nationalgrid

Appendix A

Ofgem project direction

Company Secretary
National Grid Gas Transmission
1-3 Strand,
London
WC2N 5EH

Direct Dial: 020 7901 7159
Email: andy.burgess@ofgem.gov.uk

Date: 19 December 2014

Dear Company Secretary,

Project Direction ref: National Grid Gas Transmission / In Line Robotic Inspection of High Pressure Installations / 19 December 2014

National Grid Gas Transmission plc (NGGT) submitted the project *In Line Robotic Inspection of High Pressure Installations* on 25 July 2014 to us to be considered for funding through the Gas Network Innovation Competition (NIC). In this year's decision, we selected the Project[1] for funding.[2,3]

We have issued this Project Direction to NGGT. It contains the terms to be followed by NGGT as a condition of the Project receiving funding through the Gas NIC. It must comply with these terms, which can be found in the schedule to this Project Direction.

Project Direction

Paragraph 5.66 of the Gas NIC Governance Document states that a Project Direction will:

- set out the Project-specific conditions that the Network Licensee is committing to in accepting funding;
- require the Network Licensee to undertake the Project in accordance with the commitments it has made in the Full Submission. Where appropriate, the Project Direction may therefore include extracts from the Full Submission or refer to specific sections of the Full Submission;
- set out the Approved Amount for the Project, that will form part of the calculation contained in the funding direction issued by the Authority under chapter 7 of the Governance Document;

[1] Unless otherwise specified, defined terms in this Project Direction have the meaning given to them in Appendix 1 of the Gas NIC Governance Document.
[2] https://www.ofgem.gov.uk/publications-and-updates/decision-second-year-gas-network-innovation-competition.
[3] The terms 'the Authority', 'Ofgem', 'we', 'us' and 'our' are used interchangeably in this letter. The Authority is the Gas and Electricity Markets Authority. Ofgem is the Office of the Authority.

- set out the Project Budget that the Network Licensee must report against and how variances against the Project budget will be reported and approved; and

- the mechanism for the Network Licensee receiving the Approved Amount is set out in the Funding Direction.

These are described for the Project in the schedule to this Project Direction.

Decision

Provided NGGT complies with the NIC Governance Document and with the schedule to this Project Direction, the Project is deemed to be an Eligible NIC project.[4]

This Project Direction constitutes notice pursuant to section 38A (Reasons for decisions) of the Gas Act 1986.

Yours faithfully,

Andy Burgess
Associate Partner, Transmission and Distribution Policy
For and on behalf of the Authority

[4] Eligible NIC Project has the meaning given in definitions of the National Grid Gas Plc (NTS) Gas Transporter Licence.

The Office of Gas and Electricity Markets
9 Millbank London SW1P 3GE **Tel** 020 7901 7000 **Fax** 020 7901 7066 **www.ofgem.gov.uk**

Schedule to Project Direction

1. TITLE

Project Direction ref: NGGT / *In Line Robotic Inspection of High Pressure Installations* / 19 December 2014

2. PREAMBLE

This Project Direction issued by the Gas and Electricity Markets Authority (the "Authority") to NGGT (the "Funding Licensee") pursuant to the Gas NIC Governance Document issued pursuant to Part E of Special Condition 2F (Network Innovation Competition) of the National Grid Gas Plc (NTS) Gas Transporter Licence (the "Licence") sets out the terms to be followed by the Funding Licensee in relation to *In Line Robotic Inspection of High Pressure Installations* ("the Project") as a condition of the Project being funded under the NIC and the Funding Return Mechanisms.[5]

Unless otherwise specified, defined terms in this Project Direction have the meaning given to them in Appendix 1 of the Gas NIC Governance Document.

References to specific sections of the Funding Licensee's Full Submission in this Project Direction are, for ease of reference, made by referring to the section number in the Funding Licensee Full Submission pro-forma.

3. ADEQUACY OF FUNDING AND FUNDING ALLOCATION

The Funding Licensee acknowledges that the budget allocations set out in Appendix 1 as restricted in certain circumstances described below will allow it to fulfil its obligations under this Project Direction.

4. CONDITION PRECEDENT

The Funding Licensee will not access any funds from the Project Bank Account until it has signed contracts with the Project Partners named in Table 1.

Table 1. Project partners

1. Synthotech Ltd
2. Premtech Ltd
3. Pipeline Integrity Engineers Ltd

5. COMPLIANCE

The Funding Licensee must comply with Special Condition 2F of the Licence and with the NIC Governance Document (as may be modified from time to time in accordance with Special Condition 2F and as modified and/or augmented in respect of the Project by this Project Direction) and with this Project Direction.

[5] The Funding return Mechanism is defined in 2F (Network Innovation Competition) of the National Grid Gas Plc (NTS) Gas Transporter Licence.

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Any part of the Approved Amount that the Authority determines not to have been spent in accordance with this Project Direction (or with the Gas NIC Governance Document) is deemed to be Disallowed Expenditure.

Pursuant to Special Condition 2F Disallowed Expenditure is revenue received (whether by the Funding Licensee or another Licensee) under the NIC and Funding Return Mechanisms that the Authority determines not to have been spent in accordance with the provisions of the Gas NIC Governance Document or with those of the relevant Project Direction.

Pursuant to paragraph 8.48 of the Gas NIC Governance Document, Disallowed Expenditure includes any funds that must be returned if the Project is halted without Ofgem's permission, any funds that have not been spent in accordance with the approved Project Budget contained within the Project Direction, and any unspent funds on the completion of the Project.

6. APPROVED AMOUNT FOR THE PROJECT

The Approved Amount is £5,674,505.03.

7. PROJECT BUDGET

The Project Budget is set out in Annex 1 to this Project Direction. The Funding Licensee must not spend more than 110% of any category total (e.g. "Labour") in Annex 1 without the Authority's prior written consent (such consent is not to be unreasonably withheld).

The Funding Licensee will report on expenditure against each line under the category total in the Project Budget, and explain any projected variance against each line total in excess of 5% as part of its detailed report which will be provided at least every six months, in accordance with paragraph 8.17 of the Gas NIC Governance Document. Ofgem will use the reported expenditure and explanation to assess whether the funding has been spent in accordance with the Gas NIC Governance Document and with this Project Direction.

For the avoidance of doubt this reporting requirement does not change or remove any obligations on the Funding Licensee with respect to reporting that are set out in the Gas NIC Governance Document.

8. PROJECT IMPLEMENTATION

The Funding Licensee must undertake the Project in accordance with the commitments it has made in the Full Submission approved by the Authority pursuant to the Gas NIC Governance Document and with the terms of this Project Direction. These include (but are not limited to) the following:

- (i) undertake the Project in accordance with the description set out in Section 2 (Project Description);
- (ii) provide a Network Licensee Compulsory Contribution of £630,500.56;
- (iii) complete the Project on or before the Project completion date of 26 November 2018; and
- (iv) disseminate the learning from the Project at least to the level described in Section 5 (Knowledge Dissemination).

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9. PROJECT PROGRESS THROUGH PHASES

The Funding Licensee must satisfy itself that the successful delivery reward criteria ("SDRC") for each phase have been complied with before using funding for each subsequent phase. The Funding Licensee must secure appropriate internal senior sign-off before proceeding to the next phase and publish this internal sign off no later than when submitting to Ofgem the next detailed report due in accordance with paragraph 8.17 of the Gas NIC Governance Document.

The SDRC relating to each phase (9.1 to 9.8) are detailed in Table 3 of this Project Direction. The funds relating to each phase are identified in Table 2 below.

Table 2. Project budget by phase

Phase	Budget
9.1 Solution Development	£1,671,218.19
9.2 Development Testing	£2,171,165.75
9.3 Offline Trials	£650,168.75
9.4 Online Trials	£614,519.36
9.5 Delta Proto-type	£552,846.34
9.6 Data Analysis Systems	£237,568.16
9.7 Conduct Data Analysis	£189,709.54
9.8 Implement into Business As Usual	£217,809.50

10. REPORTING

Ofgem will issue guidance (as amended from time to time) about the structure and content of the reports required by paragraph 8.17 of the Gas NIC Governance Document. The Funding Licensee must follow this guidance in preparing the reports required by paragraph 8.17 of the Gas NIC Governance Document.

As required by paragraph 8.22 of the Gas NIC Governance Document, the Funding Licensee must inform the Authority promptly in writing of any event or circumstance likely to affect its ability to deliver the Project as set out in its Full Submission.

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11. COST OVERRUNS AND DIRECT BENEFITS

The maximum amount of Discretionary Funding that the Funding Licensee can request as additional funding for cost overruns relating to the Project is 5% of the Approved Amount.[6]

12. INTELLECTUAL PROPERTY RIGHTS (IPR)

In Section 5 of its Full Submission (Knowledge Dissemination) the Funding Licensee has stated that the Project does conform to the default IPR arrangements set out in chapter 9 of the Gas NIC Governance Document and must therefore undertake the Project in accordance with the default IPR arrangements.

13. SUCCESSFUL DELIVERY REWARD CRITERIA

The Project will be judged by the Authority for the purposes of the NIC Successful Delivery Reward against the Successful Delivery Reward Criteria set out in Table 3 below (that comply with paragraphs 5.26-5.29 of the Gas NIC Governance Document).[7]

Table 3. Successful Delivery Reward Criteria

Successful Delivery Reward criterion	Evidence
(9.1) Solution Development completed by 30 October 2015: - a concept design study of robotic platform completed and scope clearly defined; - created and validated 3D models for each trial site accurately representing pipework configuration; - designed a launch and retrieval device to allow robot insertion into high pressure; - robotic platform conceptual design(s) completed, computer models and 3D prints produced, conceptual design(s) demonstrates potential to achieve objectives of travelling 100m around 2 bends taking visual readings and wall thickness measurements in buried pipework of up to 100Barg pressure.	A report will be submitted by 30 October 2015 demonstrating that these measurable activities have taken place. Documentation for SDRC 9.1 uploaded to the internal sharepoint site and project file, external version uploaded to website. Publish evidence of internal senior sign-off confirming successful completion of SDRC 9.1 no later than 19 December 2015.
(9.2) Development Testing completed by 9 September 2016: - robot access and inspection routes for all three trial sites development and validated including the formulation of Formal Process Safety Assessments; - the offline testing facility designed and distributed for competitive tender. Contract in place for its completion; - manufacture of a robotic platform primary	A report will be submitted by 9 September 2016 demonstrating that these measurable activities have taken place. Documentation for SDRC 9.2 uploaded to internal sharepoint site and project file, external version uploaded to website.

[6] This is the amount requested by the Funding Licensee in its Full Submission.
[7] These are the Successful Delivery Reward Criteria set out in the Funding Licensee's Full Submission, with the additional evidence of internal senior sign-off added by Ofgem in accordance with the conditions in this Project Direction.

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Successful Delivery Reward criterion	Evidence
solution in order to test and further develop robotic design and meet the objectives of withstanding pressure of up to 100Barg whilst travelling 100m, negotiating two bends and taking visual and wall thickness measurements. This will involve successful bench testing (simulation) in a controlled environment of up to 6m with one bend; - launch and retrieval device manufactured to withstand pressure of 100Barg and minimise venting.	Publish evidence of internal senior sign-off confirming successful completion of SDRC 9.2 no later than 19 December 2016.
(9.3) Successful Offline trials completed by 30 April 2017: - offline test rig manufactured and positioned at readiness to conduct offline trials; functional robotic platform manufactured and tested on offline testing facility to conduct visual inspection and wall thickness measurements – a minimum of 10 offline tests will take place; - establish and publish Disaster Recovery Plan for live trial sites; - successful data collection/problem identification by robotic platform in response to test scenarios.	A completion report will be submitted by 30 April 2017 which will ensure the online trials at the specified live sites: Bacton, Hatton and Lupton, can begin. Documented evidence that robotic platform can negotiate measurables for SDRC 9.3 via project website. Publish evidence of internal senior sign-off confirming successful completion of SDRC 9.3 no later than 19 June 2017.
(9.4) Successful Online trials completed by 30 September 2017: - successful insertion of launch and retrieval device into all three live sites; - undertake testing to deliver a functional robotic platform and associated tools to work up to 100Barg pressure, travel 100m, conduct visual inspection and wall thickness measurements – a minimum of 3 online tests per site will take place.	A completion report will be submitted by 30 September 2017. Document evidence that robotic platform can negotiate measurables for SDRC 9.4 via project website. Publication of successful site mapping on website and recorded in project file. Publish evidence of internal senior sign-off confirming successful completion of SDRC 9.4 no later than 19 December 2017.
(9.5) Delta Proto-type completed by 26 March 2018: - Successfully complete testing to deliver a functional robotic platform to work in 100Barg pressure, travel 100m and negotiate two bends, providing condition assessment data (visual and wall thickness measurements) – A minimum of 10 offline tests; - successfully complete testing to deliver	A report will be completed and submitted by 26 March 2018. Publish that robotic platform has achieved measurables for SDRC 9.5 via project website and documented in project life. Publish evidence of internal senior sign-off confirming successful

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Successful Delivery Reward criterion	Evidence
functional robotic platform to work in 100Barg pressure, travel 100m and negotiate two bends, providing condition assessment data – a minimum of three online tests.	completion of SDRC 9.5 no later than 19 June 2018.
(9.6) Data analysis systems in place by 6 July 2018: - an analysis of data collected by PIE; - condition assessment algorithms derived by PIE; - a site condition has been developed; - condition assessment criteria for high pressure installations has been established.	Data analysis will be documented in project file and published on external website, detailing that the measurables for SDRC 9.6 have been achieved. Publish evidence of internal senior sign-off confirming successful completion of SDRC 9.6 no later than 19 December 2018.
(9.7) Completion of data analysis and Stage 4 by 3 September 2018: - review of all algorithms to determine changes to the required inspection equipment.	A data analysis completion report will be submitted by 3 September 2018. A report for the end of stage 4 will be produced and signify the successful delivery of condition assessment via robotic data collection and algorithm utilisation. Publish evidence of internal senior sign-off confirming successful completion of SDRC 9.7 no later than 19 December 2018.
(9.8) Implement into Business As Usual completed by 12 November 2018: - Design and manufacture and deliver a pre-commercialised in line inspection platform. - Specifications 100% complete check and approved for the platform that are acceptable by National Grid as specifications suitable for company use. - Deliver an agreed mobilisation strategy to NGGT including training package for all future operators. - Operating procedures (including health and safety) written and published on project website and recorded in project file. The robotic platform to be included as standard operating practise within NGGT asset management policy.	A report will be submitted by 12 November 2018 demonstrating that the measurable for SDRC 9.8 have been achieved. Publish evidence of internal senior sign-off confirming successful completion of SDRC 9.8 no later than 19 December 2018.

The maximum amount of the Gas NIC Successful Delivery Reward (which will not exceed the Network Licensee Compulsory Contribution) that the Project will be eligible for is £630,500.56.

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14. USE OF LOGO

The Funding Licensee and Project Partners, External Funders and Project Supporters may use the NIC logo for purposes associated with the Project but not use the Ofgem or Ofgem E-Serve logos in any circumstances.[8]

15. AMENDMENT OR REVOCATION

As set out in the Gas NIC Governance Document and this Project Direction, this Project Direction may be amended or revoked under the following circumstances:

(i) if the Funding Licensee considers that there has been a material change in circumstance that requires a change to the Project Direction, and the Authority agrees (paragraph 8.23 of the Gas NIC Governance Document); and/or

(ii) if Ofgem agrees to provide Contingency Funding, which requires the re-issue of the Project Direction (paragraph 8.42 of the Gas NIC Governance Document); and/or

(iii) if the Funding Licensee applies for Discretionary Funding to cover a decrease in Direct Benefits and the Authority decides it would be in the best interest of customers to make changes to the Project Direction before the Discretionary Funding would be awarded (paragraph 8.42 of the Gas NIC Governance Document).

16. HALTING OF PROJECTS

This Project Direction is subject to the provisions contained in paragraphs 8.30 to 8.34 of the Gas NIC Governance Document relating to the halting of projects. By extension, this Project Direction is subject to any decision by the Authority to halt the Project to which this Project Direction relates and to any subsequent relevant Funding Direction issued by the Authority pursuant to Special Condition 2F.

In the event of the Authority deciding to halt the Project to which this Project Direction relates, the Authority may issue a statement to the Funding Licensee clarifying the effect of that halting decision as regards the status and legal force of the conditions contained in this Project Direction.

NOW THEREFORE:

In accordance with the powers contained in the Gas NIC Governance Document issued pursuant to Part E of Special Condition 2F of the Licence the Authority hereby issues this Project Direction to the Funding Licensee in relation to the Project.

This Project Direction constitutes notice of reasons for the Authority's decision pursuant to section 38A of the Gas Act 1986.

[8] As listed in Box 1.5 in Section 1 of the Full Submission pro-forma.

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ANNEX 1: PROJECT BUDGET

Cost Category	Cost
Labour	£1,047,955.91
Equipment	£141,773.00
Contractors	£5,069,776.68
IT	0
IPR Costs	0
Travel & Expenses	£45,500.00
Payments to users	0
Contingency	0
Decommissioning	0
Other	0
Total	£6,305,005.59

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Appendix B
Ofgem revised project direction

Schedule to Project Direction

1. TITLE

Project Direction ref: NGGT / In Line Robotic Inspection of High Pressure Installations / 19 December 2014.

2. PREAMBLE

This Project Direction issued by the Gas and Electricity Markets Authority (the "Authority") to NGGT (the "Funding Licensee") pursuant to the Gas NIC Governance Document issued pursuant to Part E of Special Condition 2F (Network Innovation Competition) of the National Grid Gas Plc (NTS) Gas Transporter Licence (the "Licence") sets out the terms to be followed by the Funding Licensee in relation to In Line Robotic Inspection of High Pressure Installations ("the Project") as a condition of the Project being funded under the NIC and the Funding Return Mechanisms.[1]

Unless otherwise specified, defined terms in this Project Direction have the meaning given to them in Appendix 1 of the Gas NIC Governance Document.

References to specific sections of the Funding Licensee's Full Submission in this Project Direction are, for ease of reference, made by referring to the section number in the Funding Licensee Full Submission pro-forma.

3. ADEQUACY OF FUNDING AND FUNDING ALLOCATION

The Funding Licensee acknowledges that the budget allocations set out in Appendix 1 as restricted in certain circumstances described below will allow it to fulfil its obligations under this Project Direction.

4. CONDITION PRECEDENT

The Funding Licensee will not access any funds from the Project Bank Account until it has signed contracts with the Project Partners named in Table 1.

Table 1. Project partners

1. Synthotech Ltd
2. Premtech Ltd
3. Pipeline Integrity Engineers Ltd

5. COMPLIANCE

The Funding Licensee must comply with Special Condition 2F of the Licence and with the NIC Governance Document (as may be modified from time to time in accordance with Special Condition 2F and as modified and/or augmented in respect of the Project by this Project Direction) and with this Project Direction.

Any part of the Approved Amount that the Authority determines not to have been spent in accordance with this Project Direction (or with the Gas NIC Governance Document) is deemed to be Disallowed Expenditure.

Pursuant to Special Condition 2F Disallowed Expenditure is revenue received (whether by the Funding Licensee or another Licensee) under the NIC and Funding Return Mechanisms that the

[1] The Funding return Mechanism is defined in 2F (Network Innovation Competition) of the National Grid Gas Plc (NTS) Gas Transporter Licence.

Authority determines not to have been spent in accordance with the provisions of the Gas NIC Governance Document or with those of the relevant Project Direction.

Pursuant to paragraph 8.48 of the Gas NIC Governance Document, Disallowed Expenditure includes any funds that must be returned if the Project is halted without Ofgem's permission, any funds that have not been spent in accordance with the approved Project Budget contained within the Project Direction, and any unspent funds on the completion of the Project.

6. APPROVED AMOUNT FOR THE PROJECT

The Approved Amount is £5,674,505.03.

7. PROJECT BUDGET

The Project Budget is set out in Annex 1 to this Project Direction. The Funding Licensee must not spend more than 110% of any category total (e.g. "Labour") in Annex 1 without the Authority's prior written consent (such consent is not to be unreasonably withheld).

The Funding Licensee will report on expenditure against each line under the category total in the Project Budget, and explain any projected variance against each line total in excess of 5% as part of its detailed report which will be provided at least every six months, in accordance with paragraph 8.17 of the Gas NIC Governance Document. Ofgem will use the reported expenditure and explanation to assess whether the funding has been spent in accordance with the Gas NIC Governance Document and with this Project Direction.

For the avoidance of doubt this reporting requirement does not change or remove any obligations on the Funding Licensee with respect to reporting that are set out in the Gas NIC Governance Document.

8. PROJECT IMPLEMENTATION

The Funding Licensee must undertake the Project in accordance with the commitments it has made in the Full Submission approved by the Authority pursuant to the Gas NIC Governance Document and with the terms of this Project Direction. These include (but are not limited to) the following:

(i) undertake the Project in accordance with the description set out in Section 2 (Project Description);
(ii) provide a Network Licensee Compulsory Contribution of £630,500.56;
(iii) complete the Project on or before the Project completion date of 26 November 2018; and
(iv) disseminate the learning from the Project at least to the level described in Section 5 (Knowledge Dissemination).

9. PROJECT PROGRESS THROUGH PHASES

The Funding Licensee must satisfy itself that the successful delivery reward criteria ("SDRC") for each phase have been complied with before using funding for each subsequent phase. The Funding Licensee must secure appropriate internal senior sign-off before proceeding to the next phase and publish this internal sign off no later than when submitting to Ofgem the next detailed report due in accordance with paragraph 8.17 of the Gas NIC Governance Document.

The SDRC relating to each phase (9.1 to 9.8) are detailed in Table 3 of this Project Direction. The funds relating to each phase are identified in Table 2 below.

Table 2. Project budget by phase

Phase
9.1 Solution Development
9.2 Development Testing
9.3 Offline Trials
9.4 Online Trials
9.5 Delta Proto-type
9.6 Data Analysis Systems
9.7 Conduct Data Analysis
9.8 Implement into Business As Usual

10. REPORTING

Ofgem will issue guidance (as amended from time to time) about the structure and content of the reports required by paragraph 8.17 of the Gas NIC Governance Document. The Funding Licensee must follow this guidance in preparing the reports required by paragraph 8.17 of the Gas NIC Governance Document.

As required by paragraph 8.22 of the Gas NIC Governance Document, the Funding Licensee must inform the Authority promptly in writing of any event or circumstance likely to affect its ability to deliver the Project as set out in its Full Submission.

11. COST OVERRUNS AND DIRECT BENEFITS

The maximum amount of Discretionary Funding that the Funding Licensee can request as additional funding for cost overruns relating to the Project is 5% of the Approved Amount.[2]

12. INTELLECTUAL PROPERTY RIGHTS (IPR)

In Section 5 of its Full Submission (Knowledge Dissemination) the Funding Licensee has stated that the Project does conform to the default IPR arrangements set out in chapter 9 of the Gas NIC Governance Document and must therefore undertake the Project in accordance with the default IPR arrangements.

13. SUCCESSFUL DELIVERY REWARD CRITERIA

The Project will be judged by the Authority for the purposes of the NIC Successful Delivery Reward against the Successful Delivery Reward Criteria set out in Table 3 below (that comply with paragraphs 5.26-5.29 of the Gas NIC Governance Document).[3]

[2] This is the amount requested by the Funding Licensee in its Full Submission.

[3] These are the Successful Delivery Reward Criteria set out in the Funding Licensee’s Full Submission, with the additional evidence of internal senior sign-off added by Ofgem in accordance with the conditions in this Project Direction.

Table 3. Successful Delivery Reward Criteria

Successful Delivery Reward criterion	Evidence
(9.1) Solution Development completed by 30 October 2015: - a concept design study of robotic platform completed and scope clearly defined; - created and validated 3D models for each trial site accurately representing pipework configuration; - designed a launch and retrieval device to allow robot insertion into high pressure; - robotic platform conceptual design(s) completed, computer models and 3D prints produced, conceptual design(s) demonstrates potential to achieve objectives of travelling 100m around 2 bends taking visual readings and wall thickness measurements in	A report will be submitted by 30 October 2015 demonstrating that these measurable activities have taken place. Documentation for SDRC 9.1 uploaded to the internal sharepoint site and project file, external version uploaded to website. Publish evidence of internal senior sign-off confirming successful completion of SDRC 9.1 no later than 19 December 2015.
(9.2) Development Testing completed by 9 September 2016: - robot access and inspection routes for all three trial sites development and validated including the formulation of Formal Process Safety Assessments; - the offline testing facility designed and distributed for competitive tender. Contract in place for its completion; - manufacture of a robotic platform primary solution in order to test and further develop robotic design and meet the objectives of withstanding pressure of up to 100Barg whilst travelling 100m, negotiating two bends and taking visual and wall thickness measurements. This will involve successful bench testing (simulation) in a controlled environment of up to 6m with one bend;	A report will be submitted by 9 September 2016 demonstrating that these measurable activities have taken place. Documentation for SDRC 9.2 uploaded to internal sharepoint site and project file, external version uploaded to website. Publish evidence of internal senior sign-off confirming successful completion of SDRC 9.2 no later than 19 December 2016.
(9.3) Successful Offline trials completed by 30 April 2017: - offline test rig manufactured and positioned at readiness to conduct offline trials; functional robotic platform manufactured and tested on offline testing facility to conduct visual inspection and wall thickness measurements – a minimum of 10 offline tests will take place; - establish and publish Disaster Recovery Plan for live trial sites; - successful data collection/problem identification by robotic platform in response to test scenarios.	A completion report will be submitted by 30 April 2017 which will ensure the online trials at the specified live sites: Bacton, Aylesbury and Cambridge can begin. Documented evidence that robotic platform can negotiate measurables for SDRC 9.3 via project website. Publish evidence of internal senior sign-off confirming successful completion of SDRC 9.3 no later than 19 June 2017.

- launch and retrieval device manufactured to withstand pressure of 100Barg and minimise venting.	
(9.4) Successful Online trials completed by 30 September 2017: - successful insertion of launch and retrieval device into all three live sites; - undertake testing to deliver a functional robotic platform and associated tools to work up to 100Barg pressure, travel 100m, conduct visual inspection and wall thickness measurements – a minimum of 3 online tests per site will take place.	A completion report will be submitted by 30 September 2017. Document evidence that robotic platform can negotiate measurables for SDRC 9.4 via project website. Publication of successful site mapping on website and recorded in project file. Publish evidence of internal senior sign-off confirming successful completion of SDRC 9.4 no later than 19 December 2017.
(9.5) Delta Proto-type completed by 26 March 2018: - Successfully complete testing to deliver a functional robotic platform to work in 100Barg pressure, travel 100m and negotiate two bends, providing condition assessment data (visual and wall thickness measurements) – A minimum of 10 offline tests; - successfully complete testing to deliver functional robotic platform to work in 100Barg pressure, travel 100m and negotiate two bends, providing condition assessment data – a minimum of three online tests.	A report will be completed and submitted by 26 March 2018. Publish that robotic platform has achieved measurables for SDRC 9.5 via project website and documented in project life. Publish evidence of internal senior sign-off confirming successful completion of SDRC 9.5 no later than 19 June 2018.
(9.6) Data analysis systems in place by 6 July 2018: - an analysis of data collected by PIE; - condition assessment algorithms derived by PIE; - a site condition has been developed; - condition assessment criteria for high pressure installations has been established.	Data analysis will be documented in project file and published on external website, detailing that the measurables for SDRC 9.6 have been achieved. Publish evidence of internal senior sign-off confirming successful completion of SDRC 9.6 no later than 19 December 2018.
(9.7) Completion of data analysis and Stage 4 by 3 September 2018: - review of all algorithms to determine changes to the required inspection equipment.	A data analysis completion report will be submitted by 3 September 2018. A report for the end of stage 4 will be produced and signify the successful delivery of condition assessment via robotic data collection and algorithm utilisation. Publish evidence of internal senior sign-off confirming successful completion of SDRC 9.7 no later than 19 December 2018.

(9.8) Implement into Business As Usual completed by 12 November 2018: - Design and manufacture and deliver a pre-commercialised in line inspection platform. - Specifications 100% complete check and approved for the platform that are acceptable by National Grid as specifications suitable for company use. - Deliver an agreed mobilisation strategy to NGGT including training package for all future operators. - Operating procedures (including health and safety) written and published on project website and recorded in project file. The robotic platform to be included as standard operating practise within NGGT asset management policy.	A report will be submitted by 12 November 2018 demonstrating that the measurable for SDRC 9.8 have been achieved. Publish evidence of internal senior sign-off confirming successful completion of SDRC 9.8 no later than 19 December 2018.

The maximum amount of the Gas NIC Successful Delivery Reward (which will not exceed the Network Licensee Compulsory Contribution) that the Project will be eligible for is £630,500.56.

14. USE OF LOGO

The Funding Licensee and Project Partners, External Funders and Project Supporters may use the NIC logo for purposes associated with the Project but not use the Ofgem or Ofgem E-Serve logos in any circumstances.[4]

15. AMENDMENT OR REVOCATION

As set out in the Gas NIC Governance Document and this Project Direction, this Project Direction may be amended or revoked under the following circumstances:

(i) if the Funding Licensee considers that there has been a material change in circumstance that requires a change to the Project Direction, and the Authority agrees (paragraph 8.23 of the Gas NIC Governance Document); and/or

(ii) if Ofgem agrees to provide Contingency Funding, which requires the re-issue of the Project Direction (paragraph 8.42 of the Gas NIC Governance Document); and/or

(iii) if the Funding Licensee applies for Discretionary Funding to cover a decrease in Direct Benefits and the Authority decides it would be in the best interest of customers to make changes to the Project Direction before the Discretionary Funding would be awarded (paragraph 8.42 of the Gas NIC Governance Document).

16. HALTING OF PROJECTS

This Project Direction is subject to the provisions contained in paragraphs 8.30 to 8.34 of the Gas NIC Governance Document relating to the halting of projects. By extension, this Project Direction is subject to any decision by the Authority to halt the Project to which this Project Direction relates and to any subsequent relevant Funding Direction issued by the Authority pursuant to Special Condition 2F. In the event of the Authority deciding to halt the Project to which this Project

[4] As listed in Box 1.5 in Section 1 of the Full Submission pro-forma.

Direction relates, the Authority may issue a statement to the Funding Licensee clarifying the effect of that halting decision as regards the status and legal force of the conditions contained in this Project Direction.

NOW THEREFORE:

In accordance with the powers contained in the Gas NIC Governance Document issued pursuant to Part E of Special Condition 2F of the Licence the Authority hereby issues this Project Direction to the Funding Licensee in relation to the Project.

This Project Direction constitutes notice of reasons for the Authority's decision pursuant to section 38A of the Gas Act 1986.

ANNEX 1: PROJECT BUDGET

Cost Category	2016 Budget
Labour	£936,061.38
Equipment	£141,773.00
Contractors	£5,424,436.16
IT	£0.00
IPR Costs	£0.00
Travel & Expenses	£45,500.00
Payments to Users	£0.00
Contingency	£0.00
Decommissioning	£0.00
Other	£0.00
TOTAL	**£6,547,770.55**

Appendix C
Stage 5 report – Synthotech

SYNTHOTECH

PROJECT GRAID

Epsilon – Stage Gate Report

Stage 5 – Business Readiness

G01-NGGT-R-0012 Rev 1.1

20 November 2018

Table of contents

Version Control

Change record

Version	Status	Date	Author(s)	Summary of changes
0.1	Draft	10/10/18	John White	New document
0.2	Draft	19/11/18	John White & Wez Little	Amends and Directors Summary added
1.0	Release	20/11/18	John White & Wez Little	Final review
1.1	Release	23/11/2018	John White & Wez Little	Comments from Dave Hardman added

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Distribution

Name	Organisation unit	Format
Simon Langdale	Synthotech	PDF
Bill McQueen	Synthotech	PDF
John White	Synthotech	PDF
Quentin Mabbutt	NGGT	PDF
David Hardman	NGGT	PDF
Josh Blake	NGGT	PDF

List of abbreviations

3D	Three Dimensional Computer Image
AGI	Above Ground Installation
Alpha	Stage 1: Prototypes 3d Printed / Subtractive Manufactured
ATEX	ATmosphères EXplosives
Beta	Stage 2: Prototype capable of bench top testing
BSI	British Standards Institute
CFD	Computational Fluid Dynamics
ConOps	Concept of Operations
COTS	Commercial Off The Shelf product
CTR	Contract Transition Review
EC	European Council
EU	European Union
FEA	Finite Element Analysis
FMEA	Failure Mode Effect Analysis
Gamma	Prototype capable of field trials
GRAID	Gas Robotic Agile Inspection Device
HSE	Health and Safety Executive
HSWA	Health and Safety at Work Act
IGEM	Institution of Gas Engineers and Managers
IP	Intellectual Property
IPR	Intellectual Property Rights
ISO	International Standards Organisation
LED	Light Emitting Diode
MOP	Maximum Operating Pressure
NDT	Non-Destructive Testing
NGGT	National Grid Gas Transmission
NIC	Network Innovation Competition
PIE	Pipeline Integrity Engineers
PIG	Pipeline Inspection Gauge
PMC	Pipeline Maintenance Centre
PSP	Project Strategic Partner
PSR	Pipeline Safety Regulations
PSSR	Pressure Systems Safety Regulations
SDRC	Successful Delivery Reward Criteria
SG	Stage Gate
SME	Subject Matter Experts
STaRS	Synthotech Test and Research Site
UMS	Umbilical Management System

Executive Summary

This document is the closure report for Stage 5 of Project GRAID. This report provides a high-level summary of the work undertaken.

The report provides some highlights of the first 4 stages along with work undertaken to close the project.

The following are the key outputs since the last report (10th October 2018)

- The robot and associated equipment has passed (25th October 2018) its final pressure acceptance test at 77 barg nitrogen and has been handed over to NGGT for storage at PMC Ambergate.
- The project scope has been 100% verified and turned into the final specification.
- The mobilisation cost calculator has been developed to enable operational costs for new inspection sites to be determined.
- The plan for training has been submitted and will ultimately depend on suitable engineers being identified to undertake the work.
- It has been agreed Synthotech will undertake all future inspection runs, maintenance or modification until such a time that this has been handed over to an agreed competent 3rd party.
- Documents required for training have been identified to allow suitable people to be trained.
- Senior Stakeholder meeting to look at how NGGT will utilise GRAID in their asset health strategy tool kit

The project formally completes on the 24th November 2018. The project has been successful in meeting its original, and in many cases outperformed its original SDRC targets.

Project GRAID has been a multiple award-winning project that has seen the successful development and deployment of a robot capable of undertaking both visual and wall thickness inspection of assets in the National Transmission System (NTS).

1. Introduction

This document is the closure report for Stage 5 which is the final stage of the GRAID project and therefore the completion Project GRAID. It focuses on reviewing the performance of the GRAID system. It provides a high-level summary of the work undertaken.

2. Previous Project stages

The project has now completed the five stages set out in the original NIC submission.

Stage One (24th November 2014-30th October 2015) focused on the development of concept designs for the platform. This stage built the case for the robot and identified the operational scenario the robot would function in. 3 concept designs were proposed, and one chosen to take forwards for further development. Four stage gate reports were generated during this stage and can be found in the annex of this report.

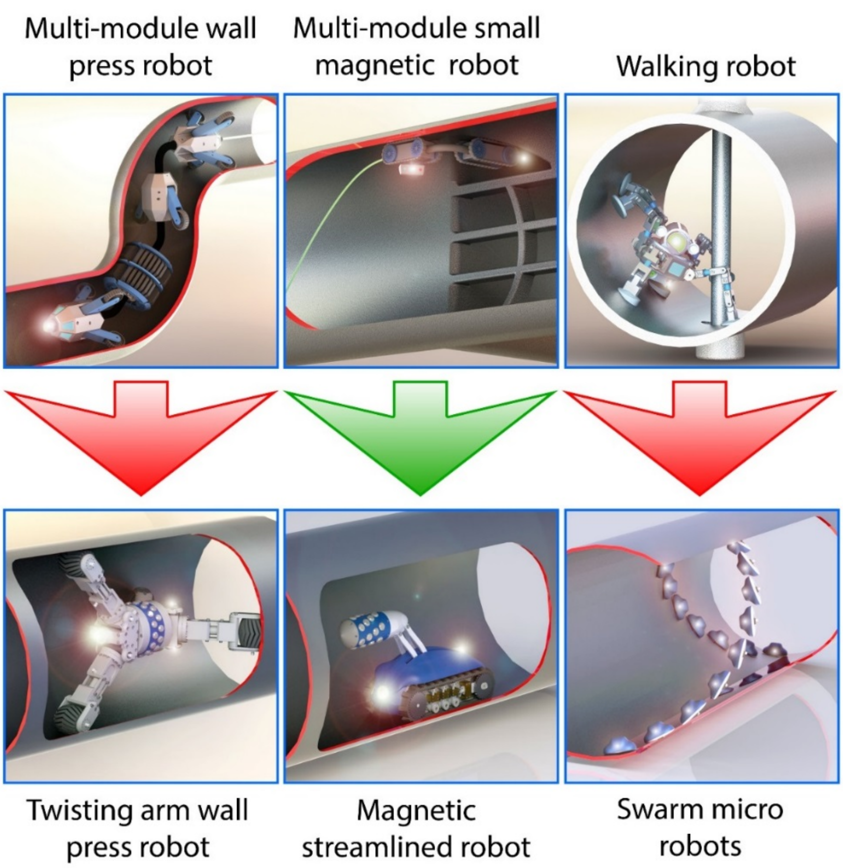


Figure 1. Concept development during stage 1

Stage Two (30th October 2015-9th September 2016) developed the magnetic concept chosen from Stage One into a prototype robot. This stage involved the manufacture and build of the first GRAID robot (not to be used at pressure). This culminated in a demonstration day at PMC Ambergate in September 2016.

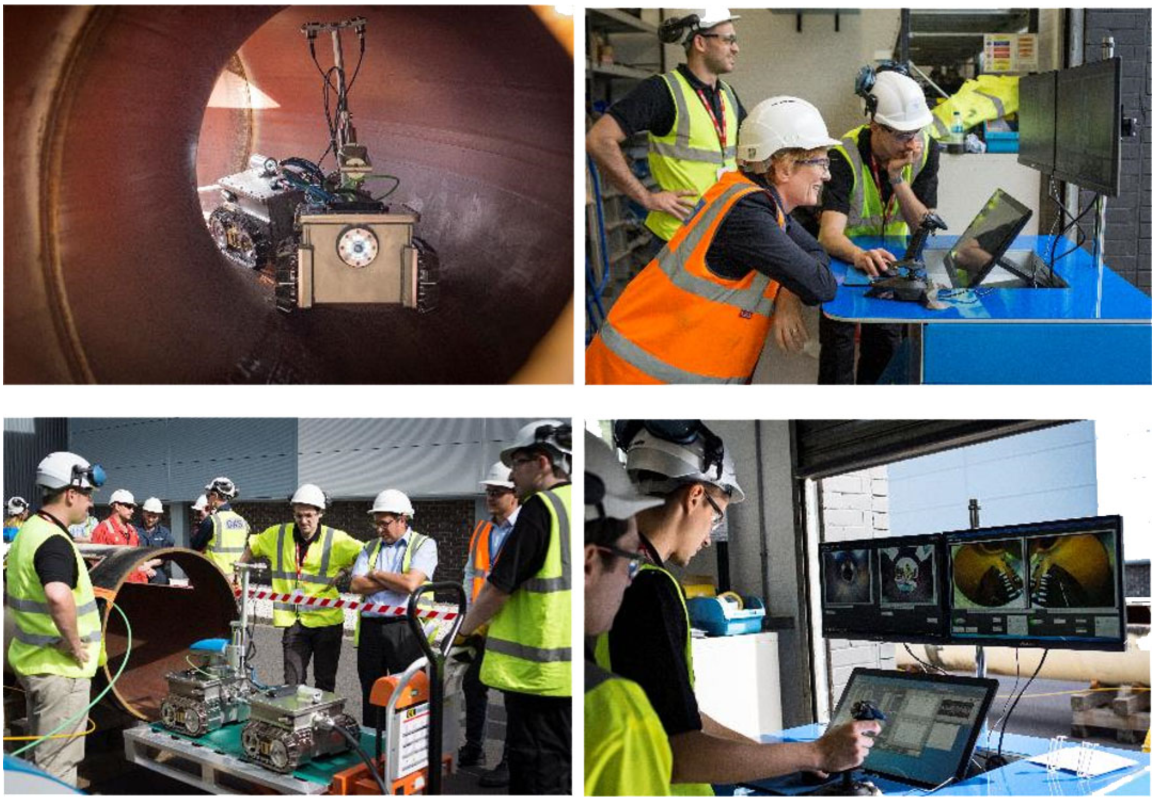


Figure 2. Beta demonstration event

Two further stage gate reports were produced during the stage. These can be found in the annex of this report.

Stage Three (9th September 2016-6th July 2018) focused on building a robot and associated system to be suitable for use at pressure (100 barg). The team also integrated the NDT system in to the platform, with Sonemat being appointed to the project. They have a unique EMAT system that was to be developed to enable wall thickness measurements to be taken.

Additionally during this phase the team started the delta design works ahead of time so that the platform that passed the final assurance test was as close to the finished solution as possible, there were a significant number of developments to the electronics, software, tracks, connectors and vision.

Offline trials were completed at STaRS and DNV Spadeadam to prove the robot could operate on a live AGI site. This phase had the greatest challenges, learning and opportunities in the project. The chassis manufacturing issue played a significant role in the testing delays, while new parts were manufactured. The project team did however overcome all the issues encountered to achieve the offline testing goals.

At the end of 2017 discussions between National Grid Innovations and Operations teams lead to the creation of a Go/No Go acceptance criteria for the robotic platform. This would allow for the robot to be used on 'live' trials on the National Transmission System. This acceptance testing was completed between March and May 2018.

The final part of Stage 3 was the first online trial at Pannal AGI in June 2018. The robot operated successfully for two weeks on site and performed successful visual and NDT inspection. Three stage gate reports were produced during this time and can be found in the annex of this report.

Figure 3. The robot at Pannal AGI

Stage four (6th July 2018-3rd September 2018) covered the second online trial, at Bacton Terminal in August 2018. The robot again performed visual and NDT inspection of the site successfully. The NDT was also developed with a standalone system tested to prove the accuracy of the sensors. The stage gate report can be found in the annex of this report.

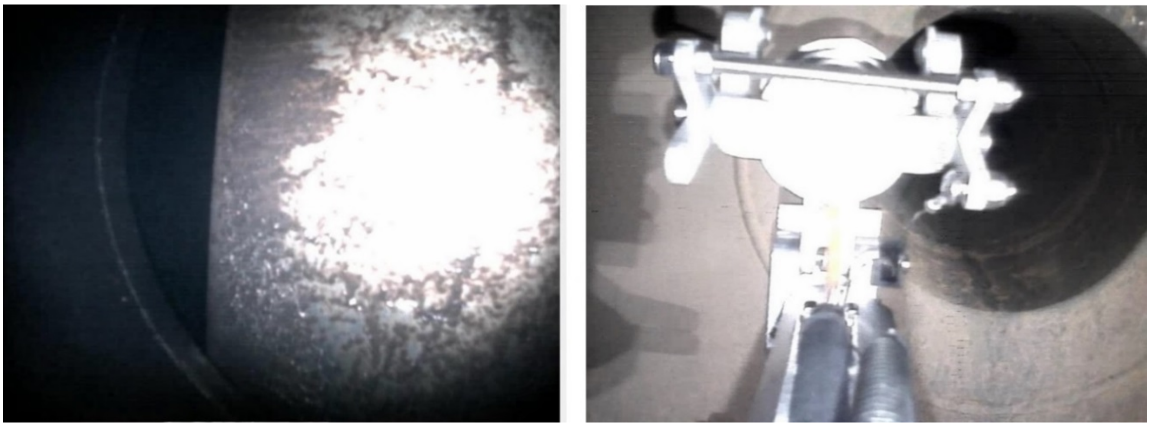


Figure 4. Visual inspection from Bacton

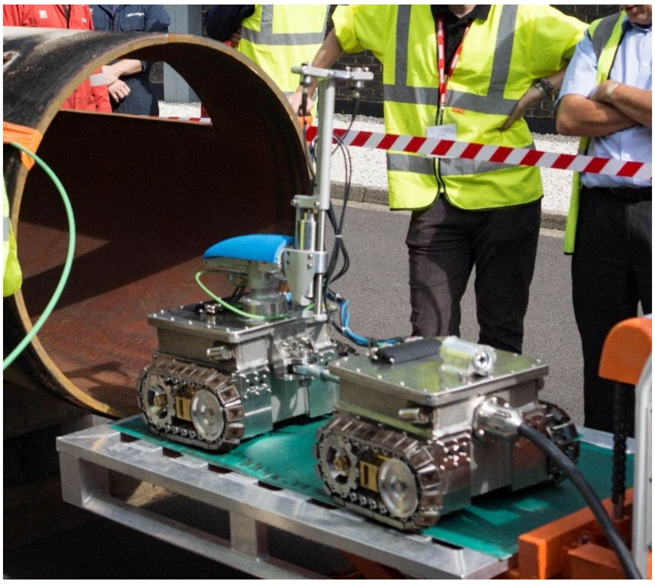
3. System Developments and Maintenance

This section of the report gives an overview of key improvements to the system undertaken since the Bacton trial. These are all minor changes but are considered completion of the Delta Design works, in readiness for the handover pressure test.

3.1 Robot

Two of the side cameras have been changed to improve the vison on the robot. These have a higher resolution and are angled further out from the robot. These should allow better visibility of the pipe surface and greater understanding of the relative positions of the two modules.

The robot tracks have been replaced as a precaution after Bacton. The tracks were however in a good condition post trial once they have been cleaned and checked for damage.



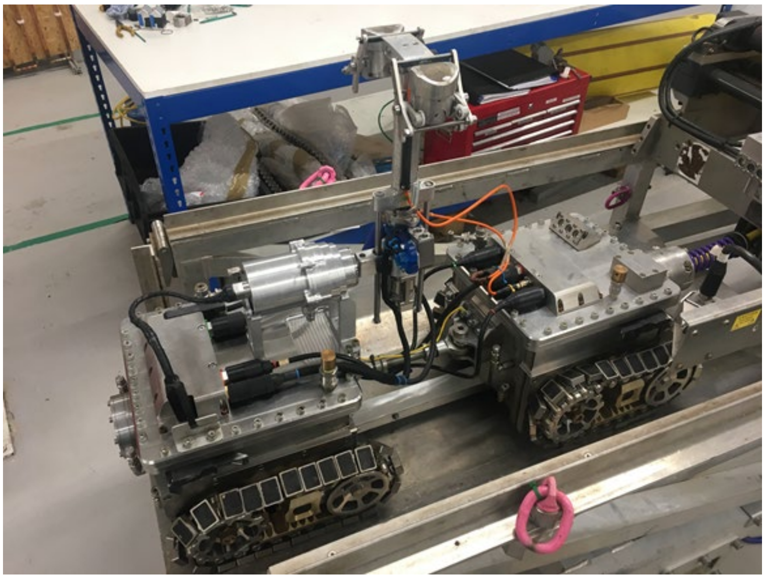


Figure 5. Beta robot on the left from (06/09/2016) Delta Robot on the right (20/09/2018)

3.2 NDT

The only change was to ensure two crimps rather than one were fitted to the wiper mechanisms on the NDT cleaning system. This followed an issue at Bacton where one of the wiper wires broke during operation. Thorough factory testing has shown the double crimp system does not fail, even after multiple deployments.

3.3 UMS

The UMS system was fitted with a new pressure sensor to replace the item that failed at Bacton. Rather than replace with the same sensor, a decision was made to use the same sensor as in the robot. This means less components need to be held in stock for spares in future and has reduced the cost of the sensor by over £500.

The modification of the UMS to allow a greater pull back was considered. This was based on the incline transition issue raised at Bacton. The drum drive was considered for upgrade but due to the relatively high cost for re-engineering, and the lack of testing time available, this was deemed to be out of scope for the project. This will be undertaken once another site for use has been identified and a suitable test plan can be implemented to prove the system update will work.

3.4 Control Centre

The control centre had a minor update to recalibrate the UMS pressure sensor.

The video software was upgraded to enable all video feeds from the robot to be recorded in higher resolution. This will improve the quality of inspection data from the robot.

4. Handover Pressure Test

The robot was handed over to NGGT on 25/10/2018 after a successful pressure test. This was conducted at PMC Ambergate.

Figure 6. Robot after final pressure test

The robot and UMS were installed into the launch vessel and tested at 77 bar nitrogen for 2 hours. The robot was stable and functioned throughout the test. [redacted]

5. Project Scope

The scope has now been used to create the product specification document.

AREA	TOPIC	IN SCOPE	OUT OF SCOPE
FLOW	Operating pressure	0-94 Barg natural gas.	Vacuum conditions, or a pressure greater than 94 Barg.
	Temperature range	0-40 degrees Celsius.	Sub-zero operations, or above 40 degrees Celsius.
	Flow Speed	0-5m/s maximum flow.	
SITE	Linear site distance travelled	100m max distance from the launcher or 2 bends (90 degrees).	more than 100m , or negotiating 100m over three 90 degree bends.
	Bend negotiation	Two 90 degree bends.	More than two 90 degree bends, Orifice plate, Compressors, Generators, Heat pumps, Butterfly valves, One-off fabricated components, Mitre joints, , Siphon pots, Process drains, Thermowells.
	Bend diameters	0 D and Above.	
	Reducers	900-750mm concentric and eccentric.	
	Below Ground transitions	30 degree inclines, 45 degree inclines.	90 degree inclines.
	Ball Valves	750 and 900mm.	less than 750mm ID, Slam shut valves, Plug valves.
	Tee negotiation	750mm and 900mm Tee.	Barred Tees.
OPERATIONS	NDT Operating Flow rate	0-3.5m/s in either direction.	Beyond 3.5m/s in either direction.
	Logistics of transport	NGGT will transport the robotic platform to and from AGI site.	Transport of robotic platform on and within an AGI site (i.e. PMC to be responsible for moving the robot and launcher on and within an AGI site).
	Operator of the robotic platform	Synthotech to operate the robot on site. All other works on site by PMC or another approved contractor.	Operated by non-competent person. For Synthotech to be liable for the decisions and actions of the third party operator.
NDT	Targeted defects	Metal loss corrosion.	Cracks, Pins holes, Welds, Stress corrosion cracking.
	Use of existing systems	EMAT probe wall measurement system on swinging arm.	Any other NDT systems.
	Sensors	Front vision camera, Rear Vision Camera, supplementary camera vision, LED lighting, Internal and External pressure sensors, internal temperature sensors, odometer.	flow measurement.
Electronic	Location device	Battery powered signal locator.	
	Communications	Hard wired (tethered) systems.	Wireless systems.
	ATEX	Not ATEX approved. Controlled via process.	ATEX Approval.
	Power source/comms	Tether umbilical feeding power to the robot and data to/from the robot.	
Mechanical	Form of the robot	twin hull tracks based robotic platform with magnetised drive enhancement.	
	Launcher vessel	UMS to be positioned within the launch vessel.	UMS outside the launch vessel requiring 100 bar running seal.

Table 1 – Project Scope.

The specification document (G01-SPC-001) covers the overall system (robot and UMS). This technical specification details the systems capabilities, features, limitations and the range of operational conditions.

1. Operational Capabilities
2. Environmental Specification
3. Electrical rating
4. Operation of GRAID

Further documents have been created for the individual sub systems:

1. Control Centre -G01-SPC-006
2. Postman Trolley -G01-SPC-007
3. Driver Cabinet – G01-SPC-008
4. Transportation Trolley – G01-SPC-009

These documents can be found in the annex to this report.

The specification documents show the robotic platform is capable of operating in the NTS and detail operating parameters and its tested limitations. The robot has proven its ability to meet the project goals set at the beginning of the project.

6. Stakeholder engagement

The robot and UMS were displayed at the Low Carbon Networks & Innovation Conference (LCNI) in Telford on the National Grid Stand. This received lots of positive feedback. This included innovation teams from all the gas distribution networks and OFGEM.

Figure 3. Robot on display at LCNI

7. Mobilisation

The robot has now been handed over to National Grid and is located at PMC Ambergate. Discussions are ongoing to use the robot at several potential AGI sites.

After discussion with NGGT at the monthly meetings a cost calculator has been developed to look at the operational costs for undertaking a survey. This is based on the mobilisation plan published in the stage gate 4 report.

The inspection is split into 4 phases:

1. Robot preparation
2. Site preparation
3. Number of inspection weeks
4. Demobilisation

The number of inspection weeks can be altered if more/less time is required on site.

GRAID site cost calculator - Moffat

Phase	Week	Day	Activity	Location	Accomodation: Hotels, subsistance	Robot Operator Staff: System Technician	Robot Operator Staff: Robot Operators	Transport: Cost per mile	Network Staff: Pressure Technician	Network Staff: Decontamination Technician	Equipment: HIAB	Equipment: Crane	Equipment: Generator	Equipment: Compressed Air	Equipment: Nitrogen	
				Cost per day	[redacted]											
Robot preparation	1	1	System check	Workshop		2										
		2	Final Pressure test (if required)	Third Party Site	2	2		170	2						1	
		3	Pressure test issue repair contingency	Workshop		2										
		4	Pressure test issue repair contingency	Workshop		2										
		5	Pressure test issue repair contingency	Workshop		2										
			Transport Launch Vessel to site	AGI							1					
Site preparation	2	6	Pressure test issue repair contingency	Workshop	2	2										
			Fit Launch vessel/bridal - Pressure Test	AGI					3		1	1			1	
		7	Pressure test issue repair contingency	Workshop		2			2							
		8	Pressure test issue repair contingency	Workshop		2			2							
		9	Transport robot to Site	AGI							1					
		10	Robot setup and site familiarisation	AGI	2		2									
Inspection week(s)	X	11	(Re-install) Robot pressurisation and/or first run	AGI	4		4		1				1		1	
		12	Second run	AGI	4		4		1				1			
		13	Third run	AGI	4		4		1				1			
		14	Forth run, depressurisation	AGI	4		4		1				1			
		15	(De-pressurisation) clean and maintenance	AGI	4		4		2	2	1		1	1	1	
			Transit to/from Moffat, start/end per week (x2)	AGI/Home												
Number of weeks planned on site				2	40	0	40	0	12	4	2	0	10	2	4	TOTALS
Demobilisation	X+1	Y1	Detach Launch vessel from pipework	AGI					3	2	1	1		1	1	
			Transport robot and launch vessel from site	Workshop							1					
		Y2	System check	Workshop		2										
		Y3	**Replace tracks + general maintenance**	Workshop		2										
		Y4	**Replace tracks + general maintenance**	Workshop		2										
		Y5	**Replace tracks + general maintenance**	Workshop		2										
			Documentation, video editing and data collation	Office			6									Total cost
					[redacted]											

Robot Operator Total [redacted] | **Network Operations Total** [redacted] | **TOTAL** [redacted]

1.System technician – capable of repair and maintenance of the robotic platform.
2.Robot operator- capable of repairing and operating the robotic platform.
3.Pressure technician – capable of pressure testing and installing/operating the launch vessel.
4.Decontamination technician- capable of cleaning the robotic platform after use.

Table 2 – Cost calculator for Moffat inspection.

The current costs for each role are only approximate at this stage and will need to be agreed with NGGT. Other costs incurred by NGGT during the operation will also need to be added to the sheet.

Synthotech are the only trained operatives of the robot at this stage so would plan to carry out all initial maintenance, modification and driving/operating of the robot. Synthotech are however committed to training NGGT or other users if requested. Identification of suitable operatives and technicians would help tailor a training package to them.

Synthotech have developed several procedures for the use and support of the robot. These documents would need to be taught to new maintenance engineers. These cover the basic tasks on the robot platform and general health checks.

The initial documents that would need to be trained for maintenance are:

1. G01-PRO-002 – GRAID bolt Toque Diagram. This document ensures the robot/pressure housings have been correctly assembled with the required torque settings.
2. G01-PRO-004 - Safely Depressurising Potentially Pressurised Chambers on GRAID Robot. This document details how to safely remove any trapped pressure from within the robot during removal from the launch vessel.
3. G01-PRO-006 - Cable Inspection Checklist. This document is a record of the inspections undertaken on key electrical cables and plugs on the system.
4. G01-PRO-009 - System Condition Checklist. The list followed before use to ensure the system has been built/maintained correctly.
5. G01-PRO-010 - System Setup and Dismantling Procedure. How to set up the system ready for use on site.
6. G01-PRO-024 - Procedure for Oil Filling Compensation Chambers. Details on oil filling the compensated chambers of the robot to protect the electronics components.
7. G01-PRO-026 - GRAID Pressure cycle log. The log of pressure cycles the robot chassis has undertaken.
8. G01-PRO-028 - Pressure Testing of Robot Chassis on Assembly. How to safely pressure test the robot chassis assemblies.
9. G01-PRO-029 - Robot Chassis Purge to Remove Oxygen. How to ensure a nitrogen purge of the Robot and UMS is completed, ensuring the robot is safe for use.
10. G01-SPC-003 – User Interface Guide. Manual of the controls for the robot and UMS systems.
11. G01-PRO-015 – GRAID Assembly Techniques. General assembly of common components on the robotic platform.
12. G01-PRO-032 – Changing the Track Assembly. Changing and Tensioning the robot tracks.
13. G01-PRO-033 – Swapping NDT. Changing NDT module from 750mm to 900mm NDT.

The maintenance engineers would also need to be familiar with the Assembly Drawing packs and Wiring Diagrams of the system for any fault finding and fitting of replacement parts. Complex repairs and/or fault finding would need to be assessed by Synthotech and may require the parts returning to Synthotech for investigation or rebuilding.

Driving the robot on site requires a lot of time to ensure any pilot can fully understand all the visual and measurement data being collated. Driving the robot requires a skill and patience that can only be gained by hours of practice.

Synthotech would recommend at least 50 days of varied system and driving experience before anyone would become fully competent at driving in all pipe sizes and geometries expected. This training would need to be undertaken in dead and live pipe scenarios and as such sessions at STARS and Spadeadam would be recommended. Any operation on a live site would also be beneficial to shadow a trained Synthotech operative for at least one inspection.

Additional documents for operation of the robot are:

1. G01-PRO-005 - Emergency Recovery Plan – GRAID Robot. This document details the steps to take in the event of an emergency on site.
2. G01-PRO-011 - System Loading and Unloading Procedure. How to launch and retrieve the robot on site.
3. G01-PRO-019 -Moving and Lifting Procedure - GRAID robot and Trolley. How to safely move the system around on site.
4. G01-PRO-025 - System Check Logsheet. Manual log sheet for the robot and UMS filled out during robot operation.
5. G01-SPC-005 - On Site COSHH products register. List of products used during normal operation and the associated safety information.
6. G01-RPT-031 - Onsite Maintenance. Document detailing what maintenance can be carried out on site during operations.

8. Future Developments

The project team at Synthotech have discussed several future developments for the platform. These can be split into two main categories:

1. Increase efficiency and performance of a future GRAID platform
2. Alternate uses for the platform

GRAID MK2

These were split onto the following key areas:

1. Faster NDT system with greater resolution
2. Improved vision for better in pipe knowledge
3. Increased pipe size range

4. Vertical climbing ability
5. Power reduction to increase safety
6. Drive improvements to reduce size
7. Weight reduction to increase agility
8. Increased operational range to 300+m
9. Electronics modules for easy service and repair
10. Smaller Launch Vessel
11. Temporary launch sites to decrease connection costs
12. Automated launch process to speed up on site process and safety
13. Smaller transportation system

Alternate uses

1. Operation in 'dead' pipelines
2. Pipe cleaning and debris extraction
3. Plug insertion and pipe isolation
4. Valve service
5. Pipeline repair
6. Long term inspection
7. Analysis and sampling of in pipe environment

Synthotech, with support from Premtech and PIE have submitted an NIC proposal (NIC-RRRI) to NGGT for further development of the platform to enable it to undertake alternate uses on the NTS. This has focused on the alternate uses listed above as its primary objectives. Many of the improvements to the system would also be incorporated to further enhance the platform if the bid is successful.

The team have also been reviewing potential inspection site drawings at Chelmsford, Kirriemuir, Moffatt and St Fergus. These sites have been identified as potential inspections for the current platform.

9. Project Directors Summary

Project GRAID has been nearly 45 months (4 ¾ year) of work for Synthotech, from initial idea and approach to NGGT, to a successful working platform. These numbers would be significant for any organisation but are possibly more significant for a SME.

GRAID has been a fantastic journey for Synthotech as a business. It has provided so many fantastic memories and achievements. It's fair to say that there have been challenges, learning and unexpected opportunities. We have through determination, belief, and collaboration delivered with our partners, a game changing piece of technology. Every contributor to the project should be immensely proud of this accomplishment.

In the early stage of the project much focus was placed on the where, what, and why, developing a clear specification for the robot. With hindsight this should have been done during the submission stage as there were significant changes to the initial specification (i.e. not 40m/s but nearer 5 m/s.) We learnt more about the NTS, the challenges of getting anything into the system, the complex geometry but more importantly why this would be critical to NGGT in the future.

There were many challenges in the early stages as the four organisations learned how to communicate and how each business differed, but a real team and comradery was borne, which even with the changes of personnel has stood the test of time. Without this trust and team work the challenges encountered during the project would have likely seen it fail or fall short of what was required.

Once a concept was developed and manufacture began, the hard work and dedication of the team became clear to see. The first prototype, showed its potential and really put the project on the world stage, this was going to happen.

There were as stated in the documents, issues with the initial build when we took it to pressure. The design intent was correct, the failure was on the 3rd party manufacture. This surely can be forgiven as it had never been done before, and subsequent manufacture by another group of 3rd parties proved just how hard it was to make a robotic platform that can protect its electronics, whist being agile at 100 barg with 5 m/s flow.

The hardest stage by far was the acceptance testing for the offline trials. This pushed not only the robot but the mental resilience of all involved, having to spend significant periods of time at Spadeadam, refining, hardening and proving the capability of the platform. The moment the platform had completed its first 100 barg pressurisation was certainly one the proudest moments in my career and in the history of Synthotech. Proving that dedication and belief will overcome any Engineering challenge.

The project progression from 100 barg test to working on a "live" network was monumentally quick, in a little over six weeks we were using the robot on a function NTS site at Pannal. Two weeks of "mundane" issues were the perfect result for all concerned, the robot performed well, providing 1000's of points of new asset health data in providing the first internal inspection of the pipeline in nearly six decades.

Merely weeks later the platform was again in action at Bacton, one of the key sites in the NTS and for nearly 5 years the intended focus of GRAID and the ultimate confirmation of the project and developments undertaken.

The collective team have delivered a ground-breaking project. The project and the team have been the recipients of many well-deserved awards and commendations. I truly believe the greatest reward for all involved is knowing that they used the innovation funding mechanism, to benefit consumers and have contributed to the next step in management of complex assets.

Synthotech are extremely honoured to have played a part in a project that from its outset chose to push boundaries of the possible, to prove that innovation is achievable with collaboration. Working together in partnership in pursuit of a shared goal and vision will always conquer any challenge and be the most rewarding personally and professionally.

So in reflection, Project GRAID has been an amazing journey, it is therefore with much sadness that this project draws to a close, but with much pride and admiration of all those who played a part no matter how small or large. More importantly with optimism and happiness that this is only the start of the journey for GRAID and its utilisation on the UK National Transmission System.

10. Conclusion

The project has proved successful in meeting the NIC SDRC requirements set out and has been successfully operated on two National Grid AGI's.

Synthotech, working in collaboration with multiple (over 50) project partners and suppliers believe we have a world class platform that is ready to inspect AGI sites for NGGT.

The system improvements recommended in this report would greater enhance its capabilities and performance [redacted]

The future developments would also mean the knowledge gained from this project could be applied to enhance other pipeline issues identified during this project.

This report, the formal handover of the platform and data folders are the completion of the project and Synthotech look forward to the future with the successful development of robotic platform that is suitable for use on the NTS.

11. Annex

Appendix D
Stage 5 report – Premtech

Project GRAID

Premtech
Stage Five Review

02	Final Issue	Ian Butt	21/11/18	L Frearson	21/11/18	Ian Butt	21/11/18
01	Draft Issue – Internal Review	Ian Butt	12/11/18	L. Frearson	21/11/18	-	-
Issue	Issue or Revision Description	Origin By	Date	Chkd By	Date	Appd By	Date

Contents

Acronyms

GRAID	Gas Robotic Agile Inspection Device
BAU	Business as Usual
AGI	Above Ground Installation
NGGT	National Grid Gas Transmission

1 Introduction

1.1 General

This document reviews and summarises the work carried out by Premtech Ltd during stage five of Project GRAID (Gas Robotic Agile Inspection Device).

At the commencement of stage five the following principle work activities and deliverables were identified:

- Review of stage four documents
- Business as usual (BAU) GRAID connections

For each of the work activities identified above, this document identifies the objectives, challenges and findings, plus the lessons learned and conclusions.

For each of the work activities discussed within this document, various reports along with supporting documentation, including drawings, have been produced. These reports and supporting documents contain further and more detailed information with regards to the work activities.

During stage five, various aspects of the work activities overlapped. However, within this document, the work is captured and discussed within single work activity.

Stage five commenced on the 04th September 2018 and was completed on the 26th November 2018.

1.2 Project Description

National Grid Gas Transmission (NGGT) aim to move away from predictive asset type modelling towards condition-based monitoring of its critical assets. These assets are ageing and many have already reached the end of their intended design life.

Partnered with three small-medium enterprises (Synthotech, Premtech and PIE (Pipeline Integrity Engineers)) which have proven records of success in innovation projects, NGGT is seeking to introduce in line inspection of pipework at high pressure gas installations in order to determine the true condition of these assets.

Project GRAID aims to design and develop a remotely operable robot that can be inserted into operational, high pressure, pipework systems to undertake both visual and physical inspection of the otherwise inaccessible buried sections of the pipework within AGI's (above ground installations). The robot will be self-powered, highly manoeuvrable and able to move throughout the pipework to assist in providing an accurate assessment of the pipework condition.

The requirement for Project GRAID is that the robot can travel 100m and negotiate two bends, a number of the options described within this report involve the connection being formed by the use of a tee, at this stage of the project it has been proven that the robotic platform is also able to negotiate and pass through tees.

1.3 Project GRAID Objectives

Project GRAID has 4 key objectives:

- To accurately and reliably determine the condition of high-pressure pipework at installations using an internal inspection robot.
- To generate a proactive, rather than reactive, risk-based approach to the management and maintenance of ageing assets based on the knowledge of the actual condition of pipework.
- Minimise the occurrence of unnecessary excavations and eradicate premature replacement of assets reducing significant carbon emissions and generating cost savings.
- Minimise the likelihood of asset failure through proactive asset management, thereby significantly reducing the risk of a high-pressure gas release into the atmosphere and the consequential financial, environmental and reputational impact.

2 Review of Stage Four Documents

During stage four, the procedures and workflows were updated to ensure any learning, best practices and developments were fully captured within the documentation. This allowed the documents to develop and remain relevant throughout the project.

The objectives of the procedures and workflows for the project were:

- Communicate the proposed project methods, workflows, and requirements to all the project partners and stakeholders.
- Provide a single point of reference and focus for the project methodologies, workflows and requirements, providing standardisation and consistency across the project.
- Give confidence and to allow the effective and efficient development of work activities and deliverables.
- Provide documents that could be updated and refined capturing lessons learned and best practices.

The procedures and workflows were reviewed during stage five and it was deemed that they did not require any further update since the documents had been updated only a few months early during stage four with no subsequent developments that would warrant an update or change to the documents. It was noted that stage five was the shortest of all the project stages.

A basis of design document (BoDD's) for the robot insertion/extraction vessel was updated during stage three, the BoDD was to allow the robot insertion and extraction vessel to be procured. This BoDD was reviewed but was deemed not to require updating during either stage four or five.

2.1 Challenges and Findings

The original documents were developed early within stage one of the project, as the project developed, the project requirements and ways of working became more refined taking on board the lessons learned, better ways of working, best practices and project partner requirements.

The premise of starting the project with initial documents that would be developed throughout the project proved to be a successful way of incorporating lessons learned, better ways of working and best practices. It was not always possible to ensure the documents were always fully up to date since reviews and updates did not take place on a continual basis - reviews were held in each stage. More regular reviews could have been considered.

During stages three and four a number of new technologies became evident and available, such as the ability to survey and develop a point cloud of a site using drone based technology, this technology can be used more cost effectively than traditional surveying techniques, but can be less accurate and is more weather dependant. Surveying with drones is still a fast moving and developing technology, it is expected that new procedures will develop within the next few years, based on this and other technologies.

The current procedures and workflows are necessary documents to support GRAID as it progresses beyond the current innovation project. The users of the procedures and workflows need to be aware that technology is changing, especially regarding surveying and 3D modelling.

2.2 Lessons Learned

The procedures and workflows allowed the project to identify and focus on the requirements for key activities during the various project stages, providing consistency were required. Once they were developed and issued, the project updated the workflows and procedures on a regular basis to ensure lessons learned, better ways of working and best practices were fully captured.

For the longer project stages the workflows and procedures should have been updated at appropriate intervals during the stage.

New technologies will greatly affect the relevance and appropriateness of workflows and procedures. Future GRAID connection projects need to be fully aware of developing and changing technologies, and assess and evaluate how they can be used to benefit future projects. The advancement and development of technologies will change the current workflows and procedures.

2.3 Conclusion and Recommendations

The workflows and procedures should be reviewed frequently, with formal lessons learned meetings held to ensure that lessons learned, better ways of working and best practices are recorded so they can be captured within developing future workflows and procedures.

The current workflows and procedures are considered suitable for the development of GRAID connections beyond the current innovation project, including the future as BAU GRAID connections.

The workflows and procedures should be continually reviewed and challenged to ensure that they remain best practice.

3 Business as Usual GRAID Connections

A requirement was established to identify, assess and evaluate sites that would be most suitable for future GRAID connections, together with where a GRAID inspection may provide most benefit to National Grid. These connections would become potential BAU GRAID connections.

The requirements for identifying a suitable GRAID site and connections point were:

- Identify, assess and evaluate sites that would/may be suitable for connections.
- Identify, assess and evaluate GRAID connection point options at identified sites.
- Consider, assess and evaluate connection options that maximise the amount of pipework, locations of interest and potential corrosion features that could be inspected.
- Determine the connections that provide most benefit.
- Alongside the benefit of each connection, the cost of each connection also requires consideration.

3.1 Challenges and Findings

To determine which sites will provide most benefit from a GRAID inspection, the following selection criteria was used:

- Age of pipework systems (inferred condition)
- Condition of pipework, if known
- Amount of pipework
- Potential for connection points
- Locations of interest

Locations of interest, were deemed to be locations that can result in increased likelihood of pipework corrosion. These locations can include pipe supports, through wall transitions, insulated/lagged pipework and above ground/below ground transitions. The locations of interest are historically locations were corrosion has tended to occur.

The desktop study identified the most likely sites, which tended to be the older compressor station sites and terminals, as these sites have large amounts of pipework with large amounts of locations of interest and a greater potential for GRAID connection points.

The preferred and most cost effective methods of launching the robotic platform within an existing site will be through an existing connection or by removing a piece of flanged equipment (filters, scrubbers, meters and spool pieces) to create a connection. By removing a piece of flanged equipment it is probable that two connections will be created, one at each end of the removed equipment. The majority of compressor stations have active and standby scrubbers or filters, where the standby scrubber or filter can be potentially removed to create the GRAID connection.

If it is not possible to launch the robotic platform by an existing connection or removing piece of flanged equipment then the existing pipework within the site will require a permanent or temporary modification. The cost of a permanent or temporary modification to create a GRAID connection can be significant.

It was noted that sites have been designed and/or modified over time without considering the needs and requirements for GRAID robot inspection. It should therefore be accepted that it will not be normal to find a connection on an existing site that can be used for GRAID connection, permanent or temporary pipework modification will normally be required.

When considering site connections, it is important to consider wider site issues, risks and constraints, these will have a large influence on the connection options selected. Some connections may not be viable when considering site issues.

3.2 Lessons Learned

The amount of possible GRAID connection options within existing sites will be limited, hence the importance to fully review all site drawings and records to determine what connection opportunities exist. It is recommended that site visits are conducted to confirm the connections are viable.

It is far easier to identify, assess and evaluate GRAID connections if there is a laser scan (point cloud) and 3D pipework model available for the site. If these are not available and reliance is placed on available 2D drawings, then the selection of suitable GRAID connections becomes much more difficult and unreliable.

Pipework arrangement geometries and configurations can vary considerably across different sites, what connection design may be suitable for one site, will not be suitable for another, hence the importance to fully review site drawings/records and conduct site visits.

A robust schedule evaluating and ranking the sites that would most benefit from robot inspection should be developed, this may typically be based on selection criteria listed above, plus also considering wider site issues. This will allow the most appropriate sites to be considered in order of need and benefit.

3.3 Conclusion and Recommendations

When reviewing sites for potential GRAID connections, it is anticipated that the existing connection options will be limited, as site have been designed and/or modified over time without considering the needs and requirements for robot inspection.

Project stakeholders should consider how future sites can be designed and modified to facility future robot inspection. It should be possible if a site is subject to a major modification or rebuild, that connection points can included within the design and left as part of that modification or rebuild. It will be more cost effective to construct GRAID connections as part of ongoing or new projects than on a standalone basis.

Ongoing project should considering leaving the site in a condition that it is ‘robot ready’, for future robot inspections. In a same way that new pipelines are designed and constructed so that they can be subject to future Inline Inspection with minimal disruption, cost and effort.

For future robot development projects, significant effort needs to be given to developing and determining the most efficient and cost effective methods to insert and extract the robot platform from a high pressure pipework system, developing technologies may improve both robot and connection design options. If the cost of the connection can be reduced, the ease and cost effectiveness of using robot inspection increases.

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Appendix E

Stage 5 report – PIE (GRAID data model)

PIE Mathematical Condition Model for Project GRAID

Report No: PIE/R/18/411

Issue: 1.0 – December 2018

Client: National Grid

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Executive summary

National Grid operates the National Transmission System (NTS) a network of high-pressure gas transmission pipelines in the UK. The NTS consists of over 7500 km of buried pipelines and 563 above ground installations (AGIs) (not including non-NTS sites and sites with no equipment).

NTS pipelines can be inspected using in line inspection tools or pigs launched from dedicated pig traps, and AGI above ground pipework is readily accessible and can be directly inspected externally. Traditionally however, below ground or enclosed pipework at AGI sites has been the least accessible pipework on the NTS,

Project GRAID (**G**as **R**obotic **A**gile **I**nspection **D**evice), funded by OFGEM / National Grid, concerns the development of a robotic inspection tool, designed, built and operated by Synthotech, which is capable of performing an internal inspection of inaccessible pipework at an AGI at full operational pressure. The GRAID robot can inspect pipework with diameters between 30” (762 mm) and 36” (914 mm). It uses an Electromagnetic Acoustic Transducer (EMAT) technology to measure pipe wall thickness, which enables the detection and sizing of external corrosion defects. As part of its development, the GRAID robot has recently completed two online trials at the Pannal and Bacton AGI sites (connections designed by Premtech Ltd), where the functionality and mobility of the mechanical systems were tested at full pressure, and the wall thickness measurement capabilities utilised.

As part of Project GRAID, Pipeline Integrity Engineers (PIE) have been requested by National Grid to construct a mathematical model to assess the condition of an AGI site. The model is to be used in conjunction with the GRAID robot, as an extension to the robot’s capabilities. The mathematical model will provide an indication as to the overall condition of the site, including areas where the GRAID robot cannot currently inspect. The model is used to determine the expected condition of the site without direct observation, based on available data sources and structural reliability techniques. The expected condition of the site pipework is determined by modelling changes to the failure frequency over time and making a comparison with an acceptable failure frequency limit. This report describes the mathematical model and presents the results of its application to the Pannal AGI site following its inspection by the GRAID robot.

The following conclusions can be made:

- A mathematical model has been developed to determine the condition of pipework at an AGI site without direct observation, based on available data sources and structural reliability techniques.
- In the model, the AGI site pipework is divided into regions based upon the associated corrosion environment and the through-thickness growth of corrosion defects over time, towards a failure point, is modelled for each region.
- The condition of any particular stretch of pipework at an AGI is measured by the time taken in years for the calculated failure frequency of the pipework to exceed an acceptable (threshold) failure frequency limit.

- The output of the model for an AGI site may be colour-coded and applied to a 3D CAD model of the site to provide a visual representation of the expected condition of the pipework.
- The accuracy of the model output is dependent upon the relevance, the quality and the quantity of the available data sources used as the model input. Approximations may be made, however this could result in a significant level of inaccuracy.
- The wall thickness measurement capabilities of the Project GRAID robot are in-line with industry standards and inspection data taken by the robot may be used within the model to inform the outcomes. However, the utilisation of data from the GRAID robot depends upon the percentage of the surface area of the inspected pipework which is scanned and whether any corrosion defects were detected.
- Application of the model to the pipework at Pannal AGI indicated that the pipework which is expected to be in the worst condition is above ground pipework at supports (underneath), which were calculated to exceed the acceptable failure frequency limit 43 years after commissioning.
- The remainder of the pipework at Pannal AGI was calculated to exceed the acceptable failure frequency limit in excess of 50 years after commissioning, and therefore beyond the original design life of the site.
-

The following recommendations can be made:

- It is recommended that the results indicated by the model are critically reviewed by National Grid's competent integrity and corrosion engineers.
- It is recommended that the model is applied to further AGI sites on the NTS and that further relevant data be made available to allow for any required recalibration of the model, leading to condition risk-ranking of all installations which will allow identification of a prioritised and optimised CAPEX/OPEX future investment profile for National Grid that efficiently manages these critical assets.

1 Introduction

National Grid operates the National Transmission System (NTS) a network of high-pressure gas transmission pipelines in the UK. The NTS consists of over 7500 km of buried pipelines and 563 above ground installations (AGIs) (not including non-NTS sites and sites with no equipment).

NTS pipelines can be inspected using in line inspection tools or pigs launched from dedicated pig traps, and AGI above ground pipework is readily accessible and can be directly inspected externally. Traditionally however, below ground or enclosed pipework at AGI sites has been the least accessible pipework on the NTS, and at the majority of sites has never been inspected. The condition of this pipework is therefore unknown and could potentially represent an increasing integrity threat for these ageing assets.

Project GRAID (Gas Robotic Agile Inspection Device), funded by OFGEM / National Grid, concerns the development of a robotic inspection tool, designed, built and operated by Synthotech, which is capable of performing an internal inspection of inaccessible pipework at an AGI at full operational pressure. The GRAID robot can inspect pipework with diameters between 30” (762 mm) and 36” (914 mm). It uses an Electromagnetic Acoustic Transducer (EMAT) technology to measure pipe wall thickness, which enables the detection and sizing of external corrosion defects. As part of its development, the GRAID robot has recently completed two online trials at the Pannal and Bacton AGI sites (connections designed by Premtech Ltd), where the functionality and mobility of the mechanical systems were tested at full pressure, and the wall thickness measurement capabilities utilised.

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1 External Corrosion at High Pressure Above Ground Installations

Corrosion occurs when two different components (or two regions on the same component) are in electrical contact with each other, are immersed in the same electrolyte, and there is a difference in electric potential between them. For external corrosion of buried pipework and pipelines, the soil backfill typically acts as the electrolyte, and the potential difference may arise due to the pipework components occupying different positions on the galvanic series, differences in oxygen concentration, different ion concentrations (resistivities) within the electrolyte, different stress levels, differences in temperature etc.

The two methods of external corrosion control used for buried pipework are the external coating, considered to be the primary corrosion defence, and cathodic protection (CP), which is the secondary defence. The external coating, depending on its age, type and condition, may be between 50 and 99% efficient at preventing corrosion of the pipework. However, no coating provides 100% protection and therefore the CP system exists to ensure that pipe steel which is exposed by defects in the coating remains protected.

Cathodic protection requires the construction of an electrochemical cell such that the pipe (the cathode) is made electrically negative in comparison to a remote sacrificial anode. The anode and the pipe must therefore be electrically connected, and both must be in contact with the electrolyte (the soil). The anode is more electrically negative than the pipe either by being lower on the galvanic scale or through the use of an applied current. The sacrificial anode will then corrode in place of the pipe.

For buried, high pressure, natural gas transmission pipelines, the three major causes of external corrosion are:

- Under-protection
- CP shielding
- Stray current

In addition to the above, external corrosion at an above ground installation (AGI) site is also complicated by:

- Above ground pipework with no CP
- Potentially aggressive corrosion environments

In this section, each of the above items are briefly described, outlining the corrosion mechanisms and the main contributing factors.

1.1 Under-Protection

Under-protection can be a common cause of pipework external corrosion. Where this exists, the main factors contributing to the corrosion problem include:

i) Inaccurate CP monitoring caused by reliance on the measurement of 'on' potentials without making allowance for the inherent 'IR drop' error in the measurement. The IR drop is the voltage drop in the pipe due to the unknown CP current (I) and the unknown soil resistivity (R).

ii) Poor maintenance of the CP system including inadequate current output from impressed current systems and failure to replace depleted anodes in sacrificial anode systems.

iii) System interruption. Operation procedures for work on AGI sites may require the CP system to be turned off to mitigate any spark risk. There is a risk that the system will be turned off early and not be turned back on again immediately following the work, which can lead to significant CP downtime. The effect of each period of downtime is cumulative [1].

The inadequate current supply caused by under-protection can result in localised corrosion on segments of buried pipework where the coating is damaged, and the bare metal is exposed. The total current demand required to protect a short segment of pipe is dictated by the area of exposed metal on the pipe, but the current supply to that segment of pipe is governed by the ground resistivity. Therefore, the CP current distribution between pipe segments will reflect the changing ground resistivity. Under-protection and corrosion occur where there is an imbalance between current supply and current demand. This can happen in localised areas of extensive coating damage, such as that caused by stone damage, soil stressing or faulty field joint coatings; or in the case of an interruption in the CP system on an AGI, where the current demand will exceed the current supply for coating defects over the entire site [1]. Under-protection is usually identified by a CIPS survey and mitigated by rectifying a CP fault.

1.2 CP Shielding

CP shielding by coating disbondment occurs when a pipe coating loses adhesion and lifts away from the pipe surface, allowing water and/or soil to penetrate. CP current flow to the pipe steel is prevented by the electrical insulation characteristics of the disbonded coating, and the presence of the water and/or soil creates a corrosive environment beneath the coating.

Corrosion due to CP shielding has been observed for all types of pipe coating, with the possible exception of fusion bonded epoxy (FBE). In practice, significant corrosion due to CP shielding is more prevalent with polyethylene (PE) based field applied tape, either as a complete pipe coating or a field joint coating; and mastic backed, heat shrinkable field joint coatings. In part this is due to the inherent characteristics of these coatings and to problems controlling application standards in field conditions. The corrosion defect distributions associated with such coatings, which occur due to CP shielding, are characteristic and easily recognised.

Note that corrosion due to CP shielding on 2 and 3-layer polyolefin, coal tar enamel and asphalt/bitumen coatings tends to occur in a random manner unless it is a direct result of field joint coating failure, so the extent of the problem may be underestimated.

In anaerobic soils, corrosion due to CP shielding commonly includes the risk of microbially induced corrosion.

1.3 Stray Current

Stray current is assumed to include all forms of uncontrolled current flow on pipework other than the intentional CP. Stray current tends to create localised concentrations of corrosion activity with greater than average corrosion growth rates. Causes of stray current corrosion include:

- Induced direct currents (DC) from parallel power lines
- Induced alternating currents (AC) from parallel power lines
- Return currents from DC traction systems such as trains and metro systems
- Fault currents from AGI site earthing systems
- DC currents from AGI security fences

In general, AGI sites are electrically isolated from pipelines by insulation joints. This usually means that stray current effects from traditional AC and DC sources are mitigated at AGI sites. However, if no insulation joints are present, or they are otherwise ineffective, the site could potentially be affected. Stray currents may also arise on an AGI site via contact with the site earthing arrangement (for example if a copper system is used), or from electric security fences which use a pulsed DC current [1].

1.4 Above Ground Pipework with No CP

For above ground pipework, the soil is replaced by the atmosphere. Unfortunately, air is a poor electrical conductor and therefore cannot act as an electrolyte in an electrochemical cell. As such, cathodic protection cannot be used to protect above ground pipework in the same way as buried pipework. For above ground pipework the external coating is the only defence against external corrosion. Areas of pipe steel which are exposed by defects in the pipe coating are therefore free to corrode as with the under-protected or CP shielded areas of pipe described above.

Above ground pipework at an AGI site is coated using a paint system, which is standard across all National Grid sites. This differs from the below ground pipework which could be coated by one of several different coatings depending on the age of site and whether the coating was field, or mill applied, including: coal tar enamel, polyethylene, fusion bonded epoxy and cold applied laminate tape. The above ground paint coating is thin and susceptible to damage during normal site maintenance activities. Therefore, unless procedures are in place to repair paint damage following maintenance activity, the above ground pipework is susceptible to corrosion where the damage has occurred [1].

Under normal conditions, exposed areas of pipe steel on above ground pipework are subject to atmospheric corrosion. Atmospheric corrosion is a process which takes place in a film of moisture on the pipe surface. The film may be so thin that it is invisible to the naked eye. The rate of atmospheric corrosion is dependent upon the local air humidity, temperature, whether the pipework is indoors or outdoors and atmospheric pollution levels. The salt content of the air has a large influence over atmospheric corrosion and therefore above ground pipework located in coastal regions is expected to corrode more quickly than pipework located in rural areas [1].

1.5 Potentially Aggressive Corrosion Environments

For buried cross country pipelines experiencing low CP current at an area of exposed metal or disbonded coating, corrosion generally occurs because of the corrosion cell set up by changes across the soil (different ion concentrations) in contact with the exposed pipe surface. Additionally, more aggressive corrosion cells may arise due to stray currents or differential aeration where concrete sleeves are used (road/river crossings) [1].

At AGI sites however, there is more potential for aggressive corrosion environments due to the more complex routeing and environmental changes through which the pipework must traverse.

Below Ground

In addition to corrosion cells arising due to differences in soil type, the use of various different pipe padding materials can create differential aeration conditions. Differential aeration corrosion occurs when pipework steel is exposed to an oxygen concentration gradient. Under these circumstances the area of steel with a lower oxygen concentration becomes anodic and the area of higher oxygen concentration becomes cathodic creating a corrosion cell. The corrosion reaction due to differential aeration is autocatalytic as the corrosion product (iron oxide) spreads out and causes other regions to become oxygen deficient promoting further corrosion [1].

On an AGI site there is an increased number of short sections of pipe and tie-in welds when compared to a cross-country pipeline. The use of field coatings is therefore greater than for a pipeline section of equivalent below ground length. As noted in section 1.2, cold applied laminate tape is often used as a field applied coating and has been implicated in corrosion due to the difficulties in achieving a good application and its vulnerability to soil stressing. The tape is prone to disbondment and therefore its use at AGI sites can lead to increased CP shielding effects. Furthermore, it is generally very difficult to perform post-construction coating surveys at AGI's using the Direct Current Voltage Gradient (DCVG) technique [1].

CP shielding can also occur in AGI sites due to below ground congestion. AGI sites may be designed to contain underground pipework systems of considerable length within a tightly spaced footprint. The density of the pipework and its proximity to other site construction features such as concrete foundations with reinforcing steel, copper grounding systems and structural pilings can prevent the CP current from achieving its desired coverage. If coating defects are then present in areas which are shielded from the CP corrosion will occur [2].

Buried pipes at an AGI may be hot or cold due to either gas compression or pressure reduction processes at the site. Certain coating types such as coal tar enamel and cold applied laminate tape become soft at higher temperatures and brittle at low temperatures which can lead to a breakdown in the protection levels they offer. In addition, corrosion growth rates double with every 10°C rise in temperature in accordance with the Arrhenius equation [1] [3].

Buried pipework at AGI sites is also prone to galvanic corrosion. Galvanic corrosion occurs due to contact between different metals within the same electrolyte. Under these circumstances the metal which is lower in the galvanic scale will corrode, with the corrosion rate being dependent upon how far apart the metals are on the scale. Galvanic corrosion can occur where the pipework makes contact with site earthing systems, or stainless-steel pipe, or where there is a transition between pipe which in soil and pipe in concrete. Galvanic corrosion can produce high corrosion growth rates [1] [4].

Transition Areas

Valve pit wall transitions at AGI sites present a very complex corrosion risk. In these areas pipes are routed through the concrete pit wall via a steel sleeve, which may also include a steel flange to anchor the sleeve to the concrete, with the annular space between the sleeve and the pipe being protected by a rubber end-seal. These rubber seals are prone to decomposition and inevitably allow water and debris to accumulate between the pipe and the sleeve, creating a potentially corrosive environment. Additionally, the steel sleeve is prone to making contact with the steel rebars within the concrete, which can lead to electrical contact between the pipe and the rebar. Corrosion at pit wall transitions therefore occurs due to the galvanic corrosion mechanism. The site CP system is unlikely to be effective at concrete pit walls due to CP shielding and current drain to the concrete rebars. Corrosion protection in the annular space is therefore entirely dependent upon the integrity of the pipe coating [1].

At the transition between above ground and below ground, the wind-water line, pipework is prone to corrosion due to the differential aeration mechanism. Buried pipework is generally laid at a standard depth of cover value between 1.1 m and 1.3 m below the surface. At this depth the soil is homogenous and tightly packed, and the oxygen content of the soil is therefore the same or similar for all buried pipework sections. Pipework which transitions between below and above ground must travel via a riser from the dense soil at standard depth of cover towards the surface where the soil is looser and more oxygen rich. The riser pipe is therefore exposed to soil of two different oxygen concentrations which, in the event of coating damage and poor CP has the potential to become a corrosion cell. Furthermore, the riser pipe often passes to the surface Terram sheeting and a thick layer of stones. The stones are a high resistance material which have the potential to shield the pipe from the CP system, and they can also damage the pipe coating [1] [5].

Above Ground

Above ground, the AGI pipework is held and stabilised through the use of periodically located pipe supports. Various types of support are in use, including jack-type and full encirclement supports. Pipe supports present another complex corrosion risk which involves a number of different corrosion mechanisms. Pipe supports are susceptible to collecting and trapping water which is held against the painted pipe surface and the support surface. However, the above ground paint coating system is designed for atmospheric exposure and not immersion in water. Over time the paint coating can soften and degrade, exposing both the pipe and support steel to the water. Contact between the pipe and support steel and water leads to the initiation of general corrosion of the pipe or support, or galvanic corrosion between the pipe and the support. A build-up of corrosion product restricts the diffusion of oxygen and the region beneath the pipe support becomes increasingly oxygen deficient in comparison to the exposed pipe at the support edges. Corrosion then continues due to the differential aeration mechanism. Above ground there is no CP and therefore corrosion is likely to be more aggressive than similar differential scenarios below ground (with the exception of areas prone to CP shielding). Similar to section 1.4, corrosion growth rates will be dependent upon the local atmosphere in terms of humidity, temperature, indoors/outdoors, salt content and atmospheric pollution levels. The problem of corrosion at pipe supports is compounded by the difficulty of inspection, although jack-type supports may be screwed down to allow the area to be fully surveyed, full encirclement supports must be removed which is expensive and therefore not regularly performed across the industry [1] [6].

Above ground pipework at AGI sites may also have sections which are lagged for insulation. The lagged sections present a similar corrosion risk to that of supports but the corrosion can occur over a larger area. Water can get beneath damaged or poorly fitted lagging and is then perpetually trapped against the surface of the pipe. The wet conditions, in combination with warmth from the pipe, leads to a breakdown in the pipe paint coating and exposes the pipe steel to the water. Galvanic or general corrosion is then free to take place, which may be exacerbated by the presence of chlorides or sulphides in the lagging material which can increase the corrosion rate. Corrosion rates are also influenced by the local atmosphere and temperature. Lagged sections of pipework may be overlooked for inspection due to the cost of removal and repair, and the fact that the lagging may show no outward signs of deterioration [1] [7] [8].

2 Probabilistic Corrosion Growth Model

The mathematical model developed by PIE for Project GRAID to assess the condition of the pipework at an AGI site involves the use of a probabilistic growth model for external corrosion. The general structure of the probabilistic corrosion growth model is summarised as follows:

- A corrosion growth rate probability distribution for the pipework under consideration is derived or chosen, taking into account the site location and design, available pipeline inspection data, CP condition data and relevant integrity data.
- Corrosion growth rates for the given pipework are selected in accordance with the growth rate probability distribution.
- Simulations of corrosion growth are carried out to determine the probability that a corrosion defect will grow from zero depth to a defined limiting depth within a given time frame. The limiting depth is calculated using pipework specific parameters and an appropriate corrosion assessment model.
- The probability of reaching or exceeding the given limiting depth, i.e. the probability of failure, is multiplied by the expected number of corrosion defects per year to calculate a value for the expected number of failures per year, i.e. the failure frequency.

- The predictions of time vs. failure frequency are compared with acceptable failure frequency values to give a measure of the pipework condition.

Given the diversity of potential corrosion environments within an AGI site, as indicated in section 1, different parts of the site will be subject to different corrosion growth rates. The site must therefore be divided into distinct regions based on each of the different corrosion environments and a separate growth rate probability distribution applied to each. In this way different values of failure frequency are calculated across the site and the pipework condition determined by the model in each region will reflect the associated corrosion environment.

The use of a probabilistic corrosion growth model allows a quantitative assessment of AGI pipework to be carried out using the site design and location, relevant corrosion data, existing pipeline inspection data and current CP condition and pipework integrity data. The method does not rely explicitly on in-line inspection data of the pipework itself, and therefore can be easily applied to areas which are inaccessible or where inspection data is incomplete. The specific requirements of the probabilistic corrosion growth model developed for the current study are given in sections 2.2, 2.3, 2.4, 2.5 and 2.6.

2.1 Structure of the Project GRAID Probabilistic Corrosion Growth Model

The structure of the probabilistic corrosion growth model to assess the condition of AGI pipework is illustrated in

Figure 1 below.

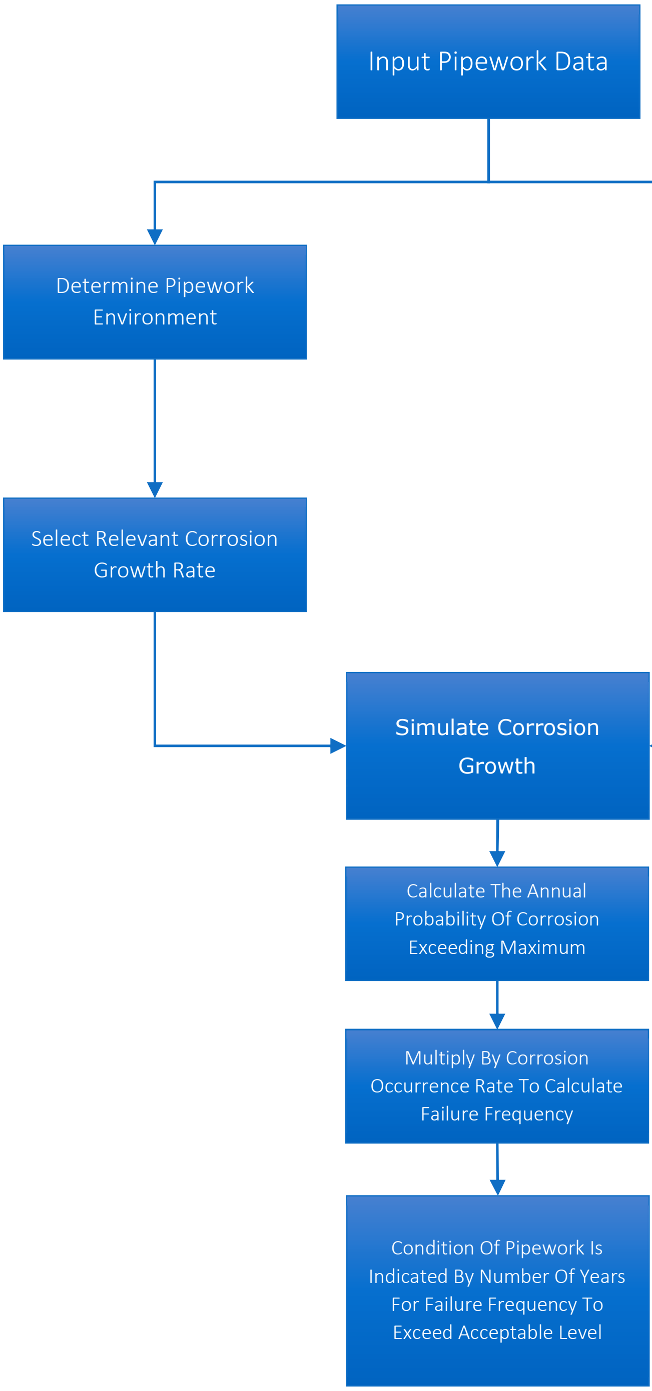

Figure 1: Probabilistic Corrosion Growth Model for Calculating Pipeline Inspection Interval

Application of the model therefore requires definition of:

- the number and location of distinct corrosion environments within the site under assessment;
- probability distributions describing the range of corrosion growth rates for each of the corrosion environments;
- a probability distribution describing the length of a corrosion defect;
- the corrosion occurrence rate, i.e. the number of corrosion defects expected to occur on the site pipework per year;

The above points are determined from the site design and location, relevant corrosion data, existing inspection data and current CP condition and pipework integrity data. In addition:

- a calculation of the maximum allowable corrosion depth;
- a method to simulate external corrosion growth between inspections and calculate the probability of failure; and
- an acceptable limit to the value of failure frequency;

are also required. Each of these requirements are discussed in detail in the following sections.

2.2 Maximum Allowable Corrosion Depth

External corrosion occurs in the pipe wall, and may be associated with a seam weld or girth weld. Metal loss due to corrosion is a time dependent degradation mechanism. If the corrosion cannot be arrested, then an assessment must consider the consequences of further defect growth (including the removal of any corrosion allowance).

External corrosion generally has an irregular profile, as shown in Figure 2.

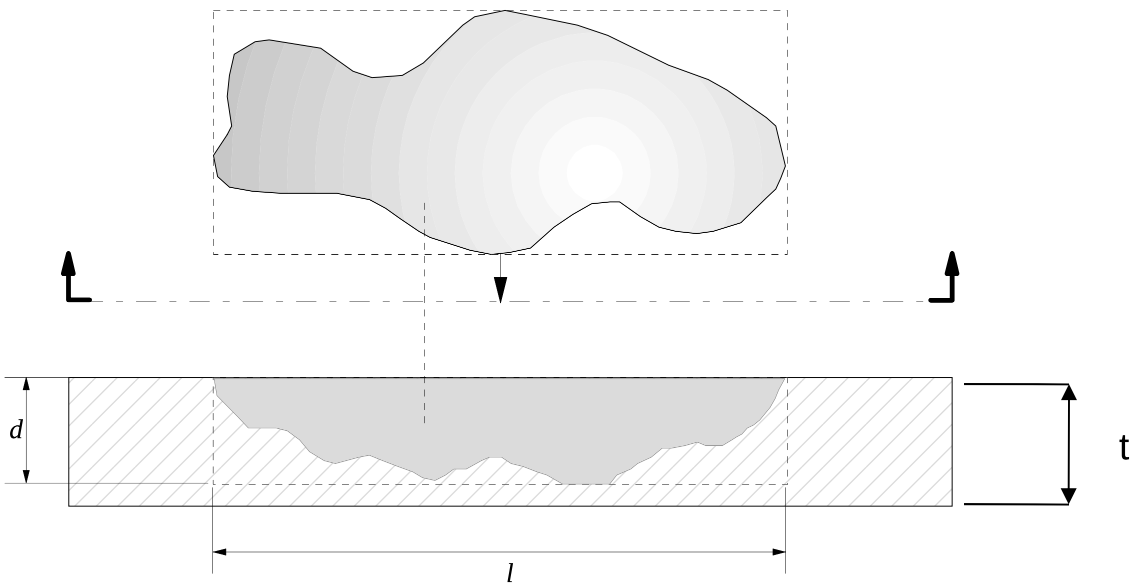

Figure 2: Typical External Corrosion Geometry

Metal loss due to external corrosion reduces the pipe wall thickness available for pressure containment. The acceptability of a corrosion defect in pipework is dependent upon:

- The pipework parameters, specifically wall thickness, pressure, and material grade.
- The corrosion parameters, specifically depth, axial length and circumferential width.

In terms of corrosion measurement during inspection, maximum depth is the easiest and most reliable measurement to obtain. Axial length, which affects the leak vs. rupture behaviour of the defect, is more difficult to obtain accurately, and this tends to be significantly over-estimated in in-line inspection reports.

There are a number of recognised and validated assessment methods for metal loss due to corrosion. For the purposes of this study, the National Grid management procedure T/PM/P/11: *Inspection Assessment and Repair of Damaged (Non-Leaking) Steel Pipelines Above 150 mm Nominal Diameter and Designed to Operate at Pressures Greater than 2 bar* [9], has been selected. The criteria for corrosion categorised as "Extreme Damage" within T/PM/P/11 are used to determine the limiting corrosion depth in the probabilistic model. Defects which are categorised as "Extreme Damage" are significant and could cause a failure of the pipework.

T/PM/P/11 is intended to be applied to transmission pipelines operating at pressures greater than 7 barg or steel distribution mains operating at pressures between 2 barg and 7 barg, however the procedure may also be applied to pipework at above ground installations provided the materials, design temperatures and loadings are within scope. It should be noted that the use of T/PM/P/11 to determine the limiting corrosion depth implies that internal pressure is the predominant loading mechanism at the AGI site under assessment. Application of the probabilistic model to a site for which this is not the case may therefore be non-conservative.

T/PM/P/11 has been chosen over more accurate assessment methods, such as the Modified B31G criterion [10] or DNV-RP-F101 [11], because it is the established procedure for defect assessment and repair used within National Grid and will therefore be directly applied to the data output of the Project GRAID robot.

It is noted that within the probabilistic model the limiting corrosion depth is the failure condition used to determine the probability of failure, that is, the probability of a through-wall, product loss incident. The time for a new corrosion defect to corrode to the limiting depth provides the basis for the probability of failure calculation. The T/PM/P11 "Extreme Damage" criteria are therefore used within the model to define the point at which failure will occur. In real terms however, corrosion which is categorised as "Extreme Damage" under T/PM/P/11, although significant, is not yet at the point of failure. The probability of failure calculation within the model will therefore be conservative.

T/PM/P/11 was originally published as BGC/PS/CP/P11 in August 1974 [9]. The limits for corrosion in T/PM/P/11 are based upon the ASME B31G failure criterion for corroded pipe, which is probably the most well-known and widely used corrosion assessment method worldwide. The criterion was derived from research conducted by the Battelle Memorial Institute in the early 1970s, and published in 1973 [12], in which 47 burst tests were performed on pipe containing real corrosion defects.

In T/PM/P/11 corrosion is defined as the result of a reaction of a metallic material with its environment causing a measurable reduction in the thickness of metal. There are two distinct types of corrosion specified in the procedure:

- General corrosion, which is defined as corrosion resulting in a reduction of metal thickness over a large area of the surface.
- Pitting corrosion, which is defined as corrosion which only affects small areas of surface pipe material, producing pits. Corrosion is considered to be a pit when the maximum surface dimension is not greater than three times the minimum wall thickness of undamaged pipe material surrounding the defect.

In T/PM/P/11 pipework defects (including corrosion, cracks, dents, gouges etc.) are categorised as either "Superficial Damage", "Moderate Damage", "Severe Damage" or "Extreme Damage". Corrosion is assigned a damage category on the basis of its type, either general corrosion or pitting corrosion, and its measured axial length and depth dimensions. The specific limits of axial length and depth corresponding to each damage category are dependent upon the hoop stress level of the pipe wall when expressed as a percentage of the specified minimum yield stress (SMYS) of the pipe steel; and the material grade of the pipe steel.

The hoop stress level in the pipe wall, f, in T/PM/P/11 is calculated using:

$$f = \frac{PD}{20t_{min}} \cdot \frac{100}{SMYS}$$

Where P is the design pressure (or maximum operating pressure for uprated or downrated pipework) in barg, D is the outside pipe diameter in mm, t_{min} is the minimum wall thickness of the pipe in mm, and $SMYS$ is the specified minimum yield strength of the pipe steel in Nmm^{-2}. The above equation applies to both straight sections of pipe and manufactured bends with a nominal bend radius greater than $10D$. If the nominal bend radius is between $1.5D$ and $10D$ the value of f calculated above should be multiplied by a factor of 1.25 to account for increased stress in the bend.

Table 2-1 shows the specific limits of axial length and depth corresponding to a categorisation of "Extreme Damage" In T/PM/P/11 for both general and pitting corrosion, on the basis of the pipe design factor and material grade. In Table 2-1 d is the effective through-thickness depth of the corrosion defect in mm, L is the effective length of the corrosion defect in mm, t is the pipe nominal wall thickness in mm, and R is the outside pipe radius in mm (i.e. $D/2$).

Design Factor and Material Grade (API 5L)	General Corrosion		Pitting Corrosion	
Up to X65 f ≤ 30% SMYS	d > 0.9t	d > 0.4t L > 0.6R f > 0.2	d > 0.9t	d > 0.6t L > 0.6R f > 0.2
Up to X65 30% SMYS < f ≤ 50% SMYS	d > 0.85t	d > 0.3t L > 0.35R	d > 0.85t	d > 0.55t L > 0.35R
Up to X65 50% SMYS < f ≤ 72% SMYS	d > 0.8t	d > 0.2t L > 0.2R	d > 0.8t	d > 0.5t L > 0.2R
Up to X65 72% SMYS < f ≤ 80% SMYS	d > 0.78t	d > 0.15t L > 0.15R	d > 0.78t	d > 0.5t L > 0.15R
X70 or X80 f ≤ 30% SMYS	d > 0.9t	d > 0.4t L > 0.6R	d > 0.9t	d > 0.6t L > 0.6R
X70 or X80 30% SMYS < f ≤ 50% SMYS	d > 0.85t	d > 0.3t L > 0.30R	d > 0.85t	d > 0.55t L > 0.30R
X70 or X80 50% SMYS < f ≤ 72% SMYS	d > 0.8t	d > 0.2t L > 0.15R	d > 0.8t	d > 0.5t L > 0.15R

Table 2-1: Limits for Extreme Damage in T/PM/P/11

It is noted that the limits defined in Table 2-1 may be used to categorise both corrosion located in the pipe body; and corrosion which is coincidental with, or lies within 10 mm of a seam weld or girth weld or the heat affected zone (HAZ); as “Extreme Damage”, provided the welds are of known high quality. T/PM/P/11 includes separate limits for defects which are located on welds or within the heat affected zone (HAZ), however for corrosion these limits are identical to those of the pipe body.

T/PM/P/11 indicates that the maximum through thickness depth of the defect may be used as the value of d in Table 2-1 and that this should yield a conservative result with respect to the effective depth. A procedure to determine the true effective depth of the defect however, is included if a more precise value is required. T/PM/P/11 also indicates that for axially orientated defects, the length of the defect in the axial direction may be used as the value of L in Table 2-1. This definition of L is applicable for defects which are inclined at up to 60° to the pipe axis. For defects with a greater inclination the effective length is defined as half the absolute defect length.

The corrosion growth rate distributions used in the probabilistic model are derived from data taken by in-line pipeline inspection tools (section 2.3.1). Pipeline in-line inspection data typically reports defects as two-dimensional boxes overlaid on the plane of the pipe surface, with dimensions which correspond to the maximum axial and circumferential extent of each defect. The maximum through-thickness depth of a defect is typically reported as the depth of the defect box.

The corrosion depth and length values for any one simulated defect, determined from the probability distributions in the model, therefore correspond to the maximum through thickness depth of the defect and the maximum length of the defect in the axial direction. Given the above definitions from T/PM/P/11 they are therefore assumed to be directly analogous to d and L in Table 2-1, and may therefore be used directly to determine if the simulated corrosion defect exceeds the "Extreme Damage" depth limit. In defining the maximum length of the defect in the axial direction as L in the model it follows that all simulated defects are assumed to be axially orientated (within ± 60° of the pipe axis), this is considered to be a conservative assumption.

Note that although interacting defects are not explicitly considered by the model, their inclusion is implicit given that pipeline in-line inspection vendors typically apply an industry standard set of interaction criteria to their inspection data to group defects, and in the case of multiple interacting defects report only the overall composite defect. The probability distributions derived from in-line inspection data will therefore include interacting defects as part of the distribution. In T/PM/P/11 defects which are considered to be interacting must also be grouped using interaction criteria and considered as a composite defect before damage categorisation limits, including those shown in Table 2-1 are applied. The limiting corrosion depth used in the model therefore also considers defect interaction. It is assumed that the interaction rules applied by in-line inspection vendors are equivalent to those applied as part of T/P/PM/P/11.

2.3 Corrosion Environments and Probability Distributions

As indicated in section 2.1, in order to construct the probabilistic model, it is required that the number and location of different corrosion environments within an AGI site is defined and that appropriate probability distributions describing the range and likelihood of the associated corrosion growth rates are derived for each.

From the background information presented in section 1, several distinct corrosion environments can be identified as potentially being present at an AGI site, these are:

- Below ground pipework with a fully functioning CP system
- Below ground pipework which is under-protected by the CP system
- Below ground pipework which is subject to coating disbondment, due to hot or cold conditions or general degradation
- Below ground pipework which is subject to stray currents
- Below ground pipework covered by padding material
- Below ground pipework with poor field joint coatings
- Below ground pipework in electrical contact with other metals
- Pipework at concrete pit-walls
- Pipework in the region of the wind-water line
- Above ground pipework
- Above ground pipework at supports
- Above ground pipework which is lagged

A comprehensive AGI site pipework condition model would ideally identify the location and consider the associated corrosion growth rates for each of these different potential corrosion environments. However, limitations on available data and knowledge of the current site status restrict the number of different environments which can be considered in the PIE GRAID model. There is no available data relating to the whereabouts or extent of, disbonded coating on below ground pipework, below ground padding materials, below ground field joints or below ground pipework in electrical contact with other metals. These specific environments therefore cannot be included.

For the remainder of the environments, there exists sufficient information and sources of data from which appropriate corrosion growth rate distributions may be derived, given a number of assumptions. In the PIE GRAID model an AGI site under assessment must therefore be split into the following regions:

- Below ground pipework with a fully functioning CP system
- Below ground pipework which is under protected by the CP system
- Below ground pipework which is subject to stray currents
- Pipework at concrete pit-walls
- Pipework in the region of the wind-water line
- Above ground pipework
- Above ground pipework at supports
- Above ground pipework which is lagged

The following sections outline the methods which may be used to derive corrosion growth rate probability distributions applicable to each of the above regions.

2.3.1 Below Ground Pipework

The corrosion growth rate distributions for below ground pipework may be derived using in-line inspection data from the inlet and outlet pipelines to the AGI site.

It is assumed that corrosion data derived from the inlet and outlet pipelines will be applicable to the below ground pipework at the site, because the pipelines are likely to have been commissioned at the same time as the AGI, were constructed using similar materials and techniques, are likely to share the same external coating type, and share a similar overall external environment (for example, soil type, water content and ground temperature will be comparable between the AGI site and the pipelines). Accepting the specific below ground corrosion environments indicated above which cannot be considered by the model, the general mechanisms of external corrosion between the pipelines and the AGI below ground pipework are likely to be the same. Therefore, a similar distribution of corrosion features would be expected to appear on both the pipelines and the below ground site pipework.

Whether the corrosion data from the pipelines is applicable to below ground pipework which is fully protected by the CP; below ground pipework which is under-protected by the CP; or below ground pipework which is subject to stray currents, is dependent upon the CP performance and history for both the pipelines and the site. The CP performance history of a pipeline or below ground AGI pipework can be determined from the CIPS completed over their operational life. The CIPS will indicate where the pipeline or pipework is protected by the CP, where it is under-protected and where it is subject to stray currents at the time of the survey (except for areas which are CP shielded). Pipelines or pipework may have complete protection, under-protection, or stray currents along their entire length, or there may be segments of each. In terms of applying the probability distributions derived from the pipelines to the below ground AGI pipework:

- A corrosion growth rate distribution derived from well protected pipeline segments may be applied to well protected regions of below ground pipe at an AGI site, but not to regions experiencing under-protection or stray currents;

- A corrosion growth rate distribution derived from under-protected pipeline segments may be applied to under protected regions of below ground pipe at an AGI site, but not to well protected regions or regions experiencing stray currents;
- A corrosion growth rate distribution derived from pipeline segments subject to stray currents may be applied to regions of below ground pipe subject to stray currents at an AGI site, but not to well protected regions or regions experiencing under-protection;

For pipelines which are experiencing segments of protection, under-protection and/or stray currents it would be possible in principle, to derive separate corrosion growth distributions for each by considering the in-line inspection corrosion data of related segments together. In practice however, this is unlikely to be straightforward due to the difficulty in matching locations between CIPS and in-line inspection data, and the general sparsity of external corrosion defects on UK pipelines.

To derive a corrosion growth rate distribution based on pipeline in-line inspection data, the following information is required dating back over the operational history of the inlet and outlet pipelines and the AGI site:

- In-line inspection reports indicating the total number of corrosion defects within each pipeline; and the location (distance, proximity to closest girth weld, circumferential orientation), depth and axial length of each corrosion defect.
- CIPS reports.
- Details of any excavations/repairs performed.

Corrosion growth rates within pipework can change over time, and if multiple repeated sets of in-line inspection data are available, multiple distributions may be derived describing the corrosion growth in different time periods. Each of these distributions may be used within the model to provide a more accurate description of the corrosion growth over the operating life of the pipework. If the complete inspection and CP history of the pipelines and AGI site is not available however, assumptions may be made based on the available information.

The corrosion growth rate distribution can be derived using the following method:

- For multiple sets of inspection data of the same pipeline, the location of girth welds and structural features must be manually aligned such that the reported distance values remain constant between inspections.
- Once the data sets are aligned, the reported corrosion defects in each inspection must be matched between inspections. This may be based on their proximity to the closest girth weld and circumferential orientation. Defect matching will indicate if a defect was present in an earlier inspection or is new.
- The depth of corrosion defects is typically reported as a percentage of the wall thickness. For each set of inspection data this must be converted to an absolute depth value using: $d = \frac{d_{\%}}{100}.t$, where $d_{\%}$ is the depth as a percentage of the wall thickness, t is the local uncorroded wall thickness in mm and d is the absolute depth of the corrosion in mm.
- Between two subsequent inspections, a corrosion growth rate is calculated for each defect in the most recent inspection which has been matched to a defect in the earlier inspection using:

$$cgr_{matched} = \frac{d_{recent} - d_{earlier}}{t_{insp}}$$

where d_{recent} is the absolute depth of the defect in the most recent of the two inspections in mm, $d_{earlier}$ is the absolute depth of the defect in the earlier inspection in mm, t_{insp} is the time between the two inspections in years and $cgr_{matched}$ is the corrosion growth rate in mm/year.

- For defects which could not be matched to any defects in the earlier inspection, and are therefore new defects, a corrosion growth rate is calculated for each defect using:

$$cgr_{new} = \frac{d_{recent}}{t_{insp}}$$

where cgr_{new} is the corrosion growth rate in mm/year.

- If the above procedure is performed for each of the inlet and outlet pipelines, like for like segments of each pipeline, that is, well protected segments, under-protected segments or segments experiencing stray currents (on the basis of the CIPS data), may be treated as a single data set from which to derive a distribution.
- A distribution may be fitted to the data set of derived values for $cgr_{matched}$ and cgr_{new} using the maximum likelihood estimation method. Appropriate distribution types for corrosion growth rates are the Weibull and lognormal distributions.
- Alternatively, if there is only one set of in-line inspection data for each pipeline, assumptions may be made regarding the corrosion growth. It may be assumed that the corrosion defects reported in available data set have grown to their measured depth over either the full operational life of the pipeline to date, or over half of the operational life of the pipeline to date. Each of these assumptions are established industry practice for estimation of corrosion growth rates on the basis of a single set of inspection data. A decision as to which approximation to use may be made on the basis of the available information regarding the pipeline.
- For pipelines with one set of inspection data, corrosion growth rates for each corrosion defect are calculated using either:

$$cgr_{full} = \frac{d}{t_{comm}}$$ for corrosion growth over the full operating life, or

$$cgr_{half} = \frac{d}{t_{comm}/2}$$ for corrosion growth over half the operating life.

Where d is the absolute depth of the corrosion defect in mm, t_{comm} is the time since pipeline commissioning in years, cgr_{full} is the corrosion growth rate derived using the full life approximation in mm/year and cgr_{half} is the corrosion growth rate derived using the half-life approximation in mm/year.

- A distribution is fitted to a data set of derived values for cgr_{full} or cgr_{half} using the maximum likelihood estimation method and a Weibull or Lognormal distribution, as above.

A Weibull distribution [13] is a continuous two-parameter probability distribution commonly used in statistics and is described by a shape parameter α, and a scale parameter β. The probability density function of a Weibull distribution is given by:

$$f(x,\alpha,\beta) = \frac{\alpha}{\beta^\alpha} x^{\alpha-1} \exp -(\frac{x}{\beta})^\alpha$$

And the cumulative distribution function is given by:

$$F(x,\alpha,\beta) = 1 - \exp -(\frac{x}{\beta})^\alpha$$

A lognormal distribution [14] is also a two-parameter continuous probability distribution. In the case of a lognormal distribution the parameters, denoted μ and σ, are the location and scale parameters of the natural logarithm of the distribution, which is normally distributed. The probability density function of a lognormal distribution is given by:

$$f(x,\mu,\sigma) = \frac{1}{x}.\frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(\ln x - \mu)^2}{2\sigma^2}\right)$$

And the cumulative distribution function is given by:

$$F(x,\mu,\sigma) = \Phi\left(\frac{(\ln x) - \mu}{\sigma}\right)$$

Where Φ is the cumulative distribution function of the standard normal distribution.

Given a set of data for which a distribution fit is required, the maximum likelihood estimation method is used to derive values for the parameters of the selected distribution type (either α and β for Weibull, or μ and σ for lognormal) which best fit the data. The method is not suited to a hand calculation and therefore a statistical software package such as Minitab [15] or SPSS [16] may be used to fit distributions to the derived corrosion growth rate data. Goodness of fit measures such as the p-value and the Anderson-Darling statistic, often calculated alongside the distribution parameters as part of the maximum likelihood estimation method, should indicate which of the distributions is the best fit to the data [15].

Figure 3 shows an example of corrosion growth rate data for corrosion defects from a single set of in-line inspection data, derived using the method shown above and the half-life approximation. The data is plotted showing how the cumulative percentage of corrosion defects in the pipeline increases with corrosion growth rate. Each point on the chart represents a single corrosion defect, the x-axis indicates the derived corrosion growth rate value and the y-axis indicates the cumulative percentage value.

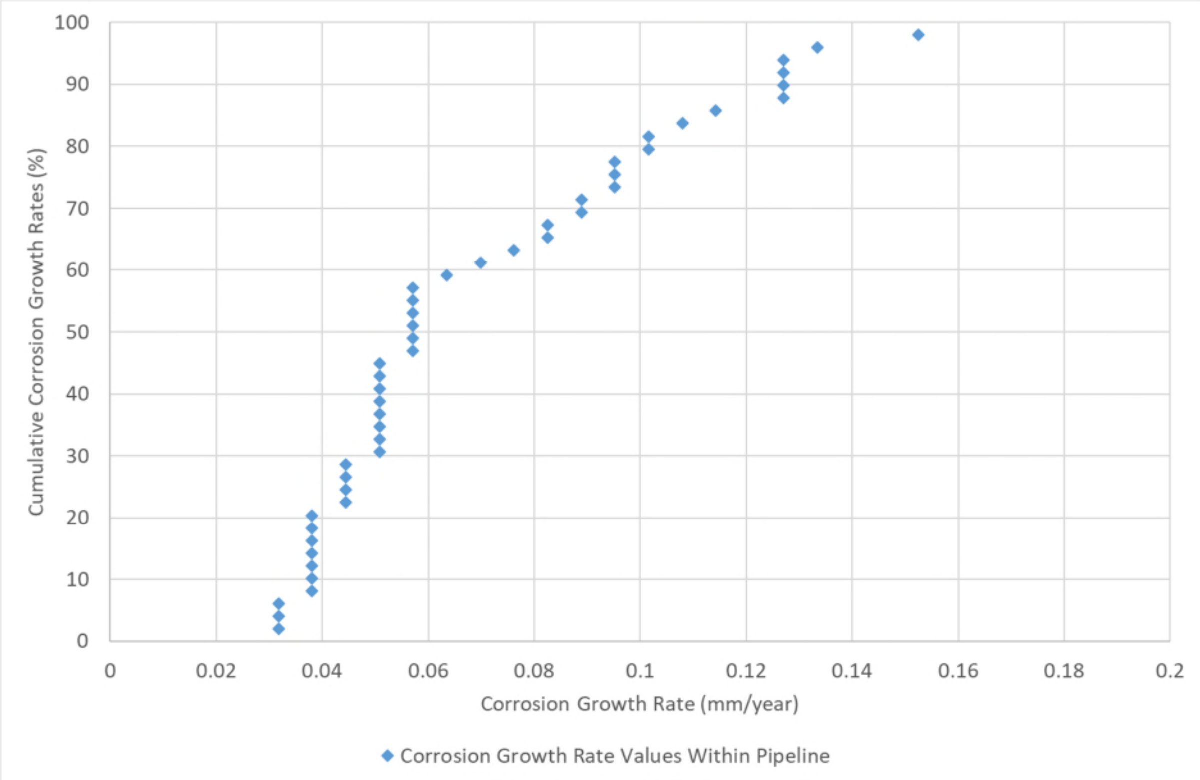

Figure 3: Cumulative Plot of Example Corrosion Growth Rates

Figure 4 shows examples of Weibull and lognormal distributions fitted to the corrosion growth rate data from Figure 3 using the maximum likelihood estimation method. In this case, the p-value and Anderson-Darling statistic indicate the lognormal distribution to be the best fit to the data. The distributions in Figure 4 are the cumulative distribution functions, the probability density functions of the fitted distributions are shown in Figure 5.

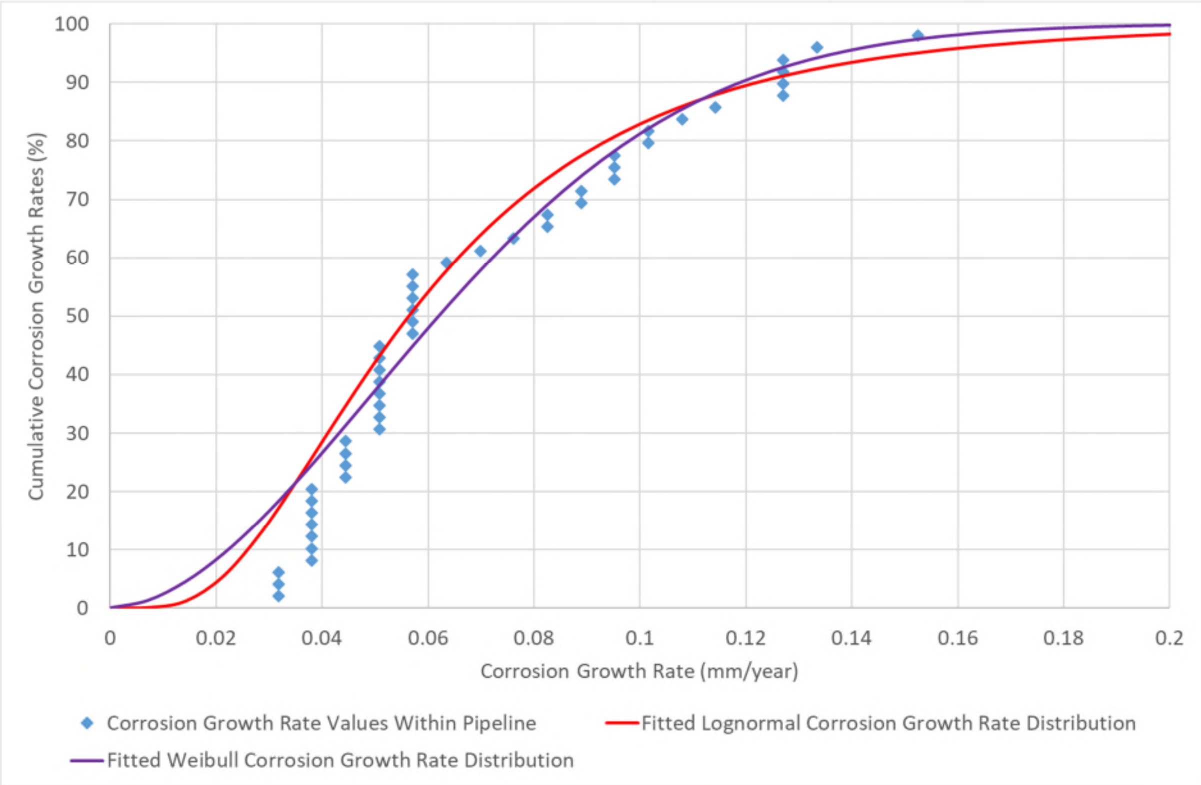

Figure 4: Example Weibull and Lognormal Cumulative Distribution Functions Fitted to Corrosion Growth Rate Data using the Maximum Likelihood Estimation Method

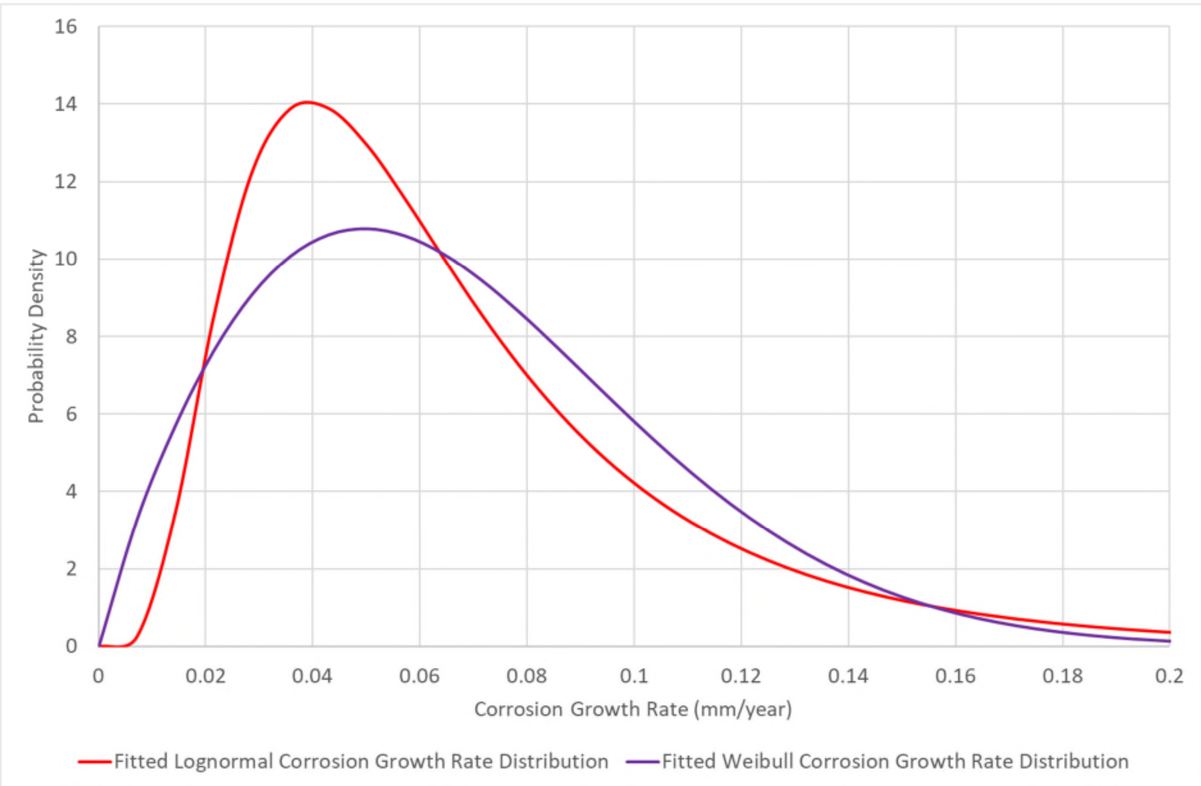

Figure 5: Example Weibull and Lognormal Probability Density Functions

If the available CIPS for the AGI site under assessment indicates that corrosion growth rate distributions are required for both of the following below ground regions:

- below ground pipework with a fully functioning CP system; and
- below ground pipework which is under-protected by the CP system;

but the available in-line inspection data does not allow distributions to be derived for both regions, then a corrosion growth rate distribution from published literature may be used in the model in its place.

Distributions representing pipelines with “low”, “average” and “high” resistances to corrosion were published as part of a review into corrosion growth rates representative of UK pipelines in 2009 [17]. These distributions were subsequently included as part of the Intervals 2 methodology used to establish appropriate pipeline in-line inspection intervals for National Grid. The distributions are based upon data from over 4000 active corrosion defects reported over approximately 15,000 km of pipelines. A recent study carried out by PIE [18] indicated that the distributions remain the best representation overall of corrosion growth behaviour for UK pipelines.

Table 2-2 shows the distribution parameters for the published distributions. All of the distributions are Weibull. The probability density functions of the distributions are shown in Figure 6. A decision as to which distribution is applied to which region may be made on the basis of the available information regarding the AGI site. In general, a high or average corrosion resistance distribution would be applied to below ground pipework with a fully functioning CP system and an average or low corrosion resistance distribution would be applied to below ground pipework which is under-protected.

Note that generalised published distributions from literature such as those shown in Table 2-2 and Figure 6 may not be applied to below ground pipework experiencing stray current effects, as this would be non conservative. This is because of the highly localised nature of stray current corrosion, which potentially has very high corrosion growth rates. A general distribution derived from many different sources would not be appropriate for address this corrosion mechanism. In this case a distribution must be derived from directly measured corrosion growth rate data.

Resistance to Corrosion	Shape Parameter, α	Scale Parameter, β
High	1.55	0.06
Average	1.5	0.125
Low	1.55	0.3

Table 2-2: Parameters for Published Corrosion Growth Rate Distributions

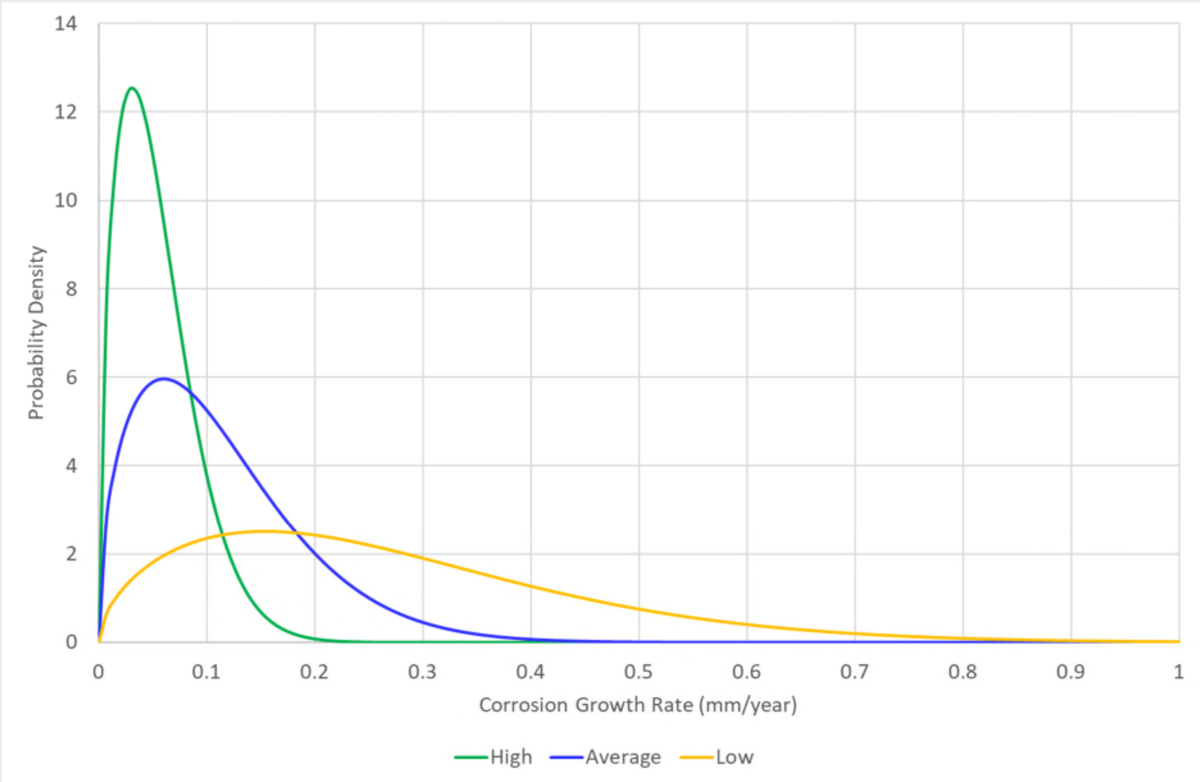

Figure 6: Probability Density Functions for Published Corrosion Growth Rate Distributions

2.3.2 Above Ground Pipework

As indicated in section 1, above ground pipework is subject to a different level of protection and different corrosion mechanisms than below ground pipework. The corrosion growth rate distributions derived for below ground pipework, using the in-line inspection data of below ground pipelines, are therefore not appropriate for direct application to the above ground pipework regions of the AGI site under assessment.

Onshore cross-country pipelines in the UK are mostly below ground and therefore in-line inspection data of above ground pipework is not usually available. Corrosion measurements of above ground pipework are usually restricted to isolated defect repairs within AGI sites, made under T/PM/P/11. Data of this type would generally allow a single corrosion growth rate value to be derived per defect repair (an assumption as to when the corrosion defect first appeared may be required). If sufficient above ground corrosion measurement data exists for either the AGI site under assessment or above ground sections of the inlet and outlet pipelines, then a corrosion growth rate distribution may be derived using a similar method to that indicated in section 2.3.2. However, it is more likely that direct corrosion measurements for above ground pipework relating to the AGI site under assessment will not be available. In this case, a corrosion growth rate distribution may be derived using a combination of published corrosion growth data, the distributions derived for below ground pipework regions at the AGI site and a number of assumptions.

The mechanism of corrosion growth for above ground pipework is atmospheric corrosion. Corrosion growth rates for atmospheric corrosion are dependent upon the local air humidity, salt content, temperature, whether the pipework is indoors or outdoors and atmospheric pollution levels. Corrosion growth ranges for atmospheric corrosion in different environments are published in Table 1 and Table 2 of the standards BS EN ISO 12944-2 [19] and BS EN ISO 9223 [20] respectively. The tables rank the corrosivity of different atmospheric environments between 6 different categories and provide an upper and lower limit for the corrosion growth after the first year of exposure for each category, for different metals. Table 2-3 reproduces the corrosion growth values published thickness loss of carbon steel. Note that in Table 2-3, the thickness loss value has been converted from µm in the original table to mm.

Corrosivity Category	Thickness Loss (mm) – Carbon Steel (After First Year of Exposure)	Examples of Typical Environments	
		Exterior	Interior
C1 – Very Low	≤ 0.0013	N/A	Heated buildings with clean atmospheres, e.g. offices, shops, schools, hotels
C2 – Low	0.0013 to 0.025	Atmospheres with low level of pollution: mostly rural areas	Unheated buildings where condensation can occur, e.g. depots, sports halls
C3 – Medium	0.025 to 0.05	Urban and industrial atmospheres, moderate sulphur dioxide pollution; coastal areas with low salinity	Production rooms with high humidity and some air pollution, e.g. food-processing plants, laundries, breweries, dairies
C4 – High	0.05 to 0.08	Industrial areas and coastal areas with moderate salinity	Chemical plants, swimming pools, coastal ship and boatyards
C5 – Very High	0.08 to 0.2	Industrial areas with high humidity and aggressive atmosphere and coastal areas with high salinity	Buildings or areas with almost permanent condensation and with high pollution
CX – Extreme	0.2 to 0.7	Offshore areas with high salinity and industrial areas with extreme humidity and aggressive atmosphere and sub-tropical and tropical atmospheres	Industrial areas with extreme humidity and aggressive atmosphere

Table 2-3: Atmospheric Corrosivity Categories and Examples of Typical Environments from BS EN ISO 12944-2 and BS EN ISO 9223

The corrosion growth values from Table 2-3 can be used to derive a growth rate distribution for above ground pipework regions using the following method:

- The corrosivity category of the above ground atmosphere at the AGI site under assessment must be determined. The site may be categorised by considering the site construction; its location with respect to the sea and urban or industrial environments; and by making reference to local weather and humidity records.

- The values for thickness loss in the first year of exposure to the atmosphere in Table 2-3 are assumed to represent a corrosion growth rate in mm/year. Note that in practice, the rate of corrosion growth may change over time due to the build-up of corrosion product and other localised effects. This assumption however is considered to be reasonable on the basis of the available information.
- The upper limit for thickness loss in the appropriate corrosivity category is assumed to represent the 80% value for the cumulative probability distribution of the above ground pipework. In other words, of all the different possible corrosion growth rates which could affect the above ground pipework regions, 80% of them will be below the upper limit for thickness loss from Table 2-3. A value of 80% is chosen to account for the upper tail of the distribution, which is not taken into account by the thickness loss ranges stated in BS EN ISO 12944-2 and BS EN ISO 9223.
- It is assumed that the shape of the distribution for below ground pipework with a fully functioning CP system[1], as derived in section 2.3.1, is also representative of the shape of the corrosion growth rate distribution for above ground pipework. As above this assumption is considered to be reasonable on the basis of the available information. The distribution for above ground pipework is therefore derived by applying a scaling factor to the distribution shape, based on the 80% cumulative probability distribution value determined above.
- The shape of the below ground distribution is indicated by the relative spacing between corrosion growth rates values when represented as a cumulative probability distribution. A dataset of spacing values relative to the 80% cumulative probability distribution value are derived using:

    - $S_{bg,80,x} = \frac{cgr_{bg,80}}{cgr_{bg,x}}$

  where $cgr_{bg,80}$ is the corrosion growth rate of the 80% cumulative probability distribution value on the below ground pipework distribution in mm/year, $cgr_{bg,x}$ is the corrosion growth rate of the x% cumulative probability distribution value on the below ground pipework distribution in mm/year, and $S_{bg,80,x}$ is the relative spacing between the 80% and x% corrosion growth rate values. The values for x must be chosen such that the derived dataset is sufficiently large to allow a distribution to be fitted to the points and must cover the entire range of the below ground pipework cumulative probability distribution.
- Equivalent cumulative probability distribution values for the above ground pipework distribution are derived by applying scaling to the relative spacing values derived from the below ground pipework distribution using:

$$cgr_{ag,x} = \frac{cgr_{ag,80}}{S_{bg,80,x}}$$

[1] Given that this is an assumption made for the purposes of the model, the choice of which below ground pipework distribution may represent the above ground pipework is arbitrary. An argument could be made to use the distribution for below ground pipework with under-protection, rather than below ground pipework with a fully functioning CP system.

where $cgr_{ag,80}$ is the corrosion growth rate of the 80% cumulative probability distribution value on the above ground pipework distribution in mm/year (taken from Table 2-3), and $cgr_{ag,x}$ is the corrosion growth rate of the x% cumulative probability distribution value on the above ground probability distribution in mm/year.

- A distribution may be fitted to the data set of derived values for $cgr_{ag,x}$ using the maximum likelihood estimation method. Appropriate distribution types for corrosion growth rates are the Weibull and lognormal distributions.

Figure 7, Figure 8, Figure 9 and Figure 10 show an example of an above ground pipework corrosion growth rate distribution derived from the associated below ground pipework with a fully functioning CP system distribution. Figure 7 shows the below ground pipework cumulative probability distribution, the curve is taken from the lognormal distribution fitted to the data in Figure 4.

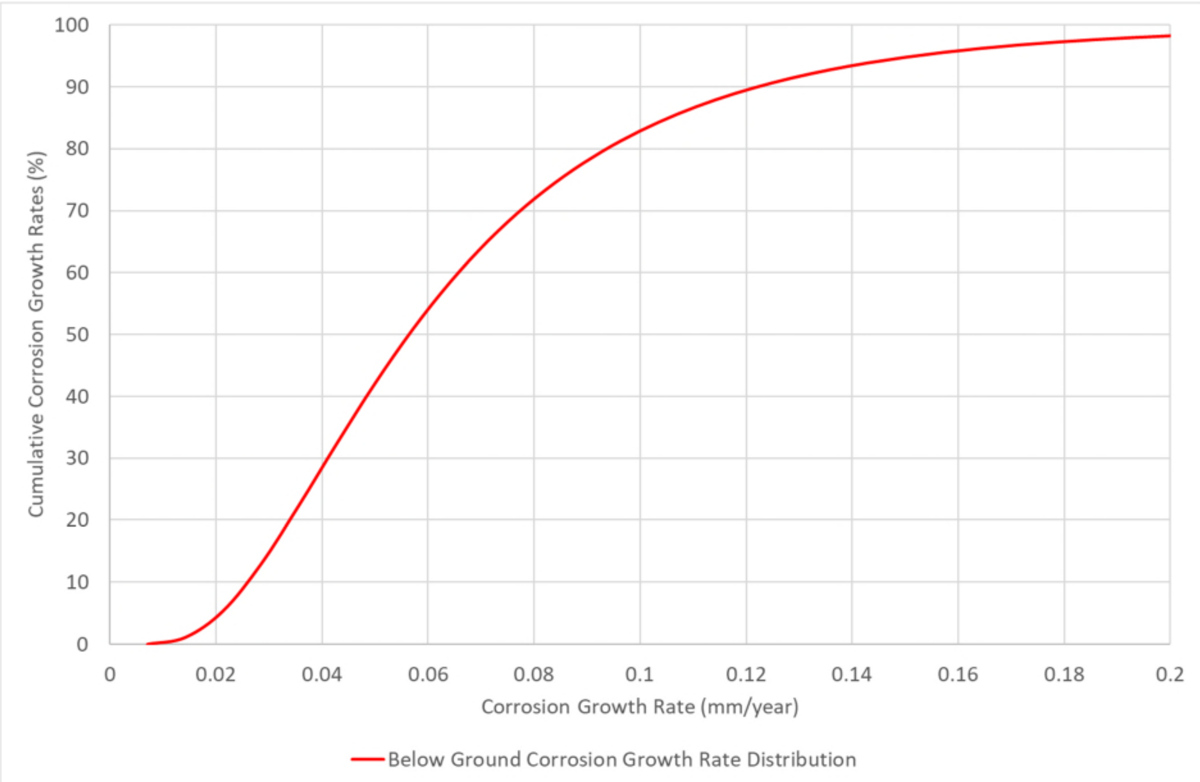

Figure 7: Cumulative Plot of Example Below Ground Corrosion Growth Rate Distribution

Figure 8 shows the values of x used to derive the $S_{bg,80,x}$ dataset. The values of $S_{bg,80,x}$ are given by the spacing between each point and the 80% cumulative probability value (circled) as indicated.

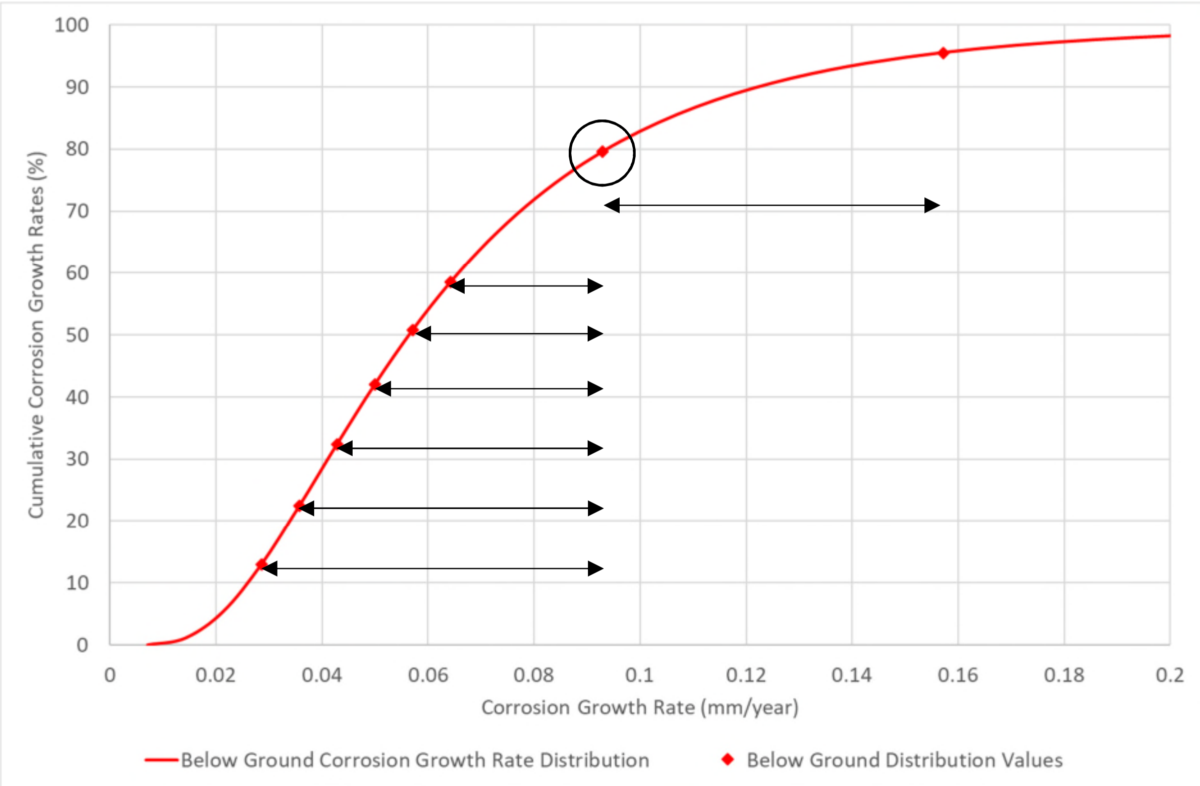

Figure 8: Cumulative Plot Showing Dataset of Below Ground Distribution Relative Spacing Values

Figure 9 shows the $cgr_{ag,x}$ cumulative probability distribution points for the above ground pipework distribution derived by applying scaling to the $S_{bg,80,x}$ dataset, based on the 80% cumulative probability distribution value taken from Table 2-3. In this example the value from the C2 – Low category has been used.

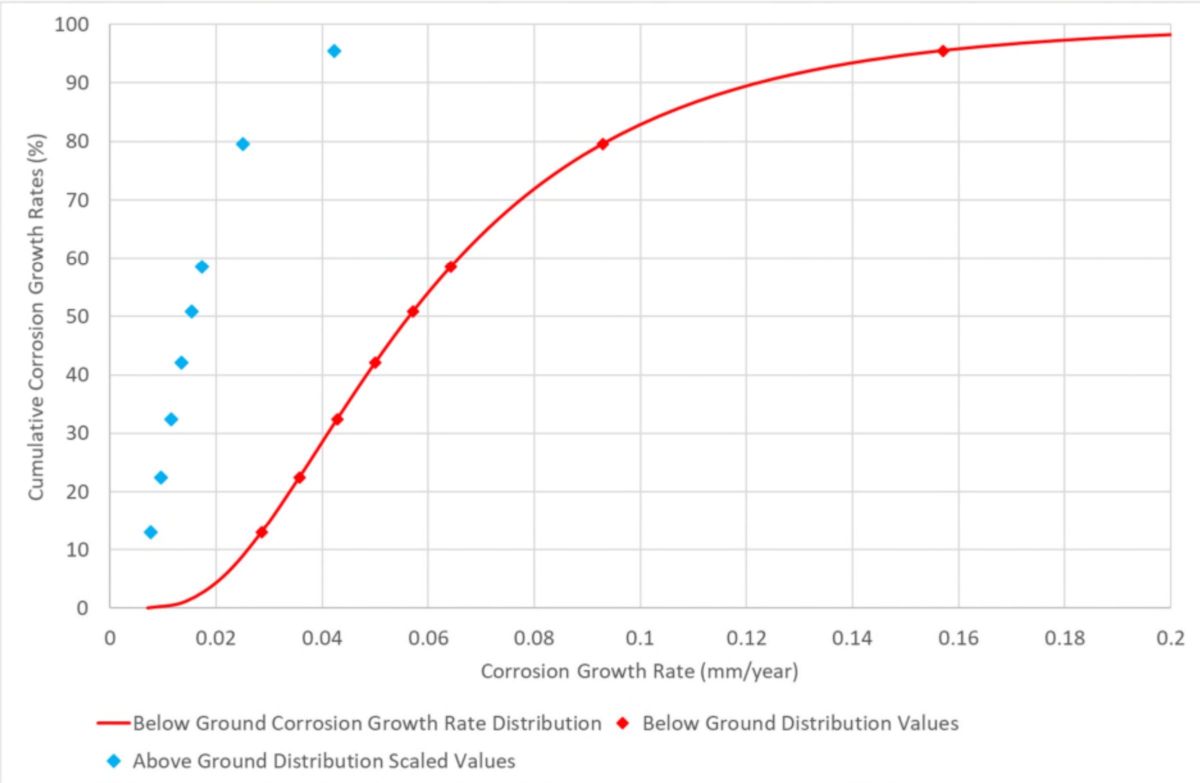

Figure 9: Cumulative Plot Showing Scaled Dataset of Above Ground Distribution Cumulative Values

Finally, Figure 10 shows the above ground pipework cumulative probability distribution, fitted to the derived above ground $cgr_{ag,x}$ points using the maximum likelihood estimation method. The distribution shown is a Weibull distribution, indicated by the p-value and Anderson-Darling statistic to be the best fit to the data.

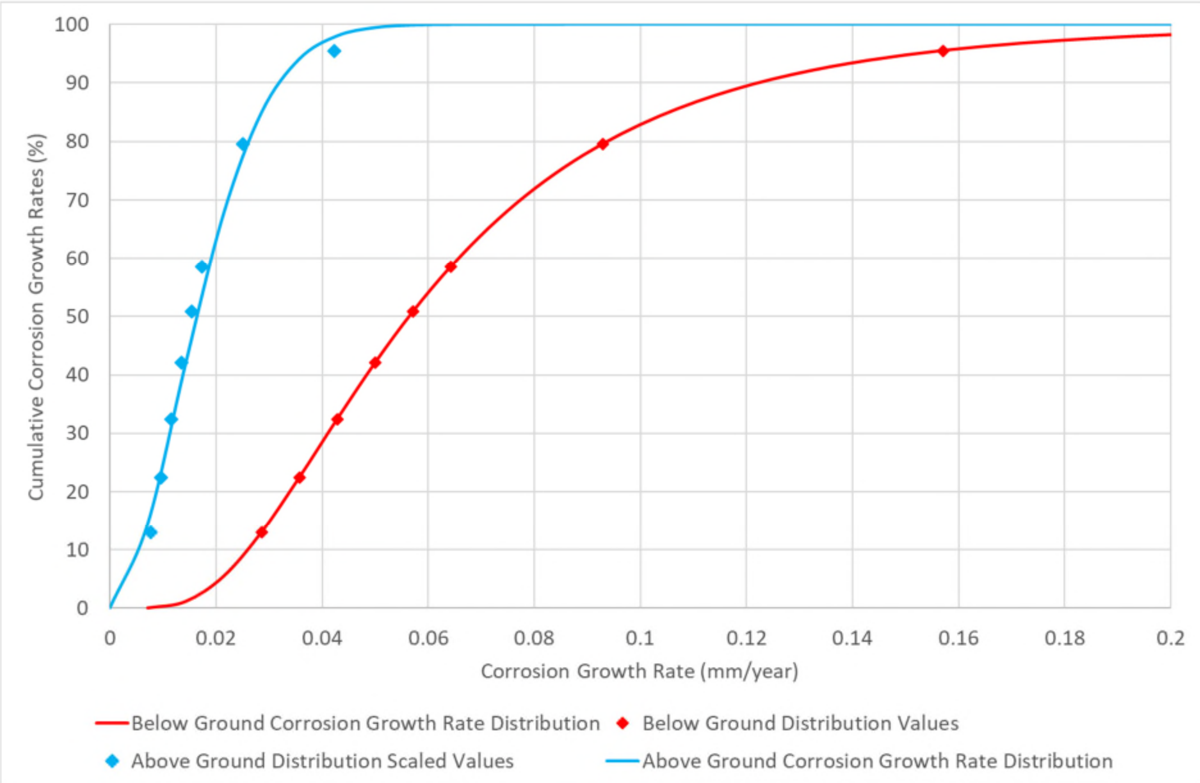

Figure 10: Cumulative Plot Showing Derived Above Ground Corrosion Growth Rate Distribution

2.3.3 Localised Aggressive Corrosion Regions

This section concerns the corrosion growth rate distributions associated with:

- Pipework at concrete pit-walls
- Pipework in the region of the wind-water line
- Above ground pipework at supports
- Above ground pipework which is lagged

As indicated in section 1, corrosion growth in these regions is highly localised and may be aggressive, with high corrosion growth rates. The more general corrosion growth rate distributions derived for below ground or above ground pipework, are therefore not appropriate for direct application.

The most reliable source of data regarding corrosion defects in these regions would generally be measurements made during a defect repair under T/PM/P/11. As for above ground pipework, data of this type would allow a single corrosion growth rate value to be derived per defect repair (an assumption as to when the corrosion defect first appeared may be required). Alternatively, as each region is a known corrosion vulnerability, corrosion growth rate data may be available from electrical resistance (ER) probe measurements. If sufficient corrosion size or measurement data exists for each of the regions present at the AGI site under assessment, then a corrosion growth rate distribution may be derived using a similar method to that indicated in section 2.3.2. However, it is more likely that direct corrosion size or growth rate measurements for one or more of the regions will not be available. In this case corrosion growth rate distributions for each of the regions may be derived from a single measured corrosion growth rate value from any one region by applying assumptions based on the different corrosion growth mechanisms. The single measured corrosion growth rate may be the maximum value from a series of ER probe measurements of a single region on the AGI site, or may be the maximum value derived from measurements taken during T/PM/P/11 investigations of corrosion defects affecting a particular region. If only one measured value is available, it may be cautiously used in the absence of further data.

From section 1.5, the mechanisms of corrosion growth for each of the above pipework regions are:

- Pipework at concrete pit-walls – Galvanic corrosion
- Pipework in the region of the wind-water line – Differential aeration corrosion
- Above ground pipework at supports – Differential aeration (primary) and galvanic (secondary) corrosion
- Above ground pipework which is lagged – Galvanic corrosion

It is not possible to associate specific characteristic values of corrosion growth rates to each different mechanism. This is because there is always a distribution of rates associated with any one scenario and therefore any mechanism can be associated with both high and low rates. However, the corrosion mechanisms affecting below ground and above ground pipework can be generally ranked from most aggressive to least aggressive:

- Stray Current Corrosion (potentially the most aggressive, but rates are dependent on the magnitude of the current)
- Galvanic Corrosion (the corrosion rate increases with increased separation of participating metals on the galvanic scale)
- Differential Aeration Corrosion (below ground scenarios with CP are likely to have lower rates than above ground scenarios where there is no CP)
- Differential Environment (including different soil types and atmospheric corrosion)

The pipework regions can therefore be ranked by their associated corrosion environment from most aggressive to least aggressive:

- Pipework at concrete pit-walls and above ground pipework which is lagged
- Above ground pipework at supports
- Pipework in the region of the wind-water line

In the above list, above ground pipework at supports is ranked below pipework at pit-walls and lagged pipework because the primary corrosion mechanism is differential aeration, rather than galvanic. Above ground pipework at supports is ranked higher than pipework in the region of the wind-water line because of the secondary galvanic corrosion mechanism, and because the below ground CP may help to reduce corrosion growth rates in the region of the wind-water line.

The above ranking can be used in conjunction with a single measured corrosion growth rate value from any one region to derive a growth rate distribution for all of the required regions using the following method:

- The single corrosion measured corrosion growth rate is assumed to represent the 80% value for the cumulative probability distribution of the specific region for which it was measured. A value of 80% is chosen to account for the upper tail of the distribution which is not likely to have been measured from limited ER probe or T/PM/P/11 data.
- It is assumed that the shape of the corrosion growth rate distribution for below ground pipework, as derived in section 2.3.1, is representative of the shape of the corrosion growth rate distribution for the specified region. A distribution is derived for this region by applying a scaling factor to the distribution shape, based on the 80% cumulative probability distribution value.
- The method to derive the distribution is identical to that of the above ground pipework method from section 2.3.2.
- It is assumed that the shape of the corrosion growth rate distribution for below ground pipework is also representative of the shape of the corrosion growth rate distributions for the remaining regions.
- Factors are therefore applied to the single measured corrosion rate to derive equivalent 80% cumulative probability distribution values for each of the remaining regions. The 80% cumulative probability distribution value for above ground pipework at supports is assumed to be 20% lower than the 80% cumulative probability distribution value for pipework at concrete pit-walls and above ground pipework which is lagged; the 80% cumulative probability distribution value for pipework in the region of the wind-water line is assumed to be 40% lower than the 80% cumulative probability distribution value for pipework at concrete pit-walls and above ground pipework which is lagged[2].
- Distributions are derived for the remaining regions using the method from section 2.3.2 by applying scaling factors to the shape of the below ground distribution, based on the derived 80% cumulative probability distribution values.

Figure 11 shows cumulative probability distributions for each of the localised aggressive corrosion regions derived using the above method with, a single corrosion growth rate value taken from an ER probe measurement in the pipework at concrete pit-walls region; and the below ground corrosion growth rate distribution based on the lognormal distribution fitted to the data in Figure 4. The data points used to scale the distributions in each case are also included. In each case the new fitted distributions are Weibull distributions, indicated by the p-value and Anderson-Darling statistic to be the best fit to the data.

[2] Note that the choice of values for the factors is based only on judgement and is used simply to represent the scale of aggressive corrosion mechanisms previously indicated. In each situation, measured corrosion growth rate data is preferable to the use of assumptions and factors.

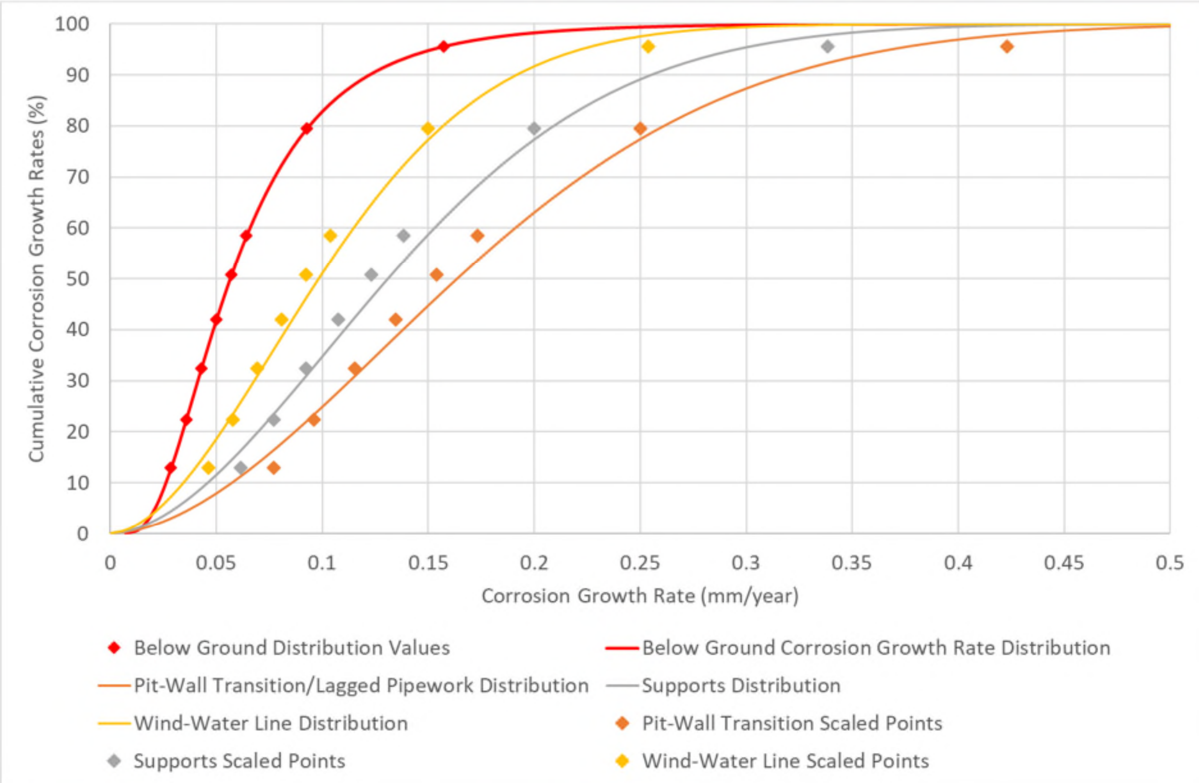

Figure 11: Cumulative Plot Showing Derived Corrosion Growth Rate Distributions for Localised Aggressive Corrosion Regions

2.4 Corrosion Length Distribution

The distributions outlined in section 2.3 are concerned with the growth rate associated with a corrosion defect. These distributions will directly affect the final depth of a simulated corrosion defect after a certain time period within the model. In order to apply the limiting corrosion depth defined using T/PM/P/11 and determine if the simulated corrosion defect resulted in a failure, the axial length of the corrosion defect must also be determined.

The axial length of each simulated corrosion defect is also determined using a probability distribution. However, in the model it is assumed that corrosion growth does not occur in the length direction. The probability distribution is therefore simply a corrosion axial length distribution, rather than an axial length corrosion growth rate distribution, and the axial length of a defect therefore remains the same throughout each simulation. The reason for this assumption is that axial length is difficult for in-line inspection tools to measure accurately and is often significantly over-estimated. The distribution of corrosion length measurements in any given set of in-line inspection data therefore tends to be very conservative. A hypothetical set of axial length corrosion growth rates derived from in-line inspection data would therefore be very high in comparison to the true rates and the results of the model would be unfairly skewed towards early failure.

The corrosion axial length distribution may be derived using in-line inspection data from the inlet and outlet pipelines to the AGI site. The corrosion length distribution is intended to reflect the length distribution of corrosion defects after a significant period of operation and therefore the most appropriate source of data from which to derive the distribution is the most recent inspection. Unlike the below ground corrosion growth rate probability distribution, it is assumed that it does not matter whether the inlet and outlet pipelines are fully protected by the CP; under-protected by the CP and/or subject to stray currents, the full set of in-line inspection data from each of the inlet and outlet pipelines may be used to derive the distribution. This assumption is made on the basis that corrosion length is more dependent upon the extent of damage to the external pipework coating, rather than the specific corrosion environment. This factor should be reflected by the general length distribution observed from the full set of in-line inspection data. For example, many of the most aggressive corrosion environments can produce very deep defects which are also very short. Conversely, a large area of coating damage in a non-aggressive corrosion environment may produce a very long, very shallow defect. By this reasoning, it is also assumed that a single length distribution may be applied all pipework regions within the model.

The corrosion axial length distribution can be derived simply by fitting a distribution to the measured corrosion axial length values from the in-line inspection data. It is not required to match repeat inspection data and defects, calculate corrosion growth rates for each defect or to convert the length into different units since in-line inspection vendors typically report axial lengths in mm. The distribution may once again be fitted using the maximum likelihood estimation method with a Weibull or lognormal distribution.

Figure 12 shows an example of axial length data for corrosion defects from a single set of in-line inspection data. The data is plotted showing how the cumulative percentage of corrosion defects in the pipeline increases with axial corrosion length. As with Figure 3 each point on the chart represents a single corrosion defect. The x-axis indicates the measured axial length value and the y-axis indicates the cumulative percentage value.

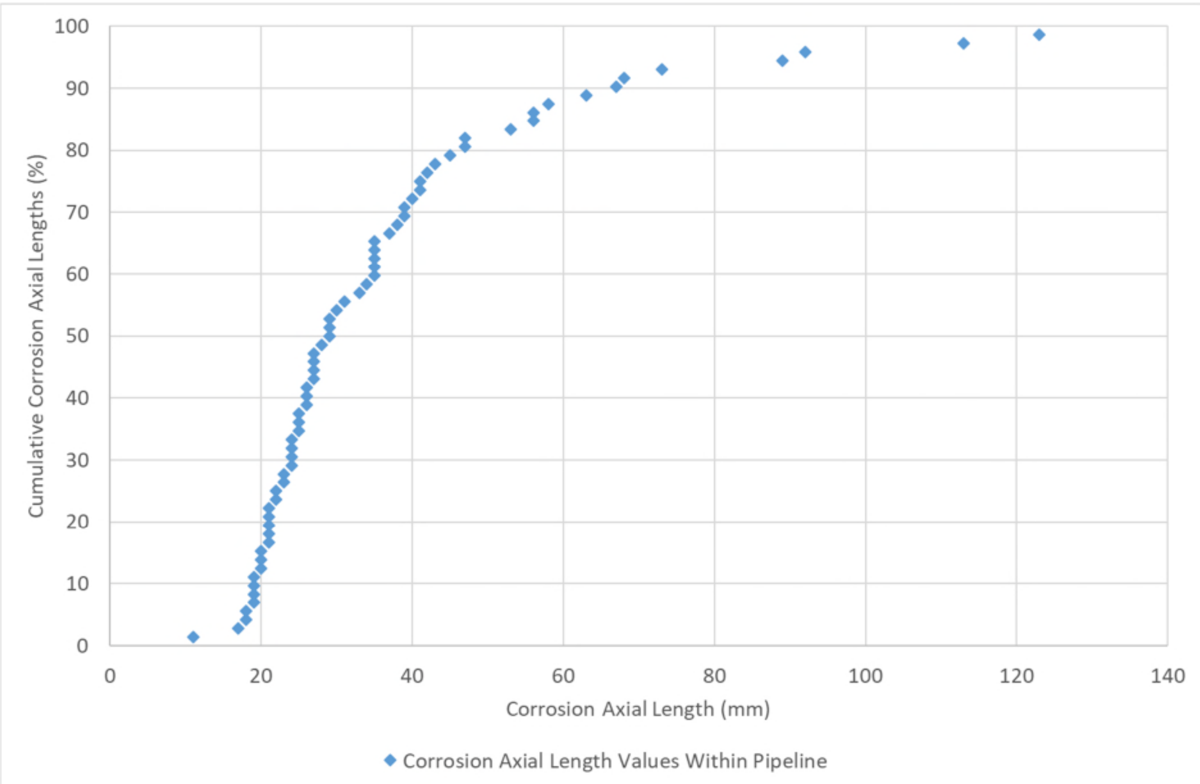

Figure 12: Cumulative Plot of Example Corrosion Axial Lengths

Figure 13 shows examples of Weibull and lognormal distributions fitted to the corrosion axial length data from Figure 12 using the maximum likelihood estimation method. In this case, the p-value and Anderson-Darling statistic indicate the lognormal distribution to be the best fit to the data. The distributions in Figure 13 are the cumulative distribution functions, the probability density functions of the fitted distributions are shown in Figure 14.

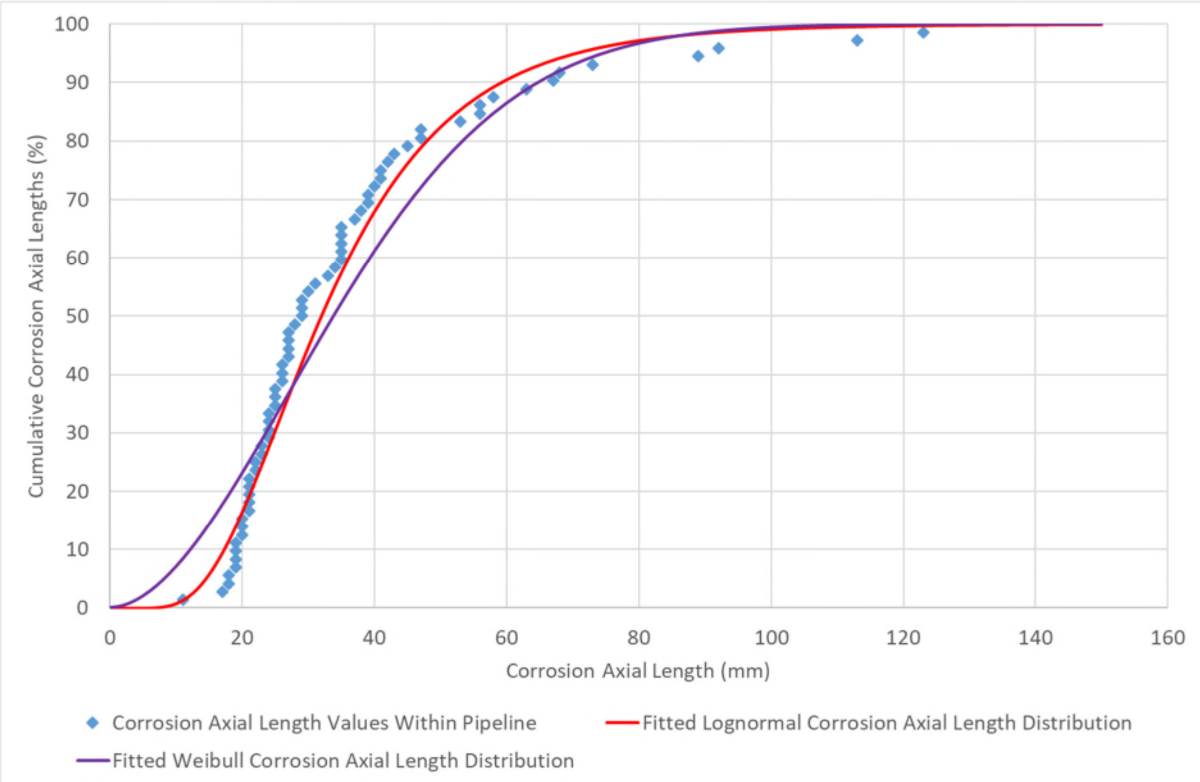

Figure 13: Example Weibull and Lognormal Cumulative Distribution Functions Fitted to Corrosion Axial Length Data using the Maximum Likelihood Estimation Method

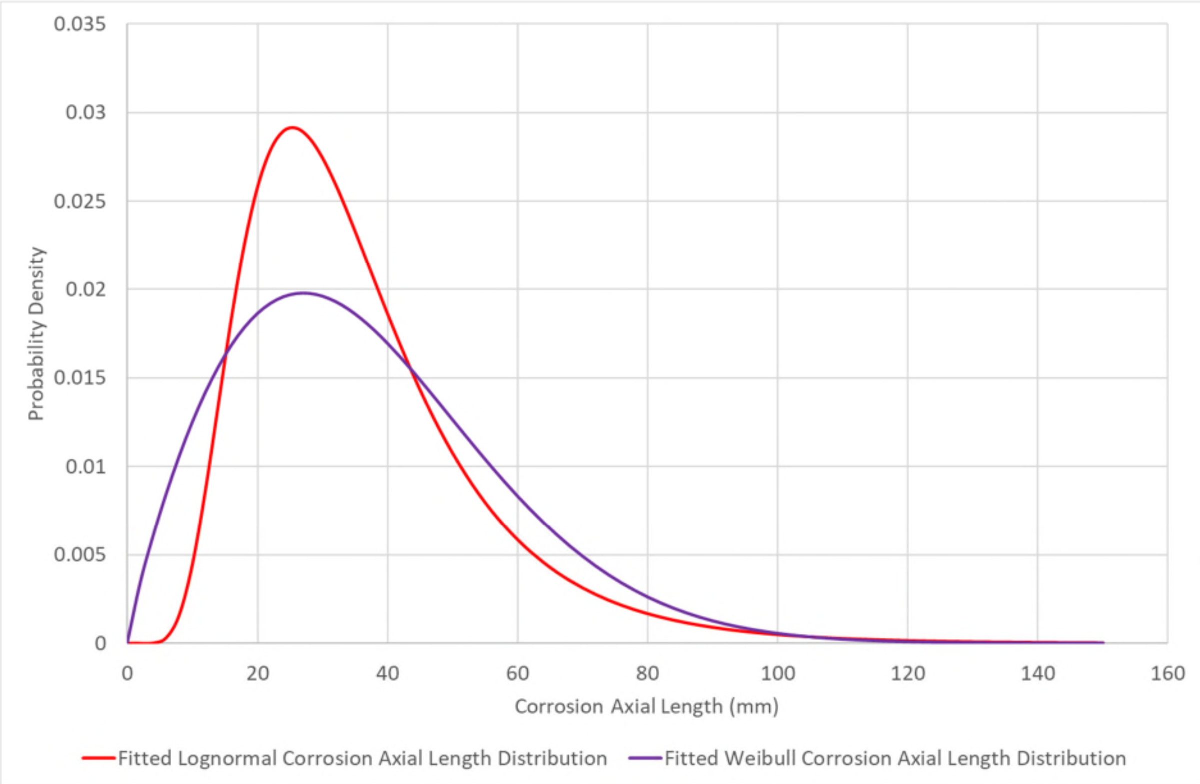

Figure 14: Example Weibull and Lognormal Probability Density Functions

2.5 Corrosion Occurrence Rate

The corrosion occurrence rate is the number of corrosion defects expected to occur on the pipework of the AGI site under assessment per year. In the model, the corrosion occurrence rate is multiplied by the probability of failure of a single corrosion defect in any given region of pipework. This results in a value for the expected number of failures per year, i.e. the failure frequency.

For the below ground pipework regions, the corrosion occurrence rate may be derived using in-line inspection data from the inlet and outlet pipelines to the AGI site. As with the corrosion length distribution from section 2.4 it is assumed that it does not matter whether the inlet and outlet pipelines are fully protected by the CP; under-protected by the CP and/or subject to stray currents, and all of the in-line inspection data may be used to derive the rate. This assumption is made on the basis that the number of corrosion defects is more dependent upon damage to the external pipework coating, rather than the specific corrosion environment and that this factor should be reflected by the number of defects observed in the entirety of the in-line inspection data.

The corrosion occurrence rate for pipework can change over time, and if multiple repeated sets of in-line inspection data are available, multiple occurrence rate values may be derived describing the frequency of corrosion defects in different time periods. Each of these rates may be used within the model to provide a more accurate description of the corrosion frequency over the operating life of the pipework. If the complete inspection history of the pipelines is not available however, a single value can be derived and applied based on the most recent available in-line inspection data.

For above ground pipework and the localised aggressive corrosion regions, deriving values for the defect occurrence rates will depend upon the availability of data from defect repairs made under T/PM/P/11 in each region, or similar data, recording the presence of corrosion defects over the operational life of the AGI site. In the absence of sufficient data to derive a rate for each required region, the rate(s) derived for below ground pipework using in-line inspection data may be cautiously used instead.

The corrosion occurrence rate can be derived using the following method:

- For multiple sets of inspection data of the same pipeline, the location of girth welds and structural features must be manually aligned such that the reported distance values remain constant between inspections.
- Once the data sets are aligned, the reported corrosion defects in each inspection must be matched between inspections. This may be based on their proximity to the closest girth weld and circumferential orientation. Defect matching will indicate if a defect was present in an earlier inspection or is new.
- A total for the number of new corrosion defects which have appeared in the time period between two subsequent inspections must be calculated.
- The surface area of the pipeline in m^2 is calculated using:

  $$A = \pi . D . l$$

  where D is the pipeline outside diameter in m, l is the length of the pipeline section in m, and A is the surface area of the pipeline in m^2.
- The corrosion occurrence rate is calculated using:

  $$cor = \frac{N_{new}}{t_{insp} . A}$$

  where N_{new} is the number of new corrosion defects between two subsequent inspections, t_{insp} is the time period between the inspections in years, and cor is the corrosion occurrence rate in number per m^2 per year. Note that It is assumed through this calculation that the defects occur with approximately equal spacing throughout the pipework. This assumption is considered to be reasonable on the basis of the available information.
- Alternatively, if there is only one set of in-line inspection data available, it may be assumed that all of the reported corrosion defects are new and that the time between inspections is the time from pipeline commissioning to the time of the available inspection. In this case the corrosion occurrence rate is calculated using:

  $$cor = \frac{N_{total}}{t_{comm} . A}$$

  where N_{total} is the total number of corrosion defects in the pipeline, and t_{comm} is the time since commissioning in years.
- Depending on the number of inlet and outlet pipelines and the available data, multiple different values of corrosion occurrence rate may be calculated covering different pipelines and different

time periods. The choice of which values to use within the model depends upon the specific circumstances of the data, for example, the number of different inspections, the time between subsequent inspections and the year in which inspections occurred. For sites with little data the choice is more likely to be straightforward, whereas some judgement may be required if available data is abundant.

2.6 Acceptable Failure Frequency Limit

The acceptable limit for the corrosion failure frequency is set based on guidance given in the following standards:

1) ISO 16708 Reliability-Based Limit State Methods for Pipeline Transportation Systems [21], this standard includes proposed failure frequency limits for various safety classes of onshore pipelines.
2) DNV-OS-F101 Offshore Standards for Submarine Pipeline Systems [11], which provides nominal failure probability limits based on failure type and safety class, including locations where failure may result in human injury.

Corrosion failures generally occur as small leaks. Additionally, failures of buried pipework in a fenced AGI site do not pose a risk to the public. Consequently, corrosion failures of buried pipework on AGI sites are considered to be safety class 1 (low) as defined in ISO 16708. An acceptable failure frequency limit for AGI sites may be derived by considering the safety class 1 (low) line of Figure C.1 from ISO 16708. A mid-range pipe diameter of 400 mm has been assumed, to derive a set limit applicable to all AGI sites on the National Grid Transmission System. From Figure C.1 the acceptable failure frequency limit is therefore 1 x 10^{-3} per km.year. This is similar to the failure probability for the ultimate limit state of a low safety class per pipeline given in DNV-OS-F101. ISO 16708 states the failure frequency limit of $1x10^{-3}$ per km.year applies to major accidents, a higher failure frequency limit may be applied to small leaks, which have lower consequences. Pipework failure frequencies published by the Health and Safety Executive (HSE) [22] indicate that for a 600 mm diameter pipe, a small hole is a factor of 17.5 times higher than a guillotine (rupture) failure. The failure frequency limit, FF_p, applied to corrosion on AGI pipework is therefore given by:

$FF_p = (1x10^{-3}).17.5 = 1.750x10^{-2}$ per km.year $= 1.75x10^{-5}$ per m.year

The above failure frequency limit relates to a linear pipeline length. The length of pipework on an AGI site is not linear, as the layout will involve parallel lengths. To derive a failure frequency limit for an AGI site, a linear pipeline length must be selected to represent the installation. It is assumed that for a typical AGI site the length of pipework within the security fence may be represented by a value of 50 m, the failure frequency limit for an AGI site, FF_s, is therefore:

$FF_s = 8.75x10^{-4}$ per year

The assumed length used to derive the above failure frequency limit is small and is therefore considered to be conservative.

The limit of 8.74 x 10^{-4} per year applies to all AGI sites on the National Grid Transmission Network and is the failure frequency limit for the entire site. In the PIE model, the expected condition of any one distinct region of pipework on the site is determined by the time required in years, for the failure frequency calculated by the model for that region to reach the failure frequency limit. To allow the calculated site failure frequency limit to be compared with the output of the model for each region of pipework, it must be divided by the total surface area of the pipework on the AGI site. This gives a value for the failure frequency in per m^2 per year for the site pipework.

The surface area of the site pipework may be determined using:

$$A_s = \pi . \sum_{i=1}^{N} D_i . l_i$$

Where N is the total number of different diameters of pipework on the site, D_i are the values of each different pipework diameter in m, l_i are the total lengths of each different pipework diameter in m, and A_s is the total surface area of the site pipework in m^2.

Therefore the failure frequency limit per m^2.year, FF_{limit}, for the site pipework is given by:

$$FF_{limit} = \frac{FF_s}{A_s}$$

2.7 Project GRAID Robot Data

The project GRAID robot is capable of measuring wall thickness from inside site pipework at full operating pressure. The measurement system used on the GRAID robot is EMAT. An EMAT transducer consists of a magnet and an electrical coil and ultrasonic waves are produced in the pipe wall by the interacting magnetic fields from both components. The ultrasonic waves which move within the pipe wall are dependent on the dimensions and properties of the pipe material. The waves are reflected by the external pipe surface, producing an echo. The echo is then detected and measured in order to calculate a wall thickness value. The presence of corrosion will result in a reduced wall thickness measurement when compared to the measurements made of undamaged pipe [23].

The EMAT system on the GRAID robot consists of two sensors mounted to the end of a single robotic arm. The arm is able to rotate through 360° allowing the sensors to take measurements at any point on the pipe circumference. Each EMAT sensor face on the GRAID robot is 22 mm in diameter [24].

In order to assess the wall thickness measurement capabilities of the GRAID robot EMAT sensors an “Enhanced NDT” work programme was undertaken over a two-week period in July 2018, at DNV-GL’s Spadeadam test facility in Cumbria. A further day of testing was undertaken at National Grid’s Eakring training facility in Nottinghamshire. The first week of the Enhanced NDT programme at Spadeadam focussed upon using the sensors to measure sets of machined defects from two different pipe spools. The second week of the programme focussed upon using the sensors to measure real defects from a third pipe spool. At Eakring, further scans of real defects were performed using three further pipe spools [24].

The defects included in the testing programme were of different axial lengths, circumferential widths and through-thickness depths. Based on their axial and circumferential dimensions, under the definitions indicated by Figure 2.2 in the Pipeline Operator’s Forum Specifications and Requirements for In-Line Inspection of Pipelines [25], the measured defects in the six test spools consisted of [26] [27]:

- 3 machined general defects
- 2 machined pitting defects

- 4 machined axial grooving defects
- 7 real general defects
- 2 real pitting defects
- 1 real axial grooving defect

Wall thickness measurements were taken at multiple points for each defect. The area of reduced wall thickness was mapped out with a grid, and readings were taken at regular spatial intervals in both the axial and circumferential directions over the pipe surface. For the machined defects:

- 85 wall thickness measurements of general defects were taken
- 3 wall thickness measurements of pitting defects were taken
- 23 wall thickness measurements of axial grooving defects were taken

And for the real defects:

- 140 wall thickness measurements of general defects were taken
- 13 wall thickness measurements of pitting defects were taken
- 4 wall thickness measurements of axial grooving defects were taken

For each point at which a wall thickness measurement was made using the GRAID EMAT sensor, a measurement was also taken for comparison, using an industry standard ultrasonic probe by an external non-destructive testing (NDT) specialist. It is noted that the above values do not include measurements which were also taken of the undamaged pipe surrounding the defects except in the case of 6 of the real general defects and 1 of the real pitting defects where the boundaries of the defects were not clear.

General comments made following the Enhanced NDT and Eakring programmes were that the sensors performed well with regards to wall thickness measurement of general defects but often had difficulty getting accurate readings for the smaller dimension pitting and axial grooving defects. The EMAT sensors were also found to experience signal scattering if the defect surface was curved, which results in no measurement being made. Additionally, it was noted that both the EMAT and ultrasonic probes were unable to obtain satisfactory measurements of the real defects from the spools at Spadeadam. In this case the defects were very shallow and the pipe wall thickness was high (approximately 26 mm thick) [28].

From the wall thickness measurements of the machined and real defects an analysis has been performed by PIE to determine initial depth sizing tolerances associated with the GRAID robot wall thickness measurement system. For the purposes of the analysis the real defects from the spools at Spadeadam have not been included. For these defects the wall thickness measurements of both the EMAT and ultrasonic probes were very close to the nominal wall thickness of the pipe spool, such that any variation between readings could potentially be attributed to noise. Additionally, there is little information on the true depth of the defects. The outcome of these particular measurements may potentially indicate the limitations of the EMAT and ultrasonic probes resulting from high wall thickness and low defect depth, however confirmation of this would require further research.

The calculated tolerance values are based exclusively upon 123 of the wall thickness measurements indicated above, confirmation of the true capabilities of the robot wall thickness measurement system would require a more detailed testing programme. The tolerances have been derived through comparison with the associated ultrasonic probe measurement, which is assumed to be the “correct” wall thickness measurement for the corresponding measurement point. The calculated tolerance values for each defect type are shown in Table 2-4. In each case the value quoted is the accuracy at 80% certainty. That is, for 80% of all measurements taken, the recorded value will be within the quoted tolerance limits. The tolerances are shown as a percentage of the pipe wall thickness.

	General	Pitting	Axial Grooving
Depth Sizing Accuracy at 80% Certainty for Machined Defects	± 0.05 t	± 0.10 t	± 0.75 t
Depth Sizing Accuracy at 80% Certainty for Real Defects	± 0.18 t	N/A	± 0.35 t

Table 2-4: Calculated Depth Sizing Tolerances for Project GRAID Robot Wall Thickness Measurement

Note that for the real pitting defect considered, a wall thickness measurement could not be obtained by both the EMAT and ultrasonic probes and therefore a tolerance was not able to be calculated. Additionally, the calculated tolerance for axial grooving for real defects would not be expected to be better than the equivalent tolerance for machined defect. The values in this case show the limitations of the data.

A comparison can be made between the values from Table 2-4 and published depth sizing tolerances from an industry standard metal flux leakage pipeline inspection tool. Table 2-5 indicates the depth sizing tolerances associated with ROSEN's MFL-A tool [29]. The GRAID tolerances for machined general and pitting defects are in line with ROSEN. For real defects, and axial grooving, GRAID appears to have a slightly lower performance than the ROSEN tool.

	General	Pitting	Axial Grooving
Depth Sizing Accuracy at 80% Certainty	± 0.10 t	± 0.10 t	± 0.15 t

Table 2-5: Depth Sizing Tolerances for ROSEN's RoCorr MFL-A Tool

Specific testing of the axial length and circumferential width sizing capabilities, and the probability of defect detection, was not performed as part of the Spadeadam and Eakring programmes. However, in terms of the length sizing tolerance, GRAID would be expected to perform better than a standard pipeline inspection tool. This is because pipeline inspection tools travel at speeds of 3 m/s or above which can result in a considerable length sizing error. The GRAID robot however, remains stationary whilst taking measurements.

If corrosion defect measurements taken by the GRAID robot are available for a site under assessment using the PIE GRAID model, the data may be used in the model to derive probability distributions or corrosion occurrence rates for the associated corrosion environment by adapting the methods described in sections 2.3, 2.4 and 2.5. In principle, a complete inspection (measurements taken of close to 100% of the surface area of the inspected section) using the GRAID robot would be considered to be the best possible data source for distributions used in the model as it would provide a true indication as to the condition of the pipework on site. The utility of GRAID robot data in practice however, will depend upon the percentage of the pipe surface area scanned in the desired regions and whether any defects are found. The corrosion occurrence rate used in the model gives the expected number of defects per m^2 of pipe. To provide useful data to the model, the GRAID robot must either find defects which can be used to derive corrosion growth rates/axial lengths or scan a sufficiently large area such that the number of defects per m^2 calculated using other methods is shown to be incorrect. The quantity of data available from the GRAID robot is expected to increase with further iterations of its design as the technology improves, therefore the data from the robot will become more influential with regards to model output over time.

2.8 Probabilistic Corrosion Growth Method

The probabilistic corrosion growth model uses a Monte Carlo method to simulate corrosion growth within the pipework and calculate the probability of failure. The full methodology for the implementation of the Monte Carlo method and calculation of the probability of failure is as follows:

1. A separate probabilistic calculation must be performed for each individual pipe joint (or other appropriately small pipework section with the same corrosion environment, geometry and operating conditions). On the basis of the AGI site design and available CIPS data, classify each pipe joint according to the pipework regions indicated in section 2.3.

2. Set the initial corrosion growth period, j, to one year.

3. Randomly select a corrosion axial length in accordance with the corrosion length probability distribution derived using the method in section 2.4.

4. On the basis of the corrosion length, determine the limiting corrosion depth for the pipework joint under consideration, as outlined in section 2.2, using the "Extreme Damage" category within T/PM/P/11.

5. Randomly select a corrosion growth rate in accordance with the appropriate probability distribution for the pipework region, derived using the methods in section 2.3.

6. Randomly select a month during the year for the corrosion growth to begin and calculate the depth that a defect, starting at a depth of zero and growing at the chosen rate, would reach at end of the corrosion growth period. Note that the corrosion growth period does not account for the start month, a corrosion defect which begins growing in January would therefore have a longer growth period than one which begins growing in December.

7. If the calculated depth exceeds the limiting corrosion depth then note the defect as having exceeded the limit. If the calculated depth is below the limiting corrosion depth then note the defect as having being within the limit.

8. The Monte Carlo method is performed by repeating steps 3 to 7 200,000 times, selecting a new axial length and a new corrosion growth rate each time. The probability of failure for the specific growth period, P_{f_j}, is given by the number of defects which exceeded the limit, $N_{faliures}$, divided by the total number of repetitions, $N_{repetitions}$:

$$P_{f\,j} = \frac{N_{failures}}{N_{repetitions}}$$

9 The value of the probability of failure is then multiplied by the corrosion occurrence rate, cor, to give the failure frequency value for the specific growth period for the pipe joint under consideration, FF_j:

$$FF_j = P_{f\,j} . cor$$

10 The overall failure frequency after j years for the pipe joint under consideration is given by the sum of the failure frequencies for each specific growth period up to that point:

$$FF_{overall\,j} = \sum_{k=1}^{j} FF_k$$

11 Steps 2 to 10 are repeated for the same pipework joint, increasing the corrosion growth period by 1 year each time until the value of $FF_{overall\,j}$ exceeds the value of FF_{limit} derived in section 2.6.

12 The final value of j, the number of years the simulation was performed for, is used as a measure of the condition of the pipework joint under consideration.

13 The process from steps 2 to 12 is repeated for the other pipework joints on the AGI site.

In summary, the model predicts the annual expected number of corrosion defects within the pipework joint exceeding the maximum allowable depth, per square metre. The above method is illustrated for a single pipework joint in the algorithm in Figure 15.

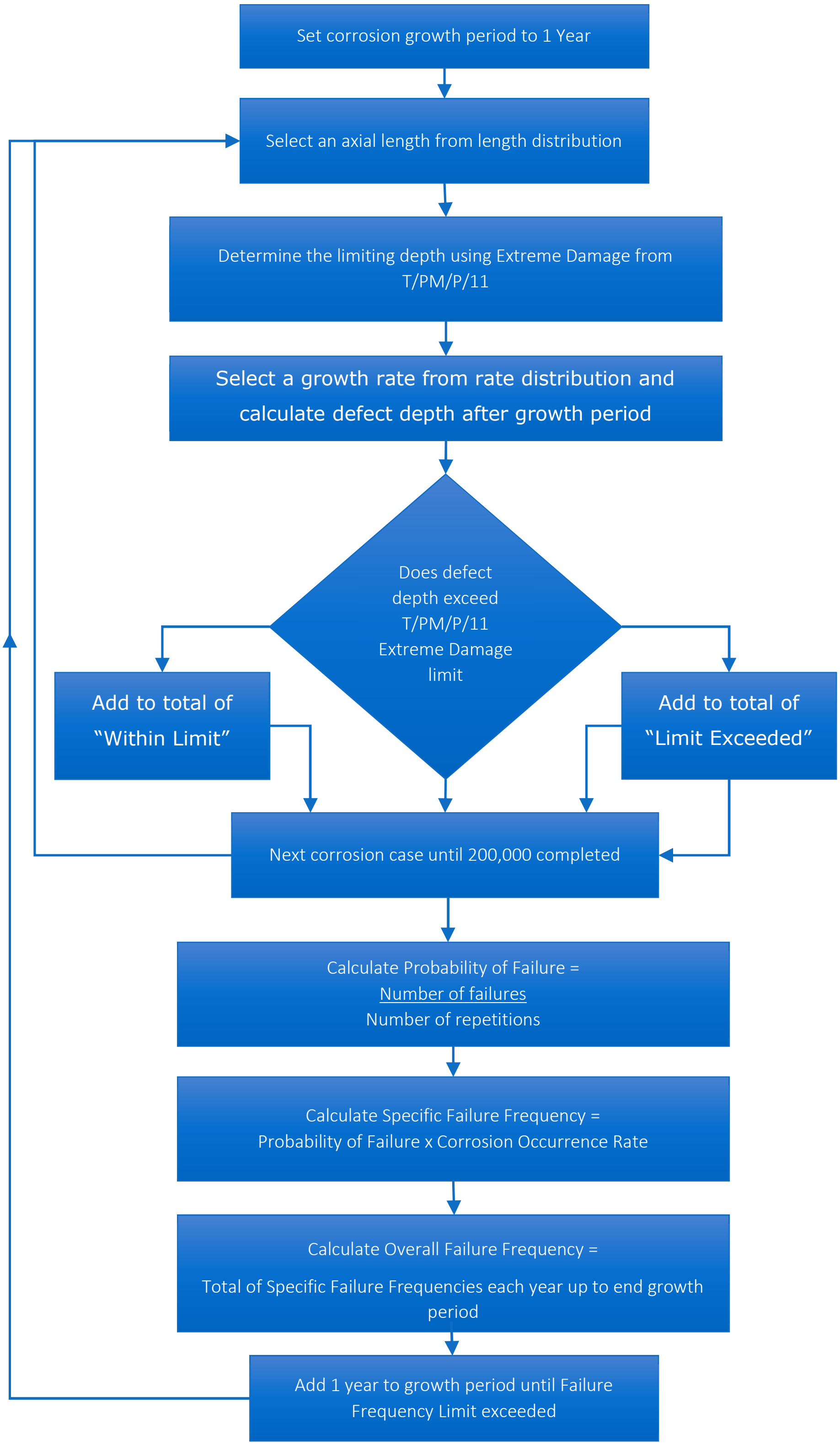

Figure 15: Algorithm Showing the Method of Probabilistic Corrosion Growth with Monte Carlo Simulation

3 Application of the Probabilistic Corrosion Growth Model to Pipework at Pannal AGI

An inspection of a 50 m section of pipework at Pannal AGI was performed by the Project GRAID robot from the 16th to the 27th of July 2018 [24]. Pannal AGI is a network offtake with NTS pig trap, located in North Yorkshire, near the town of Harrogate. The site is shared with Northern Gas Networks. The on-site pipework is made up of 762 mm and 914 mm outside diameter pipe and is located both above and below ground. The maximum operating pressure of the site is 70 barg. At Pannal AGI there is no lagged pipework or pit-wall transitions [30] [31].

The inspected section of pipework consisted of [32]:

- an above ground section including, a reducer, flanges, standard above ground pipe joints, two valves, a 90-degree bend through a tee piece (in the horizontal plane) and a 45-degree bend (in the vertical plane) leading below ground; and
- a below ground section including, a pipe spool in the wind-water line region, a 45-degree bend (in the vertical plane) and standard below ground pipe joints.

The GRAID robot took wall thickness measurements at 9 different areas within the 50 m section of pipework. The scanning areas were [33]:

- Numbered pipe supports 1, 2, 3 and 6 above ground
- Numbered welds (in the area of the field joint coating) 1, 2, 3, and 4 below ground
- The wind-water line

In each scanning area the robot took readings at between 2 and 11 different locations (along the direction of the pipe axis), and at each location measured the wall thickness at 12 equally spaced points around the pipe circumference with both sensors (i.e. two measurements for each point). The total number of wall thickness measurements taken during the inspection was 1070 [34] [35] [36] [37] [38] [39] [40] [41] [42] [43] [44].

For all measurements taken it was found that the recorded wall thickness was within the ± tolerance of the nominal wall thickness and therefore no corrosion defects (or other metal loss defects) were found during the inspection run.

Figure 16 shows the inspected section of pipework at Pannal AGI, including each of the scanning areas. The above ground supports are highlighted in red and the below ground weld areas are highlighted in pink. The wind water line region is shown in the elevation portion highlighted in blue. The full extent of the 50 m inspection route is from the pig-trap near support number 1 (in red) to weld area number 4 (in pink) [45].

The PIE GRAID model has been applied to the pipework at Pannal AGI to determine its expected condition. All of the National Grid pipework at Pannal AGI has been included in the assessment, the assessment is therefore not restricted to the 100 m inspected section.

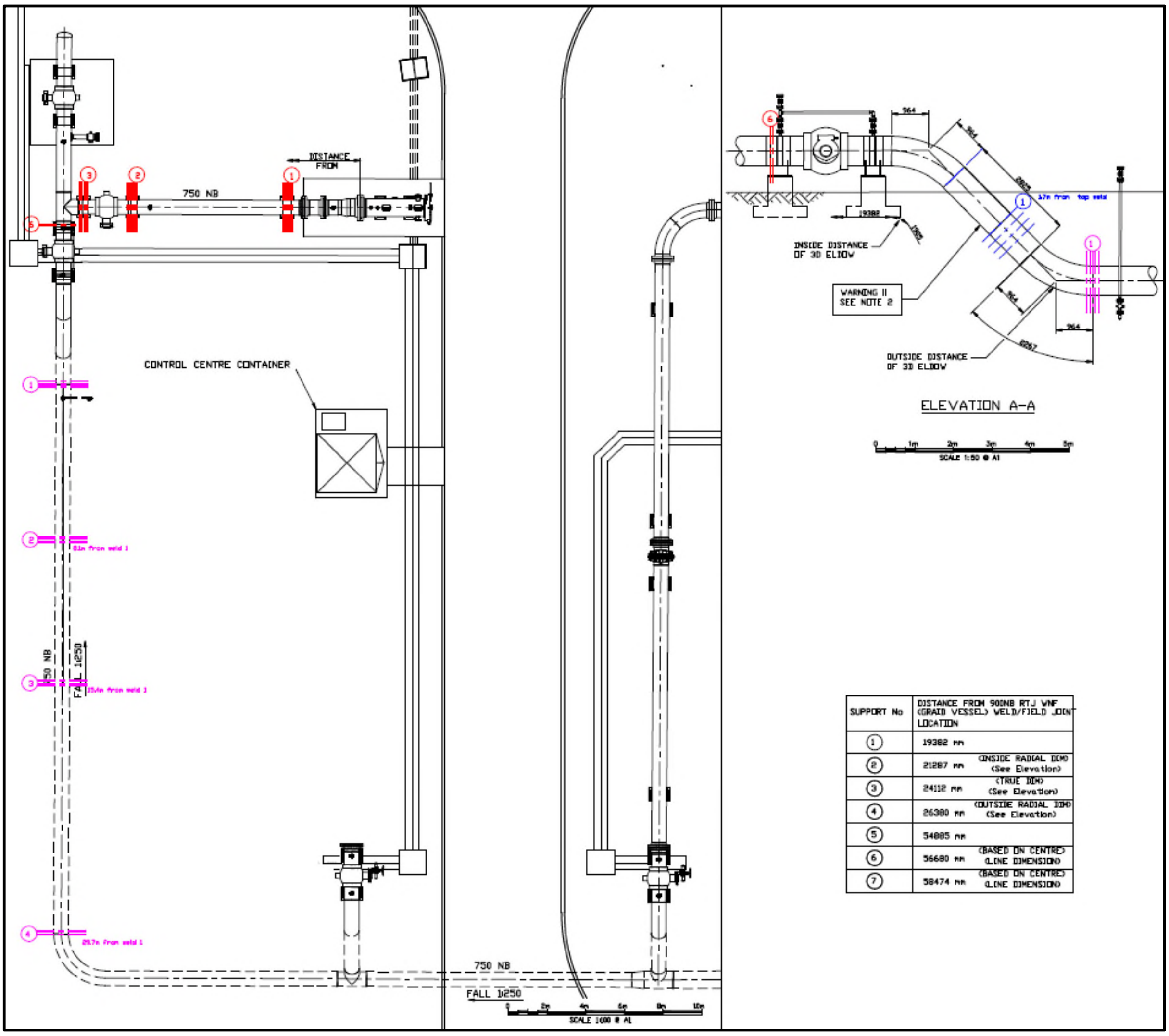

Figure 16: Inspected Section of Pipework at Pannal AGI with Scanning Regions Highlighted

3.1 Pannal AGI Corrosion Environments, Probability Distributions, Corrosion Occurrence Rate and Acceptable Failure Frequency Limit

The data available relating to Pannal AGI, from which probability distributions, the corrosion occurrence rate and the acceptable failure frequency limit can be derived, consists of:

- Pannal AGI site drawings and a list of pipework components (pipe tally) produced by Premtech in 2018 for the GRAID inspection [45] [32] [30].
- A pipework stress analysis report for Pannal AGI produced by Andrew Francis and Associates in 2018 for the GRAID inspection [31].
- In-line inspection reports for the inlet pipeline, Feeder Number 7 – Bishop Auckland to Pannal, from 1994, 1998, 2010 and 2017 [46] [47] [48] [49].
- In-line inspection reports for the outlet pipeline, Feeder Number 7 – Pannal to Cawood from 2004 and 2013 [50] [51].

- CIPS reports for Pannal AGI and the Feeder Number 7 pipeline sections within Pannal AGI from 2016 [52] [53].
- A CIPS report for a portion of the inlet pipeline, Feeder Number 7 – Bishop Auckland to Pannal, covering Sutton Howgrave to Pannal from 2011 [54].
- A CIPS report for the outlet pipeline, Feeder Number 7 – Pannal to Cawood from 2012 [55].
- P11 data for three excavations made to the inlet pipeline, Feeder Number 7 – Bishop Auckland to Pannal from 2012 [56] [57] [58].

Given that only one set of CIPS reports is available for the inlet and outlet pipelines, it is assumed that the protection level indicated by the reports applies over the entire operational life of the corresponding pipeline or the AGI site.

The CIPS reports for Pannal AGI indicate both the Feeder Number 7 pipeline sections within the AGI site boundary, and the AGI pipework, to be generally well protected by the CP system over their entire surveyed length. There were four instances on the buried AGI pipework where the measured potentials dipped but remained above the protection criterion of -850 mV. Additionally, a low level of DC stray current interference was recorded on both the on-site Feeder Number 7 pipeline sections and the AGI pipework, but was not sufficient to disrupt the protection afforded by the CP system.

On the basis of the AGI site CIPS reports and the site drawings, the different corrosion regions, in line with section 2.3, which are applicable to Pannal AGI are:

- Below ground pipework with a fully functioning CP system
- Pipework in the region of the wind-water line
- Above ground pipework
- Above ground pipework at supports

The expected condition of the pipework at Pannal AGI is therefore dependent upon probability distributions and corrosion occurrence rates for each of the above regions, which are derived in the following sections; and the local geometry and operating conditions associated with the pipework.

3.1.1 Below Ground Pipework

As noted above, on the basis of the AGI site CIPS reports the only below ground region of pipework which requires consideration at Pannal is below ground pipework with a fully functioning CP system. The CIPS reports for the inlet and outlet pipelines report an identical level of protection to the pipework within the AGI site. The reports indicate both the inlet and outlet pipelines to be generally well protected by the CP system along the entire length of the surveyed sections. There were four areas on the Sutton Howgrave to Pannal section where the measured “off” potential briefly dipped below the protection criterion of -850 mV. Additionally, there were 21 instances spread over the inlet and outlet pipelines together where the measured potentials dipped but remained above the protection criterion. A low level of DC stray current interference was also recorded on both the inlet and outlet pipeline sections, but was not sufficient to disrupt the protection afforded by the CP system.

Given the similar level of protection afforded by each CP system, it is concluded that the in-line inspection data from the Pannal AGI inlet and outlet pipelines may be used to derive a corrosion growth rate distribution which is appropriate for application to the on-site below ground pipework.

Feeder Number 7 – Bishop Auckland to Pannal (30BISPAN)

In-line inspection reports are available for the inlet pipeline Feeder Number 7 – Bishop Auckland to Pannal (30BISPAN) from inspections in 1984, 1994, 1997, 2010 and 2017. A summary of the 30BISPAN pipeline details are given in Table 3-1 and a summary of the number of metal loss and corrosion defects which were reported in each inspection is given in Table 3-2. In each inspection, the total metal loss number includes all metal loss defects including corrosion, milling and manufacturing defects. Note that a distinction between corrosion and other types of metal loss only began with the 1997 inspection.

Diameter (mm)	
Internal Diameter (mm)	
Wall Thickness (mm)	
Constructed (Year)	
Length (m)	

Table 3-1: 30BISPAN Pipeline Details

Year of Inspection	Total Number of Metal Loss Defects	Total Number of Corrosion Defects
1984		
1994		
1997		
2010		
2017		

Table 3-2: 30BISPAN Metal Loss and Corrosion Inspection History

Full details of the metal loss and corrosion defects reported by the inspection tool were not available in the inspection reports from 1984, 1994 and 1997. In each case a sample of the defect data was included, and general comments were made. A defect matching process, as outlined in section 2.3.1, therefore cannot be performed using data from any of these three inspections.

Comments made in the 1994 inspection report indicated that no growth had been observed in the two defects which had previously been reported in the 1984 inspection. The 1997 report also indicated that no growth had occurred between inspections and noted that any differences in the number of defects was due to improvements in technology and changes in defect reporting requirements. In 1997, six reported metal loss defects were excavated following the in-line inspection. Upon excavation, four of the defects were confirmed to be mid-wall laminations, with only two found to be external corrosion. The two corrosion defects were both reported with a depth of 33% of wall thickness and upon excavation were found to have depths of 19.6% of wall thickness and 14.1% of wall thickness.

For the 2010 and 2017 inspections a full set of inspection data with defect locations and measurements is available from the vendor ROSEN. It is therefore possible to perform defect matching between the 2017 and 2010 inspections. From the 23 corrosion defects reported in the 2017 inspection data it is possible to match seven of the defects to corresponding defects in the 2010 data. The seven matches include all five corrosion defects reported in 2010 and two additional defects which were originally reported in 2010 to be metal loss milling defects. The remainder of the corrosion defects in the 2017 inspection cannot be matched to corresponding defects in the 2010 data and therefore are assumed to be new corrosion defects which began growing[3] during the period between the two inspections.

The P11 data available for the pipeline relates to excavations of two smooth dents and a lamination and is therefore not relevant with regards to corrosion growth.

In accordance with the method given in section 2.3.1, the defect matching process indicated above may be used to derive a corrosion growth rate distribution for the Pannal AGI below ground pipework. In this case the data would be representative of the 7-year period from 2010 to 2017. Alternatively, data from 30BISPAN may be used to derive the distribution by making an assumption that the corrosion defects reported in the 2017 inspection grew to their 2017 measured depth over the full operational life or half the operational life of the pipeline.

Feeder Number 7 – Pannal to Cawood (36PANCAW)

For the outlet pipeline Feeder Number 7 – Pannal to Cawood (36PANCAW) it is known that inspections took place in 1982, 1991, 2004 and 2013. However, in-line inspection reports are available for only the 2004 and 2013 inspections. A summary of the 36PANCAW pipeline details are given in Table 3-3 and a summary of the number of metal loss and corrosion defects which were reported in each inspection is given in Table 3-4. In each inspection, the total metal loss number includes all metal loss defects including corrosion, milling and manufacturing defects.

Diameter (mm)	
Internal Diameter (mm)	
Wall Thickness (mm)	
Constructed (Year)	
Length (m)	

Table 3-3: 36PANCAW Pipeline Details

Year of Inspection	Total Number of Metal Loss Defects	Total Number of Corrosion Defects
1982		
1991		
2004		
2013		

Table 3-4: 36PANCAW Metal Loss and Corrosion Inspection History

For the 1982 inspection no information is available and therefore the number of metal loss defects which were reported is unknown. For the 1991 inspection, the only available information is from the 2004 inspection report. The total number of metal loss defects reported in 1991 is not known, however it is indicated that a comparison was performed between the 2004 and 1991 inspection data sets. Full details of the comparison are not available however the report notes that metal loss defects were able to be

[3] Note that the defects may have been present in 2010, but were at that stage measured to have a depth which was below the ROSEN reporting threshold. It has been assumed for the purposes of the model however, that the defects are new.

matched between the two inspections and that there was no observed corrosion growth in the interim period.

The 2004 inspection was performed by the vendor Pipeline Integrity International (PII). metal loss defects, of which were milling/manufacturing features and the remaining are assumed to be corrosion, were detected by the inspection tool. However, the location and sizing details of the metal loss features were not reported as they did not exceed the “20/40” reporting specification which was used by PII at the time. In the “20/40” reporting specification, defects which are classed as general corrosion with a measured depth of less than 20% of wall thickness, and defects which are classed as pitting corrosion with a measured depth of less than 40% wall thickness, are not reported. It is indicated in the report that the deepest metal loss defect was measured to be 28% of wall thickness.

For the 2013 inspection a full set of inspection data with defect locations and measurements is available from the vendor ROSEN. In 2013 there were metal loss defects reported, of which were classified as corrosion. The apparent reduction in the number of corrosion defects between 2013 and 2004 can be explained by improvements in technology and the use of different inspection vendors.

Given the lack of data from 1982 and 1991, and the use of the “20/40” specification in 2004 it is not possible to perform defect matching for any of the inspections on 36PANCAW. A corrosion growth rate distribution for the below ground pipework at Pannal AGI using data from 36PANCAW may therefore only be derived by making an assumption that the corrosion defects from the 2013 inspection grew to their 2013 measured depth over the full operational life or half the operational life of the pipeline.

Distribution Choice

From the available data indicated above and the method outlined in section 2.3.1, a corrosion growth rate distribution may be derived for the below ground pipework at Pannal AGI using:

- Corrosion growth rates calculated from defect matching between the 2017 and 2010 inspection data from the pipeline 30BISPAN
- Corrosion growth rates calculated from an assumption that the reported defects in the 2017 inspection of the pipeline 30BISPAN grew to their 2017 measured depth over the full operational life or half the operational life of the pipeline.
- Corrosion growth rates calculated from an assumption that the reported defects in the 2013 inspection of the pipeline 36PANCAW grew to their 2013 measured depth over the full operational life or half the operational life of the pipeline.

For the latter two options, the available inspection data from both 30BISPAN and 36PANCAW indicates that there was no, or very little, corrosion growth for most of the operational life of each pipeline. Based on the reported defects, any corrosion growth which has taken place appears to have occurred in the recent past. The most reasonable assumption regarding the derivation of corrosion growth rates is therefore to assume a half-life growth period. Also note that given the assumptions used to calculate the growth rates are the same in these cases, it is assumed that the data from both pipelines may be considered together as a single data set from which to derive a distribution.

Figure 17 shows cumulative Weibull and lognormal probability distributions, fitted to the corrosion growth rates calculated from the defect matching for 30BISPAN using the method in section 2.3.1. The distributions have been fitted using the maximum likelihood estimation method. In this case, neither distribution is a good fit to the data.

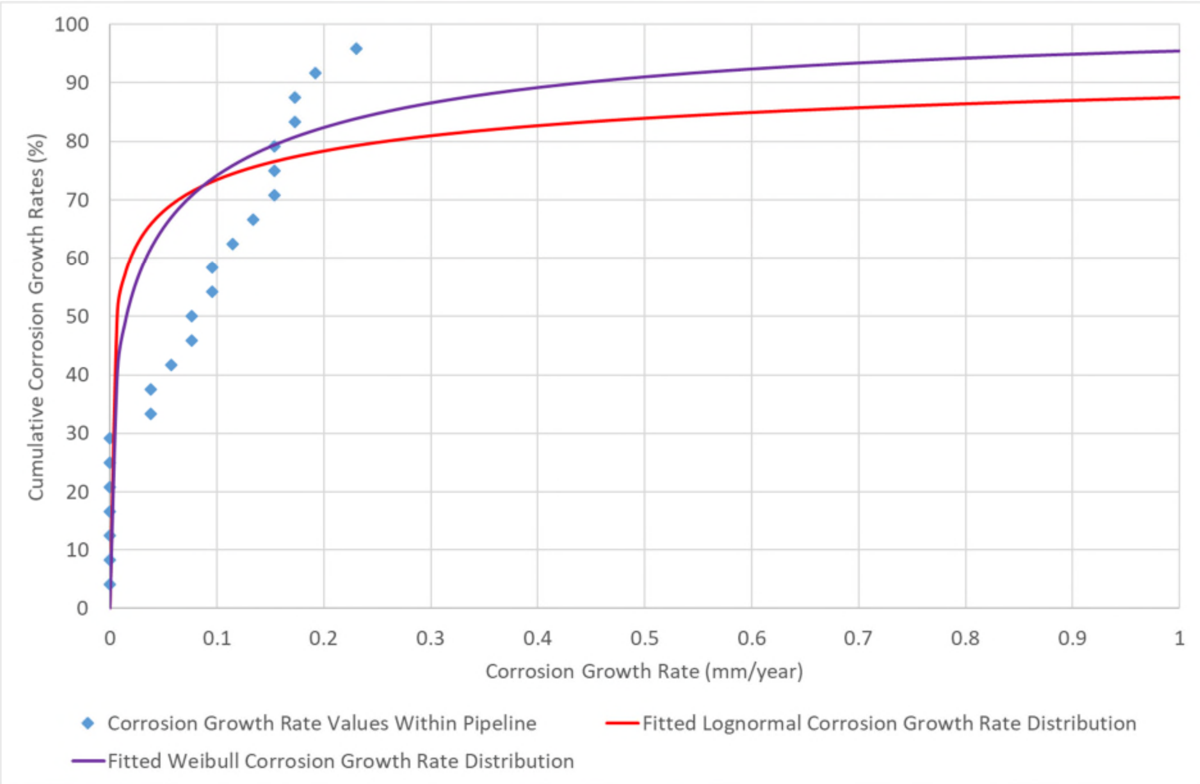

Figure 17: Weibull and Lognormal Cumulative Distribution Functions Fitted to Corrosion Growth Rates from Defect Matching for 30BISPAN

Figure 18 shows a cumulative probability distribution fitted to the corrosion growth rates calculated from the half-life growth period assumption for the combined 30BISPAN and 36PANCAW data sets, using the method in section 2.3.1. The distribution has been fitted to the data using the maximum likelihood estimation method. The distribution shown is a lognormal distribution, indicated by the p-value and Anderson-Darling statistic to be the best fit to the data.

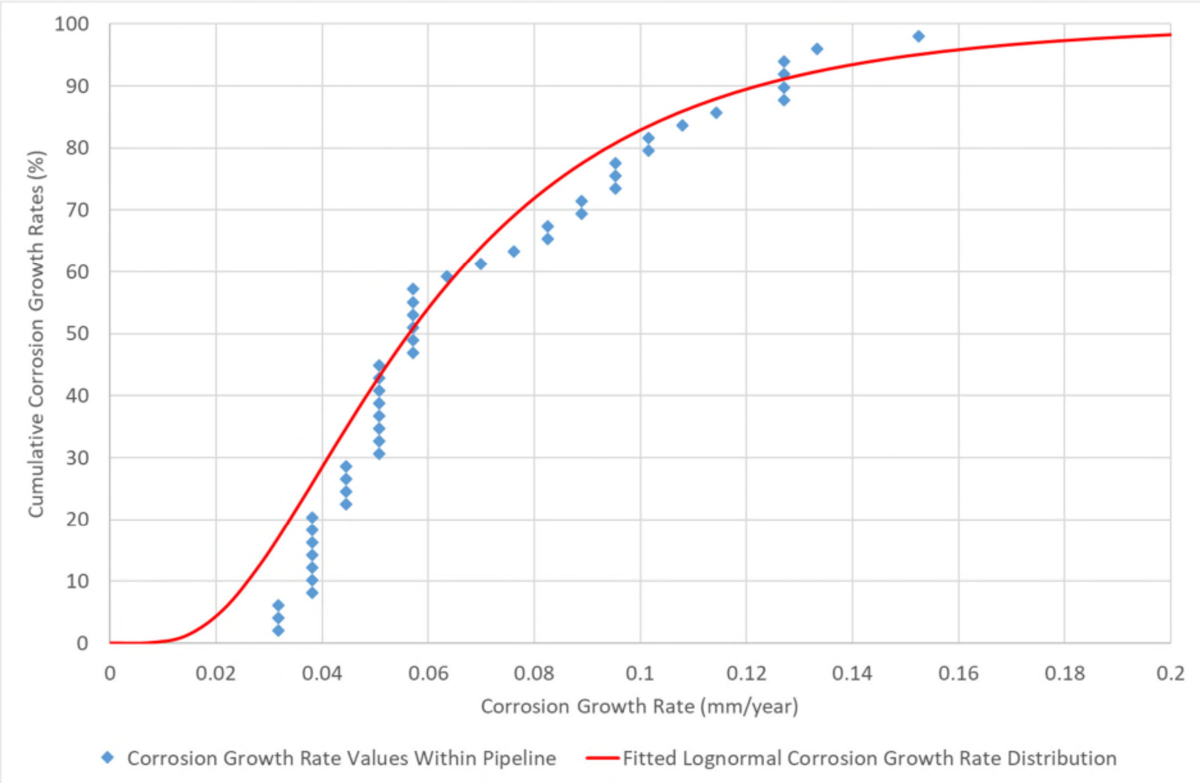

Figure 18: Lognormal Cumulative Distribution Function Fitted to Corrosion Growth Rates from Half Life Growth Period Assumption for 30BISPAN and 36PANCAW

On the basis of Figure 17 and Figure 18, the most appropriate distribution to apply to the below ground pipework at Pannal AGI is the lognormal distribution from Figure 18 as this distribution provides the best fit for each of the data sets. Furthermore, although defect matching gives the most accurate representation of corrosion growth rates associated with a pipeline over a specific period between two inspections, in this case the inspection history of the both the inlet and outlet pipelines indicates that the corrosion growth activity has changed over the operational life of each pipeline. The most active period of growth has occurred more recently, between the 2017 and 2010 inspections on 30BISPAN and the 2013 and 2004 inspections on 36PANCAW. Assuming this behaviour is representative of the below ground pipework at Pannal AGI, it would therefore be inappropriate to apply a corrosion growth rate distribution derived on the basis of the period of increased corrosion growth to the entire operational life of the pipework. The assumption that the corrosion defects have been growing for half of the operational life of each pipeline is more representative of the actual corrosion behaviour and therefore the distribution based on this assumption is the most appropriate for application in the model.

The parameters of the lognormal distribution used for the corrosion growth rates for below ground pipework at Pannal AGI are given in Table 3-5 and a plot of the probability density function is shown in Figure 19.

Parameter	Value
μ	-2.875
σ	0.603

Table 3-5: Parameters for Lognormal Corrosion Growth Rate Distribution for Below Ground Pipework at Pannal AGI

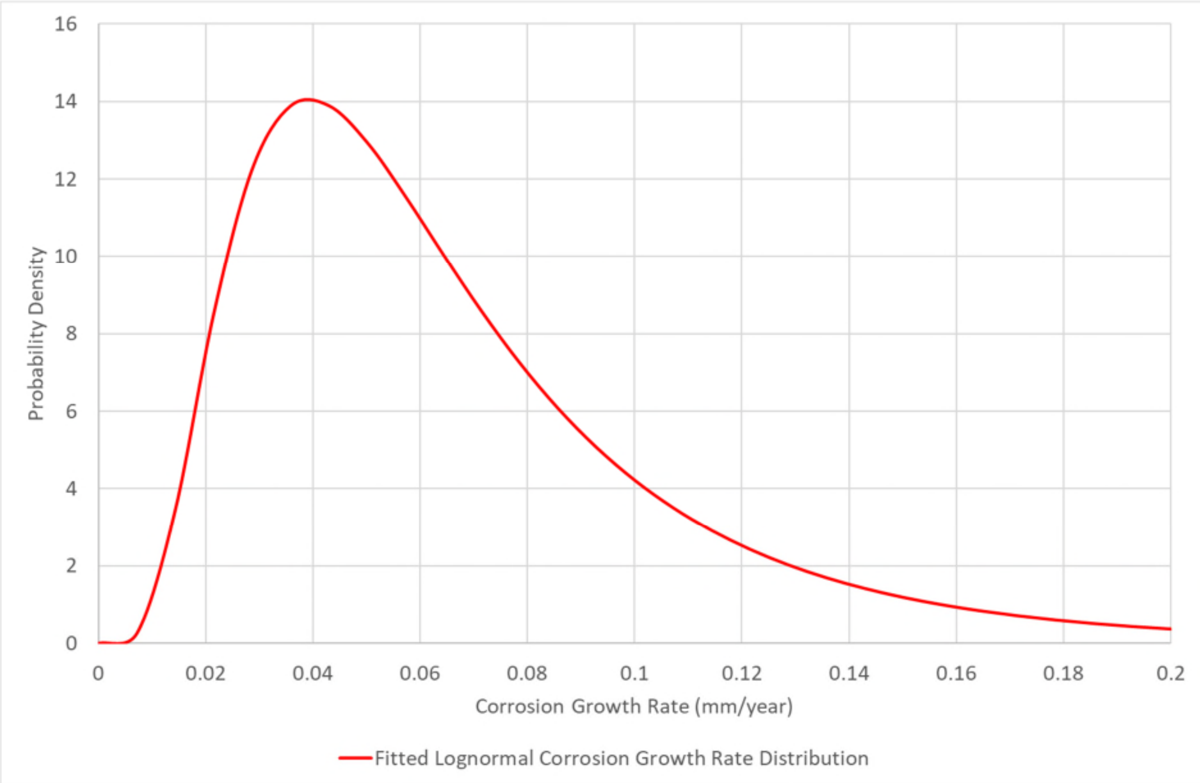

Figure 19: Pannal AGI Below Ground Pipework Corrosion Growth Rate Probability Density Function

3.1.2 Above Ground Pipework

Pannal AGI is in North Yorkshire near the town of Harrogate. The site pipework is entirely outdoors and is located in a rural area, approximately 90 km from the nearest coast. Based on Table 2-3 from section 2.3.2, the atmosphere at the site would be categorised as C2 – Low corrosivity.

From Table 2-3 the upper limit for the range of thickness loss of carbon steel associated with a C2 atmosphere is 0.025 mm. Using this value and the distribution derived in section 3.1.1 and following the method from section 2.3.2, a corrosion growth rate distribution for the above ground pipework at Pannal AGI may be derived.

The above ground pipework distribution has been derived using 8 $cgr_{ag,x}$ points scaled from the below ground pipework distribution (see section 2.3.2). Figure 20 shows the above ground pipework cumulative probability distribution, fitted to the derived above ground $cgr_{ag,x}$ points using the maximum likelihood estimation method. The distribution shown is a Weibull distribution, indicated by the p-value and Anderson-Darling statistic to be the best fit to the data.

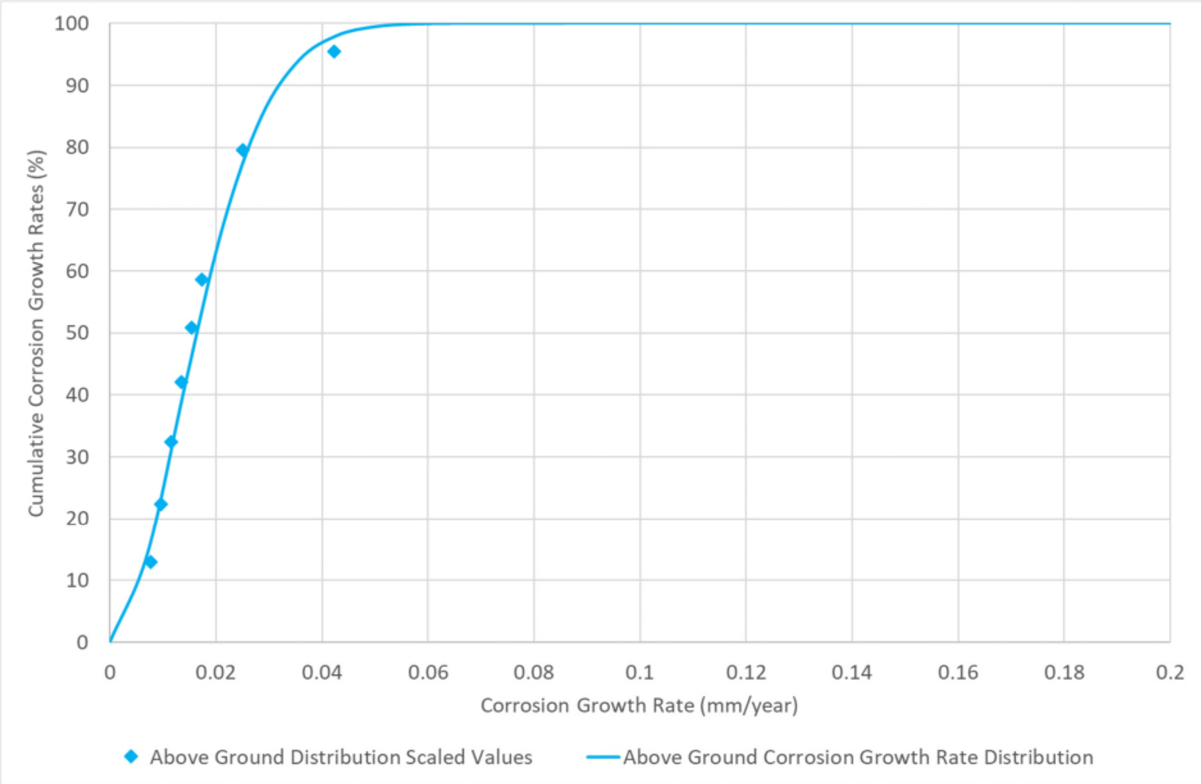

Figure 20: Pannal AGI Above Ground Cumulative Corrosion Growth Rate Distribution

The parameters of the Weibull distribution used for the corrosion growth rates for above ground pipework at Pannal AGI are given in Table 3-6 and a plot of the probability density function is shown in Figure 21.

Parameter	Value
α	1.799
β	0.020

Table 3-6: Parameters for Weibull Corrosion Growth Rate Distribution for Above Ground Pipework at Pannal AGI

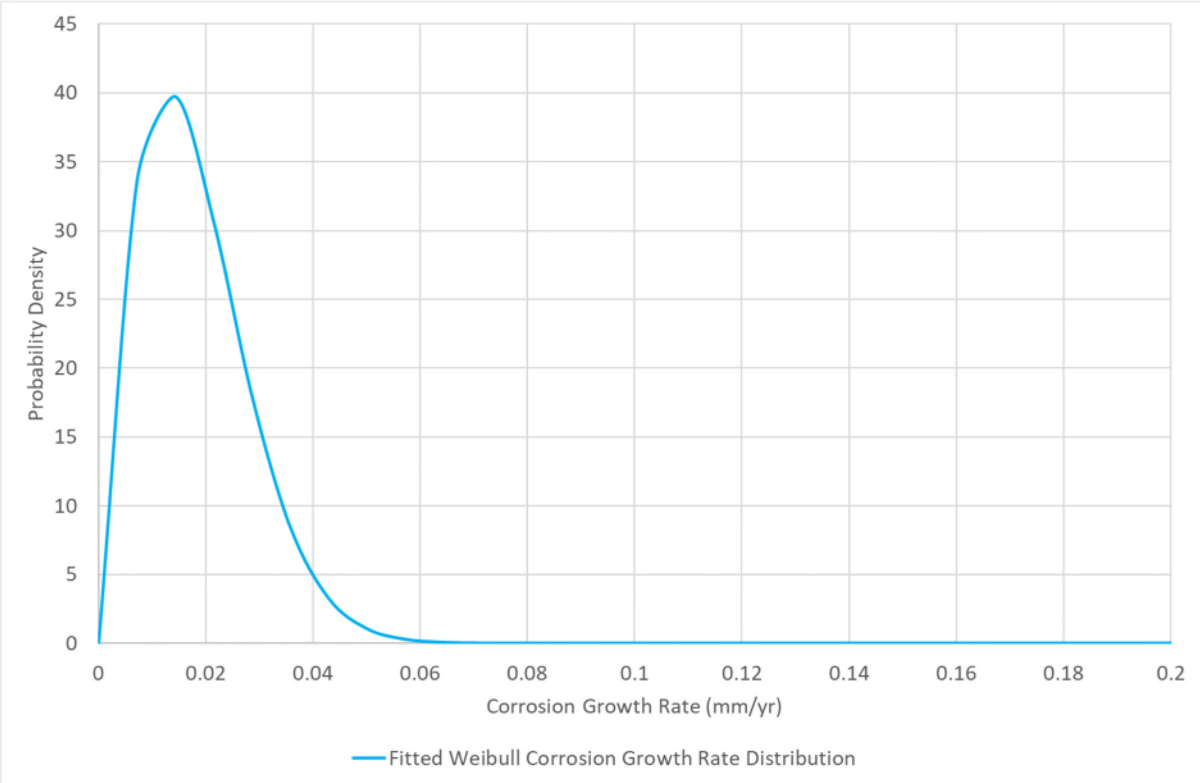

Figure 21: Pannal AGI Above Ground Pipework Corrosion Growth Rate Probability Density Function

3.1.3 Localised Aggressive Corrosion Regions

Under the definition in section 2.3.3, the localised aggressive corrosion regions present at Pannal AGI are:

- Pipework in the region of the wind-water line
- Above ground pipework at supports

Unfortunately, there is no available corrosion defect data associated with either of these regions for the site. For each of these cases a corrosion growth rate distribution must be derived from the best available information. The best available data relating to localised aggressive corrosion regions are ER probe measurements taken at Bacton AGI indicating corrosion growth rates at concrete pit-walls [1] [59]. A corrosion growth rate distribution for each of the above required regions may be derived from the maximum measured growth rate value from the Bacton AGI pit-wall data and the distribution for below ground pipework derived in section 3.1.1, by following the method in section 2.3.3. The maximum measured corrosion growth rate for the concrete pit-walls at Bacton AGI was 0.25 mm/year. Given that the conditions at Pannal AGI are likely to be different to those at Bacton AGI and the additional assumptions made in the derivation of the distributions, the limitations of the distributions with regards to how accurately the Pannal AGI growth rates may be represented are acknowledged. The distributions represent the best estimate on the basis of the current available information.

The supports and wind-water line distributions have been derived using 8 $cgr_{ag,x}$ points scaled from the below ground pipework distribution (see sections 2.3.3 and 2.3.2). Figure 22 shows the cumulative probability distributions, fitted to the derived $cgr_{ag,x}$ points using the maximum likelihood estimation method. The distributions shown are Weibull distributions, indicated by the p-value and Anderson-Darling statistic to be the best fit to the data.

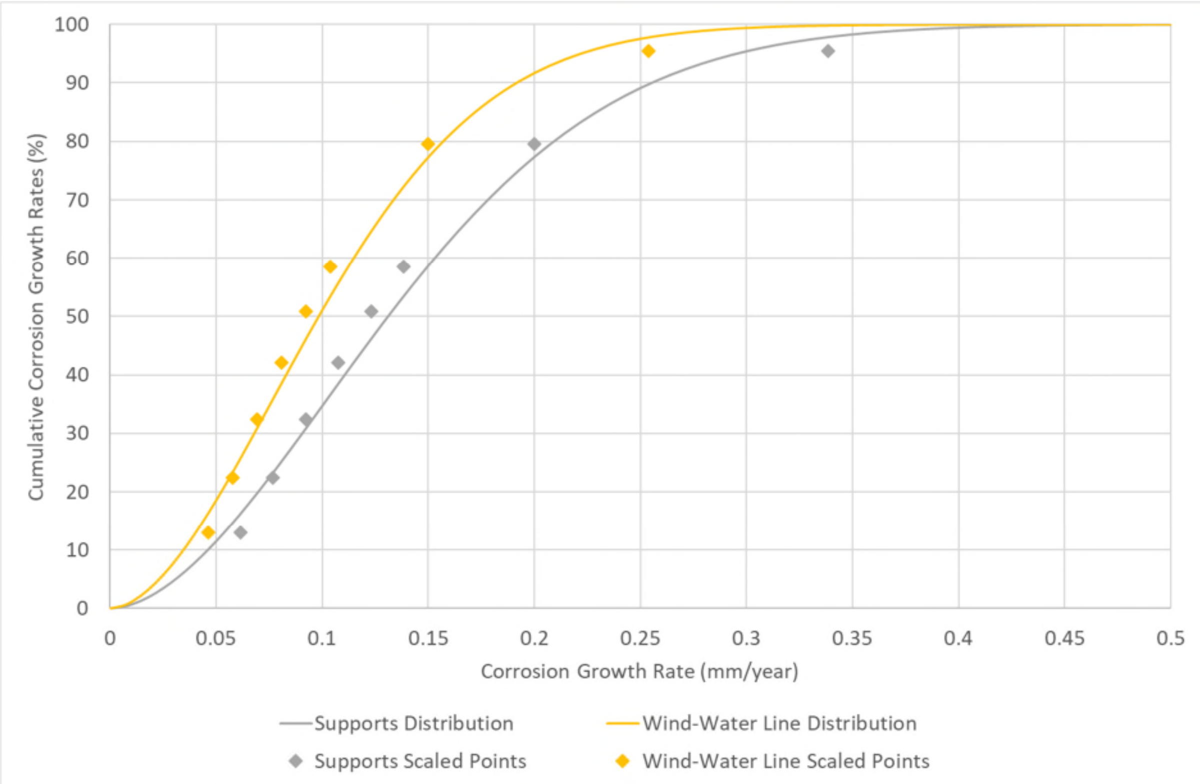

Figure 22: Pannal AGI Supports and Wind-Water Line Cumulative Corrosion Growth Rate Distributions

The parameters of the Weibull distributions used for the corrosion growth rates for the supports and wind-water line regions at Pannal AGI are given in Table 3-7 and a plot of the probability density functions is shown in Figure 23.

Region	Parameter	Value
Supports	α	1.799
	β	0.161
Wind-Water Line	α	1.799
	β	0.120

Table 3-7: Parameters for Weibull Corrosion Growth Rate Distributions for the Supports and Wind-Water Line Regions at Pannal AGI

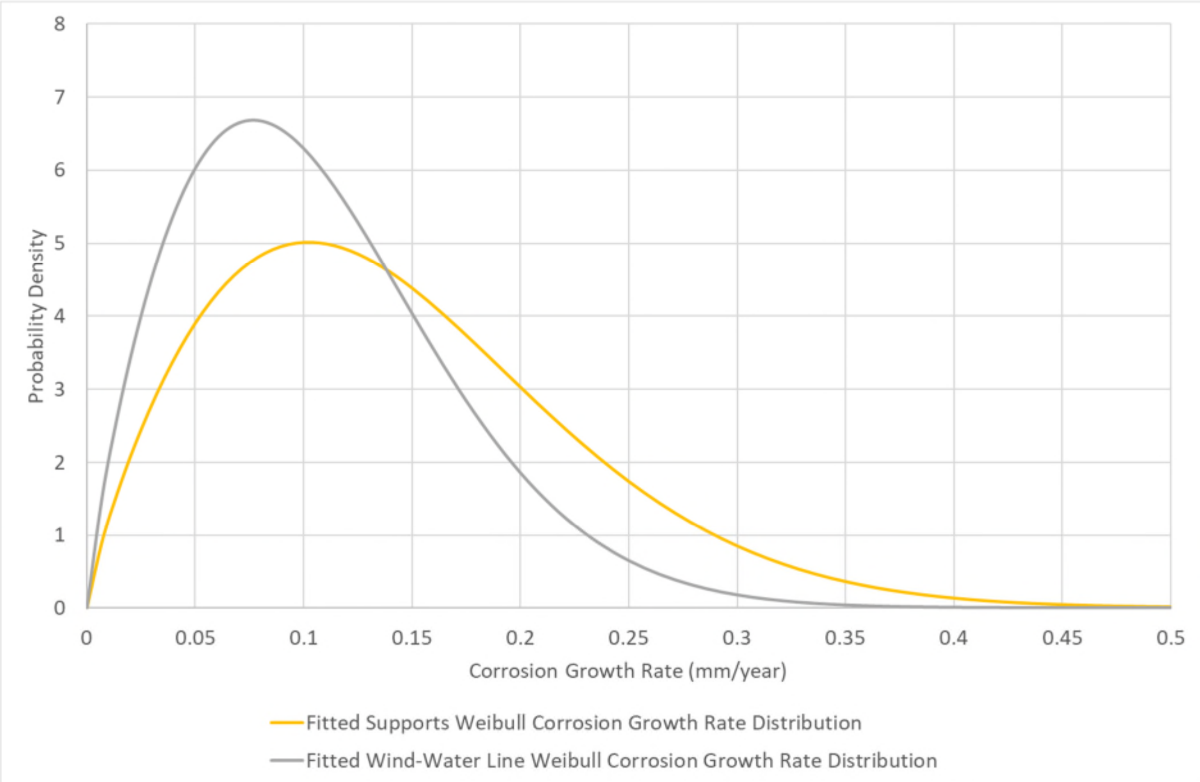

Figure 23: Pannal AGI Supports and Wind-Water Line Corrosion Growth Rate Probability Density Functions

3.1.4 Corrosion Length Distribution

The corrosion axial length distribution for the pipework at Pannal AGI may be derived from the measured lengths of the corrosion defects reported in the most recent in-line inspection data for the inlet and outlet pipelines. In this case, the relevant data is the 2017 inspection of 30BISPAN and the 2013 inspection of 36PANCAW. The in-line inspection data from each pipeline may be treated as a single data set from which to derive the distribution. The corrosion axial length distribution is derived simply by fitting a distribution to the length values from the data.

Figure 24 shows the corrosion axial length cumulative probability distribution fitted to the corrosion axial length data from 30BISPAN and 36PANCAW, using the maximum likelihood estimation method. In this case the distribution is lognormal, indicated by the p-value and Anderson-Darling statistic indicate to be the best fit to the data.

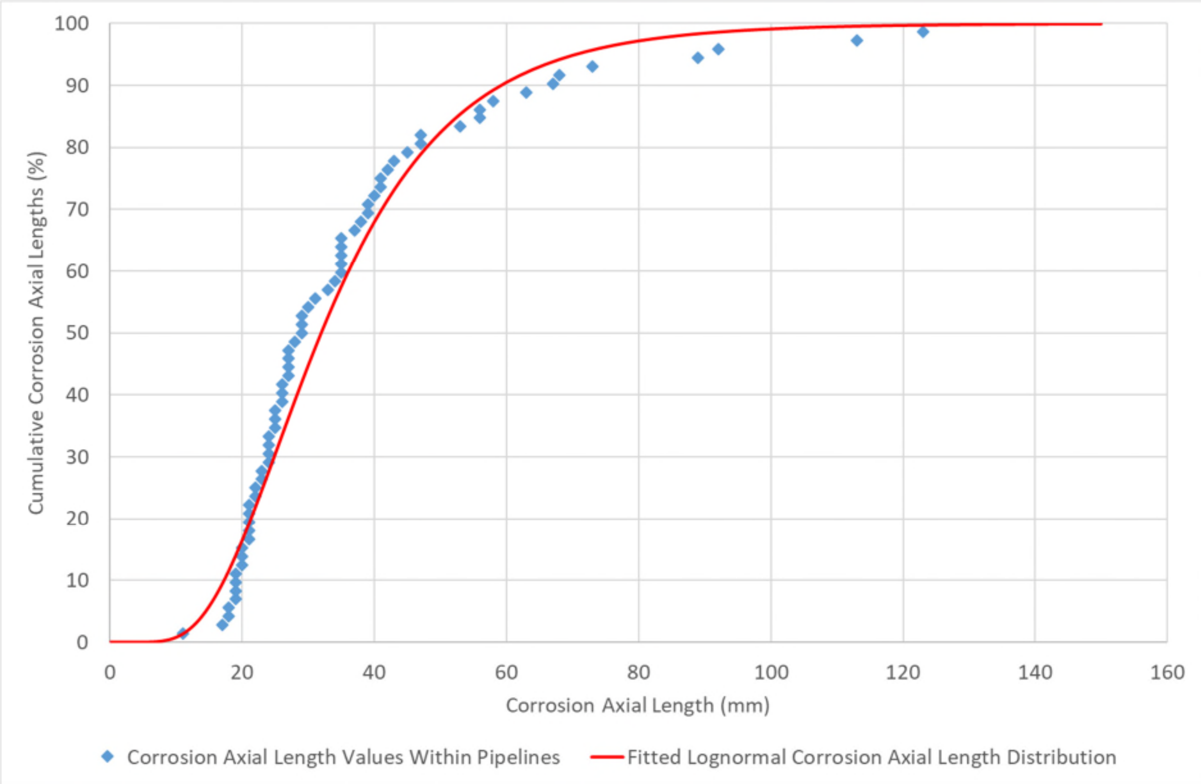

Figure 24: Pannal AGI Cumulative Corrosion Axial Length Distribution

The parameters of the lognormal distribution used for the corrosion axial length at Pannal AGI are given in Table 3-8 and a plot of the probability density function is shown in Figure 25.

Parameter	Value
μ	3.465
σ	0.480

Table 3-8: Parameters for Lognormal Corrosion Axial Length Distribution for Pannal AGI

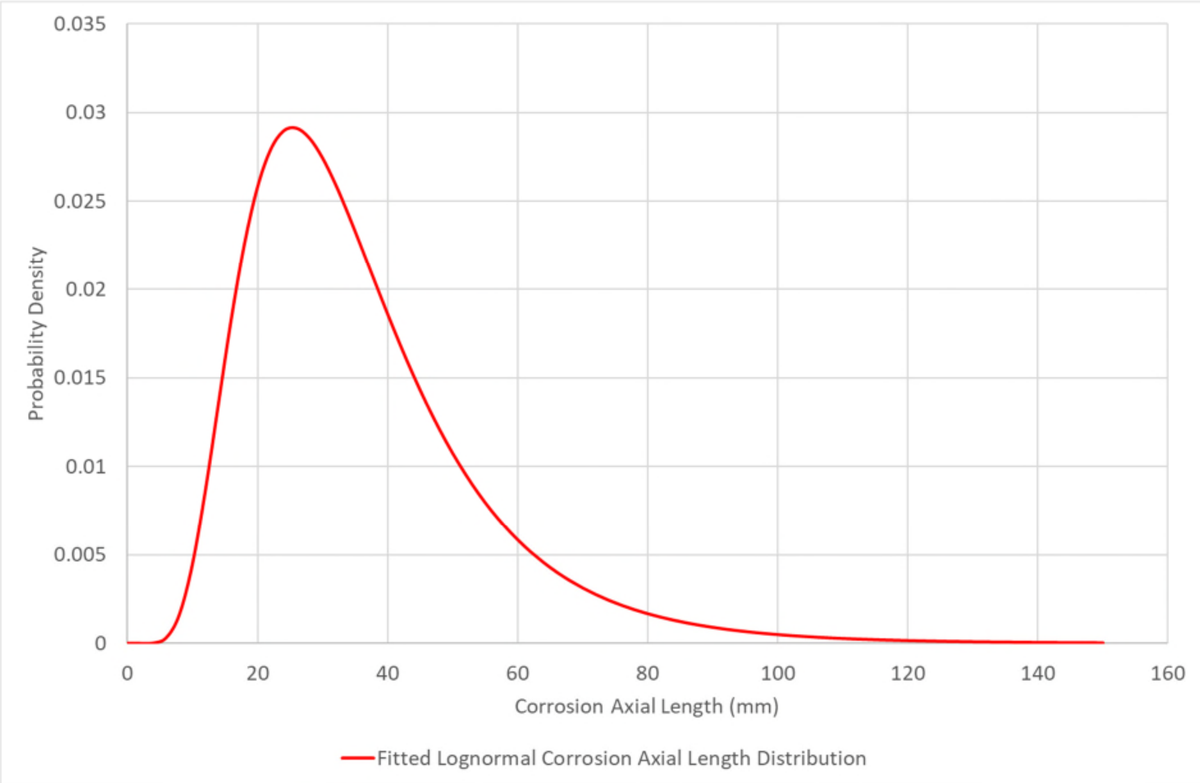

Figure 25: Pannal AGI Corrosion Axial Length Probability Density Function

3.1.5 Corrosion Occurrence Rate

Corrosion occurrence rates for site pipework may be derived by considering the number of new corrosion defects which have appeared between two subsequent inspections on either the inlet or outlet pipelines. Inspections which have taken place at different points in the operating life of the pipelines may yield different corrosion occurrence rates which can each be used in the model.

Given the availability of data relating to the in-line inspection history of both the inlet and outlet pipelines to Pannal AGI a comprehensive analysis of the number of new corrosion defects reported by each subsequent inspection is not possible. For the purposes of this assessment therefore, a single corrosion occurrence rate has been derived from the most recent in-line inspection data for the inlet and outlet pipelines. It is assumed that all of the reported corrosion defects in the most recent inspection data are new and have appeared over the time since each pipeline was commissioned. In this case, the relevant data is the 2017 inspection of 30BISPAN and the 2013 inspection of 36PANCAW.

30BISPAN and 36PANCAW were commissioned in 1969 and 1973 respectively. The time between commissioning and each pipeline’s most recent inspection is therefore 48 years and 40 years. To allow the in-line inspection data from each pipeline to be treated as a single data set from which to derive the corrosion occurrence rate for Pannal AGI, it has been assumed for the purposes of the calculation that the time between commissioning and inspection for both pipelines is the average of the actual values, i.e. 44 years.

Following the method from section 2.5 and using the data from Table 3-1, the surface area of 30BISPAN is:

$$A = \pi . D . l = \pi * 0.762 * 87689.15 = 209918.5m^2$$

Using the data from Table 3-3, the surface area of 36 PANCAW is:

$$A = \pi . D . l = \pi * 0.914 * 39311.94 = 112880.9m^2$$

From Table 3-2 and Table 3-4, the number of corrosion defects on 30BISPAN is 23 and the number of corrosion defects on 36PANCAW is 48. Therefore, the corrosion occurrence rate for Pannal AGI is given by:

$$cor = \frac{N_{new}}{t_{comm}.A} = \frac{(23 + 48)}{44 * (209918.5 + 112880.9)} = 5.0\ x\ 10^{-6} m^{-2} year^{-1}$$

3.1.6 Acceptable Failure Frequency Limit

The acceptable failure frequency limit for Pannal AGI is derived by dividing the overall AGI site limit of 8.74 x 10^{-4} failures per year, derived in section 2.6, by the total surface area of the pipework at the Pannal AGI site in m^2. This gives a value for the failure frequency in failures per m^2 per year for the Pannal AGI pipework.

From the list of pipework components (pipe tally) produced by Premtech for the Pannal AGI site, the total surface area is calculated as 1279.03 m^2. The failure frequency limit for the site is therefore given by:

$$FF_{limit} = \frac{FF_S}{A_S} = \frac{8.74\ x\ 10^{-4}}{1279.03} = 6.83\ x\ 10^{-7} m^{-2} year^{-1}$$

3.2 The Use of GRAID Data in The Assessment

As noted in section 2.7 the utility of data from the GRAID robot with regards to an assessment using the PIE GRAID model is dependent upon the percentage of the pipe surface area scanned during the inspection and whether any defects are found.

From the 1070 wall thickness measurements taken during the inspection no corrosion (or other metal loss) defects were found, the inspection is therefore unable to provide further data to the distributions derived in sections 3.1.1, 3.1.2, 3.1.3 and 3.1.4.

From the value for corrosion occurrence rate derived in section 3.1.5, the expected number of corrosion defects for the inspected 50 m section in 2018 is 0.03. Based on this value it would be expected that no defects would be detected during the inspection, even with a 100% scan of the surface area of the inspected section.

From the 1070 measurements taken using the 22 mm diameter GRAID sensors the total scanning area of the GRAID inspection was 0.41 m^2. The total surface area of the 50 m inspected section was 119.70 m^2 and therefore the scanned area represents 0.34% of the inspected section. Given the small scanning area of the inspection and the low number of expected defects, the GRAID inspection remains in line with the derived value for corrosion occurrence rate. The inspection is therefore unable to provide an updated corrosion occurrence rate value.

3.3 Model Output

From the AGI site drawings and list of pipework components (pipe tally) produced by Premtech, and details contained in the pipework stress analysis by Andrew Francis and associates, there are 25 distinct types of pipework at Pannal AGI. That is, there are 25 different combinations of:

- diameter;
- wall thickness;
- steel grade; and
- corrosion environment,

over the site, which can apply to any one stretch of pipework. Given that the above points represent the input to the PIE GRAID model, the model may potentially associate one of a maximum of 25 different values of calculated pipework condition to any one stretch of pipework, when applied to Pannal AGI. Details of the 25 different pipework types are given in Table 3-9.

No.	Object	Corrosion Environment	Diameter (mm)	Wall Thickness (mm)	Pressure (barg)	Steel Grade (API 5L)
1	Pipe	Above ground	762	15.9	70	X60
2	Tee	Above ground	762	28	70	X56
3	Support	Support	762	15.9	70	X60
4	Pipe	Wind water line	762	15.9	70	X60
5	Pipe	Below ground	762	15.9	70	X60
6	Tee	Below ground	762	28	70	X56
7	Tee	Below ground	914	30	70	X56
8	Pipe	Below ground	914	15.9	70	X65
9	Pipe	Wind water line	914	15.9	70	X65
10	Pipe	Above ground	914	15.9	70	X65
11	Tee	Above ground	914	32.5	70	X56
12	Support	Support	914	15.9	70	X65
13	Reducer[4]	Above ground	762	15.9	70	X65
14	45° Bend	Above ground	762	19.9	70	X60
15	45° Bend	Below ground	762	19.9	70	X60
16	Reducer	Below ground	762	15.9	70	X65
17	Flange	Below ground	914	15.9	70	X60
18	45° Bend	Below ground	914	19.9	70	X65
19	45° Bend	Above ground	914	19.9	70	X65
20	Tee	Above ground	914	30	70	X56
21	Flange	Above ground	914	15.9	70	X60
22	Tee	Below ground	762	29	70	X56
23	45° Bend	Wind water line	762	19.9	70	X60
24	Pig Trap Support	Support	850	15.9	70	X60
25	Tee	Above ground	762	29	70	X56

Table 3-9: Distinct Pipework Types at Pannal AGI

The PIE GRAID model has been applied to the pipework at Pannal AGI using the distributions, corrosion occurrence rate and acceptable failure frequency limit derived in section 2.6 and the list of pipework components (pipe tally) produced by Premtech. The condition of any one stretch of pipework is determined by the number of years required, from site commissioning, for the calculated failure frequency for the stretch of pipework to exceed the acceptable failure frequency limit. The calculated pipework condition (i.e. the number of years to exceed the acceptable failure frequency) for the 25 different pipework types from Table 3-9 are given in Table 3-10. The calculated values have been colour-coded from red to green to indicate their relative condition. Note that the modelling period has been capped at 200 years.

[4] Note reducers have been assumed to have the dimensions of the smallest diameter on the component.

No.	Object	Corrosion Environment	Diameter (mm)	Condition Output (Years)
1	Pipe	Above ground	762	200
2	Tee	Above ground	762	200
3	Support	Support	762	42
4	Pipe	Wind water line	762	54
5	Pipe	Below ground	762	63
6	Tee	Below ground	762	104
7	Tee	Below ground	914	111
8	Pipe	Below ground	914	63
9	Pipe	Wind water line	914	54
10	Pipe	Above ground	914	200
11	Tee	Above ground	914	200
12	Support	Support	914	42
13	Reducer[5]	Above ground	762	200
14	45° Bend	Above ground	762	200
15	45° Bend	Below ground	762	75
16	Reducer	Below ground	762	63
17	Flange	Below ground	914	63
18	45° Bend	Below ground	914	75
19	45° Bend	Above ground	914	200
20	Tee	Above ground	914	200
21	Flange	Above ground	914	200
22	Tee	Below ground	762	108
23	45° Bend	Wind water line	762	66
24	Pig Trap Support	Support	850	42
25	Tee	Above ground	762	200

Table 3-10: Calculated Condition for Pipework Types at Pannal AGI

Figure 26 shows the failure frequency calculated by the model with the evolution of time for each of the 25 different pipework types from Table 3-9. The failure frequencies are shown in comparison to the acceptable failure frequency limit which is indicated by the black horizontal line. The calculated condition values in Table 3-10 correspond to the time in years at which each calculated value of failure frequency crosses the acceptable failure frequency limit. Each curve in Figure 26 is colour-coded in line with the colour-coding used in Table 3-10.

[5] Note reducers have been assumed to have the dimensions of the smallest diameter on the component.

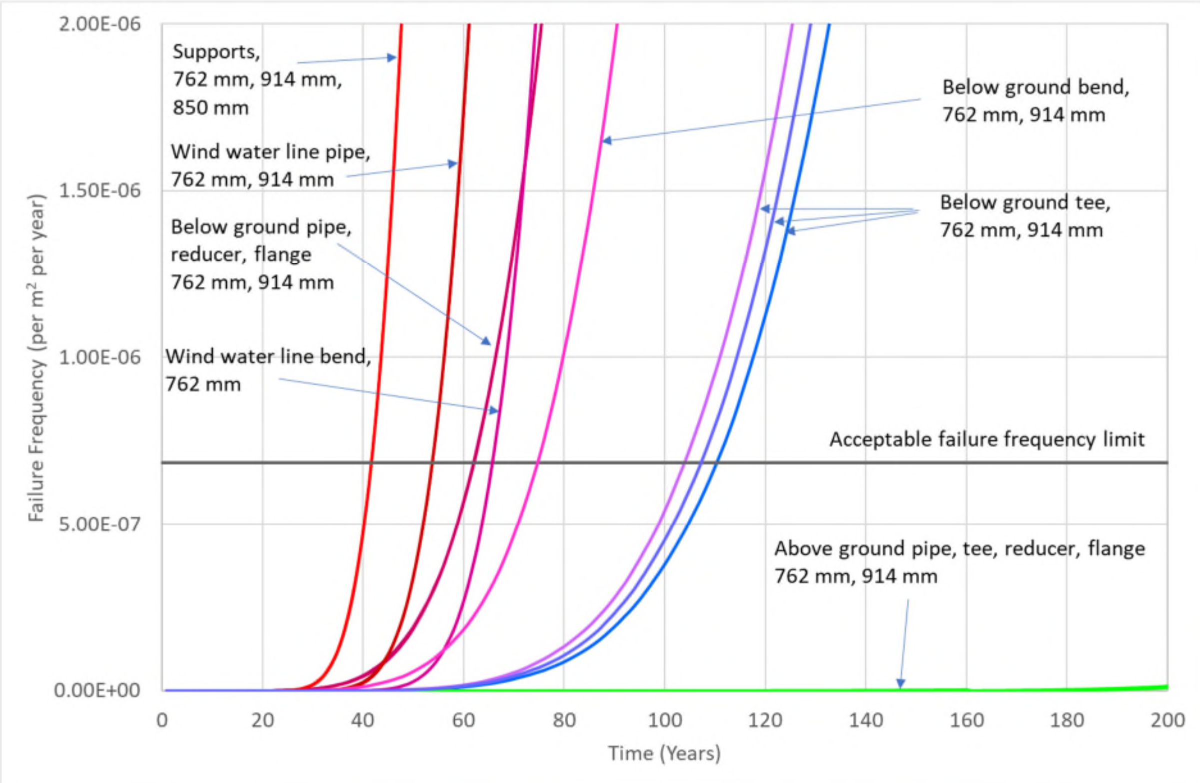

Figure 26: PIE GRAID Model Output for Pannal AGI, Failure Frequency with Time for Each Pipework Type

For the total 25 different pipework types at Pannal AGI, there are a total of 9 different condition values calculated by the model. The same condition is calculated for certain pipework types because in these cases the pipework types share the same corrosion environment and their combination of diameter, wall thickness and steel grade are such that they fall within the same limits for extreme damage in T/PM/P/11 (Table 2-1).

Figure 26 shows that with the evolution of time, each pipework type follows the latter part of a classic bathtub-type curve. The failure frequency is negligible at commissioning and remains so until a certain point in time at which a rapid increase begins. The point at which the rapid increase begins indicates that the pipework is nearing the end of its useful life.

The pipework types which exceed the acceptable failure frequency limit first are those associated with the above ground pipework at supports region. The supports exceed the acceptable failure frequency limit at 43 years. Although the pipework here is comparable to other standard below ground and above ground pipework sections in terms of diameter, wall thickness and grade, the corrosion environment is the most aggressive on site. The current age of Pannal AGI (as of 2018) is approximately 46 years, the model therefore indicates that the supports on site should have already exceeded the acceptable failure frequency limit. It is noted however that, for the purposes of this assessment, the model does not take account of any maintenance which may have taken place to the supports. Above ground pipe supports are a known corrosion risk and it is currently National Grid policy to replace them after a period of six years. Records of pipe support replacements at Pannal AGI were not available, however this data, and confirmation that there were no corrosion issues beneath the old support on replacement, could be used within the model to reduce the failure frequency back to a negligible level, extending the lifetime and therefore improving the calculated condition value. It is also accepted that the corrosion growth rate distribution for supports was derived from concrete pit-wall corrosion growth rate data measured at Bacton AGI and therefore may not be truly representative of the actual growth rates. Corrosion data associated with pipe supports specifically at Pannal AGI would allow a more accurate distribution to be derived and increase the accuracy of the calculated results.

The second pipework types to exceed the acceptable failure frequency limit are those of plain pipe (both 762 mm and 914 mm) associated with the wind-water line. These pipework types are identical to the above and below ground plain pipe sections in terms of diameter, wall thickness and grade, however it is the more aggressive corrosion environment of the wind-water line which results in a lower calculated condition value. The wind-water line regions exceed the acceptable failure frequency limit at 54 years which is in excess of the original 50-year design life of the site. As with supports the corrosion growth rate distribution was derived from concrete pit-wall data taken at Bacton AGI and therefore may not be truly representative of the actual growth rates. Corrosion data associated with the wind-water line specifically at Pannal AGI would allow a more accurate distribution to be derived and increase the accuracy of the calculated results.

The below ground pipework including plain pipe, reducers and flanges (both 762 mm and 914 mm) exceeds the acceptable failure frequency limit at 63 years. This value is in excess of the original 50-year design life of the site. The corrosion growth rate distribution associated with the below ground pipework is considered to be the most accurate of the distributions used in the assessment due to the quantity and relevance of the associated data. In terms of the pipeline data which was used to derive the distribution the in-line inspection history suggested that little corrosion growth had occurred over most of the operational life, but that there had been an increased level of activity in the recent past. However due to limited data comparisons this is not conclusive. The next scheduled in-line inspections of the inlet and outlet pipelines should provide greater clarity with additional sets of high-quality data for comparison.

762 mm 45° bends associated with the wind-water line exceed the failure frequency limit at 66 years. The increased lifetime in comparison to plain pipe at the wind-water line is due to the increased wall thickness for the bend section. The 762 mm 45° bend component has a wall thickness of 19.9 mm in comparison to 15.9 mm for the 762 mm and 914 mm plain pipe. As the extreme damage categories in Table 2-1 are based on a wall thickness percentage, the increased wall thickness of the bend allows for additional corrosion growth to occur, and therefore an increased time period, before the "failure" point is reached. A similar situation occurs with the 762 mm and 914 mm 45° bends below ground. In this case the failure frequency limit is exceeded after 75 years, compared to 63 years for the below ground plain pipe. Note that the 45° bends below ground have the same wall thickness as the 45° bends at the wind-water line. The difference between the 66 year limit for the wind-water line bend and the 75 year limit for the below ground below bend is purely down to the corrosion environment.

762 mm and 914 mm below ground tees exceed the failure frequency limit at 104, 108 and 111 years. The high resistance of the tee components is due to their very high wall thicknesses: 28 mm, 29 mm and 30 mm respectively. This results in a significantly longer lifetime compared to plain pipe sections exposed to the same corrosion environment. Note that for these components an extra millimetre of wall thickness results in approximately 3 additional years before the limit is exceeded.

Finally, the condition value for above ground pipework has been calculated at 200 years. The condition is capped at this value to avoid excessive processing times however it is clear from Figure 26 that the failure frequency for these pipework types remains close to negligible after the entire simulated time period. The high resistance of above ground pipework to corrosion is due to the location of Pannal AGI. The site is rural, outdoors and a considerable distance from the coast. The atmospheric corrosion environment is therefore the least aggressive on site by a considerable margin.

The calculated condition values and colour-coding associated with the Pannal AGI pipework may be applied site wide on the basis of the 25 different pipework types. Figure 27, Figure 28, Figure 29, Figure 30, Figure 31, Figure 32 and Figure 33 show examples of a 3D CAD model of the Pannal AGI pipework, produced by Premtech, colour-coded in line with the colour-coding used in Table 3-10 [60].

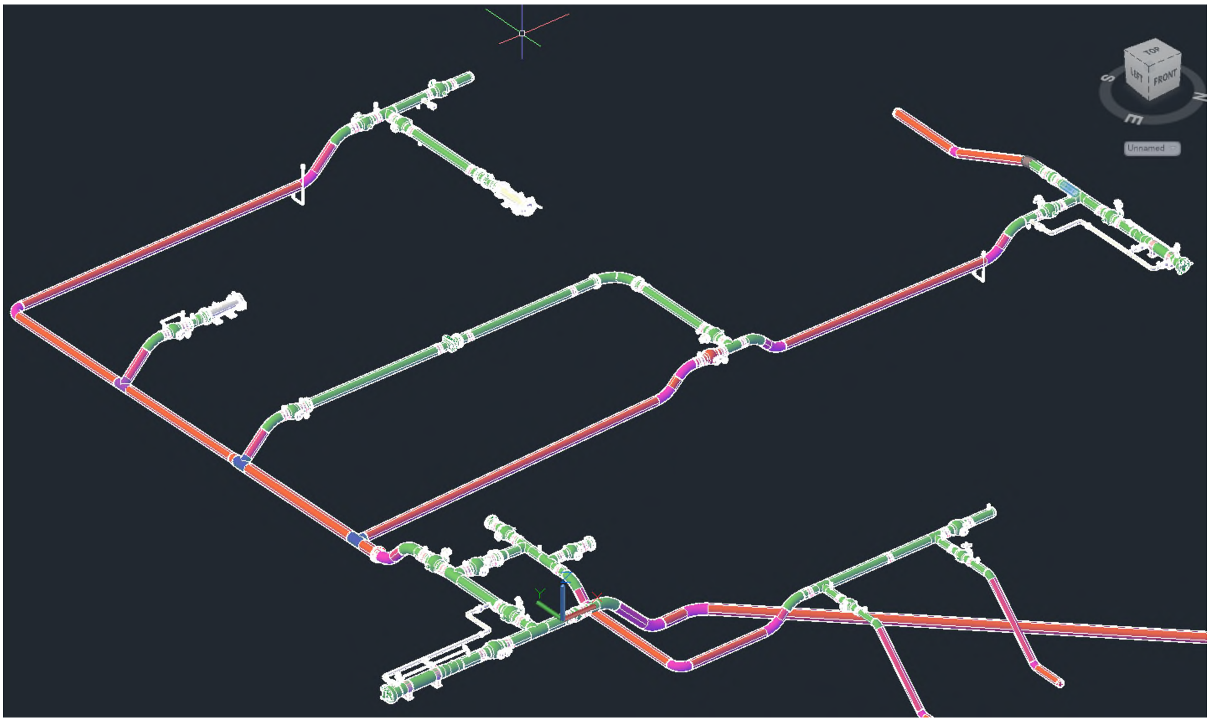

Figure 27: Pannal AGI Pipework with PIE GRAID Model Condition Colour-Coding Example 1

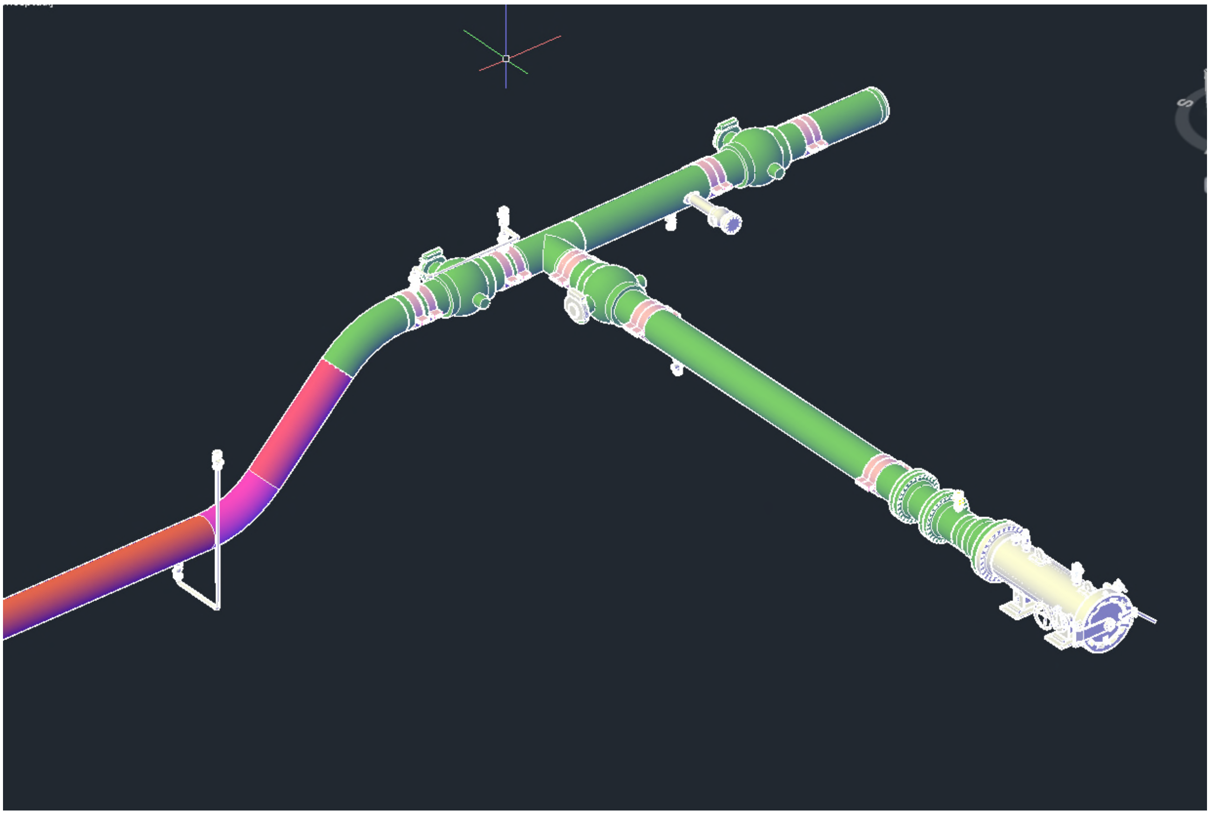

Figure 28: Pannal AGI Pipework with PIE GRAID Model Condition Colour-Coding Example 2

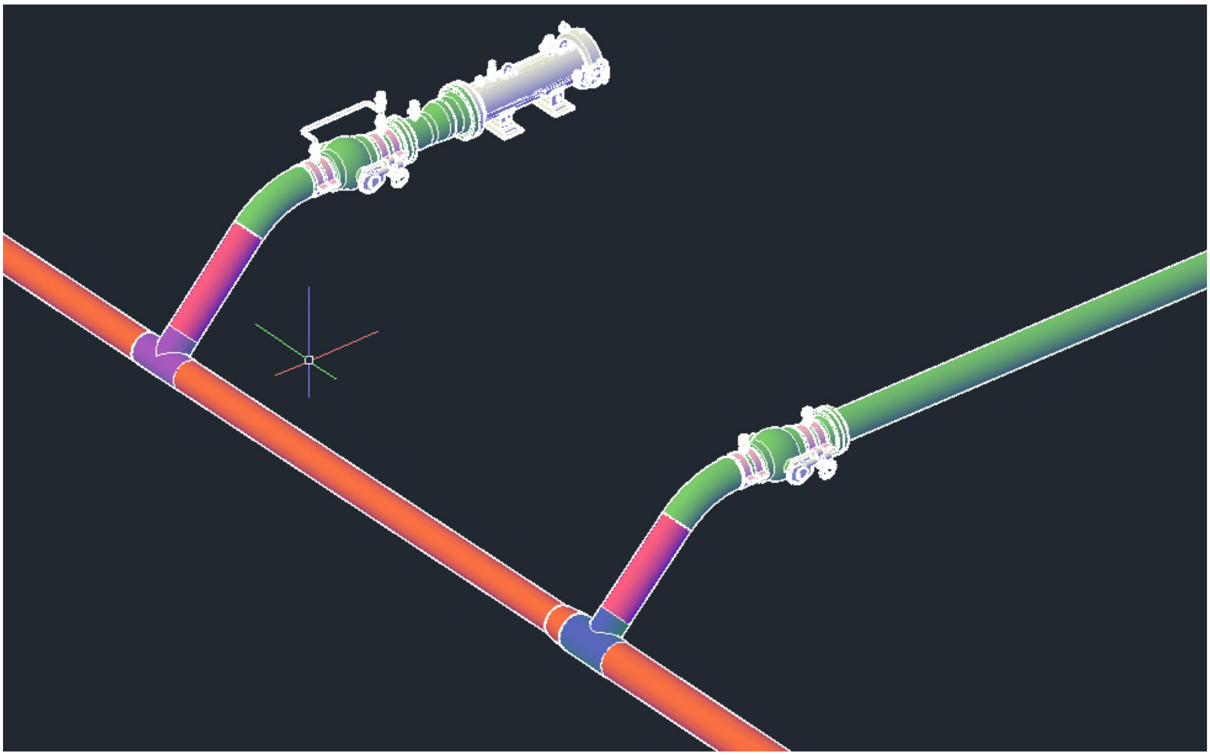

Figure 29: Pannal AGI Pipework with PIE GRAID Model Condition Colour-Coding Example 3

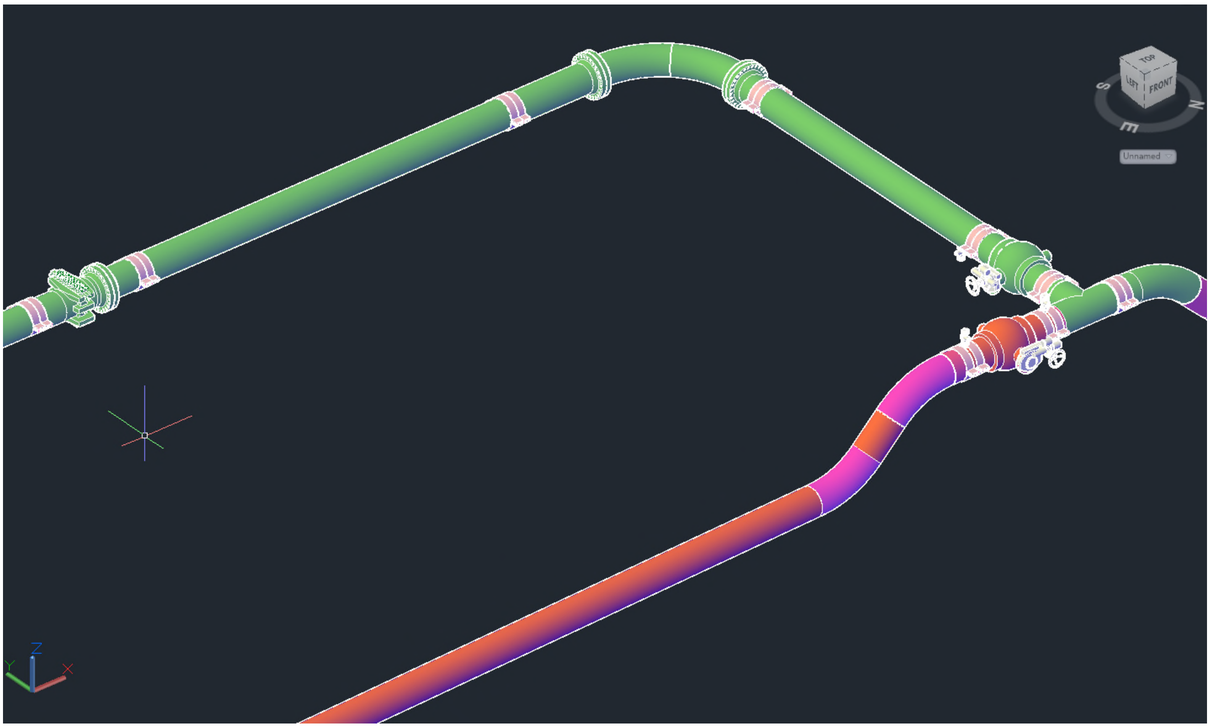

Figure 30: Pannal AGI Pipework with PIE GRAID Model Condition Colour-Coding Example 4

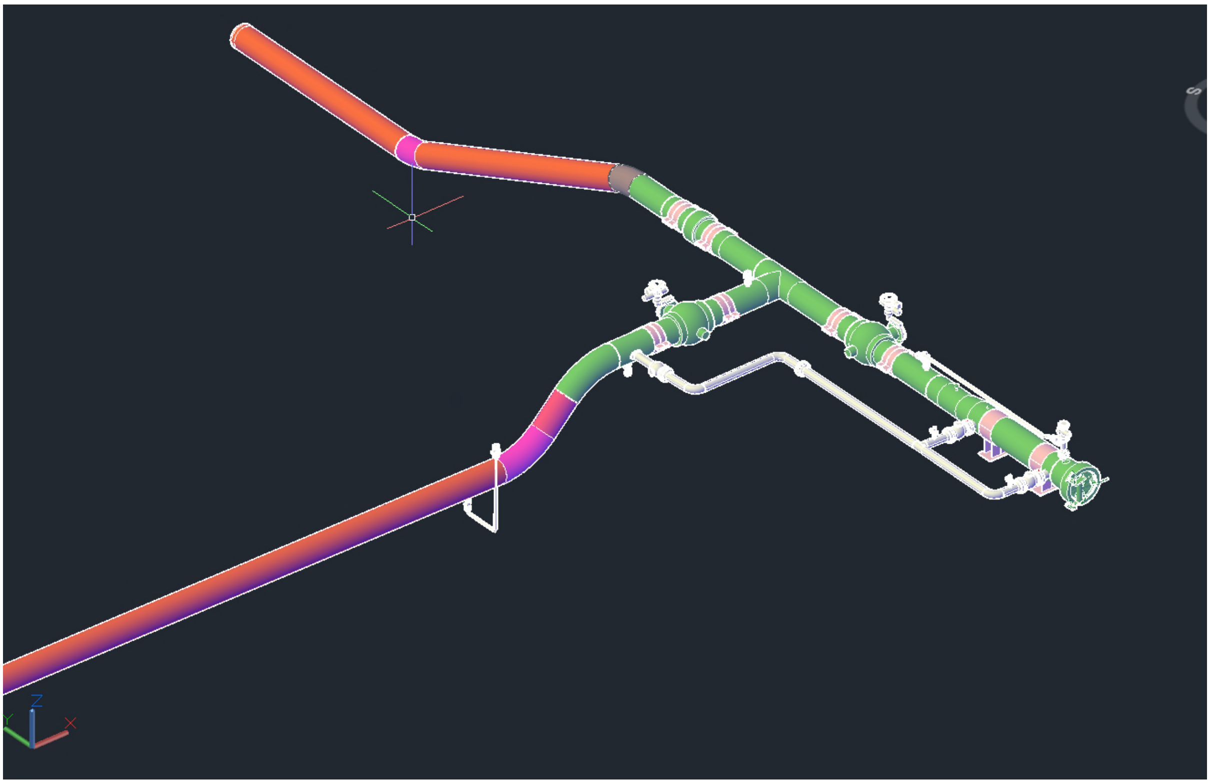

Figure 31: Pannal AGI Pipework with PIE GRAID Model Condition Colour-Coding Example 5

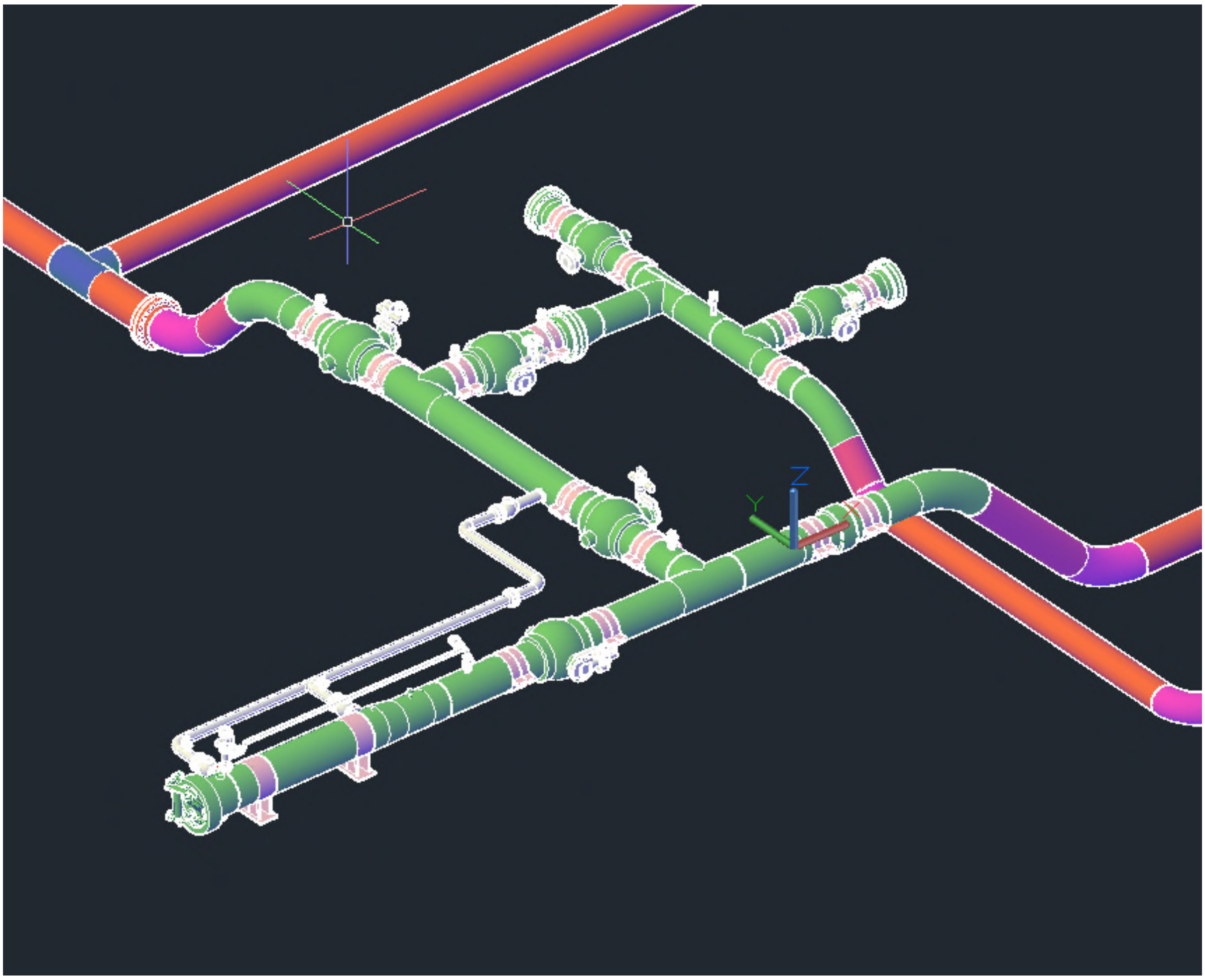

Figure 32: Pannal AGI Pipework with PIE GRAID Model Condition Colour-Coding Example 6

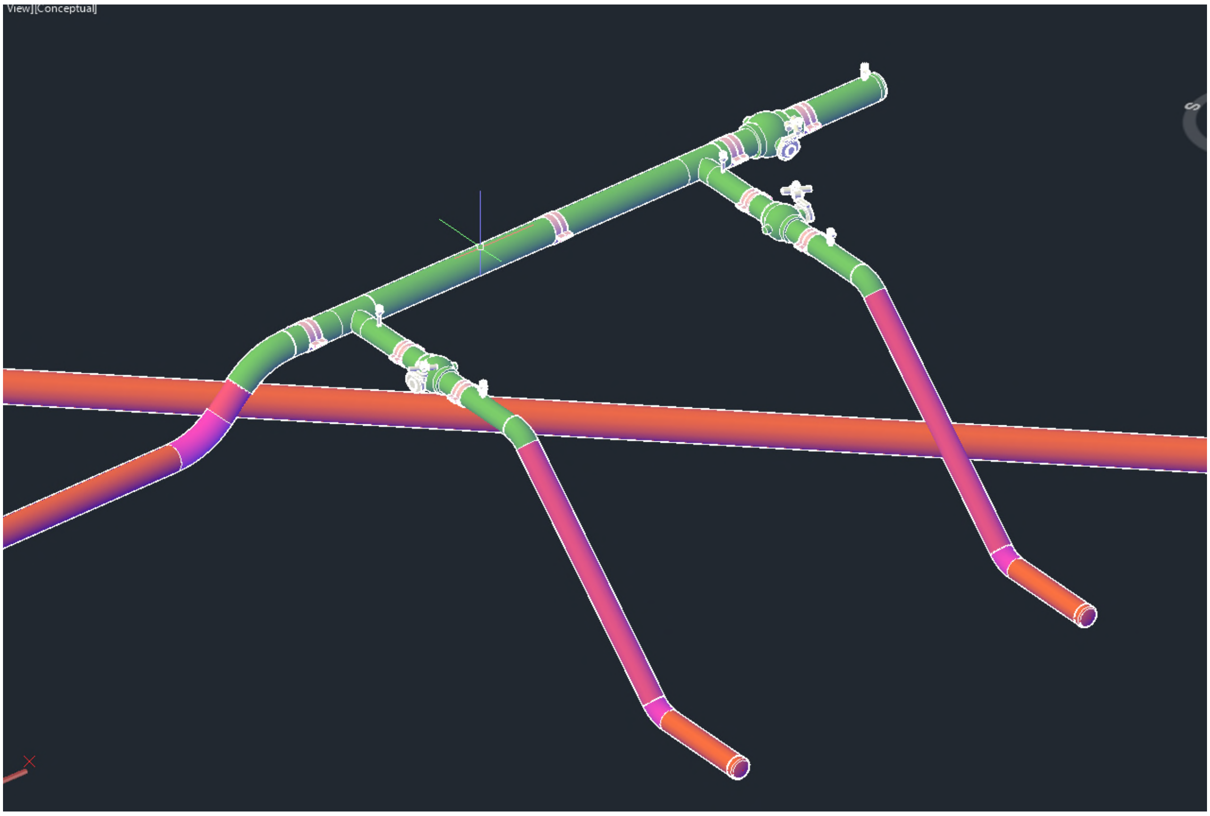

Figure 33: Pannal AGI Pipework with PIE GRAID Model Condition Colour-Coding Example 7

3.4 Bacton AGI Inspection

An inspection of approximately 280 m of pipework at Bacton AGI was performed by the Project GRAID robot from the 20st to the 30th of August 2018 [24]. Bacton AGI is a terminal, located on the Norfolk coast. The inspected pipework was of 914 mm outside diameter and was located mostly below ground. The maximum operating pressure of the site is 70 barg. Bacton AGI is a large site and contains both above and below ground pipework sections, and areas corresponding to each of the localised aggressive corrosion regions identified for consideration in section 2.3.3. Furthermore, there is a high diversity of pipework types located on the site with outside diameters ranging from 219.1 mm to 1219 mm (not including small bore pipework).

The inspected section of pipework consisted of [61] [62]:

- a short above ground section including a valve, standard above ground pipe joints and a 45-degree bend (in the vertical plane) leading below ground;
- the main leg of below ground pipework including, a pipe spool in the wind-water line region, a 45-degree bend (in the vertical plane), four pipe tees, two 22.5-degree bends, an 11.25-degree bend, a 90-degree bend (in the horizontal plane), a valve and standard below ground pipe joints;
- a "B" branch from the main leg including, a 90-degree bend through a tee piece (in the horizontal plane), a valve, two 11.25-degree bends, three further pipe tees and standard below ground pipe joints;

- a "C" branch from the main leg including, a 90-degree bend through a tee piece (in the horizontal plane), a valve, two 5.625-degree bends, three further pipe tees and standard below ground pipe joints;
- a "D" branch from the main leg including, a 90-degree bend through a tee piece (in the horizontal plane), a valve, three further pipe tees and standard below ground pipe joints; and
- an "E" branch from the main leg including, a 90-degree bend through a tee piece (in the horizontal plane), a valve, two 11.25-degree bends, three further pipe tees and standard below ground pipe joints.

The GRAID robot took wall thickness measurements at 3 different areas within the 280 m section of pipework. The scanning areas were three below ground welds (in the area of the field joint coating). In each scanning area the robot took readings at between 1 and 5 different locations (along the direction of the pipe axis), and at each location measured the wall thickness at between 7 and 21 equally spaced points around the pipe circumference with both sensors (i.e. two measurements for each point). The total number of wall thickness measurements take during the inspection was over 200 [63].

For all measurements taken it was found that the recorded wall thickness was within the ± tolerance of the nominal wall thickness and therefore no corrosion defects (or other metal loss defects) were found during the inspection run.

A complete application of the PIE GRAID model to the inspection at Bacton AGI is beyond the scope of this report however some general comments as to the potential outcomes of such an assessment may be made:

- From the available in-line inspection data, the number of corrosion defects per m for the inlet and outlet pipelines to Bacton AGI is approximately the same as the inlet and outlet pipelines to Pannal AGI. A corrosion occurrence rate for Bacton AGI is therefore likely to be similar to the Pannal AGI value.
- The depth of the corrosion defects, in terms of the percentage loss of wall thickness, on the inlet and outlet pipelines to Bacton AGI is comparable to the inlet and outlet pipelines to Pannal AGI, and the pipelines are of a similar age. The Bacton AGI pipelines however, have a higher wall thickness than those at Pannal AGI, and therefore the associated corrosion growth rates will be higher. A corrosion growth rate distribution for below ground pipework at Bacton AGI would therefore be more aggressive than that used for Pannal AGI.
- Bacton AGI is located on the coast and therefore the corrosivity of the above ground atmosphere would be classed as C5 – Very High in accordance with Table 2-3. The upper limit of carbon steel thickness loss after the first year of exposure in this category is almost 10 times higher than the associated value for the more rural Pannal AGI. A corrosion growth rate distribution for above ground pipework at Bacton AGI would therefore be more aggressive than that used for Pannal AGI.
- The corrosion data used to derive the growth rate distributions for the supports and wind-water line regions at Pannal AGI was taken from Bacton AGI ER probe data. The same data could therefore also be used to derive distributions for these regions at Bacton AGI. In this case the growth rate distributions would not be more aggressive than those used at Pannal AGI, however they would differ slightly due to the use of the Bacton AGI pipeline in-line inspection data for distribution shape. Note however that more aggressive distributions would be required, using the same data, for concrete pit-wall and lagged pipework regions in accordance with section 2.3.3.

- There is more small diameter pipework at Bacton AGI than Pannal AGI which will have a lower wall thickness and therefore a lower resistance to corrosion.

In terms of the differences between Figure 26 and an equivalent chart for Bacton AGI:

- The almost flat above ground pipework plot would be expected to increase more rapidly and cross the acceptable failure frequency limit within the 200 years simulation period.
- The plots for pipework in the below ground region would also be expected to increase more rapidly, effectively shifting the point at which the acceptable failure frequency limit is crossed to the left.
- The plots for the supports and wind-water line regions would not be expected to change significantly.
- There would be additional plots for concrete pit-wall transitions and lagged pipework which would cross the acceptable failure frequency limit before the supports plot.
- There would be additional plots for pipework with lower wall thicknesses. The exact location of the plots would depend upon the corrosion regions in which they were located however all lower wall thickness pipework would cross the acceptable failure frequency limit before higher wall thickness pipework within the same region.

It is noted that the points above assume that the same level of information is available for Bacton AGI as there was for Pannal AGI. An increase in the available corrosion or maintenance data could potentially result in a significantly different set of outcomes for Bacton AGI.

4 Conclusions

The following conclusions can be made:

- A mathematical model has been developed to determine the condition of pipework at an AGI site without direct observation, based on available data sources and structural reliability techniques.
- In the model, the AGI site pipework is divided into regions based upon the associated corrosion environment and the through-thickness growth of corrosion defects over time, towards a failure point, is modelled for each region.
- The condition of any particular stretch of pipework at an AGI is measured by the time taken in years for the calculated failure frequency of the pipework to exceed an acceptable (threshold) failure frequency limit.
- The output of the model for an AGI site may be colour-coded and applied to a 3D CAD model of the site to provide a visual representation of the expected condition of the pipework.
- The accuracy of the model output is dependent upon the relevance, the quality and the quantity of the available data sources used as the model input. Approximations may be made, however this could result in a significant level of inaccuracy.
- The wall thickness measurement capabilities of the Project GRAID robot are in-line with industry standards and inspection data taken by the robot may be used within the model to inform the outcomes. However, the utilisation of data from the GRAID robot depends upon the percentage of the surface area of the inspected pipework which is scanned and whether any corrosion defects were detected.

- Application of the model to the pipework at Pannal AGI indicated that the pipework which is expected to be in the worst condition is above ground pipework at supports (underneath), which were calculated to exceed the acceptable failure frequency limit 43 years after commissioning.
- The remainder of the pipework at Pannal AGI was calculated to exceed the acceptable failure frequency limit in excess of 50 years after commissioning, and therefore beyond the original design life of the site.
- Based on the available information, application of the model to Bacton AGI would likely indicate the majority of the pipework to be in worse condition than the pipework at Pannal AGI.

5 Recommendations

The following recommendations can be made:

- It is recommended that the results indicated by the model are critically reviewed by National Grid's competent integrity and corrosion engineers.
- It is recommended that the model is applied to further AGI sites on the NTS and that further relevant data be made available to allow for any required recalibration of the model, leading to condition risk-ranking of all installations which will allow identification of a prioritised and optimised CAPEX/OPEX future investment profile for National Grid that efficiently manages these critical assets.

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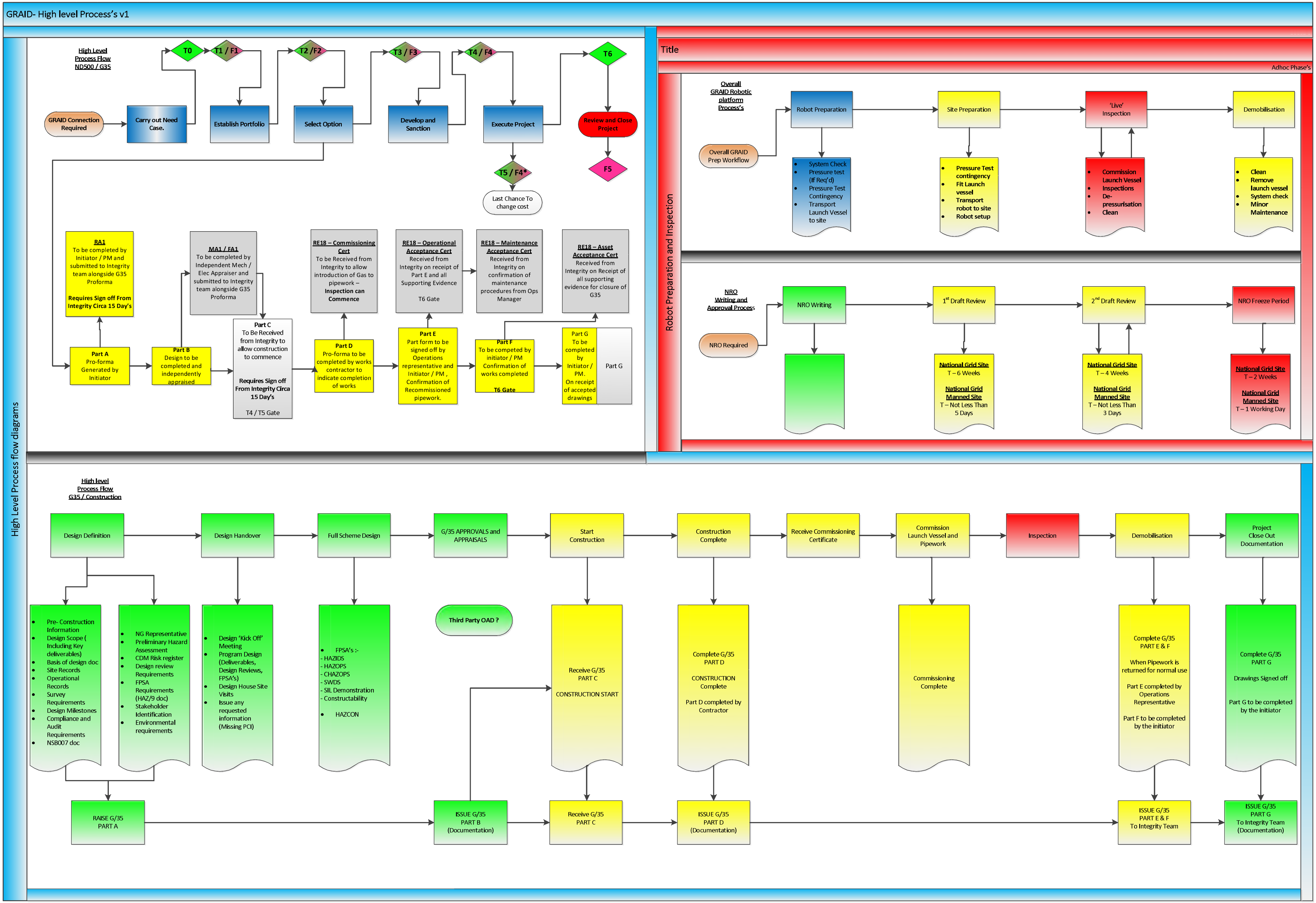
Appendix F

GRAID process flow diagram v1


GRAID- High level Process's v1
High Level Process flow diagrams
High Level Process Flow ND500 / G35
GRAID Connection Required
Carry out Need Case.
T0
T1 / F1
Establish Portfolio
T2 / F2
Select Option
T3 / F3
Develop and Sanction
T4 / F4
Execute Project
T5 / F4*
Last Chance To change cost
T6
Review and Close Project
F5
RA1 To be completed by Initiator / PM and submitted to Integrity team alongside G35 Proforma Requires Sign off From Integrity Circa 15 Day's
MA1 / FA1 To be completed by Independent Mech / Elec Appraiser and submitted to Integrity team alongside G35 Proforma
RE18 – Commissioning Cert To be Received from Integrity to allow introduction of Gas to pipework – Inspection can Commence
RE18 – Operational Acceptance Cert Received from Integrity on receipt of Part E and all Supporting Evidence T6 Gate
RE18 – Maintenance Acceptance Cert Received from Integrity on confirmation of maintenance procedures from Ops Manager
RE18 – Asset Acceptance Cert Received from Integrity on Receipt of all supporting evidence for closure of G35
Part A Pro-forma Generated by Initiator
Part B Design to be completed and independently appraised
Part C To Be Received from Integrity to allow construction to commence Requires Sign off From Integrity Circa 15 Day's T4 / T5 Gate
Part D Pro-forma to be completed by works contractor to indicate completion of works
Part E Part form to be signed off by Operations representative and Initiator / PM , Confirmation of Recommissioned pipework.
Part F To be competed by initiator / PM Confirmation of works completed T6 Gate
Part G To be completed by Initiator / PM. On receipt of accepted drawings
Part G
Title
Robot Preparation and Inspection
Adhoc Phase's
Overall GRAID Robotic platform Process's
Overall GRAID Prep Workflow
Robot Preparation
System Check
Pressure test (If Req'd)
Pressure Test Contingency
Transport
Launch Vessel to site
Site Preparation
Pressure Test contingency
Fit Launch vessel
Transport robot to site
Robot setup
'Live' Inspection
Commission Launch Vessel
Inspections
De-pressurisation
Clean
Demobilisation
Clean
Remove launch vessel
System check
Minor Maintenance
NRO Writing and Approval Process
NRO Required
NRO Writing
1st Draft Review
National Grid Site T – 6 Weeks
National Grid Manned Site T – Not Less Than 5 Days
2nd Draft Review
National Grid Site T – 4 Weeks
National Grid Manned Site T – Not Less Than 3 Days
NRO Freeze Period
National Grid Site T – 2 Weeks
National Grid Manned Site T – 1 Working Day
High level Process Flow G35 / Construction
Design Definition
Pre- Construction Information
Design Scope (Including Key deliverables)
Basis of design doc
Site Records
Operational Records
Survey Requirements
Design Milestones
Compliance and Audit Requirements
NSB007 doc
NG Representative
Preliminary Hazard Assessment
CDM Risk register
Design review Requirements
FPSA Requirements (HAZ/9 doc)
Stakeholder Identification
Environmental requirements
Design Handover
Design 'Kick Off' Meeting
Program Design (Deliverables, Design Reviews, FPSA's)
Design House Site Visits
Issue any requested information (Missing PCI)
Full Scheme Design
FPSA's :-
- HAZIDS
- HAZOPS
- CHAZOPS
- SWDS
- SIL Demonstration
- Constructability
HAZCON
G/35 APPROVALS and APPRAISALS
Third Party OAD ?
Start Construction
Receive G/35 PART C
CONSTRUCTION START
Construction Complete
Complete G/35 PART D
CONSTRUCTION Complete
Part D completed by Contractor
Receive Commissioning Certificate
Commission Launch Vessel and Pipework
Commissioning Complete
Inspection
Demobilisation
Complete G/35 PART E & F
When Pipework is returned for normal use
Part E completed by Operations Representative
Part F to be completed by the initiator
Project Close Out Documentation
Complete G/35 PART G
Drawings Signed off
Part G to be completed by the initiator
RAISE G/35 PART A
ISSUE G/35 PART B (Documentation)
Receive G/35 PART C
ISSUE G/35 PART D (Documentation)
ISSUE G/35 PART E & F To Integrity Team
ISSUE G/35 PART G To Integrity Team (Documentation)

nationalgrid

Appendix G
Related NIA projects

Appendix G
Related NIA projects

During the NIC

Standard Connections Options for New and Existing Sites

Not an NIA but a report completed within Project GRAID

December 2017

Details – This design report describes the potential methods of providing a connection for launching the Project GRAID robotic platform within new or existing Above Ground Installations (AGIs). It contains typical design drawings of standard connections that could be incorporated in to the design of a new AGI to allow future robotic inspection.

Installation Risk and Technology Assessment Model

NGGT0091

Companies – Pipeline Integrity Engineers

Start – May 2016

End – December 2017

Details – NGGT has over 200 installations on the Transmission pipeline system and 60% of these are operating beyond their original design life. This presents a major challenge to NGGT and an urgent requirement to develop innovative and cost effective solutions to assess the condition buried assets.

Inline inspection represents the most effective way of assessing the condition of buried pipework and is in the early stages of development. It will enable evidence based, targeted excavations that will reduce both the financial and environmental cost of asset management. Integral to any potential inline inspection activity is the physical connection to gain access to buried pipework. Standard connection methods have not changed for a long period of time and there is significant scope to reduce this cost by fundamentally challenging the end to end connection process and exploring new technology that will reduce cost and minimize disruption.

Novel Robotics

NGGT0063

Start – March 2015

End – August 2018

Details – National Grid Gas Transmission has identified the need to develop and demonstrate robotics technologies suitable for the inline inspection of buried pipework on AGIs. An NIC bid for 2014 has been submitted for a demonstration project in this area. The NIC bid is a medium risk project with a tight scope and making use of existing technologies, combined into a novel platform.

The work done under this studentship will push at the current technology boundary and is at a much lower technology readiness level, therefore higher risk.
The work is specifically focused on the locomotive aspects of a robot solution given the requirement to traverse changes in diameter. Pipework on AGIs can vary from 8 to 48 inch and currently there is no single robot that could successful negotiate such an extreme change. Multiple robots and careful planning of entry and exit routes would be required. This work will research and develop new locomotion concepts to overcome this challenge.

After the NIC

GRAID ART

NGGT0145

Start – March 2019

End – July 2020

Details – The GRAID ART NIA is proposing to incorporate the Acoustic Resonance Technology (ART) developed by Halfwave onto the GRAID robotic platform that has been proven during Offline and Online testing in the recent successful NIC. The project will bring together the knowledgeable contractors from the NIC project and Halfwave in order to design, build and test the technology. Testing will involve using the GRAID Offline test rig and the existing connection location at Bacton terminal.

Appendix H

Peer review letters

Cadent Gas Limited
Brick Kiln Street, Hinckley
Leicestershire LE10 0NA
cadentgas.com

Date
14 February 2019

Cadent
Your Gas Network

F.A.O Tom Neal – Innovation Delivery Manager
National Grid Gas Transmission
National Grid House,
Warwick Technology Park,
Gallows Hill,
Warwick,
CV34 6DA

Dear Tom

Project GRAID Closure Report Peer Review

Thank you for the opportunity to peer review the National Grid Gas Transmission Project GRAID Closure Report.

We found the close Down Report is generally clear and understandable. In order for us to consider if and how to implement this technology we would require further information identifying how the technology could be scaled or adapted for application in Gas Distribution networks which typically operate at lower pressures and with smaller diameter pipelines. Further we would require an indication of both the capital and operational costs associated with the equipment and whether you see these changing over time. i.e. will the costs reduce materially as the technology matures. Additionally it would helpful to understand more details of how you intend to implement in particular the 'business model'. Do you envisage this as a service that Network Operators procure in a similar vein to 'on line inspections' or do you see this as a capital investment in equipment that National Grid operatives will then be trained in using?

However on the basis of the supplied information we are happy that National Grid Gas Transmission achieved the objectives that were set out at the beginning of the Project GRAID NIC and that all required information was presented in the Closure Report.

Yours sincerely

Damien Hawke

Future Networks Manager

Cadent Gas Ltd

Northern Gas Networks

Smell gas?
Call the National Gas Emergency Service
on 0800 111 999

F.A.O Tom Neal – Innovation Delivery Manager
National Grid Gas Transmission
National Grid House,
Warwick Technology Park,
Gallows Hill,
Warwick,
CV34 6DA

25th February 2019

Project GRAID Closure Report Peer Review

Dear, Tom

Thank you for the opportunity to peer review the National Grid Gas Transmission Project GRAID Closure Report.

The Close Down Report was reviewed jointly by Andy Middleton from our Asset Integrity team and me, both having the view that it is a very comprehensive report.

The Close Down Report is well put together, relatively easy to understand considering the complexities of the project. The report provides sufficient information to enable Northern Gas networks and other Network Licensee's to effectively consider whether and how to implement the Project's learning in to its business as usual activities.

Based on the supplied information we are happy that National Grid Gas Transmission achieved the objectives that were set out at the beginning of the Project GRAID NIC and that all required information was presented in the Closure Report.

Yours sincerely

Richard Hynes-Cooper

Head of Innovation, Northern Gas Networks

we are the network

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Horley
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RH6 9HJ

F.A.O Tom Neal – Innovation Delivery Manager
National Grid Gas Transmission
National Grid House,
Warwick Technology Park,
Gallows Hill,
Warwick,
CV34 6DA

23rd January 2019

Dear Tom,

Project GRAID Closure Report Peer Review

Thank you for the opportunity to peer review the National Grid Gas Transmission Project GRAID Closure Report.

The Close Down Report is clear and understandable and provides sufficient information to enable a Network Licensee, not closely involved in the Project, to effectively consider whether and how to implement the Project's learning in to its business as usual activities

On the basis of the supplied information we are happy that National Grid Gas Transmission achieved the objectives that were set out at the beginning of the Project GRAID NIC and that all required information was presented in the Closure Report.

Yours sincerely,

K. Ellison

Keith Ellison

Innovation Project Manager

SGN

WALES&WEST UTILITIES

Tom Neal – Innovation Delivery Manager
National Grid Gas Transmission
National Grid House,
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Telephone/Ffôn: 0800 912 29 99
Fax/Ffacs: 0870 1450076
Email/Ebost: enquiries@wwutilities.co.uk
www.wwutilities.co.uk

15 February 2019

Project GRAID Closure Report Peer Review

Dear Tom

Thank you for the opportunity to peer review the National Grid Gas Transmission Project GRAID Closure Report.

The closedown report has given us a clearer understanding of what has been achieved within project GRAID and the team should be very proud of their successes. We have provided some specific feedback on the areas we felt could be improved for clarity and provide sufficient information to enable Wales & West Utilities, who have not been closely involved in the Project, to effectively consider whether and how to implement the Project's learning in to its business as usual activities.

On the basis of the supplied information we are happy that National Grid Gas Transmission achieved the objectives that were set out at the beginning of the Project GRAID NIC and that all required information was presented in the Closure Report.

Yours sincerely

LMason

Lucy Mason

Innovation Manager

Wales & West Utilities