

Some Aspects of Metrological Traceability as a Consequence of Blending Low-carbon Hydrogen to Natural Gas Pipelines in Brazil

Sergio Oliveira¹

¹ INMETRO National Institute of Metrology, Quality and Technology, Av. Nossa Senhora das Gracas, 50, predio 3, Lafor – Duque de Caxias/RJ, Brazil, spoliveira@inmetro.gov.br

Abstract – This work analyzes the readiness of low-carbon hydrogen to be blended to natural gas, or eventually a mixture of natural gas and biomethane, transmission pipelines network in Brazil with metrological traceability. An approach involving Quality Infrastructure, metrological reliability, and the description of both the main parts of natural gas networks and the hydrogen embrittlement phenomenon was used to obtain an overview of their joint effects in pipelines' parts. On analyzing all aspects described before with the most relevant international standards applicable in pipelines, there was a lack of information on Metrology quantities flow rate, pressure, density, composition, calorific value and measuring stations, so it was possible to conclude what is necessary in Brazil in terms of existing pipelines that transport natural gas to blend with hydrogen.

I. INTRODUCTION

As shown in Figure 1, Brazilian natural gas (NG) infrastructure comprises gas production pipelines (not depicted), gas gathering pipelines (in blue), gas transmission pipelines (in green), and gas distribution pipelines (not depicted) as of year 2024 [1].

Figure 2 shows the physical structure of pipeline system and its main applications in Brazil [2] as well as a highlight with a squared pink line on the transmission pipelines because they are the object of this work. Brazil has a natural gas (NG) network of about 56,000 km that includes about 6,500 km of production and gathering pipelines [1,3], about 9,500 km of transmission pipelines [2,3] i.e. the high-pressure main hub most of it near the seashore, and more than 40,000 km of distribution pipelines [4] from city gates to points of use in the internal locations of municipalities.

Taking into account Brazil's geographic area this is a relatively small pipeline system because the use of natural gas in the country started in 1999. As a comparison the EU gas network is capable of transporting and storing large quantities of energy constituting more than 200,000 km of transmission pipelines and more than 2,000,000 km of distribution network [5] whereas the USA has about a

513,000 km transmission network and a 3,700,000 km distribution network [6].

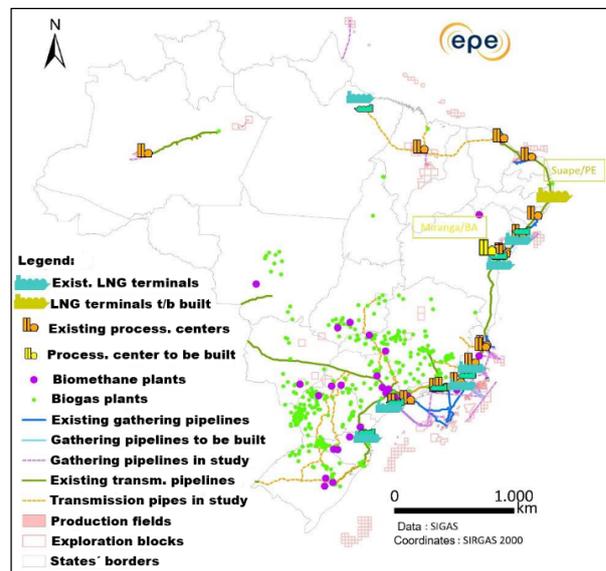


Fig. 1. Natural gas infrastructure in Brazil in 2024 including existing, to be built, and in study pipelines [1].

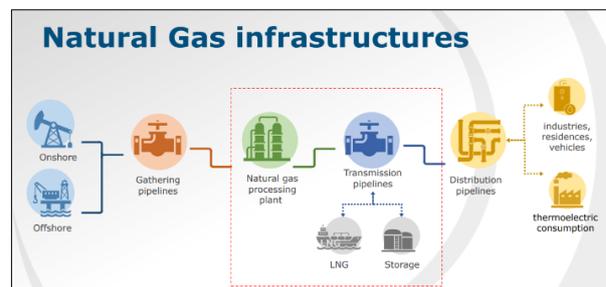


Fig. 2. Natural Gas infrastructures in Brazil, their main applications, and highlighted transmission pipelines [2].

A. Natural Gas, Biomethane and Hydrogen

Biomethane has been blended to NG in pipelines in nine Brazilian states [1,7]. This biomethane comes from the purification of biogas produced in biodigesters and

landfills [8,9,10]. Anaerobic biodigesters use residues and wastes as feedstocks that come from waste of poultry, beef, pig, sugar cane, fruit production, etc. Sanitary landfills are engineered and managed facilities for disposing the solid waste that comes from residential and industrial waste and trash.

B. Quality Infrastructure and Traceability

The first step in any initiative in terms of quality in measurements is the Quality Infrastructure (QI) [11], defined by INETQI, International Network on Quality Infrastructure, and its fifteen members – BIPM, IAF, IEC, IIOA, ILAC, IQNET, ISO, ITC, ITU, OIML, TIC Council, UNECE, UNIDO, WBG, and WTO – as “The system comprising the organizations (public and private) together with the policies, relevant legal and regulatory framework, and practices needed to support and enhance the quality, safety and environmental soundness of goods, services and processes. [...] It relies on metrology, standardization, accreditation, conformity assessment and market surveillance” [11].

The main characteristics of a quality measurement are both metrological traceability and reliability. According to “VIM” [12] metrological traceability is defined as “property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty”. Another relevant definition is the traceability chain that is defined as “sequence of measurement standards and calibrations that is used to relate a measurement result to a reference” [12].

A traceability chain is shown in Figure 3, adapted from [13], where relevant parameters are summarized in a top-down way, then the measuring quality is higher and higher from lower to higher levels as well as a lower level stage finds out its metrological traceability in a higher level stage and the last disseminates its metrological reliability to lower level stages; (inter)comparison means all participants in key/laboratorial/internal comparisons are in a unique horizontal level with the same measuring quality.

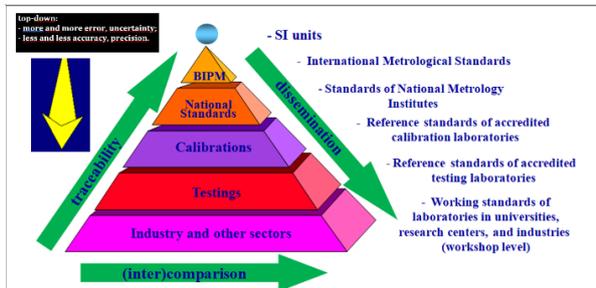


Fig. 3. A traceability chain, adapted from [13].

Figure 3 presents error and uncertainty increasing more and more top-down whereas accuracy and precision decrease more and more top-down.

A good experiment should follow the best approach i.e. the measurement reliability can follow the sketch shown in Figure 4 [13] that details the experimental testing sequence necessary for a suitable and reliable measurement approach. Such approach has to be used because there are some actions to be made before (experimental planning, experimental set-up, suitable instrumentation, traceability, calibration), during (procedures, methods, and technical standards), and after (data analysis at least if data follow a normal distribution and/or if there are outliers, an estimation of measurement uncertainty, and the creation of the respective measurements report or the calibration certificate) each experiment no matter if it is an academic test or an industrial report in a production line. This experimental sequence follows the BIPM suite of guides “VIM” [12], “SI Brochure” [14], and “GUM” [15].

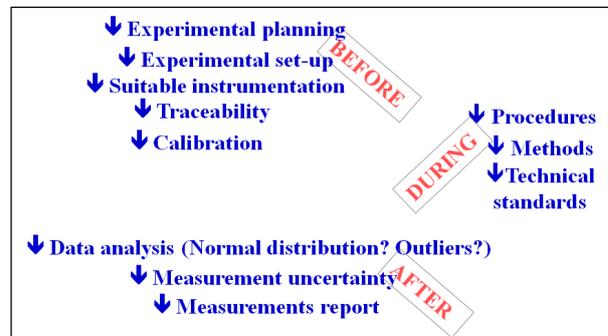


Fig. 4. Experimental testing sequence with the approach before, during, and after the experiment as components of metrological reliability[13].

II. OBJECTIVE AND JUSTIFICATION

The objective of this work is the discussion of the needs of traceability in natural gas transmission pipelines in Brazil in case hydrogen be blended with NG in the pipes taking into account the QI and the Metrology in the most relevant aspects of pipelines in Brazil. A fact is some NG pipelines have already been blending NG and biomethane produced from biogas that comes from waste, trash and residues collected in residences and industries.

The justification is the implicit concern on traceability because: a) custody transfer is an important operation that is always present; b) the design and specifications of the components have to follow established technical and metrological rules; c) the online measurements from upstream to downstream of the pipelines. In 2024 the Brazilian National Hydrogen Program called PNH2 was established by two specific Federal Laws. Since then five companies that own the main pipeline networks started a technical, logistic and economic discussion, organized by their Association of Natural Gas Transport Companies by Pipeline (called ATGAS) based on research studies to blend low-carbon hydrogen from 0% to 100% in hydrogen volume, with Life Cycle Assessment (LCA) and established frontiers, applied to existing NG pipelines.

III. NATURAL GAS NETWORKS

Natural gas networks are composed of several key parts and ancillary systems [16,17,18], all these parts in principle submitted to hydrogen effects by blending it with NG. The key parts of NG networks include pipelines, coatings, valves, compressors, meters, liquid management equipment, actuators, cathodic protection equipment, control equipment, etc.

There's a more detailed description of all parts below.

- Pipelines: These are the main arteries of the system, large pipes that carry the natural gas over long distances.
- Pipes: The main conduits for transporting natural gas. They are designed to withstand high pressures and are often made of steel; the pipes themselves are typically large, high-pressure lines, with diameters ranging from 6 to 48 inches, used for long-distance transmission.
- Compressor Stations: These stations are essential for maintaining the pressure and flow rate of the gas through the pipelines, ensuring efficient transportation. Compressors increase pressure to facilitate long-distance transport.
- Control Equipment: This includes a variety of sensors and microcontrollers, monitoring systems, and communication networks that are used to monitor the pipeline's performance, detect potential problems, and respond to emergencies. It monitors and regulates the entire system, including pressure, flow, and temperature.
- Storage Facilities: These facilities are used to store natural gas for later use, particularly during periods of high and/or seasonal demand.
- Valves: Valves are strategically placed along the pipeline network to regulate and control the flow of gas, particularly during maintenance or repairs.
- Metering Stations: These facilities measure the flow of gas through the pipelines, providing accurate data for billing and monitoring.
- Coatings: Applied to the pipes to protect them from corrosion and external damage.
- Liquid Management Equipment: Addresses any liquids that may condense within the pipeline.
- Actuators: Power the valves and other components.
- Cathodic Protection: Prevents corrosion of the pipelines by creating an electrical barrier. E.g. this system helps to further protect the pipeline from corrosion by creating an electric current that counteracts the corrosive effects of the soil.
- Welding: Pipelines are assembled through welding, which requires strict quality control to ensure the strength and integrity of the welds.
- Integrity Management: This involves a set of procedures and assessments to ensure the long-term reliability and safety of the pipeline.
- City Gate Stations: used to regulate gas flow into municipalities.
- Ancillary Systems: Include equipment like compressed air systems, which can be necessary for certain operations

as well as other supporting facilities. The last include gathering lines (collecting gas from wells), transmission lines (transporting gas over long distances), and distribution lines (delivering gas to customers by way of city gates).

- Pigs: "Pigs" in the context of natural gas pipelines are specialized devices used for various maintenance tasks, including cleaning, inspection, and separation of different product batches. These devices, often referred to as "pigging" devices, that include pig launchers and pig receivers, travel through the pipeline and perform these functions without interrupting the flow of gas.

IV. HYDROGEN EMBRITTLEMENT

Metal parts of a pipeline can have its mechanical resistance reduced by presence of hydrogen and its active role in the phenomenon hydrogen embrittlement (HE). As expected hydrogen blended to natural gas in pipelines can create conditions for the appearance of HE as well. Some authors cite details of this phenomenon in terms of materials compatibility and other conditions not only internal ones linked to microstructure conditions but also external conditions as well [19,20,21,22]. In terms of pipeline networks one can expect some parts of them to withstand problems related to HE: the pipes themselves, compressor stations, control equipment, storage facilities, valves, metering stations, city gates, and thermally affected zones of welds.

HE can have a so high effect on the material ductility that A. Islam *et al* [20] in their review of hydrogen blending into NG pipelines concluded: hydrogen blending in NG pipelines can significantly reduce carbon emissions; HE poses safety risks for pipeline materials in NG infrastructure; testing showed minimal yield strength changes after hydrogen exposure in various steels; fracture toughness of pipeline steels decreases notably with increasing hydrogen pressure; advanced testing and materials development are needed for safe hydrogen integration. According to Kappes and Perez [23], hydrogen can dissolve in the steel and cause HE, compromising pipeline structural integrity; HE caused subcritical cracking, decreased ductility and fracture toughness, and increased the fatigue crack growth rate.

V. DISCUSSION

The main parts of natural gas networks described in Section III "Natural Gas Networks" are used in any project of pipelines with not only NG but also with biomethane in Brazil and even H₂ with careful analysis due to HE.

Since there isn't an overall harmonized understanding on hydrogen uptake in pipelines to be blended with NG nor specific regulations on blending hydrogen and NG the actual attempts are concentrated on some technical testings, some insight on previous experience on hydrogen characteristics, and technical standards issued by international standardization bodies (ISO and IEC),

regional ones (mainly European standards), national ones, and professional ones (API, ASTM, and ASME), not mentioning technical reports from international forums and associations (IEA, Hydrogen Council, IPHE), and the last but the least indexed scientific papers.

The first point to be discussed is what about the technical standards relevant to the subjects posed in this paper and used in Brazil and abroad by industrial pipeline sector? This search has resulted in some relevant technical standards for the purpose of mixing hydrogen and NG: the title of each standard is a self-explanation on the subject of it. For NG there are the standards ISO 14111:1997: "Natural gas – Guidelines to traceability in analysis" [24], and ISO 14532:2014: "Natural gas – Vocabulary" [25]. For pipelines there are the API standards API 1104 "Welding and Related Tests" [26], API 5: "Specifications for Line Pipe" [27], API RP 1175 "Pipeline Leak Detection – Program Management" [28], API RP 1173 "Pipeline Safety Management Systems (SMS)" [29], API 1102 "Pipeline Crossings" [30], API 20E "Pipeline Bolts" [31], and API RP 1160 "Pipeline Mechanics" [32]. In terms of ASTM standards there are ASTM G148-97 (Reapproved 2018) "Standard Practice for Evaluation of Hydrogen Uptake, Permeation, and Transport in Metals by an Electrochemical Technique" [33], ASTM F1459:06(2024) "Standard Test Method for Determination of the Susceptibility of Metallic Materials to Hydrogen Gas Embrittlement (HGE), ASTM F2078:22: "Standard Terminology Relating to Hydrogen Embrittlement Testing" [34], ASTM F1624:12(2024) "Standard Test Method for Measurement of Hydrogen Embrittlement Threshold in Steel by the Incremental Step Loading Technique" [35], ASTM B849:02(2023) "Standard Specification for Pre-Treatments of Iron or Steel for Reducing Risk of Hydrogen Embrittlement" [36], and ASTM B850:98(2022) "Standard Guide for Post-Coating Treatments of Steel for Reducing the Risk of Hydrogen Embrittlement" [37]. For NG piping and H₂ piping there are, respectively, ASME B31.3 - 2024 "Process Piping" (for all fluids like natural gas) [38] and ASME B31.12 - 2023 "Hydrogen Piping and Pipelines" [39].

On 18 March 2025 there was a presentation in Rio de Janeiro City related to the end of project "Research and Development (R&D) Roadmap for Hydrogen Transport via Gas Pipelines", organized by ATGAS - Association of Natural Gas Transport Companies by Pipeline and CTDUT - Pipelines' Technology Center [40]. It was a 2-year project that used laboratorial real-size scale and mathematical modelling. There was a coincidence between the obtained results and literature searched for this paper: 0-2% H₂ haven't created problems for the pipelines; 20% H₂, some problems being necessary some pipe's repurposing; and 100% H₂, a lot of problems that resulted in deep repurposing.

Since Brazilian pipeline networks' subject is relatively new in comparison to European and USA ones most

transmission pipelines in Brazil use high-strength steels that are relatively less susceptible to HE.

Regarding points to be addressed for a higher understanding of hydrogen to be blended to NG pipelines, there was another coincidence by comparing the references searched for this paper and results found in ATGAS+CTDUT project [40]. E.g. due to a lack of a broad understanding it was not possible to enter deeply in some Metrology concepts in the pipeline topics: measuring stations, nozzle that injects H₂ into NG pipeline along with both the correct angle and position that H₂ need to be injected accordingly. By studying sources [1-4,7-10] there is scarce understanding about some metrological quantities and related data that are relevant like flow rate, pressure, density, composition, and calorific value. On the other hand, there are some questions that are quite well resolved in literature: risk management and analysis, existing pipeline codes, specific safety standards, costs analysis methodology & building scenarios for the future, corrosion & protective coatings, corrosion in the presence of hydrogen, influence of hydrogen on cathodic protection and external coating, hydrogen permeation under different conditions, integrity monitoring, and factors limiting hydrogen-NG mixture.

Regarding metrological traceability, INMETRO (Brazilian) National Institute of Metrology, Quality and Technology has human resources and equipment for R&D on relevant quantities applied in pipelines: a) flow rate, by way of wind tunnels and pressure losses in fluids; b) pressure by way of differential pressure measurements and pressure transducers; c) density by way of advanced methods for digital density meters; d) temperature by way of advanced sensors and thermocouples; e) gas composition by way of a complete set of chromatographs; f) materials metrology by way of advanced equipment for materials characterization; and g) mechanical metrology by way of expertise in HE, interaction of hydrogen and all types of materials, and mechanical properties' changes in pipelines in the presence of hydrogen.

As achievement, blending H₂ to NG shall reduce the emission of greenhouse gases from the process of transport NG by transmission pipelines in Brazil, being also a relevant step towards energy transition in the country.

In last, this work did not focus on the topic of digital transformation (subjects like digital certificates, digital twins, blockchain technology, digital product passport).

VI. CONCLUSIONS

This work presented the status of the transmission natural gas pipeline network in Brazil to receive hydrogen to be blended with natural gas or even with NG plus biomethane coming from biogas, waste, trash and residues.

Metrology and Traceability Chain were discussed. At the same time some relevant technical standards to be taken into account in the mixture of NG and hydrogen.

Some metrological quantities are going to be studied by

INMETRO Brazilian NMI: flow rate, pressure, density, temperature, gas composition, materials characterization, hydrogen embrittlement, and mechanical properties' changes in pipelines due to hydrogen.

A deep study on some questions are necessary in such a way Brazilian private companies that are owners of transmission pipelines be able to blend hydrogen to natural gas in its pipes: advanced Metrology concepts, the correct angle and position of nozzles that inject hydrogen into NG pipelines, and there is scarce information and data on flow rate, pressure, density, composition, and calorific value.

VII. ACKNOWLEDMENT

This author acknowledges the support of INMETRO (Brazilian) National Institute of Metrology, Quality and Technology, for the development of this work.

REFERENCES

- [1] H.B.B. Esteves *et al.*, "Methodological Technical Note - Integrated National Plan of Natural Gas and Biomethane Infrastructures - Public Consultation Version" [Title translated from Portuguese], EPE - Energy Research Office, Rio de Janeiro/RJ, Brazil, March 2025. https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-875/topico-753/Minuta_Metodologia_Plano%20Integrado_Con_sulta%20P%C3%ABblica_19.03.2025.pdf.
- [2] C.O. Castro, "South America's Natural Gas Infrastructures and Possibilities for Brazil" [Title translated from Portuguese], in Rio Pipeline 2019 - EPE Stand, EPE - Energy Research Office, Rio de Janeiro City, Brazil, September 2019. <https://www.epe.gov.br/sites-pt/sala-de-imprensa/noticias/Documents/ESTANDE%20-%20Natural%20Gas%20Infrastructures%20in%20Brazil%20and%20South%20America.pdf>.
- [3] B. Albuquerque, T.V.B. Ferreira, "2031 Ten-year Energy Expansion Plan" [Title translated from Portuguese], MME - Brazilian Ministry of Mines and Energy and EPE - Energy Research Office, Brasilia/DF, Brazil, April 2022. <https://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/plano-decenal-de-expansao-de-energia-2031>.
- [4] H.B.B. Esteves *et al.*, "Indicative Plan of Transport Pipelines 2024 – PIG 2024 – Technical Note EPE/DPG/SPG/02/2025" [Title translated from Portuguese], EPE - Energy Research Office, Rio de Janeiro/RJ, Brazil, February 2025, <https://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/plano-indicativo-de-gasodutos-de-transporte-pig-2024>.
- [5] "Gas factsheet - Key facts about gas in the EU", ACER – European Union Agency for the Cooperation of Energy Regulators", Ljubljana, Slovenia, hosted in <https://www.acer.europa.eu/gas-factsheet>, accessed on 1st May 2025.
- [6] "Pipeline Briefing Papers – A Simple Guide to Understanding Pipeline Safety, Operations and Regulations", Pipeline Safety Trust, Bellingham/WA, United States, 2024, hosted in <https://pstrust.org/briefing-papers/>, accessed on 1st May 2025.
- [7] "The Role of the Natural Gas Transport System for the Development of the Market and for the Use of Synergies with Biomethane and Hydrogen" [Title translated from Portuguese], ATGAS - Association of Natural Gas Transport Companies by Pipeline, MME: Gas to Employ - Committees 2 and 5, Rio de Janeiro/RJ, Brazil, November 2023. <https://www.gov.br/mmme/pt-br/assuntos/secretarias/petroleo-gas-natural-e-biocombustiveis/gas-para-empregar/participacao-social-no-gt-ge/apresentacao-de-contribuicoes-em-evento-promovido-pelo-gt-ge/comite-5/atgas#:~:text=Promove%20o%20aproveitamento%20dos%20res%C3%ADduos,agroindustrial%20e%20no%20setor%20sucroener%C3%A9tico.&text=A%20interconex%C3%A3o%20de%20produtores%20em,sistemas%20de%20Distribui%C3%A7%C3%A3o%20e%20Transporte>.
- [8] R.H.A. Gonzalez, H.B.B. Esteves, "Biomethane Panorama – Energetic Sugarcane Sector" [Title translated from Portuguese], CIBIOGAS Renewable Energies and EPE - Energy Research Office, Foz do Iguacu/PR and Rio de Janeiro/RJ, Brazil, December 2023, <https://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/panorama-do-biometano-setor-sucroenergetico>.
- [9] C.A.N. Teixeira, R.C. Costa, A.P.A. Mendes, M.A.R. Rocio, "Texts for Discussion: biomethane time in Brazil" [Title translated from Portuguese], BNDES – National Bank for the Economic and Social Development, Rio de Janeiro/RJ, Brazil, January 2024, <https://web.bndes.gov.br/bib/jspui/handle/1408/24146>.
- [10] A. Freddo, A.C. Vieira, D.G. Martinez, F. Alves, "Biogas Panorama in Brazil 2022 – Technical Report 001/2023" [Title translated from Portuguese], CIBIOGAS Renewable Energies, Foz do Iguacu/PR, Brazil, 2023, https://cibiogas.org/wp-content/uploads/2023/12/Panorama_do_Biogs_no_Brasil_2022.pdf?gclid=CjwKCAiAzc2tBhA6EiwArv-i6fd0mxZY0_JJVPO1rZFh_CC2xIfLcPskURYycl2_wF7hTTtkdGowKR0CVz4QAvD_BwE.
- [11] INETQI (International Network on Quality Infrastructure), "What do we do?" and "Quality Infrastructure Definition", <https://www.inetqi.net/>.
- [12] "VIM - JCGM 200:2012 International Vocabulary of

- Metrology - Basic and general concepts and associated terms (2012)", BIPM: JCGM Publications: Guides in Metrology, <https://www.bipm.org/en/committees/jc/jcgm/publications>.
- [13] A.V. Tchouvelev, S.P. Oliveira, N.P. Neves Jr., "Chapter 6: Regulatory Framework, Safety Aspects, and Social Acceptance of Hydrogen Energy Technologies", in P.E.V. Miranda (ed), "Science and Engineering of Hydrogen-Based Energy Technologies: Hydrogen Production and Practical Applications in Energy Generation", <https://doi.org/10.1016/B978-0-12-814251-6.00006-X>, Elsevier/Academic Press, London (UK)/San Diego (USA)/Cambridge (USA)/Oxford (UK), 2019.
- [14] "SI Brochure: The International System of Units (SI) – 9th Edition (2019) – Complete brochure (updated in 2024)", Bureau International des Poids et Mesures. (2024). <https://www.bipm.org/en/publications/si-brochure>.
- [15] "GUM – JCGM 100:2008 - GUM 1995 with minor corrections - Evaluation of measurement data — Guide to the expression of uncertainty in measurement", Bureau International des Poids et Mesures, <https://www.bipm.org/en/committees/jc/jcgm/publications>.
- [16] "Pipeline Briefing Paper 2 – Pipeline Basics and Specifics About Natural Gas Pipelines", Pipeline Safety Trust, Bellingham/WA, United States, 2024, hosted in <https://pstrust.org/wp-content/uploads/2015/09/2015-PST-Briefing-Paper-02-NatGasBasics.pdf>, accessed on 1st May 2025.
- [17] "Smart pigs essential to the detection of pipeline problems", IEC International Electrotechnical Commission, <https://www.iec.ch/blog/smart-pigs-essential-detection-pipeline-problems#:~:text=Pipeline%20pigging&text=It%20uses%20devices%20known%20as,batteries%20which%20are%20also%20sealed.>, accessed 1st May 2025.
- [18] "Gas Pipeline", U.S. Department of Transportation – Pipeline and Hazardous Materials, ScienceDirect, In subject area: Materials Science, hosted in <https://www.sciencedirect.com/topics/materials-science/gas-pipeline>, accessed on 1st May 2025.
- [19] K. Topolski, E.P. Reznicek, B.C. Erdener, C.W. San Marchi, J.A. Ronevich, L. Fring, K. Simmons, O.J.G. Fernandez, B. Hodge, M. Chung, "Hydrogen Blending into Natural Gas Pipeline Infrastructure: Review of the State of Technology", Technical Report NREL/TP-5400-81704, NREL National Renewable Energy Laboratory, October 2022.
- [20] A. Islam, T. Alam, N. Sheibley, K. Edmonson, D. Burns, M. Hernandez, "Hydrogen blending in natural gas pipelines: A comprehensive review of material compatibility and safety considerations", IJHE 93 (2024) 1429 – 1461.
- [21] D. Mahajan, K. Tan, T. Venkatesh, P. Kileti, C.R. Clayton, "Hydrogen Blending in Gas Pipeline Networks - A Review", Energies MDPI 2022, 15, 3582.
- [22] G. Jia, M. Lei, M. Li, W. Xu, R. Li, Y. Lu, M. Cai, "Hydrogen embrittlement in hydrogen-blended natural gas transportation systems: A review", IJHE 48 (2023) 32137-32157.
- [23] M.A. Kappes, T. Perez, "Hydrogen blending in existing natural gas transmission pipelines: a review of hydrogen embrittlement, governing codes, and life prediction methods", Corrosion Reviews 2023; 41(3): 319–347.
- [24] ISO 14111:1997 "Natural gas – Guidelines to traceability in analysis".
- [25] ISO 14532:2014 "Natural gas – Vocabulary".
- [26] API 1104 "Welding and Related Tests".
- [27] API 5L "Specifications for Line Pipe".
- [28] API RP 1175 "Pipeline Leak Detection – Program Management".
- [29] API RP 1173 "Pipeline Safety Management Systems (SMS)".
- [30] API 1102 "Pipeline Crossings".
- [31] API 20E "Pipeline Bolts".
- [32] API RP 1160 "Pipeline Mechanics".
- [33] ASTM G148-97 (Reapproved 2018) "Standard Practice for Evaluation of Hydrogen Uptake, Permeation, and Transport in Metals by an Electrochemical Technique".
- [34] ASTM F2078:22 "Standard Terminology Relating to Hydrogen Embrittlement Testing".
- [35] ASTM F1624:12(2024) "Standard Test Method for Measurement of Hydrogen Embrittlement Threshold in Steel by the Incremental Step Loading Technique".
- [36] ASTM B849:02(2023) "Standard Specification for Pre-Treatments of Iron or Steel for Reducing Risk of Hydrogen Embrittlement".
- [37] ASTM B850:98(2022) "Standard Guide for Post-Coating Treatments of Steel for Reducing the Risk of Hydrogen Embrittlement".
- [38] ASME B31.3 - 2024 "Process Piping" (for all fluids like natural gas).
- [39] ASME B31.12 - 2023 "Hydrogen Piping and Pipelines" (for hydrogen, published in 2024).
- [40] Project "Research and Development (R&D) Roadmap for Hydrogen Transport via Gas Pipelines" held on 18/03/2025, in Rio de Janeiro City downtown, organized by ATGAS - Association of Natural Gas Transport Companies by Pipeline and CTDUT - Pipelines' Technology Center.