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Impact of Sustainable Gases on Joints used in Gas Distribution Networks

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Colophon

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Preface

This literature report is part of the EDGaR research project "Impact of Sustainable Gases on Joints used in Gas Distribution Systems". It is part of the EDGaR program sub theme 1.2.

The following partners are involved in this project:

- Enexis
- Liander
- Stedin
- Kiwa

Kiwa is the project leader.

This project is closely related to the research projects with working title "Effects of Narrow Band Gases on Distribution Materials" and "Effects of Wide Band Gases on Distribution Materials". The literature reports for these projects have been numbered GT-110204 and GT-110205 respectively.

Summary

The possible influence of sustainable gases on distribution gas pipe materials is covered in two other EDGaR projects. However, every pipeline contains joints and because a pipeline system is only as strong as its weakest link, the possible influence of sustainable gases on joints in the pipelines needs to be addressed as well.
In this literature report the impact of sustainable gases on joints has been investigated. This has been done by evaluating the integrity of existing joints as well as looking to the ability to make new joints for maintenance, repair and or extension purposes of the existing gas distribution network.

In this project the following two research questions will be answered:

A. *Are the most important joint types presently used in the Dutch gas distribution grids resistant to sustainable gases?*
B. *Are the well-established maintenance, repair and extension methods for pipelines still feasible for pipelines containing (admixed) sustainable gases?*

In the first phase of this project several scientific and technological date sources of relevant literature have been studied.
The joints have been classified in joints used respectively in plastic and metal piping systems. In plastic piping systems the most used and investigated joints are respectively, PVC couplers with elastomeric seals, POM couplers and thermo fused joints (e.g. butt fusion and electro fusion). In case of steel piping systems joints which have been welded or needed threads have been investigated. Also compression joints, typically used in copper piping systems have been investigated. All the results of this literature review are summarised in the table on the next page.

It is too early to conclude definitely about the maximum allowable concentrations of gas components in sustainable gases, because a deleterious effect of certain components in sustainable gas cannot be excluded for some of the most important materials and joints in the Dutch gas network
Additional experimental work, to be focussed on gases with a possible negative effect, will therefore be performed in the following phase of this EDGaR research project.

Existing joints

Joint	Material	Sulphur containing components	H_2S	Mer-captans	Odorant	Ammo-nia	Chloride containing components	Fluoride containing components	HCl	HCN	CO	CO_2	Hydro-carbons	Aromatic hydro-carbons	O_2	H_2
Coupler body material	PVC	unknown		probably none		unknown			probably none		unknown	possibly	none, unless liquid (impact resistance)		probably none	unknown
	POM	unknown		probably none		possibly				unknown			probably none		unknown	
Coupler sealing ring	NBR	unknown	possibly	probably none		none	possibly		probably none		none		probably none, unless liquid		none	
	SBR	unknown	possibly	probably none		none	possibly		probably none		none		possibly		probably none	none
Electro fusion and butt fusion	PE	unknown		probably none		unknown			probably none		unknown	none	none, unless liquid		none	probably none
Welded	Steel	with water: possibly		probably none			Unknown				with water: possibly		probably none		with water: possibly	none
Press and compression	Cu	with water: possibly, depending on their mutual influence			probably none	with water: possibly	probably none			unknown		with water: possibly	probably none		with water: possibly	unknown

Maintenance, repair and extension methods

Joint	Material	Sulphur containing components	H_2S	Mer-captans	Odorant	Ammo-nia	Chloride containing components	Fluoride containing components	HCl	HCN	CO	CO_2	Hydro-carbons	Aromatic hydro-carbons	O_2	H_2
Coupler and pipe	PVC	unknown		probably none		un-known	possibly		probably none		unknown	possibly	none, unless liquid		unknown	
Electro fusion and butt fusion	PE	unknown		probably none		unknown			probably none		possibly		none, unless liquid		none	unknown
Welded	Steel	with water: possibly		probably none			unknown				with water: possibly		probably none		with water: possibly	probably none
Compres-sion	Cu	with water: possibly, depending on their mutual influence			probably none	with water: possibly	probably none			unknown		with water: possibly	probably none		with water: possibly	unknown

	=	The effect is unknown, but is expected to be very small or non existent.
	=	This component within the concentrations of narrow band has no effect on the material.
	=	The effect is unknown.
	=	Deleterious effects are under some conditions to be expected.

Contents

1 Introduction

1.1 Background

The possible influence of sustainable gases* on distribution gas pipe materials is covered in two other EDGaR projects ("Effects of Narrow Band Gases on Materials" [1] and "Effects of Wide Band Gases on Materials" [2]). In those two projects, only pipes and pipe segments are investigated. However, every pipeline also contains many joints. Because a pipeline system is only as strong as its weakest link, the possible influence of sustainable gases on joints in the pipelines needs to be addressed as well. Questions regarding joints in transmission pipelines are addressed in a separate proposal with the title: *From mono-gas to multi-gas: "Effect of narrow and wide band gases on integrity and safety of the Dutch gas grid.* [3]

In the present context, it is crucial to realize that the item "joints" is not limited to already existing joints in the pipelines, but also includes the normal maintenance, repair and extension methods of existing networks, because for such activities, making joints is almost inevitable. Therefore, it needs to be assessed whether long-term contact with sustainable gases could influence or hamper the applicability of well-established, everyday asset management operations on pipelines.
It needs to be ascertained whether in the case of long-term use of (admixed) sustainable gases the existing maintenance, repair and extension methods are still adequate or need to be changed in special cases or in special regions.

1.2 Goal

In this project the following two research questions will be answered:

A. *Are the most important joint types presently used in the Dutch gas distribution grids resistant to sustainable gases?*
B. *Are the well-established maintenance, repair and extension methods for pipelines still feasible for pipelines containing (admixed) sustainable gases?*

For the above two categories the following sub questions are relevant:

A. Existing joints.
   a) What are the most important joint types presently used?
   b) What are the critical (long-term) failure mechanisms of these most important joints in an environment of sustainable gases?
   c) What are the maximum allowable concentrations of various gas components in sustainable gases when using the existing Dutch gas distribution infrastructure for the transport of these gases?
B. Maintenance, repair and extension methods.
   d) What are the most important maintenance, repair and extension methods presently used?
   e) Which of these methods could be influenced most or hampered when applied to grids that have been or will be exposed to sustainable gases?
   f) What are the maximum allowable concentrations of gas components in sustainable gases when using the mentioned maintenance, repair and extension methods?

* Sustainable gases are wide band gases as defined in the EDGaR project "Effects of Wide Band Gases on Materials" [2], including LNG, SNG, raw gases and partially upgraded gases.

The main goals in this project therefore are:

- To indicate which gas components and which concentrations of certain components in sustainable gases may be harmful for the joints used in the existing Dutch gas distribution infrastructure.
- To assess which of the presently used and well-established repair, maintenance and network extension methods are also feasible in grids containing sustainable gases.
- To provide detailed technical information on maximum allowable concentrations of certain components in sustainable gases when using the mentioned repair, maintenance and extension methods.

Although life expectancy of assets is not only limited by technical aging [4], the present literature review will only be focussed on this aspect. It will be focussed on the effects of the transport of sustainable gases on existing and "future maintenance" joints. Sustainable gases are wide band gases as defined in the EDGaR project "Effects of Wide Band Gases on Materials" [2], e.g. raw gases and partially upgraded sustainable gases.

This literature review will also indicate possible gaps in the knowledge, in which area further research is necessary. Please note that the objective of this literature review is not to be exhaustive with respect to the components in wide band gas and the joints and jointing techniques used in the Dutch gas distribution network. Therefore, various trace components may be absent in defining the wide band gas composition and it is emphasised that only the most important joint types and maintenance, repair and extension methods are discussed.

1.3 Approach

Several sources of relevant literature have been studied:

- Literature already available in the database of Kiwa Technology
- The (former) Dutch monthly magazine “Gas”
- References present in the proceedings of technical conferences, such as:
  - Plastics Pipes I until XVI
  - AGA Plastic Fuel Gas Pipe Symposia
  - Plastic Pressure Pipes conferences
  - International Gas Research Conferences
- The scientific database STN Easy (FIZ Karlsruhe)
- International and national standards

The references that have been used in this report are listed in Appendix IV.

Next, these literature sources were evaluated in the light of the questions a) until f) listed in section 1.1. Many sources contain results that are not completely in the compositional area of interest of the present literature review. Therefore in many cases assumptions and extrapolations had to be made. Moreover, some sources reported contradictory results. To resolve this, differences in exposure parameters, evaluation (testing) procedures and the concentration range of influential chemical components and their combinations had to be taken into account. In case that was unsuccessful, assumptions were made or it was proposed to perform additional tests.

1.4 Reading Guide

Chapter 2 answers in which way sustainable gases are presently defined.

Chapter 3, 4 and 5 discuss the existing joints (part A). So to answer sub question a) it is important to know which kind of joint types are presently used in the Dutch gas distribution network. This is discussed in chapter 3.
Chapters 4 and 5 answer sub question b) in more detail focussing on the failure mechanisms of polymeric materials and metals respectively.

The next three chapters (6, 7 and 8) discuss the maintenance, repair and extension methods (part B). Chapter 6 therefore, continues with an overview of the most important maintenance, repair and extension methods to answer sub question d). These methods are used on existing pipes. Absorption or deposition of certain components from sustainable gases may for instance influence the quality of welds.
Sub question e) is answered in chapter 7 and 8.

This literature review will not fully answer sub questions c) and f) about which components and concentrations in wide band gases result in unacceptable lifetime reductions of certain joints or impart maintenance, repair and extension methods. Answering these questions will be the result of the experimental testing programme that is foreseen as the next phase of this EDGaR project. This experimental work will not only lead to answers about the influence of certain components in wide band gases but will also present information on these influences under practical circumstances of long-term exposure and on the maximum allowable concentrations.

At the end of each section intermediate conclusions will be presented. This literature review ends with the overall conclusions in chapter 9.

2 Definition of Sustainable Gases

As said previously, sustainable gases are wide band gases as defined in the EDGaR project "Effects of Wide Band Gases on Materials" [2], e.g. raw gases and partially upgraded sustainable gases. This means that the physical properties (like Upper Calorific Value and Wobbe Index) and the chemical composition of sustainable gases (wide band gases) are completely different from G-gas. Moreover, the composition ranges of wide band gases can be very broad.

Possible sustainable gases are:
- Gas from anaerobic digestion
- Syngas/SNG
- LNG/Natural gases from other countries
- Hydrogen

These gases are discussed in the paragraphs 2.1 until 2.4. In paragraph 2.5 a comparison in composition is made between the various sustainable gases and G-gas.

2.1 Gas from Anaerobic Digestion

In the anaerobic conversion of biomass and waste, organic materials are microbiologically converted to methane (CH_4), carbon dioxide (CO_2) and water (H_2O). This gas is also called "biogas". The rate of the anaerobic digestion is determined by the composition of the reaction mixture and its temperature. The rate of reaction increases with higher temperatures. This increase of the reaction rate is limited by the stability of the microbiological agents in this process. Temperatures up to about 55 °C are however feasible.

Examples of anaerobic conversion processes for the production of biogas are:
- Sewage treatment plants. Many of these plants produce methane rich gases in the sludge fermentation stage. Utilisation of methane from sewage plants is used on a large scale in many countries.
- Landfills. All landfills produce methane rich gases. Collection and utilisation of the gases is quite widely applied.
- Cleaning of organic industrial waste streams. Anaerobic digestion processes are often successfully applied to clean the waste streams of agricultural processing industry.
- Mesophilic and thermophilic digestion of organic waste (farm biogas plants). Compact installations convert organic waste to methane rich gases at higher temperatures. The main difference between the two methods is the digestion temperature (35 °C in the mesophilic process and 55 °C in the thermophilic process).

Although the biological processes are the same for the different methods, the chemical composition of the production gases is different. Landfill gas mainly consists of components of biological origins, but contaminants that are present in the landfill such as solvents, propellants and chemicals, can lead to unusual and unwanted trace gas components. Gas from sewage sludge digestion has less harmful components. However, traces of halogenated hydrocarbons and organosilicon components do occur. Gas from mesophilic and thermophilic digestion contains high concentrations of hydrogen sulphide (H_2S) and other sulphur-containing compounds, but contains almost no other polluting components. Appendix I shows the compositions of the different gases from anaerobic digestion.

2.2 Syngas/SNG

Syngas (from synthetic gas or synthesis gas) is a gas mixture that contains varying concentrations of carbon monoxide (CO) and hydrogen (H_2). Examples of production methods include steam reforming of natural gas or liquid hydrocarbons to produce hydrogen, the gasification of coal, biomass and the use of some types of waste-to-energy gasification facilities [5,6]. Syngas is used as intermediate in creating substitute natural gas (SNG) and for producing ammonia or methanol.

Substitute natural gas (usually abbreviated to SNG, also known as synthetic natural gas) is a generic term for natural gas substitutes that are produced by chemical processes. SNG can be made of various hydrocarbons, which could come from the heavy fractions from oil refining, coal or biomass. When using biomass it is called bio-SNG. [7]

2.3 Imported Natural Gases

This group includes all gases that are transported to the Netherlands. This could be by pipeline or as Liquefied natural gas (LNG). This is natural gas that has been converted temporarily to liquid form for ease of storage and transport. Gases from foreign countries will not have the same physical properties or chemical composition as Groningen gas (G-gas), because the natural gas could come from all over the world and every natural gas well has its own composition.

2.4 Hydrogen

Although there are still numerous questions about the actual realization of a possible transition towards a hydrogen economy, hydrogen could play an important role in the future energy supply. Currently the dominant technology for direct hydrogen production is steam reforming from hydrocarbons, which is less sustainable than for instance electrolysis of water using wind or solar power.

2.5 Chemical Composition of the Different Sustainable Gases

In Table 1 a global overview of the concentrations of different chemicals, which have been found in anaerobic digested gas, SNG, gas that has been transported to the Netherlands as LNG or by pipeline, is given. This is compared to the known concentrations of various components in G-gas [8]. The main differences between the wide band gases and G-gas can be found in the concentrations of CO, CO_2 and H_2 and various chemicals, which can especially be found in anaerobic digestion gases, such as ammonia, oxygen, aromatic hydrocarbons (including benzene and toluene), H_2S and organo-silicons.

For safety reasons G-gas is odorized in the Netherlands by adding tetrahydrothiophene (THT). Mercaptans, used in other countries as odorant, are not used for this purpose in the Netherlands. THT is a heterocyclic organic compound consisting of a five-membered ring containing four carbon atoms and a sulphur atom. The nominal content of THT in G-gas in the Netherlands is 18 mg/m^3 (n). Up to now THT is not added to sustainable band gases.

The dew point mentioned in Table 1 is the water dew point. Gas is cooled down at a certain pressure to remove moisture (water) and other components that can condensate. A lower temperature or higher pressure will make the gas 'dryer'. How much dryer the gas will be is unknown. The required water dew point for G-gas is -12 °C at 40 bar pressure, whilst for instance LNG is cooled down to -162 °C at pressures up to 60 bar [9]. It is unknown what this means for the risk of condensation of not only water, but all components that can condensate. It is clear that gases without such a drying procedure (such as gas from anaerobic digestion and SNG) will be 'wetter' and the risk of condensation has increased. This is very important in view of the occurrence of corrosion of metallic pipes.

Table 1. The minimum and maximum contents of chemicals found in anaerobic gas, SNG and imported natural gas, compared to the average chemical composition of G-Gas. Some values in mol % and mg/m³ have been converted to ppm for comparison.

Quality	**G-gas Average [8]**	**Narrow band limiting value [10]**	**Gas from anaerobic digestion***	**SNG [11]**	**Imported natural gases [11]**	**Unit**
Dew point	-12 (at 40 bar)	-10 (at 8 bar)	n.a.	n.a.	various	°C
Temperature (of feed in gas)	10	0 – 20	0 - 50	n.a.	n.a.	°C
Sulphur (total)	6.7	45				mg/m³ (n)
Inorganically bound sulphur (*H_2S*)	0.4	5	4 300			mg/m³ (n)
Mercaptane	< 1.0	10				mg/m³ (n)
Odorant value (*THT*)	17.7	> 10; nom 18; < 40	n.a.	n.a.	n.a.	mg/m³ (n)
Chlorine containing compounds	< 0.1	50	0 - 735			mg/m³ (n)
Fluorine containing compounds	< 0.1	25	0 - 256			mg/m³ (n)
Ammonia	< 0.1	4	0 – 100			ppm
Hydrogen chloride (*HCl*)	< 1.0	1	Traces			ppm
Hydrogen cyanide (*HCN*)	< 1.0	10	Traces			ppm
Carbon monoxide (*CO*)	< 100	10 000		10 000 – 700 000		ppm
Carbon dioxide (*CO_2*) in dry gas	8 900	103 000	240 000 – 520 000	20 000 – 590 000	0 - 1000	ppm
Aromatic hydrocarbons	500	10 000	Occasional traces		Occasional traces [12]	ppm
Benzene		500**	0 – 11.4			ppm
Toluene			0 – 76.2			ppm
Oxygen (*O_2*) in dry gas	< 100	5 000	0 – 26 000			ppm
Hydrogen (*H_2*)	< 0.01	12	0 – 190 mg/m³	7 - 62		vol %
Methane (*CH_4*)	81.29		40 – 68	0 – 43	70 - 99.8	mol%
Nitrogen (*N_2*)	14.32		0 – 17	0 – 50.9	0.01 – 1.8	mol%
Ethane (*C_2H_6*)	2.87			0 – 2	0.06 - 15	mol%
C_2H_y (except C_2H_6)				1 – 25		mol%
C_3H_y	0.38				0 - 10	mol%
C_4H_y	0.15				0 - 3.5	mol%
$C_{5+}H_y$	0.09			0 - 0.3	0 - 0.6	mol%
C_xH_y				0 - 0.3		mol%
phosphine	technically free	technically free	0 – 0.7			mg/m³ (n)
Organo-silicons	< 0.1	5	0 – 20			mg/m³ (n)
Volatile organic compounds (VOC)			Traces			ppm
Metals (copper, mercury)			Occasional traces			ppm

n.a. = not applicable. *empty cell = not measured.*
** In appendix I a broader overview of the chemical composition of gases from anaerobic digestion processes is given.*

A. EXISTING JOINTS

3 Most Important Types of Existing Joints

To answer sub question a) of section 1.1, the most important types of existing joints and joining techniques are identified. The applied joint types are related to the most important materials used in the Dutch distribution network. Therefore, firstly an overview of the most important materials is given and secondly the types of joints for these pipeline systems are described.

3.1 Most Important Materials

3.1.1 Distribution Mains

The Dutch distribution network contains about 124 000 km of mains, which are made from either polymeric materials (PE and PVC) or from steel (carbon steel, grey and nodular cast iron). Asbestos cement (AC) is also used in certain areas, but it is not allowed anymore for new systems. In Table 2 the length of each material in the distribution network in 2010 can be found.

Table 2. Length and MOP of distribution mains in 2010 for different types of materials [13].

Material		(Sub)total length (km)	Length (km)	MOP * (bar)	Material standard
Polyvinyl chloride (PVC)		75 062			
	High Impact PVC (PVC-HI)		*53 996*	0.1	[14]
	Unplasticized PVC (PVC-U)		*21 066*	0.1 †	-
Steel		27 484			
	Carbon steel		*19 228*	16	[15, 16]
	Grey cast iron		*6 241*	1 †	[17]
	Nodular cast iron		*2 015*	8	[18]
Polyethylene (PE)		19 529			
	2nd and 3rd generation PE		*14 422*	8 §	[19]
	1st generation PE		*5 107*	4 †§	-
Other		1 918			
	Asbestos cement (AC)		*1 719*	0.1 †	[20]
	Unknown		*199*	-	-
Total		**123 993**			

* *MOP = Maximum Operating Pressure*
† *Not allowed for new pipelines*
§ *Value may be lower. This depends on the SDR (Standard Dimensional Ratio) and the type of PE (PE80 or PE100). See references for more information.*

This table shows that PVC is the most used material in the Dutch gas network, because by far the largest part of the network (about 100 500 km, 81%) consists of low pressure distribution mains with operating pressures of 30 or 100 mbar. The rest of the network consists of high pressure distribution mains (operating pressure 1, 4 or 8 bar) in which the majority (about 14 000 km) is used at an operating pressure of 8 bar.

3.1.2 Service Lines

With more than four million connections to residential houses, industries, etcetera, connecting almost 99 % of the Netherlands to gas, service lines are an important part of the gas network. The materials of service lines (SL) are mainly steel, copper and PE (see Table 3). Based on an average length of approximately ten meter of each service line, the total length in the Netherlands is about 40 000 km.

Table 3. The materials used as service line [21].

Material
Polyethylene (PE)
PEKO (copper pipe with PE sleeve)
Copper (without PE sleeve)
Steel

3.1.3 *Conclusions*

In the distribution mains multiple materials are used of which PVC (PVC-HI and PVC-U), PE (1st, 2nd and 3rd generation) and steel (carbon steel, grey cast iron and nodular cast iron) are the most common ones. The service lines mainly consist of steel, copper (with and without PE sleeve) and PE.

3.2 Joints and Joining Techniques in Plastic Piping Systems

3.2.1 *Polyvinyl Chloride Piping Systems*

PVC-U and PVC-HI pipes are jointed by means of separate fittings containing elastomeric sealing rings. A wide variety of these so-called socket fittings are available, but most consist of a body made of PVC-HI with sealing rings that are made of NBR (nitrile butadiene rubber) and SBR (styrene butadiene rubber). Occasionally PE is also used as fitting body material.

Although the GIVEG quality mark for PVC-U gas pipes was withdrawn in 1974 [22] and SBR does not conform to the current requirements of EN 682 [23], sockets made of PVC-U and/or sockets with SBR sealing rings are to date still in operation in the existing distribution network in the Netherlands

About 7.5 million PVC couplers and 4.5 million PVC saddles are used in the Dutch gas distribution network. [24]

3.2.2 *Polyethylene Piping Systems*

PE pipes are joined to each other by thermal heat fusion or with mechanical fittings. There are typically two heat fusion jointing methods widely used in the Dutch gas distribution network: electro fusion and butt fusion.

Butt-fusion jointing is a process in which the ends of two PE pipes are heated up to the molten state and then rapidly pressed together to form a homogeneous bond. This means that the material of the PE pipes itself is used to make the joint. The butt fusion jointing method for PE pipe was developed in the nineteen-fifties [25] and is still used. To date many butt fusion joints exist. For maintenance, repair and extension of a PE pipe system, electro fusion is mostly used.

The electro fusion welding process involves the use of a moulded socket fitting containing an electrical resistive heating coil. A prepared pipe end is inserted into either side of the socket and clamped. An electrical current from a welding machine is then passed through the coil for a pre-set time and so heating of the surrounding polymer and heat transfer to the pipe wall takes place. Cold zones at the ends of the fitting contain the melt in the central section, allowing a high melt pressure to develop and the formation of a homogeneous joint. PE electro fusion fittings were first used in the late nineteen-seventies [26] that were made from PE 50 material. Later PE 80 was used. To date only PE 100 fittings are applied. Many electro fusion joints exist in the gas distribution network. Electro fusion couplers can also be utilized for quick and simple modifications to existing piping systems and is therefore the most chosen maintenance, repair and extension method.

In the Dutch gas distribution network about 1.5 million heat fusion (both electrofusion and butt-fusion) joints exist [24].

Next to these heat fusion techniques, mechanical joints, especially full-end load resistance joints (Dutch: trekvaste koppelingen) occur in PE systems. Full-end load resistance joints are joints that are designed in such a manner that in the event of an axial overload the pipe will fail first. The connection is therefore stronger than the pipe. These fittings consist mainly of a body and a sealing/grip ring and are mostly used in service lines. The fitting body of these joints can be made of copper, PVC-HI, POM (Polyoxymethylene) and/or malleable cast iron. Sealing/grip rings can be made of copper, brass, POM, cast iron and (only for sealing purposes) rubber.

POM couplers are one of the most used types of mechanical joints in the Dutch gas distribution network (no data about the number of these joints are however available). The rest of the mechanical joints are made of already investigated materials [2]. These mechanical joints are used much less than POM couplers (no data about the amount available). Furthermore, mechanical joints rarely fail due to gross failure, but rather they will start leaking, which can be found by means of above-ground leak detection. This means that mechanical joints other than POM couplers will be at worst a controllable problem. These joints are therefore not investigated in this report.

3.3 Joints and Jointing Techniques in Metal Piping Systems

3.3.1 Steel Piping Systems

Beyond domestic settings, steel pipes are often joined by welding or with mechanical joints using threaded connections.

In the Dutch gas distribution network many different welding processes are used. In general, welding a steel pipe is performed by melting the steel pipe (e.g. by an arc) and often a filler material. The pool of molten material (the weld pool) cools to become a strong joint. In the Dutch gas distribution network about 6 million welded joints exist. [24]

In threaded connections tapered threads are cut into the end of the tubing segment. Although the threads should be gas tight by themselves, a sealant is applied in the form of thread sealing compound or thread seal tape (nowadays: PTFE tape, in the past: hemp). There are about 15 million threaded joints in the Dutch gas distribution network. [24]

Another type of joint is a flange. Flanges are made from steel or cast iron and are bolted together. Between the two flanges a polymeric packing is used. Similar to mechanical joints (except threaded joints), flanges are little used (both are 0.3 million times present in the Dutch gas distribution network [24]) and will fail by small leakages that can be found with above-ground leak detection. Therefore, flanges are not investigated in this report.

3.3.2 Copper Piping Systems

Copper pipes in the gas distribution systems are typically used in service lines and are joined with press fittings or by soldering or brazing.

The press fitting is composed of a copper housing with rubber rings. The housing is compressed around the pipe to obtain a full end-load resistant joint. These press fittings are typically used in copper piping systems outside buildings. (no data about the amount available)
Inside buildings brass is used next to copper in compression fittings.

Inside buildings, joints in copper piping systems are mainly made by soldering or brazing. Soldering and brazing are both metal-joining processes whereby a filler metal is heated slightly above its melting temperature. The filler metal has a lower melting point than the material of the pipe and fitting, so only the filler metal is molten. In brazing, the filler metal melts at a higher temperature than in soldering. With soldering generally a tin-lead alloy is used as filler metal. For brazing brass or silver alloyed brass can be used. Advantage of brazing is the higher strength of the joint. When a silver alloyed brass is used, the brazed joint has an improved corrosion resistance. There are about 3 million soldered and brazed joints in the Dutch gas distribution network. [24]

It is expected that the main failure mechanism for soldered and brazed joints in copper piping systems is due to improper installation (e.g. insufficient penetration of the filler metal). Corrosion is expected to be of less importance, especially for silver alloyed filling material. Even if a leakage occurs, it is expected to be very small and can be found with above-ground leak detection, hence the risk is limited. Therefore, soldered and brazed joints are not investigated in this report.

3.4 Transition Fittings

Transition fittings allow pipes of different materials to be joined. A wide variety of joints can be made using all jointing methods mentioned in previous sections.

3.5 Summary

To date there is a wide variety of joints in operation in the Netherlands, depending on the type of pipe material. Each pipe material has its own preferred jointing technique.

The following existing joints are the most important and crucial ones.

Plastic piping systems (Chapter 4)

- PVC piping systems
    - PVC coupler with elastomeric seals (i.e. SBR and NBR) – see section 4.1
- PE piping systems
    - Heat fusion joints (electro fusion and butt fusion joints) – see section 4.2
    - POM couplers – see section 4.3

Metal piping systems (Chapter 5)

- Steel piping systems
    - Welded joints – see section 5.1
    - Threaded joints – see section 5.2
- Copper piping systems
    - Compression and press fittings – see section 5.3

4 Effects on Existing Joints in Plastic Piping Systems

In this chapter the effects of sustainable gases on the most used existing joints (see section 3.2) in plastic piping systems are described. The joints that are discussed in this chapter are:

- PVC couplers with elastomeric sealing (i.e. SBR and NBR)
- Heat fusion joints (electro fusion and butt fusion joints)
- POM coupler with NBR sealing ring

4.1 PVC Couplers with Elastomeric Seals

In the Dutch gas distribution system PVC systems are only used at low pressures (< 200 mbar). Socket fittings are used the most for joining pipelines. They mainly consist of a PVC body with elastomeric sealing rings.

4.1.1 PVC Body

Both the PVC body and the elastomeric sealing ring may be affected by sustainable gases. The effects of sustainable gases on PVC pipe material (PVC-HI, High Impact PVC, and PVC-U, Unplasticized PVC) is described in "Effects of Wide Band Gases on Distribution Materials" [2]. Because the failure mechanisms for a PVC pipe (craze growth and brittle fracture due to impact loadings) are similar to the failure mechanisms for the body of a PVC coupler, investigating the effects of sustainable gases on PVC is not repeated in this literature review.

The effects of sustainable gases on the elastomeric sealing ring will be described below.

4.1.2 Elastomeric Sealing Ring

4.1.2.1 Failure Mechanism of Elastomeric Sealing Rings

For the elastomeric sealing rings, mainly two rubber types are in use in the existing pipeline infrastructure: NBR and SBR. Since approximately 1978 (4 years after the transition from PVC-U to impact resistant PVC) SBR compounds have been replaced by NBR because SBR sealing rings have a lower resistance against methane and other hydrocarbons than NBR [27].

There are a number of factors that can influence “the sealing strength” of the rings. These are:

- Type of rubber material.
- Excessive temperature development causing the rubber to harden and lose its elastic properties. (For example high temperatures may be the result of external environmental factors and/or friction);
- Excessive squeezing due to over tightening.
- Volume swelling of the elastomeric seal due to the transported medium and in particular natural gas condensate.
- Introduction of gas components incompatible with the elastomeric material.

When comparing the influence of G-gas and sustainable gases on elastomeric seals, the most important factors are the latter two. Therefore, the focus in this report will be on these two aspects.

4.1.2.2 *The Influence of Sustainable Gases on Elastomeric Sealings*

Effects of Hydrocarbons

In sustainable gases concentrations of certain hydrocarbons other than methane (ethane, propane, etc) can be higher, especially in SNG, compared to G-gas.
According to ISO DTR 7620 [28] no negative effect of alkanes is expected towards NBR. NBR may undergo a moderate effect once in contact with unsaturated chemical compounds (e.g. ethylene, propylene, butylene) [28]. Due to the high concentrations of C_2H_y and C_3H_y (unsaturated hydrocarbons) in wide band gases, NBR may undergo negative impacts of these gases. The extent of this influence is unknown.

In several studies, it has been shown that SBR and NBR will swell in contact with aromatic hydrocarbons [27,29-31]. The effect of swelling by liquid aromatic hydrocarbons (condensate) and – after vaporisation of the condensate – subsequent extraction of plasticizer and other additives from the elastomeric components has been studied using exposure to pentane and synthetic condensate (70 % iso-octane, 30 % toluene) [27,31]. The swelling of SBR in these media showed to be several times higher than that for NBR (respectively 43 wt% for SBR and 15 wt% for NBR) [27]. Subsequent drying showed no significant differences between SBR and NBR and resulted in an extraction (mass loss) of 10 - 15 % (plasticizer loss) [31].
The mechanical properties of the swollen elastomers reduced drastically. For SBR the reduction of the mechanical properties (e.g. tensile strength, elongation at break, hardness), was up to 90 %. For NBR the reduction was up to 60 % [31]. After drying, the mechanical properties of both SBR and NBR re-gained up to 90 % of the initial values. One exception is the hardness of SBR rubbers which was slightly higher than the initial value after extraction [31].

The sealing properties of the elastomeric seal are dependent on the reaction force caused by the deformation of the seal. As a result of stress-relaxation, the reaction force decreased after swelling and subsequent extraction. If the stress-relaxation is higher, the sealing capability of the seal decreases, which may influence the leak tightness of the joint. For SBR the reaction force was reduced to about 50 %. For NBR the effect was smaller with a reduction of 25 %. [27]
Based on these findings it was recommended not to use SBR for future applications, but to use elastomeric sealing rubber with a higher resistance to hydrocarbons.

Due to the low concentrations of aromatic hydrocarbons in sustainable gas (see section 2.5) it is not expected that these components in sustainable gases will affect the elastomeric seals. However, the presence of any liquid aromatic hydrocarbons will negatively affect the mechanical properties, including the sealing force, of both SBR and NBR.

Effects of Carbon Monoxide, Carbon Dioxide and Hydrogen

ISO DTR 7620 [28] states that there is little or no adverse effect on NBR and SBR expected by exposure to CO, CO_2 and H_2. This is confirmed by elastomeric seal producers [32-34].
Also in research by the former VEG-Gasinstituut it was concluded that no negative effect would be expected for CO, CO_2 and H_2 [35]. This conclusion is based on the low solubility of these gases, because the solubility is an important (but not the only) aspect with respect to any deleterious effect. The solubility, and thus the risk on a deleterious effect, is higher when the rubber is already affected by hydrocarbons [35].

Effects of Oxygen

Oxidation can cause a degradation of the rubber [35]. Oxygen will not be harmful as long as the compound is well protected with an antioxidant and the temperature is low. Nevertheless, problems may arise if the rubbers are thin and are exposed to large deformations.

According to ISO DTR 7620 [28] and elastomeric seals producers [32-34] no negative effect on NBR by O_2 is to be expected. SBR is less protected against oxidation than NBR. According to ISO DTR 7620 [28] SBR is not resistant or strong deviant against O_2. However, due to the low O_2 concentrations in sustainable gases (see Table 1) an effect of O_2 on SBR is not expected.

Effects of Sulphur Containing Components (H2S, S and THT)

According to ISO DTR 7620 [28] a severe deleterious effect of H_2S (saturated solution) and sulphur (S) on NBR and SBR can be expected if the material is fully submerged in one of these chemicals.

On the other hand according to elastomeric sealing producers, NBR and SBR seals are relatively resistant to H_2S [32-34]. This was also concluded after a research led by the former VEG-Gasinstituut [35]. Nevertheless these results were based on low concentrations of H_2S (≤ 5 mg/m^3). The concentrations of sulphur containing chemicals (especially H_2S) are much higher in wide band gas (up to 4300 mg/m^3 for H_2S). The impact of this concentration is unknown and needs to be further investigated. The impact of this concentration is unknown. Even the effects of the currently proposed lower concentration of 160 ppm H_2S [36] are unclear. Therefore further research is needed.

Effects of Halogen Containing Components

According to ISO DTR 7620 [28] all halogen containing components may have a severe effect on the mechanical properties of NBR and SBR components. Elastomeric seal producers [32-34] also warn their customers to be careful using NBR and SBR products with halogen containing components.
Although only traces of halogen containing compounds are found in wide band gases, deleterious effects on NBR and SBR by these chemicals can therefore not be excluded.

Effects of Other Components

According to ISO DTR 7620 [28] both NBR and SBR have a moderate resistance when fully submerged in HCN. Because only traces of HCN chemicals are found in sustainable gases, these negative effects are expected to be very low.

According to ISO DTR 7620 [28] NBR and SBR have an outstanding resistance against refrigerant ammonia. The relatively low concentration of ammonia in wide band gases (up to 100 ppm) is therefore not high enough to have a deleterious effect on elastomeric seals.

4.1.2.3 *Conclusions*

Swelling of membranes and rubber rings by introduction of gas components, which are incompatible to elastomeric seals, can accelerate the failure process.

Based on various data sheets, no deleterious effect of ammonia, CO, CO_2, O_2 and H_2 is expected. However, H_2S, halogenated components, aromatics and unsaturated hydrocarbons cause swelling of elastomeric seals resulting in a decrease of functionality and possibly also a decrease of the lifetime expectancy. Therefore, special attention should be paid to the concentrations of these gases. However, it is still unknown above which concentrations certain chemicals may affect NBR and SBR rubbers. This should be investigated further.

4.1.3 *Conclusions*

Overall it can be concluded that both NBR and SBR seals can be affected by sustainable gases, especially by high concentrations of H_2S, halogenated components and higher hydrocarbons. Because sustainable gasses may have a negative effect on NBR and SBR sealing rings, the integrity of the entire socket joints may therefore be weakened. The body of a coupler will undergo the same influence of sustainable gases as PVC pipes. This is described in more detail in "Effects of Wide Band Gases on Distribution Materials" [2].

The impact of sustainable gases on PVC couplers with elastomeric seals is summarized in Table 4.

Table 4. The effects of components present in sustainable gas on PVC socket fittings with elastomeric seals. Some components will have no deleterious effect (green) or no or little deleterious effect is expected (light green). The effect of other components is unknown (light orange) or a deleterious effect may be present (orange)

	Sulphur containing components	H_2S	Mer-captans	Odorant	Ammo-nia	Chloride containing components	Fluoride containing components	HCl	HCN	CO	CO_2	Hydro-carbons	Aromatic hydro-carbons	O_2	H_2
PVC	unknown		probably none		unknown			probably none		unknown	possibly	none, unless liquid (impact resistance)		probably none	unknown
NBR	unknown	possibly	probably none		none	possibly		probably none		none		probably none, unless liquid		none	
SBR	unknown	possibly	probably none		none	possibly		probably none		none		possibly		probably none	none

4.2 Heat fusion Joints

The two most used heat fusion jointing methods in PE piping systems are butt fusion and electro fusion (see section 3.2.2). Both methods melt the PE material to obtain a strong bond after solidification. The solidified PE in both joint types is similar to the PE used for pipes. Also, the failure mechanism for heat fusion joints will be slow crack growth (SCG). It is therefore expected that the effect of sustainable gases on existing thermal fused joints is comparable to the effect of sustainable gases on PE material as described in "Effects of Wide Band Gases on Distribution Materials" [2]. In Table 5 the conclusions of this report are summarised.
The literature confirms that the strength and reliability of heat fusion joints made before adsorption of gas components is not affected. [37]

Please note that any effect cannot be excluded if PE pipes that are exposed to sustainable gases are joined by means of heat fusion. For instance, gases absorbed by the PE material may form gas bubbles during melting. This is discussed in more detail in section 6.1.2.

Table 5. The effect of components present in sustainable gases on PE. Some components will have no deleterious effect (green) or no or little deleterious effect is expected (light green). The effect of other components is unknown (light orange).

	Sulphur containing components	H_2S	Mer-captans	Odorant	Ammo-nia	Chloride containing components	Fluoride containing components	HCl	HCN	CO	CO_2	Hydro-carbons	Aromatic hydro-carbons	O_2	H_2
PE	unknown		probably none		unknown			probably none		unknown	none	none, unless liquid		none	probably none

4.3 POM Couplers with NBR Sealing Rings

Mechanical fittings with a body made from Polyoxymethylene (POM) are often used in PE gas piping systems. These so-called POM couplers were introduced in the late nineteen-seventies, and were used in the beginning only in the water industry. A few years later, POM couplers were also allowed in gas distribution systems. The coupler contains a rubber ring as sealant. Modern

POM couplers for gas contain a NBR ring with yellow colour, indicating the use for gas. POM couplers with blue NBR rings are used in water distribution systems.

4.3.1 *POM Body*

There are different types of POM polymer. In 1959, DuPont began producing a homopolymer. In 1962, Celanese brought a copolymer on the market. This company is now called Ticona. BASF is another supplier of POM copolymer. Asahi is the only other producer of POM homopolymer. Up to now only homopolymers are used for POM couplers in the gas (and water) distribution market.

4.3.1.1 *Failure Mechanism of POM Couplers*

POM can fail in a brittle manner by long-term mechanical overload and fatigue. POM of low molecular weight is much less resistant to fatigue than medium molecular weight POM. High molecular weight POM is best [38].

POM chains fail during fatigue due to chain scission (breaking of the long polymer chains). This is a chemical reaction which means that during failure of POM new chemical species are produced and that these reactions cannot be reversed. During chain scission radicals are formed which lead to further chain scission. Molecular weight reduction by fatigue is considerable. Eventually, cavitation in the material occurs (void formation) and stress whitening. The upper yield stress is also lowered by fatigue. Such a failure mechanism by chain scission is clearly different from that of PE and PVC. It is generally accepted that this failure process occurs in both POM homopolymers and copolymers.

Radical formation due to chain scission can be counteracted by stabilisers (antioxidants). The influence of the stabiliser concentration in POM on the resistance to fatigue loading was investigated [39]. When the concentration of added stabiliser decreases below 80 % of the concentration in a commercial POM copolymer Celcon M25, the resistance to fatigue loading decreases by about 75 %. This means that this is a critical stabiliser concentration for POM materials, which is needed to assure adequate performance. This could also mean that in case the added stabiliser is extracted by contact with certain chemicals from the environment or in sustainable gases, the properties of POM material could be reduced. At low stabiliser levels, room temperature ageing of POM material further aggravates the reduction in material properties.

4.3.1.2 *The Influence of Wide Band Gases on POM Couplers*

General effect of chemicals

POM is very resistant to aliphatic and aromatic vapours and liquids (gas condensates). Due to the chemical composition of (relatively polar) POM, such apolar substances, which can affect PVC and PE, do not pose a serious threat to POM.
However, POM is not resistant to strong acids like hydrogen chloride, caustic substances (strong bases), oxidising agents, esters and – to a lesser degree – ketones. In these cases polyacetal (POM) is weakened by hydrolysis, which is a chemical reaction, in which eventually formaldehyde gas is liberated from the product. It is generally accepted that POM homopolymers are much more vulnerable to the above chemicals than POM copolymers.

Although detergents are not the first chemical that comes to mind in the case of biogas, POM can be affected by certain soaps and for instance by the detergent Dreft [40].
Hawle, a manufacturer of POM couplers, also indicates that the installation of POM couplers with greasy soaps is strictly forbidden [41].
If this precaution is not followed up, POM couplers may fail, due to contact with detergents.

4.3.1.3 *Effects of Halogen Containing Components*

POM copolymer (Celcon) is not resistant to hypochlorite ions [42]. Because POM homopolymers are much more vulnerable to chemical degradation than POM copolymers, it is expected that also in this case POM homopolymer will be more vulnerable to hypochlorite ions. The cause of failure by low concentrations of hypochlorite ions is chain fracture by oxidation. Eventually a white degraded layer is formed by formation of micro voids. This layer is severely embrittled and allows crack initiation at even very low stresses.
Influential factors are stress level, concentration of hypochlorite ions, temperature and exposure time.

About 600 cracked POM fittings have been investigated [43]. They had been used for hot water pipelines and contained chlorinated water (free chlorine or chloramine). As much as 92 % of these samples showed visible degradation at the internal surface and 61 % showed surface cracks.
To simulate attack of POM during stress cracking experiments, hydrochloric acid was used as stress crack agent. Chain breaking at the exposed surfaces leading to unwanted molecular weight reduction was followed by measuring solution viscosity.

The influence of various chlorine-containing species (free chlorine at high and low concentration, dichloramine and monochloramine) in potable water on the tensile strength of a POM material was investigated [44].The intensity of the degradation effect of the chlorinated chemicals decreases in the given order.
Melt rheology on the embrittled surface layer is an effective method to monitor the degradation of POM that occurred during exposure. Observation of the viscosity decrease by degradation of the surface layer is more sensitive than tensile testing. Even a thin (0.13 mm) degraded surface layer is capable of increasing the brittleness of a whole POM tensile bar quite remarkably.
The above means that the type of chlorinated substance is very important. Free chlorine causes oxidation of POM and is therefore the most aggressive of the three substances. Therefore, it is not enough to mention the chlorine or fluorine content of biogas, but also whether any halogenated substance can be easily converted into chloride of fluoride anions [45].
The fact that even a 0.9 % solution of table salt (sodium chloride), in the presence of stresses eventually causes degradation of POM [46]emphasises this once more.

The concentration limit for chlorine and fluorine containing components in narrow band gas is low (see Table 1). Many expected components are stable chlorofluorocarbon molecules with may have little effect. On the other hand, because of the uncertainty in the extent of the influence, it is proposed to test POM with one chlorinated hydrocarbon.

Effects of Ammonium vapour

From experience it is known that POM couplers that were installed in-house and cleaned with ammonium hydroxide could fail prematurely [47]. This is likely due to the basic character of ammonium hydroxide (high pH).

POM homopolymer (Delrin ® 100AL NC010) is not resistant to 10 % ammonium hydroxide solutions during 90 days at 23 °C [48]. Water free ammonium vapour (comparable with the investigated situation) also leads to severe attack of POM homopolymer [49]. However, it is not specified in this literature source what the applied concentration of the water-free ammonium vapour was. Therefore, it is difficult to derive from this data whether POM may be vulnerable to low concentrations of ammonium vapours in narrow and wide band gases.

POM copolymers are resistant to 10 % ammonia in water [50]. This in accordance with what is known about the higher resistance of copolymers (with respect to homopolymers) to chemicals. However, POM copolymers are presently not used in Dutch gas distribution grids.

This means that the resistance of POM homopolymer to low concentrations of anhydrous ammonium vapour is not known. It is unknown what the maximum allowable ammonia concentration is, to prevent any damage during long-term exposure.

Effects of Other Components

Little is known about the effect of other components in sustainable gases than those already mentioned. Most research is performed on (hot) water systems, giving little to no information relevant to the effect of sustainable gases on POM.

Because POM couplers are used for already a few decades in G-gas without substantial problems, an adverse effect of odorant and (aromatic) hydrocarbons (including BTX) is not expected. The effect of mercaptanes is assumed to be similar to that of an odorant.

4.3.1.4 *Conclusions*

Not much is known about the effect of components in sustainable gases on POM. From experience it is known that (liquid) ammonia, which is used as cleaning agent, can have an adverse effect on POM, especially on homopolymer POM. Ammonia vapour can be present in biogas at trace concentrations as well as chlorinated hydrocarbons. Therefore testing POM in these substances is recommended.
An adverse effect of odorant and (aromatic) hydrocarbons (including BTX) is not expected

4.3.2 *NBR Sealing Ring*

See section 4.1.2.

4.3.3 *Conclusions*

The impact of sustainable gases on POM couplers has been summarized in Table 6.

Table 6. The effect of components present in sustainable gas on mechanical POM fittings. Some components will have no or little deleterious effect is expected (light green). The effect of other components is unknown (light orange).

<table>
<tr><th></th><th>Sulphur containing components</th><th>H_2S</th><th>Mer-captans</th><th>Odorant</th><th>Ammo-nia</th><th>Chloride containing components</th><th>Fluoride containing components</th><th>HCl</th><th>HCN</th><th>CO</th><th>CO_2</th><th>Hydro-carbons</th><th>Aromatic hydro-carbons</th><th>O_2</th><th>H_2</th></tr>
<tr><td>POM</td><td colspan="2">unknown</td><td colspan="2">probably none</td><td colspan="4">possibly</td><td colspan="3">unknown</td><td colspan="2">probably none</td><td colspan="2">unknown</td></tr>
<tr><td>NBR</td><td>unknown</td><td>possibly</td><td colspan="2">probably none</td><td>none</td><td colspan="2">possibly</td><td colspan="2">probably none</td><td colspan="2">none</td><td colspan="2">probably none, unless liquid</td><td colspan="2">none</td></tr>
</table>

5 Effects on Existing Joints in Metal Piping Systems

In this chapter the effect of sustainable gases on the most used existing joints (see section 3.3) in metal piping systems are described. The joints that are discussed in this chapter are:

- Welded joints in steel piping systems
- Threaded joints in steel piping systems
- Compression fittings in copper piping systems
- Soldering or brazing in copper piping systems

5.1 Welded Joints in Steel Piping Systems

The natural gas transport and distribution infrastructure contains a considerable amount of steel pipes, fittings and equipment. Due to the variety of components and age of the components a large variety of steel qualities has been applied. The applied steel qualities range from cast iron (nodular and grey cast iron), basic steel grades as St 37, modern steel grades like ASTM A106 gr. B and API 5L gr. B.
The corrosion mechanisms as described in this chapter are in general applicable to the applied carbon steel and cast iron grades, however the susceptibility to corrosion and the aggressivity of a corrosive medium can be highly dependent on the specific properties of a specific steel type.

5.1.1 Welding of steel pipes

5.1.1.1 Applied Welding Techniques

Historically for welding of steel gas pipes the most frequently used welding process was Shielded Metal Arc Welding (SMAW) (Dutch: lassen met beklede elektrode). Practically all welds in steel pipes were made using this welding process [51]. Only for thin walled pipes (wall thickness ≤ 3 mm) Oxyacetylene Welding (OAW) (Dutch: autogeenlassen) has been applied. Because of the limited wall thickness Oxyacetylene Welding in practice may be used mainly for welding of service lines.
To date additional to SMAW, also Gas Metal Arc Welding (GMAW) (Dutch: MIG/MAG lassen) is applied. Instead of Oxyacetylene Welding also the Gas Tungsten Arc Welding (GTAW) (Dutch: TIG lassen) can be applied, for example for welding of the root pass and for welding of thin walled materials.

5.1.1.2 Metallographic aspects of welding of carbon steel

After welding three zones can be distinguished in the weld: the unaffected base material, the heat affected zone and the weld metal. The weld metal consists of solidification structures, and is a mixture of molten base metal (pipe) and filler metal (welding electrode). The chemical composition of the weld metal will be a composition in between the composition of the base metal and the weld metal. Because the weld metal is in the liquid phase during the welding process, this zone is prone to the formation of welding defects like inclusions, porosities, solidification cracks, etc. During each subsequent run the metal in the heat affected zone and the weld metal is heated. The temperature of the metal rises so much that part of the material undergoes a phase transformation upon heating. In the regions where the highest temperatures are reached, i.e. adjacent to the weld zone, the temperature elevation also causes grain growth to occur. After heating the metal cools down again, mainly as an effect of heat transfer in the metal. During cooling the metal again undergoes a phase transformation. The microstructure that is formed in the heat affected zone however is not exactly the same as the structure of the base material. Depending on the cooling rate, the structure is only coarsened adjacent to the weld at a

slow cooling rate. When the cooling rate is high, hard phases such as bainite and martensite can form.
Due to the heating and subsequent cooling of the metal during welding the material has a tendency to deform, as a result of thermal expansion. Because of the fixation of the pipe ends during welding, and the tubular geometry of the pipe, there is only limited possibility for the material to deform. This is a cause for the increase of the internal stresses in the material in and near the weld. If the stresses after welding (due to both deformation and formation of hard phases) are unacceptably high (for example in case of thick walled material) the stresses can be relieved with a post weld heat treatment.

5.1.2 *Failure Mechanism of Steel Welds*

Compared to the steel pipes the corrosion behaviour of the welds is much the same as the behaviour of the pipes, there are however some differences specific to the weld area. The corrosion mechanisms generally applicable to the base metal and weld are presented in a separate report (see [2]). In this chapter, only the effects of future sustainable gasses specific to joints are presented.

The weld metal and the heat affected zone have a microstructure that is different from the base metal. These differences may lead to the occurrence of localised corrosion near the welds [52].

The height of the stress in the heat affected zone and weld is dependent on the heat treatment that is applied after welding. For thin walled carbon steel welds, normally no post weld heat treatment is applied. Due to the high internal stresses the weld zone may be more sensitive to stress corrosion cracking mechanisms.

Non-metallic inclusions and weld defects may aggravate corrosion in the weld. Non-metallic inclusions can locally affect the quality of protective surface layers formed during the corrosion process. Weld defects such as undercut and micro-cracking can lead to the formation of small corrosion cells in the weld.

Differences in the chemical composition between the weld metal and the base material can be another factor influencing the occurrence of corrosion. If the concentration of alloying elements in the weld metal is lower than in the steel, the weld metal is less noble than the base metal, which can lead to preferential attack of the weld metal. Due to the large surface of the base materials compared to the small surface of the weld, the corrosion rate of the weld metal can be high.

Also the weld geometry can lead to aggravated local attack. Excess penetration of the weld may cause turbulences in the flowing gas. Small amounts of particles (for example sand or oxides) present in the flow may result in abrasion due to the occurrence of turbulent flow.

5.1.3 *The Influence of Sustainable gases specific to Steel Welds*

5.1.3.1 *Effects of Water*

The presence of water in the gas infrastructure is one of the preconditions for the occurrence of corrosion. Natural gas with a relative humidity less than 100 % is considered non-corrosive [53], however some literature is available in which corrosion problems are described at a relative humidity of 60 – 70 % [54,55]. A relative humidity of 70% is considered critical, as above this relative humidity corrosion becomes rapid [56]. This means that even in conditions with a relative humidity below 100% corrosion can be expected, and a relative humidity above 70 % should be avoided.

5.1.3.2 *Effects of Hydrogen Sulphide*

Carbon steel is susceptible to a variety of degradation mechanisms in environments containing hydrogen sulphide, viz:

- Sulphide Stress Corrosion Cracking (SSCC) [57]
- Hydrogen Induced Cracking (HIC) [57]
- General corrosion

Sulphide Stress Corrosion Cracking (SSCC)

Generally stress corrosion mechanisms in steel are associated with hard zones in the material, caused by cold working (e.g. bending) or welding or with high strength steels. The susceptibility to stress corrosion cracking increases with the H_2S concentration and with increasing acidity of the medium. Based on the pH of the solution and the partial pressure four regimes can be identified with increasing severity of stress corrosion cracking, as is shown in Figure 1. At a partial pressure of H_2S of 3 mbar there is a transition from region 0 (no stress corrosion) to the stress corrosion regions [57,58]. A partial pressure of 3 mbar corresponds with a H_2S concentration of 333 ppm in a 8 bar(g) gas distribution system. At lower gas pressures the transition shifts towards higher concentrations of H_2S, because the partial pressure of H_2S required forms an increasing part of the gas pressure. For high pressure gas transport the transition shifts towards lower concentrations.

For the maximum concentration of H_2S in wide band gas the risk of stress corrosion cracking is low (region 0), so that no stress corrosion cracking is expected.

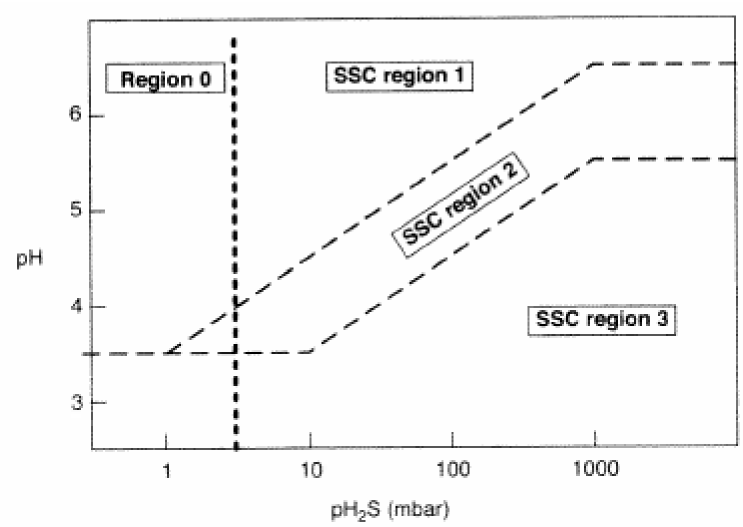

Figure 1. Regimes for stress corrosion cracking mechanisms in sour service [57]

Hydrogen Induced Cracking (HIC)

Hydrogen Induced Cracking usually manifests itself in low-strength steels whereas high-strength steels are susceptible to hydrogen embrittlement. Commonly it is called "(Hydrogen) Blistering".

Similar to SSCC, the source of hydrogen atoms is the corrosion process at the metal surface. The hydrogen atoms penetrate into the steel and diffuse until they encounter a defect, void or inclusion/matrix interface where they can recombine into molecular hydrogen. Imperfectly bonded areas found in laminations or gross inclusions are examples of such defects. Since molecular hydrogen cannot diffuse, it can build up pressure great enough to produce internal cracks. If these cracks are just below the surface, the hydrogen-gas pressure in the cracks can lift up and bulge out the exterior layer of the metal so that it resembles a blister.

A number of cracks parallel to the surface may develop through the wall and the tip of one crack may link up with another in stepwise fashion. This type of cracking is called "Stepwise Cracking". The international standard MR0175 [57] recommends to consider the susceptibility to HIC when evaluating flat-rolled carbon steel products for sour service (wet H_2S containing environment) containing even trace amounts of H_2S.

A specific form of HIC is Stress Oriented Hydrogen Induced Cracking (SO-HIC) which may take place adjacent to welds where triaxial stress states occur.

The probability of HIC is influenced by steel chemistry and manufacturing route. The level of sulphur in the steel is of particular importance. Therefore, the primary measure to prevent HIC is proper selection of the steel followed by testing of the steel batches. The corrosion testing is standardized and described in [57].The secondary measure is selection of the correct operating conditions. In [59] it is stated that the probability of HIC is not enhanced in media with $4.0 < pH < 7.5$ provided that the content of H_2S is below 1000 ppm. However, if $pH < 4.0$ or $pH > 7.5$ the probability of HIC can only be considered ‘not enhanced’ provided that the content of H_2S is below 2 ppm.

This implies that for the existing distribution network we have to consider the probability of HIC dependent on pH and content of H_2S. Most critical condition exists when $pH < 4.0$ or $pH > 7.5$ generating enhanced probability of HIC if the H_2S content exceeds 2 ppm.

General corrosion
As far as general corrosion is concerned iron sulphide (FeS) scales are formed that can decrease the corrosion rate. However, small defects in the FeS scale may cause occurrence of localised corrosion because the scale is cathodic compared to the steel. With the low allowed concentration of 160 ppm H_2S in wide band gases only a limited influence on general corrosion is to be expected, although the risk is higher than for narrow band gasses. Interactions with other gas components may affect the corrosion rate to a great extent as is described in references [1] and [2].

5.1.3.3 *Effects of Ammonia*

Steel is often used for the transport and storage of ammonia. However, at high concentrations ammonia can cause stress cracking in carbon steel. The presence of O_2 or a combination of O_2 and CO_2 is an essential precondition for the occurrence of ammonia stress cracking. Stress cracking due to ammonia is especially found in cold formed or welded materials [58]. The concentration of ammonia found in wide band gases is very low (up to 100 ppm (70 mg/m^3), see chapter 2). Because the concentration is low compared to the conditions where stress corrosion is observed, the effect on steel welds is unknown but is expected to be negligible.

5.1.3.4 *Effects of Hydrogen*

Hydrogen Stress Cracking (HSC) can occur if steel is exposed to H_2, but this only occurs at high stresses in steel types, like high strength steel and in highly stressed materials, e.g. near welds or cold deformation. No serious problems occurred during the town gas period, when concentrations up to 50 % H_2 were transported through steel mains, at low pressures (probably around 30 mbar). In town gas storage tanks operated at pressures of 8 bars, however, HSC has been detected. [60] Furthermore, hydrogen can have an adverse effect on the ductility and fracture toughness of steel. Besides, the fatigue crack growth is accelerated by the presence of hydrogen [61]. This is relevant in case of a crack-like welding defect and fatigue loading that may result from pressure fluctuations or traffic load. Compared to the crack growth rates in air, the largest effect of hydrogen is found for high values for the stress intensity factor (ΔK) as is illustrated in Figure 2 [62].

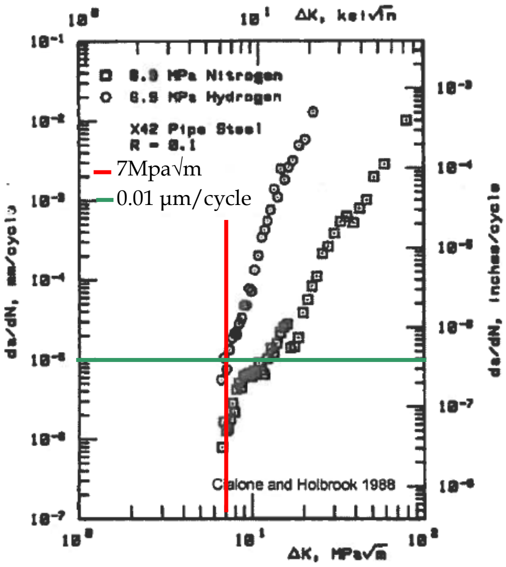

Figure 2: Fatigue crack growth rate (da/dN) as a function of the stress intensity factor (ΔK) for hydrogen and nitrogen for API X42 steel [61]

The presence of oxygen has been shown to reduce the effect of hydrogen on the crack growth rate. In the presence of H_2S the effect of hydrogen on the crack growth rate was observed to increase [62]. An analysis of the stress situation for gas distribution infrastructure was conducted [63]. The results and assumptions of this analysis are summarised in Appendix V. It can be concluded that for loads as applicable to the gas distribution infrastructure the effect of hydrogen on the fatigue crack growth is negligible, irrespective of the concentration of hydrogen. Therefore the foreseen concentrations of H_2 in wide band gas are expected to have no deleterious effects on steel in the gas distribution infrastructure.

5.1.4 Conclusions

For most components in sustainable gases the effect on welded joints is expected to be similar to the effect on steel as base material. However, there are some failure mechanisms for steel gas distribution materials which are specifically related to welding. Stress corrosion mechanisms can be observed in highly stressed regions. Possible causes for high internal stresses in materials are for example cold forming (plastic deformation) and welding. The concentration of H_2S which can be expected in wide band gasses is limited to 160 ppm. The concentration is so low that, given the maximum operational pressure in gas distribution mains, stress corrosion cracking as a result of H_2S is not to be expected.
However, another failure mechanism, viz. HIC may occur in the presence of traces of H_2S in combination with $pH < 4.0$ or $pH > 7.5$. Currently it is unknown whether these pH ranges may occur because the pH results from the presence and amount of a number of possible constituents that may be present in sustainable gases.

The stress intensity factor ΔK, which is a measure for the effect of hydrogen on the material, is influenced highly by defects which are related to welding such as high-low and welding defects such as incomplete penetration, lack of fusion etc. In the analysis of the stress intensity factor in the gas distribution infrastructure it has been found that hardly any effect of hydrogen can be expected.

Corrosion as a result of the interactions between CO_2, H_2S and O_2, is the most likely influence of sustainable gasses on welded joints in the steel gas distribution infrastructure. Factors influencing the sensitivity to corrosion of the weld zone are the heat affected microstructure around the weld, the chemical composition of the welded metal (normally slightly higher alloyed than the base metal). Therefore the exact effect on welded joints is unknown.

These conclusions are summarised in the table below.

Table 7. The effect of components present in sustainable gas on existing welded steel joints. Some components will have no deleterious effect (green) or no or little deleterious effect is expected (light green). Other components may have a deleterious effect (orange).

	Sulphur containing components	H_2S	Mer-captans	Odorant	Ammo-nia	Chloride containing components	Fluoride containing components	HCl	HCN	CO	CO_2	Hydro-carbons	Aromatic hydro-carbons	O_2	H_2
Steel	with water: possibly		probably none			unknown				with water: possibly		probably none		with water: possibly	none

5.2 Threaded Joints in Steel Piping Systems

Due to the geometry of these joint types there is a small space between the thread of the joint and the thread of the pipe. PTFE or in old couplings hemp is used to seal the joint. At these places water may penetrate from outside to inside the pipe due to capillary action. This may cause the formation of a so-called corrosion cell inside the joint, in case of differences in the chemical composition between the joint and the pipe. Because both joint and pipe are made from carbon steel, these differences are small. Therefore no additional effect is expected for threaded joints. The corrosion mechanism is the same as for the pipe material and described in "Effects of Wide Band Gases on Distribution Materials" [2].

5.2.1 Failure mechanism of PTFE

Polytetrafluoroethylene (PTFE) is mostly known under the brand name Teflon. This material is very resistant to all kind of chemicals. It is therefore not expected that any component in sustainable gases will have a negative effect on the PTFE seals in threaded joints.

5.2.2 Failure mechanism of hemp

Hemp used to be the main sealant in threaded joints during the town gas period. The hemp can therefore be categorised as very resistant to the components in town gas. However, when in 1963 the transition from town gas to natural gas occurred [64], the gas became much dryer [65]. The hemp dried out and lost its sealing properties [65].
The transition from natural gas to narrow or wide band gases will at most be equally dry, but more probably (slightly) wetter, due to the difference in water dew point (see chapter 2). Therefore the current transition to sustainable gases is not expected to have a negative effect on the hemp seals used in threaded joints.

5.3 Compression and Press Fittings in Copper Piping Systems

Brass is an alloy of copper and zinc; the proportions of zinc and copper can be varied to create a range of brasses with varying properties. For a better machinability brass fittings are often alloyed with a small quantity of lead.

5.3.1 Failure mechanism of copper and brass joints

The main failure mechanisms for copper and brass joints are: corrosion, stress corrosion cracking and for brass only: dezincification. Corrosion and stress corrosion cracking are discussed in [2].

Prerequisites for corrosion of brass are oxygen and water or moisture. In that case dezincification can occur in which zinc dissolves from brass leaving only a porous copper structure. In general the corrosion resistance of brass will decrease to some extent when the zinc content is increased [66].

From the application of brass in the drinking water distribution it is known that the presence of chloride with high water temperatures could cause dezincification [67]. Alloys containing less than 20 % zinc are not prone to dezincification [68]. When water is present in the gas distribution system, the temperature is low. Therefore the risk of dezincification of brass fittings in the gas distribution is low and will not be investigated further.

Homogeneous corrosion and stress corrosion are described in "Effects of Wide Band Gases on Distribution Materials" [2] and therefore not repeated here. The results are summarised in Table 8.

Table 8. The effect of components present in sustainable gas on newly made welded steel joints. Some components will have no deleterious effect (green) or no or little deleterious effect is expected (light green). Other components may have a deleterious effect (orange).

<table>
<tr><th></th><th>Sulphur containing components</th><th>H_2S</th><th>Mer-captans</th><th>Odorant</th><th>Ammo-nia</th><th>Chloride containing components</th><th>Fluoride containing components</th><th>HCl</th><th>HCN</th><th>CO</th><th>CO_2</th><th>Hydro-carbons</th><th>Aromatic hydro-carbons</th><th>O_2</th><th>H_2</th></tr>
<tr><td>Cu</td><td colspan="3">with water: possibly, depending on their mutual influence</td><td>probably none</td><td>with water: possibly</td><td colspan="3">probably none</td><td colspan="2">unknown</td><td>with water: possibly</td><td colspan="2">probably none</td><td>with water: possibly</td><td>unknown</td></tr>
</table>

B. MAINTENANCE, REPAIR AND EXTENSION METHODS

6 Most Important Maintenance, Repair and Extension Methods

Next to the effect of sustainable gases on the existing joints (part A, chapter 3, 4 and 5), it is also important that sustainable gases do not have a negative impact during maintenance, repair and extension of the gas distribution network. This chapter therefore identifies the most important types of maintenance, repair and extension methods. This also answers sub question d) of section 1.1.

6.1 Maintenance, Repair and Extension Methods in Plastic Piping systems

6.1.1 PVC Piping Systems

There are two maintenance, repair and extension methods widely used for PVC piping systems.

The first is placing a saddle tee on the PVC pipe and subsequently drilling a hole through the pipe. This method is used very often since it is an easy method for gas free working. It is used for connecting service lines to the mains, for placing gas bags and for making a by-pass if a main line has to be taken out of service.

The second is to cut a part of the PVC pipe using a saw, after it has been taken out of service using gas bags or valves, and place a PVC coupler with elastomeric sealing at the new formed end. This is for instance used if the main pipe has to be extended. In fact, it is the same method as used for existing joints, but in this case the PVC coupler has to be placed over a pipe that has been exposed to sustainable gases for some time.

6.1.2 PE Piping Systems

For PE piping systems similar techniques are used for closing the gas flow as for PVC piping systems. A saddle is welded on a PE pipe and a bagging-off balloon for pressures below 1 bar or a line stop for high pressures is used. Sometimes PVC saddles are also used in practice if the pressure is low, but because creep of the PE pipe cannot be prevented with inserts this is not allowed according to the standards.

Another possibility to close the gas flow is squeezing. In this case a PE pipe is placed in a type of vice, which is tightened until the gas flow stops.

For extending the main pipeline mechanical joints and electro fusion joints are used. Similar to PVC the gas flow in the pipeline is stopped first and a part has to be sawed off. Butt fusion is used far less, because the existing pipeline cannot move.

By welding saddles and electro fusion couplers the PE materials are taken to elevated temperatures. These are completely different conditions than those occurring during normal distribution. The effect of components from sustainable gases dissolved in the PE pipe wall on this process could have an adverse effect on the weld quality.

6.2 Maintenance, Repair and Extension Methods in Metal Piping Systems

6.2.1 Steel Piping Systems

Valves and line stops are used for stopping the gas flow in steel piping systems. Line stops are placed using a hot tap. In this case a saddle is welded to the steel pipe, a hole is drilled in the pipe and the line stop is placed.

For extending the steel pipe system, new steel pipes are mechanically joined or welded to the existing pipes.

6.2.2 Copper Piping Systems

Placing gas bags or line stops is not performed on copper pipes, because copper is only used in service lines. The gas flow is always stopped with valves. Reparation or extension is done by cutting the copper pipe and placing a new brass or tin/silver joint.

6.3 Summary

The following maintenance, repair and extension methods are the most important ones.

Plastic piping systems (Chapter 7)

- PVC piping systems – see section 7.1
    - Sawing off and drilling a hole in a PVC pipe
    - Placing a PVC coupler or saddle
- PE piping systems – see section 7.2
    - Sawing off and drilling a hole in a PE pipe
    - Squeezing
    - Placing a mechanical joint
    - Welding a saddle or electro fusion coupler

Metal piping systems (Chapter 8)

- Steel piping systems – see section 8.1
    - Welding a saddle to the outside of a steel pipe
    - Drilling a hole in the steel pipe
    - Placing a mechanical joint
    - Welding an existing steel pipe to a new steel pipe
- Copper piping systems – see section 8.2
    - Cutting a copper pipe
    - Placing a new brass joint or tin/silver joint

7 Effects during Maintenance, Repair or Extension Methods on Plastic Piping Systems

In this chapter the effect of sustainable gases on the maintenance, repair or extension methods in plastic piping systems are described (see section 6.1). The joints that are discussed in this chapter are:

- PVC piping systems
    - Sawing off and drilling a hole in a PVC pipe
    - Placing a PVC coupler or saddle
- PE piping systems
    - Sawing off and drilling a hole in a PE pipe
    - Squeezing
    - Placing a mechanical joint
    - Welding a saddle or electro fusion coupler

7.1 PVC Piping Systems

7.1.1 Failure Mechanisms

Sawing off or drilling a hole in a PVC pipe will become more difficult if the PVC becomes more brittle. The effects of components in sustainable gases on the embrittlement of PVC are already discussed in "Effects of Wide Band Gases on Distribution Materials" [2] with respect to impact loadings. This failure mechanism is therefore not repeated here.

For placing a PVC coupler or saddle on the existing PVC pipe it is important that the dimensions are within the original range. Absorption of gases could alter this property of the PVC pipe.

7.1.2 The Absorption of Sustainable Gases in PVC

7.1.2.1 Effects of Aromatics and Aliphatics

It is already many decades known that PVC can absorb benzene and will swell and increase in weight [69]. After six weeks of exposure to a condensate[*] the weight increased 9 % [70]. Two weeks exposure to a mixture of petroleum-ether-benzene increased the weight with 0.9 % [69]. This is much less than PE (14.7 %).

The equilibrium sorption is a function of the interaction between the small penetrating molecules and the polymer chains. Small molecules, a strong affinity and high polymer mobility result in a high sorption. The local stress is of importance as well. A higher tensile stress in the vicinity of inhomogeneities results in a higher sorption. [71]

Aliphatics have a low interaction with the polymer chains and will fill the free space between PVC molecules. Aromatics have a stronger interaction and penetrate between the PVC molecules [72]. The latter process goes faster and is found to be non-Fickian. This means that the diffusion coefficient of benzene in PVC exceeds that of n-hexane in PVC, but the diffusion coefficient is also dependant on the concentration of the absorbed liquid. [73]
It is also found for n-octane that swelling of the surface influences the absorption rate [73].

To conclude, literature reports about the swelling of PVC caused by the absorption of liquid aromatics and aliphatics, but the change in dimensions due to the absorption of gaseous

[*] Unsaturated hydrocarbons 26 %, Aromatics 56 %, Naphthenes 14 %, Paraffins 4 %

components is unknown. On the other hand, it is known from experience that the existing PVC gas distribution network has virtually no problems with swelling, while G-gas has the highest (known) concentration of (aromatic) hydrocarbons of all sustainable gases. The effect of 'new' hydrocarbons, for instance terpenes (e.g. limonene), is expected to be comparable, but this still has to be confirmed. It is therefore not expected that gaseous hydrocarbon components in sustainable band gas will have an adverse effect on the dimensions of PVC.
It should be noted however that the required water dew point for wide band gas is different than that for G-gas or even absent (see chapter 2). Due to this difference with G-gas the risk of condensation of not only water, but all components that can condensate, in wide band gas may be higher than that of G-gas. This includes (aromatic) hydrocarbons.

7.1.2.2 *Effects of CO_2*

CO2 is considerably more soluble than methane or inert gases like He, N_2 and Ar [74]. However, it is unknown how this will influence the dimensions.

7.1.2.3 *Effects of Chlorine and Fluorine Containing Components*

It is known that some organic chlorides can dissolve PVC. For instance dichloromethane is specifically used for dissolving PVC in the dichloromethane test (DCMT) as described in ISO 9852 [75]. From experience it is known that PVC will not only dissolve, but also swell will occur. The impact of chlorine and fluorine containing components in sustainable gases on the dimensions of a PVC pipe is unknown.

7.1.2.4 *Effects of Other Components*

Practically no literature about the effect on dimensions of other components present in sustainable gases was found. It is expected that low concentration components, such as HCl and HCN, will have a negligible effect on the dimensions of a PVC pipe.

From experience it is known that the odorant in G-gas does not cause any dimensional changes in the PVC and it is expected that mercaptanes will affect PVC in the same manner as odorant does.

7.1.3 *Conclusions*

It is known that aromatics, aliphatics, CO_2 and chlorine and fluorine containing components may cause swelling of the PVC. The effect of gaseous aromatics and aliphatics is known from experience to be of no significance. However, the effect of CO_2 and chlorine and fluorine containing components on the dimensions is unknown. It is expected that components such as odorant, HCl and HCN will have a negligible effect on the dimensions of a PVC pipe. These conclusions are summarised in the table below.
Also, the conclusions from [2] about the possible embrittlement (*emb*) are summarised in this table.

Table 9. The effect of components present in sustainable gases on the embrittlement (emb) and change in dimensions (dim) of PVC. Some components will have no deleterious effect (green) or no or little deleterious effect is expected (light green). The effect of other components is unknown (light orange) or a deleterious effect may be present (orange).

<table>
<tr><th></th><th>Sulphur containing components</th><th>H_2S</th><th>Mer-captans</th><th>Odorant</th><th>Ammo-nia</th><th>Chloride containing components</th><th>Fluoride containing components</th><th>HCl</th><th>HCN</th><th>CO</th><th>CO_2</th><th>Hydro-carbons</th><th>Aromatic hydro-carbons</th><th>O_2</th><th>H_2</th></tr>
<tr><td>PVC (emb)</td><td colspan="2">unknown</td><td colspan="2">probably none</td><td colspan="3">unknown</td><td colspan="2">probably none</td><td>unknown</td><td>possibly</td><td colspan="2">none, unless liquid (impact resistance)</td><td>probably none</td><td>unknown</td></tr>
<tr><td>PVC (dim)</td><td colspan="2">unknown</td><td colspan="2">probably none</td><td>un-known</td><td colspan="2">possibly</td><td colspan="2">probably none</td><td>unknown</td><td>possibly</td><td colspan="2">none, unless liquid</td><td colspan="2">unknown</td></tr>
</table>

7.2 PE Piping Systems

7.2.1 *Failure Mechanisms*

Sawing off or drilling a hole in a PE pipe will become more difficult if the PE becomes more brittle. However, PE is a very ductile material and this failure mechanism (embrittlement) is not expected for PE.

When PE pipes are squeezed, small cracks can develop. The resistance against slow crack growth (SCG) will therefore become the main failure mechanism. This failure mechanism is already discussed in "Effects of Wide Band Gases on Distribution Materials" [2] and is therefore not repeated here.

For placing a mechanical joint on the existing PE pipe it is important that the dimensions are within the original range. Absorption of gases could alter this property of the PE pipe. Moreover, absorbed gases could form bubbles in PE when it is taken to elevated temperatures for heat fusion of a saddle or electro fusion coupler.

7.2.2 *The Absorption of Sustainable Gases in PE*

7.2.2.1 *Effects of Aromatics and Aliphatics*

It is well known that PE will soften and weaken when it comes in contact with liquid aromatic hydrocarbons (including BTX) and/or liquid higher hydrocarbons [69,70]. PE can absorb about 7 wt.% of natural gas condensate [76] (the composition is given in Appendix III).

Heat fusion joining between pipes after adsorption of liquid hydrocarbons can be affected. The presence of adsorbed liquid hydrocarbons in the pipe wall can result in low-strength heat fusion joining because the adsorbed hydrocarbons will liquefy and then vaporize when heated and reduce or prevent melt fusion. Hydrocarbon contamination is usually identified by a bubbly or pockmarked melt appearance upon heater plate removal. [37]

To conclude literature reports about the absorption of liquid aromatics and aliphatics in PE, but any quantitative effect on dimensions and heat fusion due to absorption of gaseous components is unknown. On the other hand, it is known from experience that the existing PE gas distribution network has virtually no problems with swelling, while G-gas has the highest (known) concentration of (aromatic) hydrocarbons of all sustainable gases. The effect of 'new' hydrocarbons, for instance limonene, is expected to be comparable, but this still has to be confirmed. It is therefore not expected that gaseous hydrocarbon components in sustainable band gas will have an adverse effect on the dimensions or the heat fusion of PE.
It should be noted however that the required water dew point for wide band gas is different than that for G-gas or the requirement for the water dew point is even absent (see chapter 2). Due to this difference with G-gas the risk of condensation of not only water, but all components that can condensate, in wide band gas may be higher than that of G-gas. This includes (aromatic) hydrocarbons.

7.2.2.2 *Carbon Monoxide and Carbon Dioxide*

It is known from experiments at Kiwa Technology that the permeation rate of CO_2 is higher compared to CH_4 in PE pipes. This is mainly caused by the fact that the solubility of CO_2 is higher. Therefore, more CO_2 can be absorbed by the PE. The effect of CO is expected to be the same, because of the molecular structure. Nevertheless, the effect of these gases in combination with fusion of PE is yet unknown.

7.2.2.3 *Siloxanes*

It is well known that silicon-components (e.g. silicon grease) have a negative impact on the welding performance of PE segments. Silicon grease is normally not found in sustainable gases, but is used by the constructer for lubrication purposes.

In sustainable gases the presence of siloxanes can occur. These silicon containing components could therefore have a negative impact. Although for electro fusion it is necessary to scrape the outer layer of the pipe (mainly for oxidation purposes) it is possible that absorbed siloxanes affect the welding quality. Another possibility is that the cloth used by the welder to clean the outer surface of the pipe comes also in contact with the interior of the pipe, thus transferring siloxanes to the welding surface.

An overview of the siloxanes present in sustainable gases is given in Appendix IV.

7.2.2.4 *Effects of Other Components*

Practically no literature about the effect on dimensions or heat fusion of other components present in sustainable gases was found. It is expected that components of a low concentration, such as HCl and HCN, will have a negligible effect on the dimensions and heat fusion of a PE pipe.

From experience it is known that the odorant in G-gas does not cause any dimensional changes in the PE nor gives rise to any problems during heat fusion. It is expected that mercaptanes will affect PE in the same manner as the odorant does.
Also because welding in air can be performed without any problems, no effect of oxygen is expected.

7.2.3 *Conclusions*

It is known that aromatics, aliphatics and CO_2 may be absorbed by PE. The effect of gaseous aromatics and aliphatics is known from experience to be of no significance. However, the effect of CO_2 on the dimensions and heat fusion is unknown. CO is expected to have the same effect as CO_2. It is expected that components such as odorant, HCl and HCN will have a negligible effect on the dimensions and heat fusion of a PE pipe. These conclusions are summarised in the table below.
Also, the conclusions from [2] about the possible slow crack growth (*scg*) are summarised in this table.

Table 10. The effect of components present in sustainable gases on the slow crack growth (scg) and dimensions or heat fusion (abs) of PE. Some components will have no deleterious effect (green) or no or little deleterious effect is expected (light green). The effect of other components is unknown (light orange) or a deleterious effect may be present (orange).

<table>
<tr><th></th><th>Silo-xanes</th><th>Sulphur containing components</th><th>H_2S</th><th>Mer-captans</th><th>Odorant</th><th>Ammo-nia</th><th>Chloride containing components</th><th>Fluoride containing components</th><th>HCl</th><th>HCN</th><th>CO</th><th>CO_2</th><th>Hydro-carbons</th><th>Aromatic hydro-carbons</th><th>O_2</th><th>H_2</th></tr>
<tr><td>PE (scg)</td><td>probably none</td><td colspan="2">unknown</td><td colspan="2">probably none</td><td colspan="3">unknown</td><td colspan="2">probably none</td><td>unknown</td><td>none</td><td colspan="2">none, unless liquid</td><td>none</td><td>probably none</td></tr>
<tr><td>PE (abs)</td><td>possibly</td><td colspan="2">unknown</td><td colspan="2">probably none</td><td colspan="3">unknown</td><td colspan="2">probably none</td><td colspan="2">possibly</td><td colspan="2">none, unless liquid</td><td>none</td><td>unknown</td></tr>
</table>

8 Effects during Maintenance, Repair or Extension Methods on Metal Piping Systems

In this chapter the effects of sustainable gases on the most used maintenance, repair or extension methods in metal piping systems are described (see section 6.2). The joints that are discussed in this chapter are:

- Steel piping systems
    - Welding a saddle to the outside of a steel pipe
    - Drilling a hole in the steel pipe
    - Placing a mechanical joint
    - Welding an existing steel pipe to a new steel pipe
- Copper piping systems
    - Cutting a copper pipe
    - Placing a new brass joint or tin/silver joint

8.1 Steel Piping Systems

8.1.1 Failure Mechanisms

The influence of the various constituents that may be present in sustainable gases can be distinguished in effects related to the surface of equipment parts, such as corrosion, and effects related to the bulk material.

Surface related effects consist of wall thinning or adhesion of certain constituents.
Wall thinning can be restored by welding or replacement implying that wall thinning is no obstacle to welding. Adhesive constituents can be removed mechanically (such as grinding) or by cleaning. Although sustainable gases can be chemically or physically bond to the metal surface it is not expected that these attached molecules would have a negative impact on the quality of the weld. Due to the fact that the surface before welding is ground to remove corrosion products and to create a proper weld end preparation, most of the attached sustainable gases are removed. During welding of the steel pipes the temperature (~1200 °C) that is needed for welding is so high that all the gases will "evaporate" together with the gases coming from the projecting sheath. This implies that all surface related effects are not hampering the welding process provided that proper preparation of the welding area / bevel is conducted.

The effects on the bulk material may be caused by the presence of certain atomic elements which have been diffused during the operation period. The available elements are sulphur, hydrogen, carbon, nitrogen and oxygen. Due to these elements, we could consider the possibility of chemical attack (e.g. sulphidation, carburisation, nitriding, oxidation) from a theoretical point of view. However, this is not relevant for gas distribution lines because these chemical attack mechanisms take place at high temperatures. Only the element hydrogen has to be considered in more detail because this element may affect the bulk material at ambient temperatures.

8.1.2 The Influence of Hydrogen on welding of Steel

Hydrogen may originate from three different sources, viz:

- A corrosion process
- Hydrogen gas as constituent in a gas mixture
- Welding process

8.1.2.1 *Effects of Hydrogen originating from a Corrosion Process*

Corrosion may occur due to H_2S and CO_2 accelerated by the presence of chloride, ammonium or cyanide.
In case of hydrogen resulting from a corrosion process, the hydrogen may cause hydrogen embrittlement or HIC (Hydrogen Induced Cracking). Obviously, the accompanying microcracks or delaminations have a negative effect on the materials capability to withstand the internal stresses which are generated as result from welding. So, in case corrosion has taken place, inspection should be conducted to check whether cracks or delaminations are present before welding can be conducted. As long as no microcracks and delaminations can be found in case that corrosion has taken place or no corrosion has occurred at all, it can be concluded that no detrimental effect has taken place.

8.1.2.2 *Effects of Hydrogen originating from Hydrogen Gas or the Welding Process*

It is well known that hydrogen can easily migrate into the crystal structure of steel causing 'hydrogen embrittlement' if the microstructure is ferritic / bainitic / martensitic. In welded joints, hydrogen is introduced during the welding process originating from a number of sources, viz. welding consumables, moisture in the air and inadequate cleaning procedure of the welding groove. The resulting cracking mechanism is called 'cold cracking'.

It is important to understand that a major difference exists between the amount of hydrogen from exposure in hydrogen gas mixtures and the amount of hydrogen from welding processes. According to Sieverts law, the amount of diffusible hydrogen in steel at room temperature is about 0.002 ppm as result from exposure to hydrogen gas (60 bar), although hydrogen content may increase at interfaces related to inclusions and crack tips. Unfortunately, no values are available of the amount at such interfaces. The amount of hydrogen from the welding process is much higher, in the range of 2 – 10 ppm (dependent on the electrode type) in case of regular (non-humid) conditions whereas the high temperature during welding promotes the solubility of hydrogen significantly. After welding the hydrogen is present in supersaturated condition because the cooling rate after welding is high. This implies that the welding process generates a much higher amount of hydrogen than the diffusible hydrogen that originates from a hydrogen gas at 60 bar.

From the above reasoning no effect on the susceptibility to 'cold cracking' is expected from previous exposure in a hydrogen gas atmosphere. This has been confirmed by testing dedicated to 'cold cracking' in the Naturalhy programme [77]. From this testing programme, it can be concluded that no additional measures are needed to prevent 'cold cracking' during welding of steel that has been in service in hydrogen gas pressurised. This conclusion is valid for steel with carbon content up to 0.21 % and carbon equivalent up to 0.45 %, a wall thickness up to 12 mm and a hydrogen pressure up to 60 bar.
It can be concluded that the susceptibility to 'cold cracking' is not changed relative to welding of new material.

8.1.3 *Conclusion*

Welding of steel pipes which have been in service in hydrogen containing gas mixtures, is not affected implying the standard welding procedures can be followed.
The only measures to be taken are:

1. proper cleaning of the welding area / bevel to remove possible adhesive constituents.
2. in case corrosion has taken place, inspection of the welding area / bevel should be conducted to check whether cracks or delaminations are present before welding can be conducted.

Table 11. The effect of components present in sustainable gas on newly made welded steel joints. Some components will have no deleterious effect (green) or no or little deleterious effect is expected (light green). Other components may have a deleterious effect (orange).

	Sulphur containing components	H_2S	Mer-captans	Odorant	Ammo-nia	Chloride containing components	Fluoride containing components	HCl	HCN	CO	CO_2	Hydro-carbons	Aromatic hydro-carbons	O_2	H_2
Steel	with water: possibly		probably none			unknown				with water: possibly		probably none		with water: possibly	probably none

8.2 Copper Piping Systems

8.2.1 *Failure Mechanisms*

The influence of the various constituents that may be present in sustainable gases can be distinguished in effects related to the surface of components, such as corrosion, and effects related to the bulk material. Surface related effects consist of wall thinning or adhesion of certain constituents. Insufficient wall thickness of the pipe may lower the strength of a joint with press or compression fittings and hamper cutting of a copper pipe. As long as no significant wall thinning as a result of corrosion is observed no problems are expected when mounting compression fittings. Insufficient wall thickness may also cause problems in soldering or brazing new joints in existing pipelines.

Homogeneous corrosion and stress corrosion are described in "Effects of Wide Band Gases on Distribution Materials" [2] and therefore not repeated here. The results are summarised in Table 12.

Table 12. The effect of components present in sustainable gas on newly made welded steel joints. Some components will have no deleterious effect (green) or no or little deleterious effect is expected (light green). Other components may have a deleterious effect (orange).

	Sulphur containing components	H_2S	Mer-captans	Odorant	Ammo-nia	Chloride containing components	Fluoride containing components	HCl	HCN	CO	CO_2	Hydro-carbons	Aromatic hydro-carbons	O_2	H_2
Cu	with water: possibly, depending on their mutual influence			probably none	with water: possibly	probably none			unknown		with water: possibly	probably none		with water: possibly	unknown

9 Conclusions

All the results of this literature review are summarised in the table on the next page.

The following main conclusions can be drawn from this literature review:

- Existing PVC couplers with an elastomeric seal will probably not be affected by mercaptans, odorant, HCl, HCN and oxygen. However, CO_2 may have an influence on the impact resistance of the PVC body, because CO_2 has a plasticizing effect on PVC. For the same reason it may also cause a faster initiation of crazes and thus possibly negatively affect the long-term strength. CO_2 has no deleterious effect on the elastomeric sealing rings. On the other hand, the elastomeric sealing rings may negatively be affected by H_2S and halogenated components, while the effect on the PVC body is unknown. SBR will possibly be negatively affected by (aromatic) hydrocarbons. The effect of sulphur containing components is unknown for PVC, NBR and SBR. Experiments are therefore needed to determine the allowable concentration levels of these components.

- The effects of sustainable gases on existing solidified PE in thermal fused joints is expected to be comparable to the effect of sustainable gases on PE pipe material. Gases like nitrogen (N_2), oxygen (O_2) and carbon dioxide (CO_2) will have no deleterious effect on PE. It is expected for mercaptanes, odorant, HCl, HCN and H_2 that the effects, if there are any, will be rather small. It is unknown what kind of long-term effects other components, such as sulphur, H_2S, ammonia, chlorine and fluorine containing compounds and CO, will have on PE.

- Free chlorine causes oxidation of POM. It is unknown if the concentration of hydrochloride in sustainable gases is enough to cause any adverse effect. POM may be vulnerable to low concentrations of ammonium vapours in sustainable gases. An adverse effect of odorant, mercaptanes and (aromatic) hydrocarbons (including BTX) is not expected. Little is known about the effect of other components in sustainable gases than those already mentioned.

- For most components in sustainable gases the effect on welded steel joints is expected to be similar to the effect on steel as base material. Hydrogen Induced Cracking (HIC) may occur in the presence of traces of H_2S in combination with $pH < 4.0$ or $pH > 7.5$. In the analysis of the stress intensity factor in the gas distribution infrastructure it has been found that hardly any effect of hydrogen, causing Hydrogen Stress Cracking (HSC), can be expected. Corrosion as a result of the interactions between CO_2, H_2S and O_2, is the most likely influence of sustainable gasses on welded joints in the steel gas distribution infrastructure. Factors influencing the sensitivity to corrosion of the weld zone are the heat affected microstructure around the weld, the chemical composition of the welded metal (normally slightly higher alloyed than the base metal). Therefore the exact effect on welded joints is unknown. Additional experiments are therefore needed.

- It is not expected that any component in sustainable gases will have a negative effect on threaded joints in steel piping systems containing PTFE (Teflon) or hemp.

- Water is the most important factor in the corrosion of copper. This is important for the already existing joints, as for compression fittings that will be placed for maintenance or repair. With water present corrosion is affected mainly by the concentrations of oxygen, carbon dioxide, sulphur containing components and ammonia. On the basis of the literature review effects of the other components in sustainable gases on the corrosion of copper cannot be predicted. The risk of dezincification of brass fittings in the gas distribution is low.

- For maintenance, repair or extension methods, PVC pipes probably will not become brittle and the dimensions will remain within the original range. Absorption of gases could alter this property of the PVC pipe. It is known that aromatics, aliphatics, CO_2 and chlorine and fluorine containing components may cause swelling of the PVC. The effect of gaseous aromatics and aliphatics is known from experience to be of no significance. However, the effect of CO_2 and chlorine and fluorine containing components on the dimensions is still unknown. CO_2 has an influence on the embrittlement of PVC. It is expected that components such as odorant, HCl and HCN will have a negligible effect on the maintenance, repair or extension of a PVC pipe.

- Components in sustainable gases probably will not decrease the resistance against slow crack growth so that squeezing a PE pipe remains possible. For placing a mechanical joint on the existing PE pipe it is important that the dimensions are within the original range. It is known that aromatics, aliphatics and CO_2 may be absorbed by PE. The effect of gaseous aromatics and aliphatics is known from experience to be of no significance. However, the effect of CO_2 on the dimensions and heat fusion is still unknown. CO is expected to have the same effect as CO_2. Siloxanes, adhered to the internal pipe wall, may contaminate the welding surface. This will have a negative impact on the welding performances. It is expected that components such as odorant, HCl and HCN will have a negligible effect on the dimensions and heat fusion of a PE pipe.

- Welding of steel pipes which have been in service in sustainable gases, is not affected implying the standard welding procedures can be followed. The only measures to be taken are:
  1) proper cleaning of the welding area / bevel to remove possible adhesive constituents.
  2) in case corrosion has taken place, inspection of the welding area / bevel should be conducted to check whether cracks or delaminations are present before welding can be conducted.

- All the results are summarised in the table on the next page.

Existing joints

Joint	Material	Sulphur containing components	H_2S	Mer-captans	Odorant	Ammo-nia	Chloride containing components	Fluoride containing components	HCl	HCN	CO	CO_2	Hydro-carbons	Aromatic hydro-carbons	O_2	H_2
Coupler body material	PVC	unknown		probably none		unknown			probably none		unknown	possibly	none, unless liquid (impact resistance)		probably none	unknown
	POM	unknown		probably none		possibly				unknown			probably none		unknown	
Coupler sealing ring	NBR	unknown	possibly	probably none		none	possibly		probably none		none		probably none, unless liquid		none	
	SBR	unknown	possibly	probably none		none	possibly		probably none		none		possibly		probably none	none
Electro fusion and butt fusion	PE	unknown		probably none		unknown			probably none		unknown	none	none, unless liquid		none	probably none
Welded	Steel	with water: possibly		probably none			unknown				with water: possibly		probably none		with water: possibly	none
Press and compression	Cu	with water: possibly, depending on their mutual influence			probably none	with water: possibly	probably none			unknown		with water: possibly	probably none		with water: possibly	unknown

Maintenance, repair and extension methods

Joint	Material	Sulphur containing components	H_2S	Mer-captans	Odorant	Ammo-nia	Chloride containing components	Fluoride containing components	HCl	HCN	CO	CO_2	Hydro-carbons	Aromatic hydro-carbons	O_2	H_2
Coupler and pipe	PVC	unknown		probably none		un-known	possibly		probably none		unknown	possibly	none, unless liquid		unknown	
Electro fusion and butt fusion	PE	unknown		probably none		unknown			probably none		possibly		none, unless liquid		none	unknown
Welded	Steel	with water: possibly		probably none			unknown				with water: possibly		probably none		with water: possibly	probably none
Press and compression	Cu	with water: possibly, depending on their mutual influence			probably none	with water: possibly	probably none			unknown		with water: possibly	probably none		with water: possibly	unknown

	=	The effect is unknown, but is expected to be very small or non existent.
	=	This component within the concentrations of narrow band has no effect on the material.
	=	The effect is unknown.
	=	Deleterious effects are under some conditions to be expected.

I. Gas composition of different anaerobic digestion installations

Biogas	CH_4 (mol%)	CO_2 (mol%)	O_2 (mol%)	N_2 (mol%)	H_2S (ppm)	Benzene (mg/m3)	Toluene (mg/m3)	Hydrogen (mg/m3)	Ammonia (mg/m3)	Silicon components (mg/m3)	Other traces	Reference
Landfill	47 – 57	37 - 41	< 1	< 1 - 17	36 - 115	0.6 - 2.3	1.7 - 5.1					[78]
Sewage Digester	61 – 65	36 - 38	< 1	< 2	n.a.	0.1 - 0.3	2.8 - 11.8					
Farm biogas Plant	55- 58	37 - 38	< 1	< 1 - 2	32 - 169	0.7 - 1.3	0.2 - 0.7					
Landfill	59 – 68	30 - 39	n.a.	n.a.	15 - 428	21.7 - 35.6	83.3 - 171.6					
Landfill	37 - 62	24 - 29	< 1	n.a.	n.a.	<0.1-7	10 - 287					
Landfill	56	37	< 1	n.a.	n.a.	3.0	55.7					
Landfill	44	40	2.6	13.2	250	n.a.	65.9					
Sewage digester	58	39	0	3.7	63	n.a.	n.a.					
Sewage digester	63	37	n.a.	n.a.	n.a.	n.a.	n.a.					
Sewage digester	58	34	0	8.1	24	n.a.	n.a.					
Farm biogas plant (manure 33%, Crops 67%)	53.13	42.32	0.1	4.42	0.03				Traces	Traces	• Halogen components • Phosphine	[79][80]
Farm biogas plant (manure 50%, Crops 50%)	51.54	43.82	0.1	4.54	< 0.01				Traces	Traces	• Halogen components • Phosphine	
Farm biogas plant (Manure 100%)	62.84	34.86	0.05	3.57	0.04				Traces	Traces	• Halogen components • Phosphine	
Farm biogas plant (Manure 75%, Crops 25%)	57.46	37.99	0.09	4.46	< 0.01				Traces	Traces	• Halogen components • Phosphine	
Sewage Digester	61.94	37.86	0.04	0.49	-							

Biogas	CH_4 (mol%)	CO_2 (mol%)	O_2 (mol%)	N_2 (mol%)	H_2S (ppm)	Benzene (mg/m3)	Toluene (mg/m3)	Hydrogen (mg/m3)	Ammonia (mg/m3)	Silicon components (mg/m3)	Other traces	Reference
Mixture of 12 farm biogas plants	60.42	35.5	0.74	3.08	3085	traces	Traces		0.004	Not detected	• Pesticides • Volatile organic compounds • Cupper • Mercury	[81]
Farm biogas plant (manure 100%)	40 - 57	32 - 58	0.75 - 2.5		0 - 1100 mg/m3			0	Traces, max 70 mg/m^3	Traces, max 25 mg/m^3	• Halogen components • Aromatics • Volatile organic compounds	[82]
Farm biogas plant (Crops 100%)	45 - 64	33 - 51	0 - 9		0 - 450 mg/m3			0 - 190	Traces, max 70 mg/m^3	Traces, max 25 mg/m^3		
Farm biogas plant (manure 50%, Crops 50%)	47 - 54	43 - 52			150 - 800 mg/m3			0	Traces, max 70 mg/m^3	Traces, max 25 mg/m^3	• Halogen components • Aromatics • Volatile organic compounds	
Sewage Digester	63 - 67		0 - 1		0-50 mg/m3					0 - 500		

II. Halogen containing components

Component	Max. concentration ppbv	µg/m³	Reference	Component	Max. concentration ppbv	µg /m³	Reference
1,1,1-Trichloroethane		0.05	[83-85]	Chloroethane	973		[85], [86]
1,1,2-Trichloroethane		0.08	[83]	Chlorofluoromethane			[85]
1,1-Dichloroethane	113	0.01	[83], [85], [86]	Chloroform		0.16	[83], [86]
1,1-Dichloroethene	149	0.37	[83], [85], [86]	Chloromethane	1070		[86]
1,2-Dichlorobenzene		0.08	[83]	Dichlorodifluoromethane	10200		[85]-[87]
1,2-Dichloroethane	13	1.22	[83], [84], [86]	Dichloroethylene			[86]
1,2-Dichloroethene	54	0.11	[83], [85]	Dichlorofluoromethane			[85]
1,3-Dichlorobenzene		0.01	[83]	Dichlorotoluene			[87]
1,3-Dichloropropene		0.07	[83]	Ethyl chloride			[84]
1,3-Dichloropropylene	323	0.09	[86]	m-Dichlorobenzene			[87]
1,4-Dichlorobenzene		0.4	[83]	Methylene chloride	66	7.95	[83]-[87]
1-Chloro-1-fluoroethane			[84]	o-Dichlorobenzene			[87]
1-Chloropropane			[84]	p-Dichlorobenzene			[87]
Benzyl chloride			[87]	Tetrachloroethane		9.16	[83]
Bromobenzene	31		[86]	Tetrachloroethylene	68		[83]-[86]
Bromoform	100		[86]	Trichloroethene	34	62.91	[83], [85], [86]
Bromomethane	319		[86]	Trichlorofluoromethane	270		[85], [86]
Carbon tetrachloride	82	0.23	[83], [85], [86]	Trichlorotrifluoroethane	23		[85], [86]
Chlorobenzene	339	0.12	[86], [87]	Vinyl chloride	800		[86], [87]
Chlorodifluoromethane			[85]				

Blank cell = traces have been found

III. Composition of a Natural Gas Condensate

Table 13. Composition of a G-gas natural gas condensate [29].

Component	Quantity (%)
n-decane	12.9
n-undecane	9.6
n-nonane	8.1
xylenes	6.5
cumarone (coumarone)	5.8
toluene	5.0
n-octane	4.2
n-dodecane	3.8
mesithylene	3.4
benzene	2.6
n-tridecane	2.5
n-heptane	1.8
n-tetradecane	1.5
cyclo-hexane	1.1
n-hexane	0.7
n-pentadecane	0.6
iso-heptanes	0.4
n-pentane	0.3
2.3 dimethyl-butane	0.3
2.2 dimethyl-butane	0.2
iso-pentane	0.18
neo-pentane	0.14
n-hexadecane	0.1
n-butane	0.05
iso-butane	0.03
n-heptadecane	0.02

Please note that the table above only contains the components that are measurable with a gas chromatograph. It is known from infrared spectroscopy measurements at Kiwa Technology that the following aromatic components can occur in G-gas natural gas condensate as well:

- alkylbenzene
- cumene
- 1,2,4 trimethylbenzene
- naphthalene
- p-cymene

IV. Organo-silicon components

Biogas	(L1)	(L2)	(D3)	(L3)	(D4)	(L4)	(D5)	Reference
				Maximum concentration (mg/m³)				
Landfill	n.d.	6.07	0.49	0.32	12.53	n.d.	4.73	[88]
	3.2	0.9	0.44	n.d.	5.1	n.d.	0.65	[89]
	7.43	1.31	0.01	0.05	8.84	<0.01	1.09	[90]
	3.21	0.77	0.45	0.04	5.03	< 0.01	0.53	[90]
	12.0	5.0	0.84	n.d.	15.0	<0.1	3.3	[91]
	n.d.	0.87	0.088	n.d.	2.06	n.d.	47	[92]
	n.d.	0.14	0.083	n.d.	1.21	n.d.	0.40	[92]
	n.d.	0.12	0.81	n.d.	2.0	n.d.	3.33	[92]
	n.d.	0.23	-	n.d.	5.03	n.d.	0.83	[92]
	0.56	0.63	<0.1	< 0.01	< 0.67	n.d.	<0.3	[93]
	0.2	<0.2	<0.2	0.2	1.5	<0.2	22.3	[94]
Sewage sludge	n.d.	0.02	0.04	0.02	0.93	n.d.	6.03	[88]
	n.d.	0.08	0.42	n.d.	8.2	n.d.	15.5	[89]
	n.d.	<0.05	0.35	n.d.	7.7	n.d.	12.0	[89]
	0.15	0.05	0.17	0.03	6.98	0.15	9.65	[90]
	0.08	0.01	0.2	0.02	3.02	0.02	2.81	[90]
	0.07	0.008	<0.04	<0.2	0.87	<0.04	1.27	[93]
Max	**12.0**	**1.31**	**0.84**	**0.32**	**15.0**	**0.15**	**47**	

n.d. = not detected
\- = not analyzed

L1 = Trimethyl silanol
L2 = Hexamethyldisiloxane
D3 = Hexamethylcyclotrisiloxane
L3 = Octamethyltrisiloxane
D4 = Octamethylcyclotetrasiloxane
L4 = Decamethyltetrasiloxane
D5 = Decamethylcyclopentasiloxane

V. Analysis of the Stress State of the Steel Pipes in the Gas Distribution Infrastructure

The stress state in steel gas distribution pipes has been determined as well for longitudinal as for circumferential welds based on the following basic information and assumptions [63].

Basic information and assumptions

- Tube diameter: 60, 100, 200, 300, 400 and 500 mm
- Wall thickness: 3-20 mm
- Maximum difference in gas pressure 6 bar(g) (minimum pressure of 2 bar(g) in 8 bar(g) network)
- Traffic load (lorry, 30 tons, speed 50 km/h): 20 MPa
- Traffic load (lorry, 30 tons, speed 15 km/h, speed ramp): 40 MPa
- Out of roundness of the tube (peaking longitudinal welds): max 2%
- High-low in circumferential welds: 2 mm

To be able to calculate the stress intensity factor (ΔK) the following defect has been assumed, with:

- a = 0.25t
- 2C = 6a = 3t

(see Figure 3)

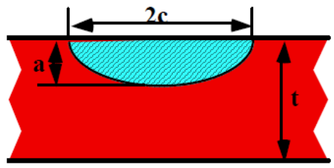

Figure 3. Assumed defect for calculation of the stress intensity factor.

The following loading frequencies have been assumed:

Source of load	Frequency [Hz]
Internal pressure changes	4×10^{-5}
Traffic (speed hump, 15 km/h)	1
Traffic (50 km/h)	10

Calculations

The stress intensity factor (ΔK) for different stress states has been calculated using the software program Signal as described in [63]. The above mentioned basic information and assumptions have been used.

Results

Source of load	Stress Intensity Factor, ΔK [MPa√m]
Internal pressure changes	1 – 2
Internal pressure with out of roundness in tube	1 – 2
Internal pressure with peaking at weld	4 – 9
Internal pressure with high-low at weld	1 – 9
Traffic loading	1,5 -3,5

Conclusion
The maximum allowable stress intensity factor of 7 MPa√m is defined. At this stress intensity factor the fatigue crack growth rate for hydrogen loaded material reaches the value of 0.01 µm/cycle, as can be seen from Figure 4. This crack growth rate is considered acceptable because it corresponds to the lower bound crack growth data from BS7910 [95] for environments without hydrogen.
From comparison between the calculated stress intensity factors for the given service conditions and the value of 7 MPa√m it can be concluded that the influence of hydrogen is negligible.

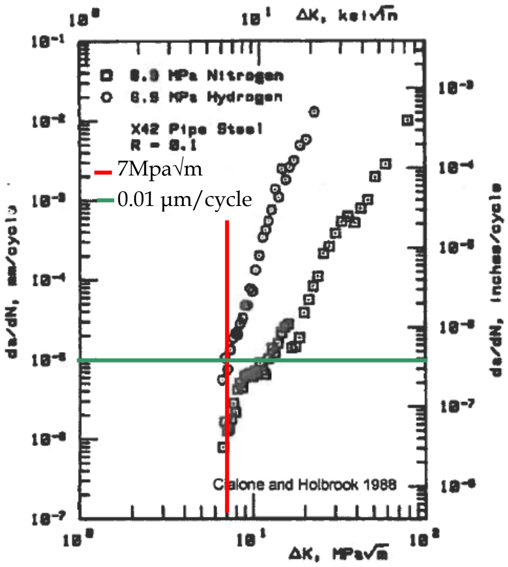

Figure 4. Fatigue crack growth rate (da/dN) as a function of the stress intensity factor (ΔK) for hydrogen and nitrogen for API X42 steel [61]

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