CAAP Quarterly Report

Date of Report: 12/31/2022

Prepared for: U.S. DOT Pipeline and Hazardous Materials Safety Administration

Contract Number: 693JK32250007CAAP

Project Title: "Accelerating Transition towards Sustainable, Precise, Reliable Hydrogen Infrastructure (Super-H2): Holistic Risk Assessment, Mitigation Measures, and Decision Support Platforms "

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For the quarterly period ending: 12/31/2022

Business and Activity Section

(a) Contract Activity

The kickoff meeting was held online on Dec. 5th, 2022

No changes to the existing agreement

Discussion about contract modifications or proposed modifications:

None.

Discussion about materials purchased:

None.

(b) Status Update of Past Quarter Activities

The research activities in the 1st quarter included: (a) Task 1 (completed): A kick-off meeting with PHMSA personnel held on Dec. 5th, 2022, to ensure that the project objectives and tasks follow the DOT and PHMSA's expectations and guidelines; (b) Task 1 (completed): A comprehensive literature review covering related topics of the proposed research, mainly including the technical challenges in the pipeline industry for hydrogen transport in terms of various perspectives, and critical factors affecting the hydrogen impacts; and (c) Task 2: A preliminary work in this stage, with emphasis on a review to summarize the current practices in risk and decision making in related oil/gas pipelines.

(c) Cost share activity

The cost share was from faculty time contribution and graduate students' tuition waiver.

(d) Summary of detailed work for Tasks 1 and 2

The following tasks presented below are included in this report:

- *Summary of the kick-off meeting*
- *Task 1 Literature review*
  - Review covering critical factors affecting the repurposed existing pipelines for hydrogen transport.
- *Task 2*
  - Knowledge gaps in risk assessment and decision tools used in the pipeline industry.

Note that the literature review in this period aims to collect information for gaining a deep understanding of the scientific and technical challenges and technical gaps for repurposing existing pipelines in the presence of hydrogen, and thus the review may pay more attention to the current state of knowledge on a broad variety of documents from domestic and international standpoints. The next report will further narrow down the contents to more specific fields associated with technical gaps in long-term hydrogen impacts on pipe materials and experimentation preparation.

Summary of activities in Task 1:

This task is to hold an online kick-off meeting with PHMSA personnel and perform the literature review. The literature review was expected to summarize the impacts of hydrogen on material/component/system levels in Task 1, assessment methods for repurposing existing gas pipelines, and unveil critical factors affecting their suitability and mitigation measures, which will direct the research to the right direction for the ongoing tasks as proposed in future quarters. Note that, we may enrich our literature review based on the evolution of knowledge of the PIs as well as the updating information from other research groups during the context of the project. To achieve that, we organized the research activities herein as summarized in **Table 1**:

- Step 1: Kick-off meeting.
- Step 2: A literature review.

Table 1. Matrix covered in Task 1

Step	Task	No.	Factors
1	Kick-off meeting	Task 1.1	• Project objectives and tasks • PHMSA's expectations and guidelines
2	Literature review	Task 1.2	• Repurposing existing pipelines and assets • Scientific/technical challenges • Critical factors affecting the hydrogen impacts

Step 1: Kick-off meeting

The online kick-off meeting with the USDOT PHMSA personnel (Robert Smith, Seif Deiab, Mary McDaniel) was held via zoom on Dec. 5th, 2022. All PIs attended the kick-off meeting. A web presentation was made to the PHMSA personnel followed by questions/answers and discussions. The meeting agenda and major activities in the kick-off meeting were shown in Table 2.

Table 2. Kick-off teleconference meeting agenda (Monday, Oct. 29th, 2018)

Items	Major Contents	Note
Objectives	a. Introduction of the framework and the role of the PHMSA b. Introduction of the project background and the expected outcomes c. Discussion of detailed contents in the proposed work d. Future plan	The TAC member, Steve, cannot make the meeting this time but will be informed in the context of the project.
Detailed Activities	a. Introduction o Bob, Seif, and Mary gave basic information about their roles in this project activity and budget management	* Bob later forwarded the links to those projects to Dr. Lin

	○ The PIs introduced themselves and showed appreciation for the support of the PHMSA b. Project Information and Discussion ○ Dr. Lin gave a short presentation, including addressing the background of this project, the motivation of the concepts, the proposed objectives and tasks, and the expected outcomes and timelines. ○ Mary expressed her questions about experimentation in Task 3 and requested more detailing. Dr. Lin responded in detail to the experimental plan, including near real-world testbed design and coupons for two loading cases (pure hydrogen and 50% blending). c. Information with existing projects and industry ○ Bob indicated that there are several CAAP and RA projects associated with hydrogen research, and suggested the research team could keep in touch with them*. The research team appreciated this suggestion and is willing to integrate different inputs from these different perspectives to enrich the scopes and outcomes. d. Student Training and Involvement ** The PIs have a strong record of participating in outreach programs to recruit high school students, as well as undergraduate and graduate students, in the PHMSA CAAP projects, and will continue fostering the next-generation workforce in the field of pipelines, with a particular focus on clean energy transport. e. Future Plan ○ Seif expressed interest to have a potential site visit in near future to NDSU. f. Other items (e.g., future R&D forum, to promote the academy-industry interaction and information exchange)	** The PIs expressed their appreciation for the effort in this PHMSA program on the high expectation of student involvement.

Step 2: Literature review

This subtask is to summarize the current knowledge on hydrogen impacts on pipelines in terms of materials/component/system levels, assessment methods, and mitigation measures.

1.1 Energy Transition and Hydrogen as a Clean Energy Carrier

Driven by the nation's clean energy and climate goals, hydrogen has been recognized as a clean, renewable energy carrier. Different from natural gas, hydrogen as an energy carrier does not emit carbon dioxide, thereby becoming a viable alternative energy option to support achieving carbon net-zero emissions in 2050. As illustrated in **Fig. 1**, the H2@Scale initiative is one of the Department of Energy (DOE) and the Department of Transportation (DOT) initiatives to set up hydrogen as one unique solution toward the target of zero-emission by 2050. Hydrogen enables offering significant opportunities to existing energy systems.

Hydrogen is becoming a popular alternative energy source. As illustrated in **Fig. 2(a)**, the International Energy Agency pointed out that the world consumed around 70 million tons of hydrogen in 2019, and the demand is predicted to continuously climb to over 500 million tons in 2070 (Chae et al., 2022). As such, large-scale gas infrastructure is expected to serve to transport hydrogen products toward its storage sites and the end users, as circled in dashed lines in **Fig. 1**. Due to its nature as the lightest, extremely flammable gas, hydrogen must be safely transported through restricted transportation strategies. While different transportation modes could be used, pipelines are still accepted as the only realistic way of transporting hydrogen over greater distances safely and cost-effectively, particularly for nations like the United States with a significant national geographical area. The hydrogen has been delivered across the United States by dedicated pipelines, and the United States has the largest active hydrogen dedicated pipeline system; as presented in **Fig. 2(b)**, there are over 2,600 kilometers of working pipelines in the United States, which is a larger amount than Europe's combined total (Romney et al., 2022).

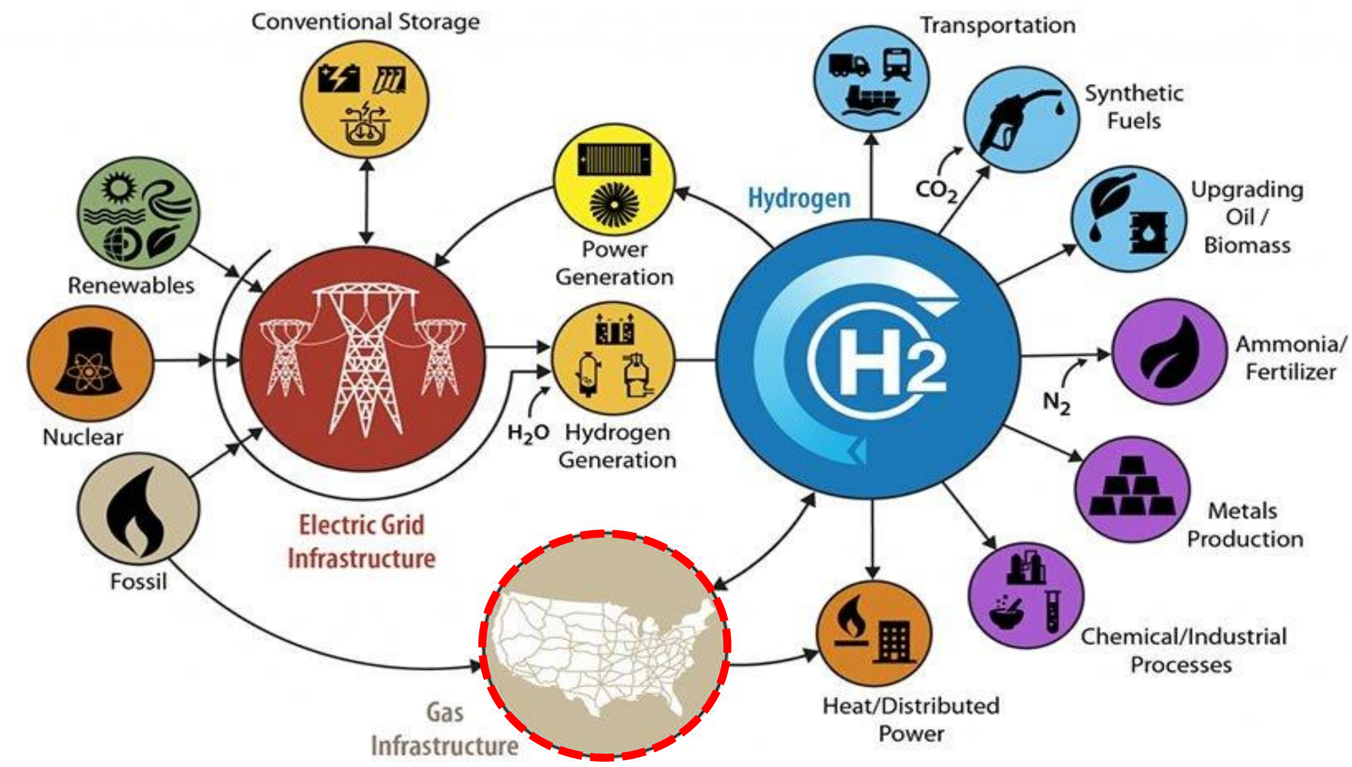


Fig. 1: H2@Scale vision (credit: National Renewable Energy Laboratory https://www.energy.gov/eere/fuelcells/h2scale)

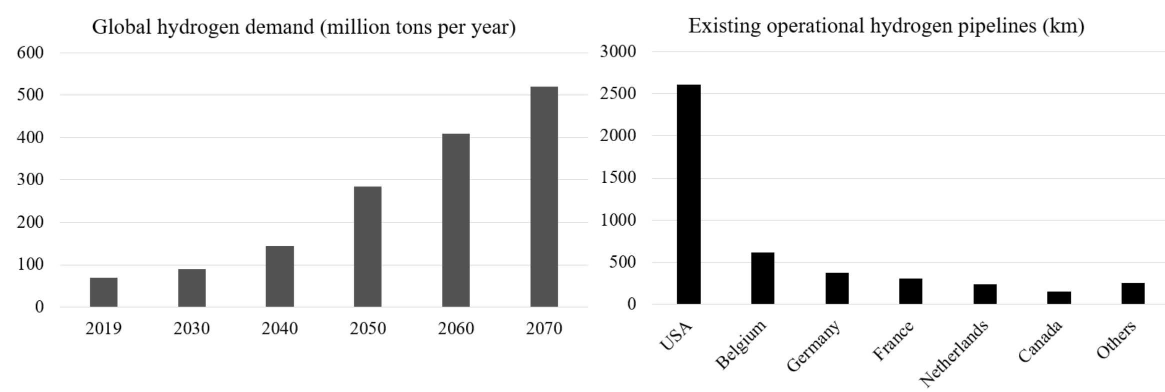


Fig. 2: (a) Global hydrogen demand and (b) Existing dedicated hydrogen pipelines **(**Romney et al., 2022; Chae et al., 2022)

1.2 Repurposing Existing Pipelines for Hydrogen Transport and Scientific/Technical Challenges

As illustrated in **Fig. 3**, considering that the United States already has the world's longest, largest gas pipeline network, with 2.6 million miles of transmission and distribution lines, repurposing these existing gas pipelines via the introduction of hydrogen into the natural gas, referred to hydrogen blends, or pure hydrogen, could make it physically ready to lead the world again in hydrogen development. Repurposing the existing pipeline network could reduce or delay decommissioning/dedicated new systems, and thus offer better solutions at this stage.

Many pilot studies and cases have already tried to blend hydrogen into existing natural gas up to 20%

by volume concentration, mainly on gas distribution lines, as well documented in multiple comprehensive reviews conducted by GTI (Zhou and Ersoy, 2010) and DOE (Nannings et al., 2010; Mlaina et al., 2013), and recently by Timerick and Green (2021), and Erdener et al. (2022).

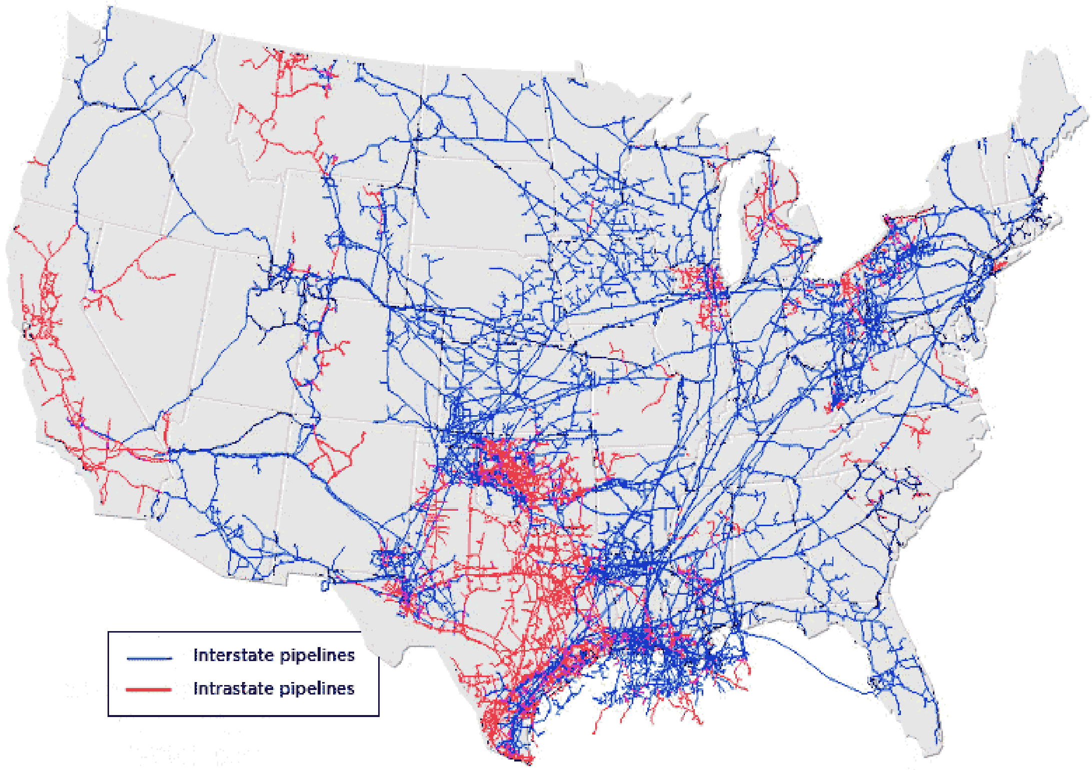


Fig. 3: The U.S. pipeline maps (Credit: Energy Information Administration, Office of Oil & Gas, Natural Gas Division, Gas Transportation Information System)

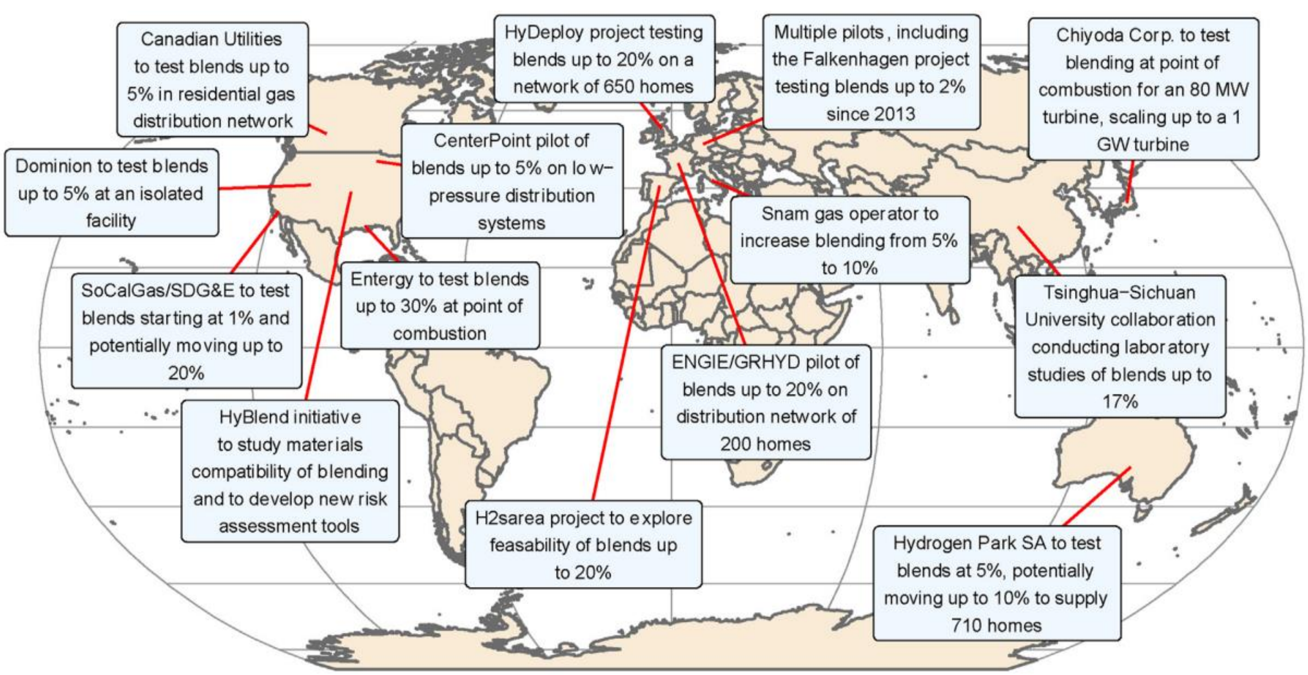


Fig. 4: Some of the announced or ongoing pilot programs for hydrogen blends over the worldwide (Erdener et al., 2022)

1.2.1 Scientific/Technical/Social Challenges

Repurposing existing pipeline systems and assets through the introduction of hydrogen into existing NG pipelines poses great challenges in pipeline integrity management by GTI (Zhou and Ersoy, 2010) and DOE (Nannings et al., 2010; Mlaina et al., 2013), and recently by Cerniauskas et al., (2020) and Erdener et al. (2022). It is mainly because pure hydrogen or hydrogen blends bring significant technical uncertainty and unknowns to the current pipeline industry, where pipeline stakeholders who are so well familiar with handling NG found they are in a dilemma for this transition from each perspective. It is not because we lack case studies, but there is no comprehensive guideline that enables providing a clear picture of handling new threats experienced due to the presence of hydrogen. As such, we could mainly categorize potential challenges into four, as illustrated in **Fig. 5**:

- **Technical perspective**

  The repurposing existing pipeline systems and assets pose great challenges in safety from material/component/system levels in the presence of hydrogen blends or pure hydrogen; Uncertainty could be from incomplete data or insufficient record for existing assets; Security (in physical and cyber bases) raises due to different gases as compared to natural gas, which could lead higher leakage or fire or explosion; Technology commonly used may not be compatible with the new purpose (e.g., commonly used inline inspection tools, ILI, could be malfunctioned when exposed to the high concentration of hydrogen) and that also demands the workforce training.

- **Geographical perspective**

  The field conditions of pipeline systems and assets capacity could differ from one location to another, and thus the risk of failure and consequence of failure could lead to different scenarios. The potential impact radius could be modified to accommodate the risk and uncertainty.

- **Environmental perspective**

  Potentially higher leakage (e.g., at locations of valves and joints), and higher risks of failure of repurposed, aged assets could lead to higher environmental risks to surrounding communities, while uncertainty associated with environmental impacts is another concern.

- **Economic/social perspective**

  Repurposing existing pipelines and assets for hydrogen blending or pure hydrogen could benefit from effective delay or reduced cost due to full decommissioning or new dedicated systems. Upgradation and modification of the existing assets may expect costs associated with more frequent maintenance with shorter service life.

Many projects across the globe are proving the concept of using hydrogen blends, but the long-term effect of hydrogen on materials and equipment is not well known, making it difficult for utilities and industries to prepare for large-scale applications (Cerniauskas et al., 2020; Erdener et al., 2022). Experience suggests that incorporating a new technology does not need sweeping changes; rather, it may be accomplished by making little adjustments to current techniques and infrastructure. PHMSA's existing guideline, the American Society of Mechanical Engineers (ASME) B31.8S Standard "Managing System Integrity of Gas Pipelines," should serve as the basis for upgrading the integrity management program (IMP). More specific challenges are summarized in the following sections.

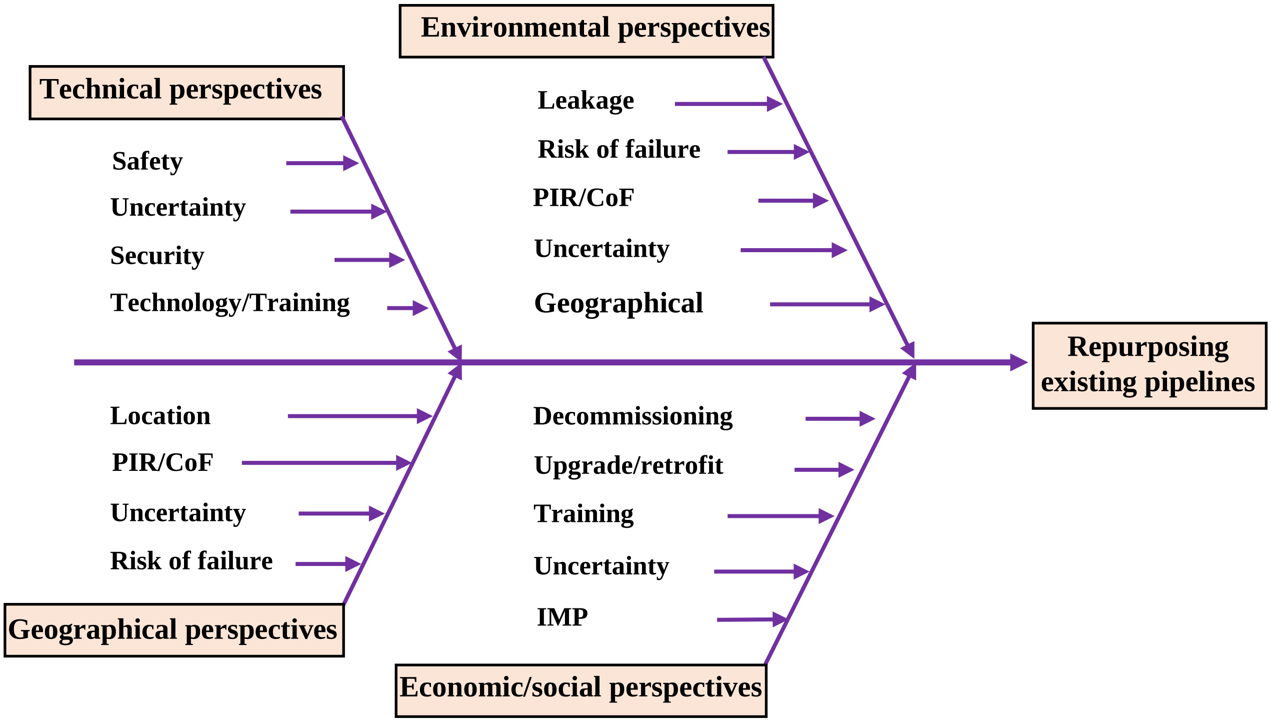


Fig. 5: Critical challenges affecting the repurposing of existing pipelines for hydrogen transport (Abbreviation used: PIR= potential impact radius; CoF= consequence of failure; IMP= integrity management program)

1.2.2 Critical Factors Affecting Repurposed Existing Pipelines for Hydrogen Transport

While many laboratory tests and pilot applications have demonstrated that hydrogen blends within 5-20% vol. could minimize the modification of existing pipeline systems, few conclusive findings about higher blending levels (over 20%) or pure hydrogen are available. A review herein was conducted to understand various factors affecting the hydrogen impacts on existing pipelines. These factors, summarized in **Fig. 6**, affect the suitability of repurposing existing pipelines for transporting pure hydrogen or hydrogen blends. This includes pipe material level (e.g., various metallic/non-metallic pipeline materials with existing flaws, legacy cast iron pipelines, welds, gaskets, cathodic protection), to component level (e.g., leakage, probability of risk of pipe components and their functionality in valves, meters, and compressors), to system level (e.g., potential impact radius, a consequence of failure) under various operational and environmental conditions (e.g., maximum allowable operating pressure (MAOP), flowrate, temperature, and geologic condition at uphill or downhill spots).

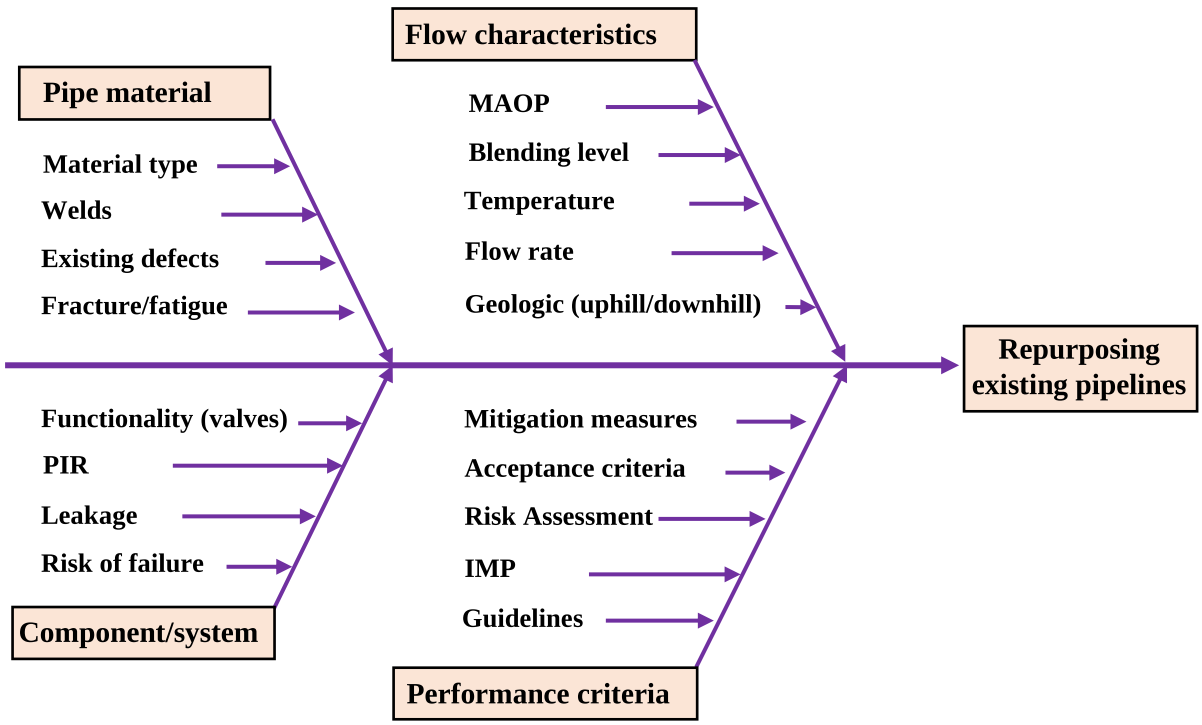


Fig. 6: Critical factors affecting the repurposing of existing pipelines for hydrogen transport (Abbreviation used: PIR= potential impact radius; CoF= consequence of failure; IMP= integrity management program; MAPO=maximum allowable operational pressure)

1.2.2.1 Pipe material

It is well known that hydrogen embrittlement of steel may occur when atomic hydrogen is cumulatively localized at grain boundaries, voids, dislocation, and existing defects, as schematically shown in **Fig. 5**. Much research (Nanninga et al., 2010; Lynch, 2012; Bhadeshia, 2016; Zhao et al., 2016; Ohaeri et al., 2018; Nguyen et al., 2021; Sun and Cheng, 2022) has been conducted to investigate and summarize the hydrogen-induced material degradation of pipeline steel, including degradation of tensile property (yield and ultimate strength), elongation/ductility, fracture toughness, and fatigue resistance (crack growth rate).

As typically illustrated in **Figs. 6(a)-6(d)**, results have demonstrated that atomic hydrogen may not influence the yield/ultimate strength of the pipe steel, but elongation or ductility of the material could be degraded significantly, particularly with an increase of steel grade (e.g., high-strength API X80 or X100 pipe steels), as shown in **Fig. 6(b)**. Fracture toughness is also observed with a certain reduction due to the exposure of hydrogen, while fatigue crack growth (rate) of X70 steel is shown in **Fig. 6(d)**, suggesting that the crack growth increases, that is, the reduction of fatigue resistance of the material, with the increase of the working pressure, as well as the increase of the concentration level of the hydrogen.

High-strength steel could require a thinner pipe wall, increases transporting pressure, and enhances transit efficiency. However, there is limited testing of higher-grade steel as some studies mentioned that gaseous hydrogen might create problems and even pipeline failure, particularly in higher-strength carbon steel pipes.[8] Avoiding the use of pipes made from high-grade steel would hinder the conversion of existing natural gas pipelines to hydrogen service and the construction of new hydrogen pipelines. Even while some studies have shown that high-strength steel is susceptible to hydrogen embrittlement and results in rapid and early failures, there is no basic metallurgical reason why lower-strength steels are appropriate while higher-strength grades are appropriate not. Even in low-strength cases, service failures have been reported. In addition, research shows that high-strength steels may be resistant to hydrogen attack if the microstructure is carefully managed.[6]

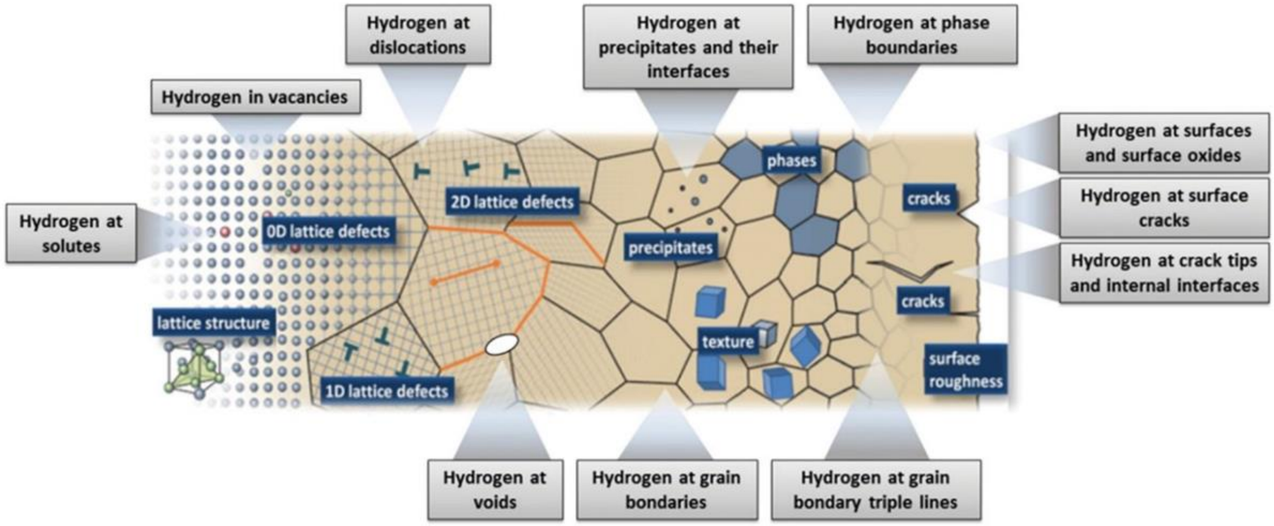
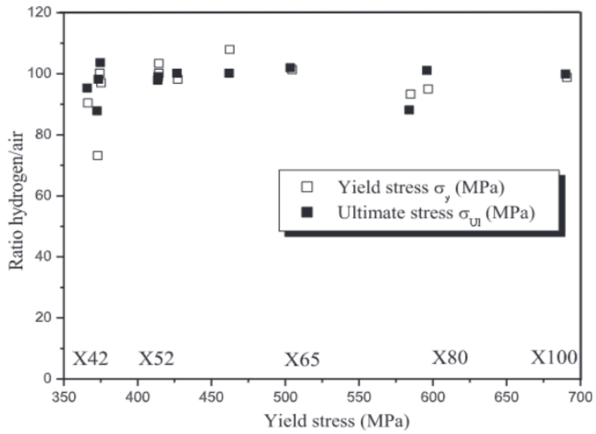
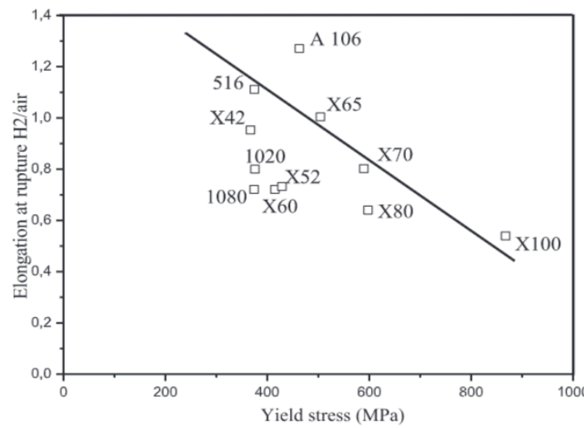


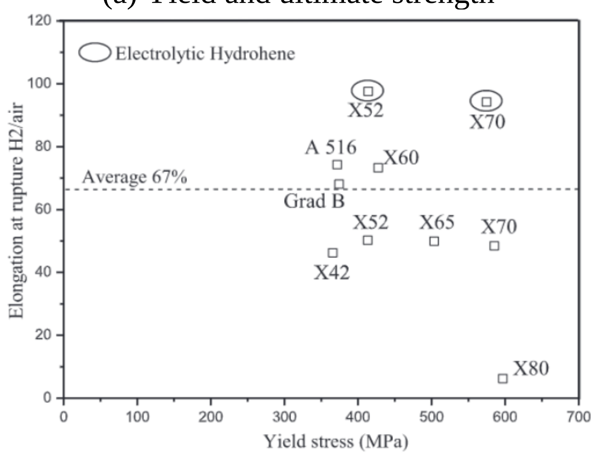
Fig. 5: Mechanisms of atomic hydrogen cumulated in various steel misstructures that could lead to material embrittlement (Sun and Cheng, 2022)



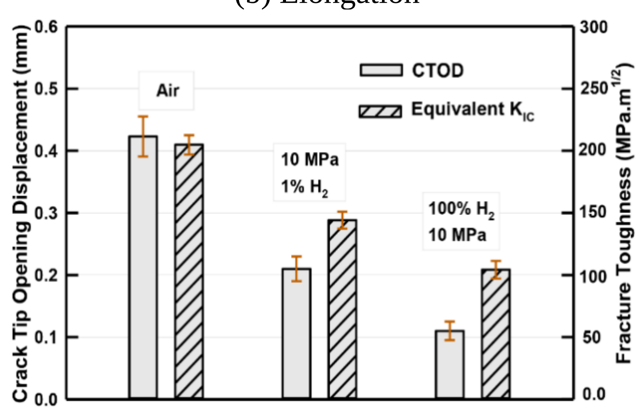
(a) Yield and ultimate strength



(b) Elongation



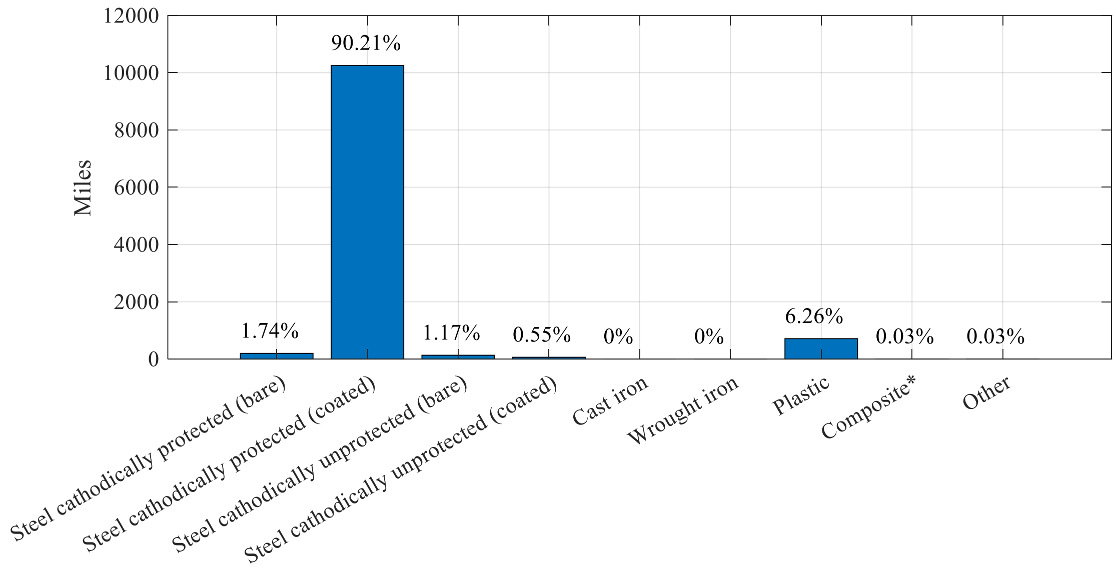
(c) Fracture toughness



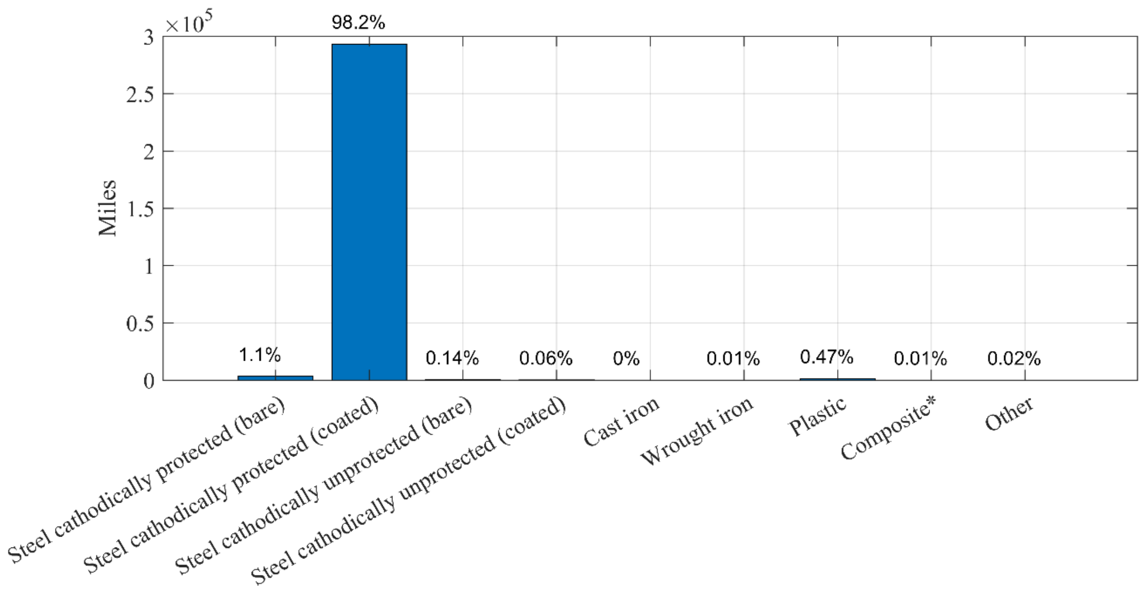
(d) Fatigue crack growth rate of X70 steel

Fig. 6: Typical hydrogen-induced material degradation in the literature (a)-(c) (Sun and Cheng, 2022) and (d) (Nguyen et al., 2021)

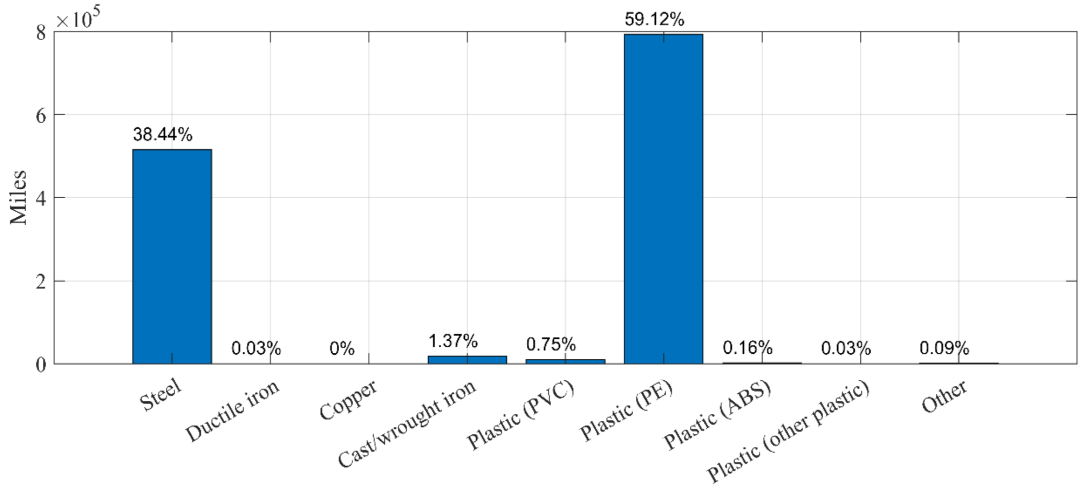
As illustrated in **Fig. 7**, PHMSA data reveal that pipeline materials in the U.S. gathering lines, transmission lines, and distribution lines, include steel, cast/wrought iron, plastic, composites, and others. Steel with cathodic protection and protective coatings is dominant in gathering and transmission lines, by over 90%, as compared to other categories. These pipe materials have higher corrosion resistance and higher damage tolerance, as compared to cast/wrought iron and bare steel that was used in the past and are vulnerable to corrosion and other mechanical damage in a brittle manner. Differently, polyethylene (PE) plastic pipes are one of the major materials used in the U.S. distribution lines at 59% and a slightly lower portion of steel at 38%. As a result, different pipe materials with different conditions (e.g., welds and existing defects) could respond in the different behavior, thereby potentially leading to different levels of degradation as described in **Fig. 7**, when exposed to hydrogen blends or pure hydrogen, and related mitigation measures for long-term impacts have to be selected accordingly, which is one of the proposed study the PIs attempt to address.



(a) Gathering lines



(b) Transmission lines



(c) Distribution lines

Fig. 7: Pipeline materials used in the U.S. natural gas pipelines

(data from PHMSA till 2022 and *use of composite pipe requires a PHMSA special permit or waiver from a state)

As such, the threats of hydrogen to pipeline materials cannot be identified without complete knowledge of the mechanics. The mechanism study can effectively assist us in quantifying the threat level and rate of hydrogen degradation; however, we must understand the general principles of hydrogen degradation to address these concerns in the design of inspection, prevention, and repair processes for IMPs.

Hydrogen-induced damage to pipeline integrity may be categorized into three basic mechanics: H_2 embrittlement, H_2 penetration absorption, and H_2 corrosion. In addition, the potential degradations caused by these mechanics are shown in **Table 3**. Even though studies have been performed to understand the concept of these interactions, the process of these interactions is still debatable when it comes to the real-world operating environment of pipelines, which must be determined before upgrading the IMPs. An example question is whether the hydrogen will be absorbed into pipeline steel. Some research mentioned that molecular hydrogen would be dissolved and absorbed into the metallic pipe wall matrix (Gallon and Van Elteren, 2021). On the contrary, another study (Sofronis and Robertson, 2006) pointed out that gaseous hydrogen is often not absorbed by steel at ambient or even slightly increased temperatures seen during pipeline operations. In the meantime, hydrogen at high temperatures (Beck et al., 1966) may lead to absorption as the molecules tend to break into individual atoms. Hydrogen adsorption is unquestionably more likely to happen in areas with pre-existing fractures, which subjecting higher stresses.[2]

Table 3. Interaction between H_2 and pipelines and potential material degradations

No.	Interaction Between H_2 and Pipelines	Potential Material Degradations
	• H_2 embrittlement • H_2 penetration-absorption • H_2 corrosion reaction	• Corrosion • Crack • Leakage • Metal loss • Fatigue crack growth rate • Yield/ultimate strength • Ductility/elongation • Fracture toughness

We will uncover and quantify the parameter that affects the hydrogen permeation, embrittlement, and corrosion reaction; the following study is to comprehensively assess and understand the hydrogen deterioration that occurs because of these interactions. A discussion about hydrogen-induced cracks is presented as an example. Hydrogen can induce cracks in the pipeline due to severe hydrogen embrittlement, which is created by a synergy of hydrogen concentration and stress level on susceptible steel materials. Typically, hydrogen embrittlement can cause several types of cracks in the pipeline, inducing hydrogen-induced cracking, stress-oriented hydrogen-induced cracking, and sulfide stress corrosion cracking (Ohaeri et al., 2018).

1.2.2.2 Component/system levels

Even though the appropriate concentration of hydrogen to send through a natural gas pipeline network varies by country and pipeline conditions, a low concentration of hydrogen in the blends results in a limited reduction in emission compared to natural gas, rendering the hydrogen proposal ineffective. Many current projects restrict the hydrogen percentage in blends to 20%, since maintaining the integrity of existing natural gas pipelines at greater costs is necessary if the hydrogen content exceeds this threshold. Therefore, it is certain that the proportion of hydrogen should be raised over time to boost efficiency. Consequently, researchers and operators are still expecting to find a good balance between the pipeline's integrity and the hydrogen's transit efficiency; moreover, this balance might vary based on the condition of the pipeline system and the domestic standard.

During the transit process, the internal pipeline surface will come into direct contact with hydrogen, making it feasible for hydrogen to attack the contact region and severely compromise the system's integrity. While several parameters, such as chemical composition, distribution, and morphology of phases, grain structure (size, shape, texture), alloying elements, etc., have been explored over the last decade, the long-term influence of hydrogen on the equipment during service life is not fully understood (Gallon and Van Elteren, 2021). In addition, there are still certain mechanisms that are debatable, such as hydrogen embrittlement, hydrogen penetration/absorption, and metallurgical impact; in addition to pipeline steel, it is required to comprehend the effect of hydrogen oxide layers and coatings. These debatable issues have a significant impact on the behavior of pipeline steel when hydrogen is introduced; to upgrade design, maintenance, and repair decisions in IMPs, comprehensive literature reviews and studies are necessary.

Transporting hydrogen or hydrogen mixtures presents a more significant challenge in terms of leakage than natural gas. When hydrogen escapes from pressurized equipment, it spontaneously ignites due to turbulent mixing with the surrounding air or other ignition causes, such as sparks from electrical equipment or valves (Chae et al., 2022; Erdener et al., 2022). Since hydrogen molecules are smaller and more mobile than methane molecules and thus readily pass seals and pipe walls, hydrogen leaks at a rate between 1.3 and 2.8 times that of methane and 4 times that of air. In addition, hydrogen embrittlement poses a possibility of pipe leaking, necessitating increased maintenance expenses for pipe replacement. As pipeline steel and joints become susceptible to leaking, the fracture toughness (the resistance to fracture due to hydrogen embrittlement) declines by more than 22 percent at a hydrogen pressure as low as 2.0 MPa (Chae et al., 2022).

Although gases are compressible and typically flow continuously, fatigue is not considered a significant hazard; however, the fatigue crack growth might be increased by ten times when hydrogen is injected (Romney et al., 2021). One reason is that the current network of pipes is mostly made of ferrous materials that are often weakened by atomic hydrogen. Hydrogen embrittlement is characterized by lower ductility, notch strengths, subcritical crack propagation under monotonic stress, and enhanced fatigue crack growth.[7] The other reason is that new and converted lines will be subjected to greater pressure swings, due to the diurnal and seasonal fluctuations in hydrogen supply and demand.

Even though the operating guidelines can be varied depending on the pipeline system and country, their experience and decision-making algorithms are still beneficial to this project. The findings from other ongoing or completed projects across the globe, including but not limited to the ones presented in **Table 4.**

Table 4. Hydrogen projects in other countries

Country	Institution	Project	Hydrogen ratio	Start date	End date	Ref.
German	E.on	H2-20 project	20%	2019	2023	1
German	E.on	H2HoWi	Up to 100%	2020	2023	2

France	ENGIE	GRHYD	20%	2014	2019	3
France	GRTgaz	JUPITER 1000	6-20%	2020	2050	4
Australia	AGN	HyP SA	5%	2020	2021	5
Australia	AGN	HyP Gladstone	10%	2019	2024	6
UK		HyDepoly	20%	2017	2020	7
Canada	ATCO	Fort Saskatchewan Blending	5%	2021	2022	8
Netherlands	KIWA	Sustainable Ameland	5-20%	2007	2011	9

Summary of activities in Task 2:

This task is to provide a review of risk assessment and risk management methods used for the pipeline industry and conduct a preliminary work to build up the GitHub platform. To achieve that, we organized the research activities herein as summarized in **Table 5**:

- Step 1: Review of risk assessment and risk management methods.
- Step 2: Preliminary work for the GitHub platform.

Table 5. Matrix covered in the Task 2

Step	Task	No.	Factors
1	Review of risk assessment and risk management methods	Task 2	• Risk assessment methods
2	GitHub platform	Task 2	• Platform to collect, store, analyze, and disseminate the inforamtion when it is ready for public

Step 1: Review of risk assessment and risk management methods

Risk assessment and risk management are critical for ensuring the safety of systems and organizations. The concept of risk has been present for a long time, as people have always had to make decisions based on their assessment of potential risks and benefits. However, the scientific study of risk assessment and risk management as a field is relatively new, having only developed in the past 40-50 years. Since its inception, the field of risk assessment and risk management has evolved significantly, and various methods and approaches have been developed to help systems and organizations identify, analyze, and evaluate risks. These methods include hazard identification, risk analysis, risk evaluation, and risk treatment, as well as other approaches such as expert judgment, scenario analysis, and probabilistic modeling. One important aspect of risk assessment and risk management is the ability to communicate risk information to different stakeholders, including decision-makers, regulators, and the public. Effective communication of risk information requires the use of clear and concise language, as well as the use of visual aids such as graphs, charts, and maps to help convey complex information. It is also important to consider the perspectives and needs of different stakeholders when communicating risk information, as different groups may have different concerns and priorities.

General risk assessment methods can be broadly classified based on the complexity of the system being analyzed and the available computation power. As shown in **Fig. 8**, for systems with lower complexity and limited computation power, classical risk assessment methods such as Failure Mode and Effects Analysis (FMEA), Fault Tree Analysis (FTA), Hazard and Operability Study (HAZOP), Event Tree Analysis, and Bow Tie Analysis (BTA) are typically used. On the other hand, with the advent of modern computers and increased computation power, more advanced risk assessment methods have been developed that either build upon or incorporate these classical methods. These methods focus on modifying existing technologies or utilizing the increased computation power to analyze and evaluate risks more effectively. The various risk assessment methods can be effective in evaluating the risks associated with a system, but they may overlap in certain areas and may require tradeoffs in terms of accuracy, budget, and safety preference. Additionally, these methods may be subject to subjectivity and lack flexibility. Despite efforts by researchers to propose new paradigms for risk assessment and risk management, a perfect solution has yet to be found for now.

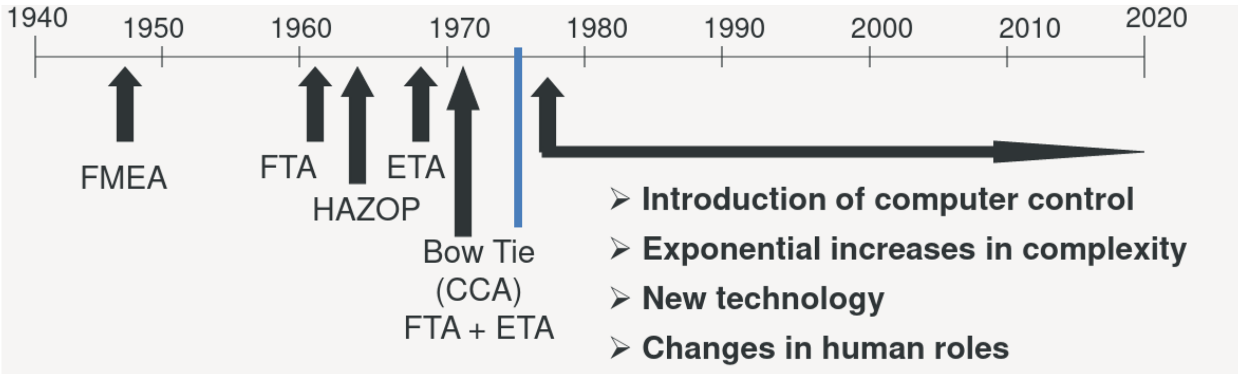


Fig. 8: Timeline of different risk assessment methodologies

This summary gave us a broad understanding of risk assessment in general. In the following section, we will delve into methods specifically related to risk assessment in the pipeline industry, including their applications and key components.

Risk assessment typically includes several key components, including hazards, consequences, likelihood, and potential mitigations. Traditional methods such as Bow Tie Analysis (TBA) often rely on these components to evaluate risks. In TBA, an acyclic graph can be used to represent hazards and their relationships, providing a clear visual representation of the risk assessment, and enabling easier interpretation of the results. This approach allows for the creation of high-level abstraction variables and allows for a more intuitive understanding of the risks faced by a system. However, these traditional risk assessment components may not be as effective in the context of modern artificial intelligence systems that rely on deep learning techniques. Deep learning models are often referred to as "black boxes" because they are difficult to interpret and understand, making it difficult to identify the specific hazards and consequences associated with their operation. This can make it challenging to apply traditional risk assessment methods to these systems and to effectively manage the risks associated with their use. Thus, to prepare the fundamental understanding and align with traditional methods we choose 1) Bow-Tie model-based causal paths, 2) Bayesian network-based causal paths as the key components category of our risk assessment review:

- **Bow-Tie model-based causal paths**

A causal path is a sequence of events or actions that leads to a particular outcome. Identifying and understanding the causal path of potential risk can help regulators identify the root causes of that risk and develop strategies to mitigate it. For example, a causal path for a potential leak or spill could include factors such as corrosion of the pipeline, failure of a valve, or a natural disaster. By identifying and analyzing the causal path, it is possible to identify the key factors that contribute to the risk and to develop strategies to address those factors. Causal paths are often represented visually, using diagrams or flowcharts to show the sequence of events or actions that lead to a particular outcome. They can be useful tools for identifying and understanding the potential risks associated with a system or process, and for developing strategies to mitigate those risks.

As mentioned above, the causal path can provide a logical reasoning process for the human mind, which can serve as a useful guide for AI model selection and construction. By following this causal path and leveraging the capabilities of deep learning, AI can gain trust and augment the decision-making ability of experts

According to ASME B31.8, there are 22 root causes for pipeline integrity management, thus at least 22 causal paths will be formulated. According to this guild line, we summarized different causal paths from previous research. Event trees and fault trees are commonly used for representing risk causal relations. Brito and de Almeida (2009) developed a risk assessment model that considers various dimensions of impact, such as external interference, erosion, mechanical failures and construction defects, earth movements and natural disasters, and unknown causes as shown in **Fig. 9**. The model also considers the decision-maker's preferences and behavior related to risk and produces multi-dimensional risk measurements. This allows for the creation of a risk hierarchy for prioritizing different sections of the pipeline.

Similarly, Fang et al. (2019) also proposed bow-tie diagrams to formulate the cause path of a gas pipeline accident in an underground utility tunnel in China as shown in **Fig. 10**. The diagram included 25 root causes and 12 consequences. Through their analysis, the authors found that the main root causes that contribute to the risk of a gas pipeline accident in a utility tunnel are "Incorrect Maintenance" and "Weld Flaw."

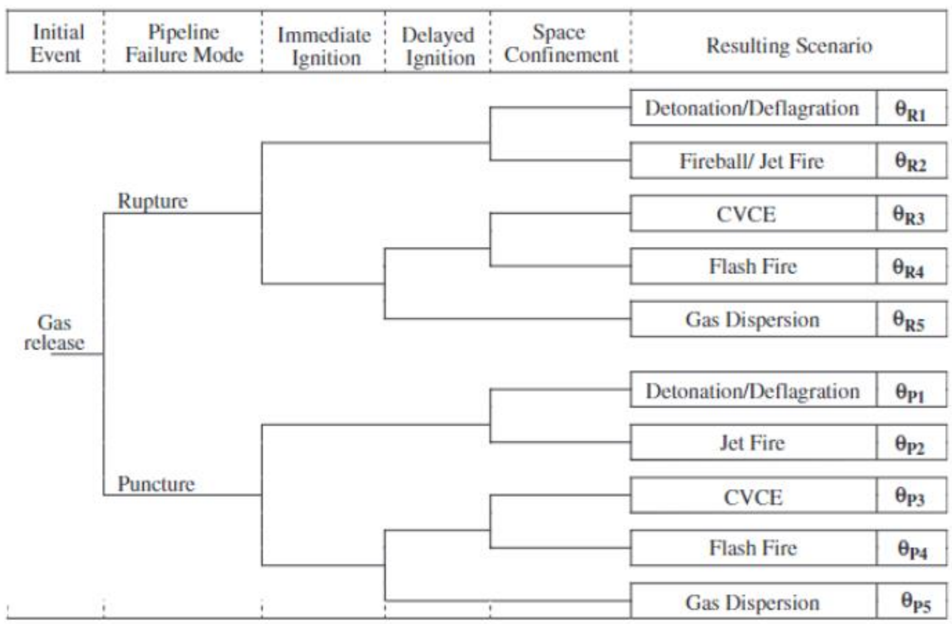


Fig. 9: Event tree for accidental release of natural gas from the pipeline (Brito and de Almeida 2009)

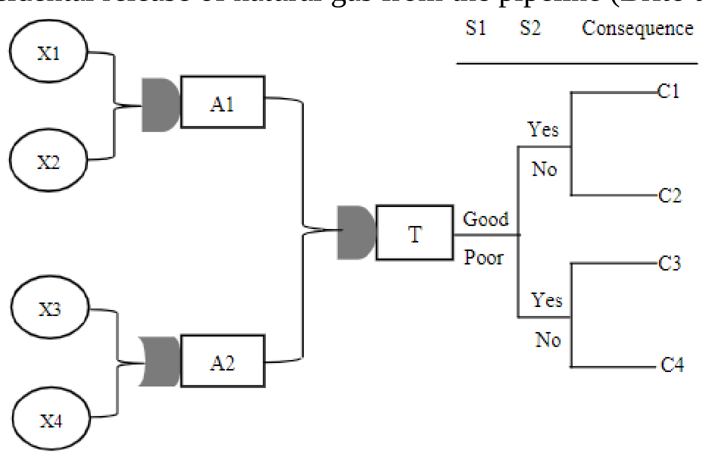


Fig. 10: A schematic diagram of the bow-tie method (Fang et al. 2019)

Markowski and Mannan (2009) discusses the use of fuzzy logic for risk assessment of major hazards associated with the transportation of flammable substances in long pipelines as shown in **Fig. 11**. They focused on three main root causes: leak, hole, rupture, and the cause path.

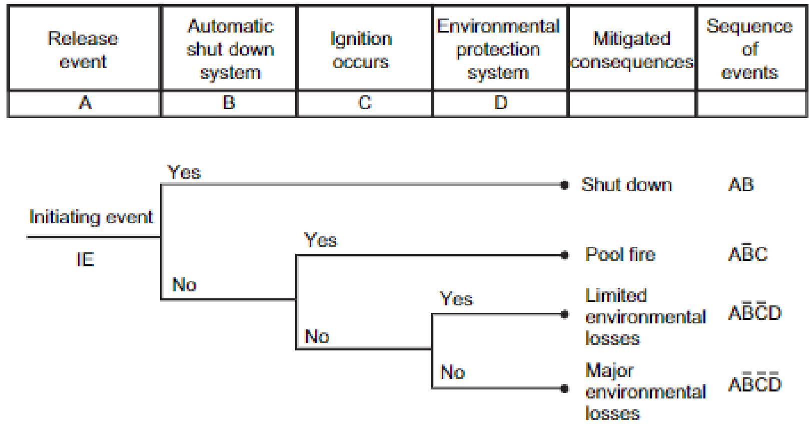


Fig. 11: event free for pipeline (Markowski and Mannan 2009)

As shown in **Fig. 12**, Vairo et al. (2021) surveyed historical accidents that occurred on NGP pipelines in the USA, Canada, and the EU, and analyzed the main factors responsible for the evolution of the accidents, including failure mode, immediate and root cause, evolving scenario, degree of confinement produced by the surroundings, and ignition timing. The authors proposed the use of a refined Event Tree framework to overcome the limitations of the widely used, overly conservative IPUKOOA approach. The root cause only includes external interference, mechanical, corrosion and ground movement. The paper concludes that the refined cause path is an effective tool for risk assessment and highlights the uncertainties and sensitivities in pipeline accident modeling.

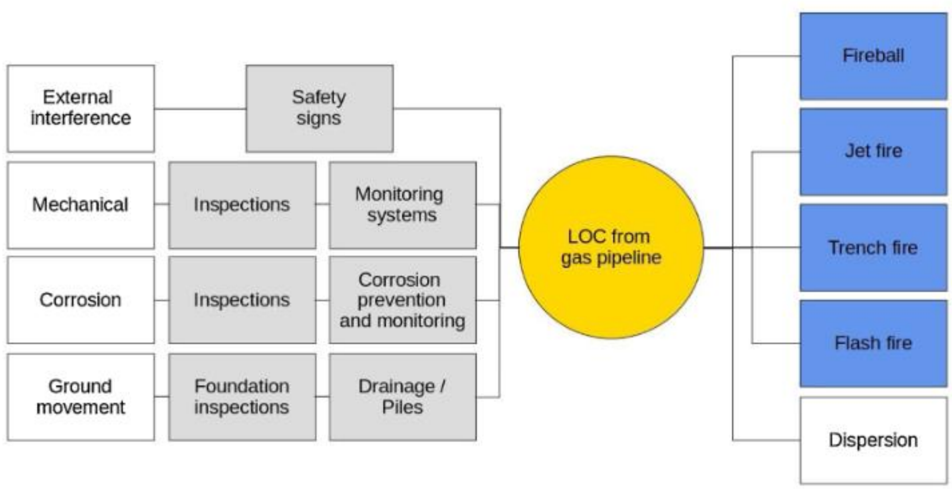


Fig. 12: bow-Tie centered on loss of containment for gas pipeline (Vairo et al. 2021)

According to ASME B31.8.S, Guzman Urbina and Aoyama (2017) proposed a fuzzy logic-based risk assessment with a focus on third-party damage, external corrosion, and internal corrosion as shown in **Fig. 13**. They also considered the safety measures and mitigation strategies that can be implemented in the cause path to decrease the risks associated with these threats. The result of the study shows that the framework can serve as a complementary step in current pipeline integrity management systems.

To further consider operational conditions, Wang et al. (2022) propose a novel analysis method called "Risk-Vulnerability" for identifying the critical components of a pipeline network (see **Fig. 14**). The Risk-Vulnerability method combines elements of risk assessment and vulnerability analysis and considers three perspectives: pipeline operating status, transmission performance, and network characteristics. This framework includes the importance of pipelines in the cause path, which can more effectively identify the critical nodes and pipelines that have the greatest impact on gas supply in a pipeline network.

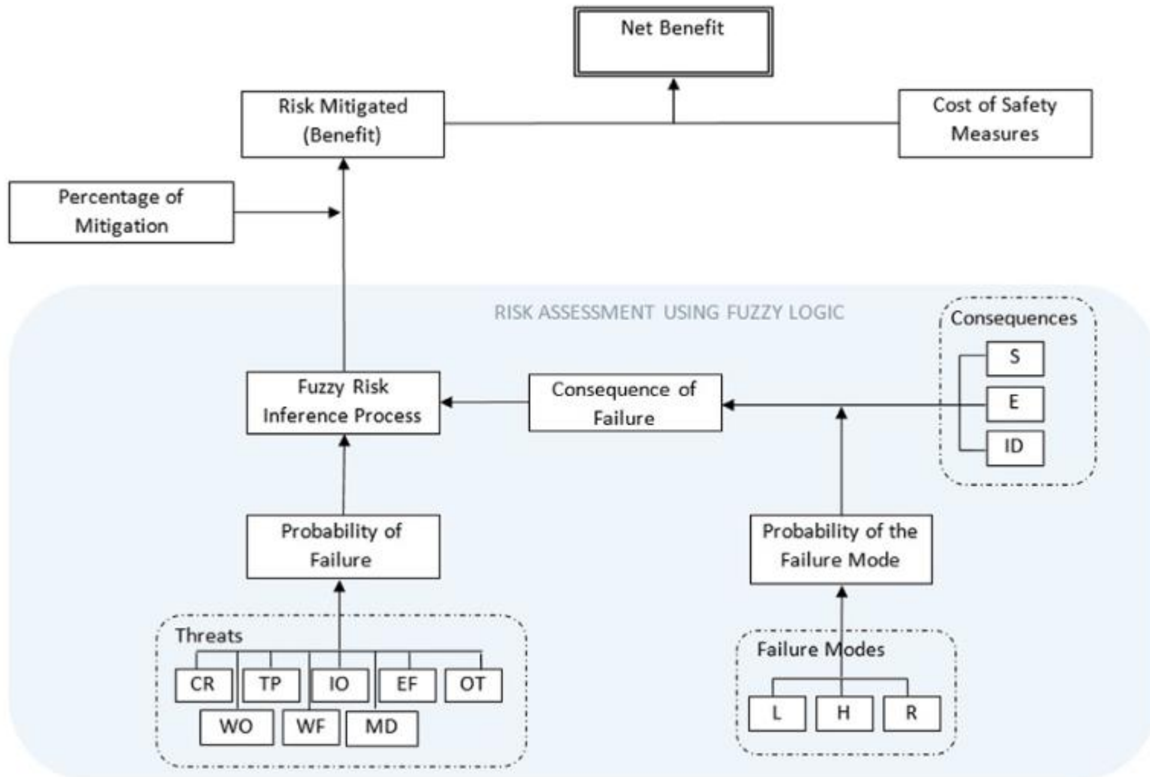


Fig. 13: Framework of benefit measurement via fuzzy risk assessment (Guzman Urbina and Aoyama 2017)

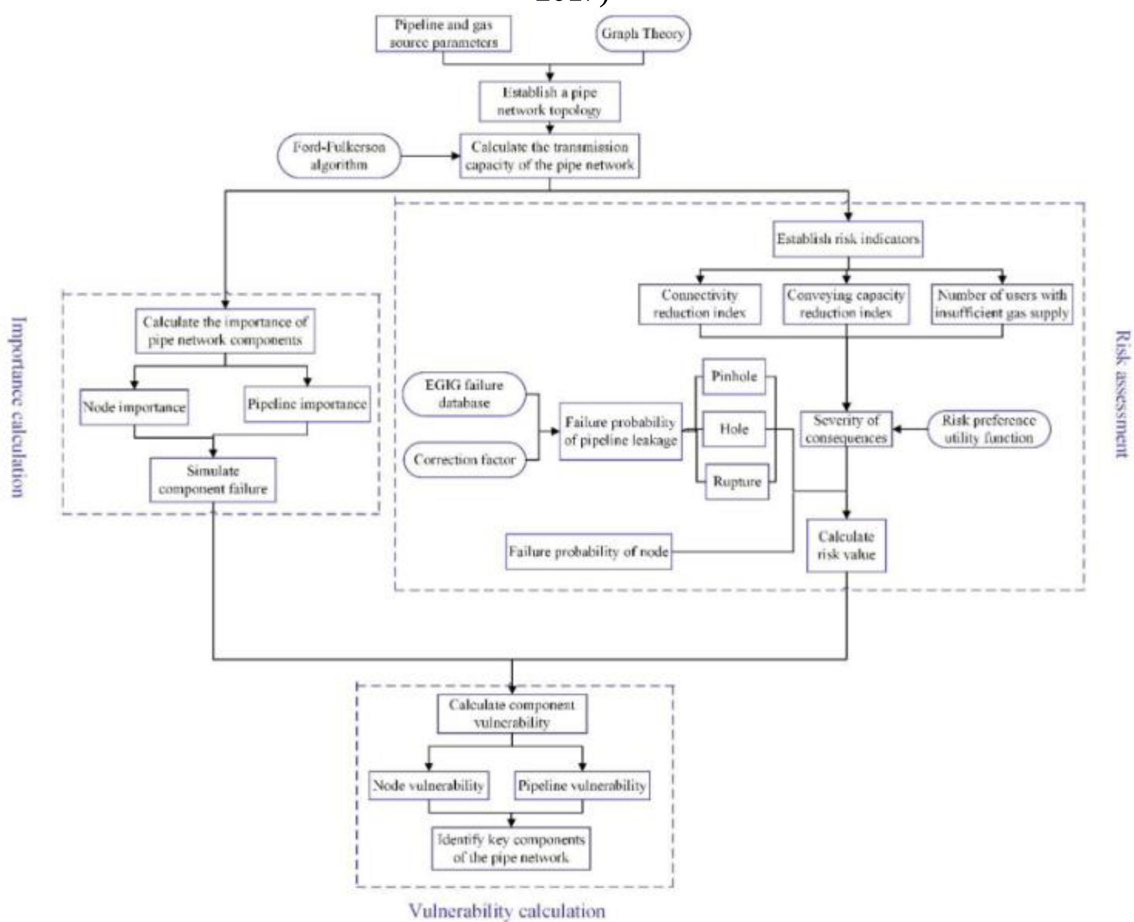


Fig. 14: Risk-vulnerability method steps used to identify critical components (Wang et al. 2022)

- **Bayesian network-based causal paths**

Bayesian networks are also a common tool to express the causal relations between different variables. Also, they are mostly used to represent and analyze probabilistic relations. It is naturally beloved by engineers to use it to calculate the likelihood. Moreover, it is a key component in causal analysis and causal inference. The dependence of variables can be used as the causal path in risk assessment. Thus, we will summarize some common causal paths in the Bayesian network.

Zhou et al. (2020) propose a Bayesian network-based risk assessment method for evaluating the potential hazards and typical accident scenarios of sewer pipelines in utility tunnels, as shown in **Fig. 15**. The proposed model was used to conduct BN inferences of sewer pipeline accident scenarios, and sensitivity analysis (SA) was conducted to identify the critical threats to the sewer pipeline. Although they inherit most causal relations from ASME B31.8 more environmental causal factors and paths are considered in this model, for example, earthquakes, unreasonable design, etc. This means, Bayesian networks are more flexible in present cause variables and highly adapted to different level variables to infer the causal effects of risk.

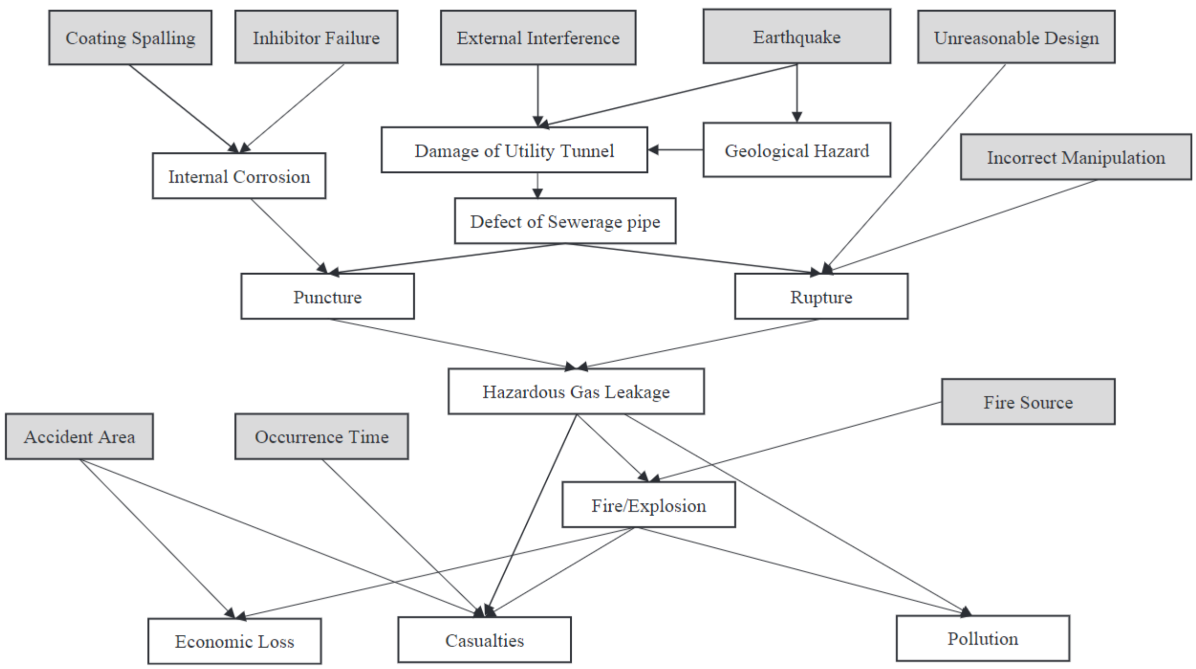


Fig. 15: Bayesian network of a sewer pipeline accident (Zhou et al. 2020)

Furthermore, as illustrated in **Fig. 16**, Arzaghi et al. (2018) demonstrate a more specific Bayesian network in a different context for risk assessment. They emphasize the ecological risk of oil spills from a sub-sea pipeline. These factors are not typically included in the causal path for traditional pipeline risk assessments but are relevant in the context of oil spills in the Arctic Ocean, for example, season, and wind, as shown in **Fig. 16**. In addition, Bayesian networks often have more complex structures than bow-tie models, due to the inclusion of fork and collider structures in the causal path. A fork structure occurs when one variable has multiple parent variables, while a collider structure occurs when two variables both influence a third variable, but there is no direct causal relationship between the two. These structures indicate that the causal relationships between variables being analyzed are more complex and may involve confounding factors. This can also provide more nuanced insights into the relationships between causal variables.

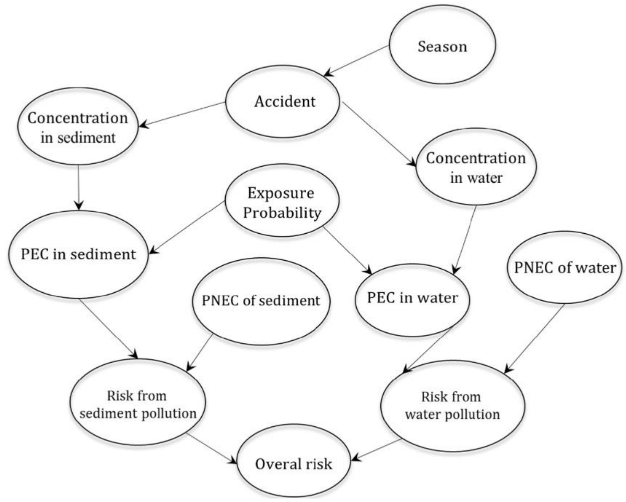


Fig. 16: Deep Bayesian networks for Ecological Risk Assessment of oil spill in the Arctic region (Arzaghi et al. 2018)

Similarly, an integrated interpretive structure modeling (ISM) and BN approach for risk assessment, as proposed by Wu et al. (2015) are shown in **Fig. 17**. ISM is a computer-aided method developed by Warfield for analyzing complex systems and identifying the factors that influence them. It can be used for distilling experts' knowledge about the causal path of the systems. These causal paths coupled with the experience path will give us a comprehensive understanding of the causal effects of the risk of the system.

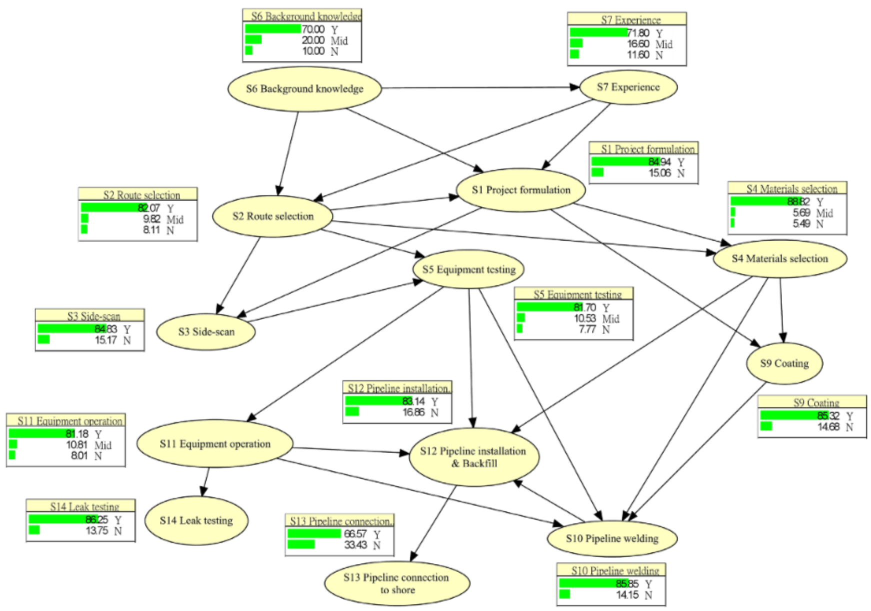


Fig. 17: Bayesian network for offshore pipeline laying project (Wu et al. 2015)

Step 2: Preliminary work for the GitHub platform

In this research period, we completed a literature review of holistic, XAI-empowered risk assessment methodologies. We also created a public GitHub repository for others to access our research progress and potentially reuse our methods in other projects, as shown in **Fig. 18**. (https://github.com/tjdxph/XAI-for-existing-pipeline-hydrogen-repurpose)

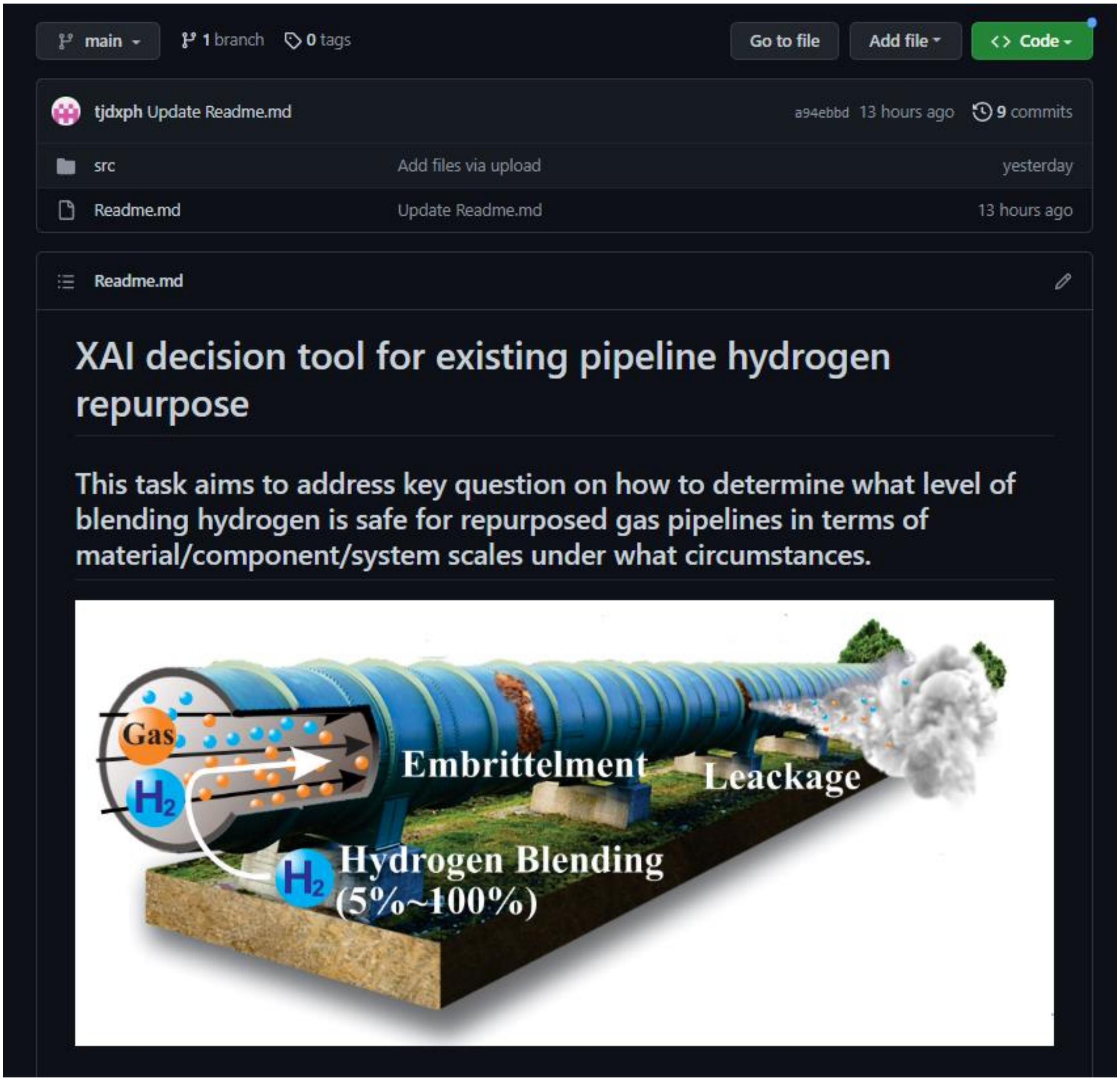


Fig. 18: GitHub repository interface for our project

(a) Description of any Problems/Challenges

No problems are experienced during this reporting period

(b) Planned Activities for the Next Quarter

The planned activities for the next quarter are listed below:

1) Focus on the research activities planned in Tasks 2.1, 3.1, and 4.1;
2) Supervise the graduate and undergraduate students in performing research Tasks 2.1 - 4.1;

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