Project GRAID

Closure report

Gas Transmission

nationalgrid

Contents

Section 1
Foreword and project background

To design and develop a remotely operable robot that can be inserted into live, high pressure 100 bar(g), mild steel pipework systems to undertake both visual and physical inspection of the otherwise inaccessible buried sections of the system. The robot will be highly articulate and able to move freely throughout the pipework.

"The collaborative project was a huge success and has provided NGGT with a tool capable of inspecting within areas of the network that were once deemed inaccessible."

Tony Green
Head of Engineering & Asset Management, Gas Transmission
National Grid

In-Line Robotic Inspection of High Pressure Installations Gas Robotic Agile Inspection Device (GRAID)

National Grid Gas Transmission (NGGT) owns and maintains the National Transmission System (NTS) covering England, Wales and Scotland and includes more than 7,000km of pipeline and over 200 Above Ground Installations (AGIs). As is common with established utility networks of this size, the age of these assets is now approaching the end of their design lives. Alongside 3rd party interference the threat of corrosion of these assets is viewed as one of the most significant risks to the network today.

To combat this, routine maintenance is performed on the equipment to ensure it is fit for purpose and, importantly, it is inspected regularly to ensure it is operating within the safe limits of its design. Inspection of our network of pipelines is currently carried out by a well-established industry using in-line inspection tools commonly known as PIGs. The same however cannot be said for the pipework found on our AGIs as the complex array of bends and joints prevent the PIGs from navigating these areas – this became the focus of the Network Innovation Competition (NIC) entry.

The Gas Robotic Agile Inspection Device or GRAID NIC was awarded in 2014 and aimed to design, develop, build and test the world's first robotic platform that can navigate this complex environment during 'live' gas conditions up to 100 bar(g). Once inside the pipework the robot is self-powered and highly articulate, able to move around bends, tees and gradients to take accurate, reliable wall thickness data.

The collaborative project with some of the UK's most innovative small and medium sized enterprises was a huge success and has provided NGGT with a tool capable of inspecting within areas of the network that were once deemed inaccessible. The impact is significant. With accurate data regarding our assets we can not only move to a proactive approach to the maintenance of our ageing assets, but also reduce the occurrence of unnecessary excavations and premature replacement of assets. This will not only save money but also contribute to the reduction of carbon emissions linked to these activities.

It is our proposal to operate the GRAID robot on up to 20 sites within RIIO-T2 and feed this data into the mathematical model that was developed during the NIC project, building a picture of the condition of our AGIs and pushing to exceed the savings proposed.

National Grid Gas Transmission are not unique in this challenge and I firmly believe that GRAID will become the tool of choice for inspecting AGI pipework both within the UK and globally.

Tony Green
Head of Engineering & Asset Management, Gas Transmission
National Grid

Section 2
Executive summary

Project GRAID successfully met all of its objectives; designing, building and testing a remotely operated robot inside National Grid's 'live' gas transmission pipelines. This unique tool is now available for operational use to inspect areas of our sites which were once thought to be inaccessible.

2.1 Project Background

National Grid currently owns over 350km of unpiggable pipework with the majority being located at high pressure installations (up to 94 bar(g)). These complex sites present a significant challenge for any robotic solution.

The solution that has been developed will enable National Grid Gas Transmission (NGGT) to look inside this complex pipework for the first time since their construction, in some cases dating back nearly 50 years. The current asset management strategy for these pipes relies on above ground survey techniques, and is based on good design and construction practices having been applied previously. This project will enable a proactive, risk based approach to the management, maintenance and replacement of these ageing assets.

The project highlights NGGT's commitment to delivering innovation that provides a more reliable and environmentally friendly approach to managing its assets and building value for gas consumers.

2.2 Scope of the Project

Traditionally the onshore pipeline industry has only been able to in-line inspect high pressure pipelines using Pipeline Inspection Gauges (PIGs). In-line inspection of pipelines provides the most accurate and reliable information on the condition of buried pipelines. Other inspection methods external to the pipeline have a number of limitations. This innovative robotic technology will however increase precision in our predictive methods. Ultimately, below ground pipework within a gas installation cannot currently be in-line inspected because of a number of engineering challenges associated with complex pipework geometries, lack of access and retrieval points and flow factors.

2.2.1 The project has four key objectives:

- To accurately and reliably determine the condition of high-pressure below ground pipework at Above Ground Installations (AGIs) 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 of circa £58m over 20 years.
- 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.

One of the key objectives of the project is to reduce carbon emissions significantly and save circa

£58m

over 20 years

Pipelines are accurately asset managed through, amongst other activities, in-line inspection i.e. inserting a device within the pipeline. Currently we in-line inspect over 7,000 kilometres (99.5%) of our National Transmission System (NTS) using PIGs. However, PIGs are not suitable for pipework on AGIs and some other pipeline sections, for a number of reasons including, most notably:

- AGIs have complicated geometries associated with both above ground and buried pipework e.g. tight bends and changing pipe diameters which PIGs cannot negotiate.
- PIGs are dependent on the flow speed of the gas for drive, and the gas flow through an AGI can be highly variable (either faster or slower than a PIG requires).

The scope of Project GRAID was therefore to design, build and test a robotic platform capable of operating within 30" and 36" diameter pipework and is able to navigate this complex landscape without relying on the flow of gas for propulsion. Once inside the network, GRAID must be able to extract reliable data.

2.2.2 Working together

National Grid collaborated with three British Small Medium Enterprises (SMEs) to develop ways to accurately assess the condition of its pipework assets that cannot currently be inspected via conventional PIGs.

Synthotech Ltd. specialises in providing innovative engineering and technical services to the utility and infrastructure sectors. It designed and built the robotic platform comprising of the visual, sensory and non-destructive testing (NDT) systems, and it also developed the user interface and control systems.

Premtech Ltd. provides engineering, consultancy and design management services for on-shore pipeline and associated installation projects of various sizes. Premtech designed the robot's launch and receive vessel, the offline test facility, the online site connections and provided design consultancy services.

It should be noted that the idea of Project GRAID was born of a conversation between both Synthotech and Premtech with the early concepts then being developed into an NIC proposal to NGGT.

Pipeline Integrity Engineers (PIE) Ltd. offers consultancy services relating to the integrity management of high-pressure gas pipelines and associated installations.

PIE provided third party assurance, supporting the technical team in developing and implementing the technical strategy, and providing integrity consultancy support in translating inspection results into asset management strategies and operational procedures.

Along the way, we have built strong relationships with other suppliers for GRAID.

DNV-GL provides classification, technical assurance, software and independent expert advisory services to the maritime, oil and gas and energy industries. The company also provides certification services to customers across a wide range of industries. DNV-GL operates its own testing and research facility in Spadeadam, Cumbria, UK, a world-leading research and testing facility working for heavy industry and government agencies. Its remote location on more than 3,500 hectares of secure Ministry of Defence land means DNV-GL can carry out explosion, fire and gas dispersion testing within a secure exclusion zone. As a result, National Grid chose DNV-GL to construct an offline test facility at Spadeadam for use during the GRAID project.

RMA is a family run business (540 employees worldwide) with its headquarters in Baden Kehl, Germany. It is a manufacturer of fittings and instrumentation for the gas sector. Four fields of economic activity "Gas Distribution", "Gas Transportation", "Gas Measurement" and "Services" involve RMA activities in the global market. RMA manufactured GRAID's launch and retrieval vessel at its facility in Germany that includes the unique through wall shaft and internal railings.

2.3 Outcomes of the Project

The purpose of the Project GRAID Network Innovation Competition (NIC) was to design, build and test a robotic platform that can navigate National Grid's unpiggable pipework during 'live' conditions and collect reliable data. By proving the integrity of the pipework the ambition was that expensive and unnecessary excavations and asset replacement activities can be prevented. Following the completion of the four year programme of works, all objectives were met for GRAID with the following key outcomes:

Pipelines are accurately asset managed through, amongst other activities, in-line inspection i.e. inserting a device within the pipeline. Currently we in-line inspect **99.5%** of our National Transmission System (NTS) using PIGs:

more than
7,000
kilometres

2.3.1 Robotic platform

The robotic platform encompasses the major outcome for the project and includes all of the concept designs, calculations, development sprints and build stages. The resulting output is an operational GRAID robot, Umbilical Management System (UMS), tether, transportation trolley, cable assembly, control desk and kiosk to house the robot operators. The entire platform has been extensively tried and tested and at the end of the project has been handed over to National Grid, ready for operational use.

2.3.2 Launch Vessel

The specially designed GRAID Launch Vessel was designed by Premtech and manufactured by RMA and enables the robot to be inserted into the National Transmission System. The vessel is rated up to 100 bar(g), includes an industry standard quick closure door system, custom designed rails for the UMS, the through wall shaft for the connectors and significantly the manual pullback mechanism. Ultimately the GRAID Launch Vessel is like a standard PIG trap albeit slightly shorter at roughly 3.5m long.

SYNTHOTECH innovative engineering | Premtech ENGINEERING EXCELLENCE | PIE | DNV·GL | rma PIPELINE EQUIPMENT

2.3.3 Offline facility

To test the GRAID robotic platform and launch vessel an offline test facility was required to ensure all the process and procedures along with the hardware itself operated as expected before it was used on the NTS. The DNV-GL Research and Test Facility at RAF Spadeadam was selected as the location of this test rig and following a design phase by Premtech, the rig was built by DNV-GL. The layout which was built using repurposed 30” to 36” transmission pipework included 90° bends, tee joints, a 45° gradient and a vertical section.

2.3.4 Online testing

As part of a separate but parallel activity, NGGT sought to sanction funding outside of the NIC process to build several permanent NTS GRAID connection points. These were located at Pannal Offtake and Bacton Terminal.

2.3.5 Pannal

In order to carry out the first trial of the GRAID robot on the NTS a low risk site was required which offered the ability to test GRAID but without impacting the flow of gas. During the inspection period the output from GRAID included over 1,000 individual wall thickness measurements and several above ground pipe supports analysed in detail to prove the integrity of the pipework encased by the support.

2.3.6 Enhanced NDT

From the beginning of the project it was always envisaged that three online trial locations would be built and inspected, however as the project progressed and further understanding was gained it was decided to carry out a period of Enhanced NDT work to replace one of the online trials. This agreement was made with confirmation from Ofgem and allowed the team to spend some time at the offline test rig in RAF Spadeadam to understand how the Electromagnetic Acoustic Transducer (EMAT) sensors reacted to real defects. The knowledge gained during this time was invaluable as the results from the sensors differ considerably on real defects and the team could record how this was visualised on the output graphs.

2.3.7 Bacton

The final online trial was completed at Bacton Terminal and was seen as a significant step forward for National Grid in accepting internal robotic inspections as a viable option. The inspection period was successful with a full 100 m survey, hundreds of wall thickness measurements, location of previously buried assets and video records of 36” ball valve actuation at site pressure.

2.3.8 Condition Model

A significant part of the original Project GRAID bid surrounded how the data that was collected would be analysed and modelled to provide a reliable decision tool for National Grid. The output model takes all the existing data sources available and combines it with known measurements from GRAID to define areas of corrosion susceptibility and the likely corrosion growth rates. This model can be re-run depending on the location in interest with a colour coded output map to be used by the National Grid Asset Health team. As the information and knowledge is built up over multiple connection points the accuracy improves and inferences can be made to prevent unnecessary excavations and early asset replacement.

Typical Above Ground Installation layout.

For more information:

Each of these separate outcomes are discussed in greater detail in Section 4 of this report.

2.4 Successful Delivery Reward Criteria (SDRC) Met

As part of the NIC submission, Successful Delivery Reward Criteria were defined for each stage of the project, with the results displayed below:

Solution Development	
Concept design study of robotic platform completed and scope clearly defined.	✓
Creation and validation of 3D models for each trial site, that accurately represent pipework configuration.	✓
Launch and retrieval device designed to allow robot insertion into high pressure installation. Design validated to minimise venting and manage pressure up to 100 bar(g).	✓
Robotic platform conceptual design(s) completed, computer models and 3D prints produced, conceptual design(s) demonstrated potential to achieve objectives of travelling 100 m around two bends and taking visual readings and wall thickness measurements in buried pipework of up to 100 bar(g) pressure.	✓

Development Testing	
Robot access and inspection routes for all three trial sites developed and validated including the formulation of Formal Process Safety Assessments (FPSAs).	✓
The offline testing facility designed and distributed for competitive tender. Contract placed for its completion.	✓
Manufacture of a robotic platform primary solution in order to test and further develop the robotic design and meet the objectives of withstanding pressure of up to 100 bar(g) whilst travelling 100 m, 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 100 bar(g) and minimise venting.	✓

Successful Online Trials Completed	
Offline test rig manufactured and positioned at readiness to conduct offline trials.	✓
Functional robotic platform manufactured and tested on offline testing facility to work in 100 bar(g) pressure (simulated), travel 100m and negotiate two bends, 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 (i.e. tactically placed corrosion, defects and oil spillage etc).	✓

Successful Online Trials Completed	
Successful insertion of launch and retrieval device into all three live sites. Third site replaced by Enhanced NDT studies following acceptance from the project team and Ofgem.	✓
Undertake testing to deliver a functional robotic platform and associated tools (condition assessment) to work up to 100 bar(g) pressure (live), travel 100m conduct visual inspection and wall thickness measurements – a minimum of three online tests per site will take place.	✓

Delta Prototype Complete	
Successfully completed testing to deliver a functional robotic platform to work in 100 bar(g) pressure (simulated), travel 100m and negotiate two bends, providing condition assessment data (visual and wall thickness measurements) – a minimum of 10 offline tests.	✓
Successfully completed testing to deliver a functional robotic platform to work in 100 bar(g) pressure (simulated), travel 100m and negotiate two bends, providing condition assessment data (visual and wall thickness measurements) – a minimum of three online tests.	✓

Data Analysis Systems in Place	
An analysis of data collected evaluated by PIE.	✓
Condition assessment algorithms developed by PIE.	✓
A site condition developed.	✓
Condition assessment criteria for high-pressure installations has been established.	✓

Completion of Data Analysis	
Based on the deliverables in Phase 1 of Stage 4 a review of all algorithms has been completed in order to determine future changes to the required inspection equipment.	✓
An end of Stage 4 report has been produced and signifies the successful delivery of condition assessment via robotic data collection and algorithm utilisation.	✓

Implementation into Business As Usual	
Design, manufacture and deliver a pre-commercialised robotic in-line inspection platform has been completed.	✓
All specifications complete, checked and approved for in-line robotic 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 (Inc. H&S) written and published on project website and recorded in project file. Robotic platform to be included as standard operating practice within NGGT asset management policy.	✓

Table 1 – SDRC criteria met.

2.5 Successful Delivery Reward Criteria Not Met in Full.

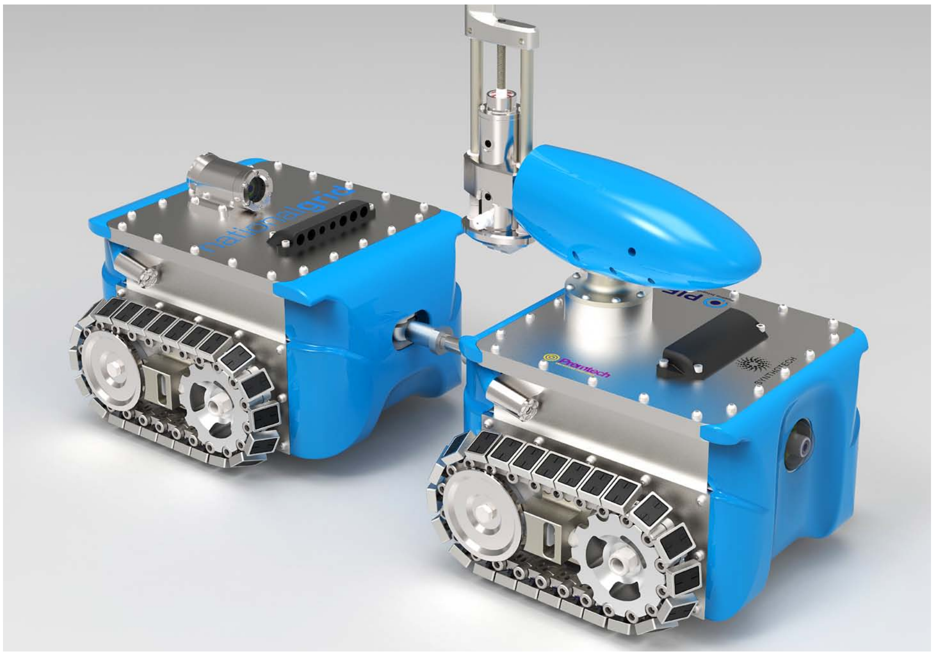
None.

2.6 Main Learning Generated by the Project

The main learning from the project can be summarised as below:

2.6.1 Robotic platform

- Whilst many people that the team spoke to at the start of the project were sceptical about sending a robot into a 'live' gas transmission environment, the conclusion of Project GRAID has shown that the concept is possible and can be completed with no impact to the operation of a site.
- The decision to build the GRAID robot with a twin chassis design was the result of considerable analysis and discussion. Having a split chassis led to challenges in communication between both parts of the robot however the benefit of this design meant the overall agility of the robot was increased to the point that travelling around tees which was originally out of scope is now a reality.
- Magnetic tracks provide sufficient adhesion to the pipe surface to keep the GRAID robot stable when navigating the pipework and stationary for collecting wall thickness readings.
- Flow conditions on site were expected to be up to 40 m/s which led to the initial design incorporating a dolphin-shaped chassis to be streamlined in the flow. In reality, the flow would never be that high and during the online trials flow was negligible on both sites due to how the site was operating during the inspection window. Flow has been tested up to 6.5 m/s during the offline trials with no impact to the driving capability of GRAID.
- No-one had attempted to operate a robot inside gas transmission pipework operating at high pressures, so the amount of footage of what it would be like in this environment was very limited. Following the online trials and reviewing the hours of footage collected, the condition of the inside of the pipework exceeded expectations especially for a site that has been operational for 50 years.
- It was possible to incorporate the tether and control of this drum inside the launch vessel therefore removing the need for a running seal which would have been a challenge at the high pressures experienced on the NTS.
- Collecting accurate data whilst inside the pipework provided considerable learning, as NDT in a high-pressure environment had not been attempted before Project GRAID. Selecting the right sensor technology for the platform that could be relied upon and remained within the scope of the NIC was a significant challenge for the engineering team.
- The EMAT sensors incorporated onto the GRAID platform provide reliable and accurate results, however the magnetic nature of the sensors attracted metallic debris from inside the pipework and so a wiper mechanism was designed to ensure the sensor surface was continually clean.
- The condition of the robot and how to clean it following an inspection was also not fully understood until the online trials. To address this a specialist cleaning provider was approached and a method of cleaning developed. Due to the good condition of the inside of the pipework inspected, GRAID did not require extensive cleaning with most of the debris on, or associated with, the magnetic tracks.



The twin chassis design of the robot.

Flow conditions on site were expected to be up to

40 m/s

2.6.2 Connection strategy

- To alleviate safety concerns regarding the introduction of an electrical source into the 'live' gas environment and possible gas/air mixes in the launch vessel, the team incorporated a nitrogen purge into the launching and retrieval processes. This removed a potentially dangerous environment from being created. The ability to easily nitrogen purge the inside of the chassis was also implemented to remove any potentially dangerous atmosphere within the chassis.
- Throughout the course of the project, several connection strategies were proposed and whilst permanent connection points were built at Pannal and Bacton, the concept of a temporary connection was extensively developed. In this way, it would be possible to remove an isolated asset such as a filter or scrubber, deploy the launch vessel and robot and then return the asset to service. This would reduce the overall cost of inspection and prevent major construction work on site.
- Laser scanning a site to develop a 3D model proved to be very beneficial for Project GRAID. The accurate model could be used for deciding the best route for the robot, be used as a navigation aid during the inspection and finally to visualise the results once collected. The method for laser scanning developed over the project with the use of drones to carry out the laser scan.

2.6.3 Condition model

- Confidence in the condition model is improved with incorporation of existing data sources such as the results of the in-line inspections upstream and downstream of the site. The more data in this area for a given site the greater the confidence in the model and therefore the results it is presenting.
- As the quantity and quality of data is improved, the condition model could be used to infer asset condition across sites with similar known service histories even if not having been inspected by the GRAID robot.

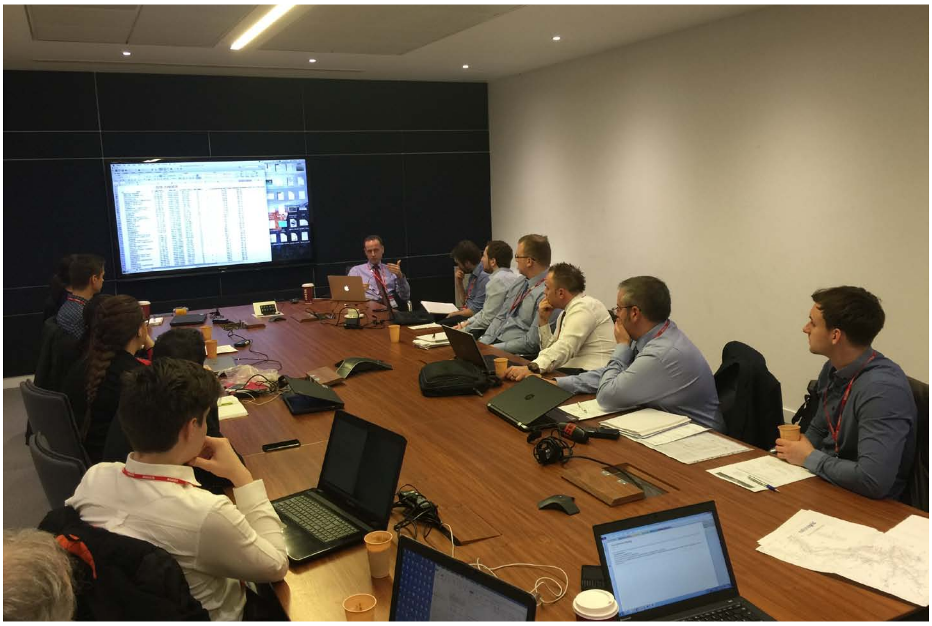
2.7 Main Learning Generated by the Method(s)

Innovation projects such as GRAID will inevitably encounter learning in how the method was implemented. Ultimately the milestones were met at project closure but several lessons were learnt to get there:

- Working as a collaborative team using project partners developed an effective team that was driven to reach the overall goal. Regular communication was carried out both via teleconferences and face-to-face meetings. In this way challenges were communicated and addressed by everyone to find a solution using the combined expertise.
- The offline trial tests were not prescriptive enough and did not include any pass/fail criteria. To give confidence to National Grid that GRAID was ready for online trials, a period of acceptance testing was agreed.
- Originally three online trial sites were proposed, however following agreement with all project partners and Ofgem it was decided that one of the trials be replaced by a period of Enhanced NDT study. In this way, the team had the opportunity to develop the launch and retrieval procedures during the two site trials but also develop an understanding of how the sensors would be affected by recording areas of corrosion.
- Additional benefit cases were developed during the online trials such as recording the integrity of an above ground pipe support and utilising the footage of the valve operations to understand its condition and whether it required maintenance or replacement.
- The importance of project dissemination not just in the UK but globally has helped to bring Project GRAID to the attention of many transmission owners who share the same challenges of inspecting unpiggable pipework.
- Preventing scope creep was important for the team to reach the original milestones within the timeframe defined. Any items which were classed as creep were discussed in full and tracked to prevent the ideas from being forgotten.
- Virtual project management tools such as SharePoint and SmartSheet were invaluable in ensuring all the project partners were aware of progress and required deliverables.

"For a project of this magnitude, regular communication between all parties was vital. Any issues or questions were discussed fully and the shared expertise used to find solutions."

David Hardman
Project Lead
National Grid



Regular communication was carried out both via teleconferences and face-to-face meetings.

Section 3
Details of the work carried out

The Project GRAID methodology consisted of five clear stages each with a dedicated time allocation and budget. In this way we could ensure that all the project partners submitted their deliverables before moving onto the next stages. The five highlighted stages and their details were:

3.1 Stage 1 – Solution Development

As with any project of this magnitude the first stage involves mobilising the project teams, setting up project plans, highlighting project risks and budget tracking methodologies. Communication strategies were also key and both those for internal and external engagement were created to be developed as the project progressed. Internally the team arranged to meet every month. To supplement this a weekly teleconference was also arranged, and finally any ad-hoc conversations were also carried out as required. Externally a communications plan was documented including a project website, monthly newsletter and attendance at a wide range of conferences and events. These are detailed fully in Section 12.

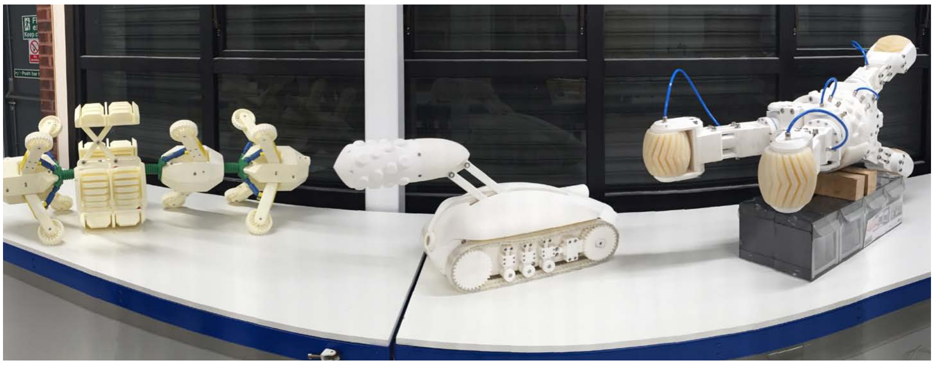
To begin the process of building the GRAID robotic platform a period of concept study, documentation of the initial design scope and specification writing was completed. A global technology review was also carried out to fully understand the industry for inspection robotics and how this was currently achieved. To ensure that the quality characteristics of the robotic platform were maintained, Synthotech established the Subject Matter Experts Consultation Group. This was a select committee of six individuals who met regularly and provided the engineering team with a deeper insight and understanding of the Gas Transmission network. The group was assembled to harness their experience across all aspects of gas transmission, from construction and design to gas quality, technology and safety management.

Using a combination of this learning the team at Synthotech could start the Alpha design phase of GRAID. Stage 1 of the design process involved the development of 3D computational models by Synthotech in accordance with the initial design scope and specifications. These 3D computational models were then printed using a technique known as ‘Rapid Prototyping’ which uses powders and plastic to print 3D models. The models were then fitted with off the shelf electrical and pneumatics/hydraulics to provide limited functionality.

Based on the knowledge gained from Stage 1 the team had to decide which of the concept designs to progress; the streamlined magnetic robot, a wall press robot or a swarm system of smaller devices. To make this decision the positives and negatives of each option were reviewed and agreed on. In summary, the wall press robot would be too heavy and take up too much of the internal pipework space. The swarm concept was too technologically challenging and the budget would not be sufficient to cover this idea, therefore the magnetic robot was selected for Stage 2.

During this phase the Project GRAID partners Premtech started to carry out the design activities for the launch vessel and offline test rig. These two unique items, required significant research and designing so that they could be functional for the project but also built in accordance with all the relevant National Grid design codes and standards. Initial Basis of Design Documents (BoDDs) were prepared and issued for both the launch vessel and test rig. Additionally, the team at Premtech started the process of analysing the online trial locations that were available across the NTS. This involved completing site surveys, asset record gathering and viewing the National Grid as-built drawings to choose the best online trial locations.

A technical assurance strategy was implemented during the early part of Stage 1 with the view to independently review and approve the technical reports that were produced as part of Project GRAID. Pipeline Integrity Engineers (PIE) joined as a project partner to provide this service, in part due to their extensive knowledge of the gas transmission industry and specifically in the Non-Destructive Testing (NDT) market. Monthly design review meetings were also conducted to share, review and challenge the design of the offline test facility.



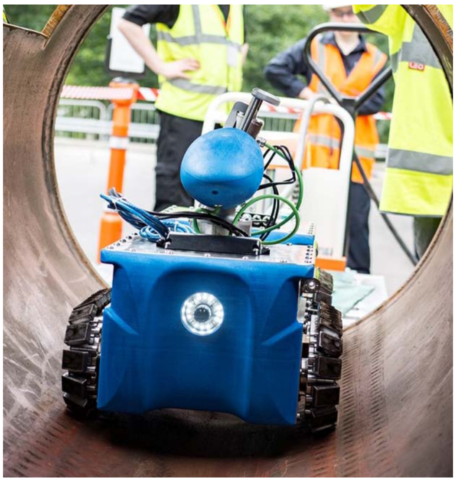
3D computational models were printed in Stage 1.

1 Solution Development → **2 Development Testing** → **3 Offline and Online Trials** → **4 Delta Prototype and Data Analysis** → **5 Implementation into BAU**

3.2 Stage 2 – Development Testing

Stage 2 saw the advancement from Alpha design phases to the Beta stage, building on the decision to progress the streamlined magnetic robot concept. At this stage the team at Synthotech moved to a more 'agile' way of working and started the development sprints. These sprints focused on specific areas of the robotic platform and included topics such as; the robot body, the Umbilical Management System (UMS) and the Operator Control System. Additionally, sprints focused on the drive mechanisms, the robot chassis, vision systems, sensors and the NDT packages.

During this process the concept of Computational Fluid Dynamics (CFD) was used to understand the drag forces that the robot would be exposed to in a simulated environment. This initial design data influenced the initial shape of the robot resulting in a configuration that would maximise downforce whilst minimising disruption to gas flow. This gave birth to the 'dolphin' design of GRAID. In completing the 'agile' sprint methodologies the team continually reviewed all aspects of GRAID including the chassis, which evolved as a greater understanding of the sub-system requirements emerged. Again, the benefits and drawbacks of a single drive unit versus an articulated double unit were reviewed and the result was to continue development with the twin chassis shape. This design process produced a highly versatile robot structure with considerable future development opportunities.



Project GRAID Beta design at the National Grid demo day.

Laser scanning

To complement the existing National Grid records for the online trial locations the team at Premtech started to collect very detailed information using laser scanning techniques of AGIs. This also highlighted the challenge to the team of connecting to an AGI that was not built with robotic inspection in mind. This connection challenge therefore instigated a report from Premtech that looked specifically at creating a new overall connection strategy for pipework at high-pressure installations. Using the methodology of spin-off NIAs and reports available to everyone, further learning into robotic inspection can be shared across the wider gas industry. For more information see Appendix G.

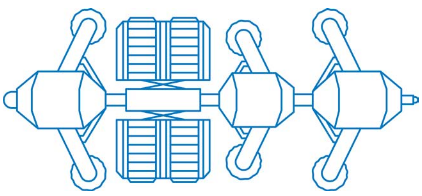
During Stage 2, Premtech further designed the Launch Vessel to a point that relied on the final robot and UMS shape to be agreed on and completed the designs of the test rig to be handed over for detailed design and build.

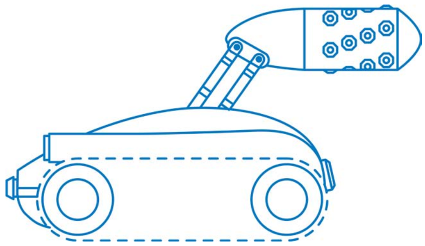
Low cost connections

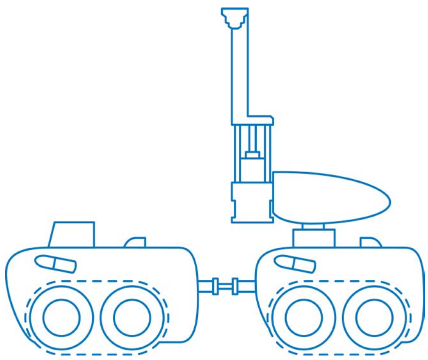
During Stage 2, PIE continued their assurance and technical guidance role with supplementary activities into the EMAT sensors and constructing a risk categorisation model by scoring the age and criticality of all the high-pressure installations on the NTS. By doing this work they were able to identify an additional five sites with potential low cost connection options where gaining data from in-line inspection would dramatically improve the accuracy of NGGT's asset condition information.

As part of the NIC project National Grid decided to apply for certain patents relating to the GRAID robot, the application for these started in Phase 2 and have been progressed throughout the programme.

The stage culminated with a demo day that was hosted at the National Grid Pipeline Maintenance Centre (PMC) depot (Ambergate, Derbyshire), allowing the Beta concept to be shown to the Senior Stakeholders. This was a significant step forward as the Beta robot could be driven around a test pipe showing the reality of operating the GRAID robot.







1 Solution Development → 2 Development Testing → 3 Offline and Online Trials → 4 Delta Prototype and Data Analysis → 5 Implementation into BAU

3.3 Stage 3 – Offline and Online Trials

Stage 3 was programmed to be the largest and most important stage of the project, encompassing both the offline and online trials of the robotic platform. This methodology was key to National Grid as offline trials provided the early assurances to the Senior Leadership team that there was confidence in GRAID ahead of 'live' trials. The online trials showed the commitment of National Grid to the wider community regarding robotic inspection of the unpiggable sections of its transmission network.

Throughout Stage 3 Synthotech moved from Beta development to Gamma design, manufacture and build stages to provide a working robot capable of undergoing the offline trial test plan. All aspects of the robotic platform were designed, manufactured and built including the robot chassis, drive mechanisms, NDT, UMS, control desk and the cabling required to connect the robot to the operator in the control kiosk. Members of the Synthotech team were then involved in driving and maintaining GRAID throughout the offline and online trials.

Premtech continued their activities during Stage 3 overseeing the Formal Process Safety Assessments for the online trial locations. Designs were then built up for the permanent connection facility at Bacton Terminal and the additional sites that GRAID was planned to inspect. Having a variety of different connection options across the NTS, and indeed on individual sites, allowed the team to choose the right site based on requirements and benefits that could be driven from inspecting there.

PIE were instrumental in the decision making process along the way, carrying out design reviews as the Gamma robot took shape and developed. Once the build was complete the team could offer guidance on developing a Non-Routine Operation (NRO) document for use during the online trials and were on hand to provide guidance around the use of EMAT sensors to inspect for corrosion.

Based on the results of a cost benefit analysis it was decided by the project team to hand the concept designs for the offline test rig to DNV-GL who could build the test rig at their dedicated Research and Test facility at RAF Spadeadam, Cumbria. Similarly, the GRAID launch vessel's designs could be finalised based on the Gamma robot shape and this was then passed to RMA to manufacture using the exact measurements from the Synthotech team. Both key items were built and made available for the offline trials to begin.

The next steps

The methodology surrounding the offline trials was to gain confidence that GRAID would operate as expected when it was brought onto the 'live' NTS network. This was a significant step to gain the Senior Leadership team's approval from National Grid to proceed to online trials. Initially a series of tests were designed to challenge the robotic platform without pressure, at pressures up to 77 bar(g) and then with pressure and flow up to 6.5 m/s. Based on this there was an additional requirement to perform acceptance testing on the offline test rig which was split into three stages, with the tests requiring completion of the agreed criteria before moving on to the next stages. The stages of acceptance were Geometry (navigating around the test rig), NDT (taking measurements of manufactured defects in the test rig) and Operational (working through the processes to be followed onsite). Ultimately, this was an additional activity during Stage 3 and increased the overall time on the offline test rig but proved invaluable in understanding the platform and addressing any issues ahead of the 'live' trials.

Once the confirmation was given to proceed to online trials by the Senior Leadership team at National Grid a series of objectives were agreed for the two-week inspection period. At first, specific days were given for the objectives but as the realities of being on an operational AGI set in, it became apparent that would not work. Instead the objectives were attempted onsite and an agreement was made in the morning about which aspects would be focused on. This was found to work better and was used at the second online trial location. A third trial location was originally proposed for the GRAID robot; however, the decision was made that significant benefit could be derived from completing Enhanced NDT analysis. This would allow the team to understand how the sensors would react to real corrosion and was agreed with Ofgem.

DNV-GL built the offline test rig at their dedicated Research and Test facility in RAF Spadeadam, Cumbria.

1 Solution Development → 2 Development Testing → 3 Offline and Online Trials → 4 Delta Prototype and Data Analysis → 5 Implementation into BAU

3.4 Stage 4 – Delta Prototype and Data Analysis

In the original proposal, it was envisaged that following the online trials there would be a period of Delta Prototyping in which adaptations could be made to the GRAID platform based on the learning so far. This stage was carried out following the first online trial and to a lesser amount after the trials had concluded due to time constraints at the end of the project. Several adaptations were carried out to the robot and UMS by Synthotech during this time, including additional cameras and software improvements.

During this stage Premtech could carry out carbon foot-printing studies based on the work that was completed versus the impact of inspecting the same area using traditional methods. An update of the Basis of Design Documents was also provided alongside completing the connection point design packs to allow the internal processes at National Grid to be signed off.

Significantly in this stage was the work completed by PIE on the data model aspect of Project GRAID. The original objectives focused not only on the robotic platform collecting meaningful data but how this data could be used for the Asset Health team within NGGT. Throughout the latter part of Stage 3 and through Stage 4, PIE started to collate all the existing data around the AGI sites that were chosen for the online trials, this included:

- Historic as-built information about the site.
- Soil and ground condition information.
- Cathodic protection information both on the site and the incoming and outgoing pipelines.
- In-line inspection data for the incoming and outgoing pipelines.
- Routine corrosion reports.
- Data provided by the GRAID team.

Utilising all this historic data the team at PIE could model the condition of the pipework on a given site using two factors; the quantity of corrosion defects and the severity of those defects. This methodology produces a condition model for the site and by using pipe segmentation a colour coded map of the site could be shown highlighting areas of high corrosion susceptibility. The model has been written in such a way that it will benefit from additional data inputs as it can be re-calculated each time GRAID data is collected on the NTS and will only increase in accuracy as the data is applied.

The complexity of Above Ground Installations.

Individual wall thickness measurements inputted into the model as recorded from the GRAID inspections:

More than

1,000

1 Solution Development → 2 Development Testing → 3 Offline and Online Trials → **4 Delta Prototype and Data Analysis** → 5 Implementation into BAU

3.5 Stage 5 – Implementation into Business as Usual (BAU)

The final stage of the proposed GRAID programme of works was to ensure that the use of robotic inspections by NGGT was implemented into BAU and benefit is continued to be driven from GRAID. Alongside all the excellent coverage robotic inspection had through GRAID, the next best way to get this type of inspection into BAU is to have it written into the working practices of NGGT. To complete this the team at National Grid first highlighted all the existing internal documents which could be amended to include GRAID robotic inspection. With this list, several meetings were then held with various members of the Policy team to understand who the owners of the documents were and how GRAID could be incorporated.

Utilising the design work from Premtech a standard connection report was created which can be used each time a new site is built. This might not provide benefit in the short term but if ever a new site is being designed then it should be done so with internal robotic inspection in mind. This is also another opportunity for the condition model as it could potentially be used to predict areas of high corrosion susceptibility and then inspection points can be designed to reach those areas.

A clear mobilisation strategy was also defined so that following the project closure on 26 November 2018 the systems and teams are now in place to provide a GRAID inspection if required. This strategy also includes a training and maintenance plan for the robotic platform which are key to the success in providing a GRAID service.

A training and maintenance plan for the robotic platform is key to the success in providing a GRAID service.

"Implementation into business as usual is absolutely key to ensuring that the GRAID robot is used across National Grid. Without this step the risk that the technology is not developed further is very real."

Tom Neal
Innovation Governance Manager
National Grid

1 **Solution Development** → 2 **Development Testing** → 3 **Offline and Online Trials** → 4 **Delta Prototype and Data Analysis** → 5 **Implementation into BAU**

Section 4
The outcomes of the project

Detail on the outcomes of the project based on the methodology used relating to all aspects of Project GRAID including the robotic platform, testing phases and the data model. A view on how the Technology Readiness Level (TRL) has changed as a result of the project.

The outcomes listed in this section clearly confirm the first two objectives of the NIC have been met, namely:

- Determining the condition of the pipework using an internal inspection robot.
- Generating a risk based, proactive approach to the management and maintenance of ageing assets.

The other two objectives of GRAID were to:

- Minimise the occurrence of unnecessary excavations.
- Minimise the likelihood of asset failure through proactive asset management.

These will be achieved as the use of the GRAID robot continues following this NIC.

With such a variety of different outcomes from Project GRAID this section has been sub-divided into the following categories:

- Robotic Platform.
- Non-Destructive Testing.
- Launch Vessel.
- Offline Trials.
- Online Trials.
- Documentation.
- Data Model.

4.1 Robotic Platform

4.1.1 Robot chassis

Designing and building the GRAID robot chassis provided the team with a significant challenge – the ambition of operating a robot in a high-pressure environment had never been attempted before and it was the chassis which would be instrumental in this. Through understanding from the Subject Matter Experts Consultation Group and colleagues at National Grid the type of environment GRAID would be in was agreed. A maximum operating pressure of 100 bar(g) was agreed which is like being around 1,000m underwater with flow conditions up to 40 m/s. These are the extreme conditions however, but it was key that GRAID could be used on all parts of the NTS and so the chassis had to withstand these conditions. Whilst a considerable amount of work was put into the first 'dolphin' concept there was simply not the requirement for such an aerodynamic design and as Table 2 shows, there is a significant benefit in moving to a twin chassis design.

> **"When this project first started, many thought it was not possible to operate a robot in 'live' gas conditions of up to 100 bar(g). I am happy to say, we proved them wrong!"**
>
> **Josh Blake**
> Technical Lead
> National Grid

	Single module	Twin Chassis
Complexity of electrical connections		
Complexity of mechanical parts		
Number of moving parts		
Ease of NDT mounting		
Space for NDT electronics		
Ease of steering the robot		
Complexity of the design		
Space for electronics		
Space for additional sensors		
Camera mounting positions		
Amount of track surface on pipe		
Track failure mitigations		
Total	4	8

Table 2 – Positives and negatives of both chassis designs. Positive Negative

Storing the vast array of electronics and components within the chassis required a significant amount of space, coupled with the requirement to protect certain equipment from the external pressure an unusual square design was chosen for both chassis. Through modelling and computational fluid dynamics it was agreed the material of choice would be 20 mm thick super duplex stainless steel. This added a significant weight to the robot but importantly would hold the pressures and stresses especially at the corners of the chassis.

Using this material in this configuration led to a series of very challenging welds to join the machined plates together, several attempts were made to complete this and at every stage the welds were X-rayed to confirm their integrity. The result was two fit-for-purpose chassis capable of protecting their contents up to 100 bar(g) whilst still retaining the agility required to navigate the complex pipework of a site. Alongside all the cameras and sensors on the chassis a final adaptation was made based on the feedback before the online trials. To remove any possibility for ignition on the inside of the chassis, the ability to purge the cavities with nitrogen was added. With no oxygen present during the introduction of GRAID to a gas environment the hazard was removed.

4.1.2 Drive Systems

Being able to navigate in the pipe in a controlled and careful manner was key to the success of the GRAID robot. Whilst other robots on the market use a wall press system to drive, GRAID could not due to the potentially high flow rates in a 'live' pipe and the large surface area this takes up causing a restriction. A magnet system, subsequently patented, was therefore used to both provide traction on the metallic pipe surface and ensure the robot was stationary when taking readings. Multiple options were considered including a magnetic underside to the robot and magnetic wheels but it was decided that a magnetic track would give the greatest traction. Two track designs were tested to understand the magnet adhesion verses manoeuvrability of the robot; one using rubber coated magnets to prevent slide and optimise adhesion, the second based on 'mecanum' wheels (a conventional wheel with a series of rollers attached to its circumference) to enable the robot to slide sideways when required.

4.1.3 Benefits of tracks

The design for rubber coated magnets forming a track was developed further and was ultimately used on GRAID. The result was between six and seven tracks in contact with the pipe at any one time and superior freedom of movement to adhere to pipe at diameters of 750 mm and above. Several tests were also carried out in a variety of oils and greases to ensure the tracks do not become inoperable from driving through any particulate in the pipework. Individual motors fitted to each of the four tracks allow the operator to control GRAID both forwards and backwards and navigate around the bends and tees found on a high-pressure gas installations. The tracks also allow the manual pull back system to operate in the unlikely event of a full system failure.

4.1.4 Patents

As part of the NIC guidance the companies involved are allowed to apply for patents based on the learning gained from the project. Several aspects of the GRAID Results were considered by National Grid to be potentially patentable, including a mobile robot for internally inspecting pipelines and a robotic system comprising two or more such robots. National Grid Gas plc. carefully assessed which aspects of the GRAID results should be patented, and the countries in which to seek such protection. Patent applications have been filed accordingly, which are currently pending.

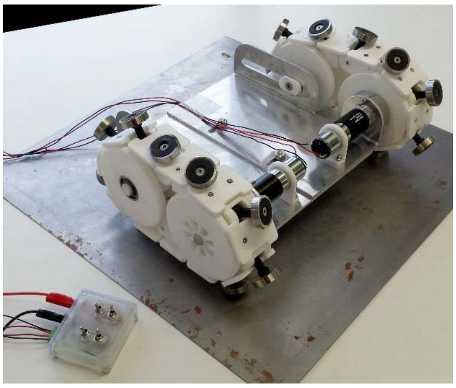
4.1.5 Vision systems and sensors

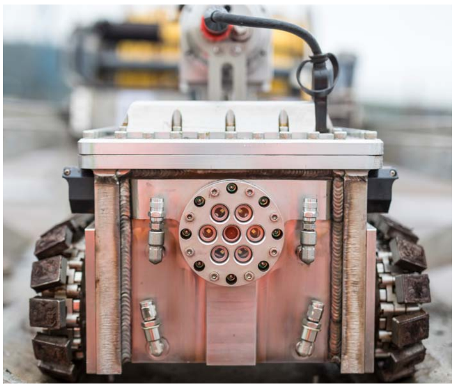
To navigate around the internal pipework there was a requirement for vision systems to be fitted to GRAID to aid the operators in understanding their surroundings and following the planned inspection routes. Synthotech were the perfect partners for this aspect as they have considerable experience in camera systems in this environment, however moving from Distribution to Transmission pressures presented substantial challenges.

The camera needed to offer clear vision, without taking too much data to transmit, all whilst being kept in a pressure-tight housing. There are a total of eight cameras on the GRAID robot; one per track, front and rear facing and two positioned at the NDT sensors. There are also four additional cameras on the UMS which aid in driving back to the launch vessel and ensuring the tether is kept neatly on the drum. Every detail was considered when designing the vision systems including the angle. Each was fitted to ensure there was a clear line of sight to the key parts of the GRAID robot. Significantly on the UMS where the vision of the cable drum is important and following feedback from the online trials a new camera was fitted pointing up the NDT arm towards the sensors.

All feeds from the cameras are sent to the Control System where they can be viewed and recorded individually or as a collective. A light source was also required for navigation purposes and it was agreed that LEDs would be fitted to each camera. The brightness of each individual LED can also be controlled to achieve the optimum level of lighting. Whilst it is very unlikely to find corrosion on the internal surface of the pipe the cameras did provide additional benefits, namely verifying the location of buried pipework and assets with as-built drawings and recording the operation of valves in 'live' conditions.


A fit-for-purpose chassis.


The tracks.

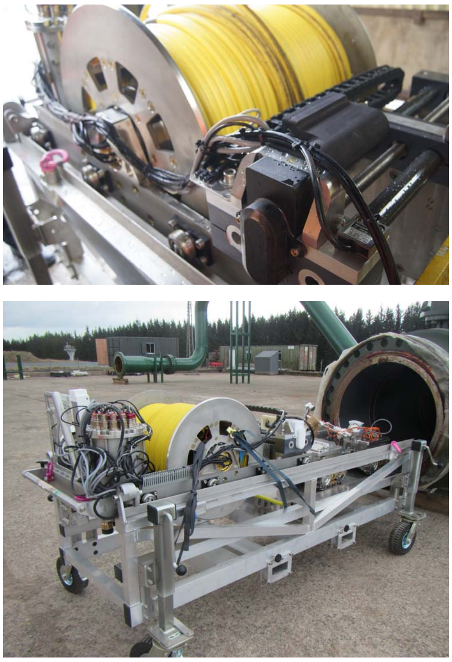

The GRAID device.

The GRAID robotic platform also includes a vast array of additional sensors which all feed back to the Control System and give the operators vital information from within the pipework. These include:

- **Temperature** – an internal sensor on each module in the chassis, in the electronic circuit areas and an external sensor on the UMS. There are also temperature sensors on the Drivers Cabinet and the Control System outside of the pressured environment.
- **Pressure** – internal sensors inside each of the modules, one on the outside of the robot and one sensor on the UMS.
- **Location** – sensors on both modules record the roll and pitch of the robot which is invaluable information especially when navigating bends in the network. There are also Hall sensors in the motor for the UMS to record how far GRAID has travelled and sensors in the motor for the NDT arm and UMS drum to notify the operator on the angle of rotation.

Each of these sensors have been specifically designed and built to carry out their role within a high-pressure gas environment. The roll and pitch sensors also perform an important backup function if visual feeds are lost on the robot which has been tried and tested, returning GRAID to the launch vessel using only these sensors.

The UMS tether, specifically designed for GRAID.



The UMS.

4.1.6 Umbilical Management System (UMS) and tether

The key function of the UMS is to connect the robot to the operator and to house the tether drum which was agreed would be installed inside the launch vessel and be exposed to the pressurised environment. Having the tether inside in this way increased the overall size of the vessel but meant there was no requirement for a running seal which was felt to be a significant design challenge at pressures up to 100 bar(g).

The UMS comprises a cable drum currently holding just over 100m of tether, four cameras strategically positioned to view all important functions and a method of connecting from the robot through the wall of the launch vessel to the driver cabinet. These external connectors are discussed further in Section 4.3. The drum includes several motors; one designed to pay out the cable at the same speed the robot is moving to prevent undue forces on the robot and another to ensure the umbilical is spooled evenly back onto the drum to prevent entanglement. These motors can operate in automatic and manual modes. The UMS includes castors which allow the everything to be pushed onto rails within the launch vessel. Once in situ the UMS will also engage onto a gear on the side of the vessel, used for manual pull back. Both are discussed further in Section 4.3.

The tether itself was specifically designed for GRAID and comprises of six power cores and 18 data cores between the robot and the UMS ensuring continuous, high quality electrical continuity with a high degree of redundancy. The power wires have been carefully selected to enable the system to safely transmit the required voltage and current, with a large (6x) factor of safety. These all have individual polyethylene insulation. The data cables are all screened pairs to ensure minimal signal loss due to noise during transmission. The cables are enclosed in two further layers of polyethylene insulating sheath and in between these layers is Vectran braid (like Kevlar).

This is the strength element that enables the tether to be used to pull the robot back in an emergency. The braid has a breaking load of over 2,000 kg – that is over four times the weight of the robot. The overall cable design has a maximum working pressure of 170 bar(g), well above expected pressures on the network.

To facilitate transportation to, from and within a site a trolley was also designed, which securely held the UMS, tether drum and robot. The transportation trolley is manually pushed around site on braked wheels and includes earthing points, is height adjustable and has both lifting eyes and forklift points to offload the equipment from a lorry. Based on feedback during the 'live' trials a jack was built into the trolley, allowing the robot to be lifted slightly so the tracks could rotate without the robot moving assisting in the maintenance and cleaning processes.

4.1.7 Driver cabinet

The purpose of the driver cabinet is to take the DC power and command signals from the control system and act as a 'junction box' to distribute and communicate power and control to the UMS and robot, within the live pipe network. As the UMS is only a short cable length from the driver cabinet, a computer can be placed nearby along with the various power distribution boards, controllers and LED/vision boards which can be utilised to power and control the UMS. As these components are external to the pressurised environment, this offers redundancy, in that were any issues to appear during operation then the Engineer can investigate inside of the Driver Cabinet and attempt to rectify, or repair/replace where necessary. The cabinet also includes an emergency stop (E-stop) button externally which after pressing can only be reset via a key. Power to the UMS and robot can also be isolated at the driver cabinet to prevent unauthorised/unintentional powering on of the robot or UMS.

The driver cabinet.

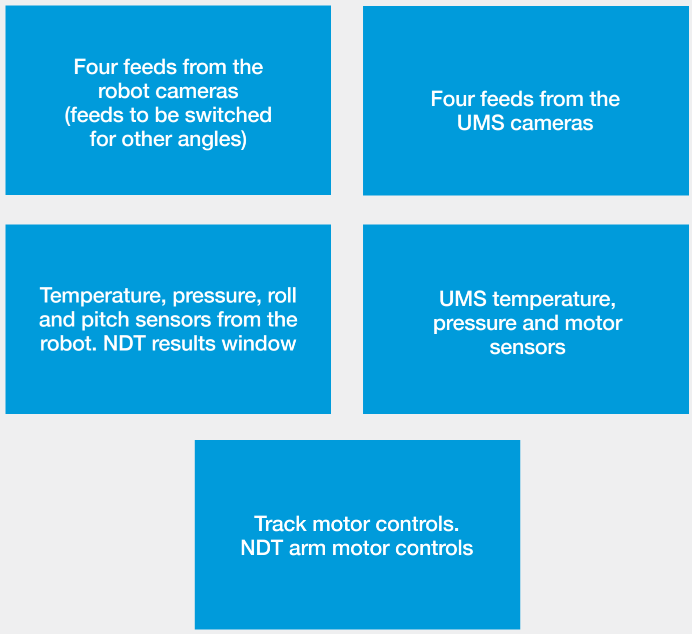


Figure 1 – Operator control system screen content.

4.1.8 Operator control system/centre

As with any robotic platform the operator control system (OCS) is vital in that it must provide all the information an operator would require, allow them to drive effectively but above all not overload them with too much information. The GRAID control system was designed with a lead driver and assistant in mind and consists of a main body housing the rack mounted computers and a total of five LCD screens, all fitted to a trolley for easy transport. The screens allow the users to see all the required information and is roughly laid out as shown above.

Synthotech were familiar with the software package LabVIEW and so it was a logical choice to develop the GRAID control system using this. The facility to record the screens was also built in so that any completed inspections can be re-run in full after the event. This can help with fault finding and using the video feeds to playback the footage to Engineers within National Grid. To aid with the safety case for GRAID a cable trolley was designed giving 50 metres of umbilical between the drivers cabinet and the OCS. This meant that the OCS did not need to comply with ATEX as it could be positioned outside a hazardous area on site.

To protect the OCS, cable trolley and robot operators a specially converted 10 ft square container was commissioned for the GRAID project. A standard container was fitted with a door, window, electronic power points and a whiteboard. It was also fitted with several anchor points which meant that the contents could all be transported to and from site together.

4.2 Non-Destructive Testing (NDT)

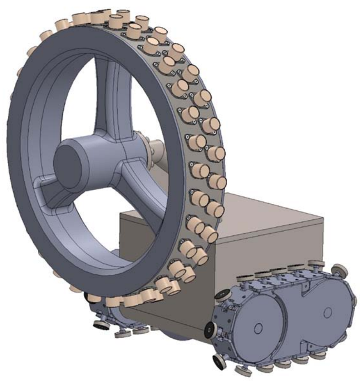
4.2.1 Acoustic Resonance Technology (ART)

Once inside the pressurised environment the GRAID team looked to the method at which wall thickness readings would be taken. A considerable amount of effort and thought was given to this by all of the project partners. In the early stages of the NIC, a global technology watch was set up by Synthotech to continually monitor the wider industry for existing systems that could be utilised to ensure the project did not create any unnecessary duplication. As a result of this, a new NDT technology was discovered that could potentially be used as the NDT payload on the GRAID robot. Acoustic Resonance Technology (ART) is a form of ultrasonic measurement patented by Halfwave that can use pressurised gas instead of a liquid as the couplant between the sensor array and the pipe wall. The result is an NDT sensor which can record the thickness of a pipe wall without the requirement to be in contact with it. Following a number of technical visits and a feasibility paper from Halfwave, it was determined that this technology would significantly surpass the requirements of the project. This unfortunately came at a cost that was beyond the budget and contractual arrangements of the GRAID project and so Synthotech re-visited the options discussed earlier in the project.

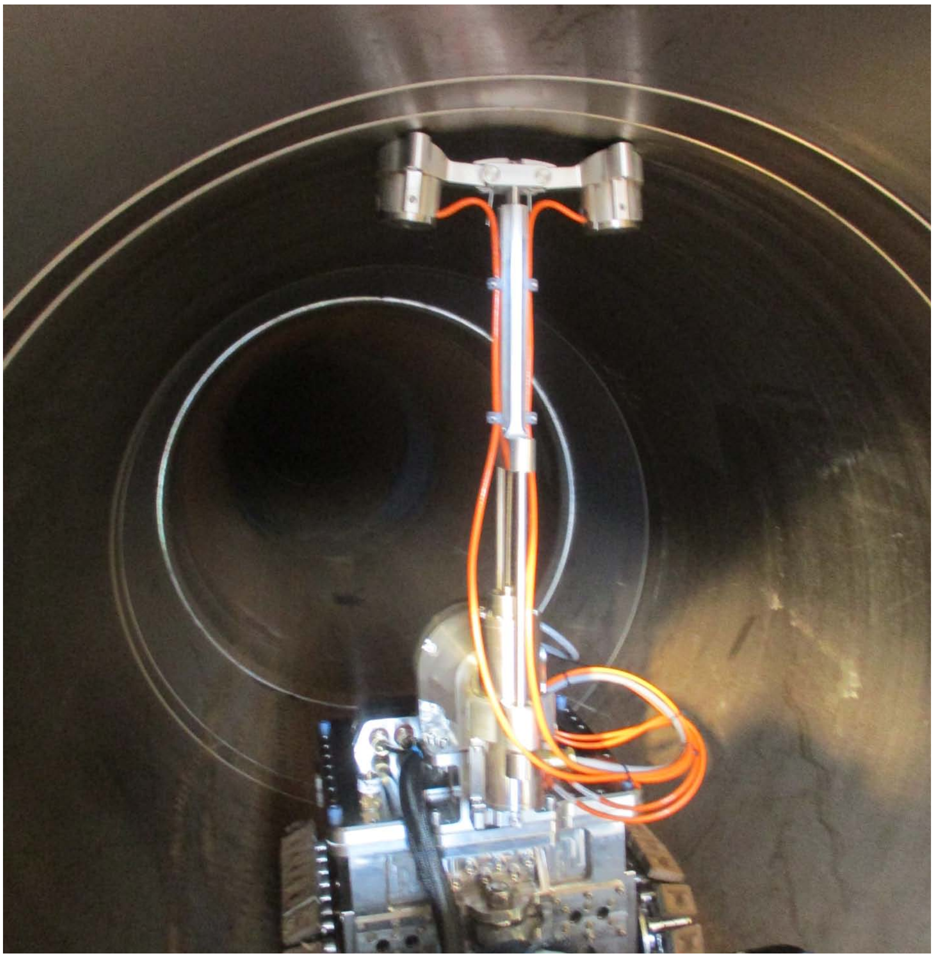
4.2.2 NDT arm

Without a full ring of sensors like the existing Pipeline Inspection Gauges (PIGs) used for reporting on corrosion on the long sections of pipeline between sites, a method was now required for the GRAID robot to rotate a sensor package to cover the full diameter of a pipe. Locating this at the front of the robot led to balancing issues and the tether at the back prevented it being sited there and so an innovative ‘Thor’s hammer’ design was used in the centre of the two modules. Two sensors were positioned such that at the six o’clock position at least one of these sensors was underneath the flexible buckle holding the two chassis parts together. The NDT motor allowed for full 360° rotation, importantly meeting the requirement to record wall thicknesses at any point from the inside of the pipe. The motor was also able to extend and retract the sensor package so that it could ‘touch onto’ the wall and take a reading. Careful torque calculations prevented the arm from extending too far but were sufficient to pull the magnetic sensors off the pipe wall.

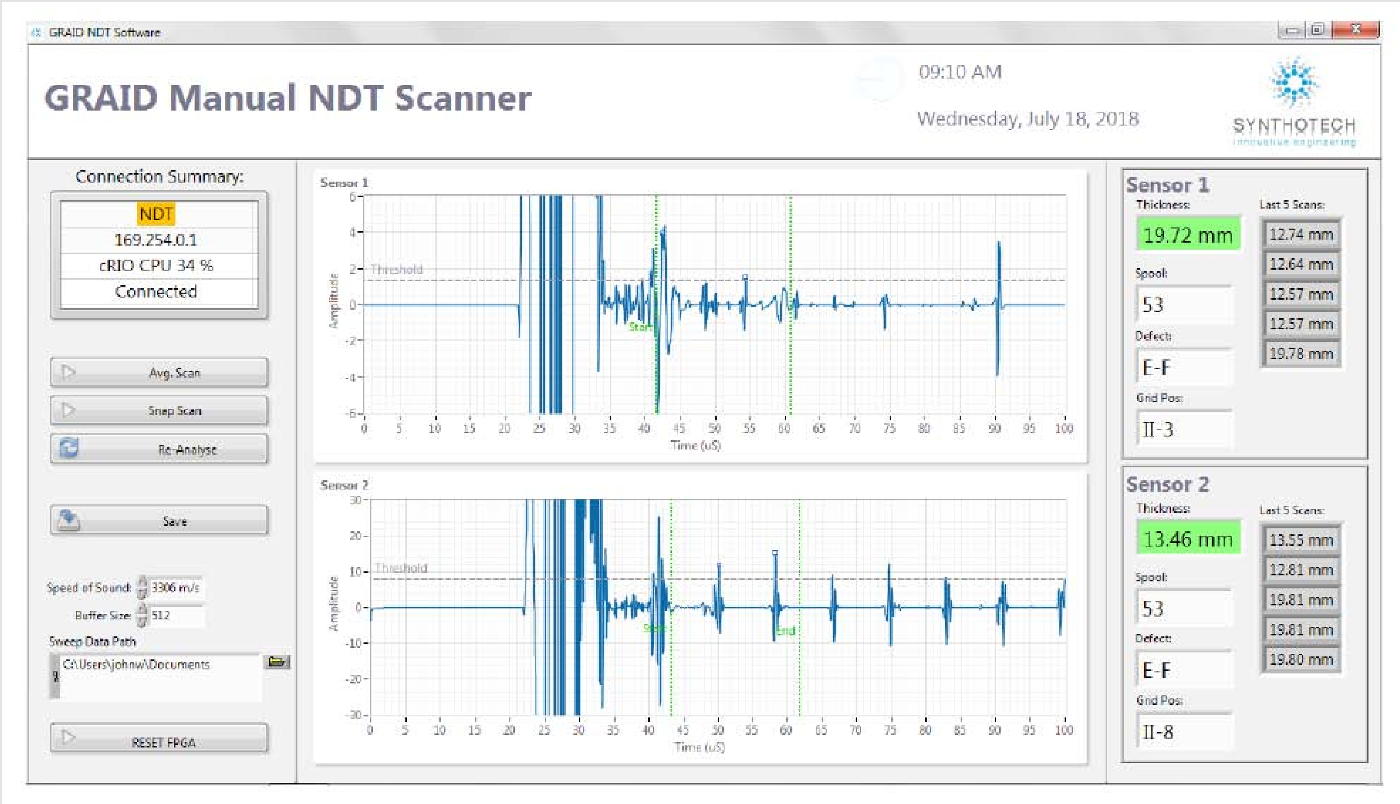
During the offline trials, it became apparent that the magnetic sensors attracted metallic particles that were in the pipework which led to a reduction in the quality of the data returned. With only a matter of months before the online trials started, wipers were designed for the sensors that used the extension movement of the arm to pull a set of brushes across the surface and back again when the arm was lowered. This mechanical method of cleaning meant there was no additional electronic requirement and they could be fitted to the arm with relative ease.



Operator control screens and a concept for ART.



NDT arm at full extension.



NDT results view.

4.2.3 Electro-Magnetic Acoustic Transducer (EMAT) sensors

EMAT sensors are industry recognised for collecting wall thickness readings, however they are historically used on the outside of the pipe which presented the team at Synthotech with a unique challenge. To assist in converting this to match the curvature of the inside of the pipe the team contacted Sonemat who work in collaboration with the University of Warwick. A section of pipe was provided to the team to remove any errors and ensure the wall thicknesses could be recorded from the inside. The result was two EMAT sensors roughly 22 mm in diameter that were housed at the end of the NDT arm. EMAT sensors do not require a couplant because sound is directly generated within the material adjacent to the transducer. The sound is then received and the time taken for this can be used to calculate the wall thickness. The result is a graph similar to the illustration above. Using the GRAID software the operator can then record what the thickness is. The current EMAT sensors take over a thousand measurements across the 22 mm square area and average these for the result. The team at Synthotech designed the software for the NDT arm to carry out a set pattern of inspecting so the whole process could be automated. For a 'sweep' scan the arm is rotated to each hour on the clock face and a reading is taken. The robot is then moved forward and the process completed again. For a 'detailed' scan the arm can be programmed to take a reading at every degree and by moving forward a very detailed map of the wall thicknesses can be created. This can all be automated removing the time consuming task from the operator who is focused on ensuring the overall system is performing as expected. Once recorded the NDT data is fed into the software where it is displayed in real time giving the operator an instant view and a choice to move on or perform more detailed analysis. Following the inspection the data is then passed to be processed into the condition model for site which is discussed further in Section 4.7.

GRAID launch vessel connected to the NTS.

4.3 Launch Vessel

The Project GRAID launch vessel was designed by Premtech in accordance with the National Grid specifications for pressure vessels to be fitted to the National Transmission System and built by RMA, who are based in Germany and supply equipment such as ball valves and PIG traps to the wider gas industry. As soon as the finer details were understood regarding the robot and UMS and how the connections would be established, this design could be finalised and sent for manufacture. The vessel has a nominal bore size of 900 mm, is around three metres in length and weighs just under six tonnes when empty. It is designed to operate up to 100 bar(g) to match the robot but was over pressure tested to 150 bar(g) as part of the factory acceptance testing. It is much like a PIG trap in that it has a door at one end and a 900 mm 'RTJ' flange at the other, with two vent stacks, one drain, a pressure indicator point, lifting eyes and two feet. However, there are some significant differences for the GRAID vessel:

- Fitted rails on the inside of the vessel allow the UMS to be slid from the transportation trolley inside without any lifting required. These rails are fixed in place and so there was a requirement for the transportation trolley to be height adjustable depending on the height of the site pipework.
- A key feature of the vessel is the gearbox assembly and wheel on the outside which is used in the instance of a complete electronic failure of the robot. Once a drive pin is removed from the gearbox a spur gear on the inside connects to the tether drum. This in turn enables the actuator wheel to be rotated and the drum turned manually, thus pulling the robot back to the launch vessel. The gearbox can give an output of 100,000 Nm which is sufficient to pull the robot back from 100m and around several bends. High gear ratios mean that very little effort is required bringing the robot back slowly.
- Finally, the vessel includes two flanged electrical connections (one for power and one for data) whereby Synthotech could utilise connectors which would allow a cable to pass from a pressurised environment to the outside world. A specialist subsea connector company Hydro Bond was requested to provide the connector setup to withstand the high-pressure differential around the cables. These connectors were fitted to the launch vessel and pressure tested during the offline trials.

Whilst the quick closure door mechanism was very familiar to the manufacturing team at RMA it is not that common on National Grid sites, however there are several key safety mechanisms which mean this type of door was chosen. As the door is closed a key is used to rotate it, which engages large teeth around the full circumference of the door. Once in the closed position a pin is pushed through the top tooth and locked in place. This pin cannot be removed if there is a pressure differential between the inside and outside of the vessel. If this pin is forced out when pressurised, then gas is released out of the top of the safety mechanism giving an audible warning. Even with these safety measures the door is very simple to open, close and operate safely. The final stage before online trials was to apply a coat of paint in accordance with the relevant National Grid specifications and stickers were applied to honour all the project partners involved.

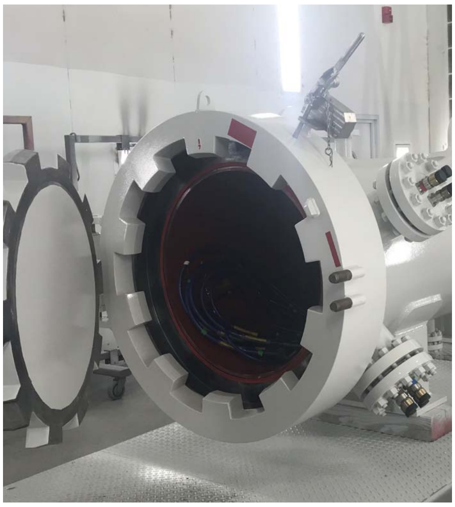
4.4 Offline Trials

4.4.1 Test Rig

Stage 3 of the GRAID NIC project was to carry out testing of the robotic platform. To begin this stage and before approaching a ‘live’ National Grid site the team completed the required offline trials. To develop the system the inspection tool required a pipework loop where it could be installed and its operation checked while driven through typical pipeline features such as elbows, tees, reducers and inclines etc. The test loop also enabled operations to be checked while under pressure using either nitrogen or natural gas and flowing conditions. Several locations for the offline test rig were proposed and a decision was made to contract the task to the team at DNV-GL’s Testing and Research Centre located at RAF Spadeadam in Cumbria. The site offered considerable benefits and had extensive experience in building and testing rigs for this purpose. During the design process a full stress analysis exercise was carried out by Pipeline Integrity Engineers to ensure the rig would be safe.

4.4.2 Final test loop

The final test loop was built using a combination of reclaimed pipework from redundant parts of the NTS and new pipe procured for the activity. In summary, the test loop facility consists of 900 mm (36”) diameter pipe with a section of 750 mm (30”) diameter pipe to introduce a diameter change. The loop is nominally 20.5m long and 8.2m wide with an inclined section rising to 4.3m from the flow loop centreline. Each spool on the test rig is flanged to allow the rig configuration to be altered to be representative of varying National Grid sites. The loop is currently in Configuration A as shown in the image below. The flow loop was supported on stands one metre above the concrete pad and a supply of both nitrogen and natural gas was connected from the test site supplies. Once complete the entire rig and launch vessel was hydrostatically tested to 125 bar(g) to ensure the integrity before gas was used. Calibrated pressure transducers and thermocouples were inserted via threadolets and high pressure sealing glands to record the relative pressure and temperature inside the test loop, along with similar measurements taken from inside the launch vessel. To simulate the likely flow characteristics in the test loop two fan units were fitted to generate velocity up to 5 m/s, the fans were calibrated to the fan speed allowing the test team to induce the required flow. Significantly the fans were also reversible which meant the robot could be observed performing operations both with a head, a tail wind and using the tees sideways flow, all ensuring GRAID experienced the scenarios it might face on a ‘live’ trial.



The launch vessel quick closure door (above) and the final test loop (right).

For testing the NDT aspect of GRAID it was decided to fit machined defects inside the test loop. This gave the team at Synthotech an area to analyse and map the defects and in the process, understand how the EMAT sensors would react to a defect in the pipe wall. Several plates were fixed to the pipe wall and reversed so the cameras could not be used to pin point the defect as in reality, the corrosion is likely to be on the outside of the pipe wall. To further assist the NDT work and to have a known value to compare the GRAID recorded thicknesses, several bands on the flow loop were ultrasonically tested from the outside to give very accurate readings as a comparison.

4.4.3 Offline trials – initial tests

The offline trials consisted of initial testing to prove the robot is capable of moving around the test loop in conditions from ambient to 55 bar(g) pressure and 5 m/s of flow and National Grid acceptance testing to confirm GRAID was ready for the online trial stage. The initial testing consisted of the below completed tests:

Test No	Report No	Description	Date Completed
1	G01-RPT-005	Can the robot successfully drive past a ball valve	10/04/17
2	G01-RPT-006	Can the robot drive past a Tee junction	10/04/17
3	G01-RPT-007	Can the robot successfully drive around a 90° swept bend	10/04/17
4	G01-RPT-008	Can the robot reach the top of the 45° slope and return safely	27/04/17
5	G01-RPT-009	Can the robot drive around a Tee	20/04/17
6	G01-RPT-010	Can the robot drive through a reducer	20/04/17
7	G01-RPT-011	Can the robot drive around two bends	27/04/17
8	G01-RPT-012	Can the robot drive past a two-inch outlet (sweepolet)	20/04/17
9	G01-RPT-013	Test UMS fits in the launch vessel	09/08/17
10	G01-RPT-014	Can the robot drive around two 90° bends	03/08/17
11	G01-RPT-015	Can the NDT take pipe thickness measurements	14/12/17
12	G01-RPT-016	Can the robot be pulled back to the launch vessel	24/08/17
13	G01-RPT-017	Test if the robot can travel 100m from the UMS	18/08/17
14	G01-RPT-022	Can the UMS withstand and operate at 100 bar(g)	29/09/17
15	G01-RPT-023	Can the robot chassis withstand 100 bar(g)	02/10/17 and 17/11/17
16	G01-RPT-024	Can the whole robotic platform withstand and operate at 100 bar(g)	30/11/17
17	G01-RPT-025	Can a robot run be completed under pressure	07/12/17
18	G01-RPT-026	Can a robot run be completed under pressure and flow	26/01/17
19	G01-RPT-027	Can a robot run be completed under pressure and reverse flow	Cancelled (not required)

Table 3 – Results of the offline trials – initial tests.

Due to scale and size restrictions it was decided not to use the test loop to carry out the 100m test of GRAID. Instead, this was carried out on a straight section of pipeline at DNV-GL Spadeadam which was sufficient in length. This was an important test, showing that both power and data could be transmitted across the full 100m distance and that the UMS drum could wind 100m of tether back in an orderly manner.

4.4.4 Offline trials – acceptance testing

At the end of 2017 it was agreed within National Grid to continue the offline trials and ensure the platform was giving the confidence to the Operations teams on site that all scenarios had been tested with a successful outcome. In order to provide this proof, a series of go/no go acceptance criteria for the robotic platform were developed and agreed with Synthotech. The additional testing also required a data logger to be created for the control system. This would store all the data from the robot during operation. Should a failure occur during use, this data can be examined for future learning and fault investigations.

The acceptance testing was split into three stages:

- Phase 1 – Robotic platform – Prove the robot can drive around the test rig.
- Phase 2 – NDT function – Prove the function of the NDT system.
- Phase 3 – Operational – Prove the durability of the robot and procedures for operation.

The agreed acceptance criteria gave defined variables that needed to be passed for the test to be signed off and were all witnessed by National Grid staff before the next phase could be started. Testing was completed between March and May 2018.

Test No	Phase	Description	Pressure (bar(g))	Medium	Flow (m/s)	Date Completed
1	1	Climb the 45° slope	50	Nitrogen	0	08/03/18
2	1	Climb the 45° slope	50	Nitrogen	1.5	08/03/18
3	1	Climb the 45° slope	50	Nitrogen	5	08/03/18
4	2	Inspect defect samples	50	Nitrogen	0	05/04/18
5	2	Inspect defect samples	50	Nitrogen	3.5	12/04/18
6	2	Inspect defect samples	40	Natural Gas	0	Cancelled, covered by #8
7	2	Inspect defect samples	70	Natural Gas	0	Cancelled, covered by #8
8	2	Inspect defect samples	70	Natural Gas	3.5	03/05/18
9	2	Inspect sweep locations 900 mm	70	Natural Gas	0	04/05/18
10	2	Inspect sweep locations 750 mm	70	Natural Gas	0	Cancelled, covered by tests at Synthotech
11	3	NRO procedures	N/A	N/A	N/A	10/05/18
12	3	12 hour endurance test	70	Natural Gas	5	09/05/18
13	3	Simulated failure	70	Natural Gas	0	10/05/18

Table 4 – Results of the offline trials – acceptance tests.

Three tests initially identified to be carried out were cancelled; these were to verify the capability of the NDT sensors, however, after further consideration were deemed not required at this stage. The tests were covered by more challenging conditions in later tests and additional preparation testing at the Synthotech STARS proving facility. Whilst this additional testing was not originally planned for and took the timelines for offline testing very close to the start of online testing, the results were good and gave all the teams at National Grid the confidence they needed to bring the GRAID platform onto a 'live' NTS site. It also gave the team at Synthotech opportunity to be familiar with the platform and develop the processes that would be used on site and an understanding of how the sensors would react to flow conditions.

4.4.5 Disaster recovery

One of the successful delivery reward criteria (SDRC) defined in the project proposal was to establish and publish a Disaster Recovery Plan for 'live' trial sites. It was vital to understand how GRAID would react to scenarios that were not routine so a plan was put in place and the team knew what to do to recover the robot. Such tests included:

- A loss of camera feeds on either the robot, the UMS or both.
- The loss of sensors on the robot, the UMS or both.
- UMS drum failure requiring manual winding back.
- Track failures in any combination from one to all four.
- The pull-back mechanism on the UMS and launch vessel were tested for straight sections, past tees, over a weld bead and around a bend.
- The effect of driving over the tether.
- The robot tips over.
- The NDT arm does not rotate and is fixed in an awkward position.
- A full power failure.

During each of these scenarios the team needed to understand what the effect on driving was, if the robot could be driven back to the launch vessel or if a manual pull-back was required. The final resort, if a pull-back exercise was ineffective would be to leave the robot in situ and plan for the works to excavate and retrieve GRAID. This topic was discussed extensively with National Grid and unlike a full-bore pipeline inspection gauge, GRAID does not prevent the gas from flowing so unplanned outages would be reduced. The Disaster Recovery Plan was established and agreed and available to the team during the online trials. This will be reviewed periodically to ensure its accuracy for any future GRAID inspections.

"It was vital to understand how GRAID would react to scenarios that were not routine so a plan was put in place and the team knew what to do to recover the robot."

John White
Senior Principal Engineer
Synthotech

Tests were carried out to create a Disaster Recovery Plan for 'live' trial sites.

4.5 Online Trials

4.5.1 Online trial processes

As with any ambitious project such as GRAID, gaining access to the National Transmission System was always going to be challenging for the team at National Grid. No-one had ever introduced a robotic platform into the network during 'live' gas conditions before and so choosing the right sites for the online trials was key. A balance was required between sites of national importance that would be higher risk but could offer higher rewards in terms of the value of the collected data versus those sites that were less vital but allowed the team to fully evaluate the robot's capability. To support this selection process and to understand fully which sites across the NTS could be inspected by means of a robotic platform (not just GRAID) a separate NIA was completed by PIE. See Appendix G. The NIA (NGGT0091 – Installation Risk and Technology Assessment Model) summarised all the AGIs and presented a prioritised list of sites in terms of their criticality. Once a site was highlighted as being of interest for a GRAID connection the following process was followed:

Example of a 3D model of an Above Ground Installation.

Review archives and as-built drawings

↓

Carry out a laser scan of the site

↓

Combine data sources to build an accurate above and below ground 3D model of the site

↓

Highlight possible GRAID connection points

↓

Develop route drawings including maximum extent and go/no go route

Figure 2 – Online trial development process.

Whilst every effort was taken to proceed with the reported connection points at the sites across the NTS, invariably there was movement. This was mainly because of additional works occurring on that site or in some cases the area GRAID was to inspect was removed as part of a sitewide asset health project. Conversations with the Gas National Control Centre (GNCC) also defined which sites we could install connections on depending on any outages that were occurring elsewhere on the network preventing further outages for GRAID related work.

Early into the GRAID project it was decided that Bacton Terminal would be chosen for a GRAID connection as a high risk, high reward site. To supplement this the first site would be a relatively low risk site with sufficient backup facilities available and so Pannal Offtake near Harrogate was chosen, this also had the benefit of being close to the Synthotech workshops for any repairs. The third site was discussed internally and with Ofgem and is covered in Section 4.5.3.

4.5.2 Online trial – Pannal Offtake

The site of Pannal is a transferred offtake currently shared between National Grid and Northern Gas Networks (NGN), it is located in the north east of England near the historic town of Harrogate. The site receives transmission gas through Feeder 7 from the north and 29 from the west. Gas is then received by NGN for distribution and transmission lines continue the feed south.

To take the GRAID robotic platform onto a 'live' NTS site for the first time it was agreed that a low risk area was chosen to minimise any impact GRAID would have. The site at Pannal was perfect for this as it included a redundant meter stream loop in the north of the site. This loop was designed and planned for another feeder connection in the future but this had never materialised. The meter loop included an orifice plate for recording the flow had it been connected. On the NTS any asset requiring modification needs to be passed through the relevant internal policies and procedures. Following analysis, the Pannal loop was deemed to pose a low risk and could be amended for a GRAID connection with little to no impact on the flows of gas through Feeder 7 and 29 to NGN. Additionally, the site was built in the 1970s so the pipework would be in the latter stages of its design life and it was close to Harrogate where Synthotech was based.

As the full meter loop was redundant the GRAID team proposed that two permanent connections were built in the area allowing the robot to return in the future with very little cost. A 90° bend, straight section and orifice plate carrier were removed from site and concrete bases installed for the connection points and to house the control kiosk. This would provide an effective trial area that included 750 mm diameter straight sections, ball valves, tee junctions, dome ends, 45° slopes and a 90° bend, all in a relatively small area of the site.

The team were on site for a total of two weeks, initially driving the full extent of the routes to map out weld locations and areas of interest to inspect further. Once complete the EMAT sensors could be used to record wall thicknesses along the route, areas of interest were around the below ground weld locations, the wind/water line as the pipework went underground and the above ground pipe supports. The latter was of particular interest to the team as there were a significant amount of full encirclement supports in a small area and many of the concrete plinths were showing signs of erosion. The replacement of such a pipe support can be very costly especially as the integrity of the pipework underneath the support is unknown leading to careful extraction of the old concrete to reduce the stress on the pipe. From the inside however, the GRAID robot can take wall thickness readings of the covered pipework and provide a view of the integrity of the pipe. This helps reduce the cost of any future work on the support and shows that GRAID can provide benefit to National Grid in above ground pipework as well as below ground. The same principle can be applied to above ground cladded pipework which is present on some National Grid AGIs, but not in the example of Pannal Offtake.

Over a thousand separate readings were taken during the two-week inspection window across a variety of locations. These were then passed to PIE who developed the condition model based on GRAID data. This is covered in Section 4.7. All the inspections that occurred on site were recorded, at which point an additional benefit was derived during the project. Up until this point there had never been footage of the inside of the transmission network during 'live' conditions and so witnessing a ball valve operate in this way was another first provided by Project GRAID. By speeding up the footage of a valve operation, Engineers at National Grid can understand how well the valve is working. For example, if the seat of the valve is seen not to engage when the valve operates this could mean that any future repair work on the valve will be ineffective and the valve should be replaced. As expected the footage of inside the network provided a large amount of discussion both internally and externally within the gas industry.

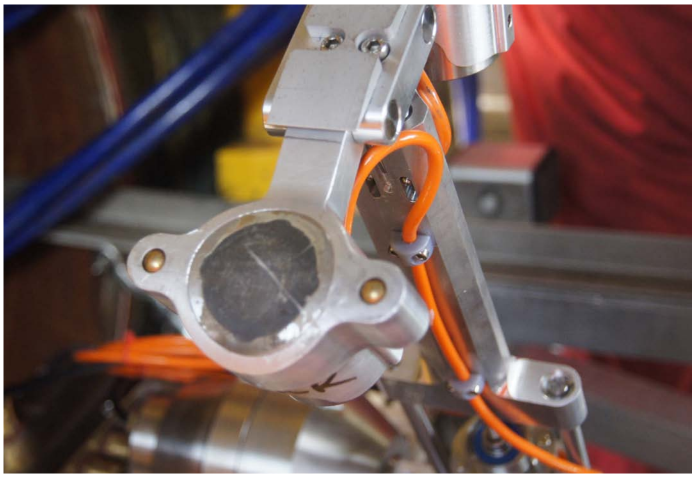
4.5.3 Enhanced NDT

Through discussions with Ofgem it was decided that the benefit from carrying out a third 'live' trial was outweighed by carrying out an enhanced period of testing with the EMAT sensors. The online trial at Pannal and the planned inspection at Bacton would provide lessons in launching GRAID on a gas site but the chance of finding reduced wall thicknesses was slim. Instead it was agreed that the EMAT sensors would be removed from GRAID and a study of how they would react to actual corrosion was completed. The tests were carried out by first applying a grid across a variety of machined and actual corrosion areas, allowing the team to understand exactly how corrosion affects the readings from the EMAT sensors. In collaboration between Synthotech, PIE and National Grid the Enhanced NDT work was completed during July 2018 at the DNV-GL Research and Test Centre at RAF Spadeadam. The scope of works was agreed by all parties and included:

- Check all sensors with calibration blocks.
  - See if the sensors all measure the same thickness accurately or if there are manufacturing tolerances to consider.
- Scan 12 known machined defects in pipe samples.
  - Using known defect sizes and depths, can the system measure accurately?
- Understand the effect of Roll and Yaw on the sensors.
  - Using a specially designed jig measure the effect robot misalignment has on the sensor.
- Measure known defects.
- Take known samples and measure known defects to understand the effect of 'real world' corrosion.

Significantly the Enhanced NDT stage looked at the repeatability of the data provided by the sensors which can be hard to prove from inside the gas pipe, this was vital to National Grid especially if an area of interest is highlighted on a site and is regularly inspected for monitoring purposes. To complete this work, a stand-alone system was designed and developed allowing the software and hardware for the EMAT sensors to work, whilst being removed from the overall GRAID platform. The outputs from the experiment were compared to the same readings taken from an industry standard ultrasonic probe and in summary the EMAT sensors performed well compared to the external method. It should be noted there were some challenges with readings from areas of smaller dimension pitting and an element of scattering on curved defects. Synthotech were however able to learn from this and understand the results, so that going forward if this pattern was observed in a 'live' site it could be assumed that there was an area of concern to investigate further.

An example of the images returned to the operator during the 'live' trials. This picture was taken at 55 bar(g).



The sensors were all checked.

Bacton Terminal.

The Project GRAID installation at Bacton Terminal.

4.5.4 Online trial – Bacton Terminal

Carrying out an inspection of the pipework at Bacton Terminal has been a significant milestone for the GRAID team from the very beginning. The high importance of the site coupled with the age and use of the asset meant that gaining actual wall thickness readings via the GRAID robot would be of huge benefit. It would also display the confidence National Grid has in the platform and the processes surrounding GRAID that we could bring a robot into the 'live' pipework at a site like Bacton. Bacton Terminal is located on the east coast of England, is the second largest AGI on the NTS and was originally commissioned in 1968. The terminal receives gas from the North Sea production facilities via Perenco and Shell, with Perenco having two incoming pipelines and Shell having four. All the streams are similar and consist of the following: filtration, gas analysis, pre-heat, flow control and connections into a manifold area. Additionally, from offshore, the terminal also receives gas via the Balgzand – Bation Leidung (BBL) connection which supplies gas from Balgzand in the Netherlands. These incoming sources of gas are then distributed to the UK via several onshore feeders. Within the terminal is a separate asset owned by UK Interconnector, which imports and exports gas to and from Belgium.

For a site of this magnitude there were several GRAID connection points possible and so Premtech were appointed to carry out a Robot Inspection Route report to analyse and compare the various options. The selection of the route considered the age of pipework, the condition of the pipework, the material it was built in, how it has been coated and finally the coverage and reliability of the cathodic protection. With these variables, the potential distance the robot could cover and the logistics of installation within the Bacton site, a connection point was decided on in the north east of site around the Shell incomers. The location provided access from the roadside, had the necessary space to install a new swan neck and 36" Cameron ball valve and importantly allowed GRAID to travel 100m through important pipework that was installed when Bacton was first commissioned. A permanent concrete pad was installed along with the required pipework to allow the GRAID launch vessel to be fitted.

4.5.5 HAZOP review

To assist the shift team in understanding what GRAID was and answer any questions, a Hazard and Operability (HAZOP) review was carried out on the GRAID installation and removal process. This was received well and no serious concerns were raised ahead of the survey. An output from the HAZOP was a question around the amount of times the launch vessel would be vented during the inspection and that it should be reduced as much as possible. This would not only save time on site but also have an environmental benefit too. To facilitate this a 24-hour pressure test was required outside of the Bacton Terminal to ensure the robot was capable of operating after being left in a pressurised environment for a prolonged period. This was completed at the test bund in the PMC depot at Ambergate, the test was successful meaning that GRAID could be left at pressure, leading to a significant saving of time and effort for the team.

Completed a
24-hour
pressure test

This was required outside of the Bacton Terminal to ensure the robot was capable of operating after being left in a pressurised environment for a prolonged period.

The EMAT testing sensors were used along the route, taking wall thickness readings in areas of interest.

Following sign off of the internal procedures the team were allowed to begin the inspection and were onsite for a two-week window which occurred during August 2018. For the first few days of inspection the team travelled the full 100m length of the tether, mapping out all the weld locations and planning the areas of interest. They were also able to locate a previously buried asset which can be used for future repair works to an onsite valve. By doing this the amount of trial holes and excavation will be reduced, helping to save time and money. The National Grid Operations team at Bacton were very engaged throughout the inspection and requested that the GRAID robot video record the operation of many of the valves on the route. This helped the team understand the condition of these valves under operation and the footage can be used for future valve remediation exercises. The EMAT testing sensors were used along the route, taking wall thickness readings in areas of interest. This data was then input into the revised software which compared the results to the expected values in a quick and easy viewer.

The new software package allows the operator to see if a collected data point is significantly below what it should be and if it is, more detailed scans can be completed before GRAID moves away from that area. Detailed analysis of the data is completed in the data modelling stages and is covered in Section 4.7, but onsite it is key to be able to take more readings in an area of interest as soon as it is discovered. The Bacton inspection was concluded with a demonstration event attended by the major Gas Distribution companies and Perenco, all parties provided positive feedback on the event.

4.5.6 Cleaning

One of the project unknowns from the very beginning was the condition of the inside of AGI pipework. The Subject Matter Experts Consultation Group set up by Synthotech carried out some research in this area and the robot was driven through in a variety of materials during testing. The team also took information from the In-Line Inspection (ILI) colleagues at National Grid as they are familiar with the materials cleaned out of the pipes between sites. Ultimately though, this was the first time anyone had driven a vehicle on the inside of a site transmission pipe and so there was an element of the unknown. To comply with the National Grid environmental regulations, each time the GRAID robot was removed from the launch vessel it would need to be cleaned so that any harmful materials were removed, specifically Normally Occurring Radioactive Material (NORM). To help in this area Pressure Force were contacted who work extensively with National Grid on cleaning the PIGs once they are removed from the pipework. To clean GRAID a simple pressure hose was used with hot water and light degreasing chemicals, the chemical composition of which was checked with the materials used on the robot, especially the rubber seals. The pressure hose could also be regulated so that no damage was caused to the robot. Pressure Force were also able to use their existing bunds which keep the wastewater contained with side panels to prevent any

The GRAID cleaning bund setup.

Drone surveying procedure.

spray leaving the bund. Whilst similar to their usual work, the GRAID robot and UMS are very different to a PIG and so several site visits were carried out along with a demonstration at RAF Spadeadam. With knowledge from these trials the following unique items were designed and built by Pressure Force:

- An elevated ramp which allowed the robot to be driven off the transportation trolley onto a non-magnetic platform with a jack in the centre. This allowed the robot to be lifted slightly so the cleaning jet could be angled under the tracks and the material removed from this hard to reach area.
- A tether cleaning device was required as the entire 100m would need to be cleaned each time the UMS and tether drum was removed. To complete this a tray was designed with sponges and the ability to connect the pressure hose allowing jets to clean the tether as it was pulled through. Once pulled through the tether could be spooled alongside the bund as it was no longer contaminated. The tether was then pulled back through the cleaning tray to clean any dirt or debris off before it was fed back onto the cable drum.

Both pieces of equipment were very successful and further developed from the first 'live' trial before being used at Bacton. Once the clean was complete the wastewater was taken out of the bund and stored in a tank before being collected by a registered disposal company for this type of waste. Geiger counters were used after the clean to test how well the NORM was removed with positive results allowing the GRAID robot to be either removed from site or worked on by the Synthotech team.

4.6 Documentation

During the four-year Project GRAID programme of works, several key documents were amended and created alongside the required Ofgem progress reports as outlined in the guidance for an NIC project.

4.6.1 Collection, modelling and design suite

One of the outputs from Premtech was to develop a suite of documents detailing the procedures that were followed to collect data regarding a potential GRAID connection point, model that information and recommend a method of connecting the launch vessel. The documents within the suite covered (see flow diagram below):

Gathering as-built drawings – Currently the only way of accurately confirming the exact position of below ground pipework is by excavation. By using detailed site drawings, a Level of Certainty (LOC) can be assumed for the below ground pipework. This procedure sets out where the drawings are located within National Grid, the types of drawings available, collating them and then highlighting any shortfalls which will need to be addressed.

Site surveying procedure – To address any shortfalls and verify the as-built drawings a laser scan of the site is required. Laser scanning is a non-destructive, non-contact technology that digitally captures the shape of physical objects using lasers. Laser scanning requires a high accuracy scanner mounted

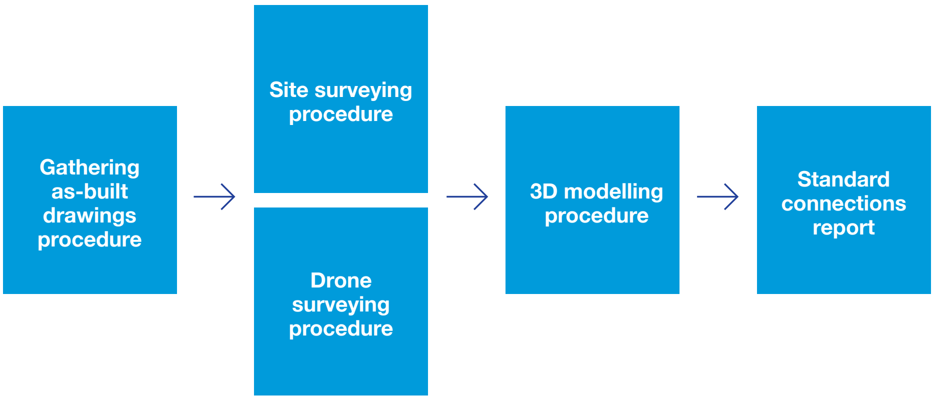


Figure 3 – Data collection, modelling and design process.

to a fixed surveyor's tripod. The scanner rotates at very high speeds while a laser delivers a reflecting beam with high precision at physical objects, potentially recording up to one million points per second. Laser scanning can measure fine details of free form shapes and can produce very precise point clouds. Laser scanning is ideal for the inspection and measurement of contoured surfaces and complex geometries that would require huge amounts of physical data to be described accurately.

Drone surveying procedure – During the GRAID project drone technology was developed further by Premtech and by the time the first Online trial at Pannal Offtake was underway this technology could be utilised. Drones can be used to capture 4K video footage and high-resolution photographs quickly and efficiently over large areas which if undertaken by traditional methods would be very time consuming.

Once video footage and photographs have been successfully obtained, it is possible to create a point cloud representation of an area or site using photogrammetry. Photogrammetry is defined as the use of photography in surveying and mapping to ascertain measurements between objects. In this context photogrammetry involves capturing multiple overlapping photographs. From these, along with measurements taken onsite, a 3D point cloud representation of the site can be produced allowing accurate measurements between objects. Using drones for surveying can speed up the entire process from a full week of work for a large site to a matter of hours.

3D model procedure – This procedure covered creating accurate 3D models of the existing National Grid assets using a combination of existing site drawings and records combined with point cloud data from laser scan surveys. AutoCAD software was used to create the 3D models allowing a digital view of a GRAID connection point and gave the teams at National Grid the ability to visualise what the launch vessel would look like attached to the NTS. This 'digital rehearsal' of the proposed works meant that any issues during construction could be designed out in the early stages to prevent expensive delays. Taking this a stage further the 3D models can be viewed using the latest virtual reality headsets such as Oculus Rift to gain a realistic view of the site.

Standard Connections Report – This design report describes the potential methods of providing a connection for launching the Project GRAID robotic platform within new or existing AGIs and contains typical design drawings of standard connections that could be incorporated into the design of a new or existing AGI to allow future robotic inspection. The preferred method of launching the robot is through an existing connection or by removing a piece of equipment (filters, meters, heat exchangers and pipework spool pieces) and returning it once the launch vessel is removed, however if this is not possible then the pipework arrangement within the AGI will require modification. Mechanical, civil and construction aspects are all considered in the report alongside the health & safety precautions that should be maintained throughout. The report was also written to apply to all the relevant National Grid policies and procedures so that a connection would be approved if designed using the outlined recommendations.

4.6.2 Carbon footprinting

Following the successful inspections at both Pannal Offtake and Bacton Terminal, Premtech were able to carry out the analysis to provide a carbon comparison for carrying out a GRAID inspection versus traditional methods. For both sites, independently, the team could use the National Grid Carbon Interface Tool (CIT) to compare the carbon costs for the following options:

- Installing a GRAID connection allowing for the routine inspection of below ground pipework without the need for excavation.
- Excavation of the pipework using a battered excavation to allow access to the pipes for inspection.
- Excavation of the pipework using a boxed excavation to allow access to the pipes for inspection.
- Replace all the existing pipework and valves with new pipework with a design life of 40 years.

From a capital carbon footprint point of view the replacement option has by far the largest impact as this not only includes the installation of the pipework but the manufacture of it too. Using capital carbon both Project GRAID and boxed excavations have similar capital carbon footprints with the battered versions being slightly more. What this comparison doesn't show is how each option affects the equivalent annual carbon footprint associated with each option. If the assumption is taken that a section of pipework is inspected every five years which is similar to many of the in-line inspection frequencies for the pipelines, then the equivalent annual carbon emissions over a 40-year design life is considerably different.

In comparison, Project GRAID has the lowest annual carbon emissions over 40 years due to the lack of excavation required. It should also be noted that this is only one variable when comparing excavation works onsite and doesn't include outage or health and safety benefits.

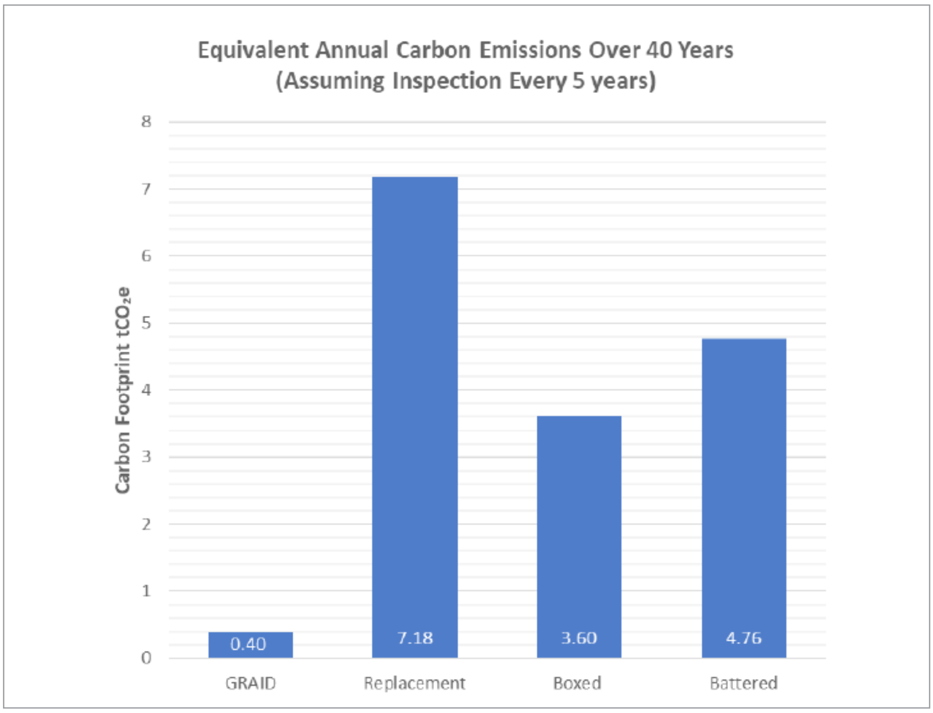


Figure 4 – Equivalent annual carbon footprint for inspection every five years. It should be noted that the full report summarised the rationale behind repeating a survey every five years. Whilst National Grid does not survey its un-piggable pipework every five years, the assumption is in line with the frequency some of the NTS pipelines are inspected with In-Line Inspection PIGs.

4.6.3 Existing and new National Grid documentation

A large quantity of documentation has been produced by the Project GRAID team throughout the project, and includes operating procedures for using the robotic platform. These documents were drafted during the offline trials and were periodically checked, used onsite, updated and re-published. Prior to the online trials starting a Safety Critical Task Analysis (SCTA) was created which covered all the tasks in the operating procedures but specifically highlighted those which have a critical safety aspect. Measures were then put in place to ensure that competent staff carried out the role and that all prior steps were complete. Handovers between different teams and personnel were also highlighted in the document to ensure this was carried out correctly and there was a clear ownership of tasks within the team. As a result of this, when the online trials began the SCTA could be used and updated if required so that following closure of the project the document had been through several iterations and is suitable for use onsite. During mobilisation and before the GRAID robot is used again the SCTA will be reviewed and checked, making any amendments before it is followed onsite.

For a complex task, such as providing a GRAID robotic inspection onsite the team developed a process flow diagram that aims to define the high level steps that need to be followed. This process starts with the inception of an idea for a GRAID connection and ends with the close out documentation and demobilisation from site. National Grid has documented many of its processes in the form of a flow diagram and so copying this format will help to incorporate GRAID into the wider systems in place at National Grid. A copy of the combined high level processes is attached to this report (Appendix F); however, a broad overview can be seen below:

Alongside all the new documents being created as part of Project GRAID there have been several existing documents highlighted that could be amended to include the use of the robotic platform. In collaboration with the Internal Policy team and following several discussions the following list was compiled:

Policy Ref	Document Name	Comments
T/PM/PS/3	Management Procedure for Ensuring Compliance with the Pressure Systems Safety Regulations 2000.	Include the GRAID launch vessel and closure mechanism.
T/SP/E/56	Specifications for Ancillary Pipeline Equipment.	Include the GRAID robotic platform.
T/PM/NDT/1	Management Procedure for Carrying Out Non-Destructive Testing.	Incorporate inspections via the GRAID robot.
T/PM/MAINT/5	Management Procedure for Maintenance Activities of Pipeline Equipment Operating Over 7 bar(g).	Incorporate inspections via the GRAID robot.
T/PM/IGEM/TD/1	The Application of IGEM/TD/1 (Steel Pipelines and the Associated Installations for High-Pressure Gas Transmission) by National Grid Gas.	Include robotic inspection capability when building a new site.
T/PM/IGEM/TD/13	The Application of IGEM/TD/13 Edition 2 (Pressure Regulating Installations for Transmission and Distribution Systems for Natural Gas) by National Grid.	

Table 5 – Existing documents which could be amended to include reference to the GRAID robotic platform.

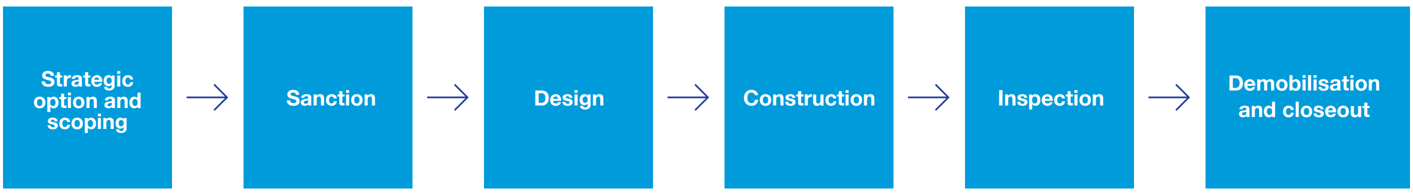


Figure 5 - Simplified GRAID process flow.

It was deemed that the On-Line Inspection or 'OLI' suite of Management Procedures would be the ideal place to store the GRAID procedure documents and as such a new document has been written to feed into this suite. For all the other amendments listed in Table 1 the relevant authors have been identified and notification has been given that a change is required. As per the process for National Grid policy changes these amendments are logged against each document and when it is updated all the changes will be made. This work will continue following the end of the NIC project and towards the next RIIO price control period. It will also be a part of much wider discussions around the policy of in-line inspection within the business.

4.7 Data Model

The complete report, detailing the condition model results and how it was calculated from Pipeline Integrity Engineers (PIE) is included in the Appendices of this report. A summary of the output is provided below:

4.7.1 Corrosion

The condition model developed by PIE aims to utilise any available data sources (including data from the GRAID robot) to present a view of the AGI site in terms of corrosion. Corrosion occurs when two different components (or two regions on the same component) are in electrical contact with each other, immersed in the same electrolyte and there is a difference in electrical potential between them. In examples of buried pipework, the soil acts as the electrolyte whereas for above ground pipework the electrolyte is water present in the atmosphere or trapped against the pipe surface. To defend against corrosion several methods are employed across the pipework owned by National Grid. In both above and below ground cases, the external coating acts as the primary defence against corrosion. For below ground only an additional method known as Cathodic Protection (CP) is used. CP cannot be used above ground due to air being a poor electrical conductor preventing an electrochemical cell forming. Corrosion can however still occur on an AGI with the major causes below ground being:

- Under protection – ineffective CP system due to lack of maintenance, inaccurate monitoring or system interruption.
- CP shielding – when pipe coating lifts away allowing water and/or soil to penetrate and prevent the CP from operating correctly.
- Stray current – uncontrolled current flow from such things as parallel overhead electricity lines or from other systems such as nearby train or metro lines.

Above ground, the lack of CP means that any damage to the external coating which is not repaired can lead to the development of corrosion. AGIs can also contain several potentially aggressive corrosion environments. These environments include areas where the pipework transitions from above to below ground, pit wall transitions, lagging and pipe supports. Each of these areas are classed as aggressive corrosion environments due to the increased potential for water to breach the coating and facilitate corrosion, and in many cases, are in inaccessible inspection areas.

4.7.2 Methodology

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:

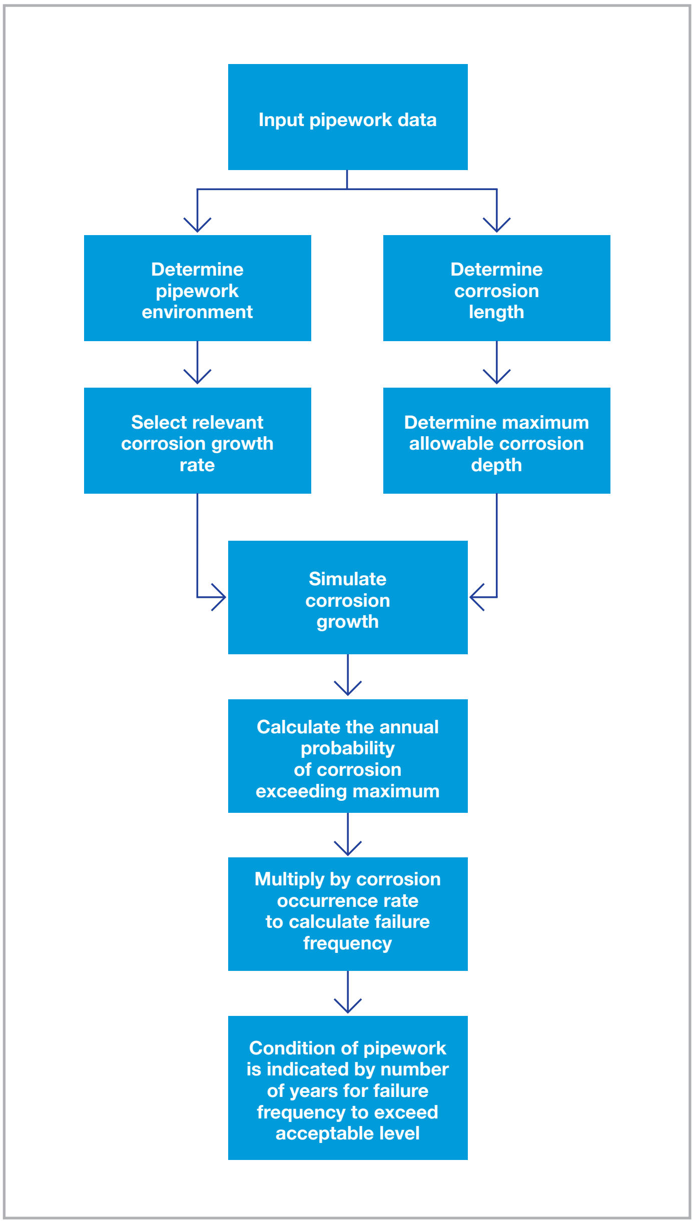


Figure 6 – Probabilistic corrosion growth model for calculating pipeline inspection interval.

In summary, the model is constructed using the following variables:

Maximum allowable corrosion depth

Utilising the National Grid standard for the assessment for metal loss due to corrosion: 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 two bar(g), a corrosion depth has been selected. In this document, corrosion is classed on a scale from "Superficial damage" to "Extreme Damage". Corrosion is assigned a category based on its type and its dimensions, both length and depth.

Corrosion environments and probability distributions

For any given AGI there could be several different corrosion environments both above and below ground, for example below ground pipework with working CP, below ground pipework with poor costing or above ground pipework at a pipe support to name a few. For each of these a corrosion growth rate distribution is required. For below ground pipework this distribution is calculated using the in-line inspection data from the inlet and outlet pipelines, as it is assumed these were commissioned at the same time as the AGI pipework and have been exposed to a similar environment. For above ground corrosion, growth rates can be derived from repair data made to AGI pipework, however this is uncommon and so published corrosion growth data, the distributions for below ground pipework and a number of assumptions may instead be used. A different growth rate has been assumed for areas of aggressive corrosion such as pit wall transitions and pipe supports. Again this is either calculated from available data or assumptions but considers the aggressive environment.

Corrosion length distribution

The above probability distributions solely focus corrosion growth in terms of depth and so as P/11 requires an axial length variable for classification, this must also be determined. This distribution was calculated using the in-line inspection data from the inlet and outlet pipelines.

Corrosion occurrence rate

The corrosion occurrence rate is the number of corrosion defects expected to occur per year. Again this is derived from the in-line inspection data and is multiplied by the probability of failure of a single corrosion defect in any given region of pipework to give a failure frequency per year.

Acceptable failure frequency limit

This limit has been set based on guidance from various standards and provides a limit for the failure frequency on a given AGI.

The probabilistic corrosion growth model uses a Monte Carlo method to simulate corrosion growth within the pipework and calculate the probability of failure. This method is also used within the Intervals 2 software ILI calculations. In summary, the model predicts the annual expected number of corrosion defects within the pipework joint exceeding the maximum allowable depth per square metre.

4.7.3 Results from the online trial locations

As detailed in Section 4.5 the first online trial was carried out at Pannal Offtake where the inspection occurred for two weeks. As part of this survey more than a thousand wall thickness measurements were taken and no metal loss defect occurrences were found. During and subsequently from this inspection the team at PIE could begin working on the condition model by analysing the existing data sources supplied from National Grid from the in-line inspection runs for the inlet and outlet pipelines. Additional sources included a stress analysis of the pipework near the inspection site and the CP data available. With reference to the corrosion environments, four were selected based on the data:

- 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.

By applying the methodology discussed fully in the PIE report and summarised above the team could generate results for the number of years it would take to exceed the acceptable failure frequency for the given pipework types at Pannal AGI. Overall the results were as expected, showing that areas of aggressive corrosion such as pipe supports were the first areas to cross the failure frequency limit followed by the transition areas between above and below ground pipework. This was deemed to be around the 40-50 years after commissioning mark. The remaining regions continue to rise culminating with the above ground pipework

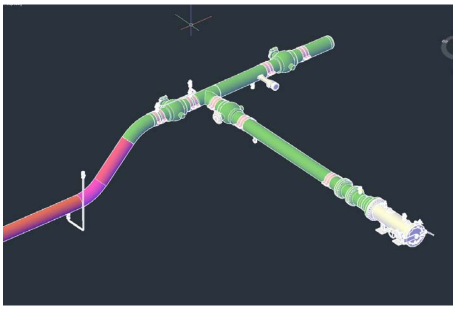


Figure 7 – Pannal AGI pipework with PIE GRAID model condition colour-coding example.

not breaching the limit during the 200 year simulation due to the rural nature of Pannal AGI showing negligible corrosion. This data was then supplied to Premtech who applied the data to the 3D model of Pannal AGI and produced 'heat maps' to visualise what the site looks like; an example is provided here.

Following the inspection at Bacton Terminal the team at PIE could summarise the main differences between the outputs from Pannal AGI. Due to several assumptions including the location of Bacton near to the coast and the amount of small diameter pipework it concluded that corrosion is likely to happen quicker at Bacton AGI than Pannal. This would need further analysis to confirm using all available inlet and outlet data from the pipelines along with data gathered from the Bacton AGI site itself.

4.8 Technology Readiness Level

As with any innovation project the Technology Readiness Level or TRL is defined at the start and the hope is that it increases as the project progresses. For a project such as GRAID the TRL has moved from a 4 – small scale prototype built in a laboratory environment to a 7 – demonstration system operating in an operational environment at pre-commercial scale. This can be seen by the Online trials carried out by the GRAID team on 'live' National Grid Above Ground Installations.

GRAID's Technology Readiness Level (TRL) has moved from a

4 to a 7

Section 5
Performance compared to the original project aims, objectives and SDRC/project deliverables

A summary of how each of the original Successful Delivery Reward Criteria (SDRC) have been met throughout Project GRAID including the title of the relevant document to provide the evidence.

Project GRAID had four key objectives from the original proposal stage:

1. To accurately and reliably determine the condition of high-pressure below ground pipework at AGIs using an internal inspection robot.
2. To generate a proactive, rather than reactive, risk based approach to the management and maintenance of ageing assets.
3. Minimise the occurrence of annual unnecessary excavations and eradicate premature replacement of assets.
4. Minimise the likelihood of asset failure through proactive asset management.

Through the process of completing the project the first two objectives have been met with the evidence presented in the SDRC tables below. Objectives 3 and 4 will be met through the onwards use of the GRAID robot which has been planned into the future asset health budgets within National Grid.

Onsite during the first 'live' trial at Pannal Offtake.

Successful Delivery Reward Criterion 9.1 – Solution Development, completed by 30/10/15

- 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 two bends taking visual readings and wall thickness measurements in buried pipework of up to 100 bar(g) pressure.

Ser	Activity	Outputs	Evidence
1	**Project Concept Study**	Review quality, environmental and/or product safety objectives. Review statutory and regulatory requirements. Complete detailed market information. Develop design requirements and specifications. Develop cost benefit analysis/life cycle costs/payback. Prepare initial drawings/rapid prototypes. Identify resource requirements for Alpha testing phase. Develop detailed plan for Alpha testing phase. Review and identify published reference material. Prepare, review and submit concept report.	Synthotech Concept & Methodologies Report dated 27 February 2015.
2	**Alpha Robot Development**	Prepare and issue project specification. Produce development sheets and development sheet index. Design review.	Synthotech Alpha Specification Report dated 13 April 2015.
		Generate Bill of Materials (BoM) and drawings. Manufacture Alpha prototype. Build Alpha prototype. Produce Alpha prototype build report.	Synthotech Alpha Phase Intermediary Report dated 20 July 2015.
		Produce test reports including failure mode effect analysis (FMEA), environmental, drop testing, ergonomic, etc. Review quality, environmental and/or product safety objectives. Review statutory and regulatory requirements. Produce R&D analysis.	Synthotech Alpha Phase Stage Report (Annex C to GRAID PPR2).
3	**Concept and Methodology Documents**	Prepare and issue initial Basis of Design Document (BoDD).	**Premtech publications:** PREM128-REP-0000-0014. PREM128-REP-0000-0015.
		Prepare and issue concept and methodology docs.	**Premtech publication:** PREM128-REP-0000-0012.
		Prepare and issue initial Design and Coordination Registers. To include Design Assumptions Register (DAR), Lessons Learnt Register and Holds and Decisions Register.	**Premtech publication:** PREM128-REG-0000-0003. PREM128-REG-0000-0005.

Ser	Activity	Outputs	Evidence
4	**Records and Surveys**	Complete as-built record gathering and reports for three site locations.	**Premtech publications:** PREM128-REP-1211-0035. PREM128-REP-7260-0036. PREM128-REP-3917-0037.
		Complete site survey – Site 1 (Bacton). Complete site survey – Site 2 (Wormington). Complete site survey – Site 3 (Tirley).	Point Cloud Outputs are on Premtech's secure server and can only be viewed using specialised software.
5	**Site Modelling**	Complete 3D pipework models – Site 1 (Bacton). Complete 3D pipework models – Site 2 (Wormington). Complete 3D pipework models – Site 3 (Tirley).	Drawing packs are confidential and stored on Premtech's secure server. Issued when required.
6	**Robot Test Facility Concept Design**	Site visit/survey.	**Premtech publication:** PREM128-PLN-0000-0020.
		Engineering Line Diagrams (ELD).	**Premtech publication:** PREM128-ELD-0000-0002.
		Location plans.	**Premtech publication:** PREM128-PLN-0000-0003.
		General arrangement drawings.	**Premtech publication:** PREM128-GEN-0000-0004.
		3D model and drawings.	**Premtech publications:** PREM128-ISO-0000-0005. PREM128-MIS-0000-0006. PREM128-MIS-0000-0007.
		Material Take Off (MTO).	**Premtech publication:** PREM128-MTO-0000-0008.
		Complete and issue conceptual design report for robot offline trial/testing facility design report.	**Premtech publication:** PREM128-REP-0000-0019.
7	**Robot Insertion and Extraction Device Design**	Develop drawings.	**Premtech drawings:** PREM128-MIS-0000-0001. PREM128-MIS-0000-0021.
		Produce detailed drawings.	**Premtech drawings:** PREM128-MIS-0000-0026. PREM128-MIS-0000-0027. Also, see drawing supplied by RMA.
		Conceptual design report.	**Premtech publication:** PREM128-REP-0000-0052.
8	**Replacement Asset Carbon Footprint**	Bacton carbon footprint report. Wormington carbon footprint report. Tirley carbon footprint report.	**Premtech publication:** PREM128-REP-0000-0051.

Successful Delivery Reward Criterion 9.2 – Development Testing, completed by 09/09/16

- Robot access and inspection routes for all three trial sites developed 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 to test and further develop robotic design and meet the objectives of withstanding pressure of up to 100 bar(g) 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 100 bar(g) and minimise venting (moved to 9.3).

Ser	Activity	Outputs	Evidence
1	**Beta Robot Development – Overall Design Control Phase 1**	Scope and specification check. Budget control and resource. System architecture drawing. Design review.	Synthotech Beta Phase Stage Gate 1 dated 15 March 2016.
	Beta Robot Development – Overall Design Control Phase 2	Integration of all work packages. Test schedule. Final assembly control. Test report collation. SDRC delivery compliance. Full system testing of the robot in a short pipe. Final design review and build reports. Design for Manufacture reviews (DFM). Implement build modifications following DFM. Demonstration day of the robot.	Synthotech Beta Phase End Stage Report dated 7 September 2016.
2	**Beta Robot Development – Operator Control Systems Phase 1**	Control systems review and architecture plan. Control centre user interface mechanical design. Control centre user interface. Signal locator. Failure mode identification system (warnings and alarms).	Synthotech Beta Phase Stage Gate 1 dated 15 March 2016.
	Beta Robot Development – Operator Control Systems Phase 2	Control system for robot. Control system hardware. Control system software. Control system for UMS. Cable routing and management Slip rings for rotational parts. Plugs and cable connectors. Design review. Part procurement. Bill of Materials generation. Robot circuit assembly. Control centre assembly. Final assembly. Individual system tests. Full control tests on the robot.	Synthotech Beta Phase End Stage Report dated 7 September 2016.

Ser	Activity	Outputs	Evidence
3	**Beta Robot Development – Umbilical Management System Phase 1**	Stakeholder engagement plan. Management of design requirements with RMA/Premtech. Calculations for power requirements. Design of cable drum. Design of link to outside recovery handle. Design of tray loading system. Quarterly technology tracker update. Quarterly review of university research papers. Quarterly patent tracker update. Quarterly standards and regulations tracker update. Design of cable pay out system. Design of cable rotation system. Design of cable systems. Through wall connector. Control system for control of motors. Design review. Cable harness/slip rings. Design of connection plug to the robot.	Synthotech Beta Phase Stage Gate 1 dated 15 March 2016.
4	**Beta Robot Development – Umbilical Management System Phase 2**	Bill of Materials generation. Part procurement. Support the production of G35 and related documentation. UMS assembly. Review and challenge operating procedures and method statements. Camera integration. Electrical wiring. Quarterly technology tracker update. Quarterly review of university research papers. Quarterly patent tracker update. Stakeholder engagement plan review. Final assembly. Spool in and out test. Electrical conductivity test. Robot plug pull test. Recovery mode test. Camera vision test.	Synthotech Beta Phase End Stage Report dated 7 September 2016.
5	**Beta Robot Development – Robotic Inspection Device Phase 1**	Vision systems. Drive systems. Non-destructive testing. Secondary sensors.	Synthotech Beta Phase Stage Gate 1 dated 15 March 2016.

Ser	Activity	Outputs	Evidence
6	**Beta Robot Development – Robotic Inspection Device Phase 2**	Vision systems. Drive systems. Non-destructive testing. Secondary sensors.	Synthotech Beta Phase End Stage Report dated 7 September 2016.
7	**Standard connections drawings and report**	Under pressure connection drawings. Shut down connection drawings. Working area requirements. Opportunities and constraints matrix. Generic Risk Register (RR). Costings. C&R meeting. Report.	**Premtech publication:** PREM128-REP-0000-0206.
8	**Robot insertion and extraction points report and drawings – Bacton**	Connection option drawings – GA's. Working area drawing. Generic RR. Launch site screening meeting. Report.	**Premtech publication:** PREM128-REP-1211-0210.
9	**Robot insertion and extraction points report and drawings – Wormington**	Connection option drawings – GA's. Working area drawing. Generic RR. Launch site screening meeting. Report.	**Premtech publication:** PREM128-REP-7260-0214.
10	**Robot insertion and extraction points report and drawings – Tirley**	Connection option drawings – GA's. Working area drawing. Generic RR. Launch site screening meeting. Report.	**Premtech publication:** PREM128-REP-4629-0212.
11	**Robot inspection route drawings and reports – Bacton**	Go/not go drawings. Areas of interest. Offsite trials matching. Launch site screening meeting. Report.	**Premtech publication:** PREM128-REP-1211-0225.

Ser	Activity	Outputs	Evidence
12	**Robot inspection route drawings and reports – Wormington**	Go/not go drawings. Areas of interest. Offsite trials matching. Launch site screening meeting. Report.	**Premtech publication:** PREM128-REP-7260-0226.
13	**Robot inspection route drawings and reports – Tirley**	Go/not go drawings. Areas of interest. Offsite trials matching. Launch site screening meeting. Report.	**Premtech publication:** PREM128-REP-4629-0227.
14	**Connection point – cost benefit analysis – Bacton, Tirley and Wormington**	Launch connection drawings. Launch connection MTO. G/19 or G/35 Assessment. Process Safety Assessment. Environmental Assessment. Operational Risk Assessment. Costings. Launch site selection meeting. Report. Site visits. Go/not go drawings. Site laser scans. Site connection drawings. Offsite trials matching. Generic RR. FPSA formulation. Costings. Report.	**Premtech publications:** PREM128-REP-0000-0228.

Successful Delivery Reward Criterion 9.3 – Successful Offline Trials, completed by 31/10/17

- Launch and retrieval device manufactured to withstand pressure of 100 bar(g) and minimise venting (passed from 9.2).
- 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 (moved to 9.4).

Ser	Activity	Outputs	Evidence
a	**Launch and retrieval device**	RMA Project GRAID launch vessel factory acceptance test document.	Project GRAID Launch Vessel FAT documents.pdf.
		Photo of the RMA launch vessel at the DNV-GL research facility, RAF Spadeadam.	Project GRAID Offline Test Rig at DNV-GL Test Facility.jpg.
		Hydrostatic overpressure test certificate following transportation to the DNV-GL research facility, RAF Spadeadam.	Project GRAID Launch Vessel Pressure Test Cert.pdf.
		Premtech report on the Project GRAID launch vessel.	Premtech – GRAID – Ofgem – Launch & Receive Vessel.docx.
b	**Offline test rig**	DNV-GL 9.3 Report.	Offline Test Rig Manufacture Report.pdf.
c	**A minimum of 10 offline tests**	Project GRAID SDRC 9.3 offline testing evidence.pdf.	Project GRAID SDRC 9.3 offline testing evidence.pdf. Evidence of collecting wall thickness measurements at pressure will be presented in the SDRC 9.4 gate report.
d	**Disaster Recovery Plan**	G01-PRO-005 – Project GRAID Live Site Disaster Recovery Plan.	G01-PRO-005 - Project GRAID Disaster Recovery Plan.pdf.
e	**Data collection in response to test scenarios**	As agreed this criterion will be delivered within the 9.4 – online trial stage gate.	N/A.

Successful Delivery Reward Criterion 9.4 – Successful Online Trials, completed by 06/07/18

- Successful data collection/problem identification by robotic platform in response to test scenarios.
- 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 100 bar(g) pressure, travel 100m, conduct visual inspection and wall thickness measurements – a minimum of three online tests per site will take place.

Ser	Activity	Outputs	Evidence
a	**Data collection in response to test scenarios**	A sample of survey data has been provided, however over 1,000 data points were collected at Pannal.	GRAID Synthotech G01-NGGT-R-0010 Supporting Information (WWL Data.pdf).
b	**Successful insertion of launch and retrieval device into all three live sites**	At the time of this report only one 'live' site has been carried out with one more planned for late August and a period of Enhanced NDT work to cover the third 'live' site.	GRAID Synthotech G01-NGGT-R-0010 Rev 0.4 9.3 report.
		In order to facilitate the Online trial connections, Premtech Limited were instructed to design and plan the required works, alongside the additional Stage 3 activities.	GRAID Premtech PREM128-REP-0000-0302 Rev 03-160718.
c	**Undertake testing to deliver a functional robotic platform**	An extensive period of Acceptance Testing was undertaken offline which gave National Grid the confidence that the GRAID robotic platform was fit for purpose.	GRAID Synthotech G01-NGGT-R-0010 Supporting Information (Offline Testing Sign Off Documentation.pdf).

Successful Delivery Reward Criterion 9.5 – Delta Prototype, completed by 03/09/18

- Successfully complete testing to deliver a functional robotic platform to work in 100 bar(g) 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 100 bar(g) pressure, travel 100m and negotiate two bends, providing condition assessment data – a minimum of three online tests.

Ser	Activity	Outputs	Evidence
a	**Successfully complete testing to deliver a functional robotic platform to work in 100 bar(g) pressure**	The Delta stage of Project GRAID was designed to respond to the lessons learnt during the online testing that the robot has completed. Following, and in some cases between the trials, several improvements were made to the GRAID platform and are detailed in full in the Synthotech report for Stage 4.	GRAID Synthotech G01-NGGT-R-0011 Rev 1 report.pdf.
b	**Travel 100m and negotiate two bends, providing condition assessment data – a minimum of three online tests**		

Successful Delivery Reward Criterion 9.6 – Data Analysis Systems in place, completed by 06/07/18

- 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.

Ser	Activity	Outputs	Evidence
a	**Analysis of data collected by PIE**	The first condition model using both existing data from the Pannal AGI site and the collected data from the GRAID robot is being developed by PIE. A report on the progress of this data analysis has been provided here.	GRAID PIE SDRC Report July 2018 ver1.0.pdf.
b	**Condition assessment algorithms derived by PIE**		
c	**Site condition has been developed**		
d	**Condition assessment criteria for high-pressure installations has been established**		

Successful Delivery Reward Criterion 9.7 – Completion of Data Analysis, completed by 03/09/18

- Review of all algorithms to determine changes to the required inspection equipment.

Ser	Activity	Outputs	Evidence
a	**Review of all algorithms to determine changes to the required inspection equipment**	Due to the later than planned online testing periods the amount of time that was given to PIE to analyse the data has been reduced. An update on the progress has been supplied in this report however the final output regarding the model will be supplied in the end of project closure report.	GRAID PIE Stage 4 Report October 2018 ver1.0.pdf.

Successful Delivery Reward Criterion 9.8 – Implementation into Business as Usual, completed by 26/11/18

- Design, manufacture and deliver a pre-commercialised in line inspection platform.
- Specifications 100% complete, check and approve for the platform that they 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 practice within NGGT asset management policy.

Ser	Activity	Outputs	Evidence
a	**Design, manufacture and deliver a pre-commercialised in-line inspection platform**	GRAID robotic platform and all the required equipment handed over to National Grid following the successful hand over pressure test.	GRAID Synthotech G01-NGGT-R-0012 Rev 1.1.pdf.
b	**Specifications 100% complete check and approved for the platform that are acceptable by National Grid as specifications suitable for company use**	Specification documents have been completed for the robotic platform and launch vessel and handed over to National Grid.	GRAID Synthotech G01-SPC-010v2.0 - General Specification.pdf. GRAID G01-SPC-010v2.0 - General Specification Confirmation.pdf.
c	**Deliver an agreed mobilisation strategy to NGGT including training package for all future operators**	Mobilisation strategy agreed between the existing project partners including a maintenance and training plan for Project GRAID.	GRAID Synthotech G01-NGGT-R-0012 Rev 1.1.pdf. GRAID Synthotech Training Plan v1.0.xlsx. GRAID Premtech PREM128-REP-0000-0502 Rev 02.pdf.
d	**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 practice within NGGT asset management policy**	Operating procedures for the GRAID robotic platform compiled by Synthotech and converted to National Grid templates to be presented on the project website. Incorporation into NGGT asset management policy has commenced with highlighted changes passed to the relevant authors for existing and new documents.	Project GRAID_SDRC_9.8_Report-End_of_Stage5.

For more information see Section 13

Section 6
Required modifications to the planned approach

A summary of the changes made to the planned methodology throughout the course of the project.

During the process of completing the Project GRAID programme of works there were several changes made to the methodology and timings. These were all discussed and agreed internally at National Grid and then with Ofgem. Each change to the planned approach offered either a benefit in output or a revision in deliverable date. It should be noted that no change carried out constituted a material change in the view of Ofgem.

6.1 Offline Test Rig

The offline test rig was a significant milestone within Project GRAID, however within the original proposal the location of this test rig was not defined. At that early stage of the project it was difficult to plan effectively for a test rig without any knowledge of the robot platform that would be tested on it. As the project progressed and the understanding increased regarding what GRAID would become the test rig was also developed. Originally the test rig was to be based at the National Grid Pipeline Maintenance Centre depot at Ambergate and as such once the project ended would be in the possession of National Grid. As this work was developed further however it became apparent that this option would be cost prohibitive and so additional options were sought. The project team approached Bilfinger, Fast Flow and DNV-GL to provide a quote to complete the offline test rig work package with the work being awarded to the Research and Test Facility owned by DNV-GL at RAF Spadeadam. Whilst the test rig is not based on a National Grid site the agreement made has allowed ongoing use of the test rig in partnership with DNV-GL who are also able to make use of the facility.

Project GRAID offline test rig upon completion.

6.2 Acceptance Testing

During the offline testing, there was an additional requirement to continue the test after the initial 10 tests as defined in the SDRCs were completed (more detail in Chapter 4.4.3). At this point the GRAID robot had proven it could hold pressure, operate in the test rig and collect data however the processes for launching were in their infancy and the team were addressing any issues arising from the testing. To gain confidence in the platform before the online trials could start an agreed, criteria based acceptance testing plan was proposed. In total this added several months onto the total time for the offline trials but importantly gave the team and National Grid the confidence to launch Project GRAID at the first trial site – Pannal Offtake.

6.3 Online Trial locations

In the original proposal for Project GRAID the team highlighted the locations of Wormington, Tirley and Bacton as locations for the online trials. As the project progressed only Bacton remained a viable trial location with sites such as Peterborough, Aylesbury, Cambridge and Horndon also being suggested but not progressed. The reasons for not continuing these sites included:

- Existing capital works within the site.
- Benefit case not strong.
- Outage requirements for the construction not possible in timeframe.

The first trial site at Pannal Offtake was not considered in the proposal stage as only compressor sites were highlighted, however the benefits of using a lower risk site were considerable for the first time GRAID would enter the NTS.

As discussed in Chapter 4.5.3 the decision was made to amend the third trial site to a period of enhanced NDT research. With two trial sites at Pannal Offtake and Bacton Terminal confirmed the team were becoming familiar with the launch and retrieval procedures but the chances of recording reduced wall thicknesses during these trials was very slim. To understand how the NDT sensors would react to an area of corrosion a series of tests were designed and completed at the DNV-GL Research and Test Facility at RAF Spadeadam and the training centre owned by National Grid in Eakring. Again, whilst not originally planned for in the proposal for Project GRAID the knowledge gained here was invaluable, giving the team an insight into what might appear on the NDT results graph if an area of corrosion was scanned.

Demo event at Pannal Offtake.

"There are always modifications to the planned approach but the sign of a good team is how they are managed."

David Hardman
Project Lead
National Grid

6.4 SDRC Changes

Throughout the process of completing the NIC project and with the full agreement and backing of Ofgem, several of the SDRC criteria deadlines were amended. These were:

- *Launch and retrieval device manufactured to withstand pressure of 100 bar(g) and minimise venting* – moved from 9.2 to 9.3 to allow for the manufacturing to complete.
- *Successful data collection/problem identification by robotic platform in response to test scenarios* – moved from 9.3 to 9.4 to allow the acceptance testing to conclude on the offline test rig.
- *Data analysis complete* – moved from 9.7 to 9.8 to allow PIE further time to complete the analysis as a result of carrying out the online trials later than originally proposed.

In response to finding more efficient, better ways of working, operating within the restrictions of a live asset base and to challenges experienced during the project, there was also a requirement to amend the overall timelines for the SDRC deliverables and the stage gates they belonged to.

The below diagram summarises the changes compared to the original proposal:

Both offline and online trial stages were extended to allow for the acceptance testing and site inspections to be completed, with the data analysis starting during the online trials as data from Pannal was available to be studied. The Delta Prototype Stage was combined with the Data Completion Stage as Delta modifications were carried out on the robot after the Pannal inspection as well as after the Bacton trial. By combining these stages and extending Stage 3 the team could complete all the trials and milestones before the project concluded on 26 November 2018.

As none of the changes mentioned above significantly changed the overall project end date or the project finances they were not viewed as material changes to Ofgem and were therefore accepted and approved.

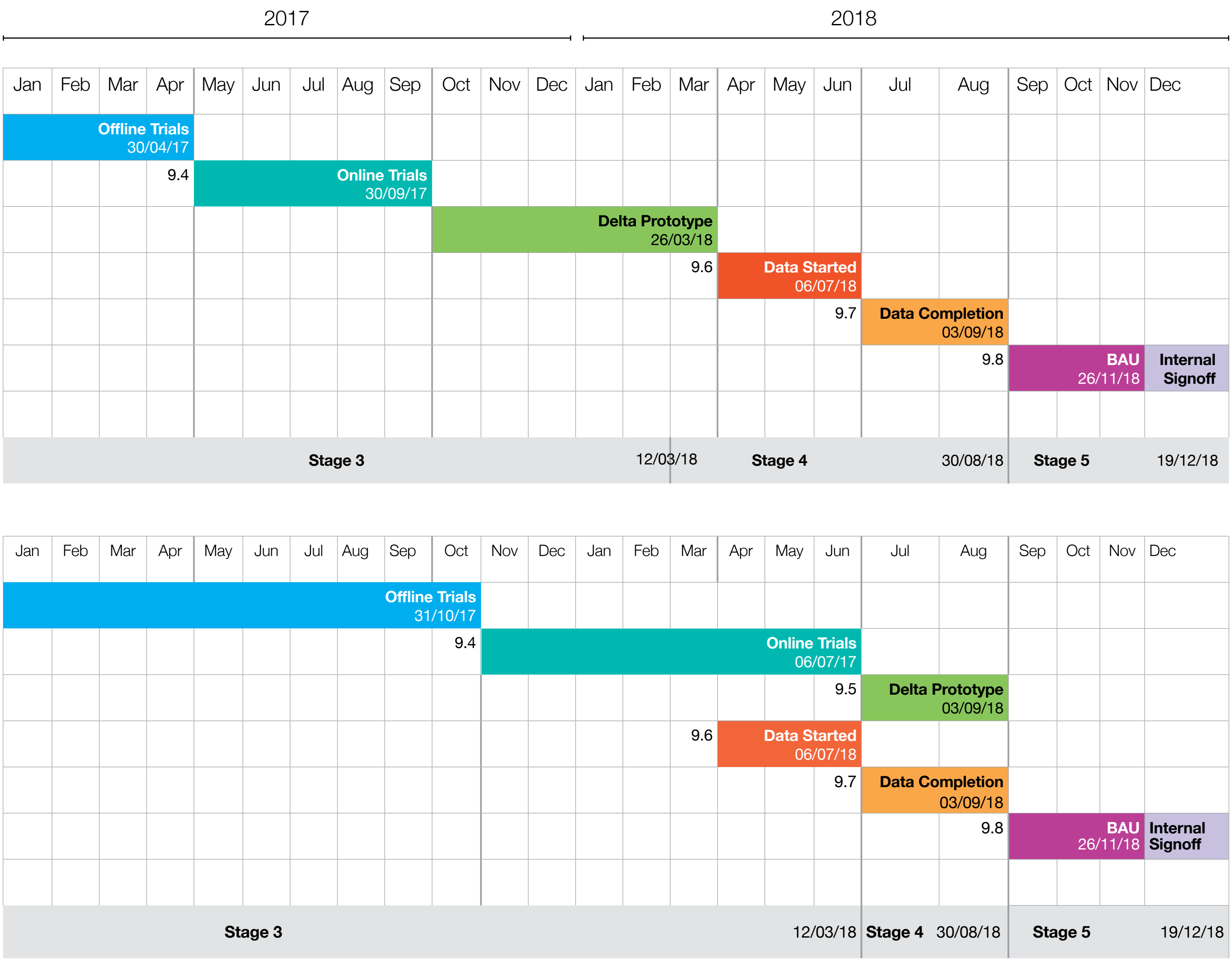


Figure 8 – Original SDRC delivery dates (top) versus the accepted changes (bottom).

Section 7
Significant variance in expected costs

A summary of the parts of the project that ended up costing more or less than expected and details as to why this was the case.

The original budget for Project GRAID was £6,547k with the project being completed for £6,506k, showing a £41k underspend. This original budgeted amount however includes a voluntary contribution of £243k from National Grid in reference to the Offline test rig. This amount was added to the budget and agreed with Ofgem in the revised direction letter dated 21 September 2016 (Appendix B). As the project has progressed to completion, the amount of voluntary contribution has been reduced to £202k, which is funded by National Grid.

Below shows a table of the final project spend against the allocated budget as per the revised Ofgem direction.

Disregarding the voluntary contribution from National Grid, Project GRAID would have concluded with an overspend of £202k, equivalent to a percentage variance of 3.71%.

The variances are explained as follows:

Labour

There was a reported reduction in National Grid labour costs resulting from several contributing factors namely using internal resource for the Project Lead role and a lower than expected Operational staff cost. Dedicated communications support on the project was set up in the early part of the project in order to establish a newsletter, website and publication presence, however, due to staff turnover this role was not backfilled and the remaining GRAID team continued the communication channels (summarised further in Section 12).

Equipment

The increase in costs within the equipment category can be attributed to the inspection costs at the second live trial site of Bacton Terminal. The construction works to build the connection at Bacton were funded through a separate internal sanction activity, however the actual inspection period was not. This included the CDM site handling, installation of the launch vessel and cleaning following the successful trial. Other costs have covered brochures and marketing material used in the dissemination events detailed in Section 12.

Project GRAID has completed at a total cost of

£6.5m

Cost Category	Budget (£k)	Actual (£k)	Variance (£k)	Variance (%)
Labour	936.06	646.58	289.48	30.93
Equipment	141.77	265.39	**-123.62**	**-87.20**
Contractors	5,424.44*	5,561.32	**-136.88**	**-2.52**
IT				
IPR Costs				
Travel and Expenses	45.50	33.43	12.07	26.53
Payments to Users				
Contingency				
Decommissioning				
Other				
Total	**6,547.77**	**6,506.72**	**41.05**	**0.63**

*includes the National Grid Voluntary Contribution of £243k.

Table 6 – final project spend against the allocated budget.

Contractors

This category has also increased throughout the project as additional work is completed that was not originally planned. From Synthotech the additional acceptance testing that was completed during the offline trials and some project management support during handovers comprised the biggest variances. Supplementary costs from PIE include audits of the project partners and support during writing the Non-Routine Operation (NRO) documents before the online trials could commence. Overall costs for Premtech were slightly lower than budgeted due to only two online trial connections requiring designing as opposed to the budgeted three.

Travel and expenses

The total cost of travel and expenses was less than budgeted but as this figure was originally a set amount spread over the project duration it was difficult to accurately budget for during the proposal stages.

As the project concluded with an overspend and the facility to apply for contingency funding from Ofgem was not enacted due to National Grid funding the overspend no unspent monies are to be returned to Ofgem as part of the Project GRAID NIC.

The GRAID robot during testing.

Section 8
Updated business case and lessons learnt for the method

A look back and update of the original business case to analyse how it has changed throughout the project including those parts which are no longer valid and new aspects which were highlighted.

During both online trials members of the National Grid Engineering community were welcomed to attend site and witness Project GRAID within the site pipework to ask questions and understand the project further.

The overall business case for Project GRAID has gained traction throughout the NIC project, as dissemination activities continued the potential that GRAID can provide both internally and externally to National Grid. The original business case of using a robotic platform to reduce unnecessary excavations and minimise the likelihood of failures by a proactive, rather than reactive asset management strategy is still very much a reality. However, to realise these benefits it will take time and require the continued use of the GRAID platform across the NTS coupled with the regular update of the condition model based on the collected results. The following factors have arisen during the project which help to strengthen and improve the original business case.

8.1 Additional Applications of the GRAID Platform

During both online trials members of the National Grid Engineering community were welcomed to attend site and witness Project GRAID within the site pipework to ask questions and understand the project further. These events were well received and generated lots of ideas for GRAID from colleagues who had not been involved from the start.

8.1.1 Pipe supports

The concept of inspecting the inside of above ground pipe supports was developed further during the first trial at Pannal Offtake due to the high number present in the study area. Significant cost is required to replace a pipe support and corresponding concrete plinth especially if the integrity of the pipe is unknown due to being covered by the support structure. Without this information, the worst must be assumed and time consuming and costly concrete removal techniques must be utilised. Using the GRAID NDT sensors the wall thicknesses behind the pipe support can be collected providing a view of the integrity and allowing the site teams to remove the concrete using the most appropriate method.

8.1.2 Valve operation

The video footage of the GRAID inspection was an area which attracted a significant amount of interest, not least because it was the first time that people had witnessed the inside of the transmission network during 'live' conditions but also the analysis of the video. By using the footage Engineers at National Grid could see how the last 40+ years of use has affected the pipework on a site and by speeding up the footage of a valve closing they can visibly see how well the asset is operating. In this example, it is evident from the footage if the seat is engaging on the valve when closing, if this is not the case then maintenance of the valve will be ineffective leading to a waste of time and money.

8.1.3 Additional assets

Alongside observing valves on site, data regarding additional assets can also be collected. One such example is the Isolation Joints (IJs) located onsite which mark the boundary between two separate cathodic protection loops. It has been found that IJs can become compromised with grease and become ineffective. GRAID can therefore be used to visualise the IJ from the inside and offer the site team valuable information before a replacement activity is scheduled. In a similar instance the GRAID platform could also be used to inspect the first 100m of the pipelines between the sites. This has historically been covered by the PIGs however the visual and NDT data from GRAID can offer insights into any features that the PIG is reporting on.

8.2 Acoustic Resonance Technology (ART)

ART was proposed as part of Project GRAID in the early stages (Section 4.2.1) however this was not progressed and replaced by the EMAT sensors which were used during the offline and online trials. The technology however does offer a significant progression for the NDT package on the GRAID robot due to the quantity of data that can be collected regarding the integrity of the pipe. Other benefits include the fact that the sensors do not need to be in contact with the pipe wall and are not magnetic so they do not attract debris. Further advances in the technology could also lead to outputs such as crack detection from the inside of the pipe becoming a reality. With a significant increase in the quantity of data collected from a site and the speed at which this could be achieved it is envisaged that inspection durations could be reduced. Current indications could provide data from the full 360° coverage of the internal pipe diameter across a 100m route within a working week of inspection time. With this level of data across several sites on the NTS it would also increase the confidence in the condition model leading to a potential to infer between sites which are similar in design, build and environment. The concept of using ART sensors on the GRAID robot is being developed further through an NIA project due to the significant benefits that could be derived. See Appendix G for more information.

8.3 External Interest

The project has been observed by much of the gas industry due to the topic of unpiggable pipework being a shared issue for anyone who manages this type of asset. Through conference presentations, networking events and live demonstrations, members of all the UK gas distribution companies had the opportunity to see GRAID and understand how it could benefit their businesses. The very nature of an NIC project is to innovate across the entire gas industry and GRAID is a great example of this. During the Bacton online trial members of Cadent, NGN, SGN and Wales & West attended site to view GRAID. Feedback was very positive with each company interested in the scope of robotic inspection for unpiggable pipework providing the platform is designed for standard distribution diameters. This was a significant step forward and proves the original business case was met for GRAID with potential to increase across the UK distribution networks. If GRAID could navigate the distribution network pipework, the data it provides could also be used to feed into the condition model developed by PIE. Much of the distribution network was built around the same time as the transmission counterparts and so learning from how this has aged over the past 40 years could benefit the wider UK and a move to a holistic UK integrity model.

Through external conferences such as World Gas, Pipeline Pigging & Integrity Management and the International Pipeline Conference the subject of GRAID has interested many global gas transmission companies. Countries such as America, Canada, France, Belgium and Australia have followed the project as they too have the same challenges with unpiggable sections of pipework.

Outside of the gas industry GRAID has attracted attention from the nuclear sector and the decommissioning of nuclear plants. In environments such as this, only robotics can safely be used due to life threatening toxic environments. Communications between National Grid and members of the oil industry have also happened.

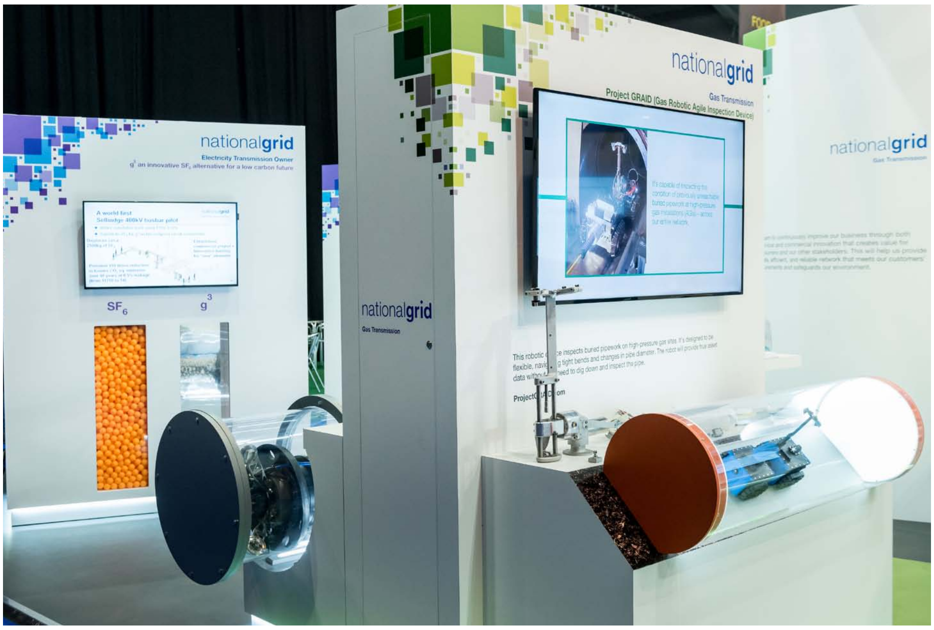
8.4 Modular Robot

As the design of the GRAID robotic platform took shape throughout Stage 2 the twin chassis design was agreed which has allowed the robot to become modular in any future iterations. This could mean that before an inspection the front chassis could be replaced for a cleaning device before a variety of NDT modules are selected for the specific interests onsite. This would make GRAID into a multi utility vehicle and perhaps carry out other activities inside the pipework such as repair works, installation tasks or even deploy small robots to carry out a variety of tasks.

8.5 De-carbonising the Gas Industry

The Future Energy Scenarios (FES) work carried out by National Grid has highlighted the continued need for gas within the UK and as such the network to transport this fuel across the country. Companies like National Grid are now focusing on the composition of gas to help meet carbon reduction targets. This includes bio-methane, shale gas and hydrogen. The move to a mix of gas throughout the network has raised many challenges in the gas industry, importantly whether the network is in a suitable condition to receive this medium and how it will be affected if introduced. GRAID can help in these areas, providing accurate, reliable and repeatable integrity data for the engineering community from the inside of the gas pipework.

For further information on the FES please see:
http://fes.nationalgrid.com/



Through external conferences the subject of GRAID has interested many global gas transmission companies.

Section 9
Lessons learnt for future innovation projects

A summary of where National Grid encountered any opportunities and challenges with the particular project in order to build on the understanding of how to undertake innovation projects effectively.

When carrying out a project of the magnitude of GRAID there are significant challenges to overcome. Up until this project no-one had built or tested a robotic platform capable of operating in transmission pressures up to 100 bar(g). This extreme environment, testing an innovation project of this size at National Grid and working as a project partnership with SMEs has led to many lessons learnt. The main points have been summarised in the table below:

Category	Description	Outcome
Collaboration	Working within the project partner structure as opposed to a customer/client relationship has been key to ensuring the right decisions for the project are made.	Opportunity.
Project Initiation	On future NIA/C's, more time needs to be spent with NGGT to define the scope of the project before design work is undertaken. More rigor needs to be applied to the estimate process before budgets and schedules are baselined.	Challenge.
Collaboration	Plan more engagement time between project partners and NGGT to enable the development process involved with complex robotics to be understood. It would reduce the duration of the 'forming and storming' periods of project team development and ensure that all parties are familiar with each other's planning and development processes.	Challenge.
Assurance	Using PIE as an independent certifier / final decision maker within the structure has been instrumental to the project success. Third party technical assurance should be considered for all innovation projects.	Opportunity.
Collaboration	Face-to-face meetings remain an invaluable form of communication and have continued regularly through the project. Use of remote collaboration tools is important but not a substitute for project partner contact. Monthly meetings rotated around the partner locations has assisted in bringing the teams closer and working more effectively. This has been bolstered by the project management team working from project partner offices periodically.	Opportunity.
Collaboration	Getting information from technical experts within NGGT has been challenging at times due to capacity issues. It was found that reducing reliance on email and using face-to-face contact proved a better way of establishing contact with the right individuals.	Challenge.
Design Process	The project tried to establish a basis of design early, when for an R&D project it is better to establish a less detailed ('course' or 'outline') basis of design document early and develop into a full basis of the design document as the rational and assumptions within the project become clear and other parallel design studies develop.	Challenge.

Category	Description	Outcome
Record Gathering	The process for requesting and collecting as-built records needs to be robust to ensure all available records are obtained. The information gathering and 3D modelling should be conducted in parallel in order to try and identify gaps and shortfalls in the as-built records.	Challenge.
Collaboration	In order to share the project plan between the partners a website planning tool called SmartSheet was set up. This service allows a project plan to be viewed by multiple people and significantly allows all contributors to amend or edit the plan. Each milestone for the partners was displayed on this view and appointed access rights allowed them to be updated. At any point, anyone with access could view the progress against the project plan.	Opportunity.
Site Selection	Prior to the selection of PMC Ambergate as the site to hold the test facility, a robust site selection process should have been conducted in accordance with the requirements of National Grid Specification T/SP/G/38, “Site Location and Layout Studies and Reviews”. This study would have identified some of the potential issues with the proposed PMC Ambergate site early, potentially resulting in an alternative and more appropriate site being established earlier.	Challenge.
Site construction Bacton	Outage conflicts not known at point of contract award. Outcome – agreed revised outage dates with all stakeholders and agreed and extension of time to contract data part one with the main works contractor.	Challenge.
Site construction Bacton	Budget costs used for Sanction Value. Outcome – negotiated reduced contractor costs post award.	Opportunity.
Offline Trials	When originally agreed for the NIC creation there was no definition in what a ‘test’ included and what the pass/fail criteria was to be for that test. As such this led to the incorporation of the acceptance testing phase during the offline trials where set criteria were agreed on. This also had a knock-on impact to the project finances.	Challenge.
Offline Trials	Carrying out the offline trials during the winter months at the DNV-GL Research and Testing facility at RAF Spadeadam created some challenges regarding the poor weather conditions and operating a robotic platform outside.	Challenge.
Laser scanning	As the project progressed, technology around laser scanning via a drone also developed. This led to a significant reduction in the time taken to scan a site for 3D modelling.	Opportunity.
Online Trials	The Non-Routine Operation (NRO) authoring was contracted out to PIE however as the work progressed it was apparent that two NROs were needed for the first online trial, one for the isolation and one for the inspection. In retrospect, it would have been better to use an internal Operations resource for the isolation NRO and PIE for the inspection NRO.	Challenge.
Online Trials	No original budget allocated to building the control cabin, writing the Safety Critical Task Analysis or the inspection period for the second Online Trial at Bacton Terminal.	Challenge.
Online Trials	The NGGT Innovation GRAID team became more involved in the site works at the first online trial location as this was not handed over to the Delivery department within NGGT.	Challenge.
Online Trials	The permitry system onsite at Bacton Terminal provided a set way of working that the team were not familiar with and this took some time to understand and follow.	Challenge.
Online Trials	There were opportunities to provide benefits to the Operations team even during the online trials, such as locating the buried asset on the GRAID route at Bacton Terminal.	Opportunity.

Category	Description	Outcome
Online Trials	The telehandler was used to transport the GRAID trolley onsite more than expected, however this was not an issue as there was one within the Bacton Terminal – should be checked for future use of GRAID onsite.	Challenge.
Online Trials	Venting the GRAID launch vessel was problematic due to the requirement to keep within a safe limit for the platform inside. A customisation on the vent could prevent the safe limit from being exceeded.	Challenge / opportunity.
Implementation into BAU	Amending existing internal documents must follow the NGGT Policy guidelines and as such, amendments to add GRAID to these documents has been logged and will be completed on the next revisions.	Challenge.
NIC Process	It would be beneficial for a mid-programme review during a long NIC to confirm that the scope is fully defined, finances are on track and the benefits proposed at the start can be realised.	Challenge.

For more information:

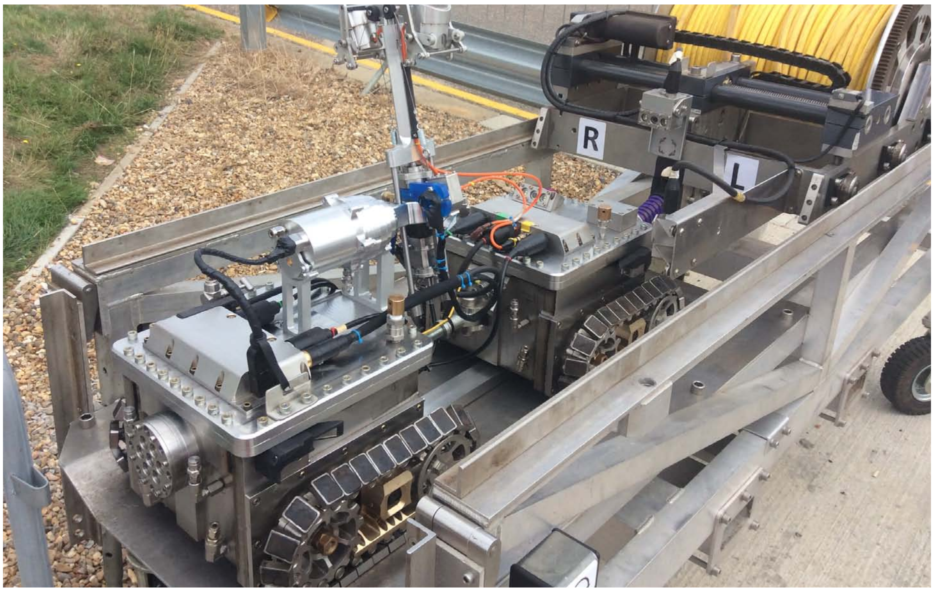
Above is a summary of learning achieved by the project team. Should further information be required please do not hesitate to contact the project team using the contact details provided in Section 15.

Note to networks:

The project team would like to support cross network lessons sharing. Please do not hesitate to contact the project team to discuss learning gained in further detail.

Section 10
Project replication

A list of all physical components and knowledge required to replicate the outcomes of this project along with an indication of the costs.



The robotic platform including robot, UMS, tether and transportation trolley.

The following information details the physical equipment, data and onsite facilities needed to replicate a project such as GRAID. As with any robotics project there are many different designs and methods to build a system such as this, but the below details what would be needed to replicate this NIC project.

10.1 Robotic Platform

10.1.1 Cost – £0.5-£1m

The robotic platform as detailed in Section 4 would need to be replicated and built which would include the robot itself, the UMS, driver's cabinet, transportation trolley and control system. The exact designs that were used for GRAID for each of these components would not necessarily need to be copied exactly, so long as the same outputs are delivered. The constraining factors arise from the environment that GRAID is designed for, including but not limited to:

- 100% gas atmosphere.
- Up to 100 bar(g).
- Up to 6.5 m/s flow.
- No form of light within the pipework.
- Complex site geometry such as bends, tees and inclines/declines.

The requirements for the tether, UMS and driver's cabinet are simply to allow power to be brought from a source to the robot and for data to feed from the robot to the control system in real time to assist in navigating the pipework.

10.2 Data

A key element of the GRAID NIC project was how the output data will be used within the business and the decisions it will help to make. For the condition model an input of data is required which include as-built drawings, material details, upstream and downstream in-line inspection data, site survey information, cathodic protection data from the site and connecting pipelines and details of any repair work carried out in the area. All this data is input into the model alongside the GRAID provided data to produce the condition information for that site. If any part of this cannot be provided, then the condition model can still be created however the confidence levels behind the model will be negatively impacted.

10.3 Onsite facilities

10.3.1 Cost – £100k for the launch vessel plus a variable amount depending on the complexity of providing a connection onsite

To physically connect the GRAID robot to a network a launch vessel will be needed that can withstand the same environment as the robot itself and must have a door mechanism to allow the robot and UMS to be inserted before sealing to allow pressurisation. The launch vessel requires a flange fitting at the other end for connection to the pipework and the ability to be connected to a source of gas supply / able to vent off the gas for depressurisation. Transportation is important, ensuring that the vessel can travel with the system and be connected to any site it may be required at.

10.3.2 Site requirements

Onsite there must be a connection point for the launch vessel to be bolted to with diameters of between 30" and 36", this was deemed the operational range of the current NDT sensors. Following the work from Premtech in the Standard Connections Report, there are a variety of ways to provide a robotic connection point ranging from a permanent, large scale construction project to temporary methodologies of removing equipment and returning them once the inspection is complete. The technique of connection is not important so long as sufficient access is provided to the area, there is a road nearby for offloading the equipment, safe site demarcation, a stable flat base for the launch vessel and welfare facilities are all provided for the inspection period. To connect the vessel a valve must be operational allowing the section of pipework to be vented and purged before work can commence. It is ideal but not a requirement that the vessel be connected straight onto the valve.

Finally, the facility to clean the robot and tether is a requirement as there is a potential for Normally Occurring Radioactive Material (NORM) to be brought out of the pipework on the GRAID robot. A cleaning bund and plan to safely dispose of the waste water would be needed to allow the equipment to leave site following an inspection.

A valve must be operational allowing the section of pipework to be vented and purged before work can commence.

It should be noted that this is a summary of the components that make up the GRAID project and it would not be practical to list all the different aspects in detail here. The Project Progress Reports (PPR) and Successful Delivery Reward Criteria (SDRC) reports provide a greater level of detail on the background and how a project like this could be replicated.

The location of these documents can be found in Section 13.

30" to 36"

Onsite there must be a connection point for the launch vessel to be bolted to with diameters of between 30" to 36".

Section 11
Planned implementation

Details on whether and how National Grid plans to implement Project GRAID in the remainder of RIIO T1 and into T2 either by modifying the network or processes based on learning from the project.

Throughout Project GRAID the robotic platform has been extensively tested both offline at the test rig and online at both Pannal Offtake and Bacton Terminal. Now that this testing is complete and the platform has proven it can provide reliable data from inside the gas transmission network during 'live' gas conditions a plan can be created to detail how this will be used going forward and the benefit it can derive.

Within the short term GRAID will be used on the National Grid transmission network to assist in the asset health programme of works, leveraging the data provided by NDT sensors to provide an accurate understanding of the current pipework integrity on sites. If GRAID can offer savings on already committed work a connection strategy will be formulated and an inspection of that pipework will be carried out.

To develop the innovation further a variety of follow on projects have been proposed to the NGGT Innovation team which focus on many aspects of the GRAID platform.

The team believe that out of these potential development routes, looking at the method of Non-Destructive Testing holds the greatest benefits for GRAID. This is being developed further with the project partners from the NIC (Synthotech, Premtech and PIE) and new partners for the NDT package and an NIA is being proposed (see Appendix G). Once complete both the quantity and quality of the data provided by GRAID will be increased substantially and help to provide further confidence to the condition model.

11.1 RIIO T2

Alongside this work, the submission to the next price control period (T2) is also being developed which will propose construction and inspection of a series of connection points across RIIO T2. The connection points will range in size and complexity and between permanent or temporary designs depending on the site layout and available routes for inspection. The sites that will be chosen for connection points will be based on a combination of the criticality work produced by PIE, internal asset health priority lists and those sites that will provide the higher benefit cases. A phased approach is being proposed with up to five construction and inspections carried out a year at the peak of the programme.

With greater levels of data being provided by the revised NDT package there is a potential to be able to use the collected data and infer to non-inspected sites that are similar to those being inspected and make assumptions on their integrity. For example, Site A is downstream from a GRAID inspected Site B. Both have been built of the same materials, exposed to similar atmospheric conditions and are in similar soil conditions so the intelligence collected from Site B could be used to infer the condition of Site A. With the right level of confidence behind the condition model this assumption could be reliable and reduce the overall number of GRAID inspections.

To exploit the GRAID platform further the technology could be utilised on the large diameter gas distribution network which also has the challenge of inspecting unpiggable pipework. The stakeholder demonstration event at Bacton Terminal attended by all the gas distribution providers in the UK confirmed that this type of technology would be welcome on their network and could be used to a higher degree if the platform was reduced in size to operate in medium diameters of between 18" and 30". Outside of the UK, the global transmission network providers also appreciate the challenge provided by unpiggable pipework and are in a similar position to the UK gas network. Providing a connection point is facilitated the GRAID robot can be operated all over the globe to deliver reliable integrity information on the asset it is inspecting.

The connection points will range in size and complexity.

By completing the planned implementation above, it is expected that the TRL for GRAID will move from a 7 – demonstration system operating in an operational environment at pre-commercial scale to a 9 – full commercial application.

Section 12
Learning dissemination

Details of the information sharing mechanisms National Grid has undertaken during Project GRAID, and what the outcomes of these mechanisms were.

Sharing the stories, updates, events and news regarding Project GRAID has been a significant part of the NIC journey from the very beginning. With such an ambitious project, many people have expressed a wish to follow the progress either from an academic, commercial or purely curiosity point of view. The following channels have been used to spread the message about Project GRAID.

12.1 External Channels

The central point for all GRAID communications is the website (www.projectgraid.com) which was set up with the sole purpose of allowing everyone to read about the project, understand any progress that was made and importantly get in contact if required. Based on a WordPress platform the blog style allowed the GRAID website to be split into articles either on News, Documents or Events. By using this popular platform, the team had access to a huge variety of features and tools including picture sliders and the ability to format the content for viewing on a mobile device. The website receives between 50 and 100 individual hits a month and between 150 and 200 page views and peaks in this trend have been noticed after significant external events. While most of the traffic is from the UK, the website has recorded interest from around the world including USA, Norway, Thailand, Australia, Canada and the Asia Pacific region. These statistics show how far a project such as GRAID can reach and the global challenge that it is addressing.

The website also includes a function to be able to subscribe to the GRAID newsletter. The newsletter, which is produced and sent via the MailChimp system, is distributed during the first week of every month and summarises the articles that have been uploaded to the website in that period. The distribution list has grown throughout the project and now totals over 2,000 contacts from a variety of sources including academic institutions, private companies and National Grid. Again, the distribution of this newsletter matches the website with most interest from the UK, Europe and US.

The website can also share articles to other social media outlets such as Facebook, Twitter and LinkedIn. These methods have been exploited to allow people to follow the progress of the project. Finally, the external National Grid website has included articles on Project GRAID to promote the work being completed.

12.2 Internal Channels

Internally to National Grid there are a variety of channels which have been exploited to share messages across the business. A regular email called ‘GTO News’ has featured many of the major milestones for GRAID and is sent to everyone in NGGT. Several pages of the company intranet have also been produced for larger articles about the robot along with slides which feature in a monthly ‘Team Talk’ for all managers to share with their teams. Via the Innovation team, Project GRAID has been able to attend internal Operations stand down events with a display stand to show the 3D printed models of the robot for context and to explain the project.

The team have applied for several awards to recognise the combined effort in completing a project such as GRAID.

12.3 Awards

During the project, the team have applied for several awards to recognise the combined effort in completing a project such as GRAID. Those that were won include:

- Innovation Project Award at the 2017 IGEM Gas Industry Awards.
- Winner for the Land Based / Onshore Pipeline Category at the Pipeline Industry Guild 2017.
- UK Winner for ‘Fit for the Future’ project at the National Grid Chairman’s Awards 2018.

12.4 Conferences and Articles

A key method of sharing the progress of Project GRAID has been through exhibiting and presenting at conferences across the UK and further afield. The table below details those events and where available provides a link to further content.

Type	Date	Name	Details / Outcome
Presentation and Exhibiting	21-23/04/15	Utility Week Live 2015.	Team exhibited and presented GRAID at the event: https://utilityweek.co.uk/utility-week-live-launches-at-birmingham-nec/
Presentation and Exhibiting	01-05/05/15	26th World Gas Conference 2015.	Robotics presentation by Synthotech which include GRAID and National Grid Innovation Stand showing the 3D printed model.
Presentation	01/10/15	UK Onshore Pipeline Operators’ Association (UKOPA) Annual Conference.	Team members presented to the UKOPA committee.
Presentation	05-09/10/15	Ageing Pipelines Conference.	PIE presented GRAID at the event: https://www.pipelinesinternational.com/2015/12/09/aging-pipelines-conference-is-a-hit-in-belgium/
Presentation	07/10/15	Institute of Engineering Technology (IET) Seminar: Robotics in Extreme Environments.	Synthotech presented GRAID at the event: http://www.synthotech.com/news/30/32/Lights-camera-action-Synthotech-takes-to-the-stage
Presentation	17/11/15	Energy Utilities Alliance (EUA) Network Engineering & Equipment Group.	http://www.synthotech.com/news/31/32/Sharing-innovation-at-EUA-Gas-2015-Synthotech-take-to-the-stage
Presentation and Exhibiting	24-26/11/15	Low Carbon Networks and Innovation Conference 2015.	Team exhibited and presented GRAID at the event: http://www.lcniconference.org/archive/2015.html
Presentation	05/02/16	University of Birmingham workshop for robotics and autonomous systems for the rail infrastructure industry.	Synthotech presented GRAID at the event: http://www.synthotech.com/news/37/32/Robotics-could-help-keep-railway-infrastructure-on-track
Exhibiting	16-19/03/16	Big Bang Fair 2016.	Team exhibited GRAID at the event.
Presentation and Exhibiting	17/05/16	Utility Week Live 2016.	Team exhibited and presented GRAID at the event: https://utilityweek.co.uk/special-report-utility-week-live-2016-reviewed/
Presentation	23-26/05/16	Pipelines Technical Conference 2016.	PIE presented GRAID at the event: https://www.pipeline-conference.com/abstracts/asset-management-high-pressure-installations-project-graid-innovation-project-develop
Live Demo	06/09/16	Internal Operations Event.	Internal event hosted at PMC depot in Ambergate: http://projectgraid.com/events/project-graid-demo-day/

Type	Date	Name	Details / Outcome
Live Demo	07/09/16	External Stakeholder Event.	External event hosted at PMC depot in Ambergate for Gas Distributions providers: http://projectgraid.com/events/project-graid-demo-day/
Presentation and Exhibiting	13-14/09/16	IGEM Annual Conference and Engineering Update September 2016.	Synthotech exhibited and presented GRAID at the event: http://www.synthotech.com/news/67/32/Come-and-see-Synthotech-this-Autumn
Presentation	21/09/16	Network Asset Performance Conference September 2016.	Team presented GRAID at the event: http://www.beama.org.uk/event/network-asset-performance-conference.html
Presentation and Exhibiting	11-13/10/16	Low Carbon Networks and Innovation conference 2016.	Team exhibited and presented GRAID at the event: http://www.lcniconference.org/archive/2016.html
Presentation	18-19/10/16	UKOPA Member's Meeting October 2016.	Team presented GRAID at the event.
Attended	30/10/16	Sprint Robotics October 2016.	Employees of Synthotech attended the event: http://www.synthotech.com/news/77/32/Synthotech-is-off-to-the-Netherlands
Publication	December 2016	IGEM's Gas International magazine.	Synthotech Design Engineer Rafal Cichosz was featured: http://projectgraid.com/documents/igem-young-persons-paper-competition-2016/
Exhibiting	27/02/2017 to 02/03/2017	Pipeline and Pigging Integrity Management 2017.	National Grid exhibited GRAID at the event: http://projectgraid.com/events/graid-at-ppim-2017-video/
Publication	24/04/17	Gas Power Heat Systems article.	This article talked about the technological developments in robotics which are changing the way we ensure the quality of our infrastructure: http://projectgraid.com/news/network-magazine/
Publication	September 2017	IGEM's Gas International magazine.	Article updated the community on the progress of Project GRAID and the benefits it will provide for National Grid.
Publication	07/09/17	The Times.	Article published in The Times: http://projectgraid.com/news/project-graid-makes-the-papers/
Presentation	13-15/09/17	Pipeline Maintenance and Integrity Management 2017.	National Grid presented GRAID at the event: http://projectgraid.com/news/project-graid-presented-at-a-european-conference/
Presentation and Exhibiting	06-07/12/17	Low Carbon Networks and Innovation conference 2017.	Team exhibited and presented GRAID at the event: http://projectgraid.com/news/project-graid-at-lcni-2017/
Exhibiting	22-23/05/18	Utility Week Live 2018.	Team exhibited GRAID at the event: http://projectgraid.com/news/project-graid-will-be-at-this-years-utility-week-live-conference/
Live Demo	20/06/18	Pannal Offtake demonstration event.	Internal demo event during the first live trial of GRAID for senior managers and engineers: http://projectgraid.com/news/we-did-it/

Type	Date	Name	Details / Outcome
Attended	25-29/06/18	World Gas Conference 2018.	Synthotech attended the event: https://wgc2018.com/program
Live Demo	23/08/18	Bacton Terminal demonstration event.	External demo event during the live trials at Bacton Terminal for Gas Distribution companies and Perenco: http://projectgraid.com/news/project-graid-completes-its-final-major-milestone/
Publication	14/09/18	Project GRAID marketing material.	A4 Brochure produced to be used at upcoming events.
Presentation and Exhibiting	21-24/09/18	National Grid Investor Relations Exhibition.	Project GRAID was a featured project at the National Grid Investor Relations Exhibition: https://www.nationalgrid.com/group/engineering-and-innovation/innovation
Attended	24-29/09/18	International Pipeline Conference 2018.	National Grid attended the event: https://www.asme.org/events/ipc
Presentation and Exhibiting	16-17/10/18	Low Carbon Networks and Innovation Conference 2018.	Team exhibited and presented GRAID at the event – full robot on display: http://projectgraid.com/news/graid-at-lcni-18/
Presentation	17-19/10/18	Pipeline Maintenance and Integrity Management 2018.	National Grid presented GRAID at the event: http://www.prosperoevents.com/upcoming-events/item/364-6th-pipeline-maintenance-and-integrity-management-for-oil-gas-industry-2018

12.5 Peer Review

The Project GRAID Closure Report was sent to representatives from SGN, Wales & West Utilities, Cadent and NGN for Peer Review ahead of sending to Ofgem. Received comments have been incorporated into this document where possible and the returned letters are located in Appendix H.

The Low Carbon Networks and Innovation conference.


Project GRAID has been displayed at various events.

Section 13
Key project learning documents

Details and web-links of the main documents relating to the project learning that have been published prior to the publication of the Close Down Report, including enough information on the content of each document so that other parties can judge whether or not the document will be of use to them.

The table below details the main learning documents with reference to Project GRAID and links to access the files from the GRAID website.

Date	Title	Details
July 2014	NIC Proposal Document – Project GRAID.	Original proposal document that was supplied to Ofgem ahead of being awarded the NIC in 2014 for Project GRAID. http://projectgraid.com/documents/project-graid-ofgem-proposal-document/
19/12/14	NGGT Project Direction – Project GRAID.	The response from Ofgem providing the Project direction for Project GRAID. http://projectgraid.com/documents/project-graid-ofgem-project-direction/
05/01/15	Project GRAID Start Up video.	https://www.youtube.com/watch?v=T_Pc_du5zbg
June 2015	Project Progress Report 1 – June 2015.	This is the Six Monthly Report delivered by National Grid Gas Transmission on their Gas Network Innovation Competition project, Project GRAID. http://projectgraid.com/documents/progress-report-jun-2015/
30/10/15	SDRC Report 9.1 Solution Development.	Successful Delivery Reward Criteria report for 9.1 covering the Solution Development stage of Project GRAID. http://projectgraid.com/documents/sdrc-9-1-solution-development-report/
December 2015	Project Progress Report 2 – December 2015.	This is the Six Monthly Report delivered by National Grid Gas Transmission on their Gas Network Innovation Competition project, Project GRAID. http://projectgraid.com/documents/progress-report-dec-2015/

Date	Title	Details
June 2016	Project Progress Report 3 – June 2016.	This is the Six Monthly Report delivered by National Grid Gas Transmission on their Gas Network Innovation Competition project, Project GRAID. http://projectgraid.com/documents/progress-report-jun-2016/
09/09/16	SDRC Report 9.2 Development Testing.	Successful Delivery Reward Criteria report for 9.2 covering the Development Testing stage of Project GRAID. http://projectgraid.com/documents/sdrc-9-2-development-testing-report/
20/09/16	Revised Project Direction.	The response from Ofgem providing the Revised Project direction for Project GRAID. http://projectgraid.com/documents/revised-project-graid-ofgem-project-direction/
December 2016	Project Progress Report 4 – December 2016.	This is the Six Monthly Report delivered by National Grid Gas Transmission on their Gas Network Innovation Competition project, Project GRAID. http://projectgraid.com/documents/progress-report-dec-2016/
31/10/17	SDRC Report 9.3 Successful Offline Trials Completed.	Successful Delivery Reward Criteria report for 9.3 covering the completion of Offline Trials stage of Project GRAID. http://projectgraid.com/documents/sdrc-9-3-offline-trials-completed-report/
December 2017	Project Progress Report 5 – December 2017.	This is the Annual Report delivered by National Grid Gas Transmission on their Gas Network Innovation Competition project, Project GRAID. http://projectgraid.com/documents/progress-report-dec-2017/
06/07/18	SDRC Report 9.4 Successful Online Trials Completed.	Successful Delivery Reward Criteria report for 9.4 covering the completion of Online Trials stage of Project GRAID. This report also covers the end of Stage 3. http://projectgraid.com/documents/sdrc-9-4-online-trials-completed-and-9-6-data-analysis-started-report/
30/09/18	SDRC Report 9.5 Delta Prototype.	Successful Delivery Reward Criteria report for 9.5 covering the Delta Prototype stage of Project GRAID. This report also covers the end of Stage 4. http://projectgraid.com/documents/sdrc-9-5-delta-prototype-and-9-7-completion-of-data-analysis-report/
06/07/18	SDRC Report 9.6 Data Analysis Systems in place.	Successful Delivery Reward Criteria report for 9.6 covering the Data systems in place stage of Project GRAID. This report also covers the end of Stage 4. http://projectgraid.com/documents/sdrc-9-4-online-trials-completed-and-9-6-data-analysis-started-report/
11/10/18	Project GRAID Closure video.	https://www.youtube.com/watch?v=z4rdRP5gVL8
03/09/18	SDRC Report 9.7 Completion of Data Analysis.	Successful Delivery Reward Criteria report for 9.7 Completion of Data Analysis stage of Project GRAID. This report also covers the end of Stage 6. http://projectgraid.com/documents/sdrc-9-5-delta-prototype-and-9-7-completion-of-data-analysis-report/
26/11/18	SDRC Report 9.8 Implement into Business As Usual.	Successful Delivery Reward Criteria report for 9.8 Implement into Business as Usual stage of Project GRAID. This report also covers the end of Stage 7. http://projectgraid.com/documents/sdrc-9-8-implement-into-business-as-usual-report/

Section 14
Data access details

National Grid has a data sharing policy in relation to NIA and NIC projects.

The purpose of this data sharing policy is to make clear how such network or consumption data can be requested by interested parties, and the terms on which such data will be made available by National Grid.

For more information please use this link:
http://projectgraid.com/documents/nic-data-sharing-policy/

Section 15
Contact details

For queries relating to Project GRAID, please contact National Grid via:

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Appendices

Appendix A – Ofgem Project Direction
Appendix B – Ofgem Revised Project Direction
Appendix C – Stage 5 Report – Synthotech
Appendix D – Stage 5 Report – Premtech
Appendix E – Stage 5 Report – PIE (GRAID Data Model)
Appendix F – GRAID Process Flow Diagram v1
Appendix G – Related NIA Projects
Appendix H – Peer Review Letters

Abbreviations

AGI – Above Ground Installation
ART – Acoustic Resonance Technology
BAU – Business as usual
BODD – Basis of Design Document
CDM – Construction Design and Management
CFD – Computational Fluid Dynamics
CP – Cathodic Protection
ELD – Engineering Line Diagram
EMAT – Electromagnetic Acoustic Transducer
FAT – Factory Acceptance Testing
FPSA – Formal Process Safety Assessment
GA – General Arrangement
GNCC – Gas Network Control Centre
GTO – Gas Transmission Operator
HAZOP – Hazards and Operability
ILI – In-Line Inspection
MTO – Material Take Off
NDT – Non-Destructive Testing
NGGT – National Grid Gas Transmission
NGN – Northern Gas Networks
NIA – Network Innovation Allowance
NIC – Network Innovation Competition
NORM – Normally Occurring Radioactive Material
NRO – Non-Routine Operation
NTS – National Transmission System
PIE – Pipeline Integrity Engineers
PIG – Pipeline Inspection Gauge
PMC – Pipeline Maintenance Centre
R&D – Research and Design
SCTA – Safety Critical Task Analysis
SDRC – Successful Delivery Reward Criteria
SME – Small Medium Enterprise
UMS – Umbilical Management System

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