De-fossilization: Lessons Learned Overcoming Challenges in Difficult Product Pipelines

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Abstract

As the industry transitions to renewables and de-fossilization of the energy sector, "new" products are being introduced into pipelines. Pipelines will remain a relevant and efficient way to transport energy over long distances, but this energy, and associated by-products, could take some form other than natural gas. Such products as hydrogen, biofuels, ammonia, carbon dioxide, steam and hot water are the talk of the pipeline industry but, are these products new?

For many years, operators of transmission and distribution pipelines have focused on the development of expertise to safely operate natural gas pipelines. Operating a pipeline with other products will bring some new challenges but it may not be necessary to start from a blank page - these products are not completely new to the pipeline industry.

This paper will share some experiences of pigging, inspection, intervention and isolation in some of these challenging products. Each product has its own characteristics that make it difficult to work with but, over the years, technology and processes have been developed to ensure that these pipelines can be cleaned, inspected, accessed and repaired. The paper will also present the experiences in developing these solutions and how this knowledge can be applied to current and emerging applications today.

The paper will present the historic development of the solutions and use case studies to illustrate how these tools and techniques can be applied today. Areas where additional development is still needed will be highlighted and current industry response will also be discussed. The aim of this paper is to share previous learning to ensure that the move to de-fossilization happens safely.

Key Words

Energy Transition, De-fossilization, Hydrogen, Carbon Dioxide, Ammonia, Pigging, Inspection, ILI, Intervention, Isolation, Repairs

Introduction

The energy industry stands at the brink of significant transformation in how energy is produced, transported, stored, distributed, and utilized. The inevitable shift away from emitting carbon dioxide and other environmentally harmful gases is apparent. However, the more challenging transition towards the reduction of fossil fuel usage, or de-fossilization, poses a stringent constraint in addition to greenhouse gas (GHG) emissions.

Hydrogen is increasingly acknowledged as a significant contributor to the clean energy plan, particularly when produced through green electricity sources such as solar, wind, wave, hydro, and hydrolysis. However, well-known challenges with hydrogen include concerns regarding efficiency, safety, and the impact on existing infrastructure during transmission, storage, and distribution. An alternative method for transporting hydrogen involves converting it to ammonia, enabling energy transportation through pipelines as well as via road, rail, and water.

In the future, the extension of carbon capture from fossil fuels is capturing carbon dioxide through direct air capture (DAC). This will necessitate new infrastructure for piping carbon dioxide to facilities for utilization or storage. We can also expect the emergence of additional products such as

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hot water and steam, driven by the increasing utilization of natural resources and waste heat. Consequently, there will be the introduction of new and potentially challenging substances within pipelines.

The question is, are these emerging products new or have they been around but somewhat under the radar due to the specialist applications or limited asset base? This paper will present three products — hydrogen, ammonia and carbon dioxide — and present the issues, solutions and lessons learned for pigging, in-line inspection and intervention and isolation which comprise important elements of pipeline operations, integrity and emergency response.

In addition to the issues and solutions, this paper will present several case studies of where these learnings have been applied and continue to be used safely, ensuring they can be developed as the world moves away from fossil fuels entirely, or at least, supplement de-fossilisation in the transition.

Hydrogen

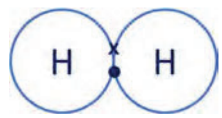

Figure 1. Hydrogen Covalent Bond

Hydrogen (H_2) is odourless, tasteless and naturally exists as a gas. Due to its molecular size, hydrogen has a higher leak potential that other petroleum gases. It can attack steels and causes hydrogen embrittlement and cracking. It is also extremely flammable, with a lower explosive limit (LEL) of 4 percent and an upper explosive limit (UEL) of 75 percent. Although hydrogen has about 2.5 times the energy density of methane, as it is less dense, it needs 3 times the volume to get the same energy compared to natural gas.

There are around 2,800 miles (4,500 km) of hydrogen pipelines globally. Worldwide, production amounts to approximately 75 million metric tons of pure hydrogen annually, with an additional 45 million metric tons as part of a gas mixture. This production level is proportional to 3% of the total global final energy demand and is akin to the yearly energy consumption of Germany [1].

Ammonia

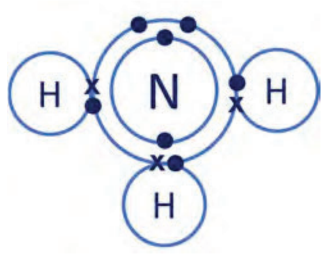

Figure 2. Ammonia Covalent Bond

Ammonia (NH_3), at ambient temperature, presents itself as a colourless gas with a strong, suffocating odour. Possessing alkaline properties, it can be corrosive, and in its pure, anhydrous form, it exhibits hygroscopic characteristics, readily absorbing moisture. It is readily absorbed in water transforming

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into a caustic substance - ammonium hydroxide. Due to its ease of compression into a liquid state, it becomes a convenient choice for bulk transportation. While non-flammable, exposure to heat causes rapid expansion, potentially leading to container failure.

Ammonia can be created through catalytic reaction of nitrogen and hydrogen under pressure and temperature. Decomposition into nitrogen and hydrogen is endothermic combined with some form of catalyst. Hence, ammonia is a stable carrier for hydrogen – NH_3 Õ 1/2 N2(g) + 3/2 H2(g). Ammonia contains 17.8% hydrogen by weight.

In the US, there is around 3,800 miles (5,100 km) of operational ammonia pipelines. On a global scale, the demand for ammonia stands at about 176 million metric tons annually. If hydrogen were to substitute 50% of the current natural gas demand, achieving this transition would necessitate a substantial 20-fold rise in the worldwide production of ammonia [2].

Carbon Dioxide

Figure 3. Carbon Dioxide Covalent Bond

Carbon dioxide (CO_2) is main greenhouse gas that is significantly contributing to global warming and as such the reduction is the key to unlocking net zero through either complete avoidance or capture.

Carbon dioxide (chemical formula CO_2) is a gas at ambient conditions. It is colourless, odourless, tasteless, non-flammable, heavier than air, high density, low viscosity and mildly toxic. Under pressure (at ambient temperature) it can phase change to a liquid. With increased pressure and temperature, it can phase change to a supercritical fluid. The "critical point" for CO_2 occurs at 88 ^{o}F (31.1 ^{o}C) and 1,070 psi (73.8 bar). Impurities present in carbon capture utilization and storage (CCUS) CO_2 can change the critical point. Current pipeline operations transport CO_2 as a dense phase (a mix of liquid and gas).

There are approximately 5,600 miles (9,000 km) of CO_2 pipelines globally [3], many are situated in North America and primarily used for enhanced oil recovery (EOR). In 2022 there were 194 large-scale carbon capture and storage (CCS) facilities globally – compared to 51 in 2019 [4].

Other Pipelines

While prevalent in certain global regions, the evolving focus on optimizing all energy sources, such as harnessing naturally occurring geothermal reserves and implementing waste heat recovery through hot water and steam systems, will broaden the spectrum of difficult product pipelines.

Pigging

Over a century of operations have demonstrated that hydrocarbon pipeline systems are susceptible to fouling or impedance of flow from a range of byproducts. As a result, pigging has evolved as an

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integral part of the operator's tool kit to keep flow at optimal levels, avoid product contamination, prevent auxiliary equipment damage and to permit the introduction of vital inline inspection or isolation technologies.

When designing pigging tools for a specific application, there is always a balance to be struck between the effectiveness of the tool in performing its intended function and the need to keep the pipeline safely in operation with a successful transit & receipt of the pig. The pigging engineer must therefore evaluate a range of variables associated with the pipelines design and geometry, product flow, pressure and temperature as well as any properties of its chemistry when selecting the materials and configuring the tool.

Whilst it is true that each pipeline offers a unique combination of challenges to consider, most pipelines have historically operated within a window of variables, determined largely whether the hydrocarbons they transport are crude or processed, in liquid or gaseous form. Therefore, pig design has centred on materials and operational processes that broadly cater to these sets of properties.

When planning to pig in pipeline products which present new challenges, the methodologies and materials need to be modified to suit. As these emerging products become ubiquitous in pipeline networks, lessons learned from previous successful in-line cleaning or inspection will be invaluable.

Issues, Solutions and Lessons Learned

Hydrogen

- **Pig Design –** Materials for sealing cups or discs need to be able to withstand dry and abrasive conditions. Metallic components should be substituted or selected to withstand Hydrogen embrittlement.

- **Operational Considerations –** Low density and compressibility requires special considerations to maintain steady and controlled velocity.

- **Safety –** Operations need to be managed to mitigate the potential risk of ignition particularly during launching and receiving of pigs when volatile gases can mix. Antistatic urethane formulas can be selected to prevent static discharge when pigs are retrieved.

Ammonia

- **Cups –** A new cup material needed to be chosen and designed to withstand ammonia corrosion. Sealing elements for launcher & receive closure doors need to be evaluated for compatibility. Most polyurethanes are not compatible and other materials such as neoprene, nitrile rubber etc. maybe needed.
- **Operator Safety –** Pigging operations requiring personnel to launch, track and receive pigs in ammonia pipelines must have the correct procedures, training and personal protective equipment (PPE) to protect against the toxic effects of inhalation, contact with skin/eyes or cold burns associated with liquid/solid phase.

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Carbon Dioxide

- **Elastomer –** Carbon dioxide can penetrate and become entrapped in elastomers, such as cups, discs and canister seals. This can then result in catastrophic damage due to rapid gas decompression. Alternate materials to polyurethane can be considered for extended exposure. There is also some concern regarding the presence of acid producing bacteria that can attack polyurethane. For short lines, cups may need to be scrapped after use and for longer runs, a different material may be needed.
- **Operator Safety –** The risk of asphyxiation should be mitigated in pigging locations where heavier than air CO_2 may accumulate. Cold burns are possible if inadequate protection is provided for contact with liquid or solid phases (e.g., **Figure *4***).

Figure 4. Removing a Cleaning Tool from a Carbon Dioxide Pipeline (Presence of Dry Ice)

Inspection

In-line inspection (ILI) has served as the cornerstone of pipeline integrity since the late 1960s, marked by the initial development and deployment of tools in pipelines (Figure 5). The toolbox includes free-swimming, tethered, and robotic tools, offering pipeline operators a versatile array for locating and sizing various features. The careful selection of tool or tools enables operators to address specific threats effectively.

The fundamental principles of ILI remain consistent for both unintelligent pigs and their intelligent counterparts, with the latter equipped with additional components. These include a power source (such as batteries), sensors to measure specific pipe characteristics, a data acquisition system, and a mechanism for tracking location (such as odometers). The supplementary equipment needs protection from the harsh internal environment of the pipeline and is frequently shielded through encapsulation or placement in pressure vessels.

The complexity of ILI tools demands a sophisticated integration of mechanical and electrical / electronic components. Typically, ILI tools are commonly employed in the inspection of

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conventional oil and gas products like crude oil, petroleum products, and natural gas. However, less prevalent are applications involving more niche-based products such as hydrogen, ammonia, and carbon dioxide, each posing unique challenges.

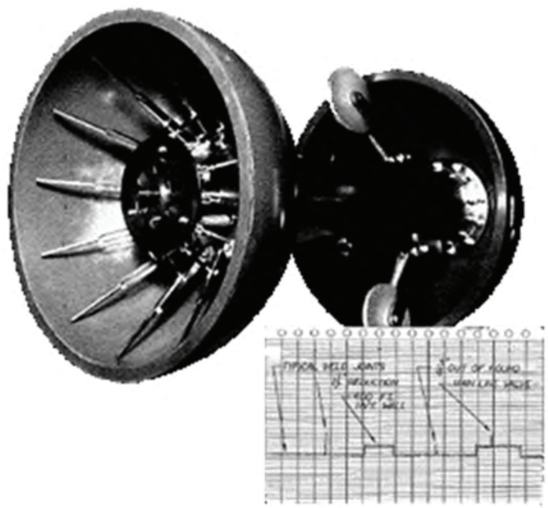

Figure 5. First In-line Inspection Tool – TDW Kaliper (geometry measurement)

Issues, Solutions and Lessons Learned

Hydrogen

The major issues that impact ILI tools, very similar to utility pigs, also included:

- **Magnets -** Encapsulation of magnets was required to protect them from hydrogen ingress. Encapsulation needs careful consideration in terms of maintaining magnetic strength to ensure saturation of the pipe wall as well as preventing ingress of the hydrogen. An impervious metallic shell was used to protect each magnet. This also meant a redesign of the magnetizer to accommodate the new magnet assembly.
- **Pressure Vessel Sealing –** A novel sealing method to safeguard the delicate electronics and batteries housed within the pressure vessels of the tool was developed.
- **Brushes –** Choosing new magnetic flux leakage (MFL) brushes to assist the magnetizer in coupling the magnetic flux to the pipe wall. These brushes are usually crafted from high-strength alloy steel, which may suffer damage or wear from exposure to hydrogen. To prevent any failure or collapse of the brush rings, a different type of steel was employed. Additionally, considering the flow dynamics, the brush ring was specifically designed to minimize drag.
- **Pressure Vessel Couplings –** A new design of body-to-body coupling system was also engineered.
- **Wiring –** Materials for the wiring was carefully selected to guarantee a secure seal and resist degradation caused by exposure to hydrogen.
- **Tool Power –** Ensuring safe operation necessitated the requirement for the tool to be intrinsically safe so there was no sparking or electrical discharge in the operational area at site.

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Some of the lessons learned:

- **Operations –** Created operational conditions to get 100% data – specially to control speed excursions. Needed to create a system with fine flow control and develop ways to minimize the effects of changes in pipe wall thickness and direction. When dealing with a product as dry and compressible as hydrogen, it is difficult to control tool speed, because there is a delayed reaction caused by the inherent product properties and the compressor distance from the ILI tool location. Given these hurdles, fine flow control was identified as a major factor in successful tool launch and velocity management during the inspection.
- **Procedures –** Special procedures were developed for launching and receiving including purging the tool pressure vessels.

Ammonia

The major issues that impact ILI tools comprise:

- **Canister Couplings –** A comprehensive reengineering was undertaken of the body-to-body coupling systems replacing the materials again to resist ammonia attack.
- **Sensors and Sensor Arms –** A redesigned sensor arm necessitated the use of materials resistant to ammonia. Additionally, a novel encapsulation process was devised for magnetic sensors to safeguard against ammonia penetration. A new odometer sensor was also developed.

Some of the lessons learned:

- **Operations –** Line cleanliness is extremely important due to the abstergent nature of ammonia which removes surface scale resulting in friable debris in the flow that can be picked up by the ILI tool. Line cleanliness can also have a significant detrimental impact on wear of cups.
- **Pipeline –** Well documented and restriction free lines are important to minimize tool damage as ammonia compatible ILI components are not as strong and robust as components compatible with other ILI inspection media. A gauge pig run is recommended prior to any inspection to evaluate ILI tool passage. Although helpful to determine minimum bore, a gauge pig cannot provide the location of a restriction.
- **Specialist Considerations –** Nitrogen gas is required to purge the trap at receive. It is used to maintain the ammonia as a liquid and force it out bottom drains. If the liquid ammonia was allowed to vaporize in the trap, it would freeze the tool causing damage to the electronics and risk loss of data.
- **Ammonia Disposal –** Special consideration is required for the disposal of waste ammonia. Typically, propane flares can be used to vaporise and burn off the ammonia. Recompression may also be a viable approach but not proven.

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Carbon Dioxide

Carbon dioxide can be transported either in the gas phase or in a dense phase. However, ILI runs occur in pipelines transporting it in the dense phase, as it is considered more efficient.

The major issues that impact ILI tools comprise:

- **High Pressure –** Special attention is crucial during flow operations when inspecting and depressurization of launch and receive traps to limit the impact of phase changes.
- **Venting/Purging –** Care and consideration is required when venting and purging traps. If executed to quickly, the rapid decompression can result in rapid cooling that can damage mechanical, electrical and elastomeric material too.

The main lessons learned:

- **Operations** - Standard ILI tools do not require modification, but care must be taken during launch, review and the inspection to ensure phase change is prevented. Inspection is easily executed with careful preparation, the right tool and processes and procedures.

NOTE: All the experience presented in this paper is for pure carbon dioxide, it is known that CCUS carbon dioxide may have a range of impurities (e.g., methane, carbon monoxide, water, hydrogen, oxygen, nitrogen, argon, hydrogen sulphide, sulphur oxides, nitrogen oxides) which may have a significant impact on tools and operating procedures.

Case Studies

The initial creation of a hydrogen-compatible ILI tool was aimed to support a U.S. operator on the Gulf Coast managing an extensive hydrogen pipeline network, comprising 22 hydrogen plants and around 600 miles (1,000 km) of pipelines [5] [6]. The pipeline construction phase commenced in May 2011 and concluded in August 2012. This pipeline encompassed 183 miles (300 km) of 18-inch diameter pipes stretching from Plaquemine, LA, to Port Neches, TX, featuring bi-directional flow capabilities. The establishment of this new pipeline network enhanced reliability for customers in the Gulf Coast region.

Due to the flammable nature of hydrogen, it falls under DOT 192 regulations (ASME B31.12 [7]), which require verification of pipeline integrity. This can be achieved through several methods, including pressure test, ILI and direct assessment. To ensure the safety of the pipeline and to comply with the government regulations, the operator needed to create a baseline inspection of the entire pipeline network. The main threat was external corrosion.

The development of a 100% hydrogen compatible ILI tool was started in 2012 with the full support of the pipeline operator. Over the period of 2012-2013, the tool went through various design changes and an operational tool was field tested in 2014. In 2015, the first successful run was achieved with 100% data coverage (Figure 6). From 2015-2023, the tool has inspected over 300 miles (500 km) of pipeline. During the inspections, several areas of alternating current (AC) induced corrosion were found.

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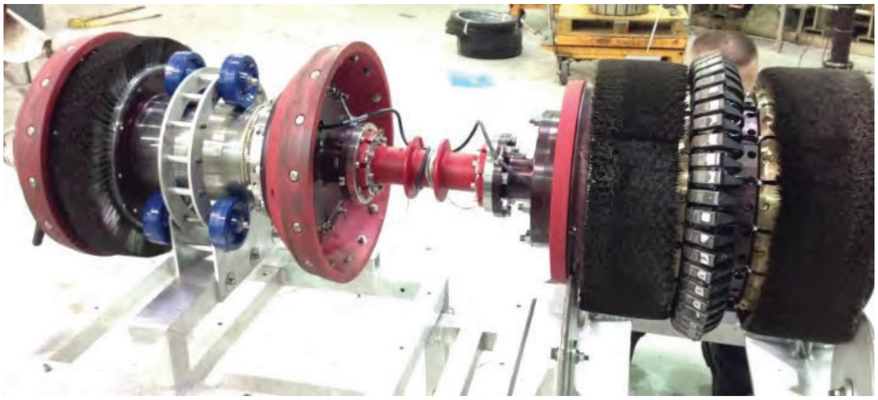

Figure 6. 100% Hydrogen Compatible Tool (18-inch, MFL)

The development of the first ammonia inspection was initiated in 2001 by a pipeline network operator in the US. The operator wanted to improve the integrity management of their 1,200 miles (1,900 km) ammonia system. The operator wanted to use best practice but also adhering to regulations that specified alternatives to ILI (e.g., hydrotesting). Hence, the decision to invest in the development of an ILI alternative. The program involved the development of MFL ILI technology with a focus on metal loss. The plan was to develop tools that called for a minimal alteration to the existing MFL tool design, employ known ammonia resistant materials, devise new methods for sensors and then to reduce costs, utilise the operators' traps (under full line conditions) to test equipment (**Error! Reference source not found.**).

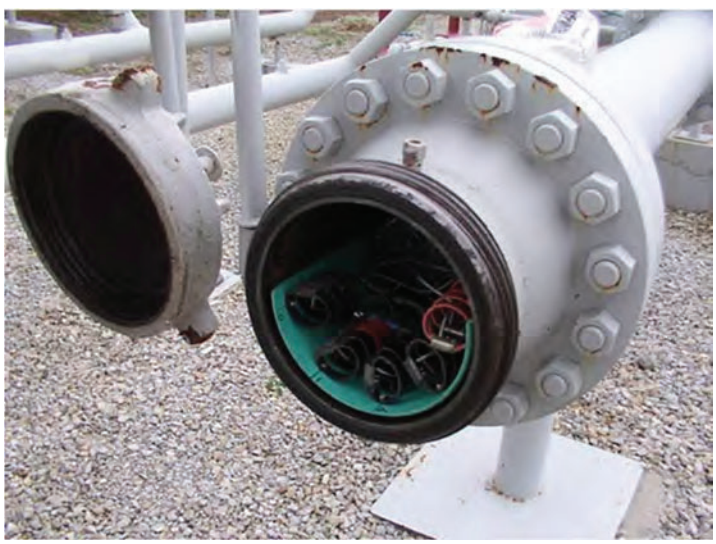

Figure 7. Equipment Testing in Ammonia Utilizing Operators Traps

Over the years 2001 – 2010, four sizes of deformation (hi-res geometry) and MFL tools were developed (4-inch, 6-inch, 8-inch and 10-inch) (

). Inertial measurement units (IMU's) are available on certain sizes. In the runs, several illegal taps and a large buckle in a high consequence area (HCA) were discovered.

After the development of the fleet of ammonia tools, over 6,700 miles (11,000 km) have been inspected. Further developments are underway to enhance the tool design for future runs.

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Figure 7. 8-inch MFL Ammonia ILI Tool (prior to launch)

Intervention and Isolation

For over five decades, pipeline operators have been familiar with the practices of intervention and isolation. This method enables the repair, modification, and/or access to pipelines without the need for venting, purging, or shutting down the line, thereby saving time and expenses. In summary, the hot tap and plugging procedure encompasses four primary steps:

1. Attaching a split tee to the pipeline (most commonly by in-service welding),
2. Hot tapping through a permanent or temporary valve. This provides access to the pipe,
3. Isolation by inserting an isolation tool inside the pipeline, and
4. Plug installation to recover the temporary sandwich valve and/or to keep the line piggable.

The hot tap and plugging methodology offer numerous configurations, and one widely used application is known as double STOPPLE^{TM} isolation with a by-pass (**Figure 8**). The possibilities are limitless, thanks to variations in split tee design and pipeline configuration.

The hot tap and plugging technique has provided support for transmission pipelines conveying natural gas or crude oil. Moreover, it has been a longstanding practice in hydrocarbon processes, where it is applied to piping transporting diverse products at varying temperatures. The knowledge and expertise developed to assist the downstream industry serve as a valuable foundation that can be harnessed to support the ongoing energy transition.

Issues and Lessons Learned

Hydrogen

Intervention and isolation represent a viable solution for pipelines that transport hydrogen. Nevertheless, specific challenges unique to hydrogen transportation must be carefully addressed for successful implementation:

- **In-Service Welding –** It is imperative to avoid any hydrogen exposure during welding, as it has the potential to induce cracking.

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- **Hydrogen Embrittlement –** Metallic components can be prone to hydrogen embrittlement, where a combination of microstructure, stress levels, and exposure to hydrogen may lead to detrimental alterations in material properties.
- **Elastomer –** From a chemical standpoint, most elastomers exhibit resistance to hydrogen. However, the primary concern with hydrogen lies in the potential for rapid gas decompression during pressure variations. If the elastomer sustains damage, it may compromise its ability to seal effectively.
- **Seals –** Hydrogen is prone to leakage through seals, threaded connections, flanged connections, and similar interfaces, posing an elevated risk due to its flammability properties.
- **Operation –** During interventions, special attention must be taken to prevent any mixing of air with hydrogen to reduce the risk of ignition/combustion/explosion.

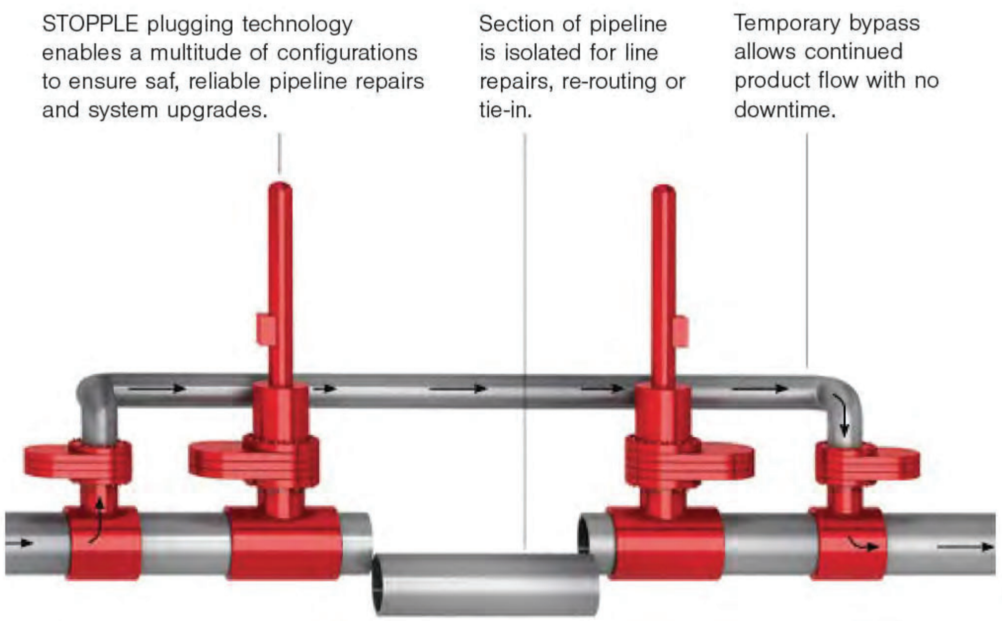

Figure 8. Schematic of Double STOPPLE^{TM} with a Separate Bypass

Some of the lessons learned:

- **Sour Services Guideline –** For many years, industry has developed solution to operate in sour service condition (H_2S). H_2S is a corrosive and toxic molecule that has already significant effect at low concentration in natural gas or crude oil. Special materials are known, and equipment can be upgraded to avoid issues related to hydrogen embrittlement.
- **Elastomers –** There are specialized elastomers designed to better withstand rapid gas decompression, typically characterized by higher hardness (e.g., Shore 90). While most elastomers used in hot tap and plugging applications need to be dependable for a brief period and are not regarded as the ultimate barrier, these specialized elastomers enhance resistance to rapid gas decompression.
- **Potential Leak Path –** Avoiding potential leak path is not new and it is a good practice for any product. The selection of a solution plays a crucial role in minimizing future risks. For instance, opting for a 3-way tee can facilitate a new tie-in without requiring a permanent

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valve. Another example involves utilizing Lock-O-Ring® PLUS completion plug as an alternative to conventional methods.

Ammonia

Intervention and isolation on liquid ammonia lines has been done for many years on pipelines crossing the United States, Ukraine and Russia. For this application, the standard equipment must be modified:

- **Corrosivity –** It is crucial to avoid the contact of zinc, copper, and brass with ammonia containing water. Certain equipment contains brass components acting as bearings that come into direct contact with the pipeline product during interventions. In such cases, it is imperative to use alternative materials to prevent adverse reactions.
- **Elastomer –** The selection of elastomers requires careful consideration. For instance, fluorocarbon elastomers are incompatible with ammonia and can lead to rapid leaks.

Some of the lessons learned:

- **Liquid –** When working on liquid pipelines, it is convenient to work in a vertical orientation using an inert gas to keep the liquid below the valve. It helps during removal of equipment to keep equipment clean by venting inert gas.

Carbon Dioxide

Carbon dioxide can be transported either in the gas phase or in a dense phase. However, most intervention and isolation applications occur in pipelines transporting it in the dense phase, as it is considered more efficient:

- **High Pressure –** Carbon dioxide is primarily transported over long distances in its dense phase, necessitating the maintenance of the product under high pressure. Special attention is crucial during depressurization and phase change processes even generating a solid phase, dry ice!
- **Elastomer –** Carbon dioxide can generate blistering and elastomer damage due to rapid gas decompression.
- **Venting/Purging –** Like any gas being transported in liquid phase, special attention must be given to product venting and change of phase. If release to fast, the cooling effect can damage the equipment.

Case Studies

An ammonia pipeline crossing Russia and Ukraine has been in operation since 1983 [8]. Its total length is 1,506 miles (2,424 km) and its diameter 14-in (350 mm). In the year 2000, TDW provided some equipment specially modified to be compatible with ammonia [9]. After a few years, the split tees were provided with LOCK-O-RING™ PLUS completion plugs to minimize the risk of leakage over time. In fact, LOCK-O-RING™ PLUS reduced the use of elastomer and threaded connections on the flange by using a completion plug with leaves actuated by a cam mechanism.

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For many years, TDW has supported a customer transporting carbon dioxide (**Error! Reference source not found.**). It started in 2005 with the initial request and the design of equipment rated to ANSI 900, designed to withstand 2200 psi (15 bar). Since then, TDW has been able to provide support every 5 years during the cleaning and inspection process. These campaigns can be challenging and being able to repair or modify the pipeline on a short section is a valuable solution to operators. In this specific case, the product was not only carbon dioxide, but contained the presence of hydrogen sulphide (H_2S) which brought additional challenges regarding the elastomer compatibility and the proper selection of materials. In 2021, TDW completed for the 4th time the hot tap and isolation on these 12-inch and 14-inch pipelines.

Figure 10. Isolation of a Carbon Dioxide Pipeline

Conclusions

In commercial terms, some emerging pipeline products have been with us for some time (hydrogen circa. 1930's, ammonia circa 1940's, carbon dioxide circa 1970's) but their widespread use has been limited. However, these pipelines have the same needs as those planned for new build or conversion and hence there is a lot to learn from their history, the technology developed as well as adapted, and the lessons learned. This paper has demonstrated that existing equipment can be adapted or developed to be applied to ensure safe operation. In some cases, the adaption is relatively simple and limited to operating procedures (e.g., carbon dioxide) but in other cases, new tools and procedures have been needed (e.g., hydrogen).

It is evident that there exists a wealth of experience to draw upon, and this knowledge can be utilized to lay the foundation for the industry's readiness when the widespread adoption of these "new" pipeline products materializes.

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