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Introduction

Statistically, pipelines provide the safest and most economical form of transportation of crude oil, natural gas, and other petrochemical commodities compared to truck, rail cars, and tankers [Cheng, 2010]. There are about 2 million kilometers of transmission pipelines worldwide. These include natural gas, oil, condensates, petroleum gas, and other refined petroleum products, as well as carbon dioxide (CO$_2$) and hydrogen. The pipelines could be very large in diameter (e.g., a Russian pipeline system has a diameter of up to 1422 mm) and can be over several thousand kilometers in length [Hopkins, 2007]. Most pipelines are buried or under the sea, but some operate aboveground.

Liquids and gases have been transported by pipelines for thousands of years. Ancient Chinese and Egyptians used pipes to transport water, hydrocarbons, and even natural gases [Hopkins, 2007]. Most of the current pipeline industry was developed to transport oil, bringing considerable profits to energy producers and pipeline operators, and development is driven by expanding energy demands. Tens of thousands of kilometers of new pipelines are constructed every year. Pipelines have become one of the most environmentally friendly and safest means of oil and natural gas transportation and contribute to strong national economies. As a consequence, they have been integrated into the components of national security in most countries.

More than 90% of pipelines are made of steel, primarily carbon steel, with aluminum, fiberglass, composite, polyethylene, and other types making up the remaining 10% [Alberta Energy and Utilities Board, 2007]. Requirements for higher capacities and operating pressure and additional economic benefits have led to a demand for

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higher-strength pipeline materials, especially high-strength steels, as well as new techniques for welding, construction, inspection, and pipeline integrity and maintenance programs.

1.1 PIPELINES AS “ENERGY HIGHWAYS”

Human beings need energy to survive. For today and tomorrow, fossil fuels, including oil and gas, are the predominant forms of energy consumed worldwide. In fact, “even if the use of renewable energies doubles or triples over the next 25 years, the world is likely to still depend on fossil fuels for at least 50 percent of its energy needs” [Chevron, 2012]. The International Energy Agency estimated in 2010 that the world oil supply rises by 85 million barrels per day and forecast that the global demand would average nearly 88 million barrels per day in 2011 [Whipple, 2010], which demonstrates a clear relationship between oil consumption and a country’s economic situation.

Oil and gas are usually found in very remote regions that are different from the locations where they are processed and consumed. Pipelines provide the necessary transportation function for this form of energy. Pipelines are regarded as “energy highways” of the global oil and gas industry, and their impact on the energy industry and the general economy therefore cannot be underestimated. In North America, a total length of over 800,000 kms of transmission pipeline network transports 97% of Canadian crude oil and natural gas from the producing regions to markets throughout Canada and the United States. Statistics show [Canadian Energy Pipeline Association, 2007] that Canadian pipelines transport approximately 2.65 million barrels of crude oil and equivalent and 17.1 billion cubic feet (bcf) of natural gas daily. Moreover, virtually all oil and gas exports—worth $60 billion in 2009—are carried by pipelines [Canadian Energy Pipeline Association, 2012]. With an asset value of approximately $20 billion, the Canadian pipelines are anticipated to double in size by 2015 to meet the oil and gas production increases that are forecast. Among the world’s nations, the United States and Canada have the largest networks of energy pipelines for both oil and natural gas.

Oil pipeline networks are classified into crude oil lines and refined product lines, and the crude oil lines are subdivided into gathering lines and trunk lines. Gathering lines are small pipelines, from 2 to 8 in. in diameter, and are used where crude oil is found deep within the Earth where it is impractical to use larger diameters [Alberta Energy and Utilities Board, 2007]. It is estimated that there are between 48,000 and 64,000 kms of small gathering lines in the United States. These small lines gather oil from many wells, both onshore and offshore, and connect to larger trunk lines ranging from 8 to 24 in. in diameter. Trunk lines include a few very large lines, such as the TransAlaska Pipeline System, which is 48 in. in diameter [Alberta Energy and Utilities Board, 2007]. There are approximately 89,000 km of crude oil trunk lines in the United States.

Gas gathering lines connect individual gas wells to field gas-treating and processing facilities or to branches of larger gathering systems. Most gas wells flow naturally
with sufficient pressure to supply the energy needed to force the gas through the gathering line to the processing plant. Like crude oil trunk lines, gas transmission systems can cover large geographical areas and be several hundreds or thousands of miles long. One of the largest natural gas supplies is in western Siberia. A large-diameter pipeline system moves gas from that area, including a pipeline almost 4600 km long, to export gas to Western Europe [Hopkins, 2007]. These trunk lines, which have diameters ranging from 40 to 55 in., constitute an impressive pipeline network. Compared to crude oil pipelines, gas transmission lines operate at relative high pressures.

Oil and gas pipeline systems are remarkable for their efficiency and low cost. Compared to other conventional means of transportation, such as rail and trucks, pipelines provide a very cheap way to transport oil. For example, for every 1000 barrel-miles of transportation of petroleum, the cost by pipeline is between 4 and 12 cents, whereas those by rail and truck are 12 to 60 cents and 52 to 75 cents, respectively [Kennedy, 1993]. Oil and gas pipelines are also energy-efficient, consuming about 0.4% of the energy content of the crude oil or gas transported per 1000 km [Marcus, 2009].

1.2 PIPELINE SAFETY AND INTEGRITY MANAGEMENT

Pipeline integrity is maintained by coating and cathodic protection (CP) as well as by comprehensive pipeline safety maintenance programs generally called pipeline integrity management (PIM) programs. A PIM is a process to develop, implement, measure, and manage the integrity of a pipeline through assessment, mitigation, and prevention of risks to ensure safe, environmentally responsible, and reliable service [Nelson, 2002]. Integrity management of pipeline systems is essential to the safe and efficient transport of oil and natural gas on the basis of safety assessment and lifetime prediction. Attempts to define pipeline performance, structural strength, and lifetime spawn a number of specialized fields, including corrosion, materials science, fracture mechanics, nondestructive evaluation, electrochemistry, environmental science, and mathematical modeling on both microscopic and macroscopic scales.

The goal of a PIM program is to ensure that the risk is “as low as is reasonably practicable” [Nelson, 2002]. An integrity management program (IMP) is usually valid for two or three years and is then updated to include new or modified processes, developed during implementation of the PIM, through multiple time-driven integrity plans. A PIM program supports monitoring, inspection, and maintenance programs to reduce greatly the risk of failures that could cause disastrous consequences to human life, the environment, and business operations.

1.3 PIPELINE STRESS CORROSION CRACKING

A number of factors contribute to pipeline failures. Although corrosion is identified as the most common cause of oil and gas transmission pipeline failure [U.S. Department of Transportation, 2005], stress corrosion cracking has been identified as leading to
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A number of pipeline leaking and/or rupture events, with catastrophic consequences [National Energy Board, 1996].

Stress corrosion cracking (SCC) is a term used to describe service failure in engineering materials that occurs by slow, environmentally induced crack propagation. The crack propagation observed is the result of the combined and synergistic interactions of mechanical stress and corrosion reactions [Jones, 1992]. For a certain material, SCC occurrence depends on both an aggressive environment and a stress, especially a tensile stress. During the operation of pipelines in the field, line pipe steels are exposed to electrolytes trapped under disbonded coating, where solution chemistry or electrochemistry is developed to support pipeline SCC [Fu and Cheng, 2010]. The stress is due primarily to the internal operating pressure or pressure fluctuation of natural gas or liquid petroleum [Zheng et al., 1997]. Moreover, soil movement–induced longitudinal stress and strain contribute to the initiation and propagation of stress corrosion cracks in pipelines [Canadian Energy Pipeline Association, 1998].

A wide variety of factors experienced by pipelines during their operation have been demonstrated to affect and contribute to SCC at somewhat different levels, such as the steel metallurgy (chemical composition, grade, microstructure, heat treatment, alloying elements, impurities, and welding), environmental parameters (soil chemistry, conductivity, seasonal dry–wet cycle, temperature, humidity, CO₂ and gas conditions, and microorganisms), coatings, and CP (type, properties, failure mode, coating compatibility with CP, and CP potential/current), stressing condition (pressure, pressure fluctuation, residual stress, longitudinal stress, local stress–strain concentration), and corrosion reaction (corrosion pits, geometry of pits, hydrogen evolution, passivity and passive film formation, active dissolution, and mass transport) [Parkins, 2000].

Pipeline SCC incidents throughout North America and the world, including in Australia, Russia, Iran, Saudi Arabic, Brazil, and Argentina, have highlighted threats to pipelines from this problem. In Canada, two major ruptures and fires on the TransCanada Pipeline System in 1995, together with further evidence of the more widespread nature of SCC, led to the initiation of a national inquiry. This was the first comprehensive inquiry in the world on pipeline SCC and has been far-reaching across Canadian pipelines and extended to other countries [National Energy Board, 1996].

In the United States, the Williams 26-in. pipeline ruptured near Toledo, Washington in 2003, resulting in the shutdown of its trunk line from Canada to Oregon [Williams Pipeline, 2003]. This pipeline had also failed in 1992, 1994, and 1999, failures all attributed to SCC. With the occurrence of SCC-caused failures of gas and liquid pipelines, an advisory bulletin was issued in 2003 to remind owners and operators of gas transmission and hazardous liquid pipelines to consider SCC as a risk factor when developing and implementing integrity management plans [Baker, 2005]. It was commented that “SCC is a serious pipeline integrity issue of concern to operators of pipelines within the United States.” When comparing the pipeline SCC statistics in the United States and Canada, it was pointed out that “the fact that SCC represents only 1.5 percent of reportable incidents in the United States versus 17 percent in Canada is due to the far greater occurrence of third party damage in the United States.”

Research on pipeline SCC could be tracked back to the 1980s, and still has global interest. Management of SCC in the modern pipeline industry has been integrated with
companies’ integrity management programs. Our understanding of this important problem has evolved to the stage that comprehensive reviews describing the scientific, technical, and practical aspects of SCC in pipelines are common, all of which have facilitated the development of this book.

In addition to SCC fundamentals, such as the metallurgical, environmental, and mechanical aspects of SCC and the correlation with various hydrogen damage and corrosion fatigue, this book covers a wide spectrum of topics. Specifically, it includes the primary characteristics of and factors contributing to pipeline SCC and reports on progress to date on the investigation and understanding of SCC in pipelines occurring in nearly neutral–pH, high-pH, and acidic soil environments. The pipeline weld poses a sensitive region to SCC. Consequently, welding metallurgy is included, and the implications of corrosion and SCC are discussed. As advanced pipeline materials, high-strength steels distinguish themselves from conventional pipeline steels with unique metallurgical, mechanical, and metallurgical microelectrochemical characteristics. All of them contribute to the occurrence of hydrogen damage, corrosion, and SCC. The corrosion- and SCC-preventive strain-based design of high-strength steel pipelines is discussed based on the latest research in this area. Finally, industrial experience in the management of pipeline SCC, including prevention, monitoring, and mitigation as well as its integration with pipeline IMP, is incorporated.

REFERENCES


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