A feasibility study of

Hydrogen Distribution

in present natural gas pipeline systems

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Contents

Abstract

A transition to CO_2 neutral energy sources would make hydrogen, with its several advantages, a potential energy carrier. However, increased use of hydrogen would necessitate an extensive distribution system. This report presents a study of to what extent it may be possible to distribute hydrogen in the present natural gas pipeline systems. The constraints and possible solutions, for a transition from natural gas to hydrogen, are discussed. A geographical survey of the natural gas industries turnover and pipeline systems characteristics is carried out where the principal surveyed markets are Western Europe and Russia. The differences between hydrogen and natural gas give rise to constraints regarding potential compatibility of hydrogen. The lower energy flow rate and the susceptibility of the pipeline materials to hydrogen embrittlement are discussed. In addition, information from literature and interviewed people within the gas industry are compiled. It is concluded that the hydrogen energy flow rate is approximately 71% that of natural gas in respect to the lower heating value. Approximately 2.8 times the compressor power is required to maintain the same prerequisites as for natural gas and about 4 times the power is needed to compensate for the lower energy flow rate of hydrogen. Materials equivalent up to the grade of X70 would be the most suitable for hydrogen service.

Nomenclature

CO_2 = Carbon dioxide

CH_4 = Methane (main substance in natural gas)

H_2 = Hydrogen

European Union members (EU15) = Austria, Belgium, Denmark, Finland, France, Germany, Greece, Republic of Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, UK.

European members of OECD = Austria, Belgium, Czech Rep., Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Republic of Ireland, Italy, Luxembourg, Netherlands, Norway, Poland, Portugal, Spain, Sweden, Switzerland, Turkey, United Kingdom.

Western Europe = European members of OECD (apart from Czech Republic, Hungary and Poland), plus Cyprus, Gibraltar and Malta.

Russia = Russian Federation

CIS = Azarbaijan, Armenia, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Moldova, Russia Fed., Tajikistan, Turkmenistan, Ukraine, Uzbekistan

API = American Petroleum Institute

ASTM = American Society for Testing and Materials

ASME = American Society of Mechanical Engineers

DIN = Deutsches Institut fur Normung

ISO = International Organization for Standardization

1 Introduction

The greenhouse effect is considered one of the most serious global hazards to the environment and the Kyoto agreement stipulates that emissions of greenhouse gases must be reduced. A global reduction of CO_2 emissions involves considerable changes in present energy systems. A transition to CO_2 neutral energy sources would make hydrogen, with its several advantages, a potential energy carrier.

A future hydrogen economy depends on the sufficient and economical availability of primary energy sources. It also depends on the existence of a transport, storage and distribution network suitable for hydrogen. An extensive infrastructure network for hydrogen has not yet been developed. Most of the hydrogen produced today is manufactured within or near oil refineries or chemical plants. As the production facilities generally are located near the industrial facilities the need for large flow rates and long distance transportation is minimized today. However, an increased use of hydrogen would necessitate an extensive distribution system.

The easiest and most inexpensive way to distribute large quantities of gaseous fuels over land is by pipeline [1]. Over the last decades the natural gas industry has developed an extensive infrastructure distribution network of pipelines which also may have a potential to carry hydrogen.

The main purpose of this project is therefore to investigate to what extent existing natural gas pipelines, or those now under construction, could be used for hydrogen service. This report will discuss the obstacles for a transition to hydrogen with the aim to clarify the present problems and possible solutions. The prerequsites presented gives an indirect indication to the economic and technical feasibility in terms of energy flow rate, compressor capacity and hydrogen embrittlement.

In section two, a geographical inventory of the present natural gas pipeline systems in Europe, Russia and the USA is presented to give an overview of the natural gas turnover which could be a potential hydrogen source if, for example, steam reforming is used at the natural gas reserve. The production, consumption, exports and the trade movements of the major markets is presented. The most important part of the survey is however the qualitatively inventory of the characteristics of the systems in terms of operating pressure, pipeline materials, diameter and length.

Section three handles the constraints of a transition to hydrogen where the main problems, concerning whether the transition is feasible, are linked to the differences between the two energy carriers. To show the effect of the differences, a comparative numerical analysis of the transmission energy flows between natural gas and hydrogen is presented. Out of these results, the compressor power required for certain flow conditions is calculated. Besides the difference in energy flow rate there is a possibility of a phenomenon called hydrogen embrittlement, which is associated with the exposure of pipelines to high pressure hydrogen gas. Section three also discusses the prerequisites for a transition to hydrogen where extracts from previous studies are compiled in order to show ways of avoiding hydrogen embrittlement. Finally, section four contains opinions from the gas industry where information, from the literature and interviewed people within the area, are compiled.

2 Natural gas turnover and distribution inventory

The natural gas industry has developed an extensive infrastructure distribution network over the last decades and is still expanding at a fast pace. Today, over 1 200 000 kilometres of pipeline extend across Europe and thousands of kilometres of pipeline interconnections and extensions are being built or planned [2]. In Western Europe, natural gas accounts for about 23 percent of the primary energy consumption [3]. France, Belgium, the Netherlands, Germany, Italy and the UK alone account for approximately 90 percent of the total gas consumption of some 365 billion cubic metres [4], where Russia, Norway, the Netherlands and Algeria are the main natural gas suppliers.

A system used for hydrogen distribution would in some respects be equivalent to the one of natural gas. The industries and other end users who today consume natural gas could be the first to convert to hydrogen. The burners used for natural gas would not have to be replaced but could be hydrogen compatible by modification to various extent [5]. A future production of hydrogen could be by steam reforming of natural gas at the present natural gas reserves. This motivates a geographic overview of the turnover quantity and the trade movements of the natural gas industry. Due to the different properties of the gases, constraints of a transition to hydrogen may arise regarding the current pipe systems build, operation and material characteristics. It is therefore relevant to survey the nature of the present natural gas systems characteristics. This inventory of the natural gas infrastructure will give an insight into hydrogens potential compatibility.

The principal surveyed markets are Western Europe and Russia. The inventory also includes the USA and in addition the Mahgreb-Europe stretch which links Northern Africa to Europe via the Gibraltar sound. The inventory in terms of consumption, production, total exports and total imports is presented in table 1. The trade movements of natural gas between the major markets, which indicate the present route and quantity distributed by pipeline, is presented in table 2 and the characteristics of the present systems is presented in table 3.

Table 1. The major natural gas markets in terms of consumption, production, exports and imports, 1998. Source: BP Statistical Review of World Energy [4]. When (-), no information available.

Major market	**Natural gas consumption* (billion m^3)**	**Natural gas production (billion m^3)**	**Total exports by pipeline (billion m^3)**	**Total imports by pipeline (billion m^3)**
USA	612.4	543.8	2.7	87.8
Russian Federation	364.7	551.3	120.3	-
UK	88.7	90.3	2.4	0.9
Germany	79.5	16.8	3.3	73.6
Italy	57.2	18.7	-	40.6
The Netherlands	38.7	63.6	36.4	5.8
France	37.5	-	-	25.9
Algeria	21.6	72.8	27.5	-
Romania	18.2	14.0	-	3.8
Belgium	13.8	-	-	10.9
Spain	13.1	-	-	7.0
Hungary	10.8	3.4	-	9.5
Poland	10.4	-	-	7.5
Turkey	9.9	-	-	6.8
Austria	7.6	-	-	6.2
Czech Republic	7.6	-	-	9.4
Slovakia	5.7	-	-	6.9
Denmark	4.8	7.6	2.7	-
Norway	3.8	47.8	42.6	-
Finland	3.7	-	-	4.2
Ireland	3.1	-	-	0.9
Bulgaria	3.0	-	-	3.8
Switzerland	2.6	-	-	2.7
Sweden	0.8	-	-	0.9
Portugal	0.8	-	-	0.9

*) Note that the difference between these consumption vs the production statistics and the trade movements in pipeline is due to variations in stocks at storage facilities and liquification plants, together with unavoidable disparties in the definition, measurement or conversion.

Table 2. Natural gas trade movements by pipeline on the European continent, 1998. Source: BP Statistical Review of World Energy [4]. When (-), no information available.

Trade movements 1998 (billion m^3)							
To:	**From:**						
	Denmark	Germany	Netherlands	Norway	UK	Russia	Algeria
Austria	-	0.3	-	0.4	-	5.5	-
Belgium	-	0.5	5.3	5.1	-	-	-
Bulgaria	-	-	-	-	-	3.8	-
Chech Rep.	-	-	-	0.8	-	8.6	-
Finland	-	-	-	-	-	4.2	-
France	-	-	5.5	10.2	-	10.2	-
Germany	1.8	-	21.1	17.5	0.9	32.3	-
Hungary	-	1.0	-	-	-	8.5	-
Ireland	-	-	-	-	0.9	-	-
Italy	-	-	3.0	-	-	16.7	20.9
Luxuembourg	-	-	0.8	-	-	-	-
Netherlands	-	-	-	5.2	0.6	-	-
Poland	-	-	-	-	-	7.5	-
Portugal	-	-	-	-	-	-	0.9
Romania	-	-	-	-	-	3.8	-
Slovakia	-	-	-	-	-	6.9	-
Spain	-	-	-	2.5	-	-	4.5
Sweden	0.9	-	-	-	-	-	-
Switzerland	-	1.5	0.7	-	-	0.5	-
Turkey	-	-	-	-	-	6.8	-
UK	-	-	-	0.9	-	-	-

Table 3. Inventory of the major markets pipeline systems characteristics. For more information regarding the pipe material, see section 3.5.3. When (-), no information available.

Market	**Major transm. company**	**Approx total pipe length** [km]	**Operating pressure** [bar]	**Pipe diameter** [mm]	**Pipe material**
Algeria	Enagas (Maghreb-Europe)	1220 (land) 46 (marine)	80 155	1180 560	X70 API 5L X65 API 5L
Austria	OMV	1 500	< 70	800-1020	L 485 MB
Denmark	DONG	-	70	approx. 800	-
France	GazDeFrance	28 000	-	250-880	-
Germany	Ruhrgas	345 000 (of which 28% is high p)	1-100	< 1200	STE480 M7 (high pressure)
Italy	ENI, SNAM	28 700 (95 000 incl.outside Italy)	-	< 920	-
Netherlands	Gasunie	11 000 (high pressure)	40, 66, 80	660	-
Poland	POGC	17 000 (high pressure) 87 000 (low/medium p)	-	-	-
Russia	Gazprom	148 800 (high pressure)	-		-
		(49679		1420)	
		(25023		1220)	
		(16508		1020)	
		(4537		820)	
		(11307		720)	
		(12202		530)	
		(28980		426)	
Spain	Enagas	2400 3600 1500	16 (grade B) 72 > 72	510-660	X60, X70 API 5L grade B
Sweden	Vattenfall Naturgas AB	400	< 80	500-600	STE415, STE480
UK	Transco	6 000	< 75	440-1030	-
USA	AGA	$420\cdot10^6$	20-140	-	X42-X80 API 5L ASTM

The information is compiled from personal contacts, the companies official web-sites and an official inventory map of the natural gas market in the CIS and Europe [3].

Regarding production and exports, the inventory shows that Russia and Algeria along with the Netherlands and Norway are the largest markets. This is of course also where the largest reserves are found. The UK is a rather large producer where most of the gas is consumed domestic.

The trade movements indicates that the main importers are Germany, Italy and France. Germany accounts for the main part of the exports from Russia, the Netherlands and Norway. The Algerian trade route mainly supplies Italy and Spain. From Algeria, there is a pipeline system directly to Italy. Unfortunately, as in the case of Russias pipeline material, no information where avalible.

All of the surveyed markets are more or less conceivable hydrogen markets as they are accustomed to the use of natural gas. If steam reforming are to be used for the production of hydrogen, the initial future producers and exporters would then most likely be the large natural gas markets of today.

The survey of the pipeline systems characteristics shows that, to a certain extent, equal systems apply for the surveyed markets. The operating pressures vary from 40 bar up to 140 bar. For these high pressure pipelines the diameter varies between 0.4 to 1.4 m. Regarding the pipe material, generally, ferritic steels are used where grades between X40 up to X80 occurs. Out of these results one can now look further into hydrogens potential compatibility.

3 Constraints and prerequisites for a transition to hydrogen

The two main problems that could arise if hydrogen issued, instead of natural gas, are linked to the different chemical and physical properties of the gases. First, along with the volumetric energy difference, the energy flow rate through a pipeline system as well as the compressor power required are both affected by the molecular differences. To illustrate the ratio, a camparative numerical analysis of the transmission energy flows of the gases respectively is carried out. In addition, the compressor power required for certain conditions is calculated.

The second problem is linked to pipeline material where it could be a problem of weakening of the pipeline steel when exposed to high pressure hydrogen, a phenomenon called hydrogen embrittlement. The prerequisites of the present pipeline systems is surveyed and embrittlement preventive measures are presented.

3.1 Energy Flow Rate

The energy content per volume, MJ/m^3, of hydrogen is 31% of the energy content of natural gas. To maintain the same energy flow rate through a pipeline, approximately three times the flow rate is required when comparing the lower heating values as above. However, flow rate calculation are more complex where the specific properties of the gases has to be considered. To show the effect of the molecule differences, a comparative numerical analysis of transmission energy flows between natural gas and hydrogen is carried out, see Appendix 4.

The energy flow rate for natural gas versus hydrogen is calculated for case studies where the parameters are the diameter, length and pressure drop. The correlation between the mass flowrate Q [kg/s], the pipe inner diameter D [m], the length L [m] of a pipeline segment and gas pressures p_1 [Pa] at the beginning and p_2 at the end of the segment is represented by the following equation [6]:

$$Q = \frac{\pi}{4} D^{2.5} (p_1^2 - p_2^2)^{0.5} \left(\frac{M}{Z\ L\ F\ R\ T}\right)^{0.5} \left(\frac{1}{\lambda}\right)^{0.5}$$

where M [kg/mol] represents the molar weight, Z the compressibility factor, F a drag factor, R [J/(mol K)] the universal gas constant, λ a friction factor and T the conducting heat which generally can be assumed to be constant over the length of the entire pipeline. The dimensionless friction factor, λ, for turbulent flow is [6]

$$\left(\frac{1}{\lambda}\right)^{0.5} = -2 \log \left(\frac{2,51}{\mathrm{Re}\sqrt{\lambda}} + \frac{k}{3,71D}\right)$$

where Re is the dimensionless Reynolds number, k [mm] is a roughness factor in the pipeline and D [mm] its inner diameter. The Reynold number, Re, depend on the mass flow rate and the diameter as [6]

$$\mathrm{Re} = \frac{4}{\pi\ \mu} \frac{Q}{D}$$

where μ [kg/(m s)] is the dynamic viscosity. For detailed expressions regarding the compressibility factor, see Appendix 1.

The ratio between hydrogen and natural gas energy flow rate for some case studies are shown in table 4. An average operating pressure of the surveyed markets proved to be approximately 80 bar which is used as the inlet pressure in the calculations. The lower heating values, H_2: 124 MJ/kg and CH_4: 50 MJ/kg has been used when converting mass flow rate into energy flow rate. Note that this comparison does not take any external limiting factors, as for example operating regulations, into consideration.

Table 4. Examples of energy flow rates of hydrogen and natural gas transmission when varying the pipe diameter, length and pressure drop.

Prerequisitions				**Energy flow rate**				
diameter (m)	length (km)	inlet pressure (bar)	outlet pressure (bar)	hydrogen (kg/s)	hydrogen (MJ/s)	natural gas (kg/s)	natural gas (MJ/s)	percentage share
0.2	300	80	70	1	169	5	240	70.4
0.5	300	80	70	16	1948	55	2734	71.2
0.8	300	80	70	55	6775	189	9466	71.6
1.1	300	80	70	127	15731	438	21920	71.8
0.8	10	80	70	357	44323	1282	64086	69.2
0.8	100	80	70	100	12414	347	17374	71.5
0.8	1000	80	70	28	3485	98	4875	71.5
0.8	300	80	79	16	1954	55	2759	70.8
0.8	300	80	60	77	9577	266	13289	72.1
0.8	300	80	50	93	11517	317	15872	72.6
0.8	300	40	20	49	6094	159	7956	76.6

Due to the dependence of the flow rate when calculating the friction factor, the flow rate result is not directly proportional to the parameter change. When changing parameter values, as in the examples above, it is clear that the pressure drop affects the percentage share of energy flow rate more than changes in pipe diameter or pipe length. The larger pressure drop the larger percentage share of energy content. There is also a correlation between high pressure and low percentage share.

It is then concluded that even though the energy content per volume, MJ/m^3, of hydrogen is 31% of the energy content of natural gas, the energy flow rate, MJ/s, is approximately 71%. If using the higher heating value the percentage share would be 87%. This result should however not be translated to how much compressor power required to compensate for the lower hydrogen energy flow rate. This is a different calculation presented in section 3.3.

3.2 How to compensate for the lower energy flow rate

Under the assumption that the same energy flow rate is to be maintained, there are three possibilities

- a larger pipe diameter
- an increased operating pressure
- a larger pressure drop.

In a present pipeline system no changes in pipe diameter can be done. The remaining two possibilities involves the pressure. It is in principal excluded to increase the pressure as the pipeline systems are constructed and restricted by standards and regulations. The regulations pertain to a certain pressure which often is near the applied operating pressure. A higher pressure would also have a negative influence on the degree of hydrogen embrittlement [7]. The remaining alternative is then a larger pressure drop which can be achieved with increased compressor capacity [5], which will be further discussed in the next section.

3.3 Pipeline compressor power requirements

Out of the previously presented energy flow rate calculations, the required compressor power to maintain a specific flow can be determined. The compressor power, P [W], is calculated via [8]

$$P = Q \frac{p_{ref}}{T_{ref}} \frac{T}{\eta} Z \frac{N \gamma}{\gamma - 1} \left(\left(\frac{p_{out}}{p_{in}} \right)^{\frac{\gamma-1}{N\gamma}} - 1 \right)$$

when using lower heat value, where Q [normal m^3/s] is the gas flow, p_{ref} [Pa] the atmospheric pressure, T_{ref} [K] the atmospheric temperature, T [K] the gas temperature, p_{in} [Pa] the inlet pressure to compressor, p_{out} [Pa] the outlet pressure from compressor, N the number of compressor stages where a role of thumb is that for each compressor stage it is possible to increase the pressure by a factor four, η (0.70) is the hydrogen and natural gas pipeline scale compressor efficiency, Z is the compressibility factor and γ the ratio of specific heats (Cp/Cv). For simplicity, we will assume that there is a single compressor at the pipeline inlet. For the same prerequisites as in table 4, the pipeline compressor power requirements are presented in table 5.

Table 5. Examples of pipeline compressor power requirements, for varity of prerequisites, and the ratio of hydrogen to natural gas compressor power needed [8]. Lower heating value is used in the calculations.

Prerequisitions				Pipeline compressor power requirements					
pipe diameter (m)	pipe length (km)	pipe inlet pressure (bar)	pipe outlet pressure (bar)	hydrogen		natural gas		$\frac{P_{H_2}}{P_{CH_4}}$	ratio if keeping the energy flow
				flow rate (m^3/s)	P_{H_2} (kW)	flow rate (m^3/s)	P_{CH_4} (kW)		
0.2	300	80	70	15	314	7	111	2.8214	4.0078
0.5	300	80	70	175	3617	76	1267	2.8553	4.0078
0.8	300	80	70	607	12583	263	4387	2.8686	4.0078
1.1	300	80	70	15731	29215	21920	10158	2.8762	4.0078
0.8	10	80	70	44323	82316	64086	29697	2.7718	4.0078
0.8	100	80	70	12414	23055	17374	8051	2.8637	4.0078
0.8	1000	80	70	3485	6472	4875	2259	2.8646	4.0078
0.8	300	80	79	175	337	77	118	2.8605	4.0390
0.8	300	80	60	9577	39058	13289	13639	2.8637	3.9739
0.8	300	80	50	11517	78568	15872	27470	2.8601	3.9418
0.8	300	40	20	546	61884	221	22406	2.7619	3.6056

The ratio if keeping the same energy flow rate of gas in the pipeline, is calculated with respect to the percentage share of energy flow rate, see table 4. This ratio decrease with the pressure drop but for a varity of prerequisites, the compressor power is about four times higher for hydrogen than for natural gas. If using the higher heating value the ratio will decrease to approximately three times higher for hydrogen than for natural gas. If it is not necessary to compensate for the lower energy flow rate, hydrogen distribution still needs approximately 2.8 times more compressor power to maintain the same prerequisites.

As mentioned in section 3.1 the best way to increase the hydrogen energy flow rate is to create a larger pressure drop. A larger pressure drop can, for example, be created if new compressor stations are inserted between the present stations or with an entire new set of hydrogen adapted compressor stations. Long distance natural gas pipelines typically have compressor every 50−80 km to boost the pressure. Recompression ratios are modest, about 1.2 to 1.3 [5]. Reciprocating compressors could be used with hydrogen to achieve recompression ratios of 1.2 to 1.8 (Christodoulou, 1984). For partially or fully turbulent flow, the volumetric flow rate is approximately 2.5 to 3 times higher for hydrogen than for natural gas and almost four times as much power would be needed to accomplish the same amount of compression as shown in table 5. However, hydrogen compressors would be spaced farther apart along the pipeline than with natural gas. Pottier (1988) mentioned that the ideal spacing for hydrogen might be twice as far apart as for natural gas. Leeth (1979) found an ideal spacing of 80−120 km. Overall, compression power requirements might be 1.5−2 times higher than for natural gas [5].

3.4 Hydrogen Embrittlement

An important phenomenon to be taken into account concerns the tendency of hydrogen to weaken the line pipe steel, especially at pressures higher than 50 bar [9]. The term hydrogen embrittlement is used to refer to several material effects of hydrogen on metals. The degree of embrittlement depends on the hydrogen purity, the types of contaminants present, stresses on the material, pressure, temperature, pipeline construction (type of welds, e t c.) and presence of cracks or other defects, as well as the material used [5].

J M Ogden, E Dennis, M Steinbugler and J W Strohbehn have written about this subject in a study called “Material issues: Hydrogen embrittlement” in their report ”Hydrogen Energy System Studies, 1995”. The report contains a detailed description of the term hydrogen embrittlement and a compilation of several scientific research results on hydrogen embrittlement from which extracts are presented in this section. For the reader not familiar with the terminology, Box 6 from the report above, contains a discussion of concepts in materials science and fracture mechanics which are used in describing and measuring hydrogen embrittlement. Also included are sample calculations of pipeline stress, crack growth and pipeline lifetime under various conditions [5], see Appendix 2.

First of all some kind of definition and origin of hydrogen embrittlement. According to Louthan and McNitt, 1977 [5], three types of hydrogen embrittlement have been identified.

1. Internal hydrogen embrittlement (I-H) can cause delayed failure in cases where hydrogen has been absorbed into the metal during plating or direct contact with gaseous hydrogen or from reactions with water during melting, casting, or welding operations. In order for embrittlement to take place, hydrogen must diffuse from within the metal to the vicinity of a crack. I-H embrittlement is most severe near room temperature.

2. Hydrogen reaction embrittlement (H-R) where a chemical reaction takes place between the hydrogen and the metal. This type of embrittlement is seen at the high temperatures and pressures in refineries. Increased temperature and pressure accelerate the reaction rate.

3. Hydrogen environment embrittlement (H-E) is the degradation of mechanical properties which takes place when metal is exposed to a hydrogen environment (e.g. a pipeline carrying hydrogen). H-E embrittlement occurs when the metal is under stress and cracks are present. Unlike I-H embrittlement there is no time delay. Embrittlement occurs once a stress level greater than the yield strength is reached. Interactions of hydrogen at the metal surface are the likely cause of H-E embrittlement [5].

According to Cialone et.al., 1984, H-E embrittlement is thought to be the most important mechanism for hydrogen pipelines [5]. For distribution in pipelines it is at conditions when hydrogen atoms diffuse into the metal structure and gather in narrow spaces and form hydrogen molecules, where the main embrittlement problem may occur. Reports show that pipeline steels are most exposed to hydrogen embrittlement at certain conditions. The pipe materials are more susceptible at

- High hydrogen purity.
  Extended static pressure tests (10,000 hours) under stress conditions close to the elastic limit show that the steel grades and welds generally used for natural gas transmission are not adversely affected by hydrogen as long as its purity is not greater than 99.5% [10].

- High pressure.
  With increasing pressure of the gaseous hydrogen the degree of embrittlement increases [7].

- Room temperature.
  Tests shows that the crack growth rate in hydrogen pipeline measured for temperatures ranging from -80°C to $+80^{\circ}$C is highest at $+20^{\circ}$C [7] , a temperature at which pipelines normally operate [11].

- Cyclic loading.
  Additional tests have shown that steelgrades, when subjected to severe cyclic stresses, appear to be rather sensitive to hydrogen embrittlement but that can be lessend by

taking certain precautions such as limiting the stress rate, using steel with a low sulphur content and applying a normalizing heat treatment to it [12]. Cyclic loading refers to the shutting down and starting up process of a system.

- Hard spots.
  The hard spots are often found at heat affected zones, for example welding areas.

3.5 Embrittlement Prevention and Control

This section presents discussions and conclusions of previous studies regarding hydrogen embrittlement prevention and control. The discussed topics are inhibitors, protective coatings and material characteristics.

3.5.1 Inhibitors

In liquid or gaseous media, certain additives, called inhibitors, can occupy, via a strong binding energy to the base metal, atom sites on the metal surfaces, thus preventing a metal hydrogen bond and thereby inhibiting the entry of hydrogen into the base metal. This beneficial effect of inhibitors on hydrogen is simply that the inhibiting species have a higher binding energy to the iron than does the hydrogen and, thereby, block sites for hydrogen adsorption.

In the study of the effect of additives in the prevention of hydrogen embrittlement, the bond energy of the hydrogen atom to the metal surface and how this bond is affected by additives must be considered. The theories of the surface chemistry for the bonding of gaseous molecules to metal surfaces have been well developed and will be used as a general guide for the understanding of the role of additives [13].

NASA/Rocketdyne studies of hydrogen environment embrittlement of metals, 1973 states that "An alternative for eliminating or deterring embrittlement was adding another gas to the hydrogen with the intent of stopping the embrittlement action. Hofmann and Rauls 1965, had looked at this idea earlier and evaluated effects of air, nitrogen, oxygen and argon. Their results showed that argon and nitrogen had little effect, but oxygen was quite effective at 1% and reduction of embrittlement was observable at 0.0001%. There is some evidence that the effectiveness of the inhibitor is a function of its absolute partial pressure, and not a function of the total pressure. [5]"

Another study in this matter is the Battelle-Columbus studies of hydrogen embrittlement in pipeline steels, 1982-1986, which states: "It is suggested that gaseous additives to inhibit embrittlement may be the best solution. It was found that embrittlement might be reduced to low levels with various gas additives (e.g. oxygen, ethylene, carbon sulfide, sulfur dioxide, nitrous oxide, carbon monoxide and ethane). Adding a few percent oxygen or sulfur dioxide to pure hydrogen essentially eliminated embrittlement, but posed safety problems. It is concluded that the ideal inhibitor gas has not yet been found which satisfies the criteria:

1. non-explosive when mixed with hydrogen
2. combustible
3. non-toxic if not burned
4. non-acidic if mixed with water
5. inexpensive [5]."

Further Rocketdyne study of hydrogen accelerated crack growth pipeline steels, 1993, states "It was shown that pre-loading the pipeline to high pressure with helium and then introducing hydrogen at the same pressure inhibited the effects of hydrogen on crack growth for several thousand loading and unloading cycles. It was proposed that loading the line initially with methane prior to hydrogen introduction might have the same inhibiting effect [5]."

In Germany, 1984, Peter Deimel and Jürgen Richter have investigated the same subject at Staatliche Materialprüfungsanstalt and states about gaseous inhibitor: "Hydrogen embrittlement is reduced by additions of inhibitors like O_2, CO, CO_2, SO_2, CH_4, C_2H_2, C_3H_8 as well as with lower hydrogen gas pressure [7]."

Finally M Mohitpour et al. states in an article "Design basis developed for H_2 pipeline" published in Oil & Gas Journal, May 28, 1990: "Inhibition possible with 0.1% O_2, with CO or with CO_2. No inhibition effect possible with N_2 or CH_4 [11]."

3.5.2 Protective Coatings – Metallic- and Nonmetallic thin films

Metallic thin films can retard hydrogen entry into the substrate metal by virtue of their low solubility for hydrogen, low diffusity for hydrogen, or surface effects involving adsorption, or by combinations of these mechanisms. Nonmetallic thin films does mainly consist of thin oxide layers.

In both cases, "thin" could mean coatings from a monolayer of atoms to something in the order of 10^{-12} m in thickness. These films offer extensive protection and appear to be abrasion proof. The beneficial effects obtained from solid films may be derived from low diffusitives plus inhibition of surface adsorption, with the latter being the most probable mechanism in most cases.

The studies presented does not discuss the cost for thin film coatings, nor if they directly can be applied to the kind of pipeline systems we refer to.

NASA/Rocketdyne studies of hydrogen environment embrittlement of metals, 1973, states: "Based on earlier work (Fidelle, 1968) and some experiments at Rocketdyne, it was concluded that the important characteristics for protective coatings are:

1. Low hydrogen permeability
2. Nonporous, i.e., free of defects
3. Completely adherent to the substrate
4. Ductile or self-healing.

The following materials have the best potential as coatings for preventing embrittlement: copper, gold, cadmium and silver-silicon. The cost of retrofitting long distance pipelines with these coatings has not been quantified, but is probably quite high [5]."

Further Battelle-Columbus studies of hydrogen embrittlement in pipeline steels, 1982-1986, states: "Remedies for embrittlement have been proposed including coating pipeline with metals or plastics, testing pipeline segments and replacing those having materials susceptible to embrittlement, and replacing the entire pipeline with hydrogen compatible steels [5]."

3.5.3 Material characteristics

The risk of hydrogen embrittlement is also depending on the type of material used where the mechanical strength and the chemical composition of the pipe material can influence the degree of embrittlement. Hydrogen environmental embrittlement takes place primarily by the development of cracks and subsequent fracture [5]. To avoid structural failures, the mechanical behavior of materials must be known under applied stresses such as pressure, temperature and chemical environment. The strength is defined as the threshold value of stress that results in deformation or cracking failure. The primary concern is that the stress not exceed the strength of the material [5]. Once a permanent deformation of the material begins, only a small increase in stress causes yielding. The value where yielding starts to become compromise the function of the structure is called the yield strength.

Tension tests are made to assess the strength and ductility of materials by slowly stretching a bar of material until it breaks. The ultimate tensile strength is the highest stress reached before fracture.

This implicate that materials less susceptible to embrittlement must have the quality of high strength and high tenacity, i.e. high tensile- and yield strength. To determine materials suitable for hydrogen service is however more complex since the mechanical strength is depending on the chemical composition which both affects the risk of embrittlement. It is therefore of interest to look further into these parameters to compare the surveyed materials properties to the statements adressing a possible hydrogen embrittlement problem.

Regarding the chemical composition it is stated that the tensile- and yield strength could be increased by raising the carbon or manganese content [26]. The complexitivity consists of that the statements regarding the hydrogen embrittlement desire decreasing the same substances. According to Mohitpour et al are steels with a low percentage of carbon and manganese less susceptible to embrittlement and attack [11]. However, for the degree of hydrogen embrittlement in steel pipelines, the parameters of influence are the materials

1. Chemical composition
2. Mechanical strength, which is indicated in respect of its
    - tensile strength
    - yield strength.

It is consequently of interest to survey the strength rates and the chemical compositions of the materials used in the present natural gas systems. Standards and grade terms for pipeline materials differs by markets. Though, the standards are rather equivialent regarding its characteristics but differs in production technique. For example API X70 is a welded pipe where ISO L485 is a seamless pipe but both have the same strength and chemical compositions [26].

A higher grade permits thinner wall for the same pressure, or more pressure for the same wall thickness. Comparing the yield strength, a pipeline made of X80 can reach a maximum operating pressure 14% higher than a pipeline made of X70. However, the reduction in wall thickness and subsequent lower cost of pipes, could be offset by the higher cost of construction. Special care in trench bottom, where a sand bed to avoid deformations in the thin pipe wall caused by stones or bottom irregularities, has to be considered [14].

Table 6 shows material equivialents and their tensile- and yield strength.

Table 6. Material equivalents by different standard and grade and their minimum tensile strength and mininum yield strength at room temperature. Source: [15] and [16].

Pipeline steel materials					
Standard and grade				**Tensile strength**	**Yield strength**
API	ISO	DIN	ASTM	Rm (N/mm^2)	Rt$_{0.5}$ (N/mm^2)
X-42	L-290	StE290		415	290
X-60	L-415	StE415		520	415
X-70	L-485	StE480		570	485
X-80	L-555	-		620	555
			A 106 B	558	240

The material grade is indicated by the yield strength of the pipeline where, for example, X60 have a minimum yield strength of 60 000 psi or less. The pressure value in the table is however converted into Nmm^{-2}. Out of table 6 it is concluded that grade X80 has the highest minimum tensile strength but this grade is not very common with respect to the inventory.

Due to the complexitivity between the mechanical strength and the hydrogen embrittlement it is not obvious that the grade with the highest minimum tensile strength is the best choice for hydrogen distribution. Tests show a correlation between hydrogen embrittlement and the tensile strength of ferritic pipeline steels [7]. Mohitpour et al. [17] recommends a *maximum* mechanical tensile strength which indicates that the grade can be too high for hydrogen distribution. Air Liquide, who operates high pressure hydrogen pipelines, also have recommendations of an upwards limited tensile strength [9].

Air Liquide furthermore have recommendations for the chemical compositions where the substances sulphur, phosphorus, chromium, molybdenum and a quota of carbon and manganese have a maximum threshold value. A table of chemical compositions of the materials of the surveyed natural gas systems, along with the recommendations for hydrogen pipelines in the Benelux region run by Air Liquide, is presented in table 7.

Table 7. The chemical composition [5] of the most common materials, as the inventory indicated, and recommendations concerning the chemical composition for hydrogen pipelines [9]. Empty posts means no information avalible.

Pipeline steel materials												
Standard and grade		**Chemical composition of pipeline steels content, weight percent**										
API	ASTM	C+Mn/6	C	Mn	P	S	Si	Al	Cr	Cu	Ni	Mo
	A 106 B	0.355	0.26	0.57	0.007	0.016	0.150	0.021	0.007	0.008	0.010	0.015
X-42		0.397	0.26	0.82	0.020	0.026	0.014	0.004	0.038	0.022	0.016	0.010
X-60		0.335	0.12	1.29	0.014	0.016	0.250	-	0.020	0.030	0.010	0.010
X-70		0.340	0.09	1.50	0.008	0.006	0.310	0.042	0.013	0.031	0.084	0.031
H_2 pipe recommend.		$\leq$0.400			$\leq$0.015	$\leq$0.015			$\leq$0.150			$\leq$0.050

According to table 7, the material grade X60 have the lowest carbon and manganese quota and the material grade X70 have the lowest sulphur content. However, all material grades surveyed meet the hydrogen pipe content requirements, except for phosphorus and sulphur in X42. The tendency for carbon and sulphur are towards lower content but the tendency for manganese is towards a higher content. To our understanding the lower carbon content needs to be compensated with higher manganese content to maintain the mechanical strength. Whether a high or low manganese content is an advantage or not for hydrogen distribution is not easy to ensure. Consequently, to what extent the influence of strength and chemical composition have on hydrogen embrittlement in general is a difficult issue.

3.6 Further aspects

There are still no codes and standards for the design, construction and safe operation of hydrogen pipeline systems. Design of hydrogen facilities still relies on each owners or operators experience and data published by researchers in the field [11]. As in the case for natural gas, different regulations apply for different countries. Though, in Western Europe most countries' individual standards are simular to those of the European EN standards. ISO standards are under development but as yet not enough to apply to a hydrogen infrastructure [18].

Regarding the present natural gas pipeline it is also of interest to know when different kind of material grade were constructed due to the lifetime of pipelines. Prior to the 1970's, most pipelines were constructed using steel having a minimum yield strength of 415 MPa which is the material equavalent to grade X60. In the intervening 25 years the use of X70 steels has become the norm [19]. Over the last five years there has been a tendency towards the use of steels with higher minimum yield strength, as grade X80.

Comparing the diffusion constants for hydrogen and natural gas we see a greater potential for hydrogen to leak through the pipeline. This could be an aspect to consider as the pipeline systems might have to undergo several modifications. Most authors who adress the possibility of using hydrogen in natural gas equipment recommend replacment of seals, joints and metering equipment with parts designed for hydrogen service [5]. However, the volumetric leak rate of hydrogen would be about 2.5–3 times that of natural gas but the energy loss would be roughly the same because of the lower volumetric energy density of hydrogen [20].

The compatibility of present compressors, along long distance natural gas pipelines, depend on the kind of compressor. Because of its lightness, hydrogen is not well suited for use in centrifugal compressors. Existing reciprocal compressors for natural gas might be modified to use hydrogen if seals and joints were replaced, to minimize hydrogen leaks, and steel parts such as valves, which are subject to fatigue stress, were replaced with parts adapted for hydrogen use (Pottier et al.1988) [5].

4 What does the gas industry say?

It is naturally of interest to know the gas industries' opinion in this matter. Therefore people within or related to the gas industry were consulted and this section is a compilation of their statements. Their statements should be regarded as subjective judgements rather than established scientific conclusions. Their replies are quoted under the following four headings.

1. To what extent is it possible to distribute pure gaseous hydrogen in the present natural gas pipelines?
2. Which are the main obstacles?
3. What to consider if you are about to build a new natural gas pipeline and you know that later on it will distribute hydrogen?
4. Do you discuss hydrogen as a future energy carrier?

4.1 To what extent is it possible to distribute pure gaseous hydrogen in the present natural gas pipelines?

Is it possible to distribute gaseous hydrogen in the present natural gas pipelines, and if so, on what condition? Is modification essential as for instance welding, compressors e t c, and is it then economically viable?

There are a couple of aspects on this matter. Here in Germany it is not possible to use natural gas pipelines for hydrogen due to regulatory differences. Hydrogen is concidered as a chemical product whereas natural gas is an energy carrier. Therefore different regulations apply. The regulations for hydrogen are much tougher than the ones for natural gas.

Technically problems might arise as far as compression and sealing is concerned. Bare in mind that in households sometimes very old installations with old seals exist.

Since hydrogen has a very low density a lot of the systems are not "leakproof" enough for hydrogen. Other safety aspects include odor. There is an odor added to natural gas so that it could be detected in case of leaks. This ought to be done in the case of hydrogen too. The consequence is that it is then not suitable (not pure enough) for chemical processes any longer [27].

[Andreas Kegl at Air Liquide, Germany, June '99]

Befintlig naturgasledning kan användas för att distribuera vätgas. Problemet är att hela regelverket kring hanteringen blir annorlunda om man distribuerar vätgas. Därför måste hela nätet gås igenom och ett nytt regelverk för distribution av vätgas upprättas. Redan nu distribueras en gas som består huvudsakligen av vätgas i vårt stadsgasnät i Stockholm så tekniskt är det inga större problem [28].

[Owe Jönsson, Svenskt gastekniskt center, Malmö, June '99]

In our present distribution system it is not possible to distribute hydrogen

- due to kind of steel, isolation flanges, seals, packing elements of valves..
- due to the low energy content of hydrogen compared to natural gas bigger diameters are necessary [29]

[Ulrich Hartmann, BEB-Technology development, Germany, June '99]

No high pressure natural gas pipelines have ever been converted to hydrogen, so nobody really knows which safety measures should be taken. Probably the pressure will have to be reduced, depending on the fracture mechanical properties of pipe material and the welds and the safety factor chosen. There could also be problems with valves and compressors.

It is not allowed to exceed the 70 bar gauge, whether transporting methane or hydrogen. For safety reasons, it is more likely that the pressure will have to be reduced than increased when transporting hydrogen [30].

[Celia Juhl, DONG, Denmark, July '99]

Since our high pressure transmission pipe lines were originally intended for natural gas, they have never been specified for hydrogen. That does not mean that they are not suitable for hydrogen, but it would certainly require an extensive study for their safety if these pipelines were to be used for hydrogen in the future. There is a phenomenon called "hydrogen corrosion" that would be (at least one of) our concern(s). The capacity of burners, but also

of pipelines, is determined by the Wobbe-index of the gas. The Wobbe-index is defined as the upper calorific value of the gas, divided by the square root of the relative density. In the case of hydrogen, the upper calorific value is lower than of natural gas, but also the specific density. Transport capacity would not be a major problem (roughly equal; for more detailed study: it slightly depends on the hydrogen/natural gas ratio) [31].
[Paul Derks, Gasuine, The Netherlands, Aug '99]

We have not investigated up to now if we can distribute the same energy content of hydrogen in our gas pipelines. But our gas net is limited to 70 bar and the distance of our compressor stations is optimized to a pressure drop of max. 30 bar [32].
[Michael Mazzucato, OMV, Austria, Sept '99]

Det kan man antagligen. Man kanske måste acceptera ett lägre energiflöde, det kanske läcker, men det är säkert möjligt utan åtgärder. Naturgasen kommer antagligen att spetsas med vätgas och eller biogas i en sådan volymprocent att dagens kunder inte behöver förändra sina anläggningar. Med tiden kommer vätgasen att accepteras i större utsträckning än idag och efter ca 20-30 år är kunderna redo för 100% vätgas. Det är antagligen inte dagens rör som kommer att distribuera 100% vätgas. När vätgasbehovet ökar kommer det troligen att motivera en egen pipeline avsedd för 100% vätgas. Den spetsade naturgasen kommer då att behövas parallellt. Man kommer nog att prova sig fram med gasblandningar och renodla efter hand. Ska 100% vätgas distribueras i befintliga rör väljer man antagligen att acceptera ett lägre energiflöde [33].
[Einar Enghede, Göteborg Energi, June '99]

Ja, det går. Materialet utgör inga problem. Man måste täta systemet genom att byta ventiler. Saknar rapporter som stöder detta, men det är den allmänna uppfattningen inom gasbranschen just nu. De svetsfogar som utförs på nybyggda gasledningar är tillräckliga för att klara vätgas [34].
[Göran Engström, Svenska Gasföreningen, June '99]

It appears that hydrogen and hydrogen blends could be used in existing natural gas local distribution systems with only minor changes. For exampel natural gas compressors would have to be replaced with equipment designed for hydrogen use. Some existing compressors might be adapted, but 50-100% more compression capacity would be needed with hydrogen [5].
[J M Ogden, E Dennis, M Steinbugler, J W Strohbehn, Material issues: Hydrogen embrittlement, Princeton, 1995]

The energy-carrying capacity of a pipeline is nearly the same for hydrogen as it is for natural gas. Compressors are also needed for hydrogen transportation, but the horsepower installed must be four times larger than for a natural gas system, and fuel gas consumption will also be higher [35].
[Dr Fashold, The methane Economy verus the Hydrogen Economy, Germany, 1988]

4.2 Which are the main obstacles?

What is your opinion about whether there could be a hydrogen embrittlement problem? Would any major extensive/expensive modifications be necessary?

Embrittlement might be a problem depending on the material. Carbon steel is not suitable exactly due to this reason [27].
[Andreas Kegl at Air Liquide, Germany, June '99]

There could be an embrittlement problem, depending on operation and third party activity. Laboratory work has shown that oxygen is a very effective inhibitor, however it has not been tested in operation. Methane does not work. It has been suggested that the effect of oxygen is, that it blocks the steel surface. DONG has not done any research in this field [30].
[Celia Juhl, DONG, Denmark, July '99]

We have not studied this problem in this context, but of course, if hydrogen would be transported in the pipeline this possibility has to be studied in advance.

The hydrogen embrittlement corrosion is produced in the presence of water (moisture) and a high voltage (about 5 volts) in the impressed current of the cathodic protection system. It is possible that this condition would not be if the pipeline is transporting dry hydrogen, but it is needed to study it [36].
[Juan Manuel Lopez Zurita, Enagas, Spain, Oct '99]

Väteförsprödning bör inte vara något problem vid temperaturer som vi pratar om här. Man bör dock vara på sin vakt, speciellt med tanke på att man lägger på ett katodiskt skydd på ledningarna och att man, vid läggning av naturgasledningar, inte väljer material med tanke på att vätgas skall tranporteras i dem [28].
[Owe Jönsson, Svenskt gastekniskt center, Malmö, June '99]

We have not investigated the embrittlement problem up to now. We have asked Mannesmann and their answer was that they expect no embrittlement problems up to 25-30% hydrogen content in natural gas with the existing pipelines [32].
[Michael Mazzucato, OMV, Austria, Sept '99]

Because of the high pressures, up to 1000 psi (70 bar), and materials used (lower strength steels), hydrogen environment embrittlement could be a serious problem for existing natural gas pipelines carrying pure hydrogen. The primary mechanisms are fatigue crack growth under cycling loading and slow crack growth under stable loads near welds and other "heat affected zones" in pipes. The situation for hydrogen/natural gas blends has not been examined explicitly. However, if embrittlement effects in pipeline steels increase as the (partial pressure of hydrogen)$^{0.36}$ as suggested in one report (Holbrook et. al., 1982), it may be difficult to carry even low concentrations of hydrogen without embrittlement problems. For example, to decrease crack growth by a factor of two as compared to pure hydrogen, the hydrogen concentration would have to be reduced to about 15% by volume [5].
[J M Ogden, E Dennis, M Steinbugler, J W Strohbehn, Material issues: Hydrogen embrittlement, Princeton, 1995]

Embrittlement only becomes critical in the transmission of very pure hydrogen (higher than 99.5%), which would not be the case where transmission of energy in hydrogen form, rather than of the pure hydrogen required in certain chemical processes, is concerned.

As concerns hydrogen transmission pipelines, the investigations of the selection of materials made partly with the support of the General Directorate XII of the EC Commission, came to the following conclusions:

- Extended static pressure tests (10,000 hours) under stress conditions close to the elastic limit show that the steel grades and welds generally used for natural gas transmission are not adversely affected by hydrogen as long as its purity is not greater than 99.5%.
- These results were confirmed by comperative burst tests of steel rupture disks in pipes used for pressurized hydrogen or helium transmission.
- Additional tests have shown that these steelgrades, when subjected to severe cyclic stresses, appear to be rather sensitive to hydrogen embrittlement but that is relative sensitivity can be lessened by taking certain precautions such as limiting the stress rate, using steel with a low sulphur content and applying a normalizing heat treatment to it.

This data must therefore be taken into account for hydrogen transmission even under operating conditions resembling those of natural gas transmission, where pressure variations are usually of medium magnintude and rather slow [21].
[J.D Pottier, Gaz de France, 1995]

4.3 What to consider if you are about to build a new natural gas pipeline and you know that later on it will distribute hydrogen?

If you are about to build a new natural gas pipeline and you know that later on it will distribute hydrogen, would you build it different then?

Yes. At least if the idea it is to transport the same quantity of energy, the pipeline should be designed taking into account this fact. This could mean a higher diameter for allowing higher gas flow and possibly the utilisation of higher wall thickness in the pipeline for allowing the operation with higher pressures. As well as, the sealing system of the different parts of the pipeline (flanges, valves, pressure gauges, ...) should be different, because the small size of hydrogen molecule could produce its leakage from the system [36].
[Juan Manuel Lopez Zurita, Enagas, Spain, Oct '99]

Yes, probably [32]
[Michael Mazzucato, OMV, Austria, Sept '99]

As you might know, in germany there are the DIN regulations which often are the same as european EN regulations. There is a special set of regulations especially for natural gas pipelines and installations depending on the pressure either DVGW (for low pressure) or TRGL (high pressure). Most of the time DVGW is applicable [27].
[Andreas Kegl, Air Liquide, Germany, June '99]

As a commercial company we build pipelines to the requirements of our customers. None of our customers have currently expressed the intention to order hydrogen now or in the fu-

ture. Each additional specification (such as hydrogen capability) means extra costs. We don't think that we can charge customers with extra costs for things that they did not ask for. A perhaps more fundamental reason is that the transport of hydrogen is just one option for a problem that has many possible approaches (none of these provide easy solutions, however). Since the (political) discussion has in fact just started, it would be too early now to jump to conclusions. The high cost of hydrogen and its safety are major drawbacks [31].
[Paul Derks, Gasuine, The Netherlands, Aug '99]

Vet man att ledningen skall användas för vätgas så skulle den troligen byggas annorlunda. Framför allt så måste dimensioner anpassas så att energiflödet genom ledningen skulle kunna vara oförändrat vid en övergång till vätgas. En anpassning till vätgas redan nu skulle kräva att staten garanterar att man kommer att använda ledningen för vätgas om 10−20 år och den typen av planekonomi finns ju inte i vår del av världen och inte i någon annan del av världen heller för närvarande. Vad jag vet så är inga större konverteringsstudier gjorda [28].
[Owe Jönsson, Svenskt gastekniskt center, Malmö, June '99]

No codes and standards exist that cover hydrogen pipelines. Companies have written their own specifications for hydrogen lines.
When the EN 10208-3 is finished, it would proberbly be the best choice [30].
[Celia Juhl, DONG, Denmark, July '99]

Om man vet att naturgasrören skulle användas till vätgasdistribution, inom 20 år, kan man acceptera en rimlig merkostnad för rörläggningen. Merkostnaden motiveras i så fall av en förlängd livslängd [37].
[Anders Hellström, Vattenfall Naturgas AB, Göteborg, June '99]

Gränsen för en merkostnad går vid 10 år. Det är inte aktuellt att tänka på vad som händer längre fram än så [33].
[Einar Enghede, Göteborg Energi, June '99]

Gränsen vid projekteringen med avseende på lönsamhet, går vid 20 år. Den allmänna känslan som finns just nu är att ren vätgas inte kommer att börja distribueras förrän om cirka 40 år. När det blir aktuellt finns det säkert teknik som är bättre än dagens för att åtgärda befintliga pipeline, eller bygga nya pipeline intill. Men så som dagens naturgasledningar byggs är de i stort sett anpassade för vätgasdistribution. För att få fram samma energimängd borde förstås diametern vara något större, men det är otänkbart att ta hänsyn till det då man bygger naturgaspipeline. Ruhrgas har som tumregel att man anpassar dimensionen på rören efter det behov man antar finns efter sju år. Det finns ingen lönsamhet att bygga rör med för stor diameter [34].
[Göran Engström, Svenska Gasföreningen, June '99]

Gränsen för en merkostnad går vid 4-5 år om det inte är en marginell merkostnad. Merkostnaden får i så fall inte överstiga 5% av den totala kostnaden. Nej 5% är alldeles för mycket. Ett par procent. Det finns ingen kommersiell möjlighet att ta hänsyn till vad som händer i framtiden [38].
[Göran Fermbäck, Birka Energi AB, June '99]

4.4 Do you discuss hydrogen as a future energy carrier?

Do you discuss hydrogen as an future energy carrier, to begin with as a mix with natural gas, and its consequences. Is it economically defensible?

No [32].

[Michael Mazzucato, OMV, Austria, Sept '99]

Currently, taking into account that there are natural gas reserves for about 60 years (at the current consumption rate), the hydrogen is nor studied as an alternative in our company.

As well as, there are some problems in mixing hydrogen and natural gas:

I. Regulations: The authorities does not allow more than a 5% variation in the calorific value of the gas and any mixtures will lead to a higher change except if only a small quantity is added.

II. Safety in utilisation: The gas appliance are designed, tested and certified to use natural gas with a narrow range of composition. The utilisation of hydrogen will lead to the necessity of changing the gas appliance, mainly the domestic ones. We have to take into account that the combustion of hydrogen is very different to the natural gas (higher combustion velocity than methane, for instance) and this could lead to malfunction in the gas appliance.

III. Safety in transportation: the molecule of hydrogen is smaller than the methane (main component of natural gas), for this reason the permeability of the different sealing devices used in the pipeline could not be appropriated for using with hydrogen. This leads to an additional leakage problem.

IV. Efficiency of appliance: the different gas appliance are regulated for using natural gas, then an appreciable change in the composition of gas means that the performances decreases (for instance, in internal combustion engines) and then more primary energy (gas) is needed for the same work. This is against the saving energy criteria followed nowadays. Of course, a lot of appliance can be adjusted for the new gas, but we have to assure a constant composition.

As can be seen, there are not only technical problems in transport another gas, but problems in the utilisation field, as well as in the regulatory one.

In principle, this means that it is not economically feasible this way of introducing the hydrogen in the market, not only for problem in the transportation but in the utilisation of it [36].

[Juan Manuel Lopez Zurita, Enagas, Spain, Oct '99]

My general opinion is that it will not be an hydrogen energy industry within the next 100 years - because of long-term good supply of natural gas and too high costs for hydrogen energy production [35].

[Dr Fashold, Ruhrgas, Germany, June '99]

To our opinion the preferred way to use hydrogen is to produce it on a local scale, close to the end-user. If locally distributed in a pure form and converted in fuel cells, its premium market value can thus be realised, without the necessity to switch-over the high pressure natural gas pipelines. The gradual mixing of hydrogen with natural gas gives poor results in terms of the cost effectiveness of this policy (CO2-reduction divided by costs) and is therefore - to our opinion - not the preferred scenario. However, hydrogen options must compete with many other options for energy conservation and CO2-reduction (such as "green" methane and

wind/water/solar power). There are no clear winners (yet) [31].
[Paul Derks, Gasuine, The Netherlands, Aug '99]

What will probably interest you is that Novem has conducted a Dutch national program (GAVE) to search for low climate impact alternative (liquid and gaseous) energy carriers. With respect to gaseous energy carriers the recommendations were (dec. 1999):
- Use the existing network for mixing of climate neutral natural gas substitutes with natural gas whenever there is an opportunity.
- Gain experience with hydrogen by building a dedicated hydrogen network on a demonstration scale. [Please note that this recommendation does not mean that existing natural gas networks are by definition not suitable; to my opinion the conversion technology currently is the biggest bottleneck.] Gasunie has contributed to the GAVE-studies and has furthermore expressed an intention to participate in a follow-up program [31].
[Paul Derks, Gasuine, The Netherlands, Jan '00]

Vi planerar att, tillsammans med Danskt Gastekniskt Center och GasTec i Holland, genomföra en studie där vi tittar på inblandning av biogas och ev väte i naturgasnät [28].
[Owe Jönsson, Svenskt gastekniskt center, Malmö, June '99]

5 Discussion

The main purpouse of the inventory was to identify the geographical trade movements and, more important, to determine the characteristics of the present natural gas systems in terms of operating pressures, diameters and materials. The survey proved to be a difficult task, especially regarding the materials. The information was principally gathered from personal contacts with the gas companies who in some cases didn't have access to the information requested. Though, out of the presented results we could look into the pipeline systems hydrogen compatibility in terms of energy flow rate, compressor capacity and hydrogen embrittlement.

To the main question in this study, if it is technically possible to distribute hydrogen in present natural gas pipeline, the answer is yes.

Although the volumetric energy content of hydrogen is 31% that of natural gas, the comparative energy flow rate showed about 71% that of natural gas. This calculation assumed the same pipeline length, pressure and diameter conditions. It should also be noted that this result is in respect to the lower heating value. According to previous studies, the percentage share would be 87% if the higher heating value were used [8]. However, if the same energy flow rate wanted, one have to compensate by increasing the compressor power. This compensation showed no favour for hydrogen service.

Regarding the compression power calculations it should be noted that this is probably not directly transferable to the distribution cost. The capital cost for new compressors, or adapting existing compressors, could affect the transmission cost. In addition, natural gas also has got a natural inlet pressure from the gasfield and would not need a starting up compression as hydrogen need. This initial compression, when hydrogen rises pressure from zero to about eighty bar, could also affect the distribution cost.

Hydrogen embrittlement as a basic materials science has been widely studied and documented. However, to apply the information from the literature directly to this study is a difficult task as a laboratory study *not* is equal to the complex conditions of a real life system. There were also some contradictions in the statements regarding the mechanical strength of a pipeline material. Mohitpour et al [11] states that pipe steels with a low percentage of carbon *and* manganese are less susceptible to embrittlement. Air Liquide, who operates a high pressure hydrogen pipeline, has a recommendation of a carbon and manganese quota less than 0.40%. On the other hand, Fashold [35] states that materials of high strength and high tenancy, i.e. high grade, should be used. If low manganese content is the predominant way to avoid embrittlement, this seems to be a contradiction since high strength materials tend to have a high content of manganese, see Table 7. A general conclusion of NASA/Rocketdyne studies, 1973, was "the stronger the steel, the greater the embrittlement." Recommendations from Air Liquide, in their H_2 pipeline specifications for metal composition, states that the mechanical tensile strenght should be $Rm \leq 530$ MPa, which exclude X70 and higher grades [9]. Material design criteria for hydrogen gas pipelines stated by Mohitpour et al. recommend a tensile strenght $Rm \leq 700$ MPa which exclude X100 and higher grades [17]. This is a difficult issue especially when low quality welds or locally hard regions of the pipe, which are present in some older pipelines, are more easily embrittled due to Battelle-Columbus studies, 1982-1986 [5]. In our opinion, there is a limit of a materials susceptibility to hydrogen embrittlement, which depend on a trade off between the mechanical strength and the chemical composition. The trend is towards a stronger and more compact material which perhaps not is the best progress for a future hydrogen service. Out of the literature studied and personal communications with experts within the area, materials up to the grade of X70 are to be used. However, in our opinion, due to these constraints we could only in round numbers indicate which materials that would be suitable for hydrogen service.

Even though it is technically possible to distribute hydrogen in present natural gas pipelines, there could be constraints regarding the operational safety. Celia Juhl at DONG [30] hints that, for safety reasons, there will probably be requirements for decreasing the operating pressure, if compared to the one of natural gas. In Germany, more strict regulations apply for hydrogen distribution since hydrogen is concidered as a chemical product whereas natural gas is an energy carrier [27].

Rules, regulations and future standard norms will apparently restrict the hydrogen distribution in present natural gas pipelines, there could be constraints regarding the operational safety. Regarding if it is technically possible is however a question of hydrogen embrittlement. Hydrogen embrittlement does not occur if the concentration of hydrogen is less than 99.5% [21]. If pure hydrogen is a nessecity, the option is to decrease the pressure which reduce the embrittlement factor. Another alternative is to add an inhibitor into the hydrogen gas which strongly reduce the embrittlement effect of the pipe material. A lot of inhibitors have been tested but so far no optimal mixture is concluded. The experts have given us different answers regarding this matter. Methane does *not* work states Juhl [30] and Mohitpour [17] but it is included in the list from Deimel [7]. Carbon monoxide, sulfur dioxide and oxygen are the most frequently mentioned useful inhibitors but causes toxic, acid or safety problems respectively. If methane, natural gas, proves to be a possible inhibitor, or can be applied as a pre-loader as Rocketdyne suggests [5], it would be an interesting option out of several aspects.

A security problem could arise if the hydrogen need to be chemical clean. In Germany there is an odor added to natural gas so that it could be detected in case of leaks. This ought to be done in the case of hydrogen too. The consequence is that it is then not suitable (not pure enough) for chemical processes any longer [27].

Finally, this study should be regarded as an *indication* of the prerequisites for hydrogen as an energy carrier. Further studies should be conducted especially regarding the material issue.

6 Conclusions

In order to survey the prerequisites for hydrogen distribution, in present natural gas pipelines, the following conclusions are stated:

- The numerical analysis showed that; although the energy content per volume unit of hydrogen is 31% of the energy content of natural gas, under the same prerequisites, the energy flow rate for hydrogen transmission is approximately 71% compared to natural gas. The percentage share depends on the pipediameter, segment length and pressure drop. It should be noted that these calculations are based on the lower heating value.

- If the *same* energy flow rate is to be achieved it is possible to bring about a larger pressure drop which can be done with increased compressor capacity.

- To keep the same energy flow rate of gas in the pipeline, the compressor power required is about 4 times higher for hydrogen than for natural gas, based on the lower heating value.

- If we do not compensate for the lower energy flow rate, hydrogen distribution still needs approximately 2.8 times more compressor power to maintain the same prerequisites as for natural gas.

- If the distance between the hydrogen compressors along the pipeline would be optimized, the compression power requirements might be 1.5−2 times higher than for natural gas[5].

- For present natural gas service, generally, ferritic steels are used where grades between X40 to X80 occur. The trend is towards the use of higher grade material.

- Hydrogen embrittlement does not occur if the hydrogen purity is less than 99.5%.

- The most promising prevention of hydrogen embrittlement is the use of an inhibitor.

- In our opinion, we could only in round numbers indicate which materials to be recommended. In terms of a possible trade off between the mechanical strength and chemical composition, materials equivalent up to the grade of X70 would be the most suitable for hydrogen service.

- A general opinion seem to be that an extensive use of hydrogen is at least fifty years ahead and by then, for the purpose of distributing 100% hydrogen, new pipelines will be built.

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Appendix 1

Comparing methane and hydrogen energy flow

The correlation between the mass flowrate Q [kg/s], the pipe inner diameter D [m], the length L [m] of a pipeline segment and gas pressures [Pa] P_1 at the beginning and P_2 at the end of the segment is represented by the following equation [6]:

$$Q \;=\; \frac{\pi}{4}\, D^{2.5}\, (P_1^2 - P_2^2)^{0.5} \left(\frac{M}{Z\;L\;F\;R\,T}\right)^{0.5} \left(\frac{1}{\lambda}\right)^{0.5}$$

where M [kg/mol] represents the molar weight, Z the compressibility factor, F a drag factor, R [J/(mol K)] the universal gas constant, λ a friction factor and T the conducting heat which generally can be assumed to be constant over the lenght of the entire pipeline. The dimensionless friction factor, λ, for turbulent flow is [6]

$$\left(\frac{1}{\lambda}\right)^{0.5} = -2\log\left(\frac{2,51}{\mathrm{Re}\sqrt{\lambda}} + \frac{k}{3,71D}\right)$$

where Re is Reynolds number, k [mm] is a roughness factor in the pipeline and D [mm] its inner diameter. The Reynold number, Re, depend on the mass flow rate and the diameter as [6]

$$\mathrm{Re} = \frac{4}{\pi\;\mu}\,\frac{Q}{D}$$

where μ [kg/(m s)] is dynamic viscosity. The Compressibility factor or compression factor, Z, is a factor indicating how easy the gas can be compressed. Z depends on the partial pressure and the gas temperature as [22]

$$Z(P,T) = \frac{PV_m}{RT}$$

where P [Pa] is the pressure, V_m [m^3/mol] the molar volume, R the universal gas constant 8,3145 [J/(mol K)] and T [K] the temperature. For an ideal gas Z=1 for all temperatures and pressures but for a real gas $PV = ZnRT$ where Z is the divergence from the ideal gas law. The compressibility factor can be estimatet by using "the Redlich-Kwong Equation of state" which calulates the real gas pressure, P_{real}. This pressure divided with the gas pressure from the ideal gas law, P_{ideal} gives the divergence Z.

$$Z = \frac{P_{real}}{P_{ideal}}$$

$$P_{ideal} = \frac{R\,T}{V_m}$$

where P_{ideal} [kPa] is the pressure for an ideal gas, R [kNm/kmol K] is the universal gas constant 8,3145, T [K] the gas temperature and V_m [m^3/kmol] is the gas volume.

$$P_{real} = \frac{R\,T}{V_m - b} - \frac{a}{\sqrt{T}\;V_m(V_m + b)}$$

where R, a, b och V_m are based on substance weight expressed in kmol and

$$a = \frac{0,42748\;R^2\;T_c^{(5/2)}}{P_c}$$

$$b = \frac{0,08664\;R\,T_c}{P_c}$$

where T_c [K] is the critical temperature and P_c [kPa] the critical pressure.

To compare the energy flow we wrote a program in Matlab, see Appendix 4.

Appendix 2

Box 6

Hydrogen Environment embrittlement: Definitions and concepts from fracture mechanics

J M Ogden, E Dennis, J W Strohbehn
Hydrogen Energy Systems Studies,
Princeton University, 1995

The most important technical issue for using hydrogen and hydrogen blends in existing natural gas pipeline is hydrogen environment (H-E) embrittlement of pipeline steels. The two most important mechanisms in H-E embrittlement of pipeline steels are thought to be:

1. hydrogen acceleratet fatigue crack growth under cycling loading (e.g. pipeline pressure variations) and
2. slow crack or subcritical crack growth under static loads (constant pipeline pressure) near welds or other heat affected zones in pipes (e.g. the "hard spots" sometimes found in older pipes due to imperfect manufacture.

In this box we review some concept from material science relevant to fatigue crack growth and slow crack growth. We discuss how these effects depend on material properties and operating conditions, and how they are measured. For a detailed discussion the reader is refered to texts on fracture mechanics (Dowling 1993, Barsom and Rolfe 1987 or Broek 1984).

Mechanical behavior of materials: Definitions

(This discussion closely follows Chapter 1 of Dowling 1993)

The study of deformation, fatigue and fracture is an important part of structural design. To avoid structural failures, the mechanical behavior of materials must be known under the applied stresses and operating conditions (pressure, temperature, chemical environment, etc.) expected for the structure.

The primary concern is that the stress not exceed the strength of the material where the **strength** is defined as the stress that results in deformation or cracking failure.

Several types of material failure can occur:

1. **deformation** takes place when the change in shape or size of a component is large enough that its function is impaired or lost,
2. **fracture** occurs when cracking separates the component into two or more pieces,
3. **corrosion** is the loss of material due to chemical action and
4. **wear** is a loss of material due to abrasion.

Hydrogen environment, embrittlement takes place primarily by the development of cracks and subsequent fracture, although some changes in other mechanical properties are also seen.

Two types of deformation occur in response to stress.

1. **Elastic deformation** is proportional to the stress applied and the original shape recovered when the stress is removed.
2. **Plastic deformation** is not recovered upon loading and is a permanent change in the shape of the component. Once plastic deformation begins, only a small increase in stress causes **yielding**.

   The value of plastic deformation where yielding starts to become compromise the function of the structure is call the **yield strength**.

Materials capable of sustaining large amounts of plastic deformation are **ductile**. Materials which fracture under small amounts of plastic deformation are **brittle**. Ductile behavior occurs in many metals such as low strength steels, copper, lead and some plastic. Brittle behavior occors in glass, stone, acrylic plastics and some metals such as strength steels.

Tension tests are employed to assess the strenght and ductility of materials by slowly stretching a bar of material until it breaks. The **ultimate tensile strength** is the highest stress reached before fracture. Tension tests can also be used to determine the yield strength. Another measure of ductility is the **stain at fracture** expressed as the **percent elongation** of the material at failure.

Fracture can occur under **static loading** (loading which is constant or varies only slowly with time. If a fracture is accompained by little plastic deformation is it termed a **brittle fracture**. **Ductile fracture** can also occur, accompanied by significant plastic deformation and/or tearing.

If a sharp flaw or crack is present, brittle fracture can occur even in ductile materials. The resistance to brittle fracture in the presence of a crack is measured by a physical property called the **fracture toughness**. Materials with a high strenght generally have a low fracture toughness and vice versa.

Environmental cracking or**stress-corrosion cracking** can occur due to a combination of chemical and stress effects. Hydrogen embrittlement is an example of this type of cracking.

Fatigue is falure due to repeated loading. In general one or more tiny cracks start in the material and these grow under cycling loads until complete failure occurs. **High cycle fatigue** occurs after large numbers of cycles (millions). **Low cycle fatigue** is caused by a relatively low number of cycles.

Cracks may be present in a material from manufacture or they may occur early in the service life. These cracks may grow by fatigue, leading to brittle or ductile fracture once the cracks are large enough. The rate at which this process takes place is measured by the **fatigue crack growth**.

Another type of environmental cracking is termed **slow crack growth** or **subcritical crack growth**. This effect takes place under static loading conditions. Here cracks can grow over a period of time, even without variable loads.

Fatigue crack growth

(Chapter 11, Dowling, 1993)

Engineering analysis of fatigue crack growth is done using the stress intensity concept from mechanics.

The **stress intensity K** quantifies the severity of the combination of the crack lenght, loading and geometry for a given situation and can be defined as:

$$K = F\ S\ (\pi\ a)^{1/2} \tag{1}$$

where:
K=stress intensity in units of pressure x(lenght)$^{1/2}$
S=applied stress, usually defined on the gross area of the uncracked member
a=crack lenght
F=dimensionless geometric factor depending on the ratio of the crack lengt a to the member width b, such that a/b=1 is complete cracking. F can be determined theoretically from the geometry and crack size. For cracks small in comparison to the thickness of the structure. F is typically close to 1. As crack size approaches the thickness of the structure, F grows rapidly.

From equation (1), we see that the stress intensity increases as the crack grows.

The **fatigue crack growth rate** is defined as the rate of change of the crack length with cycling, expressed as **da/dN** where N=the number of cycles. For cyclic loads the **stress range** ΔS is given by ΔS=Smax$-S$min, and the **stress ratio** R=Smin/Smax.

The primary factor effecting the crack growth rate is the **stress intensity range** Δ**K**.

$$\Delta K = F\ \Delta S\ (\pi\ a)^{1/2} \tag{2}$$

The stress ratio R can also be expressed as $R = K\text{min}/K\text{max}$ or in the case of pressure loading $R = P\text{min}/P\text{max}$.

The rate of fatigue crack growth for a given set of test conditions is given by the Paris Equation

$$da/dN = C\ (\Delta K)^m \tag{3}$$

where:
da/dN=growth of crack per cycle (lenght/cycle),
ΔK=range of stress intensity, calculated from equation (2),
C=a constant depending on the material and
m=the slope on a log-log experimantal plot of da/dN vs. ΔK. The value of m is generally 3 or more.

At low growth rates, the curve generally becomes steep, and approaches a minimum value of ΔK, below which cracks will not grow. This is called the **fatigue crack growth theshold,** ΔK_{th}. At high values of ΔK, the growth rate curve sometimes becomes very steep, indicating that the material is approaching failure.

Fatigue crack growth rates are measured using a **notch test**. Here a sharp notch is machined into a test specimen, which is then subjected to cyclic loading. The growth of the crack is measured and plotted versus number of cycles. ΔK is calculated from equation (2) at a series of values and plotted versus da/dN.

For a given set of test conditions, the plot of da/dN vs. ΔK is independent of the geometry of the test specimen. This allows laboratory results to be extrapolated to practical situations.

To assess the effects of hydrogen other materials properties such as the ductility and the strenght are measured for **notched** and **unnotched** specimens. These are refered to as the **notched ductility** and **unnotched ductility**, etc. The cycling time may be varied as well as the stress ratio R. To test the effects of hydrogen on fatigue crack growth, hydrogen at various pressures is introduced into the test chamber.

The R value has a strong influence on growth at low growth rates and also on the threshold ΔK_{th} initiating crack growth.

Typical curves for hydrogen accelerated fatigue crack growth in pipeline steels

When hydrogen is present the fatigue crack growth rate is accelerated as compared to inert gases such as nitrogen or helium. The stress intensity range theshold ΔK_{th} for fatigue crack growth is also lowered. The stress intensity for a crack in a pipeline can be roughly estimated by

$$K = M_p \; S_h \; (\pi \; a)^{1/2} \tag{4}$$

where:
S_h=hoopstress at the pipeline wall=$P \; R/t$
P=pipeline pressure
R=pipeline radius
t=pipeline thickness
a=crack lenght
M_p=geometric factor for pipelines=$1 + 1.61a^2/Rt$ [Broek 1984]
(M_p is approximately=1 for small cracks)

For conditions which might be present in a hydrogen pipeline
Pmax=1000psi ($\approx$ 70 bar)
R=457 mm
t=9.5 mm
a=0.5 mm
we find a stress intensity at maximum pressure of about 11.9 kpsi $(\text{in})^{1/2}$. (in=the value expressed in inch (?))
If the pipeline were cycled from 0 to 1000 psia, which might happen during a shutdown, the ΔK would be 11.9 kpsi $(\text{in})^{1/2}$. Figure B6-3 is an experimental curve showing how da7dN varies with ΔK for a pipeline material in 1000 psi hydrogen as compared to 1000 psi nitrogen, The measured threshold for fatigue crack growth in hydrogen is about ΔK_{th}=6 kspi $(\text{in})^{1/2}$, so since the stress here is larger (11,9>6), the crack would grow in this case. From the graph, the initial growth rate at ΔK=11.9 kpsi $(\text{in})^{1/2}$ would be about 5 x 10^{-4} mm7cycle. If the initial cracks were smaller, the maximum stress intensity would decrease as the $(\text{crack size})^{1/2}$. At the measured threshold for fatigue crack growth (ΔK=6 kspi $(\text{in})^{1/2}$), the threshold crack size leading to fatigue crack growth would be about 0.13 mm.

If the pressure change during cycling were lower, say 200 psi instead of 1000, the stress intensity change would be low enough (ΔK would be 2.4 kpsi $(\text{in})^{1/2} < \Delta K_{th}$) that no cracks would grow. This highlights the importance of not allowing large pressure variations, if hydrogen embrittlement due to fatigue crack growth is to be avoided.

The number of cycles to failure can be estimated as:

$$N_{if} = \frac{(1 - (a_i/a_f)^{(m/2 \; -1)}) \; a_i^{(1- \; m/2)}}{C \; (F \; \Delta S \; (\pi)^{1/2})^m (m/2 \; - 1)} \tag{5}$$

where:
a_i=initial crack size
a_f=crack size at failure (generally 25-50% of wall thickness)
N_{if}=number of cycles for the crack to grow from a_i to a_f
C, m=experimentally determined constants for da/dN vs. ΔK
F=geometric factor in equation (3)

This expression can be simplified, if we assume that a_f»a_i (e.g. the initial crack size is much less than the crack size at failure). Substituting equation (3) into (4) and (5), we find that

$$N_{if} = \frac{a_i}{(da/dN)_i (m/2 \; - 1)} \tag{6}$$

for m=3 the cycle life is about 2000 cycles.

The degrading effect of hydrogen is apparent. For a nitrogen pipeline, the number of cycles to failure would be about 100 times greater. Initial crack lenght is a key parameter. For an initial crack lenght of 1 mm, the lifetime would be reduced to less than 100 cycles. If the initial crack lenght is 2 mm, the stress intensity range is about 24 kpsi $(\mathrm{in})^{1/2}$, the initial crack growth rate $(da/dN)_i$ is about 1.5 x 10^{-2} mm/cycle and the lifetime would be about 27 cycles.

Equation (5) illustrates the sensitivity of pipeline lifetime to the initial crack size (the smaller the initial crack the longer the lifetime), strass intensity change during cycling (the larger the stress change, the shorter the lifetime). The larger m

is, the steeper the plot of $da7dN$ vs. δK and the stronger the dependence on initial carck size. It also suggests that the fatigue crack growth will be dependent on the total gas pressure change during cycling rather than the hydrogen partial pressure. Only a weak dependence on hydrogen partial pressure is seen in experiments.

The lifetime of a pipeline under hydrogen accelerated fatigue crack growth will depend on the operating conditions (high pressure swing should be avoided) and the presence of initial cracks. Although the operating conditions producing embrittlement failure for our example are fairly extreme (cycling from 0 to 1000 psia) in the presence of cracks in the 2 mm size range would mean failure after only 27 cycles. Since pipelines are in service for 30-50 years, this possibility cannot be discounted.

Hydrogen effects on slow crack growth near heat affected zones (welds and spots)

The parameter controlling slow crack growth under hydrogen loading is the stress intensity K. A specimen is loaded for a period of time and the growth of cracks is measured. It is often possible to find an experimetal relationship between **crack velocity da/dt** and K of the form

$$da/dt \;=\; A\ K^n \tag{7}$$

The time to fracture can be estimated, as above. Accelerated slow crack growth has been found near welds and heat treated zones in hydrogen environments. Again, if sufficiently large initial cracks are present, this effect might lead to failure in pipelines.

Appendix 3

Gas properties:

		unit	H_2	CH_4
M	Molar mass	kg/mol	0.002	0.016
T_b	Boiling temperature	K	20.26	111.7
T_m	Melting temperature	K	13.8	89
T_{cr}	Critical temperature	K	33.2	191.4
p_{cr}	Critical pressure	MPa	1.32	4.64
c_p	Thermal capacity	J/(kg K)	14200	2180
k	Thermal conductivity	W/(m K)	0.168	0.031
μ	Dynamic viscosity	kg/(m s)	$8.4{\cdot}10^6$	$10.3{\cdot}10^6$
ρ	Density (273 K, 1 atm)	kg/m^3	0.09	0.72
γ	Ratio of specific heats	-	1.41	1.30

Energy content, Lower Heat Value (Physics Handbook [24])

	unit	H_2	CH_4
Energy content	kWh/kg	34.5	14.4
Energy content	MJ/kg	124	50
Energy content (273 K, 1 atm)	MJ/m^3	11.16	36

Physical hydrogen data at 1,013 bar (Linde AG, Germany [39])

Density liqued H_2 (20.3 K)	kg/m^3	70.79
Density gaseous H_2 (20.3 K)	kg/m^3	1.34
Density gaseous H_2 (273 K)	kg/m^3	0.09
Energy content H_2	kWh/kg	34.5
Energy content liquid H_2	kWh/m^3	2442
Energy content gaseous H_2	kWh/m^3	3.1

Appendix 4

```
%Peo Björck and Maria Grahn, Göteborg University, 1999-12-30
%Matlab program made for comparing transmission cost of hydrogen
%versus natural gas as a ratio between the energy flow rates.
%Calculating a flow rate out of a specific pipe length, diameter and
%pressure drop with iteration for fully turbulent flow (Re>4*10^3) using
%equations from SYDGAS AB.
%Note that the compressibility factor is calculated as the pressure
%drop is linear and determined as the
%mean value between Z at the inlet pressure and Z at the outlet pressure.

L=100*10^3;                                      %[m] length of pipeline
D=0.2032;                                        %[m] inner pipe diameter
%P1=80*10^5;                                     %[Pa] inlet pressure
%P2=70*10^5;                                     %[Pa] outlet pressure
P1=68.948*10^5;                                  %[Pa] inlet pressure (1000 psi)
P2=20.6844*10^5;                                 %[Pa] outlet pressure (300 psi)

R=8.31434;                                       %[J/(mol K)] universal gas constant
T=273;                                           %[K] gas temperature
F=1;                                             %[-] dragfactor
MH2=2*10^-3;                                     %[kg/mol] Molar weight, Molecular mass
MCH4=16*10^-3;                                   %[kg/mol] Molar weight, Molecular mass
TcH2=33.2;                                       %[K] Critical temperature
TcCH4=191.4;                                     %[K] Critical temperature
PcH2=1.32*10^(3);                                %[kPa] Critical pressure
PcCH4=4.64*10^(3);                               %[kPa] Critical pressure
aH2=0.42748*R^2*TcH2^(5/2)/PcH2;                 %a-factor in Redlich-Kwong (Z)
aCH4=0.42748*R^2*TcCH4^(5/2)/PcCH4;              %a-factor in Redlich-Kwong (Z)
bH2=0.08664*R*TcH2/PcH2;                         %b-factor in Redlich-Kwong (Z)
bCH4=0.08664*R*TcCH4/PcCH4;                      %b-factor in Redlich-Kwong (Z)
Pideal=P1*10^(-3);                               %[kPa] pressure in the ideal gas law
PidealEND=P2*10^(-3);                            %[kPa] pressure in the ideal gas law
Vm=R*T/Pideal;                                   %[m3/kmol] molar volume
VmEND=R*T/PidealEND;                             %[m3/kmol] molar volume
PrealH2=(R*T/(Vm-bH2))-(aH2/(sqrt(T)*Vm*(Vm+bH2)));
PrealCH4=(R*T/(Vm-bCH4))-(aCH4/(sqrt(T)*Vm*(Vm+bCH4)));
PrealH2END=(R*T/(VmEND-bH2))-(aH2/(sqrt(T)*VmEND*(VmEND+bH2)));
PrealCH4END=(R*T/(VmEND-bCH4))-(aCH4/(sqrt(T)*VmEND*(VmEND+bCH4)));

ZH2=(PrealH2/Pideal+PrealH2END/PidealEND)/2;     %The Compressibility factor
ZCH4=(PrealCH4/Pideal+PrealCH4END/PidealEND)/2;  %The Compressibility factor


%Calculation of friction factor (1/lambda)^0.5=x
k=0.01778;                                       %[mm]roughness factor in pipeline (0.0007 inch)
dynvisH2=8.4*10^(-6);                            %[kg/(m s)] dynamic viscosity (5.9*10^-6lb/(ft s))
dynvisCH4=10.3*10^(-6);                          %[kg/(m s)] dynamic viscosity (7.3*10^-6lb/(ft s))

QH2=[];
xH2=[];
xH2(1)=-2*log(2.51+k/(3.71*D*10^3));
xH2(2)=-xH2(1);
QH2(1)=(pi/4)*((MH2/(ZH2*T*L*R*F))^(0.5))*((P1^2-P2^2)^(0.5))*(D^(2.5));
QH2(2)=-QH2(1);
n=2;
```

```
i=2;
while  abs(QH2(n)-QH2(n-1))>0.0000001;
   ReH2=4*QH2(n)/(pi*dynvisH2*D);                        %[-] Reynolds number
   while  abs(xH2(i)-xH2(i-1))>0.0000001;
      xH2(i+1)=-2*log(xH2(i)*2.51/ReH2+k/(3.71*D*10^3)); %[-] friction factor
      i=i+1;
   end
   fricH2=real(xH2(end));
   QH2(n+1)=(pi/4)*((MH2/(ZH2*T*L*R*F))^(0.5))*((P1^2-P2^2)^(0.5))*(D^(2.5))*fricH2;
   n=n+1;
end;

QCH4=[];
xCH4=[];
xCH4(1)=-2*log(2.51+k/(3.71*D*10^3));
xCH4(2)=-xCH4(1);
QCH4(1)=(pi/4)*((MCH4/(ZCH4*T*L*R*F))^(0.5))*((P1^2-P2^2)^(0.5))*(D^(2.5));
QCH4(2)=-QCH4(1);
n=2;
i=2;
while  abs(QCH4(n)-QCH4(n-1))>0.0000001;
   ReCH4=4*QCH4(n)/(pi*dynvisCH4*D);                        %[-] Reynolds number
   while  abs(xCH4(i)-xCH4(i-1))>0.0000001;
      xCH4(i+1)=-2*log(xCH4(i)*2.51/ReCH4+k/(3.71*D*10^3)); %[-] friction factor
      i=i+1;
   end
   fricCH4=real(xCH4(end));
   QCH4(n+1)=(pi/4)*((MCH4/(ZCH4*T*L*R*F))^(0.5))*((P1^2-P2^2)^(0.5))*(D^(2.5))*fricCH4;
   n=n+1;
end;

disp('The flow rate [kg/s] for hydrogen resp. natural gas is')
disp([round(real(QH2(end))),round(real(QCH4(end)))])
disp('The energy flow rate [MJ/s] for hydrogen resp. natural gas transmission is')
disp([round(real(QH2(end))*124),round(real(QCH4(end))*50)])
disp('Percent of energy transmitted if H2 instead of CH4')
disp(100*real(QH2(end))*124/(real(QCH4(end))*50))
disp('when the diameter D [m]=')
disp(D)
disp('the inlet pressure P1 [Pa] and the outlet pressure P2 [Pa] =')
disp([round(P1),round(P2)])
disp('and the pipe length [m] is')
disp(L)
disp('As a calculating control Reynolds number and friction factor for H2 resp. CH4 is')
disp([round(real(ReH2)),round(real(ReCH4)),round(fricH2),round(fricCH4)])
disp('Compressibility factor for H2 resp CH4 is')
disp(ZH2)
disp(ZCH4)
```