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NIA Project Registration and PEA Document

Date of Submission

May 2022

Project Reference Number

NIA_NGGT0186

Project Registration

Project Title

Assessment of Legacy Gas Pipeline Steels to Hydrogen Embrittlement Effects

Project Reference Number

NIA_NGGT0186

Project Licensee(s)

National Gas Transmission PLC

Project Start

September 2022

Project Duration

1 year and 7 months

Nominated Project Contact(s)

Robert Best Box.GT.Innovation@nationalgrid.com

Project Budget

£70,665.00

Summary

The proposed project addresses the call topic area of ‘low-carbon energy carrier roles in accelerating decarbonisaton pathways’ by characterising the condition of legacy gas (methane) pipeline steels after service exposure. Existing hydrogen embrittlement relationships do not properly consider the effect of steel pedigree on degradation. This research will use the results of detailed characterisation to fully document steel microstructure and rigorously track hydrogen interaction with specific features. The results will be directly relevant to assessing the suitability of the current network for hydrogen gas transport. Moreover, the learnings will inform the design and manufacture of future systems. Support involving the supply of suitable legacy specimens has been obtained from National Grid and EPRI will provide review and input on methods used and aid dissemination of findings.

Third Party Collaborators

University of Warwick

Electric Power Research Institute

Nominated Contact Email Address(es)

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Problem Being Solved

The various forms of hydrogen degradation of steel have been studied previously and a number of relationships have been established between microstructural features, hydrogen transport and trapping and the risk of hydrogen embrittlement (in a variety of forms). Thus, hydrogen was found to be trapped at temporary or permanent traps with dislocations and interfaces being preferential trapping sites. Higher strength phases, e.g. martensite, were identified as presenting the greatest risk of hydrogen-induced cracking or embrittlement

and so hydrogen embrittlement effects have been most associated with higher strength grades (X70 and above) and weldments, where rapid heating and cooling can cause localised bainitic and martensitic regions to form. As such, oil and gas exploration and transportation networks in sour environments and at low hydrogen partial pressures were the focus of research, particularly in regards of initial fabrication – clean surfaces and on-site welding.

The recent moves towards carbon-free fuels has led transportation and distribution companies, such as National Grid, to investigate piping methane / hydrogen mixes or even pure hydrogen through networks that currently only transport methane. For the example of National Grid, this network would comprise around 7,500 km of large diameter (up to 42") steel pipe carrying gas at up to 100 bar with over 80 % of the steel being X52 and X60. The X52 and X60 grades are strengthened by cold work and, mostly, by containing pearlite and so, apart from welds, should be low risk with regards to hydrogen embrittlement effects.

However, much of the methane pipeline network in the UK dates back to the 1970s or earlier, which raises a number of issues that would not have featured in hydrogen embrittlement studies. Principal amongst these are:

(i) Continuous casting techniques were introduced by European steel companies through the 1960s and were not optimised by the 1970s so that legacy steels would be more heavily segregated and contain larger non-metallic inclusion populations. Segregation can lead to local brittle zones, especially around welds and inclusions have been associated with the initiation of cracks. Existing relationships are based on average values for the steel, whereas cracking events are often associated with regions of extreme values, so that the risk may be underestimated.

(ii) The pipelines have been in service, under a pressure of methane for over 50 years in some cases and it is unclear how the structure may have altered over that period. Whilst large scale changes are not envisaged the application of elastic stresses to a pearlitic structure in the presence of hydrocarbons, there are few if any reported quantitative studies of such service exposed material.

(iii) Linked to (ii) is the condition of the inner pipeline surface; most laboratory and pre-service tests would use consistent clean surfaces, but, after 50 years service, the inner surface is expected to present a surface showing a range of oxide types and thicknesses. These surface oxides could modify the breakdown of hydrogen molecules to atomic hydrogen, its absorption by the steel and so the risk of hydrogen-induced embrittlement.

(iv) The large diameter pipes would be seam welded at the plant, which would be under controlled conditions, which could be monitored, tested and quality inspected. In-field girth welds will be subject to greater variability and may contain incipient hydrogen cracks that did not develop during methane exposure but could act as a sink for hydrogen and add to the risk of hydrogen embrittlement.

Undertaking detailed characterisation of service-exposed legacy steel pipelines to identify and quantify evidence of damage will be of significant benefit. This knowledge will also allow inform review of criteria used in existing methods assessing the risks of hydrogen embrittlement. The advanced characterisation facilities and staff expertise at The Warwick Manufacturing Group (WMG) will ensure that the techniques used are 'best practice' so that the results obtained are both rigorous and relevant

Method(s)

The project will focus on the technical feasibility of hydrogen transport within NTS pipelines, taking example material and undertaking in depth studies into the microstructure and make up of the various materials on the NTS. We will select varying ages of X52, X60, X65 and X80 pipeline materials based on their make up on the NTS today undertake baseline materials characterisation and then subject the materials to gaseous hydrogen environments to understand the impact of hydrogen on the microstructures. This work in comparison with the materials testing work underway will provide the reasoning for the results we see and provide greater insight into some of the methods of preventing failure.

The method chosen through laboratory testing is the most appropriate for the in-depth microstructure analysis planned to be undertaken as this is not feasible at a larger scale. The initial study will last 9 months and provide us guidance on which areas need further focus.

Measurement Quality Statement

The measurement approach used to meet Data Quality objectives will be through the identification of high calibre project partners whom are experts in their given field and the use of real data and materials from National Grid sites. In this instance the project will be

limited to lab testing and therefore will combine knowledge from past materials investigations with lab scale testing to inform new insights into the impact of hydrogen on varying ages of NTS materials. The lab tests will be assessed by the Warwick Manufacturing Group and published therefore peer reviewing the final outcomes.

Data Quality Statement

The project will ensure that materials and data used is of sufficient quality to deliver project objectives through the development of a robust testing plan, this will take into account all key variables and manage them through the testing. The relevant data and background information will be stored for future access within the National Grid Innovation Sharepoint site and the ENA smarter networks portal.

Scope

The project will be managed through three work packages detailed below. The purpose of which will provide a clear view of how the ages of steel material grades impacts the compatibility of hydrogen transport through our NTS pipelines. It is thought that older steel grades such as X52 will have less impact from hydrogen however older steel pipelines where not manufactured in the same method as those post the late 1970s causing the materials to contain more inclusions which are susceptible to hydrogen.

WP1 Steel homogeneity

The service exposed samples (basemetal, seam and girth weldments) will be characterised in terms of:

(i) Inclusion populations – this will be carried out using the SEM-based automatic inclusion analysis facility at WMG so that inclusion distributions, clustering, types and spatial variations through thickness and around weldments.

(ii) MicroXRF will be used to give large-scale chemical segregation maps over the same locations as in (i).

(iii) Ferrite grain size distributions and second phase volume fraction and size distributions will be determined by SEM-EBSD in the same locations as in (i).

(iv) Selected micro- and nano-hardness mapping will be carried to determine local mechanical property variations associated with the microstructural differences noted in (i) – (iii).

(v) SEM techniques will be used to identify the range of surface oxide types and thicknesses.

WP2 Hydrogen uptake

Hydrogen behaviour will be estimated on the basis of current microstructure relationships for the range of microstructures / compositions and inclusion populations identified in WP1. The behaviour of these regions will be determined using acid solution charging for slices extracted from the service-exposed samples given a consistent (clean) surface finish. Following any modification of the microstructure relationships full thickness samples will be treated as a composite with respect to hydrogen behaviour to estimate pipe hydrogen behaviour. This model will be verified using hydrogen charging for full thickness, clean surface samples. After verification / modification of the model, the effect of surface condition will be assessed by hydrogen charging tests for different service-exposed surface conditions over known microstructures already modelled.

WP3 Cracking and relation to gaseous environments / new build

Samples from service-exposed materials with a range of hydrogen behaviours will be prepared as tensile specimens and tested to failure with and without hydrogen saturation to determine the extent of hydrogen embrittlement. The mechanism of hydrogen embrittlement will be used to confirm the susceptible microstructure features identified in WPs 1 and 2 by selected X-ray CT on tested but unfractured samples (H saturated) and by SEM fractography. For the service-exposed condition showing the greatest susceptibility to hydrogen embrittlement then samples will be tested in a gaseous hydrogen environment (these tests will be outsourced) with post-test analysis at WMG to confirm comparable behaviour with acid charging tests and any differences in hydrogen uptake for a clean surface so that the model kinetics determined for acid charging can be modified for gaseous hydrogen exposure. New build pipeline is likely to be higher grade, e.g. X80, and so would have a different second phase (as noted above). In order to compare this study and the models determined with new grades then samples of X80 will be characterised; service-exposed material will be heat treated to give a comparable second phase (but the heterogeneities will still be present). The new build X80 and heat treated service-exposed

material will be subjected to acid charging to establish the effect of heterogeneities in comparison with the presence of harder second phase.

Objective(s)

As noted above, the aim of the research is to assess whether established assessments of the likelihood of hydrogen embrittlement are appropriate for service-exposed legacy steel gas (methane) pipeline. The project will involve the sourcing and detailed characterisation of a sufficient number of legacy samples (pipes with welds) to identify the range of microstructural and surface conditions representative of the current gas pipeline population. Hydrogen charging characteristics will be determined for the range of steel conditions and related to expected behaviour from established relationships. These tests will encompass service-exposed surfaces and fresh surfaces to deconvolute the effects of surface and microstructure distributions.

Consumer Vulnerability Impact Assessment

The National Transmission System (NTS) is a key UK infrastructure for the transport of Gas to consumers, including those considered vulnerable. In a scenario where hydrogen replaces methane as a household heat source, it is essential the vulnerable are not excluded by virtue of fuel inaccessibility. In cases where vulnerable consumers already utilise gas it is likely that in a net zero future the optimum option is to provide a consistent energy solution. The transition to hydrogen within the NTS provides continuity of access to the vulnerable of hydrogen as a replacement to methane, with ongoing benefits of efficiency and economy of scale within a closely regulated environment. This project supports the transition of the NTS to hydrogen which in turn supports the availability of gas to the vulnerable.

Success Criteria

The following key criteria need to be met for the project to be considered successful:

- Study objectives met to time and cost
- Microstructural examination completed to determine hydrogen impact on varying ages and grades of materials
- Determination of focus areas and key next steps

Project Partners and External Funding

WMG

Dr Martin Strangwood is an associate professor at WMG with extensive experience in composition-processing-property optimisation especially in steels and other metallic alloys. After his PhD he spent 3 years with UKAEA working on the Sizewell B primary cooling circuit and joined the University of Birmingham (where he retains a part-time position) in 1990. Since then he has or is supervising 73 PhDs, 13 MPhils, 23 PDRAs and 14 visiting fellows in a variety of subjects including structure and property scatter in steels, pipeline failure mechanisms and hydrogen uptake and storage. He has interacted with over 80 industrial and government partners and has nearly 150 ISI-rated publications.

Dr Geoff West is a senior research fellow in the ASRC at WMG and is responsible for the microscopy suite containing >£4M of equipment tailored for characterising steel material microstructures across the length scales. He currently supervises 12 PhD students, three of whom are working on EPRI related projects. He has over 20 years hands-on electron microscopy experience and works on a diverse range of industrially focussed microscopy-based projects.

EPRI

The project costs will be split between National Grid Gas NIA and EPRI. EPRI will contribute £51,500. This will benefit the consumer in reducing the total cost of the project and enable further shared learning across the gas networks and EPRI on past work and this project.

Potential for New Learning

The output from this PhD will have direct relevance to National Grid in their conversion of gas pipeline network from carrying methane to carrying hydrogen as the data obtained and the assessment of hydrogen embrittlement susceptibility with be based on their legacy

pipeline steels. The PhD characterisation and modelling work will inform National Grid in the suitability of their conversion. The issues of conversion of legacy steel pipelines from hydrocarbon gas to hydrogen gas distribution are, however, global and the participation of EPRI provides access to a network of energy / utility concerns that can disseminate the findings / benefits / concerns regarding conversion of legacy systems to a much greater international audience.

The project will confirm the impact of the effect of different pipeline manufacturing techniques through the construction of the NTS along with key differences in the material types. This is important information as it may direct which pipelines are ready for conversion and which may need additional protective systems. The learning will be disseminated through a final report issued at the end of the project. The work will be further disseminated through publications made by WMG and EPRI.

The field of hydrogen embrittlement and conversion of carbo-based gas systems to hydrogen-based ones is of great interest and so it is envisaged that a number of national, e.g. IoM3, and international, e.g. EPRI, conferences and workshops will provide suitable platforms to report the findings of this PhD to wiser materials and energy communities. Journal publications in specialist materials and energy journals will be actively pursued during the PhD. All publications will be agreed in advance with EPRI and National Grid.

Scale of Project

The scale of this activity is limited to laboratory testing and investigation into the microstructure of the pipelines and the impact of hydrogen on this. The project will be limited to a 9 month activity and on reviewing the findings may lead to further work in particular areas of interest. The PhD student supervised by Dr Strangwood and Dr West will be incorporating this work into their thesis and make this wider work available to the project partners on completion.

Technology Readiness at Start

TRL2 Invention and Research

Technology Readiness at End

TRL3 Proof of Concept

Geographical Area

The project will take place on the Warwick University Campus and led by the WMG team described above.

Revenue Allowed for the RIIO Settlement

None – Hydrogen network focussed project

Indicative Total NIA Project Expenditure

£68666 Gas Transmission NIA RIIO-2 Expenditure

£51500 EPRI funding partner contribution

Project Eligibility Assessment Part 1

Requirement 1

Facilitate the energy system transition and/or benefit consumers in vulnerable situations

Please answer **at least one** of the following:

How the Project has the potential to facilitate the energy system transition:

The project will determine the impact of a pipeline age on the material microstructure and impact of hydrogen. This will consider not only the grade of the material but the age and likely manufacturing process. Without this critical evidence hydrogen could be injected into a pipeline susceptible to hydrogen embrittlement severely reducing the lifetime of the asset.

How the Project has potential to benefit consumer in vulnerable situations:

Although this project does not directly affect vulnerable consumers the energy transition may and as such, we must consider the effect of the work we are doing through the NIA funding. The National Transmission System (NTS) is a key UK infrastructure for the transport of Gas to consumers, including those considered vulnerable. In a scenario where hydrogen replaces methane as a household heat source, it is essential the vulnerable are not excluded by virtue of fuel inaccessibility. In cases where vulnerable consumers already utilise gas it is likely that in a net zero future the optimum option is to provide a consistent energy solution. The transition to hydrogen within the NTS provides continuity of access to the vulnerable of hydrogen as a replacement to methane, with ongoing benefits of efficiency and economy of scale within a closely regulated environment. Ensuring robust NTS assets and consistent hydrogen production options will support the transition of the NTS to hydrogen which in turn supports the availability of gas to the vulnerable.

Requirement 2 / 2b

Has the potential to deliver net benefits to consumers

Project must have the potential to deliver a Solution that delivers a net benefit to consumers of the Gas Transporter and/or Electricity Transmission or Electricity Distribution licensee, as the context requires. This could include delivering a Solution at a lower cost than the most efficient Method currently in use on the GB Gas Transportation System, the Gas Transporter's and/or Electricity Transmission or Electricity Distribution licensee's network, or wider benefits, such as social or environmental.

Please provide an estimate of the saving if the Problem is solved

RIIO-1 question N/A

Please provide a calculation and/or description of the expected benefits of the solution

There will be no direct benefits from this project as it is a research activity.

Please provide an estimate of how replicable the Method is across GB

This project is focussed on metallic pipeline materials, it will therefore be relevant to any assets that utilise steel of grades X52, X60, X65 and X80.

Please provide an outline of the costs of rolling out the Method across GB.

N/A

Requirement 3 / 1

Involve Research, Development or Demonstration

Projects must have the potential to have a Direct Impact on a Network Licensee's network or the operations of the System Operator and involve the Research, Development, or Demonstration of at least one of the following (please tick which applies):

☐ A specific piece of new (i.e. unproven in GB, or where a method has been trialled outside GB the Network Licensee must justify repeating it as part of a project) equipment (including control and communications system software).

☐ A specific novel arrangement or application of existing licensee equipment (including control and/or communications systems and/or software)

☐ A specific novel operational practice directly related to the operation of the Network Licensees system

☐ A specific novel commercial arrangement

Involve Research, Development or Demonstration - Please select all that apply

☐ A specific piece of new equipment (including monitoring, control and communications systems and software)

☐ A specific piece of new technology (including analysis and modelling systems or software), in relation to which the Method is unproven

☑ A new methodology (including the identification of specific new procedures or techniques used to identify, select, process, and analyse information)

☐ A specific novel arrangement or application of existing gas transportation, electricity transmission or electricity distribution equipment, technology or methodology

☐ A specific novel operational practice directly related to the operation of the GB Gas Transportation System, electricity transmission or electricity distribution

☐ A specific novel commercial arrangement

Specific Requirements 4 / 2a

Please explain how the learning that will be generated could be used by the relevant Network Licensees

The learning from this project will provide insight into the impact of hydrogen on various metallic material structures, any metallic assets could be impacted by hydrogen and therefore this project could provide valuable insight for any network licensees with metallic assets that could be exposed to hydrogen.

RIIO-1 Question N/A

Is the default IPR position being applied?

☑ Yes

Project Eligibility Assessment Part 2

Not lead to unnecessary duplication

A Project must not lead to unnecessary duplication of any other Project, including but not limited to IFI, LCNF, NIA, NIC or SIF projects already registered, being carried out or completed. Networks must explicitly mention similar projects that they have considered and how these differ.

Please demonstrate below that no unnecessary duplication will occur as a result of the Project.

Benchmarking and literature reviews will be undertaken before commencing the project work. The team involved are academics with backgrounds in hydrogen material development whom are known as leaders in their field and have access to a wide range of data sources.

If applicable, justify why you are undertaking a Project similar to those being carried out by any other Network Licensees.

N/A

Additional Governance And Document Upload

Please identify why the project is innovative and has not been tried before

The impact of hydrogen on the microstructure of different grades and ages of NTS assets has not been conducted and is required to fully understand the impact of hydrogen.

Relevant Foreground IPR

Foreground IPR will consist of knowledge of microstructures of varying ages of NTS metallic assets and the impact of hydrogen on these systems. Known data on NTS assets will be shared to enable improved insights from the laboratory test work.

Data Access Details

Closure and technical reports will be made available through the ENA smart networks portal and via university and EPRI publication. Further data can be shared upon request through the innovation .box - box.GT.innovation@nationalgrid.com

Please identify why the Network Licensees will not fund the project as a part of it's business and usual activities

Hydrogen development activities are not included in the RIIO-2 final determination, this work is to be managed through the innovation funds and reopeners.

Please identify why the project can only be undertaken with the support of the NIA, including reference to the specific risks (e.g. commercial, technical, operational or regulatory) associated with the project

Hydrogen has not yet been confirmed as a net zero energy solution for the UK and may not be transported in the NTS. Work must be undertaken to inform decisions on this net zero energy option.

This project has been approved by a senior member of staff

☑ Yes