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PROGRAM TO EVALUATE READINESS LEVELS OF PIPELINE-ORIENTED TECHNOLOGIES

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ABSTRACT

Technology plays a critical role in the oil and gas sector, and the pipeline industry is no exception. Maintaining the integrity of high pressure oil and gas pipeline requires the use of advanced technologies. A challenge that confronts every pipeline operator is the risk posed in the deployment of unproven technologies, especially those associated with the inspection, assessment, monitoring, and rehabilitation of their systems. Use of unproven technologies and concepts puts pipeline operators at risk.

The concept of Technology Readiness Levels (TRLs), commonly used in the aerospace and defense industries, provides the pipeline industry with a proven means for evaluating and assessing technologies used to enhance integrity management efforts. This paper presents details on technology readiness levels ranging from *Proof of Concept* to *System Operation*. The adoption and implementation of the TRL approach will minimize operator risk and foster the deployment of advanced technologies, thus enhancing the safe operation of high pressure pipelines. Three TRL-oriented case studies will be included evaluating the monitoring of pipelines using fiber optics, inspection using three-dimensional imaging, and reinforcement using optimized composite technologies.

INTRODUCTION

This paper has been prepared to present and discuss Technology Readiness Levels (TRLs), based in-part on a review of concepts presented API Recommended Practice 17N (June 2017), *Recommended Practice on Subsea Production System Reliability, Technical Risk, and Integrity Management*; particularly, Annex E: New Technology Qualification [1]. **Figure 1** provides a graphic showing what is called the "TRL Ladder", which ranges from TRL 0: *Basic Unproven Concept* to TRL 7: *Field-Proven" System Operation*. TRLs provide an effective means for evaluating the "operational readiness" of a given technology. Although the focus of this paper and the included case studies are onshore-related, the TRL concept has universal applicability for both technologies used both onshore and offshore.

It is essential that technologies function as designed to ensure they perform reliably when placed in service. When technologies fail to perform as designed, system integrity is placed at risk, leading to potential failures that could impact environment, safety, and asset performance. At the heart of every technology integration are the concepts of risk and reliability. Many technologies used in the pipeline industry are used to support integrity management efforts; a few examples include in-line inspection, advanced repair methods, material characterization, and in situ monitoring. The challenge facing every pipeline operator is to understand the uncertainties associated with the technology performance and risk mitigations, while considering for deployment in their system.

The TRL framework utilizes seven assessment stages to provide a structured framework to ensure that a given technology performs as designed and promoted. If gaps in technology performance exist, the TRL framework allows key stakeholders with a platform to not only evaluate "next steps" but provides them with a vehicle for verifying a technology's ability to reach designated performance levels. In the absence of such framework, technology developers and users are often "shooting in the dark" in terms of defining the capabilities of a given technology. Further, the TRL framework provides regulators with a reference to define for operators and technology companies what is expected from their perspective in terms of ensuring code compliance.

In terms of participants in the technology development and implementation process, there are three major groups as illustrated in **Figure 2**. These participants include:

- Operators / technology users, plus regulatory agencies
- Technology providers and service companies
- Technology investors

Each of these participants are interested in the successful deployment of technologies, although their motivations and means for quantifying success are somewhat different. TRLs provide an effective means for evaluating the "operational readiness" of a specific technology. It is essential that technology function as designed and performs reliably in service. The following sections of this paper discuss in detail elements of the TRL framework, case studies where three technologies are evaluated relative to their respective TRLs, and recommendations on methods for integrating new technologies to pipeline application.

ELEMENTS OF THE TRL FRAMEWORK

One goal of this paper is to provide readers with a framework for determining where a particular technology is in terms of the overall TRL framework. In other words, is the technology still at TRL 2: *Demonstration by Testing* or is the technology further along this process and actually at TRL 4: *Prototype Validation*? Knowing how to distinguish between the different phases is important for the following reasons.

- It is easy for technology developers to believe they are farther along in the TRL process than they actually are. This is not a technical issue; rather, it is an emotional issue and requires that the technology developer divorce themselves from the design and development process to conduct an objective assessment of where they are in the process. Oftentimes, third party organizations with technology experts or potential technology users are ideally-suited to partner with innovators in going through this process.

- Knowing where a technology resides in the TRL process permits stakeholders including technology innovators, users (i.e., operators), regulators, service companies, and investors to better understand where they are and where they need to be. It does not benefit key stakeholders to believe a technology is further along in the TRL process than they really are. The TRL process provides a framework for knowing where to focus to ensure the technology development process advances appropriately, with the eventual goal of every technology to achieve TRL 7: *System Operation*.
- The TRLs allow interested parties, namely technology innovators, developers, users, and investors, to have a framework against which to measure the technology development stage. This ensures that the technology development process advances at a reasonable pace, ensuring internal accountability among team members regarding performance expectations and associated risks of achieving the desired TRL levels.

The sections that follow provide details on each element associated with the technology readiness levels as outlined in API RP 17N. This presentation is made primarily from the viewpoint of the "innovator", the individual or company responsible for the technology's creation, development, and eventual implementation. It is important to note that at each stage of the TRL process, it is essential that innovators identify design gaps and issues before proceeding to the next TRL.

TRL 0: Basic Unproven Concept

This is where technology development all starts; the proverbial "back of the napkin" stage of the design process. At this stage engineers are likely to deploy first principles to ensure the technology is adequately designed to meet the rigors associated with the specified design requirements. Unfortunately for technology innovators, the design at this stage is little more than an idea. It is challenging to attract the interest of operators, investors, or regulators at this stage of the TRL process.

TRL 1: Proof of Concept

Once an innovator has come up with a concept, it is necessary to conduct a paper study that involves a low-level analysis. This TRL often involves conceptual drawings, as well as a design package that includes anticipated loading conditions to which the technology will be subjected. Oftentimes, design engineers will utilize finite element analysis to not only evaluate adequacy of their design, but also provide illustration materials that can be shown to illustrate the capabilities and merits of the given technology.

TRL 2: Demonstration by Testing

In order for a technology to progress to TRL 2, the innovator should have confidence in the technology's ability to perform based on analytical and numerical modeling results. From a technology development process, numerical modeling provides a low-cost alternative to functionality testing involving lab mock-ups. Successful completion of TRL 2 is achieved when mock-up testing demonstrates ability of the technology to perform at the required level, even if this involves sub-scale testing.

TRL 3: Prototype Development

Prototype development is the natural evolution following the mock-up testing associated with TRL 2. At this stage of the TRL process, innovators should start "pushing the envelope" and looking for ways to make the technology fail. The importance of this stage cannot be over-stated. Failure to address technology shortcomings can lead to disastrous and costly mistakes in subsequent TRLs. If innovators have not brought in outside subject matter experts up to this point, this would be an appropriate stage in which to integrate outside expertise. The goal in TRL 3 is to conduct reliability modelling and testing to achieve confidence in technology performance.

TRL 4: Prototype Validation

The authors have conducted too many full-scale tests to count over the past 20 years; however, one point is clear – *full-scale testing is expensive*. Before any full-scale testing efforts are started, it is strongly recommended that two things happen. First, engage third party testing services; as a minimum, engage a subject matter expert (SME) to provide consulting services even if the design company plans to conduct in-house testing. Integrating SMEs at this stage, if not sooner, is wise because their participation will reduce the likelihood of wasting both time and money. Secondly, it is essential that any full-scale testing capture actual service loading conditions. When technologies fail in service, it is often due to failure on part of technology designers to anticipate actual service conditions. This is especially true when "combined" loads are present and contribute to in-service failures. The goal in TRL 4 is to conduct full-scale testing to simulate actual service loading conditions.

TRL 5: System Integration Testing

Having successfully completed full-scale testing efforts associated with TRL 4, the next step is field deployment with limited functional loading. Operators and regulators are often hesitant to adopt new technologies where technology failure can jeopardize pipeline integrity. However, the risk associated with technology integration is significantly reduced if a comprehensive full-scale testing program integrates all possible "high risk" loading conditions (i.e., it is usually impractical, unnecessary, and inefficient to test all possible loading conditions).

Prior to this point in the technology assessment and integration process most work has been conducted by the technology innovators and their supporting investors. However, this stage of the TRL process represents a partnership between the technology innovator and pipeline operator. In high risk applications regulatory oversight might also be required. The ideal technology deployment is integration of the technology in a low risk environment where failure of the technology does not put pipeline integrity at risk. For example, a new repair technology can be installed on a pipeline not having defects but monitored to ensure it performs as designed. The goal of TRL 5 is field deployment or demonstration with limited functional loading.

TRL 6: System Installation

There is an improved confidence in the ability of the technology to perform as it progresses up the TRL ladder. TRL 5 represents a milestone in the technology development process as it typically represents the first time the technology has been deployed in the field in close to or real environment. However, because the technology has not been "fully-loaded" interpretation of performance is limited. On the other hand, TRL 6 involves full loading in the field that includes monitoring; it is a natural progression from TRL 5. With today's technology advances, the ability to monitor new technologies has been greatly enhanced; examples include fiber optic sensors and wireless monitoring.

Prior to full-acceptance of a technology, regulatory bodies prefer to see technology performance specification and comprehensive monitoring program that includes a partnership between technology innovators and operators. This stage of the TRL is often more about technology evaluation than technology development. At this point in the technology implementation process it is too late to go "back to the drawing board." TRL 6 can be actually be more expensive than the full-scale testing work associated with TRL 4 as it is often time consuming and can require significant resources from the operator.

TRL 7: System Operation

Reaching TRL 7 is the goal of every technology innovator and company, as well as operators and regulators. Reaching TRL 7 means that the technology can be used without reservation. The concern typically moves from "will the technology work?" to "how can we properly install and use the technology to ensure it works?". The challenges associated with TRL 7 are not any less rigorous than any of the other TRLs; however, the questions now asked are different than before. Oftentimes, it is at this stage that the subject of Quality Control and Quality Assurance become very important. Prudent technology innovators and companies should consider the importance of quality and impose some form of Quality Management System (QMS) early in the technology development process. In terms of TRLs, a QMS should likely be in place by the time TRL 3 is reached.

Part of the implementation process associated with TRL 7 is in-service review of monitored data. Depending on the technology, this might or might not be a long-term endeavor. Although TRL 5 and 6 are phases associated with the "trial run" of in-field technology implementation, it is advisable to maintain a continuous monitoring mindset if at all possible.

CASE STUDIES

To assist the reader with understanding how TRLs can be used to evaluate specific technologies, three case studies are presented. There are literally hundreds of potential examples, however, three case studies have been selected to address topics including reinforcement / rehabilitation, inspection, and monitoring. For each case study details are provided that include an industry need (i.e., problem statement), technology background, technology assessment in terms of the "current" TRL, and recommendations for moving the technology implementation up the TRL ladder.

For each case study a Technology Assessment Chart is presented to provide a visual demonstration of the technology's TRL. These charts are provided in **Table 1** through **Table 3**. The primary objective in going through this process is to help identify gaps for technology innovators and users before advancing to the next TRL. This will ensure the desired TRL is achieved before deploying the best possible technology in the field.

It should be noted that these case studies are only presented as examples. The authors are not advocating the technical merits of their implementation in actual pipeline systems. Operators are encouraged to pursue and advance the TRLs for these and other technologies to improve operational efficiencies, improve safety, and lower operational risks.

Case Study #1: External Pipeline Reinforcement for Overburden Loading

In operating pipelines operators are often required to accommodate post-construction activities that include additional overburden loads associated with the construction of highways and railroad crossings. Several options exist when these situations arise including re-routing, pipeline lowering, casing installation, replacing with thicker pipe, and installing concrete slabs over top of the pipeline. While all of these options are technically-viable, each presents certain challenges. Federal regulations require that reinforcing technologies demonstrate performance using engineering testing and analyses [2].

A technology company developed an innovative method for installing steel sleeves using an advanced bonding adhesive overwrapped with a high strength composite material. The objective was to externally-reinforce stiffness of the pipe to improve its ability to withstand overburden loading. Finite element modeling and full-scale testing were conducted to optimize the design and validate overburden capacity of the reinforcement.

Figure 3 provides images associated with a finite element analysis conducted to measure stresses in the reinforced pipe, while **Figure 4** shows the experimental test set-up that involved the reinforcement of a 24-inch x 0.,250-inch, Grade X42 pipe. The steel sleeve thickness was 0.25 inches and the composite overwrap was approximately 0.50 inches thick. During testing the pipe was pressurized to 72% SMYS and an external compression force of 400,000 lbs. (1,780 kN) was applied. Two tests were run that included reinforced and unreinforced conditions. Test results showed that installation of the reinforcement increased stiffness of the pipe by a factor of 150% and at the maximum testing load the maximum hoop strain (driven by compression loading) was approximately one-half the strain measured in the unreinforced sample.

Table 1 provides the Technology Assessment Chart for this particular technology. As noted in this table, a TRL of 5 has been assigned for this particular technology due to completion of the prototype validation testing. To increase the readiness level for this particular technology, the technology development company was encouraged to complete the following activities:

1. Identify a pipeline operator who will support a field trial.
2. Additional engineering analysis work might be required to optimize design of the reinforcement. Study of alternatives and cost-benefit analysis will help support discussions with operators.
3. Regulatory compliance likely to be required; recommend integrating regulatory review as soon as practical.
4. Long-term monitoring advised, including implementation of strain gages or fiber optics to monitor external reinforcement.

Case Study #2: Advanced Inspection Technology

One of the challenges currently facing operators is accurate characterization of crack-like features in pipelines, especially with regards to long seam welds. With advances in in-line inspection technologies, the need for advanced inspection technologies for in-the-ditch validation using reliable technology has never been more important. An advanced inspection technology has been developed that permits three-dimensional characterization of crack-like features. The technology is in the early stages of development, but benchmark testing has shown promising results with greater resolution that conventional ultrasonic methods.

Figure 5 includes two images of crack-like features captured by this advanced inspection technology. Software was developed to support the images generated by this technology using complex stitching techniques to combine multiple viewpoints, permitting inspection personnel to rotate images to permit three-dimensional views of each feature.

Table 2 provides the Technology Assessment Chart for this particular technology. As noted in this table, a TRL of only 2 has been assigned because of the absence of a working prototype. To advance the readiness level for this particular technology the technology development company was encouraged to complete the following activities:

1. Develop a working prototype that simulates desired field performance capabilities.
2. Additional lab testing required to validate technology; sufficient sampling size required to achieve industry consensus and buy-in.
3. Look at operational efficiency prior to field deployment to minimize time required in the ditch.
4. Need to identify a pipeline operator who will support a field trial.

Case Study #3: Advanced Inspection Technology

Under certain environmental conditions, transmission pipelines are subjected to movement. Oftentimes the forces generated are sufficient to cause leaks or ruptures, as seen in some vintage girth welds and wrinkle bends. The pipeline industry has used various means of monitoring pipeline movement over the years, including installation of conventional and vibrating wire strain gages. Projects employing these measurement devices are often expensive and these measurement devices typically stop working over a period of time.

An alternative technology gaining acceptance is the use of fiber optic sensing devices. Shown in **Figure 6** is a photograph showing a fiber optic cable adjacent to a conventional strain gage. Fiber optic technology has the dual benefit of being both a measurement device, as well as a transmission vehicle for transporting data over long distances. Strain gage cable measurement losses are measured over distances of feet (or meters), whereas fiber optic losses are quantified over distances of miles (or kilometers).

A program was conducted that involved full-scale testing to measure strains generated during full-scale bend testing, as well as a field trial where instrumentation was installed on a pipeline that experienced lateral displacement. Instrumentation of the measurement devices allowed the operator to monitor lateral displacement of the pipeline to ensure that unacceptable levels of movement did not occur. **Figure 7** provides a photograph showing the bending test set-up to validate fiber optic technology, while **Figure 8** shows excavation of the pipeline in preparation for installation of monitoring devices. The operator recognized this program as a field trial as a means for evaluating future implementation of this technology on a larger scale across their pipeline system.

Table 3 provides the Technology Assessment Chart for this particular technology. As noted in this table, because of its relatively advanced assessment and validation a TRL of 5 has been assigned for this technology. To increase the readiness level for this particular technology, the following recommendations were made to the technology development company to increase their TRL:

1. Identify other operators who will support a field implementation study (TRL 6) based on the completed, successful field trial.
2. Build into system the concept of "scalability" as this technology will likely involve system-wide integration. Data system must be robust enough to handle large amounts of data.
3. Look for partners with the ability to evaluate / interpret data required to make operational "fitness for purpose" assessment decisions.

DISCUSSION

It is recognized that most readers of this paper will see the presented material from a purely-technical standpoint; however, the commercial aspects should not be discounted as returns on investment are an essential consideration for the successful deployment of any technology. This section of the paper provides the reader with two concepts introduced by the authors that address how technologies can be positioned both technically and commercially. The first concept, the *Technology Implementation Process*, provides a means for accelerating the time required for operator acceptance and technology implementation. The second concept involves six elements that can be used to ensure high quality technologies are produced and implemented; these six elements are identified by the Q-STEPS acronym.

To serve the overall needs of the energy industry, including being an attractive place for investment money, it is essential that every aspect of the technology development process be evaluated. If technology development issues or deficiencies are identified, they must be addressed. The goal for every technology company is to get the right technology into the hands of people and companies who need it.

The Technology Implementation Process

The technology implementation process is a means for providing a means for accelerating technology acceptance that involves four steps: Critique, Calibrate, Certify, and Connect. Optimizing technologies based on the TRL framework is a necessary, but insufficient step for achieving buy-in from industry, especially operators and regulators who are often averse to implementing new technologies. The sections that follow provide further details on this process, which is shown graphically in **Figure 9**.

<u>Critique:</u> At its core, to critique means "conducting a detailed analysis and assessment". In terms of a technology assessment this means evaluating if the technology can perform as designed. Often this involves evaluating the technology relative to a specific industry standard, although in the absence of an industry standard technology providers must clearly understand needs of their industry to ensure their technology meets those needs.

<u>Calibrate:</u> Having completed the "critique" phase of the process, the technology must be calibrated, or optimized, to meet specific needs of industry. Often this is an iterative process, where the technology provider transforms their technology using the TRL ladder from technology concept (TRL 1) to qualification testing (TRL 5), with the eventual goal of proving the technology's worthiness through sustained operation in the field (TRL 7). Ensuring the technology has been calibrated requires advanced engineering, often involving numerical modeling, full-scale testing, in situ monitoring, and material selection. It is essential that the calibration process vet any performance deficiencies before they are put into service. Failure in the field is not an option and a well-designed calibration phase will ensure this does not happen.

Certify: When third party organizations certify technologies, it provides an unbiased assessment, ensuring that the technology either meets the requirements of a given standard or the technology can perform at levels its provider claims it can. Having a technology that has been certified achieves two important objectives. First, any performance deficiencies will likely be identified by the third-party organization and can then be addressed. Secondly, pipeline operators and regulators generally prefer that third parties evaluate technologies prior to their use on actual pipelines. Both of these objectives can be important for companies seeking to get their technologies to market.

Connect: Even though a technology might be completely-suited to meet the needs of a given market, a gap often exists in connecting the technology provider with technology users (e.g., oil and gas operators). This connection is critical in terms of financial sustainability for the technology provider, but equally critical for the operator to ensure they are using the best and safe technologies to maximize safety, reduce risk, and achieve maximum operational efficiencies. Although connecting technology providers and users will occur at the early stage of the technology assessment process, the context here is a final connection after a rigorous technology development and assessment process has been completed. As stated previously, the end goal for every technology company is to "commercially" connect technology developers and users by getting the right technology into the hands of people and companies who need it.

The Q-STEPS Program

Many of today's technology assessments and certification programs focus primarily on quality, where technology companies are evaluated on their proficiency in implementing and maintaining Quality Management Systems (QMSs). While quality plays a central role in sustained development, manufacturing, and implementation of today's technologies, quality alone is not sufficient for ensuring the ability of a technology to perform at the levels required by the oil and gas industry.

The Q-STEPS process was developed based on observed gaps in the marketplace; the Q-STEPS acronym stands for the following elements shown graphically in **Figure 10**:

- Quality
- Ease-of-use
- Service
- Performance
- Training
- Safety

It has been observed by the authors that even though a company and its technologies might be able to meet the requirements of an industry-standardized QMS [3], there was no assurance their technologies could perform to the level required by oil and gas pipeline operators. Q-STEPS has been introduced to support the TRL process, the latter of which is mainly focused on achieving high levels of technology performance.

A critically-important area when considering the implementation of technology is performance, the "P" in the Q-STEPS system. At a fundamental level, performance implies that the technology is able to meet the minimum functional requirements imposed by industry. Oftentimes this involves the ability of a technology to meet the minimum design requirements of a particular code or standard. One of the most significant challenges that befalls technology companies is anticipating operating and environmental conditions to which their technology will be subjected and ensuring the performance of their technology is adequate to meet those demands. Reliable, long-term performance is predicated on the ability of a technology company to anticipate these conditions and demonstrate performance through laboratory full-scale testing and field trials. This is often best-accomplished through third-party testing, were an independent investigator is able to assess whether or not the technology meets industry's requirements.

The following sections provide brief explanations on the six elements of the Q-STEPS program and how each element has been formulated to holistically evaluate if a technology company can demonstrate that its technology has been designed, manufactured, and implemented to meet the rigorous demands of the oil and gas industry.

Quality: In the context of this discussion, quality implies the ability of the manufacturer to consistently deliver a quality product at both the manufacturing and field deployment levels. This involves a review of documentation from the technology provider to ensure necessary protocols are in place for demonstrating proficiency in quality. Examples include but are not limited to design documentation with supporting calculations, detailed drawing packages, calibration certificates, procedures and checklists for field deployment. Ensuring safety or PPE (personal protective equipment) requirements identifying in the procedures are of utmost importance since some might need operator agreement to consider and implement during deployment.

Service: For established companies, the concept of service implies the ability of the company to provide services that meet or exceed the needs of the customer. This is often accomplished using third party, independent surveys. For early-stage companies not having a large client base where conducting a survey might not be feasible, documentation should be available to demonstrate how clients receive equipment in a timely manner and that upon delivery, all required equipment is accounted for to ensure proper operation of the technology.

Training: Training programs are required to ensure that technologies perform as designed. From a review standpoint, evidence of a comprehensive training program is necessary to ensure personnel operating the technology have adequate knowledge and proficiency to safely operate the technology. The training program must ensure that properly-trained individuals can identify when the technology is malfunctioning and if necessary, be sufficiently-trained to remedy the situation.

Ease-of-use: Although it is recognized that not all technologies are simple to operate, prudent manufacturers and technology companies should undergo a process to ensure the operation of their technologies are no more complicated than necessary. Quite often technologies fail in service because of operator error, as opposed to tool malfunction.

Documentation should be available to demonstrate efforts have been made to simplify operation of the technology. Oftentimes, a Failure Modes and Effects Analysis (FMEA) will identify operational areas of concern in a technology's design and operation that can be remedied prior to field deployment.

Performance: To demonstrate proficiency from a performance standpoint, the technology company is required to show through independent testing that the technology can perform to the level promoted by the technology company. Calibration certificates should be available for all measurement devices, where applicable. Finally, to ensure quality results are produced safeguards should be in place to notify field personnel when the tool is not functioning properly.

In many situations, industry standards are available for technology companies by establishing minimum design and performance requirements. However, it is incumbent on technology companies to understand the operating and environmental conditions to which their technology will be exposed. Industry standards establish a minimum level of performance; however, in-service failure can and do result when technology companies fail to anticipate actual in-service conditions. Example of "unanticipated" conditions include cyclic loading (such as pressure) and elevated operating temperature.

Safety: Safety is the top priority for everyone in the oil and gas industry. In the context of the Q-STEPS program, safety implies that the technology company has made every effort to ensure the safe deployment of their technology, including the development of supporting documentation and clearly spelling out the training and qualification requirements for operators and field personnel.

CLOSING COMMENTS

Technology plays a critical role in oil and gas pipelines around the world. Use of unproven technologies puts pipeline operators at risk. This paper has provided an overview of the Technology Readiness Levels. The TRL platform utilizes seven assessment stages to provide a structured framework for the pipeline industry to ensure that critical technologies perform as designed and promoted. If gaps in technology performance do exist, the TRL framework allows key stakeholders with a platform to not only evaluate "next steps" but provides a means for verifying a technology's ability to reach designated performance levels. In absence of this type of framework, technology developers and users are often "shooting in the dark" in terms of defining the capabilities of a given technology.

Technology innovators, pipeline operators, and regulators are encouraged to use the TRL platform as a means for evaluating current and future technologies to ensure that on a world-wide basis pipelines are operated, monitored, and maintained in a manner that minimizes operational risks and maximizes public safety.

REFERENCES

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2. Pipeline Safety: Gas and Hazardous Liquid Pipeline Repair, Federal Register, Vol. 64, No. 239, Tuesday, December 14, 1999, Rules and Regulations, Department of Transportation, Research and Special Programs Administration, Docket No. RSPA-98-4733; Amdt. 192-88; 195-68 (Effective date: January 13, 2000).
3. ISO 9001, *Quality Management Systems – Requirements*, 2015 Edition.
4. Q-STEPS™ document published by ADV Integrity, Inc., 2018.

Table 1: Technology Assessment Chart (*External Reinforcement Case Study*)

TRL Phase	Description	Satisfactory Demonstration	Notes / Commentary
0	Basic Unproven Concept	YES	Basic design
1	Proof of Concept	YES	
2	Demonstration by Testing	YES	Early testing, including corrosion reinforcement
3	Prototype Development	YES	
4	Prototype Validation	YES	ASME PCC-2 testing, full-scale compression
5	System Integration Testing	NO	Need to identify pipeline operator for field trial
6	System Installation	NO	
7	TRL 7: System Operation	NO	

Recommended course of action:
1. Need to identify a pipeline operator who will support a field trial.
2. Additional engineering analysis work might be required to optimize the design of the reinforcement.
3. Regulatory compliance likely to be required; recommend integrating regulatory review as soon as practical.
4. Long-term monitoring advised, including implementation of strain gages or fiber optics to monitor external reinforcement.

Table 2: Technology Assessment Chart (*Advanced Inspection Technology Case Study*)

TRL Phase	Description	Satisfactory Demonstration	Notes / Commentary
0	Basic Unproven Concept	YES	
1	Proof of Concept	YES	Initial inspection work very promising
2	Demonstration by Testing	YES	Benchmark testing complete
3	Prototype Development	NO	Need to build and validate working prototype
4	Prototype Validation	NO	
5	System Integration Testing	NO	
6	System Installation	NO	
7	TRL 7: System Operation	NO	

Recommended course of action:
1. Need to develop a working prototype that simulates desired field performance capabilities.
2. Additional lab testing required to validate technology; sufficient sampling size required to achieve industry consensus and buy-in.
3. Look at operational efficiency prior to field deployment to minimize time required in the ditch.
4. Need to identify a pipeline operator who will support a field trial.

Table 3: Technology Assessment Chart (*Fiber Optic Monitoring Case Study*)

TRL Phase	Description	Satisfactory Demonstration	Notes / Commentary
0	Basic Unproven Concept	YES	
1	Proof of Concept	YES	
2	Demonstration by Testing	YES	Numerous lab tests, instrumentation validated
3	Prototype Development	YES	
4	Prototype Validation	YES	
5	System Integration Testing	YES	Promising field trial results
6	System Installation	NO	Need to monitor pipeline with known movement
7	TRL 7: System Operation	NO	Make plans for system-wide integration

Recommended course of action:

1. Need to identify an operator who will support a field implementation study.
2. Build into system the concept of "scalability" as this technology will likely involve system-wide integration. Data system must be robust enough to handle large amounts of data.
3. Look for partners with the ability to evaluate / interpret data required to make operational assessment decisions.

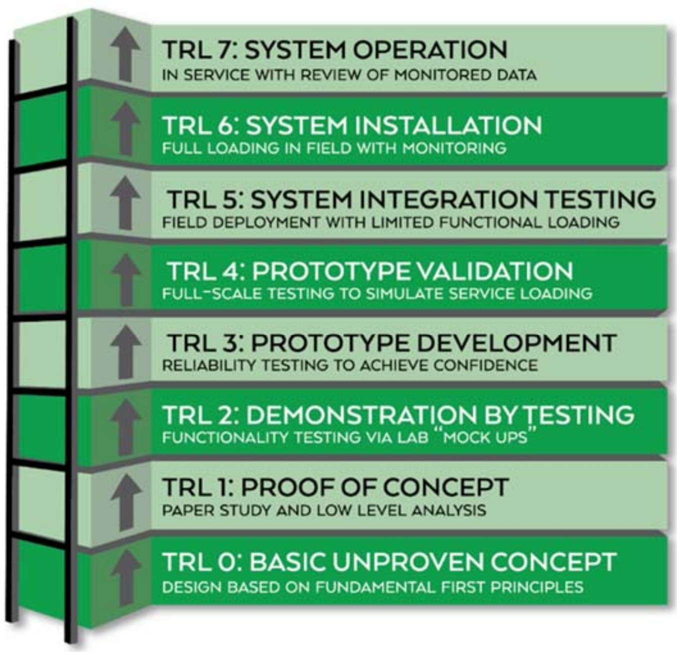

Figure 1: Technology Readiness Levels of the TRL Ladder

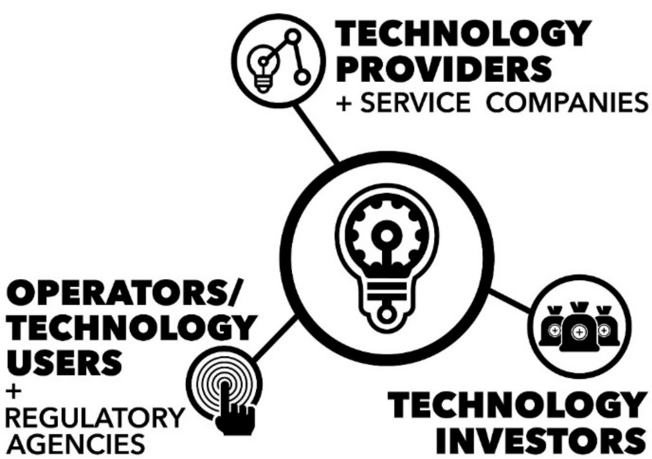

Figure 2: Participants in the technology development and implementation process

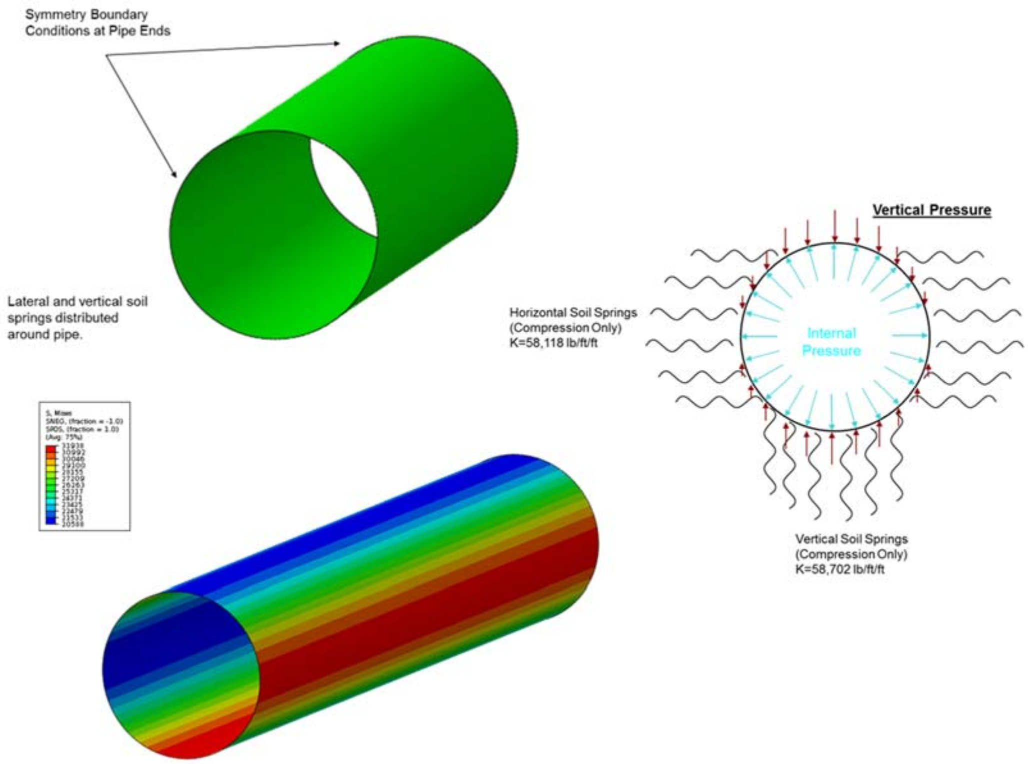

Figure 3: Finite element model results (Case Study #1)

Figure 4: Full-scale compression testing (Case Study #1)

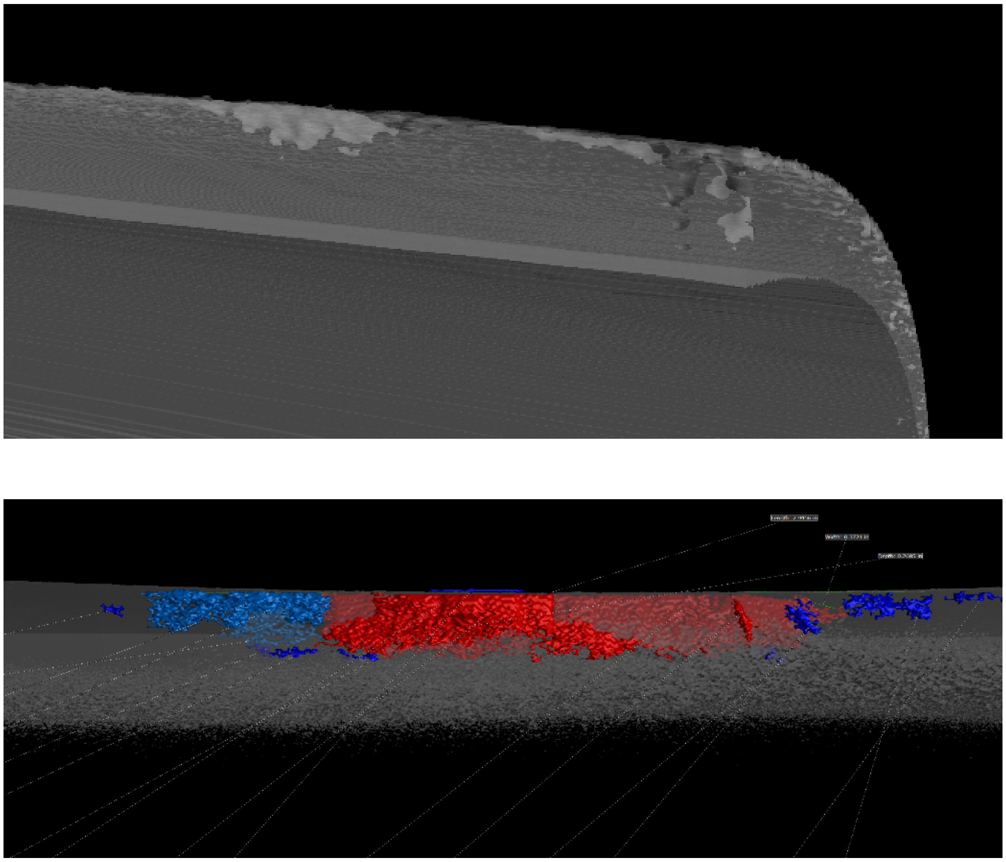

Figure 5: Screen capture images taken of cracks in actual pipeline materials (Case Study #2)

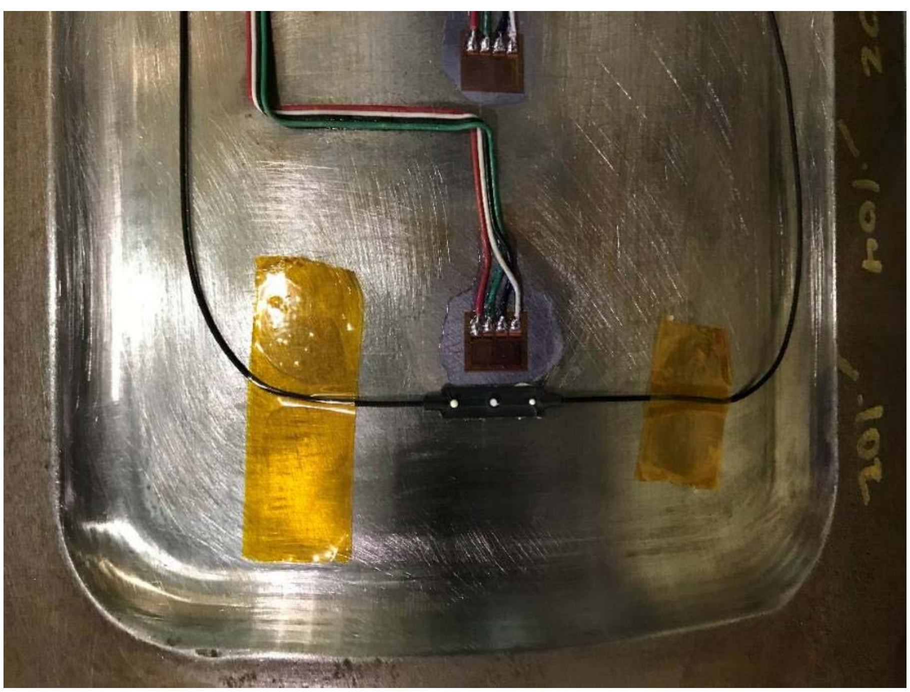

Figure 6: Photograph showing fiber optic cable adjacent to a conventional strain gage (Case Study #3)

Figure 7: Photograph showing bending test set-up to validate fiber optic technology (Case Study #3)

Figure 8: Excavation of pipeline in preparation for installation of monitoring devices (Case Study #3)

Figure 9: Four C's of the Technology Implementation Process

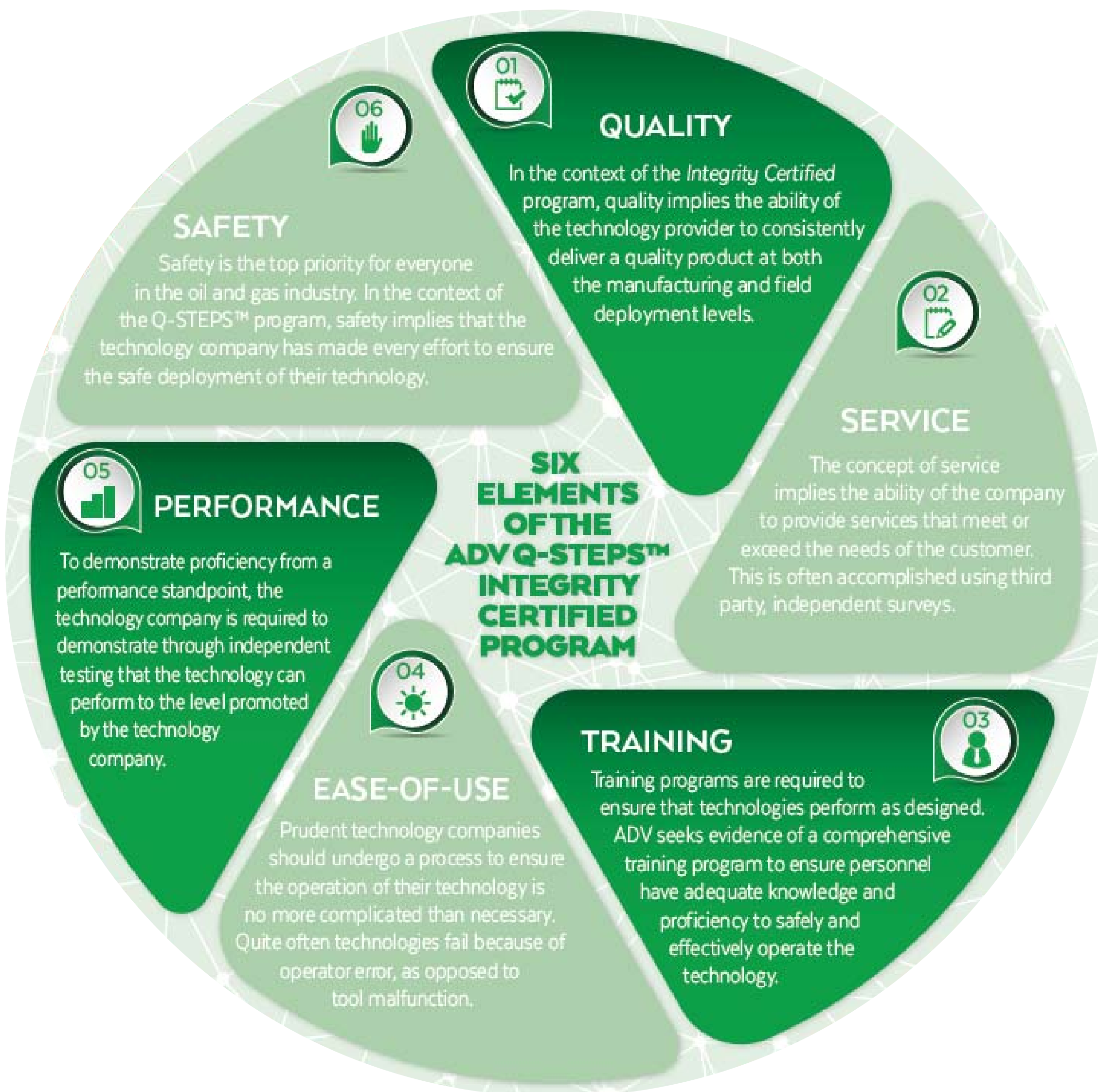

Figure 10: Graphical representation of the six elements associated with the Q-STEPS program
(Taken from Q-STEPS^{TM} document published by ADV Integrity, Inc. (ADV)) [4]