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THE VALUE OF THE EXISTING NATURAL GAS SYSTEM FOR HYDROGEN, THE SUSTAINABLE FUTURE ENERGY CARRIER
(PROGRESS OBTAINED IN THE NATURALHY-PROJECT)

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ABSTRACT

Hydrogen is foreseen as an important energy carrier in the future sustainable energy society. The transition towards the situation in which hydrogen becomes an important energy carrier will be lengthy (decades), costly and needs a significant effort for R&D. In view of this, an examination of the potential of using the existing natural gas pipeline system for the transmission and distribution of hydrogen is a logical first step.

The NATURALHY-project investigates the conditions under which hydrogen can be added to natural gas with acceptable consequences for safety, durability of the system, gas quality management and performance of the end-user appliances. Membranes will be developed to subtract hydrogen from a hydrogen/natural gas mixture for use by hydrogen powered equipment.

The NATURALHY-project is the main European project on hydrogen delivery, in which 39 partners participate. The project is financially funded by the European Commission, and is recognised by the International Partnership for the Hydrogen Economy.

The existing natural gas system has been designed for natural gas. The physical properties of hydrogen differ 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 in order to up-date the tools of integrity management previously assessed with only natural gas. Therefore the following subjects will be assessed: effect of H2 on failure behaviour and corrosion of transmission pipes and their burst resistance, permeability and ageing of distribution pipes, reliability and ageing of domestic gas meters, tightness to H2 of domestic appliances and their connections.

In terms of safety, the addition of hydrogen to the natural gas within the pipeline has the potential to change (increase) the level of risk presented to the public, because of the different physical and chemical properties of this gas. In particular, hydrogen could increase the likelihood of failures occurring and might increase the severity of the consequences due to the increased reactivity of hydrogen. Therefore, within the NATURALHY project, the risks presented to the public by operating a natural gas network conveying a mixture of natural gas and hydrogen must be examined. A major part of this work will be to assess the fire and explosion hazards presented by accidental releases of natural gas/hydrogen mixtures for comparison with natural gas alone. This will be achieved by conducting large scale experiments and developing improved mathematical models.

By combining new information on failure frequency with a revised assessment of the consequences, the risks presented to the public by the proposed introduction of hydrogen can be re-assessed. In particular, by varying the level of hydrogen, it may be possible to identify the maximum ‘safe’ level which could be introduced whilst maintaining an acceptable risk to the public.

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1. INTRODUCTION

Hydrogen is foreseen as an important energy carrier in the future sustainable energy society. Hydrogen can be produced in many sustainable ways (electrolysis using wind energy, gasification of biomass), and can be used for highly efficient electricity production in fuel cells for domestic, industrial and transportation applications. However, the very significant technical, economic and institutional changes required to establish the "hydrogen economy" will take several decades to implement. These changes will concern all individual elements of the energy system-production, delivery, storage, conversion and end-use applications. These elements are interrelated and interdependent, and, as a consequence of this, there is a "chicken and egg" dilemma regarding market segment development and how supply and demand will push or pull these activities.

In any transition scenario for the full hydrogen economy and in all variants of hydrogen economies, there must be a connection (pipeline) between the hydrogen production and the appliance powered by hydrogen. The distance between the hydrogen production and the appliance will range from several centimetres to several thousands of kilometres depending on the nature of the production, whether centralised, decentralised or hybrid, and its use (e.g. possible hydrogen production in Norway and transmission to Central Europe).

The transition towards the situation in which hydrogen is an important energy carrier will be lengthy (decades), costly (as an illustration, at today's prices, the cost to build from scratch the European natural gas system would be several times 10^{11} Euro) and needs a significant effort for R&D. Transmission and distribution of natural gas is the core business of several partners of the NATURALHY project. In order to prepare themselves for a role in "hydrogen", they have made a preliminary examination of the possibilities of using their existing natural gas systems as the connection between hydrogen production and appliances powered by hydrogen. In fact, it is an obvious and pragmatic step to assess the existing situation for adaptation to new opportunities, and in this way to break the "chicken and egg" dilemma.

Moreover, the preparation is important because hydrogen might offer interesting future business opportunities for natural gas transporters but is also necessary as the EU Directive 2003/55/EC states that "*… taking into account the necessary quality requirements, biogas and gas from biomass or other types of gas are granted non-discriminatory access to the gas-system, provided such access is permanently compatible with the relevant technical rules and safety standards. These rules and standards should ensure, that these gases can technically and safely be delivered into, and transported, through the natural gas system and should also address the chemical characteristics of these gases…*". Although not explicitly stated in this Directive, it also applies to biogas that contain hydrogen. In addition, it can be argued that "or other types of gas" include hydrogen produced as for instance a by-product of a chemical process.

The NATURALHY-project, prepared by all stakeholders involved and crucially including the main gas industry, aims to investigate comprehensively the practical means of using the existing natural gas infrastructure for hydrogen accommodation and delivery.

2. OVERVIEW OF THE NATURALHY-PROJECT

As the physical and chemical properties of hydrogen differ significantly from natural gas, it is generally speaking not possible to simply replace the natural gas completely by hydrogen in the existing natural gas system. However, using the existing system for mixtures of natural gas and hydrogen will offer the possibility to accommodate significant volumes of hydrogen and a unique opportunity to connect hydrogen producers and end users on the short term and at relatively low cost.

These mixtures can be used as such in the existing natural gas appliances (and thereby potentially offer reduced CO_2 emissions) but also in combination with membranes to split the gas stream near the end user, the mixtures can be used to supply high purity hydrogen to hydrogen end users, At least during the transition phase leading to the situation when hydrogen becomes an important energy carrier, this option is interesting and will promote public acceptance of hydrogen, due to the excellent safety record of the natural gas industry. It will also catalyse developments in hydrogen production and end use, and will give more time to define the future energy system and the requirements in sufficient detail. In this respect, the competition of hydrogen with other sustainable energy carriers including large volumes of mainly methane containing biogas will be of particularly importance.

By adding hydrogen to natural gas, the physical and chemical properties of the mixture will differ from “pure” natural gas and this may have a major effect on:

- The safety aspects related to the transmission, distribution and end-use of the gas;
- The durability of the transmission and distribution pipeline systems and the end user infrastructure (hydrogen may diffuse into materials and change the mechanical properties):
- The gas quality management issues related to the gas delivery;
- The performance of end use appliances.

In this paper we will further highlight the work included in the NATURALHY-programme focussing on the impact of hydrogen added to natural gas on the durability aspects of existing natural gas delivery system and on the safety aspects related to the transmission, distribution and use of hydrogen/natural gas mixtures.

The NATURALHY-approach and the main field of activities are indicated in Figure 1.

The main objectives of the NATURALHY-project are:

- To define the conditions under which hydrogen can be added to natural gas in the existing natural gas system (transmission-distribution-end use infrastructure and appliances) with acceptable safety risks, impact on the integrity of the system and consequences for gas quality management and to the end user. The main technical deliverable of the project concerns an expert system (called the “Decision Support Tool”) that determines the maximum percentage of hydrogen that can be added to natural gas supplied in a given section of a natural gas pipeline system and identifies the factors that limit the percentage.
- To develop techniques (membranes) to separate hydrogen from hydrogen/natural gas mixtures;
- To assess the socio-economic and Life Cycle aspects of the NATURALHY-approach.

The following work packages consisting of several coherent tasks have been defined (between brackets the work package leader):

- Socio-economic and Life Cycle Analysis (Warwick University)
- Safety (Loughborough University)
- Pipeline durability (Gaz de France)
- Pipeline Integrity (TNO)
- End Use and membranes (Warwick University)
- Decision Support Tool (ISQ)
- Dissemination (Exergia)
- Project management (Gasunie Engineering and Technology)

In addition, GERG has an important advising role in the management of the project.

Besides the organizations mentioned above the following organizations participate which are particularly active in the gas business: BP Gas Marketing Limited, DBI Gas- und Umwelttechnik GmbH, DEPA, DGC, GE PII, IGDAS, IFP, Naturgas Midt-Nord I/S, Shell Hydrogen, Statoil ASA, Total S.A. and TRANSCO (part of National Grid Transco plc).

Apart from the consortium of partners actually executing the research program, the NATURALHY Strategic Advisory Committee has been established. This Committee addresses the strategic aspects of the project and establishes a platform for dissemination and for promoting public understanding and acceptance, and consists of the stakeholders including governments, decision makers, regulators, NGO’s active in the fields of hydrogen, energy, natural gas, safety or environment. At the moment of preparing this paper the Committee includes amongst others the following organisations: IGU (link Dr. B. Harris), IEA, Ruhrgas, ENItecnology, GERG, DVGW, IAHE, NaturCorp, CONTINUON, UK Health Safety Executive, HYSAFE, HYWAYS, EU-Commission, NL Ministry of Economics, EU-Parliament (Link Mr. G. Adam), US Department of Energy, CEN (link Dr. C.

Beckervordersandforth). Discussions with several hydrogen producers about participation are ongoing.
Very recently, the NATURALHY-project has been recognised in the framework of the International Partnership for the Hydrogen Economy (IPHE, a world wide initiative to coordinate hydrogen research). This recognition opens the way to further international collaborations with organisations and projects active in the fields relevant to the NATURALHY-project.

The NATURALHY-project started on 1st May 2004, and its duration is 5 years. The total project budget amounts to 17.3 MEURO and is financially funded by the European Commission within the 6th Framework Programme for Research, Technological Development and Demonstration.

3. THE EFFECTS OF INJECTING HYDROGEN ON THE DURABILITY AND INTEGRITY OF THE EXISTING NATURAL GAS INFRASTRUCTURES

The existing natural gas system has been designed for natural gas. The physical properties of hydrogen differ 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 in order to up-date the tools of integrity management previously assessed with only natural gas.

3.1 Durability of Steel for Transmission Pipes with H2

Transmission pipes in the existing natural gas grids operates under high pressures for example from 40 bar up to 100 bar. The steels (low carbon steels) used for building the transmission grids have been developed with higher and higher mechanical strength; the steel X42 is one of the oldest, used in the 60's and today operators start to use the X80. But higher is the yield strength, lower is the resistance to crack growth. This risk is well managed for natural gas, and should be assessed for hydrogen. It is well known that hydrogen might initiate brittleness of steel pipes, which affects the failure resistance of the pipe and has consequences for the safety and the lifetime of the pipeline [1, 2]. The degradation mechanism of a pipeline by hydrogen is a very complex matter: for instance, preliminary experiments showed that the sensitivity of a pipeline for degradation by hydrogen is effected by amongst others the history of the pipeline.
Therefore, the aim of using the steel grids designed for natural gas for transport of H2 requires extended studies about the effect of hydrogen on the properties of these steels and understanding of the mechanisms;

- Tests will be executed on laboratory specimens as well as a few tests on real structures containing defects, to quantify the effect of hydrogen on structures with typical in-service damage; measurement of fracture toughness and fatigue crack growth on steels with defects (welds, gouges, cracks, corrosion pitting) and without defects.
- Moreover the effect of addition of H2 on the evolution of the defects existing in the pipes will be investigated, and the existing defect assessment criteria will be adapted to take into account an increasing percentage of H2 in the natural gas.
- Some demonstrative tests will be carried on at full-scale under H2 pressure; fatigue tests and burst tests on parts of pipes with well-controlled defects. The results will be exchanged with the Work Package on Safety (see §4)).
- The special case of the rapid propagation of crack, following the opening of the gas pipe, will be 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.

3.2 Durability of Polymer for Distribution Pipes with H2

The poly-ethylene (PE) is the mostly used material for local distribution of natural gas at low pressures, from 16 bar down to few mbar. The main concern about pipes made in polymer like the poly-ethylene (PE) is its permeability to H2 which may induce leakage of gaseous H2 and therefore a dangerous situation. Measurements were done on PE80 material samples in various conditions of pressure, H2 content and temperature. Results showed that H2 diffuses quicker than CH4 and with larger quantity (Figure 2). Results will be used for calculating the potential leakages on distribution network and these data will be useful for assessing the risks (see §4).

Literature survey is quite fine on ageing of PE in H2 gas atmosphere. This subject will be studied under H2 pressure (up to 100 bar) with different H2 content in CH4 (up to 100%). The ageing tests will be accelerated by means of temperature increases (up to 60°C). Tests at 10°C will simulate the actual thermal conditions. Mechanical and physical-chemical techniques will be used for investigating the evolution of the PE properties and micro-structure with ageing conditions.

3.3 Durability of Domestic Gas Meters

The most common domestic gas meters are membranes meters, made with a polymeric membrane which is sensitive to H2 permeation. Several potential effects of H2 are expected;

- Potential influence on metering accuracy; the fact that hydrogen particles are smaller than natural gas ones may cause leakages through the membrane. In such a case, the measuring accuracy would be impaired,
- Potential influence on safety; the dimensions of hydrogen particles may lead to a leakage into the atmosphere through connection sealing,
- Potential influence on durability; hydrogen may damage the internal parts of the meter.

Then, the meters will be tested regarding their reliability for H2 metering and ageing behaviour of the membrane in presence of hydrogen.

3.4 Integrity Management; Updating for Natural-gas+H2 Mixtures Delivery

All results obtained on Durability will be used for providing the lifetime estimation for the different parts of the gas networks (transmission, distribution and inner grids) and for adjusting the existing tools used for integrity management of the pipelines designed for natural gas.

The most common integrity problems in the existing transmission pipelines include external corrosion and mechanical damage.

3.4.1 Defect Criticality

With regard to the foreseen application of hydrogen to natural gas, one of the most interesting issues is the so-called defect criticality. The current practice for determining whether a defect is critical and needs to be repaired are based on defect geometry, material properties and to a certain extent service use. However, if the hydrogen or hydrogen mixture within the pipeline acts to change the pipe material properties, in particular with respect to crack propagation, these criteria may need to be revised. Therefore, the critical issue to be investigated is related to the question which type of defects and up to which size can be judged to be acceptable. Within the population of the current acceptable defects, there may be a certain group that become critical under hydrogen service.

Another aspect which will be of interest, will be the potential for acceleration of fatigue - type failures. Typically in a natural gas transmission system, the number of pressure cycles is so small that defects surviving the hydrostatic test after construction will not fail from fatigue during the life of the pipeline. Thus a number of pipe material or weld defects may exist in today's pipeline networks that are non-injurious and essentially undetectable with the inspection technology in use. If it can be shown that these types of defects may grow more rapidly in the presence of hydrogen, a new inspection technique may have to be adopted to detect and eliminate these defects in a timely fashion.

3.4.2 Development of Inspection Effectiveness

It will be important to verify whether the existing inspection tools (for pigging e.g. Magnetic Flux Leakage) are capable of detecting the smaller defect sizes. Possibly, improvements on the detection capability of existing inspection techniques are needed to meet the more stringent detection requirement. A large testing and validation programme is foreseen to demonstrate the capability of existing techniques.

3.4.3 Development of Repair Strategies

Certain non-acceptable defects can be repaired by different kinds of techniques like grinding, weld deposit, metallic sleeves, composite sleeves to save money comparing to the cost of cut and replacement of pipe defective sections.

Due to mechanical steel properties affected by hydrogen around the defects, the current repair criteria for gas pipelines should be changed. For example, the steel toughness affected by hydrogen could modify the weld deposit conditions, the maximum acceptable sizes of grinding, and the maximum acceptable sizes of defects to repair by sleeves.

In addition, it will be interesting to consider the possibility of crack formation under a mechanical reinforcement repair. A crack, if it forms under the mechanical reinforcement, could propagate along the pipe and away from the area being reinforced.

3.5 Integrity Management Tool

At present asset owners make use of Integrity Management Tools to support the process of decision-making and selection of cost effective, appropriate measures to control the structural integrity. Possible measures are monitoring, non destructive examination (pigging and non pigging), excavations and various repair strategies. The Integrity Management Tool should integrate all the available data and models to enable risk management (Figure 3).

In the project a tool will be developed consisting of models and data in order to take account of the presence of natural gas containing hydrogen. The tool will cover a number of parameters, e.g.: percentage of hydrogen gas mixture, material of construction, operating conditions and condition of cathodic protection. Eventually, the Integrity Management Tool will yield an inspection and maintenance plan based on the specific circumstances.

4. THE RISKS TO THE PUBLIC ASSOCIATED WITH INTRODUCING HYDROGEN INTO A NATURAL GAS PIPELINE SYSTEM

As a result of many years experience, the hazards associated with operating natural gas pipeline systems are well understood. Within Europe, a risk based approach is taken in relation to most hazardous industries installations, such as gas pipeline operations, whereby the risk to the public is assessed by considering both the likelihood of a failure occurring and the consequences that failure may have on a member of the public. To determine the overall risk, a wide range of potential failure scenarios (such as third party damage, corrosion and mechanical failure) and failure sizes (from small leaks to total pipeline rupture) would be considered and the consequences on an individual located in the vicinity of the pipeline assessed. Criteria for what is deemed an ‘acceptable risk’ to present to the public as a result of operating the pipeline system have been agreed with regulatory bodies and pipeline operators endeavour to ensure that their operations do not exceed this risk level.

The addition of hydrogen to the natural gas within the pipeline has the potential to change (increase) the level of risk presented to the public, because of the different physical and chemical properties of this gas. The main two contributors which could result in an increased risk are:

- Increased likelihood of failure occurring due to an adverse affect of hydrogen on pipeline materials (such as corrosion, degradation, permeation)
- Increased consequences following failure due to the increased reactivity of hydrogen compared to natural gas (such as increased severity of explosions).

The first item is considered in more detail within the Durability Work Package of the NaturalHY Project as discussed in Section 3 above. The results of this work will allow estimation of the failure probability of potential failure mechanisms for a system conveying natural gas/hydrogen mixtures. The second item is studied in more detail within the Safety Work Package. The Safety Work Package will then reassess the risks presented to the public by combining new information on failure frequency with a revised assessment of the consequences. In this way, it is the intention to assess any unacceptable change in the risk presented to the public by the proposed introduction of hydrogen into a natural gas pipeline system. In particular, by varying the level of hydrogen considered, it may be possible to identify the maximum ‘safe’ level.

4.1 Scope of the Safety Studies

As mentioned above, the Safety Work Package will reassess the risks presented to the public by combining new information on failure frequency with a revised assessment of the consequences. To this end, a large part of the Safety Work Package is aimed at understanding the hazards which may arise following an accidental release of hydrogen/natural gas from a pipeline system and assessing how this differs (if at all) from natural gas.

Failures from the high pressure pipeline system are most likely to give rise to large jet fires in the open air. For natural gas pipelines, the hazard distances in this situation are dominated by the thermal radiation hazard, as any overpressure developed as a result of ignition has been shown to be insignificant. However, due to the increased reactivity (burning velocity) of hydrogen, it is possible that the overpressure hazard may need to be reconsidered and its contribution to the risk presented to an individual assessed.

Large failures in process areas or where significant levels of congestion (obstacles) might be present can give rise to a large gas/air cloud which, if ignited, can produce a Vapour Cloud Explosion (VCE) generating damaging overpressures. For natural gas/air mixtures, research has shown that whilst damaging overpressures can be produced, the risk of deflagration to detonation transition (DDT) occurring (whereby a step change in the explosion severity results) is remote, and furthermore, any flame passing out of a congested region into an uncongested region will decelerate. However, it is known that hydrogen/air mixtures can undergo DDT and consequently, it will be crucial to identify the maximum percentage of hydrogen that can be introduced into the natural gas without the probability of DDT being unacceptably high.

Failures from the low pressure distribution system can give rise to gas/air mixtures forming within buildings served by the gas supply system, such as domestic properties and commercial or industrial buildings. In such cases, there is a potential for a confined explosion to occur resulting in a hazard to persons within the building either directly (burns or overpressure injury) or indirectly (crush injuries as a result of building collapse). The introduction of hydrogen may change the characteristics of the formation of a flammable accumulation within a building and may also change the severity of the explosion, for example, it may increase the likelihood of building collapse.

As fire and explosion phenomena are strongly scale dependent, it is extremely difficult to study such hazards in the laboratory. Hence, all the above aspects are to be studied by undertaking large scale experimental studies which will provide data for the development and validation of improved mathematical models of the fire and explosion hazard arising following the introduction of hydrogen into a natural gas pipeline system. These large scale studies will be supported by a detailed examination in a laboratory facility of the laminar and turbulent burning velocity of hydrogen/natural gas mixtures as these parameters are crucial for understanding and predicting large scale explosion behaviour, especially in relation to the potential for a detonation to occur. Using the data from all the experimental work, mathematical models previously developed by the natural gas industry for assessing gas accumulation, fire and explosion hazards will be extended to allow their use for assessing natural gas/hydrogen mixtures. In addition, a computational fluid dynamic CFD model developed by the nuclear industry for hydrogen accumulation will also be applied to natural gas/hydrogen mixtures.

To date, work has commenced primarily on two topic areas: large scale experiments to study gas accumulation and explosions in a confined region; and the experimental assessment in a laboratory facility of the laminar and turbulent burning velocities.

4.2 Determining Laminar and Turbulent Burning Velocities

A 380mm diameter, fan-stirred explosion bomb is being used for these experiments, located at the University of Leeds in the UK (Figure 4). A large number of experiments are to be performed enabling a comprehensive study of methane and hydrogen/methane mixtures containing up to 50% hydrogen to be completed with Equivalence Ratios (ER) from 0.5 to 1.3. (Equivalence Ratio is defined as r x (*mass of fuel/mass of air)* where *r* is the air:fuel ratio required for stoichiometric combustion). The turbulence level has also been varied. For laminar flames, the results have been compared with other experimental data from the literature for methane and methane/hydrogen mixtures, and with the predictions of a detailed chemical kinetic model [3]. The experiments have confirmed that for methane the laminar burning velocity varies with Equivalence Ratio, with the peak occurring at ERs of between 1 and 1.1. For 50% hydrogen in methane, the peak laminar burning velocity occurred between an ER of about 1.1 and 1.2. Adding hydrogen to the methane also resulted in increased laminar burning velocities compared to methane (Figure 5). This Figure also demonstrates good agreement between the experimental data and predictions made using the detailed kinetic scheme. Little burning velocity data exists for turbulent methane/hydrogen mixtures, so the comprehensive measurements being gathered at present will represent of unique database for use by the project.

4.3 Large Scale Experiments to Study Gas Accumulation and Explosions in a Domestic Property

A series of 10 experiments have been conducted in which gas (methane and hydrogen/methane mixtures) has been released into a test rig representing a typical domestic room. The test rig was constructed from steel and was 3m by 3m by 2.3m high and the experiments were conducted at the Advantica Test Site in Cumbria, UK. To simulate the circumstances typical of a domestic environment, the gas release was at a low pressure (30 or 20mbar) representing the typical pressure upstream and downstream of a domestic gas meter. Leak sizes from 2 to 10mm diameter were studied representing a leaking joint and complete failure of an internal gas pipe. An accumulation of gas above the lower flammability limit is more likely to be produced if the released gas occupies only part of the room. For this reason and since the gas is a buoyant gas, the test conditions selected were those most likely to give rise to a gas layer being formed in the upper half of the room. Consequently, the gas was released vertically upwards and the ventilation regime used was an upward crossflow, whereby air entered through a low level vent on one wall and gas mixture left through a high level vent on the opposite wall. A typical domestic door was fitted in one wall. During the experiments, the gas concentration was measured with time at 20 locations throughout the enclosure using oxygen depletion cells. The experiments confirmed that the gas concentrations were uniform in the horizontal plane and varied only with height. Figure 6 shows typical gas concentrations against height at various time intervals, measured at the instrument locations during a test in which methane was released vertically upwards from a 5mm diameter hole positioned 1.1m above the floor for a period of about 1000 seconds. This figure shows that the gas accumulation formed as a layer above the height of the release point. In some experiments, where a flammable accumulation was produced, the gas/air mixture was ignited using an electric spark. The door provided a low failure pressure vent. Explosion overpressures were measured both within the enclosure and outside.

5. REFERENCES

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Acknowledgments

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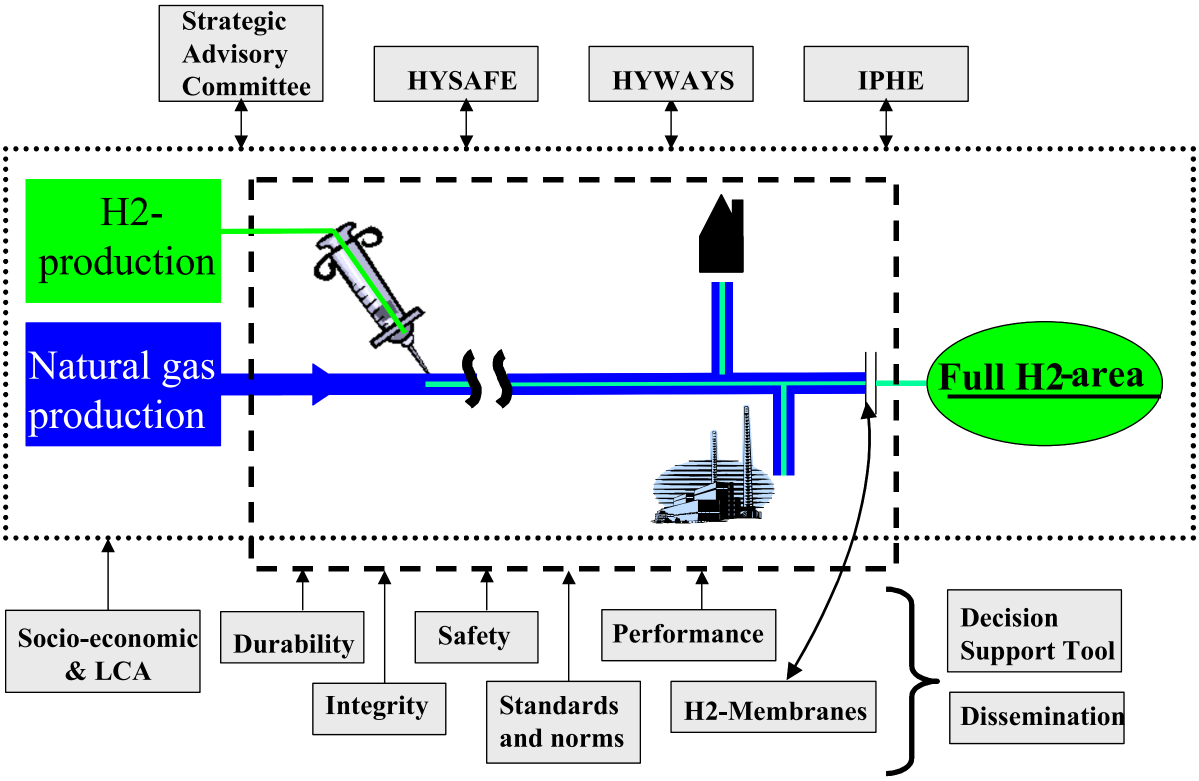

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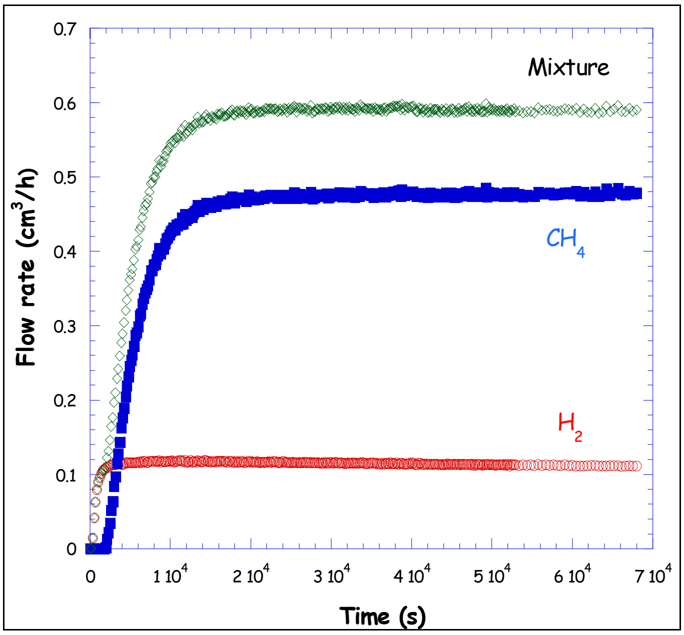
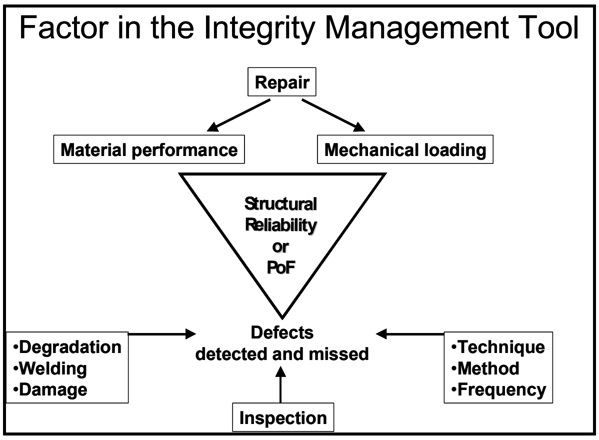


Figure 2. Permeation of PE80 to hydrogen, methane and their mixture (90%CH4-10%H2) (at 80°C and 21 bar)



Integrity Management Tool

Outcome

- Residual lifetime or PoF
- Needed measures on inspection
- Needed measures on repair

Selection of proper measures dependent on:

- Percentage of hydrogen in mixture
- Material of construction
- Operating conditions
- Environmental conditions: soil, population
- Age of pipeline, historical inspection data
- CP measurement data and level of protection
- Coating survey measurements

Figure 3. The Integrity Management Tool

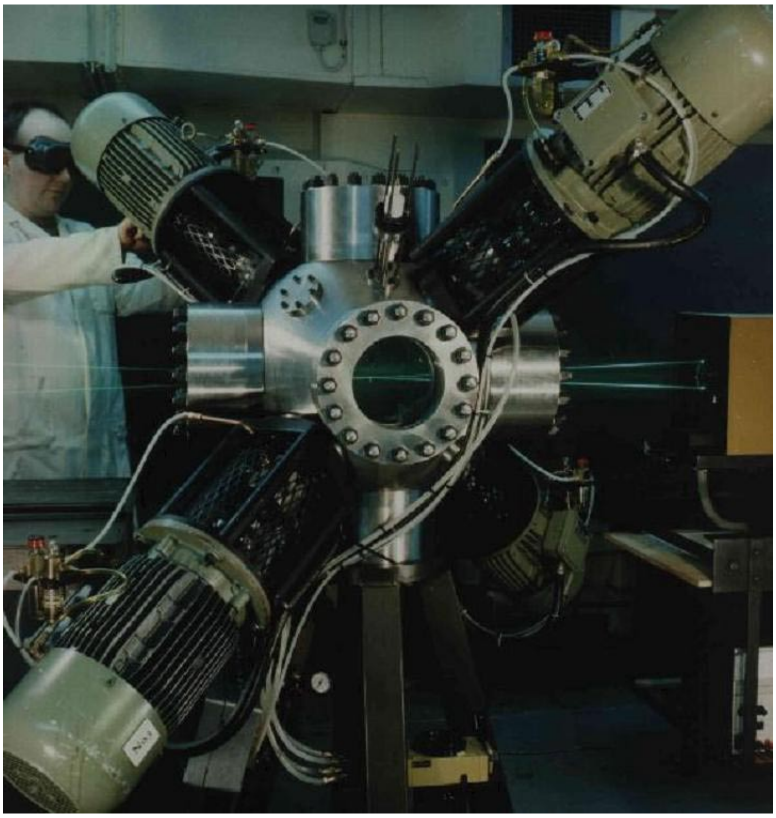


Figure 4: Fan stirred explosion bomb at Leeds University

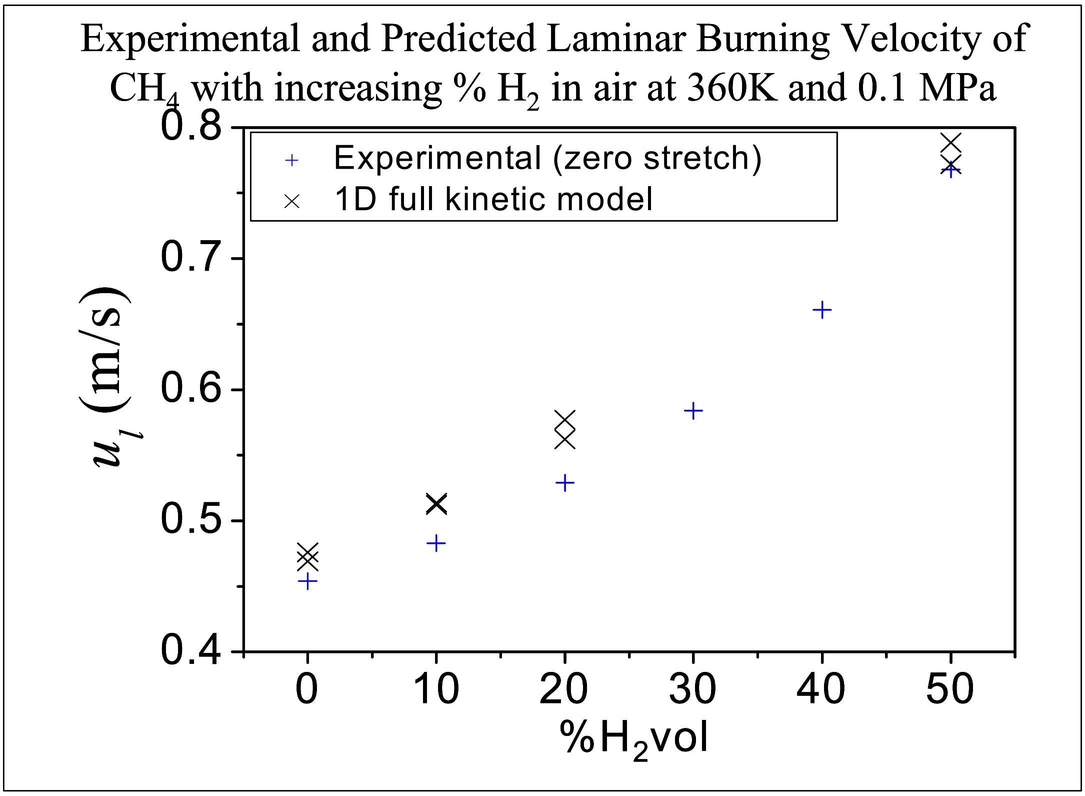


Figure 5: Laminar Burning Velocity of hydrogen/methane mixtures

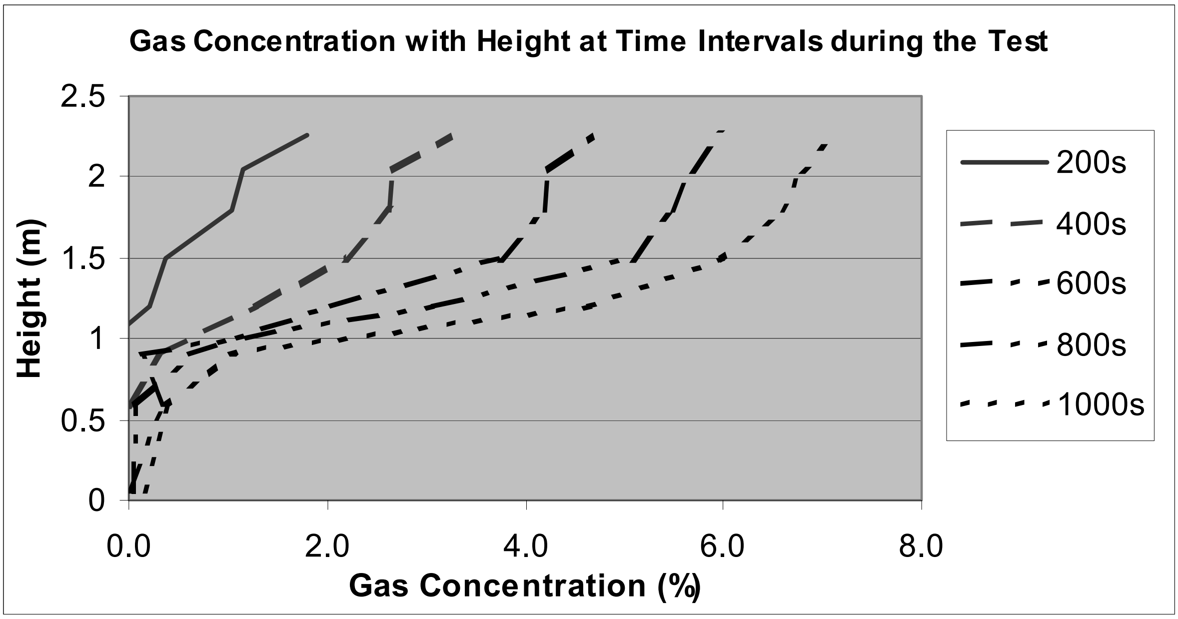


Figure 6: Gas Concentration with Height above the Floor within the Room at Various Time Intervals during a test (methane from a 5mm hole located 1.1m above the floor)