifier.

EoL_2	= EoL_1 * FV_1
	= 2.8 * 1.1
	= 3.09

EoL_2 = 3.09

12.7.2.1.   END OF LIFE VALUE FINAL – ($TCEOL_{Y0}$)

DETERMINE THE CHANGE BETWEEN EOL_2 AND $TCEOL_{Y0}$

= Min (Max [EoL_2, Max of the Minimum EoL's], Max EoL_{y0}]

= Min (Max [3.09, 0.5], 10]

= Min (3.09 ,10)

= 3.09

$TcEoL_{y0}$ = 3.09

12.7.2.2.   FORECASTING FUTURE EOL – (TCEOL$_{YN}$)

EoL_{New}	EoL value of a new asset	= 0.5
EoL_{Max}	EoL value of an asset at end of life	= 7
L_E	Expected Life	= 50
Age	Age of an asset	= 36
Age_{Thres}	Threshold age of a new asset	= 10
B_I	**INITIAL AGING RATE**	= 0.04796
B_{y0Cap}	Recalculation Cap	= 1.5
B_{y0Col}	Recalculation Collar	= 0.75
$F_{age,lo}$	Lower increasing age threshold	= 1.0
$F_{age,up}$	Highest increasing age threshold	= 1.5
EoL_{lo}	Lower value where age increases	= 2.0
EoL_{up}	Upper value where age increases	= 5.5
Δt	Years to age (Future Year – Present)	= 3

CHECK TO SEE IF AGE LIES BELOW THRESHOLD AGE

If asset age is less than the threshold age of a new asset, then find Initial aging rate. Else recalculate a new aging rate. Then jump to Step 6.

If	Age <	Age_{Thres}	**Then**	$B_{final} = B_i$
			Else	$B_{final} = B_{y0}$
36	≠	10	∴	$B_{final} = B_{y0}$

FIND INITIAL AGING RATE (B_I)

B_i $= \ln(EoL_{END}/EoL_{NEW}) / L_E$

$= \ln(5.5 / 0.5) / 5$

= 0.04796

Jump immediately to Step 6.

FIND RECALCULATED AGING RATE (B_{Y0})

B_{y0} $= \ln(EoL_{y0} / EoL_{NEW}) / Age$

$= \ln(3.09 / 0.5) / 36$

= 0.0506

CALCULATE THE AGING RATIO (B_{RATIO})

B_{ratio} $= B_{y0} / B_i$

$= 0.0506 / 0.04796$

= 1.06

FIND IF (B_{RATIO}) IS CLOSER TO CAP (B_{Y0CAP}) OR COLLAR (B_{Y0COL})

If	$B_{ratio} > B_{y0Cap}$	Then	$B_{final} = B_i * B_{y0Cap}$
Else	$B_{ratio} < B_{y0Col}$	Then	$B_{final} = B_i * B_{y0Col}$
Else	$B_{y0Col} < B_{ratio} < B_{y0Cap}$	Then	$B_{y0} = B_{Final}$

$0.75 < 1.06 < 1.5$ ∴   Bfinal   = By0

=   **0.0506**

CALCULATE AGING REDUCTION FACTOR – (F_{AGE})

F_{age} $= F_{AGE,LO} + ((EoL_{y0} - EoL_{lo})/(EoL_{up} - EoL_{lo})) * (F_{age,up} - F_{age,up})$

$=1.0 + ((3.09 - 2.0) / (5.5 - 2.0)) * (1.5 - 1)$

$= 1.1557$

= 1.16

CALCULATE AGEING CONSTANT FOR FUTURE YEARS – (B_{YN})

B_{yn} $= B_{final} / F_{age}$

           $= 0.0506 / 1.16$

           $= 0.0437$

CALCULATE THE EOL VALUE FOR YEAR N – (EOL_{Y3})

$TxEoL_{y3}$ $= EoLy0 * e\wedge (B_{yn} * 3)$

           $= 3.09 * e\wedge (0.0437 * 3)$

           $= 3.52$

$TxEoL_{y3} = 3.52$

CALCULATE YEARS TO REACH NOMINAL END OF LIFE.

Years to EoL $= \ln (EoL_{Max} / EoL_{y0}) / B_{yn}$

           $= \ln (7 / 3.09) / 0.0437$

           $= 18.71$ Years

YEARS TO NOMINAL END OF LIFE = 18.71 Years

12.8.   OVERALL TRANSFORMER SYSTEM

12.8.1.   FINAL EOL VALUE – ($TEOL_{Y0}$)

12.8.1.1.   CALCULATE OVERALL EOL_{Y0} VALUES

TEoLy0 $= Max [TxEoL_{y0}, TcEoL_{yn}]$

           $= Max [1.56, 3.09]$

           $= 3.09$

$TEoL_{y0} = 3.09$

12.8.2. FUTURE EOL VALUE – ($TEOL_{YN}$)

12.8.2.1.   CALCULATE OVERALL EOL_{YN} VALUES

TEoLy0 $= Max [TxEoL_{y0}, TcEoL_{yn}]$

           $= Max [1.74, 3.53]$

           $= 3.53$

$TEoL_{yn} = 3.53$

12.8.3.   OFGEM CONVERSION

Eol_{yx} Value	Ofgem Category
0-1.5	1
1.5-4	2
4-6	3
6-7.5	4
7.5-15	5

Both values would suggest this asset has an Ofgem health of 2

12.9. PROBABILITY OF FAILURE FOR THE SYSTEM

12.9.1. CONDITIONAL PROBABILITY OF FAILURE

$TEoL_{y0}$	Overall Transformer EoL	= 3.09
Fr_D	Defect Failure Rate in system	= 0.05
Fr_{Mi}	Minor Failure Rate in system	= 0.00488
Fr_S	Significant Failure Rate in system	= 0.00188
Fr_{Ma}	Major Failure Rate in system	= 0.00075
C	C value for system	= 1.086
EoL_{Lim}	End of Life Limit for a Failure	= 4
EoL_{Avg}	Average End of Life for a Failure	= 4
Mod_X	The Failure Modifier	= 1
K_D	Calculated K Value of a Defect	= 0.00135
K_{Mi}	Calculated K Value of a Minor	= 0.00013
K_S	Calculated K Value of a Significant	= 0.00005
K_{Ma}	Calculated K Value of a Major	= 0.00002

For defect failure rates, greater than zero.

12.9.1.1. DETERMINE CALCULATION TO USE WHEN FINDING RELATIVE FAILURE

If $TEoL_{y0} < EoL_{LIM}$ Then

$(1 + (C*EoL_{Avg}) + ((C*EoL_{Avg})\,^2) / 2 + ((C*EoL_{Avg}))\,^3 / 6) * Mod_X$

Else

$(1 + (C*EoL_{y0}) + ((C*EoL_{y0})\,^2) / 2 + ((C*EoL_{y0}))\,^3 / 6) * Mod_X$

12.9.1.2. PERFORM EACH CALCULATION FOR RELATIVE FAILURE – (R_X)

3.09 < 4 $\therefore$ R_X =

$= (1 + (C*EoL_{Avg}) + ((C*EoL_{Avg})\,^2) / 2 + ((C*EoL_{Avg}))\,^3 / 6) * Mod_X$

$= 1 + (1.086*4) + (1.086*4)\,^2 / 2 + (1.086*4)\,^3 / 6 * 1$

$= 5.344 + 9.435 + 13.662 * 1$

R_x **= 28.44**

Ordinarily there would be different average and limit numbers per failure mode based on the failure modifier (Mod_X) value changing per failure, but our model at this moment has incomplete data so it is returning the same results for each relative PoF value.

12.9.1.3. CALCULATE POF PER FAILURE – (POF_X)

Defect   - PoF_D $= R_D * K_D$

$= 28.44 * 0.00135$

= 0.03833

Minor   - PoF_{Mi} $= R_{Mi} * K_{Mi}$

$= 28.44 * 0.00013$

= 0.003697

Significant   - PoF_S $= R_S * K_S$

$= 28.44 * 0.00005$

= 0.00142

Major   - PoF_{Ma} $= R_{Ma} * K_{Ma}$

$= 28.44 * 0.00002$

= 0.000568

12.9.1.4. CALCULATE CONDITIONAL PROBABILITY OF FAILURE – (POF_{COND})

PoF_{Cond} $= Sum\ (Po_{FD},\ PoF_{Mi},\ PoF_{S},\ Pof_{Ma})$

          $= 0.03833 + 0.003697 + 0.00142 + 0.000568$

          = 0.04409

12.9.2. NON-CONDITIONAL PROBABILITY OF FAILURE

Fr_D	Defect Failure Rate in system	= 0.001
Fr_{Mi}	Minor Failure Rate in system	= 0.0015
Fr_S	Significant Failure Rate in system	= 0.0007
Fr_{Ma}	Major Failure Rate in system	= 0.0002
EoL_{Lim}	End of Life Limit for a Failure	= 4
EoL_{Avg}	Average End of Life for a Failure	= 4
Mod_F	The failure modifier	= 1

12.9.2.1. FIND PROBABILITY OF FAILURE FOR EACH FAILURE – (POF_X)

PoF_D $= Mod_F,\ /\ EoL_{Avg}\ *\ Fr_D$

           $= (1\ /\ 1)\ *\ 0.001$

           = 0.001

PoF_{Mi} $= Mod_F,\ /\ EoL_{Avg}\ *\ Fr_{Mi}$

           $= (1\ /\ 1)\ *\ 0.0015$

           = 0.0015

PoF_S $= Mod_F,\ /\ EoL_{Avg}\ *\ Fr_S$

           $= (1\ /\ 1)\ *\ 0.0007$

           = 0.0007

PoF_{Ma} $= Mod_F,\ /\ EoL_{Avg}\ *\ Fr_{Ma}$

           $= (1\ /\ 1)\ *\ 0.0002$

           = 0.0002

12.9.2.2. CALCULATE NON - CONDITIONAL PROBABILITY OF FAILURE – (POF_{NONC})

PoF_{Nonc} $= Sum\ (PoF_D,\ PoF_{Mi},\ PoF_S,\ PoF_{Ma})$

          $= 0.001 + 0.0015 + 0.0007 + 0.0002$

          = 0.0034

12.9.3. OVERALL PROBABILITY OF FAILURE FOR THE ASSET

12.9.3.1. CALCULATE PROBABILITY OF FAILURE – (POF)

PoF for Asset $= Sum\ (PoF_{Cond},\ PoF_{Nonc})$

          $= 0.04409 + 0.0034$

          = 0.04749

PoF OF ENTIRE ASSET = 0.04749

Asset Risk	Term adopted that is synonymous with Condition Risk in the Direction
Asset Class	All lead and subassets involved with
COMAH	Control of Major Accident Hazards
Conditional Factors	Factors that lead to an assets failure due to its physical condition
Consequence	Outcome of an event affecting objectives*
Consequence of Failure	A consequence can be caused by more than one Failure Mode. This is monetised values for the Safety, Environmental, System and Financial consequences
CUSC	Connection and Use of System Code
EKP	Economic Key Point
EoL Modifier	End of Life number that modifies or is modified to produce an End of life value
EoL Value	The target EoL value used for forecasting and consequence calculations
Event	Occurrence or change of a particular set of circumstances*
Failure	A component no longer does what it is designed to do
Failure Mode	A distinct way in which a component can fail
FMEA	Failure Modes and Effects Analysis
FMECA	Failure Modes, Effects and Criticality Analysis
HILP	High Impact, Low Probability
Intervention	An activity (maintenance, refurbishment, replacement) that is carried out on an asset to address one or more failure modes
Level of risk	Magnitude of a risk or combination of risks, expressed in terms of the combination of consequences and their likelihood*
Likelihood	Chance of something happening*
MITS	Main Interconnected Transmission System
Modified Anticipated Life	The anticipated life value gathered from manufacturer data that is modified with respect to how much the asset is doing and where it is located.
NETS SQSS	National Electricity Transmission System Security and Quality of Supply Standard
NEDeR	National Equipment Defect Reporting Scheme
Network Risk	The sum of all the Asset Risk associated with assets on a TO network
NGET	National Grid Electricity Transmissions
NOMs	Network Output Measures
NonConditional Factors	Factors that affect asset performance due to its operating circumstances
Probability of Failure	The likelihood that a Failure Mode will occur in a given time period
RIGs	Regulatory Instructions and Guidance
Risk	Effect of uncertainty on objectives*
Risk management	Coordinated activities to direct and control an organization with regard to risk*
SHE-T	Scottish Hydro Electricity - Transmissions
SP-T	Scottish Power - Transmissions
Specific Degradation	Processes inside assets that give a good indication of asset failure
TO	(Onshore) Transmission Owner
TEC	Transmission Entry Capacity (in MW)
VOLL	Value of Lost Load

*Refer to of the Common Methodology for source of these definitions

This Glossary will continue to be updated as the methodology is developed.