Gas Transmission Network Asset Risk Metric (NARM) Methodology

Probability of Failure Supporting Document

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1. Introduction

This document is aimed at stakeholders who wish to obtain a more detailed understanding of how asset failure and deterioration rates, or Probability of Failure (PoF), are calculated in the National Gas Transmission (NGT) Network Asset Risk Metric (NARM) Methodology. Both condition and non-condition related failure modes and consequences are considered, but can be separated out, if required, for future NARMs output reporting. It is expected that outputs reporting will only include condition-related monetised risk, whereas for investment planning both condition and non-condition related monetised risk will be used.

All NGT assets are modelled using Pipeline or Above Ground Installation (AGI or Site) asset risk models. A risk model describes the relationships between the failure rate (likelihood of failure per annum) and the assessed consequences of failure (number of events and monetary value of consequence, per-annum), which are then combined to calculate the annualised monetised risk of each individual asset.

The approach taken allows asset-level monetised risk analysis to be undertaken. However, there are key differences between how Pipelines and Sites assets have been treated in the asset risk models which underpins how the failure rate analysis was undertaken.

Changes to this document, since the originally published NOMs Methodology, are limited to changes made following completion of the Validation Report. These changes have already been incorporated into the Baseline Network Risk Output (BNRO) assessments carried out as part of the RIIO-2 submission and incorporated into the new RIIO-2 License Special Conditions 3.1 and 9.2. The treatment of PoF in long term monetised risk benefit (LTRB) calculations is discussed in the Long-Term Risk & Network Risk Outputs Supporting Document.

2. Pipelines

Each pipeline is broken down into sections (which are a proxy for the distance between girth welds), which allows the localised consequences of failure to be assessed (e.g., proximity to population; major roads/railways etc.).

Pipeline assets are recorded as a single data entity for each 12-metre section of pipeline (the primary asset), which has recorded attributes relating to protection by a secondary asset. For example, protection of the pipeline from interference damage by a marker post or by nitrogen sleeves. Secondary assets can influence the failure rate of the primary pipeline asset according to industry-standard rules based on real-world observations. Defined secondary assets include:

- Cathodic Protection (CP) Test Post, which is used to test the health of the CP system
- CP System – rectifier and ground bed, which protects the pipe from corrosion.
- Impact Protection - protection around/near a pipe that protects the pipe from external damage by 3rd parties

- Sleeve – protection that wraps around the pipe. This may be filled with nitrogen to provide additional corrosion protection
- Marker Posts – posts that indicate the presence of an underground pipe to minimise risk of damage by people working in proximity
- River Crossing – a pipe that goes under a riverbed
- Pipe Bridge – a pipe that goes over ground (generally over transport infrastructure, or a water course) and is supported by a civil structure.

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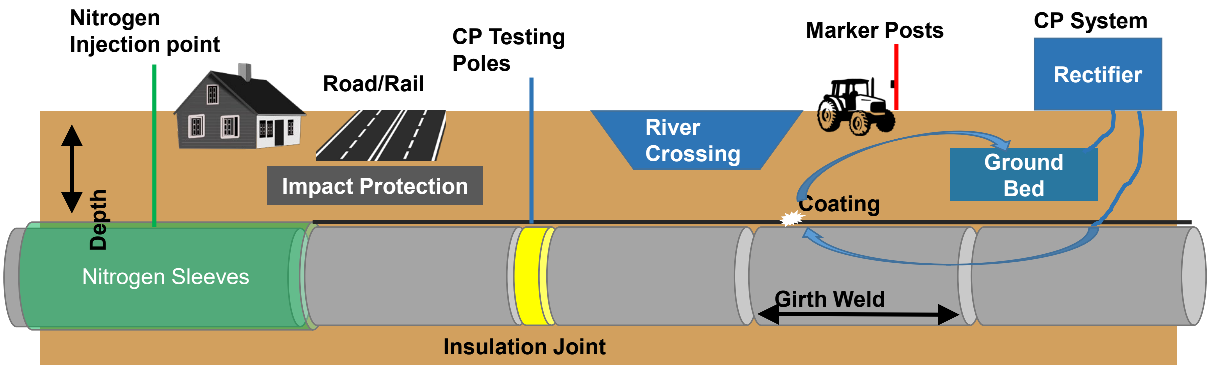

Figure 1 The relationships between primary & secondary pipelines assets

Defect rates are taken from either In Line Inspection (ILI) survey data (primary assets), or from historical Ellipse data (secondary assets). IGEM TD/2[1] provides a well-trusted source for the estimation of failure rates using data collected from ILI surveys and from individual pipelines attributes. The calculated failure rates have been validated against available industry data sources, such as EGIG[2] and the UKOPA database[3].

3. Sites

Sites assets are recorded as a combination of individual equipment (which corresponds to the lowest level of asset stored in our asset register), plus an allocated failure mode associated with the asset. If an asset has multiple failure modes, then there will be multiple lines for each asset within the Sites model database.

[1] Edition 2 – Assessing the risks from high pressure Natural Gas pipelines, amended July 2015. http://shop.igem.org.uk/products/180-igemtd2-edition-2-assessing-the-risks-from-high-pressure-natural-gas-pipelines.aspx

[2] EGIG – Gas pipelines incidents, 9th Report of the European gas pipeline Incident Data Group (period 1970-2013)

[3] UKOPA Pipeline Product Loss Incidents and Faults Report (1962-2013)

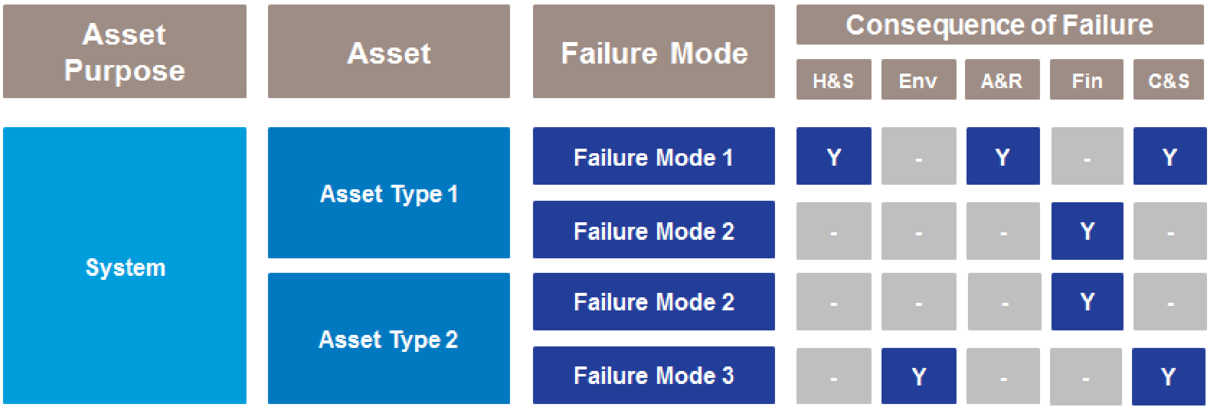

Figure 2 Mapping Assets to Failure Modes. Asset Types 1 & 2 have a shared failure mode (FM 2), but also two different failure modes (FM 1 on Asset Type 1 and FM 3 on Asset Type 2)

A single defects rate is calculated for each asset type using historical asset data, which is then converted into a failure rate per asset-failure mode (FM) combination using industry data sources[4].

[4] OREDA Offshore Reliability Data 5th Edition 2009 Volume 1 Topside Equipment, prepared by SINTEF, distributed by Det Norske Veritas (DNV))

4. Pipelines Probability of Failure Modelling

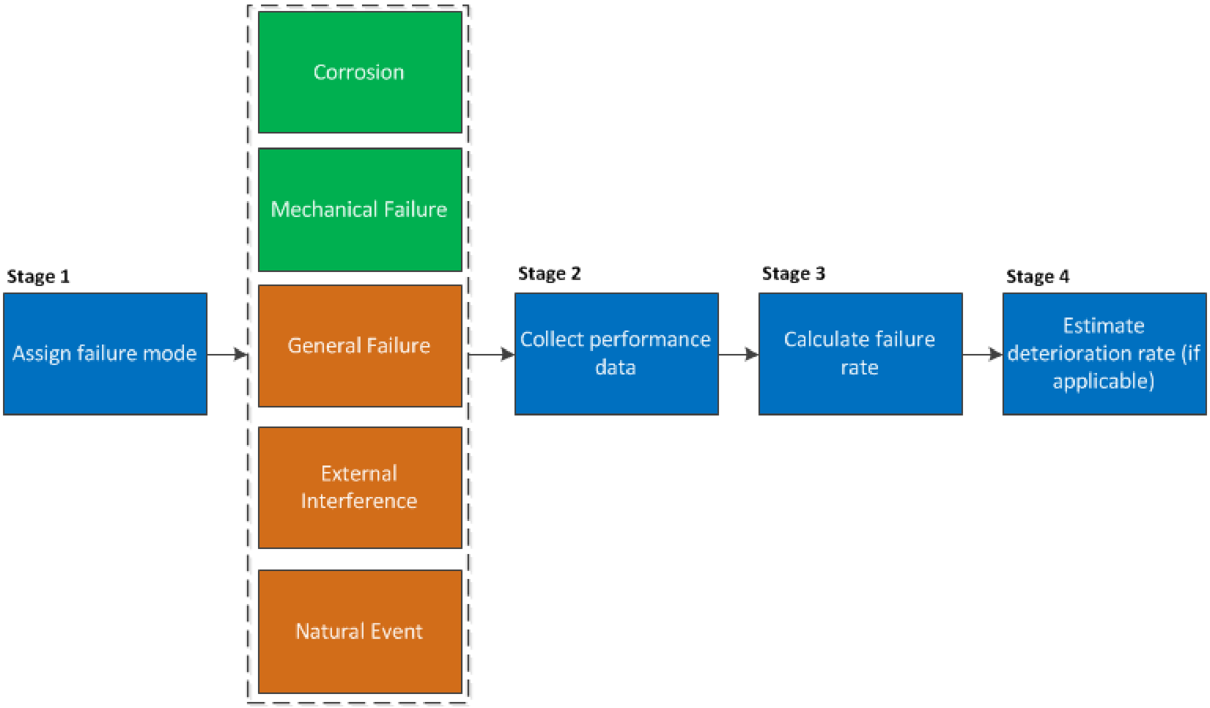

Figure 3 Overview of Pipelines defect/failure rate modelling approach

4.1. Modelling Methodology

Of the failure modes identified for pipelines assets, the following are related to the condition of the pipeline (marked in green in Figure 3):

- Corrosion[5]
- Mechanical failure[6]

The remaining failure modes are assumed to be non-condition related. The approach taken is summarised below:

4.1.1. Stage 1 – Assign failure modes

It is assumed that all pipelines could fail by one of the five failure modes listed in . The frequency of which an individual asset could fail will depend upon its pipeline characteristics, plus any afforded protection (or otherwise) generated by an associated secondary asset.

4.1.2. Stage 2 – Collect performance data

Each pipeline has multiple attributes and performance data parameters associated with it, stored within a pipelines database which feeds the risk model. These performance attributes

[5] Section 4.2 of this document
[6] Section 4.3 of this document

are used to calculate current failure and future deterioration rates. Examples of pipelines performance data include:

- Corrosion defects (from ILI)
- Pipe/coating corrosion factor
- Impact protection condition (inferred protection)
- CP condition (inferred protection)
- Depth of cover etc.

The prime source of data is an NGT IT system which holds spatial and attribute data for the Pipelines network as well as defects identified through ILI surveys (e.g., metal loss). This system has been supplemented by further data sources, such as the Pipeline Data Book, Asset Register, IGEM TD/2 and EGIG reports. External experts were engaged to help identify best practice and to devise infill rules where gaps existed in the base data using their world-wide knowledge of the gas pipelines industry

4.1.3. Stages 3 & 4 – Calculate failure and deterioration rates

For primary assets (pipelines), different failure and deterioration rate assumptions and calculations are used for each failure mode. Deterioration rates only apply to condition-related failure modes, as non-condition failures are effectively random events. The approaches and data sources for each failure mode are summarised in Table 1.

Table 1 Primary asset failure rate approaches

Failure Mode	Approach	Source
Corrosion	Initial defects rate based on pipeline attributes. Deterioration based on a modelled defect growth rate based on the current and future CP protection	IGEM TD/2 (Section A4.3) UKOPA database Intervals2 See Sections 4.2.1 and 8.1.2
Mechanical Failure (Material & Construction defects)	Initial defects rate based on pipeline attributes. Exponential deterioration rate based on pipeline age.	Wall thickness – TD/2 page 47, Table 7 Material Grade - EGIG page 43, Fig 50 Age deterioration - EGIG page 41, Fig 46 See Section 8.1.3
General Failure	Default defects rate per length of asset. No deterioration assumed	IGEM TD/2 page 50 (from UKOPA)
External Interference	Initial defects rate based on pipeline attributes and location.	Surveillance – TD2 page 29, Fig 11

Failure Mode	Approach	Source
	No deterioration assumed	Depth – TD2 page 28, Fig 10 Wall thickness – TD2 page 27, Fig 9 Design Factor – TD2 page 27, Fig 8 Rural/Urban – TD2, 8.1.5 Diameter - TD2, page 44, Fig 13 Impact Protection and condition – TD2, page 39, Table 3 Protected Markers - TD/2, page 39, Table 3 Other Services – Expert Knowledge See Section 8.1.1
Natural Events (Ground Movement)	Industry standard defects rate value adjusted by pipeline attributes and localised risk potential. No deterioration assumed	IGEM TD/2 (Section A4.5) UKOPA database EGIG (Fig 50 for diameter relationship)

Secondary assets only have a single failure mode relating to functional failure, which is defined as the inability to deliver their pipeline protection function). Various approaches have been taken to assess secondary asset failure and deterioration rates, as summarised in Table 2. Defect rates are taken from asset surveys (such as CP test post readings) and routine maintenance, unless otherwise stated.

Table 2 Secondary asset failure rate approaches

Secondary Asset	Approach	Source
Cathodic Protection (CP System & CP Test Post are modelled individually)	Deterioration models developed based on expected life & projected protection to beyond 10 years of asset life	NGT expert elicitation
Nitrogen Sleeves (and Slabs)	Deterioration model developed using sleeve risk ranking model and fitted to Weibull curve	Models for Classifying the Health Indices of Block Valves, Sleeves & Above Ground Crossings, PIE 2 Note (TN125, Nov 2014)
River Crossings	Initial failure rate derived from length of vulnerable pipework & EGIG ground movement failure rate for rivers. No deterioration rate assumed.	Gas Pipelines Incidents 9th Report of the European Gas Pipeline Incident Data

Secondary Asset	Approach	Source
		Group (1970-2013), EGIG 14.R.0403, Feb 2015
Natural Events (Ground Movement)	Industry standard defects rate value adjusted by pipeline attributes and localised risk potential. ○ No deterioration assumed	IGEM TD/2 (Section A4.5) UKOPA database EGIG (Fig 50 for diameter relationship)

A worked example for Pipelines asset failure rate estimation is shown in Appendix A.

A brief narrative of each failure mode applied in the pipelines model is provided below, including details on how the rate of failure for the Cathodic Protection (CP) system secondary asset is estimated as an example of the calculation for all secondary assets.

4.2. Corrosion

As per IGEM TD/2, corrosion events include stress corrosion cracking and alternating current / direct current induced corrosion. Internal corrosion is assumed to be insignificant due to the high quality of gas transported. Relationships to model the rate of corrosion defects have been modelled using UKOPA data.

4.2.1. Corrosion defect growth rate (wall thickness loss)

The input to the corrosion model is the number of observed corrosion defects measured through In Line Inspection (ILI) surveys.

First an adjustment is made for pipeline depth, pipes that are laid closer to the surface are likely to have greater corrosion rates. An adjustment is then made to account of any pipe coatings applied, with epoxy resin providing the most protection and bitumen the least. A further adjustment is applied to reduce the corrosion rate on pipe sections with a fitted shell or sleeve.

Observed corrosion defects will increase in depth over time (wall thickness will reduce) as the pipe wall corrodes and will eventually become defects significant enough to require action to resolve, such as installation of a pipe shell to protect the pipe from further damage.

Our corrosion model takes account of the reduction in the rate of metal loss when a pipeline is effectively protected using cathodic protection (CP). CP performance is measured during routine pipeline surveys and the protection afforded is recorded as a value in millivolts (mV). This value is used to determine the amount of corrosion protection (resistance) offered by the CP system (Table 3).

Table 3 CP health indicators linked to pipeline corrosion resistance

Resistance to corrosion	CIPS Pipe to Soil Potential
Very high, negligible corrosion rate	< -950 mV

Resistance to corrosion	CIPS Pipe to Soil Potential
High resistance (average resistance in anaerobic soil)	-950 to -850 mV
Average resistance	-850 to -550 mV
Low resistance	> -550 mV

Using the actual fault data and assessed corrosion defect growth rates, taken from the UKOPA data set, a probability distribution of corrosion growth (reduction in wall thickness) is fitted to a Weibull distribution for each assessed band of pipeline corrosion resistance (High, Medium, or Low) Expected values for each band of corrosion resistance are shown in Figure 4. Figure 4 shows a good fit between modelled and assessed growth rates. The growth rates apply to existing/known defects only. An approach to estimate the number of new defects is described below.

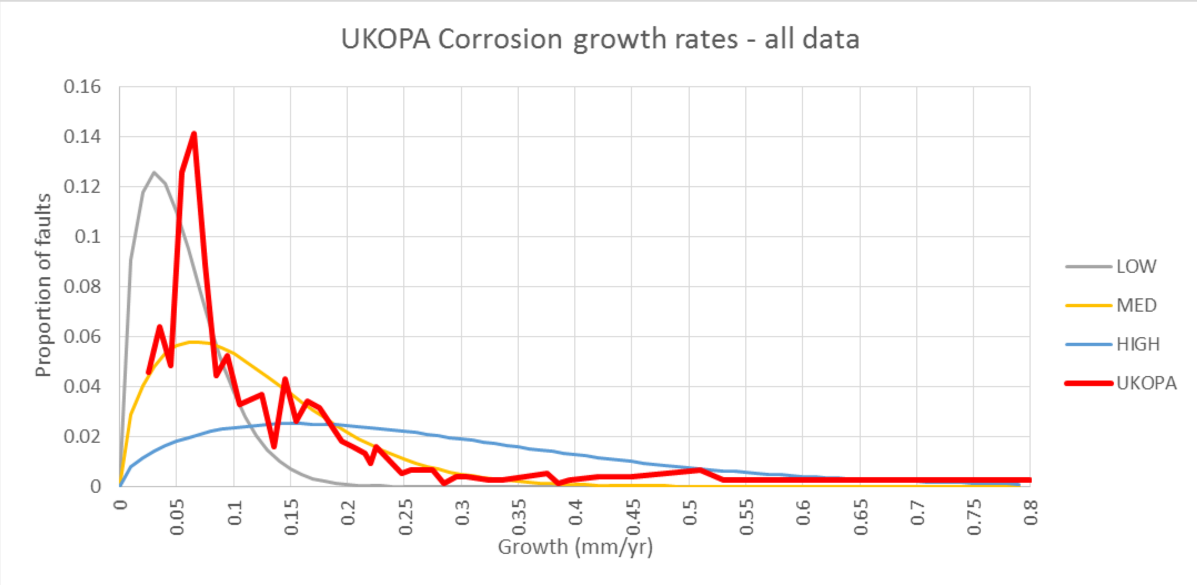

Figure 4 Modelled corrosion growth rates. Legend is corrosion rate, not corrosion resistance

Table 4 Corrosion rate values based on corrosion resistance assessments

Corrosion resistance	Corrosion Rate Expected Value (mm/year)
High (Low corrosion rate)	0.05
Medium (Medium corrosion rate)	0.12
Low (High corrosion rate)	0.27

The above corrosion resistance, which is applied per 12-metre pipeline section, is used to predict the rate of corrosion growth, expressed as remaining wall thickness. The likelihood of a failure (e.g., a leak) is then predicted using the modelled remaining wall thickness. The rate of deterioration of the protection of the CP system is estimated using observed numbers of corrosion defects using ILI survey data.

4.2.2. Growth in numbers of corrosion defects

All corrosion defects are recorded as part of the ILI runs and assigned to individual pipe segments across the network. These defects are then grown over time into corrosion faults (major) using the wall thickness loss model (see Corrosion growth model).

To estimate the future number of defects, that do not currently exist but are expected to materialise in the future, the number of defects per pipe is first calculated using existing ILI data. As we have split the pipeline network into granular sections there are many pipe sections with zero defects. Clearly, new defects will appear in the future and will be detected by future ILI surveys. To correctly model future corrosion risk we need to predict this future corrosion defect appearance rate.

Version 2.0 of the Probability of Failure supporting document estimated this defect appearance rate using only using a historic analysis of ILI identified trends and linear regression (Figure 5). We have now adopted an approach aligned to the Gas Distribution Networks and our HSE-approved Intervals2 model used for risk-based pipeline inspection frequencies.

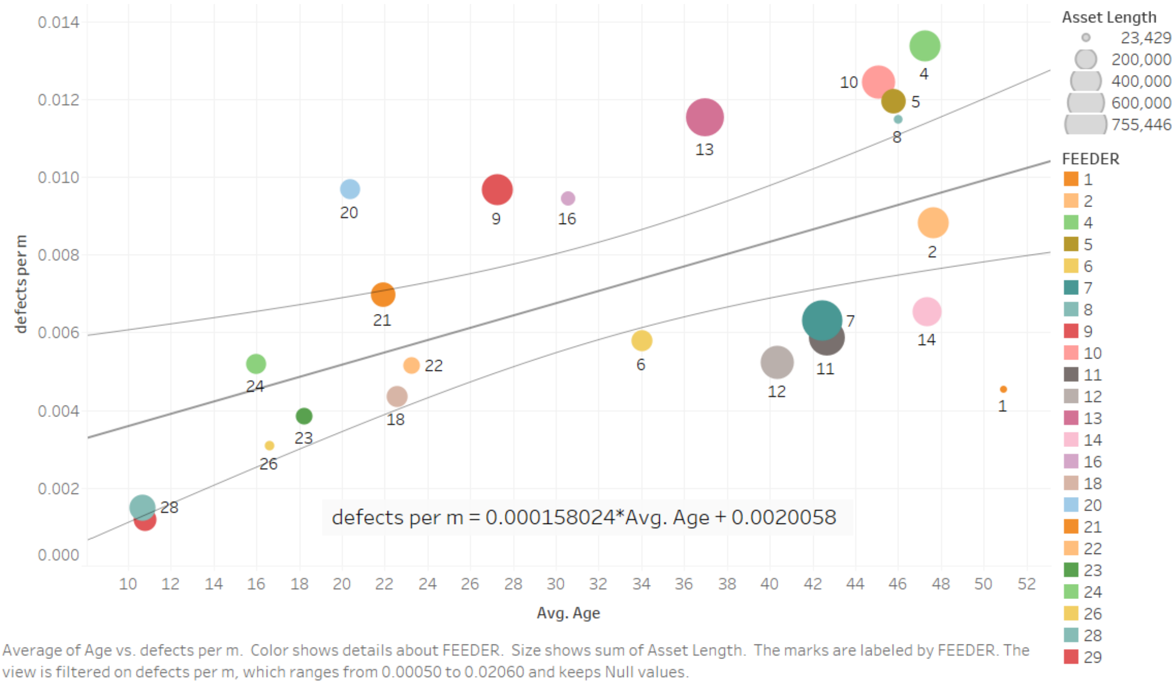

Figure 5 Defect appearance rate linear regression (based on historic ILI surveys per pipeline)

The factors now influencing defect appearance are now considered. These include (from Intervals2):

- Pipeline coating type
- Pipelines depth
- Presence of an Alternating Current (AC) source

We then apply the corrosion defect appearance rate to reflect a linear annual increase in the numbers of defects, without intervention. The defects appearance rate remains at circa 1000 per year. This approach enables us to better model locational parameters that impact of defect appearance and model the benefits of defect resolution more accurately.

4.3. Mechanical Failure

As per IGEM TD/2, mechanical failures refer to observed material and construction defects, collected through ILI surveys. This value applies to the whole pipeline section of the ILI run and corresponds to the steady-state defects rate for the pipelines. This value is then adjusted based on localised pipeline characteristics, and the installed environment, using UKOPA and EGIG data and modelled relationships.

Observed mechanical defects are used as the starting point for the failure rate assessment. Further factors are then applied to adjust the modelled failure rate based on localised pipeline characteristics and environments and to estimate a potential likelihood of failure for pipelines that have no historical defects.

IGEM TD/2 states that the rate of mechanical failures is observed to be inversely proportional to the wall thickness. A power-law relationship was derived from UKOPA data to model this impact on the predicted failure frequency.

The likelihood of failure is reduced if a pipe casing is present because of historic repairs undertaken.

Using EGIG (Figure 50), a factor was applied to account for differences in observed defects rates based on the age, design, and construction standards of the pipeline (recorded as the Material Grade). Based on EGIG analysis (Figure 46), a deterioration rate was applied based on observed material defects collected from industry data sets.

4.4. General Failure

General failures relate to other causes of pipeline failure, such as fatigue and operational errors. They are random in nature and not related to pipeline condition. A steady-state failure rate was derived from analysis of the UKOPA industry data set. This rate is assumed to not deteriorate over time.

4.5. External Interference

External interference relates to pipeline damage caused by 3rd parties, such as farming machinery and excavations occurring in the vicinity of the pipeline. This is the most likely failure mode for pipelines by a considerable margin demonstrating the importance of pipeline protection activities, such as line walking and aerial surveillance.

External Interference is assumed to be a random event and not related to pipeline condition and as such no deterioration is assumed. If the installed environment of the pipeline changes (such as localised development, or changes in depth of cover) we would expect the likelihood of a failure to change. Time-varying changes in pipeline environments are not currently modelled as the data does not exist. At present, we assume that existing and future measures to protect pipelines will maintain this level of risk over time.

An example of the external interference PoF calculation is shown in Appendix A.

4.6. Natural Events

The Natural Events failure ground movement risk caused by natural events such as flooding and natural landslides. They are random in nature and not related to pipeline condition.

A relationship between failure risk and pipe diameter has been derived using EGIG data and is used to estimate the base failure rate. This relationship models the increased protection provided by larger diameter pipes and greater wall thickness.

As per TD/2, the landslide potential for each pipeline length has been assessed and used to factor the failure risk accordingly. A further factor is applied to account for proximity of mines and quarries in the proximity of the pipeline section.

The assessed failure rate is assumed to remain constant over time, although the methodology allows for time-varying factors in the rate of natural events failures to be modelled (e.g., flooding impact of climate change) once the data exists. This has been identified as a future enhancement to the Methodology.

4.7. Secondary Asset Functional Failure

As described previously, all secondary assets have only a single failure mode, **functional failure**, or the loss of capability to adequately protect the primary pipeline asset. All secondary assets are modelled in similar ways. Condition data for each secondary asset type includes data sourced from direct measurements; industry standard documents; and data elicited from asset subject matter experts (Table 1). The failure modelling approach is identical for all secondary assets.

To calculate the failure rate for secondary, or ancillary, pipelines assets we have adopted a two-step process. The first step is to calculate the effective age of the asset. The observed/measured condition of the asset is used, as shown in Figure 6. The example shows that this asset has an observed condition of Asset Health 2 and therefore the effective age of the asset is estimated to be 9 years instead of the actual age of 17 years.

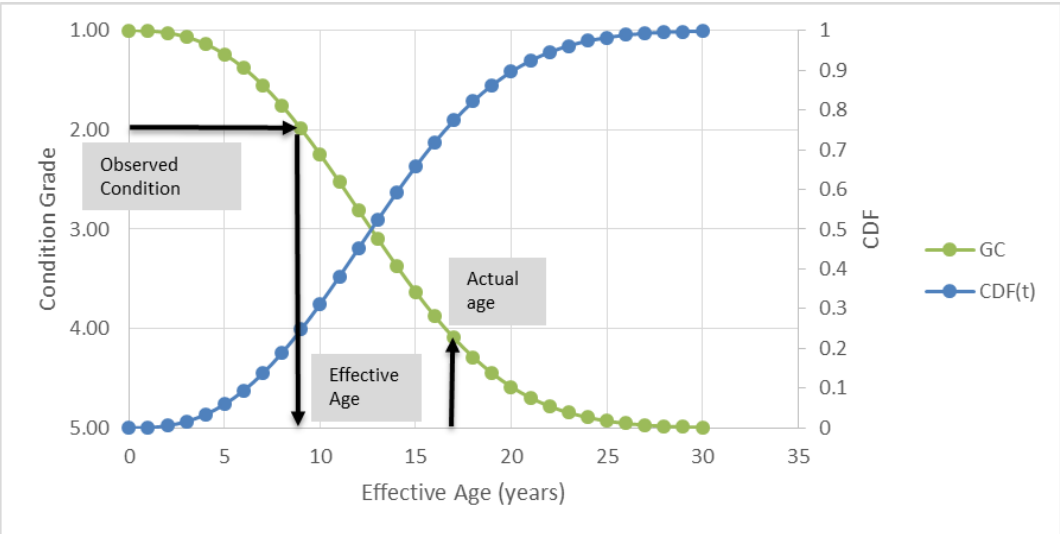

Figure 6 Using Condition (Asset Heath) scores to calculate Effective Age from Actual Age

The second step uses the effective age as an input to either a repairable failure model or a stochastic renewal process model.

A repairable failure model assumes that upon asset failure, the effected repair restores the asset condition to 'as bad as old' condition and fails at the same rate as modelled prior to the "minimal" repair.

For end-of-life failures, a stochastic renewal process is used to model the expected failure rate 'as good as new' upon failure and subsequent repair or replacement. For secondary assets this intervention is usually replacement asset or major overhaul, which is generally a much greater cost than the minimal repair assumed for the reparable model.

For secondary assets, both repairable and end-of-life failures are modelled together, as shown in below. The red line represents a failure rate that is strictly increasing and is used to represent a repairable asset. The green line models a stochastic renewal process that approximates the continuous probability of end-of-life failure. When the asset age is greater than the median of its expected lifetime (elicited from NGT experts, see Appendix D) the failure rate reverts to its long-term average failure rate (at 13 years for the example below) and the cost of replacement (or major overhaul) incurred.

It should be noted that this is a reactive, not proactive intervention and cannot be traded against other intervention types. This is because the asset has failed and are no options other than replacement at this stage. However, we do model proactive interventions against the primary pipelines asset which assesses the benefits on am improved secondary asset on primary asset risk. An example of this is a CP system intervention. We model the benefit on the **pipeline** of different levels of CP protection, which means we can then proactively decide to intervene on the CP system rather than allow the pipeline to continue to deteriorate.

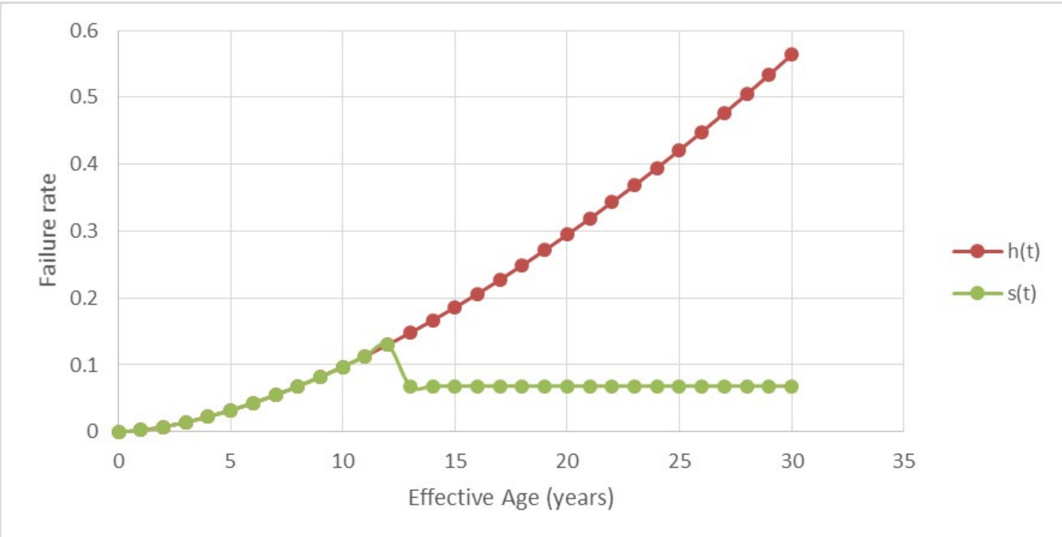

Figure 7 Example of the failure rate models used for secondary pipelines assets

Only Financial risks are modelled through this stochastic renewal process. The Safety, Availability, Societal and Environmental risks arising from the presence, or absence, of these secondary pipelines assets are modelled using the IGEM TD/2 failure rate prediction models relating to the primary pipelines assets (see Section 4).

5. Sites Probability of Failure Modelling

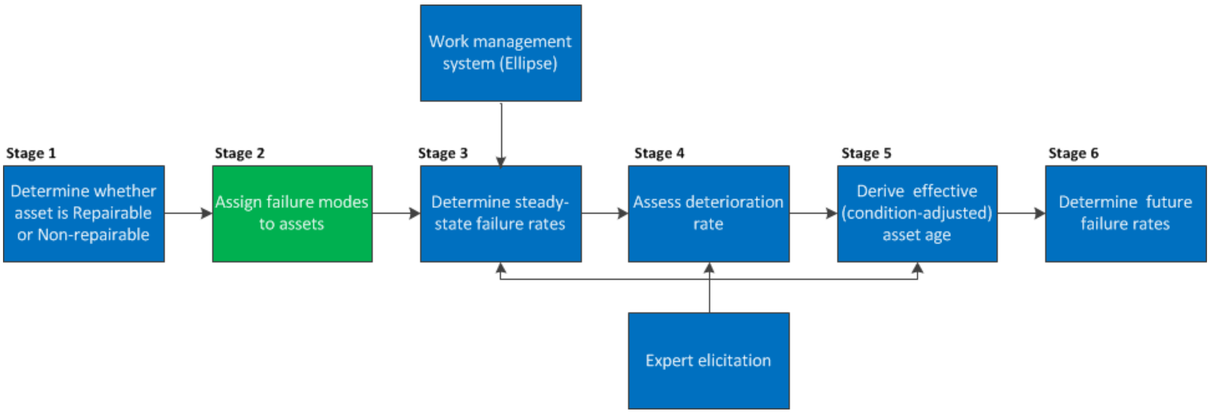

Figure 8 Overview of the Sites model defects/failure rate modelling approach

5.1. Modelling Methodology

All Sites asset failure modes are assumed to be condition-related and are driven by assessed or assumed condition (Asset Health). As discussed below, the estimated total defects rate for each asset is disaggregated into defects rates for each relevant failure modes using industry data served proportions (OREDA Offshore Reliability Data, 5th Edition 2009, Topside Equipment). The failure mode then drives the appropriate failure consequences and service risk valuations. A list of all failure modes is provided in Appendix C.

The approach taken is summarised below.

5.1.1. Stage 1 – Determine whether asset is repairable or non-repairable

Each asset –failure mode combination has been assigned with **repairable** or **non-repairable** flag in our risk models:

A **repairable** asset, when it fails, can be returned to normal operating condition and performance through repair. There is a period after installation (referred to as the *gamma* age) where it is assumed the number of defects remains constant (each repair returns the asset to the steady-state defects rate commensurate w+ith its current condition). This steady-state defects rate is determined using historical work management system defect data or through elicitation workshops with asset SMEs. This defects frequency (steady-state, plus deterioration following the *gamma* age) is referred to as the **repairable failure rate** in the Methodology. Assets with a *gamma* age of zero are deemed to have already reached the point where defects rates start to increase year-on-year, but the asset is still repairable (unless obsolete).

A **non-repairable** asset, when it fails, must be replaced. Deterioration of failure rates starts from the time of installation (no *gamma* value applies). This failure frequency is referred to as the **end-of-life hazard rate**.

5.1.2. Stage 2 – Assign failure modes to assets

Using industry data sources (OREDA), relevant “modes” (or more accurately consequences) of failure were assigned to each asset. Using OREDA, the proportion of total observed defects resulting in a specific mode of failure was derived and assigned to each asset[7]. This was further used to identify which specific service risk categories (Safety, Environmental, Availability/Reliability, Financial and/or Social) should arise should a specific failure consequence occur.

5.1.3. Stage 3 – Determine steady-state failure rates

Steady-state defect rates were estimated using historical defects data or where insufficient data was available elicited values were used. Defect rates are converted to failure rates by multiplying the measured defects rate by the failure mode proportions derived from OREDA data.

5.1.4. Stage 4 - Assess deterioration models and derive deterioration rates

Deterioration rates were estimated for groups of similar assets through expert elicitation workshops. Using the range of responses provided, three separate model types (Weibull or bi-Weibull) were produced for use in the failure rate analysis:

- Repairable asset deterioration model (asset can be repaired upon failure with no impact on function)
- Non-repairable deterioration model (asset must be replaced upon failure)
- Asset Heath versus age models, to derive a condition-adjusted age value (effective age) using available Asset Health data from condition surveys

5.1.5. Stage 5 – Assess asset Effective Age based on condition assumptions

The Asset Health versus age models (Stage 4) convert the true (or actual) asset age (taken from our asset register) into a higher or lower effective age based upon the assessed condition (from site surveys/maintenance). Asset-specific failure rates and deterioration models can then be applied to each asset, which varies based on its assessed condition. Each asset therefore has an individual deterioration rate based on its assessed condition, age, and the population average PoF for the asset type. For assets where condition data is not available, for example Electrical & Instrumentation (E&I) the effective age and true age are assumed to be equivalent.

5.1.6. Stage 6 – Calculate failure rates (current and future)

Finally, the derived failure rate and deterioration models are used to calculate the current failure rate value for the asset, depending upon its effective age and the time elapsed since the base year by referencing the appropriate bi-Weibull or Weibull curves. This approach is

[7] It should be noted that OREDA is predominantly for offshore assets, so some extrapolation was required to map to our onshore assets. This extrapolation was carried out by industry experts.

illustrated in .

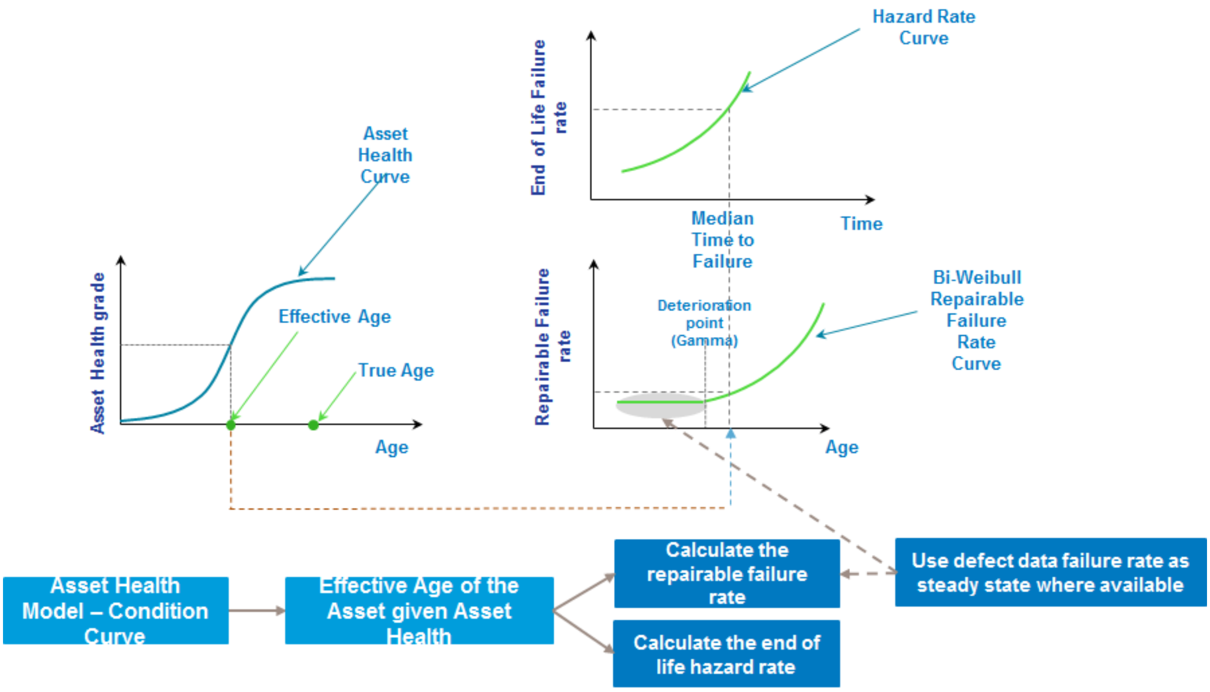

Figure 9 Deriving failure rates for repairable and non-repairable assets

The output is a unique deterioration rate, for each asset-failure mode combination, with an assigned deterioration model - repairable or non-repairable. The failure rate changes over time according to the this assigned deterioration model until an intervention takes place to change the asset condition or other underlying asset characteristics, at which point new failure rate assumptions are applied.

It should be noted that due to lack of granularity in assigned Asset Health condition scores, it was decided:

- Where an Asset Health grade is 5 (end of life) use the **effective age**
- Where an Asset Health grade is less than 5, use the **actual age**

NGT has recently implemented a new defects management system and process that will continue to improve the quantity of assessed condition grades. Once a good population of granular condition grades is available all non-E&I assets will use the effective age to drive deterioration assessments.

A worked example for sites failure rate deterioration, as assets age, is shown in Appendix B.

6. Probability of Failure Validation

Version 2.0 of the NOMs Methodology described how the initial validation of the PoF for sites and pipelines assets was carried out. This has been superseded by the NARMs Methodology Validation Report, which is part of the NGT NARMs Methodology document suite.

National Gas are undertaking a Digital Asset Management Programme across RIIO-2 and into RIIO-3 that will see updates to the Enterprise Asset Management system that supplies Key data into the Narms Methodology. With the improvements opportunities for Improved asset data quality and increased digitalisation will occur. National Gas will use this opportunity to validate the assumptions surrounding Probability of failure as well as the benefits of interventions.

7. Document Control

Version	Date of Issue	Notes
1.0	3rd April 2018	Draft NOMs Methodology version ready for public consultation
2.0	22nd May 2018	Final NOMs Methodology version sent for Ofgem acceptance
3.0	17th May 2021	Draft NARMs Methodology version ready for public consultation updated following RIIO-2 business plan submission
4.0	13th August 2021	Final NARMs Methodology submitted for Ofgem approval
4.1	5th December 2022	Draft NARMs Methodology submitted for Ofgem approval
5.0	25th June 2024	Draft NARMs Methodology version ready for public consultation

8. Appendix A

8.1. Pipelines Probability of Failure Worked Examples

The worked examples below each relate to a different 12-metre section of Pipeline.

Detailed calculations are shown for the External Interference, Corrosion and Mechanical failure modes, as the primary failure risks experienced by high pressure pipelines. The failure rate equations used in the Pipelines risk model for each failure mode, which are generally taken directly from IGEM TD/2 and adjusted using individual pipeline performance/attribute data, are complex. As such, modelled outputs have been validated through comparison with expected industry values (see Section 6). All equations and default values are taken from IGEM TD/2, supplemented by expert judgement/analysis for additional factors not considered in TD/2.

8.1.1. External Interference failure rate calculation

This section explains the External Interference failure rate calculation applied in the Pipelines model, which is broken down into nine separate elements:

1) Convert values calculated as failures per 1000 kilometres per year to units of failures per asset per year.

$$[ASSET\_LENGTH] \times \langle Scalar\_Ext\_Interference \rangle$$

2) Changes the likelihood of failure based on frequency of asset surveillance (e.g., aerial). A surveillance frequency of 14 days is assumed (IGEM TD/2, Figure 11).

$$0.42 \times \ln \mathbf{14} - 0.0866$$

3) Changes the likelihood of failure based on the depth of cover (IGEM TD/2, Figure 10).

$$3.052 \times e^{-1.033 \times [DEPTH\_M]}$$

4) Estimates the protection afforded by the wall thickness of the pipe. The failure frequency reduces as the original wall thickness increases (IGEM TD/2, Figure 9).

$$4.7115 \times e^{-0.31 \times [ORIGINAL\_WALL\_THICKNESS\_MM]}$$

5) Incorporates the amount of in-built impact protection offered by the pipes through its design and manufacturing process (IGEM TD/2, Figure 8).

$$0.4868 \times e^{0.97 \times [DESIGNFACTOR]}$$

6) The likelihood of failure is increased by a factor of 4 if in an urban area when compared to a rural area (IGEM TD/2, section 8.1.5).

$$IF[RURAL\_URBAN] = 'RURAL' \; THEN \; \mathbf{1} \; ELSE \; \mathbf{4}$$

7) Calculates the likelihood of failure for a generic pipeline, in units of *failures per 1000km per annum*. The failure likelihood reduces as the pipeline diameter increases. This is converted into *failures per asset* units in 1) (IGEM TD/2 Figure 13).

$$0.3305 \times [DIAMETER]^{-0.076}$$

8) Applies a factor to model the protection benefits offered by nitrogen sleeves and slabs, which varies based on the assessed condition of the secondary asset. The factors applied for different Condition Grades are taken from PIE Technical Note TN125, Nov 2014. Full protection is applied when the Condition Grade (Asset Heath) is 1 or 2, reducing the failure rate by a factor of 0.15). No impact protection (AH5) or unknown condition will assume that no protection is afforded by the secondary asset.

$$IF\ [CG\_IMPACT\_PROT] = 1\ THEN\ 0.15$$

$$IF\ [CG\_IMPACT\_PROT] = 2\ THEN\ 0.15$$

$$IF\ [CG\_IMPACT\_PROT] = 3\ THEN\ 0.43$$

$$IF\ [CG\_IMPACT\_PROT] = 4\ THEN\ 0.72$$

$$IF\ [CG\_IMPACT\_PROT] = 5\ THEN\ 1.00$$

$$ELSE\ 1.00$$

9) Considers the additional protection provided by the presence of a Marker Post. If Marker Post is present, the likelihood of failure is reduced by a factor of 0.125 (IGEM TD/2 Table 3).

$$IF\ [NUM\_PROTECT\_MARKER\_POST] > 0\ THEN\ 0.\mathbf{125}\ ELSE\ \mathbf{1}$$

Where:

ASSET_LENGTH - the length of the pipe section

Scalar_Ext_Interference - the expected value for external interference on an average/typical pipeline (based on actual observed interference events), as per UKOPA database and IGEM TD/2. This is adjusted up or down based on the performance parameters below

DEPTH_M - the assessed depth of cover for the pipeline (in metres)

ORIGINAL_WALL_THICKNESS_MM - the original wall thickness of the pipe (in millimetres)

DESIGNFACTOR – the design factor assigned to the pipe by the manufacturer based on designed-in protection against impact damage

RURAL_URBAN - a flag to indicate whether the pipe section is laid a rural or urban population area

DIAMETER - the pipeline diameter (in mm)

CG_IMPACT_PROT - the assessed condition the impact protection. Value is zero if condition is unknown.

NUM_PROTECT_MARKER_POST - the number of marker posts installed to indicate the position of the pipeline and prevent accidental damage

Example calculation for External Interference for a pipe section with attributes listed in Table 5.

Table 5 External Interference Failure Example: List of Attributes

Attribute	Value in This Example
ASSET_LENGTH	11.67 metres
DEPTH_M	1.2 metres
ORIGINAL_WALL_THICKNESS_MM	12.7 millimetres
DESIGNFACTOR	0.652
RURAL_URBAN	RURAL
DIAMETER	900 millimetres
CG_IMPACT_PROT	0 (steel nitrogen sleeving but of unknown condition)
NUM_PROTECT_MARKER_POST	0

Red values denote the output of the sub calculation for each step:

1)

$$\mathbf{11.67}\ metres\ \times (1 \times 10^{-6})\ [1.167 \times 10^{-5}]$$

Scalar_Ext_Interference is equal to 1×10^{-6} (converts units of *per 1000 kilometres* to *per metre*), which is then multiplied by the pipe length. This provides an overall value in *per asset* units.

2)

$$0.42\ \times\ \ln \mathbf{14}\ - 0.0866\ [1.0218]$$

Based on the current 14-day surveillance frequency, the likelihood of failure is increased by a factor of 1.0218.

3)

$$3.052\ \times\ e^{-1.033 \times [\mathbf{1.2m}]}\ [0.884]$$

A depth of cover of 1.2 metres reduces the likelihood of failure by a factor of 0.884.

4)

$$4.7115\ \times\ e^{-0.31 \times [\mathbf{12.7mm}]}\ [0.092]$$

A 12.7-millimetre wall thickness reduces the likelihood of failure by a factor of 0.092.

5)

$$0.4868\ \times\ e^{0.97 \times [\mathbf{0.652}]}\ [0.916]$$

A design factor of 0.652 reduces the likelihood of failure by a factor of 0.916.

6)

$$IF[RURAL\_URBAN] = 'RURAL'\ THEN\ \mathbf{1}\ ELSE\ \mathbf{4}\ [1]$$

The pipeline lies in a rural area; therefore, the likelihood of failure is unchanged (factor of 1).

7)

$$0.3305 \times [\mathbf{900mm}]^{-0.076}\ [0.197]$$

A pipeline diameter of 900 millimetres gives a failure rate of 0.197 failures/1000km/year (IGEM TD/2 Figure 13).

8)

$$ELSE\ 1.00\ [1.00]$$

CG_IMPACT_PROTECTION for this asset is zero. We know that the asset does have a steel nitrogen sleeve, but it is of unknown condition. We therefore assume the worst-case scenario that the asset has no impact protection afforded by the sleeve (factor of 1.00). If this asset was to be targeted for replacement, the first step would be to survey the nitrogen sleeve to assess its true condition prior to more costly interventions being planned.

9)

$$IF\ [NUM\_PROTECT\_MARKER\_POST] > 0\ THEN\ \mathbf{0.125}\ ELSE\ \mathbf{1}\ [1]$$

The pipeline section is not protected by a marker post; therefore, the likelihood of failure is unchanged (factor of 1).

So, bringing together all the elements of the External Interference failure rate calculation with the attributes from Table 5 results in the calculation below.

$$\boldsymbol{External\ interference\ failure\ rate\ for\ 12m\ section\ of\ 900mm\ Feeder\ 10\ pipeline} = (1.167 \times 10^{-5}) \times 1.0218 \times 0.884 \times 0.092 \times 0.916 \times 1.00 \times 0.197 \times 1.00 \times 1.00 = \mathbf{1.749 \times 10^{-7}}\ failures/year$$

No deterioration is assumed to apply for the External Interference failure mode.

8.1.2. Corrosion defect failure rate calculation

This section explains the Corrosion Defect failure rate calculation applied in the Pipelines model, which is broken down into eight separate elements:

1) Convert values calculated as failures per 1000 kilometres per year to units of failures per asset per year.

$$[ASSET\_LENGTH] \times \langle Scalar\_Corrosion \rangle$$

2) A factor is applied to model the increased risk of corrosion failure, if there is an electricity transmission route within 50 metres of the 12m pipeline section.

$$IF[\mathrm{ELEC\_TRANSMISSION\_50M}] = "No"\ THEN\ \mathbf{1}\ ELSE\ < \mathrm{Elec\_Transmission\_Factor} >$$

3) Calculates the maximum depth of metal loss (mm) of the 12-metre pipeline section from the maximum metal loss percentage of the original wall thickness. The corrosion failure frequency increases as the maximum depth of metal loss increases. Assumed maximum metal loss of 20% as a higher percentage of metal loss requires excavation & defect resolution.

$$\frac{[ORIGINAL\_WALL\_THICKNESS\_MM] \times MIN(20, [MAX\_METAL\_LOSS\_DEPTH\_PERC])}{100}$$

4) Calculates the low corrosion growth rate (low cgr) by the number of years that the pipeline section is in this band.

$$Det\_Corrosion\_Low \times MIN\left((DYEAR - 2017), MAX\left(0, \frac{-850 - CIPS\_PS\_OFF}{Det\_CIPS}\right)\right)$$

5) Calculates the medium corrosion growth rate (med cgr) by the number of years that the pipeline section is in this band.

$$Det\_Corrosion\_Med \times MAX\left(0, \left(MIN\left((DYEAR - 2017) - MAX\left(0, \frac{-850 - CIPS\_PS\_OFF}{Det\_CIPS}\right), MAX\left(0, \left(\frac{-550 - CIPS\_PS\_OFF}{Det\_CIPS}\right) - MAX\left(0, \frac{-850 - CIPS\_PS\_OFF}{Det\_CIPS}\right)\right)\right)\right)\right)$$

6) Calculates the high corrosion growth rate (high cgr) by the number of years that the pipeline section is in this band.

$$Det\_Corrosion\_High \times MAX\left(0, (DYEAR - 2017) - MAX\left(0, \left(\frac{-550 - CIPS\_PS\_OFF}{Det\_CIPS}\right)\right)\right)$$

7) Calculates the total wall thickness loss as a percentage of the original wall thickness.

$$\frac{Original\ Wall\ Thickness + low\ cgr + med\ cgr + high\ cgr}{[ORIGINAL\_WALL\_THICKNESS\_MM]}$$

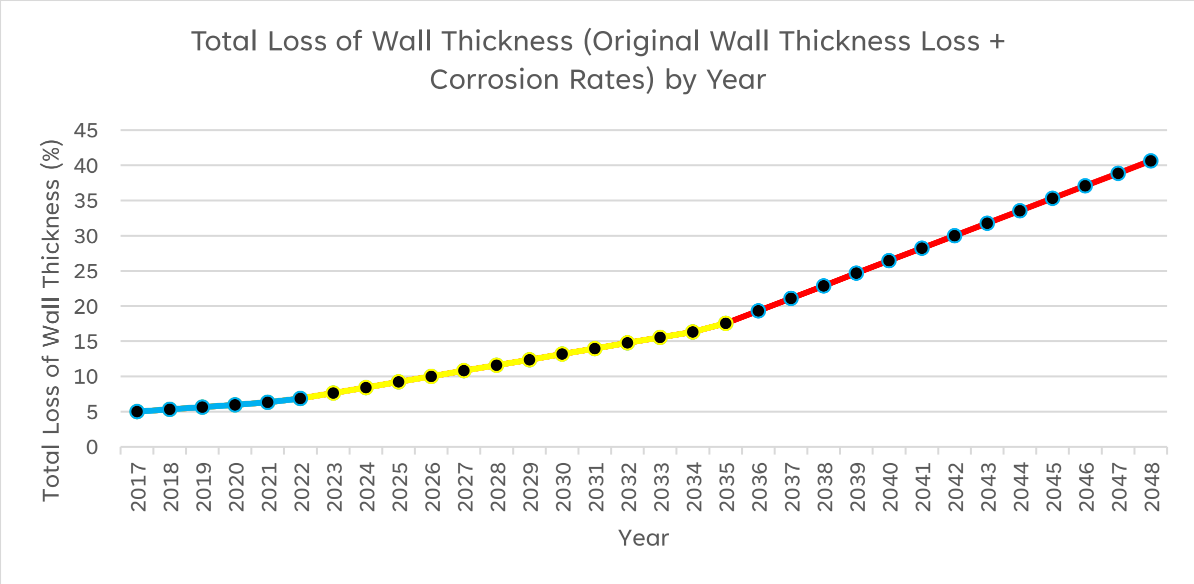

Figure 10 Increase in rate of corrosion due to cathodic protection system deterioration.

8) Weibull curve of total wall thickness loss percentage.

$$Weibull(total\ wall\ thickness\ loss\ percentage, Shape, Scale)$$

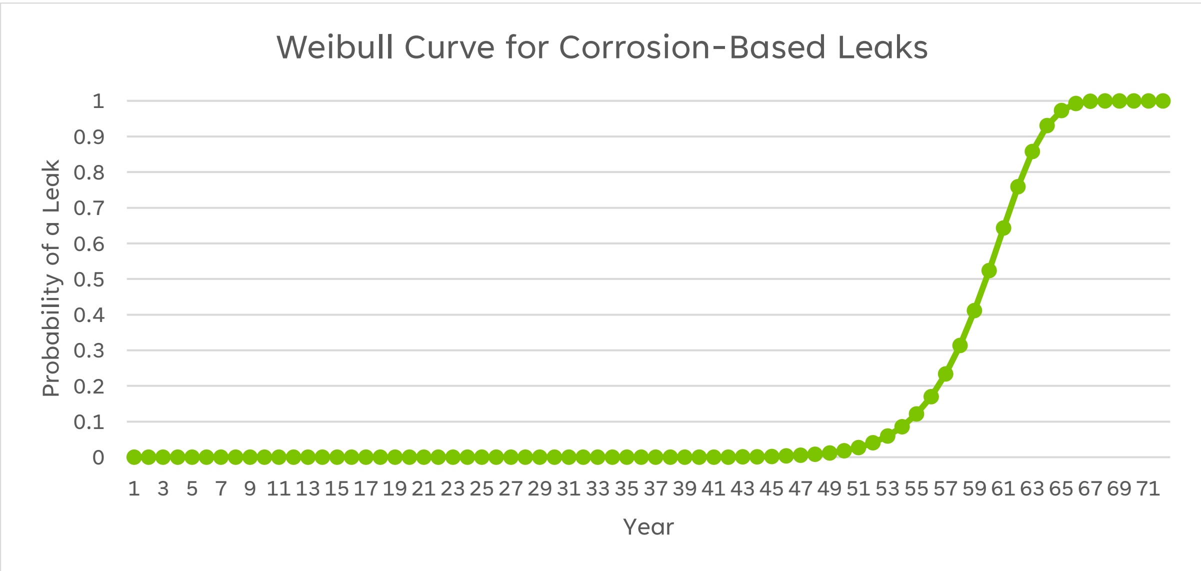

Figure 11 Probability of a leak as corrosion hole size approaches 100% wall thickness loss

Where:

ASSET_LENGTH - the length of the pipe section, up to 12 metres

Scalar_Corrosion - the expected value for Corrosion failures on an average/typical pipeline (based on actual observed interference events), as per UKOPA database and IGEM TD/2. This is adjusted up or down based on the performance parameters below

ELEC_TRANSMISSION_50M – a variable that flags whether a given 12-metre pipeline section is within 50 metres of a high-voltage electricity transmission route

Elec_Transmission_Factor – the multiplicative factor applied to the equation if there is a high-voltage electricity transmission route in proximity to a 12-metre pipeline section.

ORIGINAL_WALL_THICKNESS_MM - the original wall thickness of the pipe (in millimetres)

MAX_METAL_LOSS_DEPTH_PERC – the maximum value for metal loss, taken as a depth percentage of the original wall thickness of the 12-metre pipeline

Det_Corrosion_Low – the annual deterioration rate of the low corrosion band (mm/year)

Det_Corrosion_Med – the annual deterioration rate of the medium corrosion band (mm/year)

Det_Corrosion_High – the annual deterioration rate of the high corrosion band (mm/year)

DYEAR – current year

CIPS_PS_OFF – the CIPS survey reading (mV)

Det_CIPS – the annual deterioration rate of the CP protection (mV/year)

Shape – the shape of the Weibull curve

Scale – the scale of the Weibull curve

Example calculation for Corrosion Defect failure for a pipe section with attributes listed in Table 6.

Table 6 Corrosion Defect Failure Example: List of Attributes

Attribute	Value in This Example
ASSET_LENGTH	10.74 metres
ELEC_TRANSMISSION_50M	No
ORIGINAL_WALL_THICKNESS_MM	15.2 millimetres
MAX_METAL_LOSS_DEPTH_PERC	5%
Det_Corrosion_Low	0.05mm/year
Det_Corrosion_Med	0.12mm/year
Det_Corrosion_High	0.27mm/year
CIPS_PS_OFF	-954mV
Det_CIPS	23mV/year
Shape	16.2
Scale	0.92

Red values denote the output of the sub calculation for each step:

1)

$$10.74\,metres\ \times (1 \times 10^{-6})\ \ [1.074 \times 10^{-5}]$$

Scalar_Corrosion is equal to 1x10^{-6} (converts units of *per 1000 kilometres* to *per metre*), which is then multiplied by the pipe length. This provides an overall value in *per asset* units.

2)

$$[\text{ELEC\_TRANSMISSION\_50M}] = \text{"}No\text{"}\ \ [1]$$

There are no high-voltage electricity transmission routes in proximity to the 12-metre pipeline section, so the likelihood of failure is unchanged (factor of 1).

3)

$$\frac{[15.2mm] \times MIN(20{,}5)}{100}\ [0.76mm]$$

The maximum wall thickness loss of 5% for a 15.2mm thick pipeline is 0.76mm.

4)

$$0.05\text{mm/year} \times \text{MIN}\left((2022 - 2017), \text{MAX}\left(0, \frac{-850\text{mV} - (-954\text{mV})}{23\text{mV/year}}\right)\right)\ [0.226\text{mm}]$$

Between 2017 and 2022, 0.226 millimetres of wall thickness is lost due to the low corrosion growth rate.

5)

$$0.12mm/year \times MAX\left(0, \left(MIN\left((2022 - 2017) - MAX\left(0, \frac{-850mV - (-954mV)}{23mV/year}\right), MAX\left(0, \left(\frac{-550mV - (-954mV)}{23mV/year}\right) - MAX\left(0, \frac{-850mV - (-954mV)}{23mV/year}\right)\right)\right)\right)\right)\ [0.057mm]$$

Between 2017 and 2022, 0.057 millimetres of wall thickness is lost due to the medium corrosion growth rate.

6)

$$0.27mm/year \times MAX\left(0,(2022-2017) - MAX\left(0,\left(\frac{-550mV - (-954mV)}{23mV/year}\right)\right)\right) \text{ [0mm]}$$

Between 2017 and 2022, no wall thickness is lost due to the high corrosion growth rate.

7)

$$\frac{0.76mm + 0.226mm + 0.057mm + 0mm}{15.2mm} \text{ [0.0686]}$$

This element is the sum of elements 3, 4, 5 & 6. Between 2017 and 2022, wall thickness loss has increased from 5% to 6.86% due to the corrosion growth rates.

8)

$$Weibull(\,0.0686, 16.2, 0.92)\ [5.498 \times 10^{-19}]$$

This element take element 7 as the first input of the Weibull curve.

So, bringing together all the elements of the Corrosion Defect failure rate calculation with the attributes from Table 6 results in the calculation below.

$$\boldsymbol{Corrosion\ interference\ failure\ rate} = (1.074 \times 10^{-5}) \times (1.00) \times (5.498 \times 10^{-19}$$
$$= \mathbf{5.905 \times 10^{-24}}\ failures/year$$

8.1.3. Mechanical defect failure rate calculation

This section explains the Mechanical Defect failure rate calculation applied in the Pipelines model, which is broken down into six separate elements:

1) Convert values calculated as failures per 1000 kilometres per year to units of failures per asset per year.

$$[ASSET\_LENGTH] \times \langle Scalar\_Mechanical \rangle$$

2) Estimates the protection afforded by the wall thickness of the pipe. The failure frequency reduces as the original wall thickness increases (coefficients are derived from a fitted curve from TD/2 page 47, Table 7).

$$122.25 \times [ORIGINAL\_WALL\_THICKNESS\_MM]^{-1.777}$$

3) Applies a factor to model the material failure, which varies based on the material grade. (a higher value corresponds to a higher failure rate). Based on EGIG 9th report, Figure 50.

$$IF[MATERIAL\_GRADE] = 'GRADE\ B'\ THEN\ \mathbf{2.14}$$

$$IF[MATERIAL\_GRADE] = 'X35'\ THEN\ \mathbf{6.43}$$

$$IF[MATERIAL\_GRADE] = 'X42'\ THEN\ \mathbf{2.14}$$

$$IF[MATERIAL\_GRADE] = 'X46'\ THEN\ \mathbf{3.86}$$

$$IF[MATERIAL\_GRADE] = 'X52'\ THEN\ \mathbf{4.29}$$

$$IF[MATERIAL\_GRADE] = 'X56'\ THEN\ \mathbf{2.14}$$

$$IF[MATERIAL\_GRADE] = 'X60'\ THEN\ \mathbf{1.00}$$

$$IF[MATERIAL\_GRADE] = 'X65'\ THEN\ \mathbf{0.71}$$

$$IF[MATERIAL\_GRADE] = 'X80'\ THEN\ \mathbf{1.14}$$

$$ELSE\ \mathbf{2.54}$$

4) The age of the asset, from year of installation. Older assets will carry a higher risk.

$$0.244 \times e^{0.0896 \times ([DYEAR]-[YEAR\_INSTALL])}$$

5) A factor is applied to model the protection benefits offered by a repair casing, if it is present on the 12m pipeline section.

$$IF[NUM\_REPAIR\_CASINGS] = 0\ THEN\ \mathbf{1}\ ELSE\ \mathbf{0.001}$$

6) The number of verified defects from ILI run data on the 12-metre pipeline section, usually zero verified defects but there can be more than one for a given 12 metre pipeline section.

$$[NUM\_MECHANICAL\_DAMAGE]$$

Where:

ASSET_LENGTH - the length of the pipe section, up to 12 metres

Scalar_Mechanical - the expected value for mechanical failures on an average/typical pipeline (based on actual observed interference events), as per UKOPA database and IGEM TD/2. This is adjusted up or down based on the performance parameters below

ORIGINAL_WALL_THICKNESS_MM - the original wall thickness of the pipe (in millimetres)

MATERIAL_GRADE – the material failure factor, based on which material a pipeline section is made from. Value is 2.54 if material grade is unknown.

DYEAR – current year

YEAR_INSTALL – the year that the pipeline section was installed.

NUM_REPAIR_CASINGS – whether there is a pipe casing present or not, on the 12m pipeline section as the likelihood of failure is reduced if a pipe casing is present because of historic repairs undertaken.

NUM_MECHANICAL_DAMAGE – The number of verified defects from ILI run data on the 12-metre pipeline section, usually zero verified defects but there can be more than one for a given 12 metre pipeline section.

Example calculation for Mechanical Failure for a pipe section with attributes listed in Table 7.

Table 7 Mechanical Failure Example: List of Attributes

Attribute	Value in This Example
ASSET_LENGTH	11.94 metres
ORIGINAL_WALL_THICKNESS_MM	7.14 millimetres
MATERIAL_GRADE	X46
YEAR_INSTALL	1993
NUM_REPAIR_CASINGS	0
NUM_MECHANICAL_DAMAGE	1

Red values denote the output of the sub calculation for each step:

1)

$$\mathbf{11.94}\ \mathit{metres} \times (1 \times 10^{-6})\ \ [1.194 \times 10^{-5}]$$

Scalar_Mechanical is equal to 1x10^{-6} (converts units of per 1000 kilometres to per metre), which is then multiplied by the pipe length. This provides an overall value in per asset units.

2)

$$122.25\ \times\ [\mathbf{7.14}\boldsymbol{mm}]^{-1.777}\ [3.7173]$$

A 7.14-millimetre wall thickness increases the likelihood of failure by a factor of 3.7173.

3)

$$\boldsymbol{X46}\ [3.86]$$

The pipeline section is made from X46 material grade, which increases the likelihood of failure by a factor of 3.86.

4)

$$0.244\ \times\ e^{(0.0896 \times (\mathbf{2022}\, -\, \mathbf{1993}))}\ [3.2799]$$

The pipeline section was installed in 1993, the model assumes the current year is 2022. This increases the likelihood of failure by a factor of 3.2799.

5)

$$IF[NUM\_REPAIR\_CASINGS] = 0\ THEN\ \mathbf{1}\ ELSE\ \mathbf{0.001}\ [1]$$

The pipeline section does not have a pipe casing present, so likelihood of failure is unchanged (factor of 1).

6)

$$NUM\_MECHANICAL\_DAMAGE\ =\ 1\ [1]$$

There is 1 verified defect from ILI run data on the pipeline section, so likelihood of failure is unchanged (factor of 1).

So, bringing together all the elements of the Mechanical failure rate calculation with the attributes from Table 7 results in the calculation below.

$$\boldsymbol{Mechanical\ interference\ failure\ rate\ for\ 11.94m\ section\ of\ pipeline}$$
$$= (1.194 \times 10^{-5}) \times (1.4909) \times (3.86) \times (3.2799) \times (1) \times (1)$$
$$= \mathbf{5.619 \times 10^{-4}}\ failures/year$$

9. Appendix B

9.1. Sites Probability of Failure Worked Examples

As described above, each unit of analysis in the Sites model corresponds to an individual asset (Equipment) and its failure mode (FM). For this worked example, the Asset-FM selected is a loss of unit trip failure of the Unit A Power Turbine at Wormington Compressor Station. Due to the way the Sites model has been built the method used to estimate failure rates over time will be largely identical for all assets, so only a single example is required. The calculated failure rates will vary depending upon:

- Asset type (Repairable or Non-repairable)
- Effective Age of the asset
- Deterioration model applied (Repairable or Non-repairable)
- Current year of the analysis (the time elapsed since the base year for which calculated/derived steady-state failure rates apply)

In the current Sites model, most assets are deemed to be repairable (i.e., the failure rate is constant until the *gamma* age, at which point deterioration starts to occur at the elicited rate.

An identical approach is used for non-repairable assets, except the equations used in Stage 1 are slightly different (excluding the g*amma* age).

Table 8 shows all the failure modes and repairable high-speed machinery at Wormington Compressor station.

Table 8 All Repairable High-Speed Rotating Machinery Assets & Failure Models at Wormington Compressor Station

Equipment ID	Process	Equipment Description	Stream
2028646 Loss of Unit - Trip	Unit Control System	ENGINE & ENGINE ENCLOSURE EQUIP	UNIT B
2038292 Loss of Unit - Trip	Unit Control System	AVON PH1 ENGINE EQUIP	UNIT A
2028634 Loss of Unit - Trip	Power Turbine	POWER TURBINE EQUIP	UNIT A
1065543 Loss of Unit - Trip	Unit Control System	GAS GENERATOR START SHAFT SPEED PICK-UP	UNIT A
1065434 Loss of Unit - Trip	Unit Control System	AVON GAS GENERATOR	UNIT A
1065573 Loss of Unit - Trip	Power Turbine	POWER TURBINE	UNIT A
2028619 Loss of Unit - Trip	Unit Control System	ENGINE & ENGINE ENCLOSURE EQUIP	UNIT A
2028663 Loss of Unit - Trip	Power Turbine	POWER TURBINE EQUIP	UNIT B
1065373_ Loss of Unit Gas Drive – Trip	Air Intake	GAS GEN B'PASS DOOR POSITION OPEN/HIGH	UNIT A
1065895 Loss of Unit - Trip	Power Turbine	POWER TURBINE	UNIT B

9.1.1. Stage 1 – Repairable or non-repairable asset

The Unit A Power Turbine is classified as a repairable asset. The following equation is used to model the current failure rate for repairable assets after the Gamma age is reached. The defects rate prior to Gamma is the steady-state repair rate (1/ETA_1_REPAIR):

The Expected Number of Failures that are repairable (defects/year)

$$= \left(\frac{1}{\mathbf{ETA\_1\_REPAIR}}\right) + \left(\frac{\mathbf{BETA\_2\_REPAIR}}{\mathbf{ETA\_2\_REPAIR}}\right) \times \left(\frac{[age - \mathbf{GAMMA\_2\_REPAIR}]}{\mathbf{ETA\_2\_REPAIR}}\right)^{\mathbf{BETA\_2\_REPAIR}-1}$$

where ***age*** is in years and:

ETA_1_REPAIR is the defects rate on the "steady-state / flat" part of the Repairable failure Bi-Weibull model

ETA_2_REPAIR and **BETA_2_REPAIR** – are the scale and shape parameters for the deteriorating part of the repairable failure Bi-Weibull model.

GAMMA_2_REPAIR – is the time or age (in years) when the deteriorating part of the repairable failure Bi-Weibull begins – the Gamma Age.

The elicited values derived for the Asset-FM combinations shown in are as follows:

Table 9 Deterioration model parameters

Equipment ID	True Age (Days)	Effective Age (Days)	ETA_1_REPAIR	ETA_2_REPAIR	BETA_2_REPAIR	GAMMA_2_REPAIR
1065573 Loss of Unit – Trip	9772	1977	81.27	12.019	2.883	7

The deterioration model parameters (ETA_2_REPAIR, BETA_2_REPAIR and GAMMA_2_REPAIR) will be the same for all High-Speed Rotating Machinery assets as they were derived using the same elicitation questions.

9.1.2. Stage 2 – Assign failure modes

The failure mode for our selected asset is "Loss of Unit – Trip". The following consequences and failure mode proportions have been assigned to the Loss of Unit – Trip failure mode. These values are common to all assets with the same Loss of Unit – Trip failure mode within the Sites model.

Table 10 Failure mode proportions for Loss of Unit – Trip (aligned with OREDA)

Attribute	Description	Value/Setting
FAILURE_MODE_PROPORTION_EC	Proportion of defects causing a Loss of Unit – Trip failure	0.16
PROB_OF_EXTERNAL_EVENT	External (road/rail) consequence?	N
CONGESTED_AREA	Congested area consequence?	N
SAFETY_IGNITION_YN	Ignition consequence?	N
ENVIRONMENT_INCIDENT_YN	Environmental compliance consequence?	N
EMISSIONS_YN	Emissions consequence?	Y
SITE_PERMIT_BREACH_YN	Site permit breach consequence?	N
NOISE_YN	Noise nuisance consequence	N
UNIT_UNAVAIL_YN	Unit unavailability consequence?	Y
STATION_UNAVAIL_YN	Total station unavailability consequence?	N
STATION_UNAVAIL_PART_YN	Partial station unavailability consequence?	N
GAS_VOL_SHRINKAGE	Shrinkage consequence	N
INCREASED_MAINTENANCE	Increased future maintenance costs consequence	Y

Table 10 is used as follows to calculate failure rates in the Sites model. For the Loss of Unit – Trip failure mode of the Wormington Unit A Power Turbine, 16% of modelled defects will result in 1) Unit Unavailability consequences (Availability & Reliability), 2) Emissions events (Environment) and 3) result in Increased Maintenance costs (Financial).

It is important to note that this 'Yes/No' flag for a specific failure consequence **does not indicate the order of magnitude of any failure consequence**, just that a consequence may occur. For example, if the Wormington Unit A Power Turbine trips, we estimate that there is a 16% chance that each loss of unit trip will generate an emissions event of unknown magnitude (at this stage in the process).

For low frequency, high impact events such as fires or explosions, there may be many failure events that could cause a fire or explosion but due to other controls in place to mitigate the event (such as SIL) relatively few will result in an actual fire or explosion.

9.1.3. Stage 3 - Estimate current defects and failure rates

The steady-state defects rate for our High-Speed Rotating Machinery assets is shown as the ETA1_Repair column in Table 11, expressed as a Mean Time Between Failure (MTBF). The MTBF (in days) is the reciprocal of the steady-state defects rate and represents the elapsed time between defects.

All assets in common equipment groups (e.g., Power Turbine or Gas Generator) will share the same steady-state defects rate (prior to adjustment by Effective Age).

Table 11 Failure Rate (Nr/Year) derived from elicited MTBF values

Equipment ID	ETA_1_REPAIR (MTBF) (days)	FAILURE_RATE (nr/year)
1065573 Loss of Unit – Trip	81.27	0.012304663

Defect rates are converted to failure rates using failure mode proportions (FAILURE_MODE_PROPORTION_EC), as per Stage 2, as not all defects will become failures and generate consequences.

9.1.4. Stage 4 - Derive deterioration models and rates

High Speed Rotating Machinery Assets were treated as an individual category for estimating deterioration rates. The results of the elicitation for this asset group are shown in Figure 12 below:

Where each curve relates to the responses of individual experts and the black dotted line refers to the combined result from all experts. These curves are the end-of-life probability distribution functions, which are then used to form the hazard functions which calculate annual defects rate as the asset ages.

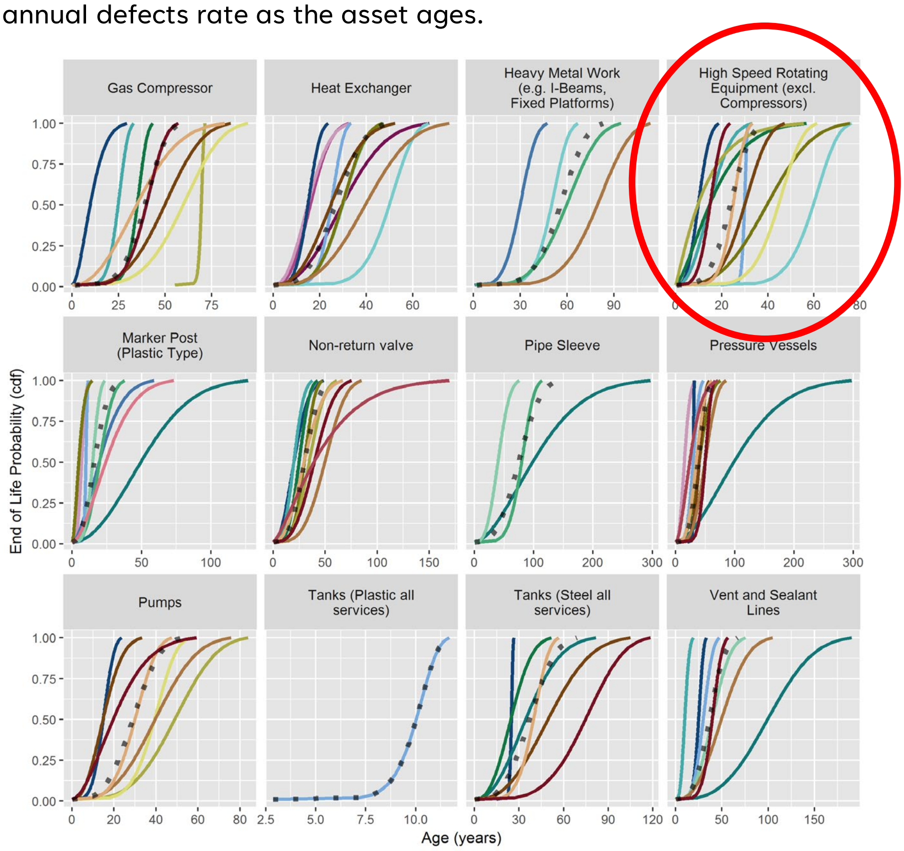

Figure 12 Elicited deterioration curves for repairable, mechanical assets in the Sites model

From the elicited curves shown in , the following bi-Weibull parameters were calculated for High Speed Rotating Machinery assets. These values apply to all assets which are classified as High-Speed Rotating machinery in the Sites model.

Table 12 bi-Weibull model parameters for High Speed Rotating Machinery

Equipment ID	ETA_2_REPAIR	BETA_2_REPAIR	GAMMA_2_REPAIR
1065573 Loss of Unit - Trip	12.019	2.883	7

9.1.5. Step 5 – Assess asset Effective Age based on condition data

It was observed previously that the True Age (ACTUAL_AGE_DAYS) and Effective Age (CONDITION_EFFECTIVE_AGE) values are different in the Sites model. For Power Turbine assets we convert the True Age to a condition-adjusted (Effective) Age using an Asset Health versus Age model, derived using elicitation workshops and outputs fitted to a Weibull model. These models use the assessed Asset Heath (As new is equal to Asset Health Grade 1; Poor condition, overdue for replacement is equal to Asset Health Grade 5) to adjust the defects rate to better represent the actual likelihood of a specific asset failing. This enables more localised targeting of high-risk assets for investment.

The following equation is used to adjust True Age to Effective Age using the assessed Asset Health.

$$\boldsymbol{Condition\ Grade} = \mathbf{1 + 4 \times (1 - exp\,(-}\left(\frac{\boldsymbol{age}}{\mathbf{CONDITION\_SCALE}}\right)^{\mathbf{CONDITION\_SHAPE}}\mathbf{)}$$

Where the condition grade (Asset Health) is available, we can use the inverse of this function to determine the Effective Age of the asset.

$$\boldsymbol{Effective\ Age} = \mathbf{(CONDITION\_SCALE\,)} \times \left(\boldsymbol{log}\frac{\mathbf{4}}{\mathbf{5} - \boldsymbol{Grade}}\right)^{\frac{\mathbf{1}}{\mathbf{CONDITION\_SHAPE}}}$$

Where age is in Years and **CONDITION_SCALE** and **CONDITION_SHAPE** are the scale and shape for the Weibull probability distribution of the equipment condition grade respectively.

Table 13 Condition Shape and Scale parameters for High Speed Rotating Machinery

Equipment ID	CONDITION_SHAPE	CONDITION_SCALE
1065573 Loss of Unit – Trip	8.676	2.64

The impact of this is to change the True (actual) age of the Power Turbine from 9772 days to an Effective Age of 1976 days, thus reducing the failure rate estimated based on average condition (AH3). This can be justified due to the significant investment undertaken through compressor station monitoring and maintenance.

Table 14 Wormington Power Turbine True Age and Effective Age

Equipment ID	ACTUAL_AGE_DAYS	CONDITION_EFFECTIVE_AGE_DAYS
1065573 Loss of Unit – Trip	9772	1977

9.1.6. Stage 6 – Calculate failure rates (current and future)

We now have all the information to calculate the failure rate for the Unit A Power Turbine at Wormington in the current year and for any future years using the deterioration model. This is an important precursor for economic justification of long-term investments.

As a Repairable asset, the failure rate will remain constant at the stead-state value until the Gamma age is reached, from which point the current failure rate will begin to deteriorate. The Unit A Power Turbine is over 7 years old and already on the deteriorating portion of the Bi-Weibull curve, therefore the Gamma age will have no effect on these example calculations (Year 6 or Year 25).

The expected number of defects that are repairable (nr/year) =

$$\left(\frac{1}{\mathbf{ETA\_1\_REPAIR}}\right)+\left(\frac{\mathbf{BETA\_2\_REPAIR}}{\mathbf{ETA\_2\_REPAIR}}\right)\times\left(\frac{[age-\mathbf{GAMMA\_2\_REPAIR}]}{\mathbf{ETA\_2\_REPAIR}}\right)^{\mathbf{BETA\_2\_REPAIR}-1}$$

Therefore:

The Expected Number of failures that are repairable (nr/year) =

$$(\boldsymbol{FAILURE\_MODE\_PROPORTION\_EC})\times\left(\frac{1}{\mathbf{ETA\_1\_REPAIR}}\right)+\left(\frac{\mathbf{BETA\_2\_REPAIR}}{\mathbf{ETA\_2\_REPAIR}}\right)\times\left(\frac{[age-\mathbf{GAMMA\_2\_REPAIR}]}{\mathbf{ETA\_2\_REPAIR}}\right)^{\mathbf{BETA\_2\_REPAIR}-1}$$

In Year 6 (True Asset Age = 36 years), the expected Loss of Unit – Trip failure rate is:

$$(\mathbf{0.16})\times\left(\frac{1}{81.27}\right)+\left(\frac{2.883}{12.019}\right)\times\left(\frac{\left[\left(\frac{1977}{365}\right)+6-7\right]}{12.019}\right)^{2.883-1}=0.038\text{ / year}$$

We would expect 0.038 Loss of Unit – Trip failures (or 1 failure in 26 years) arising from [1/0.16 x 0.038] 0.23 total defects/year (1 defect every 4 years).

In Year 25 (True Asset Age = 51 years), the expected Loss of Unit – Trip failure rate is:

$$(\mathbf{0.16})\times\left(\frac{1}{81.27}\right)+\left(\frac{2.883}{12.019}\right)\times\left(\frac{\left[\left(\frac{1977}{365}\right)+25-7\right]}{12.019}\right)^{2.883-1}=0.844\text{ / year}$$

We would expect 0.844 Loss of Unit – Trip failures (or 1 failure in 1.2 years) arising from [1/0.16 x 0.844] 5.3 total defects per year. At this stage the asset is well beyond its normal asset life and the undertaking repairs no longer returns the asset to its previous level of performance.

10. Appendix C

10.1. Sites Asset Failure Modes / Consequences

Table 15 Sites Subprocesses and Failure Mode Descriptions

SUBPROCESS	FAILURE_MODE_DESCRIPTION
132KV COMPOUND SYSTEM	Loss of electric drive unit - trip
ABOVE GROUND PIPEWORK SYSTEM	Corrosion no leak - pressure reduction
ABOVE GROUND PIPEWORK SYSTEM	Gas leak loss of Part of site minor leak
ABOVE GROUND PIPEWORK SYSTEM	Gas leak loss of Part of site significant leak
ACCESS & SITE SERVICES SYSTEM	Fail to access site for maint/ emergency
AFTER COOLER SYSTEM	Corrosion minor leak
AFTER COOLER SYSTEM	Corrosion no leak
AFTER COOLER SYSTEM	Electric fault loss of aftercooler high outlet temp - trip
AFTER COOLER SYSTEM	Gas leak significant
AGI STATION PIPEWORK	Corrosion no leak
AGI STATION PIPEWORK	Gas leak minor
AGI STATION PIPEWORK	Gas leak significant
AIR INTAKE SYSTEM	Loss of station gas drive - trip
AIR INTAKE SYSTEM	Loss of unit gas drive - trip
ALL IN ONE GAS MEASUREMENT SYSTEM	Loss of gas quality information
ALL IN ONE GAS MEASUREMENT SYSTEM	Minor gas leak from instruments
ALL IN ONE GAS MEASUREMENT SYSTEM	Significant gas leak from instruments
ANCILLARY EQUIPMENT SYSTEM	Corrosion no leak
ANCILLARY EQUIPMENT SYSTEM	Gas leak minor
ANCILLARY EQUIPMENT SYSTEM	Gas leak significant
ANCILLARY EQUIPMENT SYSTEM	Unable to isolate for maint/emergency
ANCILLARY VALVES SYSTEM	Corrosion no leak
ANCILLARY VALVES SYSTEM	Gas leak minor
ANCILLARY VALVES SYSTEM	Gas leak significant
ANCILLARY VALVES SYSTEM	Unable to isolate for maint/emergency
BATTERY CHARGER & BATTERIES SYSTEM	Power failure leading to loss of control
BATTERY CHARGER & BATTERIES SYSTEM	Power failure leading to loss of station

SUBPROCESS	FAILURE_MODE_DESCRIPTION
BATTERY CHARGER & BATTERIES SYSTEM	Power failure leading to loss of unit
BELOW GROUND PIPEWORK SYSTEMS	Corrosion no leak - pressure reduction
BELOW GROUND PIPEWORK SYSTEMS	Gas leak minor
BELOW GROUND PIPEWORK SYSTEMS	Gas leak significant
BOUNDARY PRESSURE CNTRL & PROT SYS	Reduction in pipeline capacity if unavailable
BUILDING & ENCLOUSURES SYSTEM	Structural damage leak affecting electrical control equipment loss of control / monitoring
BUILDINGS SYSTEM	Structural damage leak affecting electrical control equipment loss of control / monitoring
BURIED INOPERABLE VALVES SYSTEM	Corrosion no leak
BURIED INOPERABLE VALVES SYSTEM	Gas leak minor
BURIED INOPERABLE VALVES SYSTEM	Gas leak significant
BYPASS PROCESS PIPEWORK SYSTEM	Corrosion no leak
BYPASS PROCESS PIPEWORK SYSTEM	Gas leak minor
BYPASS PROCESS PIPEWORK SYSTEM	Gas leak significant
BYPASS PROCESS PIPEWORK SYSTEM	Mechanical electrical elements failing - loss of monitoring and control
CAB VENTILATION SYSTEM	Loss of unit - Instrumentation or Electrical fault
CATHODIC PROTECTION SYSTEM (SI)	Increased corrosion on pipe
CMS - ANTI-SURGE CONTROL SYSTEM	Failure to control surge damage unit
CMS - ANTI-SURGE CONTROL SYSTEM	Loss of unit - trip
CMS - HMI/SCADA SYSTEM	Loss of remote monitoring / control
CMS - PLC/DCS SYSTEM	Loss of local control
CMS - STATION PROCESS CONTROL SYSTEM	Loss of local control
COMPRESSOR SEAL SYSTEM (DRY)	Filter blockage - unit trip
COMPRESSOR SEAL SYSTEM (DRY)	Filter blockage detection failure
COMPRESSOR SEAL SYSTEM (DRY)	Loss of gas unit
COMPRESSOR SEAL SYSTEM (WET)	Filter blockage - unit trip
COMPRESSOR SEAL SYSTEM (WET)	Filter blockage detection failure
COMPRESSOR SEAL SYSTEM (WET)	Loss of gas unit
COMPRESSOR SEAL SYSTEM (WET)	Oil spill from wet seal

SUBPROCESS	FAILURE_MODE_DESCRIPTION
COMPRESSOR TEE SYSTEM	Need further information
CONDENSATE TANK SYSTEM	Vessel corrosion
CONDENSATE TANK SYSTEM	Vessel failure significant gas release
Control Loop	Loss of site - trip
Control Loop	Loss of unit - trip
CONTROL MONITORING & PROTECTION SYSTEM	Station failure to operate
CONTROL MONITORING & PROTECTION SYSTEM	Unit failure to operate
CRITICAL VALVES SYSTEM	Gas leak minor
CRITICAL VALVES SYSTEM	Gas leak significant
CRITICAL VALVES SYSTEM	Unable to isolate for maint/emergency
DETECTOR	Fire alarm evacuation may cause unit trip
DISCHARGE PROCESS PIPEWORK SYSTEM	Corrosion no leak
DISCHARGE PROCESS PIPEWORK SYSTEM	Corrosion on pipework - no leak
DISCHARGE PROCESS PIPEWORK SYSTEM	Filter blockage - unit trip
DISCHARGE PROCESS PIPEWORK SYSTEM	Filter blockage detection failure
DISCHARGE PROCESS PIPEWORK SYSTEM	Gas leak minor
DISCHARGE PROCESS PIPEWORK SYSTEM	Gas leak minor from Pipework
DISCHARGE PROCESS PIPEWORK SYSTEM	Gas leak significant
DISCHARGE PROCESS PIPEWORK SYSTEM	Gas leak significant from Pipework
DISCHARGE PROCESS PIPEWORK SYSTEM	Mechanical electrical elements failing - trip
DISCHARGE PROCESS PIPEWORK SYSTEM	Temperature control loss - trip
DISTRIBUTION BOARD & POWER CIRCUITS SYS	Loss of control / monitoring
DISTRIBUTION BOARD & POWER CIRCUITS SYS	Loss of unit - trip
DISTRIBUTION BOARD + POWER CIRCUITS SYS	Loss of control / monitoring
DISTRIBUTION BOARD + POWER CIRCUITS SYS	Loss of unit - trip
DISTRIBUTION BOARDS SYSTEM	Loss of control / monitoring
DISTRIBUTION TRANSFORMER SYSTEM	Loss of control / monitoring

SUBPROCESS	FAILURE_MODE_DESCRIPTION
DISTRIBUTION TRANSFORMER SYSTEM	Loss of unit
DOMESTIC PRESSURE REDUCTION STREAM	Corrosion no leak
DOMESTIC PRESSURE REDUCTION STREAM	Gas leak minor
DOMESTIC PRESSURE REDUCTION STREAM	Gas leak significant
DOMESTIC PRESSURE REDUCTION STREAM	Loss of stream regulator slam shut - trip
DOMESTIC SERVICES SYSTEM	Utility leakage
DRAINAGE & SEWAGE SYSTEM	Environment spill off site
DRAINAGE SYSTEMS	Environment spill off site
DRIVE COOLING SYSTEM	Filter blockage - unit trip
DRIVE COOLING SYSTEM	Filter blockage detection failure
DRIVE COOLING SYSTEM	Loss of electric drive unit - trip
DUCTING SYSTEMS	N/A
DUMMY CODE	N/A
EARTHING & LIGHTNING PROTECTION SYSTEM	Loss of lightning protection
EARTHING + LIGHTNING PROTECTION SYSTEM	Loss of lightning protection
EARTHING CABLES SYSTEM	Electric trip - loss of monitoring/ control
EARTHING SYSTEMS, CABLES & ELECTRODES	Electric trip - loss of monitoring/ control
EARTHING, CABLES & ELECTRODES SYSTEM	Electric trip - loss of monitoring/ control
ELECTRIC COMPRESSOR PACKAGE SYSTEM	Loss of electric drive unit - trip
ELECTRIC DRIVE OIL SYSTEM	Filter blockage - unit trip
ELECTRIC DRIVE OIL SYSTEM	Filter blockage detection failure
ELECTRIC DRIVE OIL SYSTEM	Loss of electric drive unit - trip
ELECTRIC SURFACE HEATING	Loss of preheat - pipework ices up
ELECTRICAL GENERAL	Loss of control / monitoring
ELECTRICAL SYSTEM	Loss of control / monitoring
EMERGENCY LIGHTING	Loss of illumination in emergency
EMERGENCY LIGHTING CIRCUITS SYSTEM	Loss of illumination in emergency
ENGINE & ENGINE ENCLOSURE SYSTEM	Loss of unit - trip
ENGINE GOVERNOR SYSTEM	Loss of unit - trip

SUBPROCESS	FAILURE_MODE_DESCRIPTION
ENHANCED GAS SYSTEM	Gas leak minor
ENHANCED GAS SYSTEM	Loss of gas quality information
EXHAUST SYSTEM	Loss of environmental protection / monitoring
EXHAUST SYSTEM	Loss of unit - trip
EXIT GAS QUALITY SYSTEM	Loss of gas quality information
FENCING + PLANTING STRIP SYSTEM	N/A
FILTER	Corrosion no leak
FILTER	Filter blockage - maintenance
FILTER	Filter blockage detection failure
FILTER	Gas leak minor
FILTER	Gas leak significant
FILTRATION STREAM	Corrosion no leak
FILTRATION STREAM	Filter blockage - maintenance
FILTRATION STREAM	Filter blockage detection failure
FILTRATION STREAM	Gas leak minor
FILTRATION STREAM	Gas leak significant
FIRE & GAS SYSTEM	Loss of unit - trip
FIRE SYSTEM	Loss of fire protection if incident occurs
FIRE SYSTEM	Loss of site - trip
FIRE SYSTEM	Loss of unit - trip
FIRE WATER SYSTEM	Loss of fire protection if incident occurs
FIXED TOOLS SYSTEM	Unable to maintain equipment
FLOW WEIGHTED AVERAGE GAS SYSTEM	Loss of gas quality information
FUEL GAS SYSTEM	Filter blockage - unit trip
FUEL GAS SYSTEM	Filter blockage detection failure
FUEL GAS SYSTEM	Gas leak minor
FUEL GAS SYSTEM	Gas leak significant
FUEL GAS SYSTEM	Loss of unit
FWACV GAS QUALITY SYSTEM	Loss of gas quality information
FWACV METERING SYSTEM	Loss of gas quality information

SUBPROCESS	FAILURE_MODE_DESCRIPTION
GAS COMPRESSOR SYSTEM	Filter blockage - unit trip
GAS COMPRESSOR SYSTEM	Filter blockage detection failure
GAS COMPRESSOR SYSTEM	Loss of unit - trip
GAS GENERATOR STARTER PACKAGE SYSTEM	Loss of unit - trip
GAS GENERATOR SYSTEM	Loss of unit - trip
GAS METERING SYSTEM GENERAL ASSETS	Corrosion no leak
GAS METERING SYSTEM GENERAL ASSETS	Gas leak minor
GAS METERING SYSTEM GENERAL ASSETS	Gas leak significant
GAS METERING SYSTEM GENERAL ASSETS	Metering fault inaccurate reading
GAS QUALITY MEASUREMENT SYSTEM	Gas leak minor
GAS QUALITY MEASUREMENT SYSTEM	Loss of gas quality information
GAS QUALITY SYSTEM GENERAL ASSETS	Gas leak minor
GAS QUALITY SYSTEM GENERAL ASSETS	Loss of gas quality information
GAS SYSTEM	Gas leak minor
GAS SYSTEM	Loss of gas quality information
GAS TRANSMISSION SUB-SITE	Need further information
GAS VENTING SYSTEM	Loss of vent capability
GENERAL PIPEWORK SYS	Corrosion no leak
GENERAL PIPEWORK SYS	Gas leak minor
GENERAL PIPEWORK SYS	Gas leak significant
GENERAL PIPEWORK SYS	Mechanical electrical elements failing - loss of monitoring and control
GG LUBE & HYDRAULIC OIL SYSTEM	Failure of lube oil system leading to unit trip
GG LUBE & HYDRAULIC OIL SYSTEM	Filter blockage - unit trip
GG LUBE & HYDRAULIC OIL SYSTEM	Filter blockage detection failure
GG LUBE & HYDRAULIC OIL SYSTEM	Oil leak
GG LUBE & HYDRAULIC OIL SYSTEM	Oil leak leading to cab fire
GSMR GAS QUALITY SYSTEM	Loss of gas quality information
HANDLING & TESTING OF MINERAL OIL	N/A
HARMONIC FILTER CONTAINER	Loss of unit - Instrumentation or Electrical fault

SUBPROCESS	FAILURE_MODE_DESCRIPTION
HEATING & VENTILATION SYSTEM	Unable to maintain suitable temperature in control room
HEATING PRESSURE REDUCTION STREAM	Corrosion no leak
HEATING PRESSURE REDUCTION STREAM	Gas leak minor
HEATING PRESSURE REDUCTION STREAM	Gas leak significant
HEATING PRESSURE REDUCTION STREAM	Loss of control stream - trip
HEATING PRESSURE REDUCTION STREAM	Low outlet temp
HEATING STREAM	Corrosion no leak
HEATING STREAM	Gas leak minor
HEATING STREAM	Gas leak significant
HEATING STREAM	Low outlet temp
HIGH VOLTAGE SWITCHBOARD SYSTEM	Loss of electric supply to site
INRUSH LIMITING RESISTOR SYSTEM	Loss of electric drive unit - trip
INSTRUMENT POWER SUPPLIES SYSTEM	Gas leak minor
INSTRUMENT POWER SUPPLIES SYSTEM	Loss of control / monitoring
INSTRUMENT POWER SUPPLIES SYSTEM	Loss of instrumentation - station
INSTRUMENT POWER SUPPLIES SYSTEM	Loss of unit - Instrumentation or Electrical fault
INSTRUMENTATION SYSTEM (AGI)	Gas leak minor
INSTRUMENTATION SYSTEM (AGI)	Loss of control / monitoring
INTEGRATED SITE SECURITY	Security system failure
IRIS TELEMETRY SYSTEM	Loss of remote monitoring / control
LAND & BUILDINGS	Structural damage leak affecting electrical control equipment loss of control / monitoring
LAND AND BUILDINGS SYSTEM	Structural damage leak affecting electrical control equipment loss of control / monitoring
LGT SYSTEM	Corrosion no leak
LGT SYSTEM	Gas leak minor
LGT SYSTEM	Gas leak significant
LGT SYSTEM	Loss of odourisation
LIFTING EQUIPMENT SYSTEM	Unable to maintain equipment
LIGHTING CIRCUITS SYSTEM	Loss of illumination
LIGHTING COLUMN CIRCUITS SYSTEM	Loss of illumination

SUBPROCESS	FAILURE_MODE_DESCRIPTION
LIU METERING SYSTEM	Corrosion no leak
LIU METERING SYSTEM	Gas leak minor
LIU METERING SYSTEM	Gas leak significant
LIU METERING SYSTEM	Metering fault inaccurate reading
LOW VOLTAGE SWITCHBOARD SYSTEM	Electric trip - loss of monitoring/ control
LV SWITCHBOARD & CONTROL GEAR SYSTEM	Electric trip - loss of monitoring/ control
MACHINERY OPTIMISATION SYSTEM	General instrumentation fault
MACHINERY OVER-SPEED PROTECTION SYSTEM	Loss of unit - trip
MAGNETIC PARTICLE DETECTION SYSTEM	Loss of unit - Instrumentation or Electrical fault
MCC SWITCHBOARD SYSTEM	Electric trip - loss of monitoring/ control
MCC SWITCHBOARD SYSTEM	Loss of electric supply to site
METERING GENERAL	Corrosion no leak
METERING GENERAL	Gas leak minor
METERING GENERAL	Gas leak significant
METERING GENERAL	Metering fault inaccurate reading
METERING STREAM	Corrosion no leak
METERING STREAM	Gas leak minor
METERING STREAM	Gas leak significant
METERING STREAM	Metering fault inaccurate reading
METERING SYSTEM	Corrosion no leak
METERING SYSTEM	Gas leak minor
METERING SYSTEM	Gas leak significant
METERING SYSTEM	Metering fault inaccurate reading
MISCELLANEOUS ELECTRICAL EQUIPMENT	Failure to control or monitor plant on site
MOBILE PLANT & EQUIPMENT SYSTEM	N/A
MOBILE PLANT + EQUIPMENT SYSTEM	N/A
MODULAR BOILER SYSTEM	Low outlet temp
MOTOR	Motor inoperable
NITROGEN GENERATOR SYSTEM	Failure of compressor gas seal

SUBPROCESS	FAILURE_MODE_DESCRIPTION
NITROGEN SNUFFING SYSTEM	Unable to snuff out flame from vent stack
NON CRITICAL VALVES SYSTEM	Corrosion no leak
NON CRITICAL VALVES SYSTEM	Gas leak minor
NON CRITICAL VALVES SYSTEM	Gas leak significant
NON CRITICAL VALVES SYSTEM	Unable to isolate for maint/emergency
NON SIL RATED INSTRUMETED LOOP	Loss of remote monitoring / control
NON-FIXED TOOLS SITE REGISTER SYSTEM	N/A
OIL STORAGE SYSTEM	Corrosion no oil leak
OIL STORAGE SYSTEM	Leak oil spill
OIL SYSTEM	Corrosion no oil leak
OIL SYSTEM	Failure of lube oil system leading to unit trip
OIL SYSTEM	Leak oil spill
PANEL	Loss of control / monitoring
PIGTRAP SYSTEM	Corrosion no leak
PIGTRAP SYSTEM	Door seal failure
PIGTRAP SYSTEM	Gas leak minor
PIPE CP SYSTEM (ICS)	Increased corrosion on pipe
PORTABLE & TRANSPORTABLE EQUIPMENT	N/A
PORTABLE ACCESS SYSTEM	N/A
PORTABLE FIRE EXTINGUISHERS SYSTEM	N/A
POWER CIRCUITS SYSTEM	Loss of control / monitoring
POWER FACTOR CORRECTION SYSTEM	Loss of control / monitoring
POWER GAS EQUIPMENT SYSTEM	Corrosion no leak
POWER GAS EQUIPMENT SYSTEM	Gas leak minor
POWER GAS EQUIPMENT SYSTEM	Gas leak significant
POWER GAS EQUIPMENT SYSTEM	Loss of power - gas supply instrument trip
POWER SUPPLY UNIT (DUAL CAB)	Electric trip - loss of monitoring/ control
POWER TRANSFORMERS	Electric trip - loss of monitoring/ control
POWER TURBINE SYSTEM	Filter blockage - unit trip
POWER TURBINE SYSTEM	Filter blockage detection failure

SUBPROCESS	FAILURE_MODE_DESCRIPTION
POWER TURBINE SYSTEM	Loss of unit - trip
PRA STREAMS & SUPPLY SYSTEM	Corrosion no leak
PRA STREAMS & SUPPLY SYSTEM	Filter blockage - maintenance
PRA STREAMS & SUPPLY SYSTEM	Filter blockage - unit trip
PRA STREAMS & SUPPLY SYSTEM	Filter blockage detection failure
PRA STREAMS & SUPPLY SYSTEM	Gas leak minor
PRA STREAMS & SUPPLY SYSTEM	Gas leak significant
PRA STREAMS & SUPPLY SYSTEM	Loss of stream regulator slam shut - trip
PRE-HEATING SYSTEM	Corrosion no leak
PRE-HEATING SYSTEM	Gas leak minor
PRE-HEATING SYSTEM	Gas leak significant
PRE-HEATING SYSTEM	Pre heat trip low outlet temp
PRESSURE REDUCTION STREAM	Corrosion no leak
PRESSURE REDUCTION STREAM	Gas leak minor
PRESSURE REDUCTION STREAM	Gas leak significant
PRESSURE REDUCTION STREAM	Loss of stream regulator slam shut - trip
PRESSURE REDUCTION SYSTEM	Corrosion no leak
PRESSURE REDUCTION SYSTEM	Filter blockage - unit trip
PRESSURE REDUCTION SYSTEM	Filter blockage detection failure
PRESSURE REDUCTION SYSTEM	Gas leak minor
PRESSURE REDUCTION SYSTEM	Gas leak significant
PRESSURE REDUCTION SYSTEM	Loss of stream regulator slam shut - trip
PRESSURE TRANSMITTER (Non Flow)	Loss of gas quality information
PROCESS COMPRESSED AIR SYSTEM	Workshop tools and equipment
PROCESS OPERATIONS SYSTEM	Corrosion no leak
PROCESS OPERATIONS SYSTEM	Gas leak minor
PROCESS OPERATIONS SYSTEM	Gas leak significant
PROCESS OPERATIONS SYSTEM	Pre heat trip low outlet temp
PROCESS PRE-HEATING SYSTEM	Corrosion no leak
PROCESS PRE-HEATING SYSTEM	Gas leak minor

SUBPROCESS	FAILURE_MODE_DESCRIPTION
PROCESS PRE-HEATING SYSTEM	Gas leak significant
PROCESS PRE-HEATING SYSTEM	Pre heat trip low outlet temp
PROTECTION RELAYS	Loss of control / monitoring
PT/COMP OIL SYSTEM	Failure of lube oil system leading to unit trip
PT/COMP OIL SYSTEM	Filter blockage - unit trip
PT/COMP OIL SYSTEM	Filter blockage detection failure
PT/COMP OIL SYSTEM	Oil leak
PT/COMP OIL SYSTEM	Oil leak leading to cab fire
RECYCLE PROCESS PIPEWORK SYSTEM	Corrosion no leak
RECYCLE PROCESS PIPEWORK SYSTEM	Gas leak minor
RECYCLE PROCESS PIPEWORK SYSTEM	Gas leak significant
RECYCLE PROCESS PIPEWORK SYSTEM	Mechanical electrical elements failing - trip
REMOTE CP TR UNITS	Increased corrosion on pipe
REMOTELY OPERABLE VALVES SYSTEM	Corrosion no leak
REMOTELY OPERABLE VALVES SYSTEM	Gas leak minor
REMOTELY OPERABLE VALVES SYSTEM	Gas leak significant
REMOTELY OPERABLE VALVES SYSTEM	Unable to isolate for maint/emergency
RESIDUAL CURRENT DEVICES	Electric trip - loss of monitoring/ control
RESIDUAL CURRENT DEVICES SYSTEM	Electric trip - loss of monitoring/ control
SAFETY RELATED PLC/DCS SYSTEM	Loss of unit - Instrumentation or Electrical fault
SCRUBBER	Blockage - maintenance
SCRUBBER	Blockage detection
SCRUBBER	Corrosion no leak
SCRUBBER	Gas leak minor
SCRUBBER	Gas leak significant
SCRUBBER A SYSTEM	Blockage - maintenance
SCRUBBER A SYSTEM	Blockage detection
SCRUBBER A SYSTEM	Corrosion no leak
SCRUBBER A SYSTEM	Filter blockage - maintenance
SCRUBBER A SYSTEM	Filter blockage detection failure

SUBPROCESS	FAILURE_MODE_DESCRIPTION
SCRUBBER A SYSTEM	Gas leak minor
SCRUBBER A SYSTEM	Gas leak significant
SCRUBBER B SYSTEM	Blockage - maintenance
SCRUBBER B SYSTEM	Blockage detection
SCRUBBER B SYSTEM	Corrosion no leak
SCRUBBER B SYSTEM	Filter blockage - maintenance
SCRUBBER B SYSTEM	Filter blockage detection failure
SCRUBBER B SYSTEM	Gas leak minor
SCRUBBER B SYSTEM	Gas leak significant
SCRUBBER C SYSTEM	Blockage - maintenance
SCRUBBER C SYSTEM	Blockage detection
SCRUBBER C SYSTEM	Corrosion no leak
SCRUBBER C SYSTEM	Filter blockage - maintenance
SCRUBBER C SYSTEM	Filter blockage detection failure
SCRUBBER C SYSTEM	Gas leak minor
SCRUBBER C SYSTEM	Gas leak significant
SCRUBBER D SYSTEM	Blockage - maintenance
SCRUBBER D SYSTEM	Blockage detection
SCRUBBER D SYSTEM	Corrosion no leak
SCRUBBER D SYSTEM	Gas leak minor
SCRUBBER D SYSTEM	Gas leak significant
SITE CP SYSTEM (SACRIFICIAL ANODE)	Increased corrosion on pipe
SITE CP SYSTEM (ICM)	Increased corrosion on pipe
SITE CP SYSTEM (ICS)	Increased corrosion on pipe
SITE CP SYSTEM (MIXED)	Increased corrosion rate
SITE SECURITY SYSTEM	Security system failure
SPECIAL GAS QUALITY SYSTEM	Loss of gas quality information
STANDBY GENERATOR SYSTEM	Loss of standby power control monitoring issues if required
STRUCTURES SYSTEM	Structural damage leak affecting electrical control equipment loss of control / monitoring
SUBPROCESS	FAILURE_MODE_DESCRIPTION

SUBPROCESS	FAILURE_MODE_DESCRIPTION
SUCTION PROCESS PIPEWORK SYSTEM	Corrosion no leak
SUCTION PROCESS PIPEWORK SYSTEM	Filter blockage - maintenance
SUCTION PROCESS PIPEWORK SYSTEM	Filter blockage - unit trip
SUCTION PROCESS PIPEWORK SYSTEM	Filter blockage detection failure
SUCTION PROCESS PIPEWORK SYSTEM	Gas leak minor
SUCTION PROCESS PIPEWORK SYSTEM	Gas leak significant
SUCTION PROCESS PIPEWORK SYSTEM	Mechanical electrical elements failing - trip
SUPPLY REGULATOR SYSTEM	Corrosion minor leak
SUPPLY REGULATOR SYSTEM	Corrosion no leak
SUPPLY REGULATOR SYSTEM	Corrosion significant leak
SUPPLY REGULATOR SYSTEM	Loss of gas supply to preheater or actuators
TELEMETRY SYSTEM	Loss of control / monitoring
TERMINAL INCOMER SYSTEM	Loss of pressure temperature information
TERMINAL PROCESS PIPEWORK SYSTEM	Corrosion no leak
TERMINAL PROCESS PIPEWORK SYSTEM	Filter blockage - maintenance
TERMINAL PROCESS PIPEWORK SYSTEM	Filter blockage detection failure
TERMINAL PROCESS PIPEWORK SYSTEM	Gas leak minor
TERMINAL PROCESS PIPEWORK SYSTEM	Gas leak significant
TERMINAL PROCESS PIPEWORK SYSTEM	Mechanical electrical elements failing - loss of monitoring and control
TERMINAL PROCESS PIPEWORK SYSTEM	Mechanical electrical elements failing - trip
UNINTERRUPTIBLE POWER SUPPLY SYSTEM	Power failure leading to loss of control
VALVE	Gas leak minor
VALVE	Gas leak significant
VALVE	Unable to isolate for maint/emergency
VALVES & EQUIP - CRITICAL NON ROV	Corrosion no leak
VALVES & EQUIP - CRITICAL NON ROV	Gas leak minor
VALVES & EQUIP - CRITICAL NON ROV	Gas leak significant
VALVES & EQUIP - CRITICAL NON ROV	Unable to isolate for maint/emergency
VALVES & EQUIP - CRITICAL ROV	Corrosion no leak
VALVES & EQUIP - CRITICAL ROV	Gas leak minor

SUBPROCESS	FAILURE_MODE_DESCRIPTION
VALVES & EQUIP - CRITICAL ROV	Gas leak significant
VALVES & EQUIP - CRITICAL ROV	Unable to isolate for remote maint/emergency
VALVES & EQUIP - NON-CRITICAL	Corrosion no leak
VALVES & EQUIP - NON-CRITICAL	Gas leak minor
VALVES & EQUIP - NON-CRITICAL	Gas leak significant
VALVES & EQUIP - NON-CRITICAL	Unable to isolate for maint/emergency
VIBRATION MONITORING SYSTEM	Loss of unit - Instrumentation or Electrical fault
VOLUMETRIC REGULATOR STREAM	Corrosion minor leak
VOLUMETRIC REGULATOR STREAM	Corrosion no leak
VOLUMETRIC REGULATOR STREAM	Corrosion significant leak
VOLUMETRIC REGULATOR STREAM	Filter blockage - maintenance
VOLUMETRIC REGULATOR STREAM	Filter blockage detection failure
VOLUMETRIC REGULATOR STREAM	Loss of stream regulator slam shut - trip
WATER BATH HEATER (AGI)	Corrosion no leak
WATER BATH HEATER (AGI)	Gas leak minor
WATER BATH HEATER (AGI)	Gas leak significant
WATER BATH HEATER (AGI)	Low outlet temp
WATER WASH SYSTEM	Unable to wash engine

11. Appendix D

11.1. Elicitation Approach

The deterioration rate assumptions are a sensitive element of the long-term monetised risk benefit (LTRB) assessment. We have used the same deterioration assumptions to inform:

- Our RIIO-1 rebasing exercise
- Our RIIO-2 business plan submission (cost-benefit analysis)
- Our RIIO-2 NARMs submission (life of an intervention)
- Future changes to deterioration rates will require a full update to the NARMs BNRO calculations.

Using historical data to determine the deterioration characteristics of the different asset types is not easily attainable. Typically, the data that is available in systems do not always provide evidence of deterioration. This can be for several reasons, for example, the full life behaviour of assets is missing as assets are replaced before they reach an end of life event. Furthermore, defects data may not cover a sufficiently long observation period.

To determine based on cost benefit and risk performance when in the future to replace or refurbish equipment, it is necessary to understand the current performance of the assets (i.e., based on current recorded performance) and predict how the assets will perform in the future as they deteriorate. To determine frequency of asset failure and its change over time we have developed models derived from a formal expert elicitation process.

Several key elements are vital to ensuring that the models are fit for purpose:

1. A wide variety of experience is consulted
2. The information captured is not directly about the model form/shape, but rather information/data points used to derive the final models.
3. The information is captured as point estimates and with the uncertainty around the estimates
4. The information is provided by individuals rather than through a single consensus – this provides the opportunity to explore where variability is arising
5. The resultant model curves are reviewed by the group and a consensus for the curve and the sensitivity ranges to be tested agreed
6. The outputs from use of the models are benchmarked against industry models and any significant differences are tested through further sensitivity analysis and validated with industry experts
7. The failure rates predicted from models have been compared to those derived for the RIIO-1 business plan submission and the comparison indicates that the RIIO-1models predict shorter lifetimes

The above principles have been applied in developing the elicited models. Using a structured web-based survey tool within a workshop environment, NGT experts with varying experience and expertise were consulted and their views captured as data points and used in derivation of the models. The roles of the individuals included Operations, Maintenance, Investment Planning, Engineering and Asset Management.

Four types of models have been developed:

- Repairable failure model versus age – used to calculate the failure rates and the deterioration over time that when it fails, can be restored
- Non-repairable failure model versus age (i.e., end of life probability) – used when the asset fails and cannot be restored and therefore requires replacement
- Asset Health versus age model – which is used to determine the Effective Age of assets given Asset Health
- Time to Restore (which could be a repair, or replacement activity to restore service) models

Elicited failure rate models are combined with the defects data failure rates to ensure that the starting position for defects frequency is reflective of the current asset base.

Failure models based on defects data were developed for all 228 defined Equipment Groups (). These provide a steady-state defects frequency that represents the current performance of the assets.

Table 16 Asset types (Equipment Groups) used for PoF and deterioration assessments

EQUIPMENT GROUPS
ACTUATOR
ACCUMULATOR
AFTER COOLER EQUIPMENT
AIR CONDITIONING UNIT
AIR INTAKE EQUIPMENT
ALTERNATORS
VALVE - ANCILLARY
ALARM
BATTERY
BATTERY SYSTEM
BLOW-IN DOOR
BOILERS
BYPASS
CAB VENTILATION
CAMERA
BUILDING
CIRCUIT BREAKER

EQUIPMENT GROUPS
CLADDING
CMS-ANTI SURGE CONTROL EQUIP
CMS-HMI/SCADA EQUIP
CMS-PLC/DCS EQUIP
CMS-STATION PROCESS CONTROL EQUIP
COMPRESSOR SEAL
CARD READER
CATHODIC PROTECTION
CONTACTOR
CONTROL DEVICE
CONTROL PANEL
CONTROL SYSTEM
CONTROLLER
COMPUTER
CONDENSATE TANK
VALVE - LOCALLY OPERATED
SWITCHBOARD - LV
GAS COMPRESSOR
GAS CYLINDER
GAS EQUIPMENT
GAS GENERATOR
INDICATOR
ISOLATOR
LIGHTING
GAS VENTING
SECURITY
INSTRUMENTATION
JUNCTION BOX
METER
MACHINERY OIPTIMISATION EQUIPMENT
OVERSPEED PROTECTION

EQUIPMENT GROUPS
HEATER
SWITCHBOARD - HV
GENERATOR
OIL EQUIPMENT
HARMONIC FILTER
LIFTING EQUIPMENT
INVERTER
PIPEWORK - DISCHARGE PROCESS
DUCTING
DUMMY
EXHAUST
ELEMENT
FILTER
DISTRIBUTION BOARD
EARTH BAR
EARTHING
DOMESTIC SERVICES EQUIPMENT
FAN
DESICCANT DRIER
EMERGENCY LIGHTING
FIRE SYSTEM
FUEL GAS EQUIP
TRANSMITTER - DP PRESSURE
DRAINAGE
FENCE
HEAT EXCHANGER
ENGINE
ENGINE GOVERNOR
DETECTOR
DIESEL ENGINE
ELECTRICAL COMPRESSOR DRIVE

EQUIPMENT GROUPS
FLOW CONTROL
SENSOR
SEPERATOR
CONTROL LOOP - SIL
SOCKET
PIPEWORK - SUCTION PROCESS
TRANSFORMER
VESSEL
TANK
SOLENOID
STANDBY GENERATOR
STARTER
SCRUBBER
THERMOSTAT
TRANSMITTER
TRAP
VALVE
SWITCH
TEMPERATURE MONITORING
TRACE HEATING
UPS
MOTOR
PRA STREAMS + SUPPLY EQUIP
RADIO HANDSET
NITROGEN GENERATOR UNIT
PIPEWORK
PIR
RECTIFIER
VALVE CONTROL CABINET
VALVES - CRITICAL - NON REMOTE OPERATION
VALVES - CRITICAL - REMOTE OPERATION

EQUIPMENT GROUPS
VIBRATION ELEMENT
VISUAL ALARM
TRANSMITTER - PRESSURE
PRESSURE VESSEL
PROCESS PREHEATING EQUIPMENT
PROCESS COMPRESSED AIR
SPEED ELEMENT
PIPE SUPPORT
STRAINER
PIPEWORK - RECYCLE PROCESS
MONITOR
ROAD
OIL STORAGE
POWER GAS EQUIPMENT
PANEL
PANIC GATE
REGULATOR
VALVE - RELIEF
PUMP
PUSHBUTTION
POWER SUPPLY
POWER TURBINE
PERIMETER CONTROL CABINET
WATER BATH HEATER
WATER SYSTEM
WEATHER STATION
IS BARRIER BOX
IS JUNCTION BOX
MAGNTETIC PERTICLE EQUIPMENT
GEARBOX
KIOSK

EQUIPMENT GROUPS
LAN SWITCH
DIFFERENTIAL TEMPERATURE SWITCH
ELECTRICAL
GAS SYSTEM
EQUIPMENT RACK
ETHERNET SWITCH
FUSE BOARD
GAS QUALITY SYSTEM
DRY GAS SEAL
EXCHANGER
EXPANSION TANK
PIPEWORK - ABOVE GROUND
ACCESS & SITE SERVICES SYSTEM
ACCESS GATE
ACOUSTIC SENSOR
ADACS UNIT
PIPEWORK - IMPULSE
PIPEWORK - SMALL BORE
PIPEWORK - STATION
AIR BLOWER
AIR COOLER
ANALYSER
BARRIER
PIPEWORK - BELOW GROUND
BREAK GLASS UNIT
VALVE - BURIED INOPERABLE
BURSTING DISC
BUSBAR
CALORIMETER
CP POST
VALVE - CRITICAL

EQUIPMENT GROUPS
CONCRETE VENTED (DUCTING SYSTEM)
LAND AND BUILDINGS
LIMIT SWITCH
LINK BOX
LOCAL DISPLAY
GAS ODOURISATION EQUIPMENT
IGNITOR
PIPEWORK - GENERAL
INTERCOM
INTERPOSING RELAY
IR LIGHT
BOUNDARY PRESSURE CONTROL
RELAY
CP SYSTEM
VALVE - REMOTE OPERATION
RCD
ODORANT VESSEL
ODORISER
ORIFACE PLATE
ORIFICE CARRIER
PHASE REVERSAL UNIT
PIG TRAP
ROUTER
TELEMETRY
PITS AND CHAMBERS
WASHER
SUPPLY REGULATOR SYSTEM
SAFETY RELATED PLC/DCS EQUIP
SATELLITE EQUIPMENT
LEVEL SWITCH
SIGNAL CONVERTOR

EQUIPMENT GROUPS
SILENCER
TRANSMITTER - TEMPERATURE
SURGE PROTECTOR
PIPEWORK - TERMINAL PROCESS
TIMER
SEWAGE PLANT
TRANSDUCER
TRANSIENT BARRIER
VALVE POSITIONER
VALVES - NON CRITICAL - NON REMOTE OPERATION
VALVE - SLAMSHUT
VAPOUR SEPARATOR
TRIP AMPLIFIER
VOLUMETRIC REGULATOR STREAM EQUIPMENT
PRE-HEATEING SYSTEM
PRESSURE REDUCTION
VALVE - PROCESS
PROTECTION RELAY
PROTOCOL CONVERTOR
POWER TRANSFORMER
PURYFYING UNIT
VALVE - NON-CRITICAL
VALVE - NON-RETURN VALVE
CONTROL LOOP - NON SIL
POWER FACTOR CORRECTION EQUIPMENT

To predict the change in this frequency of failure over time, the steady state failure rates are combined with the deterioration models developed from the information captured in the Elicitation process.

Elicited models were developed to cover all Equipment Groups. However, to ensure that the elicitation process was practical, the EGIs was grouped into 41 Elicitation Model Groups. These groups are shown in .

Table 17 Elicitation groupings applied in Sites model

Elicitation Groups
Actuators (All Types including Electric, Gas, Gas Hydraulic)
Pressure Vessels (Cast Steel Pressure Containing Equipment, Scrubbers, Pig Traps, Filters)
Heat Exchanger (All Types, Shell and Tube, Plate, Gas/Water, Gas/Oil)
Lighting & Small Power (All Types, General LV Equipment, Light Fittings, Small Heaters, Small Supply Circuits)
Fine/Sheet Metal Work (All Types - Ducting, Sheet Metal Clad Enclosures, Plenum Chambers, Fencing, Palisade, Weld-Mesh, Gates)
Standby Generator (All Types of electricity generation, Gas Turbine or Diesel)
Ball Valves (In any gas service, Remote Operable, Locally Actuated, Manual, or Process Valves)
Field Equipment (Instrumentation - Press, Temp, Vibration, Smoke, UV, Speed, Flow, CCTV Cameras - General Field Based Equipment)
Batteries (Lead Acid)
Power Supply (Electrical Electronic Power Supply Equipment including Transformer Rectifiers, Chargers, Rectifier/Inverters)
Boilers (including water bath heaters)
Buried Pipework (Buried Pipework, Coated and CP Protected)
Brick Buildings (Offices, Plant Rooms)
Switchgear (Motor Control Cubicles, Contactors, Miniature Circuit Breakers)
Cladding (All Types including Thermal and Acoustic)
Logic Controller (PCB Based Control Equipment, Including Processors and I/O Cards, Fire and Gas Panels, PLC's, Flow Computers)
Supervisory PC based workstations
Compressor Seals (Dry Gas Type)
Tanks (Steel Tanks in all services, Oil, Fuel, Water, Condensate)
Gas Compressor (Main Line Large Bore Gas Compressor)
Gas Analysers (Chromatograph excluding Micro)
High Speed Rotating Equipment (Gas Generators, Power Turbines, not including Compressors)
Electric Motor (LV)
HV Electrical (In-Rush Limiting Resistors, Capacitor Banks, Inductors, not Transformers, Motors, or Thyristor Drives)
Pumps (All Types, Including Fire Pumps, Lube Oil Pumps, Drainage Pumps)
Heavy Metal Work (Larger Cross Section Steel Work, I-Beams, Fixed Platforms, Pipe Saddles, Pipe Anchors)
Above Ground Pipework (General Carbon Steel Painted Pipework All Sizes)

Ducting (Surface containment including chambers)
Earthing and Lightening Protection (External Exposed Copper Conductor Systems)
Exhaust System (Gas Generator Exhaust Stack including Bullet)
Transformers (All Types including HV and LV, ancillary and VSD)
Ancillary Compressors (Small Ancillary Compressor Plant for Instrument Air and N2 Generation)
Concrete Civils (All Types of Steel Reinforced Concrete, Bunds, Pits, Blast Walls)
Control Valves (All Types - Globe, Vball, Large Network Flow Control, Smaller Pressure Regulators, Throttle Valves)
Thyristor Drive (VSD Drive Control System)
Roads and Footpaths (All Surface Types, Concrete, Macadam)
Drainage (Earthenware and concrete including chambers)
Gas Analysers (Micro chromatograph)
Compressor Seals (Wet/Oil Type)
Marker Post (Plastic Type)
GRP Enclosures (All Types - Telemetry Huts to Electrical & Instrument Enclosures)

There are separate models for each Group for:

1. Condition (Asset Health) versus effective age
2. Repairable asset failure rate versus age
3. Non-repairable asset failure rate versus age
4. Time to Restore following failure – Failure Type A (small repair); Failure Type B (large repair); Failure Type C (replacement)

Figure 13 below shows an example for the curves generated for Asset Health versus Effective Age. The different coloured lines are the model curves derived based on an individual respondent's responses. The black dashed line represents the curve derived using all respondents' responses. All curves consider the uncertainty the respondents have included in their survey responses. The y-axis shows the Asset Health Grade varying with age (x-axis). Each tile shows the curves for one Elicitation Group.

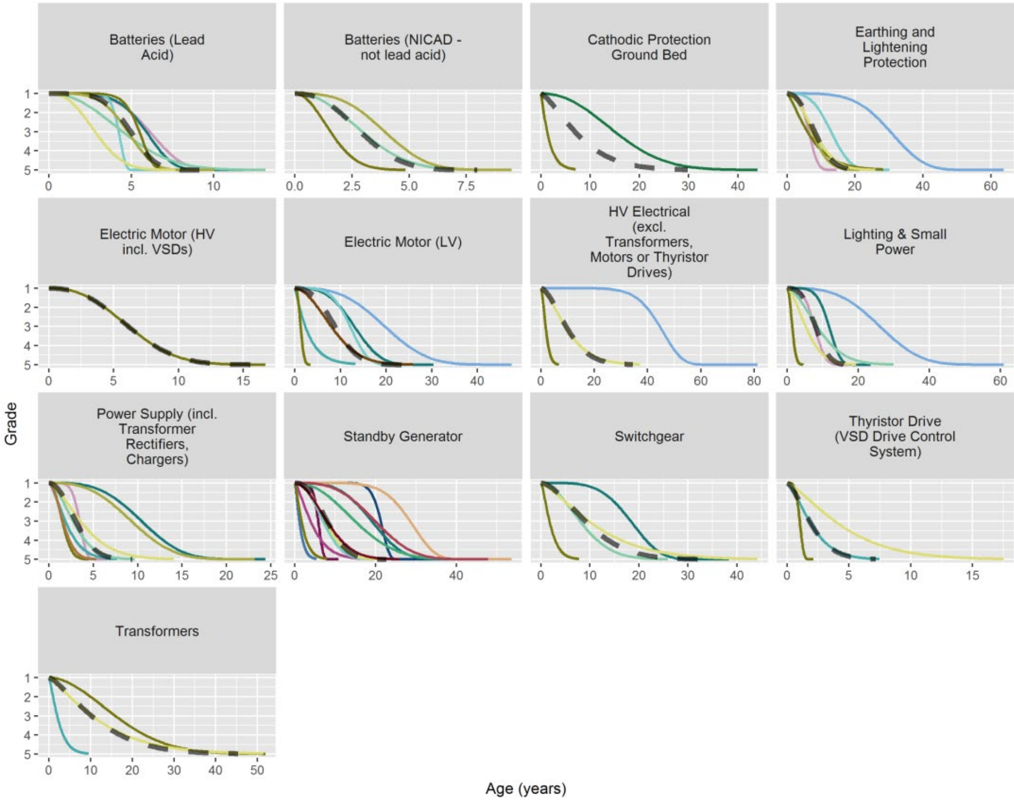

Figure 13 Examples of elicited deterioration curves for adjusting actual, to effective (condition-adjusted) age

12. Appendix E

12.1. Probability of Failure Definitions

The following definitions apply in relation to defects and failure rates apply when reading this document:

Defect – a problem with an asset identified through routine surveying or maintenance or may be reactively identified as a fault requiring action to resolve (e.g., a corrosion defect). A defect is converted to failure using the failure mode proportions estimated from industry data (OREDA).

Failure, or functional failure – a defect giving rise to functional failure (or the inability for the asset to perform its desired function) and therefore generating consequences on the NTS (although the consequences may be unlikely or small, e.g., a pin hole corrosion leak).

Base rate – the assessed defects/failure rate in the base year of the analysis (Year 0). Year 0 uses 2017 defects data and we have assumed that 2021 (Year 0 of RIIO-2) has an identical defect rate due to ongoing Asset Health interventions.

Steady-state rate – the defects/failure rate between asset installation and the *gamma* age, where defects/failure rates start to increase annually. Prior to the *gamma* age the rate is constant (hence steady-state). Base and steady-state rates can be assumed to be equivalent in this document.

Current rate – the defects/failure rate in the year of interest for the analysis (Year 1 onwards)

Contact:

Jonathan Lewis

Asset Strategy

E: Jonathan.Lewis@nationalgas.com

nationalgas.com