STANDARDS RESEARCH

Coatings and Liners for Hydrogen Service Pipelines

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Executive Summary

Transporting hydrogen by pipeline may be considered an efficient, economical and safe method to support Canada's goal of net-zero greenhouse gas (GHG) emissions by 2050.

Canada possesses an extensive pipeline network that can be considered for potential repurpose for hydrogen service, in conjunction with blending hydrogen into the natural gas grid. Coatings and liners used in pipeline infrastructure are essential for preserving asset integrity and ensuring the protection of personals, assets, local communities and the environment. It is important to align regulations, codes and standards (RCS) with new coating and liner technologies to support the safe, efficient and effective operation of hydrogen pipelines.

The purpose of this report is to review potential coating and liner technologies, and identify the need for standards-based solutions to support their use on hydrogen and hydrogen/natural gas pipeline systems. This report provides a comprehensive review of potential coating and liner technologies for hydrogen pipeline and equipment, as well as the relevant standards, codes, best practices and regulations.

In addition to protecting pipeline infrastructure from corrosion and mechanical damage, coatings and liners could potentially help mitigate the technical challenges posed by gaseous hydrogen and new technologies used in hydrogen service pipelines. These challenges include gaseous hydrogen embrittlement (HE), low energy transportation efficiency, repurposing existing natural gas pipelines for hydrogen service, blending hydrogen into natural gas pipelines, and the side effects of HE inhibitors.

Some existing and emerging technologies for hydrogen pipeline coatings and liners include polymer, metal, ceramic and composite systems, which may be able to address the challenges mentioned above.

- **Polymer:** Polyethylene (PE) and epoxy resin are the most widely used coating and liner systems in natural gas pipelines, and can withstand typical operating conditions of a hydrogen pipeline. Commercial flow efficiency epoxy coatings are most likely applicable to hydrogen pipelines. Polyvinyl alcohol (PVA) and polyvinylidene chloride (PVDC) show good hydrogen barrier performance, but ease of application and chemical resistance need to be improved.
- **Metal:** Nickel, zinc, copper, aluminum and stainless steel may be expected to perform effectively as a hydrogen barrier coating due to low permeability and maturity of application methods.
- **Ceramic:** Oxides and nitrides may show efficient hydrogen barrier performance, but their use in hydrogen pipelines is restricted by their brittle nature and challenges in scaling-up. Black oxide and vitreous coatings can be applied to large pipeline structures.
- **Composite:** Fiber reinforced polymers (FRP) and spiral interlocking pipes have been used for hydrogen service pipelines. Their performance attributes for hydrogen permeation, mechanical strength, flow efficiency and corrosion resistance depend on the material selected for individual layers and their fabrication methods.

For external coatings on hydrogen pipelines, their function is similar to those applied on natural gas pipelines. Existing technologies, best practices, standards and regulations for external coatings can be applied to hydrogen pipelines with revision in order to comply with the more stringent safety requirements expected to emerge in the coming years, as outlined in the international hydrogen pipeline standards.

Internal coatings or liners used in hydrogen pipelines must maintain their material properties and structural integrity – either completely unchanged or within permissible limits. A product qualification protocol can reference existing standards for internal coatings and liners in natural gas pipelines, with modifications to test conditions and acceptance criteria to align with hydrogen pipeline requirements.

Commercially available internal coatings and liners made of epoxy, PE, and FRP are expected to meet the minimum requirements for hydrogen service. The best practices for these coatings and liners as per natural gas pipelines may also be applicable to hydrogen pipelines, as long as they continue to fulfill their intended purposes, such as friction reduction, corrosion protection and erosion resistance.

While the effectiveness of coatings and liners in addressing the challenges of hydrogen pipelines has not been experimentally proven, their potential to mitigate HE and improve flow efficiency is recognized. To promote the advancement of hydrogen service pipelines and coating and liner technologies, there are opportunities to streamline the process through standardization. The following recommendations are prioritized to facilitate safety, quality, economy, innovation and sustainability.

- Establish stand-alone standards for pipeline internal coatings, following the style of external coating standards like CSA Z245.20 series and CSA Z245.30.
- Standardize material qualification protocols for hydrogen service pipelines as a precondition of standardizing hydrogen infrastructure components, such as coatings and liners.
- Standardize qualification protocols for internal coatings and liners as HE mitigation measures when the best practice of testing hydrogen barrier performance is established by industry or academia.
- Standardize the best practice of adopting internal coatings and liners in pipeline rehabilitation derived from technical specifications provided by various manufacturers and contractors.
- Standardize the best practice and qualification protocols of emerging coatings and liners for hydrogen pipeline service.

> **"Canada is anticipated to be a major global hydrogen exporter, with hydrogen production expected to increase five- to nine-fold between 2030 and 2050."**

1 Introduction

Hydrogen has been increasingly recognized as a crucial element in achieving net-zero greenhouse gas (GHG) emissions by 2050. Canada is anticipated to be a major global hydrogen exporter, with hydrogen production expected to increase five- to nine-fold between 2030 and 2050 [1], [2].

Hydrogen can be stored and transported in gaseous and liquid forms, as well as bound to liquid organic hydrogen carriers [3]. Tube trailers or truck tanks carrying compressed gaseous hydrogen or liquefied hydrogen are primarily used for regional distribution due to their flexibility, mature technology and low total investment cost. As transportation distances increase, pipelines carrying gaseous hydrogen offer exceptional advantages in terms of cost per mile, efficiency, capacity and safety [4]. Current hydrogen producers in Canada rely on various production methods and feedstocks. Large distances between producers and domestic and international markets necessitate efficient, economical and safe transportation methods.

Pipeline is identified as one of the candidate transportation methods, with high technical readiness and massive existing infrastructure that can be repurposed for hydrogen service, whether for pure or blended gaseous hydrogen [4]. Canada possesses an extensive pipeline network of 840,000 km, with the majority of pipelines located in Alberta [5]. While Alberta currently has over 100 km of pipelines that transport pure hydrogen to industrial users, there are no large, high-pressure pipelines in Canada that deliver pure hydrogen to major demand centers [6]. The country's pipeline infrastructure is primarily designed to transport crude oil, natural gas, refined crude oil products and natural gas liquids to refineries, processing plants and major demand centers in Canada and the United States. In addition to constructing dedicated hydrogen infrastructure, repurposing existing pipelines may be considered a feasible approach to addressing the hydrogen transportation capacity shortage in a timely manner. The cost for this repurposing is estimated at 10–35% of new construction costs [7].

To reduce the impact on end-user appliances and transportation infrastructure, blending hydrogen with natural gas is generally viewed as an early step toward achieving net-zero GHG emission goals. Several hydrogen blending pilot projects are underway worldwide, helping to build experience in engineering, operation and regulation of infrastructure [8]. Northern Gas Networks ran the Winlaton blending project in the U.K. from 2021 to 2022 [9]. It supplied 668 houses and other community buildings with a 20% hydrogen (v/v) blend. Earlier, Keele University tested a 20% hydrogen (v/v) blend in a private university network, fueling 100 homes and 30 university buildings [8]. ATCO began delivering a blend of natural gas containing 5% hydrogen (v/v) into a subsection of the Fort Saskatchewan natural gas distribution system in October 2022, supporting 2,100 customers for residential and business needs [10]. Enbridge Gas, in partnership with Cummins, made the first North America hydrogen-blending pilot with 2% blending ratio to serve 3,600 customers of Markham community in January 2022 [11].

In order to achieve the ambitious target of net-zero emissions by 2050, many projects with 100% hydrogen have been introduced. APA group repurposed a 43-km section of the Parmelia Gas Pipeline to pure hydrogen service in Australia and the two-phase feasibility study was completed in 2023 [12]. The pilot study determined that the 50-year-old, electric-resistance-welded (ERW), API 5L grade X52 line pipe of DN350 nominal size can deliver satisfactory performance. It provides a safe operating envelope at 5.6 MPa maximum allowable working pressure (MAOP), with pressure cycles limited to 20% MAOP (daily) and a 10-year maximum in-line reinspection interval [13]. PipeChina tested on multi-segment pipes pressurized at 6.3 MPa for 30 days in 2023 and confirmed the compatibility with pure hydrogen, providing barrier performance and sealing of the various connection points [14].

Although 100% hydrogen service pipelines have existed for decades, they are mainly for the needs of petrochemistry plants operated at low pressures and are not internally coated [15]-[17]. However, coatings and liners have proven to be effective in safeguarding natural gas pipeline infrastructure and are expected to continue to play a crucial role in the evolving energy landscape. Their use in pipeline infrastructure is an essential element in preserving asset integrity and protection of personals, assets, local communities and the environment [15].

Over the years, a multitude of codes, standards, and regulations have been established to provide guidance for coating and liner applications. As new coating and liner technologies are developed to support the safe, efficient and practical operation of hydrogen pipelines, it is important to align these innovations with existing regulations, codes and standards (RCS) framework. Additionally, emerging products and guidelines based on early deployments and trials should be documented and integrated into the overall RCS framework upon commercialization.

The purpose of this report is to review the current landscape for using coatings and liners on equipment and pipeline systems for gaseous hydrogen and hydrogen-blend service. This includes conducting a needs assessment to identify issues, gaps and discrepancies related to relevant codes and standards. The report provides insight into priority coating and liner types, qualification protocols, the current landscape of RCS, and recommendations related to standardization.

2 Methods

The research methods mainly consist of a literature review of information available in the public domain. This includes current related RCSs, academic and industry publications, textbooks, news articles, corporate disclosures and regulatory filings, company websites and market reports. Literature sources were identified from Canadian federal and provincial open government portals, Alberta Innovates' internal library service, and standard databases of various organizations such as CSA, American Society of Mechanical Engineers (ASME), ASTM International, The Association for Materials Protection and Performance (AMPP), International Organization for Standardization (ISO), American Petroleum Institute (API), SAE International and Plastics Pipe Institute (PPI). The keywords used in document scanning were hydrogen pipeline, hydrogen permeation, flow efficiency, hydrogen blending, hydrogen embrittlement, coating, liner, mitigation measures, etc.

The gaps identified from the literature review were prioritized based on urgency and significance. Potential approaches to address the standards gaps considered the feasibility of solutions, for example, technology readiness and alignment with international RCSs.

Seven industry and regulator representatives were approached to supplement the literature review and gap analysis, based on their shared experiences in the following topics:

- Operation conditions of pipelines transporting hydrogen, natural gas, and natural gas blended with hydrogen
- Specification of coatings and liners used on natural gas pipelines, and hydrogen and hydrogenblending pilot projects
- Coatings and liners used for hydrogen embrittlement mitigation and improving flow efficiency
- Canadian and international standards applicable to hydrogen pipelines, as well as coatings and liners for hydrogen applications
- Suggestions on standardizing the qualification procedure of coatings and liners for hydrogen pipelines

3 Results and Discussion

3.1 Hydrogen Pipeline Technical Challenges

There have been hydrogen pipelines operating worldwide for many decades, and their safety records are widely regarded as good [15]. These pipelines are typically used for transporting hydrogen or synthesis gas to petrochemical plants over short distances, and they operate at low pressures ranging from 60 to 350 psi [15]–[17]. However, this experience does not necessarily extrapolate to longdistance transmission pipelines designed to carry hydrogen, including blends up to 100% at pressures up to 100 bar (1450 psi) for the energy market [18]. The safety margins, design requirements, operational conditions and relevant RCSs for these high-pressure, long-distance pipelines differ significantly from those of the shorter, lower-pressure pipelines [15]. This report's discussion primarily pertains to high-pressure, long-distance pipelines intended for the transportation of natural gas blended with hydrogen up to 100% for use in the energy market [15].

The pipeline infrastructure for hydrogen service faces unique technical challenges, which need to be addressed for safe and reliable operation. These include hydrogen embrittlement (HE) and hydrogen's lower energy transporting capacity than natural gas. Transitional technologies, such as repurposing existing pipelines and blending natural gas with hydrogen, make service conditions even more complex and further increase the technical difficulties mentioned above.

Operating pipelines with low transportation pressure or low hydrogen blending ratios can reduce these detrimental impacts on pipeline materials and avoid equipment upgrade costs [19], [20]. However, the decrease in energy transporting capacity resulting from lower pressure and blending ratios is only a temporary solution, and is not an ideal long-term solution for the rapidly expanding hydrogen market.

3.1.1 Gaseous Hydrogen Embrittlement (HE) in Steel

Hydrogen molecules at the surface of steel materials undergo dissociative adsorption creating atomic hydrogen at the steel surface that can dissolve in and diffuse through the interstitial sites of the steel lattice structure [21]. The interactions between hydrogen atoms and existing metallurgical imperfections – such as dislocations, voids, inclusions, precipitations and boundaries – can reduce the ductility and fracture toughness of metallic materials, leading to various types of embrittlement, environment-assisted cracking and fatigue failure [22]. Hydrogen embrittlement (HE) is identified as a primary cause of failure in steel materials exposed to hydrogen-containing environments [23], jeopardizing the integrity of pipeline infrastructures and posing risks to energy, environmental and community safety. The susceptibility of pipelines to HE increases with the steel grade (e.g., as tensile strength increases) and hydrogen partial pressure, (i.e., pressure exerted by hydrogen in a blend mixture). Research has shown that the presence of residual stress, and metallurgical and surface defects caused during pipeline manufacturing, welding and handling can increase the susceptibility of material to HE [24].

The HE mechanism consists of six steps:

1. Generation of hydrogen (H) atom
2. Adsorption of H atom on the steel surface
3. Absorption of H atom in the steel subsurface
4. Diffusion of H atom through the steel lattice
5. Trapping of H atom at metallurgical imperfections
6. Degradation of mechanical properties

Gaseous HE differs from the widely studied aqueous HE, particularly in the first three steps listed above. For example, in the first step, H_2S in aqueous solution can ionize to release H+ and sulfide ions, while steel is corroded to release ferreous ions and electrons, ultimately forming H atom and iron sulfide as corrosion byproducts [24]. The formed H atoms in the second step adhere to the metal surface (H_{ad}) and, as shown in Equation 1, in the third step either combine to form H_2 (gas evolution) or get absorbed into the metal matrix (H_{abs}). Since sulfide is a hydrogen recombination poison, the amount of H_{ad} that recombines to form H_2 on the surface is greatly reduced, thereby increasing the amount of H_{abs} in the metal matrix. [24]

Equation 1:

$$2H^+ \text{(aqueous)} + 2e^- \rightarrow 2H_{ad} \rightarrow H_2 \text{ (gas evolution)}$$
$$\searrow 2H_{abs}$$

In the case of hydrogen transported by pipeline, H atoms are generated by a dissociative desorption mechanism [21]. In the first step, hydrogen molecules (H_2) adhere to the steel surface (H_{2ad}) and then split into H atoms (H_{ad}) when meeting thermodynamic conditions. In the third step, Had either recombine to form H_2 or get absorbed into the metal matrix (H_{abs}). The three steps at the interface between the gaseous environment and steel substrate are:

Equation 2:

$$H_2 \text{ (gaseous)} \rightarrow H_{2ad} \rightarrow 2H_{ad} \rightarrow 2H_{abs}$$

Understanding the different mechanisms of aqueous and gaseous HE is essential for developing and selecting effective mitigation measures for hydrogen pipelines, since the existing best practices of addressing aqueous HE might be suitable for mitigating gaseous HE. Theoretically, a mechanism that impedes one or more steps in Equation 2 can mitigate gaseous HE.

3.1.2 Hydrogen Energy Transporting Capacity through Pipelines

Another technical challenge in pipeline transportation is the lower energy transporting capacity of gaseous hydrogen [20]. Hydrogen has approximately three times lower calorific value than natural gas, 3.5 kWh/Nm^3 versus 11 kWh/Nm^3, respectively. However, hydrogen can be transported three times faster than natural gas, depending on the operating conditions. Consequently, the energy transporting capacity of pure hydrogen is 80–90% of natural gas [7]. However, three times more compressor power is required for hydrogen transport compared to natural gas in order to achieve a similar energy flow, due to the difficulty in compressing hydrogen gas [26]. In practice, the high flow rate makes hydrogen more sensitive to the roughness of pipeline inner surface, which leads to more turbulence and energy loss than transporting natural gas. The low energy transporting capacity and compression efficiency require investments in equipment upgrading and compressors for transporting hydrogen [20].

3.1.3 Repurposing Natural Gas Pipelines for Hydrogen Service

Despite lower costs, repurposing existing natural gas pipelines for pure hydrogen or hydrogen blends, as opposed to constructing new pipelines, presents additional technical challenges. Pre-existing defects, such as corrosion, cracks and dents, can lead to hydrogen trapping and enhance the HE sensitivity of pipeline steel [27]. Pipelines built decades ago were made of steel fabricated using legacy metallurgical procedures, which typically contain more impurities and are more prone to HE than modern steels. Some research suggests that legacy pipelines exhibit increased brittleness due to aging in underground environments for decades [28]. The change in mechanical properties of steel increases pipeline integrity risk in terms of HE. Moreover, rough surfaces caused by pre-existing defects can increase flow friction and turbulence, leading to energy losses and impeded flow. Legacy pipelines are more susceptible to HE and low efficiency issues than new pipelines, requiring rehabilitation approaches during repurposing projects.

3.1.4 Hydrogen Injection for Gas Blending

Injecting hydrogen into natural gas flow to obtain hydrogen/natural gas blends can cause sudden transitions in the properties of gas flow, impacting the operation of pipelines. A numerical approach demonstrates that the hydrogen injected into natural gas networks at steady state leads to pressure drop at the injection port and potential stress concentration at the vicinity, as well as poor mixing [29], [30]. Due to the lower molecular mass and buoyancy force, hydrogen concentrations, and therefore HE risks, are higher near the upper pipe wall [30].

The conventional pipeline static mixer can improve the homogeneity of blending gases by inducing turbulence. However, the higher flow velocity of gaseous hydrogen already increases the likelihood of turbulent flow, which intensifies the risk of acoustic-induced vibration. As such, installation of a static mixer may increase the risk of fatigue failure on pipelines [31].

3.1.5 Inhibitors for Mitigating Gaseous Hydrogen Embrittlement

Laboratory evidence supports the use of low oxygen (O_2) and carbon dioxide (CO_2) concentrations to mitigate gaseous HE of pipelines carrying hydrogen gas [32]. Studies [33] have shown that absorption of atomic oxygen on iron surfaces is much more favorable than atomic hydrogen, thereby reducing atomic hydrogen ingress into iron by suppressing the reaction described in Equation 2. However, it is worth noting that the presence of moisture in the gas flow renders the inhibitors corrosive to the pipeline steel. This poses a threat to pipeline integrity and increases flow resistance due to corrosion on the inner surface of pipeline.

3.2 Internal and External Coatings and Liners for Hydrogen Transportation

3.2.1 Significance of Coatings and Liners for Pipelines

According to CSA Z662 [34], an internal liner is defined as a tubular product that is inserted into buried piping to form a corrosion-resistant barrier or separate free-standing, pressure-retaining piping. Coatings, on the other hand, are applied to the internal or external surface of piping, forming a continuous film. They protect assets from corrosion, abrasion and mechanical damage, facilitating operational efficiency during handling and servicing. Coatings need to bond to the substrate to provide proper protection, while an annulus space may exist between an internal liner and piping. The differences in installation methods and product forms between liners and coatings can affect their protective mechanisms and scenarios of application.

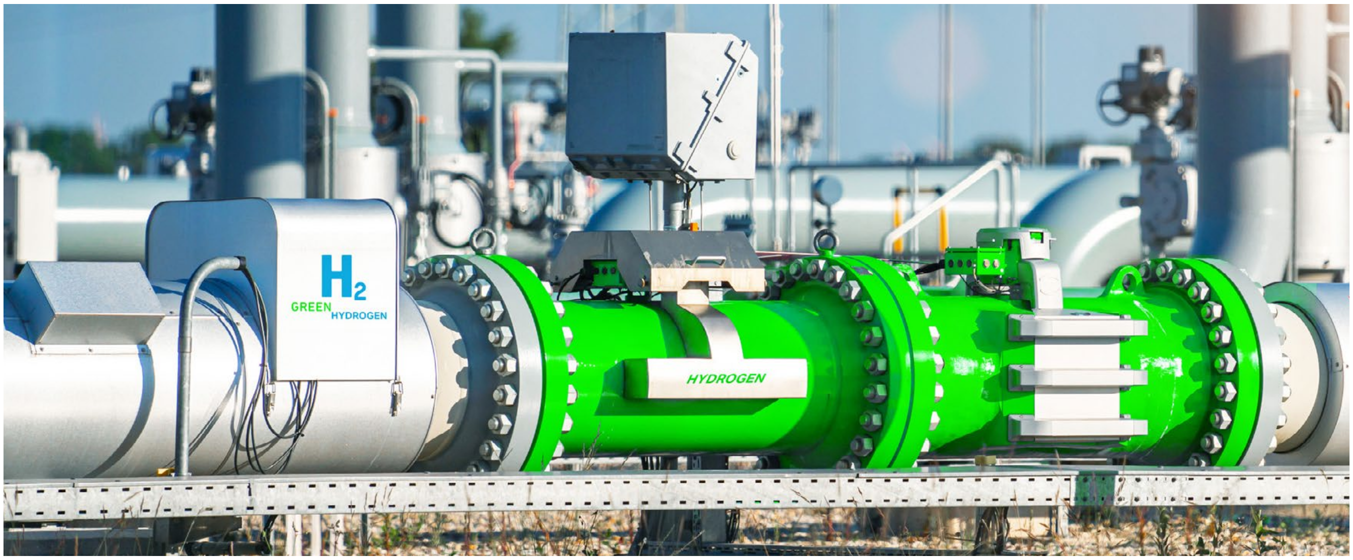
Liner products generally have a larger thickness than coating products, and may be more likely to be used in harsher environments due to better barrier performance and a more robust structure. Pull-in-place lining is the industry standard method for installing liner products in pipelines. Their ease of use makes liners an essential tool in pipeline rehabilitation – to arrest structural degradation or repair damage of a pipeline component in order to extend its service life [35]. Use of liners for pipeline rehabilitation has a significantly lower cost and service downtime in comparison to the pipeline replacement.

Meanwhile, coatings are more versatile in terms of function, and broader compatibility with pipeline components of various diameters and complex structures.

Liners and internal and external coatings have been used to maintain integrity of natural gas pipelines for decades [36].

Liners and internal coatings provide:

- Corrosion protection of pipelines during transport, storage, installation, hydrostatic testing, commissioning and operation
- Easier and faster commissioning of the pipeline due to faster drying compared to uncoated pipes after hydrostatic testing
- Simplification of the inline inspection procedure by improving mobility of the testing equipment travelling down an internally coated pipe
- Resistance to gas impurities and moisture, and inhibition of black powder formation within the gas pipeline, which can lead to erosion failures and damage of pipeline equipment



External coatings:

- Protect pipelines from corrosion and mechanical damage during transport, storage, installation, commissioning and operation
- Improve cathodic protection effectiveness while reducing impressed current
- Serve as a thermal insulator
- Assist in push and pull installation of pipeline by reducing slide friction

Hydrogen gas pipelines can benefit from the above merits of coatings and liners, and coatings and liners may also be expected to be practical measures to protect pipelines from gaseous HE, while improving flow efficiency at higher transport pressures and hydrogen blending ratios. The economic benefits of internal flow efficiency coatings are more substantial at higher gas flow rates [31], as hydrogen flows faster at the same pressure than natural gas.

High-grade pipeline steel can be used to construct efficient pipeline systems with higher operating pressures and larger diameters using less material. However, high-grade steel is more sensitive to HE than mild steel [37]. Internal coatings and liners can enable safer use of high-grade steel in hydrogen pipelines.

Rehabilitation is usually required before repurposing existing pipelines for hydrogen service, and applying internal coatings, liners or both can provide their functional restoration [38]. To address the key challenges of transporting hydrogen in pipelines, the internal coatings and liners should have low hydrogen permeability and a smooth surface. Additional important coating and liner properties include [39]:

- Retention of designed properties and structural integrity during handling, storage, installation, operation, and inspection
- Compatibility with other pipeline protection technologies such as cathodic protection (CP) and pipeline inspection gauge (PIG)
- Ease of application and repair
- Resistance to environmental conditions and geohazards, e.g., earthquake, landslides and floods
- Nontoxicity to environment and end user

3.2.2 Polymers

Polymers are the most widely used coating and liner material in the pipeline industry, owing to advantages such as ease of processing, cost-effectiveness, corrosion resistance and mechanical characteristics. The nature of some polymers and processing methods allows for an extremely smooth coating surface finish, facilitating the flow of contained gaseous hydrogen. Various polymer types have been tested for gaseous hydrogen permeation [37], [40]–[44], as summarized in Table 1.

Table 1: H_2 Permeability of various polymers at room temperature

Plastic	H_2 Permeability mol/(m•s•Pa)
Low-density polyethylene (LDPE)	$1.33 – 2.84 \times 10^{-15}$
High-density polyethylene (HDPE)	$4.93 – 9.25 \times 10^{-16}$
Epoxy	$1.71 – 4.05 \times 10^{-16}$
Polypropylene (PP)	1.38×10^{-14}
Poly methyl methacrylate (PMMA)	1.24×10^{-15}
Poly vinyl alcohol (PVA)	5.02×10^{-18}
PVA+ glutaraldehyde (PVA+GA)	2.81×10^{-18}
Poly vinyl chloride (PVC)	8.17×10^{-16}
Poly vinylidene chloride (PVDC)	1.60×10^{-17}
Poly vinyl fluoride (PVF)	1.8×10^{-16}
Polystyrene (PS)	7.58×10^{-15}
Polytetrafluoroethylene (PTFE)	3.20×10^{-15}
Fluorinated Polyimides	$1.60 – 36.2 \times 10^{-15}$

Elastomer	H_2 Permeability mol/(m•s•Pa)
Poly butadiene (BR)	1.41×10^{-14}
Polyurethane (PU)	$6.63 – 60.6 \times 10^{-16}$
Chloro-isobutene-isoprene rubber (CIIR)	8.57×10^{-16}
Chloroprene rubber (CR)	$2.23 – 4.55 \times 10^{-15}$
Isobutene-isoprene rubber (IR)	2.42×10^{-15}
Natural rubber (NR)	4.09×10^{-15}
Acrylonitrile-butadiene rubber (NBR)	$1.45 - 8.43 \times 10^{-15}$
Acrylonitrile-isoprene rubber (NIR)	2.49×10^{-15}
Styrene-butadiene rubber (SBR)	2.98×10^{-15}
Chloro-sulfonyl-polyethylene (CSM)	$1.31 – 3.68 \times 10^{-15}$
Terpolymer of ethylene, propylene, and a diene (EPDM)	6.96×10^{-15}
Fluoro rubber (FKM), Viton A, Viton GF	$3.50 – 7.32 \times 10^{-15}$
Silicone rubber (vinyl and methyl substituents) (VMQ)	1×10^{-13}

Although no polymeric coating is entirely impermeable to hydrogen molecules, many polymer properties or characteristics impact gaseous permeability in a polymer. The permeability of polymers to other various gases has been widely studied [45]–[47], and existing guidance for the selection of material and development of products may also be expected to be applicable to hydrogen gas, as outlined below.

- **Polymer type and crystallinity**: Permeability of gases through polymers generally increases from elastomers over amorphous polymers to semi-crystalline polymers, due to crystallinity and changes in free volume.
- **Density**: Higher density polymers have lower permeability as they have less free volume between the molecules of the polymer structure. The crystallinity and density of a polymer are strongly related – higher crystallinity results in higher density and lower permeability.
- **Molecular branching:** Complex and bulky side-chain species of polymers can hinder chain movement and decrease permeability of gases, as compared to a completely linear polymer.
- **Molecular mass** of polymers has little effect on permeability, except at a very low range of molecular masses.
- **Orientation or alignment of polymer molecules**: An extruded polymer that exhibits chain alignment in the direction of extrusion may have lower permeability than the same polymer that was solution-cast.
- **Crosslinking** decreases the permeability of polymers, especially for higher degrees of crosslinking (above the entanglement molecular weight) and for permeants that are larger than the distance between crosslinks.
- **Glass transition temperature (Tg)**: Permeation rates of gases above polymer Tg are much higher than below the polymer Tg, due to increased free volume and chain movement at higher temperatures.
- **Plasticizer additives** increase polymer permeability by reducing polymer density and Tg.
- **Humidity or water vapor in a gaseous stream** increases the permeability of some hydrophilic polymers.
- **Solution cast films** have variable permeabilities depending upon the kind of solvent used and the drying technique. Poor solvents tend to yield films of higher permeability due to contracting polymer chains and greater free volume.
- **Fillers**: Inorganic fillers, such as silica or clay, provide a physical barrier to diffusion and decrease permeability. The effect depends on the type, shape and amount of filler, and its interaction with the polymer.
- **Structure-property relationships**: Polar groups in the polymer molecule are expected to impede the diffusion and solubility of non-polar hydrogen molecules due to a like-dissolves-like principle.

3.2.2.1 Polyethylene (PE)

Polyethylene (PE) is a widely used thermoplastic material in the pipeline industry due to its high chemical resistance, wear resistance and favorable mechanical properties. Its weak adhesion to smooth metal surfaces often leads to its use as the top layer of a composite multilayer coating [48]. Four types of polyethylene coatings are available for external use – PE tapes, dual-layer PE, three-layer PE and multicomponent PE coatings. PE can also be engineered into liners and inserted into pipelines for internal protection.

PE generally exhibits good resistance to acids, alkalis and most solvents, with its properties varying depending on its density and additives. Additives and fillers can enhance certain properties, such as resistance to ultraviolet (UV) light degradation and permeation. The various types of PEs are primarily differentiated by resin densities and molecular weights, ranging from low-density PE (LDPE) to ultra-high molecular weight PE (UHMWPE). As density increases, the barrier performance against foreign species, including hydrogen molecules, improves due to a more compact microstructure [42]. PE sheaths and liners are manufactured using an extrusion process, with polymer chain alignment in the extrusion direction providing enhanced hydrogen barrier performance [41].

> “Epoxy is a widely used polymer-based coating, characterized by a high degree of cross-linking, excellent adhesion to steel substrates, and broad chemical resistance.”

To date, gas permeation tests have primarily focused on virgin PE materials, rather than the extensive range of PE coating and liner products. Various coating application methods, such as heat shrink sheathing, manual tape wrapping and powder coating could affect the coating and liner microstructures, and subsequently performance such as hydrogen barrier [41]. Field repairs and joining of liner products are inevitable during the actual installation process. Methods like patch and butt-fusion joining should exhibit different hydrogen permeabilities compared to the base material, due to change in microstructure. The adhesion of PE can be improved by applying mechanical and wet chemical treatments or gas-phase processes to the material before or during manufacturing. This typically increases the coating's polarity and enhances molecular interaction with steel [48]. However, the effect on hydrogenbarrier performance of the PE product form (i.e., coating or liner), application, repair, joining and changes in polarity has not been extensively explored in the literature.

3.2.2.2 Epoxy Resins

Epoxy is another widely used polymer-based coating, characterized by a high degree of cross-linking, excellent adhesion to steel substrates, and broad chemical resistance. Additionally, epoxy resins are permeable to cathodic protection currents, therefore allowing the currents to reach pipeline steel substrate for better corrosion protection [39]. Epoxy coatings can be categorized into two-part and fusion-bonded epoxies.

- Two-part epoxies are applied by mixing resin and curing agent, and applying the thoroughly mixed product to a prepared surface. They are easy to process and apply, whether in a plant or in the field, and typically cure in ambient environments without post-treatment. Automatic spray methods offer the fastest application with higher control over coating thickness and uniformity, while hand application is best for repairs.
- Fusion-bonded epoxies are powdered thermosetting materials bonded to a steel surface through a heat-generated chemical reaction. In plant environments, these are applied to preheated pipes using fluid beds, air sprays or electrostatic spray methods [49].

Many commercial epoxy products [50]–[52], have been used as internal coatings for gas pipelines to increase flow efficiency. These are advertised as having increased chemical resistance to natural gas, H_2S, and CO_2 mixtures, indicating potential suitability for pipelines transporting hydrogen gas with corrosive impurities.

Like PEs, additives can be incorporated into epoxy resins to enhance specific properties. Studies on underground storage have shown that some additives, such as fly ash, can further reduce hydrogen permeability through the coating [53]. Due to the vast number of commercially available products and their composition variations in epoxy base materials, hardening agents and final structures, the hydrogen permeability and diffusion properties of each epoxy must be investigated and tested separately. For instance, studies have tested butanediol-based and bisphenol-diglycidyl-ether epoxy with different amines as hardening agents. Although gases other than hydrogen were used to test permeability, the epoxy cured with aliphatic amines exhibited the highest gas barrier properties among the materials tested [40]. The excellent adhesion performance of epoxies is attributed to its hydrogen bonding to iron oxide (substrate) [54]. This type of dipole-dipole interaction may impede the generation of atomic hydrogen, hindering hydrogen permeation at the coating/steel interface as described in Equation 2. However, hydrogen behavior at the coating/steel interface has not been studied extensively.

When exposed to pure hydrogen at 100 bar, pipes with minimum yield strength of 485 MPa coated with a flow efficiency two-component epoxy coating containing 82–97% volume of solid, applied at thickness between 61 µm and 120 µm, showed no degradation, blistering or adhesion when tested under ISO 15741 conditions [55]. The test specimens suggested that the small molecular size of hydrogen did not affect the internal flow coating's resistance under spontaneous pressure fluctuations. Although this type of testing has not been widely reported, epoxy coating products may be expected to exhibit similar resistance performance, since the gaseous hydrogen is inert to epoxy at ambient temperature.

3.2.2.3 Polyvinyl Chloride (PVC)

Polyvinyl chloride (PVC) exhibits low permeability to gases and is employed in various industries for barrier and corrosion-resistant products [56], [57]. The manufacturing of PVC products typically involves solvent casting, where PVC is dissolved in tetrahydrofuran and subsequently cast onto a steel surface. While PVC products are not popular for pressurized gas pipelines as internal coatings and liners due to their brittleness at low temperatures and inconvenience of application, their performance can be modified by adding plasticizers or incorporating nanoparticles or silicas to create composite coatings [58]. This approach improves the overall properties of PVC, which may make it more suitable for various applications.

3.2.2.4 Polyvinyl Alcohol (PVA)

Polyvinyl alcohol (PVA) is distinguished from other polymers due to its low hydrogen permeability. However, it has not been used as a coating in the pipeline industry because of its high water uptake and even solubility in water. The formation of hydrogen bonds within the polymer structure creates folded and compacted regions that are impermeable to hydrogen, making PVA a potential option for preventing HE. PVA coatings are fabricated using solution casting with water as a solvent. PVA solutions can either be dissolved directly in water or mixed with another solution, such as glutaraldehyde. After casting the solutions onto the steel surface, they can be left to dry under ambient conditions.

To address PVA's negative aspects such as water uptake, researchers have studied cross-linking PVAbased composites to enhance the overall performance of the material [59]. Cross-linking PVA, with or without additional reagents, lowers gas permeability due to a denser molecular polymer structure. When added, glutaraldehyde serves as an effective reagent in promoting cross-linking, resulting in a less swollen coating overall. PVA exhibited higher barrier properties compared to various commercially available epoxies and PVC, primarily due to its internal cross-linking. Moreover, modelling has demonstrated that cross-linked PVA coatings with a thickness of 2 mm can prolong hydrogen diffusion time within the coating to up to seven years, and possibly longer if the polymer internal structure is optimized [40].

3.2.2.5 Polyvinylidene chloride (PVDC)

Polyvinylidene chloride (PVDC), primarily used in the packaging industry, is known for its low permeability to gases and water vapor. Although it shares similarities with thermoplastic materials such as PE and PVC, its use in the pipeline industry has been limited due to drawbacks similar to PVC. However, innovative solutions are helping increase applications of PVDC in the pipeline industry. A waterborne PVDC-acrylic co-binder has been developed and introduced as an alternative waterborne option for epoxy anticorrosive primers [60]. The co-polymerization of PVDC with acrylates combines its high barrier properties, adhesion and uniform film formation with the durability and flexibility properties of acrylates. The PVDC-acrylic coating product has demonstrated comparable oxygen and water vapor barrier performance to virgin PVDC, suggesting its potential application as a hydrogen barrier as well.

3.2.2.6 Multilayered and Other Polymers

Multilayered polymer coatings also present a potential option for hydrogen applications, with studies on such coatings demonstrating promising results. For instance, polyethyleneimine (PEI) and polyacrylic acid (PAA) were alternately layered in a thin film on a polyethylene terephthalate (PET) support, achieving a total thickness of 305 nm [61]. This coating reduced the nonpolar oxygen transmission rate by 1,700 times compared to the baseline PET in testing. Similar coating performance can be speculated for nonpolar hydrogen. Furthermore, PET combined with graphene oxide to create a 10bilayer coating decreased the hydrogen transmission rate by 78.8% compared to the baseline PET [62].

Despite these outcomes, complexities in fabrication make the application of such multilayered coatings challenging for larger pipe areas and buried piping. Field applications, in particular, favor coatings that can be applied near ambient temperature, require minimal to no heating or chemical treatment for curing, and are cost-effective without the need for expensive materials.

The characteristics of various polymer coating and liner systems reviewed in Section 3.2.2 are summarized in Table 2.

Table 2: Comparison of polymer-based coating and liner systems

Items	PE	Epoxy Resins	PVC	PVA	PVDC	Multilayered and Other Polymers
Commercial readiness in pipeline industry	Mature product lines for internal, external coatings and liners	Mature product lines for internal and external coatings	Mature product lines for external coatings, liner product is emerging	No commercial product exists	Commercial product is emerging	Most of them are at concept and prototype stages
Commercial application method	**In-plant:** Extruding, Casting, Spraying **In-field:** Wrapping	**In-plant:** Spraying **In-field:** Brushing, Spraying	**In-plant:** Casting for liner **In-field:** Wrapping for external coating, Thermal expansion for liner	N/A	Brushing, spraying	Depends on coating properties and requirements
Hydrogen Barrier Performance	Average in polymer category	Average in polymer category	Average in polymer category	Good in polymer category	Good in polymer category	Depends on coating structure and design
Flow assisting performance	Not reported	Commercial products exist	Not reported	Not reported	Not reported	Not reported
Resistance to corrosion	Good with long time industrial record	Good with long time industrial record	Good with long time industrial record	Poor due to notable water up taking	Good with short time industrial record	Depends on coating structure and design
Resistance to mechanical damage	Good	Usually inferior in bending resistance	Usually inferior in bending resistance	Not reported	Not reported	Depends on coating structure and design

3.2.3 Metals

Metals are commonly used as coating materials for protecting steel from HE. Gold, chromium, aluminum, copper, nickel and tungsten exhibit low permeability to atomic hydrogen and can significantly reduce hydrogen absorption in steel. However, not all metals are suitable for this purpose – lead and tin have been found to accelerate the electro-diffusion of hydrogen in iron [63]. Furthermore, the application of metal coatings is typically energy intensive. This, coupled with the high cost of noble metals, makes metal coatings a viable alternative only for protection under extreme service conditions.

The most widely used metal coating application methods for oil and gas equipment include plating, cladding, hot dipping and thermal spray. Plating involves either an electrochemical or chemical process for depositing a dissimilar metal on a substrate. In contrast, the other three methods overlay molten or red-hot metal onto the substrate through physical or mechanical processes. While electroplating and electroless plating typically result in a smooth surface finish, the coarse surface resulting from the thermal spray method can be detrimental to flow efficiency. To achieve the best barrier performance comparable to the bulk material, metal coatings may require high temperature annealing to remove metallurgical defects after application. This process can, however, alter the microstructure and mechanical properties of pipeline steel. Hot dipping application and weld cladding can reduce application time, but may still cause substantial thermal impact on thin substrates. An exception is the hot roll cladding of stainless-steel layers on pipes. This process is usually integrated into regular pipe manufacturing processes, wherein heat treatment is controlled to ensure the appropriate mechanical properties of the substrate. Applying a polymer sealer after application serves as an alternative option for avoiding high-temperature impact. However, the higher gas permeability of polymers would be the weak point in hydrogen barrier coatings. The reactions involved in electroplating and electroless plating can release atomic hydrogen into the steel substrate. To relieve HE, a heat treatment at 150–180°C may be recommended for retaining the pipeline steel's mechanical properties [64].

The electrochemical hydrogen charging method is widely used to test the aqueous HE sensitivity of metals. However, that method neglects the dissociation of the hydrogen molecule described in Equation 2 at the metal surface, and caution should be taken when interpreting the data. Most gaseous hydrogen permeability results for various metals are currently tested at 400-500 °C temperatures and steady-state flux, the related results are available in the reference [65]. The hydrogen permeability of metals follows an exponential relationship with temperature and activation energy, so the actual hydrogen permeability at room temperature is estimated to be several orders lower than the results reported at high temperatures, making the measurement very challenging [66]. Therefore, only one result measured at room temperature was identified throughout reviewed publications – the hydrogen permeability of AISI-1020 steel was ~ 1×10^{-14} mol/(m·s·$Pa^{0.5}$). [66].

3.2.3.1 Pure Metal

Nickel is frequently mentioned as a pipe coating for hydrogen adaptations, as it exhibits a lower diffusivity of atomic hydrogen than common steels. Its hydrogen diffusivity is 2.2×10^{-13} m^2/s at 25°C, compared to most steels at approximately 10^{-10} m^2/s. Nickel is typically deposited by electroplating onto a steel surface, upon which a nickel-coated sample is heat-treated to allow any hydrogen induced into the steel to escape, as well as chromated to improve corrosion resistance [40].

Zinc is commonly used as a galvanic protection layer for steel structures. Zinc can either be electroplated or applied via hot dip in a molten zinc bath, known as galvanization. The latter method is popular in the pipeline industry because of high thickness build-up, cost-effectiveness and minimal post-processing requirements. Zinc coating has been demonstrated to be a potential effective hydrogen barrier for steels at room temperature due to its lower hydrogen diffusion rates [67].

Aluminum can be coated on steel structures using the hot-dipping method. During the dipping process, aluminum diffuses into the steel, creating an inter-metallic layer at the interface, enhancing strong bonding between the coating and the substrate.

> **“Stainless steel cladding serves as a cost-effective alternative to solid stainless-steel pipes, offering cost savings of 20–50%.”**

Aluminum can spontaneously form a layer of aluminum oxide on the exposed surface, which provides high resistance to abrasion and corrosion. Aluminum oxide ceramic is characterized by lower hydrogen permeability than aluminum metal, further improving the performance of hydrogen barrier coating [37].

Tungsten’s properties include a high melting point, high thermal conductivity, and low sputtering yield if deposited via sputtering. Vacancies or defects in the bulk metal coating can act as trapping sites to decrease diffusivity and solubility of hydrogen, with experimental results showing an average permeation reduction factor of 50 for a 1.5 µm coating [68].

Cadmium is another electroplating metal with lower hydrogen diffusivity than common steels and ability to mitigate corrosion. Similar to nickel electroplating, the process can induce hydrogen to permeate the steel, and a post-coating heat treatment must be performed for diffusible hydrogen to escape the metal [64]. However, after testing, cadmium-coated samples experienced HE, suggesting cadmium is not an ideal candidate for hydrogen pipelines [40].

Beryllium may have hydrogen-barrier properties, but results from hydrogen testing are varied, likely due to experimental difficulties stemming from nuances in working with beryllium films. Films are made using a vacuum hot press, where various grain sizes influence bulk transport properties [65].

3.2.3.2 Alloys

Stainless steel cladding serves as a cost-effective alternative to solid stainless-steel pipes, offering cost savings of 20–50% [69]. The cladding thickness typically ranges from 1.5 to 5mm, with 3mm recommended for most applications. Clad steel pipe manufacturing, properties and testing, as well as inspection and maintenance are specified in API SPEC 5LD [70]. Protection from HE depends on formation of an interdiffusion layer at the interface between the cladding and base metal. The interdiffusion layer at the interface has been shown to enhance bonding strength and hydrogen-barrier performance [71].

Electroless plated nickel coating is a commercial product that results in a uniform nickel-phosphorus layer, which has been successfully used as an internal coating on pipelines and fittings to counter corrosion and abrasion [72]. Unlike electroplating, this process is an autocatalytic reaction that does not require passing an electric current through the bath and substrate. Electroless plating creates an even metal layer regardless of surface geometry, whereas electroplating creates an uneven current density due to substrate shape [73]. The flexibility in plating volume and thickness, ability to achieve a bright finish with minimal surface roughness, and the mature application methods make electroless plating a candidate for hydrogen pipeline coatings.

Electroplated zinc-nickel (Zn-Ni) alloy coatings have been tested for hydrogen effusion at room temperature and at 200 °C. Standard surface preparation involved heat degreasing, pickling and electrolytic degreasing. The electroplating process was varied to get different microstructures. The Zn-Ni alloy displayed less hydrogen absorption than zinc alone due to the nickel-rich interlayer [74].

Nickel-cobalt (Ni-Co) alloys have been used as corrosion- and abrasion-resistant coatings, and have shown promising experimental results for HE reduction. In one study, Ni-Co was electroplated onto steel fasteners in accordance with ASTM B994, and tested in accordance with ASTM F519 and ASTM G59 for HE and electrochemical corrosion rates, respectively. Ni-Co decreased hydrogen production on the coating surface and prevented hydrogen permeation [75], [76].

3.2.4 Ceramics

Ceramics, which can be categorized into nitrides, carbides, and oxides, may be options for hydrogen permeation barriers due to their dense microstructures and lower gas permeabilities compared to the previously described polymer and metal coatings. High-quality ceramic coatings are typically applied using chemical or physical vapor deposition under vacuum conditions. These methods produce a smooth surface that can effectively reduce flow friction. For large-scale industrial production, thermal spray is often employed. Similar to thermal sprayed metal coating, this technique can result in a higher volume of defects that can act as shortcuts for hydrogen permeation. Additionally, the brittle nature of ceramics can lead to cracking during these application processes, which can compromise the coating's effectiveness. Coating performance then depends on service conditions, although metal surface defects and localized stresses can wear out or destroy coatings [40]. Most ceramic coatings are primarily used for mitigating hydrogen embrittlement at high temperatures, the related hydrogen permeability results measured at 400 °C are available in the reference [65]. Like metals, hydrogen permeability results at ambient conditions are rarely reported but can be estimated based on extrapolation methods. Although ceramics can provide better hydrogen barrier performance than the metal materials due to several orders of magnitude lower permeability, its brittleness nature might be a prohibiting factor in pipeline application.

3.2.4.1 Oxides

Black oxide processing is a chemical-conversion coating commonly used in the manufacturing industry that produces a magnetite (FeO) layer on a component's surface. The black oxide layer forms when a component is immersed in an alkaline salt solution at temperatures of 130–150 °C. Unlike other coatings and plating processes, black oxide coating chemically reacts with the steel, integrating the oxide with the substrate. A typical black oxide layer is about 1–2 μm thick [77]. Given its ease of application, black oxide coating is a potential candidate for hydrogen pipelines.

Commercial vitreous coating can be melted using induction heating or a furnace, and applied inside pipelines for corrosion and erosion protection [78]. The application method for this coating balances coating quality and film build-up efficiency, making it a suitable candidate for scaling up and hydrogen service applications. As a result, there is significant ongoing research on development and optimization of its use in hydrogen-related industries [79].

Aluminum oxide, or alumina, has been tested for high-temperature permeation. Deposition of aluminum oxide in a film form requires high substrate temperatures and specific parameters, such as filtered arc discharge, so only metal substrates that withstand 900 °C heat treatments can be coated this way.

Chromium oxide inhibits oxidation of bulk metal stainless steel. Experimental results are inconclusive due to inconsistent parameters across the literature. However, there is potential to use a combination of chromium oxide and alumina as a hydrogen permeation barrier [65].

Silicon oxide, or silica, is typically used to prevent oxidation in optical mirror aluminum layers. For permeation testing, it has been deposited on austenitic chromium-nickel-molybdenum stainless steel (AISI 316 grade, as per SAE J1086 classification [80]). However, the result was not promising, suggesting that silicon oxide should not be used as a hydrogen barrier [65].

Aluminum oxide and chromium oxide have been identified as effective permeation barriers for fusion material systems due to their effectiveness at preventing HE in precipitation-hardening steels. However, they have been observed to be susceptible to fracturing or spalling at ambient temperatures in pipelines. Experiments showed that for austenitic chromium-nickel (18% Cr, 8% Ni) stainless steel alloys (AISI 304 as per SAE J1086 classification [80]), cracking and flaking occurred in tensile and fatigue tests, and embrittlement occurred at those coating cracks [81].

3.2.4.2 Nitrides

Dense packing and uniformity are key characteristics of nitrides as hard coatings and decoration films [65]. Nitrides exhibit good mechanical properties and remain inert in harsh environments. Nitride coatings are typically deposited using physical vapor deposition methods, such as magnetron sputtering and arc ion plating, or chemical vapor deposition [82].

Silicon nitrides are generally formed using low-pressure chemical vapor deposition and have shown low hydrogen diffusivity [83]. Fused silica and silicon nitrides can trap hydrogen in deep layers or chemically bind it, with only small amounts of hydrogen located in diffusible sites. The permeation barrier efficiency of silicon nitrides heavily depends on the amount of bound hydrogen. Thereby silicon nitride can maximize hydrogen permeation barrier performance when chemically bonded H is contained in the film. However, manufacturing dense and flowless films on large steel infrastructure is challenging.

Titanium nitrides and boron nitrides can be deposited via a magnetically enhanced plasma ion plating method, and display comparable hydrogen permeability results [84]. Altering the deposition method to magnetron sputtering can improve the material's performance as a hydrogen barrier coating. Aluminum addition in the titanium nitride coating forms an alumina barrier to oxidation of titanium, creating a more stable coating than titanium nitride. Experimentation reveals that a 40:60 Al:Ti ratio offers the best hydrogen permeation reduction factor among other ratios [85].

Tungsten, aluminum, zirconium and chromium nitride coatings created via physical vapor deposition have also been recently investigated [65]. An experiment aimed to decrease the formation of grain gaps in a chromium nitride coating to mitigate hydrogen permeation pathways. Magnetron sputtering was employed to deposit the coating, as the low deposition temperature minimally affects the phase and structure of the steel substrate. The technique is droplet-free, producing coatings with relatively few pores and holes. During deposition, ion bombardment was used to prevent gap formation, therefore improving coating adhesion, increasing coating compactness, and enhancing hydrogen permeation resistance. The hydrogen diffusion coefficient and permeability of the modified coating were 52.6 and 24.1 times lower than the unprotected substrate, respectively. The sample also demonstrated high HE resistance during tensile tests [82].However, the nitride coatings are typically applied on a bench-top scale, and their application to larger engineering structures such as pipelines has not been reported.

3.2.4.3 Carbides

Carbides would not be comparable to nitrides or oxides as hydrogen barrier coatings due to relatively high permeability values, as shown in the reference [65]. Titanium carbide has received more attention for hydrogen permeation mitigation, but chemical vapor deposition onto a molybdenum alloy and austenitic stainless steel was challenging and ineffective [65].

Non-brittle tungsten carbide ceramic coatings, produced through a high-velocity air fuel (HVAF) process, minimize heat load into the pipe surface and decarbonation of coating. They are advertised as providing high wear and abrasion protection, as well as permeation resistance to gases and liquids [86]. The success of commercial carbide coatings on petroleum processing equipment indicates the feasibility of carbide coating systems and application methods for pipelines.

3.2.5 Composites

Composite coatings refer to any combination of coating types and can be designed for a specific application. The following is a brief overview of potential composite coatings for hydrogentransporting pipelines.

Fiber reinforced polymers (FRP) are popular composite materials used in the manufacture of liners and pipes. Various types of resins, including thermosetting polyester, epoxy and phenolic resin, are used to achieve specific characteristics in pipe products. The most commonly used reinforcement is fiberglass, but carbon fiber can be used for high-pressure hydrogen tanks, due to its superior strength and light weight. It has been reported that barrier films made of ethylene vinyl alcohol (EVOH) lining on fiberreinforced thermoplastic composites, such as polyamide 6, polyamide 12, polyamide 410, polyphthalamide and polyphenylene sulfide, can achieve low hydrogen permeation rates, provided the damage-free microstructure stays intact [87].

Coating of cerium oxide deposited on glass flakes subsequently embedded in epoxy resin reduced the permeability coefficient of base polymer by 65.64% [88]. This reduction was assigned to longer tortuous permeation pathways. Additionally, corrosion resistance of the cerium oxide film, and hydrophobic properties of the filler and the oxide, can provide extra protection to the asset [88].

Self-healing aluminum-aluminum oxide multilayer barrier coatings to prevent hydrogen from diffusing to a steel substrate are being developed [89]. The metal interlayer provides physical and mechanical compatibility with the underlying metal, and the formation of extended space-charge zones at the oxide-metal interface repels hydrogen [89]. After mechanical damage, the composite's micro-cracking resistance and self-healing potential preserved the hydrogen barrier performance. The coating strength was noted to be 2.5 times higher than the highest-performing single-aluminum oxide layer [89].

Aluminum oxide-erbium oxide composite ceramics were reported to function as hydrogen-isotope permeation barriers. The coatings showed good crystallinity and surface morphologies. However, hightemperature material treatment and prolonged exposure to deuterium increased oxygen vacancies, and subsequent deuterium permeation. Other potential promising ceramics for hydrogenisotope permeation barriers include chromium oxide and yttrium oxide [90].

Graphene coatings have low permeability, high thermal stability, and are chemically inert and mechanically robust. Multi-layered graphene (MLG) was deposited *in situ* to mitigate HE of a pipe steel with a minimum yield strength of 485 MPa (API 5L X-70 grade) [91]. The diffusion coefficient and permeability were reduced significantly compared to the uncoated substrate. However, a practical and effective technique to deposit graphene coatings on pipeline steel *in situ* has yet to be developed [92].

Another emerging type of coating are 2D materials with a nanosheet physical barrier for hydrogen. They are applied on pipe steel using a spin-coating process. The experimental hydrogen permeability was found to be a third of that of the substrate, with the diffusion coefficient also decreasing. However, the colloidal suspension used for the coating application embrittled the sample surface, limiting hydrogen resistance improvements [93].

Multilayered composite liners containing polymer and continuous metallic foil layers have been shown to significantly decrease gas permeability and carbonic acid corrosion rates compared to LDPE, HDPE and other polymers tested. The coatings studied contained nylon, polyethylene and aluminum layers, with the metallic foil layer providing physical impermeability to gas diffusion [94].

A new composite pipeline technology named Mobile Automated Spiral Interlocking Pipe (MASIP) consists of an inner HDPE liner pipe, intermediate layers of high-strength steel (equivalent to X120 specification from Swedish Steel Docol 1000), and outer layers for environmental protection. MASIP was tested for burst strength, bending stress and gas permeation. The research project also developed a flow loop design for extended durability trials. The composite pipeline demonstrated to be compatible with 100% high-pressure hydrogen gas, as well as other fluids such as CO_2, water oil and natural gas [95].

3.3 Regulations and standards for internal and external coatings and liners for pipeline infrastructure

3.3.1 Regulations

Canadian regulations related to pipeline coating and liners can be classified into two main categories – service-oriented (e.g., pipeline and pressure equipment) and content-oriented (e.g., toxic substances and volatile organic compounds). Standards referenced in the regulations define precise requirements and guidelines.

3.3.1.1 Pipeline and pressure equipment regulations

Canada's natural gas pipeline network can be grouped into four main types of pipelines – gathering pipelines, feeder pipelines, transmission pipelines and distribution pipelines [96]. Transmission pipelines, which serve as major conduits across provincial or international boundaries, are typically regulated by the Canadian federal government through the Canadian Energy Regulator *Onshore Pipeline Regulations* (SOR/99-294) [97]. Provincial regulators oversee the regulation of the other three pipeline types. The regulatory oversight at the provincial level varies depending on factors such as the operating pressure and purpose of the pipelines [98]. The regulation and registration of pressure equipment of intraprovincial pipelines is handled at the provincial level only. The regulator and applicable regulations of pipeline and pressure equipment are summarized in Table 3. As the hydrogen value chain develops, there is an expectation that natural gas transmission, distribution and to some extent the feeder pipelines will be constructed or repurposed to handle hydrogen and hydrogen/natural gas blends [15]. It is important for the current regulatory framework to be prepared and adaptable to accommodate this expanded scope, potentially requiring legislative adjustments for appropriate oversight and compliance [99].

In terms of technical standards for design, construction, operation, maintenance and decommissioning of oil and gas pipelines, federal and provincial pipeline regulations refer to CSA Z662. Protective coatings play a vital role in pipeline integrity management programs, which are mandatory at both the federal and provincial levels, as seen in Table 3. However, the current federal and provincial regulations do not explicitly address hydrogen. For instance, the *Onshore Pipeline Regulations* (OPR) reference CSA Z662 requirements applicable only to pipelines transporting liquid or gaseous hydrocarbons, which may include blended gaseous hydrogen (OPR Section 4.1) [97].

The regulatory approval of pressure-vessel and piping design, including the selection and use of coatings and liners for pressure equipment, aligns with requirements specified in CSA B51.

Table 3: Pipeline and pressure equipment safety Authority Having Jurisdiction (AHJ) in Canada

Jurisdiction	Regulator and relevant activities	Regulation names and designation	Requirements of coating and liner for pipeline and equipment regulations
Federal	▪ Canadian Energy Regulator (CER) regulates oil and gas pipelines [97]	▪ Onshore Pipeline Regulations (SOR/99-294)	▪ Refers to CSA Z662 for pipeline transporting liquid or gaseous hydrocarbons only
Alberta	▪ Alberta energy regulator (AER) regulates all energy-extraction related pipelines [99] ▪ Rural Utilities Branch regulates gas distribution pipelines under 700 KPa (102 psi) ▪ Alberta Utilities Commission (AUC) regulates utility pipelines ▪ Alberta Boilers Safety Association (ABSA) regulates pressure equipment	▪ Pipeline rules (Alberta Regulation 91/2005) ▪ Pressure equipment safety regulation (Alberta Regulation 49/2006)	▪ Refers to CSA Z662 for pipeline ▪ Refers to CSA B51 for pressure equipment ▪ Approval of non-standard materials or methods by the discretion of regulator
British Columbia	▪ BC Energy Regulator (BCER) regulates oil and gas pipelines over 100 psi ▪ BC Utilities Commission (AUC) regulates distribution pipelines ▪ Technical Safety BC regulates boilers and pressure vessels	▪ Pipeline regulation (B.C. Reg. 289/2020) ▪ Power engineers, boiler, pressure vessel and refrigeration safety regulation (B.C. Reg. 255/2022)	▪ Refers to CSA Z662 for design, material, integrity management and damage prevention programs ▪ Non-standard materials or methods are not specified
Saskatchewan	▪ Saskatchewan's Ministry of the Economy	▪ Saskatchewan Pipelines Code (Directive PNG034)	▪ Refers to CSA Z662 for materials and design ▪ Approval of non-standard materials or methods by the discretion of regulator
Ontario	▪ Ontario Energy Board regulates energy operations, including oil and gas pipelines ▪ Technical Standards and Safety Authority grants licenses for natural gas distribution and transmission systems, oil pipeline systems, and pressure vessels	▪ Natural Gas Facilities Handbook ▪ Environmental Guidelines for Hydrocarbon Projects ▪ Boilers and Pressure Vessels Safety Program Code Adoption Document	▪ Refers to CSA Z662 for design ▪ Approval of non-standard materials or methods by the Technical Standards and Safety Authority ▪ Refers to CSA B51 for pressure equipment
Quebec	▪ *Regie de l'énergie* regulates energy operations, including hydrocarbon exploration and associated systems ▪ Government of Quebec	▪ Regulation Respecting Hydrocarbon Exploration ▪ Regulation Respecting Pressure Vessels	▪ Refers to CSA Z662 for integrity management programs ▪ Documentation of technical specifications for pipeline construction to be submitted for approval by regulator ▪ Refers to CSA B51 for pressure vessels
New Brunswick	▪ New Brunswick Energy and Utilities Board (EUB) regulates utilities and oil and gas pipelines	▪ Pipeline Act	▪ Refers to CSA Z662 for design and operation of pipelines transporting liquid or gaseous hydrocarbons or minerals ▪ EUB to approve non-standard designs in the absence of comparable CSA or other applicable standards

3.3.1.2 Regulations for Coating and Liner Contents

All coating and liner products used in Canada are subject to regulatory compliance with safety requirements throughout their lifecycle, including development, manufacturing, trade, application, service and disposal. In addition to the regulations governing pipelines and pressure equipment, the use of coating and liner products must also adhere to the regulations listed in Table 4 to mitigate any potential detrimental impacts on the environment, individuals and properties. The applicable regulations were developed under the *Canadian Environmental Protection Act, 1999*, on the recommendation of the Minister of the Environment and the Minister of Health.

Table 4: Federal environmental and safety regulations related to coatings and liners

Designation	Title
SOR/2006-347 [100]	2-Butoxyethanol Regulations
SOR/2009-162 [101]	Chromium Electroplating, Chromium Anodizing and Reverse Etching Regulations
SOR/2018-83 [102]	Consumer Products Containing Lead Regulations
SOR/2019-51 [103]	Environmental Emergency Regulations
SOR/2013-88 [104]	Export of Substances on the Export Control List Regulations
SOR/94-261 [105]	Masked Name Regulations
SOR/2016-151 [106]	Multi-sector Air Pollutants Regulations
SOR/2002-374 [107]	New Substances Fees Regulations
SOR/2005-247 [108]	New Substances Notification Regulations (Chemicals and Polymers)
SOR/2005-248 [109]	New Substances Notification Regulations (Organisms)
SOR/2000-107 [110]	Persistence and Bioaccumulation Regulations
SOR/89-501 [111]	Concentration of Phosphorus in Certain Cleaning Products Regulations
SOR/2014-254 [112]	Products Containing Mercury Regulations
SOR/2012-285 [113]	Prohibition of Certain Toxic Substances Regulations, 2012
SOR/2012-134 [114]	Regulations Designating Regulatory Provisions for Purposes of Enforcement (Canadian Environmental Protection Act, 1999)
SOR/2011-90 [115]	Release and Environmental Emergency Notification Regulations
SOR /2016-193 [116]	Surface Coating Materials Regulations
SOR/2003-283 [117]	Solvent Degreasing Regulations
SOR/2008-197 [118]	Storage Tank Systems for Petroleum Products and Allied Petroleum Products Regulations
SOR/2006-298 [119]	Virtual Elimination List
SOR/2021-268 [120]	Volatile Organic Compound Concentration Limits for Certain Products Regulations

3.3.2 Standards

Standards for coatings and liners used in gas pipeline and pressure equipment services are generally established by international associations and standards development organizations, as reviewed in this report. Standards related to coatings and liners have been classified into three types depends on the level of systems addressed [39].

- Standards that cover the aspects of assets and equipment systems such as pipelines, pressure equipment and hydrogen appliances. These standards are often directly referenced by regulations and govern the entire lifecycle of the assets and equipment, including the incorporation of coatings and liners as functional components.
- Standards that provide recommended practices for coatings and liners, such as surface preparation, application, installation, qualification, repair and product specifications. These standards are often referenced by standards for assets and equipment as integral parts of product selection, design guidance and quality management protocols.
- Standards that focus on the testing properties of coatings and liners, including adhesion strength, dry film thickness, density, chemical resistance and other relevant characteristics. Those standards are commonly cited by other standards as modules to reduce repetition and provide consistency.

3.3.2.1 Standards for Assets and Equipment

Standards in this category address the technical requirements throughout the entire lifecycle of assets and equipment. The service scope and technical aspects of coatings and liners outlined in these standards are directly tied to the regulations for the assets and equipment.

3.3.2.1.1 Pipeline Standards

Currently, Canadian regulations refer to the 2023 edition of CSA Z662 at both federal and provincial levels, which sets out the minimum requirements for pipelines in the oil and gas industry. This includes requirements for pipeline system design, construction, operation, maintenance, deactivation and abandonment, as well as requirements for coatings and liners in pipeline systems. However, the standard does not specify requirements for pipelines for 100% hydrogen service, although updates to the 2023 edition include requirements for hydrogen/natural gas blends.

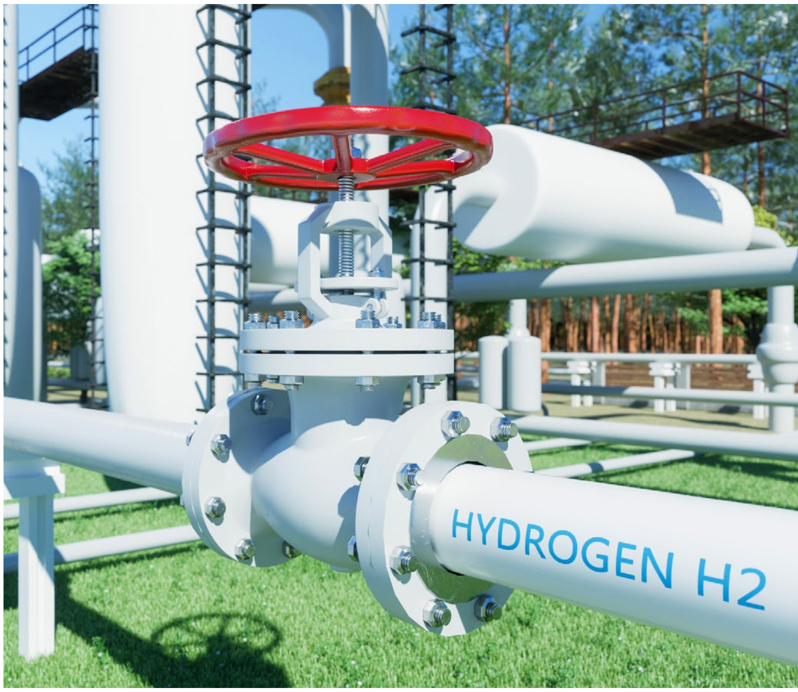


Table 5 shows international pipeline standards that specifically address hydrogen service or have expanded their scope to include hydrogen services, similar to CSA Z662. The primary focus of the coating, cladding and lining defined in these standards is to protect the substrate from corrosion, erosion and abrasion. Specific provisions addressing coating, cladding and lining for gaseous HE mitigation and improving flow efficiency are not included yet. DVGW G-409 references ASME B31.12 for general material recommendations, but does not specify the requirements of coatings and liners under hydrogen conditions. Additionally, BSI PD 8010 provides guidance on the application of anti-friction internal coatings intended for natural gas pipelines, which may be adopted for hydrogen flow efficiency coatings with proper modification in test conditions and acceptance criteria.

Table 5: Standards addressing hydrogen pipeline service

Designation	Title	Publication date
ASME B31.12	Hydrogen piping and pipelines	2019
BSI PD 8010-1	Pipeline systems - Part 1 Code of Practice, Steel pipelines on land	2015
CGA G-5.6	Hydrogen pipeline systems	2013
CSA Z662	Oil and gas pipeline systems	2023
EN 14161	Petroleum and natural gas industries pipeline transportation systems	2011
NEN 3650 series of Standards	Requirements for pipeline systems	2020
NEN 3651	Additional requirements for pipelines in or nearby important public works	2020
ISO 13623	Petroleum and natural gas industries - pipeline transportation systems	2017
IGEM/TD/1 Edition 6	Steel pipelines for high pressure gas transmission supplement 2	2021
DVGW G 409	Conversion of high-pressure gas steel pipelines for a design pressure of more than 16 bar for transportation of hydrogen	2020
IGC Doc 121/14	Hydrogen pipeline systems	2014

CGA G-5.6 and ASME B31.12 are the dedicated design and construction standards for piping and pipelines in hydrogen service, addressing various aspects of gaseous hydrogen transportation and distribution systems. They encompass design principles for parts, equipment, vessels, pipelines and stations, as well as construction, operation, maintenance and protective measures. Additionally, information regarding material performance, metallurgy considerations, and environmental degradation mechanisms are provided in the documents. CGA G-5.6, harmonized with EIGA Doc. 121/04 [19], is applicable to hydrogen blending ratios of 10–100%, with a maximum total pressure of 21 MPa (3000 psi). However, the requirements for coatings and liners reference NACE RP0169 [121], which addresses the protective pipeline coating for external corrosion only and is not tailored for hydrogen service. ASME B31.12 covers high-pressure piping with the maximum operating pressure (MOP) up to 100 MPa (15,000 psi), and transport pipelines up to 21 MPa (3,000 psi). Notably, the standard specifies mandatory criteria for using flow liners based on the size of expansion joints and flow velocity. The general guidance of using internal and external coating systems as corrosion mitigation measures is outlined in the standards, but the technical details are not specified.

It is crucial that coatings and liners maintain their integrity during pipeline operation, as well maintenance activities such as storage, transportation, bending, installation, welding, backfilling, hydrostatic testing, inspection, repair, repurposing and rehabilitation of the pipeline system. The requirements for coating and liner integrity during pipeline operation and maintenance are summarized in Table 6.

Table 6: Requirements of coatings and liners for evaluation of performance on pipelines

Requirements	Liner	Internal Coating	External Coating
Ease of installation, application, and repair	Applicable	Applicable	Applicable
Continuity (Holiday)	Applicable	Applicable	Applicable
Adhesion	Subject to product specification and design requirements	Applicable	Applicable
Flexibility	Applicable, extra flexibility is needed for spoolable pipe used as liner	Applicable, depends on bending of pipe	Applicable, depends on bending of pipe
Resistance to weathering	Applicable, if long term outdoor storage is needed	Applicable, if outdoor storage is needed without protections such as end caps and tarp	Applicable, if it is for above ground service and subject to outdoor storage without protections such as end caps and tarp
Resistance to sunlight radiation	Applicable, if long term outdoor storage is needed	Applicable, if outdoor storage is needed without protections such as end caps and tarp	Applicable, if it is for above ground service without protections such as end caps and tarp
Resistance to chemicals	Applicable, chemicals from conveyed flow and annulus space	Applicable, chemicals from conveyed flow	Applicable, chemicals from atmospheric, buried or submerged environments
Resistance to mechanical damage	Applicable, damage from erosion, pigging, slide installation	Applicable, damage from erosion and pigging	Applicable, damage from handling installation, backfilling and soil movement
Resistance to cathodic disbondment	Nonapplicable	Nonapplicable	Applicable
Resistance to pressure	Applicable, pressure from flow, usually fluctuated	Applicable, pressure from flow, usually fluctuated	Applicable, pressure from soil (buried) or water (submerged), usually constant
Resistance to temperature	Applicable, temperature from flow (constant or fluctuated), thermal gradient (cold wall effect)	Applicable, temperature from flow (constant or fluctuated), thermal gradient (cold wall effect)	Applicable, temperature from flow (constant or fluctuated), extreme environment conditions (arctic area)
Resistance to microbiology activities	Applicable, microorganism from conveyed fluid and annulus space	Applicable, microorganism from conveyed fluid	Applicable, microorganism from atmospheric, buried, or submerged environments

To address the coatings and liners requirements listed in Table 6, CSA Z662:23 refers to a range of standards that provide specifications and qualification protocols outlining test methodology, test conditions (i.e., expected service conditions), and acceptance criteria of test results for various coatings and liner products. The standards referenced in CSA Z662:23 are classified based on coating types and summarized in Table 7. Verification of these standards' requirements for hydrogen pipelines is necessary before they can be suitably referenced for hydrogen service.

Table 7: Standards cited by CSA Z662:23 for specifying and qualifying various coating and liner

Designation	Title	Coating and liners	Publication date
External Coating			
CSA Z245.20	Plant-applied external fusion bond epoxy (FBE) coating for steel pipe	FBE	2022
CSA Z245.21	Plant-applied external polyethylene coating for steel pipe	PE	2022
CSA Z245.22	Plant-applied external polyurethane foam insulation coating for steel pipe	PU foam	2022
CSA Z245.30	Field-applied external coatings for steel pipeline systems	Liquid-applied epoxy, FBE, polymeric tape, heat shrinkable sleeve, PU foam insulation, fibre-reinforced petrolatum, paraffin-filled or visco-elastic systems	2022
Internal coating and liner			
CAPP Best Management Practices	Use of High Density Polyethylene (HDPE) Lined Pipelines	HDPE	2022
CSA B137.4	Polyethylene (PE) piping systems for gas services	PE	2020
ASTM D3350	Standard Specification for Polyethylene Plastics Pipe and Fittings Materials	PE	2021
PPI TR-4	PPI HSB Listing of Hydrostatic Design Basis (HDB), Hydrostatic Design Stress (HDS), Strength Design Basis (SDB), Pressure Design Basis (PDB) and Minimum Required Strength (MRS) Ratings for Thermoplastic Piping Materials or Pipe	PE, PVC, Crosslinked polyethylene (PEX)	2021
CSA B137.12	Polyamide (PA) piping systems for gas services	PA	2020
ASME B16.40	Manually Operated Thermoplastic Gas Shutoffs and Valves in Gas Distribution Systems	PA	2019
API 15LE	Specification for Polyethylene Line Pipe (PE)	PE	2022
ASTM D3261	Standard Specification for Butt Heat Fusion Polyethylene (PE) Plastic Fittings for Polyethylene (PE) Plastic Pipe and Tubing	PE	2016

Designation	Title	Coating and liners	Publication date
Internal coating and liner			
ASTM F2206	Standard Specification for Fabricated Fittings of Butt-Fused Polyethylene (PE)	PE	2019
ASTM F1973	Standard Specification for Factory Assembled Anodeless Risers and Transition Fittings in Polyethylene (PE) and Polyamide 11 (PA11) and Polyamide 12 (PA12) Fuel Gas Distribution Systems	PE, PA	2021
CSA B137.19	Crosslinked polyethylene (PEX) piping systems for gas services	PEX	2023
ASTM F2905/ F2905M	Standard Specification for Crosslinked Polyethylene (PEX) Line Pipe for Oil and Gas Producing Applications	PEX	2022
CAPP Best Management Practices	Use of Reinforced Composite Pipe (Non-Metallic Pipelines)	Reinforced composite	2022
API 15HR	Specification for High Pressure Fiberglass Line Pipe	Reinforced composite	2021
API 15S	Spoolable Reinforced Plastic Line Pipe	Reinforced composite	2023
API 17J	Specification for Unbonded Flexible Pipe	Reinforced composite	2021
API 17K	Specification for Bonded Flexible Pipe	Reinforced composite	2022

3.3.2.1.2 Pressure Vessel and Equipment Standards

In Canada, pressure equipment regulations reference CSA B51 [122] for the requirements of boilers, pressure vessels and pressure piping. Part 2 of CSA B51 [123] outlines requirements for use of metallic and non-metallic liners in high-pressure cylinders for storage of natural gas, hydrogen blends and hydrogen as fuels for automotive vehicles. Considering the similarities in high-pressure conditions between hydrogen pipelines and automotive pressure cylinders, the CSA B51, Part 2 requirements for use of liners may apply to pipelines. For the purpose of adoption in CSA Z662, they should be reassessed in accordance with the requirements outlined in Table 6. Steel (including stainless steel) used as liner and body material of the storage pressure cylinders complies with the requirements of ISO 98091 [124] and ISO 11114-4 [125], which define limits for tensile strength. When body and liner materials are made of non-metallic materials, such as aluminum, resins, fibers and plastics, factors for consideration include their resistance to temperature, impact, gas composition, chemicals, and cyclic and static pressures.

The CSA B51 Part 2 qualification process for materials of pressure-vessel body and liner involves mechanical testing and environmental resistance testing. ISO 9809-1 [124], ISO 7866 [126], ASTM E8 [127], ISO 148-1 [128] and ASTM E23 [129] are adopted for mechanical property testing of these materials. Environmental resistance is evaluated using ISO 306 [130], NACE TM 0177 [131], and ISO 7866 [132]. Additional cylinder material requirements include fracture performance, leak testing, hydrostatic-pressure proof testing, hydrostatic-pressure burst testing, pressure-cycling testing, bonfire testing, penetration testing, flaw tolerance testing, accelerated stress rupture testing, drop testing, permeation testing, environmental testing and gas-cycling testing. It is important to note that metal liners are considered impermeable to gas in this standard and are exempt from gas permeation testing of fuel storage cylinders. While all of the mentioned tests refer to pipeline applications, the assumption of gas impermeability does not apply to transportation pipelines, as they are designed for much longer service than vehicle cylinders under CSA B51, and the effect of gaseous hydrogen permeation on material performance shall be emphasized.

CSA B51 Part 2, on the other hand, assumes application of coatings, and establishes their acceptance criteria only for external protection of hydrogen storage cylinders. The typically required tests include adhesion, flexibility, resistance to impact, chemical resistance, resistance to UV radiation, salt fog resistance, and resistance to chipping. The testing requirements are similar to those for external coatings on natural gas pipelines as shown in Table 6. This similarity suggests that the existing testing protocols for external coatings are versatile and may be applied to hydrogen equipment and assets after engineering evaluation.

Other documents potentially relevant for selection and characterization of coatings and liners in hydrogen service pipelines are the CSA series of standards containing requirements for hydrogen vehicle components and refueling station equipment, which include coating and liner products as critical components. ANSI/CSA HGV 4.1 [133] outlines safety requirements for gaseous hydrogen-dispensing systems. In this standard, coatings are externally applied to enclosures. The selection of materials for hydrogen service equipment is outlined in CSA CHMC1 [134], a standardized testing methodology for material compatibility with compressed hydrogen applications and ASME B31.12 [135]. CSA/ANSI HGV 4.2 [136] specifies requirements for hoses and hose assemblies used for dispensing compressed gaseous hydrogen to vehicles. The hoses and assemblies are usually lined with hydrogen barrier materials, so the relevant qualification protocol for hoses can benefit standardizing liners and coatings used for hydrogen pipelines. These relevant protocols include tests for leakage, hydrostatic strength, electrical resistance, mechanical strength, environmental exposure and permeation under typical service conditions.

The ASME Boiler and Pressure Vessel Code (BPVC) is globally recognized as a comprehensive set of standards widely used in the manufacturing, construction, and operation of boilers and pressure vessels. Within the BPVC, Section VIII-3 KD-10 specifically addresses high-pressure vessels and provides fracture mechanics-based rules for designing pressure vessels intended for hydrogen service up to 103.4 MPa (15,000 psi), the same MOP as set in ASME B31.12 for high-pressure piping. This section of BPVC emphasizes the requirements of fatigue cycles and fracture toughness for materials used in hydrogen service, which have been incorporated into numerous industry standards governing materials selection and equipment design. The requirements for fatigue cycles and fracture toughness of materials apply to internal coatings and liners for hydrogen pipelines and should be included in their qualification protocols.

3.3.2.2 Standards for Specification and Recommended Practices of Coatings and Liners in Specific Applications

At present, there is a lack of standards for performance and best practices for application, inspection, testing, handling and storage for coatings and liners specifically in hydrogen pipelines. Nevertheless, it is important to note that the specification of coatings and liners for corrosion protection in gas pipelines has already been established within the oil and gas industry. These existing specifications should be reviewed and possibly modified and supplemented to address the integrity and effectiveness of coatings and liners in hydrogen transportation systems. However, it should be recognized that the unique challenges posed by hydrogen, such as embrittlement and low transportation efficiency, present a significant path to be traversed in terms of seeking standardized solutions.

3.3.2.2.1 Materials for Hydrogen Service

Guidelines and information related to material selection in hydrogen service can be found in documents listed in Table 8. A comprehensive review of the pipeline materials, compatibility with hydrogen and standardization is provided in another CSA research report [137]. These documents are regularly updated to incorporate new findings from industrial practices and laboratory testing. However, these standards are developed for various hydrogen applications, and therefore some of them require technical reassessment before being adopted for hydrogen pipelines.

Table 8: Standards and reports addressing material selection for hydrogen service

Designation	Title	Publication date
ASME B31.12	Hydrogen Piping and Pipelines	2019
ANSI/CSA CHMC 1	Test methods for evaluating material compatibility in compressed hydrogen applications – Metals	2018
ANSI/CSA CHMC 2	Test methods for evaluating material compatibility in compressed hydrogen applications – Polymers	2019
ISO/TR 15916	Basic considerations for the safety of hydrogen systems	2015
CGA G-5.6	Hydrogen Pipeline Systems	2013
SAND2012-7321	Technical Reference for Hydrogen Compatibility of Materials	2012

According to non-mandated Appendix A-2 of ASME B31.12 and ISO/TR 15916 Annex C, aluminum, aluminum alloys, carbon steel (ASTM A106 Grade B, ASTM A53 Grade B, and API 5 L Grades X42 and X52), copper, copper alloys and austenitic stainless steels with greater than 7% nickel (e.g., 304, 304L, 308, 316, 321, 347) may be acceptable for dry gaseous hydrogen service. However, nickel and nickel-based alloys, as well as nickel steels, are listed in ASME B31.12 Appendix A-2 as not accepted for hydrogen gas service due to their susceptibility to gaseous HE. The acceptance criteria for material selection are based on structural performance, for example, resistance to fatigue cracking. As such, nickel and nickel-based alloys with low permeability of atomic hydrogen may be excluded from this provision when being used as coatings and liners, as they are not pressure contained and do not need to comply with the design operating pressure of a pipeline [34]. Further study is required to confirm the acceptance criteria for coating and liner material, as the failure of coatings and liners under high-pressure hydrogen-gas conditions could result from mechanisms other than fatigue cracking. Potential hydrogen barrier performance of coatings and liners such as electroless nickel plating (nickel phosphate), zinc, ceramic and composite systems have yet not been examined.

The various commercial polymer products, such as PTFE, chloroprene rubber, polyester fiber, polyester film, nitrile, polyamides and polychlorotrifluoroethylene, are classified as suitable for gaseous hydrogen services by ISO/TR 15916 Annex C. It should be noted that the suitability of a polymer is primarily determined by its resistance to rapid depressurization rather than hydrogen permeability. Additionally, CGA G-5.6 specifies the maximum temperature limits for different plastic materials in hydrogen service.

ANSI/CSA CHMC 1 and ANSI/CSA CHMC 2 standards focus on metals and polymers, respectively, outlining material qualification protocols (e.g., test methodology, test conditions and defined acceptance criteria) for compressed hydrogen applications. ANSI/CSA CHMC 1 defines the compatibility of metals with hydrogen conditions through acceptance criteria for various tests. These include slow strain rate tensile testing (ASTM G142 and ASTM G129), hydrogen-assisted cracking threshold stress intensity factor (ASTM E1820), fatigue crack growth rate (ASTM E647), and fatigue life tests (ASTM E1012, ASTM E466 and ASTM E606). However, important parameters of fatigue testing listed in ANSI/CSA CHMC 1, such as a fixed R-ratio of 0.1±10% and frequency of 1 Hz, are specifically tailored

> **“The existing standards for external coatings developed for the oil and gas pipelines can be effectively applied to pipelines used for transporting hydrogen and hydrogen-natural gas blends due to the similarities in used coating and liner types, corrosion protection requirements, and the environmental conditions to which they are exposed.”**

for equipment on hydrogen vehicles. Gas pipelines typically experience pressure fluctuations with higher R-values and lower frequencies [138], suggesting that the ANSI/CSA CHMC 1 qualification protocol for compatibility in compressed hydrogen applications may be overly strict for pipeline use.

In ANSI/CSA CHMC 2, the performance of polymer materials in the presence of hydrogen is evaluated based on hydrogen diffusion, permeability, physical stability (dimensional, mass, appearance, and density), changes in tensile properties (ASTM D638, ISO 527, ASTM 412 and ISO 37), impact strength (ISO 179 and ISO 8256), durometer hardness (ASTM D2240), dynamic wear (ASTM G133), material contamination (ISO 14687, SAE J2719), hydrogen static exposure, initial cycling, and extended aging. The standard provides a way to measure hydrogen compatibility of polymer materials on a rating scale for comparison with other materials, which can serve as specification acceptance levels for a given application. Similar to CSA CHMC1, it is necessary to customize the testing items and parameters for pipeline applications.

3.3.2.2.2 External Coatings for Oil and Gas Pipeline

The existing standards for external coatings developed for the oil and gas pipelines may be applied to pipelines used for transporting hydrogen and hydrogen-natural gas blends due to the similarities in used coating and liner types, corrosion protection requirements, and the environmental conditions to which they are exposed. The external coatings for pipelines are typically classified into two types – plant-applied and field-applied – which are covered by CSA Z245.20 series and CSA Z245.30, respectively. The required tests applicable to hydrogen pipelines identified from these CSA standards are summarized in Table 9. The test conditions and criteria for evaluating test results for coatings applied to oil and gas pipelines might need adjustment to meet the strict safety requirements of hydrogen pipelines.

The ISO 21809 series of standards addresses similar external coating application aspects as the CSA Z245.20 series and CSA Z245.30. Specifically, ISO 21809-3 [139] covers the surface preparation, application, qualification and testing of thermal spray aluminum coating, which is recognized as a potential option for hydrogen barrier coatings. ISO 21809-11 [140] defines the technical requirements for on-site coating rehabilitation or repair, providing guidance and qualification criteria for each step involved. This includes coating assessment for both new and existing coatings, removal of degraded coatings, surface preparation, and on-site or *in situ* application of external coatings. NACE RP0105 [141] follows a similar approach for coating repair and rehabilitation, but specifically focuses on liquid-epoxy coatings. The principles and practices outlined in these standards for rehabilitation can be applied when repurposing existing pipes for hydrogen service.

Table 9: Required tests for qualifying external pipeline coatings

Required items	Plant-applied coatings			Field-applied coatings		
	FBE	PE	PU foam	Liquid-applied or fusion bond epoxy coating	Polymeric tape and sleeves	Fibre-reinforced petrolatum, paraffin-filled, or visco-elastic systems
Material characteristic	Powder material – cure time, gel time, moisture content, particle size, density and thermal characteristics Cured material – cure time, cure degree, porosity, thickness, porosity and surface roughness	Epoxy primer – density, viscosity, epoxy equivalent weight, total amine value and gel time Coating material – density, elongation at break, flow rate, hardness, heat aging, tensile tress at yield, oxidative-induction time in oxygen, brittleness temperature, stress-cracking resistance and softening point	Compressive strength, density, open cell content, water absorption and thermal conductivity (K-factor)	Thickness, hardness, thermal characteristics, cure degree and porosity	Thickness, appearance	Thickness, appearance
Adhesion	Knife adhesion test	Peel adhesion test	Creep test	Knife adhesion test	Peel adhesion test	Peel adhesion test
Resistance to mechanical damage	Flexibility, gauging, impact resistance tests	Flexibility, impact resistance tests	Impact energy test, axial shear strength	Flexibility, gauging, impact resistance tests	Tensile strength, elongation, hardness, flexibility, lap shear and impact resistance	Lap shear, impact resistance
Resistance to cathodic disbondment	Cathodic disbondment test	Cathodic disbondment test	Not required on insulation layer	Cathodic disbondment test	Cathodic disbondment test	Cathodic disbondment test
Resistance to temperature	Adhesion test after high temperature water immersion	Adhesion test after high temperature water immersion	Aging test	Adhesion test after high temperature water immersion	Adhesion test at maximum service temperature	Drip resistance, Adhesion test at maximum service temperature

3.3.2.2.3 Internal Coatings for Pipeline

Internal coatings and liners provide sufficient corrosion protection during pipe storage, transportation, construction, hydrostatic test, and operation. Additionally they assist gas flow efficiency, but the Canadian regulations and CSA standards currently do not address this application of internal coatings and liners. ISO 15741 [142], EN 10301 [143], and API RP 5L2 [144] are recognized standards for friction reduction coatings used on gas pipelines. These standards define the application of internal coatings to reduce friction and pressure drop while conveying non-corrosive gases. The coating specifications and application practices outlined in these standards primarily focus on two-part liquid epoxy coatings. The qualification tests for properties listed in Table 6 include:

- **Liquid epoxy:** Density (per ISO 2811), viscosity (per ISO 2431), non-volatile matter (per ISO 3251 by mass and ISO 3233 by volume), ash, pot life and infrared spectrograms
- **Cured coating:** Film thickness, adhesion (per ISO 2409), Buchholz hardness, resistance to neutral salt spray (per ISO 7253), resistance to artificial aging, bend test (per ISO 6860), resistance to gas pressure variations, water immersion (per ISO 2812-2), chemicals (per ISO 2812-1) and hydraulic blistering

EN 10310 [143] and API RP 5L2 [144] specifically address polyamide powder and fusion bond epoxy (FBE) internal coatings for gas pipelines, respectively. These standards provide guidelines for the qualification of uncured coating materials, considering the unique characteristics of each coating type. The testing items for cured coatings are generally similar to those used for liquid epoxy coatings. It is important to note that the mentioned standards do not explicitly address the friction reduction performance of internal coatings. This omission is due to the complex nature of friction reduction, which is influenced by factors such as flow conditions, pipe geometry and coating properties. Additional study is required for developing testing methods assessing the performance of internal coatings in terms of friction reduction in gas pipeline applications.

3.3.2.2.4 Polymer Pipe (Liner)

Polymer pipes, such as PE (polyethylene), HDPE (high-density polyethylene) and PEX (cross-linked polyethylene), offer versatile options for various applications, serving as either standalone pipelines or liners within steel pipes. The specification, design and use of these polymer piping systems are thoroughly addressed by comprehensive standard specifications, test methods and codes established by ASTM, AWWA, CSA and ISO, to name a few. These standards address the quality and performance of polymer pipes through rigorous testing and evaluation procedures. Additionally, the Plastics Pipe Institute (PPI) publishes Technical Reports (TRs) and Technical Notes (TNs) that provide valuable insights and guidelines for the proper application and installation of polymer pipes. These resources have been extensively reviewed in external sources [145], [146].

Reinforced polymer pipes are anticipated to play a role in hydrogen transportation, owing to their enhanced properties compared to conventional polymer pipes. Organizations such as API, ASTM and CSA have developed a comprehensive series of standards that encompass various aspects related to reinforced polymer pipes. These standards cover a wide range of topics, including performance requirements, design considerations, suitable materials, rigorous testing procedures, inspection guidelines, marking specifications, proper handling and storage practices, shipping requirements, repair methods, installation procedures and integrity management protocols. The related standards are identified and summarized in Table 10.

Table 10: Standards for reinforced polymer pipes

Designation	Title	Publication date
API RP 15CLT	Recommended Practice for Composite Lined Steel Tubular Goods	2018
API Spec 15HR	High-Pressure Fiberglass Line Pipe	2021
API Spec 15LR	Specification for Low Pressure Fiberglass Line Pipe	2018
API Spec 15S	Spoolable Reinforced Plastic Line Pipe	2022
API RP 15SA	Integrity Management of Spoolable Reinforced Line Pipe	2022
API RP 15SIH	Installation and Handling of Spoolable Reinforced Line Pipe	2021
API RP 15TL4	Recommended Practice for Care and Use of Fiberglass Tubulars	2022
API TR 17TR1	Evaluation Standard for Internal Pressure Sheath Polymers for High Temperature Flexible Pipes	2003
API Spec 17J	Specification for Unbonded Flexible Pipe, Fourth Edition	2021
ASTM D2992	Standard Practice for Obtaining Hydrostatic or Pressure Design Basis for “Fiberglass” (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe and Fittings	2022
ASTM D2996	Standard Specification for Filament-Wound “Fiberglass” (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe	2017
ASTM D2997	Standard Specification for Centrifugally Cast “Fiberglass” (Glass-Fiber-Reinforced Thermosetting-Resin) Pipe	2021
ASTM D3517	Standard Specification for “Fiberglass” (Glass-Fiber-Reinforced Thermosetting-Resin) Pressure Pipe	2019
ASTM D3754	Standard Specification for “Fiberglass” (Glass-Fiber-Reinforced Thermosetting-Resin) Sewer and Industrial Pressure Pipe	2019
ASTM D5685	Standard Specification for “Fiberglass” (Glass-Fiber-Reinforced Thermosetting-Resin) Pressure Pipe Fittings	2019
ASTM F1488	Standard Specification for Coextruded Composite Pipe	2019
ASTM F2896	Standard Specification for Reinforced Polyethylene Composite Pipe for The Transport of Oil and Gas and Hazardous Liquids	2017
ASTM F3346	Standard Specification for Polyethylene of Raised Temperature/Aluminum/Polyethylene of Raised Temperature (PERT/AL/PE-RT) Composite Pressure Pipe	2019
ASTM F3508	Standard Guide for In-Situ Pipeline Renovation as Dual-Wall Composite Pipeline by Push/Pull Installation of Compressed-Fit Shape-Memory-Polymer Tubular (SMPT)	2021
AWWA C903	Polyethylene-Aluminum-Polyethylene Crosslinked Polyethylene Composite Pressure Pipes 1/2 in. (12mm) Through 2 in. (50 mm) for Water Service	2021
BS EN 13121-3	GRP tanks and vessels for use above ground-Design and workmanship	2016
CSA S807	Specification for fibre-reinforced polymers	2019
NACE TM0298	Evaluating the Compatibility of FRP Pipe and Tubulars with Oilfield Environments	2015
PIP PN01FE0A01	Piping Material Specification 1FE0A01 150 PSI, Glass Fiber Reinforced Epoxy (RTR), Adhesive, Process and Utilities	2007
PIP PN01FV0A01	Piping Material Specification 1FV0A01 150 PSI, Glass Fiber Reinforced Vinyl Ester (RTR), Adhesive, Process and Utilities	2007
PIP PNSC0037	Aboveground Reinforced Thermosetting Resin (RTR) Piping System Requirements	2006

The API standard series specifically addresses polymer pipe products with pressure ratings ranging from 1 to 34.5 MPa (150 to 5000 psi) and diameters up to 610 mm (24 inches). This wide range of specifications covers the majority of service requirements for gas feeder, transmission, distribution mains and service pipelines. These standards govern fiberglass pipes made of typical thermosetting resins such as epoxy, polyester, vinyl ester and phenolic. The API standard series define a type of pipe known as spoolable reinforced line pipe, which consists of three layers – a liner, a reinforcement layer comprising helically wrapped steel or nonmetallic reinforcing elements, and an outer shell. To ensure the pipe is easily spoolable for storage, transport and installation, thermoplastic polymers are commonly employed in these three layers.

Currently, there is no dedicated polymer pipe standard specifically tailored for hydrogen service. Given the similarities between natural gas and hydrogen service requirements, the existing specifications and qualification protocols designed for natural gas may be used for hydrogen service with proper modifications. It has been observed that the permeation of hydrogen through the walls of PE pipes is approximately four to five times faster than that of methane. Despite this faster permeation rate, the overall gas permeation loss is still relatively small and may be considered acceptable as standalone pipeline from safety, economic and environmental perspectives [147]. However, it is important to exercise caution when using polymer pipes as liners for steel pipes in hydrogen service due to the challenging characteristics of hydrogen. The leakage of hydrogen gas into the annular space is expected to be higher compared to natural gas service, which necessitates a reassessment of the impact on the steel pipe and the design of venting mechanisms such as threadolet. Furthermore, it may be advisable to exclude reinforcement elements that are susceptible to HE, such as steel wire, from hydrogen services. Other considerations that may be incorporated into the qualification protocol for polymer pipes include evaluating the structural integrity of the pipe under hydrogen permeation and rapid depressurization, as well as assessing the effects of hydrogen impurities on the aging properties of the polymer materials.

3.3.2.2.5 Existing Coating and Liner Technologies Envisioned for Hydrogen Pipeline and Pressure Equipment

Various coating technologies – including electroless plating, electroplating, thermal spray, cold spray, hot dipping, cladding, physical vapor deposition (PVD), chemical vapor deposition (CVD) and conversion coating – have proven successful in coating steel structures. However, no dedicated standard specific for applying coatings and liners on pipelines using these methods has been identified.

For application of coatings, standards provide guidance on substrate preparation, plating methods, quality assurance and coating specifications. The list of specific standards for electroless plating can be found in Table 11, while electroplating standards are summarized in Table 12. The electroless plating standards cover a range of coatings, including the conventional nickel-phosphorus alloy coating, as well as using ceramic, PTFE, titanium and boron compositions as fillers for electroless plating. Electroplating methods are suitable for chrome, nickel, cobalt, zinc and alloy coating systems. However, standards related to the electronics industry (e.g., gold, silver), substrates other than steel or plastic (e.g., molybdenum, titanium, tungsten), and coating systems that are not suitable for hydrogen services (e.g., lead, tin) are excluded from the list of standards provided in Tables 9 and 10. It is important to note that both electroless and electroplating methods can introduce dissolved hydrogen into the steel substrate. To prevent HE, a baking process is required, especially after electroplating, to remove absorbed hydrogen and minimize the risk of embrittlement in the coated steel [64].

Table 11: Standards for electroless plating of metal coatings and liners

Designation	Title	Publication date
ASM Ni-332	Electroless Nickel – Chemically Deposited Nickel Phosphorus Alloy	1986
ASM Ni-340	Enplate Electroless Nickel – Chemically Deposited Nickel Phosphorus Alloy	1986
ASM Ni-343	ENPLATE NI-423 – High Phosphorus Electroless Nickel	1986
ASTM B607	Standard Specification for Autocatalytic Nickel Boron Coatings for Engineering Use	2021
ASTM B733	Standard Specification for Autocatalytic (Electroless) Nickel-Phosphorus Coatings on Metal	2022
ASTM B999	Standard Specification for Titanium and Titanium Alloys Plating, Electrodeposited Coatings of Titanium and Titanium Alloys on Conductive and Non-Conductive Substrate	2022
ISO 4527	Metallic coatings. Autocatalytic (electroless) nickel-phosphorus alloy coatings. Specification and test methods	2003
ISO 23363	Electrodeposited coatings and related finishes. Electroless Ni-P-ceramic composite coatings	2020
ISO 23363	Electrodeposited coatings and related finishes - Electroless Ni-P-ceramic composite coatings	2020
ISO 2361	Electrodeposited nickel coatings on magnetic and non-magnetic substrates - Measurement of coating thickness - Magnetic method	1982
MIL-DTL-26074F	COATINGS, ELECTROLESS NICKEL REQUIREMENTS FOR (SUPERSEDING MIL-C-26074E)	2003
NACE 6A287	Electroless Nickel Coatings	1997
SAE AMS2404J	Plating, Electroless Nickel	2018
SAE AMS2405E	Electroless Nickel Plating Low Phosphorus	2013
SAE AMS2433D	Plating, Nickel-Thallium-Boron or Nickel-Boron Electroless Deposition	2020
SAE AMS2454A	Plating, Electroless Nickel-Phosphorus, Co-Deposited with Polytetrafluoroethylene (PTFE)	2021
SAE AMSC26074D	Electroless Nickel Coatings	2013

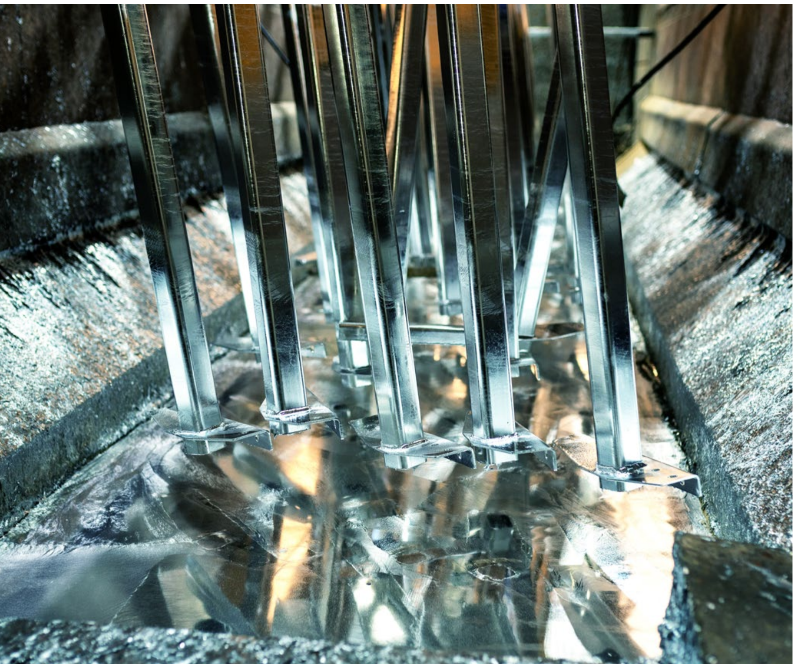
Table 12: Applicable standards for electroplating metal coatings and liners

Designation	Title	Publication date
ASTM B177/B177M	Standard Guide for Engineering Chromium Electroplating	2021
ASTM B183	Standard Practice for Preparation of Low-Carbon Steel for Electroplating	2022
ASTM B322	Standard Guide for Cleaning Metals Prior to Electroplating	2020
ASTM B633	Standard Specification for Electrodeposited Coatings of Zinc on Iron and Steel	2023
ASTM B689	Standard Specification for Electroplated Engineering Nickel Coatings	2023
ASTM B727	Standard Practice for Preparation of Plastics Materials for Electroplating	2020
ASTM B766	Standard Specification for Electrodeposited Coatings of Cadmium	2023
ASTM B841	Standard Specification for Electrodeposited Coatings of Zinc Nickel Alloy Deposits	2018
ISO 19598	Metallic coatings. Electroplated coatings of zinc and zinc alloys on iron or steel with supplementary Cr(VI)-free treatment	2016
ISO 2081	Metallic and other inorganic coatings. Electroplated coatings of zinc with supplementary treatments on iron or steel	2018
ISO 2082	Metallic and other inorganic coatings. Electroplated coatings of cadmium with supplementary treatments on iron or steel	2017
ISO 27830	Metallic and other inorganic coatings. Requirements for the designation of metallic and inorganic coatings	2017
MIL-STD-2197A	Brush Electroplating on Marine Machinery	2012
SAE J474	Electroplating and Related Finishes	2023

Standards that provide specifications, methods, applications, procedures and quality management protocols for thermal and cold spraying techniques are summarized in Table 13. Various parameters are assessed for coating quality, including porosity, oxide content, macro and micro-hardness, bond strength and surface roughness.

Table 13: Standards for thermal and cold spraying metal coatings and liners

Designation	Title	Publication date
ASTM E1920	Standard Guide for Metallographic Preparation of Thermal Sprayed Coatings	2021
ASTM B695	Standard Specification for Coatings of Zinc Mechanically Deposited on Iron and Steel	2021
ASTM B696	Standard Specification for Coatings of Cadmium Mechanically Deposited	2023
ASTM B816	Standard Specification for Coatings of Cadmium-Zinc Mechanically Deposited	2021
AWS C2.16/C2.16M	Guide For Thermal-Spray Operator Qualification	2017
AWS C2.18	Guide For the Protection of Steel with Thermal Sprayed Coatings of Aluminum and Zinc and Their Alloys and Composites	2001
AWS C2.21/C2.21M	Specification for Thermal Spray Equipment Acceptance Inspection	2015
NACE No. 12/AWS C2.23M/SSPC-CS 23.00	Specification For the Application of Thermal Spray Coatings (Metallizing) Of Aluminum, Zinc, And Their Alloys and Composites for The Corrosion Protection of Steel	2016
EN 17001	Thermal spraying. Components with thermally sprayed coatings. Coating specification	2018
EN 17002	Thermal spraying. Components with thermally sprayed coatings. Thermal spray procedure specification	2018
EN ISO 12670	Thermal spraying. Components with thermally sprayed coatings. Technical supply conditions	2015
EN ISO 12679	Thermal spraying. Recommendations for thermal spraying	2015
EN ISO 12683	Mechanically deposited coatings of zinc. Specification and test methods	2004
EN ISO 14918	Thermal spraying. Qualification testing of thermal sprayers	2018
EN ISO 14921	Thermal spraying. Procedures for the application of thermally sprayed coatings for engineering components	2010
EN ISO 14922	Thermal spraying. Quality requirements for manufacturers of thermal sprayed coatings	2021
EN ISO 14924	Thermal spraying. Post-treatment and finishing of thermally sprayed coatings	2005
EN ISO 2063	Thermal spraying — Metallic and other inorganic coatings — Zinc, aluminum and their alloys	2019
MIL-STD-3021	Materials Deposition, Cold Spray	2008
MIL-PRF-32577	COATING SYSTEM, NONSKID, METALLIC THERMAL SPRAY APPLICATION	2017
SAE AMSC81562A	Coatings, Cadmium, Tin-Cadmium and Zinc (Mechanically Deposited)	2018



> “Hot dipping is a well-established method for producing zinc and aluminum coatings on pipelines.”

Hot dipping is a well-established method for producing zinc and aluminum coatings on pipelines. Standards pertaining to this process are summarized in Table 14. Various pipe standards comprehensively cover the specifications, properties, methods, and requirements for zinc (galvanized) coatings. However, the standardization of aluminum coatings is currently limited to corrugated steel pipes. It is important to note that zinc coatings, known as sacrificial coatings, can react to impurities present in the hydrogen gas stream such as moisture and CO_2. Therefore, when designing and implementing a quality control program for zinc coatings, it is necessary to consider the standards for gas quality in pipeline transportation.

Table 14: Standards for hot dipping pipes with zinc and aluminum coatings and liners

Designation	Title	Publication date
ASTM A53/A53M	Standard Specification for Pipe, Steel, Black and Hot-Dipped, Zinc-Coated, Welded and Seamless	2022
ASTM A929/A929M	Standard Specification for Steel Sheet, Metallic-Coated by the Hot-Dip Process for Corrugated Steel Pipe	2018
CSA G164	Hot Dip Galvanizing of Irregularly Shaped Articles, Includes Update No. 1 (2020)	2018
ISO 1461	Hot dip galvanized coatings on fabricated iron and steel articles – Specifications and test methods	2022
ISO 16172	Steel sheet, metallic-coated by the continuous hot-dip process for corrugated steel pipe	2018

API SPEC 5LD specifically addresses seamless and welded steel pipes with a stainless steel or corrosion-resistant alloy clad layer. These pipes are suitable for use in pipeline transportation systems within the petroleum and natural gas industries due to enhanced corrosion-resistant properties. The grades conform to API 5L standards, covering the range from X42 to X80 (specified minimum yield strength 290 to 555 MPa) and the nominal size ranges from 25 mm (1 inch) to 2,134 mm (84 inches). API SPEC 5LD standard provides guidelines for the manufacturing and performance of clad pipes in pipeline applications, while ISO 24139 series complement this standard by addressing similar aspects related to clad pipe components, such as bends and fittings. The cladding pipes and components specified by standards mentioned above can be used for hydrogen service if they meet the relevant requirements outlined in ASME B31.12.

A list of existing standards pertaining to physical and chemical vapor deposition techniques is summarized in Table 15. The existing standards should be reassessed for pipeline applications since they are currently applicable to electronics, medical devices and automotive applications. It is important to exercise caution as certain vapor deposition methods subject the substrate to elevated temperatures, which can potentially alter the metallurgical microstructure and affect the mechanical performance of the pipeline substrate.

A compilation of relevant standards pertaining to conversion coating methods, including black oxide coating, is summarized in Table 16. The conversion coating method is employed to improve the performance of original coatings by transforming the metallic components into ceramic counterparts, such as nitrides or oxides. As such, the conversion coating method can potentially be used as a post-treatment in conjunction with various metal coatings to create high-performance hydrogen-barrier composite systems, such as Al/Al_2O_3 as reviewed in Section 3.2.5. Black oxide coating, unlike other conversion coatings, oxidizes the steel substrate instead of pre-formed metal coatings. The virgin black oxide coating can only provide mild corrosion protection, so additional post-treatments or integration with other corrosion protection methods may be necessary, depending on specific requirements.

Table 15: Standards for vapor deposition of metal and ceramic coatings and liners

Designation	Title	Publication date
ASTM B699	Standard Specification for Coatings of Cadmium Vacuum-Deposited on Iron and Steel	2021
ASTM B874	Standard Specification for Chromium Diffusion Coating Applied by Pack Cementation Process	2018
ASTM B875	Standard Specification for Aluminum Diffusion Coating Applied by Pack Cementation Process	2018
BS EN 2535	Aerospace series. Vacuum deposition of cadmium	2022
BS ISO 21874	PVD multi-layer hard coatings. Composition, structure and properties	2019
MIL MIL-DTL-83488D	COATING, ALUMINUM, HIGH PURITY	1999
SAE AMS03_28PT1A	Physical Vapor Deposition of Metals: Physical Vapor Deposition of Aluminum for Protection Against Corrosion	2017
SAE AMS03_28PT2A	Physical Vapor Deposition of Metals: Physical Vapor Deposition of Cadmium for Protection Against Corrosion	2017
SAE AMS03_28PT3A	Physical Vapor Deposition of Metals: Physical Vapor Deposition of Titanium Nitride for Surface Protection	2017
SAE AMS2427D	Aluminum Coating Ion Vapor Deposition	2018
SAE AMS2444A	Coating, Titanium Nitride Physical Vapor Deposition	2019

Table 16: Standards for conversion coating of metal and ceramic composite coatings

Designation	Title	Publication date
ASTM B201	Standard Practice for Testing Chromate Coatings on Zinc and Cadmium Surfaces	2019
ASTM B252	Standard Guide for Preparation of Zinc Alloy Die Castings for Electroplating and Conversion Coatings	2020
ASTM B449	Standard Specification for Chromates on Aluminum	2022
ASTM B850	Standard Guide for Post-Coating Treatments of Steel for Reducing the Risk of Hydrogen Embrittlement	2022
ASTM B921	Standard Specification for Non-hexavalent Chromium Conversion Coatings on Aluminum and Aluminum Alloys	2018
ASTM B940	Standard Practice for Testing Non-Chromate Coatings on Zinc and Cadmium Surfaces	2020
EN 12487	Corrosion protection of metals. Rinsed and non-rinsed chromate conversion coatings on aluminum and aluminum alloys	2007
EN 2437	Aerospace series. Chromate conversion coatings (yellow) for aluminum and aluminum alloys	2002
EN 4729	Aerospace series. Trivalent chromium based chemical conversion coatings for aluminum and aluminum alloys	2017
EN ISO 10111	Metallic and other inorganic coatings. Measurement of mass per unit area. Review of gravimetric and chemical analysis methods	2019
EN ISO 2106	Anodizing of aluminum and its alloys. Determination of mass per unit area (surface density) of anodic oxidation coatings. Gravimetric method	2020
EN ISO 3613	Metallic and other inorganic coatings. Chromate conversion coatings on zinc, cadmium, aluminum-zinc alloys and zinc-aluminum alloys. Test methods	2021
EN ISO 9717	Metallic and other inorganic coatings. Phosphate conversion coating of metals	2017
ISO 11408	Chemical conversion coatings. Black oxide coating on iron and steel. Specification and test methods	1999
MIL-DTL-5541F	CHEMICAL CONVERSION COATINGS ON ALUMINUM AND ALUMINUM ALLOYS	2006
MIL-DTL-81706B	CHEMICAL CONVERSION MATERIALS FOR COATING ALUMINUM AND ALUMINUM ALLOYS	2004
MSS SP-157	Quality Standard for Phosphate Surface Protective Coatings for Valves, Fittings, and Related Steel Piping Components	2020
SAE AMS03	Chromate Conversion Coatings (Chromate Filming Treatments) Grades: Standard and Brushing for Aluminum and Aluminum Alloys	2018
SAE AMS2473J	Chemical Film Treatment for Aluminum Alloys General Purpose Coating	2020
SAE AMSC5541A	Chemical Conversion Coatings on Aluminum and Aluminum Alloys	2000

3.3.2.3 Standards for Testing Coatings and Liners of Hydrogen Pipeline Application

The methodologies for testing general physical and chemical properties of raw and bulk materials may not be applicable for the study of coatings and liners, and thus are excluded from this report. Only the standards that specifically address testing of coatings and liners are reviewed in this section.

3.3.2.3.1 Methodology of Testing Hydrogen Barrier Performance

There is currently a lack of standard methodology that evaluates the barrier performance of coatings and liners to high-pressure gaseous hydrogen. Many testing techniques developed for this purpose are adaptations of methods from the existing standards that are not specific to high pressure gaseous hydrogen. These adapted methods are expected to be standardized in future for hydrogen pipeline applications.

ASTM D1434 [148] standardizes the method of measuring gas transmission rate (GTR), permeance and permeability in homogeneous materials. Commercial testing equipment can test gas permeability for various products such as plastic films, composite films, barrier materials, sheets, metal aluminum foils, thin sheets, rubber, porcelain, infusion bags, solar panels, coating sheets and medical patches. The working principle involves inducing a pressure difference between the two sides of a sample, allowing gas permeation along the pressure gradient, measuring the pressure change in the lower-pressure chamber over time, and calculating the gas transmission rate, permeance and permeability coefficient. However, the method tests free film samples and does not take the interface between coating and substrate into account. To test hydrogen permeation through coated pipeline samples, a few modifications are needed:

- Redesign the chamber to fit thicker samples and accommodate higher test pressures.
- Replace the pressure sensor with a high-precision hydrogen probe, since the permeation rate through coated steel is much lower than the individual coating layer.

The Devanathan-Stachurski cell (ASTM G148 [149] and ISO 17081) is a typical method used for testing hydrogen permeation originating from electrolyte. This setup has been modified for evaluating the permeability of gaseous hydrogen through X80 pipeline steel, with the hydrogen charging cell being replaced with a high-pressure autoclave [150]. The setup can be adopted to test coated samples with the coating facing the autoclave side. An *in-situ* silver decoration technique using a light microscope is useful for identifying hydrogen flux through grain boundaries on iron samples [151]. The ease of use and independence from the substrate make this method suitable for testing the integrity of a broad range of coating types, including polymers, metals, ceramics and composites.

Quality control and product screening in the manufacturing industry often prefer pass/fail test methods that detect changes in the mechanical properties of samples under loads that ultimately lead to fracture. Several standards, such as ASTM F519 [152] and ASTM F1940 [153], are used to investigate the likelihood of materials being affected by hydrogen during coating and plating applications. Notched or smooth samples in various shapes are subjected to tensile or bending loads after the plating process, and those that do not fracture after a specific period (typically 200 hours) are considered acceptable [152], [153]. The method can be adopted in conjunction with high-pressure hydrogen exposure, testing the susceptibility of coated samples to gaseous HE.

Standard ASTM G129 [154] uses slow strain rate (SSR) tests to investigate the resistance of metallic materials to environmentally assisted cracking. While popular in academia, this method may not be applicable for testing cracking in coatings, as the coating failure may happen before the failure of the tensile sample that coating is applied to. Researchers have reported modified testing setups that resolve some of these issues, such as replacing solid tensile bars with tubular samples and applying hydrogen pressure inside the tubular specimen, so that the leaking of hydrogen prior to sample failure can be used as an indicator of validating test results [155]. *Ex situ* methods derived from this principle have been reported for testing the hydrogen barrier performance of epoxy coatings on pipeline steel after hydrogen exposure [156]. Martensite steel, which is more sensitive to HE than pipeline steel, could be used in sample preparation to reduce testing errors caused by hydrogen escaping from a sample.

Full-scale testing can be seen as the final design verification that checks the assumptions used in the design. When a system involves many variables and components, the scaling effect becomes more pronounced, making it challenging to understand the interrelationship among variables through smallscale tests. Full-scale tests use full-size pipes as samples (unlike benchtop-scale tests that use small-size specimens) and they can evaluate the performance of non-uniform product effected by complex parameters such as design, manufacture and handling. The full-scale test specimens can include various defects and features, making the test instrument useful to assess legacy pipelines repurposed for hydrogen service, and the effectiveness of rehabilitation approaches such as coatings and liners.

3.3.2.3.2 Methodology of Testing Flow Efficiency

Measuring the surface roughness of a coating is a practical method used in the industry to quantify coating performance in assisting gas flow. For natural gas pipelines, surface roughness requirements for the South Stream offshore pipeline project [31] have been established as the maximum peak-to-valley surface roughness (Rz) ≤ 10 μm, measured in accordance with ISO 4287 [157], currently replaced by ISO 21920-2 [158]. Portable surface roughness testers are available in the market to measure the roughness of coatings. The testers consist of a stylus attached to an arm that records the surface topography and calculates various roughness parameters over a specified distance. However, the measured geometric surface roughness value is not the same as hydraulic roughness value for reduction in flow friction. Although there is a correlation between them, the hydraulic roughness value is influenced by various parameters, such as the pressure and temperature of the gas and the diameter of the pipe, and must be determined experimentally or estimated by empirical models. The models are reviewed comprehensively [159], but neither experimental nor numerical methods have been standardized. Full-scale testing is of interest to pipeline

designers and operators who seek a balance between efficiency and cost. The UKbased utility company National Grid built a hydrogen flow loop to verify the compatibility of X52 pipeline steel and welding in the presence of a 30% hydrogen and 70% methane blend [160]. While the loop was capable of pressure cycling, it was not designed for consecutive continuous flow. To ascertain hydraulic roughness values in a practical and realistic manner, it is critical to use a once-through, adequately extensive loop system as testing platform. Similarly, the best practices of building and operating gas loop systems for flow efficiency study are lacking.

3.3.2.3.3 Methodology of Testing Applicability, Sustainability and Integrity

A holistic evaluation of coatings and liners is necessary for compliance with pipeline design requirements and functionality under varying environmental and operational conditions, as outlined in Table 6. The qualification protocol and product specifications encompass testing methodologies, parameters and acceptance criteria for evaluating the performance of coatings and liners. These variables, such as assigned test parameters and criteria of test results, are typically specified in standards addressing specific application and recommended practices (e.g., the standards reviewed in sections 3.3.2.1 and 3.3.2.2). Meanwhile, the testing methodologies remain relatively stable and are consolidated into individual standards to minimize redundancy and potential inconsistencies among standards. Table 17 provides an overview of representative test methods commonly used for evaluating coatings and liners in pipeline applications.

Table 17: Representative standards for testing pipeline coatings and liners

Test Method	Evaluated properties	Representative standards or clause
Surface preparation	Cleanness and profile of substrate	SSPC-SP 5/NACE No. 1, SSPC-SP 6/NACE No. 3, SSPC-SP 10/NACE No. 2
Knife Adhesion	Adhesion	ASTM D6677, ASTM D3359, ISO 21809-2 Annex A.4, ISO 21809-3 Annex Q, API 5L2 Appendix D
Autoclave/Hydrostatic Pressure Test	Resistance to pressure, chemicals and temperature	NACE TM0185, API 5L7 Appendix 10, ISO 15741 Annex C, ISO 15741 Annex D
Cathodic Disbondment	Compatibility with cathodic protection technology	CSA Z245.20 Section 12.8, CSA Z245.21 Section 12.3, ASTM G8; ASTM G42; ASTM G95; ASTM D 6676/D6676M, ISO 21809-1 Annex H, ISO 21809-2 Annexes A.9, A.10, ISO 15711, NACE TM0115, NACE TM0404 Section 11, NACE TM0304 Section 11 A.15, ISO 21809-3 Annex G, NACE SP0394 Appendix F, API 5L9 Appendix G, API 5L7 Appendix 11
Chemical Resistance	Resistance to chemicals and temperature	API 5L7 Appendix 12, API 5L9 Appendix H, NACE TM0174 Procedure B, ASTM D543 Procedure I, NACE TM0174 Procedure A, ASTM C6943, NACE TM0174 Procedure A, ASTM D870
Electrochemical Impedance Spectroscopy (EIS)	Barrier performance to electrolyte	ISO 16773-2
Evaluation of Blistering	Integrity	ASTM D714, ISO 4628-2
Evaluation of Chalking	Integrity	ASTM D4214, ISO 4628-6
Evaluation of Checking	Integrity	ASTM D660, ISO 4628-4
Evaluation of Cracking	Integrity	ASTM D661, ISO 4628-4
Evaluation of Flaking	Integrity	ASTM D772, ISO 4628-5
Evaluation of Rusting	Integrity	ASTM D610, ISO 4628-3
Film Thickness	Thickness and Uniformity	ASTM D7091, ISO 21809-1 Annex A, ISO 21809-3 Annex B, ISO 2178
Flexibility	Resistance to bending	CSA Z245.20 Section 12.11, ISO 21809-1 Annex I, ISO 21809-2 Annex A.13, NACE TM0404 Section 12, NACE TM0304 Section 12, NACE SP0394 Appendix H, Procedure A, API 5L7 Appendix 13, API 5L9 Appendix I.1 Mandrel Method ASTM D522/D522M ISO 6860
Gel Time of Epoxy Powder	Work time of applying FBE	CSA Z245.20 Section 12.2, ISO 21809-1 Annex J
Glass Transition Temperature (Tg) and/or Heat of Fusion (ΔH)	Thermal characteristics	ASTM D3418, ASTM E1356, CSA Z245.20 Section 12.7, ISO 21809-1 Annex D, ISO 21809-2 Annex 8, ISO 21809-3 Annex P, ISO 11357-2, ISO 11357-3, NACE SP0394 Appendix D, API 5L9 Appendix C, API 5L7 Appendix 5
Gouge Resistance	Resistance to mechanical damage during sliding installation	CSA Z245.20 Section 12.15, CSA Z245.21 Section 12.7, NACE TM0215
Heat Ageing	Resistance to high temperature and air	CSA Z245.21 Section 12.6, ISO 21809-3 Annexes M & N
Holiday	Film continuity	NACE SP 0188, ASTM G62, ASTM D5162, ISO 21809-1 Annex B, ISO 21809-3 Annex C

Test Method	Evaluated properties	Representative standards or clause
Impact Resistance	Resistance to mechanical damage during backfilling and handling	CSA Z245.20 Section 12.12, ASTM G14, ASTM D2794, ISO 21809-1 Annex E, ISO 21809-2 Annex A.14, ISO 21809-3 Annex D, NACE SP0394 Appendix I, API 5L9 Appendix J, API 5L7 Appendix 14
Infrared Spectra Analysis	Molecule functional groups	CSA Z245.20 Section 12.10, ISO 21809-2 Annex A.12, API 5L9 Appendix K, API 5L7 Appendix 15
Interface Contamination	Cleanness of substrate	CSA Z245.20 Section 12.9, ISO 21809-2 Annex A.11, NACE SP0394 Appendix K, API 5L9 Appendix K
Lap Shear Strength	Resistance to axile movement	ASTM D1002, ISO 21809-3 Annex J
Peel Adhesion	Adhesion strength	CSA Z245.21 Section 12.4, ISO 21809-3 Annex H, ISO 21809-1 Annex C, ISO 813 (Modified)
Penetration (Indentation) Resistance	Resistance to acupuncture and indentation	ASTM G17, ISO 21809-1 Annex F, ISO 21809-3 Annex E
Porosity of the Coating	Porosity on the interface and cross-section	CSA Z245.20 Section 12.10; ISO 21809-2
Pull – Off Adhesion	Adhesion strength and fracture mode	ASTM D4541, ASTM D7234, ISO 4624, API 5L7 Appendix 9
Salt Spray	Resistance to offshore conditions	ASTM B117 ASTM G85 ISO 9227 ISO 11997-1
Salt Spray / UV Exposure	Resistance to offshore conditions	ASTM D5894, ISO 11997-2
Shore Hardness	Surface hardness	ASTM D2240, ASTM D3363, ISO 868
Soak Adhesion	Resistance to high temperature water soaking	CSA Z245.20 Section 12.14, ISO 21809-1 Annex L, ISO 21809-2 Annex A.16, ISO 21809-3 Annex I, NACE SP0394 Appendix J, API 5L9 Appendix J, API 5L7 Appendix 16
Specular Gloss	Surface gloss	ASTM D523
Specific electrical insulation resistance	Electrical resistance	ISO 21809-3 Annex F, ASTM D257
Taber Abrasion	Abrasion resistance	ASTM D4060, ISO 9352
Tensile Strength and Elongation	Mechanical properties	ASTM D638, ASTM D2370, ISO 527-3
UV Exposure	Resistance to UV radiation	ASTM D4587 ASTM G154 ISO 16474-3 ASTM G151
Water Absorption	Water up-taking in submersion condition	ASTM D570, ISO 62
Water Vapor Transmission	Barrier performance to water vapor	ASTM D1653, ASTM E96 / ASTM E 96M
Xenon Exposure	Resistance to sunlight radiation an elevated temperature	ASTM G155

3.4 Standardization gaps and recommendations

3.4.1 Critical Needs and Potential Gaps in Regulations and Standards

Current studies and pilot projects discussed in Section 1 provide evidence that natural gas blend ratios of 20% hydrogen by volume or less are safe for transport using existing pipeline infrastructure with minimal or no modifications. For example, Alberta Utilities Commission is in the process of removing the legislative barrier to blending up to 20% [99]. To transport blends with higher hydrogen content, improving material durability and optimizing design in existing natural gas pipelines will be necessary. The literature review has highlighted the technical challenges associated with transporting hydrogen and natural gas/hydrogen blends via natural gas pipelines. However, there remains a lack of consensus among technical experts regarding the long-term effects of high-pressure gaseous hydrogen on pipeline integrity. The literature review suggests the potential benefits of using coatings and liners to mitigate risks associated with hydrogen transport through pipelines. Still, coatings and liners seem to have low priority in current projects and studies exploring conversion of natural gas pipelines, as evidenced by the scarcity of reports found in the literature scan.

Activities for the repurposing of existing pipelines for hydrogen service, and the construction of new pipelines designed for up to 100% hydrogen, primarily focus on the implementation of external coatings for corrosion protection. Meanwhile, the use of internal coatings and liners in these projects has been notably absent [13], [16], [161]. Moreover, the effectiveness of coatings and liners in addressing the unique challenges associated with hydrogen pipelines has not yet been experimentally verified at pilot scale [162], [163]. To advance standardization for hydrogen blending in natural gas pipelines, it is imperative to support research aimed at a deeper understanding of the issues and the exploration of mitigation approaches.

Crucial to the development of codes and standards for coatings and liners for hydrogen blending in natural gas pipelines is extensive research and development of methodologies for the evaluation of coating and liner behavior and performance throughout the entire lifespan of a pipeline. This includes various phases such as handling, storage, transportation, bending, installation, welding, backfilling, hydrostatic testing, inspection, operation, repair, repurposing and rehabilitation of the pipeline system.

While industry knowledge in this area has been steadily improving, there is still a substantial need for research and development to gain a comprehensive understanding of how different coatings and liners perform in terms of barrier properties and flow efficiency when exposed to hydrogen gas and gas blends. This understanding is essential for addressing the unique technical challenges associated with hydrogen pipelines, as discussed in Section 3.1. Furthermore, the industry has established practices for maintaining the integrity of coatings and liners during pipeline activities, and protecting pipelines from corrosion and mechanical damage using these coatings and liners. Leveraging this practical experience can contribute to the standardization of coatings and liners for hydrogen service.

3.4.1.1 Coating and Liner for Pipeline Envisioned for Hydrogen Service

The characteristics of potential coatings and liners for hydrogen pipeline service are reviewed in Section 3.2 and summarized in Table 18.

Table 18: Comparison of polymer, metal, ceramic and composite coating and liner characteristics as applicable for hydrogen pipelines

Item	Polymer	Metals	Ceramic	Composite
Commercial products	▪ PE (Internal and external) ▪ Epoxy (internal and external) ▪ PVA (Internal) ▪ PVDC (Internal)	▪ Nickel (Internal) ▪ Zinc (Internal) ▪ Copper (Internal) ▪ Aluminum (Internal) ▪ Stainless Steel Cladding (Internal)	▪ Black oxide (Internal) ▪ Vitreous coatings (Internal)	FRP liner (Internal)
Commercial application method	**In-plant:** Extruding, Casing, Spray **In-field:** Brush, Spray, Wrapping	**In-plant:** ▪ Electroplating ▪ Electroless plating ▪ Hot dipping ▪ Hot roll cladding ▪ Weld cladding ▪ Thermal spray **In-field:** ▪ Thermal spray ▪ Weld cladding	**In-plant:** ▪ Oxidation ▪ Molten application ▪ Thermal spray **In-field:** ▪ Thermal spray	FRP liner is manufactured in plant and installed in field
Hydrogen Barrier Performance	PVA and PVDC have much lower hydrogen permeability than the more widely used epoxy and PE	Widely used Nickel, Zinc, Aluminum and Stainless steel should be good as hydrogen barrier materials	Most of ceramic materials should be good as hydrogen barrier materials	Depends on the performance of inner layer
Flow assisting performance	Epoxy is the most widely used for natural gas flow enhancement and demonstrated compatible with hydrogen conditions	Electroplating and electroless plating can achieve smooth surface	PVD and CVD can produce smooth surface	Depends on the surface roughness of inner layer
Resistance to corrosion and abrasion	PE and epoxy are good for most of oil and gas transporting conditions including the corrosive impurities in hydrogen flow	Noble metals and corrosion resistance alloy can provide good performance	Best performance but heavily depends on thickness and defections	Depends on the material selected for inner layer and external layer
Resistance to mechanical damage	PE and epoxy with proper thickness show high performance	Good due to combination of toughness and ductility	Usually, poor due to brittle feature	Depends on the main and reinforce layers
H_2 permeability data availability and evaluation methods for HE mitigation	Available for free film Method in need to test coated sample with interface involved	Available for high temperature Method in need to coated sample at pipeline operation conditions		Resources for polymer pipe and liner might be applicable to polymer-based composite
Qualification protocol for pipeline service	Comprehensive	Individual test methods are available. Qualification protocol dedicated to pipeline is not available		The polymer's qualification protocol might be applicable to polymer-based composite

Several notable gaps have emerged from the comparison provided in Table 18:

- **Practical application methods:** There are practical challenges for the application of some highperformance coatings and liners to large-scale infrastructure, such as cost, strict application conditions and difficulty in scaling-up. To address those issues, further research and development efforts are required to expand the engineering limits of application equipment and reduce associated costs.
- **Compatibility with existing procedures:** Certain high-performance coatings envisioned for hydrogen pipelines such as metal and ceramic coatings may not align with current pipeline manufacturing, handling, joining, inspection and commissioning processes. As shown in Table 18, for example, the ceramic coating is brittle, so the coated pipe cannot be bended in the field. Some of the metal and ceramic coatings are not weldable. The inspection of metal and ceramic coatings is different from polymer coatings. This suggests a potential need to revise existing best practices throughout the entire lifespan of a pipeline to accommodate these advanced coatings.
- **Qualification protocol applicability:** Existing qualification protocols for pipeline coatings and liners are primarily designed for polymer systems. They may not be directly applicable or suitable for evaluating metal, ceramic and composite coating systems. For example, the holiday detector used for polymer coating cannot be used for metal coating. Polymer coating test conditions and criteria are not applicable for ceramics. Thus, there is a need for specialized protocols in these cases.
- **Failure analysis under hydrogen service conditions:** Studying the failures of coatings and liners operating under hydrogen pipeline conditions is crucial for technological advancement and quality management. Unfortunately, research in this area has been limited, highlighting a significant gap in our current knowledge base.

3.4.1.2 Gaseous HE Mitigation

The literature review and interviews have revealed that no internal coating or liner has been employed to mitigate gaseous HE in hydrogen pipelines. Furthermore, no existing standards or regulations provide guidelines for hydrogen barrier coatings and liners for prevention of HE. However, there are noteworthy research reports suggesting the potential effectiveness of internal coatings or liners in mitigating gaseous HE, with a few industry and academic efforts to verify their viability, as discussed in Section 3.2.

Hydrogen permeability serves as a critical parameter for assessing the performance of coatings and liners as hydrogen barriers. Extensive testing results have been generated for materials in film form using standardized test methods, offering valuable benchmarks for evaluating materials intended for use as hydrogen barrier coatings and liners. It is important to recognize that coatings applied to pipelines are bonded to the substrate and do not function as a free film. Therefore, the development of standardized methods to test the coated sample, accounting for both coating material properties and interfacial effects, is crucial for qualifying hydrogen barrier performance. In contrast, assessing the hydrogen barrier performance of liners that do not bond to the pipeline substrate can be accurately accomplished using standardized methods outlined in ASTM D1434.

Currently, there is a substantial body of research on the hydrogen permeability of polymer materials, while data on the hydrogen permeability of other potential materials for hydrogen pipeline service remains relatively limited. Establishing a comprehensive database of hydrogen permeability measurements for coatings and liners made from a range of materials, including polymers, metals, ceramics and composites, would greatly benefit industry, regulators and innovators.

Given that HE is a time-dependent process and no material is entirely impermeable to hydrogen atoms, the development of standardized methods for testing the gaseous HE resistance of pipelines equipped with internal coatings and liners is essential. Such methods would serve to qualify these coatings and liners as viable HE mitigation strategies and would enable the evaluation of their long-term performance, which is a concern of industry experts and regulatory bodies. Additionally, achieving consensus and standardization on acceptance criteria for coatings and liners as long-term HE mitigation approaches – such as specific hydrogen permeability thresholds, the duration of HE resistance and the extent to which mechanical properties of the pipeline substrate are maintained after hydrogen exposure – should be a vital component of forming the expected qualification protocol.

3.4.1.3 Improving Gas Flow Efficiency

The pipeline industry acknowledges the advantages of flow-efficient coatings, and several existing standards could guide the adoption of these coatings in natural gas pipelines. In comparison with corrosion protective coatings and liners, the implementation of flow-efficient coatings is typically at the discretion of the pipeline owner and designer, rather than being mandatory requirements of current Canadian pipeline regulations and standards.

While there are existing standards relevant to flow-efficient coatings, these standards primarily emphasize the coating integrity during various pipeline activities. They do not explicitly address the performance of these coatings in reducing friction within the pipeline. Moreover, this study's literature review did not identify any standards specifically dedicated to flow-efficient liners.

The current method for evaluating the friction reduction performance of coatings relies on surface roughness measurements. Surface roughness assessment follows standardized procedures for quantifying geometric surface irregularities, as in ISO 21920-2 and ISO 12085 [164]. However, there is a lack of consensus and standards regarding the numeric criteria for evaluating friction reduction based on surface roughness measurements. Furthermore, hydraulic roughness, which is a critical factor in determining friction-reduction performance, lacks standardized experimental or numerical methods for its evaluation. The absence of such standardized methods poses a challenge when assessing and comparing the friction-reduction capabilities of different coatings and liners.

3.4.1.4 Corrosion and Mechanical Protection

The use of coatings and liners to prevent corrosion and mechanical damage throughout a pipeline's lifespan is well-established within the current Canadian regulatory and standard framework. However, the existing pipeline regulations need to be reviewed and amended to provide clarification regarding hydrogen blending ratios within natural gas pipelines, as reported, for example, by the Alberta Utilities Commission [99], and to account for the unique properties of hydrogen.

The current editions of Canadian standards, such as CSA Z662, the CSA Z245.20 series and CSA Z245.30, provide comprehensive guidelines for the qualification, performance and best practices associated with the application, inspection, testing, handling and storage of external coatings on pipelines. However, they are missing requirements for coating performance criteria specific to hydrogen service, such as hydrogen permeability. The review of standards addressing coatings and liners for pressure equipment and vessels for hydrogen service, as discussed in Section 3.3.2.1.2, could help establish and harmonize these requirements.

The standards for internal coatings and liners referenced in CSA Z662:23 cover a limited range of polymer coating and liner types, such as epoxy, polyethylene (PE), polyvinyl chloride (PVC), polyamide (PA) and reinforced composites. While these standards can be modified to accommodate emerging coating and liner systems, such as polyamide vinyl (PAV), polyvinylidene chloride (PVDC) and polymerbased composites, no established pipeline standards currently apply to metal and ceramic-based coating and liner systems for hydrogen service. The technical feasibility and economic viability of adopting these innovative coating and liner systems for pipeline structures necessitate further investigation.

3.4.2 Recommendations for Standards

This section prioritizes several recommendations for regulations and standardizations to accelerate the safe and efficient integration of hydrogen into our energy infrastructure. These recommendations aim to bridge existing gaps, foster collaboration among interested parties, and create a conducive environment for research and innovation in the field of hydrogen pipeline coatings and liners.

> **Recommendation #1:** Establish stand-alone standards dedicated for pipeline internal coatings, following the style of external coating standards CSA Z245.20 series and CSA Z245.30.

The current Canadian standards for internal coatings and liners specified in CSA Z662 lack detailed requirements. These standards primarily focus on corrosion protection and, although they reference a list of international standards for liner products, they do not provide sufficient guidance for internal coatings. To address this gap, it is recommended to update the existing standards and create dedicated standards for internal coatings, following the style and structure of existing external coating standards such as CSA Z245.20 series and CSA Z245.30.

The proposed internal coating standard could initially focus on epoxy coating systems, as they are the only available gas flow-efficient coatings in the market and have demonstrated compatibility with the operational conditions of hydrogen pipelines. By developing this dedicated standard, the industry can benefit from a comprehensive set of guidelines and best practices that specifically address the needs of internal coatings in pipelines. Such a standard could reference existing internal epoxy coating standards reviewed in Section 3.3.2.2.4, modifying requirements as necessary to reflect the unique operational conditions of hydrogen pipelines.

While the initial standard may primarily cover epoxy coatings, future updates could include additional coating systems and methodologies for evaluating friction reduction performance, as research and understanding in flow science advance.

> **Recommendation #2:** Standardize material qualification protocols for hydrogen pipelines as a precondition of standardizing hydrogen infrastructure components, such as coatings and liners.

To address the unique material requirements for hydrogen pipelines, it is recommended to develop standardized material qualification protocols. ANSI/CSA CHMC 1 and ANSI/CSA CHMC 2, which provide standard material qualification procedures for the automotive industry, can serve as a foundation for these protocols.

The applicability of testing conditions and criteria for screening tested materials should be evaluated and, where feasible, the test methods should be adapted from existing standards. The testing conditions and acceptance criteria should align with the requirements outlined in key hydrogen pipeline standards such as CGA G-5.6, ASME B31.12 and CSA Z662 hydrogen service requirements.

Developing this standard for material qualification can benefit the hydrogen pipeline industry by helping to ensure that materials used in pipeline construction meet the demands of hydrogen transportation. It will also encourage the development of equipment and technologies tailored to hydrogen pipelines, including innovative coating and liner products and application methods.

> **Recommendation #3:** Standardize qualification protocols for internal coatings and liners as HE mitigation measures when the best practice of testing hydrogen barrier performance is established by industry or academia.

To enable manufacturers and innovators to evaluate the performance of coating and liner products for HE mitigation, it is recommended standardized qualification protocols be established. These protocols should provide a systematic approach for assessing the effectiveness of coating and liner materials in mitigating HE.

The protocols should consider multiple parameters for quantifying HE mitigation performance. These parameters could include specific hydrogen permeability, the duration before HE failure occurs, and the extent to which the mechanical properties of the pipeline substrate are maintained after exposure to hydrogen. All tests should be conducted on coating products in their functional forms, such as coated steel panels or internally coated pipe spools. Testing hydrogen permeability might be conducted on liners with free-standing configurations, such as free films or tubular liners, but other parameters should be tested on liners in their functional forms, such as pipe spools with liner insertion. Many testing methods have been discussed in Section 3.3.2.3.1, but industry and academia have not reached a consensus of best practices for evaluating HE mitigation performance.

The testing conditions and acceptance criteria within these protocols should align with the requirements specified in key hydrogen pipeline standards, including CGA G-5.6, ASME B31.12 and CSA Z662 hydrogen service requirements. It may be advisable to adopt conservative acceptance criteria, given the current lack of clarity regarding long-term material durability under the conditions of high-pressure gaseous hydrogen. Stricter testing methods, conditions, and criteria should be applied when coating and liner products are intended for use in pipeline rehabilitation scenarios.

> **Recommendation #4:** Standardize the best practice of adopting internal coatings and liners for pipeline rehabilitation derived from technical specifications provided by manufacturers and contractors

Pipeline rehabilitation is a crucial step in repurposing existing natural gas pipelines for hydrogen service. However, there is currently a lack of detailed best practices for using internal coating and liner materials in pipeline rehabilitation within Canadian regulations and standards. To address this gap, it is recommended to develop standardized best practices for the use of internal coating and liner materials specifically in the context of pipeline rehabilitation. These best practices should provide clear guidelines for assessing integrity risks, selecting appropriate rehabilitation methods, and defining expected performance outcomes.

Given that internal coating and liner materials have distinct product forms, application methods and applicability, it is advisable to address them separately within the best practice guidelines. The guidelines can include a summary of common rules and principles derived from technical specifications provided by various manufacturers and contractors. In addition, the qualification protocols for internal coating and liner materials used in pipeline rehabilitation should align with the requirements outlined in CSA Z662 and CSA Z245 series, as well as the standards proposed in Recommendations #2, #3 and #4. These protocols should outline performance criteria that meet safety requirements for hydrogen pipeline rehabilitation, as well as standards for repurposing of existing natural gas pipeline for hydrogen service.

> **Recommendation #5:** Standardize best practices and qualification protocols of emerging coatings and liners for hydrogen pipeline service

Several promising polymer, metal, ceramic and composite materials reviewed in Section 3.2 have properties that can address the challenges identified in Section 3.1 for hydrogen pipeline service. However, the practical application of these materials as coatings or liners on pipelines may not be realized until advancements in technology make the process economically and technically feasible. To address the integrity and performance of emerging coating and liner materials for hydrogen pipeline service, it is recommended to develop standardized best practices and qualification protocols.

These best practices should cover all aspects of the lifespan of hydrogen pipelines, including handling, qualification, manufacturing, storage, application, transportation, installation, inspection, repair, commissioning, operation, maintenance, rehabilitation and abandonment. The current experience and established standards for polymer coatings and liners used on steel pipelines may not be applicable to the emerging coating, liner and even pipeline technologies, suggesting a need for extensive research ahead of standardization. The testing methods included in the qualification protocols can reference the standardized methods reviewed in Section 3.3.2.3.3, with specific adjustments made according to the material type of the emerging coating and liner. Additionally, the testing conditions and acceptance criteria outlined in the qualification protocols should be determined based on the requirements established within the discussed best practices.

4 Conclusions

This report has provided a review of potential coating and liner technologies for hydrogen pipelines and equipment, as well as the relevant standards, codes, best practices and applicable Canadian regulations. In addition to protecting the pipeline infrastructure from corrosion and mechanical damage, coatings and liners are envisioned as potential mitigation measures addressing the unique technical challenges posed by gaseous hydrogen and new technologies in hydrogen pipelines. These challenges include gaseous hydrogen embrittlement (HE), energy transportation efficiency, repurposing existing natural gas pipelines for hydrogen service, blending hydrogen into natural gas pipelines, and the side effects of HE inhibitors.

Some existing and emerging technologies, including polymer, metal, ceramic and composite systems, may be feasible for hydrogen pipeline applications as internal coatings and liners, and can help address the challenges mentioned above.

- **Polymers:** Polyethylene (PE) and epoxy resin are the most widely used coating and liner systems in the current natural gas pipeline industry, and they can withstand operational conditions of hydrogen pipelines. Commercial flow efficiency epoxy coatings are most likely applicable to hydrogen pipelines. Polyvinyl alcohol (PVA) and polyvinylidene chloride (PVDC) show good hydrogen barrier performance, but ease of application and chemical resistance need to be improved by further study.
- **Metals:** Nickel, zinc, copper, aluminum and stainless steel may perform as hydrogen barrier coatings, due to low permeability and maturity of application methods.
- **Ceramics:** Oxides and nitrides show higher hydrogen barrier performance, but their use in hydrogen pipelines is restricted by their brittle nature and challenges in scaling-up application methods. Black oxide and vitreous coatings may be more practical than the other ceramic coatings since their application methods are applicable to large pipeline structures.
- **Composites:** Fiber reinforced polymers (FRP) and spiral interlocking pipes have been used for hydrogen pipeline applications. Their performances in hydrogen permeation, mechanical strength, flow efficiency and corrosion resistance depend on the material selection in individual layers and fabrication methods.

For external coatings on hydrogen pipelines, function is similar to those applied on natural gas pipelines. This suggests that existing technologies, best practices, standards and regulations relevant to current external coatings can be applied to hydrogen pipelines with revisions in order to comply with the more stringent safety requirements outlined in the international hydrogen pipeline standards.

The minimum requirements for internal coatings or liners used in hydrogen pipelines are to maintain their material properties and structural integrity – remaining either unchanged or within permissible limits. The qualification protocol can reference existing standards for internal coatings and liners in natural gas pipelines, with modifications to test conditions and acceptance criteria to align with hydrogen pipeline requirements. Commercially available internal coatings and liners made of epoxy, PE and RFP may be expected to meet the minimum requirements for hydrogen service. The established best practices associated with these coating and liners, as standardized for natural gas pipelines, remain applicable to hydrogen pipelines, as long as they continue to fulfill their intended purposes, such as friction reduction, corrosion protection and erosion resistance.

While the effectiveness of coatings and liners in addressing the unique challenges of hydrogen pipelines has not been experimentally proven, their potential to mitigate hydrogen embrittlement and improve flow efficiency is considered. To promote the advancement of hydrogen pipelines and coating and liner technologies, there are opportunities to streamline the process through standardization. The following recommendations are prioritized to facilitate the safety, quality, economy, innovation and sustainability of transition to hydrogen era.

- Establish stand-alone standards dedicated for pipeline internal coatings, following the styles of external coating standards like CSA Z245.20 series and CSA Z245.30.
- Standardize material qualification protocols for hydrogen pipeline as a precondition of standardizing hydrogen infrastructure components, such as coatings and liners.
- Standardize qualification protocols for internal coatings and liners as HE mitigation measures when the best practice of testing hydrogen barrier performance is established by industry or academia.
- Standardize the best practice of adopting internal coatings and liners in pipeline rehabilitation derived from the technical specifications provided by manufacturers and contractors.
- Standardize the best practice and qualification protocols of emerging coatings and liners for hydrogen pipeline service

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