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Original article

Hydrogen Conversion of Existing Pipelines: Integrity Solutions

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ABSTRACT
Background: In the global transition to low-carbon energy, hydrogen is becoming an important energy carrier. Adapting existing pipelines for hydrogen transportation can reduce costs and accelerate the development of hydrogen infrastructure. However, the use of pipelines in a hydrogen environment is associated with risks such as hydrogen embrittlement and metal cracking. Kazakhstan still lacks practical experience in the operation of hydrogen pipelines, which makes the task of assessing the technical condition of existing pipelines and their adaptation for operation with hydrogen urgen.
Aim: To conduct a comprehensive analysis of the integrity of the pipeline operated in an aggressive hydrogen sulfide environment and to assess the possibility of its repurposing for hydrogen transportation taking into account international standards and methods of strength calculation.
Materials and methods: The data of in-line inspection (ILI) including ultrasonic testing of wall thickness were used in the work. API 579 standards were used for defects assessment. Calculations were performed using NIMA software, which allows analyzing data on laminations and cracks in metal.
Results: The analysis identified six sections with laminations, of which five were found to be acceptable for service at the current operating pressure of 75 bar. One defect (#6) was classified as unacceptable, requiring either immediate repair or a reduction in operating pressure to 52 bar.
Conclusion: The study confirmed that conversion of existing gas pipelines for hydrogen transportation is feasible provided thorough diagnostics and compliance with international standards for strength assessment. Implementation of regular pipeline condition monitoring and development of a phased repair strategy to improve infrastructure reliability in hydrogen environment is recommended.
Keywords: *hydrogen transportation; pipeline conversion; hydrogen embrittlement; strength assessment; pipeline defects; laminations; cracks; integrity.*

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Оригинальное исследование

Конверсия существующих трубопроводов для водорода: решения по обеспечению целостности

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АННОТАЦИЯ

Обоснование. В условиях глобального перехода к низкоуглеродной энергетике водород становится важным энергоносителем. Адаптация существующих трубопроводов для транспортировки водорода может снизить затраты и ускорить развитие водородной инфраструктуры. Однако использование трубопроводов в водородной среде связано с рисками, такими как водородное охрупчивание и растрескивание металла. В Казахстане пока отсутствует практический опыт эксплуатации водородопроводов, что делает актуальной задачу оценки технического состояния существующих трубопроводов и их адаптации для работы с водородом.

Цель. Провести комплексный анализ целостности трубопровода, эксплуатируемого в агрессивной сероводородной среде, и оценить возможность его перепрофилирования для транспортировки водорода с учетом международных стандартов и методов расчета прочности.

Материалы и методы. В работе использованы данные внутритрубной диагностики, включая ультразвуковой контроль толщины стенок. Для оценки дефектов применялись стандарты API 579. Расчеты проводились с использованием программного обеспечения NIMA, которое позволяет анализировать данные о расслоениях и трещинах в металле.

Результаты. В ходе анализа выявлено шесть участков с расслоениями, из которых пять признаны допустимыми для эксплуатации при текущем рабочем давлении 75 бар. Один дефект (№6) классифицирован как недопустимый, что требует либо немедленного ремонта, либо снижения рабочего давления до 52 бар.

Заключение. Исследование подтвердило, что перепрофилирование существующих газопроводов для транспортировки водорода возможно при условии тщательной диагностики и соблюдения международных стандартов оценки прочности. Рекомендовано внедрение регулярного мониторинга состояния трубопровода и разработка стратегии поэтапного ремонта для повышения надежности инфраструктуры в условиях водородной среды.

Ключевые слова: *водородный транспорт, переоборудование трубопроводов, водородное охрупчивание, оценка прочности, дефекты трубопровода, расслоения, трещины, целостность.*

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Түпнұсқа зерттеу

Сутегі үшін қолданыстағы құбырларды конверсиялау: тұтастықты қамтамасыз ету шешімдері

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АННОТАЦИЯ

Негіздеу. Төмен көміртекті энергияға жаһандық көшу жағдайында сутегі маңызды энергия тасымалдаушысына айналады. Қолданыстағы құбырларды сутекті тасымалдауға бейімдеу шығындарды азайтып, сутегі инфрақұрылымының дамуын тездетуі мүмкін. Алайда сутегі ортасында құбырларды пайдалану барысында сутектің сынуы және металдың жарылуы сияқты тәуекелдері де бар. Қазақстанда сутек құбырларын пайдалануға тәжірибе әзірше жоқ, бұл қолданыстағы құбырлардың техникалық жай-күйін бағалау және оларды сутегімен жұмыс істеуге бейімдеу міндетін өзекті ете түседі.

Мақсаты. Агрессивті күкіртсутекті ортада пайдаланылатын құбырдың тұтастығына кешенді талдау жүргізу және халықаралық стандарттар мен беріктікті есептеу әдістерін ескере отырып, оны сутекті тасымалдау үшін қайта бейіндеу мүмкіндігін бағалау.

Материалдар мен әдістер. Жұмыста қабырға қалыңдығын ультрадыбыстық бақылауды қоса алғанда, құбырішілік диагностика деректері пайдаланылды. Ақауларды бағалау үшін API 579 стандарттары қолданылды. Есептеуле NIMA бағдарламалық жасақтамасын қолдана отырып жүргізілді, бұл металдағы қабаттар мен жарықтар туралы деректерді талдауға мүмкіндік береді.

Нәтижелері. Талдау барысында қатпарлануы бар алты учаске анықталды, олардың бесеуі қазіргі жұмыс қысымы 75 бар кезінде пайдалануға рұқсат етілген деп танылды. Бір ақау (№6) қолайсыз деп жіктеледі, ол жедел жөндеуді немесе жұмыс қысымын 52 барға дейін төмендетуді қажет етеді.

Қорытынды. Зерттеу сутекті тасымалдау үшін қолданыстағы газ құбырларының мақсатын өзгерту мұқият диагностикалау және халықаралық беріктікті бағалау стандарттарын сақтау арқылы мүмкін екенін растады. Сутегі ортасы жағдайында инфрақұрылымның сенімділігін арттыру үшін құбырдың жай-күйіне тұрақты мониторингті жүргіздіру, енгізу және кезең-кезеңмен жөндеу стратегиясын әзірлеу ұсынылады.

Негізгі сөздер: *сутекті тасымалдау, құбырларды қайта жабдықтау, сутектің сынғыштығы, беріктігін бағалау, құбыр ақаулары, қатпарлану, жарықтар, тұтастық.*

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Introduction

In the context of the global transition toward low-carbon energy systems, hydrogen has emerged as a key energy carrier with the potential to significantly reduce greenhouse gas emissions. Its application spans across various sectors, including transportation, industry, and power generation, offering a sustainable alternative to fossil fuels. One of the critical challenges in scaling up hydrogen infrastructure lies in the development of efficient and safe transportation methods. Among these, the repurposing of existing natural gas pipelines for hydrogen transport presents a cost-effective and timely solution.

However, the adaptation of pipelines for hydrogen service introduces complex technical challenges, particularly related to material degradation phenomena such as hydrogen embrittlement and cracking. These issues are exacerbated in environments containing aggressive agents like hydrogen sulfide (H_2S), which can further compromise pipeline integrity. In Kazakhstan, where practical experience with hydrogen pipelines is still limited, the need for rigorous assessment methodologies and international standard compliance becomes especially urgent.

This diploma project aims to evaluate the feasibility of repurposing an existing gas pipeline in Kazakhstan for hydrogen transportation. The study focuses on assessing the structural integrity of the pipeline under hydrogen service conditions, using data from in-line inspections and applying recognized standards such as API 579 and ASME FFS-1. By leveraging advanced diagnostic tools and simulation software, the project provides a comprehensive analysis of lamination defects and their impact on pipeline safety and performance.

Materials and methods

This study was based on data obtained from the in-line inspection (ILI) of a 20-inch, 12 km long seamless X60 steel gas pipeline in Kazakhstan, originally constructed in 2003 and currently operated at 75 bar in sour gas service. The inspection was carried out using a magnetic flux leakage (MFL) tool, which identified multiple lamination-type anomalies. To verify the findings, excavation of selected sites was performed, and conventional ultrasonic testing (UT) was conducted in-field to accurately measure defect dimensions, wall thickness, and depth characteristics.

Six lamination anomalies were confirmed through UT, classified by location (internal or external surface breaking) and geometric properties such as length, width, and remaining wall thickness (T1 and T2). The anomalies were further analyzed using NIMA – integrity management software developed by ROSEN, which supports evaluation of in-line inspection data and assessment of remaining strength and serviceability.

The structural integrity of each anomaly was assessed using the API 579 Level 2 methodology, modeling laminations conservatively as planar defects (crack-like). The assessment accounted for parameters including original wall thickness (11.1 mm), material properties (Charpy impact toughness of 38 J), and local defect geometry. As hydrogen pipeline operation could not be tested directly, a sour service environment (with high H_2S content) was used as a proxy

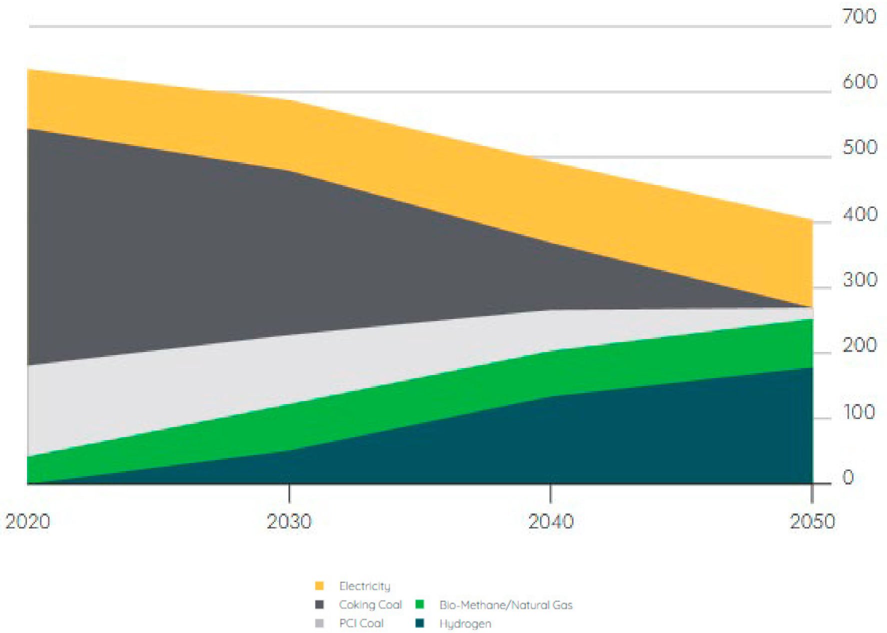

Figure 1. Expected consumption of various energy types based on company statements from industrial sectors [1]

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to simulate degradation mechanisms similar to hydrogen embrittlement.

Relevance of hydrogen as an energy carriery

Hydrogen energy is increasingly recognized as a vital component in achieving global decarbonization and net-zero emissions by 2050. Its versatility allows for applications across various sectors, including transportation, industry, and power generation, offering a clean alternative to traditional fossil fuels. Moreover, hydrogen serves as an energy carrier and storage medium, facilitating the integration of renewable energy sources int the grid [2, 3].

The use of hydrogen H_2 is considered harmless and green for the earth's atmosphereand essential under the Paris Agreement, which define the path to reduce greenhouse gas emissions. This is supported by Fig. 3, which shows the expected future share of energy sources based on industrial company statements (TWh On Y-Axes, Years on X-Axes). To remind, the use of hydrogen as an energy carrier has many drivers, including zero emissions from the combustion process (1):

$$2H_2 + O_2 \rightarrow 2H_2O + \Delta Q \qquad (1)$$

Alternatively, burning the same methane produces CO_2 (2):

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O + \Delta Q \qquad (2)$$

In addition to above, China Hydrogen Alliance suggested that by 2030, hydrogen energy will reach production of 35 million tons, which is 5% of China's energy supply, and by 2050, it will reach production of 60 million tons, which will be equal to 10% of China's energy supply. At present, China is one of the leaders in the production of Fuel cell electric vehicles (FCEV), vehicles powered by hydrogen, which is one of the facts that this type of energy storage & usage has a future [4].

Overview of regional H_2 projects and focus on pipeline repurposing

In Central Asia, the development of the hydrogen energy sector is growing. In Mangistau Oblast of Kazakhstan it is planned to create a project on green hydrogen production with capacity of 2 million m_3 by 2032 [5]. In the Republic of Uzbekistan based on the existing ammonia production plant, the company ACWA Power, to build a facility for the production of green ammonia, it is planned in the first phase of work to produce 3000 tons of green ammonia, and in the second phase of already produce 500,000 tons per year [6]. Given the expected amount of hydrogen production it is important to define the most effective means of transportation. Pipelines as one of the most efficient and safe option will play an important role in delivering hydrogen to consumers. As shown on Fig. 2 transportation of energy by pipelines according to [7] will be 2–4 times cheaper than by overhead power connections.

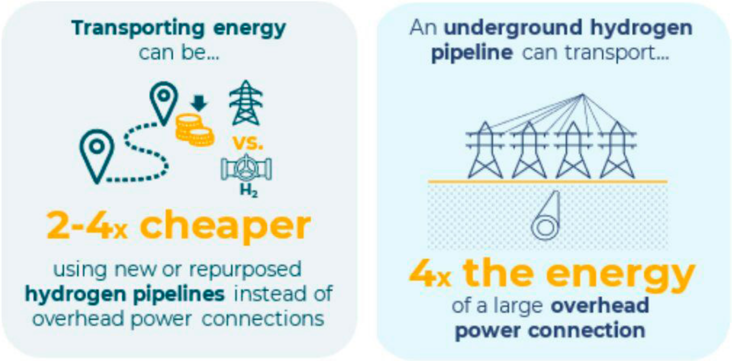

Figure 2. European Backbone efficiency estimate [7]

Table 1. Comparison of Hydrogen Transportation Methods

Transportation method	Advantages	Disadvantages
Gaseous hydrogen (pipeline)	Cost-effective for large-scale, continuous supply	High initial capital expenditure
	Compatible with underground storage	Requires advanced R&D on pipeline materials and system design
	Environmentally safe	
Containers (trucking)	Zero hydrogen losses during transport	Economically viable only for small-scale supply
	No need for on-site storage infrastructure	High per-unit transportation costs
Liquid hydrogen (cryo-tanks)	High energy and storage density	Liquefaction is energy-intensive and expensive
	Economical for medium-range distribution	Requires complex cryogenic infrastructure
		Complex technique
Bonded hydrogen (carriers)	Potentially low-cost over long distances	Complex hydrogen release process
	Utilizes existing infrastructure	Risk of contamination from impurities
	Operates under moderate temperature and pressure	Often requires return of spent carrier material

Hydrogen can be transported in different ways and in different aggregate states. The paper [8] provides a comparison of these methods.

Gaseous hydrogen: is transported through pipelines, both special and existing pipelines for natural gas. The method is efficient for large volumes and continuous deliveries but requires significant capital investment and complex R&D on pipe materials.

Liquefied hydrogen: is transported in cryogenic tanks. This is convenient for medium distances and volumes, provides high storage density, but requires energy-intensive liquefaction and is accompanied by evaporation losses.
Containerized transportation of gaseous hydrogen is convenient for small volumes and lack of infrastructure but has high cost and limited capacity.
Transportation in bound form: such as ammonia or metal hydrides, is promising due to the use of existing infrastructure and high storage density but requires additional transformation and development of safe technologies. A comparison is presented in Tab.1.
However, as shown on Fig. 3, in accordance with [7], the construction of new pipelines will take about 7 years based on the following industry standards:
– ASME B31.12 – Hydrogen Piping and Pipelines;
– ASME Boiler and Pressure Vessel Code – Section VIII Division 3;
– API 579/ASME FFS-1;
– ANSI/CSA CHMC 1 – Test Methods for Evaluating Material Compatibility in Compressed Hydrogen Applications – Metals.

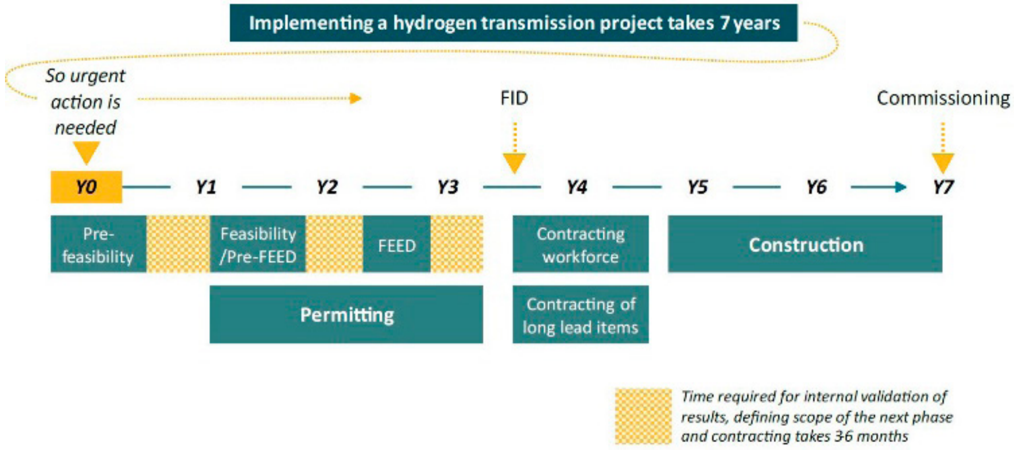

Figure 3. European Backbone Implementing a hydrogen transmission project [7]

Therefore, to achieve climate goals, the industry requires immediate solutions like existing pipeline repurposing. In accordance with European Backbone [9] by 2040 more than 60% of the future H_2 pipeline network will be repurposed from existing natural gas pipelines. The Fig. 4 below shows the vision of the European Backbone taking into account hydrogen pipelines map of 2040. Although pipeline repurposing is not yet being considered in Kazakhstan, this study will focus on the integrity assessment of the pipeline in an H_2 environment to demonstrate the proposed approach.

Pipeline operation in a hydrogen environment

The pipeline fitness-for-service assessments are based on degradation mechanisms, steel grade of the pipe, pipe wall thickness, and the condition of the pipe material. Hydrogen environment creates a specific mechanism of degradation due to the absorption and diffusion of atomic hydrogen (H_2) within the microstructure of pipeline steel, which can lead to hydrogen embrittlement (HE) and potential cracking [10]. Hydrogen embrittlement occurs due to the penetration and diffusion of atomic hydrogen into the metal, reducing the strength and ductility of the metal, thereby exposing the metal to the risk of cracking. This phenomenon has been described in [9] and illustrated on Fig. 5. The mechanisms of HE in repurposed natural gas (NG) pipelines remain a topic of debate, with two prevailing theories: hydrogen-enhanced localized plasticity (HELP) and hydrogen-enhanced decohesion (HEDE).
However, there is growing consensus that hydrogen-induced cracking typically occurs only in the presence of pre-existing flaws or cracks. This phenomenon is often explained by Hydrogen-Environment Assisted Cracking (HEAC), where hydrogen dissociates and absorbs at crack tips, embrittling the crack front and facilitating its propagation under stress.
While some studies suggest that gaseous hydrogen could also induce cracking away from the bulk material, this is generally considered possible only under exceptional conditions over time, particularly in susceptible microstructures such as hard spots or at stress risers like deformations. A common problem will be hydrogen cracking and embrittlement of the metal.
The presence of hydrogen in the mixture of the transported product resulted in a 20–80% reduction in the ductility of the metal, in some studies a reduction of 85% was observed at a hydrogen concentration of 1%. Consequently, even insignificant hydrogen content contributes to the acceleration of fatigue crack growth [10].

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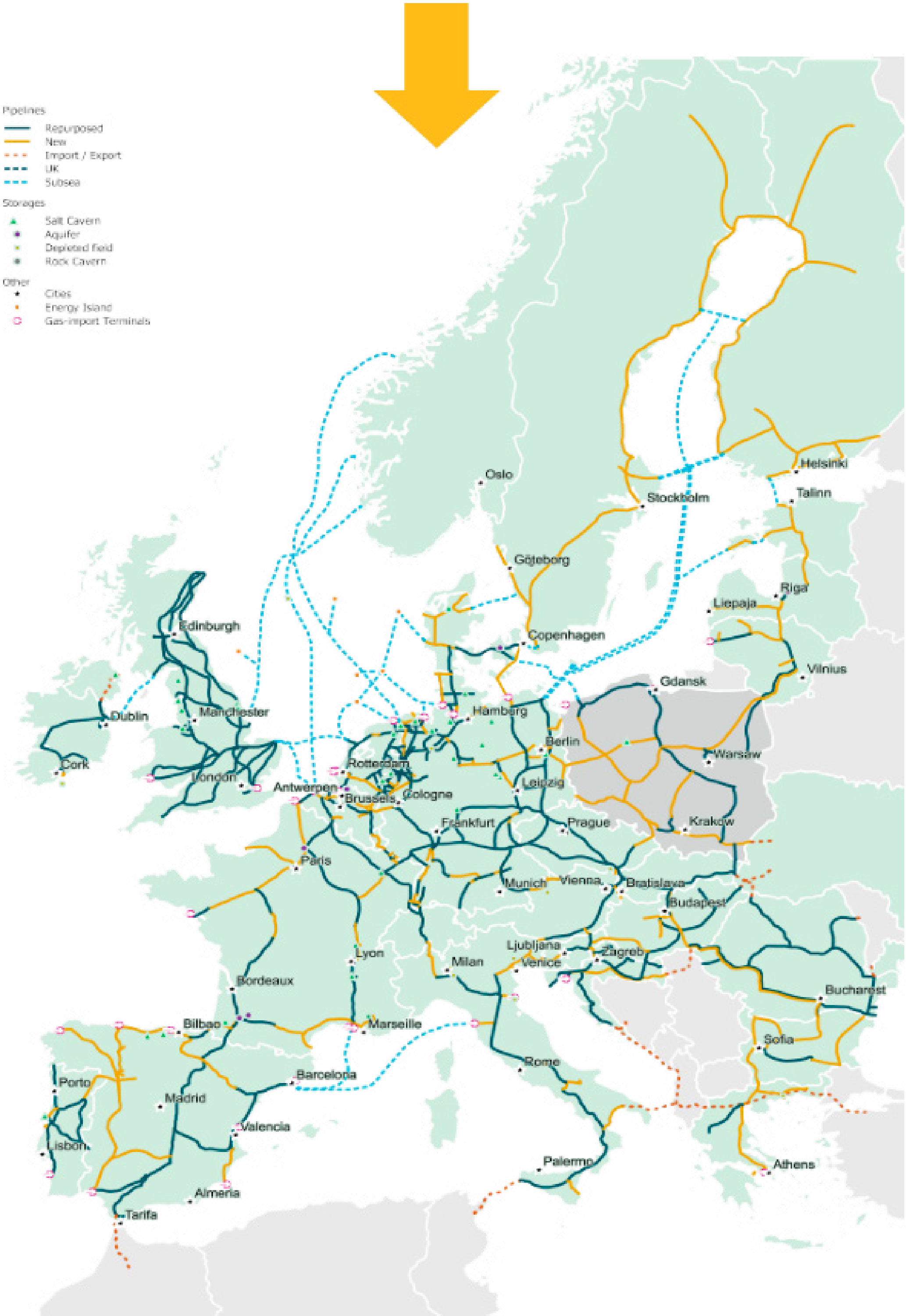

Figure 4. European Backbone vision to the map of Hydrogen pipelines by 2040 [9]

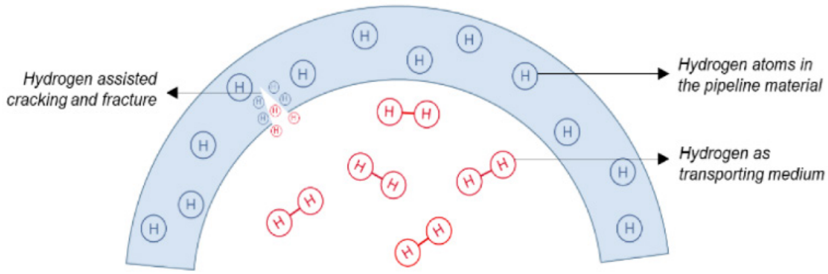

Figure 5. H_2 atoms diffused in the pipeline material, and its interaction causing cracking [10]

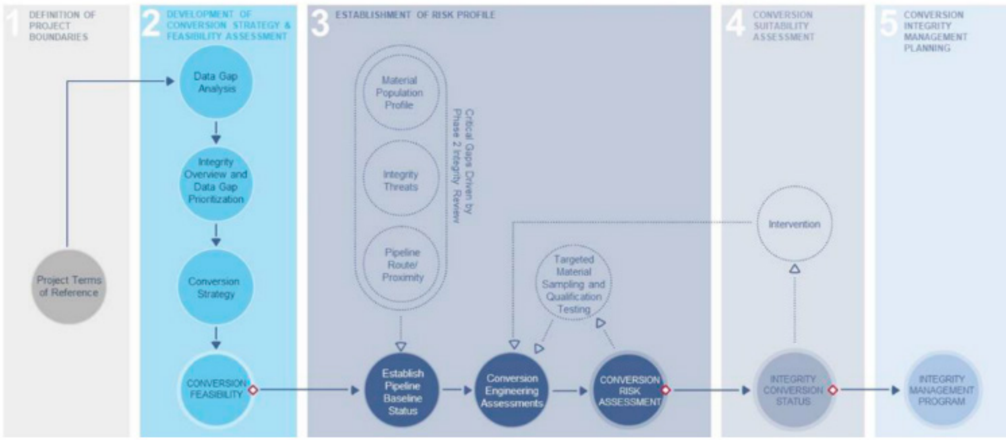

Figure 6. Pipeline H_2 Repurposing Framework [10]

Pipeline H2 Repurposing – Case study in Kazakhstan

General Approach and Assumptions

In [10] a phased approach to H_2 repurposing was proposed. It is summarized in the figure below.

Within the scope of this study, the authors will focus on Phase 2 of the framework related to calculation of laminations under H_2 conditions using API and ASME standards.

Lamination is the separation of metal into layers characterized by a concentration of non-metallic elements such as oxides and other impurities. The sources of these defects are usually inclusions and porosity. Laminations can be classified as follows:

– Internal;

– Surface breaking (external or internal).

Following assumptions are applied for the API 579 (Level 2) assessment:

1.Lamination will be modeled as a crack in the pipe.

2.Calculations will consider a gas medium with high H_2S content, as hydrogen modeling is technically unfeasible within this project because have some software restrictions but as mentioned in the works [10, 11] we can apply this assumption and this assumption is justified.

3.Blistering does not affect the load bearing capacity of the pipe wall.

4.Geometric irregularities and additional bending stress were not considered.

As part of this study, the NIMA software, developed by ROSEN, was utilized. NIMA is a cloud-based Software-as-a-Service (SaaS) solution designed for the comprehensive analysis of inspection data, including in-line inspection (ILI) and non-destructive testing (NDT) results. This platform enables a detailed defect assessment, remaining life evaluation, and the development of data-driven maintenance strategies.

By leveraging NIMA SaaS, operators can enhance pipeline integrity management, streamline decision-making processes, and reduce the risk of failures and unplanned downtime. Its cloud-based architecture ensures scalability, real-time data accessibility, and seamless integration with existing pipeline integrity workflows, ultimately improving the efficiency and reliability of pipeline operations [12].

Input Data Review

As demonstrated earlier, there is currently no operational experience with pipelines transporting pure hydrogen in Kazakhstan. Therefore, the authors suggest considering a pipeline operating in a sour environment (containing hydrogen sulfide, ~5% wt.) as the most comparable in terms of degradation mechanisms. Tab. 1 presents the technical characteristics of Pipeline X.

For an accurate strength calculation in NIMA, it is essential to define the parameters utilized provide a detailed explanation of the key lamination parameters considered in the assessment.

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Pipeline was inspected with UT-WM ILI technology. The anomalies have been verified further by conventional UT. The findings of the inspections are summarized in Tab. 4.

Results of Lamination Assessment

The above data sets have been integrated and assessed against industry standards in the NIMA Integrity Management platform.

As shown in Fig. 8 and 10, the acceptability of an anomaly depends on its position relative to the criticality curves, which determine its severity and required action.

In Fig. 9, four # (1, 2, 3, and 4) are identified with values below the permissible limits, confirming their suitability for continued operation. #5 remains operational at pressures up to 75 bar but is unsuitable at 97 bar, while #6 is classified as unacceptable.

The results of the API 579 (Level 2) [13] assessment summarized in the Tab. 5. The analysis of lamination calculations in axial cracks revealed that #6 does not meet permissible standards. Based on the two evaluation charts, either immediate reconstruction or a reduction of operating pressure to 52 bar is required. #5, classified as unacceptable based on axial dimensions, is deemed acceptable according to circumferential dimensions. However, the assessment at 65 bar confirms that #6 remains unacceptable for further operation for both options.

As a result, two possible approaches for maintaining pipeline integrity to be considered:

– Immediate repair without waiting for the scheduled shutdown;

– Reduce operating pressure to an acceptable level and defer repairs until the scheduled shutdown.

Table 2. Pipeline characteristics

Parameter	Value
Pipe diameter	20 inches
Length	12 km
Product	Sour Gas
Steel Grade	X60 (SMYS 420 MPa, SUTS 520 MPa)
Pipe Type	Seamless
Construction Date	2003
Wall Thickness	11,1 mm
Original MAOP	97 bar
Current MOP	75 bar
Charpy Toughness	38 Joules full size (minimum specified)

Table 3. Anomaly parameters

Anomaly Parameter	Definition
Lamination class	Classification of lamination (e.g., parallel, inclined – with exit to inner surface)
Length	Length of delamination in longitudinal direction
T_1	Minimum thickness between lamination and the inner pipe wall surface
T_2	Maximum thickness between lamination and inner pipe wall surface
TC	Pipe wall thickness in the delamination area (unbroken section)
Depth used for the assessment lamination	Depth used for the assessment evaluation

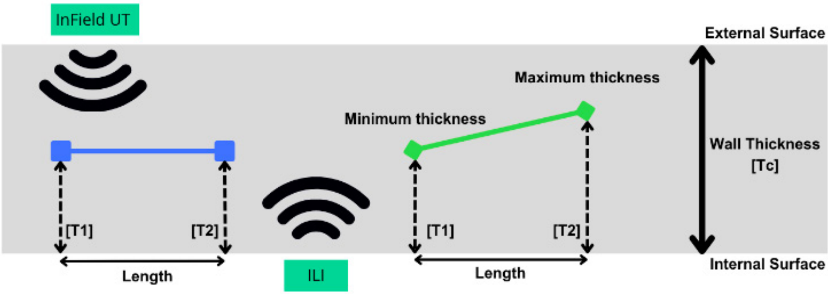

Figure 7. Layout of parameters on the pipe wall

Table 4. The findings of the ILI and in-field verification

№	Wall Thickness	Infield UT Reported Dimensions, mm				Lamination Classification	Assessment Depth, mm	Assessment Length, mm
		T1	T2	Length	Width			
1	11.1	6.72	2.30	310	50	External Surface Breaking	6.52	325
2	11.1	6.25	1.50	365	100	External Surface Breaking	6.05	365
3	11.1	6.55	1.67	400	105	External Surface Breaking	6.35	400
4	11.1	6.10	2.50	575	65	External Surface Breaking	5.9	575
5	11.1	7.05	2.00	670	85	External Surface Breaking	6.85	670
6	11.1	9.70	2.55	850	240	Internal Surface Breaking	9.5	850

Assessment Depth is calculated according to below formula: Assessment Depth = Wall Thickness – (Wall Thickness – T1)

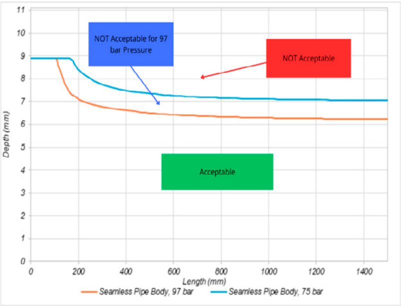

Figure 8. Acceptable axial crack zones on the pipe body

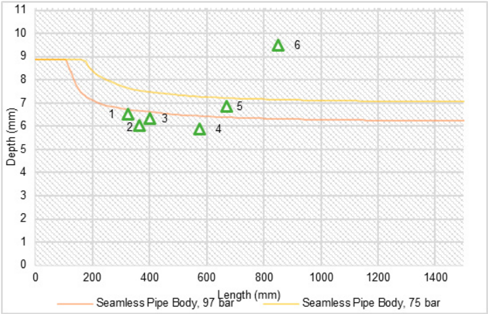

Figure 9. Axial cracks on the pipe body

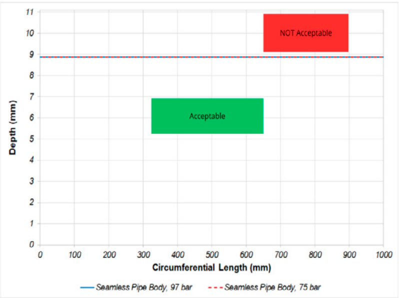

Figure 10. Acceptable circumferential crack zones on the pipe body

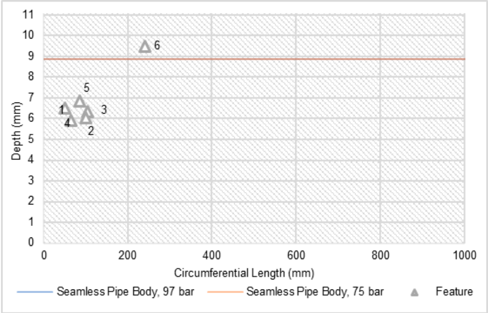

Figure 11. Circumferential cracks on the pipe body

Table 5. Final results of lamination assessment (assessment pressure 65 Bar) in sour service against API 579 (Level 2)

ID	Wall Thickness, mm	Assessment Depth, mm	Assessment Length, mm	Width	Lamination Classification	API 579 (Level 2) Assessment Result
1	11.1	6.52	325	50	External Surface Breaking	Acceptable
2	11.1	6.05	365	100	External Surface Breaking	Acceptable
3	11.1	6.35	400	105	External Surface Breaking	Acceptable
4	11.1	5.9	575	65	External Surface Breaking	Acceptable
5	11.1	6.85	670	85	External Surface Breaking	Acceptable
6	11.1	9.5	850	240	Internal Surface Breaking	**Unacceptable**

Conclusion

This study provides a comprehensive evaluation of the feasibility of repurposing an existing natural gas pipeline in Kazakhstan for hydrogen transportation, addressing critical challenges such as hydrogen embrittlement and material degradation. Given the nascent state of hydrogen infrastructure in Kazakhstan, this research represents a pivotal step in understanding the structural implications of pipeline conversion for hydrogen service.

The integrity of the pipeline was rigorously assessed through the analysis of lamination defects under sour service conditions. Utilizing ultrasonic wall thickness measurements and in-line inspection data, six pipeline sections were examined for structural vulnerabilities. The evaluation, conducted using NIMA software and guided by API 579 Level 2 and ASME standards, identified one critical defect (#6) that surpassed safety limits, necessitating immediate remedial actions such as repair or operational pressure reduction. Furthermore, the study investigated hydrogen embrittlement mechanisms, including hydrogen-enhanced localized plasticity (HELP) and hydrogen-enhanced decohesion (HEDE), to assess the long-term risks associated with hydrogen exposure.

A significant contribution of this research liesin its methodological approach to evaluating pipeline integrity under hydrogen conditions. By drawing parallels with pipelines exposed to sour service environments, which exhibit analogous degradation patterns, the study offers valuable insights into hydrogen-induced material risks. The applicatio of industry-standard fitness-for-service methodologies establishes a replicable frame work for assessing hydrogen conversion feasibility in other regions.

The findings highlight the necessity of proactive integrity management strategies when adapting existing infrastructure for hydrogen transportation.

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Future research should prioritize real-world hydrogen testing, the effects of varying hydrogen concentrations on pipeline integrity, and the advancement of enhanced monitoring techniques to ensure long-term pipeline safety. As Kazakhstan progresses toward a hydrogen economy, the methodologiesand outcomes of this study will serve as a critical foundationfor the safe and efficient transformation of pipeline networks to support hydrogen energy initiatives.

ADDITIONAL INFORMATION

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Authors' contribution. All authors made a substantial contribution to the conception of the work, acquisition, analysis, interpretation of data for the work, drafting and revising the work, final approval of the version to be published and agree to be accountable for all aspects of the work. The greatest contribution is distributed as follows: Ildar Akhmetov – collection, processing, and analysis of experimental data, conducting research, detailed analysis and interpretation of results, manuscript writin; Abdugaffor Mirzoev – manuscript editing, analysis revision and review.

ДОПОЛНИТЕЛЬНО

Источник финансирования. Автор заявляет об отсутствии внешнего финансирования при проведении исследования.

Конфликт интересов. Автор декларирует отсутствие явных и потенциальных конфликтов интересов, связанных с публикацией настоящей статьи.

Вклад авторов. Все авторы подтверждают соответствие своего авторства международным критериям ICMJE (все авторы внесли существенный вклад в разработку концепции, проведение исследования и подготовку статьи, прочли и одобрили финальную версию перед публикацией). Наибольший вклад распределён следующим образом: Ахметов И. – сбор, обработка и анализ экспериментальных данных, проведение исследования, детальный анализ и интерпретация результатов, написание рукописи; Мирзоев А. – редактирование рукописи, вычитка и проверка выполненного анализа.

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