HyDelta 2

WP5 – Safe operations on the high-pressure transmission grid

D5.2 – Report on safe isolation, depressuring, and evacuating of high-pressure hydrogen pipelines and installations for maintenance purposes.

Status: final

Dit project is medegefinancierd door TKI Nieuw Gas | Topsector Energie uit de PPS-toeslag onder referentienummer TKI2022-HyDelta.

Document summary

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Document historie

Versie	Datum	Auteur	Verbonden aan	Samenvatting van de wijzigingen
1	12 mei 2023	Robert Mellema Dennis van Putten Pieter Wolff	DNV	1e Conceptversie
2	27 juni 2023	Robert Mellema Dennis van Putten Pieter Wolff	DNV	2e Conceptversie
3	29 juni 2023	Robert Mellema Dennis van Putten Pieter Wolff	DNV	Concept tbv Supervisory Group

Verspreidingsniveau

PU	Publiek	X
RE	Beperkt tot Project partners inclusief Expert Assessment Group Externe entiteit met wie een geheimhoudingsplicht bestaat	

Document review

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Summary

Maintenance on high-pressure hydrogen pipelines, such as the Hydrogen Network Netherlands needs strategic consideration and planning. In this report, we provide an overview of the guidelines and methodology for isolating and evacuating a high-pressure pipeline or installation for a maintenance operation. The dialogues with various experts from the hydrogen gas industry provided a diverse range of perspectives and knowledge, helping to validate the nuances of different methodologies better. The general methodology of the maintenance procedure consist out of a few steps:

1. Identify the sections that need maintenance
2. Isolate the section that needs maintenance, utilizing valve schemes or stopples
3. Depressurize the system
4. Evacuate hydrogen with nitrogen, utilizing pigging, purging, or dilution techniques
5. Ensure secondary isolation and a bleed mechanism is in place
6. Execute maintenance operations
7. Flush the maintenance area with nitrogen before reintroducing hydrogen

The different evacuation and isolation methods impose slightly different methodologies, which will be explored in this report.

When isolating between valve schemes, evacuation with a separation PIG minimizes the mixing of hydrogen and nitrogen. The report discusses leakage rates along the pig for different types of pigs. These rates will be approximately 20-30% higher for hydrogen operations compared to using natural gas. Although the leakage is higher, the amount of back mixing is still very limited compared to the other techniques described in this report. Separation pigs will have an increased stick-slip behaviour since the reduction of the acoustic impedance increases 3 to 4 times. However, valve schemes with pigging facilities can be typically distanced 50 km to 100 km apart, this method requires closing down a large section of the pipeline. The process of pigging becomes less feasible for very long pipelines due to the large loss of gas volume and possible disruption of flow from suppliers and to industrial consumers.

If it is not feasible to start a pigging operation over a large section of pipeline due to loss of large volumes of hydrogen, a smaller section, between two valve schemes without the necessary facilities to perform a pigging operation, can be isolated and evacuated by performing a purge or dilution-based purge with nitrogen gas. The section cannot always be evacuated by purging due to physical constraints, such as stratification or the presence of dead volumes, dilution can be used to lower the concentration of hydrogen gas till acceptable levels. Evacuation by displacement or purging has its challenges, especially for long pipeline sections where stratification can occur. The minimum velocity requirements to prevent stratification for hydrogen and natural gas are computed and show that the velocity requirements are higher for hydrogen. The diffusion fronts of hydrogen and natural gas are computed in this report, demonstrating that the diffusion front length is velocity-independent and results in approximately equal volumes of remaining gas-air mixtures at different velocities. The distance of these valve schemes varies within the network, but can be up to up to 50 km apart. When these distance between valve schemes is high, the amount of hydrogen volume lost can still be quite large.

When it is more feasible to isolate and evacuate a smaller section, stopples can be installed to provide temporary isolation. Sections isolated with stopples can be sufficiently small to allow for the installation of a bypass, thus ensuring the continuity of gas flow to preserve gas supply within the hydrogen network.. The current procedures used for the natural gas network will not suffice for the hydrogen network, since they do not provide a double block and bleed. Alternatives techniques, such

as hydraulic stopples or a stopple train, due provide a double block and bleed and are discussed. These alternative techniques will need different equipment than the equipment currently in use and will need further research before applied in the field.

In complex systems or installations, such as the hydrogen storage facility HyStock, it is impossible to avoid dead volumes or spaces where the hydrogen flow is limited in the installation. Here, a dilution-based purge should be used. Alternating the pressure in the spaces with restricted gas exchange can also contribute in achieving a suitable dilution-based purge. Although this method will use an increased amount of nitrogen since it requires multiple purge-cycles for a successful purge, theoretical analyses and experimental data indicated that pockets of hydrogen would mix more efficiently with nitrogen compared to natural gas pockets, approximately 3.8 times faster.

These isolation methods and their preferred evacuation methods are described in the report. Table 9-1 shows an overview of the different techniques used.

Table 9-1 Summary of advantages and disadvantages of different isolation and preferred evacuation techniques

Isolated section	Preferred evacuation technique	Advantages	Disadvantages
Between valve schemes with pigging facilities (50~100 km distance)	Purging with a separation PIG	-Minimizes the mixing of hydrogen and nitrogen -No stratification problems and smaller diffusion front -Evacuation method is similar to natural gas	-Large loss of gas volume -possible disruption of suppliers and industrial consumers -Higher flowrates along the pig w.r.t. natural gas pigging
Between valve schemes without pigging facilities (10~50 km distance)	Purging	-No disruption of suppliers and industrial consumers -Evacuation method is similar to natural gas	-Possible large loss of gas volume -Stratification issues will arise more often w.r.t. natural gas
Installing temporary seal with stopple	Purging	-Limited loss of gas volume -Possibility to install temporary bypass	-Current evacuation methods used for natural gas will not suffice -More research needed on stopple trains and hydraulic stopples
Valve schemes (installation, complex piping systems)	Dilution-based purge	-Can be applied in many cases -More effective hydrogen dilution w.r.t. to natural gas dilution.	-Multiple cycles of nitrogen purging needed before successful purge.

Samenvatting

Onderhoud aan hogedruk waterstofpijpleidingen, zoals het Waterstofnetwerk Nederland, vereist strategische overweging en planning. In dit rapport geven we een overzicht van de richtlijnen en methodologie voor het afsluiten en evacueren van een hogedrukpijpleiding of installatie voor een onderhoudsoperatie. Dialogen met diverse experts uit de aardgas- en waterstofgasindustrie leverden een breed scala aan perspectieven en kennis op, die hielpen om de nuances van verschillende methodologieën beter te valideren. De algemene methodologie van de onderhoudsprocedure bestaat uit enkele stappen:

1. Identificeer de sectie die onderhoud nodig hebben
2. Sluit de sectie die onderhoud nodig heeft af, met behulp van afsluiterschema's of stoppels
3. Verlaag de druk in het systeem
4. Verdring waterstof met stikstof, met behulp van een pig, verdringing, of verdunningstechnieken
5. Zorg voor secundaire afsluiting en een ontluchtingsmechanismes
6. Voer onderhoudswerkzaamheden uit
7. Spoel het onderhoudsgebied met stikstof voordat je opnieuw waterstof introduceert

De verschillende afsluit- en evacuatiemethoden vereisen enigszins verschillende methodologieën, die in dit rapport worden onderzocht.

Wanneer er afsluiting tussen afsluiterschema's plaatsvindt, kan waterstof verdrongen worden met behulp van een scheidingspig om de vermenging van waterstof en stikstof te minimaliseren. De lekkage door stroming langs verschillende types pigs zal ongeveer 20-30% hoger zal zijn voor waterstofoperaties (in vergelijking met het gebruik van aardgasoperaties). Hoewel de lekkage hoger is, is de hoeveelheid terugmenging nog steeds zeer beperkt in vergelijking met de andere technieken die in het rapport worden beschreven. Scheidingspigs zullen een verhoogd stick-slip gedrag vertonen bij waterstofleidingen, omdat de akoestische impedantie 3 tot 4 keer toeneemt. Afsluiterschema's met piggingfaciliteiten kunnen meer dan 50 km uit elkaar geplaatst zijn. Dit betekent dat er een groot deel van de pijpleiding moet worden gesloten. Het gebruik van een scheidingpig wordt minder haalbaar voor zeer lange pijpleidingen vanwege het grote verlies aan gasvolume en de mogelijke onderbreking van levering van- leveranciers en naar industriële verbruikers.

Als het niet haalbaar is om een pigging-operatie te starten over een groot stuk pijpleiding vanwege het verlies van grote volumes waterstof kan er een kleiner leidingdeel, tussen twee afsluitschema's zonder de nodige faciliteiten voor een pigging-operatie, afgesloten worden. Verdringing of verdunningtechnieken met stikstofgas kunnen gebruikt worden om de waterstof te evacueren. De sectie kan niet altijd worden geëvacueerd door verdringing vanwege fysische beperkingen, zoals stratificatie of de aanwezigheid van dode volumes. In dat geval kan verdunning gebruikt worden om de concentratie waterstofgas te verlagen tot aanvaardbare niveaus. Evacuatie door verdringing heeft zijn uitdagingen, vooral voor lange pijpleidingsecties waar stratificatie kan optreden. De minimale snelheidseisen om stratificatie voor waterstof en aardgas te voorkomen, worden berekend en tonen aan dat de snelheidseisen hoger zijn voor waterstof. De diffusiefronten van waterstof en aardgas zijn berekend in dit rapport, waaruit blijkt dat de lengte van het diffusiefront snelheidsonafhankelijk is en resulteert in ongeveer gelijke volumes van overgebleven gas-luchtmengsels bij verschillende snelheden. De afstand van deze klepschema's varieert binnen het netwerk, maar kan tot wel 50 km uit elkaar liggen. Wanneer deze afstand tussen klepschema's hoog is, kan de hoeveelheid verloren waterstofvolume nog steeds vrij groot zijn.

Wanneer het voordeliger is om een kleinere leidingsectie te evacueren, kan de leiding afgesloten worden door tijdelijke stoppels te plaatsen. Secties die afgesloten zijn met stoppels zijn vaak klein genoeg zijn om een bypass te installeren, waardoor de continuïteit van de gaslevering binnen het waterstofnetwerk gewaarborgd kan worden. blijft. De huidige onderhoudsprocedures, gebruikt bij onderhoud met stoppel, die gebruikt worden voor het aardgasnetwerk zijn niet voldoende voor het waterstofnetwerk, omdat ze geen double block and bleed bieden. Alternatieve technieken, zoals hydraulische stoppels of een stoppeltrein, bieden wel een dubbele block and bleed en worden besproken in het verslag. Deze alternatieve technieken zullen ander apparatuur nodig hebben dan momenteel gebruikt wordt en de technieken vereisen meer onderzoek voordat ze in het veld kunnen worden toegepast.

In complexe systemen of installaties, zoals de waterstofopslagfaciliteit HyStock, zijn veel dode volumes of ruimtes waar de waterstofstroom beperkt is. Hier moet een verdunning-gebaseerde verdringing worden gebruikt. Het afwisselen van de druk in de ruimtes met beperkte gasuitwisseling kan bijdragen om een geschikte verdunning-gebaseerde verdringing sneller te bereiken. Hoewel deze methode een verhoogde hoeveelheid stikstof zal gebruiken omdat het meerdere verdringingscycli vereist voor een succesvolle verdringing, tonen theoretische analyses en experimenteel onderzoek aan dat waterstofvolumes ongeveer 3.8 keer sneller mengen met stikstof in vergelijking met aardgasvolumes.

Tabel 9-1 Overzicht van de voordelen en nadelen van verschillende afsluit- en evacuatietechnieken

Afgesloten sectie	Voorkeurs-evacuatietechniek	Voordelen	Nadelen
Afsluitschema's met pig faciliteiten (50~100 km afstand)	Verdringing met een scheidingpig	- Minimaliseert de vermenging van waterstof en stikstof - Geen stratificatie-problemen en kleinere diffusiefront - Evacuatiemethode is vergelijkbaar met aardgas	-Groot verlies van gasvolume - Mogelijke leveringsonderbreking leveranciers en industriële consumenten - Grotere lekkage langs de pig t.o.v. aardgas
Tussen afsluit-schema's zonder pig faciliteiten (10~50 km afstand)	Verdringing	- Geen verstoring van leveranciers en industriële consumenten - Evacuatiemethode is vergelijkbaar met aardgas	- Mogelijk groot verlies van gasvolume - Stratificatieproblemen zullen eerder voorkomen t.o.v. aardgas
Tijdelijke afsluiting met installeren van een stoppel	Verdringing	- Beperkt verlies van gasvolume - Mogelijkheid om een tijdelijke bypass te installeren	- Huidige evacuatiemethoden gebruikt voor aardgas zullen niet volstaan - Meer onderzoek nodig naar stoppeltreinen en hydraulische stoppels
Afsluitschema's schemes (installatie, complexe leidingsystemen)	Verdunning	- Kan in meeste situaties worden toegepast - Meer effectieve waterstofverdunning t.o.v. aardgas verdunning	- Meerdere cycli van stikstof verdringing nodig voordat succesvolle verdringing

Content

1 Background

The Netherlands, like the rest of the world, faces the significant challenge of transitioning to a CO_2-neutral energy supply. One of the forms of energy that will contribute to this is hydrogen. CO_2-free gases such as green hydrogen are essential for the sustainability of the industry and consumer market.

Between 2025 and 2030 Gasunie will construct the Hydrogen Network Netherlands, a high-pressure hydrogen transmission pipeline system, into use. This hydrogen network will be vital to upscale the usage of hydrogen in the Netherlands. This system will connect to multiple industrial areas and potentially regional distribution grids, allowing for more widespread use of hydrogen as a clean and sustainable energy source. The high-pressure Hydrogen Network Netherlands is designed as a single-ring network with multiple points of entry for hydrogen supply.

Both the Transmission System Operator (TSO) and Distribution System Operators (DSOs) will need to adapt their infrastructure to accommodate the transportation and distribution of hydrogen. When the infrastructure is adapted to accommodate hydrogen, both TSO and DSOs will have a crucial role to play in managing and maintaining the installations and pipelines that transport and distribute hydrogen. The TSO is responsible for managing the high-pressure transmission pipelines that connect hydrogen production sources to major industrial areas and regional distribution networks. This will involve performing maintenance and repairs on the pipelines, as well as ensuring that they are operated safely and efficiently. On the other hand, DSOs will be responsible for managing the distribution pipelines that distribute hydrogen to the smaller industries and consumers within their service area. They will be responsible for ensuring that the hydrogen is delivered safely and reliably to homes and businesses and will also be responsible for performing maintenance and repairs on the distribution pipelines.

To perform maintenance on pipelining and installations, it is sometimes necessary to isolate and evacuate specific sections of the pipeline or installation. The TSO and DSOs should follow guidelines that comply with the safety regulations and standards. For natural gas systems, these guidelines and procedures are well established, and governed by industry organizations and regulatory bodies. This research aims to re-evaluate the technical steps needed when a hydrogen high-pressure pipeline or installation is decommissioned and/or recommissioned for maintenance. This research aims to identify and address challenges and considerations that arise when working with high-pressure hydrogen pipelines or installations, as opposed to natural gas pipelines and installations. Some of the conclusions made for high-pressure systems will also have insightful applications for maintenance techniques applicable in the distribution network with lower-pressure classes.

This research has been conducted within the scope of the national research program, HyDelta. This program is aimed at the safe integration of hydrogen into the existing infrastructure for gas transport and distribution. Its primary objective is to overcome barriers to innovative hydrogen projects, thereby facilitating the advancement of hydrogen technologies.

2 Overview steps for maintenance on hydrogen infrastructure

There are few references or experiences available in the literature for maintenance operations on high-pressure pipelines or installations for hydrogen transport. To address this gap, this research will try to set guidelines for operational procedures based on the knowledge and experiences within both the natural gas and the hydrogen industry. The guidelines and operational procedures mentioned will be complemented with some theoretical comparisons that describe the different physical effects between hydrogen evacuation and natural gas evacuation. The guidelines have been developed through collaborative discussions with industry experts and examination of the current techniques. This contains different methods to isolate or evacuate a hydrogen pipeline and installations, with essential considerations for the safe and efficient evacuation of hydrogen pipelines. These guidelines for operational procedures are primarily focused on the high-pressure infrastructure operated by the TSO. However, some of the described practices may also provide insights into maintenance operations for pipelines in other pressure classes. The examination of some physical effects when evacuating hydrogen (relative to natural gas evacuation) offers insights that apply to both TSOs and DSOs.

A pipeline or installation can have many reasons that it needs maintenance, such as section replacements, branch additions, or emergencies. Special consideration should be given to questions related to the safety hazard posed by ignition resulting from the interaction of hydrogen with air, which is a challenge within the context of a hydrogen infrastructure. To mitigate the risk of ignition during maintenance activities on hydrogen infrastructure, it is crucial to remove hydrogen with inert gas, such as nitrogen. When air is introduced in the system during the maintenance operation, the air also needs to be purged with nitrogen, thereby limiting the contact of hydrogen with air within the hydrogen infrastructure.

This section will provide general steps that need to be taken to safely perform maintenance on hydrogen pipelines or installations. Section 3 will provide an overview of different situations and corresponding evacuation techniques. A more in-depth analysis of the different methods for specific situations will be given in sections 4 to 7. Chapter 8 will provide background analytical measurement tool than can be utilized to monitor the gas concentration during maintenance operations.

1. Identify the sections that need maintenance and which part can should be isolated

Before an evacuation can start, the pipeline sections or installations requiring purging should be identified and isolated. The purpose of the operation, such as repairing a section of the pipeline, may influence which areas need to be purged. The section should be mapped to take into consideration what branches, bypasses, siphons, etc. are present to determine if the pipeline or installation is amenable to be purged using a separation pig or if alternative methods for purging need to be used. Furthermore, end-users near the maintenance location should be mapped to determine what section should be isolated while remaining operational. Since the network will have multiple points of entry for hydrogen suppliers, the hydrogen can flow in multiple directions, but during the initial construction phase, the ring might not yet be fully connected, which could result in a shutdown of a large section of the hydrogen infrastructure. Since the Hydrogen Network Netherlands is initially designed as a single-ring pipeline, there should be inventoried if a local temporary bypass is needed during the maintenance operations.

2. Isolate section, if necessary, place temporary isolating facilities

After mapping and identifying the section that will be evacuated, this section should be isolated from the rest of the hydrogen grid. When a section is still under high pressure, a section can be isolated by closing existing valve schemes, these are located roughly 50 kilometres apart from each other. It is generally preferred to isolate between valve schemes with facilities to evacuate the hydrogen with a separation PIG to avoid stratification or diffusion front problems (as described in sections 5.1 & 5.2), these valve schemes are distanced can be distanced 100 kilometres apart. When a section that needs isolation is smaller stopples can be used to close off the area that needs maintenance. For low-pressure hydrogen infrastructure below 200mbar, bellows or inflatable gas stoppers could be used

3. **Depressurize the system**

When a section is isolated, the system can be depressurized by recompression the hydrogen, into a next pipeline section, stored in gas storage trucks, flaring If no other options are possible venting the excess hydrogen gas. Due to the high risk of ignition associated with hydrogen, safe operation of flaring is described in Hydelta 2 work package 5.1. It is not necessary to depressurize the system to atmospheric conditions before starting the evacuate the hydrogen by displacement with nitrogen. Starting with nitrogen displacement at higher pressures makes it possible to use recompression more effectively.

4. Evacuate the hydrogen with nitrogen, utilizing pigging, purging, or dilution techniques

The hydrogen in the system can be now displaced with an inert gas, like nitrogen, by either using a separation pig, purging, or dilution. Purging is the process of entirely clearing out gas from a system. Dilution is used when a gas cannot be entirely cleared out and involves decreasing the concentration of the gas to reduce its concentration to a desired level. Since hydrogen has different physical and chemical properties (besides the higher safety hazard), hydrogen evacuation might require a different evacuation approach than used in the natural gas evacuation. Sections 4-7 will contain a more in-depth analysis of different physical effects during evacuation.

5. Ensure secondary isolation and a bleed mechanism is in place

After a section or system is depressurized and hydrogen is evacuated, secondary isolation needs to be placed (or existing valves can be closed) depending on the primary isolation used and the volume (length) of the isolated section. Often, secondary isolation includes a bellow installed through a torr-nipple or a second pre-existing valve. The combination of two separate barriers allows for a double block and bleed (DBB), a safety procedure that involves having double isolation with a vent to make sure any leaked hydrogen will be released in the air and not towards the maintenance site. An extra torr nipple can be used to install a vent.

6. Execute maintenance operations

If all measures described above are in place, the maintenance operation can be executed. Modifications are carried out under air conditions to prevent the risk of suffocation, using bellows in the pipeline to prevent the outflow of nitrogen from the pipeline. During the maintenance procedure, the concentrations of hydrogen, nitrogen and oxygen should be monitored to remain outside of the explosion limits mentioned in Appendix A.1

7. Flush the maintenance area with nitrogen before reintroducing hydrogen

When the maintenance operation is completed, the maintenance site (between the bellows) will have a mixture of air and nitrogen. Therefore, before the introduction of hydrogen, the isolated section should be purged with nitrogen again before removing the bellows. Once it is determined that there is no more air in the section, the bellows can be removed and subsequently the nitrogen can be displaced with hydrogen. After all nitrogen is removed from the pipeline, the pipeline will be repressurized with hydrogen to bring it to normal operation conditions, after which the valves can be opened and the hydrogen can be brought back to flowing conditions.

These maintenance guidelines for hydrogen pipelines are discussed with industry experts during a brainstorming session in a multidisciplinary setting. This encompassed operational, and safety technical perspectives, among others. The goal of this collaborative, cross-disciplinary exercise was to facilitate discussions on the different isolation and evacuation techniques to evaluate the safety and feasibility of such guidelines for high-pressure hydrogen pipelines. The minutes of this meeting can be found in Appendix.

3 Determination of isolation and evacuation techniques.

Before starting your maintenance operation, there must be decided what isolation method and evacuation methods are suitable for the section. To determine what kind of isolation method is most preferable we created Figure 3-1; a general guideline of what kind of isolation method can be used and what kind of evacuation can be used.

The most straightforward technique for isolation is to use existing valves, found at valve schemes or near an installation. When pipelines need to be evacuated over longer distances, and an inert gas such as nitrogen is used for displacement, it is almost always preferable to employ separation pigs to minimize the mixing of hydrogen and nitrogen as much as possible.

A distinctive aspect of the Hydrogen Network Netherlands is its singular pipeline design. This design choice, while cost-effective and efficient imposes a significant challenge for maintenance operations. Any work required, without a temporarily bypass, on a single pipeline results in a complete shutdown of the hydrogen flow throughout that particular section. This could have consequences for the transmission of hydrogen therefore requiring the installation of a temporary bypass. The distance between valve schemes with facilities for launching or receiving pigs can be more than 100 kilometres apart from each other. This implies that isolating long sections of pipelines or important installations could affect flowing condition of both (some) consumers and/or suppliers. Furthermore, while the circular Hydrogen Network Netherlands is still being constructed (estimated construction time will be till 2030) and is not yet circular, parts outside the isolated section might also experience a shutdown of hydrogen flow because production and offtake are situated at both sides of the isolated section. It is useful to isolate a smaller section to ensure the flow of the network. Also, shutting-down such large section of pipeline for a pigging operation will result in the loss of large volume of hydrogen. Guidelines and more detailed information can be found in chapter 4.

One could also isolate a section between valve schemes without pigging facilities. The distance between valve schemes will be dependent on the amount of branches, suppliers, and industrial consumers located near each other, but can be roughly 50 km distanced. Since all branches to the suppliers or to the customers will have a valve schemes, there will be no loss of flowing condition for consumers or suppliers. However, evacuation without a separation pig would require a purging operation, this might not always be possible due to stratification problems. As Figure 3-1 shows, the critical velocity (velocity needed the perform a successful purge) should be taken into consideration and is different for hydrogen than natural gas. These topics are further discussed in chapter 5

Installing a temporary bypass from- and to either side of the closed-off sections can ensure flowing conditions. When isolating between valve schemes, installing a bypass might not always be feasible due to the large distance between valve schemes. In these cases, one could isolate a smaller pipeline section by installing temporary stoppers called stopples. The advantages and disadvantages of using a stopple will be discussed in chapter 6.

Installations in a pipeline network include various valves and valve schemes and can be evacuated with a dilution-based purge as discussed in chapter 7.

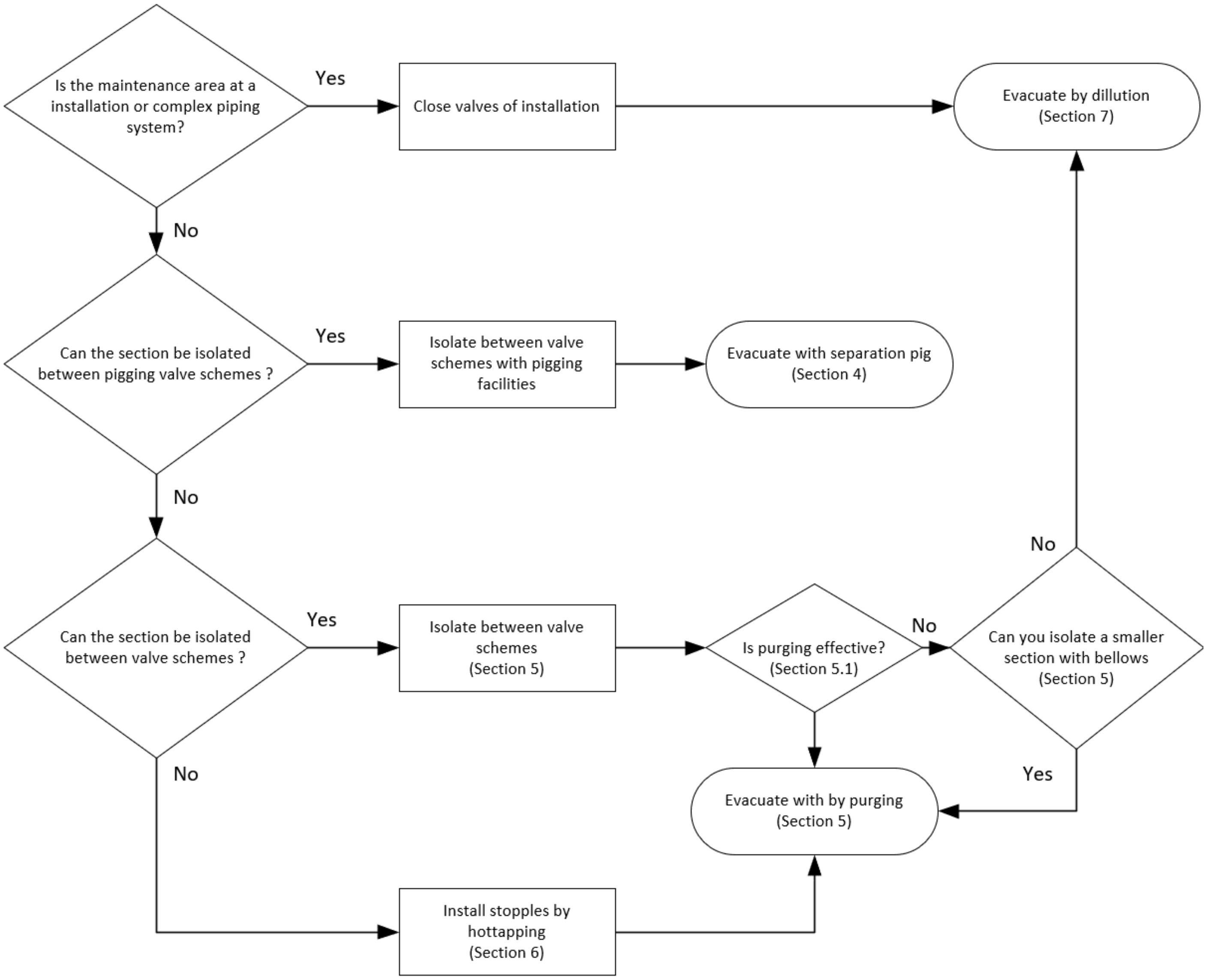

Figure 3-1 - Determination of isolating and evacuation method based on available section

When a section from the hydrogen network is successfully isolated, the hydrogen needs to be expelled from the maintenance area. This is done by first depressurization of the pipeline system, a fundamental operation during maintenance procedures or in response to emergency shutdown protocols. After the isolation phase, depressurization is achieved by recompressing the hydrogen from the isolated section into the hydrogen infrastructure. To avoid the loss of hydrogen, the evacuation with nitrogen is already starting at a higher hydrogen pressure to enable recompression as long as possible and reduce the loss of hydrogen by flaring to a minimum. The system is further depressurized by flaring. The purpose of venting or flaring is to carry the purged gas from the isolated section to a point from which the purged gas can be removed safely without being a hazard to the surroundings, the workers or the environment. Further information about flaring, including guidelines for safe implementation, can be found in the documentation of work packages of Hydelta 2 work package 5.1.

After depressurizing the system, the hydrogen in the section can be evacuated with different methods. During the execution of the evacuation process, displacement or dilution with nitrogen is employed to expel the hydrogen gas through designated escape vents, where it can be recompressed or flared, with the use of an inert gas like nitrogen. Ideally, there is minimal to no intermingling between nitrogen and hydrogen. However, depending on the geometry of the closed section, there may be some degree of mixing. Especially in sections with a lot of dead volumes or complex installations, the purging process primarily relies on dilution that requires a specific way of operation.

When dealing with long and wide high-pressure pipelines, purging might not always represent a viable option due to the inherent physical limitations of the purging process. The volume of gas required for effective purging can be substantial and problems, like stratification, can cause significant problems. For these pipelines, using a separation pig is a more favourable alternative to evacuate the section. Pigs are inserted into the pipeline and propelled along its length by the flow the nitrogen. Pigs can efficiently displace hydrogen without mixing or stratification problems.

4 Maintenance operation with separation PIG

When pipelines need to be depressurized over longer distances, and an inert gas such as nitrogen is used for displacement, it is preferable to employ separation pigs to minimize the mixing of hydrogen and nitrogen as much as possible.

If a pipeline or part of an installation is piggable, a separation pig can be used as a barrier between the displacing gas and the gas that needs to be evacuated. For the evacuation operations, different pig types may be selected and this choice will influence the potential leakage of the displacement gas towards the gas to be evacuated. The leakage depends on the type of pig and the type of displacement gas used for driving the pig.

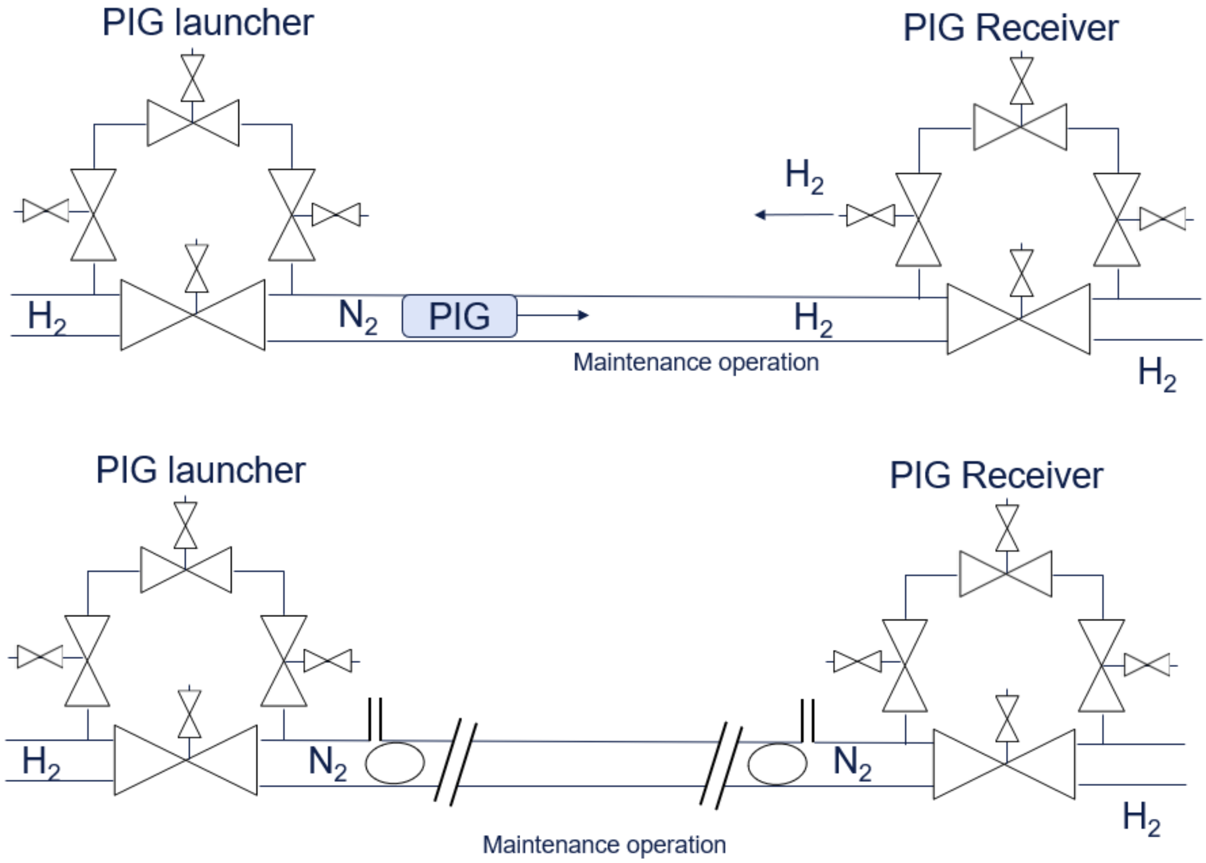

Figure 4-1 Schematic overview of maintenance operation with separation pig. In the upper image the evacuation is still ongoing and in the lower schematics the operation can be started.

1. When a section between two valve schemes equipped with pig facilities is isolated, the pipeline segment is depressurized till pressure level at which he recompression unit can effectively be used.
2. The hydrogen is be displaced with nitrogen, using a separation pig in the process. For a hydrogen system, measures must be taken to prevent air entrapment in pig launchers and receivers, particularly considering the broader explosion limits of hydrogen compared to natural gas. The formation of a flammable mixture must always be avoided. Therefore, the pig launcher and receiver should be equipped with provisions for purging to ensure that there is no air entrapped in the system before launching a pig.
3. Applying pressure on the nitrogen side creates a driving force with an overpressure of 2-3 bar. This technique facilitates the displacement of the separation pig within the pipeline to push away the hydrogen. Given the anticipated large volumes of hydrogen that require

displacement, recompression recommended. When recompression is no longer possible, a flare facilitates the safe and controlled burning of excess hydrogen.

4. The remaining nitrogen gas within the pipeline is depressurized to match atmospheric pressure levels. Installing bellows within the pipeline is a key measure to create a double block and bleed that can be flushed with nitrogen to prevent hydrogen escaping from the pipeline to the maintenance site. The process as the maintenance operations are conducted under air conditions to mitigate the risk of suffocation
5. Once the modification has been successfully completed, the pipeline segment that underwent this modification is then refilled with nitrogen. Following this, the bellows, having served their purpose, are carefully removed.
6. The pipeline can be purged with hydrogen an repressurized to operational levels, marking the completion of the procedure.

Despite its usefulness, the process of pigging becomes less feasible for very long pipelines due to the large loss of gas volume. Some of the gas in front of the pig can be recompressed, but the remaining gas needs to be flared and cannot be economically collected or reused. This not only leads to economic loss, but it also can have a significant environmental impact. The shutdown can also cause a significant disruption to the supply chain, affecting suppliers and industrial consumers who rely on the consistent and reliable flow of gas from the pipeline, especially if the ring network is not yet completed.

Research has shown that the dynamic behaviour of a pig in a hydrogen pipeline differs from that in a natural gas pipeline. Due to the lower density of hydrogen, stick-slip behaviour is amplified, leading to a less uniform movement of the pig through the pipeline. The amplified stick-slip behaviour can lead to a pig becoming sticked within the pipeline. The water hammer effect with hydrogen is 3-4 times smaller than with natural gas due to the low density of hydrogen. Due to the water hammer effect, a pressure surge caused by a sudden change in the fluid's velocity (the pig being sticked), can sometimes be used to dislodge a sticked pig. While this irregular movement may not pose a direct issue for the evacuation process of pigs, it can lead to less favourable behaviour when using pigs for inspection purposes. Also, measurements during an in-field analysis will be less reliable.

4.1 Pig differential pressure and leakage

The movement of the pig through the pipeline is influenced by a certain differential pressure, which varies depending on the type of pig used. The projected differential pressure over the pig can be approximated using the empirical formula:

$$\Delta p = \frac{K}{D}, \tag{1}$$

with D representing the internal diameter in inches, the differential pressure expressed in bar, and the K-value depending on the pig type used, as detailed in Appendix A.3.1. For instance, in a 6-inch pipe, a double disk pig (K=6) generates a differential pressure of 1 bar. Using the established differential pressure and the leakage mechanism, a qualitative estimation of the leakage rate can be made. Two potential leakage mechanisms are considered: a thin-film annular flow (viscous flow) and leakage resulting from openings created by irregular surfaces (non-viscous flow).

When a pig with a relatively long contact area with the pipeline wall is used (e.g., a foam pig), potential leakage may occur through the clearance between the pipe wall and the pig, a situation depicted in Figure 5-2.

In appendix A.3.1.2 can be seen that when using hydrogen as the driving gas (i.e. when a separation pig is used after maintenance has been completed) the leakage is roughly 20% higher compared to when natural gas is used. However, when a separation pig is employed before maintenance (i.e. when nitrogen is used as driving gas), no change is anticipated in the leakage behaviour compared to the standard natural gas evacuation procedure.

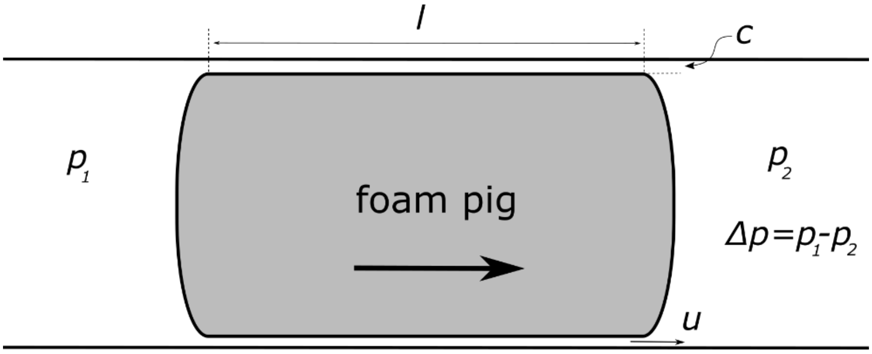

Figure 4-2 Geometrical representation of a foam pig and the leakage mechanism

If the leakage is caused by a small cavity between the pipe wall and the pig due to imperfections in the pig disk or small ripples on the pipe's inner surface, the flow through that opening is propelled by the differential pressure. This leakage mechanism is illustrated in Figure 5-3.

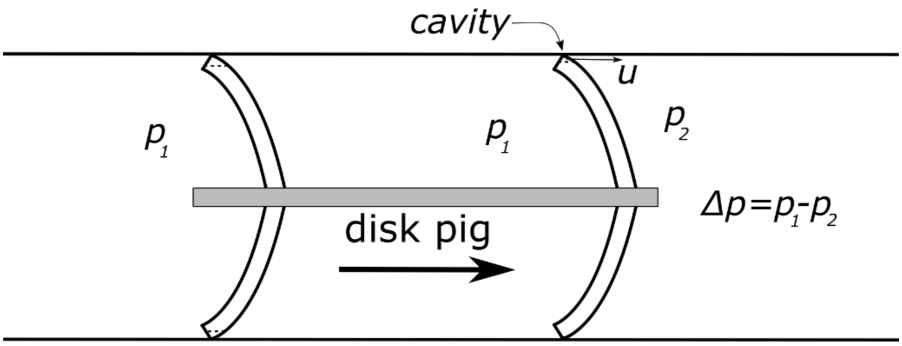

Figure 4-3 Geometrical representation of a disk pig and the leakage mechanism

According to Appendix A.3.2, leakage resulting from small cavities will be about 30% higher for hydrogen compared to when natural gas is used.

It is noteworthy that the theory about the various leakage mechanisms can also be applied to other potential leakage phenomena, including valves, stopples, and bellows. Each of these components requires an assessment to determine the expected type of leakage will be either thin film leakage, cavity leakage, or a combination of both. In general, all components that have a certain leakage rate will be roughly 20% to 30% higher for hydrogen as compared to using natural gas.

5 Maintenance operation between valve schemes without pigging facilities

In case the pipeline or the installation is not piggable, purging may be used to evacuate the gas. During a purging operation, two main effects need to be taken into account: stratification of the two gases, and the formation of a diffusion front due to turbulent dispersion. The stratification process will occur when the velocity of the purge gas is too low, i.e. below a certain critical velocity. When the velocity is well above this critical velocity, turbulent dispersion will occur that leads to the formation of a diffusion front. The determination of the length of this front is important to quantify the volume of mixed (off-spec) gas.

When choosing to isolate a section between valve schemes without pig facilities, the section can still be isolated using existing valve schemes. This gives the advantage that no stopples need to be inserted. As a result of the different densities of hydrogen and nitrogen and the velocity of the nitrogen front, a certain degree of stratification (layering of gasses) can occur, with the heavier nitrogen settling beneath the hydrogen. Stratification can occur over a large pipeline length and result in a substantial amount of off-spec gas. Stratification primarily occurs in laminar flow and straight pipelines. Bends and other deviations from a straight line promote radial mixing. A careful consideration of the gas velocity versus pipeline diameter is made in section 5.1 and calculations of the diffusion front for hydrogen can be found in section 5.2. When stratification issues arise, an different isolation method can be used the minimize the amount section size. Depending on the length and diameter of the section you can either purge or use a dilution based purge (see section 7).

Case I: Purge the whole area between valve schemes

When purging the whole section between two valves schemes, it can be better to start with displacement with nitrogen at a more elevated pressure to facilitate the recompression of hydrogen gas. A higher pressure the velocity of the nitrogen front will be lower at the same nitrogen injection rate.

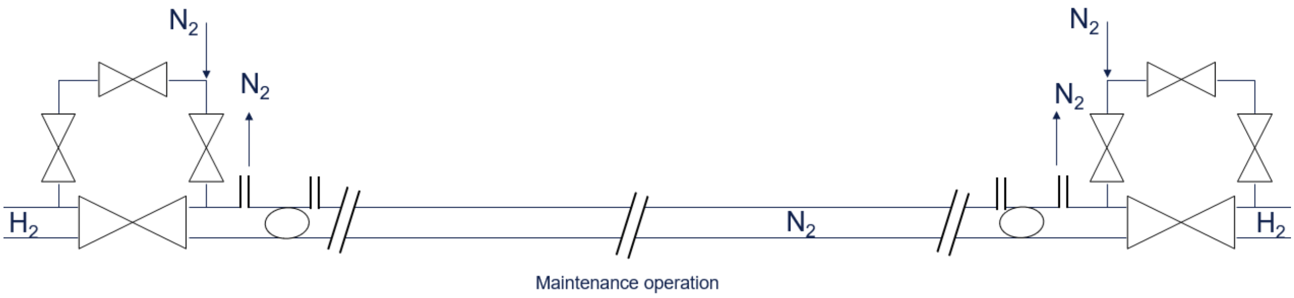

Figure 5-1 Schematic overview of case I maintenance operation with purging

1. When a section between two valve schemes is isolated, the pipeline segment can be to be depressurized by means of recompression.
2. The hydrogen can be displaced with nitrogen. Nitrogen can be injected to facilitate more hydrogen recompression.
3. When no more recompression is possible, a flare facilitates the safe and controlled burning of excess hydrogen, thereby ensuring safety. By using a flare in this context, we can effectively manage and control the process and depressurize till atmospheric pressure.
4. Utilizing bellows within the pipeline is a key measure taken to prevent nitrogen from escaping the pipeline during these modifications. The bellows act as a protective barrier, sealing the

pipeline and ensuring safety after the depressurization process is finished and before the actual maintenance work will be started . An extra torr nipple will be placed between the valve scheme and the bellow to ensure a block and bleed situation to avoid hydrogen reaching the site at which the maintenance work is carried out in case there is any leakage from the valve scheme. The maintenance operations are conducted under air conditions to mitigate the risk of suffocation.

5. Once the modification has been successfully completed, the pipeline segment that underwent this modification is then refilled with nitrogen to remove any air present. Following this, the bellows, having served their purpose of preventing nitrogen outflow, are carefully removed.
6. The nitrogen can now be displaced by hydrogen, and the whole section between the two valve schemes can be repressurized to its operational level with hydrogen

Case II: Partially purge section

When the section between two valve schemes is not easily purged, a smaller section, that is more easily purged, can be isolated with bellows. Therefore, it has been suggested to place bellows through Tor nipples in the depressurized pipeline to isolate a smaller section near the work area. As an additional safety measure, two bellows can be used (per side), where the space between those bellows can be purged with nitrogen to ensure a double block and bleed in the depressurized pipeline section. In addition, the use of bellows via Tor nipples to isolate the work area can be a challenge, as the bellows must be properly secured to prevent them from rupturing or leaking during use. The pressure between the bellows should not exceed 200mbar and should be monitored.

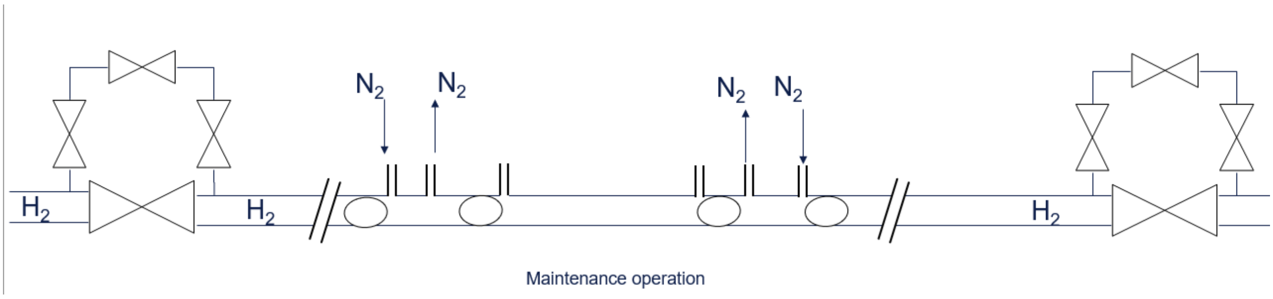

Figure 5-2 Schematic overview of case II maintenance operation with purging

1. When a section between two valve schemes, the pipeline segment is depressurized by means of recompression and/or flaring till atmospheric pressure.
2. On both sides of the maintenance area, a bellow is placed and the area between the bellow is slowly displaced with nitrogen. A flare facilitates the safe and controlled burning of excess hydrogen, thereby ensuring safety. By using a flare in this context, we can effectively manage and control the process.
3. To ensure a double block and bleed situation, secondary bellows are placed on each side. Here, on both sides of the, nitrogen is flushed between the two bellows to prevent hydrogen escaping from the pipeline towards the maintenance site. The bellows act as a protective barrier, sealing the pipeline.
4. The area between the inner bellow needs to be flushed with air before the actual maintenance work is carried out The maintenance operations are conducted under air conditions to mitigate the risk of suffocation.
5. Once the modification has been completed, the maintenance section, the section between the bellows need to be purged with nitrogen to remove any excess air and can be removed. Subsequently, the nitrogen between the outer bellows needs to be replaced by hydrogen and the outer bellows can be removed.

6. Following this, the bellows, having served their purpose of preventing nitrogen outflow, are carefully removed, and the whole section between the two valve schemes can be repressurized with hydrogen.

5.1 Critical velocity

Due to the distinct densities of hydrogen and nitrogen, stratification, or gas layering, inevitably occurs. This causes nitrogen, being denser, to settle beneath hydrogen, and may lead to significant volumes off-spec gas. Stratification primarily occurs in laminar flow and straight pipelines. Bends and other deviations from a straight line promote radial mixing. The relationship between gas velocity and pipeline diameter, analyzed carefully in Appendix, is crucial in this context.

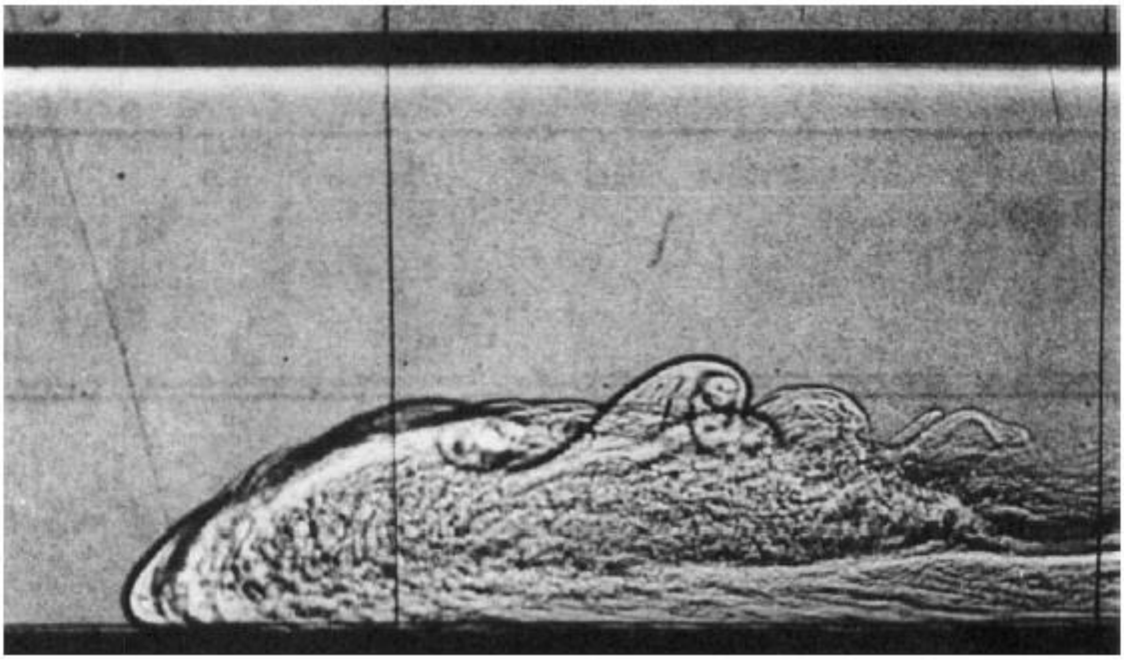

Figure 5-3 Example of stratification

In an idealized scenario, the velocity of the gravity-driven wave, which moves the gas along the pipeline, can be determined. This velocity is proportionate to the Froude number, a dimensionless value describing the fluid dynamics of the system.

$$v^* = 0.75\sqrt{\tilde{g}D}, \qquad (D > D^*). \tag{1}$$

So, for hydrogen-nitrogen purging, the velocity should be approximately 2.2 times higher than for natural gas-nitrogen purging when considering the stratification condition.

In addition to satisfying the Froude number condition, the flow of the driving gas must also be turbulent, known as the common Reynolds number condition. The Reynolds number is a dimensionless quantity that predicts the onset of turbulence based on a transitional value (Re^*=2300). For smaller diameters, the Reynolds condition is the most stringent

$$v^* = \frac{2300\nu}{D}, \qquad (D \leq D^*). \tag{2}$$

Considering this turbulence or Reynolds condition, the velocity should be approximately 7.3 times higher for a hydrogen-nitrogen purge compared to a natural gas-nitrogen.

The critical diameter for hydrogen/nitrogen can be found by equalizing equations **(1)** and **(2)** and assuming hydrogen as the purge gas, this results in:

$$D^* = \left(\frac{2300\nu}{0.75\sqrt{\tilde{g}},}\right)^{\frac{2}{3}} \approx 0.19, \qquad \textbf{(3)}$$

which is significantly higher than the value for natural gas/nitrogen. Considering both conditions the minimum purging velocity can be calculated, see Figure 5-4. These theoretical results can be validated utilizing the purging experiments

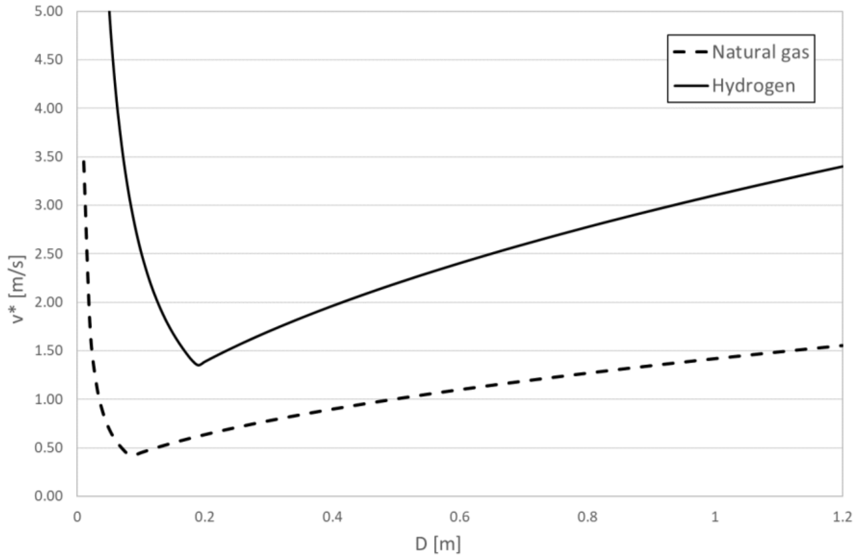

Figure 5-4: Minimum velocity requirement to prevent stratification for hydrogen and natural gas as driving gas.

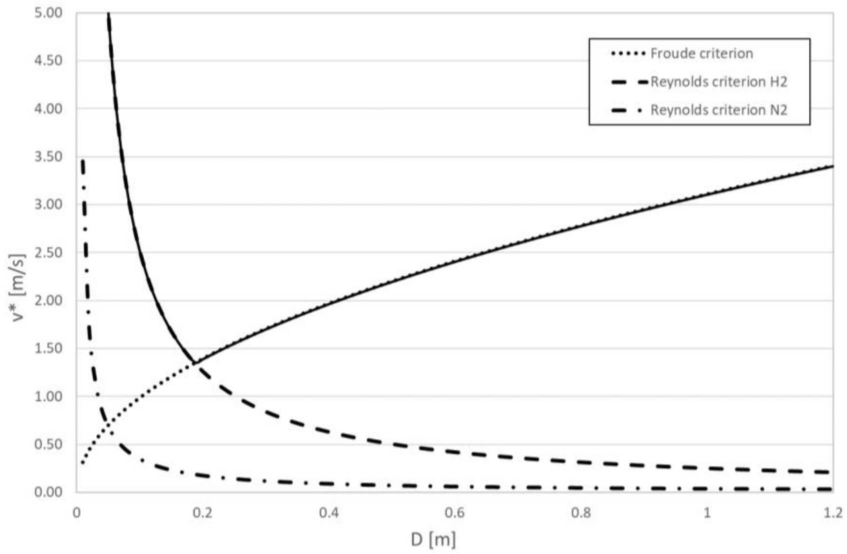

Figure 5-5: Minimum velocity requirement to prevent stratification for hydrogen and nitrogen as driving gas. The solid line indicates the maximum critical velocity for both stratification and turbulence for hydrogen.

5.2 Diffusion front

If an adequately high purging velocity is applied to prevent stratification, a diffusion front will still emerge due to turbulent dispersion. Various studies have explored this axial turbulent diffusion process, starting with the work of Taylor and subsequently leading to numerous publications that model the turbulent dispersion coefficient. Generally, for one-dimensional pipe flow, it's assumed that this coefficient is solely dependent on the Reynolds number."

The process that causes the mixing of the diffusion front is turbulent dispersion. Typically, other processes like molecular diffusion are orders of magnitude lower in terms of the diffusion coefficient. To gain insight into the turbulent dispersion a literature study has been performed considering theoretical models, lab experiments, and full-scale experiments.

One can calculate the diffusion front length by taking the analytical solution of the instationary diffusion equation, see e.g. [16]. Taking the value of the composition of the purge gas at 0.02 and 0.98, since the front will exhibit a smooth transition between the gases, the distance between these values is a measure of the diffusion front

$$\Delta x = 2.08\sqrt{DL}. \quad \textbf{(4)}$$

This means that for a pipeline with $D = 0.1m$ and a propagation length of $L = 1000m$, the diffusion front becomes $\Delta x = 20.8m$. Observe that the equation for the diffusion front due to turbulent dispersion is not gas property dependent and will be similar for hydrogen and natural gas. Also, it does not depend on the velocity.

The results of the Kiwa experiments in [10] were used to check the outcome of the equation **(4)**. For the 100mm experiment, the diffusion front very closely resembles the theoretical prediction. The experiment shows that the diffusion front length is indeed velocity-independent and results in approximately equal volumes of remaining gas-air mixtures for different velocities. The results for the 200mm pipe do not agree well with equation **(4)** although the diffusive front length also seems velocity independent.

6 Maintenance operation with stopples

A stopple is a type of plugging device or fitting used to temporarily isolate a section of a pipeline that can be installed without stopping the flow of hydrogen gas inside the pipe. Stopples are particularly beneficial in situations where a pipeline section requires isolation for maintenance or modification purposes, but existing valves or shut-off mechanisms are situated too far away. The stopple acts as a temporary seal inside the pipeline, effectively isolating the section that requires attention. They offer the opportunity to close off or isolate short sections of a high-pressure pipeline as an alternative to a complete pipeline shutdown of a section.

To achieve this, a plugging head is inserted into the pipeline through a hot tap connection. Hot tapping is a process that involves attaching and adding an split T-connection equipped with a full bore valve to an existing system without interrupting the gas flow, and with no release or loss of product. This outlet offers the opportunity to not only install a stopple for isolation but also offers the chance to install a bypass. Isolating smaller sections of pipeline can be a feasible way to install a bypass that diverts the flow of hydrogen while maintenance, repairs, or modifications are carried out on the main pipeline. Installing a bypass might not be feasible when larger sections of the pipeline need to be shut down.

Once the plugging head is in place, it forms a seal against the internal walls of the pipeline, usually by utilizing the pressure difference within the pipeline. When the plugging head of the stopple is inserted, the pressure on the upstream side of the seal will be greater than the pressure on the downstream side, which is depressurised to carry out the maintenance activities. This pressure difference forces the plugging head against the inner surface of the pipeline, enhancing the seal's stability and effectiveness. The usage of a stopple is a proven technique in natural gas; an example guideline of a maintenance operation with stopples is described below and shown in Figure 6-1.

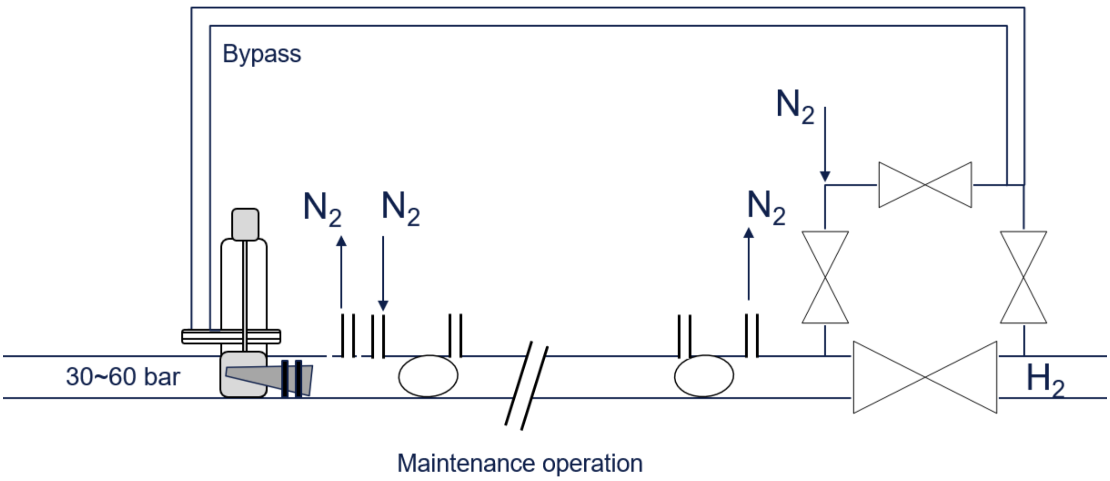

Figure 6-1 Schematic overview of maintenance operation with a stopple train.

1. Install a hot tap for a bypass and a stopple. Make sure the cavity of in which the cutting equipment is situated is flushed with nitrogen before cutting, to prevent air and hydrogen mixture. A bypass can be installed between two stopple locations (hot taps) or between a stopple location (hot tap) and valve scheme to ensure hydrogen flow.
2. Use the stopple(s) to plug the pipeline section that requires maintenance.
3. The pipeline segment can depressurized till atmospheric pressure by means of recompression and/or flaring. The hydrogen can be displaced with nitrogen. Nitrogen can be injected before reaching atmospheric pressure to facilitate more hydrogen recompression.

4. Purge the remaining hydrogen between the stopples with nitrogen
5. After depressurizing and purging the piping between two stopples, a secondary blockage should be inserted between the stopple and the gas operation. Whereas bellow can act as a secondary blockage to take care of any gas leakage from the stopple and prevent gas volume between the stopple and the bellow to enter the maintenance area, secondary stopples or a stopple train will be provide a double block and bleed at these higher pressures option (more info can be found in this chapter). Purge the space between the stopple head and the bellow (or secondary stopple) with inert gas to create a double block and bleed, this will require an extra torr nipple.
6. Once the maintenance operation has been successfully completed, the pipeline segment that underwent the modification is then purged with nitrogen to take out any air that might be trapped during the operation.
7. Once the bellow are removed, the section can be purged and filled with hydrogen. When the stopples are removed, the bypass can be disconnected.

Currently, bellows used in natural gas procedures are used up to a pressure difference of 200 mbar on both sides. Since stopples do not use valve schemes with a double block a bleed, an secondary isolation method needs to be installed that can withstand the higher pressures when the first stopple fails. Also, while flushing nitrogen between bellows, there should be no pressure build-up above 200mbar, therefore, the in- and out flow of nitrogen should be monitored.

Early experiments on a high-pressure pipeline at the safety campus Enschede (performed by Gasunie) show that leakage almost always occurs due to imperfect sealing, for example, due to the presence of drill cuttings and debris on the bottom of the pipeline. Although a successful hot tapping trial was carried out in Enschede with a single stopple and bellows seal, with 60 bar of hydrogen, the results of a similar trial with a double stopple (without bellows, a so-called stopple train) were less successful.

It should be noted that a stopple only works well there if there is a pressure difference between both sides of the stopple. When using a stopple train, the inner stopple, therefore, does not work until the outer stopple has let through enough gas to fill the space between the two stopples sufficiently to allow the inner stopple to close properly. It poses a challenge to adequately monitor if the second stopple head has an adequate seal for proper closure. There will be two torr nipple required between the two stopple head to adequately remove hydrogen between the two stopple heads and put differential pressure with nitrogen between the two stopple heads. The distance between the two stopples is approximately equal to the diameter of the pipeline, this option will need further investigation before it can be utilized in the field.

However, there are some concerns about using this type of traditional stopples for hydrogen. To avoid problems with stopples as much as possible, hydraulically lockable stopples are preferably used. These stopples provide a much better seal because the valve seal can be pressed against the pipe wall with great force and are widely and successfully used. Currently Gasunie does not use such hydraulic stopples because for natural gas there is no necessity to use a double block and bleed configuration , but has to consider using these stopples for hydrogen as well as natural gas abroad.

7 Evacuate of complex systems, installations or non-purgeable pipelines

While the complete elimination of mixing remains difficult in practical applications, minimizing dilution or mixing can yield a more effective purge. In practical installations, it may not always be possible to completely eliminate the presence of dead volume, or areas where the flow of hydrogen is restricted. In this case, there can be chosen for a dilution-based purge. Alternatively, by alternating pressure in the spaces with the limited gas exchange can also facilitate an adequate dilution-based purge.

There was a suspicion that, in closed volumes (vessels, T-pieces), pockets of hydrogen would mix less efficiently with nitrogen than in the case of natural gas displacement. However, theoretical analyses have shown that the opposite is likely to be true. There is no experimental literature that confirms the mixing behavior of hydrogen and nitrogen with respect to natural gas and nitrogen. Therefore, DNV performed an experimental analysis to determine the difference between hydrogen-nitrogen mixing and methane-nitrogen. In practice, gas pockets can be avoided by raising and lowering the pressure several times to alternately empty and refill the pockets.

When performing a dilution exercise, the purge gas will be added to the volume and increased to a certain pressure p. The pressure is relieved by atmospheric pressure (p_{atm}) and therefore the concentration of the gas to be purged will reduce with approximately the ratio of these pressures (p/p_{atm}). This assumes that the gases are well-mixed and this depends on the injection velocity of the gas, i.e. the generation of turbulent mixing. In some parts of the volume to be purged it may be possible that no/low flow occurs, i.e. dead ends or large volumes. In those cases, the mixing depends on molecular diffusion between the two gases and the buoyancy between these gases. These processes are competing, but molecular diffusion is typically a very slow process. The final result of these competing processes is difficult to quantify, but one can compare the situation of natural gas-nitrogen to the case of hydrogen-nitrogen to estimate the relative effect.

This analysis starts with the dimensional analysis of the two competing processes, which are governed by the Peclet number for molecular diffusion and the Froude number. Taking the ratio of the two numbers leads to a dimensionless number that is independent of the velocity

$$\left(\frac{\mathrm{Pe}}{\mathrm{Fr}}\right)^2 = \frac{\tilde{g}D^3}{E^2}, \qquad \textbf{(1)}$$

where E is now the molecular diffusion coefficient. The higher this dimensionless number the more the gases will remain separated, the lower this number the more dominant the molecular diffusion is and the more mixed the two gases will be. The number will increase when the density difference increases (increasing $\tilde{g}$) or the volume increases (increasing D^3). Calculations of equation **(10)** show that this number is higher for the natural gas-nitrogen system than for the hydrogen-nitrogen system, so the hydrogen-nitrogen mixture will mix faster (approximately 3.4 times as fast) than the natural gas-nitrogen mixture. This is mainly due to the molecular diffusion coefficient which is more than 4 times higher for the hydrogen-nitrogen mixture.

Since no experimental data could be found in the literature, DNV designed a dedicated setup for determining the difference between hydrogen-nitrogen and methane-nitrogen mixing, see Figure 7-1. The top section of the pipeline is filled with low-density gas (i.e. hydrogen of methane), and the lower section is filled with nitrogen. These sections are separated by a ball valve. Both the top and lower sections are at atmospheric pressure. In the lower nitrogen section (at approximately half the section length) a gas chromatograph (GC) is connected. At the bottom of the section a hose is connected (that was used for nitrogen purging of the lower section) which still contains nitrogen, and this hose is left open such that the GC will not pull a (partial) vacuum on the test setup. For each test (hydrogen and methane) the valve is opened at $t = 0$, and the mixing velocity can be determined by sampling the hydrogen/methane concentration in time. The results are provided in Figure 7-2 and confirm that hydrogen mixes faster than methane (approximately 3.8 times faster).

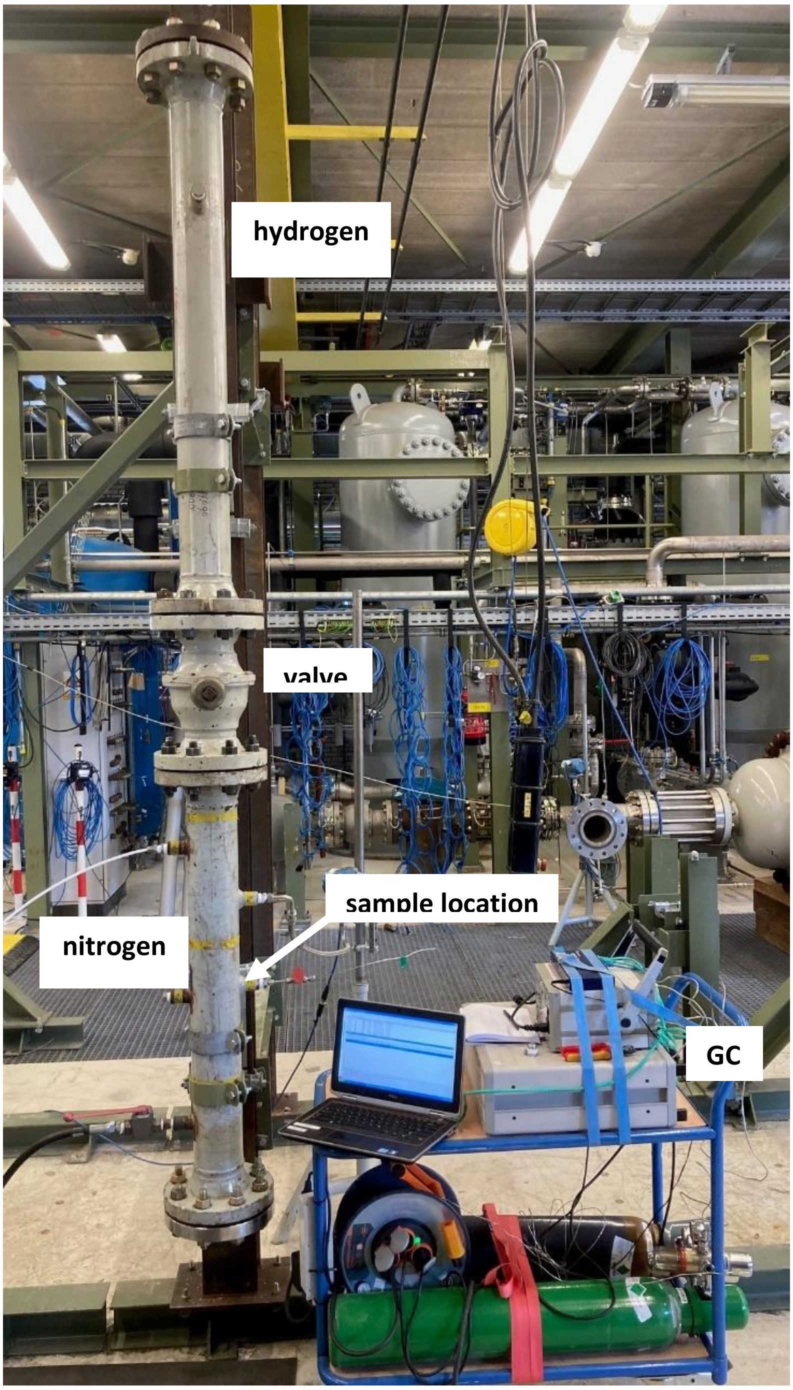

Figure 7-1 DNV test setup for determining mixing velocity of gases

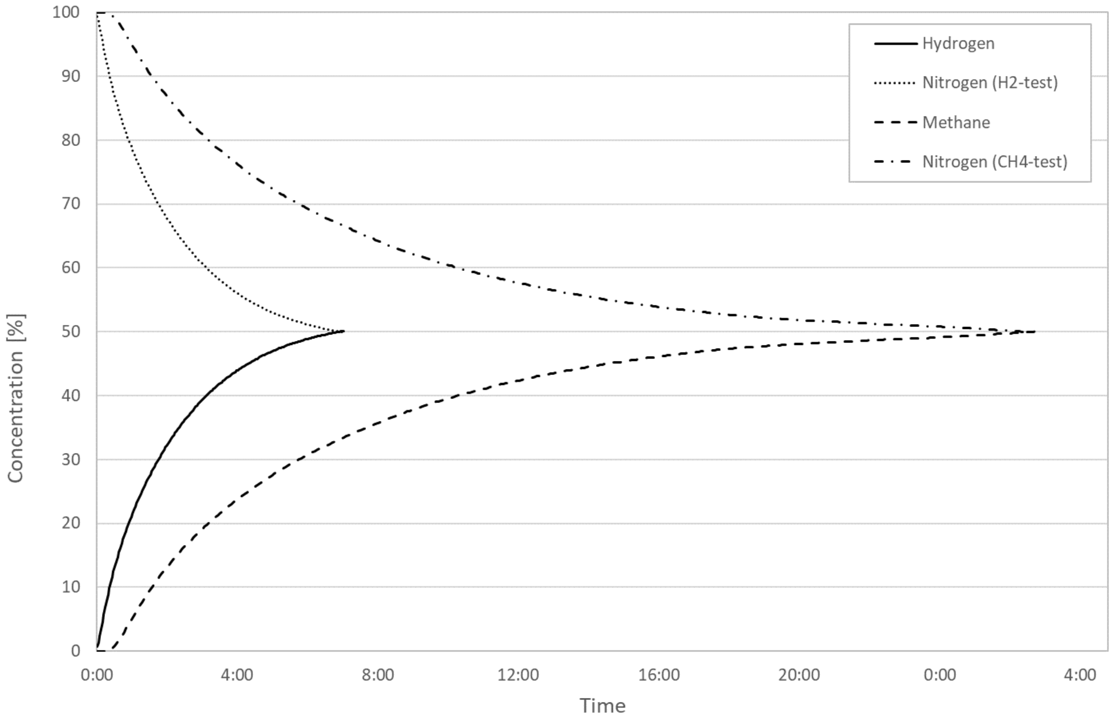

Figure 7-2: Test results of mixing velocity of gases for hydrogen and methane

8 Monitoring

During the purging process, it is essential to have a multi-gas monitoring or detecting instrument calibrated for the gases involved to analyse the gas escaping from the purge vent. This instrument is also necessary after purging operations as a combustible gas indicator, an oxygen indicator, and for other needs as the purge requires. It is important to note that different gas components have varying sensitivities towards the presence of hydrogen in natural gas. For example, new gas chromatographs (GCs) are needed to measure the gas composition of hydrogen.

Thermal conductive sensors and catalytic bead sensors are two common types of gas sensors. Both thermal conductivity and catalytic bead sensors are commonly used for hydrogen pipeline gas monitoring. Thermal conductivity sensors are particularly useful for detecting the presence of hydrogen in a gas mixture. These sensors work by measuring the difference in thermal conductivity between the gas mixture and a reference gas, such as nitrogen or air. Thermal conductivity sensors can provide real-time information on the presence and concentration of hydrogen in a pipeline. Catalytic bead sensors work by detecting changes in the electrical conductivity of a heated bead coated. They are particularly sensitive to the presence of combustible gases and can provide accurate information on the concentration of hydrogen in a pipeline.

It necessary to determine the end-points (when is the purge successfully finished) of the purging, such that there will be no more hydrogen in the pipeline when maintenance starts. When maintenance starts, air will form a potentially explosive mixture. Regular assessment of the effectiveness of the purging process is essential to ensure that the desired level of safety is being achieved. The assessment can be carried out by monitoring the concentration of hydrogen in the purged gas mixture and ensuring it is below the lower flammability limit.

9 Recommendations

This research studied different evacuation methods based on the isolation of pipeline sections, focusing on their advantages and disadvantages. Not every method is suitable in every situation, rather, each method has its own set of advantages and conditions in which it is most effective.

Although evacuation with the use of a separation pig seems favorable, because it poses no stratification problems and has a smaller diffusion fronts its disadvantages including a large loss of gas volume, potential disruption of suppliers and industrial consumers. The use off valve schemes closer to each other will have less volume loss and the risk to disrupt the flow from suppliers and to industrial consumers is less because of the shorter distance, but a successful purge operation might not always be possible if the two valve schemes are situated to far from each other. Furthermore, the Hydrogen Network Netherlands will be not be fully finished until 2030, giving rise to the issue that not all pipelines, installations, suppliers, and industrial consumers are connected to the ring structure and therefore the isolation of a single pipeline section could result in interruptions and might impose non-flowing conditions further down the hydrogen infrastructure.

To maintain flowing conditions, a bypass can be installed, but this solution requires the isolation of only a small section of the pipeline. The use of stopples could substantially decrease the length of the section requiring closure. Hence, the employment of stopples could prove to be a highly effective solution in maintaining flow. With the use of stopples, pipeline sections can be isolated without significantly disrupting the overall system. This solution also reduces the loss of gas volume, minimizing waste and increasing the overall efficiency of the system. The potential to install a temporary bypass further enhances the flexibility and adaptability of this approach.

However, it's worth noting that the implementation of stopples in hydrogen pipelines is not without its challenges. Currently used evacuation methods used for the natural gas infrastructure may not suffice. Further research into safe application of alternative stopple methods is needed. Procedures to safely operate stopple trains with a pressure differences on both heads should be investigated. Alternatively, the procedures and equipment needed to safely operate a hydraulic stopples should be researched. Here, hydraulic stopples are a more versatile option to investigate, since they do not need a pressure difference to be operated.

Procedures to evacuation installations, such as HyStock for storage of hydrogen, are similar to the procedures currently used in the natural gas. Due to the faster mixing between nitrogen and hydrogen, the dilution-based purge might be more efficient for hydrogen installations. It is recommended to perform research to more complex infrastructure to confirm this.

The choice of an evacuation method should be made based on the specific conditions of the pipeline or installation segment that requires maintenance. In all cases, efforts should be made to minimize the disruption to suppliers and industrial consumers and the loss of gas volume due to economic and environmental reasons. A summary of all advantages and disadvantage of different methods can be found in Table 9-1.

Table 9-1 Summary of advantages and disadvantages of different isolation and preferred evacuation techniques

Isolated section	Preferred evacuation technique	Advantages	Disadvantages
Between valve schemes with pigging facilities (50~100 km distance)	Purging with a separation PIG	-Minimizes the mixing of hydrogen and nitrogen -No stratification problems and smaller diffusion front -Evacuation method is similar to natural gas	-Large loss of gas volume -possible disruption of suppliers and industrial consumers -Higher flowrates along the pig w.r.t. natural gas pigging
Between valve schemes without pigging facilities (10~50 km distance)	Purging	-No disruption of suppliers and industrial consumers -Evacuation method is similar to natural gas	-Possible large loss of gas volume -Stratification issues will arise more often w.r.t. natural gas
Installing temporary seal with stopple	Purging	-Limited loss of gas volume -Possibility to install temporary bypass	-Current evacuation methods used for natural gas will not suffice -More research needed on stopple trains and hydraulic stopples
Valve schemes (installation, complex piping systems)	Dilution-based purge	-Can be applied in many cases -More effective hydrogen dilution w.r.t. to natural gas dilution.	-Multiple cycles of nitrogen purging needed before successful purge.

10 Appendix

A Physical Effects on the various hydrogen evacuation techniques

To carry out a successful purging operation with hydrogen and nitrogen, certain factors must be considered. The established theory of purging applies to various gases but has been predominantly utilized in the context of natural gas. The established theories can be used to perform estimating calculations for a better understanding of purging a hydrogen pipeline.

After the pipeline has been isolated and reduced in pressure, the most appropriate evacuation method relies on many factors: e.g. the type of installation/pipeline, pipeline diameter/length, piggability, etc. A flow chart of the different selection criteria is provided in Figure A-1. For each of the decision criteria and the respective effects, a dedicated section has been assigned to describe the difference between hydrogen compared to common natural gas evacuations. The impact of the change from natural gas to hydrogen can then be used to update existing evacuation procedures.

The main divisor in the scheme is the question if the line is piggable. In the current scheme, a gas evacuation should always be done with a pig when possible. This is due to the strong stratification properties between the hydrogen and nitrogen, as will be described in section A.3.1, and the potential operational distortions (e.g. temporary shortage of purge gas) during an evacuation procedure.

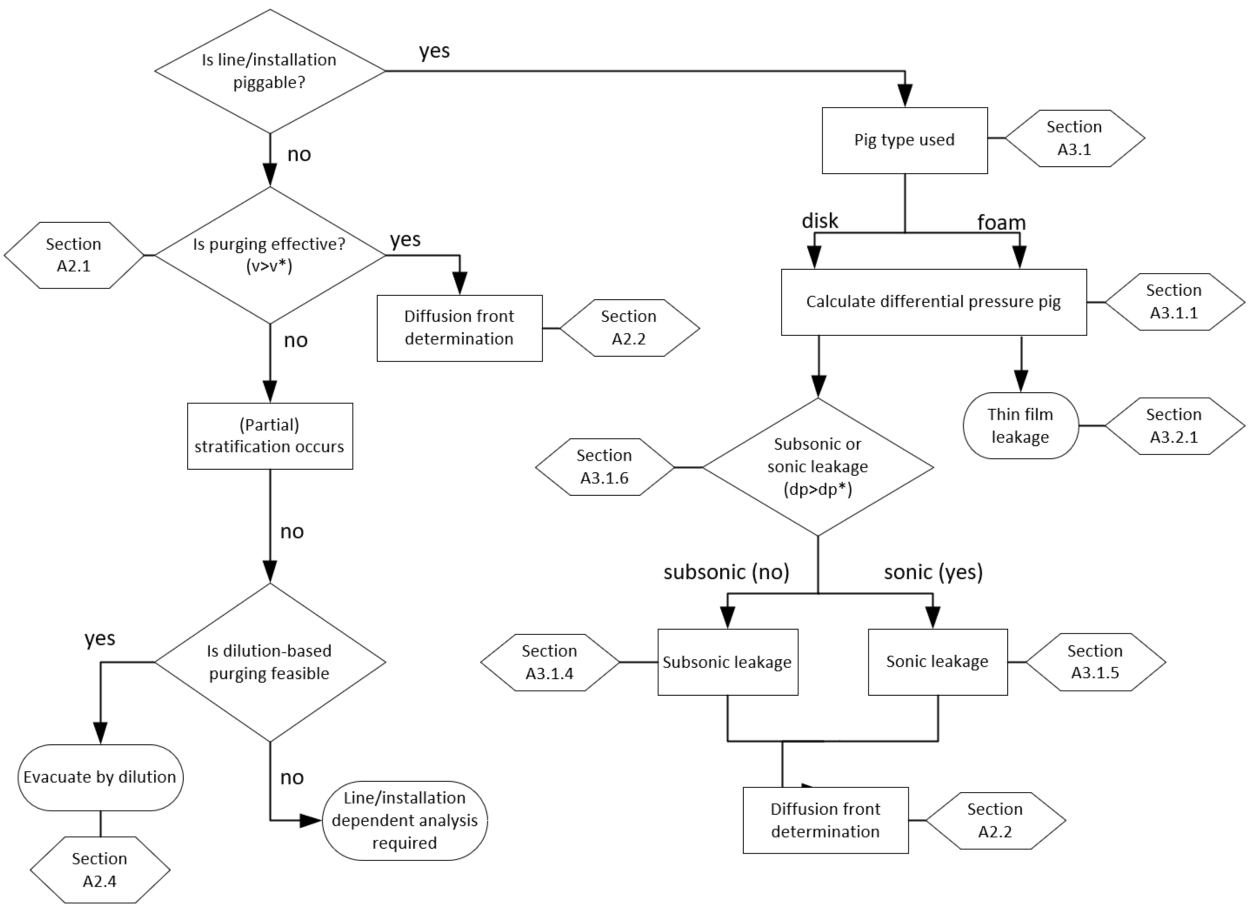

Figure A-1: Decision tree for gas evacuation of pipelines and installations.

A.1 Physical properties:

Natural gas and hydrogen have different chemical and physical properties and that influences the systems and infrastructure required for their safe and efficient distribution. This chapter will provide an overview of the key differences between natural gas, primarily composed of methane (CH_4), and hydrogen gas (H_2) which can play a role in the transportation of these gasses. Fundamental physical and chemical properties of both gases, such as their flammability limits, densities, and viscosities are essential for assessing the current protocols and guidelines for safe operation in the industry. The chapter will focus primarily on the physical and chemical properties of natural gas and hydrogen, their implications for pipeline maintenance procedures, and on their influence on physical processes are explored in greater depth in subsequent chapters.

Table A-1 shows a selection of the physical and chemical combustion properties of methane and hydrogen that influences gas transportation, evacuation and combustion. This table also displays the relevant values for nitrogen, as it is assumed in the report that nitrogen is used as an inert gas during maintenance operations on Hydrogen Network Netherlands .

Table A-1: Physical properties of methane/hydrogen and nitrogen at φ=1 (λ=1)

	S_L (cm/s)	Viscosity (10-5 Pa s)	Density (kg/m3@0 C, 1atm)	LFL		UFL		Min. Ignition energy (millijoule) stochiometric
				Vol% in air	λ	Vol% in air	λ	
Natural Gas	36	1.10	0.09	4.99	2.00	14.73	0.61	0.24
Hydrogen	252	0.88	0.72	4.07	9.87	74.24	0.15	0.017
Nitrogen	-	1.70	1.25	-	-	-	-	-

[1]calculated for a stochiometric methane/hydrogen-air mixture after compression

The likelihood that hydrogen is ignited is predominantly reliant upon two fundamental elements. Firstly, the formation of a combustible mixture of air and gas; secondly, the presence of an ignition source possessing sufficient ignition energy.

An air-gas (or nitrogen) mixture is combustible fit the concentrations are within a certain flammability limit. Knowledge of the flammability limits of hydrogen gas in air is a fundamental requirement for a successful purging operation. The lower flammable limit (LFL) of hydrogen is the concentration of hydrogen in the air below which a flame cannot propagate. This concentration is also known as the lower explosive limit (LEL) of hydrogen. As the concentration of hydrogen is progressively increased in air, a point is eventually reached where the concentration is too high to support a flame, which is known as the upper flammable limit (UFL) of hydrogen. The UFL can also be considered the upper explosive limit (UEL) of hydrogen for practical purposes.

Table 1-1 shows that hydrogen's LFL and UFL are approximately 4% and 75% by volume in air, respectively. In contrast, natural gas, primarily composed of methane, has an LFL of approximately 5% and a UFL of approximately 15% by volume in air. This wider flammability range of hydrogen means that it can ignite and burn over a broader concentration range than natural gas, presenting additional safety concerns during pipeline maintenance. Before performing maintenance on hydrogen pipelines, it is essential to purge the lines with inert gas, such as nitrogen, to minimize the risk of ignition. The flammability end-point diagram shown in Figure A-2 can be used as a useful tool to understand the impact of combustible gas mixtures of nitrogen, air, and hydrogen. The diagram highlights the flammability zone for these mixtures. The axes of the diagram represent the concentrations of the three components. When the concentration of the gas mixture is inside the red triangle, the mixture is within the flammability limit.

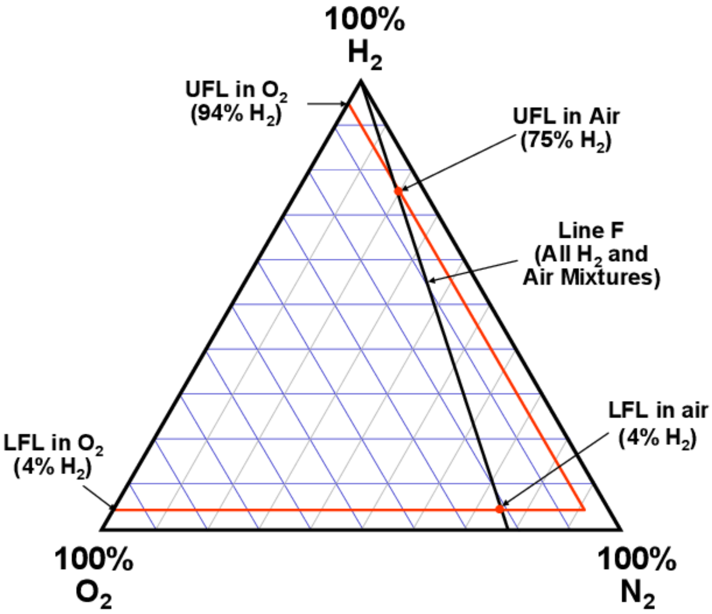

Figure A-2: Flammability Diagram for Hydrogen/Air/Nitrogen at 20 °C and 1 bar [1]

Hydrogen higher flammability limits do not make hydrogen more prone to (unwanted) ignition. When an external energy source interacts with a combustible mixture of gas and air it can ignite. This energy source could include heat, electrical sparks, a chemical reaction, or compression. The external energy catalyses a chain reaction between the gas and the oxygen, leading to the subsequent ignition of the entire combustible composition.

The minimum extern energy needed, called the minimum ignition energy, of hydrogen is very low (0.017 mJ) for stoichiometric mixtures. This means that it takes very little energy to ignite a mixture of hydrogen and air, which can be a safety concern in certain situations. The minimum ignition energy is dependent on the ratio of gas and air within a mixture. This correlation is clearly depicted in Figure 1-2, where it can be observed that hydrogen consistently requires lower ignition energy as compared to natural gas, specifically methane. This suggests that the energy threshold to initiate combustion in a hydrogen-air mixture is consistently lower than that of a methane-air mixture.

Besides a broader flammability region and reduced ignition energy, hydrogen also has a higher flame propagation speed, which ranges between 265 and 325 cm/s. Natural gas has a flame propagation between 35 and 45 cm/s, implying that flames fuelled by hydrogen have the capacity to spread significantly faster than those fuelled by methane. which means that hydrogen flames can propagate faster than those of methane.

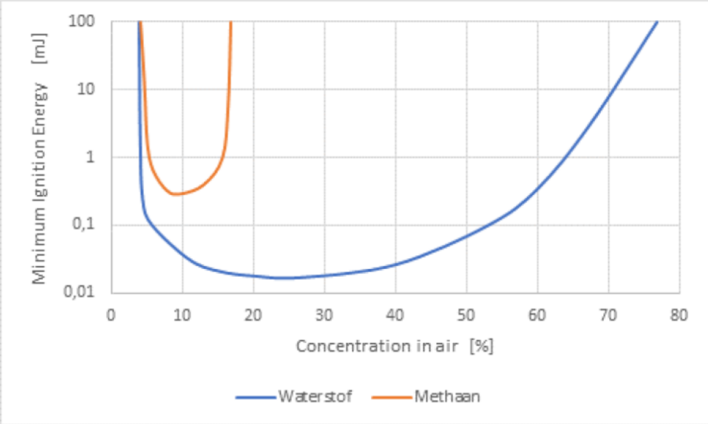

Figure A-3: Minimum ignition energy of hydrogen and methane at various concentrations in air

A.2 Evacuation by purging

In case the pipeline or the installation is not piggable, purging may be used to evacuate the gas. During a purging operation, two main effects need to be taken into account: stratification of the two gases, and the formation of a diffusion front due to turbulent dispersion. The stratification process will occur when the velocity of the purge gas is too low, i./e. below a certain critical velocity. When the velocity is well above this critical velocity, turbulent dispersion will occur that leads to the formation of a diffusion front. The determination of the length of this front is important to quantify the volume of mixed (off-spec) gas.

A.2.1 Stratifcation

The fundamental principle behind stratification is the formation of a so-called gravity-driven wave, which will transverse at the bottom of the pipeline, which has been theoretically assessed by ref [13] for liquid-liquid flows. A visual example of such a wave is depicted Figure A-4. where the lower layer is saline water and the upper layer fresh water (the gravity-driven wave travels from right to left).

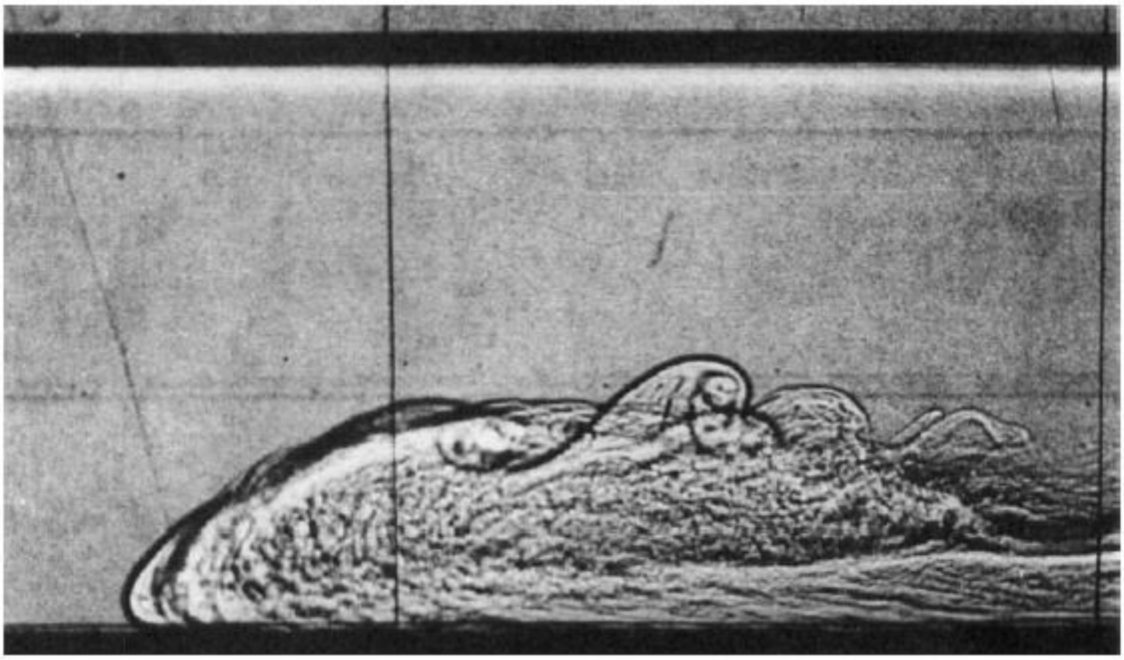

Figure A-4 : Experimental visualization of a gravity driven wave in liquid-liquid flow, taken from ref [13].

The velocity of the gravity driven wave can be calculated assuming certain idealized conditions. The proportionality of the velocity scales with the Froude number and the condition applied in pipeline purging guidelines [9] are

$$\mathrm{Fr} = \frac{v}{\sqrt{\tilde{g}D}} > \mathrm{Fr}^*, \text{ so: } \quad v > \mathrm{Fr}^*\sqrt{\tilde{g}D}, \tag{1}$$

where Fr^* is typically between 0.65 and 0.75 [9], and $\tilde{g}$ is the buoyancy compensated gravitational acceleration defined as:

$$\tilde{g} = g\frac{\Delta\rho}{\rho}, \tag{2}$$

In literature also the Richardson number, denoted by Ri, is presented as a critical parameter for stratification, see e.g. [10] and [11]. It is noted that the Richardson number is related to the Froude number as: $\mathrm{Ri} = 1/\mathrm{Fr}^2$, and therefore leads to similar expressions for critical stratification values. A summary of critical values from the literature (both Ri^* and Fr^*) can be given in terms of the Froude number:

- $\mathrm{Fr}^* = 0.65 - 0.75$: IPC pipeline purging guideline by Johnson [9]
- $\mathrm{Fr}^* = 0.75$: EN 12327 specification [4]
- $\mathrm{Ri}^* = 0.25$: Kiwa report [10] based on (https://glossary.ametsoc.org/wiki/Critical_richardson_number) which is equivalent to $\mathrm{Fr}^* = 2$
- $\mathrm{Ri}^* = 0.8$: based on the theoretical study of Leach [11], which is equivalent to $\mathrm{Fr}^* = 1.1$

Whatever the exact critical value the effect of changing from natural gas to hydrogen can be qualitatively calculated by evaluating equation **(2)**. This leads to the result that for hydrogen the purge velocity should be about 2.2 times higher to prevent stratification.

Next to the Froude number condition, it is also required that the flow of the driving gas is turbulent, which is the common Reynolds number condition, based on the turbulent transition at $\mathrm{Re}^* = 2300$:

$$\mathrm{Re} = \frac{\rho v D}{\mu} = \frac{vD}{\nu} > \mathrm{Re}^*, \qquad \text{so: } v > \frac{\mathrm{Re}^*\nu}{D}, \tag{3}$$

where μ and ν are the dynamic and kinematic viscosity, respectively. As observed from Figure A-5, the experimental data for natural gas/nitrogen show that the Froude number condition in equation **(1)** is most stringent for larger diameters ($D > 5"$). Below this critical diameter, the Reynolds number condition in **(3)** is most stringent and the experimental data deviates from the stratification curve. This data is however based on natural gas/nitrogen purging and this critical diameter needs to be re-established for hydrogen/nitrogen purging.

So, for the determination of the critical purging velocity, the $\mathrm{Fr}^* = 0.75$ from the IPC guideline and EN 12327 is used, and the critical velocity becomes

$$v^* = 0.75\sqrt{\tilde{g}D}, \qquad (D > D^*). \tag{4}$$

So, for hydrogen-nitrogen purging, the velocity should be approximately 2.2 times higher than for natural gas-nitrogen purging when considering the stratification/Froude condition.

For smaller diameters, the Reynolds condition is the most stringent

$$v^* = \frac{2300\nu}{D}, \qquad (D \leq D^*). \tag{5}$$

So, for hydrogen-nitrogen purging, the velocity should be approximately 7.3 times higher than for natural gas-nitrogen purging when considering the turbulence/Reynolds condition.

The critical diameter for hydrogen/nitrogen can then be found by equalizing equations **(1)** and **(2)** and assuming hydrogen as the purge gas, this results in:

$$D^* = \left(\frac{2300\nu}{0.75\sqrt{\tilde{g}},}\right)^{\frac{2}{3}} \approx 0.19, \tag{6}$$

which is significantly higher than the value for natural gas/nitrogen. Considering both conditions the minimum purging velocity can be calculated, see Figure A-6

It is noted that the stratification equation in **(1)** is symmetric (i.e. it does not matter if nitrogen is the driving gas or hydrogen), whereas the turbulent flow condition depends on the driving gas. Therefore, the critical diameter changes when using nitrogen as the purge gas: $D^* \approx 0.05$, and the critical velocity is dominated by the stratification condition for most typical diameters, see Figure A-7.

These theoretical results can be validated utilizing the purging experiments as performed in [10]. The experiments were performed under several velocities, ranging from 0.2-1 m/s, for a 200mm pipe. Looking at Figure A-5, these velocities are (well) below the critical velocity as estimated by theory and significant effects should have been observed. This is however not the conclusion of the experimental tests in [10]. The stratification phenomenon is observed in the first horizontal section of the test setup with a front propagating towards the first observation point at approximately 50 m from the injection. An estimation of the front can be made based on the propagation velocity and the difference between the top and bottom composition measurement and results in a front length of approximately 16m, which does indicate significant stratification. Also, the fact that the front becomes compact in the upward-sloping pipe indicates stratification.

So, the conclusion could be that stratification is occurring, however, it does not necessarily lead to a volume that cannot be purged. One of the phenomena that could be responsible for this is the effect of turbulent dispersion which will be treated in the next section.

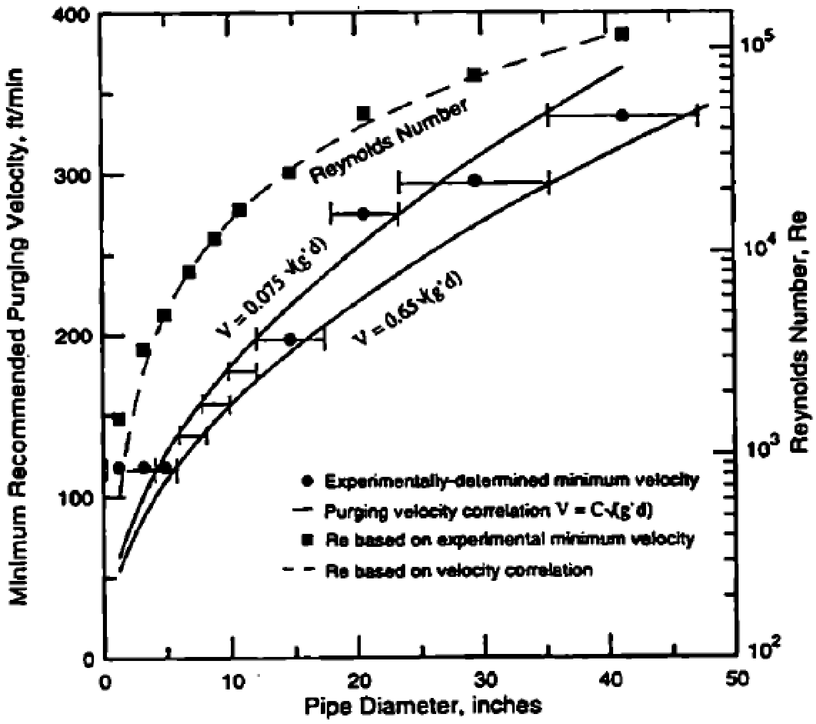

Figure A-5 : Minimum velocity requirement to prevent stratification, taken from ref [9]. Note: the upper solid line contains a typo, the constant should be 0.75.

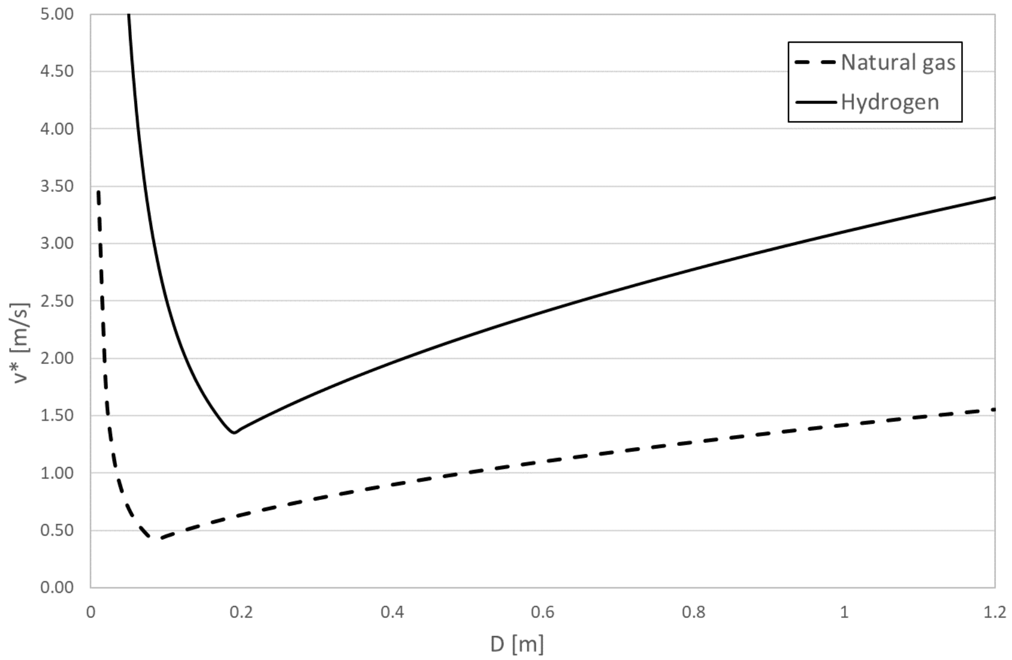

Figure A-6 : Minimum velocity requirement to prevent stratification for hydrogen and natural gas as driving gas.

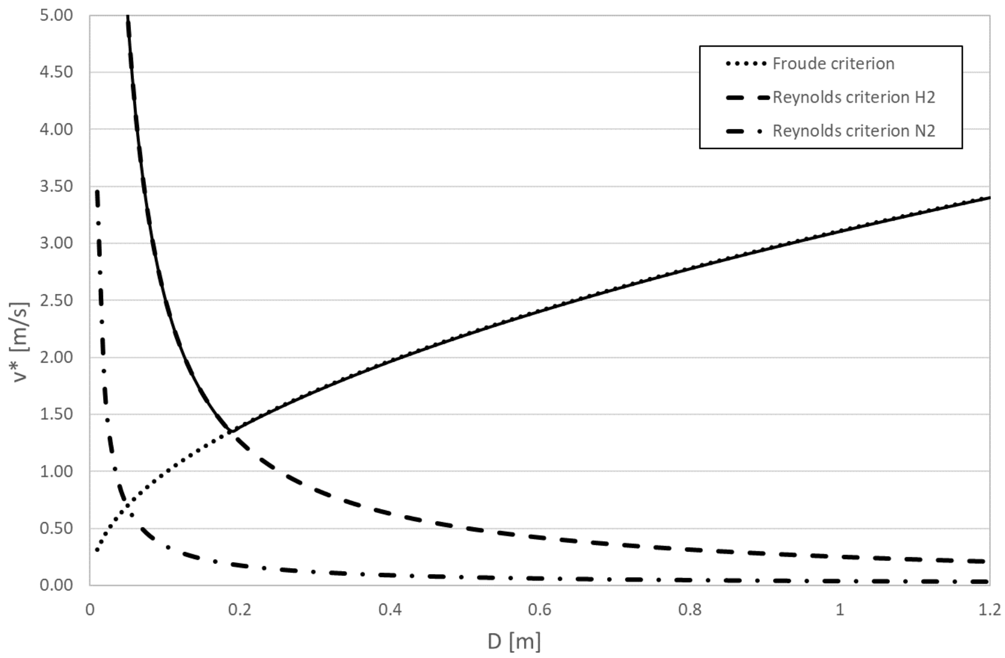

Figure A-7 : Minimum velocity requirement to prevent stratification for hydrogen and nitrogen as driving gas. The solid line indicates the maximum critical velocity for both stratification and turbulence for hydrogen.

A.2.2 Diffusion Front

When stratification can be prevented by applying a sufficiently high purging velocity, still a diffusion front will appear caused by turbulent dispersion. Several studies have been performed on the process of axial turbulent diffusion starting with the work of Taylor [17]. This work led to multiple publications, see e.g. refs [1], [3], [6], and [12], on the modelling of the turbulent dispersion coefficient, also referred turbulent diffusion coefficient. For one-dimensional pipe flow, it is generally assumed that this coefficient is a function of the Reynolds number only.

The process that causes the mixing of the diffusion front is turbulent dispersion. Typically, other processes like molecular diffusion are orders of magnitude lower in terms of the diffusion coefficient. To gain insight into the turbulent dispersion a literature study has been performed considering theoretical models, lab experiments, and full-scale experiments. The first model for turbulent dispersion was developed by Taylor [17] and proved that the diffusion coefficient due to turbulent dispersion, denoted by E, could be written as a function of the pipe Reynolds number when written in the dimensionless form:

$$\frac{E}{vD} = \frac{1}{\text{Pe}} = f(\text{Re}), \quad \textbf{(7)}$$

The left-hand side of equation **(7)** is a dimensionless form of the diffusion coefficient, which is the inverse Péclet number. The different theoretical models based on the Péclet-Reynolds domain and lab experiments were presented in [18] and provided in Figure A-8. Although there is some scatter in the data, the results for the theoretical models seem to fit well with the lab experiments.

Also, large-scale experiments have been carried out in the past of which one data set is generated by Gasunie, see the series of publications by Hoelen [8], and can be presented in the same way, see Figure A-9. In this figure, also the results obtained from a test in 2017 at the Pernis mixing station are added. As a reference, the model of Taylor has been plotted in the figure (dashed line) to emphasize the difference between the lab-scale experiments in Figure A-8 and the full-scale experiments in Figure A-9. It is anticipated that in these large-scale experiments also effects of stratification may have occurred which leads to larger diffusion fronts than for pure turbulent dispersion. So, for the turbulent dispersion, the high Reynolds number limit of the Taylor model is used:

$$\frac{E}{vD} = 0.2. \qquad \textbf{(8)}$$

Although there is a small dependence of the inverse Péclet number on the Reynolds number, the choice of assuming it constant is justified for a large Reynolds range and simplifies the calculation of the diffusion front.

One can calculate the diffusion front length by taking the analytical solution of the instationary diffusion equation, see e.g. [16]. Taking the value of the composition of the purge gas at 0.05 and 0.95, since the front will exhibit a smooth transition between the gases, the distance between these values is a measure of the diffusion front

$$\Delta x = 2.08\sqrt{DL}. \qquad \textbf{(9)}$$

This means that for a pipeline with $D = 0.1m$ and a propagation length of $L = 1000m$, the diffusion front becomes $\Delta x = 20.8m$. Observe that the equation for the diffusion front due to turbulent dispersion is not gas property dependent and will be similar for hydrogen and natural gas. Also, it does not depend on the velocity.

The results of the Kiwa experiments in [10] were used to check the outcome of the equation **(4)**. For the 100mm experiment, the diffusion front very closely resembles the theoretical prediction. The experiment shows that the diffusion front length is indeed velocity-independent and results in approximately equal volumes of remaining gas-air mixtures for different velocities. The results for the 200mm pipe do not agree well with equation **(4)** although the diffusive front length also seems velocity independent.

The inverse experiments where hydrogen is used as the purge gas show significantly different results compared to using nitrogen, see [10]. This may be because as explained in Figure A-7, using hydrogen as a purge gas may lead to the driving gas not becoming turbulent. Also, the chosen geometry of the test setup may have contributed to these differences.

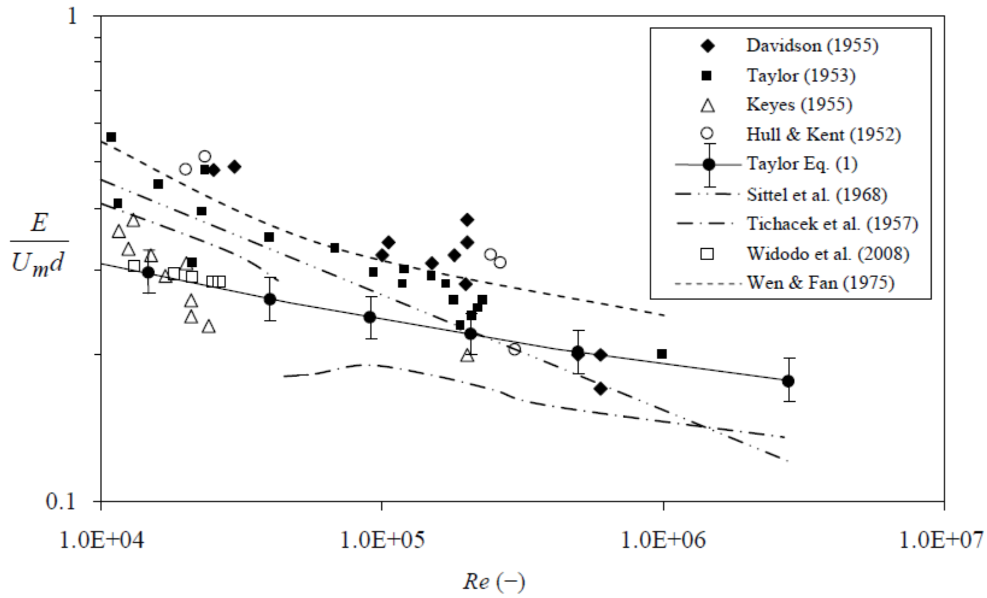

Figure A-8 : Comparison of theoretical turbulent dispersion models and lab experiments, taken from reference [18]; U_m is the bulk velocity (equivalent to v) and d is the diameter of the pipe (equivalent to D)

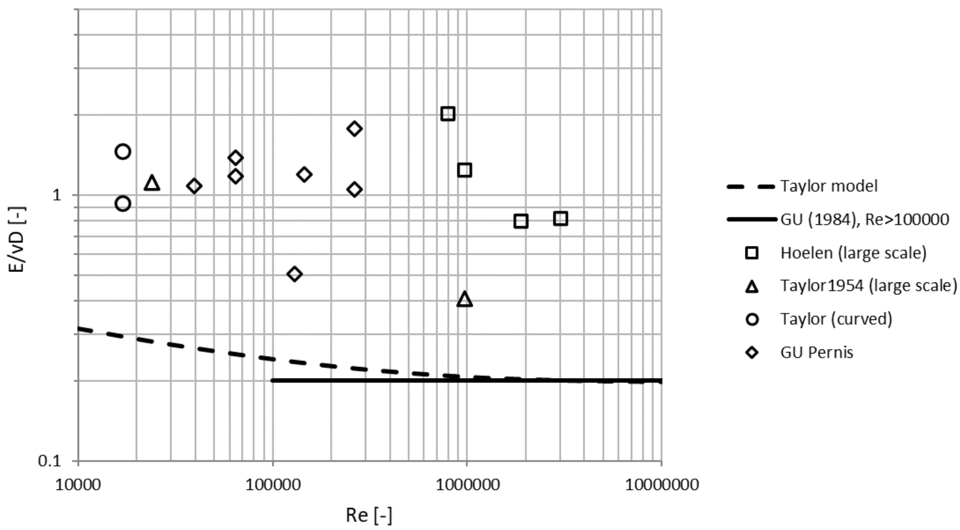

Figure A-9 : Comparison of theoretical turbulent dispersion models and experimental data for large-scale experiments

A.2.3 Pipeline and installation considerations

In some situations, a pipeline or installation may have a favourable or non-favourable geometry for purging. It is difficult to make a general statement about this since installations can differ in configurations and shape. For an upward-sloping geometry, it is favourable to inject the nitrogen at the lowest point and bleed off the hydrogen at the highest point at the end of the purging volume. When hydrogen is used as the purging gas, the process should be inverted. This is a general statement that also applies to large volumes in e.g. compressors and vessels. Also, in pipelines with vertical T-branches, the light or heavy gas may be captured in upward or downward orientations, respectively.

For complex installations, a detailed analysis should be performed to consider the above-mentioned items. If purging remains a difficult process and dead volumes cannot be prevented, a dilution method can be performed, which will be described in the next section.

A.2.4 Dilution

When performing a dilution exercise, the purge gas will be added to the volume and increased to a certain pressure p. The pressure is relieved to atmospheric pressure (p_{atm}) and therefore the concentration of the gas to be purged will reduce with approximately the ratio of these pressures (p/p_{atm}). This assumes that the gases are well-mixed and this depends on the injection velocity of the gas, i.e. the generation of turbulent mixing. In some parts of the volume to be purged it may be possible that no/low flow can be enforced, i.e. dead ends or large volumes. In those cases, the mixing depends on molecular diffusion between the two gases and the buoyancy between these gases. These processes are competing, and molecular diffusion is typically a very slow process. The final result of these competing processes is difficult to quantify, but one can compare the situation of natural gas-nitrogen to the case of hydrogen-nitrogen to estimate the relative effect.

This analysis starts with the dimensional analysis of the two competing processes, which are governed by the Peclet number for molecular diffusion and the Froude number. Taking the ratio of the two numbers leads to a dimensionless number that is independent on the velocity

$$\left(\frac{\mathrm{Pe}}{\mathrm{Fr}}\right)^2 = \frac{\tilde{g}D^3}{E^2}, \quad \textbf{(10)}$$

where E is now the molecular diffusion coefficient. The higher this dimensionless number the more the gases will remain separated, the lower this number the more dominant the molecular diffusion is and the more mixed the two gases will be. The number will increase when the density difference increases (increasing $\tilde{g}$) or the volume increases (increasing D^3). Calculations of equation **(10)** show that this number is higher for the natural gas-nitrogen system than for the hydrogen-nitrogen system, so the hydrogen-nitrogen mixture will mix faster (approximately 3.4 times as fast) than the natural gas-nitrogen mixture. This is mainly due to the molecular diffusion coefficient which is more than 4 times higher for the hydrogen-nitrogen mixture.

A.3 Evacuation by PIG usage

If a pipeline or part of an installation is piggable, a separation pig can be used as a barrier between the purge/driving gas and the gas that needs to be evacuated. For the evacuation operations, different pig types may be selected and this choice will influence the potential leakage of the purge gas towards the gas to be evacuated. The leakage depends on the type of pig and the type of purge gas used for driving the pig. This section concludes with an analysis of the different leaking mechanisms and the influence of the gas properties on these leaking mechanisms. Also, some considerations on pig operations are provided.

A.3.1 Pig types

Different types of pigs exist, from simple foam pigs to complex inline inspection tools, see Figure A-10. For the evacuation of pipelines, mostly the foam or disk-type pigs without diagnostic electronics are used as separator devices. These pig types are highlighted in the blue box in Figure .

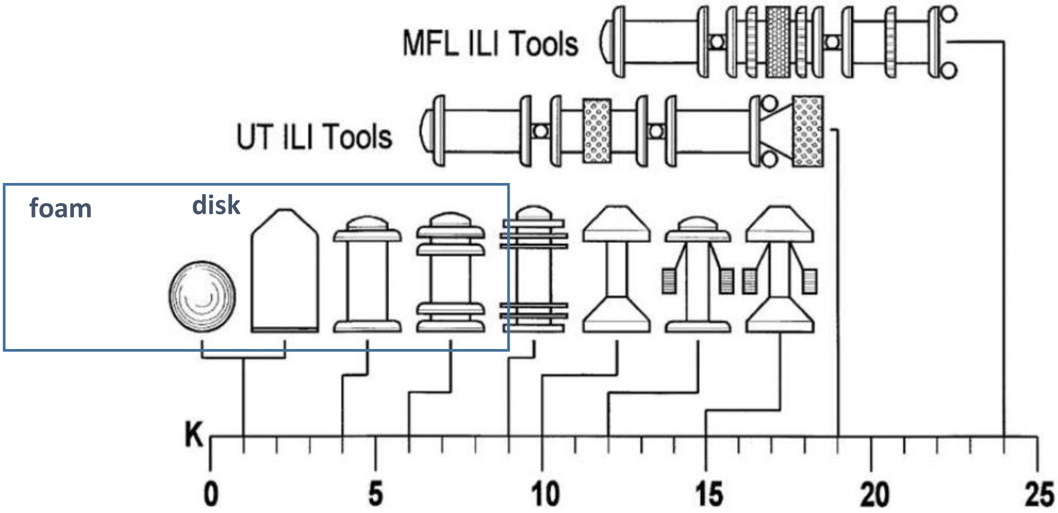

Figure A-10: Different pig types and corresponding resistance coefficients, taken from [7]

A.3.1.1 Pig differential pressure and leakage

Depending on the type of pig a certain differential pressure is required to move the pig through the pipeline. The expected differential pressure over the pig can be estimated by the empirical relationship:

$$\Delta p = \frac{K}{D}, \tag{11}$$

where D is the internal diameter in inches, the differential pressure in bar, and K-value depends on the type of pig used, see the horizontal axis in Figure . So, for a 6-inch pipe a double disk pig ($K = 6$) produces 1 bar differential pressure. Based on the determined differential pressure and the leakage mechanism, a leakage rate can be determined qualitatively.

The leakage is considered for two different leakage mechanisms: a thin-film annular flow (viscous flow) and leakage due to an opening caused by non-smooth surfaces (non-viscous flow). The latter non-viscous flow regime can be either subsonic (differential pressure-driven orifice flow) or sonic (choked flow). In the next subsections, these fluid dynamical mechanisms are described in more detail and their dependence on the physical properties of the driving gas are explained.

It is noted that the theoretical framework of the different leakage mechanisms can be applied to other leakage phenomena as well, e.g. valves, stopples, and bellows. An assessment is needed for each of these components to determine what type of leakage is expected, i.e. thin film leakage or cavity leakage.

A.3.1.2 Thin film leakage

When a pig is used that has a relatively long contact area with the wall (e.g. a foam pig), a potential leakage can occur through the clearance between the pipe wall and the pig. This thin annular clearance has a relatively long length, l, compared to the clearance width, c, i.e. $l \gg c$. This situation is illustrated in Figure A-11

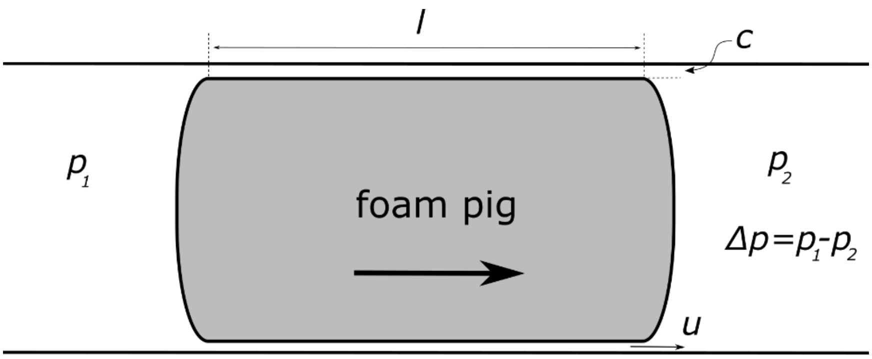

Figure A-11: Geometrical representation of a foam pig and the leakage mechanism

The differential pressure of such an annular clearance can be calculated based on the friction factor, f, and is given by

$$\Delta p = \frac{f}{4}\frac{l}{c}\,\rho u^2, \tag{12}$$

where ρ is the density of the gas and u is the leakage velocity. For the laminar flow regime and annular flow, the friction factor has the form [14]

$$f = \frac{64}{\mathrm{Re_c}} \cdot \phi(\alpha), \quad \mathrm{Re_c} = \frac{\rho u 2c}{\mu}. \tag{13}$$

$\mathrm{Re_c}$ is the Reynolds number of the flow through the clearance and $\phi(\alpha)$ is a function describing the shape of the annular clearance. For small clearance compared to the diameter of the pipe, i.e. $c \ll D$, this function becomes $\phi(\alpha) \approx 1.5$ [14]. Now by combining equations **(12)** and **(13)**, the leakage velocity can be determined

$$u = \frac{c^2 \Delta p}{12 \mu l}, \tag{14}$$

This leakage form is expected when a foam pig is used or when the disks of the pigs are pliable (or made of a soft material) causing a small clearance between the pig and the pipe wall over a longer distance.

The equation for the leakage flow does not provide a quantitative value for the leakage flow, since that depends on the exact measures of the clearance, which is typically not known. What it provides is the dependence of this leakage on the physical properties of the used driving gas. The geometrical parameters (c, l) do not depend on the gas, also the differential pressure based on equation **(11)** depends solely on the geometry. Therefore, the leakage is inversely proportional to the dynamic viscosity

$$u \propto \frac{1}{\mu}. \tag{15}$$

This means that when using hydrogen as the driving gas (i.e. when a separation pig is used after maintenance has been completed) the leakage is approximately 20% higher compared to using natural gas. When using a separation pig before the maintenance (i.e. when nitrogen is used as driving gas) no change is expected in the leakage behaviour from the normal natural gas evacuation procedure.

A.3.1.3 Flow through cavity

If the leakage is caused by a small cavity between the pipe wall and the pig, i.e. due to imperfections in the pig disk or small ripples on the inner surface of the pipe, the flow through that opening is driven by the differential pressure. This leakage mechanism is visualized in Figure A-12 and is expected when the length of the cavity is of the same order as the width, i.e. $l \approx c$. The leakage flow is limited by the disk with the smallest cavity. In the example of Figure A-12, the pressure is allowed to equalize between the driving gas and the space between the disks assuming the cavities on the left disk to be larger than the right disk. The flow through this cavity can either be subsonic (section A.3.1.4) or sonic (section A.3.1.5), depending on the differential pressure (see section A.3.1.6).

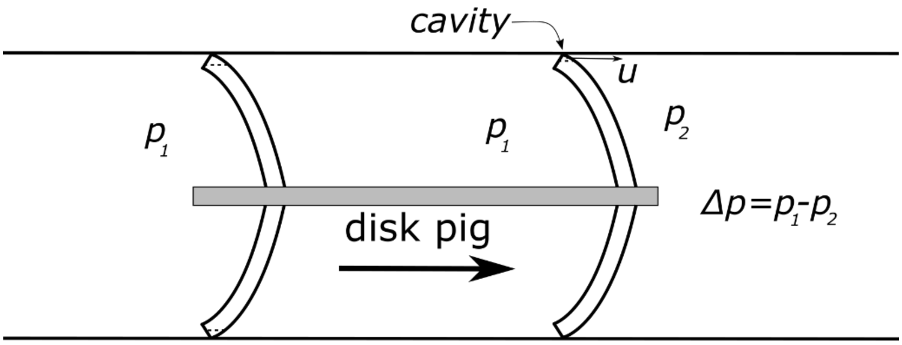

Figure A-12: Geometrical representation of a disk pig and the leakage mechanism

A.3.1.4 Subsonic orifice flow

In the case the differential pressure remains below the critical value, see section A.3.1.6, the flow through a small cavity can be derived from the Bernoulli equations for an inviscid (a near zero-viscosity flow), incompressible flow and is given by:

$$u = C_d \sqrt{\frac{2\Delta p}{\rho}} \,, \tag{16}$$

where C_d is typically between 0.4 and 0.8, depending on the shape of the hole. As an example, an orifice plate $C_d = 0.6$. The discharge coefficient partly corrects the assumption of an inviscid flow and may depend on the Reynolds number.

Equation **(16)** shows that the leakage velocity of a subsonic orifice flow depends on the differential pressure and is inversely proportional to the density. As explained in section A.3.1.1, the differential pressure is geometry dependent and is expected not to depend on the physical properties of the driving gas. Therefore, the leakage is inversely proportional to the square root of the density:

$$u \propto \sqrt{\frac{1}{\rho}} . \tag{17}$$

This means that when using hydrogen as the driving gas (i.e. when a separation pig is used after maintenance has been completed) the leakage is approximately 30% higher compared to using natural gas. When using a separation pig before the maintenance (i.e. when nitrogen is used as driving gas) no change is expected in the leakage behaviour from the normal natural gas evacuation procedure.

Since hydrogen pipelines are expected to be operated under relatively clean gas conditions, the pipe wall is expected to exhibit fewer imperfections as compared to natural gas pipelines where potential liquids and corrosion products may be present in parts of the pipeline. It is difficult to quantify this effect at this stage.

A.3.1.5 Sonic flow

In the case of a differential pressure exceeding the critical value, see section A.3.1.6, the flow through the cavity may become sonic. At these choked flow conditions, the leakage velocity is equal to the speed of sound. The speed of sound needs to be taken at the conditions at the minimum area of the cavity, indicated by c^*. This condition can be converted to the conditions of the driving gas by using isentropic relations [2], which results in:

$$u = c^* = \sqrt{\kappa Z^* R T^*} = \sqrt{\kappa \frac{p}{\rho}\left[\frac{2}{\kappa+1}\right]^{\frac{\kappa+1}{\kappa-1}}}\,. \tag{2}$$

The isentropic coefficient κ is nearly equal for hydrogen and nitrogen, which leaves the effect of pressure and density. Since the differential pressure on the pig is expected to be independent on gas composition, the pressure in the driving gas is expected to be similar for nitrogen and hydrogen. Therefore, the leakage is inversely proportional to the square root of the density:

$$u \propto \sqrt{\frac{1}{\rho}}\,. \tag{3}$$

This means that the same conclusions can be drawn as in section A.3.1.4, i.e. the leakage is approximately 30% higher for hydrogen as compared to using natural gas.

A.3.1.6 Sonic vs subsonic flow

Based on the equations for the leakage velocities, one can determine the condition at which the flow becomes sonic. Writing equation **(16)** in terms of Mach number with the help of equation **(2)** leads to:

$$M = \frac{u}{c} = C_d \sqrt{\frac{2}{\kappa\left[\frac{2}{\kappa+1}\right]^{\frac{\kappa+1}{\kappa-1}}}}\sqrt{\frac{\Delta p}{p}}\,. \tag{4}$$

In other words, at sonic conditions ($M = 1$), the relative differential pressure should be

$$\frac{\Delta p}{p} = \frac{\kappa\left[\frac{2}{\kappa+1}\right]^{\frac{\kappa+1}{\kappa-1}}}{2C_d^2}\,. \tag{5}$$

For $C_d = 0.6$, which results in $\frac{\Delta p}{p} \approx 0.65$. So, when the differential pressure on the pig exceeds 65% of the driving pressure, the flow through the cavity becomes sonic. For the case where the pressure in the gas to be evacuated is atmospheric, this leads to a required differential pressure of 2 bar on the pig, which is very uncommon as explained in section A.3.1.1.

A.3.2 Pig operations

For hydrogen applications, different pig designs are used. These hydrogen pigs typically have a different material for the discs to reduce the risk of electrostatic build-up and resist decomposition, see [5]. This may influence the friction characteristics of the pig and therefore the pressure drop, however no confirmation in the literature could be found.

One of the concerns of pig operations in hydrogen is the stick-slip behaviour of the pig leading to more unstable pig runs. The moment a pig comes to hold in a pipeline, a water-hammer type pressure wave is generated which increases the pressure at the tail of the pig (and at the same time an expansion wave is generated at the head of the pig). If this pressure increase is large enough the pig will continue its run. This stick-slip effect is typically appointed to the density of the gas, i.e. the higher the density the less the risk of stick-slip behaviour and the more stable the run. Elaborate analyses were performed in [15], where the full coupled problem of the fluid dynamics of the gas and the mechanical dynamics of the pig were analysed. If we focus on the effect of the sudden stop of the pig and the pressure effect, the differential pressure caused by the sudden decrease of the gas velocity can be described by the Joukowski equation for the water-hammer:

$$\Delta p_J = \rho c \Delta v, \qquad \textbf{(6)}$$

where the ρc is the acoustic impedance of the medium, Δp_J is the increase in pressure at the tail side of the pig and Δu is the difference in gas velocity (which for a full stop is equal to the driving velocity). So, when using the same gas, the stick-slip behaviour is indeed governed by the density, since the speed of sound will remain approximately the same. However, when the gas is changed, also the speed of sound changes. The difference between the standard natural gas/nitrogen case and hydrogen is a reduction of the acoustic impedance between 3 and 4. So when the pig is stopped with the same driving velocity, the increased pressure at the tail side of the pipe will be approximately 3-4 times lower. This makes the pig more susceptible to stick-slip behaviour under hydrogen conditions. For evacuation purposes the velocity of the pig is less important since no data is collected during the pig run (constant pig velocity is a requirement for proper data acquisition), therefore a solution could be to increase the pig velocity when possible.

Also, the above-mentioned analysis can be performed on the basis of the increase in total pressure when the gas velocity decreases. For an isentropic flow, this leads to the Bernoulli equation for the increase in pressure

$$\Delta p_B = \frac{1}{2} \rho \Delta v^2, \qquad \textbf{(7)}$$

Which effect is dominant can be shown by taking the ratio of the two expressions for the differential pressure

$$\frac{\Delta p_J}{\Delta p_B} = \frac{2}{M}, \quad M = \frac{\Delta v}{c} \qquad \textbf{(8)}$$

where M is the Mach number. This means that for low pig velocities, the water hammer effect (Joukowski equation) is dominant.

B Notulen discussiepanel evacueren en vullen van waterstofleidingen

MoM.nr.: 10365965-5-1

NOTULEN Aan: Deelnemers aan het overleg over het evacueren en vullen van waterstofleidingen

Van: DNV Energy Systems
Datum: 24-05-2023
Opgesteld. door: Robert Mellema

Verslag van overleg over het evacueren en vullen van waterstofleidingen

Tijd/Locatie: 04-04-2023, DNV kantoor Groningen
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Inleiding

In het kader van het HyDelta 2.0, werkpakket 5 heeft DNV opdracht gekregen een richtlijn samen te stellen met betrekking tot het veilig en effectief drukloos maken en weer vullen van waterstofleidingen. Het gaat hierbij om leidingen die reeds gevuld zijn met waterstof.

In dit verband is een aantal Gasunie deskundigen uitgenodigd om over verschillende aspecten van het drukvrij maken en vullen van waterstofleidingen te overleggen. Het overleg heeft plaatsgevonden aan de hand van een presentatie die door DNV was voorbereid. Dit verslag geeft een samenvatting van hetgeen besproken is, niet per sé in chronologische volgorde.

Stoppelen

Bij gasklussen wordt waar nodig gebruik gemaakt van stoppels om het leidingdeel waarin de werkzaamheden moeten worden uitgevoerd af te sluiten van de rest van het gasnet om de werkzaamheden veilig uit te kunnen voeren. Via een (tijdelijke) omloopleiding kan het transport in de onderhavige leiding worden voortgezet. Stoppels zijn tijdelijke afsluiters die via een aanboring in de leiding kunnen worden ingebracht en door uitgeklapt/gedraaid te worden een blokkade in de leiding vormen. Dit is bij aardgas een bewezen techniek waarbij tevens een balg wordt ingebracht tussen de stoppel en de gasklus om daartussen een ruimte te creëren die bijvoorbeeld met stikstof gespoeld kan worden om de vorming van een explosief gas/lucht mengsel te voorkomen bij (enig) doorlekken van gas door de stoppel. Bij de tijdens het overleg getoonde afbeelding wordt opgemerkt dat de balg aan de verkeerde zijde van de Tor-nippel is afgebeeld, maar dit zou betekenen dat het afgesloten leidingdeel niet kan worden gespoeld maar alleen drukvrij kan worden gehouden (Bleed). Het spoelen met lage druk stikstof zou juist een veiliger atmosfeer kunnen creëren; hiervoor zou een extra nippel moeten worden toegevoegd.

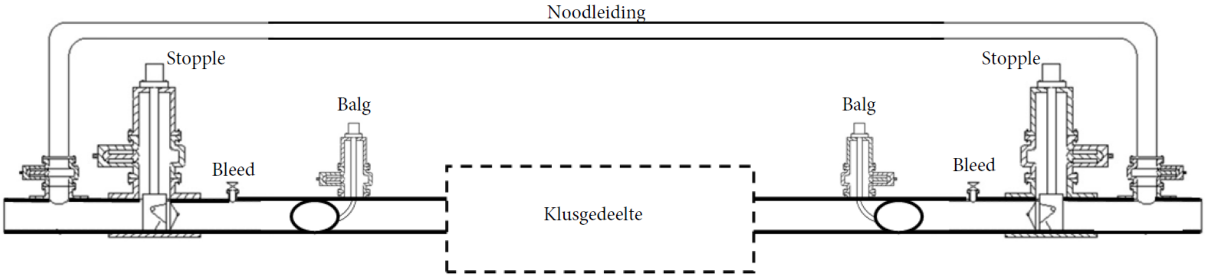

Figure B-1 Voorbeeld-opstelling van klusoperatie met twee stopples

Er worden vraagtekens geplaatst bij het toepassen van stoppels bij waterstof; er treedt bij aardgasklussen vrijwel altijd lekkage op als gevolg van een onvolkomen afsluiting, bijvoorbeeld door de aanwezigheid van boorspanen en -gruis op de bodem van de leiding. Dit is de reden dat stoppelen tot een minimum wordt beperkt. In Enschede is echter een geslaagde proef uitgevoerd met een enkele stoppel en balg afsluiting zoals hierboven getoond met 60 bar waterstof, maar de resultaten van eenzelfde proef met een dubbele stoppel (zonder balg, een zogenoemde stoppeltrein) waren minder goed. Bij de proeven is gebruik gemaakt van een camera om de plaatsing van de stoppels en het wegvegen van het boorgruis met de stoppel te ondersteunen en dit werd als zeer nuttig ervaren.

Er worden ook vraagtekens geplaatst bij de sterkte van balgen en het risico op scheuren/doorlekken ;dit wordt echter weersproken. In de praktijk mogen balgen gebruikt worden tot een drukverschil van 200 mbar aan beide zijden, maar balgen zijn voldoende sterk om veel grotere drukverschillen te weerstaan (4 bar werd genoemd). Wel moeten ze afdoende worden beschermd tegen vuur en vonken of mechanische belasting, bijvoorbeeld door het plaatsen van rioolstoppers indien de afstand tussen balg en de gasklus niet groot genoeg is (> 3 m.)

Om problemen met stoppels zoveel mogelijk te vermijden wordt gesuggereerd gebruik te gaan maken van hydraulisch arreteerbare stoppels. Deze stoppels geven een veel betere afsluiting doordat de klepzitting met grote kracht tegen de buiswand gedrukt kan worden (smartplug isolation system van TD williams of TechnoPlug tm of remote techno plug tm., filmpje Hot Tapping&Plugging: leak tight Double Block and Bleed isolation. Bij Gasunie wordt geen gebruik gemaakt van dergelijke hydraulische stoppels maar in het buitenland worden deze al veelvuldig met succes toegepast. Daarvoor is het wel nodig dat speciale apparatuur wordt aangeschaft.

Verder wordt opgemerkt dat de bij Gasunie momenteel in gebruik zijnde stoppels alleen goed werken indien een zeker drukverschil over beide zijden van de stoppel bestaat. Bij gebruik van een stoppeltrein werkt de binnenste stoppel derhalve niet totdat de buitenste stoppel zoveel gas heeft doorgelaten dat de druk in de ruimte tussen beide stoppels voldoende is gevuld om ook de binnenste stoppel goed af te laten sluiten. De afstand tussen beide stoppels komt bij benadering overeen met de leidingdiameter.

Uit de discussie kan worden geconcludeerd dat er bezwaren bestaan tegen de momenteel bij Gasunie gebruikte stoppels; het gebruik daarvan zou tot een minimum moeten worden beperkt. Voor het gebruik van stoppels in waterstofleidingen zijn aanpassingen aan de gevolgde werkwijzen en gebruikte apparatuur nodig. Ten aanzien van het gebruik van dubbele en/of hydraulische stoppels moet nog ervaring worden opgedaan.

Inblokken tussen afsluiters

In plaats van lokaal aangebrachte stoppels kan ook worden overwogen gebruik te maken van reeds bestaande afsluiters in het leidingdeel waarin de gasklus uitgevoerd dient te worden. Er wordt dan gebruik gemaakt van dubbele block & bleed afsluiterschema's. Het voordeel is dat geen stoppels geplaatst hoeven te worden; door het gebruik van balgen dichtbij de gasklus kan het volume aan lucht dat in de leidingdelen aan weerzijden van de gasklus komt worden beperkt. Voordeel is dat niet de gehele inhoud van de leiding hoeft te worden verdrongen. Als extra veiligheidsmaatregel wordt een tweede balg ingezet waarvan het geïsoleerde leidingdeel wordt gespoeld met stikstof.

Verdringing met pigs

Wanneer leidingen over grotere afstanden drukvrij gemaakt moeten worden waarbij voor het verdringen gebruik wordt gemaakt van een inert gas zoals stikstof dient altijd gebruik te worden gemaakt van scheidingspigs om opmenging van waterstof en stikstof zoveel mogelijk te vermijden.

Ten aanzien van het gebruik van pigs in waterstofleidingen worden de volgende opmerkingen gemaakt:

- Er dienen maatregelen te worden genomen om luchtinsluitingen in pig launchers en receivers te voorkomen, vooral gelet op de ruimere explosiegrenzen van waterstof ten opzichte van aardgas. Er wordt hierbij wel opgemerkt dat het effect van een eventuele ontbranding van de waterstof in een pig-trap mogelijk beperkt zal zijn door de geringe volumes en de lage energie-inhoud van waterstof. Dit zal echter wel nader onderzocht dienen te worden. Vorming van een brandbaar mengsel zal echter altijd voorkomen moeten worden. De pig launcher en receiver zal moeten beschikken over voorzieningen om het te kunnen spoelen en ook evacueren met een vacuümpomp kan worden overwogen.
- Onderzoek van DNV heeft uitgewezen dat het dynamische gedrag van een pig in een waterstofleiding afwijkt van die in een aardgasleiding. Door de geringere dichtheid van waterstof wordt het stick-slip gedrag versterkt waardoor de pig zich minder gelijkmatig door de leiding zal voortbewegen. Dit kan minder gunstig zijn bij het gebruik van inspectiepigs maar hoeft voor scheidingspigs niet direct een probleem op te leveren. Het 'waterslageffect' met waterstof is 3-4 maal kleiner dan met aardgas door de geringe dichtheid van waterstof.
- Verder onderzoek van DNV heeft uitgewezen dat de lekkage van pigs tussen pijpwand en pig met waterstof 20-30% groter zal zijn dan met aardgas. Dit is echter gestoeld op een theoretische beschouwing; experimenteel onderzoek zal nodig zijn om e.e.a. te bevestigen.

Verdringing zonder pigs

Indien het niet mogelijk is om gebruik te maken van pigs dient verdringing plaats te vinden door het injecteren van het verdringende gas (bijvoorbeeld stikstof) rechtstreeks achter het te verdringen gas (bijvoorbeeld waterstof). Door het ontbreken van een fysieke scheiding tussen beide gassoorten zal opmenging plaatsvinden waardoor een deel van het waterstof in de leiding off-spec en dus onbruikbaar zal worden. Ten aanzien hiervan wordt het volgende opgemerkt:

- Er wordt gesteld dat leidingen met een lengte van meer dan 2.5 km altijd piggable zijn zodat scheidingspigs kunnen worden toegepast. Afhankelijk van o.a. eisen ten aanzien van externe veiligheid zouden ook kortere leidingen piggable uitgevoerd moeten worden.
- In bepaalde gevallen, afhankelijk van de geometrie van het systeem is het mogelijk om de met waterstof gevulde leiding herhaaldelijk met stikstof te vullen en het waterstof/stikstof mengsel vervolgens af te blazen; de verdunning met stikstof wordt hierdoor steeds groter.
- Als gevolg van de verschillende dichtheden van waterstof en stikstof zal een zekere mate van stratificatie – laagvorming – optreden waarbij de zwaardere stikstof onder de waterstof geraakt. Stratificatie kan zich over een grote leidinglengte voordoen en resulteren in veel off-spec gas. Stratificatie doet zich vooral voor bij laminaire stroming en in rechte leidingen. Bochten en andere afwijkingen van de rechte lijn zorgen voor menging in radiale richting. Er dient een zorgvuldige afweging van de gassnelheid versus de leidingdiameter te worden gemaakt waarbij de conclusie is dat indien turbulente stroming niet kan worden gegarandeerd er altijd een pig moet worden toegepast.

- Het mengfront bij turbulente stroming is onafhankelijk van de gaseigenschappen en is bij waterstof dus gelijk aan aardgas.
- Er bestond het vermoeden dat bij afgesloten volumes (vaten, T-stukken) pockets van waterstof slechter mengen met stikstof dan in het geval van aardgas verdringing. Nadere analyses hebben echter geleerd dat juist het omgekeerde het geval zal zijn. Dit moet echter nog experimenteel bevestigd worden. In de praktijk worden pockets vermeden door de druk enkele malen te verhogen en te verlagen om de pockets wisselend leeg te laten lopen en weer te vullen.
- Voor het verdringen installatieonderdelen (of leidingdelen) waarbij stratificatieproblemen ontstaan kan er worden gekozen om desbetreffende sectie in te blokken en verticaal te spoelen. Daarbij wordt het zwaardere gas (stikstof) aan de onderkant ingespoten/uitgelaten en het lichtere gas(waterstof) aan de bovenkant uitgelaten/ingespoten. Dit is vooral bij ondergrondse leidingen lastig te realiseren omdat dit zal leiden tot extra ruimte in de werkput vanwege de benodigde apparatuur.

Door DNV is een beslisboom voor het gasvrij maken van waterstofleidingen gemaakt; hierin wordt in hoofdzaak onderscheid gemaakt tussen leidingen die wel of niet piggable zijn. De slides die tijdens de bespreking zijn getoond zullen samen met dit besprekingsverslag onder de deelnemers worden verspreid.

Brandstofcel voor drukloos maken leiding?

Aangezien er onvoldoende kennis is over het gebruik van compressoren bij waterstof, wordt fakkelen gezien als hoofdmogelijkheden voor het drukloos maken van leiding. Dat kan betekenen dat er grote gasvolumes verloren gaan tijdens het drukloos maken van langere leidingen. Een mobiele brandstofcel zou een mogelijkheid zijn om de waterstof nuttig te besteden. Om een mobiele brandstofcel te gebruiken moet de waterstof voldoende zuiver zijn hetgeen in de praktijk zal betekenen dat zuivering moet plaatsvinden. Bovendien is het onduidelijk wat er met de geproduceerde elektriciteit en warmte moet worden gedaan.

Waterstofklus als aardgasklus?

Tenslotte wordt opgemerkt dat het wellicht werkbaarder zal zijn om bij klussen aan waterstofleidingen eerst de waterstof te verdringen met aardgas en dan de gasklus uit te voeren als zijnde een ‘gewone’ aardgasklus. Na beëindiging van de werkzaamheden zou het aardgas weer met waterstof kunnen worden verdrongen. Het voordeel van de voorgestelde werkwijze is dat minder speciale aanpassingen hoeven te worden gemaakt en dat de uitvoering van gasklussen kan worden gedaan volgens een door en door bekende en bewezen werkwijze.

Door een deelnemer aan de vergadering wordt erop gewezen dat in het kader van leveringszekerheid bij het gebruik van de enkel uitgevoerde leidingen in de backbone, hydraulische stoppels in combinatie met een double block & bleed systeem en een (korte) omloopleiding de hoogste leveringszekerheid biedt. Wel zal nader onderzoek naar het gebruik van een dergelijk systeem moeten worden gedaan.

C Research questions

This report on safe isolation and evacuating of high-pressure hydrogen pipelines and installations for maintenance purposes consisted was subjected to scope changes throughout the project due to the fast-paced hydrogen industry. The latest scope consisted some research question. The Expert Assesment Group (EAG) emphasized that the content should be based on guidelines with a general approach of evacuation without assessing current protocols.

How can high-pressure hydrogen pipelines & installations be safely evacuated?

This report assesses multiple evacuation methods currently used in the natural gas industry; displacement with a pig, purging, and dilution-based purging. The report discusses guidelines on the different situations in which the evacuation method can be used and their respective advantages and disadvantages. The general guidelines are situated dependent but will generally consists out of the following steps:

1. Identify the sections that need maintenance
2. Isolate the section that needs maintenance, utilizing valve schemes or stopples
3. Depressurize the system
4. Evacuate hydrogen with nitrogen, utilizing pigging, purging, or dilution techniques
5. Ensure secondary isolation and a bleed mechanism is in place
6. Execute maintenance operations
7. Flush the maintenance area with nitrogen before reintroducing hydrogen

Table 9-1 shows a more, in-depth, overview of the advantages and disadvantages for different evacuation guides.

What consideration should be taken into account?

Besides guidelines some consideration where assessed for hydrogen evacuation:

- The leakage rate along a (separation) pig will be roughly 20 to 30% higher with hydrogen w.r.t. natural gas. In general, thin film driven leakages are 20% higher and cavity driven leakages are 30% higher for hydrogen.
- A (separation) pig will be more susceptible to stick-slip behaviour in a hydrogen pipeline, due to higher acoustic impedance and a pipeline that has dry gas.
- The minimum velocity requirement to prevent stratification is higher form hydrogen than natural gas.
- Diffusion front due to turbulent dispersion is not gas property dependent and will be similar for hydrogen and natural gas, but the minimum velocity requirement turbulence for hydrogen should considered when purging from nitrogen to hydrogen.
- Thin film driven leakages are 20% higher for hydrogen w.r.t. natural gas, cavity driven leakages are 30% higher.
- Hydrogen-nitrogen mixture will mix faster (approximately 3.4 times as fast) than the natural gas-nitrogen mixture, resulting a faster dilution-based purge.

What is the best way to convert pipelines from natural gas to hydrogen?

Converting a pipeline from natural gas to hydrogen is mainly focused on cleaning the pipeline. Can be found in an detailed paper "Conversion of a natural gas pipeline to hydrogen transport and the effects of impurities on the hydrogen quality (Gas Analysis 2022, 11th International Gas Analysis Symposium & Exhibition, DNV Energy Systems, Henk Top)"

The main focus of converting a pipeline from natural gas to hydrogen will be cleaning the pipelein. Behaviour of contaminants found in the mentioned natural gas pipeline during the pipeline's transition from natural gas to hydrogen and their effect on the hydrogen quality is discussed.

The contaminants found in natural gas pipelines is vast and can be categorized into solids, liquids, and volatile/gaseous components. To mitigate the impacts of such impurities on the hydrogen transported in repurposed pipelines, a detailed cleaning procedure must considered. This paper outlines the steps undertaken to clean the pipeline prior to the actual transition, demonstrating the effects of these measures by presenting the concentration of various contaminants during and after the pipeline's conversion from natural gas to hydrogen.

The conversion guide from natural gas to hydrogen consists of five steps:

1. Initial cleaning using cleaning pigs to expel loose dirt and liquids from the pipeline, which remains filled with natural gas.
2. Displacement of natural gas by nitrogen, employing a pig run to isolate the natural gas from the nitrogen, while preserving the pipeline under a low-pressure nitrogen atmosphere.
3. Conduct necessary alterations and/or replacements on the pipeline, and perform essential maintenance during a period when the pipeline is sustained at low pressure and filled with nitrogen.
4. Cleaning pig run under a nitrogen atmosphere, monitoring contaminants in nitrogen to assess whether the criteria for transitioning to hydrogen transmission have been met.
5. Displacement of nitrogen by hydrogen using a pig to isolate the nitrogen from the hydrogen.

Based on the contaminants collected during the pipeline's cleaning, the paper proposes some preliminary criteria for the cleaning process:

- Liquids/solids/sludge; a maximum of 1 litre of material for pipe diameters up to 12 inches and up to 2 litres of material for pipe diameters larger than 12 inches (irrespective of pipeline length).
- Hydrocarbons limited to 1000 ppm.
- Water dewpoint less than -8 degrees at 70 bar.

Measurements taken during and after the transition indicate that contaminant levels remain extremely low.

How can HyStock be safely commissioned and decommissioned?

Since the report focused is based on guidelines with a general approach of evacuation. The evacuation of HyStock was only mentioned as an example during discussions. More information on current procedures for installations or details on the HyStock were not received. Given that we received few details about the installation itself and the other part, and the nature of the report is about general guidelines, there was no specific assessment of the HyStock installation. The report did focus on the dilution-based purge needed for the HyStock installation with experimental research about dilution-based mixing.

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