Quadrennial Technology Review 2015

Chapter 7: Advancing Systems and Technologies to Produce Cleaner Fuels

Technology Assessments

Bioenergy Conversion

Biomass Feedstocks and Logistics

Gas Hydrates Research and Development

Hydrogen Production and Delivery

Natural Gas Delivery Infrastructure

Offshore Safety and Spill Prevention

Unconventional Oil and Gas

U.S. DEPARTMENT OF ENERGY

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Natural Gas Delivery Infrastructure

Chapter 7: Technology Assessments

Introduction and Background

The U.S. natural gas delivery system is an extensive network composed of over 315,000 miles of transmission pipeline and over 2.1 million miles of distribution mains.[1] In 2015, this system moved over 25 trillion cubic feet (tcf) of natural gas,[2] providing transport for fuel that is critical to meet the nation's energy needs and to sustain the U.S. economy. Every day, these pipelines carry natural gas to industrial, commercial, and residential customers, providing a chemical feedstock for industrial processes, fuel for electricity generation, and heat for businesses and homes.

Advances in unconventional gas production technology have driven down costs, enabled a rapid increase in domestic gas production, and are driving expansion of the nation's gas pipeline infrastructure. In the decade between 2002 and 2012, U.S. natural gas production increased 25%.[3] An abundant gas supply resulted in the domestic price of natural gas dropping to $3.35/thousand cubic feet at the end of 2012, and natural gas prices fell by 75% from 2005 to 2013.[4] As a result, natural gas has become more affordable in the United States, reducing consumers' energy expenses and boosting the global competitiveness of domestic manufacturers. In addition, the country's legacy distribution pipeline infrastructure is gradually being replaced, mainly to ensure that it continues to operate safely. Between 2005 and 2013, more than 9% of pre-1970 transmission lines and distribution mains were replaced.[5] However, projected pipeline replacement rates, as reported in Table 2-3 of the Quadrennial Energy Review for a select group of regulated utility distribution systems, vary considerably and can range from about one decade to more than eighty years.[6]

Some natural gas that enters the transmission system is used to fuel pipeline compressors, is vented, or leaks. Roughly 9% of the nation's delivered natural gas is consumed by equipment that is used for natural gas production, processing, and for the operation of transmission infrastructure, primarily for compressors that push the natural gas through the pipelines. Some natural gas is vented during maintenance or during pipeline operation, or is leaked from different parts of the system. Although new pipes, compressors, and components with higher efficiency and reliability are being installed, pipeline operators generally replace legacy infrastructure only when it is economical to do so or when safety or environmental mandates require it. The economic potential of natural gas that is consumed in the transmission and distribution system, either via use or leaks, is lost. In addition, methane, the primary component of natural gas, is a powerful greenhouse gas. Thus, fugitive emissions and losses from leaks in natural gas infrastructure negatively impact both the environment and the economy. Reducing methane emissions is important in today's marketplace and environment.

While some energy is needed to move natural gas through the pipeline network, a natural gas transportation system that consumes or loses too much natural gas is inefficient. Yet "efficiency" can be measured in several ways, and losses occur at numerous locations within the transmission and distribution network.[7]

Hydraulic efficiency measures the pressure drop that occurs as gas moves through the pipeline network. It is affected by factors such as pipeline geometry, pipe surfaces, etc.

Thermal efficiency refers to the conversion of chemical energy to mechanical energy when natural gas is consumed as a fuel. It is impacted by factors such as the design of the engine used to drive compression (centrifugal versus reciprocating), engine maintenance, etc.

Compressor efficiency measures the energy used to compress natural gas in the system as opposed to merely heating it. It is influenced by factors such as the internal aerodynamics of the compressor and manifold.

Hydraulic, engine, and compressor inefficiencies can all be minimized but never eliminated, because of thermodynamic constraints. For example, the maximum theoretical thermal efficiency of an engine is determined in part by the combustion temperature of the fuel compared to the ambient temperature. Some energy is lost as waste heat even in an ideal, unattainable scenario.

Pipeline systems are designed to efficiently supply natural gas at a planned rate. Compressors may not operate as efficiently if demand deviates from the designed optimum supply rate. Natural gas demand is seasonal, so natural gas systems must often operate at supply rates that are different than their designed optimum, lowering their efficiency. In addition, supply and demand can vary regionally over time. Because natural gas systems can last for decades, they may operate at flow rates significantly different than they were designed for—lowering efficiency—as populations shift, old sources of natural gas are depleted, and new sources of natural gas are developed.

Various technologies and strategies have been implemented for monitoring pipelines, from physically walking the lines to satellite surveillance. The most common technology to protect pipelines from occasional leaks is computational pipeline monitoring or CPM. CPM takes information from the field related to pressures, flows, and temperatures to estimate the hydraulic behavior of the product being transported. Once the estimation is completed, the results are compared to other field references to detect the presence of an anomaly or unexpected situation, which may indicate a leak.

Emerging technologies can play an important role in reducing leaks and increasing system efficiency if they offer superior performance and/or a lower cost than existing CPM technologies. High-efficiency next-generation compressors, novel sensors and controls, pipeline inspection and repair technologies, external leak detection and flow rate quantification technologies, and advanced pipeline materials can further increase the efficiency of the nation's natural gas pipeline infrastructure, conserving a critical domestic energy resource while simultaneously reducing greenhouse gas emissions. These five areas have been identified as priority R&D topics through extensive engagement with industry, national lab, university, and public experts and are discussed individually in the following sections of this technology assessment.

High Efficiency Next Generation Compressors

R&D Drivers and Current State of the Art

With the expected future expansion of the nation's midstream infrastructure, there is a need for improved natural gas compression systems and/or controls to reduce CO_2, CH_4, and other emissions; increase operational efficiency; and potentially increase the capacity for in-pipe gas storage, which would provide better response to quickly changing gas demand profiles.

Compressors and compressor stations are the largest sources of gas consumption and losses from the natural gas system, accounting for approximately 86% of gas that is lost in the transmission and distribution network.[8] The majority of this gas (76%) is burned to power the reciprocating and centrifugal machinery that moves natural gas through the system,[9] and another 8% of the lost gas leaks from the seals in this equipment. An additional 1% of lost natural gas is emitted unburned in the exhaust of these systems. Finally, roughly 1% of natural gas lost from the U.S. pipeline network leaks from the valves and piping within the stations that house the system's compressors.[10] Given that compressors and compressor stations are where the majority of losses occur, technologies in this area represent a major opportunity for increasing the efficiency of the transmission and distribution system.[11,12]

Some amount of energy must be expended to move natural gas through pipelines, due to the movement of a compressible gas through a hydraulically inefficient system. Compression for natural gas transmission is provided by two types of compressors. Centrifugal compressors combust natural gas to rotate turbine blades, which compress the gas. Centrifugal compressors were traditionally equipped with wet seals, in which oil blocks the flow of natural gas out of the compressor into the surrounding air. Natural gas is soluble in these oils and will slowly dissolve into the oil and diffuse through it until the gas can escape into the air, typically at rates of up to 200 scfm (standard cubic feet per minute).[13]

Reciprocating compressors are powered by large internal combustion engines that compress natural gas with a piston in a cylinder. Rod packing seals are placed around the piston to prevent the escape of gas. However, friction between the seal and the rod packing case slowly wears out the seals, which must be regularly replaced to minimize leakage.

Natural gas pipeline systems can last for decades. They are designed to maximize the efficiency of supplying expected peak loads. Natural gas demand exhibits both daily and seasonal variation. Deviations from expected load and high ramp rates can diminish system efficiency.

R&D Challenges and Opportunities

"Next generation" compressors must be designed for increased efficiency, operational flexibility, long service life, and reduced methane emission levels from combustion, venting, and fugitive sources.[14] Research and development opportunities for improving technologies that could be part of next generation compressor designs fall generally into the four categories below.

Centrifugal compressor technology R&D opportunities include the following:

- Develop low-maintenance, low-cost dry seal designs that minimize methane leakage where the drive shaft enters the compressor housing.
- Broaden the operational window at which centrifugal compressors operate efficiently through design of automatically variable inlet and diffuser vanes.
- Improve the design of hermetically sealed compressors to allow scale-up to high-flow / low-compression ratio transmission uses.
- Develop improved low-maintenance, low-friction bearing technology.
- Develop alternatives to start-up and shut-down methods which result in gas venting and improve methods for capturing, converting, and reusing vented gas.

Reciprocating compressor technology R&D opportunities include the following:

- Design low-maintenance, low-cost, improved piston rod sealing technologies that are either low- or zero-emission and incorporate a static sealing system as part of the design.
- Design high-efficiency, long-life intake and outlet valves.
- Develop more efficient pulsation control designs for reduced power and pressure losses.
- Develop better damping materials and devices for vibration control.
- Develop alternatives to start-up and shut-down methods which result in gas venting and improve methods for capturing, converting, and reusing vented gas.

Technologies to reduce emissions from prime mover combustion has R&D opportunities such as the following:

- Explore further the application of exhaust gas recirculation (EGR) technology to natural gas engines, for example related to the design of retrofit systems on existing units that do not employ EGR technology.
- Develop advanced ignition technologies to reduce fuel losses from incomplete combustion.
- Design improved nonselective catalytic reduction (NSCR) systems in rich-burn natural gas-fired reciprocating engines to maximize the reduction of methane emissions.
- Develop advanced catalyst formulations to effectively reduce CH_4 emissions at exhaust temperatures ranging from 400 F to 1100 F.
- Explore various waste heat recovery techniques such as organic Rankine Cycle (ORC) to increase engine efficiency.

Sensor technology R&D opportunities include the following:

- Develop low-maintenance, long-life sensors for monitoring compressor systems.
- Design sensor control systems that rely more on model-based control and require placement of fewer sensing devices in critical compressor components which can then require shutdown for maintenance or repair.

Novel Sensors and Controls

R&D Drivers and Current State of the Art

Operators desire a lower cost method of identifying leak locations without having to rely on high-cost monitoring equipment. The RD&D of "smart" sensors within natural gas pipelines could improve cost-effective communication of a variety of operational parameters (e.g., pressure, Btu quality, internal pipe corrosion, and flow rate), provide a continual leak detection capability, and support the quick isolation and shutdown of discrete sections of pipeline in cases where ruptures have occurred. Such sensors could facilitate the development of a "decision support system" that integrates leak detection, leak flux quantification, and integrity-related data to enable a predictive capability. Such a system would employ a variety of mathematical tools to predict the likelihood of CH_4 emissions and proactively direct and prioritize inspection efforts.

While compressor stations are a major source of natural gas transmission leaks, leaks in the pipeline can be difficult to detect and can have catastrophic consequences. Sensors that detect strain and damage can assist pipeline operators in their inspection and maintenance schedules, thus ensuring that potential risk management problem areas are identified early.

Better collection and implementation of data derived from sensors will reduce pipeline degradation, leaks, and accidents. Better data use can allow more efficient delivery of natural gas to markets with irregular demand. Data is not aggregated at an industrial level today, and not in a standardized way. Tools for data analysis are inadequate for the breadth of data across the industry. Much of the data is proprietary or confidential and may be coupled with security risks, and companies may be reluctant to publish information about their issues, troubles, or incidents. Even with better sharing of data, analytical tools cannot yet capture and synthesize data sufficiently to maximize safety and efficiency.

R&D Challenges and Opportunities

Examples of desired technologies that are responsive to this need for novel sensors and controls to mitigate methane emissions and enhance operational efficiency include:

- miniaturized, robust sensors that perform well in harsh environments;
- sensor applications that make use of nanotechnology;

- automated, networked, scalable sensing and control systems; and
- automatic metering addition of linear displacement sensors (real-time monitoring through supervisory control and data acquisition or SCADA systems).

Further R&D on each of these technologies would advance their capabilities to provide significant cost-effective capabilities for system sensing and data collection, providing the foundation for analysis of the state of the system and appropriate control and correction.

Decision support systems must be capable of merging disparate data sources from SCADA systems, advanced metering infrastructure, and sensor networks dispersed throughout the infrastructure system into a knowledge base that can integrate these data into actionable responses needed by the operator.

The comprehensive situational awareness that such a decision support system would support multiple analytical and optimization frameworks, as illustrated by the following examples:

- Better load forecasts, network monitoring, and demand management techniques would enable improved asset utilization and capital deployment, and increase the useful life of equipment.
- Robust and flexible infrastructure would better respond to consumer needs and enable pipelines and local distribution companies to safely and efficiently increase capacity and actively manage volume, pressure, and temperature using a network of sensors, two-way communications, and automation.
- Direct communication would allow natural gas suppliers to respond to fluctuations in electricity production more quickly and efficiently. Fast-ramping gas-fired power generation can complement variable renewable resources to improve electricity reliability and security.
- Integration with cyber-security systems would allow potential for identifying and preventing cyber-attacks on the natural gas delivery infrastructure.

Real-time information about weather, demand, infrastructure, and operating conditions should be shared among all parties. Demand forecasts for electricity should be made available to gas suppliers, helping ensure fuel is available when and where it is needed. Energy market information should be made available, allowing tighter coordination between pipeline and electric grid operators. New and advanced in-pipe real-time gas sensors that communicate with the pipelines Supervisory Control and Data Acquisition system (SCADA) will enable improved coordination of wholesale natural gas and electricity market scheduling as the nation increasingly relies on gas for electric generation. This will help ensure the reliable and efficient operation of both the interstate natural gas pipeline and electricity systems.

Pipeline integrity management monitoring of GHG emissions, response to accidents, and optimization of replacement programs would all be greatly enhanced by the existence of a cohesive decision support system. Such a system may also support the development of federal, regional, and state regulatory policy optimized to achieve societal public benefit objectives, such as GHG reductions. A properly balanced infrastructure management and development program would help ensure an energy delivery system capable of supporting sustained economic growth across all sectors.

A number of potential research opportunities to improve pipeline operational efficiency relate to both sensors and the management/application of the data they produce, such as:

- Improve standards for pipeline data collection/sharing/safeguarding.
- Improve analytical tools for increasing pipeline safety/efficiency and reducing methane emissions.
- Improve pipeline sensor and control data protocols.
- Develop smart systems to mitigate human error and maximize efficiency.

Pipeline Inspection and Repair Technologies

R&D Drivers and Current State of the Art

Research on lower cost, more effective technologies for inspecting pipelines internally and externally could enable the identification and discrimination among different types of internal and external pipe anomalies, the navigation through a variety of pipeline sizes and configurations, and the evaluation of pipeline conditions quickly from a distance and without the need for major excavation. These would have substantial safety, emissions, and cost benefits. In addition, R&D on cost-effective and safe technologies and/or methodologies that would permit pipelines to be inspected and repaired without CH_4 emissions, and potentially tested without the use of water (see hydro-testing in glossary), could enable implementation of a more systematic and comprehensive inspection regime.

R&D Challenges and Opportunities

The following list includes examples of technology R&D opportunities involving pipeline inspection and repair that could lead to avoidance of pipeline blowdown and venting:

- Improved inline inspection technologies including low-cost robotic platforms.
- "Smart ball" technology to perform internal pipe inspection.
- Portable compression or transfer compressor or other novel alternatives to capture natural gas that would otherwise be emitted.
- Real-time pipeline surface corrosion detection through ultrasonic testing.
- Modeling to support direct assessment of corrosion and defects.
- Technologies that facilitate live insertion and removal of pipeline components.

Long-range guided-wave ultrasonic testing is being developed to detect metal loss in pipelines in real-time. R&D is needed to reduce false positives and enable the calculation of likely failure pressures. Corrosion modeling R&D work is needed to enable determination of where corrosion is most likely, and direct assessment is needed. Corrosion modeling would also aid in determination of appropriate intervals for direct assessment.

Several research goals related to pipeline repair technologies that are focused on live pipeline component replacement have been identified. Repairing pipelines without the need to shut down segments and vent gas prior to repairs could significantly reduce methane emissions. The development of new protocols for testing live-switched components and advanced-geometry components suitable for direct insertion have been identified as two important areas for research.

New components will be needed that can easily be inserted into an operating transmission pipeline with minimal intrusion. For example, high-pressure "cut-in" valves could be installed on existing pipelines, but such valves would need to be both high in strength and have a low-profile design for easy insertion.

Another area identified as a research opportunity is the development of safe and practical alternatives to hydro-testing pipelines after construction or repair. Hydro-testing, while generally thought to be a safer alternative in the event of a rupture during a test, involves environmental impacts related to the use and disposal of test water and the venting of methane during the procedure.

External Leak Detection and Flow Rate Quantification Technologies

R&D Drivers and Current State of the Art

Pipeline systems span vast distances, typically underground, and often in remote areas. Thus, emissions can be difficult to detect, particularly for leaks that emit very small amounts of natural gas. For this reason there is a continuing need for external (as opposed to internal pipeline inspection) natural gas leak detection and flux quantification technologies that can both reliably detect CH_4 leaks and accurately estimate the rate at which CH_4 is flowing from the leak.

This critical need for the development of new detection and flux quantification technologies, as well as a need for objective and transparent field validation of existing commercial technologies that claim to be able to detect and quantify leaks, were identified during the PHMSA Government and Industry Workshop held August 6–7, 2014, in Chicago. At the PHMSA Workshop, several dozen attendees from industry, academia, and other stakeholder groups agreed that an important research gap was the need for a scientific evaluation framework for assessing the viability and performance of leak detection and quantification technologies and methodologies with regard to their operational characteristics, "fitness for purpose," environmental impact, reliability, robustness, sensitivity, and accuracy. In addition, workshop participants identified a concurrent need for objective field validation studies carried out under this framework to verify gas leak detection and quantification technologies and methodologies.

In particular, the workshop participants highlighted the need for technologies that could quantify flow rates from nonhazardous leaks (low-volume leaks that do not present an immediate hazard nor demand immediate repair for safety reasons), as a means for prioritizing these leaks for remedial action. Accordingly, PHMSA has recently announced research solicitations targeting these areas.

ARPA-E has recently selected eleven research projects focused on the development of infrared and spectrometry-based sensors for detecting and quantifying methane leaks above ground. The objective of this research is a suite of natural gas leak detection and flux quantification technologies that are reliable and economical to apply, and that have proven capable of meeting expected performance standards. Using such technologies, companies will be able to effectively find leaks and prioritize them for repair on the basis of their individual contribution to CH_4 emissions.

R&D Challenges and Opportunities

No single method for detecting the presence of natural gas or leaks in the system works for all situations. Each method has a different cost, sensitivity to methane, and susceptibility to interference. Some methods are stationary and others are suitable for mobile detection platforms, which include ground vehicles, aerial vehicles, and in-pipe mobile platforms. Some methods detect the concentration of natural gas in the immediate local atmosphere, whereas others detect a total amount along a line of sight.

While a number of such technologies are currently being developed or have been recently proposed through the Pipeline Research Council International (PRCI) research efforts, and the recent ARPA-E and PHMSA solicitations, the DOE Natural Gas Infrastructure R&D and Methane Mitigation Workshop held in Pittsburgh on November 12–13, 2014, identified additional specific research goals related to methane leak detection: ubiquitous low-cost methane sensing technologies along the midstream natural gas infrastructure system (stations, components, pipelines); autonomous detection technologies; and improved quantification of methane emission.

Some examples of existing technologies for external leak detection and methane quantification include:

- cavity ring-down spectroscopy
- open-path laser spectrometry
- external cable leak detection systems
- small unmanned aerial system platforms for remote sensing detection
- mass spectrometry
- flame ionization detection
- electrochemical detectors
- acoustic techniques

Direct detection of methane often takes advantage of methane's infrared (IR) absorption bands at 3020 cm^{-1} and 1300 cm^{-1}. These absorption bands allow detection by IR spectroscopy techniques that include tunable laser diode absorption spectroscopy and cavity ring-down spectroscopy. Additional techniques include mass spectrometry, flame ionization detection, and electrochemical detectors. Detection methods may also be coupled with chromatography to separate gas components before they reach the detector. Acoustic techniques can be used to detect leaking gas and defects in materials. Networks of pressure sensors along pipelines are used to detect changes in performance that indicate leaks.

Advanced Pipeline Materials

R&D Drivers and Current State of the Art

R&D to develop advanced materials with capabilities to reduce leaks and eliminate need for cathodic protection would enable the design of high-performance elements within midstream systems, be they pipelines, flow control components, sensors, compressors, or metering and gas handling equipment. Advanced manufacturing processes must also be developed to create next generation pipeline systems that can achieve new levels of efficiency and safety. Applications involving advanced materials can directly reduce the likelihood of methane leaks or indirectly improve the efficiency of midstream infrastructure operation.

About 40% of U.S. pipelines date from the 1960s or earlier, before the first pipeline regulations.[15,16] Pipelines develop leaks for numerous reasons, including corrosion, improper fabrication or construction, and damage. Since pipelines are typically buried, they are subject to potentially corrosive soil chemistry on the outside of the pipe. To minimize external corrosion in steel pipes, cathodic protection is used, resulting in additional energy consumption and natural gas system losses. Pipelines may also have corrosion inside the pipe due to reactions with impurities in the natural gas. In general, leak rates from pipelines in the high-pressure natural gas transmission system are low, and when they occur they are quickly identified and repaired for safety reasons. However, leaks from pipelines are more common in the distribution network, particularly in cast iron and unprotected steel mains that are susceptible to corrosion over time.[17]

A unique opportunity exists to incorporate emerging technologies into the nation's natural gas pipeline network since major construction and replacement efforts are planned. Billions of dollars of new transmission pipelines are being added to the U.S. network to accommodate the country's increased natural gas production from unconventional natural gas resources and shale resources, and distribution system line replacement is ongoing because of state policies.[18] However, including emerging technologies for new natural gas pipelines will not be easy; it can take a decade or more for a new material or component to be approved for use in natural gas delivery systems, and sufficient data on the performance, durability, and safety of the innovation must be presented before it will be accepted by regulators and operators.

New pipeline materials have the potential to increase the lifetime of existing networks, reduce leaks, and eliminate the need for cathodic protection. Liners and coatings may be used to rehabilitate and extend the life of older pipelines, providing a cost-effective way to reduce leaks without wholesale replacement of the line. In addition, new component geometries and methods could be developed to allow the installation of components without depressurizing lines to avoid blowdowns. And if blowdowns are needed, improved capture technologies could prevent natural gas from being vented directly to the atmosphere during maintenance. The following section outlines potential opportunities for additional technology development.

R&D Challenges and Opportunities

Some identified R&D opportunity areas related to the following are discussed more fully below.

- processes/standards for composite pipe integrity assessment
- low-cost methods/materials for joining and tapping composite pipes
- conforming, high-strength liner materials for internal pipe repair
- low-cost methods/materials for tapping liners
- processes/standards for liner integrity assessment
- self-healing pipeline coatings
- field-applicable pipeline coatings

Composite materials' high strength leads to fewer leaks during the useful lifetime of the pipeline, reducing losses and emissions. In addition, composites are far less susceptible to corrosion, so they do not require cathodic protection systems. Further, composite pipes are more compatible with multiple fuels, such as hydrogen/methane blends, which are expected to be more common in the future. Composites can include layers to prevent permeation and loss of hydrogen, and composites are not subject to embrittlement, which can occur with steel pipes when in contact with hydrogen.

Composite pipe technology already exists and has been approved for use in select situations, including offshore pipes and risers in gathering operations. However, composite pipe is more expensive than steel. In addition, joining and tapping composite pipes is so challenging that they tend to be used in single segments with few or no taps. Processes for joining and tapping composite pipes are underdeveloped, and each new join or tap requires a means for predicting and testing its effect on pipeline integrity. Moreover, because composite pipe material is not yet widely used, basic guidelines are still nascent, including standards for use in the gas industry, techniques for proper quality assurance and control, methods for short- and long-term lifetime prediction, and methods for risk assessment. Finally, composite pipes do not yet have a fully developed repair protocol.

Replacement of existing pipeline infrastructure is expensive, especially in populated areas.[19] Liners made of composites or other high-strength materials can be inserted into existing metal pipes to increase the effective lifetime of the pipe without retrenching, saving millions in installation costs. Generally speaking, two types of liners exist. Nonstructural liners rely on the existing pipe for support. Thus, the integrity of the original pipe must be preserved, and small gaps in the host pipe can result in liner blow-out. Structural liners, however, are self-supporting and effectively replace the original pipe, which remains in place but no longer needs to maintain its structural integrity.

While structural liners avoid the need for retrenching, they present their own installation challenges. Use of structural liners requires re-tapping all existing taps, a costly process that can weaken the liner, particularly if tapping is not performed properly. In addition, large-diameter liners cannot pass through sharp bends in the pipe. Structural liners also must be strong enough to maintain integrity when gas that has permeated through the liner but not through the host pipe supplies back-pressure when the line is depressurized.

Coatings are used today to help protect steel pipelines from corrosion and the leaks that can result from corroded pipe. External coatings are applied to the exterior of the pipe to prevent corrosion from soil or air, while internal coatings are used on the inside of the pipe to prevent microbial growth or to resist corrosion from water, condensate, and impurities in natural gas. Factory-applied coatings are applied before delivery and, because conditions can be controlled carefully during application, include a wider variety of coating materials. However, factory-applied coatings must be highly durable so they remain undamaged during pipeline installation, which can include insertion into a horizontal bore. Field-applied coatings, in contrast, can be put on during or after installation. However, factors such as temperature and humidity are difficult to control in the field. Variations in these factors can impact the quality of the coating; cold weather, in particular, can lead to poor coating quality. In addition, most coatings require specific surface preparation processes. These processes can be difficult to conduct in the field, leading to greater likelihood of defects or damage of the coating during installation. It is also difficult to achieve the same level of performance when coatings are applied during cold weather.

Today's coatings can be very effective if they are applied properly and not damaged during installation. Coatings that are easier to apply in the field under a wide range of conditions would represent a major advance over current coatings, and could be more widely used to prevent corrosion and gas migration. In addition, coatings that are "self-healing," or able to repair themselves after being damaged, would also reduce leaks, especially in pipes that are damaged by accidental "dig in" events in which a buried pipeline is damaged during unauthorized excavation on or around the pipeline right-of-way.

The use of the natural gas pipeline network to deliver other gases or fuels including pure hydrogen or mixed (natural gas/hydrogen gas) gas or other drop-in fuels, without significant modification, could provide major cost/schedule benefits in the transition to a possible hydrogen energy economy. Natural gas is presently transported long distances at high pressure (generally between 500 and 1200 psig) and distributed at lower pressure (below 100 psig) to end-users. Similar practices are likely to emerge for hydrogen. High-pressure natural gas (and hydrogen) pipelines today use steel alloys, while natural gas "distribution" pipes can be made of a variety of materials such as cast iron, copper, steel, or plastic (PVC or PE). The process of transitioning to hydrogen delivery via the existing network is complicated by the diversity of materials used in natural gas piping systems and the diversity of operating strategies adopted by utility operators. Steel and plastic are the primary materials, but even these materials will have subsets that may be more or less acceptable for hydrogen service. The aging effects of natural gas service, coupled with the new environment of hydrogen service, need to be quantified to ensure safe service conditions. For example, carbon steels are susceptible to hydrogen embrittlement and cracking.

Plastic materials may also experience a loss in ductility or reduction in other mechanical properties either through aging or through exposure to some gas concentrations under certain operating temperature and pressure conditions. The development of the technical basis for qualifying the use of existing natural gas pipeline materials (steels and plastics) for hydrogen service is proposed. Research is needed on the effects of hydrogen service on physical and mechanical properties such as tensile strength and fracture resistance, and on their impacts on pipeline burst pressure and flaw tolerance. Hydrogen embrittlement can include surface cracking, slow crack growth, loss of ductility, and increases in fracture stress. This deterioration can lead to premature failure, possibly with little warning. Safety is paramount to all aspects of natural gas operations, so before hydrogen gas can be introduced into the pipeline, operators must be assured that embrittlement risks have been minimized. For steel pipes, there is considerable debate whether or not hydrogen gas would have a significant effect on operating performance. The reliability of the hydrogen pipeline system is of the utmost concern for the DOE, DOT, NIST, other regulators, and stakeholders, whether using the existing natural gas delivery system or installing new dedicated hydrogen delivery systems. To this end, it is critical that a complete understanding of the effects of hydrogen embrittlement/degradation processes in these pipeline materials is developed to support the basis for qualification of the materials and existing system for hydrogen service and future multi-fuel service on existing and new natural gas pipelines.

Endnotes

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Acronyms

ARPA-E	Advanced Research Projects Agency-Energy
CH_4	Methane
CO_2	Carbon dioxide
EGR	Exhaust gas recirculation
EIA	Energy Information Administration
EPA	Environmental Protection Agency
GHG	Greenhouse gas
GT	Gigatonnes
IR	Infra-red
MMcf	Million cubic feet
MMcf/day	Million cubic feet per day
NSCR	Nonselective catalytic reduction
ORC	Organic Rankine cycle
PHMSA	Pipeline and Hazardous Materials Safety Administration
PRCI	Pipeline Research Council International
R&D	Research and development
RD&D	Research, development, and demonstration
SCADA	Supervisory control and data acquisition
Scfm	Standard cubic feet per minute
Tcf	Trillion cubic feet
U.S.	United States

Glossary

Acoustic	Pertaining to sound. Generally, acoustic describes sound or vibrational events, regardless of frequency.[20]
Anthropogenic	Made or generated by a human or caused by human activity. The term is used in the context of global climate change to refer to gaseous emissions that are the result of human activities, as well as other potentially climate-altering activities, such as deforestation.[21]
Blowdown	The process of reducing gas pressures by means of releasing such pressures to the atmosphere.[22]

Catalyst	A substance that changes the speed or yield of a chemical reaction without being consumed or chemically changed by the chemical reaction.[23]
Cathodic Protection	A technique to prevent the corrosion of a metal surface by making that surface the cathode of an electrochemical cell.[22]
Cavity Ring-down Spectroscopy	A highly sensitive direct absorption technique based on the rate of absorption of light circulating in an optical cavity for identifying the chemical constitution of a substance.
Chromatography	A technique used to separate different substances in a mixture.[23]
Combustion	Chemical oxidation accompanied by the generation of light and heat.[21]
Composite Materials	A material made from two or more constituent materials with significantly different physical or chemical properties that, when combined, produce a material with characteristics different (improved) from the individual components.
Damping	Restraining of vibratory motion, such as mechanical oscillations, noise, and alternating electric currents, by dissipation of energy.
Degradation	A deleterious change in the chemical structure, physical properties or appearance of a material.[22]
Depressurization	A condition that occurs when air pressure inside a structure is lower than air pressure outside.[23]
Distribution Mains	Generally mains, services, and equipment which carry or control the supply of gas from the point of local supply to and including the sales meters.[22]
Ductility	The ability of a material to be elongated (stretched) in tension.
Electrochemical	The direct process end use in which electricity is used to cause a chemical transformation.[21]
Emissions	Anthropogenic releases of gases to the atmosphere. In the context of global climate change, they consist of radiatively important greenhouse gases (e.g., the release of carbon dioxide during fuel combustion).[21]
Exhaust Gas Recirculation	An emissions reduction technique that recirculates a portion of an engine's exhaust gas back to the engine cylinders.
Flame Ionization Detection	A technique that measures the concentration of organic species in a gas stream.
Flux	The flowrate per unit cross-sectional area.[23]
Friction	The resistance that one surface or object encounters when moving over another.

Fugitive Emissions	Unintended leaks of natural gas or volatile organic compounds during the production, processing, transmission, and/or transportation of fossil fuels.
Greenhouse Gas	Those gases, such as water vapor, carbon dioxide, nitrous oxide, methane, hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride, that are transparent to solar (short-wave) radiation but opaque to long-wave (infrared) radiation, thus preventing long-wave radiant energy from leaving Earth's atmosphere. The net effect is a trapping of absorbed radiation and a tendency to warm the planet's surface.[21]
Hermetically	Completely sealed, especially against the escape or entry of air.
Hydraulic Efficiency	Measures the pressure drop that occurs as gas moves through the pipeline network. It is affected by factors such as pipeline geometry, pipe surfaces, etc.
Hydrogen Embrittlement	The process whereby hydrogen causes steel components to become less resistant to breakage and generally much weaker in tensile strength.[20]
Hydrogen	A colorless, odorless, highly flammable gas used in hydrogenation of petroleum and for producing ammonia. Also, an important constituent of manufactured gas.[22]
Hydro-testing	A hydrostatic test in which pressure vessels such as pipelines, plumbing, gas cylinders, boilers and fuel tanks can be tested for strength and leaks. The test involves filling the vessel or pipe system with a liquid, usually water.
Infrared	Relating to electromagnetic radiation between microwaves and red visible light in the electromagnetic spectrum, having frequencies between 300 gigahertz and 400 terahertz and wavelengths between 1 millimeter and 750 nanometers.
Ionization	The process by which a neutral atom loses or gains electrons, thereby acquiring a net charge and becoming an ion.[23]
Methane	A colorless, flammable, odorless hydrocarbon gas which is the major component of natural gas. It is also an important source of hydrogen in various industrial processes. Methane is a greenhouse gas.[21]
Microbial	Involving a minute life form; a microorganism.
Midstream	The petroleum industry sector that involves the transportation and storage of crude oil, natural gas, or refined petroleum products.
Natural Gas	A gaseous mixture of hydrocarbon compounds, the primary one being methane.[21]

Nonselective Catalytic Reduction	Process that uses a catalyst reaction to simultaneously reduce NOx, CO, and hydrocarbon (HC) to water, carbon dioxide, and nitrogen.
Open-path Laser Spectrometry	An optical remote sensing technique that provides the capability to remotely monitor and measure trace gases and aerosols by guiding a laser beam across a large open atmospheric path.
Prime Mover	Mechanical equipment, such as an engine or turbine, which converts the energy of a fuel or fluid into mechanical power, usually rotational.[22]
Pulsation	A periodically recurring alternate increase and decrease of a quantity (as pressure, volume, or voltage).
Rankine Cycle	The thermodynamic cycle that is an ideal standard for comparing performance of heat-engines, steam power plants, steam turbines, and heat pump systems that use a condensable vapor as the working fluid. Efficiency is measured as work done divided by sensible heat supplied.[21]
Strain	The ratio of the elongation to the gauge length of the test specimen, that is, the change per unit of original length. It is expressed as a dimensionless ratio.[22]
Supervisory Control and Data Acquisition	A system of remote control and telemetry used to monitor and control the transmission system.[21]
Tapping	The process of cutting threads in a round hole so that other fittings or equipment can be screwed into the hole. Also to make an opening in a vessel or pipe.[22]
Thermal Efficiency	Refers to the conversion of chemical energy to mechanical energy when natural gas is consumed as a fuel.
Transmission Pipeline	Pipelines (mains) installed for the purpose of transmitting gas from a source or sources of supply to one or more distribution centers, to one or more large volume customers, or a pipeline installed to interconnect sources of supply. In typical cases, transmission lines differ from gas mains in that they operate at higher pressures, are longer, and the distance between connections is greater.[22]
Ultrasonic	Relating to acoustic frequencies above the range audible to the human ear, or above approximately 20,000 hertz.
Vented Gas	Natural gas that is disposed of by release to the atmosphere.[21]