PIPELINE SYSTEMS AND STRUCTURAL INTEGRITY MANAGEMENT

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Summary

Much has changed since the days when oil was shipped in barrels carried by horse-drawn wagons, as the rapid expansion of technology over the past several decades in other industries has had a parallel impact in the oil and gas industry and in pipeline systems. Proactive integrity management can help offset public perceptions of system safety while ensuring the existing and future assets perform at maximum utilization.

Analysis of incident statistics indicate the expectation that higher pipeline pressure is associated with an increased incident frequency is no longer realized, which reflects the emergence of incident causes beyond the direct control of the industry. Managing this scenario will require the pipeline industry to work broadly with other stakeholders. System condition monitoring and the use of appropriate criteria to assess and prioritize the need and timeline for rehabilitation or changes in operation is central to integrity management. While tools exist currently and are broadly used to monitor condition, they involve some degree of uncertainty such that a finite probability remains incidents will occur that are currently beyond the best efforts of the pipeline owner/operator. Opportunities exist for the pipeline industry in collaboration with the government and viable technology developers to address threats that can be proactively managed by developing appropriate (practical, effective, reliable …) technology. Near-term

examples include leak, limit-states, and encroachment and contact detection, which are emerging today, while the longer term holds promise for “smart” pipeline systems that recognize pending problems and respond prior to an incident occurring – while redirecting product to avoid firm-delivery issues and bottlenecks. With existing Supervisory Control and Data Acquisition (SCADA) technology as a backbone much seems plausible using sensor-based condition monitoring to detect such concerns, to balance network demands to relieve bottlenecks and manage upsets, and to deploy emergency response to maximize public safety and environmental protection.

1. Introduction

As petroleum-based products were found merchantable for lighting and other purposes, demand focused in larger urban centers motivated developing the means to move these products from oil fields in the supply basin to nearby market centers. Pipelines were eventually recognized as the safest and most economical means to transport petroleum products from the supply basis and import locations to the markets. The purpose of this paper is to provide some history on the evolution of pipeline systems, to detail differences in pipeline systems depending on the products transported, and thereafter to present integrity considerations in the management of such systems. Because petroleum products were first discovered in the United States (US), this early history is focused there.

2. Historical Background for Pipeline Systems

Early on, petroleum products were moved from the oil fields to nearby railheads via horse-drawn carts using large wooden barrels, the volume of which remains in use today as the unit of measure for transported quantity. This mode of transportation is illustrated in a photograph on the Association of Oil PipeLines (AOPL) website (http://www.pipeline101.com/history). Such transport remained effective so long as demand was limited and supply basins were located close to the markets, which was the case for early demand that supplied lighting with oil from fields located in sites such as Pennsylvania, Texas, and California – which were close to the major demand centers.

As petroleum products were found merchantable, their demand grew whereas nearby resources began to dwindle, which forced deeper wells at supply basins at sites increasingly remote to the markets. These changes paved the way for pipelines to replace aboveground modes of shipping, although the barrel remained the measure of quantity delivered. This scenario continues in play today, with current supply being imported, whereas domestic supplies are sought from remote and pristine areas like Alaska. In all such cases, pipelines are used to move the imported as well as domestic supply to markets, whether in the lower forty-eight US states or in countries all around the world.

As the supply basins become increasingly remote, a system of pipelines developed to transport these products from the supply points to the market centers, terminals, or hubs. Thus a cross-country infrastructure of pipelines develops that traverses throughout the country, with eventual interconnects with border countries. Construction tended to occur first through the regions traversed the easiest, and leading to the largest markets – tracking the so-called “path of least resistance.”

Early construction often traversed farm-fields, through which construction made use of backhoes and various ditching practices, with the pipeline built along and lowered onto the ditch bottom as a string. Because the ditch bottom was smooth it also served as the foundation for the pipeline, with native soil returned to the ditch as bedding and padding, as well as cover for the pipeline. A-frames were used to lower-in the pipe string, which gave way to side-booms beginning in the 1930s. Figure 1 illustrates the evolution of construction practices. This figure indicates machine-made bends replaced couplings and other historical field-bending practices used to change the direction of the pipeline beginning in the 1940s. As the threat of corrosion was recognized, over-the-ditch coating methods were developed, with such coatings also beginning broad use in the 1940s. About this same time quality girth-welding practices became prevalent, replacing the early oxy-acetylene practices. Figure 1 summarizes the evolution of these and many other historic pipeline construction practices, indicating the timeline over which these practices were prevalent, specifically in regard to the US for this figure.

Figure 1. Evolution of construction practices

In analogy to Figure 1, Figure 2 presents the historical evolution of the line pipe used in constructing the US pipeline infrastructure, which was the first such system. Processes noted there include furnace butt-welding, continuous butt-welding, lap and hammer welding, low-frequency electric resistance welding (ERW), flash welding, single submerged arc welding (SAW), some early seamless (SMLS) variations, high-frequency ERW (HFERW), and double submerged arc welding (DSAW) as either straight seam or spiral seam. Of these, the continuous butt-weld SMLS, HFERW, and DSAW processes remain in widespread use today worldwide.

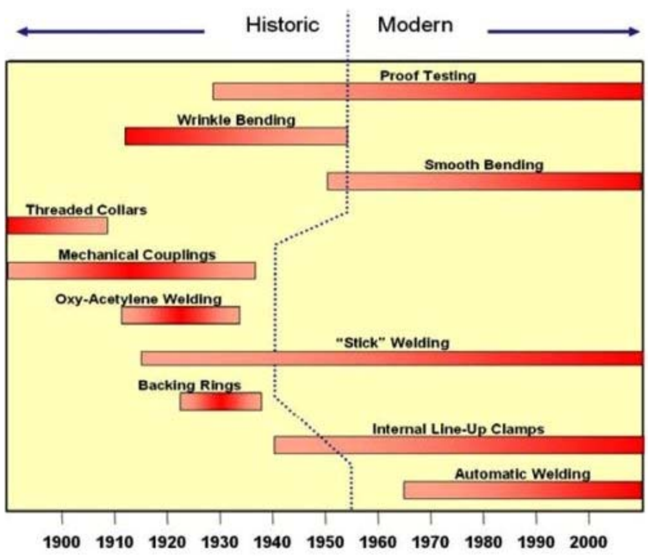

Figure 2. Evolution of pipe making practices

New technology coupled, with economic drivers, leads to the introduction of new processes along with the modification or improvement of existing processes, followed by the abandonment of others to enhance safety and control capital expenditures (CAPEX) and operating expenditures (OPEX). Acceptance of a new product like, line pipe, fittings, prime-movers, and so on, is controlled by engineering specifications and quality control procedures at the time the product is manufactured. Such specifications are developed based on the parameters of the pipeline system's service. Quality control (QC) and quality assurance (QA) procedures often based on nondestructive inspection (NDI) are used to verify that the product or system as delivered meets the engineering specifications. As time passes and technology evolves, more stringent engineering specifications and improved QA/QC procedures develop, which can effectively eliminate incidents associated with the line pipe and pipeline construction aspects of the pipeline system.

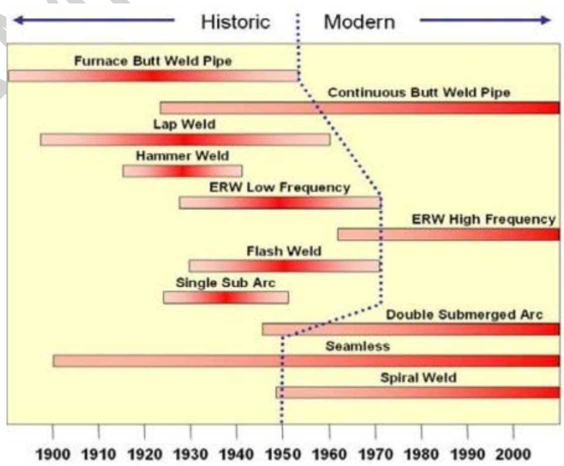

Figure 3. Contrasting vintage to modern equipment a) 1950s vintage auger loaded cylindrical-screen machine b) modern integral in-line flat-screen bed and pad machine

Because when possible construction first tends to occur through the regions traversed the easiest on paths leading to the largest markets, in the US and where possible elsewhere in the world, pipeline construction first traversed the flatlands. Construction through wet or swampy areas as well as hilly or mountainous areas occurs when such features cut through the path between the supply site and the market. But, as time passes and/or demand shifts, or the topography of the country dictates, pipelines have been built across quite difficult geographic boundaries between the supply points and the markets. Where mountains are encountered, or construction passes through hard, rocky terrain –appropriate protection is afforded the pipeline. Likewise, where large rivers must be traversed the pipeline crosses these features with safety as a primary concern – which in today's construction often occurs via directional drilling to pass the pipeline below the riverbed or past other surface obstructions. Finally, where instability can occur as in earthquake-prone regions, or the pipeline must cross ecologically unusual or pristine regions, provision is made to do this safely while protecting the environment and ensuring the survival of the flora and fauna. Directional drilling equipment, ditching machines, bedding and padding machines, and so on, have evolved to meet these challenges.

For example, Figure 3 shows the evolution of bedding and padding machines, through a contrast of the 1950s versus current technology. Comparison of these views indicates similar concepts are used, the major differences being efficiency and effectiveness to enhance productivity while ensuring safety.

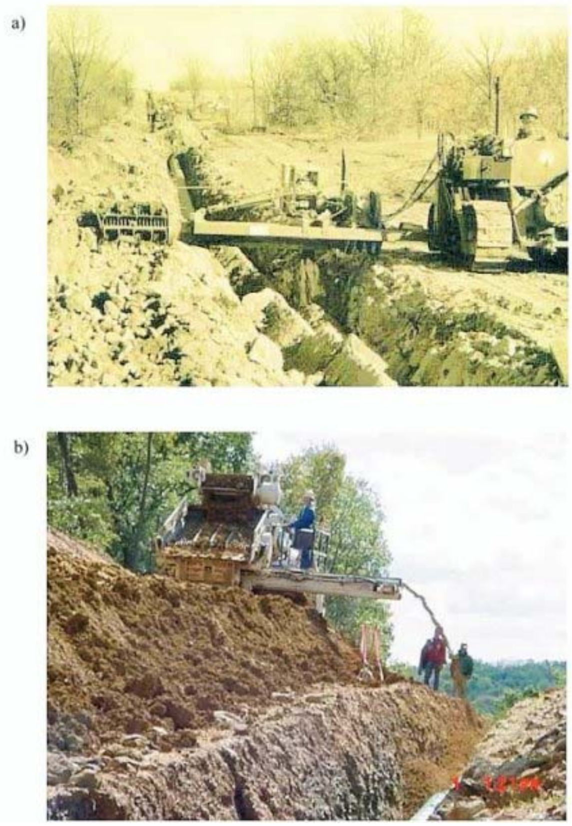

Figure 4. Directional drilling (at pull-through)

Figure 4 shows a view in the pull-stage of a directional drill, a process that can place the pipeline well below the river bottom, thus avoiding possible failure due to scour as can occur for pipelines laid on the bottom. This is central to avoiding failures due to flooding.

Figure 5 shows construction through mountainous territory that often tracks ridges where feasible, and so provides reasonable access while limiting the ecological upset. There are many challenges in such construction, particularly ascending and descending major grades.

Figure 5. Typical mountain ridgeline construction

Figure 6 shows a view of a post-construction view for arctic conditions, which shows the pipeline positioned on offsets above the ground. This practice helps to manage the thermal profile of the pipeline, which helps to limit the ecological impact and structural implications associated with permafrost. As needed, such offsets rise above the grade to facilitate unimpeded migration of reindeer or other species as might be needed. Successful passage through geographic barriers as shown in these views using modern practices is improbable given the practices of the 1960s and earlier.

Figure 6. Typical arctic aboveground construction

While the early, thick compliant bitumen/tar-based, over-the-ditch pipeline coatings were well suited to protecting pipelines from construction-related damage and corrosion, such coatings were prone to "dry-out" due to the effects of aging and temperature on their volatile constituents. Because coatings were not used in the earliest construction, "bare" pipe was eventually protected against corrosion by use of cathodic protection (CP). And, as the early coatings dried out and became less functional, CP was added to those systems to protect against corrosion. Recognizing the problems with early coatings, alternative more reliable coatings evolved. Modern mill-applied fusion-bonded epoxy coatings coupled with field-applied epoxy or urethane coatings or mill and/or field-applied primer plus multi-layer tape coatings have evolved. These modern coating systems reduce the time on the construction spread at the same time they improve the metal-loss protection and reduce the demand on the CP system – all substantial benefits as compared to the early schemes.

3. Hydrocarbon Pipeline Infrastructure and Its Importance

As market demand grows, the pipeline infrastructure develops to meet the needs whose scope depends on the demand, the proximity of demand to supply centers, domestic versus imported supply, and the history of that demand. Where demand is broad, the infrastructure evolved can be extensive, showing evidence of supply points, which appear as hubs for the pipeline network. Where domestic supplies exists, those hubs fall within the boundaries of the country, whereas when the demand is met by imports those hubs show cross-border interconnects, or the hubs lie near the coast, or major rivers, where facilities to offload ships develop.

Perhaps the most comprehensive pipeline network in the world has developed in the US, driven in part by the observation that this is also the oldest network, with a number of interconnects into Canada who supplies a range of hydrocarbon products.

Figure 7 illustrates the natural gas transmission network in the US, where historical as well as current supply sources are quite evident. The interstate natural gas transmission network represented in this figure as dark lines comprises almost 500 000 km. The crude oil transmission and gathering pipelines in the US comprises about 120 000 km, with another roughly 130 000 km in hazardous liquid transmission service. Less extensive networks have developed in Mexico, which also has interconnects into the US.

Figure 7. Gas transmission pipeline network (US)

Large although less dense pipeline networks are developing in parts of Europe and Asia, as is apparent in Figure 8, which for the scale used represents roughly one third the land mass shown in Figure 8 for the US. With the change in scales between Figures 7 and 8 accounted for it is clear that the US network is much more extensive and concentrated around supply basins as compared to that of Europe, and its interconnections east and south.

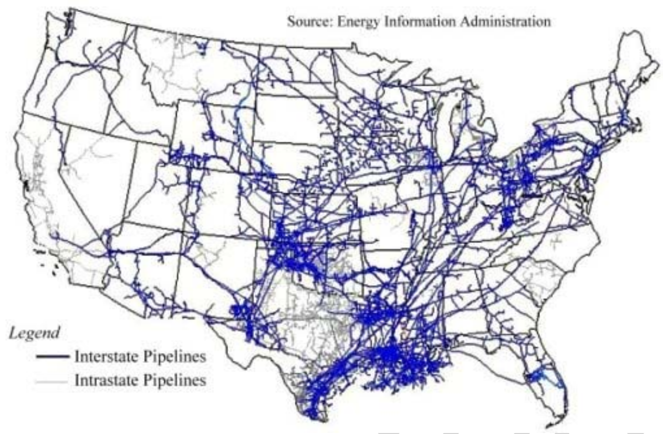

Figure 8. Transmission pipeline network (~Europe)

The networks in many other countries and continents are equally modest as compared to the US or even as compared to Europe, whereas for other developing areas such networks are just beginning to evolve. As Figures 7 and 8 imply, transmission pipelines are used to move natural gas as well as crude and refined petroleum products. Pipelines are used to transport water and other commodities, but such topics are beyond the present scope.

For countries where an extensive network of hydrocarbon transmission pipelines has developed, the fuels and other products they transport are essential to the local quality of life. The AOPL indicates that interstate pipelines in the US deliver over 12.9 billion barrels of petroleum each year. At 42 gallons per barrel this is a significant amount, comprising about two-thirds of the oil shipped in the US. Of this, roughly 7.6 billion barrels is crude oil, with the remaining 5.3 billion barrels being refined petroleum products. For nations that have extensive pipeline networks in many ways their economic health depends on the enormous quantities of oil moved each day. For example, in the US about 97-percent of energy consumed in transportation is supplied by petroleum. Petroleum derived fuels – for example gasoline for cars, diesel for trucks and locomotives, and other fuels for ships and airplanes – all are refined from crude oil, which is moved first by pipelines as crude oil for refining, and then again is transported by pipelines to distribution centers.

While pipelines employ a relatively small number of people, the fuel delivered by pipelines directly underlies a significant number of jobs. More than one-tenth of the American workforce is employed in transportation and related industries. These industries employ truck drivers, warehouse and shipping labor, pilots, bus drivers and so on, all of whom run their vehicles with pipeline-supplied fuels. The US defense services is another major employment sector that relies on pipelines. The defense services buy more refined oil products than any other single buyer in the world – about $3.6 billion for fuel every year, much of which is delivered by pipeline. The AOPL indicates that more than 100 defense services installations in the US have direct connections to the interstate pipeline network to meet their needs for petroleum supplies. It follows that the network shown in Figure 7 plays a critical role in the lives of many Americans, and that a significant percentage of the economic benefits from the nation's industrial sector rely on petroleum-based raw materials made possible by the oil pipeline industry. Hydrocarbon pipelines also play an essential role in the public sector, providing fuels to heat and/or cool the nation's homes.

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Bibliography

As the documentation, technology, and philosophy associated with the integrity management for pipeline systems is very extensive, a very comprehensive bibliography could be cited. However, most of this literature is available from websites or cited in the references for a few related papers. As such this bibliography begins with a series of websites that are grouped in terms of regulators, industry technology developers, select major operators, industry agencies and standards organizations, which are followed by a few select references. These websites and the papers cites will open the door to the technologies that underlie integrity management, as well as provide entrée to the various philosophies implemented to ensure safety of both the public and the environment.

- **Regulator: Website**

United States Department of Transportation (PHMSA): http://ops.dot.gov
National Energy Board of Canada: http://www.neb.gc.ca
United Kingdom Health and Safety Executive: http://www.hse.gov.uk
Industry Technology Developers: Website
Pipeline Research Council International: www.prci.com
Gas Technology Institute (subsumed the Gas Research Institute): http://www.gastechnology.org

- **Select Major Operators: Website**

TransCanada Pipelines: www.transcanada.com
Enbridge: www.enbridge.com
Exxon Mobil: www.exxonmobil.com
British Petroleum: www.bp.com

- **Industry Agencies and Standards Organizations: Website**

American Society of Mechanical Engineers: http://www.asme.org
American Society for Testing and Materials: www.astm.org
Interstate Natural Gas Association of America: www.ingaa.org
American Gas Association:www.aga.org
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Biographical Sketches

Dr Brian Leis was born in Kitchener, Ontario, Canada in 1947, being educated at the University of Waterloo with degrees in Civil Engineering and Applied Mechanics. Dr. Leis' expertise is damage mechanics, including fatigue and fracture analysis, and related degradation due to environmental and thermal effects, in metallic and nonmetallic materials (primarily polymers). He has almost 35 years experience using linear and nonlinear stress and fracture analysis methods and related experimental methods to characterize degradation and fracture in practical settings. Most of his work has been done to develop advanced structures and solve practical industrial problems, which in many instances has led to the development of new technology and / or experimental practices. Dr. Leis is currently principal investigator and/or project manager for several major projects involving the performance and integrity of pipelines and other structures. His current client base involves the PRCI, EPRG, INGAA, GTI/GRI, and several domestic, as well as Mexican, European, and Pacific-rim transmission companies.

Dr Leis. has served as a witness at the US NTSB Hearing on In-Line Inspection and Pipeline Integrity (2002). He has given testimony to the GAO for input to US congressional hearings in regard to current regulations on integrity management plans and practices, and served as a witness to the Canadian National Energy Board at Hearing GH-3-98 (the Alliance Pipeline) and Hearing MH-2-95 (Causes, Mitigation, and Control of Stress-Corrosion Cracking) representing the Canadian Energy Pipeline Association.

Dr. Leis has co-edited four major books on fatigue and fracture and contributed five chapters to three monographs on fracture. Including in his publications are more than 95 referred papers, a focus of which has nonlinear fracture mechanics and damage mechanics analysis, including environmental and thermal effects, which over the last 25 years have focused on damage and fracture mechanics and their application to pressure vessels and piping systems.

Co-Author **Dr Xian-Kui Zhu** was born in Hubei, China in 1962, being educated in China at Hohai University in Engineering Mechanics and at Tsinghua University in Solid Mechanics. Dr. Zhu's expertise is solid mechanics and computation mechanics, including elastic-plastic fracture mechanics, fatigue and damage mechanics, material strength and structural mechanics, and the finite element and boundary element methods. He has more than 20 years research experience using theoretical, numerical and experimental methods for linear and nonlinear structural stress analysis, fracture, fatigue and damage analysis, structural reliability and probability analysis, thermal and mechanical analysis, welding modeling and simulation, and material mechanical and fracture property testing and application. His research areas cover various engineering fields, including mechanical, civil, nuclear, aerospace, naval, automotive, pressure vessel and pipeline engineering. Recently, Dr. Zhu works on projects from both government and industry with a focus on the structural integrity and failure analysis for gas and oil transmission pipelines, such as the structural design and flaw assessment using advanced elastic-plastic fracture mechanics techniques and the determination of the plastic collapse loads, the remaining strength of corrosion defects and the fatigue-damage lives of imperfect pipelines.

In addition to many conference papers and technical reports, Dr. Zhu has co-edited two technical conference proceedings and published 70 referred papers in technical journals in his research fields.