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NATURALHY

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

Integrated Project

6.1.ii Call 1 Sustainable Energy Systems

Report

Assessment of repair and rehabilitation technologies relating to the transport of hythan (hydrogen- methane-mixture)

WP-4

Report No. R0016-WP4-P-0

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Problem formulation:

Assessment of repair and rehabilitation technologies relating to the transport of hythan (hydrogen-methane-mixture).

In connection with the investigation of the possibility, to transport hydrogen in the existing natural gas system, an assessment of the practised repair technologies relating their suitability for the transport of hythan is to do.

The assessment is to illustrate based on objective criteria, which are compiled in an evaluation matrix.

The problem formulation is divided into the following tasks:

1. Investigation of the state of the art of repair technologies for low pressure, but especially for high and medium pressure.
2. Developing of an evaluation matrix for the objective assessment of the suitability of the investigated repair technologies relating to the transport of hythan.
3. Presentation of the technological and economical consequences of the repair technologies relating to the transport of hythan.
4. Representation of the results in a report.

List of contents

List of used abbreviations and formula symbols

c_{Zo}	upper ignition limit [volume %]
c_{Zu}	lower ignition limit [volume %]
d	relative density [-]
d_a, d_i	outside / inside diameter [mm]
Δp_v	loss of pressure [bar]
H_i	net calorific value (formerly H_u) [kWh/m³]
H_S	gross calorific value (formerly H_o) [kWh/m³]
K	compressibility factor [-]
k	roughness [mm]
L	pipe length [m]
ν	kinematic viscosity [m²/s]
p	partial pressure, $p = p_e + p_{amb}$ [bar]
P	permeation coefficient [cm³ (STP) / m x bar x d]
p_{amb}	ambient pressure [bar]
p_e	overpressure [bar]
p_n	normed pressure [bar], p_n = 1.01325 bar
Re	Reynolds number [-]
r_i	fraction [-]
s	wall thickness [mm]
τ	time [d]
t	temperature [°C]
T_n	normed temperature [K], T_n = 273.15 K
V	permeated gas volume [cm³ (STP)]
$\dot{V}$	gas volumetric flow rate [m³/h]
w	flow rate [m/s]
W_S, W_i	upper / lower Wobbe index [kWh/m³]
λ	pipe friction coefficient [-]
ρ	density [kg/m³]

DOT	U.S. Department of Transportation
GG	grey cast iron
STP	standard temperature and pressure (p=1.01325 bar, T=273.15 K)
PE	polyethylene
PE-HD	polyethylene with high density, also HD-PE (ρ=0.940…0.965 g/cm³)
PE-X	cross-linked polyethylene
PP	polypropylene
PU / PUR	polyurethane
LP	low pressure $p_e < 0.1$ bar
MP	medium pressure $p_e = 0.1 \ldots 1$ bar
HP	high pressure $p_e > 1$ bar

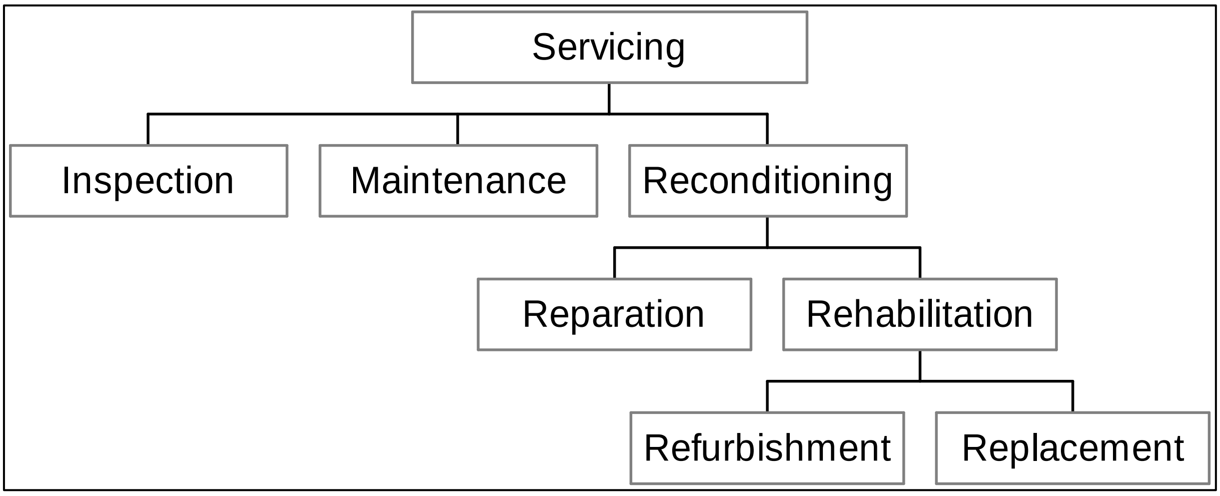
Definitions

Rehabilitation: Refurbishment and replacement to maintain the functionality of the existing gas distribution system. [2]

Refurbishment: Rehabilitation of an existing pipe with a not-self-supporting lining (for example soft lining). [2]

Replacement: Substitution of an existing defective pipe by installing a new pipe. [2]

Reparation: Removing of damage by an individual action. [2]



Graph 1.1: Refurbishment and replacement as components of rehabilitation [2]

1. Introduction

This report is a contribution to the EU-Project NATURALHY.

Natural gas + Hydrogen = NATURALHY.

The general objective of the Project NATURALHY reads as follows:

„Preparing for the hydrogen economy by using the existing natural gas system as a catalyst (NATURALHY) “

NATURALHY is a Project which is partially financed by the EU. The main objective of NATURALHY is to prepare the European countries for the hydrogen economy by identifying and removing potential barriers regarding the introduction of hydrogen into society, using the existing natural gas system. [10]

The aim of the report is to asses the suitability of the existing repair and rehabilitation technologies for the transmission resp. distribution of hythan and to infer the resulting technological and economical consequences. The investigations focussed on distribution and transmission pipelines with an operation pressure in the range of ten bars. A few in lining resp. repair methods are designed for pressures higher than ten bars.

For all reflections in this report the hydrogen ratio for hythan is set to 50 percent by volume.

2. Abstract

The objective of this report is to give an overview of the repair and rehabilitation technologies which are available at the moment and to determine their suitability for the use with hythan conducting pipelines in an evaluation matrix.

Hythan is a hydrogen-methane-mixture. For the reflections made in this report the fraction of hydrogen is set to 50 volume %.
Due to the partially considerable differences between natural gas and hydrogen the entrainment of hydrogen causes a change in several characteristic parameters, which are important for the technological use.

Above all, the net and gross calorific value of hythan drops to about 65 % of $H_{i,\text{Natural gas H}}$ and $H_{S,\text{Natural gas H}}$. Due to the considerable difference in density and, consequently, in viscosity between natural gas and hydrogen, the Wobbe index falls from 14.71 kWh/m³ (STP) (natural gas H) to 12.88 kWh/m³ (STP) (hythan). The lower supply of energy can be compensated by raising the pressure in the system. This action, however, has to be checked for the current project.

The large fraction of hydrogen causes an enlargement of the ignitable range of a hythan-air-mixture compared to natural gas and the necessary ignition energy falls. Due to the properties of typical ignition sources and the gas industry's long-standing experience with hydrogen-containing gases, no raised danger for hythan has to be expected.

Altogether, the suitability of 4 repair and 16 rehabilitation technologies has been investigated in view of the use with hythan conducting pipelines. The assessment was made by means of an evaluation matrix, in which the specifications, which were retrieved from the companies, were marked.

The criteria are:

- Permeation of CH_4 / H_2
- Chemical resistance against CH_4 / H_2
- Reduction of the initial diameter
- Available diameter
- Maximum pressure range
- Maximum continuous length per one phase of construction
- Durability of the rehabilitated segments

In the evaluation matrix the criteria were marked according to their significance for the suitability of the technologies for hythan.

From the results of the evaluation matrix can be inferred that the suitability of the technologies for hythan is mainly dependent on the used materials.
The best-suited material for repair is steel. When choosing the steel, however, attention has to be paid, that no (hydrogen) corrosion occurs at the welding seams.
The best suited materials for rehabilitation are pipelines and pipe liners made of HD-PE, PE-X, coated aramid fibre and laminated composite pipe-system with an aluminium-barrier.

As to the kinds of technologies, it can be concluded, that a renewal of the old pipe with pipe-bursting or draw-in technologies and rehabilitation with braided-hose-relining is preferable to foil-hose-relining.

The ranking of the trademarks and the recommendation for suitable technologies were developed considering the criterions listed above and the current available corresponding information how the techniques fulfil the criterions.
At the time of the report preparation only a few information about permeation was available. To pay attention to this situation, to new developments and to enhancements of existing technologies a regular revaluation of the ranking is recommended. The interval should follow new developments/cognitions and should not exceed a ten-year duration.
The fact that only little information is available about the permeation through the used materials (e.g. PUR) calls for special action in this field.

3. Hythan

3.1 General information

Hydrogen + Methane = Hythan

Hythan is a mixture of hydrogen and methane. It differs from natural gas in terms of fluidic properties, burning behaviour and other relevant characteristics. The resulting general technological influences and consequences for existing technologies will be illustrated in the following chapters.

Regarding the hydrogen fraction of 50 percent by volume, hythan is very similar to town gas, which was especially being used in East Germany for several years (Tab. 3.1: Composition of fuel-gas). From this fact some conclusions can be drawn concerning security questions and the handling of hythan.

Other parameter like caloric value and Wobbe index differ from those of town gas.

Tab. 3.1: Composition of fuel-gas [3]

Fuel-gas	Composition in volume %								
	H_2	CO	CH_4	C_2H_6	C_3H_8	C_4H_{10}	ΣC_nH_m	CO_2	N_2
Town gas	51.0	18.0	19.0	-	-	-	2.0	4.0	6.0
Natural gas H	-	-	93.0	3.0	1.3	0.6	-	1.0	1.1
Hythan	50.0	-	46.5	1.5	0.65	0.3	-	0.5	0.55

By adding 50 % hydrogen to natural gas the net calorific value $H_{i,Hythan}$ drops to 6.69 kWh/m³ (STP), which is equivalent to 64.5 % of $H_{i,Natural\ gas\ H}$.

The gross calorific value $H_{S,Hythan}$ drops to 7.51 kWh/m³ (STP), which is equivalent to 65.4 % of $H_{S,Natural\ gas\ H}$ (equation 3.1).

$$H_{S,Hythan} = r_1 \bullet H_{S,1} + r_2 \bullet H_{S,2} = 0.5 \bullet 11.48 \frac{kWh}{m^3} + 0.5 \bullet 3.54 \frac{kWh}{m^3} = 7.51 \frac{kWh}{m^3} \quad \text{(Equ. 3.1)}$$

The following gross calorific values for hythan in dependence of the hydrogen concentration (Tab. 3.2) result from equation 3.1.

Tab. 3.2: H_i of Hythan

Hi of Hythan				**Hi of hydrogen and natural gas H**	
fraction ri		Hi [MJ/m³]	Hi [kWh/m³]	Hi [MJ/m³]	
Natural gas H	Hydrogen			Natural gas H	Hydrogen
1	0	37.35	10.38	37.35	10.783
0.9	0.1	34.69	9.64		
0.8	0.2	32.04	8.90	Hi [kWh/m³]	
0.7	0.3	29.38	8.16	Natural gas H	Hydrogen
0.6	0.4	26.72	7.43	10.38	2.995
0.5	0.5	24.07	6.69		
0.4	0.6	21.41	5.95		
0.3	0.7	18.75	5.21		
0.2	0.8	16.10	4.00		
0.1	0.9	13.44	3.73		
0	1	10.78	3.00		

The upper Wobbe index of hythan drops from 14.71 kWh/m³ (STP) (natural gas H) to 12.88 kWh/m³ (STP).

$$W_{S,Hythan} = \frac{H_{S,Hythan}}{\sqrt{(r_1 \bullet d_1 + r_2 \bullet d_2)}} = \frac{7.51\,kWh}{\sqrt{(0.5 \bullet 0.61 + 0.5 \bullet 0.0695)}\,m^3} = \underline{\underline{12.88\frac{kWh}{m^3}}} \quad \text{(Equ. 3.2)}$$

Due to the decrease of calorific value and Wobbe index higher flow pressure and / or technological modifications at gas appliances may be necessary.

Also, the density goes down considerably (equation 3.3), which has a positive effect on the weight related power density and to the loss of pressure in pipelines.

$$\rho_{Hythan}(i.N.) = \rho_{EG} \bullet r_{EG} + \rho_H \bullet r_H = 0.79\frac{kg}{m^3} \bullet 0.5 + 0.0899\frac{kg}{m^3} \bullet 0.5 = \underline{\underline{0.44\frac{kg}{m^3}}} \quad \text{(Equ. 3.3)}$$

3.2 Combustion calculation

The biggest advantage of hythan is that hydrogen is emission-free if it is generated using renewable energies.

Caused by the zero-emission combustion and the big fraction of hydrogen in hythan the emissions diminish considerably compared to the combustion of natural gas.

Table 3.3 shows the exhaust gas streams resulting from the combustion calculation (Appendix 1 – Combustion calculation) related to the fuel-gas flow. In table 3.4 the exhaust gas streams per kilowatt-hour (related to net calorific value H_i) are shown.

Tab. 3.3: Comparison of exhaust gas components (related to fuel-gas flow)

Exhaust gas component	**Natural gas H**	**Hythan**
v_{CO2} [m^3CO_2/m^3B]	1.063	0.532
v_{N2} [m^3N_2/m^3B]	8.962	4.481

Tab. 3.4: Comparison of exhaust gas components (related to energy)

Exhaust gas component	**Natural gas H**	**Hythan**
v_{CO2} [m^3CO_2/kWh]	0.102	0.080
v_{N2} [m^3N_2/kWh]	0.863	0.670

Hence it appears that the combustion of hythan causes 50 % less harmful emissions than the combustion of natural gas if the fuel-gas flows are equal.
Related to the net calorific value the combustion of hythan causes 22.35 % fewer emissions than the combustion of natural gas.

3.3 Permeation

Permeation stands for the penetration of gas trough a solid substance without any leaking. The process consists of adsorption, diffusion, desorption, solubility and migration. [9]
Fick's law is used to calculate the permeated gas volume for pipelines (equation 3.4). It is linear dependent on diameter and length of the piping section.

$$V = P \bullet \frac{\pi \bullet d_a \bullet L \bullet p \bullet \tau}{s}$$ (Equ. 3.4) [1]

The abbreviations stand for:

- V … permeated gas volume [cm³ (STP)]
- P … Permeation coefficient [cm³ (STP) / m x bar x d]

- d_a … Outside diameter of the pipe [mm]
- L … Pipe length [m]
- p … Partial pressure of the gas [bar]
- τ … Time [d]
- s … Wall thickness [mm]

Sometimes the formula statements and abbreviations for the permeation coefficient vary.

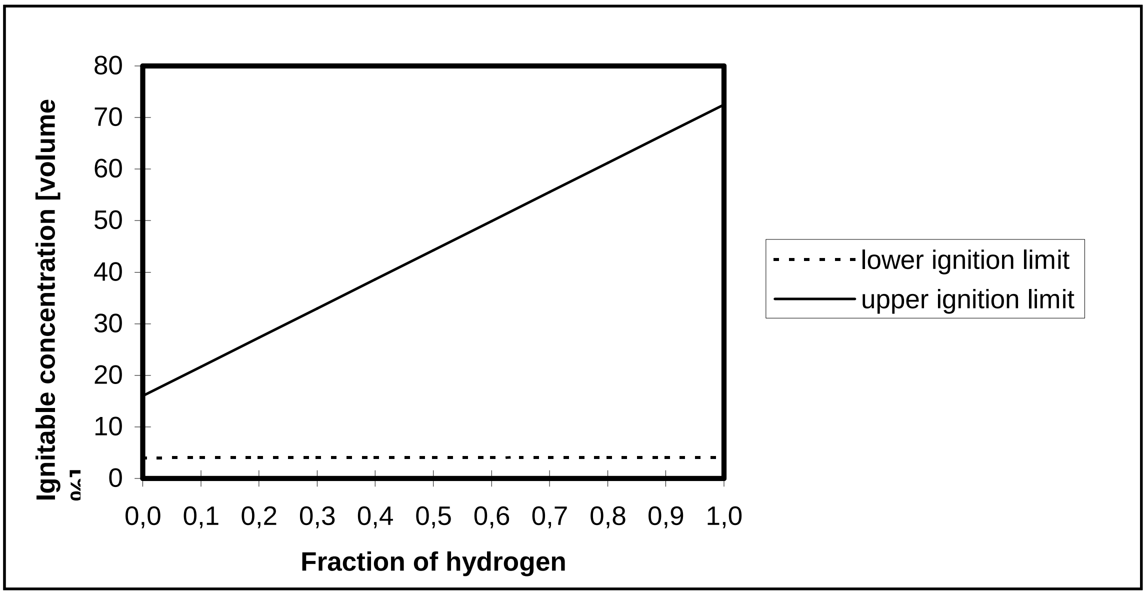
Permeation coefficients of natural gas and hydrogen are only known for some standard materials.
As there aren't any analyses regarding the permeation of hythan, the permeation coefficient of hythan has to be assumed based on the permeation coefficients of natural gas and hydrogen.
From the existing measurement values (for example Tab. 3.5) it can be inferred, that the permeation coefficient of hydrogen is above all for plastic pipelines, depending on the material, multiple bigger than the permeation coefficient of natural gas.
The permeation coefficient of hythan will be probably in the middle of those of hydrogen and methane.
Because of the ratio of volume flow to permeation coefficient a significant change of concentration is unlikely.

Tab. 3.5: Permeation coefficients of HD-PE-pipes, t = 20 °C [1]

Medium	**P** [cm³ (STP) x m^{-1} x bar^{--1} x d^{-1}]
Natural gas	0.056
Hydrogen	0.22

3.4 Inflammability limits

As there aren't any measurements of inflammability limit of hythan, a linear behaviour of the ignitable concentration for a hythan-methane-mixture can be assumed (Graph 3.1 / Table 3.6).



Graph 3.1: Inflammability limits of hythan

That leads to the following values for hythan:

Tab. 3.6: Inflammability limits of fuel-gas

Fuel-gas	**Inflammability limit** (in air, 20 ℃)	
	c_{Zu} Volume %	c_{Zo} Volume %
Hydrogen [3]	4.1	72.5
Natural gas H [3]	4.0	16.0
Hythan (50 % H_2)	4.05	44.25

3.5 Ignition energy

The minimum ignition energy of methane is 0.29 mJ, the one of hydrogen 0.017 mJ. The minimum ignition energy of hythan will probably be very low, similar to the one of hydrogen.

The self-ignition temperatures are 560 ℃ for hydro gen and 595 ℃ for methane. Such high temperatures are unlikely for a standard operation in pipelines. [3]

3.6 Loss of pressure

The loss of pressure is one of the most important parameter when designing the compressor rating. It changes in accordance with the pipe's inside diameter, the roughness of the inside wall and the conveyed gas.
The following calculation allows a comparison between natural gas and hythan (in equal environmental conditions).

Exemplary calculation for hythan:

A steel pipe; DN 200 (d_a=219.1 mm, s=5 mm, k=0.5 mm); length = 1000 m;

$\dot{V}$ =1800 m³/h = 0.5 m³/s; p_e=1 bar; t=10 °C;

That is equivalent to a standard volumetric flow rate of 3450 m³/h.

$$\boxed{\dot{V} = w \bullet A = w \bullet \frac{d_i^2 \bullet \pi}{4}} \text{ (Equ. 3.5)}$$

That means for a constant volume flow:

$$\boxed{\dot{V} = w_1 \bullet A_1 = w_2 \bullet A_2}; \boxed{w_2 = w_1 \bullet \frac{A_1}{A_2}} \text{ (Equ. 3.6)}$$

The loss of pressure is calculated:

$$\boxed{\Delta p_V = \lambda \bullet \frac{\rho}{2} \bullet \frac{L}{d_i} \bullet w^2 = \lambda \bullet \frac{\rho}{2} \bullet \frac{L}{d_i} \bullet \left(\frac{\dot{V}}{\frac{d_i^2 \bullet \pi}{4}} \right)^2 = \lambda \bullet \rho \bullet 8 \bullet \frac{L}{d_i^5} \bullet \frac{\dot{V}^2}{\pi^2}} \text{ (Equ. 3.7)}$$

To determinate the pipe friction coefficient λ the Reynolds number is needed:

$$\boxed{Re = \frac{w \bullet d_i}{\nu}} \text{ (Equ. 3.8)}$$

With the kinematic viscosity ν (dependent on the pressure)

$$\boxed{\begin{aligned} \nu &= \frac{p_{Tab.}}{p} \nu_1 \bullet r_1 + \nu_2 \bullet r_2 \\ \nu &= \frac{1\,\text{bar}}{2.01325\,\text{bar}} 106 \bullet 10^{-6} \frac{m^2}{s} \bullet 0.5 + 14.9 \bullet 10^{-6} \frac{m^2}{s} \bullet 0.5 = \underline{\underline{30.026 \bullet 10^{-6} \frac{m^2}{s}}} \end{aligned}} \text{ (Equ. 3.9)}$$

and the gas flow rate (Equ. 3.5)

$$\boxed{w = \frac{\dot{V} \bullet 4}{d_i^2 \bullet \pi} = \frac{0.5\,m^3 \bullet 4}{s \bullet (0.2091\,m)^2 \bullet \pi} = \underline{\underline{14.56 \frac{m}{s}}}}$$

the result from equation 3.8 is:

$$Re = \frac{14.54\,\frac{m}{s} \bullet 0.2091\,m}{30.026 \bullet 10^{-6}\,\frac{m^2}{s}} = \underline{\underline{101256}}$$

Re=101256 > Re_{krit}=2320

If the Reynolds number is bigger than the critical Reynolds number, there is turbulent flow in the pipeline.

To find out the range of roughness, the quotient of diameter and roughness has to be calculated:

$$\frac{d}{k} = \frac{209.1\,mm}{0.5\,mm} = \underline{\underline{418.2}}$$ (Equ. 3.10)

In Graph 3.2 the pipe friction coefficient λ or rather the range for the calculation of the exact pipe friction coefficient has to be determined.

The intersection point of the two lines (Reynolds number and d/k) is found in the crossover range between hydraulic smooth and rough.

The according λ-value is 0.025.

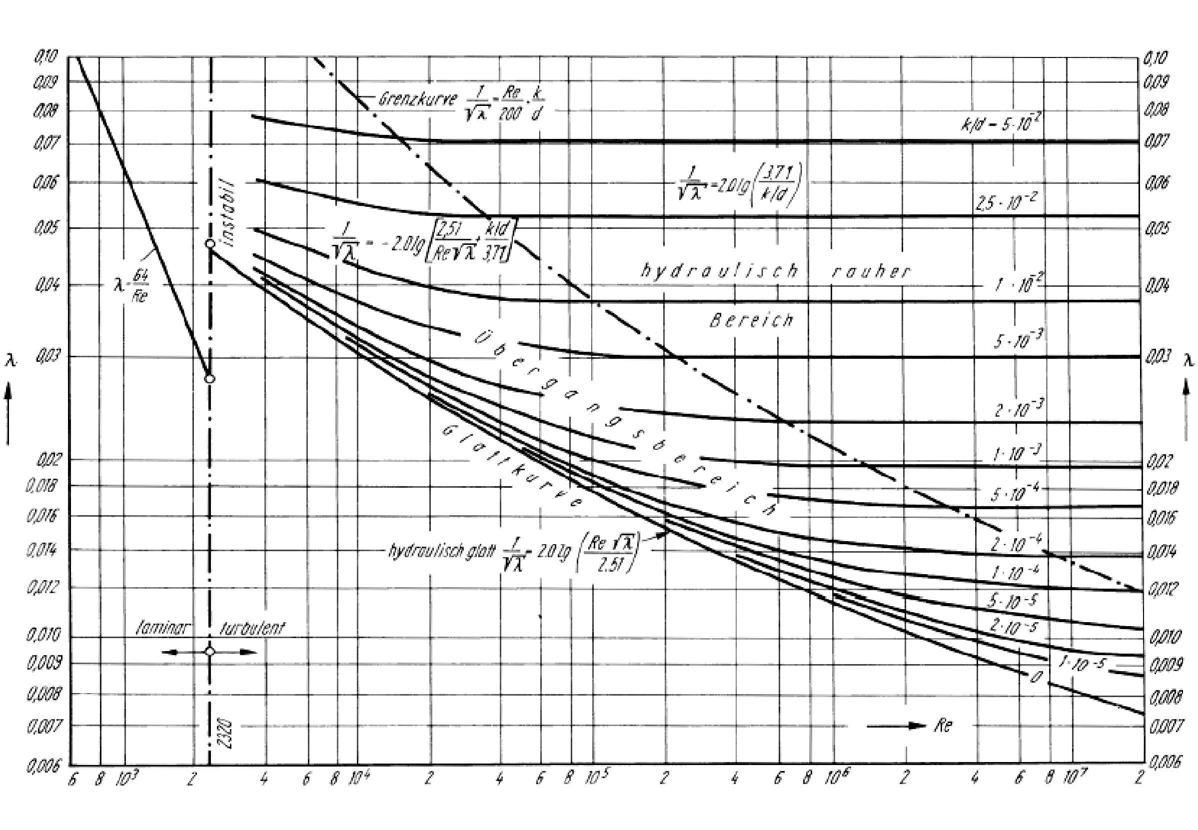
To check, the λ-value is set into the following equation (Prandtl and Colebrook):

$$\frac{1}{\sqrt{\lambda}} = -2 \bullet lg\left(\frac{2.51}{Re \bullet \sqrt{\lambda}} + \frac{k}{d} \bullet 0.269\right)$$ (Equ. 3.11) [3]

$$\frac{1}{\sqrt{0.025}} = -2 \bullet lg\left(.\frac{2.51}{101256 \bullet \sqrt{0.025}} + \frac{0.5}{209.1} \bullet 0.269\right)$$

$$6.325 \approx 6.194$$

The rough equality shows that the determination of the pipe friction coefficient was sufficiently exact.



Graph 3.2: Re, λ-Diagram [3]

The density of the compressed gas is calculated with the following equation:

$$\rho_r = \rho_{n,r} \frac{p \bullet T_n}{p_n \bullet T} \bullet \frac{1}{K} \quad \text{(Equ. 3.12)}$$

With K=1 (The compressibility can be neglected for H_2 and CH_4 up to 20 bar) result of equation 3.13 is:

$$\rho_{r,Hythan} = 0.44 \frac{kg}{m^3} \frac{2.01325\,bar \bullet 273\,K}{1.01325\,bar \bullet 283\,K} \bullet \frac{1}{1} = \underline{\underline{0.84 \frac{kg}{m^3}}} \quad \text{(Equ. 3.13)}$$

From equation 3.7 results the loss of pressure for the line section:

$$\Delta p_V = 0.025 \bullet 0.84 \frac{kg}{m^3} \bullet 8 \bullet \frac{1000\,m}{0.2091^5\,m^5} \bullet \frac{(0.5\,m^3)^2}{\pi^2 s^2} = \underline{\underline{10645.3\,Pa}} \mathrel{\hat{=}} \underline{\underline{0.106\,bar}}$$

The **exemplary calculation for natural gas** is made with the same formulas and environmental parameters as for hythan.

$$\nu = \frac{p_{Tab.}}{p} \nu_n = \frac{1\,bar}{2.01325\,bar} 14.9 \bullet 10^{-6} \frac{m^2}{s} = \underline{\underline{7.4 \bullet 10^{-6} \frac{m^2}{s}}}$$

$$Re = \frac{14.54 \frac{m}{s} \bullet 0.2091\,m}{7.4 \bullet 10^{-6} \frac{m^2}{s}} = \underline{\underline{410853}}$$

λ determined from Graph 3.2 = 0.025; verification with equation 3.11:

$$\frac{1}{\sqrt{0.025}} = -2 \bullet \lg\left(\frac{2.51}{410853 \bullet \sqrt{0.025}} + \frac{0.5}{209.1} \bullet 0.269\right)$$

$6.325 \approx 6.332$ → The accuracy of the determination is sufficiently exact.

$$\rho_{r,ErdgasH} = 0.79 \frac{kg}{m^3} \frac{2.01325\, bar \bullet 273\, K}{1.01325\, bar \bullet 283\, K} \bullet \frac{1}{1} = \underline{\underline{1.514 \frac{kg}{m^3}}}$$

$$\Delta p_V = 0.025 \bullet 1.514 \frac{kg}{m^3} \bullet 8 \bullet \frac{1000\, m}{0.2091^5\, m^5} \bullet \frac{(0.5\, m^3)^2}{\pi^2 s^2} = \underline{\underline{19187.8\, Pa}} \mathrel{\hat{=}} \underline{\underline{0.192\, bar}}$$

During the transport of hythan the loss of pressure in the pipeline goes down to 55 % of the loss of pressure of natural gas (with equal volume flow rate) due to the difference in density of hythan and methane.

To get an equal thermal load at the gas consumer installation, the volumetric flow rate must be adjusted by increasing the pressure. The multiplier "x" for the overpressure is calculated by using the advanced Wobbe index W_e in the following equation:

$$W_{eS,n,Hythan} \overset{!}{=} W_{eS,n,Natural\ gas\ H}$$

$$H_{S,n,Hythan} \bullet \sqrt{\frac{p_{e,Hythan}}{d_{Hythan}}} \overset{!}{=} H_{S,n,Natural\ gas\ H} \bullet \sqrt{\frac{p_{e,Natural\ gas\ H}}{d_{Natural\ gas\ H}}}$$

$$p_{e,Hythan} = \frac{(H_{S,n,Natural\ gas\ H})^2}{(H_{S,n,Hythan})^2} \bullet \frac{d_{Hythan}}{d_{Natural\ gas\ H}} \bullet p_{e,Natural\ gas\ H} \quad \text{(Equ. 3.14)}$$

with $p_{e,Hythan} = x \bullet p_{e,Natural\ gas\ H}$ follows

$$x = \frac{(11.48\, kWh/m^3)^2}{(7.51\, kWh/m^3)^2} \bullet \frac{(0.5 \bullet 0.61 + 0.5 \bullet 0.0695)}{0.61}$$

$$\underline{\underline{x = 1.3}}$$

For this example, an overpressure p_e = 1.3 bar for hythan is needed.

Due to the increase of pressure, the density and so the loss of pressure will rise, too.

$$\nu = \frac{1\, bar}{2.31325\, bar} 106 \bullet 10^{-6} \frac{m^2}{s} \bullet 0.5 + 14.9 \bullet 10^{-6} \frac{m^2}{s} \bullet 0.5 = \underline{\underline{30.036 \bullet 10^{-6} \frac{m^2}{s}}}$$

$$Re = \frac{14.54 \frac{m}{s} \bullet 0.2091\, m}{30.036 \bullet 10^{-6} \frac{m^2}{s}} = \underline{\underline{100595}}$$

λ determined from Graph 3.2 = 0.0265; verification with equation 3.11:

$$\frac{1}{\sqrt{0.0265}} = -2 \bullet \lg\left(\frac{2.51}{100595 \bullet \sqrt{0.0265}} + \frac{0.5}{209.1} \bullet 0.269\right)$$

$\boxed{6.143 \approx 6.198}$ → The accuracy of the determination is sufficiently exact.

$$\rho_{r,Hythan} = 0.44\,\frac{kg}{m^3}\,\frac{2.31325\ bar \bullet 273\ K}{1.01325\ bar \bullet 283\ K} \bullet \frac{1}{1} = 0.97\,\frac{kg}{m^3}$$

$$\Delta p_V = 0.0265 \bullet 0.97\,\frac{kg}{m^3} \bullet 8 \bullet \frac{1000\ m}{0.2091^5\ m^5} \bullet \frac{(0.5\ m^3)^2}{\pi^2 s^2} = 13031{,}8\ Pa \mathrel{\hat{=}} 0.130\ bar$$

In spite of the higher required overpressure for hythan, the required compressor rating (overpressure + loss of pressure) for hythan is lower than for natural gas H for a pipeline which is longer than 5 km (for this example).

4. Repair and rehabilitation technologies

4.1 General information

The following information about repair and rehabilitation technologies has been obtained by literature- and internet-investigation. The information provides an overview of the technologies available at the moment. The investigation was done very comprehensive. Nevertheless it is possible that not all technologies, which are available on the market, were considered in the report.
The process descriptions are split into repair and rehabilitation technologies. They are sorted in alphabetical order according to “process” – “company”.
Exchange technologies for gas pipes are listed under “rehabilitation technologies”.
The process descriptions are the preparation for the assessment, whether the use of the technologies for hythan conducting pipelines is possible or if there are restrictions.

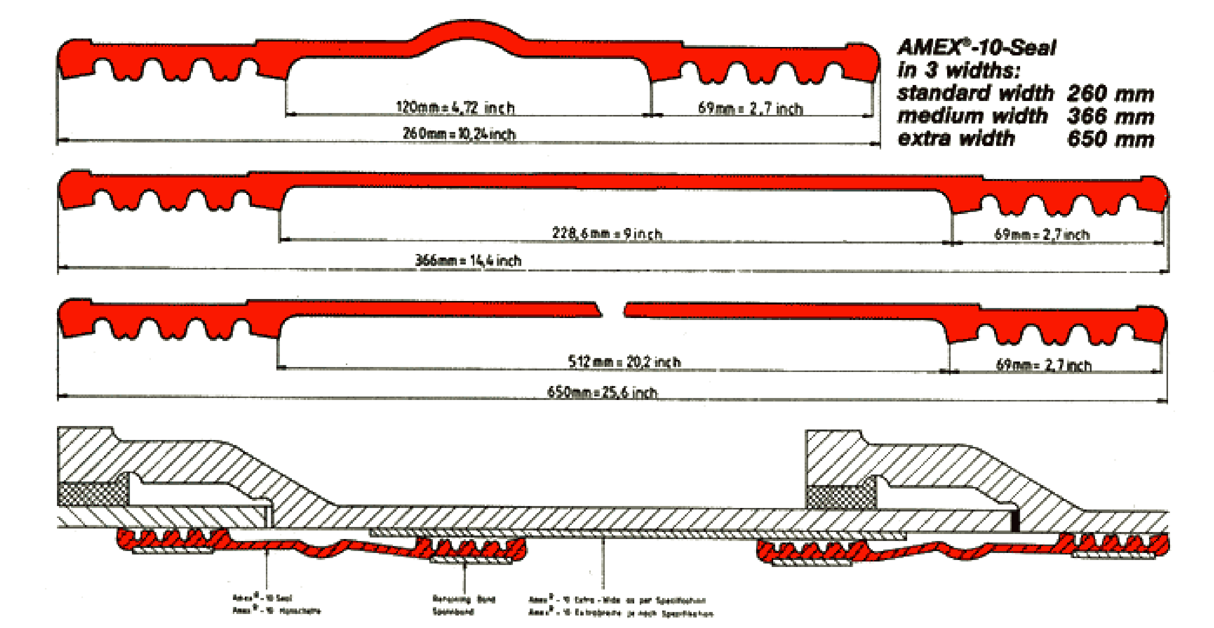
For repair and rehabilitation frequently used conventional materials are PE or steel. The chemical resistance and the permeation coefficients regarding CH_4 and H_2 are shown in table “Ranking of permeation” (Appendix 2).

4.2 Repair technologies

4.2.1. AMEX©-10 – AMEX

“AMEX©-10“ is a repair technology for gas-distribution pipelines.

The AMEX©-10-sleeve (Graph 4.1) is put against the pipe’s inside wall after cleaning the pipe. It covers the damaged part and is pressed against the pipe with pressing rings.



Graph 4.1: Amex©-10 – Seal [11]

Tab. 4.1: Specifications of AMEX 10

Permeation of hythan	There are no existing measurements available.
Interaction of hydrogen with the material	Chemical resistance is unknown.
Reduction of the initial diameter	Negligible, because there is only a short section of the pipe concerned.
Available diameter	≥ DN 500
Maximum pressure range	10 bar
Maximum continuous length per one phase of construction	Only for leaky sleeves and single damage.
Durability of the rehabilitated segments	> 50 a
Costs per meter	Depends on the current project.
Certificate	DIN-DVGW NG 5113 AR 0598
Contact / further information	http://www.amex-10.de

4.2.2. <u>GasSealer™ Sleeve – Linkpipe</u>

“GasSealer™ Sleeve” is a repair technology for gas-distribution pipelines made out of steel.

Epoxy resin coated steel sleeves are placed at the damaged part and get fixed by the internal ratchet locking mechanism of the sleeves at the pipe’s inside wall.

The resin cures at ambient temperature and seals the damaged part.

The used materials are stainless steel or grey cast iron with a sealing coating of epoxy resin for the sleeve.

Graph 4.2: Sleeve inserting / Sleeve installed [12]

Tab. 4.2: Specifications of GasSealer™ Sleeve

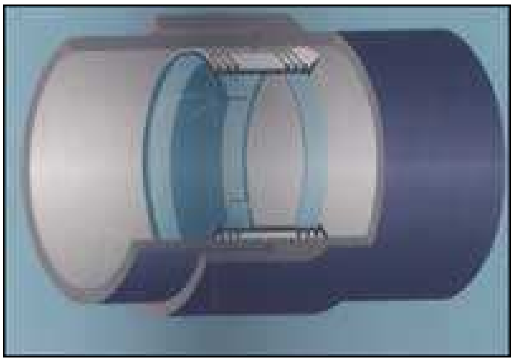
Permeation of hythan	There are no existing measurements available.
Interaction of hydrogen with the material	Chemical resistance is granted.
Reduction of the initial diameter	Negligible, because there is only a short section of the pipe concerned.
Available diameter	DN 100 … DN 1400
Maximum pressure range	1 bar (cast iron) and 10 bar (steel)
Maximum continuous length per one phase of construction	Only for leaky sleeves and single damage.
Durability of the rehabilitated segments	> 50 a
Costs per meter	Depends on the current project.
Certificate	No information.
Contact / further information	http://www.linkpipe.com

4.2.3. WECO® – PRS-Rohrsanierung / Rabmer

“WECO®“ is a repair and rehabilitation technology for gas- distribution pipelines made out of PE, steel, cast iron and cement.

An endless manufactured rubber sleeve is put against the damaged pipe’s inside wall. It is fixed with steel-retaining-straps (Graph 4.3) to obtain a mechanical sealing of the damaged point.

The used materials are NBR (nitrile-butadiene rubber) for the sleeve and RSt 60.2 for the retaining straps.



Graph 4.3: WECO – sleeve [13]

Tab. 4.3: Specifications of WECO®

Permeation of hythan	There are no existing measurements available.
Interaction of hydrogen with the material	Chemical resistance is granted.
Reduction of the initial diameter	12 mm (Negligible, because there is only a short section of the pipe concerned).
Available diameter	DN 600 … DN 3000
Maximum pressure range	15 bar
Maximum continuous length per one phase of construction	Only for leaky sleeves and single damage. 150 … 400 m difference between the trenches.
Durability of the rehabilitated segments	> 50 a
Costs per meter	It depends on the current project.
Certificate	DIN-DVGW 96.O.1e 1047
Contact / further information	http://www.prsrohrsanierung.de http://www.rabmer.at

4.2.4. <u>WeldWrap – WrapMaster, Inc.</u>

“WeldWrap“ is a repair technology for gas- distribution and transport pipelines made out of steel.

After cleaning the pipe’s outside wall a wraparound-sleeve (Graph 4.4) is wrapped around the damaged part of the pipe and agglutinated with the pipe. The corrugated surface of WeldWrap prevents a displacement of the windings.

The used materials are a laminated, magnetic detectable fibreglass for the sleeves and epoxy resin as cementing material.

Similar technologies are PermaWrap and Plug-n-Wrap of the same company. They differ as to the used materials and the working process.

Graph 4.4: Installation of WeldWrap [14]

Tab. 4.4: Specifications of WeldWrap

Permeation of hythan	There are no existing measurements available.
Interaction of hydrogen with the material	Chemical resistance is granted.
Reduction of the initial diameter	There is no reduction of the initial diameter, because the repair is made on the outside wall.
Available diameter	DN 100 … DN 1400
Maximum pressure range	The maximum pressure range is equivalent to the pressure range of the pipeline before the repair.
Maximum continuous length per one phase of construction	Only for leaky sleeves and single damage.
Durability of the rehabilitated segments	> 50 a
Costs per meter	Depends on the current project.
Certificate	DOT-Certification
Contact / further information	http://www.wrapmaster.us

4.3 Rehabilitation technologies

4.3.1. Compact Pipe – Wavin GmbH

“Compact Pipe“ is a pipe system for the trenchless draw-in method Close-fit-Lining. During the manufacture a C-shaped folded PE-pipe (Graph 4.5) is inserted in the carrier pipe. Then it is heated with steam to restore the original circular shape and pressed against the pipe’s inside wall with compressed air.

Compact Pipe is made of PE 80 or PE 100.

Graph 4.5: Compact Pipe before / after the installation [15]

Tab. 4.5: Specifications of Compact Pipe

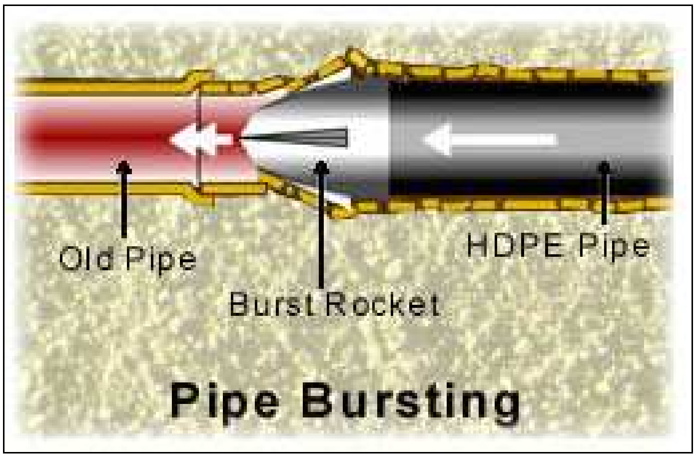
Permeation of hythan	There are no existing measurements available.
Interaction of hydrogen with the material	Chemical resistance is granted.
Reduction of the initial diameter	3,9 mm … 23,6 mm (dependent on the pressure stage and the SDR-category)
Available diameter	DN 100 … DN 500
Maximum pressure range	4 … 10 bar (It depends on the diameter and the used materials)
Maximum continuous length per one phase of construction	600 m (Dependent on the diameter)
Durability of the rehabilitated segments	> 50 a
Costs per meter	Depends on the current project.
Certificate	DVGW-Certification
Contact / further information	http://www.wavin.de

4.3.2. <u>egeplast SLA 2.0 / 3L - Egeplast</u>

“egeplast SLA 2.0 / 3L“ is a laminated composite pipe system for the trenchless rehabilitation and installation of gas-distribution pipelines.

The installation is carried out with burst-lining (Graph 4.6, Graph 4.11) or other relining-technologies (Graph 4.17).

The used material is PE 80 / PE 100 with a barrier of aluminium to reduce the gas-diffusion to a minimum.



Graph 4.6: Burst-lining (procedure) [16]

Tab. 4.6: Specifications of egeplast SLA 2.0 / 3L

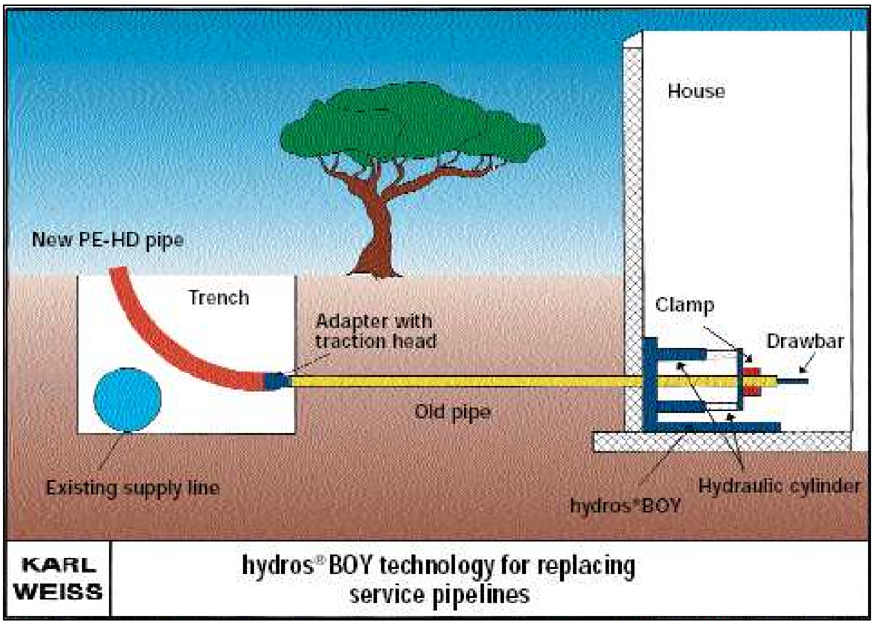
Permeation of hythan	There are no existing measurements available.
Interaction of hydrogen with the material	Chemical resistance is granted.
Reduction of the initial diameter	4 … 74 mm
Available diameter	DN 25 … DN 630
Maximum pressure range	4 bar (PE 80), 10 bar (PE 100)
Maximum continuous length per one phase of construction	200 m
Durability of the rehabilitated segments	> 100 a
Costs per meter	Depends on the current project.
Certificate	DVGW-Certification
Contact / further information	http://www.egeplast.de

4.3.3. hydros® _BOY – Karl Weiss Technologieunternehmen GmbH & Co. KG

“hydros®_BOY“ is a trenchless relining technology for the rehabilitation and installation of service lines.

The pipeline, which is to be exchanged, is removed using a hydraulic cylinder (Graph 4.7). The new pipe is brought in the same working cycle.

The used materials are PE-HD with an additional outside protection or ductile materials.



Graph 4.7: hydros®_BOY [17]

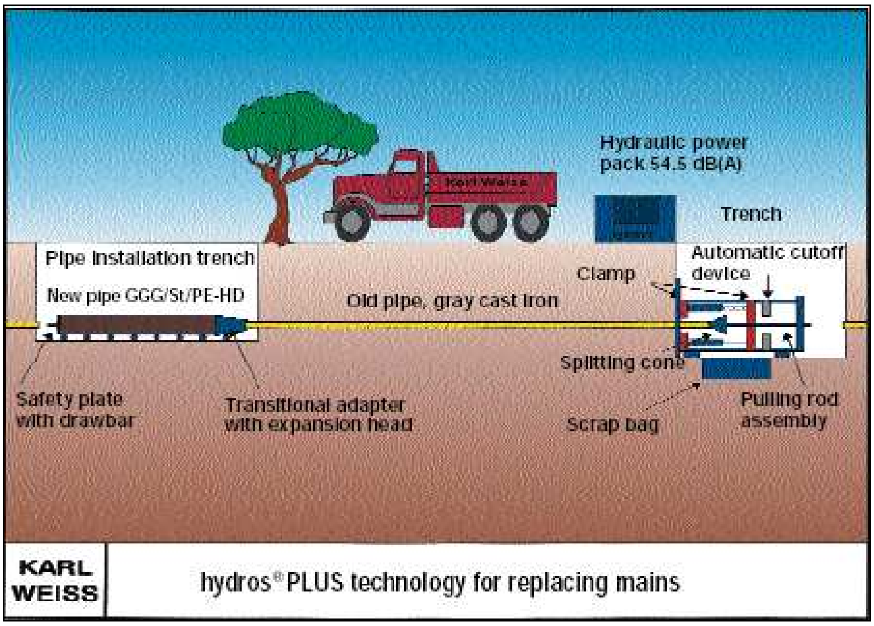
Tab. 4.7: Specifications of hydros®_BOY

Permeation of hythan	There are no existing measurements available.
Interaction of hydrogen with the material	Chemical resistance is granted.
Reduction of the initial diameter	Enlargement of diameter by using an expansion cone is possible.
Available diameter	≤ DN 60
Maximum pressure range	From 8 bar (HD-PE) up to the maximum pressure range of the pipeline before the repair (steel, GG).
Maximum continuous length per one phase of construction	25 m
Durability of the rehabilitated segments	> 50 a (Depends on the used materials)
Costs per meter	Depends on the current project.
Certificate	DIN 30658-1 / G478 / W322-1 / VP404
Contact / further information	http://www.karl-weiss.com

4.3.4. hydros® _PLUS – Karl Weiss Technologieunternehmen GmbH & Co. KG

“hydros®_PLUS“ is a trenchless relining technology for the exchange of gas-distribution pipelines.

The installation (Graph 4.8) and the used materials are the same as those of “hydros®_BOY“.



Graph 4.8: hydros®_PLUS [17]

Tab. 4.8: Specifications of hydros®_PLUS

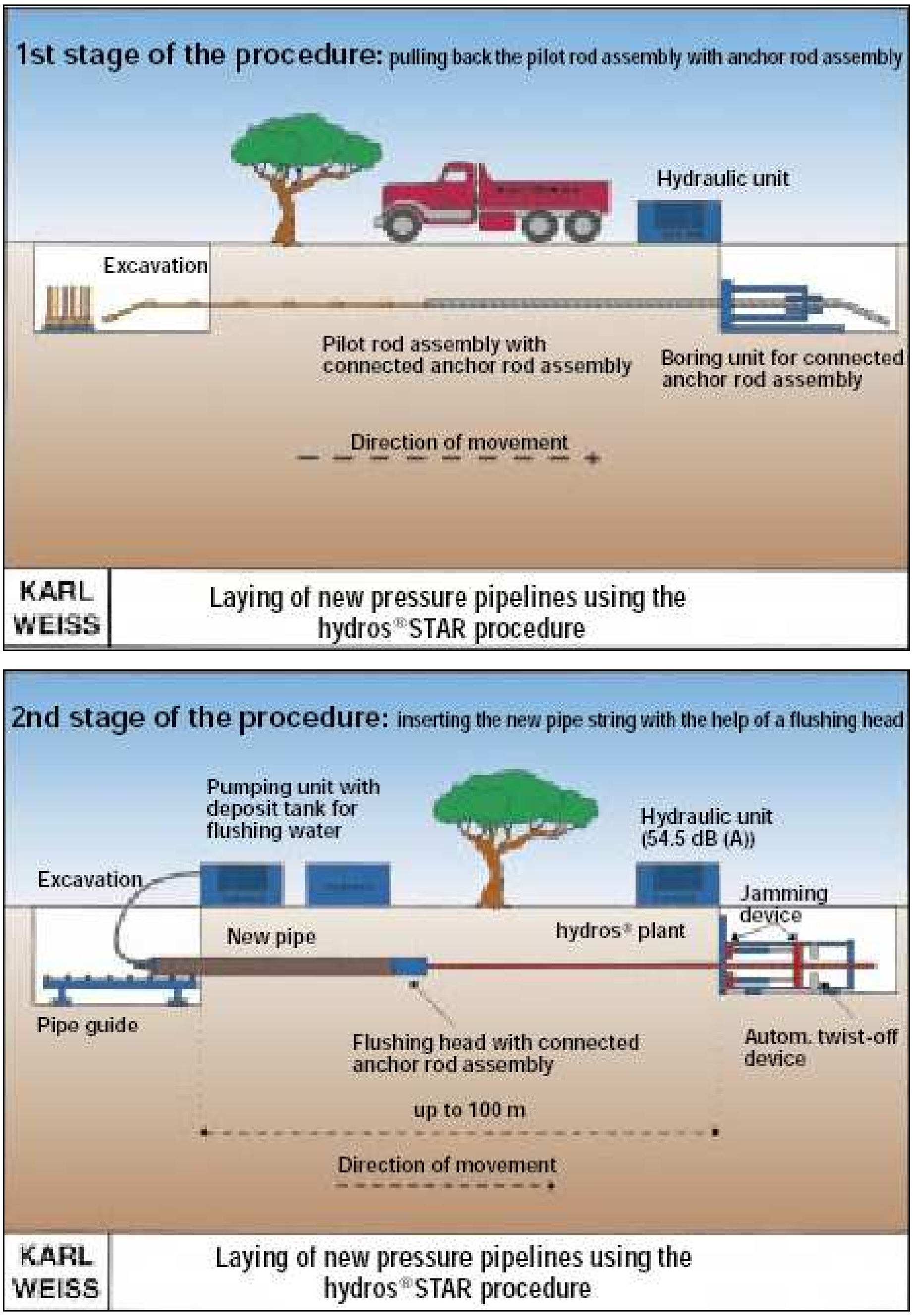
Permeation of hythan	There are no existing measurements available.
Interaction of hydrogen with the material	Chemical resistance is granted.
Reduction of the initial diameter	Enlargement of diameter by using a expansion cone is possible.
Available diameter	DN 100 … DN 400
Maximum pressure range	From 8 bar (HD-PE) up to the maximum pressure range of the pipeline before the repair (steel, GG).
Maximum continuous length per one phase of construction	170 m with intermediate trenches all 15…50 m (Depends on the diameter and the character of soil)
Durability of the rehabilitated segments	> 50 a (Depends on the used materials)
Costs per meter	Depends on the current project.
Certificate	DIN 30658-1 / G478 / W322-1 / VP404
Contact / further information	http://www.karl-weiss.com

4.3.5. hydros® _STAR – Karl Weiss Technologieunternehmen GmbH & Co. KG

"hydros®_STAR" is a trenchless relining technology for the installation of gas-distribution pipelines and the exchange of pipelines with enlargement of the initial diameter.

A pilot bore is made (Graph 4.9) and with the flush head the new pipe is drawn through the bore.

The used materials are PE-HD with an additional outside protection against the shards of the former pipe or ductile materials.



Graph 4.9: hydros®_STAR [17]

Tab. 4.9: Specifications of hydros®_STAR

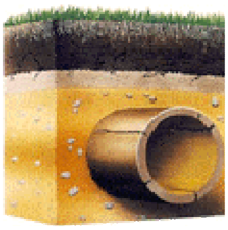
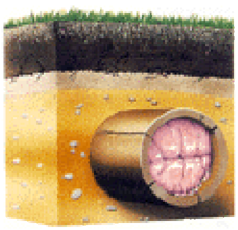
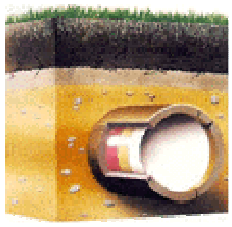
Permeation of hythan	There are no existing measurements available.
Interaction of hydrogen with the material	Chemical resistance is granted.
Reduction of the initial diameter	Enlargement of diameter by using an expansion cone is possible.
Available diameter	DN 100 … DN 600
Maximum pressure range	From 8 bar (HD-PE) up to the maximum pressure range of the pipeline before the repair (steel, GG).
Maximum continuous length per one phase of construction	170 m with intermediate trenches all 15…50 m (Depends on the diameter and the character of soil)
Durability of the rehabilitated segments	> 50 a (Depends on the used materials)
Costs per meter	Depends on the current project.
Certificate	DIN 30658-1 / G478 / W322-1 / VP404
Contact / further information	http://www.karl-weiss.com

4.3.6. PHOENIX® – PRS-Rohrsanierung / Rabmer

"PHOENIX®" is a trenchless braided-hose-relining-technology for the rehabilitation of gas-distribution pipelines.

After cleaning the carrier pipe the braided hose / resin system is inserted by using the inversion technology (Graph 4.10). The hose is pressed against the pipe's inside wall with steam pressure (p=0.5 … 2 bar, t=100 °C) and the resin cures.

The used materials are a polyester yarn with an interior coating of PP (polypropylene) for the braided hose and a two-component epoxy adhesive.

 **Cleaned pipe** **ready for rehabilitation**	 **A liner being** **reverted in the pipe**	 **Pipe after** **successful rehabilitation**

Graph 4.10: PHOENIX® [18]

Tab. 4.10: Specifications of PHOENIX®

Permeation of hythan	There are no existing measurements available.
Interaction of hydrogen with the material	Chemical resistance is granted.
Reduction of the initial diameter	6 mm
Available diameter	DN 100 … DN 1000
Maximum pressure range	16 bar
Maximum continuous length per one phase of construction	500 m
Durability of the rehabilitated segments	> 50 a
Costs per meter	Depends on the current project.
Certificate	DIN- and DVGW-Certification
Contact / further information	http://www.prsrohrsanierung.de

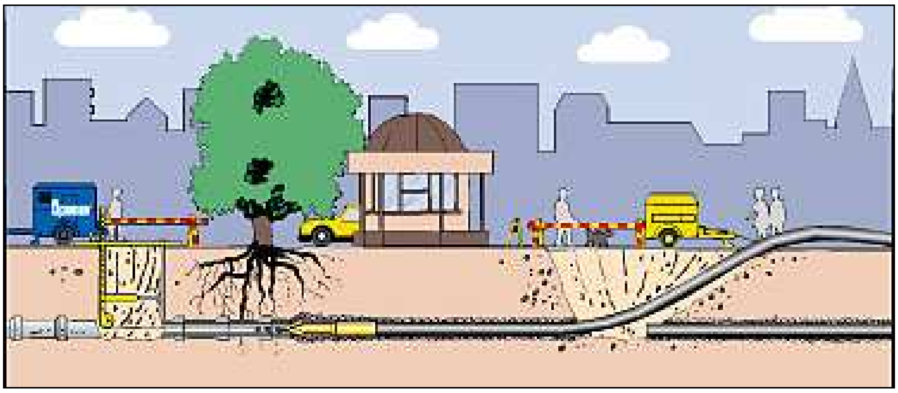
4.3.7. Pipe bursting – Collex NoDig / Uponor / Wirsbo Pex GmbH

“Pipe bursting“ is an exchange technology for gas-distribution pipelines.

A conical bursting tool is drawn or pushed through the pipeline, which is to be substituted (Graph 4.11, Graph 4.6). The tool shatters or splits the old pipe and draws the new pipeline through the bore. The shards of the old pipe remain in the soil.

The new pipeline can be larger than the initial diameter depending on the used bursting tools.

The used materials are PE-X or HD-PE.



Graph 4.11: Pipebursting [19]

Tab. 4.11: Specifications of Collex / Uponor / Wirsbo Pipe bursting

Permeation of hythan	There are no existing measurements available.
Interaction of hydrogen with the material	Chemical resistance is granted.
Reduction of the initial diameter	Enlargement of diameter is possible.
Available diameter	DN 25 … DN 250
Maximum pressure range	8 bar
Maximum continuous length per one phase of construction	500 m
Durability of the rehabilitated segments	> 50 a
Costs per meter	Depends on the current project.
Certificate	DVGW-Certification
Contact / further information	http://www.nodig.com.au http://www.uponor.com http://www.wirsbo.de

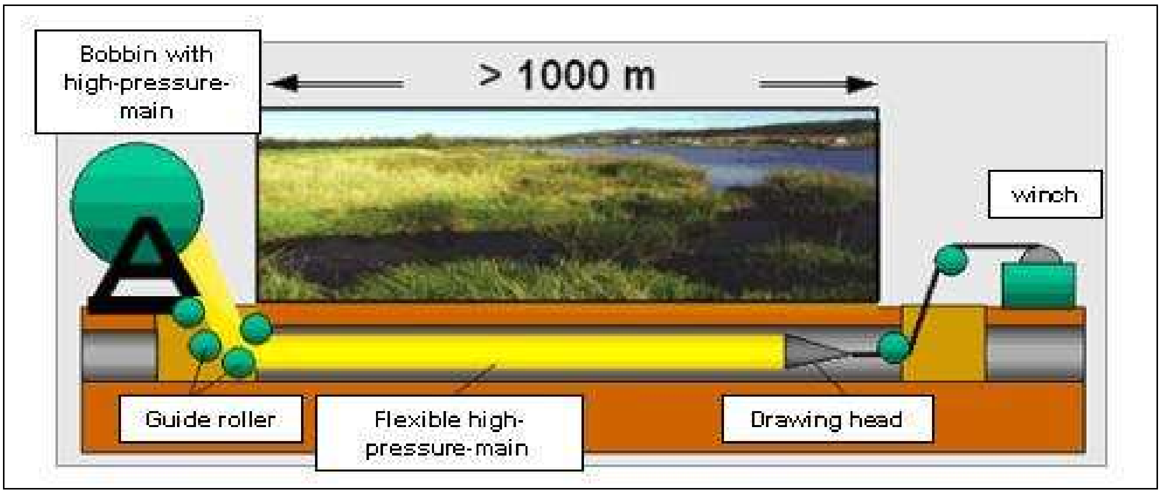
4.3.8. **Primus Line – Rädlinger primus line GmbH**

“Primus Line“ is a trenchless braided-hose-relining-technology for the rehabilitation of gas-distribution pipelines.

A self-supporting, flexible braided hose is drawn into the carrier pipe (Graph 4.12). The pressure is taken up completely by Primus Line. The carrier pipe remains as a static buttress against the earth thrust.

No cleaning or preparation of the inside diameter is necessary (except roots or sharp edges) because the carrier pipe and the hose will not be cemented.

The used material is a seamless woven aramid fibre which is embedded in high-performance plastics.



Graph 4.12: Primusline (procedure) [20]

Tab. 4.12: Specifications of Primus Line

Permeation of hythan	There are no existing measurements available.
Interaction of hydrogen with the material	Chemical resistance is granted.
Reduction of the initial diameter	22 mm (5 mm annular space + 6 mm wall thickness)
Available diameter	DN 150 … DN 500
Maximum pressure range	25 bar
Maximum continuous length per one phase of construction	1000 m
Durability of the rehabilitated segments	> 50 a
Costs per meter	Depends on the current project.
Certificate	DVGW – Certification
Contact / further information	http://primusline.raedlinger.com

4.3.9. <u>SANILINCK Standard – Sanivar AG</u>

“SANILINCK Standard“ is a trenchless foil-relining-technology for the rehabilitation of gas-distribution pipelines.

After cleaning the carrier pipe the adhesive filled foil hose is inserted by using the inversion technology (Graph 4.13, Graph 4.10). The hose is pressed against the pipe’s inside wall with compressed air. When the adhesive has cured the pipe end is fixed with sleeves and adhesive and the house connection lines are remilled by a robot.

The used materials are PUR for the foil hose and nitrile rubber for the sleeves.

Graph 4.13: Inversion technology [21]

Tab. 4.13: Specifications of SANILINCK Standard

Permeation of hythan	There are no existing measurements available.
Interaction of hydrogen with the material	Chemical resistance is granted.
Reduction of the initial diameter	5 … 7 mm
Available diameter	DN 30 … DN 500
Maximum pressure range	4 bar
Maximum continuous length per one phase of construction	250 m
Durability of the rehabilitated segments	≤ 50 a
Costs per meter	80 … 200 €, depends on the current project.
Certificate	DIN-DVGW-Certification SVGW-Certification
Contact / further information	http://www.sanivar.ch

4.3.10. SANILINE G – Sanivar AG

“SANILINE G“ is a trenchless draw-in technology for the rehabilitation of gas-distribution pipelines.

The installation is the same as those SANILINCK Standard (Graph 4.13).

The used material is a laminated plastic fabric.

Tab. 4.14: Specifications of SANILINE G

Permeation of hythan	There are no existing measurements available.
Interaction of hydrogen with the material	Chemical resistance is unknown.
Reduction of the initial diameter	5 … 7 mm
Available diameter	DN 80 … DN 600
Maximum pressure range	4 bar (in Germany), 5 bar (in Switzerland)
Maximum continuous length per one phase of construction	250 m
Durability of the rehabilitated segments	≤ 50 a
Costs per meter	80 … 200 €, depends on the current project.
Certificate	DIN-DVGW-mark of conformity NG-5152AT0268, valid till 31.08.08 SVGW-Certification Nr. 99-038-7, valid till 28.02.09.
Contact / further information	http://www.sanivar.ch

4.3.11. starline® _200 – Karl Weiss Technologieunternehmen GmbH & Co. KG

“starline®_200“ is a trenchless braided-hose-relining-technology for the rehabilitation of house service connection lines.

A braided hose is drawn in the cleaned carrier pipe and agglutinated with the pipe’s inside wall. There can be up to five 90°-bendings o verridden.

The used materials are a polyester yarn with an interior coating of PU for the braided hose and a solventless two-component epoxy adhesive.

Tab. 4.15: Specifications of starline®_200

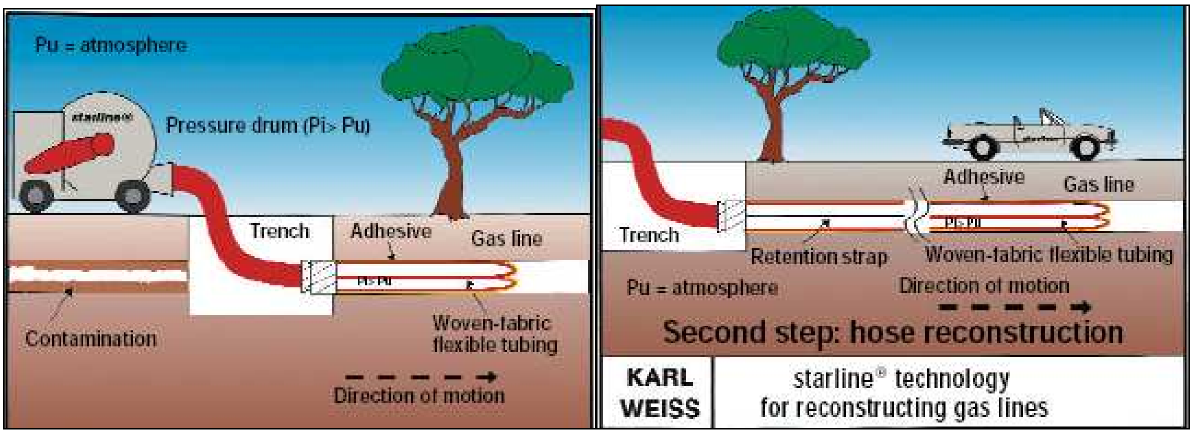
Permeation of hythan	There are no existing measurements available.
Interaction of hydrogen with the material	Chemical resistance is granted.
Reduction of the initial diameter	6 mm
Available diameter	DN 20 … DN 50
Maximum pressure range	4 bar
Maximum continuous length per one phase of construction	60 m
Durability of the rehabilitated segments	> 50 a
Costs per meter	Depends on the current project.
Certificate	DIN 30658-1 / G478 / W322-1 / VP404
Contact / further information	http://www.karl-weiss.com

4.3.12. starline® 2000 – Karl Weiss Technologieunternehmen GmbH & Co. KG

"starline®_2000"is a trenchless braided-hose-relining-technology for the rehabilitation of gas-distribution pipelines.

After cleaning the carrier pipe the adhesive filled braided hose is inserted by using the inversion technology (Graph 4.14). The hose is pressed against the pipe's inside wall with compressed air.

The used materials are a polyester fabric for the braided hose and a solventless two-component adhesive.



Graph 4.14: starline® - technology [22]

Tab. 4.16: Specifications of starline®_2000

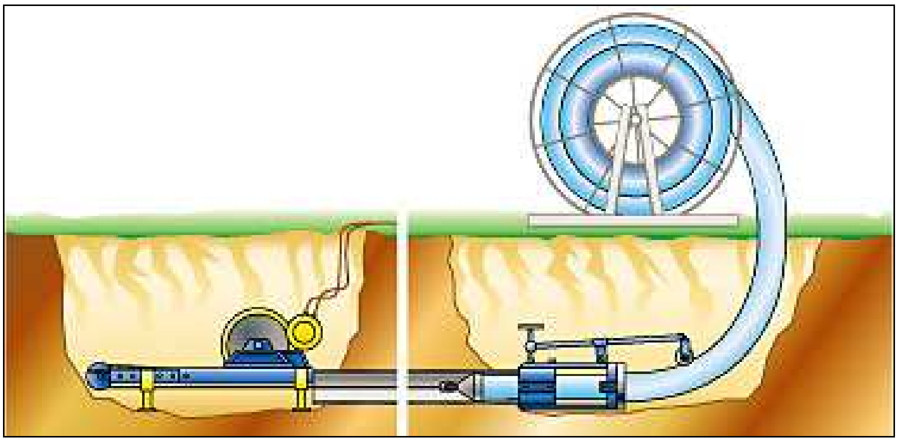
Permeation of hythan	There are no existing measurements available.
Interaction of hydrogen with the material	Chemical resistance is granted.
Reduction of the initial diameter	6 mm
Available diameter	DN 100 … DN 600
Maximum pressure range	4 bar
Maximum continuous length per one phase of construction	600 m (Depends on the diameter)
Durability of the rehabilitated segments	> 50 a
Costs per meter	Depends on the current project.
Certificate	DIN 30658-1 / G478 / W322-1 / VP404
Contact / further information	http://www.karl-weiss.com

4.3.13. Swage-Lining – Advantica / Rabmer / Wirsbo Pex GmbH

“Swagelining“ is a trenchless draw-in technology for the rehabilitation of gas-distribution pipelines.

A PE-pipeline is drawn under tensile stress through a mould into the carrier pipe (Graph 4.15). As a result the initial diameter of the pipe decreases by 10…20 %. When the pipe is drawn in completely, the tensile stress is taken away and the pipe recovers its previous diameter and applies to the carrier pipe’s inside wall.

The used materials are PE-X or HD-PE.



Graph 4.15: Swage-Lining [19]

Tab. 4.17: Specifications of Swage-Lining

Permeation of hythan	There are no existing measurements available.
Interaction of hydrogen with the material	Chemical resistance is granted.
Reduction of the initial diameter	2,3 mm… 22,7 mm (dependent on the pressure stage and the SDR-category)
Available diameter	DN 100 … DN 750
Maximum pressure range	8 bar
Maximum continuous length per one phase of construction	500 m
Durability of the rehabilitated segments	> 50 a
Costs per meter	Depends on the current project.
Certificate	DVGW-Certification
Contact / further information	http://www.advantica.biz http://www.rabmer.at http://www.wirsbo.de

4.3.14. U-Liner® – PRS-Rohrsanierung / Rabmer / Rehau AG+Co

“U-Liner®“ is a trenchless draw-in technology for the rehabilitation of gas-distribution pipelines.

A pipeline, which was deformed after the manufacture, is drawn into the carrier pipe (Graph 4.16). Then it is heated with compressed steam and the U-liner gets back into its previous shape and applies at the carrier pipe’s inside wall.

The used material is HD-PE.

Graph 4.16: U-Liner – technology [18]

Tab. 4.18: Specifications of U-Liner®

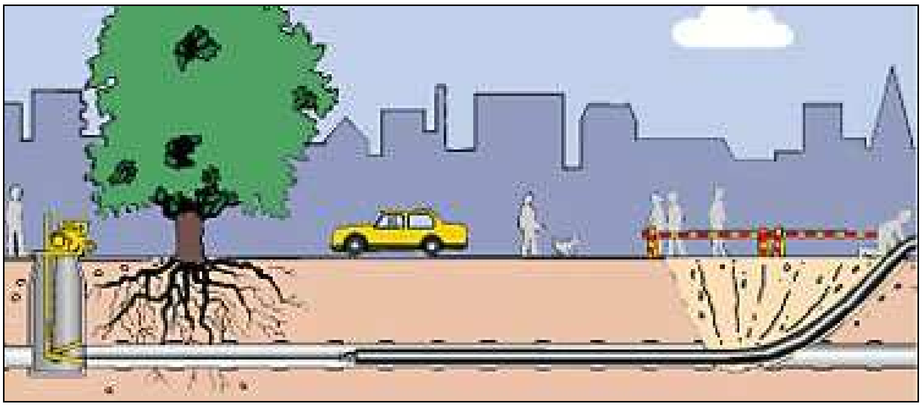
Permeation of hythan	There are no existing measurements available.
Interaction of hydrogen with the material	Chemical resistance is granted.
Reduction of the initial diameter	12 … 36 mm
Available diameter	DN 100 … DN 400
Maximum pressure range	4 bar
Maximum continuous length per one phase of construction	600 m for DN 100 and 100 m for DN 400
Durability of the rehabilitated segments	> 50 a
Costs per meter	Depends on the current project.
Certificate	DVGW-Certification
Contact / further information	http://www.prsrohrsanierung.de http://www.rabmer.at http://www.rehau.de

4.3.15. Sliplining – Uponor / Wirsbo Pex GmbH

“Sliplining” is a trenchless relining technology for the rehabilitation of gas-distribution pipelines.

A PE-pipe is drawn into the carrier pipe (Graph 4.17) and the pipe’s ends are weld together. The new pipe’s outside diameter must be smaller than the inside diameter of the carrier pipe.

The used materials are PE-X or HD-PE.



Graph 4.17: Sliplining – technology [19]

Tab. 4.19: Specifications of Sliplining

Permeation of hythan	There are no existing measurements available.
Interaction of hydrogen with the material	Chemical resistance is granted.
Reduction of the initial diameter	2,3 mm… 22,7 mm
Available diameter	DN 25 … DN 250
Maximum pressure range	8 bar
Maximum continuous length per one phase of construction	500 m
Durability of the rehabilitated segments	> 50 a
Costs per meter	Depends on the current project.
Certificate	DVGW-Certification
Contact / further information	http://www.uponor.com http://www.wirsbo.de

4.3.16. <u>Wavin TS – Wavin GmbH</u>

“Wavin TS“ is a three-layer pipe system for the exchange of distribution pipelines with technologies like burst-lining or pipe-splitting.

The installation is carried out as the one of “Pipe bursting – Uponor / Wirsbo Pex GmbH” (Graph 4.6, Graph 4.11).

The pipe consists of a median layer made of PE 100 and an inside and outside layer made of the PE 100-material XSC 50 as a protective layer against mechanical influences resulting from the installation process or fragments of the former pipeline.

Tab. 4.20: Specifications of Wavin TS

Permeation of hythan	There are no existing measurements available.
Interaction of hydrogen with the material	Chemical resistance is granted.
Reduction of the initial diameter	The old pipe can be substituted with a PE-pipe of equal or larger diameter.
Available diameter	DN 32 … DN 225
Maximum pressure range	10 bar
Maximum continuous length per one phase of construction	600 m (Depends on the diameter)
Durability of the rehabilitated segments	> 50 a
Costs per meter	Depends on the current project.
Certificate	DVGW-Certification
Contact / further information	http://www.wavin.de

5. Evaluation matrix and criteria

5.1 General information

The evaluation matrix contains the criteria which are most relevant to asses the different technologies. The information regarding the criteria was retrieved from the offering companies.
The criteria were weighted according to their influence relating to the suitability of the investigated technologies. The higher the value of the weight the larger is the influence of the criterion on the assessment.
The fulfilment of the criteria is reflected by marks. The best mark is “1” (very good), the worst “5” (insufficient) complying with “Appendix 4 – Catalogue of marks”.
The matrix is working on the minimum principle. That means that the technology with the lowest sum of marks is the best-suited technology for the repair or rehabilitation of hythan-transporting pipelines.

5.2 Evaluation matrix

Below, the evaluation matrix is shown as an example (Tab. 5.1).
The complete matrix with the values of all investigated technologies can be found in “Appendix 3 – Evaluation matrix”.
The working method of the matrix is illustrated below:

$$\boxed{\text{provisional result} = \text{weight} \bullet \text{mark}} \quad \text{(Equ. 5.1)}$$

$$\boxed{\text{sum} = \sum (\text{provisional results})} \quad \text{(Equ. 5.2)}$$

Tab. 5.1: Evaluation matrix (cut-out)

			Company Technology	
Criterion		**Weight**	**Mark (1...5)**	**Provisional result**
Suitability for hythan	Permeation of hythan	4	1	4
	Interaction of hydrogen with the material	5	3	15
Technological criteria	Reduction of the initial diameter	3	4	12
	Available diameter	2	5	10
	Maximum pressure range	2	1	2
	Maximum continuous length	2	2	4
	Durability of the rehabilitated segments	4	3	12
			Sum:	**59**

5.3 Explanation of the used criteria and their weightings

The primary objective of this assessment is to verify whether the existing technologies are suitable for the use under hythan-atmosphere or not. This is reflected in the weights of the considered criteria.

Economical and further technological details were considered, too.

As for some criteria, there aren't any or only insufficient data, the respective criteria won't be considered in the evaluation matrix for reasons of comparability.

Permeation of hythan

The permeation of hythan gets the weight "4" because permeating hythan means loss. Because of the low ignition energy and the large ignitable range (Tab. 3.6: Inflammability limits of fuel-gas) special precautions, especially for technologies with annular space, are necessary.

Interaction of hydrogen with the material

The interaction of hydrogen / hythan with the used materials is a very important criterion which gets the weight "5". If there are any reactions between hythan and the pipeline, used adhesives or other components, the functionality and safety of the pipeline might be impaired.

Reduction of the initial diameter

The reduction of the initial diameter gets the weight "3". If the pipe's cross-section is reduced the transported gas-volume per unit of time falls. This effect can be compensated by increasing the compressor-power. Dependent on the flow rate and the maximum pressure range such a procedure isn't always possible. Besides, an increase of the compressor-power leads to higher running costs and can cause succession-investments.

Repair technologies are used for small-area damage only. In that case the reduction of initial diameter is irrelevant and won't be considered in the evaluation matrix.

Available diameter

The availability of diameter gets the weight "2". A small selection of diameter reduces the technological applicability and an enlargement of diameter allows only selected technologies.

Maximum pressure range

The maximum pressure range gets the weight “2”. An exceedance of the maximum pressure range is not allowed (exclusion-criterion!) and a pressure-reserve should be kept for an operational increase of pressure.

Maximum continuous length per one phase of construction

The maximum continuous length gets the weight “2”. In order to keep the impairment of the environment as small as possible in residential areas, areas with a high volume of traffic and in protected areas, as little as possible surface construction works should be carried out. Besides, the maximum continuous length has an economic effect, because if the number of trenches increases, the costs for construction works will rise, too.

The maximum length, as the reduction of initial diameter, won’t be considered for repair technologies in the evaluation matrix.

Durability of the rehabilitated segments

The durability of the rehabilitated segments gets the weight “4”. It is an important factor as it influences the economic efficiency and the sustainability of the used technologies.

Costs per meter

The costs per phase of construction or per meter and the durability of the rehabilitated segments determine the economic efficiency of the technology.

As the costs always depend on the current problem and as estimates are only for a few technologies available, the costs won’t be considered in the evaluation matrix.

Certificate

The certificate won’t be considered in the evaluation matrix as it is safe to assume that only approved technologies and materials will be used.

5.4 Distribution of marks

There are marks awarded from “1” to “5”. “1” stands for “very good” and “5” stands for “insufficient”. To ensure an objective distribution of marks there is a catalogue (Appendix 4 – Catalogue of marks). The catalogue describes which criteria must be fulfilled in which way to reach which mark.

5.5 Evaluation of the matrix

Below, the evaluation and the distribution of points in the evaluation matrix (Appendix 3) is shown.

Tab. 5.2: Result of the evaluation matrix

Repair technologies			
Place	**Company**	**Technology**	**Points**
1	Linkpipe	GasSealer Sleeve	38
2	PRS-Rohrsanierung / Rabmer	WECO®	48
3	WrapMaster, Inc.	WeldWrap	50
4	Amex	Amex©-10	74

Rehabilitation technologies			
Place	**Company**	**Technology**	**Points**
1	Collex NoDig / Uponor / Wirsbo Pex GmbH	Pipe bursting	42
2	Egeplast	egeplast SLA 2.0 / 3L	46
3	Karl Weiss Technologieunternehmen GmbH & Co. KG	hydros®_PLUS	48
3	PRS-Rohrsanierung / Rabmer	PHOENIX®	48
4	Advantica / Rabmer / Wirsbo Pex GmbH	Swage-Lining	51
4	Rädlinger primus line GmbH	Primus Line	51
5	Karl Weiss Technologieunternehmen GmbH & Co. KG	hydros®_STAR	52
5	Wavin GmbH	Wavin TS	52
6	Karl Weiss Technologieunternehmen GmbH & Co. KG	hydros®_BOY	58
6	Sanivar AG	SANILINCK Standard	58
6	Wavin GmbH	Compact Pipe	58
7	Uponor / Wirsbo Pex GmbH	Sliplining	59
8	Karl Weiss Technologieunternehmen GmbH & Co. KG	starline®_2000	60
9	PRS-Rohrsanierung / Rabmer / Rehau AG+Co	U-Liner®	68
10	Karl Weiss Technologieunternehmen GmbH & Co. KG	starline®_200	74
11	Sanivar AG	SANILINE G	90

Basically, none of the repair and rehabilitation technologies has to be excluded from the use with hythan. For unknown permeation coefficients and chemical resistance bad marks have been given, too. After investigating the materials the place of the technologies may change.

Because of the high weighting of the criteria “permeation” and “chemical resistance”, the technologies using the most suitable materials rank first.
These materials are mainly steel (for repair), HD-PE, PE-X, the coated aramid fibre (Rädlinger) and the laminated composite pipe-system with aluminium-barrier (egeplast).
When using steel, there is the danger of hydrogen corrosion mainly on the welding seams for some kind of steel. That would cause leaks and damage at the pipeline.

For materials which are resistant against hydrogen and natural gas, a problem regarding the resistance against hythan is unlikely, too.

To give definite statements about the suitability of the technologies and materials regarding the use with hythan, it is necessary to make further investigations.
For the different used materials analyses regarding permeation and chemical resistance have to be made.

6. Technological and economic consequences

6.1 Permeation

For natural gas, the loss of permeated gas volume is usually insignificant.
Due to the bigger permeation coefficient of hydrogen and hence of hythan compared to natural gas (Appendix 2 – Ranking of permeation), substantially higher volumetric flow rates than in pipelines conducting natural gas may result depending on the used materials. Regarding economic and safety aspects, these volumetric flow rates may be questionable.

If an annular space is left between new- and carrier-pipe at rehabilitated pipelines, an ignitable gas-air-mixture could occur due to permeation which would cause a safety problem (Tab. 3.6: Inflammability limits of fuel-gas).
To avoid explosions respiration nozzles with ignition breakdown protection for the annular space and periodical flushing have to be planned. The design of the respiration nozzles and the time intervals of flushing depend on the dimensions of the annular space and the permeation coefficients of the used materials. [4]

Due to the missing data on permeation of hythan, no precise statements about leakage flow rates and necessary flushing intervals can be made. Specifications about the permeability of the used materials for several gases are shown in "Appendix 2 – Ranking of permeation".

Ignition sources (electrical and mechanical sparks; open fire; electrostatics; pyrophoric substances; shock wave ignition; lightning strike) inside the annual space and around the respiration nozzles during the operating time or possible works have to be avoided to prevent the reaching of the minimum ignition energy (chapter 2.4). [4]

The low calorific value of hydrogen leads to a partial compensation of the increased permeated volume. The result is a buffering of the energetic loss and due to that a buffering of the monetary loss caused by permeation.

According to the latest findings the increased permeation of hydrogen causes neither a safety relevant nor an economic danger. After determining the permeation coefficients the economic effect should be investigated thoroughly.

Besides, a safety relevant investigation, above all for repair and rehabilitation technologies with annual space, is recommended.

6.2 Loss of pressure

The inserting of pipelines, pipe liners and braided hoses in a carrier pipe results in reduction of the initial diameter.

As the volumetric flow rate and the pressure from before the rehabilitation is usually needed, the gas flow rate has to be raised. That results in a rising loss of pressure and, consequently, in a rising compressor rating.

Plastic pipelines are less rough than the initial steel pipeline, so the reduction of the initial diameter can, for large diameters, be partially compensated.

The following calculation shows the loss of pressure in a pipeline after rehabilitation with a technology with annual space.

The **example calculation for hythan after the rehabilitation** is made according to the same equations and environmental parameters as for hythan before the rehabilitation (chapter 2.6).

$\dot{V}$ =1800 m³/h = 0.5 m³/s; p_e=1 bar; t=10 °C.

The new pipeline is a PE-X-pipeline with d_a=200 mm and SDR 11 (s=18.1 mm). Because of that, the pipe's inside diameter is reduced to d_i=163.8 mm and the roughness falls to k=0.01 (tabular value for plastic pipelines).

$$\nu = 30.026 \bullet 10^{-6}\ \frac{m^2}{s}$$

$$w = \frac{\dot{V} \bullet 4}{d_i^2 \bullet \pi} = \frac{0.5\ m^3 \bullet 4}{s \bullet (0.1638\ m)^2 \bullet \pi} = 23.73\ \frac{m}{s}$$

The flow rate is too high for an MD-system (7 … 18 m/s) and must be adjusted by reducing the volumetric flow rate or raising the pressure in the pipeline. To keep the example calculations comparable, the flow rate will be maintained (for this example).

$$Re = \frac{w \bullet d_i}{\nu} = \frac{23.73\ m \bullet s \bullet 0.1638\ m}{s \bullet 30.026 \bullet 10^{-6}\ m^2} = 129454$$

Re=129454 > Re_{krit}=2320 → turbulent flow in the pipeline

$$\frac{d}{k} = \frac{163.8\ mm}{0.01\ mm} = 16380$$

The intersection point of the two lines (Reynolds number and d/k) is found in the hydraulic smooth range.

The according λ-value is 0.017. To check, the λ-value is set into the following equation 6.1 (Nikuradse) [3]:

$$\boxed{\lambda = 0.0032 + 0.221 \bullet Re^{-0.237} = 0.0032 + 0.221 \bullet 129454^{-0.237} = 0.0168} \quad \text{(Equ. 6.1)}$$

$\boxed{0.017 \approx 0.0168}$ → The rough equality shows that the determination of the pipe friction coefficient was sufficiently exact.

That results in the loss of pressure for the line section:

$$\boxed{\Delta p_V = 0.0168 \bullet 0.84 \frac{kg}{m^3} \bullet 8 \bullet \frac{1000\ m}{0.1638^5\ m^5} \bullet \frac{(0.5\ m^3)^2}{\pi^2 s^2} = \underline{\underline{24252\ Pa}} \mathrel{\hat{=}} \underline{\underline{0.2425\ bar}}}$$

The loss of pressure before the rehabilitation was 0.106 bar.

Hence it appears, that the reduction of the initial diameter causes a rise of the flow rate, which has a considerable effect on the loss of pressure in pipelines, above all for small diameters, and so to the necessary compressor rating.

Alternative technologies are for example burst-lining, which is a substitution of the old pipeline by a new pipeline of the same or bigger diameter, or relining technologies with foil hoses, which cause only a little reduction of the initial diameter (Appendix 5 – Nominal diameter).

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Appendix 1 – Combustion calculation (Natural Gas)

The calculation is made exemplary for the following parameters:
Air: p=1,02 bar, t=20 ℃, φ=60%, λ=1,15 ? wL = 0,014 m³H2O/m³L
Gas: p=1,05 bar, t=12 ℃, φ=20% ? wg = 0,0027 m³H2O/m³B

Fuel gas				Minimum need of oxygen (λ=1)		Exhaust gas component (λ=1)					
Component	Fraction	net calorific value $H_{i,n}$		f,O	O,min	f,CO_2	v,CO_2	f,N_2	v,N_2,min	f,H_2O	v,H_2O,min
	(dry)	Gas	Fraction								
-	-	MJ/m³	MJ/m³	-	m³O_2/m³B	-	m³CO_2/m³B	-	m³N_2/m³B	-	m³H_2O/m³B
H_2[b]		10,783	0,000	0,5						1	0,000
CH_4[b]	0,930	35,883	33,371	2	1,860	1	0,930			2	1,860
C_2H_6[b]	0,030	64,345	1,930	3,5	0,105	2	0,060			3	0,090
C_3H_8[b]	0,013	93,215	1,212	5	0,065	3	0,039			4	0,052
n-C_4H_{10}[b]	0,006	123,810	0,743	6,5	0,039	4	0,024			5	0,030
CO_2[b]	0,010					1	0,010				
N_2[b]	0,011							1	0,011		
O_2[b]				-1	0,000						
w_g	(0,0027)									1	0,003
Σ	1,000	$H_{u,n}$ =	37,256	o_{min} =	2,069	v_{CO2} =	1,063				

Combustion air	λ=1	Minimum need of air l_{min}=o_{min}/0,21 = 9,852 m³L/m³B	$v_{N2(L)}$ =0,79?l_{min}=0,79? (atmospheric nitrogen)	9,852	m³N_2/m³B	1	7,783			
						vN2,min =	7,794			
			$v_{H2O(L)}$ = w_l ?l_{min} = (air humidity)	0,014	9,852	m³H_2O/m³B			1	0,138
									$v_{H2O,min}$=	2,173
	λ>1	Effective combustion air	l = λ ?lmin =	1,15	9,852	m³L/m³B =	11,33	m³L/m³B		

Exhaust gas	λ=1	Minimum exhaust gas (dry)	$v_{min,t}$ = v_{CO2} + $v_{N2,min}$ =	8,857	m³tA/m³B
		Minimum exhaust gas (humid)	$v_{min,f}$ = $v_{min,t}$ + $v_{H2O,min}$ =	11,030	m³fA/m³B

						in Vol-% dry		humid	
Exhaust gas	λ>1	Exhaust gas component	v_{CO2} =	= 1,063	m³CO2/m³B	CO_2[a]=	10,3	r_{CO2} =	8,5
			v_{O2} = 0,21 (λ-1) lmin	= 0,310	m³O2/m³B	O_2[a]=	3,0	r_{O2} =	2,5
			v_{N2} = $v_{N2,min}$ + 0,79 (λ-1) lmin	= 8,962	m³N2/m³B	N_2[a]=	86,7	r_{N2} =	71,5
			v_{H2O} = $v_{H2O,min}$ + wl (λ-1) lmin	= 2,193	m³H2O/m³B			r_{H2O} =	17,5
		Effective combustion air (dry)	v_t=v_{CO2}+v_{O2}+v_{N2}=	10,335	m³tA/m³B	$CO_{2,max}$[a]=	v_{CO2}/$v_{min,t}$?100%		
		Effective combustion air (humid)	v_f=v_t+v_{H2O}=	12,529	m³fA/m³B	$CO_{2,max}$[a]=	12,0 %		

Appendix 1 – Combustion calculation (Hythane)

The calculation is made exemplary for the following parameters:
Air: p=1,02 bar, t=20 ℃, φ=60%, λ=1,15 ? wL = 0,014 m³H2O/m³L
Gas: p=1,05 bar, t=12 ℃, φ=20% ? wg = 0,0027 m³H2O/m³B

Fuel gas				Minimum need of oxygen (λ=1)		Exhaust gas component (λ=1)					
Component	Fraction	net calorific value $H_{i,n}$		f,O	O,min	f,CO_2	v,CO_2	f,N_2	v,N_2,min	f,H_2O	v,H_2O,min
	(dry)	Gas	Fraction								
-	-	MJ/m³	MJ/m³	-	m³O_2/m³B	-	m³CO_2/m³B	-	m³N_2/m³B	-	m³H_2O/m³B
H_2[b]	0,500	10,783	5,392	0,5						1	0,500
CH_4[b]	0,465	35,883	16,686	2	0,930	1	0,465			2	0,930
C_2H_6[b]	0,015	64,345	0,965	3,5	0,053	2	0,030			3	0,045
C_3H_8[b]	0,007	93,215	0,606	5	0,033	3	0,020			4	0,026
n-C_4H_{10}[b]	0,003	123,810	0,371	6,5	0,020	4	0,012			5	0,015
CO_2[b]	0,005					1	0,005				
N_2[b]	0,006							1	0,0055		
O_2[b]				-1	0,000						
w_g	(0,0027)									1	0,003
Σ	1,000	$H_{u,n}$ =	24,020	o_{min} =	1,035	v_{CO2} =	0,532				
Combustion air, λ=1	Mindestluftbedarf			$v_{N2(L)}$ =0,79?l_{min}=0,79?		4,926	m³N_2/m³B	1	3,892		
	$l_{min}=o_{min}/0,21$=	4,926	m³L/m³B	(atmospheric nitrogen)				vN2,min =	3,897		
				$v_{H2O(L)} = w_l$?l_{min} =			0,014	4,926	m³H_2O/m³B	1	0,069
				(air humidity)						$v_{H2O,min}$=	1,588
Combustion air, λ>1	Effective combustion air			l = λ ?lmin =			1,15	4,926	m³L/m³B =	5,67	m³L/m³B
Exhaust gas, λ=1	Minimum exhaust gas (dry)			$v_{min,t} = v_{CO2} + v_{N2,min}$ =						4,429	m³tA/m³B
	Minimum exhaust gas (humid)			$v_{min,f} = v_{min,t} + v_{H2O,min}$ =						6,016	m³fA/m³B
Exhaust gas, λ>1	Exhaust gas component							in Vol-%			
								dry		humid	
		v_{CO2} =			=	0,532	m³CO2/m³B	CO_2[a]=	10,3	r_{CO2} =	7,9
		v_{O2} = 0,21 (λ-1) lmin			=	0,155	m³O2/m³B	O_2[a]=	3,0	r_{O2} =	2,3
		v_{N2} = $v_{N2,min}$ + 0,79 (λ-1) lmin			=	4,481	m³N2/m³B	N_2[a]=	86,7	r_{N2} =	66,2
		v_{H2O} = $v_{H2O,min}$ + wl (λ-1) lmin			=	1,598	m³H2O/m³B			r_{H2O} =	23,6
	Effective combustion air (dry)			$v_t=v_{CO2}+v_{O2}+v_{N2}$=		5,168	m³tA/m³B	$CO_{2,max}$[a]=	$v_{CO2}/v_{min,t}$?100%		
	Effective combustion air (humid)			$v_f=v_t+v_{H2O}$=		6,766	m³fA/m³B	$CO_{2,max}$[a]=	12,0 %		

Appendix 2 – Ranking of permeation

Lfd. Nr.	Material	Technology	Permeation [cm^3 / m d bar]				Ranking-position	Chemical resistance	
			H_2	O_2	CO_2	CH_4			
			Ratio of the permeation coefficients to each other [based on HD-PE]						
			3,9	1,3	5	1		H_2	CH_4
1	PE 80 / 100 + aluminum barrier	Egeplast	Gasdicht	Gasdicht	Gasdicht	Gasdicht	1	Yes	Yes
2	Steel	GasSealer Sleeve	Gasdicht	Gasdicht	Gasdicht	Gasdicht	1	Yes	Yes
3	PE-X	Pipe bursting Swagelining	1,45E-08	4.84E-09 [5]	1,86E-08	3,72E-09	2	Yes	Yes
4	Aramid fibre with a plastic-coating	Rädlinger PrimusLine	0,0062	0,0021	0,0080	0.0016 [6]	3	Yes	Yes
5	PUR	SANILINCK Standard	0,1872	0,0400	0.2400 [7]	0,0480	4	Yes	Yes
6	HD-PE	hydros_BOY hydros_PLUS hydros_STAR Pipe bursting Swagelining U-Liner Sliplining	0.2200 [1]	0.0720 [1]	0.2800 [1]	0.05600 [1]	5	Yes	Yes
7	Polyester yarn with a PP-coating	PHOENIX	0,2535	0,0845	0,3250	0,0650	6	Yes	Yes
8	Polyester yarn with PU-coating	starline_200 starline_2000	0,2535	0,0845	0,3250	0,0650	7	Yes	Yes
9	PE 80 / PE 100	Compact Pipe Wavin TS	1,7784	0,5928	2.2800 [8]	0,4560	8	Yes	Yes
10	Fibreglass	WeldWrap	No existing measurements available				9	Yes	Yes
11	Laminated plastic fabric	SANILINE G	No existing measurements available				9	?	Yes
12	NBR	WECO	No existing measurements available				9	Yes	Yes
13	Rubber	AMEX-10	No existing measurements available				9	?	Yes

Underlined values are tabular values. The other values are calculated from the ratio of the permeation coefficients to each other.

Appendix 3 – Evaluation matrix (repair technologies)

			Amex		Linkpipe		PRS-Rohrsanierung / Rabmer		WrapMaster, Inc.	
			Amex©-10		Gassealer Sleeve		WECO®		WeldWrap	
Criterion		**Weight**	**Mark (1...5)**	**Provisional result**	**Mark (1...5)**	**Provisional result**	**Mark (1...5)**	**Provisional result**	**Mark (1...5)**	**Provisional result**
Suitability for hythan	Permeation of hythan	4	5	20	1	4	5	20	5	20
	Interaction of hydrogen with the material	5	5	25	1	5	1	5	1	5
Technological criteria	Reduction of the initial diameter	3	1	3	1	3	1	3	1	3
	Available diameter	2	3	6	3	6	1	2	3	6
	Maximum pressure range	2	3	6	3	6	2	4	1	2
	Maximum continuous lenght	2	1	2	1	2	1	2	1	2
	Durability of the rehabilitated segments	4	3	12	3	12	3	12	3	12
			Sum:	**74**	**Sum:**	**38**	**Sum:**	**48**	**Sum:**	**50**

Appendix 3 – Evaluation matrix (rehabilitation technologies page 1)

			Wavin GmbH		Egeplast		Karl Weiss Technologieunternehmen GmbH & Co. KG		Karl Weiss Technologieunternehmen GmbH & Co. KG	
			Compact Pipe		egeplast SLA 2.0 / 3L		hydros®_BOY		hydros®_PLUS	
Criterion		**Weight**	**Mark (1...5)**	**Provisional result**	**Mark (1...5)**	**Provisional result**	**Mark (1...5)**	**Provisional result**	**Mark (1...5)**	**Provisional result**
Suitability for hythan	Permeation of hythan	4	4	16	1	4	3	12	3	12
	Interaction of hydrogen with the material	5	1	5	1	5	1	5	1	5
Technological criteria	Reduction of the initial diameter	3	3	9	5	15	1	3	1	3
	Available diameter	2	5	10	4	8	5	10	5	10
	Maximum pressure range	2	2	4	2	4	3	6	3	6
	Maximum continuous lenght	2	1	2	3	6	5	10	3	6
	Durability of the rehabilitated segments	4	3	12	1	4	3	12	3	12
			Sum:	**58**	**Sum:**	**46**	**Sum:**	**58**	**Sum:**	**54**

			Sanivar AG		Sanivar AG		Karl Weiss Technologieunternehmen GmbH & Co. KG		Karl Weiss Technologieunternehmen GmbH & Co. KG	
			SANILINCK Standard		SANILiNE G		starline®_200		starline®_2000	
Criterion		**Weight**	**Mark (1...5)**	**Provisional result**	**Mark (1...5)**	**Provisional result**	**Mark (1...5)**	**Provisional result**	**Mark (1...5)**	**Provisional result**
Suitability for hythan	Permeation of hythan	4	2	8	5	20	4	16	4	16
	Interaction of hydrogen with the material	5	1	5	5	25	1	5	1	5
Technological criteria	Reduction of the initial diameter	3	3	9	3	9	5	15	3	9
	Available diameter	2	4	8	4	8	5	10	4	8
	Maximum pressure range	2	4	8	4	8	4	8	4	8
	Maximum continuous lenght	2	2	4	2	4	4	8	1	2
	Durability of the rehabilitated segments	4	4	16	4	16	3	12	3	12
			Sum:	**58**	**Sum:**	**90**	**Sum:**	**74**	**Sum:**	**60**

Appendix 3 – Evaluation matrix (rehabilitation technologies page 2)

			Karl Weiss Technologieunternehmen GmbH & Co. KG		PRS-Rohrsanierung / Rabmer		Collex NoDig / Uponor / Wisrbo Pex GmbH		Rädlinger primus line GmbH	
			hydros®_STAR		PHOENIX®		Pipe bursting		Primus Line	
Criterion		**Weight**	**Mark (1...5)**	**Provisional result**	**Mark (1...5)**	**Provisional result**	**Mark (1...5)**	**Provisional result**	**Mark (1...5)**	**Provisional result**
Suitability for hythan	Permeation of hythan	4	3	12	3	12	1	4	2	8
	Interaction of hydrogen with the material	5	1	5	1	5	1	5	1	5
Technological criteria	Reduction of the initial diameter	3	1	3	3	9	1	3	4	12
	Available diameter	2	4	8	3	6	5	10	5	10
	Maximum pressure range	2	3	6	1	2	3	6	1	2
	Maximum continuous lenght	2	3	6	1	2	1	2	1	2
	Durability of the rehabilitated segments	4	3	12	3	12	3	12	3	12
			Sum:	**52**	**Sum:**	**48**	**Sum:**	**42**	**Sum:**	**51**

			Advantica / Rabmer / Wirsbo Pex GmbH		PRS-Rohrsanierung / Rabmer / Rehau AG+Co		Uponor / Wirsbo Pex GmbH		Wavin GmbH	
			Swage-Lining		U-Liner®		Sliplining		Wavin TS	
Criterion		**Weight**	**Mark (1...5)**	**Provisional result**	**Mark (1...5)**	**Provisional result**	**Mark (1...5)**	**Provisional result**	**Mark (1...5)**	**Provisional result**
Suitability for hythan	Permeation of hythan	4	3	12	3	12	3	12	4	16
	Interaction of hydrogen with the material	5	1	5	1	5	1	5	1	5
Technological criteria	Reduction of the initial diameter	3	2	6	5	15	4	12	1	3
	Available diameter	2	4	8	5	10	5	10	5	10
	Maximum pressure range	2	3	6	4	8	3	6	2	4
	Maximum continuous lenght	2	1	2	3	6	1	2	1	2
	Durability of the rehabilitated segments	4	3	12	3	12	3	12	3	12
			Sum:	**51**	**Sum:**	**68**	**Sum:**	**59**	**Sum:**	**52**

Appendix 4 – Catatogue of marks

Criterion: Permeation of hythan

The distribution of marks for permeation is made in accordance with “Appendix 2 - Ranking of permeation”, as there are only a few values for hydrogen and natural gas and no values for hythan.

Mark	Limiting value
1	Ranking-Position 1 … 2
2	Ranking-Position 3 … 4
3	Ranking-Position 5 … 6
4	Ranking-Position 7 … 8
5	Ranking-Position 9

Criterion: Interaction of hydrogen / methane with the used materials

The chemical resistances are shown in “Appendix 2 - Ranking of permeation“.

Mark	Limiting value
1	Chemical resistance is granted.
2	
3	
4	
5	Chemical resistance is not granted or unknown.

Criterion: Reduction of the initial diameter

For reasons of comparability of the different technologies and diameter an inside diameter / reduction - ratio was adopted → DRR (Diameter-Reduction-Ratio).
The calculated DRR-values are shown in “Appendix 5 - Diameter”.

Mark	Limiting value
1	≥ DRR 40 and no reduction (neglected for repair)
2	≥ DRR 30
3	≥ DRR 20
4	≥ DRR 10
5	< DRR 10

Criterion: Available diameter

For reasons of comparability of the different technologies the whole range of available diameter was set to 100 %. The percentage of the available diameter of the technologies leads to the mark. (Appendix 5 - Diameter)

Mark	Limiting value
1	≥ 60 %
2	≥ 45 %

3	≥ 30 %
4	≥ 15 %
5	< 15 %

Criterion: Maximum pressure range	
Mark	**Limiting value**
1	Maximum pressure range ≥ 16 bar
2	Maximum pressure range ≥ 10 … 16 bar
3	Maximum pressure range ≥ 8 … 10 bar
4	Maximum pressure range ≥ 4 … 8 bar
5	Maximum pressure range < 4 bar

Criterion: Maximum continuous length per one phase of construction	
Mark	**Limiting value**
1	≥ 500 m
2	≥ 250 … 500 m
3	≥ 150 … 250 m
4	≥ 50 … 150 m
5	< 50 m

Criterion: Durability of the rehabilitated segments	
Mark	**Limiting value**
1	≥ 100 a
2	≥ 75 a
3	≥ 50 a
4	≥ 25 a
5	< 25 a

Appendix 5 – Nominal diameter

Reduction of the initial diameter					
Diameter		Reduction		DRR	
from	to	from	to	from	to
500	1400	0,0	0,0	/	/
100	1400	0,0	0,0	/	/
600	3000	0,0	0,0	/	/
100	1400	0,0	0,0	/	/
100	500	3,9	23,6	25,6	21,2
25	630	4,0	74,0	6,3	8,5
20	60	0,0	0,0	/	/
100	400	0,0	0,0	/	/
100	600	0,0	0,0	/	/
100	1000	6,0	6,0	16,7	166,7
25	250	0,0	0,0	/	/
150	500	22,0	22,0	6,8	22,7
30	500	5,0	7,0	6,0	71,4
80	600	5,0	7,0	16,0	85,7
20	50	6,0	6,0	3,3	8,3
100	600	6,0	6,0	16,7	100,0
100	750	2,3	22,7	43,5	33,0
100	400	12,0	36,0	8,3	11,1
25	250	2,3	22,7	10,9	11,0
32	225	0,0	0,0	/	/

Forming of marks		
Mark for DRR		Average value
from	to	
1	1	1
1	1	1
1	1	1
1	1	1
3	3	3
5	5	5
1	1	1
1	1	1
1	1	1
4	1	3
1	1	1
5	3	4
5	1	3
4	1	3
5	5	5
4	1	3
1	2	2
5	5	5
4	4	4
1	1	1