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Identifying Research, Development, and Training Needs for Oil and Gas Pipeline Safety and Security

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16. Abstract

Pipelines are by far the most important mode of petroleum transportation in the United States because of their remarkable efficiency and low transportation cost. Pipelines carry two-thirds of the energy consumed by our nation and are recognized as the safest and most economical way to distribute vast quantities of oil and gas from production fields to refineries to consumers for a foreseeable future. This sophisticated network of gathering and distribution system comprises 2.3 million miles of pipelines-varying in size from 2 inches to 60 inches in diameter. Pipelines are vital to nation's economy and are a significant part of national critical infrastructure.

The pipeline infrastructure and the volume of products transported have continued to grow as demand for energy has increased. Over the next two decades, the demand for energy is projected to reach record levels. This increased demand for energy combined with the expansion of the cities and suburban areas will require the pipeline infrastructure not only to expand but to reliably and safely deliver energy services in support of the nation's economy. United States has a well-developed system for protection of public and environment from dangers of oil and gas pipeline failures. However, there is always a chance that a pipeline can leak. Pipeline leaks can be dangerous to people, to the natural environment, to public land, and private property. Furthermore, the tragic events of September 11th terrorist attacks have focused the attention on the security of nation's energy sources and the critical energy and transportation infrastructure systems. Therefore, pipeline security and safety has become a high-profile, national concern.

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TABLE OF CONTENTS

CONTENTS	**PAGE #**
INTRODUCTION	1
DAMAGE DETECTION AND PREVENTION	2
CORROSION	4
LEAK DETECTION	6
INTEGRITY MANAGEMENT	7
IMPROVED MATERIAL PERFORMANCE	10
PIPELINE SECURITY	10
CONCLUSION	11

INTRODUCTION

Pipelines are by far the most important mode of petroleum transportation in the United States because of their remarkable efficiency and low transportation cost. Pipelines carry two-thirds of the energy consumed by our nation and are recognized as the safest and most economical way to distribute vast quantities of oil and gas from production fields to refineries to consumers for a foreseeable future. This sophisticated network of gathering and distribution system comprises 2.3 million miles of pipelines-varying in size from 2 inches to 60 inches in diameter. Pipelines are vital to nation's economy and are a significant part of national critical infrastructure.

The pipeline infrastructure and the volume of products transported have continued to grow as demand for energy has increased. Over the next two decades, the demand for energy is projected to reach record levels. This increased demand for energy combined with the expansion of the cities and suburban areas will require the pipeline infrastructure not only to expand but to reliably and safely deliver energy services in support of the nation's economy. United States has a well-developed system for protection of public and environment from dangers of oil and gas pipeline failures. However, there is always a chance that a pipeline can leak. Pipeline leaks can be dangerous to people, to the natural environment, to public land, and private property. Furthermore, the tragic events of September 11^{th} terrorist attacks have focused the attention on the security of nation's energy sources and the critical energy and transportation infrastructure systems. Therefore, pipeline security and safety has become a high-profile, national concern.

Pipeline reliability is directly related to pipeline safety; pipelines that fail do not deliver fuel. To maintain pipeline integrity and promote pipeline longevity, it is necessary to insure that the pipeline meets operating and safety requirements during design, construction and installation, and operations. In design stage, the proper steel must be selected to withstand temperature, pressure, and environmental conditions. Most pipelines are coated on the exterior to protect against corrosion and other damage. Some pipes are coated on the interior to improve flow conditions or to protect against corrosion by fluids being transported. The overwhelming bulk of oil and gas pipeline construction is done by welding individual joints of pipe together particularly in large, long distance pipeline. The use of proper welding techniques and procedures will avoid damage to coating and pipe. Comprehensive inspection of completed welds is a safety requirement. Pipeline corrosion can result in damage to the pipeline. Cathodic protection has long been used to protect the buried pipelines from corrosion.

Pipelines will ultimately fail and integrity cannot be guaranteed 100%, but careful monitoring, inspection, and maintenance programs greatly reduce the risk of failures that could cause disastrous consequences to human life, the environment, and business operations.

The extensive pipeline system in the United States has been in place for decades. The greatest needs in pipeline safety relate to existing facilities as opposed to new pipeline projects. While it is important to have better coating, better steel, and new damage and defect resistant pipelines, the fact remains that the existing pipeline infrastructure poses the largest potential risk to public. As pipeline infrastructures age, inspection and maintenance programs are needed to prevent structural integrity problems, especially those that jeopardize public safety, the business operation, or the environment. However, the selection of appropriate, yet cost-effective, methods is still widely considered to be more of an art than science. Therefore, the focus should be on developing better testing, monitoring, and operating the existing pipeline infrastructure.

Considerable progress has been made in United States to improve pipeline safety. However, engineering and scientific analysis of pipeline safety issues indicates that much remains to be done. To manage the risks inherent in pipeline transportation, research and development (R&D) programs are essential to improve the technology for the detection, diagnosis and remediation of safety problems. The major pipeline safety R&D areas include damage prevention and leak detection, enhanced operations, controls and monitoring, and improved materials performance,. The following sections provide a brief review, the state of technology, and the research needs for each area.

Damage Detection and Prevention

Pipelines are damaged as results of external force, corrosion, and mechanical failures. External force which includes 3rd party damage, incorrect operations, and natural phenomena such as floods and landslides, are the most prevalent root cause in the pipeline incidents. It is generally agreed that third-party damage is the primary cause of most pipeline accidents. Pipelines were once found mostly away from population centers, people and activity. However, suburbanization and increased construction activity have increased the risk of accidents, caused by construction equipment striking pipelines, with tragic consequences. The damage from outside forces, such as excavation, does not always results in instant and deadly consequences. Damage to pipelines from construction may remain undetected and leave the potential for a future rupture.

This type of damage ranges from actual strikes of pipeline causing coating or pipe wall damage to land movement or abnormal loading that may be caused by near misses which result in undermining or washouts. Ageing and corrosion possibly can affect the extent of damage caused by third party activity and therefore the likelihood of pipeline failure. This phenomenon has not been studied to date.

One of the most powerful and useful failure prevention methods is public education. “Dig Safely” and Common Ground, are examples of efforts in the public safety and education arena. There are several types of measure that are used to prevent damage caused by third party activity. Pipeline damage prevention measures are designed to:

- Alert third parties to the presence of the pipeline prior to commencing their activities. These measures include reinforced concrete slabs, tiles or steel plates, and high tensile netting that are buried above the pipeline and/or Marker posts that are placed at strategic point along the length of the pipeline.

- Limit the extent of pipeline damage caused by third activity such as increased wall thickness which could be used in areas where the pipeline is considered to be at increased risk from third party activity or where the pipeline is routed underneath a road or railway. These technologies are suitable only over short distances.

- Monitor the activities conducted along the pipeline route to ensure that nothing is in such close proximity to a pipeline that it could result in damage. These measures generally take the form of some kind of surveillance activity such as aerial, vantage point, or walking surveys. These measures also detect pipeline damage caused by natural phenomena such as ground movement. Since, building and excavation activities last relatively a short period of time; the surveys must be conducted relatively frequently which makes them expensive.

Various technologies are now being considered or pursued for third-party detection system. Satellite surveillance may be used as an alternative to aerial methods. Satellite surveillance generally involves taking a picture of the pipeline route which is subsequently updated at regular intervals. Currently, the resolution is not suitable for the type of geography found in the U.S. Satellite imaging technology is however constantly improving and satellite surveillance may become a more feasible option in the future. Global Positioning Systems can be used to locate the position of mechanical excavation equipment in relation to the pipeline. This will provide the pipeline operator with the ability to know exactly where activities are being undertaken.

This technique requires that mechanical excavation equipment being fitted with positioning systems. This might be practical for equipment belonging to the pipeline operator, but many incidents are caused by third parties who might not have the positioning systems installed. The pipeline itself does not require the installation of surveillance equipment; but a digitized map of the pipeline layout must be available. Other techniques include electromagnetic detection which utilizes a variable current to set up a magnetic field around the pipeline. A magnetic field sensor once installed on the excavation equipment would then be able to detect the magnetic field. This measure can be effective over relatively long sections of pipeline. However, mechanical excavation equipments would have to have the detection system installed. The current can only travel few miles, so booster transmitters must be installed.

In summary, a range of promising remote monitoring systems have been evaluated for third-party detection system; ranging from motion detection systems to satellite surveillance. However, a cost-effective third-party detection system that provides a reliable signal on near real-time basis to allow operators to take responsive action is not currently available. This might prove a suitable topic for further research.

Corrosion

Experience has shown that corrosion is one of the main threats to the integrity of pipelines. Corrosion, if left undetected, will eventually lead to breach of pipeline wall resulting in the loss of containment which causes damage to property along the pipeline, and downtime. Corrosion can occur both on the inside wall and outside surface of the pipeline. The most common form of the external corrosion is the general or pitting corrosion that results in loss of metal in steel pipe in the form of small pits. This kind of underground corrosion is caused by flow of electric current between areas of different electric potential. Most pipelines are coated on the exterior to protect against corrosion and other damage. The coating inhibits the flow of electric current from the pipe and resulting loss of steel. In addition, cathodic protection (CP), which applies electric current to the pipeline surface, has long been used to protect the buried pipelines from the effects of external corrosion. A number of factors can influence the ability of CP to protect the pipeline against corrosion. They include attenuation of current along the pipeline, interference effects from other pipelines and power lines (stray Alternating Current), and current distribution. It is therefore critical to monitor the pipe condition to ensure adequate CP is being provided to pipe. Generally, the CP system troubleshooting techniques are labor-intensive and are subject to interpretation.

The prevention of corrosion is an ongoing challenge in pipeline operations. Unfortunately, corrosion in pipelines cannot be totally avoided especially in aged pipelines and some material loss is almost always experienced. It is then necessary to ensure that this is kept within acceptable limits to avoid any defect that can eventually lead to service disruptions and the risk of environmental incident. A variety of inspection techniques and technologies are used to monitor pipeline conditions to assess corrosion-caused metal loss. Tools for detecting metal loss, primarily from corrosion, are based either on electrical/magnetic measurement or acoustic measurements. However, there is a need for non-intrusive methods for coating and external pipe condition assessment.

A less common type of corrosion is stress corrosion cracking (SCC) also known as environmentally assisted cracking. SCC manifests itself as micro cracks that grow to form macro cracks leading to pipeline failure. SCC is caused by the combined influence of pipe stress, metallurgy, and electrochemistry all which must be present simultaneously to cause of SCC. SCC was first detected in natural gas pipelines. The failures in petroleum liquid pipelines can be more random and more catastrophic because of the phenomenon known as cycling, pressure surges that cause cracks to grow. Currently, there are no tools or mechanisms available to confidently identify the susceptibility of pipeline to SCC. In addition, there is a need for further inspection capabilities to detect and characterize SCC.

Internal corrosion is generally caused by impurities in the hydrocarbon stream including water, organic acids, dissolved salts, carbon dioxide (CO_2), hydrogen sulphide (H_2S), oxygen, sand, and scales. CO_2 and H_2S in water form corrosive acids which can cause general corrosion and pitting. In addition, the reactions between steel and H_2S generate hydrogen, which can cause hydrogen blistering and stress corrosion cracking. In general, internal corrosion could be attributed to the increased water content and decreased flow velocity. In pipeline systems where water collects, bacterial colonies can form deposits on metal surfaces and produce organic acids that accelerate corrosion and cause localized pitting. This form of corrosion, which is known as microbially induced corrosion (MIC), often creates leaks in wells and pipes carrying natural gas, water, and chemicals. Several techniques are being applied for the detection, prevention, and monitoring of the internal corrosion. Some pipes are coated on the interior to protect against internal corrosion. Biocidal chemicals are often used to fight MIC. These treatments are not only costly, but they can also have a harmful environmental effect. Alternative biocides that are less toxic than those now in use, carbon steels that resist MIC and improved on-line MIC detection methods are being considered. Accurate and consistent monitoring of internal corrosion is a difficult task and it should be emphasized that no single method is considered adequate. Improved MIC detection systems are needed in order to preserve and assure the integrity and serviceability of pipelines.

Leak Detection

Leak Detection is an important part of pipeline operation. Seepage leaks represent a hard to identify pollution source and safety concern. If left until they are discovered visually on surface after affecting water quality, such leaks will cause great damage that is very expensive and difficult to remediate. Early detection of leaks can greatly reduce the loss of product from the pipeline and danger of pollution. Fugitive leaks can be a major source of methane emissions from natural gas facilities. Left uncontrolled, fugitive methane emissions can, at the least, add up to significant economic loss, or can, at worst, pose safety hazards.

Operators are required to inspect pipeline routes periodically. Traditionally, pipelines were inspected visually by traversing the route on the ground. Natural gas pipeline can be inspected for leaks with surface sampling instruments using the flame-ionization principle. This type of equipment typically finds leaks resulting from stress corrosion cracks, seam leaks, and leaks in the welds. In the United States, pipeline operators rely on directed inspection and maintenance (DI&M) programs to identify and repair leaks. Current DI&M techniques and technologies for detecting gas leaks e.g. soap bubble screening, acoustic detector, toxic vapor analyzer (TVA) and organic vapor analyzer (OVA), require an operator to visit and screen every component by placing the screening instrument in the immediate vicinity of the potential leak. This approach is time consuming, inefficient, and costly, when operators must screen hundreds or thousands of components at each site. Other leak detection methods include:

- Monitoring inflow and outflow to a segment of the system,
- acoustic emission inspection systems,
- instrumented pigs, and
- Ultrasonic methods.

Aerial surveillance of the pipeline right-of-way to look for any discoloration of plants and grasses as a potential indicator of the pipeline leak has been used extensively. Now, with addition of instrumentation and monitoring equipment such as flame-ionization detectors and GPS systems, aerial inspection can also provide more rapid and precise location of leaks. Infrared laser camera based on backscatter absorption gas imaging (BAGI) or image multi-spectral sensor (IMSS) technologies are now being considered for remote leaks detection. Microwave radar which works based on change in radar reflection, refraction, and scattering properties of leak plumes with respect to the surrounding air has been also investigated for remote and fast imaging of gas leaks for protection of natural gas pipeline infrastructure.

The ability of leak detection systems to identify and report low-level leaks, especially in high consequence areas and where groundwater sources exist is a source of concern. To reduce the potential impacts to public water supplies from existing pipeline infrastructure, rapid detection of groundwater invading seepage leaks is most important. Existing computer balancing models are not sensitive enough to detect small leaks and longitudinal detection systems are most often considered too expensive to implement, especially along existing pipelines. Additional research is required to evaluate various methods that can produce reliable results at affordable cost. Research is also needed to identify and evaluate technologies that can be deployed without the need to excavate existing facilities

Integrity Management

The goal of integrity management is to use inspection, monitoring, and maintenance to prevent structural integrity problems, especially those that jeopardize public safety, the business operation, or the environment. Pipelines become damaged and/or otherwise deteriorate in some manner. It is believed that most deterioration occurs in the form of corrosion even with the application of corrosion prevention coatings or devices. Dents or other geometric compromises of pipeline shape can be caused by physical contact, stress, or deformation induced by improper installation, erosion, or shifting of the substrate. Dents can affect the strength and performance of the pipeline and may result in damage to critical interior or exterior protective coatings. Therefore, as pipeline ages, inspection and maintenance programs are needed to insure that the pipeline continues to meet operating and safety requirements. There are three aspects to consider in dealing with pipeline integrity: prevention of loss, detection of loss, and response in the event of a loss. To prevent loss of integrity, pipeline inspections are a first-line defense. They may be proactive (i.e., searching for potential problems) or reactive (i.e., looking for damage already present that may cause imminent danger or loss of integrity).
Countless factor working alone or in conjunction, affect pipeline integrity. Several actions are employed to assess integrity, prevent failure, and mitigate damage. These actions may be introduced at design, such as upgrading materials and increasing wall thickness or performed during construction, such as carrying out weld checks, coating inspection, and hydrostatic pressure testing. They are deployed during operations, such as conducting internal inspections with in-line inspection devices and making predictive assessments.

Pipeline monitoring programs are used to keep track of the effects of corrosion or mechanical damage. They could also provide information on dents and other damage that may eventually cause failure and leaks. Integrity Management is a systematic process that continually assesses, evaluates, and remediates the integrity of systems through prevention, detection and mitigation practices. Pipeline integrity can be determined through direct assessment methods, hydrostatic testing and internal inspection tools. Direct assessment methods include various types of cathodic protection surveys, such as close interval surveys to ensure that the pipe is not corroding. Pipe surfaces are frequently examined when and where possible. On-land procedures of excavating sections of buried pipeline have been an extensive practice for many years in order to observe pipe surfaces and evaluate corrosion conditions. This practice is expensive and at best, can only expose a limited portion of a major line. Since large sections of a line may go unexamined by this method for a time, extensive damage could go undetected and result in a line failure. Such a practice on offshore pipelines is basically impractical because of the water environment and other factors. However, the need and concern for detecting and evaluating possible corrosion to offshore pipelines is just as great if not more.

Hydrostatic testing involves pressuring the pipe to a level equal to or above its normal operating pressure. The hydrostatic test establishes the pressure carrying capacity of a pipeline and may identify defects that could affect integrity during operation. Axial flaws such as stress corrosion cracking, longitudinal seam cracking, selective seam corrosion, long narrow axial (channel) corrosion and axial gouges can be detected with a hydrostatic test. Hydrostatic testing requires the large quantities of test water, which in some areas may be difficult. The test water may require treatment prior to discharging or disposal. Finally, hydrostatic testing requires the pipeline to be out of service for a period of time thus potentially curtailing the availability of fuels.

Internal inspections of the pipelines involve the use of sophisticated technological tools, known as “smart pigs.” Pipeline pigs are cylinder-shaped electronic devices that are inserted into the pipeline and propelled by the flowing liquid. They are used for a variety of purposes in both liquid and natural gas pipelines. Mechanical pigs have been long been used to clean pipelines, and to separate different fluids in a pipeline. Today’s smart pigs are sophisticated instrumentation packages that move through the pipeline and check for cracks, corrosion damage, out-of-roundness, and other defects. They contain complex electronic systems that provide an extensive array of data about pipe conditions and detect problems that might lead to failure.

As smart pig technology has evolved, pipeline operators have required the use of specialized smart pigs. Specialized smart pigs have evolved into three types: Metal Loss, Crack Detection, and Geometry Tools. The metal loss pigs utilize Magnetic Flux Leakage (MFL) or Ultrasonic tools (UT). MFL tools can determine the location and position of the metal loss anomaly and detect if a corrosion anomaly is internal or external to the pipe wall. It also provides data which allows for calculation pipe's remaining strength. Axially-oriented flaws such as stress corrosion cracking, selective seam corrosion and axial gouges are difficult to detect with MFL pigs. UT transmits an ultrasonic pulse into the pipe wall and directly measures its thickness. It is generally not used for oil pipelines. Crack detection tools are the more recent integrity assessment tools are divided into 3 category including Ultrasonic, Transverse Magnetic Flux Leakage, and Elastic Wave tools. Geometry tools gather information about the physical shape, or geometry, of a pipeline. Some pigs use simple electromagnetic transmissions systems to send the data to hand-held receivers on the surface of the ground or contained in remotely operated undersea vehicles. Some pigs use global positioning survey (GPS) techniques for location through a satellite network.

Many pipeline due to sharp bends, dented lines and systems without ready access cannot be inspected with smart pigs. Roughly 20 percent of the main liquid pipelines and as much as 70 percent of gas pipelines are considered "non-piggable" due to insufficient flows, sharp bends, and various cost-prohibitive factors. Office of Pipeline Safety (OPS) reported that only about 37 percent of U.S. pipeline miles are inspected by smart pigs. Hydrostatic tests are generally the preferred integrity assessment method when the pipeline is not capable of being internally inspected with smart pigs but it can be very costly. Clearly, other technology would be desirable if it produced results and gave the operator assurance the lines in question could meet operational requirements. Predictive assessment is cost-effective alternative pipeline inspection and monitoring technology for pipelines that cannot accommodate smart pigs. The objective of predictive assessment is to acquire an acceptable level of confidence in structural integrity of the pipeline based integrating the information obtained from indirect measurements such as Close Interval Survey (CIS) and Direct Current Voltage Gradient (DVG), and direct measurements from bell-hole excavations and the physical characteristics and operating history of the pipeline. One of the emerging technologies is long-range ultrasonic inspection. Long-range ultrasonic testing or guided wave ultrasonic testing (GWUT) technology offers a cost-effective method of compliance when used with the direct assessment method. While there is no one technology that can cover all inspection situations, GWUT coupled with CIS and other emerging technologies, will be important tools in maintaining any pipeline integrity program.

In summary, pipeline operators use a combination of inspection techniques to ensure the safety and reliability of the pipeline infrastructure. To obtain an accurate analysis of pipeline integrity and conditions increasingly sophisticated inspection methods have been developed. However, the need for additional technology development for nondestructive evaluations of “unpiggable lines” and detection of material defects remains.

Improved Material Performance

Development of new materials for pipes that would be tougher, more resistant to corrosion, and able to withstand higher pressures is considerable interest word-wide amongst major pipeline operators. Examples of potential material include:

- High-strength steels for long distance gas transmission pipelines. Pipelines that are constructed from such materials will have higher capacity obtained from being able to operate the pipeline at a higher pressure.

- Fiber-reinforced polymeric composites used in pressure retaining structures are an attractive alternative to products made from conventional materials due to their corrosion resistance and high strength-to-weight ratio.

- Application of ceramics for the wear and corrosion protection of piping systems.

- Development of internal coatings that could be applied to existing pipes for improved strength as well as to make them smoother to reduce frictional losses.

The reluctance in adopting composite materials, however, is due to a limited understanding of the material behavior under a variety of loading and environmental conditions.

Pipeline Security

The tragic events of September 11 terrorist attacks have focused our nation’s attention on the security of our energy resources and our critical energy transportation infrastructure systems. Pipeline system presents a tempting target.

Therefore, it is critical to protect the pipeline infrastructure and to reliably deliver energy services in support of the nation's economy. Pipeline operators have implemented many measures to increase security of the nation's pipeline system. Some were simple actions such as further restricting access to above ground facilities and instructing employees to report unusual activity. Some are more involved such as coordinating protection with the local law enforcement and re-evaluating back-up pipeline control centers.

To verify the security of pipeline system is a major challenge. To address pipeline infrastructure security, it is important to develop long-term plans for protecting a transportation system vital to our economy and security from terrorist attack. American Petroleum Institute (API) and Association of Oil Pipe Lines (AOPL) have developed a guideline for security practices and risk management. However, the need for development of innovative technologies for improving security, counter measures, and response activity still remains. In addition, an outreach program to increase the security awareness of infrastructure owners and operators and promote sharing of best practices and lessons learned is desirable.

CONCLUSIONS

The national pipeline infrastructure is both vast and varied. The ability to remotely and inexpensively monitor and assess the pipeline integrity could provide improved means for service-life prediction and defect detection to ensure operational reliability. The role of technology in assuring infrastructure integrity and reliability is significant. To meet challenges of enhanced pipeline safety and reliability in a competitive environment, it is necessary to develop and combine new technologies in an innovative way. The technology development must not simply provide new or enhanced capability; it must be provided at low cost or it will not be widely adopted in practice. The areas that are in need of additional technology development include pipeline ROW monitoring for real-time warning of proximity, line hits and damage, inspection tools to detect and characterize corrosion (SCC and MIC), non-intrusive methods for coating and external pipe condition assessment, non-destructive evaluations of unpiggable lines, development and evaluation of new materials for pipeline and pipeline coating and pipeline security, counter measures and response activity.