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NATURALHY

“Preparing for the hydrogen economy by using the existing natural gas system as a catalyst”

Integrated Project

6.1.ii Call 1 Sustainable Energy Systems

Final publishable activity report

Period covered from: 1 May 2004 up to 31 October 2009 Date of preparation: 25 March 2010

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Project coordinator organisation name: N.V. Nederlandse Gasunie

Final version

LIST OF CONTENT

DISCLAIMER

OVERALL SUMMARY

Hydrogen is an important element of a sustainable energy society: it can be produced in many ways including electrolysis of water, using electricity produced from wind or solar energy, or gasification of biomass and coal. It can be an important part of the synthesis gas (syngas) produced in a coal or biomass gasifier, or of (waste) gases of industrial processes. Pure hydrogen can be converted by fuel cells into electricity with high efficiencies. The pollutant emissions from the controlled combustion of hydrogen are very low.

The first logical step towards a transitional delivery system suitable for hydrogen and hydrogen-containing gases must be an investigation of the extent to which the existing assets, including the existing natural gas infrastructure, can be used for hydrogen delivery.

Generally speaking, a network designed for natural gas cannot be used for pure hydrogen for a number of reasons without modifications to network components or the way it is operated and maintained. However, the existing natural gas transmission, distribution and end use systems could be used for mixtures of natural gas and hydrogen given appropriate modifications. The mixture can be used as such and, if required, hydrogen appliances could be fuelled with “pure” hydrogen by developing devices to extract hydrogen selectively from the mixture.

Of course, for the accommodation of gases which contain a certain percentage of hydrogen it is important that the physical and chemical characteristics related to the composition of the gas fit sufficiently with the characteristics of natural gas, and do not initiate unacceptable risks for, for instance, the integrity of the gas system. The physical and chemical properties of hydrogen differ significantly from those of natural gas and the addition of a certain percentage of hydrogen to natural gas might have a direct impact on, for instance, the combustion properties, the diffusion into materials and the behavior of the gas mixture in air. In particular, the addition of hydrogen to natural gas may have an impact on, inter alia, the following aspects:

- Safety related to the transmission, distribution and use of gas.
- Integrity of pipelines.
- Gas quality management.
- The performance of end user appliances.

In order to determine the contribution the existing natural gas system could offer for hydrogen delivery, the following main objectives of the NATURALHY project have been defined:

- To define the conditions under which hydrogen (pure, or as a part of a mixture with other gases) can be added to natural gas in the existing natural gas system (transmission, distribution, end use, infrastructure and appliances) with regard to acceptable safety risks, benefits, impact on the integrity of the system, and consequences for gas quality management and for the end user.
- To develop technical options (particularly membranes) to separate hydrogen from hydrogen/natural gas mixtures;
- To assess the socio-economic and life cycle aspects of the NATURALHY approach, thus illustrating the real value of the NATURALHY project.

NATURALHY has been a significant project extending from May 2004 to end October 2009 to assess the capability of the natural gas networks to deliver hydrogen with many hours dedicated to testing and production of what is a vast array of data, much of it new. It is almost impossible to summarize the project in a short space and, in fact, unfair to do so. Indeed care must be taken in looking at summary results from this project and jumping to conclusions.

The data is often complex, with many provisos, given the immensity of what has been attempted and, for the most part, achieved. The reader is therefore urged not to grasp at what looks like a favourable or even an unfavourable result, without a deeper analysis of their own specific system.

1. Nevertheless, some attempt must be made to display the key findings of NATURALHY and they are presented below, but should be read while bearing in mind the remarks above.
    - With regard to durability of the materials used in the existing gas infrastructures, the obtained results show that addition of hydrogen gas in methane (main component of the natural gas) does not dramatically damage the studied materials in the foreseen range of hydrogen portion which is less than the half of H2 in natural gas.
    - Both cases of steels, representative of the old generation of steels (X52) and the new one (X70), for transmission pipes, can sustain some hydrogen addition without decreasing either the fracture toughness below the current threshold of design, or the fatigue crack growth resistance below the common standard values (BS 7910). The limit of hydrogen addition could even reach 50 %vol. according to the steel type and the operation conditions.
    - The polymer material (polyethylene, PE) used for the modern distribution pipelines, is obviously sensitive to hydrogen permeation through the pipe wall thickness; the hydrogen permeability is higher than the permeability of methane in the same conditions of operation. But the effect of ageing of hydrogen is not significant over the lifetime of PE pipes.
    - At the end of the gas chain, the most common domestic gas meters with a polymeric membrane are not show-stoppers and can reliably meter mixtures of hydrogen with NG up to 50 %vol. of H2.
    - The effect of hydrogen on the tightness of the materials for inner grids was another durability and safety concern. The range of materials used for these piping of gas installation in house is very wide. Among the steels and polymers of different types of tested piping and connexion, the rubber hose only failed the tightness tests.
2. Considering integrity, it is very important to know if additional measures regarding are needed to ensure a reliability level comparable to the currently operated natural gas system if hydrogen is transported in the existing pipelines. This is especially true for the inspection and repair of defects in particular for crack like defects as they can change their growth behaviour significantly when hydrogen is added. The main findings of the investigations performed on pipeline integrity and resource allocation are:
    - Adopted inspection tools based on MFL and TRIAX technologies are capable to detect crack like defects. EMAT technologies are even better suited to detect and size cracks and comparable defects. The technologies needs to verify in field tests the promising results that were achieved in the project by using pipe spools containing artificial and real defects.
    - The repair technologies “Clock Spring”, “Metallic Sleeve” and “Weld Deposit” were assessed as suitable for repairing hydrogen containing pipelines even though the performance was slightly reduced in some cases.
    - In a chosen example the effect of hydrogen on inspection and repair frequencies were calculated and the corresponding cost were determined. A moderate increase of costs for inspection and repair activities was observed as a consequence of hydrogen concentrations up to 50%, which is assessed as a very promising result.

Summarising the results overall, it can be stated that appropriate pipeline integrity management can be put in place for the transportation of natural gas and hydrogen mixtures by adopting existing systems especially in the field of pipeline inspection and optimising repair intervals.

3. It was anticipated that adding hydrogen to the gas infrastructure may affect both the likelihood and severity of untoward events and hence potentially increase the risk to the public. NATURALHY has established:
    a. that escapes of natural gas/hydrogen mixtures within buildings behave in a similar way to natural gas, in terms of the nature of the gas/air mixture produced. However, the gas concentration and volume of the accumulation increases as hydrogen is added but these increases are slight for hydrogen addition up to 50% by volume;
    b. within buildings, the severity of explosions is only slightly increased for hydrogen addition around 20%. Analysis has suggested that the explosion frequency could increase by up to a factor of 2 as a result of adding 20% by volume hydrogen to natural gas. However, the current risk is very low and even with a 2x increase the risk remains within generally acceptable limits;
    c. from the point of view of the pipeline operator, the principal hazard posed by the failure of transmission pipelines is that of a large fire. Project results suggest that the addition of hydrogen increases the risk to an individual at locations near the pipeline but decreases the risk at locations further away, as the extent of the hazardous region is reduced;
    d. pipeline operators need to assess the background level of leakage from their pipeline networks, since methane is greenhouse gas. A study of the expected background level of leakage has shown that the level of leakage overall is very small and poses no hazard from a safety point of view. Indeed, the addition of hydrogen results in a slight decrease in the level of methane emissions to the atmosphere from the gas infrastructure, which is beneficial from an environmental perspective.

4. Regarding the end users of natural gas with hydrogen added, particular attention goes to domestic appliances as personal health and home safety are at stake and tens of millions of appliances per country are involved. It’s important to note that:

    - the maximum hydrogen concentration for the domestic market in any country is determined by the safe operation of properly adjusted conventional domestic appliances as well as by the local conditions of natural gas quality (range and current value of Wobbe Index);
    - for properly adjusted appliances and favourable conditions of natural gas quality, conventional domestic appliances can accommodate up to 20% of hydrogen;
    - for poorly adjusted appliances and/or unfavourable conditions of natural gas quality, no hydrogen admixture is allowed;
    - stationary gas engines and gas turbines need readjustment and/or modification;
    - feedstock processing and industrial combustion applications require case by case consideration;

5. Gas quality issues have been considered, in the case of adding hydrogen to the natural gas network, as well as the effect on downstream gas quality as hydrogen is selectively withdrawn by end-users. In a scenario where end users at different points in the network may be taking out hydrogen at different quantities and qualities, there will be an effect on the gas quality of the remaining natural gas mixture. However, analysis shows that the downstream gas quality will not be adversely affected since the Wobbe index and heating value can be assumed to still remain within the statutory requirements. But it should be noted that resulting hydrogen concentration variations can be expected to pose problems to gas engines, gas turbines and industrial applications.

6. Thin-film Palladium-based Membrane systems have been developed that generate a very good hydrogen flux. These operate at around 300C. Carbon-based membranes operating at 30-90C have been optimised for high flux and hydrogen recovery. These materials show better performance than current commercial polymer membranes .Fibre spinning techniques have been employed to produce these membranes in the form of hollow tubes which can be bundled into a membrane system.

7. The Decision Support Tool (DST) has two functions: to inform what is expected in material and device behaviour at particular hydrogen percentages; and to simulate, using its ‘what-if’ analysis, the actual pipeline degradation behaviour over certain periods of time.
   The analysis comprises risk assessment, cost assessment, evaluation, and proposal of rules, guidelines and procedures that will mitigate the expected increase of risk and/or costs when applying the gas mixture to the pipeline network.

   It also provides a comprehensive toolbox that enables the user to simulate a Gas Technology Network (GTN) to enable comparisons between a GTN with or without hydrogen addition. The DST is extremely flexible and is able to carry out GTN simulation and comparison of any two configurations over a period of up to 50 years, yielding cost, safety and integrity calculations for all selected sections.

8. The potential benefits of adding hydrogen to the natural gas system have been addressed in a review of life cycle and a socio-economic assessment and it has been possible to quantify benefits. However, the following conclusions are, necessarily, qualitative:

   - the addition of hydrogen to natural gas can make a significant reduction in total greenhouse gas emissions if it is sourced from certain forms of biomass (forestry residues, straw and miscanthus), wind power (both onshore and offshore) and nuclear power. Depending on circumstances, hydrogen production from fossil fuels with carbon capture and storage (CCS) also offer some advantages. However, reductions in total greenhouse gas emissions with these sources of hydrogen are generally lower;
   - potential benefits of selective extraction of hydrogen depend on the actual performance of the separation technology and the subsequent use of the hydrogen (including its required purity) and the residual gas (which still contains some hydrogen). However, overall air quality benefits (especially lower sulphur dioxide, oxides of nitrogen and particulate emissions) can arise if hydrogen is subsequently used in transportation and displaces conventional diesel fuel;
   - the addition of hydrogen can be an effective means of "greening" natural gas so that the mixture is used directly in existing appliances for heat production and electricity generation. With this option, the potential benefits are mainly as a practical measure for mitigating global climate change and increasing energy security, depending on the original source of the hydrogen.

In a few words and certainly not striving to be comprehensive, it can be concluded the results indicate that from the safety, integrity and durability point of view (safety considering pipeline operations and pipeline integrity; durability considering the life span of pipeline systems) the acceptable hydrogen level can be significant (several tens of percent) depending on the mitigating measures taken by the operator. The safe use of a natural gas-hydrogen mixture in buildings (severity of explosions) and the performance characteristics of some existing gas appliances determine the ceiling. Safe use in buildings and with properly adjusted conventional appliances a limit of approximately 20% hydrogen in the mixture is not leading to unacceptable consequences. However for poorly adjusted appliances and/or unfavourable conditions of natural gas quality, no hydrogen admixture is allowed without mitigating measures.

In all cases it might be possible to increase the maximum allowable percentage of hydrogen if additional measures are taken. The feasibility of these additional measures will be addressed by the results of life cycle and socio economic assessment as well as the Decision Support Tool (DST) that was developed to give pipeline operators a tool in hands to determine the allowable hydrogen percentage in their grids. The costs associated with additional measures need to be looked at in perspective of the very large investments needed to construct extensive, new networks to transport hydrogen.

NATURALHY has kept abreast of the developments in other hydrogen projects in Europe and the USA. Most research is concentrated on hydrogen for automotive purposes, like fuel cells and light weight hydrogen storage tanks. Only a very limited number of research project is dedicated to the examination of the existing natural gas networks for transport of hydrogen or a hydrogen – natural gas mixture. Some materials research is taking place in the USA under government contract (DOE).

The results obtained by NATURALHY are clarifying and elaborating the feasibility of using the existing gas grid for the transmission of natural gas - hydrogen mixtures. At the completion of the project it can be concluded that research performed within the framework of the NATURALHY project has not identified any major barriers to the addition of hydrogen at a useful level in the existing natural gas networks. In addition to answering the essential question of “what is the maximum allowable percentage of hydrogen”, it has also considered that the option of “greening” natural gas may be more feasible and attractive than transporting a mixture for subsequent separation of the hydrogen at the point of end use.

1 INTRODUCTION

1.1 HYDROGEN AS A FUEL

Hydrogen is widely proposed as an important energy carrier in the future sustainable energy society, as a means of increasing security of supply and reducing carbon dioxide and other emissions associated with pollution and global warming. More particularly, it is believed that utilizing hydrogen and gases containing hydrogen will make a significant contribution to security of supply by utilizing locally available primary energies like gasified biomass; reducing CO_2 emissions by replacement of fossil fuels with hydrogen from renewables, or from fossil fuels with CO_2 sequestration, or by the implementation of the process for removing carbon (as a solid) from natural gas to produce "hydrogen-enriched natural gas". These options contribute to de-carbonisation and greening of our energy economy.

As hydrogen can be converted into electricity and vice-versa with high efficiency, it has potential for the indirect storage of electrical energy (e.g. in case electricity production from wind and solar energy exceeds the demand). This technology also increases the option for utilizing (waste) gases that contain hydrogen and enable the development of power plants based on coal and biomass gasification in combination with carbon capture and storage (CCS) to reduce greenhouse gas emissions, in spite of the fact that the gasification process demands a high load factor. Furthermore, hydrogen could improve local air quality by replacing petrol and diesel in cars and buses.

1.2 HYDROGEN DELIVERY

Gas network operators are very interested in de-carbonising natural gas and in adding sustainable produced gases to natural gas infrastructures since this leads to de-carbonising of their business operations, provides new business opportunities as well as improves corporate image. Hydrogen can be used as a pure gas (for example in fuel cells, internal combustion engines and turbines) and also as a mixture with natural gas in internal combustion engines, stationary applications and in some fuel cells.

However, because of a lack of infrastructure, the transition towards large scale production, delivery and use of hydrogen will be long-term, extremely costly and only achievable with a substantial research and development effort over many years. The first logical step towards a transitional delivery system suitable for hydrogen and hydrogen-containing gases must be an investigation of the extent to which the existing assets, including the existing natural gas infrastructure, can be used for hydrogen delivery.

1.3 NATURALHY APPROACH

The NATURALHY project aims to support the transition towards widespread use of hydrogen by utilising existing and highly developed European natural gas networks for the delivery of hydrogen to end-users. The project focused on the transmission, distribution and use of mixtures of hydrogen and natural gas. Techniques to separate hydrogen from said mixtures were investigated as well. This approach obviates the need to construct a wholly new distribution infrastructure, which (like the natural gas network developed over decades) would require an investment of presumably many hundreds of billions of Euro.

In general, it is not possible to simply replace natural gas by hydrogen in existing natural gas networks as the physical and chemical properties of hydrogen differ significantly from natural gas. Safety and durability of the natural gas grid, as well as the performance of end use appliances, would be fundamentally affected. Nevertheless existing natural gas networks could be suitable for mixtures of natural gas and hydrogen and the concept of transporting and using mixtures safely was the specific focus of investigation in the NATURALHY project. The purpose of this project was to define the conditions under which the existing natural gas network (transmission and distribution system, end user infrastructure and end user appliances) could be used for mixtures of natural gas and hydrogen. In addition, within the scope of the NATURALHY project, innovative membranes have been developed that allow the selective withdrawal of hydrogen from a mixed natural gas/hydrogen stream. Such development offers a unique opportunity to connect hydrogen producers and end users in the short term at relatively low cost. The concept which underpins the approach adopted by the NATURALHY project, further catalyses developments in hydrogen production and end use and, during the transitional phase, provides more time to define the future, including the role of hydrogen therein, in sufficient detail.

The strategic aspects of the project and its relevance to current world-wide activities in introducing hydrogen have been addressed in the Strategic Justification for the project and this can be found at the NATURALHY website: http://NATURALHY.net/docs/Strategic_justification_NATURALHY.pdf

Thus the main aim of the NATURALHY project has been to define the conditions under which the existing European wide natural gas network (transmission and distribution system, end-user infrastructure and end user appliances) can be used for hydrogen - natural gas mixtures. Furthermore, the project aimed to further develop techniques to separate hydrogen from said mixtures, and to determine the overall socio-economic and environmental benefits of the NATURALHY approach. It should be emphasised that the NATURALHY project focused on potential showstoppers.

The NATURALHY approach leads to two specific options depending on future development scenarios:

- The addition, distribution and end-use of mixtures of natural gas and hydrogen will be a significant contribution to the “greening of gas” i.e. to reduce global warming impacts of natural gas operation and use.
- The transmission and distribution of hydrogen in natural gas networks and then separation of the hydrogen provides a real opportunity for end users to obtain pure, or nearly pure, hydrogen for a variety of applications, thus helping to create “local hydrogen centres” and enabling the accelerated transition towards a hydrogen energy society.

To realize these goals the effect of the addition of hydrogen on the operation of gas networks and end use appliances have been assessed. For the second option low cost and efficient means for separating hydrogen from the natural gas / hydrogen mixture have been developed.

1.4 NATURALHY IN THE WORLD

The NATURALHY Project has been a world-wide forerunner in researching the detailed impacts hydrogen addition has on the existing natural gas networks. This work has attracted interest from international gas operators and gas research organisations. Strong links have been forged with European, US and Asian organisations attaching great importance to delivering hydrogen to end users. In addition to the execution of the agreed work programme within the NATURALHY project, which is overseen by the Project Executive Committee, views were exchanged with a Strategic Advisory Committee consisting of a select group of representatives from relevant national and international organisations such as the International Gas Union, International Hydrogen Energy Association, the European Gas Research Group (GERG), the European Commission and European Parliament, United States Department of Energy, and the United Kingdom Health and Safety Executive.

1.5 NATURALHY OBJECTIVES

Principal technical and strategic project objectives of the project are listed below.

- **To define the technical conditions under which hydrogen can be accommodated in the existing natural gas system** with acceptable risk and avoiding unacceptable leakage and significant degradation of the system and consequences for the end users. Work Packages WP2, WP3, WP4, and WP5 have focussed on their respective programmes of safety, integrity, durability and end use appliances to cover the essential aspects of the existing natural gas network and end use.

- **To carry out life cycle assessment (LCA)** as a means of comparing the major resource inputs and environmental outputs of current natural gas and related systems and transitional natural gas/hydrogen systems including methods of hydrogen production.(WP1)

- **To analyse the socio-economic aspects** of transitional natural gas/hydrogen systems and compare these with current natural gas and related systems with particular reference to job creation and maintenance, capital investment and total internal costs.(WP1)

- **To develop innovative devices (membranes)** to separate hydrogen from natural gas - hydrogen mixtures: these devices will enable an early establishment of hydrogen growth centres that will advance a gradual transition to the full hydrogen economy. (WP5)

- **To assess the current situation of standards and regulations** regarding natural gas/hydrogen mixtures and to identify necessary modifications and to initiate required changes.(WP7)

- **To develop a Decision Support Tool** for assessing the technical suitability of an existing natural gas system (transmission, storage, distribution, end user infra structure and end user appliance) for mixtures of natural gas/hydrogen and to develop models for determining the environmental, employment and economic aspects of the whole chain from sustainable hydrogen production up to and including end user appliances (WP1,WP2,WP3,WP4,WP5,WP6)

- **To motivate all stakeholders** in the whole chain from production up to and including end use to welcome “hydrogen”. Such stakeholders consist of among others, the public, end users, manufacturers of appliances, owners and operators of gas transmission grids, hydrogen producers, local, regional and national authorities, manufacturers of all kinds of equipment and components for gas, etc. This objective was met in cooperation with among others the HyWays Integrated Project and the HySafe Network of Excellence (WP1,WP2,WP3,WP4,WP5,WP6,WP7):

The main technical deliverable of the project is an expert system, the “Decision Support Tool”, which can be used to determine the maximum percentage of hydrogen that can be added to natural gas supplied in any given section of a natural gas pipeline system and identify the factors that limit the percentage.

It should be noted that although the objectives of the NATURALHY project concern hydrogen-natural gas mixtures, the outcomes are very relevant for defining the conditions under which the existing natural gas system can be used for biogas, hydrogen produced from syngas, and other sustainable produced gases containing a certain amount of hydrogen, including SNG. Moreover, the information gained in this project can be used to determine to which extent the existing pipeline network can be used for the delivery of pure hydrogen. In this specific case, changing the operational conditions, particularly the pressure regime, and some of the hardware (e.g. compressors) would seem to be a necessity.

1.6 ORGANISATION OF THE WORK

In order to meet the objectives mentioned in paragraph above, a set of coherent Work Packages, detailed below, has been defined within the NATURALHY project. The way they cohere is indicated in the following diagram.

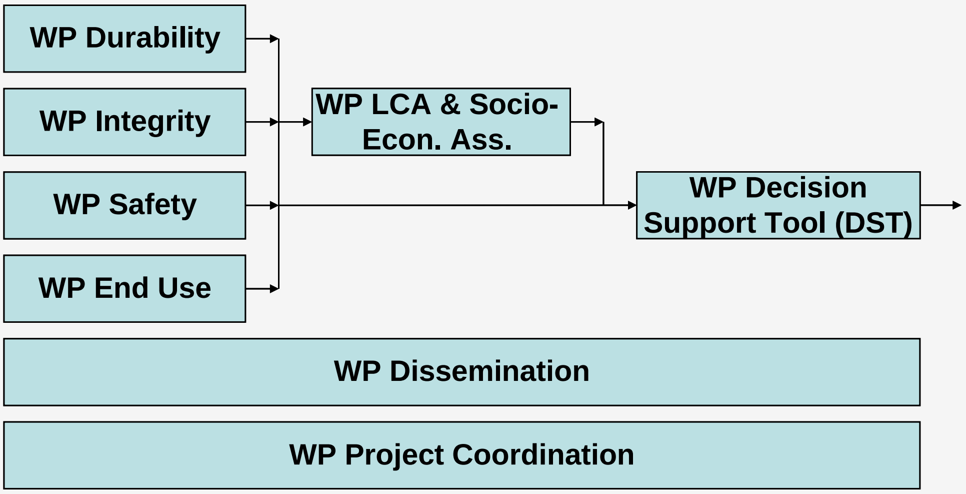

Figure 2.1 Schematic overview of the main relations between the Work Packages defined

WP1 Life Cycle and Socio-economic Assessments comprises a comparison of the main natural resource requirements, environmental impacts, employment consequences and economic costs over the complete life cycle of current natural gas and related energy systems and the proposed transitional natural gas/hydrogen systems from source to point of use.

WP2 Safety enables the risks presented by the transmission, distribution and use of a hydrogen/natural gas mixture to be compared with those for natural gas. To ensure credibility amongst system operators, the major hazard scenarios previously studied for natural gas and pure hydrogen are re-examined experimentally for hydrogen/natural gas mixtures. Tests include investigation of explosions and build up of gas in confined/vented enclosures and congested regions, high pressure jet fires and pipeline fires. Large scale experimental testing is crucial to the NATURALHY project as fire and explosion phenomena are scale dependent. The results are used to modify existing risk assessment methodologies, developed originally for natural gas. The modified risk assessment methodologies are currently used to undertake risk assessments to compare with those completed for the existing natural gas system.

WP3 Durability determines the effects of hydrogen on the durability of materials and components used in the natural gas transmission and distribution networks and end user infrastructure. Existing defect assessment criteria are adapted to take into account an increasing percentage of hydrogen in natural gas. The results are being processed to produce durability lifetime models. This will enable the assessment of the ageing of materials and components and to provide a practical way of evaluate the system lifetime given its characteristics and the percentage of hydrogen.

WP4 Integrity provided a specification for an Integrity Management Tool (IMT). The specification developed support the operators to modify the existing Integrity Management Systems (IMS) covering the needs raised by the challenge to transport hydrogen-natural gas mixtures in the existing pipelines, which were constructed to carry natural gas. The activities cover the identification of defects sensitive to hydrogen, their critical sizes as well as inspection and repair technologies. Furthermore the effect of introducing hydrogen in natural gas on the costs for operating the integrity management was investigated.

WP5 End Use examines the implications of providing distributed pipeline natural gas/hydrogen mixtures to end-users and the effect on existing appliances. A survey and analysis of existing data has been undertaken to assess the impact of added hydrogen on the performance characteristics of existing natural gas appliances including, domestic and industrial burners, particularly industrial burners used for glass industry. This has led to an understanding of the requirements for existing and new appliances to operate safely and efficiently with increasing levels of hydrogen. A R&D programme was conducted to develop high efficiency membranes and to provide options for separating hydrogen from the distributed hydrogen/natural gas stream for end-use applications at various scales. Methods for ensuring the gas quality as hydrogen is progressively removed are assessed.

WP6 Decision Support Tool develops an expert system to assess the suitability of an existing gas system (including transmission and distribution pipelines, end user appliances and operational aspects) to cope with whichever hydrogen/natural gas mixture is proposed. With this tool, NATURALHY deals with the fact that no general, simplistic figures on acceptable hydrogen percentages to be added to natural gas can be determined. As explained before, the determination of the suitability of a natural gas system for hydrogen must be made by a rigorous examination of the specific conditions pertaining.

WP7 Dissemination ensures that the results of the NATURALHY project are made available to targeted technical/scientific stakeholders and decision makers at various levels. It achieves this via a series of appropriate actions, including publications, workshops, technology transfer activities and regular interfaces with government bodies, safety authorities, standards bodies, consumer organisations, environmentalists and decision-makers at both national and European levels.

Each Work Package is led by a Work Package leader (WP-leader), which are indicated below.

Number	**Work Package**	**WP-leader, person + contact information**
WP1	Life Cycle and Socio-Economic Assessment	University of Loughborough*), Nigel Mortimer, +44 1904 410 643, n.d.mortimer@lboro.ac.uk
WP2	Safety	University of Loughborough, Geoff Hankinson, +44 1509 222540, g.hankinson@lboro.ac.uk
WP3	Durability	GDF SUEZ (previously Gaz de France), Isabelle Alliat, +33 149225871, isabelle.alliat@gazdefrance.com
WP4	Integrity	DBI GUT**), Gert Müller-Syring, +49 3412457129 Gert.Mueller-Syring@dbi-gut.de
WP5	End-use	University of Oxford*), Ashok Bhattacharya & Costa Komodromos, +44 1865 273627, ashok.bhattacharya@eng.ox.ac.uk
WP6	Decision Support Tool	Instituto de Soldadura e Qualidade (ISQ), Peter Bartlam, +35 1214229014, pbartlam@isq.pt

WP7	Dissemination[1]	Exergia, George Vlondakis, +302106996185, vlondakis@exergia.gr
WP8	Project management	N.V. Nederlandse Gasunie, Onno Florisson, +31 50 700 9732, NATURALHY@gasunie.nl

*) at the start of the project, University of Warwick (UK) was leading these two Work Packages; on its request Warwick was discharged and as from November 2006 the partners mentioned in the table took over.
**) at the start of the project Netherlands Organisation for Applied Scientific Research (TNO) was leading this Work Package: on its request TNO was discharged, and from May 2006 DBI-GUT took over this task;

1.7 THE NATURALHY CONTRACTORS

The following table shows the partners involved.

NATURALHY partners and their nationalities			
N.V. Nederlandse Gasunie	NL	Instituto de Soldadura e Qualidade	P
Högskolan | Borås	SE	Leeds University	UK
BP Gas Marketing Limited (BP)	UK	Loughborough University	UK
Commissariat àl’énergie atomique	F	Türkiye Bilimsel ve Teknik Arastirma Kurumu	TR
Comp. d’Etudes des Technologies de l’ Hydrogè	F	Netherlands Organisation for Applied Scient. Research	NL
Computational Mechanics International	UK	Nederlands Standaardisatie Instituut (NEN)	NL
European Ass. for Promotion Cogeneration	B	National Technical University of Athens	EL
Centro Sviluppo Materiali Spa	I	Norwegian University of Science and Technology	NO
DBI Gas- und Umwelttechnik	D	X/ Open Company Limited	UK
Hellenic Gas transmission System Operator	EL	Ecole d’ingénieur de Metz	F
Danish Gas Technology Centre	DK	SAVIKO Consultants ApS	DK
Energy Research Centre of the Netherlands	NL	Shell Hydrogen B.V	NL
EXERGIA, energy and Environment Consultants S.a	EL	STATOIL ASA	NO
Technische Universität Berlin	D	SQS Portugal	P
GDF SUEZ	F	Total S.A	F
General Electric PII Ltd	UK	Naturgas Midt-Nord	DK
EUROGAS – GERG (European Gas Research Group)	B	PLANET-Planungsgruppe Energie und Technik GbR	D
The Health and Safety Executive	UK	National Grid Gas plc	UK
Istanbul Gas Distribution Co. Inc	TR	University of Oxford	UK
Institut Français du Pétrole	F	University of Warwick*	UK

* The University of Warwick left the consortium during the course of the project

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[1] The NATURALHY project website can be found at: www.NATURALHY.net

2 LIFE CYCLE AND SOCIO-ECONOMIC ASSESSMENT – WORK PACKAGE 1

2.1 OBJECTIVES

The main objectives of Work Package 1 of the NATURALHY Project consist of providing the means to conduct life cycle assessment of the major natural resource inputs and environmental outputs, and socio-economic assessments of economic costs and employment (or job creation) for current natural gas and related energy systems, and transitional natural gas/hydrogen systems. For this purpose, life cycle assessment concentrates on primary energy inputs relevant to energy resource depletion, greenhouse gas emissions, including carbon dioxide, methane and nitrous oxide, associated with global climate change, hydrogen emissions (when known), air quality pollutants, consisting of sulphur dioxide, oxides of nitrogen and particulates, and ionising radiation (when determined). Socio-economic assessments focus on internal economic costs and estimates of direct and indirect employment. A modular approach is necessary to ensure that all components of the systems under investigation can be evaluated in a coherent and effective manner. Meaningful and persuasive comparison of the relative benefits of current natural gas and related energy systems, and transitional natural gas/hydrogen systems is based on recording the information and presenting calculations in a standard and transparent format.

2.2 CONTRACTORS

The contractors involved in this Work Package were Loughborough University (leader), COGEN Europe, ECN – Energy Research Centre of the Netherlands, ISQ - Instituto de Soldadura e Qualidade, PLANET – Planungsgruppe Energie und Technik GbR, SAVIKO Consultants ApS, and Technische Universität Berlin.

2.3 METHODOLOGY AND SCOPE

In order to achieve these objectives, it was necessary to develop a series of electronic workbooks which could represent the relevant technologies adequately, provide a transparent means of documenting calculations, data and sources, and present results in a clear and understandable form. Using previous experience, it was decided to use MS Excel as a basis for these workbooks. A standard structure was devised for these workbooks so that they consist of a series of the following specific worksheets:

- Version worksheet; documenting the author, date and main modifications of the latest version of the workbook
- Input/Output worksheet; a table for entering values of the key parameters for the technology being evaluated with their details and default values
- Unit Flow Chart worksheet; a visual representation of the process stages which constitute the technology being evaluated with details of parameters which specify these stages
- Life Flow Chart worksheet; a visual representation of the phases of the technology being evaluated with details of parameters which specify these stages
- Allocation worksheet; a means of partitioning environmental impacts, employment implications and economic costs between multiple outputs from the technology being evaluated
- Global Warming Potentials worksheet; a means of specifying global warming potentials for greenhouse gases
- Time Profile worksheet; a specification of the phases of the technology being evaluated mainly consisting of construction, operation and maintenance, and decommissioning
- Summary worksheet; a tabular and graphic summary of results from the evaluation of environmental impacts, employment implications and economic costs for the technology in question
- Process Stage worksheets; a collection of calculation worksheets which represent the individual process stages of the technology being evaluated
- Reference worksheet; a record of the sources of data used in the workbook

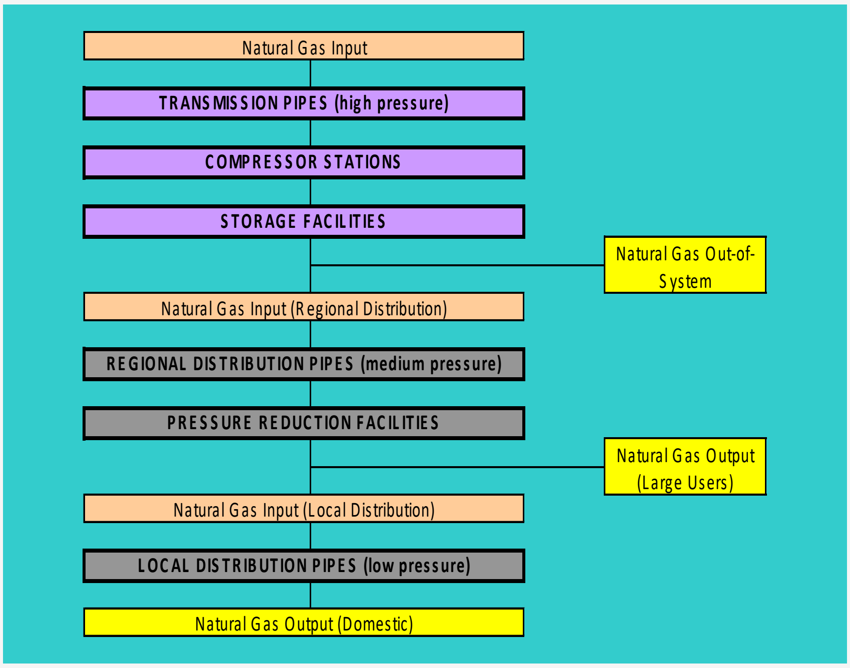
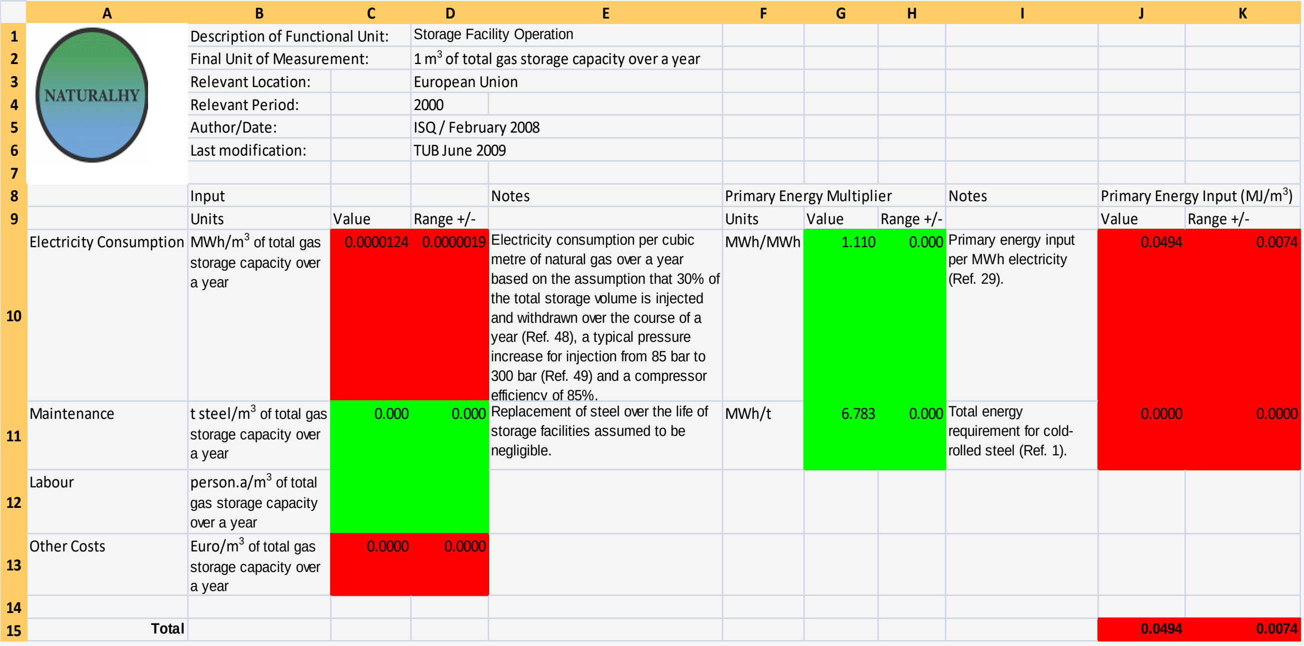


Figure 3.1 Unit Flow Chart for a natural gas network

Amongst the most important components of the workbook are the Unit Flow worksheet, as this describes and specifies the essential components of any given technology, the individual Process Stage worksheets, as these contain the basic calculations for environmental impacts, economic costs and employment implications, and the Summary worksheet, as this presents the results of all calculations. A simplified representation of the Unit Flow Chart (Figure 3.1) for a natural gas network shows that the technology is composed of a series of specified processes, or components.

The individual Process Stage worksheets all have the same regular layout to assist data entry, analysis and presentation. An example of part of a Process Stage worksheet (Figure 3.2) indicates that the basic features of the process under consideration, such as its nature (functional unit), its units of measurement, relevant location and period, the author of the worksheet and when it was last modified, are summarised in Rows 1 to 6 of the worksheet. Descriptions of the inputs to a process are described briefly in Column A, units of measurement in the Column B, with data values and ranges in Columns C and D, respectively, and supporting notes, including references, in Column E. The multipliers used to convert these into environmental impacts, economic costs and employment effects, and estimated results are then recorded, in subsequent columns. In this example, the units of the primary energy multipliers are specified in Column F, their values and ranges with supporting notes are provided in Columns G, H and I, respectively, and results, in the form of the estimated values and ranges of the primary energy inputs, are presented in Columns J and K, respectively. This layout is repeated across the workbook for other multipliers and results.



	A	B	C	D	E	F	G	H	I	J	K
1	NATURALHY	Description of Functional Unit:		Storage Facility Operation							
2		Final Unit of Measurement:		1 m^3 of total gas storage capacity over a year							
3		Relevant Location:		European Union							
4		Relevant Period:		2000							
5		Author/Date:		ISQ / February 2008							
6		Last modification:		TUB June 2009							
7											
8		Input			Notes	Primary Energy Multiplier			Notes	Primary Energy Input (MJ/m^3)	
9		Units	Value	Range +/-		Units	Value	Range +/-		Value	Range +/-
10	Electricity Consumption	MWh/m^3 of total gas storage capacity over a year	0.0000124	0.0000019	Electricity consumption per cubic metre of natural gas over a year based on the assumption that 30% of the total storage volume is injected and withdrawn over the course of a year (Ref. 48), a typical pressure increase for injection from 85 bar to 300 bar (Ref. 49) and a compressor efficiency of 85%.	MWh/MWh	1.110	0.000	Primary energy input per MWh electricity (Ref. 29).	0.0494	0.0074
11	Maintenance	t steel/m^3 of total gas storage capacity over a year	0.000	0.000	Replacement of steel over the life of storage facilities assumed to be negligible.	MWh/t	6.783	0.000	Total energy requirement for cold-rolled steel (Ref. 1).	0.0000	0.0000
12	Labour	person.a/m^3 of total gas storage capacity over a year									
13	Other Costs	Euro/m^3 of total gas storage capacity over a year	0.0000	0.0000							
14											
15	**Total**									**0.0494**	**0.0074**

Figure 3.2 An example of part of a Process Stage worksheet

The complete series of Process Stage worksheets for any given technology supplies relevant data to the Summary worksheet where final results are derived and presented. As each Process Stage worksheet provides results in units relevant to the process under consideration, these results are converted to appropriate units for the entire technology, as a collection of processes, specified by the Unit Flow Chart worksheet. Such results are detailed in tabular form and presented in graphical form. An example of the graphical presentation of results (Figure 3.3) shows the contributions of different aspects of natural gas network operation to the delivery of natural gas to large users.

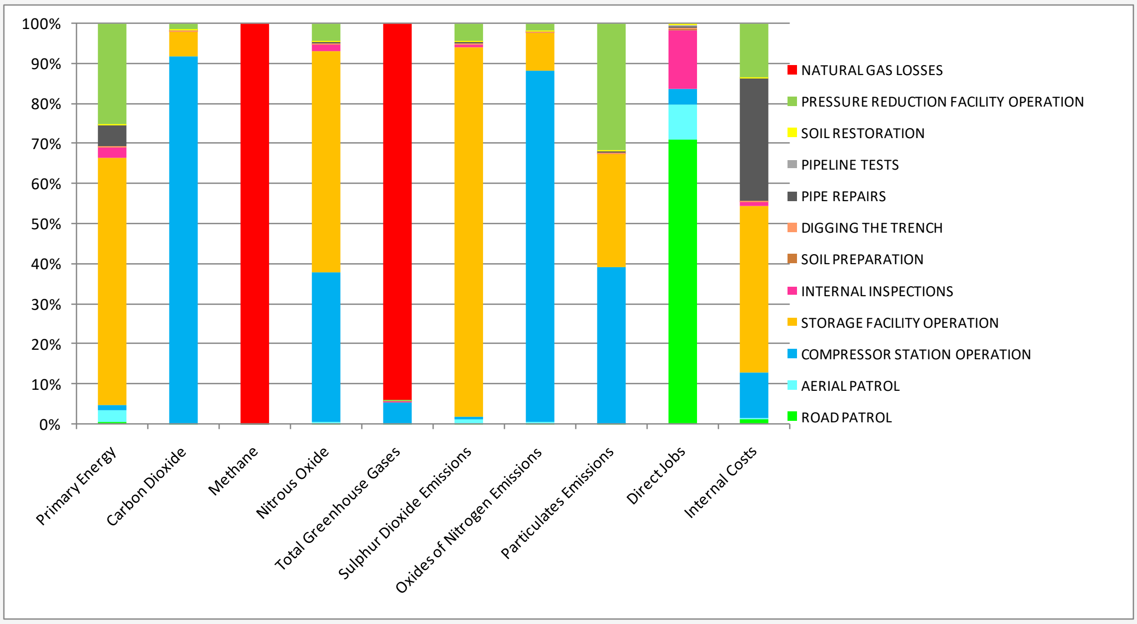


Figure 3.3 An example of the graphical presentation of results showing the contributions of different aspects of natural gas network operation to the delivery of natural gas to large users.

During the NATURALHY Project, workbooks were produced for a number of relevant technologies. However, essential workbooks, which were required for the Decision Support Tool (DST developed by Work Package 6, represent the following technologies:

- Natural gas supply
- Natural gas network construction
- Natural gas network operation
- Natural gas network decommissioning
- Natural gas hydrogen network operation

Whilst such workbooks could not address the exhaustive engineering complexity and detail of actual natural gas networks, parameters were selected to ensure necessary functionality which would enable results to represent specified networks appropriately. For this purpose, the main parameters for the user to specify any given natural gas network consist of:

- Natural gas flow rates (m^3/h):
    - Out-of-system users (to other natural gas networks)
    - Large users (to industrial consumers)
    - Local users (to commercial and domestic consumers)
- Transmission pipes (head stations):
    - Length (km), diameter (mm) and wall thickness (mm)
    - Repair frequency (number/km.a)
- Transmission pipes (high pressure):
    - Natural gas losses (%)
    - Pipes (16 possible options) defined by total length (km), diameter (mm), wall thickness (mm) and material (steel)
    - Road, aerial and internal inspection frequencies (fraction of pipeline inspected/a)
    - Repair frequencies (number/km.a)
    - Length of pipe removed during decommissioning (km)
- Compressor stations:
    - Total number of reciprocating engine and turbine compressor stations
    - Land area (ha/station)
    - Compression ratios for reciprocating engine and turbine compressor stations (m^3/m^3)
    - Annual maintenance and repair costs (% of initial capital costs)
    - Material recycled during decommissioning (%)
- Storage facilities:
    - Number of injection/withdrawal wells
    - Well volume (m^3)
    - Annual maintenance and repair costs (% of initial capital costs)
- Regional distribution pipes (medium pressure):
    - Natural gas losses (%)
    - Pipes (16 possible options) defined by total length (km), diameter (mm), wall thickness (mm) and material (steel, polyvinylchloride, polyethylene and iron)
    - Road and aerial inspection frequencies (fraction of pipeline inspected/a)
    - Repair frequencies (number/km.a)
    - Length of pipe removed during decommissioning (km)
- Pressure reduction facilities (large):
    - Number
    - Natural gas capacity (m^3/h)
    - Annual maintenance and repair costs (% of initial capital costs)

    - Material recycled during decommissioning (%)
- Local distribution pipes (low pressure):
    - Natural gas losses (%)
    - Pipes (16 possible options) defined by total length (km), diameter (mm), wall thickness (mm) and material (steel, polyvinylchloride, polyethylene, iron and copper)
    - Repair frequencies (number/km.a)
    - Length of pipe removed during decommissioning (km)

2.4 RESULTS

Various results can be generated using the natural gas workbooks produced from the NATURALHY Project. For example, the relative contributions to total primary energy, emissions and economic costs of the natural gas delivered by the network to out-of-system users, large users and local users can be evaluated (Figure 3.4).

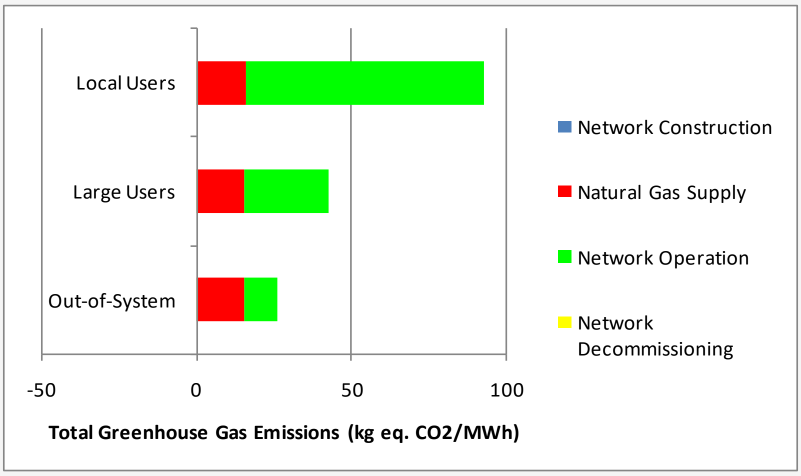


Figure 3.4 For example, the relative contributions to total primary energy, emissions and economic costs of the natural gas delivered by the network to out-of-system users, large users and local users

Apparent differences are due to the proportions of natural gas flowing through different parts of the network and the significance of different components in the network (leakages, compressor station and storage operations, etc.). Similarly, the breakdown of total greenhouse gas emissions for natural gas delivered to different users by phase of development (natural gas supply, and network construction, operation and decommissioning) can be determined (Figure 3.5). From this example, it can be seen that network construction and decommissioning are relatively insignificant contributions to the total greenhouse gas emissions of natural gas delivery to end users. The contributions of network operation varies depending on the nature of the user and extent to which they rely on different parts of the network to obtain natural gas; only part of the transmission network is used to supply out-of-system users, parts of the transmission and regional distribution networks are used to supply large users, and parts of the transmission and regional distribution networks and all the local distribution network are used to supply local users.

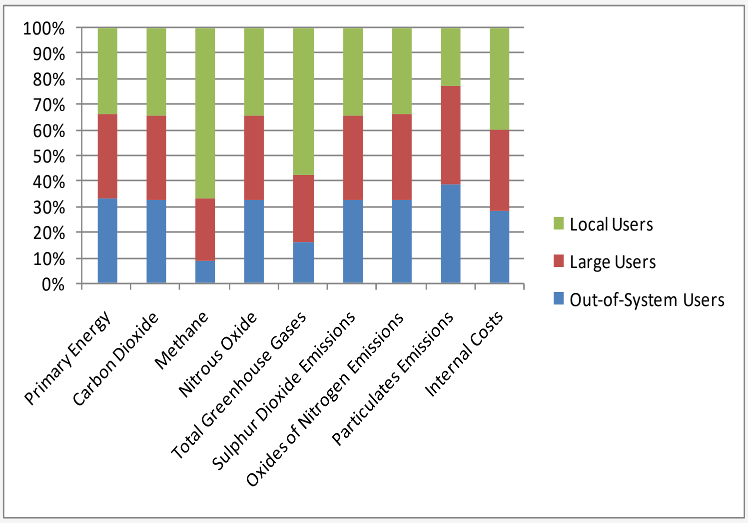


Figure 3.5 The breakdown of total greenhouse gas emissions for natural gas delivered to different users by phase of development (natural gas supply, and network construction, operation and decommissioning)

The workbook for natural gas network operation provided the basis of developing the essential workbook which represents the operation of an existing network with the addition of hydrogen. This consists of the injection of hydrogen from given sources, its transport as a mixture with natural gas through the network, its possible removal using specified separation technologies, and its eventual use (as hydrogen or in a mixture with natural gas). The original source of hydrogen is one of a number of important factors which determine the relative advantages or disadvantages of transporting this energy carrier with natural gas in existing networks. Hence, it was necessary to assemble representative results for the generation of hydrogen from different sources as well as conventional energy technologies and a variety of relevant end use applications. For ease of use, these results were incorporated into a Library of Results which represents 97 technology options. Significant differences in results are apparent, as demonstrated by the example of total greenhouse gas emissions (Figure 3.6) for hydrogen generation. These results can be compared with the total greenhouse gas emissions for the conventional supply, delivery and combustion of natural gas (indicated by the red dashed lines).

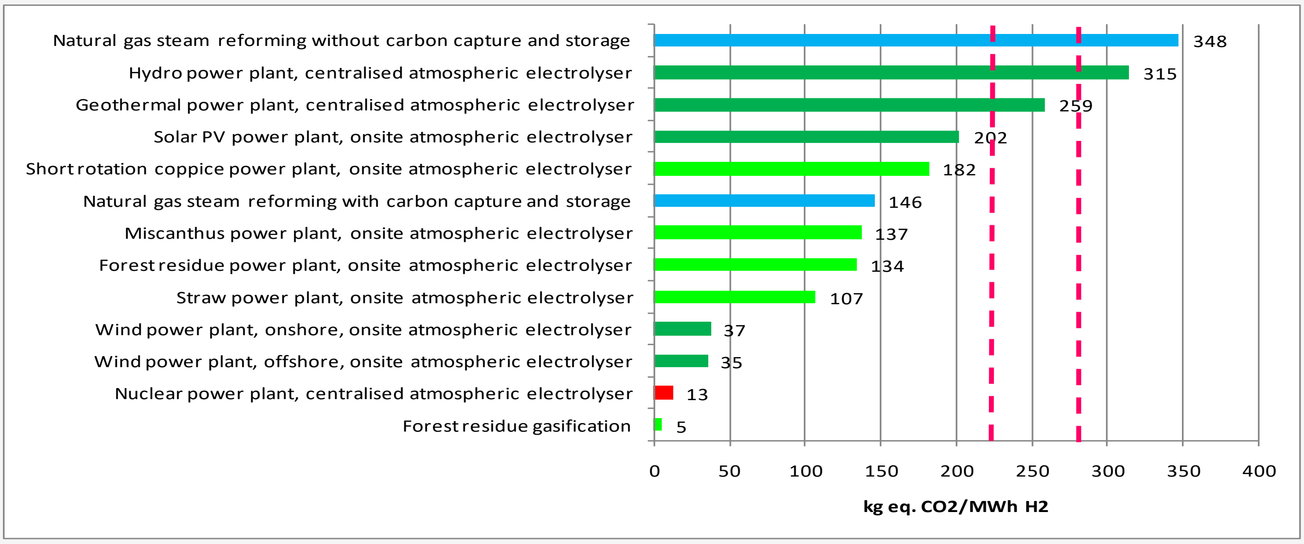


Figure 3.6 Total greenhouse gas emissions for different scenarios of hydrogen generation

Complete analysis can be undertaken with the natural gas hydrogen network operation workbook which incorporates the following key parameters:

- Amount of hydrogen injected (% by volume)
- Relative contributions of hydrogen from different sources (%)
- Injection point (start of transmission or regional distribution network)
- Separation point (end of transmission or regional distribution network)
- Hydrogen separation technology (pressure swing absorption, carbon membrane, palladium membrane, or hybrid system):
    - Purity of separated hydrogen (%)
    - Hydrogen content of residual gas (%)
    - Heat requirements of separation technology (MJ/kg H_2)
    - Electricity requirement of separation technology (kWh/kg H_2)
- Hydrogen re-compression (for direct use or transport filling station supply):
    - Inlet and outlet pressures (kPa)
    - Single unit output rating (Nm^3/h)
    - Number of single units
    - Load factor (%), annual operating time (h/a) and lifetime (a)

3 SAFETY – WORK PACKAGE 2

3.1 OBJECTIVES

The key objective of the Safety Work package was to compare the hazards and risks presented to the public by the existing infrastructure conveying natural gas with the hazards and risks presented by the same infrastructure assuming that a natural gas/hydrogen mixture is conveyed.

3.2 CONTRACTORS

The contractors involved in this Work Package were Loughborough University (leader), Leeds University, CEA, Shell Hydrogen, National Grid and the UK Health and Safety Executive.

3.3 METHODOLOGY AND SCOPE

In order to be able to achieve this objective, it was necessary to modify the risk assessment methodologies used for the natural gas infrastructure to enable them to be used for natural gas/hydrogen mixtures. Risk is combination of the likelihood of an adverse event and the consequences of that event. Hence, in order to modify the risk assessment for natural gas/hydrogen mixtures, it is necessary to consider both the likelihood and consequences of releases of such natural gas/hydrogen mixtures. Specific aspects that have required modification include:

- The probability of an accidental release from different parts of the gas infrastructure and the probability of ignition of the gas mixture
- The assessment of the consequences of gas dispersion, fires and explosions involving natural gas/hydrogen mixtures
- The data on the properties of natural gas/hydrogen mixtures particularly in relation to the turbulent combustion of such mixtures in air and ignition energy

Determining the failure probability involved using information from the literature and results of work performed within Work Packages 3 (Durability) and 4 (Integrity) of the NATURALHY project. Modelling the consequences of gas dispersion, fire and explosions has been achieved using ‘engineering type’ models which are often used for risk assessment purposes and through the use of more complex Computational Fluid Dymanic (CFD) approaches. In order to develop and validate the mathematical models, experimental data on gas dispersion, fire and explosion phenomena for natural gas-hydrogen-air mixtures was required. As such phenomena are strongly scale dependent, large scale experiments have been performed as part of the Safety Work Package to study gas build up, fire and explosions. Laboratory scale experiments have also been conducted to obtaining specialised data on the turbulent combustion parameters (such as turbulent burning velocity) which are important when modelling explosion events. Ignition energy of methane/hydrogen mixtures was also determined through laboratory scale experiments.

The purpose of the gas industry is to provide energy to the population for use in their homes and also for commercial and industrial premises. By its very nature, the gas infrastructure comes into close contact with the public. Clearly pipelines are needed to convey the gas to the areas where people live and hence pipelines will be located near people’s homes. From the gas meter onwards, the gas is in very close proximity with people and how they care for and maintain their own internal gas pipework and appliances can affect their safety. For these reasons, in considering the risk to the population and how this may change if hydrogen is added to the network, two key areas have been considered:

1. The risk posed by a failure on the high pressure pipeline system and

2. The risk posed by an escape of gas from the low pressure pipelines close to buildings or from pipework and appliances internal to the property which could lead to gas accumulation within the property and a gas explosion.

In addition to the above hazard and risk assessments, the Safety Work package was also requested to review the incidental low level of leakage from the pipeline system due to minor imperfections. For the system operating with natural gas, this is not a safety issue (although it is important from an environmental perspective since methane is a strong greenhouse gas). The purpose of the review was to ensure that the addition of hydrogen does not result in this leakage creating an additional hazard and to reassess the level of leakage of methane.

3.4 RESULTS

Incidental Leakage

Incidental leakage from the gas pipeline infrastructure arises mostly as a result of poor or damaged joints or minor defects in the pipe wall. The vast majority of this leakage occurs on the lower pressure parts of the system, especially where older materials, such as cast iron mains, are used. The level of leakage is very low typically less than 1% of the gas conveyed and presents no safety hazard. A theoretical assessment of the effect on leakage of adding hydrogen to a pipeline system was undertaken. This included both low and high pressure pipelines. Using information gathered within Work Package 3 (Durability) on the permeability of polymer pipelines to methane and hydrogen (which showed that polymers were more permeable to hydrogen than to methane), the losses through polymer pipe wall permeation were also considered.

It was found that the addition of hydrogen to the pipeline system reduced the mass leakage rate slightly, for the level of hydrogen addition envisaged by NATURALHY. For example, for 20% (by vol) hydrogen addition, the total mass leakage reduced by a factor of 0.91 and the methane mass leakage by 0.89. However, the addition of hydrogen to natural gas would result in a reduction in the rate of energy delivery if the system continued to operate at the same pressures. One option is to slightly increase the delivery pressure to maintain the energy delivery rate, but the increased pressure would increase the leakage. For a system with 20% (by vol) hydrogen addition, operating at slightly higher pressure to achieve the same energy delivery rate, the total mass leakage would reduce by a factor of 0.96 and the methane mass leakage by 0.93.

In conclusion, it was found that following the introduction of hydrogen the incidental leakage is not a safety issue and that overall the mass leakage reduces slightly. In particular, the methane leakage reduces, which is beneficial since methane is a greenhouse gas. Despite the increased permeability of plastic pipelines to hydrogen, the leakage from this mechanism is negligible and there is insufficient residence time of the gas in the pipelines for any noticeable change in gas composition to arise as a result of preferential loss of hydrogen through polymer pipe walls.

Hazards of Gas Build Up, Fire and Explosion

Gas build up behaviour of natural gas/hydrogen mixtures was studied during two large scale experimental programmes, the first involving releases at low pressure into a room typical of a domestic building and the second involving high pressure releases into a larger enclosure representing a commercial premise or industrial housing. The data was used to develop engineering type mathematical models and a CFD model. It was found that the gas build up behaviour of the mixtures was similar to that of natural gas and no separation of the hydrogen from the mixture occurred. Due to the higher volume flowrate for the same size of release, higher gas concentrations were achieved. However, the increase in concentration was less than expected associated with the increase in volume flowrate, due to an increase in the buoyancy driven ventilation generated by the accumulation itself. Overall, the increase in steady state concentration following a release of a methane/hydrogen mixture compared to methane is slight for hydrogen concentrations in the fuel of up to 50% (by vol), but more significant thereafter, especially for hydrogen concentrations in the fuel over 70%. The volume of the flammable accumulation may also increase.

Large scale experiments to study high pressure jet fires and fires following the rupture of an underground transmission pipeline were undertaken (Figure 4.1). During the experiments the flame length and thermal characteristics were measured and used to develop and validate engineering models of the fire event. It was found that the addition of 25% (by vol) hydrogen made little difference to the fire characteristics, however, the mass outflow was reduced and the pipeline depressurised more quickly for the mixture. This results in a slightly reduced extent of the hazardous region for the natural gas/hydrogen mixture. For the jet fires, a slight increase in the heat loading to an engulfed obstacle was measured during tests involving the natural gas/hydrogen mixture, most likely associated with an increase in the convective heat transfer from the high velocity flame.

The severity of explosions was studied at large scale during 3 experimental programmes, one studied confined vented explosions in a large enclosure and the other two programmes studied vapour cloud explosions in congested regions of pipework. Mathematical modelling using both engineering type models and CFD models was undertaken. The explosion models also required information on the laminar and turbulent burning velocity of methane/hydrogen mixtures and this was achieved through an extensive programme of laboratory experiments in a specialised test facility (Figure 4.2).

Figure 4.1 a large scale rupture from an underground transmission pipeline

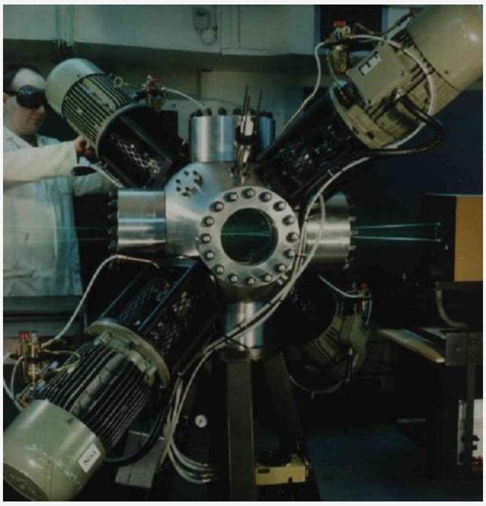


Figure 4.2 Laboratory experiment to study the laminar and turbulent burning velocity of methane/hydrogen mixtures

For confined vented explosions, the results showed that the severity of explosions increased as hydrogen was added but the increase was slight for 20% (by vol) hydrogen addition but more significant for 50% addition. A modified version of the Shell model SCOPE was used to model the explosions satisfactorily. A CFD model was also developed and used to explore the impact of varying hydrogen addition and this suggested that a more significant rate of increase in overpressure could be expected for hydrogen additions over 45% (by vol).

Vapour cloud explosions (VCEs) in a compact cubical region of pipework, with gas compositions ranging from 100% methane to 100% hydrogen with 3 mixtures in between, also showed that the addition of 50% (by vol) hydrogen increased pressures significantly and a transition to detonation was observed for 100% hydrogen. VCEs in a long congested region (Figure 4.3), which provided a longer path length for flame acceleration showed that for 40% (by vol) or more addition of hydrogen would give rise to accelerating flames and potential for a transition to detonation. In circumstances involving high levels of congestion and a high speed flame venting into the congestion, continued flame acceleration and damaging pressure levels could also be experienced for lower levels of hydrogen addition. However, reduced congestion levels had a significant impact on reducing overpressures. Engineering and CFD models were also applied to model these VCEs.

Figure 4.3 Site to study Vapour Cloud Explosions in a long congested region

Overall it was concluded that the severity of explosions increases as hydrogen is added to natural gas, but the increase is small for hydrogen addition up to 30% (by vol). For 40% (by vol) or more, a significant increase in explosion severity can be expected.

Risk from Transmission Pipeline System

'Risk' is a measure of the number of fatalities per year and combines the likelihood of a pipeline failure with the consequences. So that: Risk = Frequency of Pipeline Failure x Probability of Ignition x Consequences of the Fire. The risk can be expressed as 'Individual Risk', defined as the likelihood of a person at a particular distance from the pipeline becoming a fatality in a year, or 'Societal Risk' which provides an overall measure of the risk to the population as a whole. In order to evaluate this risk, a computer model (called LURAP) was developed which includes methods to evaluate the failure frequency of pipelines conveying a natural gas/hydrogen mixture, an estimation of the ignition probability and the assessment of the consequences of the fire. It considers both small failures of pipelines (called punctures) and complete breaks (called ruptures). However, the risk is dominated by the rupture of the pipeline. LURAP is available through the Decision Support Tool (DST) developed by Work Package 6 of the NATURALHY project.

The failure frequency of natural gas pipelines can be determined based on historical information available in incident databases. This information is included within LURAP as a function of the pipeline parameters (such as diameter, wall thickness etc). Additionally, a correlation based method for calculating failure frequency due to third party damage was also included in LURAP and this approximates the results of a structural reliability approach. The advantage of this method is that mitigating measures, such as the use of increased depth of cover or concrete slabbing can be assessed. For use with natural gas/hydrogen mixtures, it was essential to consider if any of the failure mechanisms might be affected by the introduction of hydrogen. In collaboration with partners from Work Package 3 and 4 it was concluded that the only failure mechanism which would be affected by the introduction of hydrogen was that of failures arising from fatigue crack growth of sharp crack-like defects, where disassociation of hydrogen molecules into atomic hydrogen could detrimentally affect the material properties of the steel. Using a methodology developed within Work Package 4, and data obtained by Work Package 3 to describe the rate of crack growth, the impact on failure frequency was considered for realistic initial crack sizes. It was found that, for mixtures containing up to 50% (by vol), provided that an appropriate integrity management strategy was adopted, the failure frequency for crack-like defects should not increase above that already experienced for natural gas.

Incident database information was also used to provide 3 different approaches to assessing the ignition probability of natural gas pipeline failures. Conservative estimates of the ignition probability of hydrogen pipeline failures were made and a method developed to determine the ignition probability of mixtures. The resulting ignition probabilities for mixtures depend to some extent on the approach adopted for natural gas, but always increase as hydrogen is added.

A model of the thermal characteristics of the pipeline fire was developed and validated against the large scale data described above. However, the effect of thermal radiation on people is a function of both the level of radiation and the time of exposure – termed the 'thermal dose' measured in thermal dose units (tdu = $(\mathrm{kW\ m^{-2}})^{4/3}$ s). Typically a level of 1800 tdu would result in 50% fatalities and 1050 tdu corresponds to a 1% chance of becoming a fatality. It was also assumed that persons in the vicinity will attempt to escape and are likely to find shelter within 30 seconds. To provide a conservative approach, LURAP determines the distance to 1050 tdu over a 30 second period and uses this as a criteria for fatalities. In reality the outflow and fire event following rupture of a pipeline is a highly transient event and so the radiation will vary with time and distance following the rupture. However, prediction of the outflow is complex, so the approach taken by LURAP is to approximate the transient event by a steady outflow. The determination of the steady outflow level includes factors which are a function of the gas composition and so take into account the different mass outflow and more rapid depressurisation expected for pipelines which include some hydrogen. The approach was validated against the experimental data and against benchmark exercises for natural gas and found to predict the extent of the hazard region within ±10%.

Using LURAP, predictions of individual and societal risk have been made for typical pipelines. The addition of up to 50% (by vol) hydrogen slightly increases the risk to an individual close to a pipeline, but reduces the risk at locations further away, associated with the reduced extent of the hazardous region. Similarly, for societal risk, the frequency of low consequence events (small number of casualties) is expected to rise but high consequence events (involving large number of casualties) are expected to involve fewer casualties and be less frequent.

Risk from Explosions in Domestic Properties

The risk to the public from explosions in domestic properties can be assumed to be related to the explosion frequency. Hence a probabilistic methodology was developed to determine the change in explosion frequency that may arise if hydrogen is introduced into the gas infrastructure. The model starts by considering a large number of potential releases of varying sizes into different size rooms and with a range of typical ventilation rates. The build up of gas with time is then determined for each of these situations. In many cases, the release may not have the capacity to form a flammable accumulation, in which case, no explosion can result. However, for those cases which can form a flammable mixture, the model considers the build up of gas with time (of day) and the possible sequence of events which could follow. In particular, the gas release may be detected by the resident. Whether or not this occurs and how quickly it occurs, depends upon if the building is occupied and whether or not the occupants are present at the time. Furthermore, it depends upon the time of day, as occupants may be present but asleep during night-time hours, making detection of leaks which start during the night less likely.

Having detected a gas escape, many residents will take action to mitigate the consequences, such as isolation of the gas supply and/or opening windows/doors, thereby preventing an explosion occurring. In most cases, the residents will also report the escape to the gas company and an engineer will be dispatched to take mitigating action if not already taken by the resident.

However, all of the above events take time, and the time intervals between commencement of a release and its detection, or between detection and reporting, or between reporting and arrival of the engineer, may vary in length according to the time of day and the behaviour of the resident, and these variations are included by assigning probabilities to each of the alternatives at each step of the process.

During all the time from the moment that the gas release commences until mitigating actions are taken, there is the potential that a flammable accumulation could be ignited. Hence at all steps along the process, the possibility of ignition is considered. Ignition could arise as a result of household appliances such as refrigerators or boilers which activate automatically, or could occur due to the actions of the occupants of the property – such as light switches or striking matches. The estimation of ignition probability was assisted by laboratory scale data obtained to determine the minimum ignition energy of methane/hydrogen mixtures across the flammable range.

By evaluating the probabilities of each step of this process, it is possible to determine the probability of an explosion given that an escape of gas has occurred. Using historical data on the number of gas escapes per year, it is then possible to determine the number of explosions per year. Taking pessimistic assumptions about the ignition probability, it was found that the addition of 20% hydrogen (by vol) could result in a 2-fold increase in explosion frequency whereas for 50% the increase could be up to 4-fold. However, the current risk is very low and even with this increase, the risk remains within generally acceptable limits.

3.5 CONCLUSIONS

The Safety Work Package has considered the change in the risks presented to the public following the addition of hydrogen to the natural gas infrastructure, particularly focussed on levels of hydrogen up to 50% by volume. The nature and characteristics of gas releases, build up, fire and explosions have been studied for natural gas/hydrogen mixtures and the failure frequency and ignition probability of accidental releases have been re-assessed.

The extensive body of large scale and laboratory scale data generated by the Safety Work Package provides a valuable resource to research workers and gas industry safety engineers, which can be used to develop and validate modelling approaches to hazard assessment and inform decisions about the potential for introducing hydrogen into pipeline networks. The mathematical modelling undertaken within the project demonstrated this capability and has shown how the level of hydrogen introduced affects the severity of the hazard and hence the level of risk.

The overall conclusion from the Safety Work Package is that up to 30% by volume of hydrogen could be added to the natural gas within the current gas infrastructure without adversely affecting the risk to the public significantly and without any additional mitigation measures.

The addition of 40 to 50% by volume of hydrogen would probably also be achievable without unacceptably increasing the risk to the public from the pipeline system or from explosions in properties. However, it is recognised that in some circumstances the increase in the severity of the explosions may be undesirable and pose an additional hazard. Therefore, it would be prudent to consider the adoption of mitigation measures in situations where the explosion severity could be increased.

4 DURABILITY - WORK PACKAGE 3

4.1 OBJECTIVES

The existing natural gas system has been designed for natural gas. The physical properties of hydrogen differ substantially from natural gas and consequently the impact of hydrogen added to natural gas on the durability of the materials of the grids should be studied. Durability of pipeline materials is an important issue concerning the technical/economic lifetime of the transmission system and it is also a key aspect regarding safety risks. Work Package 3 aims to establish the acceptable percentage of hydrogen that can be mixed with natural gas, given its effects on the characteristics of the component parts and materials employed in the existing natural gas infrastructure, including transmission, distribution (including domestic gas meters) and inner grids, taking into account the requirement to maintain safe operation.

Considering the huge amount of materials forming the existing pipeline networks over Europe and the inner grids, a dedicated selection of few materials was decided and focused on the materials for pipelines themselves. The other major equipment studied were domestic gas meters and the materials used for inner grids. Therefore WP3 provides answers on the selected materials regarding their ability to delivery mixtures of NG+H_2, and the method for assessing the durability of materials.

4.2 CONTRACTORS

The contractors involved in this Work Package were GDF SUEZ (leader), CEA, CMI-Beasy, CSM, DBI-GUT, DESFA (DEPA), ENIM, GASUNIE, IFP, IGDAS, ISQ, STATOIL, TNO, TOTAL.

4.3 DURABILITY OF STEELS FOR TRANSMISSION PIPES WITH HYDROGEN

Transmission pipes in the existing natural gas grids operate under high pressures, for example from 40 bar up to 100 bar. The low carbon steels used for building the transmission grids have been developed with increasingly higher mechanical strength; the steel X42 is one of the oldest, used in the 1960’s while today operators have started to use the X80. However, the higher the yield strength, the lower is the resistance to crack growth. This risk is well managed for natural gas, but should be assessed for hydrogen.

Although the interaction of hydrogen with steels has been largely studied, the aim of using the steel grids designed for natural gas for transporting hydrogen requires extended studies about the effect of hydrogen on the properties of these steels (mechanical strength and fracture behaviour) as well as an understanding of the mechanisms.

Tests on 2 steels currently used in existing pipeline grids (X52 and X70) were executed on laboratory samples, to quantify the effect of hydrogen on their fracture toughness and fatigue crack growth resistance. Some demonstrative tests were carried on at full-scale under hydrogen pressure; burst tests were performed on parts of pipes with well-controlled defects (cracks). The special case of the rapid propagation of crack, following rupture of the gas pipe, was studied by numerical modelling. It is expected that due to their different thermo-dynamical properties, the crack arrest will happen sooner in case where hydrogen is present in the gas pipe.

Assessment of the effect of H_2 on fracture toughness of steels
The effect of pressurized H_2 on fracture toughness performance is not fully clarified yet. Although wide variation results, the trend is that the fracture toughness decreases with increasing H_2 pressure. At a typical pressure of a natural gas pipeline (69 bar) the toughness can decrease by 30 -50%. However, even if the fracture resistance

would be reduced, no embrittlement was noticed, and the mechanical behaviour of the X52 and X70 steels can still be considered as ductile.

Effect of H_2 on the fatigue crack behavior of steels

The effect of hydrogen on fatigue performance of natural gas pipelines can be described as follow;

- The hydrogen can have a significant effect on fatigue performance. This includes both the fatigue threshold value and the fatigue crack growth rate. It is strongly dependent on the actual test conditions and the amount of H_2.
- Under simulated in-field conditions (pressurized gas and in-field ΔK values) the performance is far better than under (not realistic) laboratory conditions.
- Under simulated in-field conditions a blend of 75% natural gas and 25% H_2 is allowed for the X70 material, without a degradation of the fatigue performance.
- Under simulated in-field conditions a blend of 50% natural gas and 50% H_2 is allowed for the X52 material, without a degradation of the fatigue performance.
- If 100ppm (or better still 250 to 500 ppm) O_2 is added in 100% pressurized H_2, the fatigue performance is comparable to that in 100 % natural gas.

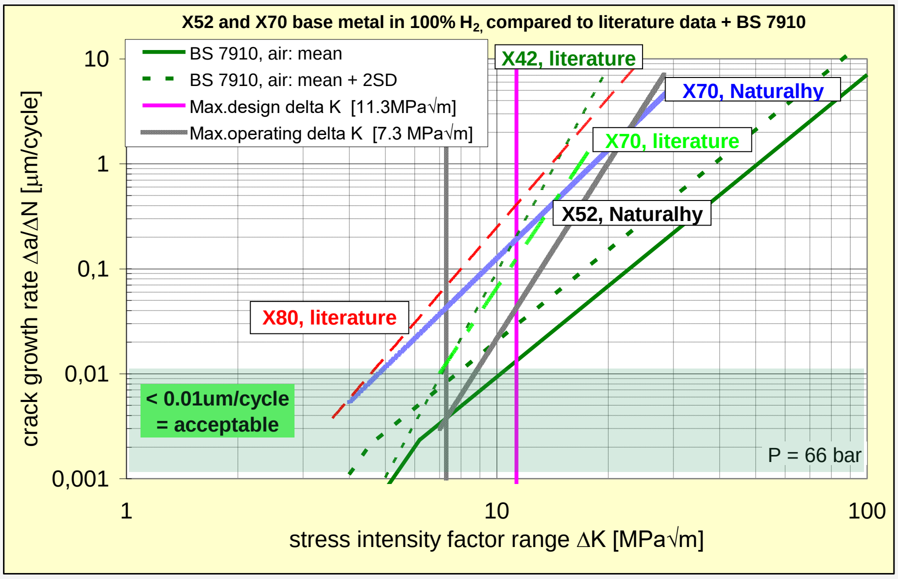


Figure 5.1 Fatigue crack growth of X52 and X70 base materials in 100% H_2.

Conclusion on durability of steels for transmission pipes with hydrogen

The final results give confidence in the NATURALHY approach and the technical feasibility of injecting H_2 in existing NG transmission pipelines. Although the fatigue behaviour is the most critical situation, gas mixtures up to 50% vol. H_2 may be acceptable depending on the steel type and the operating conditions. Moreover, tests have shown that pipe bursts will not increase with the addition of hydrogen, and that hydrogen has no effect on internal pipe coatings.

Before injecting H_2 in the existing NG transmission grids, the other devices along the transmission grids have to be investigated. In addition, the effect of H_2 on compression stations needs clarification, which like storage were outside the scope of the NATURALHY project.

4.4 DURABILITY OF POLYMERS FOR DISTRIBUTION PIPES WITH HYDROGEN

The poly-ethylene (PE) is the mostly used polymer material for local distribution of natural gas at low pressures, from 16 bar down to few mbar. The main concern about pipes made of polymers like polyethylene is its permeability to hydrogen which may induce leakage of gaseous H_2 and therefore a dangerous situation, unreliable metering, and potential damage due to ageing.

The aim of this study was to be able to compare the gas losses of the natural gas service in comparison to the transportation of hydrogen rich gases depending on the hydrogen concentration. Three different polymers were studied ; PE80, PE100 and PVC-HI (ductile PVC), and electro-fusion welds.

Assessment of the impact of H_2 on the polymers for distribution grids : permeability

Properties of polyethylene (PE80 grade) was studied on samples (sheets, of approximately 2 mm thickness, processed by compression moulding of pellets). The crystallinity rate of the PE samples, determined by DSC measurements, was near 50%. Permeation measurements on the PE80 were performed in various conditions of temperature, pressure, and H_2 content (pure CH_4, 10% H_2 - 90% CH_4, 20% H_2 - 80% CH_4, pure H_2).

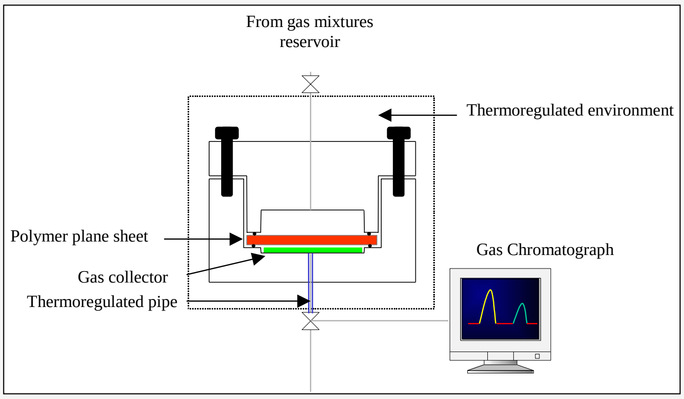


Figure 5.2 Testing facility for permeation (IFP)

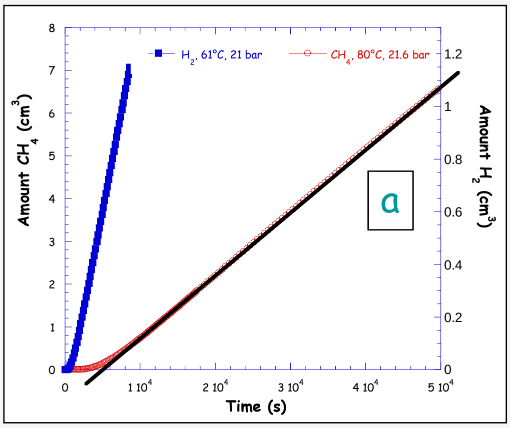


Figure 5.3 Example of measurement of gas permeates.

It was noticed that for a given temperature, each gas (either H_2 or CH_4) keeps its intrinsic permeability coefficient whatever the composition of the feed mixture is. No particular interaction could be noticed, that is to say, no mixture effect occurs. From the experimental results, it is possible to extrapolate and to obtain the permeability coefficients values at lower temperatures such as 10°C or 0°C.

By comparing the behaviour of the two single gases, one can see that the permeability of H_2 is larger than those of CH_4 whatever the temperature. The activation energy of the permeability phenomenon through PE 80 for hydrogen is weaker than that for methane. As a consequence, the decrease of permeability with temperature is slower with hydrogen than with methane.

Permeation results were used for calculating the potential leakages on distribution. Below is an example of theoretical calculation of gas leakages due to permeation for the case of a PE pipe distributing at 4 bar a mixture of 80% NG + 20% H_2 :

- Permeation leakage of H_2 = 2,3 litre/ km / day,
- Permeation leakage of CH_4 = 1,1 litre / km / day.

For comparison, the gas leakage for the same PE pipe distributing only CH_4 would be :

- Permeation leakage of CH_4 = 1,4 litre / km / day.

Permeation results were also used for assessing the consequences on safety. According to the assessment performed by the University of Loughborough within the WP2 Safety, it was concluded that the H_2 losses due to permeation is extremely small compared to the leakage from small defects in the pipe wall and that the leakage rates are insignificant from a safety perspective.

H_2 permeability of PE and PVC pipes

Tests on pipe specimens made of PVC-HI (ductile PVC) and PE 100 material with diameters of 110 and 160 mm were performed, with a mixture of methane and hydrogen at a total pressure of 10 bars and a temperature of 16°C. Baseline tests were performed with pure methane. The permeability results from discs and pipes are consistent.

From the results obtained it can be concluded that the transport of hydrogen through polymers is significantly elevated in comparison to methane. In particular the transport of hydrogen through PE pipes turned out to be 6 to 7 times higher than for methane.

Examples of H_2 leakages due to gas permeation are given below for the case of a 110 mm-pipe distributing H_2 at 200 mbar ;

- Permeation leakage of H_2 of a PE100 pipe = 5,0 liter / km / day,
- Permeation leakage of H_2 of a PVC-HI pipe (including joints) = 13,2 liter / km / day.

Assessment of the effect of H_2 on ageing of PE

The literature is quite thin on ageing of PE (PE80 and PE100) in hydrogen gas atmosphere. Therefore this subject was studied under hydrogen pressure (up to 100 bar) with different H_2 content in CH_4 (up to 100%). The ageing tests were accelerated by means of temperature increases (up to 60°C). Tests at 10°C simulated the actual thermal conditions. Mechanical and physical-chemical techniques were used for investigating the evolution of the PE properties and microstructure with ageing conditions.

Depending on the ageing conditions, significant variations have been measured despite the discrepancy inherent in the samples themselves. Taking into account the corresponding discrepancies, neither a major nor catastrophic influence of ageing (in the range studied) has been identified. However, a small increase in permeation coefficients was observed which is essentially linked to the increase of solubility in the material.

As a conclusion, the change in tightness performance with age remains small with respect to industrial use of these PE materials.

Conclusion on H_2 permeability effect

The PE is sensitive to gas permeation ; H_2 diffuses quicker than CH_4 and with larger quantity. But the performance of all materials (PE and PVC) for hydrogen rich gases were not alarming from an engineering point of view. It was noticed that hydrogen has no significant effect on the ageing of PE pipes.

Leakages due to gas permeation through the wall of pipes were taken into account in economics (loss of fuel) and environment (GHG emission) assessments in the WP1.

4.5 RELIABILITY OF DOMESTIC GAS METERS WITH POLYMER MEMBRANES

The most common domestic gas meters are membrane meters, made with a polymeric membrane which is sensitive to hydrogen permeation. Several potential effects of hydrogen were expected, for example, influence on metering accuracy and safety due to leakages, and on durability (physical damage).

Figure 5.4 Domestic gas meters tested

Hence, domestic meters from 3 European manufacturers (Gallus (France), Dresser (Italy), Elster (Germany)) were tested regarding their reliability for hydrogen metering of the membrane in presence of hydrogen. The meters were tested with 2 different mixtures (100% CH_4, 50% H_2 – 50% CH_4). Using a flow of 50-50 CH_4-H_2 mixture produced little difference in metering (<2%), and the lower the flow rate, the lower the difference with the CH_4 reference performance.

Conclusion on H_2 effect on reliability of domestic gas meters

The tests on the effect of mixtures up to 50% hydrogen on domestic gas meters suggest that any reduction in accuracy is within currently-acceptable standards.

4.6 EFFECT OF H_2 ON THE TIGHTNESS OF THE MATERIALS FOR INNER GRIDS

In order to evaluate the suitability for hydrogen service (up to 50% hydrogen), connection types (i.e. connection between end-using devices and house installation) and gas-valve combinations of end use devices, both designed for applications in houses, have been investigated. Specimens were chosen which were believed to have a significant market share in the future.

The test samples were investigated according to the guidelines DVGW VP 614, DIN EN 161 and DIN EN 13611 and DIN 3387. In part, the test criteria were enhanced, in particular the pressure of impact by test gas investigation. This pressure was enhanced, compared to the DIN 3387, for most of the connection tests to ensure sufficient gas capacity for the gas analysis after the test period. This was an additional investigation not foreseen by the guidelines but important in order to determine the difference between the hydrogen and methane gas loss through the connections.

The gas-valve combinations EUROSIT 630 by SIT la Precisa Padova and the compact assembly CG10 by Kromschröder were tested according to the guidelines DIN EN 161 and DIN EN 13611. Both samples passed the tests successfully with the methane-hydrogen mixture (50 % H_2 - 50 % CH_4).

Figure 5.5 Gas-valve combination ; Kromschröder compact assembly CG 10.

The investigated in-house connections passed both the static bending test and the subsequent leakage test with the hydrogen-methane mixture (8 of the 9 specimens passed the test performed with the CH_4-H_2 gas mixture). One specimen, a flexible rubber hose, failed the test.

Conclusion on H_2 tightness of devices in inner grids

The currently used gas-valve combinations are suitable for the hydrogen service (50 % H_2, 50 % CH_4), and 8 of 9 specimen of in-house connections passed the tightness tests (rubber hose).

5 INTEGRITY – WORK PACKAGE 4

5.1 OBJECTIVES

The main objective of the Integrity Work package was to provide support to pipeline operators on when and how to inspect and repair pipelines that convey natural gas and hydrogen mixtures.

5.2 CONTRACTORS

The contractors involved in this Work Package were TNO Science & Industry, Computational Mechanics BEASY, GDF SUEZ, PII Ltd. (A member of GE Energy Group), Istanbul Gas Distribution Co. Inc. (IGDAS), N.V. Nederlandse Gasunie, Instituto de Soldadura e Qualidade (ISQ), Turkish Scientific and Technical Research Council (TUBITAK), StatoilHydro and Total.

5.3 METHODOLOGY AND SCOPE

In order to support the pipeline operators to maintain a proper pipeline integrity management (IM) for pipelines that conveys mixtures of natural gas and hydrogen the main components of the IM have been investigated. The investigations comprises the expected effect of hydrogen on the existing defects, a comprehensive sensitivity analysis, the estimation/calculation of the probability that a pipeline will fail as well as the inspection and repair technologies of pipelines. The results have been summarised in reports and are used in the Decision Support Tool of WP6.

5.4 RESULTS

Description of realistic defects

The first step in order to develop the basis for modified IM is to establish a clear picture of the defects that exist in natural gas pipelines. This concerns the number, the type, the distribution and the shape of defects. The most important criterion for the evaluation of the critically in the presence of hydrogen is the stress a defect can put on the material and the rate at which the event occurs. Blunt defects like corrosion cause only low stresses but sharp defects like cracks can cause significant stresses and under typical pipeline fatigue loads hydrogen can significantly accelerate crack growth. Beyond this, cracks can reach a state in which their growth is unstable. Therefore cracks and crack like defects are considered to be more critical than corrosion defects, when hydrogen is introduced.

Defect criticality

As well as the defect type, it is very important to know the critical size of defects. Cracks can grow over time (cracks are time dependent defects) so knowledge of the crack growth rate in a certain timeframe can provide the critical initial defect size by back-calculation assuming a particular design life. The critical initial defect size should not be exceeded at the beginning of the period under review. Sensitivity analyses show that, under the selected assumptions, the effect of hydrogen on materials considered to be sensitive, is minor up to concentrations of 50% (by volume) compared to the effect of pure hydrogen. Nevertheless a clear impact on the acceptable initial crack size was observed especially for axial defects (Figure 6.1).

Furthermore, a tool (POF tool) able to calculate the probability that a pipeline or a defect (crack and corrosion) will fail or lead to failure and the failure rate was developed.

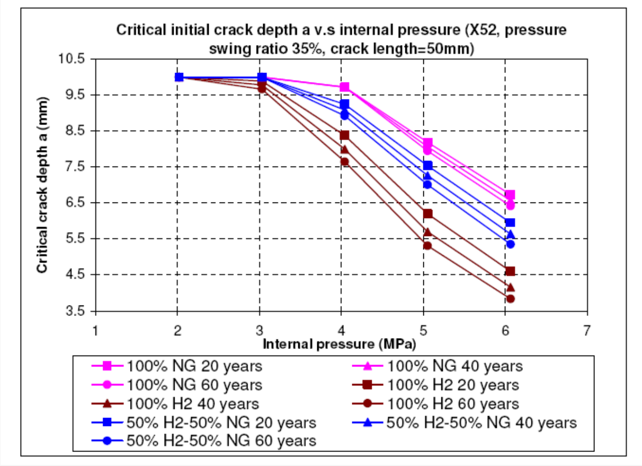


Figure 6.1 Defect criticality

Performance of current inspection tools and identification of needs for improvements

The performance of the currently applied inspection tools were investigated regarding their ability to detect, identify and size corrosion and crack like defects. The obtained information was compared to the critical defect sizes in order to set up specifications for improved inspections tools that fulfil the requirements for pipelines conveying natural gas and hydrogen mixtures.

Improvements inspection and monitoring tools

Modified MFL, TRIAX and EMAT inspection tools have been tested in order to determine their abilities to detect crack like defects. The investigated inspection methods have shown that they are candidate technologies having the potential to meet the required detection expectations. Nevertheless the investigated tools show different performances.

Improvement of Cathodic Protection Integrity management

A prototype of an integrated remote monitoring system which includes data collection system and a modelling simulation tool for assessing the performance of the CP system with a level of accuracy suitable for coated pipelines has been proven feasible. One advantage of the system is that a real time display of the protection levels along the pipeline is feasible allowing improved supervision. This helps pipeline operators to manage the integrity of pipelines, to reduce costs and/or maintain the same level of integrity if hydrogen is added to natural gas pipelines.

Figure 6.2 Cathodic Protection system

Repair methods

Three currently applied repair methods have been investigated regarding their suitability for hydrogen service. The work was focussed on the ability of the repair measure to take on the pipeline load and to study the effect of hydrogen on welding activities. The investigated repair methods (“Clock Spring”, “Metallic Sleeve” and “Weld Deposit”) were assessed as suitable for repairing hydrogen containing pipelines even though the performance was slightly reduced in some cases.

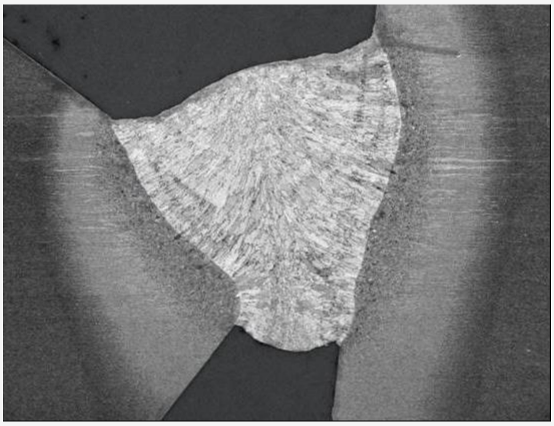


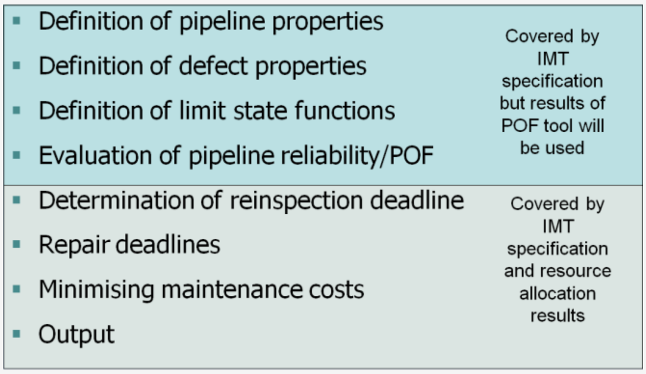
Figure 6.3 A weld repair

Resource allocation

The costs for modifying the IM-systems in place are strongly dependent on the individual situation especially on the hydrogen concentration, defect distribution, material properties, loads and integrity targets. Therefore an example was performed using material data provided by WP3, defect distributions which reflect pipes in a medium condition with a maximum operation pressure of 66 bars and aiming to meet a Probability Of Failure (POF) integrity target for corrosion and for cracks after 50 years of operation, which is in line with the failure statistics of European transmission pipelines for natural gas. For the example, it can be concluded that for high concentrations of hydrogen (50%) in natural gas pipelines a slight effect on the inspection and repair frequency is expected. Within the chosen example an increase of total costs (inspection and repair for corrosion and cracks) of the order less than 10% was calculated.

Integrity Management Tool specification

A comprehensive report describing the principles comprising the specification of pipeline and defect properties and limit state functions, as well as the optimisation of the inspection and repair activities were documented. The IMT and the POF tool also developed within WP4 are integrated to the extent that the POF tool computes the failure probabilities which are needed for the IM. The reports provide the basic information and guidelines for calculation. The efficiency of the set up specification was tested by setting up a demo tool.



▪ Definition of pipeline properties ▪ Definition of defect properties ▪ Definition of limit state functions ▪ Evaluation of pipeline reliability/POF	Covered by IMT specification but results of POF tool will be used
▪ Determination of reinspection deadline ▪ Repair deadlines ▪ Minimising maintenance costs ▪ Output	Covered by IMT specification and resource allocation results

Figure 6.4 The set up of the Integrity Management Tool

5.5 CONCLUSIONS

Work on the pipeline integrity management performed within the project show that when hydrogen is added to the pipelines constructed to convey natural gas crack like defect are most critical. Corresponding defect sizes have been determined and candidate inspection technologies have been selected and tested leading to promising results. Furthermore repair technologies were proven to be suitable when hydrogen is added to the existing system. The effect on the costs has been calculated for an example and comprehensive guidance is given for:

- calculating of the probability that a pipeline will fail within a given time (POF software tool)
- developing modified integrity management systems suitable to cover the effect of hydrogen and
- determining the corresponding cost for the adapted integrity management systems

It can be concluded that from the integrity management point of view, hydrogen can be transported by the existing natural gas system providing small adaptions of the existing IM are executed. The necessary adaptions are strongly linked with the hydrogen concentration and the conditions of the grids to be considered. The necessary modifications are not significant up to about 50% hydrogen for the considered cases but a detailed investigation for every case is mandatory and can possibly lead to lower limitations on the hydrogen concentration permissible.

6 END USE- WORK PACKAGE 5

6.1 OBJECTIVES

The End-Use work package focussed on the potential impacts of adding hydrogen to natural gas networks on end use applications, and the possibility to withdraw hydrogen from the mixture for differing applications, and consequent impact on gas quality as a result of hydrogen withdrawal.

The efficient separation of hydrogen is a key component of initiating a hydrogen infrastructure while development of highly efficient membranes offers the potential to obtain hydrogen of different purities at low cost and at a range of scales.

The objectives of End-Use work package were:

- Investigate and Assess the impact of hydrogen addition on existing appliances
- Develop advanced membrane materials to enable separation of hydrogen from natural gas/hydrogen mixtures thereby encouraging potential growth of local hydrogen centres.

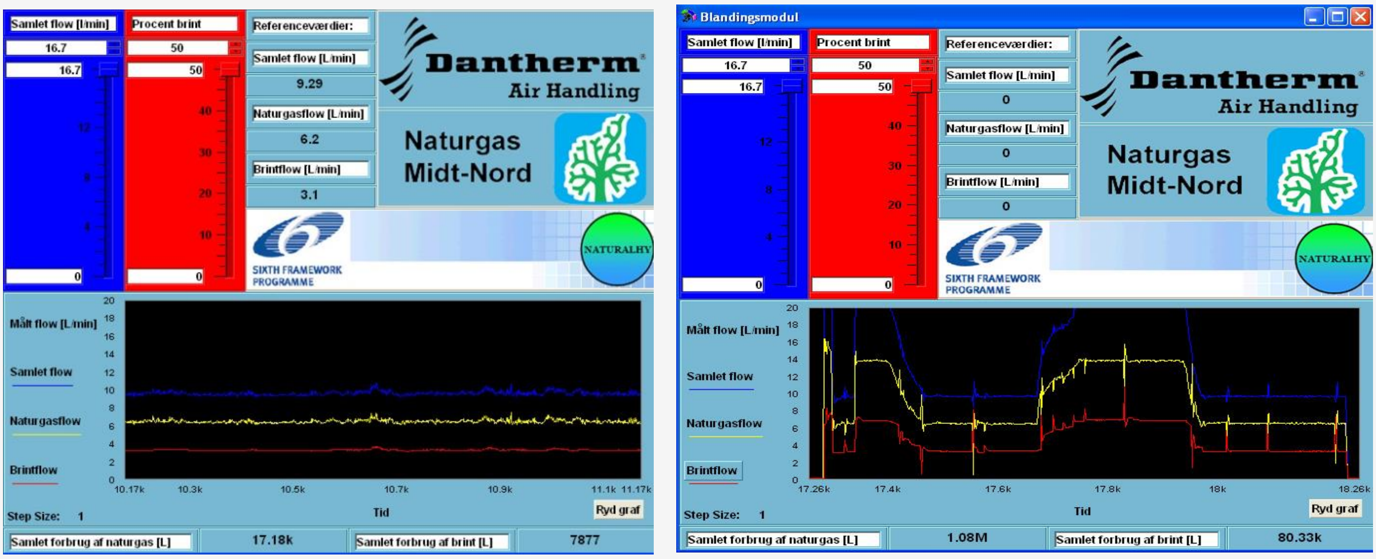
6.2 CONTRACTORS

The partners involved are University of Oxford, NTNU, CETH, Gasunie, DGC and Midt-Nord

6.3 WORK PERFORMED

Testing performance domestic boilers with hydrogen/natural gas

In addressing objective 1, thorough testing of domestic boilers in the laboratory (by Danish Gas Centre) and in a 12 month field trial (by Midt-Nord) was carried out with considerable success. Modern pre-mixed boilers were shown to operate at high levels of hydrogen (at least 50% v/v) under all seasonal conditions with no problems, while an older partially pre-mixed boiler was less tolerant, up to a maximum of 40% hydrogen in the natural gas.



Samlet flow [l/min] 16.7
Procent brint 50
Referenceværdier:
Samlet flow [L/min] 9.29
Naturgasflow [L/min] 6.2
Brintflow [L/min] 3.1
Step Size: 1
Samlet forbrug af naturgas [L] 17.18k
Samlet forbrug af brint [L] 7877

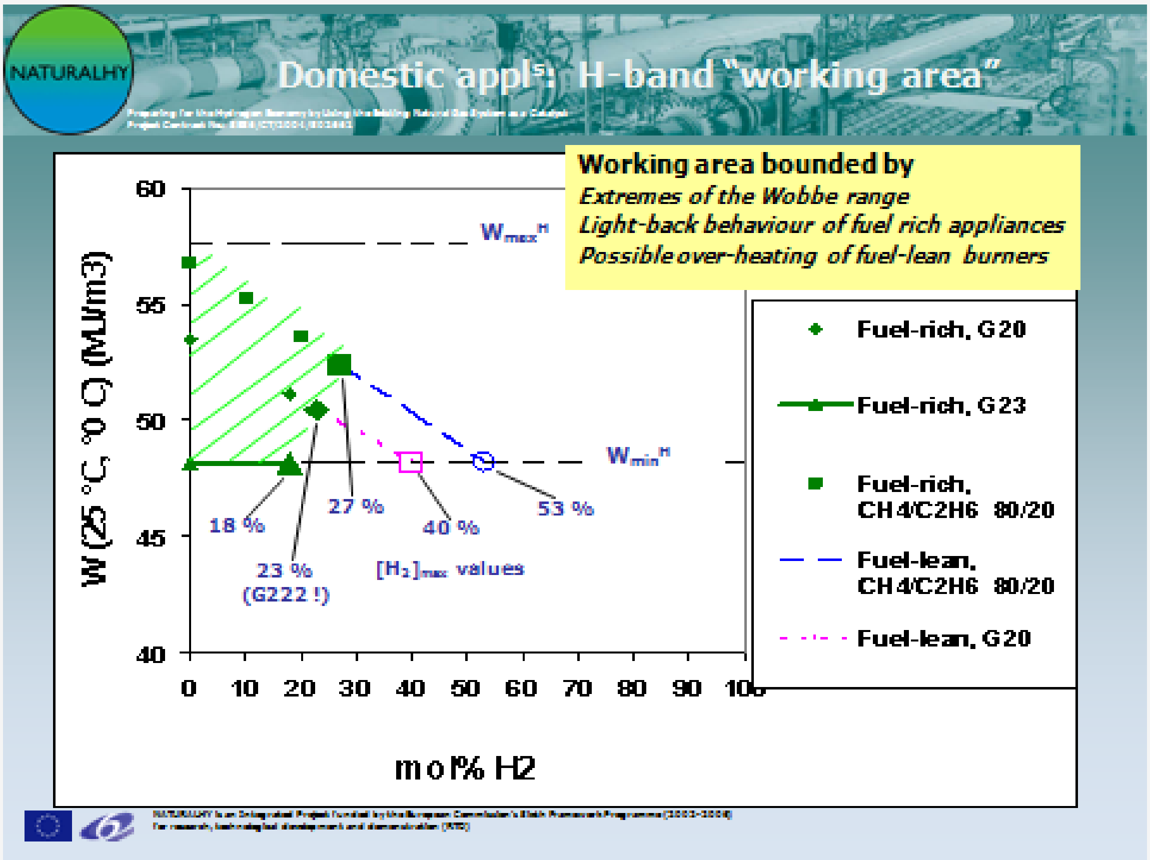
Blandingsmodul
Samlet flow [l/min] 16.7
Procent brint 50
Referenceværdier:
Samlet flow [L/min] 0
Naturgasflow [L/min] 0
Brintflow [L/min] 0
Step Size: 1
Samlet forbrug af naturgas [L] 1.08M
Samlet forbrug af brint [L] 80.33k

Figure 7.1 Screen shots of testing domestic boilers with hydrogen/natural gas mixtures

Understanding the impact of hydrogen on combustion properties

In parallel with the experimental programme, a rigorous analysis of the impact of hydrogen addition was undertaken by carrying out a literature survey and by analysing the effect of added hydrogen on the combustion characteristics of the gas mixture on a range of appliances including domestic and industrial appliances.

The main results show that existing fuel-rich domestic appliances are prone to light-back and thus limiting the amount of hydrogen that can be added safely. The exact level of hydrogen is strongly dependent on the type and properties of natural gas supplied in the network. A “working area” can be defined that shows the safety boundary for fuel rich appliances (Figure 7.2).



Domestic appl^s: H-band “working area”

Working area bounded by

Extremes of the Wobbe range

Light-back behaviour of fuel rich appliances

Possible over-heating of fuel-lean burners

Figure 7.2 H-band-like distribution, the working area for domestic appliances

Thus, for fuel rich appliances (worst case scenario), avoiding light-back will limit hydrogen addition to:

~28% hydrogen addition to a natural gas at the maximum of the H-band

~23% hydrogen addition to a gas equivalent to pure methane

~18% hydrogen addition for a gas where the resulting Wobbe index of the mixture is kept at the minimum of the H-band.

It is important to note that for poorly adjusted domestic appliances and/or unfavourable conditions of natural gas quality, no hydrogen admixture is allowed.

Stationary gas engines, gas turbines, natural gas feedstock processing and industrial combustion applications require consideration from case to case.

Development of membranes for hydrogen separation

In addressing objective 2, parallel developments of two types of membrane materials were undertaken: development of selective carbon based membranes, and, development of ultra-thin Palladium based membranes for producing pure hydrogen. Substantial progress was achieved in both research programmes. Highly efficient carbon molecular sieve membranes were prepared by special routes designed to control and optimise controlled pore structure. These materials showed high selectivity and permeability of hydrogen. Some progress was also made in forming the membranes into hollow tubes by special spinning techniques, suitable for packaging into a practical membrane module.

Ultra- thin, 3micron Palladium based membranes were prepared by a range of techniques including electroless plating and magnetron sputtering. Electroless plating of Palladium onto a porous alumina substrate has given membranes that meet the 2010 DOE targets for hydrogen flux at 400C. Similar routes to palladium alloyed with silver and copper have not given successful membranes. Manufacturing defects in the ceramic supports have been shown to give rise to pin-hole leaks and mechanical problems. The application of a fine pore (20nm) surface coating smoothes out most substrate defects, but improved substrates are still required.

Figure 7.3 8 μm Pd membrane supported on ceramic substrate

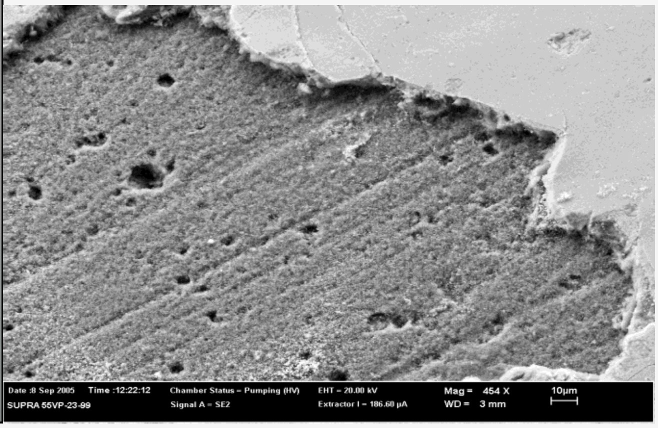


Figure 7.4 Ceramic substrate with 10 μm alumina sol gel coating

A series of membranes were prepared by Magnetron vacuum sputtering by a specialist company using a 77%Pd/23%Ag source. The Pd alloy was deposited on silicon, porous steel and polymer supports. These were 3micron thickness, and required chemical, peeling using potassium hydroxide, to remove them from the support surface. Although initially it proved difficult to obtain pin-hole free membranes, in the final stages of the project a new method was employed that gave coherent Pd/Ag membranes supported on porous supports.

Process development has been directed towards a conceptual process for producing PEM fuel cell grade hydrogen in a 2 stage process utilising a first stage carbon based membrane followed by a Pd based membrane to deliver 100 m^3/hour of hydrogen; this scale represents a small refuelling station for hydrogen vehicles. The first stage effectively increases the hydrogen partial pressure of hydrogen that improves substantially the performance of the Pd membrane in the second stage. The process is shown in Figure 7.5.

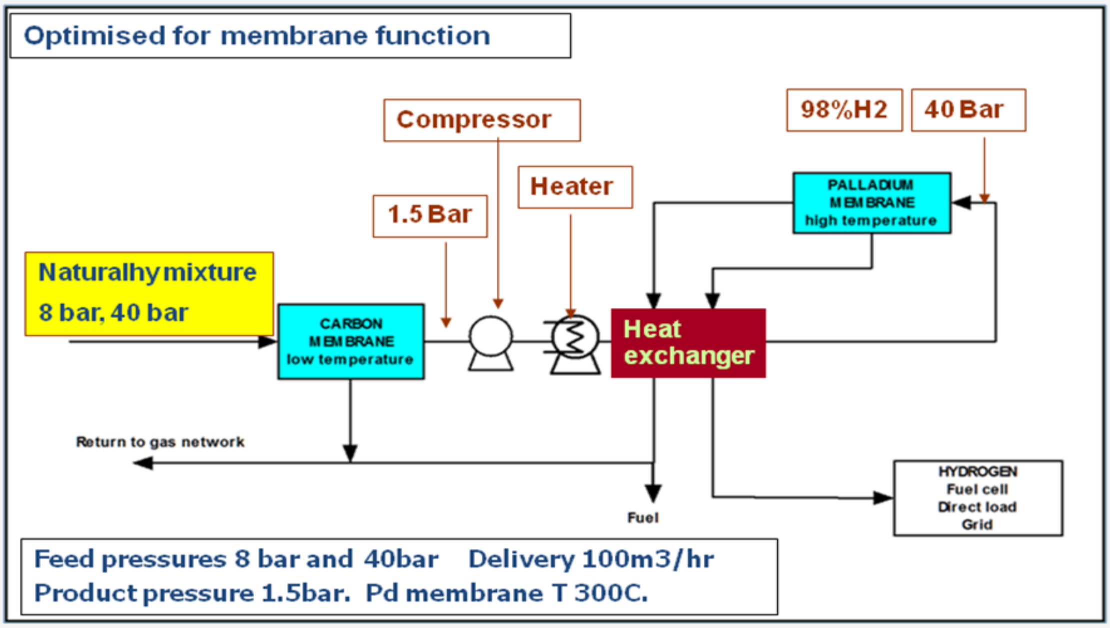


Figure 7.5 Conceptual scheme for separation of hydrogen from hydrogen/natural gas mixtures

This process has been optimised and analysed to derive performance and cost factors. Manufacturers and engineering contractors have been approached in an effort to obtain current costs for alternative separation options, principally pressure swing adsorption (PSA) plants. Although it proved very difficult to obtain real costs from commercial suppliers, some estimated costs were provided and these, together with existing literature data were used to compare likely costs of PSA with membranes.

Following this work, the technical and economic performance of membranes and the options for hydrogen separation have been assessed. In particular, membranes have been compared with pressure swing adsorption (PSA) route in terms of efficiency, and capital and operating costs for three scales:

- Small scale separation to deliver <50 m^3/hr hydrogen suitable for fuel cells
- Intermediate scale (refuelling station) delivering 100 m^3/hr hydrogen
- Large scale separation (1000 m^3/hr) of hydrogen suitable for gas turbines

Overall, the work on separation indicates that NATURALHY membranes can deliver 98% hydrogen using carbon membranes alone at low cost, or with the palladium membrane in series, high purity hydrogen at lower capital costs compared to PSA.

The quality of Supply to downstream hydrogen users as hydrogen is withdrawn along the network will depend on a number of factors.

- Rate of hydrogen extraction is roughly proportional to the hydrogen partial pressure

- Users’ capital and running costs are very dependent on the partial pressure of H_2
- Local domestic supply could be subject to considerable variation in hydrogen concentration as domestic hydrogen extraction becomes more common
- Larger users will probably be located at higher pressure sources and have a more predictable effect on local hydrogen depletion
- The increasing separation and use of hydrogen will most likely result in a requirement for a unified standard for acceptable variation in hydrogen concentration

Results from the WP relating to the performance and costs of the membranes relative to commercial PSA have been derived and provided to the Socio-economic analysis Work Package and as input into the Decision Support Tool.

A number of papers and presentations relating to the above work have been published (see chapter 11).

7 DECISION SUPPORT TOOL – WORK PACKAGE 6

7.1 OBJECTIVES

The main objective of the Decision Support Tool (DST) Work Package was to develop a software tool to enable a Natural Gas Company to perform a what-if analysis on what happens to a specific Gas Transport Network (GTN) when specific hydrogen percentages are transported. The DST is a PC based software tool enabling a company to introduce a configuration layout of a specific gas transport network or section and evaluate what are the consequences of carrying hydrogen and compare it with any other configuration over a number of active years.

7.2 CONTRACTORS

The contractors involved in this Work Package were Instituto de Soldadura e Qualidade (WP Leader), DESFA, Gasunie, GDF Suez, National Technical University of Athens, SQS Portugal, The Open Group, University College of Borås and University of Oxford.

7.3 METHODOLOGY AND SCOPE

The Work Packages of the NATURALHY project have delivered a massive amount of information on the economics, societal and environmental aspects of transporting hydrogen over a natural gas transmission network and on a wide range of materials' properties and behaviour, on separation membranes performance and costs for several end user applications, such as industries, filling stations, etc., on pipeline integrity and on gas transport network safety performance when carrying hythane – the mixture of hydrogen and natural gas.

It must be stressed that the DST is focused on an overall and general type of analysis and not on replacing, for instance, commercially available pipeline integrity management systems which carry integrity analysis to a much more detailed level. In addition, the massive amount of detailed information on actual pipeline conditions and behaviour that is required in order to enable a more thorough analysis is either simply not available at gas company level or requires a data collection cost that is not acceptable for the obtainable increase in accuracy.

The DST has two main uses: firstly to inform, through its Information Repository, what is expected in material and device behaviour when certain hydrogen loads/percentages are applied and secondly to simulate, using its what-if analysis capabilities, the actual pipeline degradation behaviour over certain periods of time being also able to apply, on the pipeline model, mitigation measures. Thus, the NATURALHY-DST key goals are to (i) enable editing, analysis and annotation of a pipeline network, so relevant information may be found and extracted at later stages, (ii) to allow comparison of parameters and measures amongst several pipeline network trunks and terminal points and (iii) to compute, from the information included by the operational Work Packages, a parameter set condensate which will yield a comprehensive what if analysis of applying different load balances of hydrogen and natural gas of different subsections of the network;

The above-mentioned analysis comprises risk assessment, cost assessment, evaluation, and proposal of rules, guidelines and procedures that will mitigate the expected increase of risk when applying the gas mixture to the pipeline network.

The methodology adopted throughout the duration of the project has been to work in a highly integrated way with the 5 technical Work Packages in order to determine the type of project results that would be produced and to develop a consensus on the use and presentation of the results to be finally included in the DST. This included determining which results would be implemented in the network simulation what-if analysis and which results would simply be implemented in the Information Repository for access by the end user.

In particular the following Work Packages presented their key results for use in the DST.

- WP1 (Life Cycle and Socio-economic Assessment). Baseline and Intermediate Scenario EXCEL workbooks, integrated in the DST for network analysis.
- WP2 (Safety). LURAP risk assessment tool, integrated in the DST for network analysis
- WP4 (Integrity). Probability of failure tool, integrated in the DST for network analysis
- WP5 (End Use). Membrane hydrogen separation options. Effects on gas quality and appliances.

Based on the preliminary discussions and inputs from the Work Packages the first stage of WP6 was completed with the generation of the DST Concept Document. The software development stages adopted the Dynamic Systems Development Methodology – DSDM which is an internationally recognised software development framework. The significant development steps included the development of a functional prototype, system architecture definition, Global Data Model and Final Specification of User Requirements. Finally as the final data and results became available from the Work Packages the main software development proceeded with the construction of the DST. The testing stages of the DST consisted of two parts. The first part included the testing of the network layout simulation functionality with the verification of analysis results based on a Benchmark Configuration consisting of a fictional network with 12 different pipe sections. The final deployment and validation testing stage consisted of the simulation and analysis of real natural gas networks using data for sections of the Portuguese and Greek gas transmission networks.

7.4 RESULTS

The DST follows the generally adopted software interface behaviour for MS/Windows systems. The tool interaction itself is organised around a number of tab selected forms, a toolbox and a control toolbar and the DST is focused on enabling effective *what-if* analysis, thus making it very simple:

- to establish/modify H_2 load conditions;
- to modify pipeline layouts;
- to compare risk, integrity and cost results derived from the several H_2 Load conditions;
- to compute and simulate the pipeline behaviour over a period of time and, finally
- to keep a track record of the user interactions and results of analyses.

The DST works on a local database that contains a selected number of data fields from the Gas Company mainstream PIM system; these data fields are complemented with specific DST fields, namely the ones carrying H_2 related information. The tool is able to export some data elements through its reporting facility.

Thus, a DST Configuration is a Gas Transport Network (GTN) topology able to be analysed and compared; it is an abstract description of the gas infrastructure which is the basis for simulation purposes. An energy infrastructure generally covers the whole supply chain, from energy source to end use. The Decision Support Tool (DST) covers the mid- and downstream part of the energy chain. The network representation covers the midstream, i.e. the transmission, distribution and end use parts of the network.

The DST Menu Bar

DST provides the user with a traditional Menu Bar, containing the commonly used options for opening and editing Configurations. In the menu strip, the following options are available:

Configuration Edit Report Compare Window Help

The DST Desktop

Below in Figure 8.1 the Menu Bar, there is a grey empty area where all Configuration screens may be laid. It is the DST desktop.

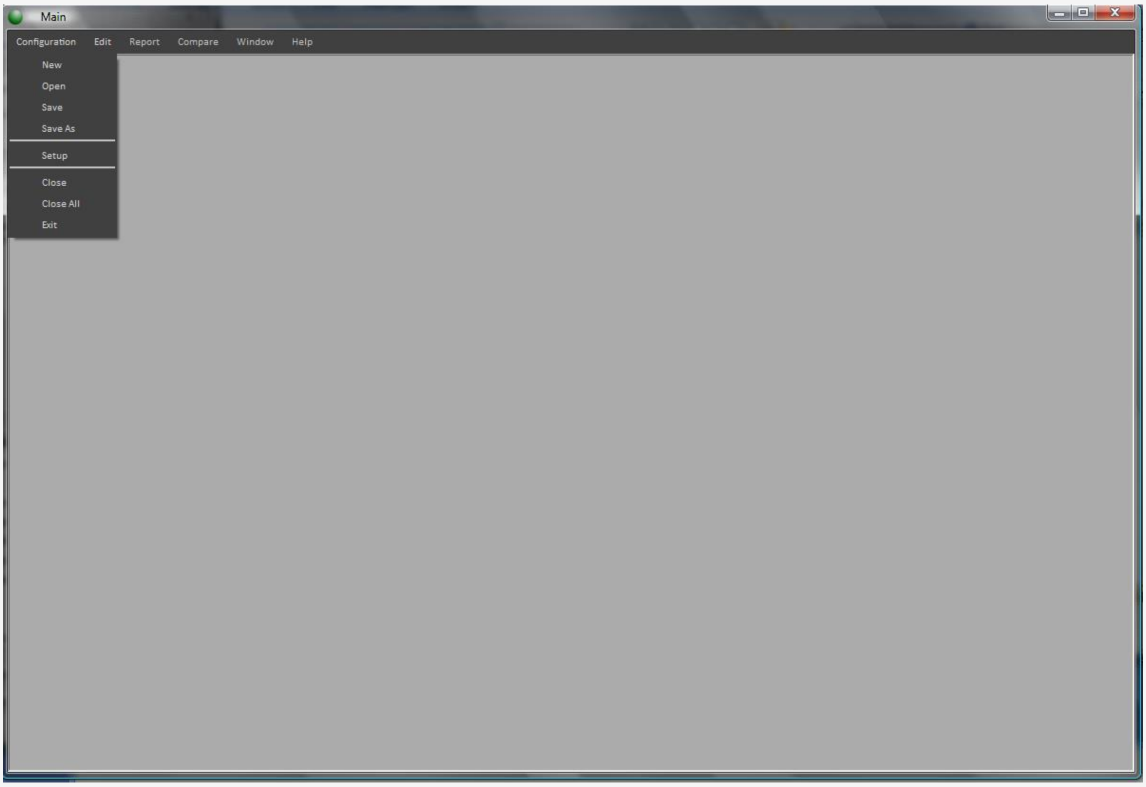


Figure 8.1 DST Desktop

Summary of
Configuration Information

Name	New Configuration
Baseline year	2009
Date created	2009-10-05
Last modification date	2009-10-05
Created by	
Company	ISQ
Notes	These are my special notes. I do really like the colors of the DST as they represent the modern Porsche Design approach. Simply love them and can't stop looking at them. God bless the designer

Figure 8.2 Configuration Form

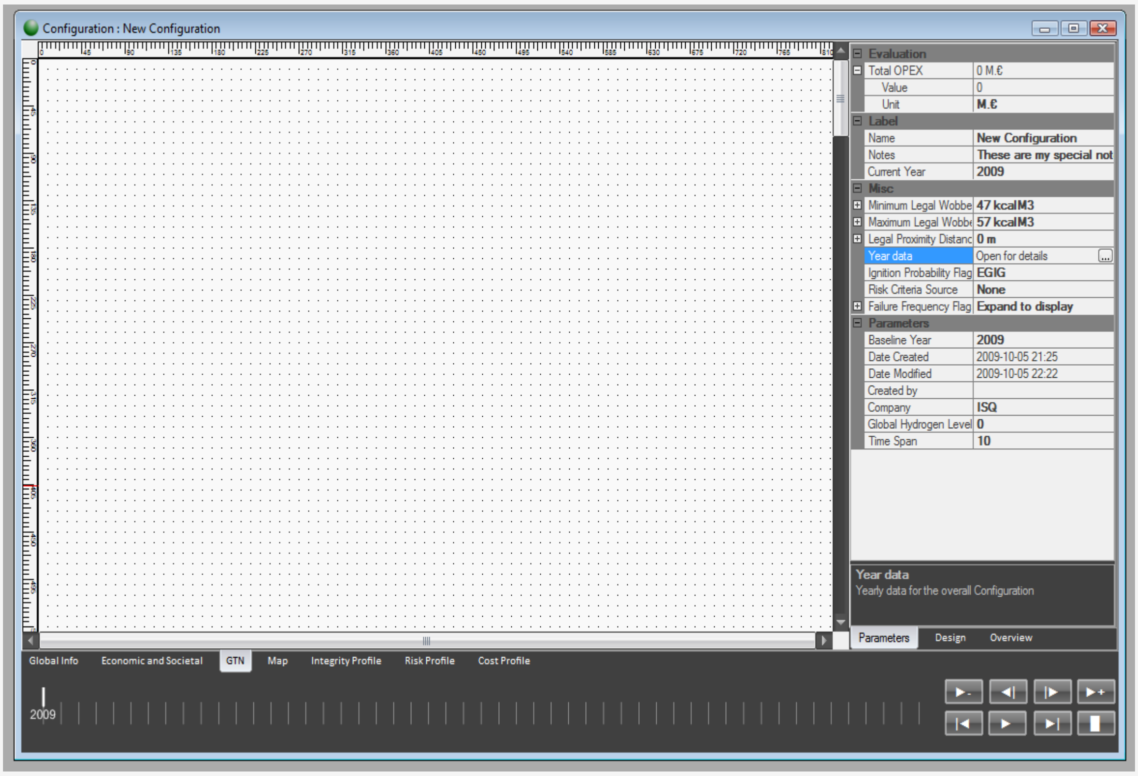
The DST Configuration Form

This is the master DST form. It aggregates all information related to a Configuration and it organises the information in a number of tabbed sub-forms. This form contains two main areas: the tabbed sub-form area, which varies accordingly to the selected set of DST interface functions, such as for designing a new *Configuration* and a timeline, that enables the simulation over the time.

The GTN Layout Form

The GTN sub-form is provided to enable the user to lay out a complete GTN. As previously stated, it is very important to keep in mind that the DST is not a PIM replacement tool. The GTN form comprises two principal areas: a drawing area, to the left, that can be seen in the figure, as a white dotted area, and a tool and control tabbed area, with 3 tabs: Parameters, Design and Overview.

The layout synoptic is laid on the GTN working area using a set of design tools and elements and their specific properties are shown and can be edited in the Parameter tab.



Evaluation	
Total OPEX	0 M.€
Value	0
Unit	**M.€**
Label	
Name	**New Configuration**
Notes	**These are my special not**
Current Year	**2009**
Misc	
Minimum Legal Wobbe	**47 kcalM3**
Maximum Legal Wobbe	**57 kcalM3**
Legal Proximity Distanc	**0 m**
Year data	Open for details
Ignition Probability Flag	**EGIG**
Risk Criteria Source	**None**
Failure Frequency Flag	**Expand to display**
Parameters	
Baseline Year	**2009**
Date Created	2009-10-05 21:25
Date Modified	2009-10-05 22:22
Created by	
Company	**ISQ**
Global Hydrogen Level	**0**
Time Span	**10**

Year data
Yearly data for the overall Configuration

Figure 8.3 The GTN Layout Form

The GTN Design Toolbox

The DST provides the User with a comprehensive toolbox that enables him or her to completely lay out a GTN. Access to the toolbox is made through the *Design* tab on the tabbed work area.

The Toolbox contains four sets of buttons: a first set, on top, contains the four buttons that permit the insertion of pipelines, one button per accepted pipeline type; just below, there are the 10 buttons for the additional 10 possible types of GTN elements, described below.

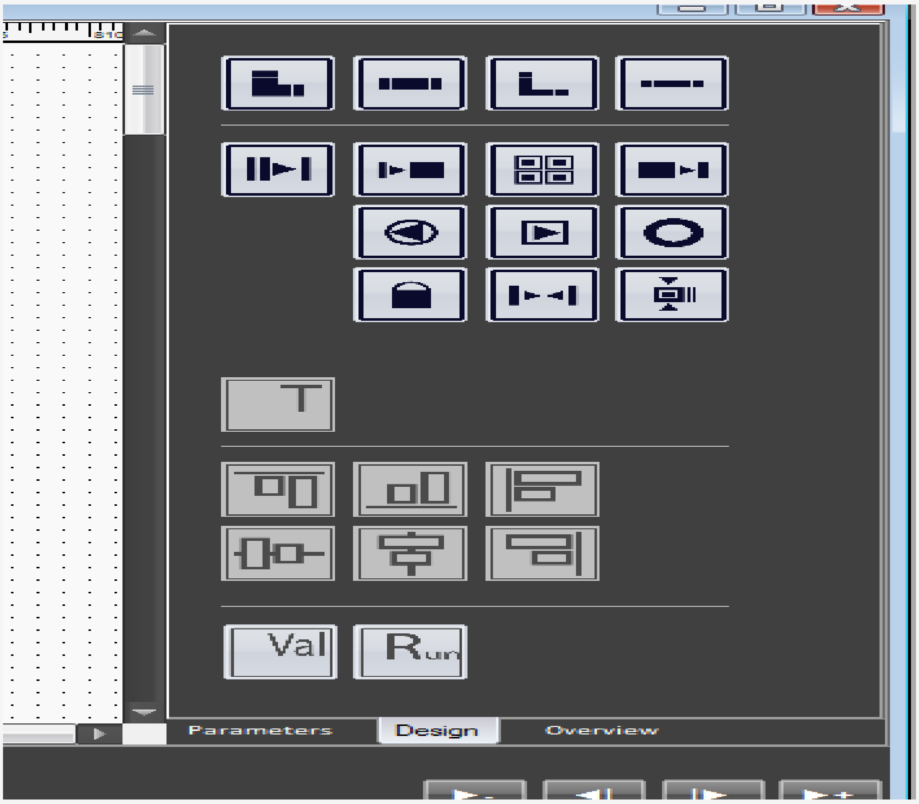


Figure 8.4 The GTN Design Toolbox

GTN Elements

Representation of the Gas Transport Network is based on laying out a number of network elements selected from a total of 11 different available element types or building blocks each one containing a number of parameters or Properties.

Element name	Symbol		Element name	Symbol
Pipeline	▬		Reducing Station	⊳
Hydrogen Extraction	‖▶|		Connecting Point	○
Entry	|▶■		Buffer	☗
Distribution Network	⊞		Valve	|▶◀|
Exit	■▶|		Blending Station	▼▲
Compressor Station	◀			

Figure 8.5 The GTN Elements

Configuration Parameters

The user is able to specify specific parameters which appear in the Property Sheet area and are grouped in 3 main domains: *Device* specific. *Miscellaneous* and *Operation Parameters***.** The *Device* parameters describe the major characteristics of the *Device*, which can be any of the GTN elements. The *Misc (Miscellaneous)* Parameters contain parameters that cannot be grouped in the two specific clusters.

Hydrogen Extraction

The Hydrogen extraction element enables the user to insert at any point an extraction of Hydrogen. In order to facilitate the extraction parameterisation, the DST provides a number of possible generic applications and helps the end user to select, according to its forecasts, the actual and detailed parameters.

The predefined Hydrogen applications include:

Parameter	*Description*	*Notes*
H_2 End Use Application	The selected End Use application of the H_2 extraction	User selectable from one of the following: • Refuelling Station • Industrial Production • Medical Facility • Gas Turbine • Fuel Cell – PEM
H_2 Extraction Volume"	Volume requirements for the extraction	User selectable from one of the following: Small scale: < 50 m3/hr Intermediate scale: 100m3/hr Large scale: 1000 m3/hr

The User is then able to select the appropriate separation option from available membrane and PSA solutions and the appropriate parameters such as purity.

The DST Results

The DST performs three specific analyses on a *Configuration* using the tools embedded in the DST. These are as follows:
Integrity, analysis results from the POF Tool of the network simulation.
Safety, analysis results from the LURAP tool of the network simulation
Economic and Societal, analysis results from the life cycle workbooks of the network simulation.
The results are charted in the form of profiles.

Integrity Profile

The Integrity Profile form contains a total of seven charts plus a property sheet where all output values are numerically displayed. The charts are organised in specific groups as defined below.

- Leakage Probability of Failure by Cracks/Corrosion/3rd Party Damage
- Rupture Probability of Failure by Cracks/Corrosion/3rd Party Damage
- Number of forecasted repairs

The Safety Profile

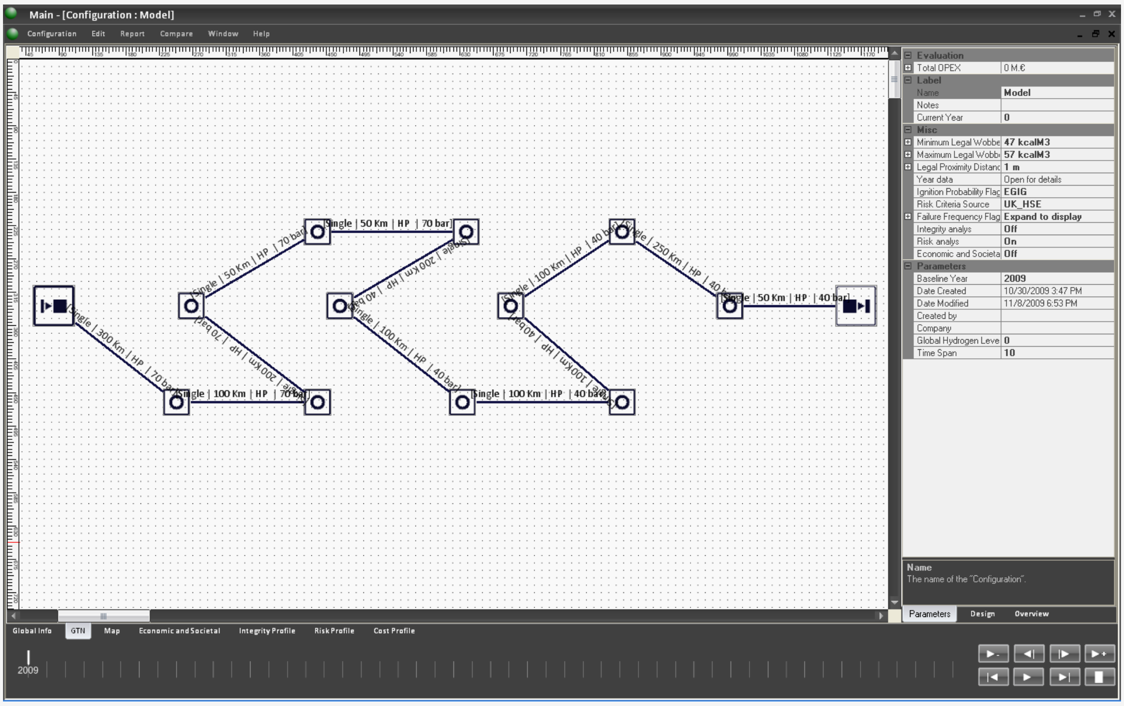
Opposite to the concept of addressing failure of only one pipeline at a time, the Safety Analysis performs calculations both for a specific pipeline, yielding the Individual Risk which represents the risk of casualty of a person living at specified distances from the pipeline and a global computed risk for the network, the Societal Risk, yielding the risk of exceeding a number of fatalities.

These risks are presented in the two related charts presented in the Risk Profile form. A third chart plots the Societal Risk over the years having pre-selected, by a button, the number of casualties.

Testing and Verification of the Tool

The testing and verification of the functionality of the DST has been undertaken by creating a Benchmark Configuration of a fictional pipeline network. This consists of a network of 12 various pipe sections which is based on the LURAP work carried out within WP2 by Loughborough University on risk assessment methodology. For the testing and verification of LURAP all twelve pipe sections are analysed but for the testing and verification of the POF Tool only two pipe sections are analysed. The results have been correlated against the results produced by the Work Packages.

The GTN Layout of the Benchmark Configuration is shown in Figure 8.6 and typical results of the Safety Profile (LURAP) and the Integrity Profile (POF Tool) are shown in Figure 8.7 and Figure 8.8 respectively.



Evaluation	
Total OPEX	0 M.€
Label	
Name	Model
Notes	
Current Year	0
Misc	
Minimum Legal Wobbe	47 kcalM3
Maximum Legal Wobbi	57 kcalM3
Legal Proximity Distanc	1 m
Year data	Open for details
Ignition Probability Flag	EGIG
Risk Criteria Source	UK_HSE
Failure Frequency Flag	Expand to display
Integrity analys	Off
Risk analys	On
Economic and Societa	Off
Parameters	
Baseline Year	2009
Date Created	10/30/2009 3:47 PM
Date Modified	11/8/2009 6:53 PM
Created by	
Company	
Global Hydrogen Leve	0
Time Span	10

Name
The name of the "Configuration".

Figure 8.6 The GTN Layout of the Benchmark Configuration

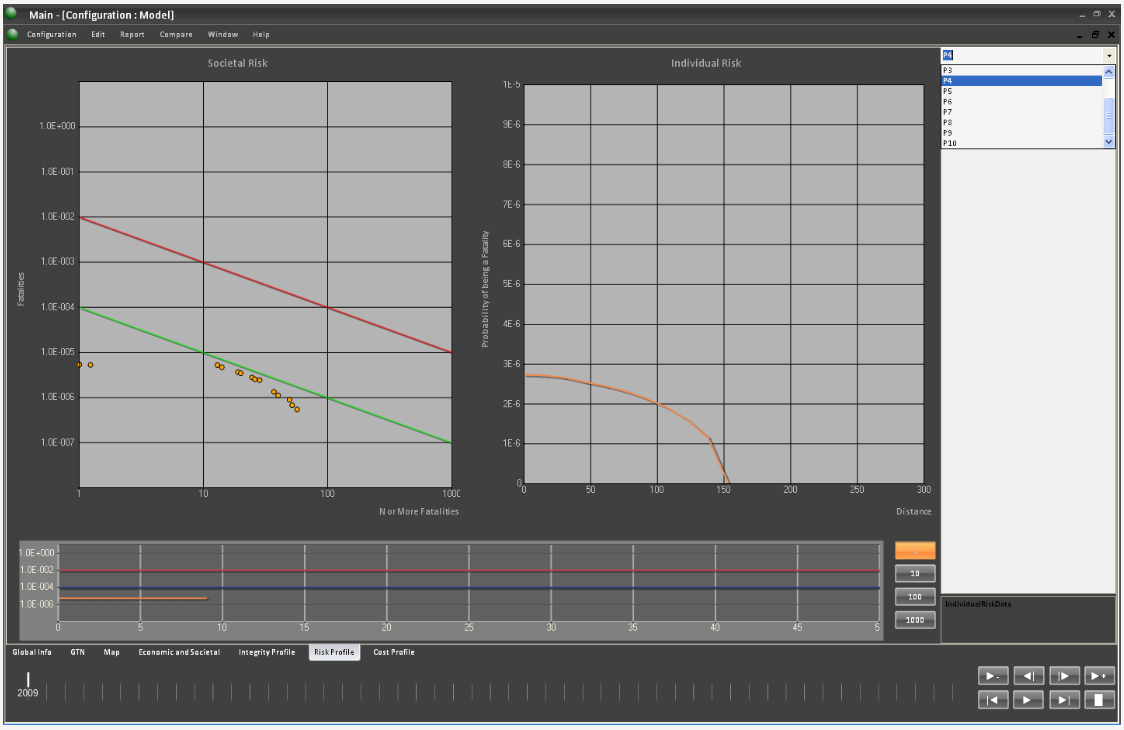


Figure 8.7 DST Interface – Safety Profile

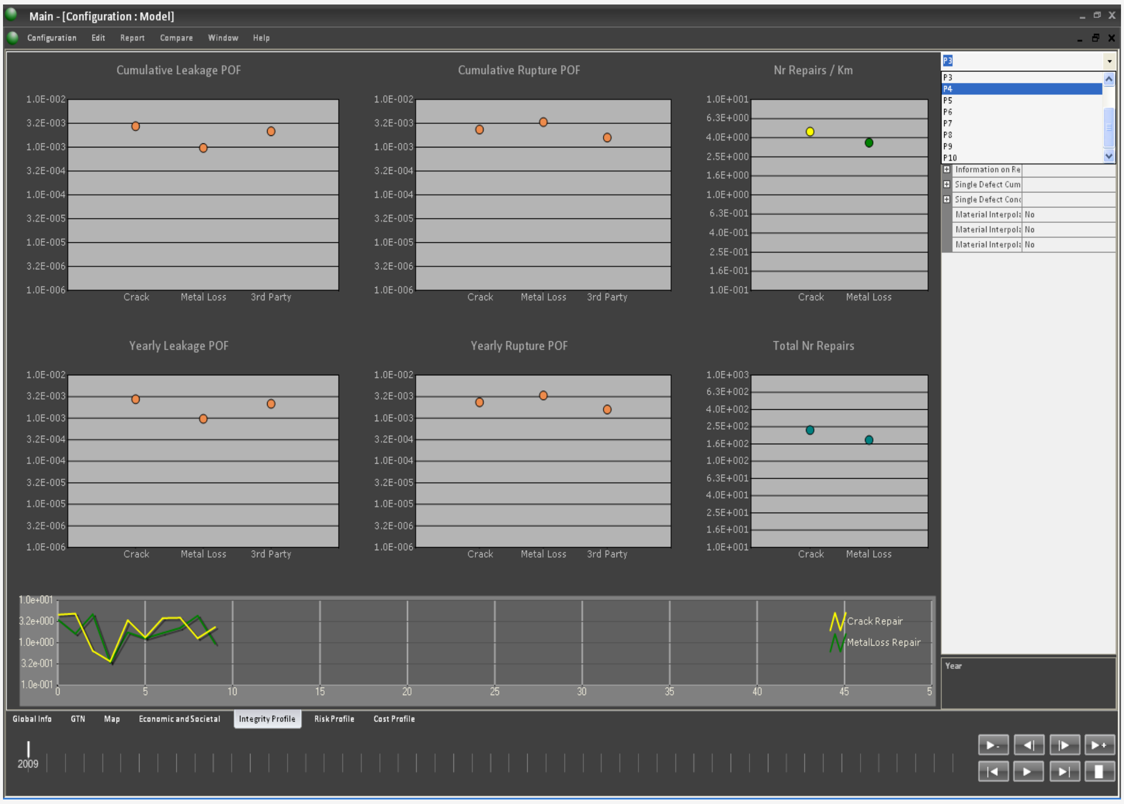


Figure 8.8 DST Interface – Integrity Profile

7.5 CONCLUSIONS

The development of the DST has been successfully completed, tested and verified. In the verification testing the DST has proven to be very user friendly in terms of setting up the simulation of network configurations and in producing what-if analyses of the effects of hydrogen on a network using the LURAP and POF tools. However the objectives have not been fully met in that user trials have been more limited than planned and will therefore be ongoing beyond the project. Additionally some of the project results are not yet fully integrated into the DST due to the delays in the Work Packages and in some cases the non-availability of results and reports within the project timescale.

8 DISSEMINATION-WORK PACKAGE 7

The main objective of the Workpackage “Dissemination” was to disseminate effectively the results of the NATURALHY project via a series of appropriate actions, including:

- publications, both printed and electronic;
- a series of workshops targeted at various user groups and stakeholders
- regular interfaces with government bodies, decision-makers at both national and European levels, safety organisations, standards bodies, consumer organisations, etc.

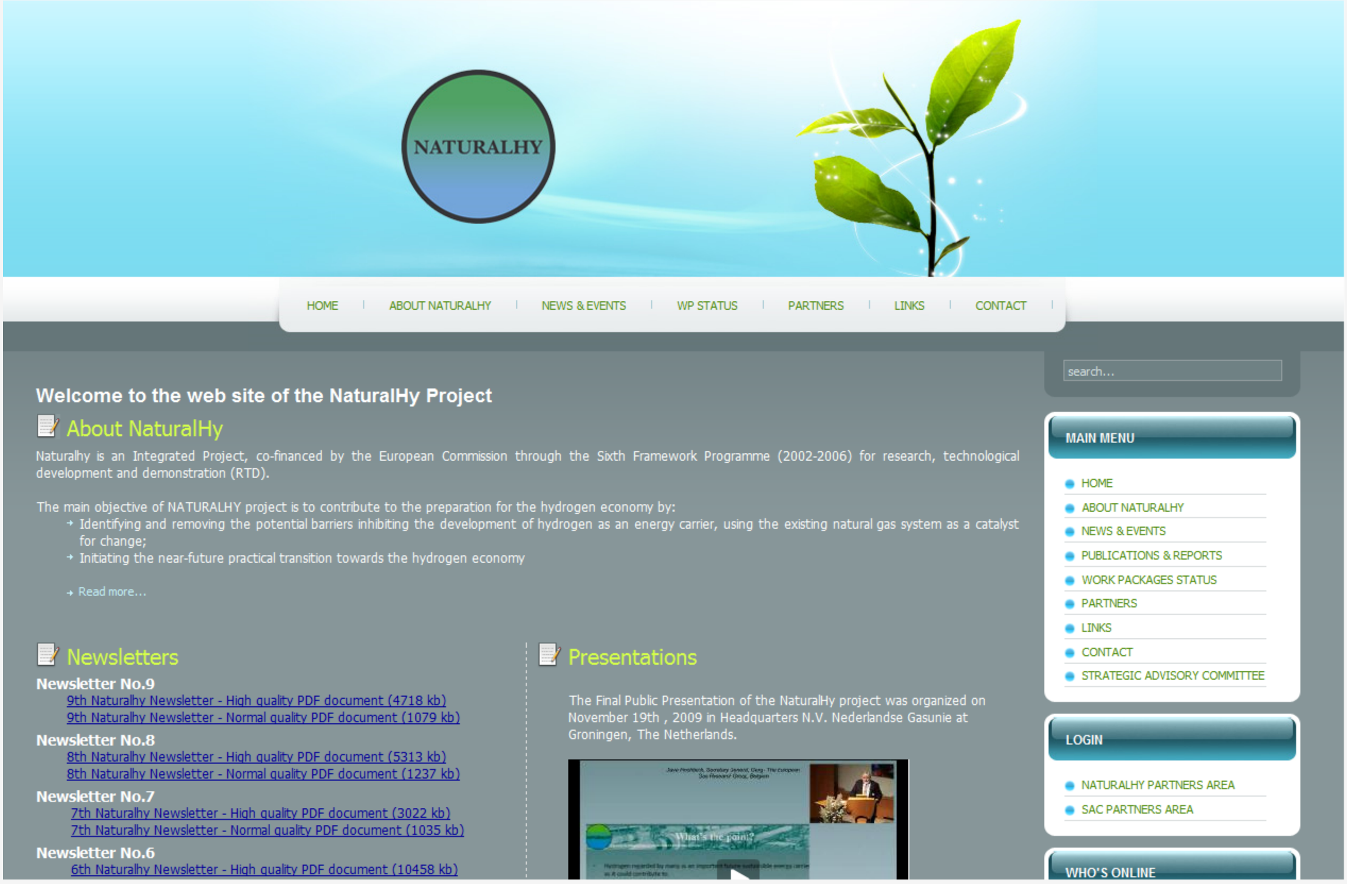
In addition, the workpackage, included a subtask for investigating the situation regarding relevant standards and for providing proposals regarding steps to be undertaken in the standardisation field.

The work package built on the results achieved by the other work packages in order to serve the aforementioned objectives.

The results of the work package is described in the following paragraphs.

8.1 PROJECT WEB SITE

A project web site was established right after the commencement of the project work (www.naturalhy.net). The web site became the main outlet for the distribution of information and results of the project work, including sections such as: Reports, Presentations, Publications, News, etc. Towards the end of the project, the web site was completely redesigned in order to freshen up its appearance and to obtain a more modern look and functionality.



Welcome to the web site of the NaturalHy Project

About NaturalHy

Naturalhy is an Integrated Project, co-financed by the European Commission through the Sixth Framework Programme (2002-2006) for research, technological development and demonstration (RTD).

The main objective of NATURALHY project is to contribute to the preparation for the hydrogen economy by:

- Identifying and removing the potential barriers inhibiting the development of hydrogen as an energy carrier, using the existing natural gas system as a catalyst for change;
- Initiating the near-future practical transition towards the hydrogen economy

Read more...

Newsletters

Newsletter No.9
9th Naturalhy Newsletter - High quality PDF document (4718 kb)
9th Naturalhy Newsletter - Normal quality PDF document (1079 kb)
Newsletter No.8
8th Naturalhy Newsletter - High quality PDF document (5313 kb)
8th Naturalhy Newsletter - Normal quality PDF document (1237 kb)
Newsletter No.7
7th Naturalhy Newsletter - High quality PDF document (3022 kb)
7th Naturalhy Newsletter - Normal quality PDF document (1035 kb)
Newsletter No.6
6th Naturalhy Newsletter - High quality PDF document (10458 kb)

Presentations

The Final Public Presentation of the NaturalHy project was organized on November 19th , 2009 in Headquarters N.V. Nederlandse Gasunie at Groningen, The Netherlands.

Figure 9.1 Home page of the NATURALHY Web Site

The site received a significant number of visits, which increased from app. 400 visits per month during the first months after launching the site to more than 3000 visits per month during the last period of the project.

8.2 NATURALHY NEWSLETTERS

A series of 9, six-monthly Newsletters were prepared and published. The Newsletters were 4-pages, full colour publications, including articles that presented results from the NATURALHY project activities, in various stages of its development.

The Newsletters were distributed during the various events and conferences where NATURALHY participated. They were also emailed to the members of the mailing list which was established during the course of the project, and they were available for downloading through the project web site. More than 16,000 copies of the newsletters were downloaded from the project web site during the project duration.

ISSUE 6 // NOVEMBER 2007

NATURALHY

"Preparing for the Hydrogen Economy by Using the Existing Natural Gas System as a Catalyst"
Project Contract No.: SES6/CT/2004/502661

NATURALHY is an Integrated Project funded by the European Commission's Sixth Framework Programme (2002-2006) for research, technological development and demonstration (RTD)

Towards a Hydrogen Economy

Gordon Adam, former MEP, Barbara Lowesmith, Loughborough University of Technology, U.K and Dave Pinchbeck, General Secretary, GERG - The European Gas Research Group

It must be 20 years or so since I drove a hydrogen powered vehicle. If I had not known, I would not have been able to spot the difference from driving a normal car. Only steam came out of the exhaust. No pollution and no CO2.

In those days the European interest in hydrogen was as an energy vector related to oil prices and the possible exhaustion of oil and gas supplies. Hydrogen was seen as having the potential to keep road transport moving. I even saw a drawing of what a hydrogen aeroplane might look like. The hydrogen programme of those days went onto the back burner as oil and gas supplies eased. Time has moved on. The concerns are now focused on reducing carbon dioxide emissions and hydrogen is back into the research programmes of the European Union.

My general attitude to energy supply has always been that it makes sense to examine and, where possible, exploit all energy sources. So, I have in those general terms supported research work that the EU has undertaken into the contribution that hydrogen might make. But it was not until I was asked to become a member of the Strategic Advisory Committee of the NATURALHY project that I became aware of the huge range of issues that have to be investigated before a hydrogen economy could become a reality. Clearly, anything approaching another "Hindenburg" disaster must be avoided. It is an interesting question as to how far that disaster affected the development of air transport.

Putting to one side the question of how the hydrogen is produced, for hydrogen to be used on any sizeable scale raises huge questions in relation to its transportation. Can it be transported in the existing natural gas grid system? If so, that would save a huge investment expenditure. Might it be possible to transport both hydrogen and natural gas together? Can they be readily separated along the system? More intriguingly, can a hydrogen/natural gas mixture be used as an interim stage towards hydrogen on its own, but with the advantage of reducing the carbon content of the gas? Could, in fact, such mixtures be used in existing appliances which burn natural gas?

▸▸ PAGE 2

TABLE OF CONTENTS

EDITORIAL

With this sixth Newsletter on the NATURALHY project we would like to update you on the progress of our project, which investigates the potential of the existing natural gas system for the delivery of hydrogen. The main objective of the project is to identify and if possible remove the potential barriers inhibiting the development of hydrogen as an energy carrier, using the existing natural gas systems as a catalyst for change. As a first logical step in the transition towards the hydrogen economy, the project focuses on using the existing natural gas grid for the delivery of hydrogen/natural gas mixtures from the perspective of the "greening of gas" but also perhaps to deliver 'pure' hydrogen where necessary. The addition of hydrogen to natural gas affects the chemical and physical properties of the gas and will have an impact on the safety aspects related to the transmission, distribution and end use of the gas. In the main article of this issue we focus on the values of the NATURALHY research programme placed in a historical context by Dr. Gordon Adam, former Member of the European Parliament and a member of the NATURALHY Strategic Advisory Committee. Dr. Adam, C. Eng., MIMMM, FEI, served as a Member of the European Parliament from 1979-2004 and Vice-President Energy, Research & Technology Committee 1984-1999. He is currently a Senior Advisor, Energy Policy Consulting European Advisor, Major Energy User's Council and Chairman, Northumbria Energy Efficiency Advice Centre.
The second article in this issue provides an overview of the current status of the Naturalhy project and relates the latest results of the Work Packages to the overall objectives of the Naturalhy project.
If you have any questions or would like to discuss certain aspects of the NATURALHY-approach with us, than please react through our website www.naturalhy.net.

The project coordination team
Geert Tielsma, Folkert Koopman
and Friedrich Walbek

Newsletter No. 6 (November 2007)

ISSUE 7 // MAY 2008

NATURALHY

"Preparing for the Hydrogen Economy by Using the Existing Natural Gas System as a Catalyst"
Project Contract No.: SES6/CT/2004/502661

NATURALHY is an Integrated Project funded by the European Commission's Sixth Framework Programme (2002-2006) for research, technological development and demonstration (RTD)

Vapour Cloud Explosions involving Natural Gas/ Hydrogen Mixtures

Figure 1: The VCE Test Rig

The Safety Work Package of the Naturalhy project is comparing the current hazards and risks presented to the public by the existing gas infrastructure conveying natural gas with the hazards and risks presented by the same infrastructure assuming that a natural gas/hydrogen mixture is conveyed. One particular hazard that needs to be assessed is the consequence of a gas/air mixture accumulating and then getting giving rise to an explosion. It is well known that hydrogen is more reactive than natural gas and 100% hydrogen mixed with air can produce explosions of a greater severity than natural gas/air mixtures in the same circumstances. So the question arises, how does the severity of explosions change as hydrogen is added to the natural gas?

Firstly, we need to understand what is meant by an explosion and how explosions cause harm. When flammable gas mixtures burn, a large increase in volume occurs, principally due to the high temperature of the combustion products formed. If this process occurs within a confined (or semi-confined) region, such as a building or enclosure, the presence of the confining walls prevents free expansion of the combustion products and results in the generation of pressure. This is the key mechanism for the generation of pressure in confined explosions.

It has also been observed that gas explosions can generate pressure without the presence of confining walls. These are referred to as Vapour Cloud Explosions (VCEs). In this case, the flame front travels through the unconfined gas cloud. If the flame is traveling quickly, the gas/air mixture ahead of the flame is unable to move away quickly enough to allow free expansion of the combustion products formed by the flame. Hence a pressure wave is formed ahead of the flame front. The presence of obstacles (called congestion)

▸▸ PAGE 2

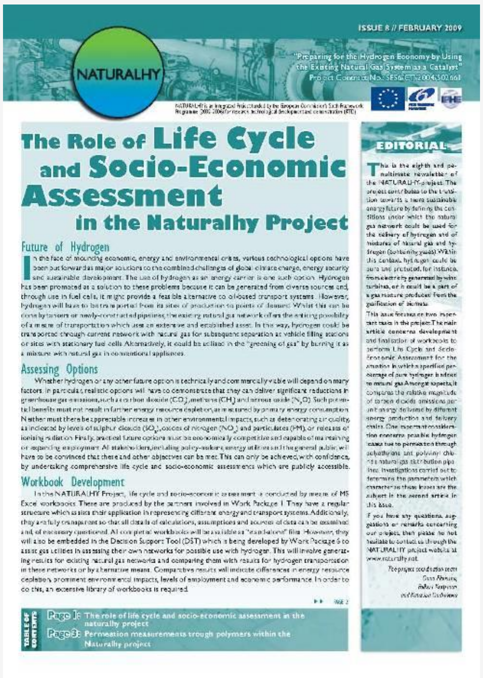
TABLE OF CONTENTS

EDITORIAL

With this seventh Newsletter on the NATURALHY project we would like to update you on the progress of our project, which investigates the potential of the existing natural gas system for the delivery of hydrogen.
The main objective of the project is to identify and if possible remove the potential barriers inhibiting the development of hydrogen as an energy carrier, using the existing natural gas system as a catalyst for change.
As a first logical step in the transition towards the hydrogen economy, the project focuses on using the existing natural gas grid for the delivery of hydrogen/natural gas mixtures from the perspective of the "greening of gas" but also perhaps to deliver 'pure' hydrogen where necessary.
The addition of hydrogen to natural gas affects the chemical and physical properties of the gas and will have an impact on the safety aspects related to the transmission, distribution and end use of the gas.
The main article of this issue is dedicated to the progress obtained in the Safety workpackage related to Vapour Cloud Explosions (VCE) with Natural Gas / Hydrogen mixtures up till 50 % Hydrogen.
The results show clearly the importance of congestion in creating turbulence which enhances the severity of the VCEs.
The second article in this issue focuses on a statistics software tool developed for the prediction of the Probability Of Failure (POF) of a pipeline based upon the behaviour of defects and the type of inspection technique selected.
If you have any questions or would like to discuss certain aspects of the NATURALHY-approach with us, than please react through our website www.naturalhy.net.

The project coordination team
Geert Tielsma
Folkert Koopman
and Friedrich Walbek

Newsletter No. 7 (May 2008)



ISSUE 8 // FEBRUARY 2009

NATURALHY

"Preparing for the Hydrogen Economy by Using the Existing Natural Gas System as a Catalyst"
Project Contract No.: SES6/CT/2004/502661

The Role of Life Cycle and Socio-Economic Assessment in the Naturalhy Project

Future of Hydrogen

Assessing Options

Workbook Development

EDITORIAL

TABLE OF CONTENTS
Page 1: The role of life cycle and socio-economic assessment in the naturalhy project
Page 3: Permeation measurements trough polymers within the Naturalhy project

ISSUE 9 // OCTOBER 2009

NATURALHY

"Preparing for the Hydrogen Economy by Using the Existing Natural Gas System as a Catalyst"
Project Contract No.: SES6/CT/2004/502661

DST - The Naturalhy Decision Support Tool

The GTN layout form

EDITORIAL

TABLE OF CONTENTS
Page 1: DST - The Naturalhy Desicion Support Tool
Page 2: Improved corrosion integrity management of pipelines using remote monitoring and modelling
Page 3: LURAP: A risk assessment methodology for transmission pipelines conveying natural gas/hydrogen mixtures

Newsletter No. 8 (February 2009)

Newsletter No. 9 (October 2009)

Figure 9.2 Samples of Newsletters published

8.3 WORKSHOPS AND EVENTS

A series of four workshops were organised on an annual basis, starting from the second year of the project's duration, so as to reach a scientific audience and present and discuss the project findings. All workshops were organised within international scientific events, so as to maximise the attention received on the project and the audience size.

The workshops were organised at:

- Zaragosa, Spain, on November 22, 2005 during the 2nd European Hydrogen Energy Conference EHEC 2005
- Amsterdam, Netherlands, on May 30 within the Conference "Transmission of CO2, H2, and biogas: exploring new uses for natural gas pipelines"
- Paris, France on October 9th, 2008 within the International Gas Research Conference, that was held on October 7-10, 2008.
- Ajaccio, Corsica – France during the International Conference on Hydrogen Safety.

In total, more than 250 attendants participated in these events. Attendants included engineers, scientists and decision makers from the gas sector from Europe, USA and Asia. Lively discussions followed the presentations made by NATURALHY members in each event, thus providing a valuable insight to NATURALHY project work

Figure 9.3 Impression of the 3rd NATURALHY Workshop (IGRC 2008, Paris)

Further to the above workshops, NATURALHY also participated in several other international events in order to present and discuss its scientific findings. These events included mostly international conferences e.g. the 17th World Hydrogen Energy Conference, the Forum Hydrogen Pipeline Transmission of the International Pipeline Conference 2006, the World Gas Conference 2006, the European Hydrogen and Fuel Cell Technology Platform, the 2nd European Hydrogen Energy Conference, (EHEC 2005), the International Conference on Hydrogen Safety (ICHS 2005, 2007 and 2009), the 3rd GCC-EU Advanced Oil and Gas Technology Conference in November 2005 in Kuwait, etc.

Particular notice should be made to the event which was organized for the presentation of the NATURALHY Project to the Committee on Industry, Research and Energy (ITRE) of the European Parliament, on May 31, 2009.

Finally, the NATURALHY results were presented at the Final Public Presentation, which was dedicated to NATURALHY and that took place at the headquarters of the project coordinator N.V. Nederlandse Gasunie, in Groningen, the Netherlands on 19th November 2009.

8.4 NATURALHY BROCHURE

A NATURALHY Brochure was prepared, in order to provide the ultimate dissemination publication of the project and to provide an insight to the major findings of the project activities. The brochure is a 32, full color A4 pages and includes articles on the role of hydrogen in the transition towards a sustainable energy society; the NATURALHY approach and what can the natural gas system offer for the delivery of hydrogen; the impact of adding hydrogen to natural gas on the durability of the network; the measures that should be taken to control and monitor the condition of the network; the impact of adding hydrogen to natural gas on safety aspects; the impact of adding hydrogen to natural gas on end user aspects; the separation of hydrogen from hydrogen/natural gas mixture and its impact on the quality of the remaining gas; how to assess a specific network for the NATURALHY concept; the overall benefits of adding hydrogen to natural gas and concluding remarks.

The brochure was made available in hardcopy format and in electronic format, available for downloading from the project web site.

8.5 WORK ON STANDARDISATION

One of the objectives of the NATURALHY project is to assess the current situation of standards and regulations regarding hydrogen/natural gas mixtures and to identify necessary modifications and eventually to initiate required changes. It is understood that some aspect of the gas system will be affected more than others by the injection of hydrogen. It can be expected that standards related to the chemical (gas) composition, performance of end user appliances, safety distances (safety risks) have to be revised. Also, depending on the technique of production, (standard) requirements for the entry point and the injection will be necessary.

Since the start of the NATURALHY project we have seen several developments in relation to the possible future use of the (European) gas grid. Next to addition of hydrogen into the natural gas grid, the injection of other non-conventional sources like methane rich gases were being considered and discussed more and more. In the meantime CEN/TC 234 decided to install a new working group, CEN TC/234 WG9 Non conventional gas injection into gas grids to start standardization development. Within this working group the development of a CEN Technical report Gases from non-conventional sources — Injection into natural gas grids — Requirements and recommendations started . It covers the state of the art in the treatment, injection, transportation, distribution and utilization of gases from non-conventional sources, including hydrogen, in the natural gas system. It also tries to foresee the possible developments in this field in the nearer future.

The scope of the CEN Technical Report covers the utilization of non-conventional sources like methane rich gases from gasification or fermentation processes; hydrogen-rich gases from gasification or other chemical processes and hydrogen produced by electrolysis (generally using renewable energy).

The main aspects to be covered by the CEN/TC 234/WG 9 are the technical, gas quality and most important (long term) safety and integrity aspects related to the delivery of such gases by the existing natural gas networks, and concern particularly the processes injection in the gas networks, metering and billing, transmission and distribution, and end use. The production and upgrading processes will only be described as far as relevant for the other processes.

For the moment the focus within this standards development will be mainly on the biogas but in the following years this CEN document should be considered in addition to any existing National standards covering installations for manufacture, extraction, treatment, injection, transport and utilization of non conventional gases. It may also support any future directive or ordinance in this field.

The CEN/TC 234/WG 9 already is aware of the NATURALHY project and furthermore will take into account the results of the NATURALHY project. Furthermore, CEN/TC 234/WG 9 will be the basis for relevant future standardization initiatives related to the injection of hydrogen into the gas grid. The working group will only work on standardization of main aspects and not on all individual aspects as discussed in this report. However, they can and most probably will act as initiator to other working groups and Technical Committees and working groups in and outside CEN.

To enable a market introduction of gas/hydrogen mixtures, all technical barriers should be taken away by amending the existing relevant national and European standards and development of new European standards. The impact of revision of standards should not be underestimated due to the huge number of standards involved. Next to both the European and the national standards also branch codes do exist and next to that a lot of companies do have their own companies standards which include by reference a mix of the above mentioned codes and standards and additional company specific issues. Furthermore a lot of the standards are linked by references to European and national legislation but also to for instance certification schemes and training plans.

9 COORDINATION - WORK PACKAGE 8

9.1 PROJECT MANAGEMENT STRUCTURE

The project management structure is based on highly linked team organization with assigned responsibilities and roles (Figure2)

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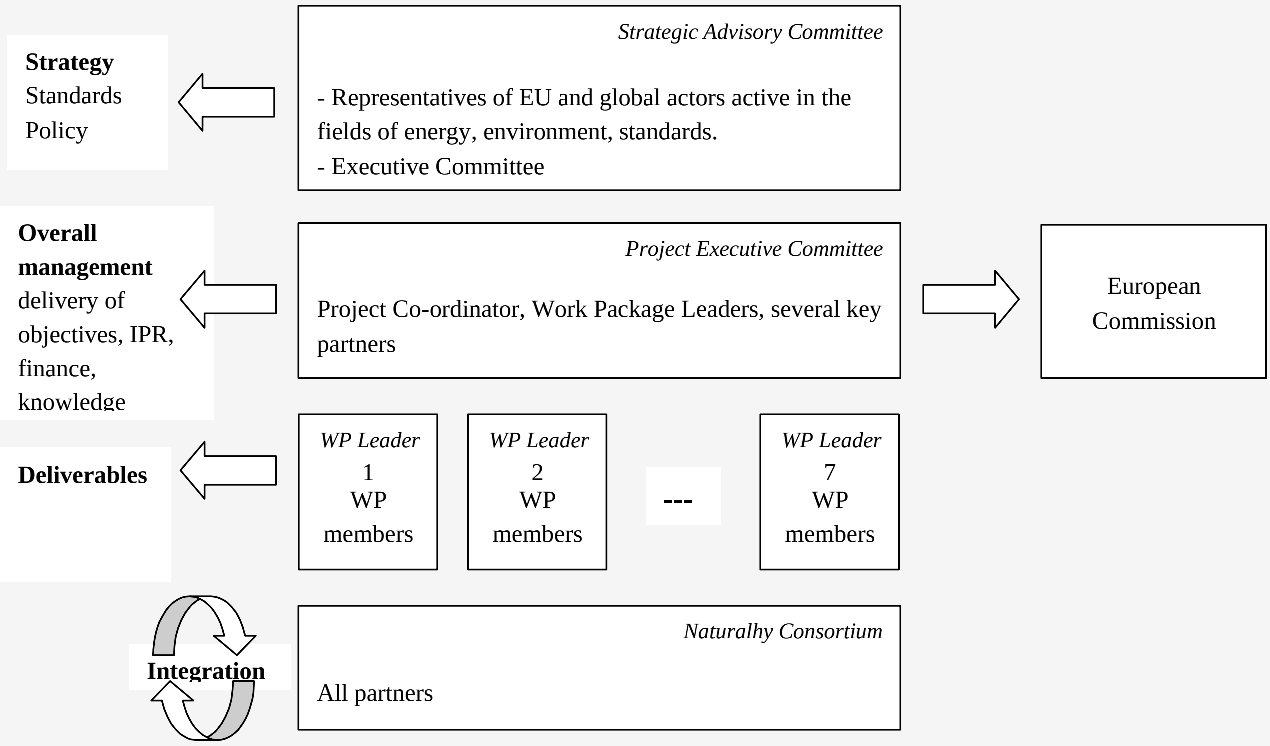

Figure 10.1 The management structure of the NATURALHY-project

The **Project Executive Committee (PEC)**, as the core group responsible for the successful completion and delivery of the Project, was delegated by the full project Consortium to oversee the management of the project, and the Committee reported to the full Consortium at the annual all-partner meetings. The Committee is a management team that consisted of the Work Package leaders, the GERG representative and the project coordinator. This Committee met at least every 6 months and at appropriate phases of the project

The activities of this Committee were focused on:

- Overall Project management: to approve the progress of the Project and to solve any bottlenecks. The project coordinator prepared progress reports based on the information of the partners, compared the actual progress with the planning and prepared appropriate proposals to deal with any discrepancies. The Work Package leaders have prepared substantial contributions to the regular progress reports and the final reports. The Committee tuned the programs and activities carried out within the Work Packages, solved bottlenecks and took care of information exchange among and towards the partners. Particular effort has been paid to project integration: if the output from one Work Package is aimed to be the input of another Work Package, the type of data, the planning of the delivery, the format of the data, the conditions for which the data is valid etc. has to be agreed in detail.

- Financial management: Administrative aspects of the financial management were carried out in compliance with the EC contract and the Consortium Agreement by the project coordinator and his staff: project finance needed the approval of the Executive Committee and the Party(ies) concerned.
- Management of knowledge resulting from the project and of legal issues: Knowledge management concerns issues like ownership of results, access rights, commercialization of results, and was a basic responsibility of the PEC. As a part of this, the Work Package leaders have paid particular attention to the quality of reports prepared by the members of its Work Package.
- Information management: The Consortium Agreement determines that all information produced within the project was confidential unless the PEC decided otherwise. The project coordinator took the lead for requesting such approval. All documents relevant for the project have been made accessible for all partners (supported by the project website). Communications with the Commission were also one of the responsibilities of the project coordinator.

The **7 Work Package Committees** defined comprise the partners that carried out the RTD programme for NATURALHY. For the co-ordination of each Work Package, a dedicated Committee was established, that was led by a well-experienced partner (the Work Package leader). The Work Package co-ordination was focussed on progress obtained in the Tasks and on completion of the Work Programme by planning details of specific activities, liaising with Work Package participants, checking milestones, organising deliverables, and assisting integration with other related Work Packages. These Work Package Committees met regularly, at least every 6 months.

The **Full Project Consortium** of partners met annually (including at the kick-off meeting). These meetings took take place over two days and had agreed timetable and agenda to ensure all business were completed and that all partners were well informed. The agendas were dedicated to project business aspects including the status of the project, specific results obtained and problems surmounted, updates from the Commission, financial issues, IPR and dissemination issues. Furthermore, there was room for partners to interact, discuss detail project developments, discuss project plans etc (Integration). Any major changes to the Project needed the approval of the Full Project Consortium.

The **Strategic Advisory Committee (SAC)** was aimed at addressing the strategic aspects of the project and to establish a platform for dissemination and for promoting public understanding and acceptance. It comprised selected representatives and advisors of European decision makers, regulators, authorities and policy groups in the fields of energy, environment and legislation, together with the members of the NATURALHY Project Executive Committee. Among others, the following entities have participated in this Committee: US DOE (US), International Gas Union (Global), Naturgas Energia (ES), TPAO (TR), Health & Safety Executive (UK), EON-Ruhrgas (DE), DVGW (DE), Alliander (NL), Air Liquide (FR), AKZO NOBEL (NL), IEA GHG(UK) , HYSAFE (DE), Roads2Hycom (UK), Wuppertal Institute (DE), Bellona (NO), European Natural Gas Vehicle Association (ENGVA, NL), European Commission, ENI (IT), Linde (NL), Gordon Adams (former MEP, UK). This Committee has discussed the strategic aspects of the project and it was the ‘vehicle’ by which the NATURALHY-members informed the Committee of the vision and results of the Project, so that these were taken into account in their own processes. In return, the NATURALHY members were informed about the current relevant developments in politics, legislation, other projects etc. The resulting advices and guidance from this Advisory Committee have been taken into account by the PEC very seriously, and several of them have led to adjustments of the NATURALHY project program. So, this Committee had a critical role in ensuring a perfect match between the Project objectives and the real long term (political) needs; moreover, the Committee was a platform for the dissemination of results on an international and global level and for promoting public understanding, awareness and acceptance of the introduction of hydrogen energy into EU society.

The **Project coordinator and his staff** formed a dedicated team for the co-ordination activities: The main management activities of the project coordinator and his staff involved

- Co-ordination at consortium level of the technical activities of the project by informal contacts and formal meetings;
- Focal point of information and collaboration with related projects and initiatives;
- Close liaison with the EC-representative, both formally and informally, to ensure the EC is closely informed of developments;
- The overall legal, contractual, ethical, financial and administrative management of the consortium;
- Preparing, updating and managing the Consortium Agreement between the participants;
- Examination of the progress and the quality of the execution of the work, and motivating and encouraging Parties;
- Preparation of progress and final reports on the basis of contributions from the Parties;
- Co-ordination at consortium level of knowledge management and other innovation-related activities;
- The implementation of competitive calls by the consortium to find new participants;
- Overseeing science and society issues, related to the research activities conducted within the project.

At the completion of the Project, it can be concluded that the management structure defined at the start worked out very well for this project. It turned out to be efficient and effective. Nevertheless, the effort initially planned by the PEC-members for the project management has been exceeded by far: the effort demanded for a proper project management was significantly underestimated at the start of the project.

9.2 NATURALHY CONNECTED TO THE WORLD

The communication with stakeholders and other on-going research projects is essential to ensure that:

- The NATURALHY project maintains an awareness of, and takes into account, developments in the fields relevant to the project;
- The NATURALHY results find a broad acceptance;
- The NATURALHY results establish a benchmark and, hence, are integrated into other research projects.

Therefore, the following arrangements have been made in addition to the comprehensive dissemination programme executed in the framework of Work Package 7:

- The NATURALHY Strategic Advisory Committee (SAC) was established as described above.
- The NATURALHY project has been recognised as a project in the International Partnership for the Hydrogen Economy, and aims at worldwide collaboration with other projects and organisations.

Finally, several NATURALHY partners participated in various national and international platforms, forums, working groups etc. in which NATURALHY results were introduced. In return, these partners also gathered relevant information and views which were fed back into the project.

10 FURTHER INFORMATION ABOUT NATURALHY

The NATURALHY project included a comprehensive dissemination programme to inform all stakeholders including the general interested public as well as for experts in the different fields of expertise, of the results (and during the project execution, the progress). The public part of the project website www. NATURALHY.net includes copies of for instance scientific papers, presentations, newsletters, the NATURALHY brochure, the NATURALHY Workshop presentations, the presentations at the NATURALHY Final Public Presentation and the public final report.

The table below shows the presentations given as congresses and the papers published, ordered by work package. Most of these papers and presentations are available on the project website www. NATURALHY.net

NATURALHY IN GENERAL			
NATURALHY, using the existing natural gas network for hydrogen delivery: final results	Presentation	Onno Florisson (N.V. Nederlandse Gasunie)	DOE Workshop Hydrogen Pipeline Working Group Meeting, Boulder US, 26+27 Aug. 2009
“NATURALHY”: First step in assessing the potential of the existing natural gas network for hydrogen delivery	Paper	Onno Florisson (N.V. Nederlandse Gasunie)	INGAS2009, Istanbul, 9-10 June 2009
The NATURALHY Project: Questions and Answers	Presentation	Nigel Mortimer,(Loughborough University)	Presentation of the NATURALHY project to the Committee on Industry, Research and Energy (ITRE) of the European Parliament, 31 March 2009
“NATURALHY”: Assessing the potential of the existing natural gas network for hydrogen delivery	Presentation	Onno Florisson (N.V. Nederlandse Gasunie)	IEA workshop “Large-scale Hydrogen Infrastructure and Mass Storage”, Amsterdam, 12-13 Feb. 2009
NATURALHY: The first step in assessing the potential of the European natural gas network for Hydrogen delivery	Presentation	Gjalt Tiekstra (N.V. Nederlandse Gasunie)	PWG meeting organised by the US DOE, Sandia Laboratories, CA, USA, 20-21 February 2008
The NATURALHY-project: Preparing for the hydrogen economy by using the existing	Presentation	Onno Florisson (N.V. Nederlandse Gasunie)	Winter meeting of the European Industrial Gases Association

natural gas system as a catalyst			(EIGA), Brussels, 25 Jan. 2007
The NATURALHY-project: first step of the determination of the potential of the existing natural gas network for hydrogen delivery	Presentation	Onno Florisson (N.V. Nederlandse Gasunie) and Isabelle Alliat (Gaz de France)	Forum Hydrogen Pipeline Transmission, IPC/ASME International Pipeline Conference, Calgary, 25 Sept. 2006
Preparing for the hydrogen economy by using the existing natural gas system as a catalyst (NATURALHY)	Presentation	Onno Florisson (N.V. Nederlandse Gasunie)	European Hydrogen and Fuel Cell Technology Platform, Brussels, 6-9 Dec. 2006
The value of the existing natural gas system for hydrogen, the sustainable future energy carrier (progress obtained in the NATURALHY-project)	Paper	Isabelle Alliat (Gaz de France) Onno Florisson (N.V. Nederlandse Gasunie), Dr. Barbara Lowesmith & prof. Geoff Hankinson (Loughborough University),	World Gas Conference 2006
The NATURALHY-project: The potential of the existing natural gas system for hydrogen	Paper	Onno Florisson (N.V. Nederlandse Gasunie)	2nd European Hydrogen Energy Conference (EHEC 2005), Zaragoza, 22-25 Nov. 2005
Preparing for the hydrogen economy by using the existing natural gas system as a catalyst-an overview of the NATURALHY project	Presentation	Rolinda Huizing (N.V. Nederlandse Gasunie) Dave Pinchbeck (GERG)	3rd European Forum Gas, Warsaw, Poland, September 2005
Natural gas, hydrogen and sustainability	Article	Onno Florisson (N.V. Nederlandse Gasunie) Bob Harris (Broadfern Consultants)	Petroleum Economist, Fundamentals of the World Gas Industry, 2005
A step towards the hydrogen economy by using the existing natural gas grid	Presentation	Onno Florisson (N.V. Nederlandse Gasunie)	Conference “Natural gas: a reliable and versatile source”, Milan, 14 Dec. 2004

A practical step towards "hydrogen": The conditions under which the existing natural gas system can be used for mixtures of hydrogen and natural gas (the NATURALHY -project)	Paper	Onno Florisson (N.V. Nederlandse Gasunie)	International Gas Research Conference, Vancouver, Nov. 2004
NATURALHY-project: Preparing for the Hydrogen Economy by Using the Existing Natural Gas Pipelines as a Catalyst	Presentation	Onno Florisson (N.V. Nederlandse Gasunie)	Panel Forum "Challenges of hydrogen pipeline transmission, IPC/ASME, Calgary, 4 Oct. 2004
Natural gas, the bridge to sustainability (including the NATURALHY-project")	Presentation	Onno Florisson (N.V. Nederlandse Gasunie)	International Workshop "EU-Russian cooperation on research for hydrogen and fuel cells", Moscow, 29-30 Sept. 2004
NATURALHY-project: Preparing for the Hydrogen Economy by Using the Existing Natural Gas Pipelines as a Catalyst	Presentation	Onno Florisson (N.V. Nederlandse Gasunie)	Conference "Hydrogen in Europe", College of Europe, Brugge, 23-24 June 2004
NATURALHY-project: Preparing for the Hydrogen Economy by Using the Existing Natural Gas Pipelines as a Catalyst	Poster	Onno Florisson (N.V. Nederlandse Gasunie)	Eurogas Conference "The Conditions for Sustainable Development in the Enlarged European Natural Gas Market", Brussels, 30 March 2004
NATURALHY-project: Preparing for the Hydrogen Economy by Using the Existing Natural Gas Pipelines as a Catalyst	Paper	Onno Florisson & Rolinda Huizing (N.V. Nederlandse Gasunie)	Temadag on Britt, Hørsholm DK, 18 March 2004
LIFE CYCLE AND SOCIO-ECONOMIC ASSESSMENT – Work Package 1			
Life Cycle and Socio-Economic Assessment of the Natural Gas System in Transition to Hydrogen	Paper	Nigel Mortimer (Loughborough University)	17th World Hydrogen Energy Conference, 15-19 June 2008, Brisbane , Australia

Supplying Energy to a changing World	Presentation	Technische Universiät Berlin	17th World Hydrogen Energy Conference, 15-19 June 2008, Brisbane , Australia
Life Cycle Assessment of Natural Gas Systems	Paper	Nigel Mortimer (Loughborough University)	International Gas Union Research Conference, Oct 2008, Paris
Life Cycle Assessment of the Transition to the Hydrogen Economy	Article	Nigel Mortimer (Loughborough University) and G. Tiekstra (NV Nederlandse Gasunie)	International Energy Agency Greenhouse Gas Issues, 2008
Grids for the Future – Natural Gas Todday, Hydrogen Tomorrow	Article	G. Tiekstra (NV Nederlandse Gasunie) and Nigel Mortimer (Loughborough University)	DVGW Energie/ Wasser Praxis, 2008
SAFETY – Work Package 2			
Vented Confined Explosions involving methane/hydrogen mixtures	Paper	Lowesmith B J, Mumby C, Hankinson G and Puttock JS	HYSAFE conference 2009
The effect on safety of adding hydrogen to the natural gas system	Paper	Lowesmith B J	7th European Forum Gas (EFG 2009), Madrid, Spain, 19 June 2009
Turbulent Burning rates of methane and methane-Hydrogen Mixtures	Article	M. Fairweather, M.P. Ormsby, C.G.W. Sheppard, R. Woolley	Combustion and Flame, 156(4), 780-790, 2009
Ignition Energy and Ignition Probability of Methane-Hydrogen-Air Mixtures	Paper	Hankinson G, Mathurkar H, Lowesmith B J	HYSAFE conference 2009
Gas Build up in a Domestic property following releases of Methane Hydrogen mixtures	Paper	B.J. Lowesmith, G. Hankinson, C. Spataru, M. Stobbart	International Journal of Hydrogen Energy (2009)
Explosion Hazard for Natural Gas/Hydrogen Mixtures	Presentation	B.J. Lowesmith	Presentation of the NATURALHY project

			to the Committee on Industry, Research and Energy (ITRE) of the European Parliament, 31 March 2009
Predictions of the consequences of natural gas hydrogen explosions using a novel CFD approach	Paper	Woolley, R.M., Fairweather, M., Falle, S.A.E.G., and Giddings, J.R.	18th European Symposium on Computer Aided Process Engineering, Computer-Aided Chemical Engineering, June 2008
Gas Build up in a Domestic property following releases of Methane Hydrogen mixtures	Paper	Lowesmith, B.J., Hankinson, G., Spataru, C. and Stobbart, M.	HYSAFE conference, September 2007
The Laminar Burning Properties of Premixed Methane-Hydrogen Flames Determined Using a Novel Analysis Method	Paper	A.A. Burluka, M. Fairweather, M.P. Ormsby, C.G.W. Sheppard and R. Woolley.	Third European Combustion Meeting ECM 2007
DURABILITY - Work Package 3			
A fatigue initiation parameter for gas pipe steel submitted to hydrogen absorption".	Paper	J. Capelle, J. Gilgert, G. Pluvinage	International Journal of Hydrogen Energy, Volume 35, Issue 2, January, Pages 833-843, (2010).
Two-Parameter Approach : (Kρ – Tρ) Constraints Effects Estimation in Pipelines with notches	Presentation	Hadj Meliani, Z. Azari, Y. Matvienko and G. Pluvinage	CAM 2009, Alger (2009)
Hydrogen Effect On Fatigue And Fracture Of Pipe Steels;	Presentation	J.Capelle , J.Gilgert, And G. Pluvinage,	International Conference of Hydrogen Safety ICHS 09, Ajaccio, Septembre (2009).
Defect assessment on pipe used for transport of mixture of hydrogen and natural gas	Presentation	J.Capelle , J.Gilgert, And G. Pluvinage,	International Conference of Hydrogen Safety ICHS 09, Ajaccio, Septembre

			(2009)
Failure risk of a pipe used for transport of a mixture of natural gas and hydrogen in x52 steel.	Presentation	G. Pluvinage, J. Capelle and J.Gilgert	International Conference of Fracture ICF12 Ottawa Juillet (2009).
Hydrogen effect on fatigue and fracture of a pipe steel API 5lx52	Presentation	J. Capelle, J. Gilgert, G. Pluvinage,	9ème congrès de Mécanique Marrakech (Maroc), 21 – 24 Avril (2009).
Hydrogen effect on local fracture emanating from notches in pipeline with steel API X52	Paper	J. Capelle, I. Dmytrakh, G. Pluvinage	Problems of Strength N°5, 401, (2009).
Electrochemical hydrogen absorption of API X52 steel and its effect on local fracture emanating from notches	Paper	J. Capelle, I. Dmytrakh, G. Pluvinage	Structural integrity and Life , Vol.9, N°1,pp3-8 (2009).
Constraint parameter for a longitudinal surface notch in a pipe submitted to internal pressure	Presentation	M. Hadj Meliani , M.Benarous, Z.Azari & G.Pluvinage	Congrés CMT 85, Timisoara , Roumanie, novembre (2008)
“ Electrochemical hydrogen absorption of api x52 steel and its effect on local fracture emanating from notches	Presentation	. Capelle, I. Dmytrakh, G. Pluvinage	Congrès NT2F8 , Slovénia, Octobre, (2008).
Gouge assessment for pipes and associated transferability problem	Presentation	Pluvinage, J. Capelle And M. Hadj Meliani	NT2F8 , Slovénie, Octobre, (2008).
Sensitivity of Pipelines with steel API X52 to hydrogen embrittlement	Paper	J. Capelle, J. Gilgert, I. Dmytrakh, G. Pluvinage	International Journal of Hydrogen Energy, (September 2008)
Mesofracture approach of gouge defect assessment in pipes and associated transferability problem”	Presentation	G Pluvinage, J. Capelle And M. Hadj Meliani “	Mesomechanics Tomsk Russie September, (2008).
Defect assessment on pipe transporting a mixture of natural gas and hydrogen”	Presentation	G. Pluvinage	ICFQ Conference Alger Juin (2008).
Hydrogen effect on local fracture	Presentation	J. Capelle, I. Dmytrakh,	Int Conference of

emanating from notches in pipeline with steel API X52		G. Pluvinage	Strength of Material Kiev, Ukraine June, (2008).
« Les problèmes de sécurité du transport et du stockage de l'hyudrogène »	presentation	G Pluvinage J Capelle et J. Gilgert	Congr7s JET 08Marrackech, Maroc ,07 - 09 mai (2008).
"Sensitivity to hydrogen embrittlement of X52, X70 and X100 pipe steels",	Presentation	J. Capelle and G Pluvinage	SteelConférence 2008, Buenos Aires, Argentine, Mai, (2008
Durability of existing Natural Gas Infrastructures	Presentation	Isabelle Alliat (Gaz de France)	PWG meeting organised by the US DOE, Sandia Laboratories, CA, USA, 20-21 February 2008
Measurement of the resistance to fracture emanating from scratches in gas pipes using non-standard curved specimens	Paper	J. Capelle, J. Gilgert, Yu.G. Matvienko, G. Pluvinage	International Journal of Pipes and Pressure Vessels, (2007)
Comparison of methods to measure the resistance to fracture emanating from scrathes in gas pipes	Presentation	J. Capelle, J. Gilgert, Yu. G. Matvienko G. Pluvinage	ICF Fracture Mechanics in Design of Fracture Resistant Materials and Structures, Moscow, july (2007).
Comparison of methods to measure the resistance to fracture emanating from scratches in gas pipes	Presentation	J. Capelle, J. Gilgert, Yu. G. Matvienko G. Pluvinage	New trends in Fatigue and Fracture NT2F7 Miskolc ,May (2007).
Evaluation of the effect of corrosion defects on the structural integrity of X52 gas pipelines using the SINTAP procedure	Paper	H. Adib, S. Jallouf, C. Schmitt , A. Carmasol and G. Pluvinage ,	International Journal of Pressure Vessels and Piping Volume 84, Issue 3 , March, Pages 123-131, (2007)
Pipe failure assessment based on limit analysis, failure assessment diagram and subcritical crack growth"	Paper	G Pluvinage	Physico mechanical mechanics of materials p119-127,Vol 1-(2006).
Hydrogen effect on fatigue life of a pipe steel	Presentation	J Capelle, J . Gilgert G Pluvinage	Kiev XIII International Colloquium "Mechanical Fatigue of Metals" Kiev

			(Ukrainia) September 25 to 28, (2006).
Structural integrity evaluation of X52 gas pipes subjected to external corrosion defects using the SINTAP procedure	Paper	Adib-Ramezani , J. Jeong, G. Pluvinage	International Journal of Pressure Vessels and Piping pp1–13,(2006)
Calcul du facteur de sécurité associé à la ténacité d'un tuyau de faible épaisseur.	Presentation	J. Capelle et G Pluvinage	Alep , Congrés Franco-Syrien de Mécanique, Mai (2006).
Les approches modernes du coefficient de sécurité. Applications aux canalisations transportant de l'hydrogène ou un mélange de gaz naturel et hydrogène	Presentation	Capelle J et G Pluvinage	Hydrogène et énergies renouvelables » - « sécurité de l'hydrogène » 16 Metz Décembre (2005).
Quels outils pour le dimensionnement des canalisations transportant de l'hydrogène pur ou en mélange, Analyse limite ou mécanique de rupture « Hydrogène et énergies renouvelables »	Presentation	Pluvinage G	Hydrogène et énergies renouvelables » - « sécurité de l'hydrogène » 16 Metz Décembre (2005).
Calcul de la sécurite et de la fiabilité de réservoir sous pression d'hydrogène	Presentation	Jalouf S et Pluvinage G,	Hydrogène et énergies renouvelables » - « sécurité de l'hydrogène » 16 Metz Décembre 2005.
INTEGRITY – Work Package 4			
Integrity Issues	Presentation	Gert Müller-Syring (DBI-GUT)	PWG meeting organised by the US DOE, Sandia Laboratories, CA, USA, 20-21 February 2008
Permeation Measurement on Polymer Pipes	Paper	Gert Müller-Syring and S. Schütz (DBI-GUT)	International Gas Union Research Conference, Paris, 2008
Intelligent remote monitoring system for cathodic protection of transmission pipelines and A computational approach for	Papers	A. Peratta, J. Baynham, R. Adey; CMI Beasy Ltd, G.F. Pimenta, ISQ and A. Peratta, J. Baynham,	NACE Corrosion Exhibition & Conference. Exhibit display and Conference, March 2009, Atlanta, Georgia, USA

assessing coating performance in cathodically protected transmission pipelines		R. Adey; CMI Beasy Ltd	
Computational modelling of CP systems for pipelines in multi layer soil	Paper	A. Peratta, J. Baynham, R. Adey; CMI Beasy Ltd	Electrocor Conference, May 2009, Bologna, Italy
Prediction of Third Party Damage Failure Frequency for Pipelines Transporting Mixtures of Natural Gas and Hydrogen'	Paper	L. Zhang, R.A. Adey, Beasy	ICHS Conference, September 2009, Ajaccio, Corsica, France
Reliability Analysis of Pipelines Containing Cracks and Corrosion Defects	Paper	Lie Zhang and Robert Adey, Beasy	International Gas Union Research Conference, Paris, 2008
Predicting the Probability of Failure of Gas Pipelines Including Inspection and Repair Procedures	Paper	L. Zhang, R.A. Adey, Beasy	ICHS 2007 Conference, September 2007, St. Sebastian Spain
END USE- Work Package 5			
The recovery by carbon molecular sieve membranes of hydrogen transmitted in natural gas networks,	Article	Grainger, DR and Hägg, M-B	Int J Hydr Energy 33 (2008) 2379-2388
Evaluation of cellulose-derived carbon molecular sieve membranes for hydrogen separation from light hydrocarbons	Article	Grainger, DR and Hägg, M-B	J Membrane Sci 306 (2007) 307-317
Application of carbon molecular sieve membranes in a mixed hydrogen natural gas distribution network	Abstract	Jon Arvid Lie, David Grainger, May-Britt Hägg, NTNU	European Congress of Chemical Engineering (ECCE-6) Copenhagen, 16-20 September 2007
Safe operation of Natural gas appliances fuelled with hydrogen/natural gas mixtures (progress obtained in the NATURALHY project)	Paper	De Vries, H., Florisson, O, Tiekstra, G, N.V.Nederlandse Gasunie	HYSAFE conference, September 2007
Injection of hydrogen into the European gas network- and	Abstract	May-Britt Hägg, NTNU	North American

recovering the same from the gas mix by use of CMS-membranes at the end-user.			Membrane Society 2007
Investigation of using the existing gas network for transport of hydrogen-and using membranes at the end user for separation of H2-natural gas	Paper	Jon Arvid Lie, May-Britt Hägg, NTNU	Journal of Membrane Science 284 (2006) 79–86
Carbon membranes from metal loaded cellulose, and the application of an external field for improved performance	Abstract	Jon Arvid Lie, May-Britt Hägg, NTNU	9th International Conference on Inorganic Membranes, June 25-29, 2006, Lillehammer, Norway
Hydrogen recovery in a combined natural gas-hydrogen distribution network using carbon molecular sieve membranes	Paper	David Grainger, Jon Arvid Lie, May-Britt Hägg, NTNU	WHEC 16 / 13-16 June 2006 – Lyon France
DECISION SUPPORT TOOL – Work Package 6			
Presentation of DST Architecture	Presentation	The Open Group	Enterprise Architecture Practitioners Conference, Seattle, USA, 2 Feb. 2010
Possibilities of utilization of Hydrogen / Natural Gas mixtures in existing natural gas supply grids	Paper	N. Papageorgiou, E. Kakaras, J. Chomatas, D. Giannakopoulos, C. Fournaris, Ch. Adamopoulos	1st National Hydrogen Conference of Greece, Athens
Dissemination – Work Package 7			
No specific publications apart from Newsletters and Brochure which are available at the NATURALHY website			
PROJECT MANAGEMENT – Work Package 8			
Publications included in this listing under 'NATURALHY IN GENERAL'			