Pipeline Coatings

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NACE INTERNATIONAL

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1 Introduction

1.1. Pipelines and Pipeline Integrity Management

Pipelines have effectively and efficiently transported large quantities of crude oil, natural gas, and diluted bitumen from production sites (usually remotely located) to refineries and markets. Compared to other transport modes such as rail, truck, and boat, pipelines are safer, more economic, and emit less carbon as they transport cargo across provinces, countries, and continents [Behar and Al-Azem, 2015]. With rapidly growing global demands for energy, oil and gas production has expanded substantially due to major technological advances. This expansion drives the increased need for new pipelines. For example, the U.S. is expected to achieve an average of 12.2 million barrels per day (bpd) with the production of oil, liquefied natural gas (LNG), and condensates, making it the world's largest producer of combined crude liquids [Cope, 2014]. In Canada, it is forecasted that by 2018, approximately 3.37 million bpd oil sands will be produced [Cope, 2015]. As a result, various ambitious plans have been proposed for new-build and expansions of pipelines to gather oil/gas products for delivery to markets.

Great effort has been made by multiple parties including pipeline operators, regulators, researchers, and society to keep pipelines away from risks of degradation and failure that could cause catastrophic consequences, such as energy loss, environmental and ecological damage, and even fatal accidents. Indirect negative impacts (e.g., public image, market share of pipeline companies, etc.) are difficult to estimate. Therefore, the management of pipeline system integrity and safety has been the fundamental and core business for all pipeline operating companies.

Pipeline integrity management (PIM) is the process to develop, implement, measure, and manage a pipeline's integrity through assessment, mitigation, and prevention of risks. The PIM ensures a safe, environmentally responsible, and reliable service [Nelson, 2002]. The importance of the PIM program is obvious. It can maintain the safe and reliable operation of pipelines for energy transport, improve pipeline system sustainability, and reduce operating risks by optimizing operational and capital expenditures, maximizing pipeline life cycle and reliability, and managing potential risks and threats. It also increases shareholder and public confidence in pipelines.

Generally, a PIM program consists of several interrelated modules (i.e., identification of potential risks for specific pipeline segments or the whole system, assessment of possible failure modes and associated consequences, implementation of preventive actions and mitigation measures, and recommendations for further program improvement). The design and implementation of the PIM program is highly specific and must consider actual conditions where a pipeline is operated. For example, the long-distance transmission of oil and gas through pipelines is usually subject to threats from external environments. As a result, attention should be paid to monitor, mitigate, and prevent external risks. For upstream-gathering pipelines, the carried fluid is usually highly corrosive and can also be erosive when a high content of solid sands is contained. Risks of pipeline failure are primarily internal. Thus, integrity management should focus on potential internal risks.

The PIM program usually includes five steps to maximize pipeline integrity and safety [Focke, 2015]. These include:

1. **Data gathering and alignment**. Pipeline operators collect all relevant data from various sources to the pipeline, including its design, construction, coating and welding, in-line inspection (ILI), cathodic protection (CP) monitoring, maintenance, repair, etc. The data identify existing critical features along the pipeline for scheduling rehabilitation measures. Moreover, data from any single inspection and monitoring cycle should be compiled and compared with data collected from previous inspections/monitoring of the same segment. Accurate data alignment is required for further improvement of the PIM program and pipeline integrity.
2. **Feature assessment**. After relevant data are collected and filed in a data processing system, it can be used to calculate technical parameters (for example, the maximum allowable operating pressure, the growth rate of the features, coating and CP performance, remaining service life of the pipe, integrity of welds, etc.). Data will also be analyzed for irregularities such as flaws, metal loss, cracks, etc. Established models and the comparison between historical data records allow for mechanic and quantitative analysis. Each identified feature is to be assessed separately.
3. **Condition analysis**. In condition analysis, inspection data and calculated parameters are used to generate a ranking or an index number that determines a pipeline's fitness-for-service. The risk of failure can be estimated for individual inspection features, for pipe segments, or for a whole pipeline.
4. **Risk assessment**. Risk assessments consider the probability of failure occurring on pipeline segments and the potential consequences to public safety, the environment, and operators' financial stability.
5. **Integrity planning**. For identified features and potential risks, integrity planning is conducted by relevant parties to address pipeline issues. Planning action measures is included in the work management systems.

1.2. Coatings for Pipeline Corrosion Prevention

Corrosion is one of the key mechanisms affecting the durability and integrity of pipelines. Coatings in conjunction with CP provide the primary means to protect a pipeline from corrosion attack, mechanical damage, and geotechnical threats, and to maintain a pipeline's integrity in soil or water environments. In particular, the coating forms the first line of defense against a pipeline's external corrosion. However, a coating can degrade or fail at various stages of pipeline design, construction, and operation. Stages include coating manufacturing, application on pipes either in the plant or in the field, transportation, installation, and operation of the coated pipe. Moreover, the pipeline infrastructure around the world is aging. Statistics show [Hopkins, 2007] that over 50% of the oil and gas pipeline systems in the U.S. are over 40 years old, and 20% of Russia's oil and gas pipelines are nearing the end of their design life. Aged pipeline assets, including the coatings, become important challenges to the integrity of pipeline systems.

The principle of the strategy to combine coating with CP in PIM is that the coating, if it is intact and adheres well to the pipe's steel substrate, effectively separates the pipe from the environment, and at the same time, reduces the CP current demand. Where coating has failed, the CP acts as a backup to protect the pipeline from corrosion. However, when both coating and CP fail, the pipeline becomes susceptible to external corrosion and/or stress corrosion cracking (SCC). Industrial experiences have shown that coating failure is always the prerequisite for corrosion and SCC to occur on pipelines [National Energy Board, 1996; Cheng, 2013]. Due to its essential role in pipeline integrity maintenance, the coating has been integral to the PIM program and should be considered as a part of the whole pipeline system.

In the PIM program's five-step process as described earlier, coatings are involved in at least three steps (i.e., data gathering and alignment, condition analysis, and integrity planning). All data about the coating selected and applied to the pipeline (including its type and manufacturing, the plant-applied procedure, the field-applied coating and its compatibility with the main line coating, history of uses, performance status, periodic inspection records, etc.) should be collected and integrated into the PIM program. The data, especially the coating performance inspection results, will be analyzed along with other inspection data to evaluate the performance and status of the coating and the pipeline. Moreover, the compatibility of the coating with CP will be evaluated to determine the CP effectiveness once the coating has failed, such as when it disbonds from the pipe steel. Analysis results and the coating performance evaluation will guide the actions and rehabilitation plans required to improve pipeline integrity.

Generally, factors to be considered during the selection and design of pipeline coatings include but are not limited to:

- mechanical properties of the coating
- chemical and electrochemical properties of the coating
- susceptibility to coating damage with pipe handling during installation and repair
- soil chemistry
- compatibility for in-situ joint coating
- coating compatibility with CP
- estimated service life of the coating

All of these can affect pipeline integrity and thus the safety of the pipeline system. In addition to their corrosion resistance, selected coatings for pipeline use must be resistant to mechanical damages resulted from pipe handling, trench backfill, soil conditions, and the suitability of field joint coatings. The coating must serve as an effective barrier that separates the pipeline steel from the environment, providing long-term pipeline protection. It must remain intact and adhered, assuring both corrosion resistance and mechanical strength.

In summary, an ideal pipeline coating should be worker-safe, environmentally friendly, durable, and able to seal all substrate metal surfaces from the service environment. It must also be resistant to environmental, mechanical, and chemical damage during application, handling, burial, and service. It should be applied efficiently and effectively under the restricted environmental and work conditions in the field. Finally, it should come at a reasonable cost, even though cost should not be the main decision point in coating selection.

A wide variety of coatings have been used for corrosion protection and integrity maintenance for oil and gas pipelines over the last several decades [Niu and Cheng, 2008]. These include coal tar, asphalt, polyethylene (PE) coatings, fusion-bonded epoxy (FBE) or dual layer FBE coatings, three or multi-layer polyolefin (PE or polypropylene) coatings, composite coatings, etc. Although most of these coatings have successfully maintained pipeline integrity, challenges remain for the industry with various exceptional applications as well as oil/gas production activities conducted in increasingly remote, geographically difficult areas. These include extremely cold weather, unstable geotechnical conditions (such as slopes, earthquake zones, permafrost or semi-permafrost, etc.), microbial activity, and water and gas permeability over the long term. The industry has long pursued novel and effective pipeline coating technologies to meet these integrity-related challenges.

1.3. Contents of the Book

The evolution and development of pipeline coating technology can be traced to the 1940s and continues to be of global interest. Currently, design, selection, application, uses, and management of coatings has been integrated with pipeline systems' PIM programs. Our understanding of pipeline coatings has evolved to a stage that delivers a comprehensive review describing the scientific, technical, and practical aspects of pipeline coatings. All of these facilitated the development of this book.

The book begins with a review of coating fundamentals in Chapter Two, where the evolution of coating technology and the principles for coating formulation are introduced. Guidelines for coating design, selection, and application are briefly presented. The structure of a coating system and the high-performance coating's essential properties and characteristics are covered in detail. Some standard testing methods for determining and evaluating coating properties are included.

Coatings used in the oil/gas pipeline industry are covered in Chapter Three. Generally, pipeline coatings are divided into two categories (plant-applied and field-applied coatings). The chapter describes primary coatings in both categories such as coal tar, asphalt, PE, liquid epoxy, FBE, and high-performance composite coating (HPCC), as well as field-applied liquid coatings (i.e., tape coatings, shrink sleeve, wax, mastics and many others) in terms of their structures, properties, products, and applications.

Coating failures encountered on pipelines in the field are reviewed in Chapter Four, which includes an analysis of its effect on pipeline integrity. Both permeable coatings and impermeable coatings receive particular attention, and their interactions with CP are discussed. The shielding effect of coating failures under a variety of scenarios is included to provide an understanding of this industry-important problem. The tests and results described in this chapter come from the authors' research activities. This first-hand information provides recommendations to the industry for avoiding incompatibility between pipeline coating candidates and CP.

SCC has been a primary mechanism resulting in pipeline failure [National Energy Board, 1996]. It has been acknowledged [Cheng, 2013] that SCC occurrence is subject to coating failures. Chapter Five focuses on mechanistic aspects of the essential role of coating failures in pipeline SCC, including its initiation and propagation. Both near-neutral pH and high-pH SCC on pipelines are introduced, and correlations between the type and properties of coatings and their failure mechanisms are established. Discussions detail the development of solution chemistry and electrochemistry under disbonded coating to support SCC. Again, the majority of the results discussed in this chapter come from the authors' research experiences. After following this content, readers may connect coating performance with the potential occurrence of pipeline SCC.

Techniques for characterizing coating properties and testing coating performance in the field and research laboratory are covered in Chapters Six and Seven, respectively. The discussion provides insights essential to a complete testing and evaluation program for pipeline coating candidates, and for predicting long-term coating performance. Depending on an individual technique's capability and actual coating property needs, one can choose a testing method from convenient, simple inspection tools to complex, research-oriented equipment.

Various coating application techniques are introduced in Chapter Eight, which covers almost all important issues required for understanding what is necessary when a coating is applied to metal substrate, including pipelines. The content is based on realistic experiences.

Finally, industrial experience with inspection and management of pipeline coatings is included in Chapter Nine. Inspections have been integral to the PIM program and ensure the integrity and safety of pipeline systems.

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