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Study to Evaluate the Regulatory Acceptance of Non-Traditional Pipe

Prepared for:

Interstate Natural Gas Association of America

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December 2022

WHEN TECHNOLOGY WORKS, TREMENDOUS THINGS ARE POSSIBLE.

Study to Evaluate the Regulatory Acceptance of Non-Traditional Pipe

Final Report

Prepared for

INGAA

Washington, D.C.

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SUBJECT: Report on Study to Evaluate Non-Traditional Pipe Technologies

Ben,

ADV Integrity, Inc. is pleased to present to INGAA the report titled the *Study to Evaluate the Regulatory Acceptance of Non-Traditional Pipe*. Raghu and I have enjoyed the opportunities to interface with the steering committee. This body of work will significantly impact the use of non-traditional pipe technologies in the gas transmission pipeline industry. It will also provide a framework for future efforts and initiatives, including the potential for multiple Joint Industry Programs involving collaborative efforts between technology providers, users, regulatory agencies, trade associations, and research organizations.

Please let me know if you have any questions about this report. We look forward to continuing our work with you and the INGAA members on this important study.

Regards,

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EXECUTIVE SUMMARY

Pipeline transportation is the backbone of energy transmission worldwide. For many years, pipelines have transported oil, natural gas, refined products, and a variety of chemicals. For the most part this has been achieved using welded steel pipelines. However, with the onset of energy transition initiatives and clean energy requirements, the midstream landscape is set to change with increased transportation demand for super critical CO_2, hydrogen, and renewable natural gas. Transporting these products along with the aging infrastructure requires the use of non-traditional materials, as well as a host of techniques to permit monitoring of these new pipeline systems. Additionally, novel materials and techniques will also have to pass muster with the regulatory agencies.

This report dealt with the various conventional and innovative solutions required to address future transportation challenges associated with non-traditional pipelines (NTP). The focus of this report was to systematically evaluate various options the pipeline industry has associated with non-traditional pipe materials, along with sensing and monitoring technologies that are essential for the success of this system solution. The report included a detailed risk analysis of the current pipeline infrastructure with special emphasis on non-traditional pipes and potential risk mitigation options. This was followed by a summary of the various technologies available, their pros and cons, current maturity, and the key risks that the technologies address. This report also incorporated a detailed survey conducted with various operators and technology providers, to assess the gaps, opportunities, and potential path forward from their perspective. Lastly, this report included a technology implementation plan that takes into consideration inputs from the operators and vendors, states of various technologies involved, risks and mitigation, and additional work and initiatives that the pipeline community should initiate to expedite the qualification and acceptance of the various non-traditional pipe and associated technologies.

This report identified non-traditional pipe technologies and provided a roadmap for how they can be used to prepare the current pipeline infrastructure for future transportation challenges. The significant conclusions from this body of work included the following points.

- The maturity of non-traditional pipe application and implementation was not consistent across the industry. Significant effort needs to be put towards standardizing designs, manufacturing, quality assurance, and inspection to ensure consistent implementation of NTPs.
- To ensure quality products can be produced, the inspection technologies must be developed and vetted to ensure that NTPs are manufactured and deployed with the highest level of care.
- The emerging energy landscape presents significant new opportunities for pipeline companies by integrating NTP technologies. Examples include the transport of CO_2.
- Sensing and monitoring techniques must be developed, matured, validated, and incorporated in the deployment of NTP technologies; this being a great enabler to license to operate, techno-

economics[1] and regulatory approval efforts. Additionally, the ability to monitor NTPs with on-board sensing technologies will significantly enhance their acceptance and approval among pipeline regulators.

- Increased need and urgency were apparent for closer collaboration between pipeline companies and technology companies to co-develop, qualify, and get NTP to technology readiness levels. This must be extended to a unified approach for addressing regulatory approval by all parties concerned.
- A three-year road map is presented at the end of this report and will serve as template for developing detailed action and implementation plans for accelerated acceptance and deployment of NTP technologies.

One of the reasons that technologies fail to achieve a high level of adoption in the energy industry is a failure to build a framework for identifying why specific technologies are required, where they can be used, how they should be used, and what processes should be used to ensure they are appropriately implemented. This body of work seeks to address this shortcoming. Using the framework outlined in this document will permit INGAA and the pipeline industry to appropriately identify and implement non-traditional pipe technologies to ensure they are used to meet the future demands associated with the transportation of emerging fuels.

[1] In the context of this discussion, techno-analysis (or technical economic analysis) is the detailed examination of pipeline and market conditions required for the investment in a technology considering technology characteristics, project costs, operational costs and revenues, non-economic factors, and pipeline location.

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NOMENCLATURE

ALARP	As Low as Reasonably Practicable
AMPP	The Association for Materials Protection and Performance (formerly NACE)
API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
CRI	Commercial Readiness Index
ESG	Environmental, Social, and Governance
FCP	Flexible Composite Pipe
FMEA	Failure Modes & Effects Analysis
HDPE	High-density polyethylene
IMCI	Integrity Management Continuous Improvement (an INGAA initiative)
NTP	Non-traditional Pipe
OFD	Outside Force Damage
PA	Polyamide is a polymer that contains recurring amide groups as parts of the main polymer chain
PE	Polyethylene
PEEK	Polyetheretherketone is a high-performance semi-crystalline engineering thermoplastic
PHMSA	Pipeline and Hazardous Materials Safety Administration
PPS	Polyphenylene sulfide (a high-performance, engineering thermoplastic)
PRCI	Pipeline Research Council International, Inc.
PVDF	Polyvinylidene fluoride (trade name, Kynar®) is a high purity engineering thermoplastic
QA	Quality Assurance
RAL	Regulatory Acceptance Level
RNG	Renewable Natural Gas
RPN	Risk Priority Number
TRL	Technology Readiness Level

1.0 INTRODUCTION

Pipeline transportation of hydrocarbons, hydrogen, and carbon dioxide is the most cost-effective means of energy transport and in some cases storage. In recognition of this observation, INGAA developed the IMCI 2.0 (Integrity Management Continuous Improvement) that laid out the vision for pipeline transportation companies for the future, encompassing the role of clean energy that will increasingly become a larger part of the transportation mix. INGAA proposed five guiding principles for IMCI:

- Net Zero[2]
- Safety
- Improving by learning
- Implementing and continuous improvement of pipeline safety systems
- Ongoing and deliberate engagement with stakeholders.

As part of these five guiding principles, eight priority issues were identified for the pipeline safety task force and were translated to initiatives. This report addresses item #8 in the listing below, *Regulatory Acceptance of Non-Traditional Pipe*.

1. Regular Stakeholder Engagement
2. Transportation and Storage of Hydrogen
3. Transportation and Storage of Renewable Natural Gas (RNG)
4. Development of ANSI Standard for Geohazards
5. Integration of Electro-Magnetic Acoustic Transducer In-Line Inspection into Standards
6. Rupture Detection and Response
7. Managing Emissions from Integrity and Maintenance Work
8. Regulatory Acceptance of Non-Traditional Pipe

Meeting the above eight priority issues calls for seeking and implementing novel and out-of-the-box solutions. It is recognized that non-traditional pipe (NTP) and non-traditional uses of existing pipe are key enablers to meet the above stipulations in the emerging energy transition environment. Non-traditional pipes encompass composite pipes, composite repairs, and a host of connection technologies. Non-traditional uses of the existing steel pipe infrastructure (e.g., installing NTP technologies as liners) will require that they be assessed and validated for transporting newer fluids like carbon dioxide and hydrogen. All these new technologies will have to be supported by robust inspection, monitoring, and sensing technologies along with novel means of assessing collected data. Further, extensive testing and analysis will be required to validate the NTP technologies.

[2] Net zero refers to the balance between the amount of greenhouse gas produced and the amount removed from the atmosphere. Net zero is achieved when the amount added is no more than the amount taken away.

This report provides a technology road map and robust management plan for implementing NTP. It also identifies and mitigates the risks associated with the deployment of NTP technologies (i.e., people, environment, and economics) to address both regulatory approval and license to operate. The body of work included in this report represents a bold look at enabling the use of NTP by developing a strategic approach to safety, license to operate, efficiency, and economics, while keeping in mind the corporate and societal needs of a net zero and robust environmental, social, and governance (ESG) portfolio.

2.0 COMMERCIAL AND REGULATORY CONSIDERATIONS

This section of the report provides commentary on the economic and regulatory drivers that support the need for NTP technologies in the future operation of the current pipeline infrastructure. The technical benefits associated with the deployment of NTPs are addressed throughout this document; however, it is important to consider the economic / commercial elements that impact early adoption and sustained future use, as well as regulatory considerations that are required for initial deployment.

2.1 Commercial Elements

The primary focus for pipeline operators is the safe transportation of products, which includes solutions to meet the stringent safety and license to operate requirements. Safety concerns must be carefully balanced with techno economic considerations (both operational and capital) to ensure that pipeline operations are economically viable. At the same time, corporations must also be cognizant of the demand to meet societal needs that include net zero and ESG requirements.

For the energy transition sector, some of the costs involved can be offset through tax credit incentives like 45Q[3]. However, future economics will have to be sustained with limited or no government support. Today's pipeline companies are cognizant of the challenges associated with these future conditions. Hence, initiatives are required to seek new technologies and implementation routes to optimize costs without compromising requirements associated with safety and societal needs.

Non-traditional pipe and non-traditional uses of existing pipe provide attractive avenues to co-manage both commercial and regulatory requirements. Some of the advantages include:

- A quicker transition to the hydrogen economy due to the inherent advantage of composite materials, including lack of susceptibility to hydrogen induced cracking that occurs in carbon steel pipelines.
- Development and qualification of new materials and pipe solutions that ensure reliability, while reducing construction and installation costs.
- Options and protocols to reuse existing infrastructure for emerging transportation needs for CO_2 and hydrogen. This includes the use of the existing steel pipeline infrastructure as a conduit for spoolable pipe technologies and Smartpipe®.
- Sensing and monitoring techniques wherein many cases are embedded in the pipe of choice, which enables a real time understanding of the integrity and consequently and optimized factor of safety
- Improve novel computational, analysis, and testing methods to increase confidence in the developed solutions with NTP technologies.

[3] First introduced in 2008, Section 45Q of the Unites States Internal Revenue Code provides a tax credit for CO2 storage. The policy is intended to incentivize deployment of carbon capture, utilization, and storage (CCUS). It provides an incentive for capturing carbon and storing it underground in geologic or saline formations, underground through oil recovery and in products through CO_2 utilization.

2.2 Regulatory Requirements

While new technologies and solutions are being proposed for various pipeline applications, it is imperative that they secure the appropriate regulatory approvals for implementation. Therefore, pipeline operators constantly must work with the technology companies and regulators to ensure that the proposed solutions have risks that are as low as reasonably practicable (ALARP), such that clearly identified risk management programs are implemented.

Realistically, engaging regulatory agencies and companies selling NTP technologies, along with non-traditional uses of existing pipe, will present a challenge of additional work for pipeline companies. However, technology adoption among regulatory agencies often has less to do with the technical validity of solutions, and more to do with how well the risks associated with a solution are identified.

For NTPs, the benefits in terms of safety, societal needs, and economics are compelling. However, it is important to recognize that their deployment and implementation will require significant effort be expended to ensure regulatory approval.

This report provides content that is devoted to articulating a path that can be taken to achieve regulatory approval and compliance. The approach taken is summarized below and articulated in greater detail in RISKS AND KNOWLEDGE GAPS section of this report.

- The overall risk analysis of the system is presented
- Technology assessment road map is presented
- The level of risk before and after mitigation through the implementation of new technology, is clearly articulated for each technology.
- The level of maturity, both technical and commercial along with gaps and gap closures are identified
- General guidelines for implementation, including specific actions for regulatory approval are presented.

Pipeline companies have a significant role to play in this effort. Most technologies for NTP are point solutions in that they address a specific need. Pipeline operators, along with subject matter experts and consultants, must be able to translate the implementation of NTPs into a system level solution that includes associated risk and integrity management elements before presenting to regulators.

3.0 TECHNOLOGY AND ENGINEERING STATE-OF-THE-ART

This section of the report provides commentary on the various technologies associated with non-traditional pipe technologies, as well as evaluating the general state-of-the-art for each respective technology.

3.1 Non-traditional Pipe Definition

Non-traditional pipe (NTP) is a generic term; hence a definition of this term is made to provide context in terms of what is presented in this report. NTP encompasses all types of composite pipes and liners, composite solutions for repair and reinforcement, and repurposing carbon steel legacy pipe. The discussion on NTP pipe will also include commentary on inspection, monitoring, and sensing technologies (both active and passive), and novel analysis, testing, and validation techniques. The components of the NTP technologies are divided into four sections as outlined below in Table 1.

Table 1: Components of NTP Technologies

Hardware	Inspection/Monitoring /Sensing	Analysis	Testing
• Composite pipe • Composite liners • Composite reinforcement and repairs, including crack arrestors • Connectors	• Pipe inspection such as Inline Inspection (ILI) • Stress and strain • Permeation • Leaks • Corrosion and degradation • Crack growth • NDE for composites	• Stress analysis and finite element modeling • Fracture mechanics analysis • Composite mechanics and fatigue life assessment	• Subscale testing • Full scale testing • System level testing with all components integrated • Testing in specific environments

3.2 Application Sectors

NTP has found widespread usage in conventional oil and gas, natural gas transport, and liquefied gas applications. Additionally, the emerging energy transformation environment is also demanding the use of NTPs in carbon capture and sequestration, and the emerging hydrogen transportation economy. The functional requirements for non-traditional pipes in each of these above-mentioned sectors have some commonalities along with specific requirements pertaining to each sector. Table 2 that follows, summarizes traditional and specific functional requirements for NTP technologies.

Table 2: Functional Requirements of NTPs

Applications	Major Functional requirements	Additional Functional Requirements (Examples)
Conventional energy transport-oil and gas	Pressure containment Corrosion resistance Material compatibility Fatigue, fracture, environmental cracking Resistance to party damage	
Renewable natural gas	Pressure containment Corrosion resistance Material compatibility Fatigue, fracture, environmental cracking Resistance to party damage	
Carbon capture and sequestration	Pressure containment Corrosion resistance Material compatibility Fatigue, fracture, environmental cracking Resistance to party damage	Non-metallic compatibility in supercritical CO2 Resistance to running brittle & ductile fracture Permeation resistance Girth weld integrity Monitoring
Hydrogen transport and storage	Pressure containment Corrosion resistance Material compatibility Fatigue, fracture, environmental cracking Resistance to party damage	Resistance to hydrogen cracking Fatigue properties in hydrogen Leak-prevention & monitoring and detection Permeation resistance Girth weld integrity Fracture control

3.3 Composite Pipe

Most used composite pipes in onshore and offshore applications fall under two major product types: (1) stick built and (2) spooled pipe.

Stick-built pipe is generally rigid pipe wound with fiberglass within an appropriate binder. Spoolable pipe is the more commonly used form of non-metallic pipe owing to the variety of advantages it possesses.

Spoolable composite pipes initially originated for the offshore sector and with time, applications have migrated into very impactful applications onshore. The cost of manufacturing, ease of installation, and improvements in technology have been the primary drivers in achieving a wider acceptance of both thermoplastic composite and/or reinforced thermoplastic spoolable pipe technologies.

Several vendors offer high end spoolable composite pipe or flexible composite pipe (FCP). These are either fully bonded or unbonded composites (cf. Table 3). These have traditionally not made their way into the onshore arena, primarily because of the level of design and the increased costs involved. On the other hand, there are composite pipe manufacturers that are specifically servicing the onshore transportation pipeline sector. These products offer a lower cost and greater flexibility, like in situ manufacturing (i.e., Smartpipe®) and the ability to deploy them as monolithic pipes or in special cases as rehabilitation liners. Onshore composite pipes are now deployed in many oil and gas applications but are in some cases limited because of the choice of non-metallics, their ability to handle special fluids, and higher temperatures.

The table below summarizes the classes of composite pipes that are presently available for both onshore and offshore pipelines. Although the present study primarily targets onshore pipelines, many of the attributes that have been qualified for offshore, such as supercritical CO_2 transport, hydrogen, collapse strength and resistance to rapid decompression, can be leveraged for future onshore applications.

Table 3: Types of Composite Pipe

Type	Internal Liner / Layer	Reinforcement Layer	Outer Layer
Un-bonded	Thermoplastic liner (HDPE/PE)	Metallic armor wire	Thermoplastic wear layer
Un-bonded	Thermoplastic liner (HDPE)	Fiberglass/ Aramid	Thermoplastic wear layer
Bonded	HDPE	Carbon fiber	Wear layer
Bonded	PEEK	Carbon fiber	Wear layer
Bonded	PPS/PA	Aramid	Wear layer
Bonded	PVDF/PA	Carbon fiber	Wear layer

Refer to Appendix 1 and 2 for detailed descriptions of each composite pipe type, key gaps and risks, and information on the technology and commercial maturity level for each.

3.4 Composite Liners

Increasingly, composite liners are being considered for rehabilitating the legacy steel pipe infrastructure, especially the high pressure transmission systems. This application is used both for corrosion protection and in many new cases, to provide pressure reinforcement. Composite liner technology offers several advantages. First, it is an enabler for enhanced risk management and demonstrates the license to operate in terms of environmental and human consequences. Secondly, composite liner usage significantly improves the life cycle cost, including challenges associated with right-of-way access and excavation costs required for pipeline repairs. Lastly, as the fluids being transported get more aggressive in terms of corrosivity or compatibility, composite liners make a compelling and attractive case for maintaining the license to operate. The liners do have to be carefully evaluated for their compatibility and ability to be spooled and pulled through the existing pipeline infrastructure. Refer to Appendix 1 for a detailed description of each liner technology.

3.5 Composite Repairs

Since the early 1990s the pipeline industry has used composite materials to repair corrosion in gas and liquid transmission pipelines. Much of the research associated with the development of composite repair systems has been funded by the gas transmission pipeline industry, with an emphasis on repairing high pressure pipelines. The primary use of composite materials has been to repair corrosion, although research dating back to the mid-1990s has also been conducted for repairing dents and other mechanical damage (the latter being accompanied by grinding to remove any gouges or indications of cracked material). Over the past decade, efforts have been undertaken to evaluate the ability of composite materials to reinforce wrinkle bends, branch connections, elbows/bends, girth welds, and even crack-like features.

In the mid-1990s, industry began using wet lay-up systems, which significantly expanded the technology market for composite repair, as well as increasing the number of features that could be reinforced. The first system on the market was a private label product known as StrongBack that is manufactured by Air Logistics Corporation (Azusa, California). StrongBack is a composite reinforcement product that is water activated, resin impregnated, and uses glass fiber remediation materials. In the past several years, Air Logistics has also brought to industry an additional water-activated system, Aquawrap™. This system has undergone extensive testing, including full-scale testing to address its use in repairing mechanical damage [5]. In 1997, Armor Plate, Inc. started a research program to develop the Armor Plate® Pipe Wrap system [6], which employs a fiberglass material that is impregnated with unique epoxy systems to address specific environmental conditions, such as underwater applications, high temperatures, and cold weather.

Prior to 2000, pipeline companies were generally hesitant to use products other than Clock Spring® because of waiver requirement (refer to details in following section of this paper). However, effective January 13, 2000, the Office of Pipeline Service (OPS) permitted the use of composite materials if the following criterion was satisfied in terms of repairing dents and corrosion [7].

> *… repaired by a method that reliable engineering tests and analyses show that can permanently restore the serviceability of the pipe.*

Once the 2000-edition of the OPS ruling came out, use of composite materials in repairing pipelines increased significantly. In a similar fashion, the number of manufacturers interested in this repair technology also increased.

In 2000 WrapMaster, Inc. started a testing program to assess the capabilities of PermaWrap™, which is a system similar to Clock Spring® in that it employs a hard shell with an adhesive installed between layers.

Over the past decade there has been some consolidation of the technology companies, including the CSNRI organization that now includes technologies from four companies including Clock Spring, NRI, Citadel, and Milliken. A list is provided below that includes manufacturers and companies who have developed and tested their technologies. As noted, some of these companies are no longer in existence.

Numerous other companies are continuing to pursue the development of products of this repair genre. With improved innovations and technology, along with proper use of engineering evaluation methods and testing, the pipeline industry will benefit. The focus must remain on the requirement that these composite systems permanently restore the serviceability of pipelines.

In addition to the innovative efforts on the part of composite repair technology companies, two major factors have contributed to the widespread of adoption of composite repair technologies among the pipeline industry. The first is the development and acceptance of consensus-based composite repair design standards, such as ASME PCC-2 and ISO 24817. The second contributing factor is the large number of research programs focused on composite repair systems that have been sponsored by research organizations, pipeline operators, composite technology companies, and regulatory agencies. The sections that follow provide a brief overview of the design standards and the industry-wide research programs.

3.5.1 Composite Repair Design Standards

From a design standpoint, any composite repair system that is used to repair a pipeline must demonstrate that it can meet the requirements of industry standards, such as ASME PCC-2 and/or ISO 24817. Composite manufacturers must be able to produce documentation from a third-party organization demonstrating their compliance with these standards, including meeting the required material and performance properties. Additionally, when composite materials are used to repair and/or reinforce anomalies in addition to corrosion (i.e., dents, branch connections, wrinkles, etc.), it is essential that testing be conducted to demonstrate that adequate performance levels can be achieved. Examples are available in the open literature on how these types of qualification programs are accomplished [8].

The ASME PCC-2 standard provides prescriptive guidance on the design of a composite repair system for reinforcing corrosion features subject to static pressure loads. An adequate level of conservatism exists in the ASME PCC-2 design approach so that a system that meeting its minimum design requirements typically has a 50-year design life when considering the reinforcement of a 75% deep corrosion features subjected to aggressive pressure cycling that might exist in a liquid transmission pipeline. However, what is lacking in ASME PCC-2 is adequate design guidance for the reinforcement of the following components, features, and defects:

- Mechanical damage and dents
- Pipe bends and fittings like elbows, tees, and branch connections subject to internal pressure and bending loads as might be expected with geohazard loading conditions
- Defects in girth welds subject to axial tension and bending loads as might be expected with geohazard loading conditions
- Reinforcement of selective seam corrosion and groove-like features
- Elevated temperature conditions, especially in combination with aggressive pressure cycling
- Reinforcement of crack-like features
- Effects of environmental effects including the installation of composites underwater and a

means for quantifying potential material degradation.

The absence of prescriptive guidance in relation to the above items has contributed to the need for extensive research to validate composite repair technologies. Some of this research is discussed in the following section. Fortunately, most of the composite repair technologies that have been tested in these research programs have performed well and permitted each composite manufacturer to develop their own internal design methods and calculators.

3.5.2 Composite Repair Research Programs

Since 2005, over 25 industry-sponsored studies have been organized involving full-scale destructive testing as a means for qualifying and evaluating composite repair technologies used to reinforce a wide range of pipeline anomalies, features, and operating conditions. Provided below are 15 composite repair companies with technologies that have been evaluated in these studies. These technologies have included E-glass, carbon, and Kevlar fibers systems integrating polyester, methacrylate, urethane, and epoxy resin / matrix systems. Several of these companies have multiple technologies that have been tested. In the final analysis, more than 1,000 separate samples have been evaluated via full-scale testing when considering all of the combined testing efforts.

1. Armor Plate
2. Air Logistics
3. Clock Spring (now CSNRI)
4. Citadel (now CSNRI)
5. EMS Group (no longer in business)
6. Furmanite (now TEAM)
7. Milliken / Pipe Wrap (now CSNRI)
8. Neptune Research (now CSNRI)
9. Omega Wrap
10. Pipestream (no longer in business)
11. T.D. Williamson
12. Walker Technical (now ICR Integrity)
13. Wrap Master
14. Western Specialties
15. 3X Engineering

In addition to the testing efforts, two literature studies have been commissioned by PRCI including the MATR-3-3, *State-of-the-art Assessment*, and MATR-3-10, *Composite Repair Guideline Document*, studies. Further, PRCI commissioned ESR Technologies under the technical oversight of Mr. Richard Lee to conduct the NDE-2-3 study focused on evaluating various inspection techniques applied to composite wrap repairs.

Listed below are the titles of the research programs, along with the sponsoring organizations. Also included in the list are studies conducted by pipeline operators and the papers presented at the International Pipeline Conference that provide results from these studies.

1. PRCI MATR-3-4 Buried Pipe Corrosion Reinforcement Pipe Study (3-year and 10-year)
2. PRCI MATR-3-5 Dent Reinforcement Study
3. PRCI MATR-3-6 Vintage Girth Weld Reinforcement Study
4. PRCI MATR-3-7 Subsea Reinforcement 10,000-hr Study
5. PRCI MATR-3-9 Re-rate Study
6. PRCI MATR-3-11 Load Transfer / Effects of Pressure
7. PRCI MATR-3-12 Inspection of Delamination and Disbondment Defects
8. PRCI MATR-3-13 Evaluating Installation Techniques for Pipeline Repair Methods
9. PRCI MATV-1-2 Wrinkle Bend Study
10. Minerals Management Service (MMS)[4] Offshore Study
11. Composite Manufacturer-sponsored *Dent Validation Collaborative Industry Program* (DV-CIP); in partnership with in-line inspection efforts provided by ROSEN
12. Composite Manufacturer-sponsored Crack Reinforcement
13. Composite Manufacturer-sponsored Effects of Installation Pressure
14. Composite Manufacturer-sponsored Crack Arrestor
15. Composite Manufacturer-sponsored Wrinkle Bend
16. BSEE 10,000-hr Offshore Study (reinforcement of corrosion in a subsea environment)
17. PHMSA Onshore Study (study addressed topics such as cyclic pressure and effects of pressure during installation)
18. Operator Study: El Paso Wrinkle Bend Reinforcement Program (IPC2008-64039)
19. Operator Study: Chevron High Temperature Program (IPC2016-64211, IPC2016-64213, IPC2016-64214)
20. Operator Study: TransCanada Pipeline Large Diameter Elbow Reinforcement Program (IPC2016-64311)
21. Operator Study: Alyeska Pipeline Filler Material Assessment Program (IPC2016-64104)
22. Operator Study: Boardwalk Pipeline Reinforcement of LF ERW Pipe Program (IPC2016-64082)
23. Operator Study: TC Energy Composite Reinforcement Leaks Program (IPC2020-9757)
24. Operator Study: Boardwalk Reinforcement of Wrinkle Bends Subject to Bending Loads
25. Joint Industry Program with eight pipeline companies and three repair companies: Composite Reinforcement of Crack-like Features Study (IPC2022-87282, *Use of Carbon Composite Repair Technologies to Reinforce Crack-like Flaws in High Pressure Pipelines*)
26. Joint Industry Program with six pipeline companies and one repair company: Composite Reinforcement Vintage Girth Welds Study

[4] The Minerals Management Service (MMS) was an agency of the United States Department of the Interior (U.S. DOI) that managed the nation's natural gas, oil, and other mineral resources on the outer continental shelf. MMS started in 1982 and was dissolved in October 2001. Today BSEE functions as the organization carrying out many of the roles originally commissioned for MMS to conduct.

The extensive body of work reflected in the above listing has permitted the pipeline industry to confidently integrate the use of composite materials for reinforcing a wide range of features and defects. The intent of these programs has been to validate their capacity to provide long-term reinforcement of high pressure pipelines.

3.6 Crack Arrestors

As larger portions of the nation's steel infrastructure are being considering for repurpose for the energy transition, the need to address the risks of running ductile fracture increases. Despite expanded material testing, validation, and stress analysis, it is believed that a large number of pipelines will require some form of crack arrestor to mitigate the extent of damage arising from running fractures. Crack arrestors are a common and cost-effective solution for mitigating running ductile fractures.

Generally, crack arrestors are a mechanical means for increasing the local circumferential stiffness of a transmission pipeline. The running fracture is "arrested" when it impacts the crack arrestors. Historically, crack arrestors have involved either thicker sections of pipe or mechanical clamps that are bolted on the outside of the pipe. Another option is to use composite crack arrestors.

In the context of NTP applications, composite crack arrestors can either be rigid coils, such as the Clock Spring or WrapMaster systems, or wet-wrap technologies employing either E-glass or carbon fiber technologies. The crack arrestors are spaced at discrete intervals along the pipe, where the spacing is based on detailed designs to ensure that the running fracture can be managed adequately so that only a designated section of pipe is sacrificed. Crack arrestors depend on two primary factors for their success: (1) choosing of the right composite crack arrestors with an optimized stiffness (i.e., not too stiff as to cause ring off in the pipe material) and (2) detailed design, stress analysis and validation and verification testing.

With the advent of novel composites and winding solutions, crack arrestor designs must be prudently tested in their installed state to enable a high degree of confidence in this solution.

3.7 Connectors

Composite pipes, both stick-built and spooled, are joined using specialty connectors, mostly provided by the pipe manufacturer. Connections can be metallic, non-metallic, flanged or swaged. Because of the specialty nature of its manufacturer, details of the design are generally not available and therefore special attention must be paid to analyzing the risk, de-risking, and qualification before its full deployment. Of particular interest is performance of connectors when subjected to combined loading conditions that include internal pressure, tension / compression, and bending. Operating conditions that involve elevated temperature also required additional consideration as in-service failures have been attributed to deleterious performance under these conditions.

3.8 Inspection, Monitoring, and Sensing

The importance of having adequate inspection monitoring and sensing cannot be overemphasized. This section of the report provides commentary on how inspection and sensing technologies can be used with NTPs and provides details on several of the sensors used in this application.

3.8.1 Importance of Novel Techniques and Integrating NTPs

The ability to understand and continuously measure potential damage to NTPs ensures advanced analysis techniques can assess the condition and residual life of these components. These translate into three significant benefits that include:

- Leak detection
- Online, real time indication of the reliability and integrity of the pipeline system
- Monitoring damage and progression.

Several techniques that include electrochemical, resistance, permeation, and physical measurement of the pressure containing barrier are extensively used to monitor corrosion damage in steel pipelines. The materials used in composite pipes are different than those used in steel pipelines; hence, developing and deploying novel techniques to address this challenge are required. Structural health monitoring utilizes a host of new techniques, and many can be built into composite pipes.

Composite pipeline technology presents contradicting opportunities and challenges. Composite solutions traditionally have a higher design factor than those used for conventional steel pipelines, owing to material and design uncertainties. However, the construction methodology for composite pipe enables the insertion of various sensing devices into the pipe body during manufacture. This is a great enabler to ensure the license to operate and alleviate certain public perceptions concerning the safety in using nonmetallic pipe for energy transport. Such sensors can facilitate the development of a “decision support system” that integrates leak detection, leak flux quantification, and integrity-related data to enable a predictive capability. This can also help optimize the design in terms of material selection and pipe geometry.

Because of the benefits associated with embedded sensing technologies, a larger number of pipe manufacturers are incorporating technologies to continuously sense and monitor the pipeline condition, features that are built-in during fabrication, construction, or post-construction retrofits. Most composite pipes can be supplemented with some form of monitoring and sensing to closely monitor the pipe health and to ensure that (1) it is operating within design limits, (2) sensing extraneous factors like chemical degradation, geotechnical activities or third-party damage that can adversely affect the performance of the composite pipe , and / or (3) detecting leaks.

Pipeline integrity management monitoring of greenhouse gas (GHG) emissions, response to accidents, and optimization of replacement programs would all be greatly enhanced by the existence of a cohesive decision support system. Such a system may also support the development of federal, regional, and state regulatory policies optimized to achieve societal public benefit objectives, such as GHG reductions. A properly balanced infrastructure management and development program will help ensure an energy delivery system capable of supporting sustained economic growth across all sectors.

The following section aims to shed additional light on a select few emerging technologies that show promise for non-metallic/composite pipeline integrity.

3.8.2 Inspection, Monitoring, and Sensing Techniques

The graphic in Figure 1 below shows a host of inspection, monitoring, and sensing techniques used for pipeline monitoring. Since sensing and monitoring assumes a greater significance for NTP (as pointed out in previous sections of this report), much of the following discussions concentrate on these topics. For this report, only the emerging and more promising techniques identified in Figure 1 are chosen for further discussion.

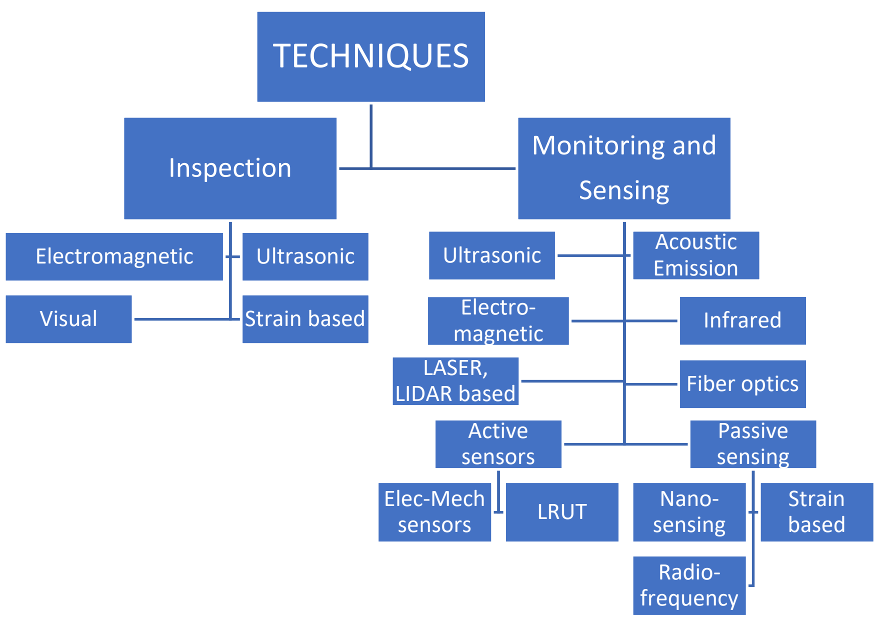

Figure 1: Inspection, Monitoring, and Sensing Techniques

3.8.3 Fiber Optics

Fiber optic sensing can be effectively utilized for measurement of parameters such as temperature, pressure, strain, vibration, inclination, load, and displacement. This technology enables the monitoring of these parameters across extended zones, enables fast response, and permits unique tracking abilities.

Fiber optic sensing is extensively used for securing pipeline integrity. Applications of fiber optics include detection of leaks, geohazard, and intrusion monitoring. Additionally, the onset of several damage mechanisms can be detected by prudent deployment of fiber optic sensing, external to the pipeline or embedded in composite pipes during fabrication.

Leak detection utilizes the distributed temperature sensing, and in addition ground water and geological movement can also be detected. The distributed temperature and strain sensing is very sensitive to movements of soil along the pipeline right away and can effectively detect and monitor hazard movements. The fiber optic systems also enable vibration and acoustic sensing and detect intrusion to preventing third party damage.

Composite pipes can particularly benefit from fiber optic monitoring. Because of the way they are fabricated, fiber optic sensors can be incorporated in the pipe during manufacture, enabling the pipe to be “smart” when deployed. The ability of embedded fiber optics to sense and monitor transients, offer a unique opportunity to obtain the license to operate in areas susceptible to stress and fluid transients in high consequence areas (HCA) that are of particular concern in the energy transition environment.

3.8.4 Emerging Technologies: Passive Sensors

Nano sensors have been developed for sensing and monitoring crack growth, both in passive and active modes. These are techniques still in their infancy with a significant amount of testing and validation required before full deployment. However, some of the attributes of these sensors, including the potential low cost, passive sensor that can be interrogated using device like an RFID reader and the ease of deployment, make it very attractive as a tool for future integrity monitoring, especially for NTP technologies.

Another similar application uses battery free antenna technology for wireless strain and crack sensing. Here while experiencing deformation, the antenna shape changes causing a shift in its electromagnetic resonance frequency. The interrogation system utilizes the principle of electromagnetic backscattering and the use of radio frequency identification technology. This again is a technique in development and shows promise when matured.

Another technique developed in The Netherlands, involves sensors that can be interrogated by RFID readers, with the potential of embedding them in composite pipes. The sensors are claimed to withstand the temperatures experienced during the manufacturing of the pipe.

All these technologies can detect and monitor strain and cracking, a key necessity especially for the energy transition infrastructure pipelines that will experience fluctuating pressures and axial loading due to factors like gas decompression and slugging.

It is important to note that the above sensors will have to be deployed in locations with the highest probability of damage initiation and propagation; therefore, pre-work will have to be done to determine these hot spots using stress analysis, prior experience, and damage information.

3.8.5 Electro-mechanical sensors (EMS)

Micro electromechanical sensors are also potential devices for monitoring pipeline integrity. These sensors are generally active devices, that is they require powering the device for it to be active. EMS sensors, due to their small dimension, low power consumption, superior performance, and low cost, enable them to be deployed in large numbers. Micro electromechanical sensors are at a higher level of maturity than the passive sensors discussed above.

3.8.6 Acoustic and Ultrasonic Techniques

Ultrasonic technologies using low and high frequencies are available for inspection, monitoring, and sensing of composite materials. Some techniques, generally higher frequency (MHz) are used to assess the integrity of the composite material itself that include breakage of components, disbonding, delamination, etc. Lower frequency (kHz) ultrasonics using torsional or longitudinal waves, are used to assess the condition of the underlying steel, when composites are used as repair or reinforcement solutions.

Acoustic emission (AE) utilizes the noise emanated during the onset of damage. Defects can be located and sized based on available triangulation techniques and signal processing. AE is used extensively for structural steel and tank monitoring, and of late for structural health monitoring of composite materials.

3.8.7 Use of Digitalization in Conjunction with Sensing

The sensing and monitoring techniques noted above can be further enhanced by pairing them with digitalization techniques. This can be married through an IoT (Internet of Things) system to carry out real time analytics and prediction of system health and end of life. Many vendors have system agnostic platforms that can accept and analyze data from these various sources. In addition, techniques like machine learning can be used in conjunction with data from the sensors to further enhance the system integrity.

3.9 Testing, Validation & Verification

Traditionally, most of the current infrastructure for pipeline transportation consists of steel pipes joined by welding. The different properties of various grades of steel, its mechanical and corrosion properties are reasonably well understood, enabling the use of analytical design to build and operate infrastructure. This is not always the case when NTPs are employed, especially composite pipes and connections.

As noted in previous discussions, composite pipes can be manufactured through a variety of different routes with different materials being used as liners, reinforcement, and protective layers. Each of these imparts a unique mechanical and chemical resistance property to the composite pipe. In addition, many new composite pipes also incorporate sensors that must perform alongside the pipe hardware. Understanding the composite pipe properties entails understanding the properties of each component of the pipe, along with its performance as a system level in its fully manufactured condition. As of now, design methodologies for composite pipes are not as mature as those used for steel, which necessitates the need for higher design factors to account for potential uncertainties.

Given these uncertainties, testing of non-traditional pipe assumes huge significance. Testing of the various constituents, components, and at a system level must be an essential part of the qualification exercise to ensure that the composite pipe design is safe and optimized (limit the extent of overdesign), so that adequate component and system properties are present to address the mechanical and chemical environment. The tests will have to be carefully designed to ensure that the functional requirements stipulated for the infrastructure are adequately demonstrated and the threshold values ensured so that safe designs can be implemented. This must include the NTP and any embedded sensors.

The different types of NTPs, even among composite pipes, will require that testing and validation be carried out on a case-to-case basis to address the environment it encounters. Sub-scale and full-scale testing must be designed to simulate the potential failure modes to ensure that the components, composite pipe, and connectors qualify to a performance standard when exposed to these critical environments. As indicated earlier, composite pipes are also increasingly employed to combat highly corrosive and aggressive chemical environments. This includes high levels of corrosive fluids, water, supercritical CO_2, and hydrogen; therefore, it is imperative that NTPs have adequate resistance to the failure modes pertaining to the chemical environments.

4.0 RISKS AND KNOWLEDGE GAPS

As with the use and deployment of any new technology, it is essential to identify knowledge gaps and associated potential risks. Once gaps and risks have been determined, it is possible to integrate improvements in design and employ certain de-risking measures to ensure that the new technology achieves the desired level of performance.

This section of the report provides commentary on an extensive study that identified potential causes of failure. Subsequent material in this section of the report address risk in the context of failure modes.

4.1 Causes of Failure

A comprehensive study was conducted by Canadian oil and natural gas producers in 2017 on the use of reinforced composite pipe. A couple of interesting observations were taken from this study. The incident rate per 1,000 kilometers of pipe per year showed a dramatic decline from 2002 to 2017. Composite pipes, both stick-built pipe and spool pipe have a higher failure incident rate than steel and polyethylene pipe. The pressure test failure rates for spool pipe appear to be consistently higher than stick-built pipe for this data set; however, it is not clear if the failures were in the pipe or the joints.

The Canadian study consolidated common and recurring causes of failures and provided a good starting point for any kind of damage analysis for composite pipe. The predominant cases of failure occurred due to the following:

- Damage resulting from installation & construction practices
- Corrosion of steel pipe and fittings associated with composite pipe
- Third party damage
- Mechanical failures of valves or fittings
- Cyclic/impact loading
- Axial overstress
- Chemical incompatibility
- Miscellaneous pipe failures.

The same document developed statistics around which of these are the predominant failure modes. For stick-built pipes, internal corrosion, construction damage and joint failure appeared to be the three predominant failure mechanisms. However, for spooled pipe, pipe body failure, construction damage and overpressure/over stress appear to be the major failure reasons.

The construction damage failures appear to be mostly from inadequate construction practices like pipe supports, impact loads from dropped objects, and lack of understanding of potential geotechnical loads. A significant number of pipe failures appear to be at the pipe joints (i.e., connections), indicating that this should be an item of focus when using non-traditional pipe. Failure was identified from excessive axial and shear stresses and impact loads from process fluctuations like water hammer and cyclic pressure loading.

These predominant reasons for failure must be aligned with the failure modes of composite pipes and the overall risk analysis to determine the appropriate technical assurance process for the use of non-traditional pipe.

4.2 Failure Modes of Composite Pipe

The DNV-GL-ST-F119 standard is a comprehensive document on thermoplastic composite pipes. It goes through the general design philosophy and design basis, material selection, failure modes, and the type of qualification required for composite pipes. This document lists 24 different modes of failure for composite pipes. It is extremely detailed, and in the opinion of the authors, needs to be tailor made for specific applications, since all failure modes will not be applicable to all NTPs. To that extent the relevant sections of the document will have to be extracted and developed into fit-for-purpose functional specifications for particular use cases.

The focus of this discussion is on the damage mechanisms that have been identified relevant to NTPs in Table 4 and how the failure modes can be mitigated through prudent technology implementation, engineering, and operational activities.

Table 4: Composite pipe failure modes and mitigation options

Failure mode	Design	Testing	Materials Selection	Process control (manufacturing, QA)	Operational Control
Ply failure					
Matrix cracking					
Delamination					
Permeability					
Polymer fracture					
Plastic deformation					
Maximum deformation					
Disbonding					
Crazing					
Impact					
Mechanical damage					
Wear & Tear					
Chemical degradation					
Swelling					
Leaching					
RGD					
UV					
Thermal softening/morphology					
Cyclic load/Life					
Stress rupture					

The first column in Table 4 shows the various failure modes. Subsequent columns list the potential mitigation option that include:

- Design
- Testing
- Materials Selection
- Process control (Manufacturing, QA)
- Operational Control

The cells marked in **GRAY** indicate potential risk mitigation for a given failure mode. Table 4 shows that most of the failure modes and composite pipe can be mitigated through proper design, material selection, and testing. However, once in operation, the causes of failure can be mitigated through various operational control measures.

4.3 Risk Analysis and Risk Matrix

Since the pipeline infrastructure of the future will consist of both steel and composite materials, either alone or in combination, identification of risks must be addressed separately. Table 5 below details out various failure mechanisms of the steel and composite pipeline systems, respectively.

Table 5: Example pipeline failure mechanisms (steel and composite)

Steel	Composite
• Corrosion • Environmental cracking • Hydrogen embrittlement • Corrosion and corrosion fatigue • Low temperature brittleness • Running ductile fracture • Welding failure due to quality, stress state and environmental conditions • Failure of fittings • Overload	• Material degradation due to fluids being transported and permeation such as hydrogen • Failure of joints/connectors due to quality, stress, and environmental conditions • Environmental cracking of steel reinforcements (i.e., composite pipe technologies that employ steel) • Construction related damage • Third party damage • Overload

A prudent approach to risk management can ensure that the risks involved with NTP technologies are mitigated to ALARP. The approach used is listed below.

- The predominant damage mechanisms are identified for the specific type of component i.e., composite, steel, connectors…etc.
- The probability of occurrence and the consequence of the damage are assessed.
- The product of the consequence and probability is reported as the risk score.

- The inability to inspect or preemptively detect the damage mechanism is tabulated as lack of inspectability.
- The risk number is multiplied by the lack of inspectability score to arrive at the risk priority number. This number takes into consideration the risk and the ability to detect or preempt the risk if it occurs.
- Now, the potential de-risking options are evaluated for each damage mechanism. There could be multiple de-risking options for each damaged mechanism.
- The same exercises are then repeated for the risk and risk priority number after incorporating the de-risk options that could be a hardware solution, a monitoring or inspection solution, or a combination of the two.
- It must be kept in mind that the risk assessment and the inspectability scores are somewhat subjective. A scale of 1 to 5 is assigned to capture the relative nature of each of these elements.
- The risk and the risk priority number for the various components for all identified damage mechanisms are detailed in Appendix 4. On the right side of each table in the appendix, the specific de-risking actions are identified. These would form the foundation for further work towards acceptance of the various non-traditional pipe and non-traditional use of pipe options in the future
- The various identified de-risking methods are now compared against the current maturity for each technology. This enables an assessment the technology readiness level and the technology maturation level along with gap closure activities that need to be addressed to get this technology to acceptance, both from a commercial and regulatory standpoint.

4.4 Risk Analysis Results

Table 6 and Table 7 provide examples of the risk analysis being conducted for composite pipe and steel pipe, respectively. These tables represent the level of risk associated with different failure modes prior to any de-risking actions. The assessment presented for steel pipelines (Table 7) is included as a role for a certain class of NTPs (spoolable pipes and liners) to serve as the primary carrier of product and replace the traditional steel pipeline. Refer to Appendix 4 for a detailed risk analysis table for all NTP components.

Table 6: Risk Analysis of Composite Pipe (Example)

Cause	Before De-Risking				
	Probability	Consequence	Risk score	Lack of Inspectability	RPN
Liner degradation by fluid	4	4	16	5	80
Permeation	4	4	16	5	80
Joint failure	4	4	16	5	80
Steel winding failure	4	4	16	5	80
Construction related	3	3	9	5	45
Weather and outside force damage	4	4	16	5	80
Overload	4	4	16	5	80
Reinforcement failure	4	4	16	5	80
Sensor failure	4	4	16	4	64

Table 7: Risk Analysis of Steel Pipe (Example)

Cause	Before De-Risking				
	Probability	Consequence	Risk score	Inspectability	RPN
Corrosion	4	4	16	5	80
Environmental cracking	4	4	16	5	80
Hydrogen embrittlement	4	4	16	5	80
Corrosion and corrosion fatigue	4	4	16	5	80
Low temperature brittleness	3	4	12	5	60
Running ductile fracture	4	4	16	5	80
Weld failure due to quality, stress state and environmental conditions	4	4	16	5	80
Failure of fittings	4	4	16	5	80
Overload	4	4	16	5	80

5.0 DE-RISKING NON-TRADITIONAL PIPE

The de-risking methodology presented in this report addresses the key risks in the following fashion.

- The assessment includes analysis solutions, inspection solutions and hardware solutions, bolstered by robust testing to verify the outcomes.
- The de-risking methodology identified will be clear and defensible.
- The de-risking methodologies will be mindful of regulatory drivers and how they can address regulatory concerns.
- De-risking will strive to build inspection and monitoring into the program from the beginning; this might necessitate the development / integration / implementation of new technologies at an early stage of the technology development process.

This process consists of the following steps (Refer to Section 4.4).

- For components like NTP, steel pipe, connectors, crack arrestors, the predominant damage mechanisms are identified.
- The probability of occurrence and the consequence of the damage mechanism is assessed.
- The product of the consequence and probability is reported as the risk score
- The inability to inspect or preemptively detect the damage mechanism is tabulated as "difficulty to inspect" or "lack of inspectability".
- The risk number is multiplied by the lack of inspectability score to arrive at the risk priority number. This number takes into consideration the risk and the ability to detect or preempt risk, if it occurs.
- The potential risking options are evaluated for each damage mechanism. There could be multiple risk options for each damaged mechanism.
- The same exercises are then repeated for the risk and risk priority number after incorporating the de risking options-the de risking options could be a hardware solution, a monitoring or inspection solution or a combination of the two.
- It must be kept in mind that the risk assessment and the inspectability scores are subjective-and therefore a scale of 1 to 5 is assigned to capture the relative nature of each of these elements.
- The risk and the risk priority number for the various components for all identified damage mechanisms as shown in Appendix 4. The tables in the appendix include the Risk Priority Number, before and after risking.
- Further to the right to the table in each case, the specific de-risking actions are identified. These would form the foundation for further work towards acceptance of the various non-traditional pipe and non-traditional use of pipe options in the future
- The various identified de-risking methods are now compared against its current maturity. This includes the TRL and CRI. This enables the assessment of the technology readiness level and the

gap closure activities that need to be undertaken to obtain regulatory and business technology acceptance

5.1 Results

An example for composite pipe with a steel winding, is shown below in Table 8. The risk element and RPN values before and after de-risking are shown in this table. In the "After De-Risking" columns are provided the reduced risks due to the selected mitigation techniques. The superscripts correlate to the selected mitigation techniques that are listed below. On average, the proposed mitigative efforts reduce the RPNs by a factor of 3.5. A summary of the risk assessment is provided in Appendix 4.

Elements of the FMEA

There are three (3) major elements involved in an FMEA: occurrence, severity, and detection. To each of these factors a number, or ranking, is assigned when conducting an FMEA.

For the **Occurrence (O)** element, the prevailing question is how often are failures occurring relative to a particular component? For pipelines the element will focus on the risk of a particular anomaly. The next element is **Severity (S)**. As implied, the goal here is to quantify the severity of a failure relative to system functionality. Lastly, the third element involves **Inspectability (I)**, which centers around inspectable is a particular issue or anomaly (e.g., how detectable is the issue?). Once the "scoring" process is completed, a **Risk Priority Number (RPN)** is calculated as the product of all three elements (i.e., RPN = O x S x I).

One of the defining features of the FMEA is the ability to quantify the impact a failure mode will have on a system; allowing the resulting risks, or threats, to be ranked in order of severity. Consequently, scoring plays an essential role in FMEAs.

To each of the elements (severity, occurrence, and inspectability) values are assigned ranging from 1 to 10; provided below is a detailed explanation that can be used for providing guidance for each of the three elements of the FMEA.

Occurrence (O): How often does this risk cause a failure/incident?

- 1 - 3: This risk never or rarely leads to an incident or failure
  - 1 - Team is confident that the risk has / will never cause incident / failure
  - 2 - There may be none or one instance where this risk causes incident / failure, team is confident that this risk will not cause incident / failure
  - 3 - Team is confident that this risk will not cause incident / failure, but recognizes a higher potential than from a score of 1 or 2
- 4 - 6: This risk has previously caused an incident or failure
  - Likelihood of anticipated occurrence increasing from 4 - 6
- 7 - 10: This risk has caused numerous incidents or failures
  - Risk is known to cause incident/failure, assigned 7 - 10 from less to most likely to occur
  - 7 - Incident/failure is likely, team is presently concerned
  - 10 - Incident/failure is imminent

Severity (S): If this risk causes a failure/incident, what is the extremity of the consequences?

- 1 - 3: Consequences are easily mitigated
- 4 - 6: Consequences are not as easily mitigated; however, are not deemed catastrophic
    - An incident or failure with this risk would have more serious consequences
    - Possibly due to a more extreme event or a more difficult containment
- 7 - 10: Consequences of failure through this risk have the potential to be dire
    - Catastrophic failure, major spill, injury, etc.

Inspectability (I): How likely are we to detect this risk before a failure/incident occurs?

- 1 - 3: This risk is not likely or impossible to go undetected during routine inspection
    - 1 - Team is certain that risk would be detected prior to incident/failure
    - 3 - Team is very confident that risk would be detected prior to incident/failure
- 4 - 6: This risk is typically detected within a time span to allow mitigation before an incident or failure occurs
    - 4 - This risk is identified long before action is required
    - 6 - This risk is likely to be detected before an incident/failure occurs but the risk may be near a critical concern when detected
- 7 - 10: This risk is essentially undetectable due to location, nature, or infrequency of required detection method (current measures)
    - 7 - Current detection methods are unlikely to discover risk before incident/failure
    - 10 - Team is certain that risk would go completely undetected until incident/failure occurs

Table 8: Risk Profiles before and after De-Risking with De-Risking activity for Composite Pipes

Cause	Before De-Risking				After De-Risking			
	Probability	**Severity**	**Inspectability**	**RPN**	**Probability**	**Severity**	**Inspectability**	**RPN**
Fluid degradation	4	4	5	80	2[1]	4	2[2]	16
Permeation	4	4	5	80	2[1]	4	2[2]	16
Joint failure	4	4	5	80	TBD	4	TBD	
Steel winding failure	4	4	5	80	2[1]	4	2[3]	16
Construction related	3	3	5	45	3[4]	3	2[6]	18
Weather & outside force damage	4	4	5	80	3[5]	4	2[6]	24
Overload	4	4	5	80	3[7]	4	2[6]	24

Proposed mitigation techniques, numbers below correspond to superscripts in above table.

1	**2**	**3**	**4**	**5**	**6**	**7**
Material selection	Fiber optics (Left side of bowtie)	Resistance measurement	Quality assurance	ROW control	Fiber optics (Right side of bowtie)	Operational control

5.2 Gaps

The following section is a compilation of the gaps in knowledge / needs to be addressed for fully embracing NTPs for transportation in the future. This also keeps in mind that newer applications from energy transition, transportation of super critical carbon dioxide and hydrogen, along with various biofuels will increase the use of NTPs in the energy transportation mix.

It is also realized that because of practical and techno-economic considerations, a good portion of the steel pipeline infrastructure for transportation will be repurposed from the existing oil and gas portfolios using NTPs. The gaps therefore address these scenarios. Provided in Table 9 that follows is a compilation of the gaps and gap closure requirements

Table 9: Risks, Gaps, and Gap Closure Requirements

:omponent/Systemm	Risk	Ability to Implement Gaps in Knowledge, Experience	Design, Guidelines	Published info	Standards and Regulations	Environmental resistance	Mature monitoring and sensing	Construction & Installation practices, guidelines QA	Validation, Verification, Testing protocols, info-Component & System	Lifecycle estimation	Research (Internal)	Research JIP
Composite Pipe	Human factors, OFD		Yellow	Red	Red		Red	Yellow	Yellow	Yellow	Yellow	Yellow
Composite Pipe	Operational / process control		Yellow	Yellow	Red		Red	Yellow	Red	Yellow	Yellow	Yellow
Composite Pipe	Transient loads (Fluid hammer, surge, cyclic loads..)		Red	Yellow	Red		Red	Yellow	Red	Yellow	Yellow	Yellow
Composite Pipe	Construction & Installation related failures		Red	Yellow	Red		Red	Red	Red	Yellow	Yellow	Yellow
Composite Pipe	Fluid incompatability		Red	Yellow	Red	Red	Red	Yellow	Red	Yellow	Yellow	Yellow
Composite Pipe	Geotechnical load uncertainity		Red	Yellow	Red		Red	Red	Red	Yellow	Yellow	Yellow
Composite Pipe	Reinforcement failure		Red	Red	Red	Red	Red		Red	Yellow	Yellow	Yellow
Composite Pipe	Sensor availability/failure		Red	Red	Red		Red	Red	Red	Yellow	Yellow	Yellow
Connectors	Construction & Installation related failures		Yellow	Red	Red		Red	Red	Yellow	Yellow	Yellow	Yellow
Crack Arrestor	Design, QA, Mfg.		Yellow	Yellow	Red		Red	Red	Red	Red	Yellow	Yellow
	Installation		Yellow	Yellow	Red		Red	Yellow	Red	Yellow	Yellow	Yellow
	Assessment		Yellow	Yellow	Red		Red	Yellow	Red	Yellow	Yellow	Yellow
Repair	Design, QA, Mfg.		Yellow	Yellow	Red		Red	Yellow	Yellow	Yellow	Yellow	Yellow
	Installation		Yellow	Yellow	Red		Red	Yellow	Yellow	Yellow	Yellow	Yellow
	Assessment		Yellow	Yellow	Red		Red	Yellow	Yellow	Yellow	Yellow	Yellow
Steel	Running fracture		Yellow	Yellow	Yellow	Yellow	Red	Yellow	Yellow	Yellow	Yellow	Yellow
Steel	Low temperature brittle fracture		Yellow	Yellow	Yellow	Yellow	Red	Yellow	Yellow	Yellow	Yellow	Yellow
Steel	Overload failure-girth welds		Yellow	Yellow	Yellow	Yellow	Red	Yellow	Yellow	Yellow	Yellow	Yellow

Color-coding:

Green	Extensive work completed; confidence in performance
Yellow	Some work already done; Additional work required
Red	Very little work done, Significant work required
	Non-colored cells indicate insufficient data available to make an assessment

5.3 Key Gaps and Learnings from the Analysis

A summary of the gap analysis is listed below.

- Composite Pipe & Connectors
  - A more detailed understanding of the design and operational envelopes for composite pipes and connections to the various environments must be developed.
  - Development of analytical methods to fully leverage composite pipe design-fit for purpose designs with optimized factor of safety, like ASME Section 8, Division 3 for steel. This will enable the optimization of cost of composites and enabling its faster adoption.
  - Engineering, design guidelines, of composite pipes with and without embedded sensors must be formalized. A unified means of design- design principles, factor of safety, derating guidelines, etc.
  - An understanding of the various operational modes of pipeline systems in energy transition, to ensure that all the potential operation States and consequently loading and environmental conditions are addressed during the risk management, design, and validation testing of non-traditional pipe.
  - A deeper understanding of the compatibility of the various composite materials individually and in a system mode to various new fluids like dense phase carbon dioxide.
- Crack arrestors
  - Design and acceptance guidelines
  - Validation work, including full-scale testing, to validate optimized designs
- Sensors
  - Significant focus and additional work to develop, mature, qualify and implement new sensors and sensors embedded systems.
  - Ability to assess the integrity of composite infrastructure- and ability to predict its longevity. Techniques for inspection monitoring and sensing exist but are not fully matured to enable its confident adoption.
  - Increased collaboration between engineering, operations, and technology to expedite the path to TRL-5.
- Quality assurance, Testing & Validation
  - A unified criteria for validation and verification of non-traditional pipe as a component and system- given the various permutations and combinations that are possible with liners, metrics, reinforcement.
  - Unified functional requirements, requirements identification, quality assurance during manufacture and installation
  - A formal process for the assessment, evaluation, testing and validation of for repurposing existing infrastructure for the energy transition, is currently in its infancy and will have to be developed.
- Regulatory Approvals

- From experience, regulatory approval is often preceded by validation work to ensure that a particular technology meets performance-based requirements.
- In addition to validation work, industry standards are an essential part of the regulatory approval process. Having standards permits regulators to compare technology performance to a known performance criteria and alleviates the potential for subjectiveness and bias.

6.0 INDUSTRY SURVEYS, GAPS, AND KEY LEARNINGS

As part of the report, a survey of the industry was carried out to understand the finer aspects of experience, deployment and gaps with non-traditional pipe and associated sensing and monitoring techniques. The survey questions were sent to all INGAA members- both operators and technology providers. A listing of the survey questions sent is enclosed in Appendix 2 and includes the complete survey results.

6.1 Summary of Survey Results

- In total, 14 responses were received from the survey. 6 of those operators were mostly natural gas transportation companies. The remaining 8 were technology and product suppliers, including 6 composite repair companies and 2 composite pipe manufacturers.
- At the onset, it will be stated that what is presented here is a result from an extremely small sample set, although it is believed that the responses do reflect a majority opinion from INGAA. In the future a more detailed survey must encompass responses from majority of the INGAA members.
    - This is required primarily to have a clear understanding of the operating envelope offered by the various NTP technology providers in terms of temperature, pressure, fluid compatibility etcetera.
- An interesting observation was the perfect alignment between the issues and challenges perceived by the survey group and what was being proposed through this report.

6.2 Insights and Key Learnings

- One of the obvious observations is that composite repair technology is considered a mature technology and is being employed by various operators. Composite repair technology also has the advantage of regulatory acceptance as a viable means of extending the life of existing infrastructure.
- One of the key gaps from the operator survey was the limited level of inspection, monitoring and sensing carried out on composite pipe to assess its condition and remaining life.
- Is also obvious that non-traditional pipe technology providers have only limited deployment of sensors embedded in their composite pipe products. Thus far we have identified one provider, although they have not responded to this survey.
- Sensing and monitoring are key to the successful and reliable acceptance and deployment of NTPs, and this has also been highlighted in the technology assessments in the earlier chapters.
- Regulatory acceptance is pointed out as a gap both by operators and technology providers. Significant and concentrated effort must be put in place to ensure gap closure and expeditiously obtain regulatory approval for non-traditional pipes.

- In addition to conventional natural gas and water, operators see NTP opportunities in the emerging fields of energy transition such as hydrogen, carbon capture, renewable natural gas etc.
- The survey also highlights some significant differences in operator and vendor perceptions on NTP – on barriers to acceptance. It is very important that these differences be discussed in a transparent manner and reconciled as future acceptance of non-traditional pipe will significantly hinge on this unified approach. Table 10 below highlights the differences in acceptance barriers.

Table 10: Barriers to NTP Adoption - Operators and Technology Providers

Barriers – Operators view	Barriers- Technology Providers
• Regulatory barriers • Technology readiness • Quality assurance and reliability • Lack of design guidelines and adopted industry standards	• Lack of resources at the operator level to test and approve products • “Not being the first to deploy” attitude • Perception and lack of awareness leading to limited confidence in NTP solutions • Cultural and social barriers • Surprisingly, the technology providers all felt that there are adequate design guidelines, and their product meets industry standards. • Technology readiness, QA, reliability was not perceived as barriers

7.0 TECHNOLOGY ROADMAP

The risk analysis in the earlier section identifies specific risk mitigation measures, many of them are technology plays that need to be assessed, matured, and implemented. This section addresses the technology assessment and roadmap. This section consists of two separate parts, the first part articulates the methodology used for technology assessment with its various elements, and the second part addresses the technology roadmap for each prioritized and identified technology detail in the Appendix 1.

7.1 Roadmap Methodology

1. Based on the risk analysis, various functional requirements of the initiatives are identified.
2. These are translated into point technology or system level technology initiatives.
3. The widely accepted technology readiness level assessment developed by NASA is used for guidance. Figure 2 below graphically demonstrates the various technology readiness levels. Along with it, the commercial readiness index of the technology is also assessed. This is important because technology providers are generally different from the operators, and the commercial element is key to the successful development and implementation of a solution.
4. Using the functional requirement criteria, and their level of maturity, the technological readiness level of each technology is identified.
5. Gaps in knowledge, risk, reliability, assurance…etc.,. are clearly identified and compiled as gap closure initiatives.
6. Once these initiatives are identified, the necessary testing, evaluation, assurance and demonstration are determined.

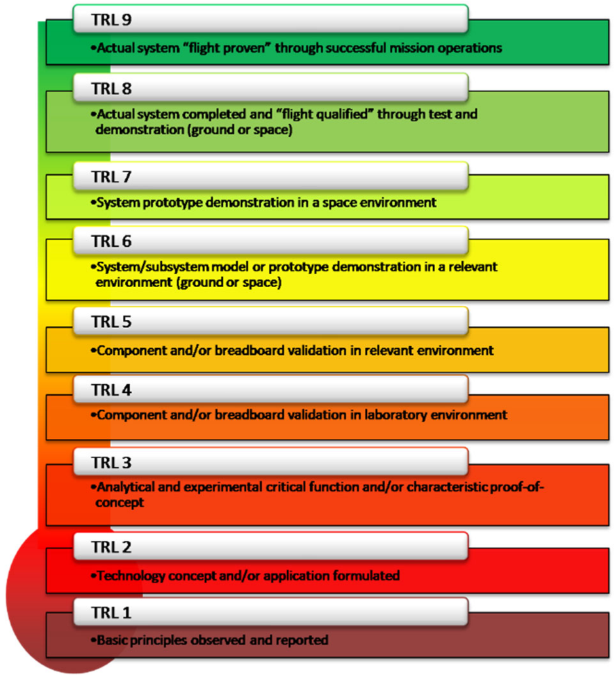

Figure 2: TRL Tiers

7.2 The RoadMap for Each Prioritized and Identified Technology

Basis the methodology defined in the earlier section, a summary of the various technologies assessed for meeting the various functional requirements of risk, is presented in the following Table 11.

The table addresses the functional requirements addressed by a particular technology, its maturity and typical gap closure. The green indicates that the technology potentially addresses the risk functional requirement. The amber indicates additional work to be carried out to demonstrate a given technology. The red indicates significant work to reach an acceptable maturity level.

Appendix 1 looks at each of those technologies in greater detail with a narrative to complement the color code assessments shown in this table. Review this table in conjunction with Appendix 1 to get a fuller picture of the overall framework.

Also included is Appendix 3 that provides a framework for how technical, regulatory, and commercial assessment levels interact together in relation to technology integration in the pipeline industry. Although most readers will be familiar with the Technology Readiness Level (TRL), most readers will not be familiar with the Commercial Readiness Index (CRI) and the Regulatory Assessment Level (RAL), the latter of which was developed for this study.

Table 11: Functional Requirements, Maturity and Gap Closure for various NTP technologies

Area of Assessment	Bonded TCP	Unbonded TCP	Crack arrestors	Composite Repair Systems	Connector	Sensor Fiber optics	Passive sensor technology	Ultrasonic	Acoustic Emission
Functional Requirement Addressed									
Reliability	[green]	[green]	[green]	[green]	[green]	[green]	[green]	[green]	[green]
Safety	[green]	[green]	[green]	[green]	[green]	[green]	[green]	[green]	[green]
License to operate	[green]	[green]	[green]	[green]	[green]	[green]	[green]	[green]	[green]
Life cycle cost	[amber]	[amber]	[amber]	[green]	[amber]	[amber]	[amber]	[amber]	[amber]
Maturity									
Technology Readiness Level (1 to 9)	6-7	6-7	6	8	7	4-5	4	4	7
Commercial Readiness Index (1 to 6)	1	1	1	5	1	3	0	3	3
Regulatory Acceptance Level (1 to 5)	2	2	2	5	2	1	1	1	1
Gap closure									
Component test	[amber]	[amber]	[amber]	[green]	[amber]	[amber]	[amber]	[amber]	[amber]
System test	[red]	[red]	[red]	[green]	[red]	[red]	[red]	[red]	[red]
Assurance	[red]	[red]	[red]	[green]	[red]	[amber]	[amber]	[amber]	[amber]
Standards	[red]	[red]	[red]	[green]	[red]	[amber]	[amber]	[amber]	[amber]
Partner/Vendor	[green]	[green]	[amber]	[green]	[green]	[amber]	[amber]	[amber]	[amber]

[green]		Functional requirements addressed
[amber]		Some work already done; additional work required
[red]		Minimal work done; significant work required

7.3 Roadmap Summary

This section summarizes the roadmap developed, incorporating the content of this report, analysis, and inputs from the survey with various technology providers and operators. What is highlighted here are the key elements that require to be incorporated in the roadmap and implementation plans. Refer to Section 8.0 for a discussion on proposed implementation plans and three-year road map.

The summary is categorized under five headings.

- Knowledge
- Standards
- Assurance
- Regulatory
- Alignment

Knowledge-almost all the major gaps in technology from this study point to two areas: (1) sensor, monitoring and inspection technologies - identified as key success factor for the expeditious and successful adoption of non-traditional pipe (2) Technology and analytical methods required to demonstrate the validity of non-traditional pipe in hitherto severe environments like supercritical CO_2.

Standards-in all areas of NTP, there is an urgent need to have unified standards, guidelines for design, quality assurance and construction. The absence of standardization is limiting the fast adoption of non-traditional pipes.

Assurance- both technical assurance and quality assurance. Like standards, a unified and aligned set of assurance practices must be developed to ensure a higher level of confidence in the implementation of NTPs. This encompasses additional analytical work, testing and validation. With increased use of sensing elements in non-traditional pipes, system level testing must be an integral part of the technical assurance process.

Regulatory-currently, regulatory approval of NTPs is done on a case-to-case basis using special permits. Ideally, NTPs should be elevated to the same scrutiny and acceptance as steel pipe. This requires concentrated actions over a definite period to ensure regulatory buying and acceptance.

Alignment-adoption and regulatory acceptance of NTPs can only be accomplished through collaborative and aligned effort between technology providers, operators, engineering companies and regulatory authorities. Therefore, at every step of the way, operators and technology providers must work very closely to develop products and assurance and acceptance criteria to mitigate potential risks from this new technology. The survey highlighted the need for a concentrated effort for the parties to be aligned for combined success.

8.0 IMPLEMENTATION OF NON-TRADITIONAL PIPE

The selection maturation and implementation of the various non-traditional pipe technologies will obviously be dictated by specific company infrastructure, business plans and the extent and intent of participation in the energy transition environment. Taking into consideration the risk analysis and the various inputs from operators and technology providers, a general technology implementation staircase can be developed.

8.1 Implementation Plan

- The technology implementation plan should be thought of as a long-term initiative, with a staged approach for specific deliverables that will enable the success and implementation of subsequent steps. As the risk analysis indicates, there are sufficient high priority common themes that need to be worked on, irrespective of the technology that is picked for maturation and implementation. Refer to Figure 3 for a proposed technology implementation plan that spans three phases over a 3-year period.

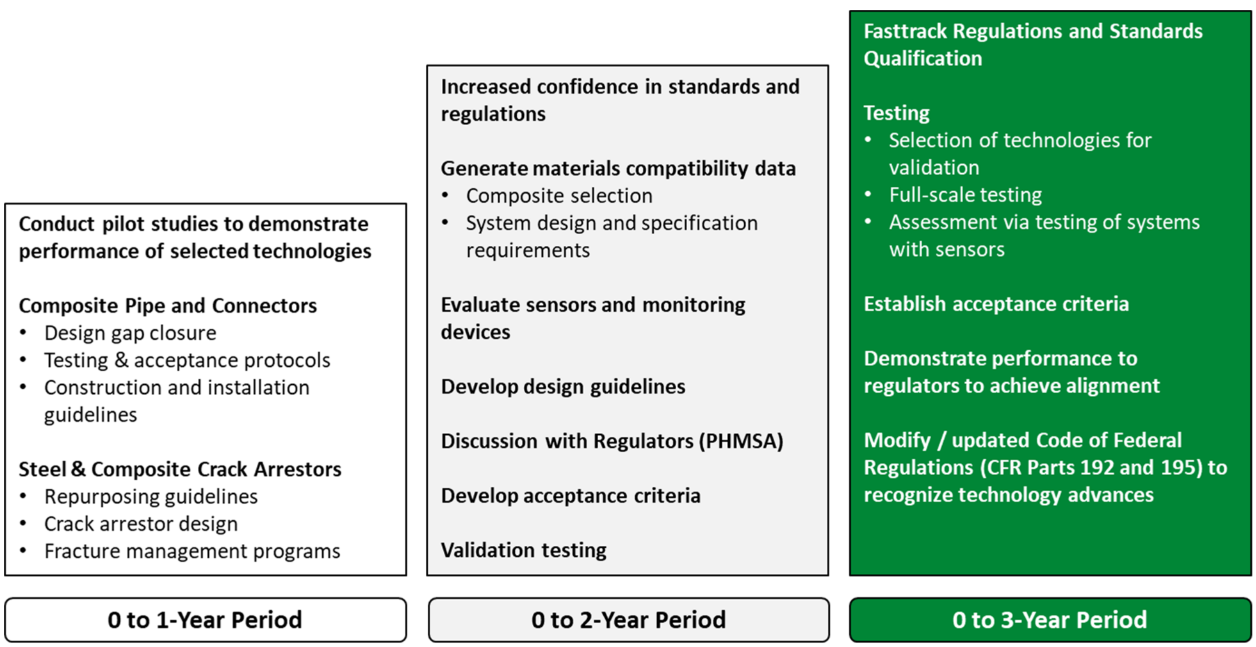

Figure 3: Non-traditional Pipe Implementation Roadmap

- **Phase-1** is expected to take about 12 months from inception. This phase of work primarily addresses demonstration of the technology as a system. This will include developing clear guidelines for the design and acceptance of flexible composite pipes, crack arresters and connectors. This phase should also include developing guidelines, demonstration and acceptance criteria for infrastructure that will be repurposed for transporting new fluids like hydrogen and dense space CO_2. Clear guidelines should also be developed at this stage for demonstrating the reliability and acceptability of the NTP as a system that incorporates the pressure containing hardware along with embedded sensors and monitoring devices.

- **Phase 2** builds on the work completed in Phase 1 by increasing confidence in standards and representations made to the regulatory agencies. This phase of work should also include additional testing to demonstrate material compatibility, programs to evaluate sensors and monitors, and protocols to test systems as a whole. At the end of this phase, the industry should be able to have clear design guidelines, and risk mitigation and acceptance criteria which can then be presented to the regulators for consideration.
- **Phase 3** will culminate with an acceptance of the design criteria along with regulatory approval for the proposed initiatives. This phase will also include system reliability tests (e.g., full-scale testing of the system incorporating sensors).

Ideally, Phases 1, 2, and 3 will commence simultaneously, but will have different completion dates owing to the scopes of work involved.

- Implementation of the technology program will also require an independent integrator and management of the program.

8.2 Regulatory Acceptance

Regulatory acceptance of NTPs is foremost in the minds of both operators and technology vendors. Therefore, this section highlights specific actions that can be completed to facilitate regulatory acceptance.

- NTPs are challenged by multiple touch points that include technology development, assurance, validation, and acceptance. Simultaneous to the touch points activities require a unified and systematic approach for communicating with regulators.
- Proactive engagement with regulatory authorities, communicating salient developments in technology, qualification and risk management and soliciting opinions from regulatory groups are essential actions in this path.
- A clear articulation of the functional needs of a non-traditional pipe and validation and verification (contemplated to demonstrate the functional requirement), is essential at the onset to achieve early alignment with regulatory authorities.
- Understand the key regulatory concerns to attain confidence in the outcomes at every step along the way. Being cognizant of de-risking activities is critically important to this stage.
- Simultaneously, showcase the technology and its robustness, including discussions on risk management at public end technical forums and with standards authority interactions.
- Proactive engagement of standards organizations (i.e., ASME, API, AMPP, etc.) for alignment and eventual development of future standards focused on NTP technologies into the CFR.

As stated at the beginning of this report, one of the reasons that technologies fail to achieve a high level of adoption in the energy industry is a failure to build a framework for identifying why specific technologies are required, where they can be used, how they should be used, and what processes should be used to ensure they are appropriately implemented. The framework outlined in this report provides the pipeline industry with a program to utilize non-traditional pipe technologies to ensure they are used to meet the future demands associated with the transportation of current and emerging fuels.

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APPENDIX 1: TECHNOLOGY ASSESSMENT SUMMARY

Table A-1a: Thermoplastic Composite Pipe-Unbonded

Technology	Thermoplastics composite pipe-unbonded
Summary	This is a technology for manufacture of composite pipe that incorporates an inner layer, reinforcement, and an outer layer. These three discrete layers are not bonded to each other. A variety of inner liners are currently in the market-polyethylene and high-density polyethylene. The reinforcement which is generally metallic, or a non-metallic wire is wound around the inner layer to provide hoop stress and other load carrying resistance depending on the type and orientation of the winding. The outer layer generally consists of a thermoplastic material primarily to combat wear.
Size	Various
Pressure	Various
Tech. Gaps	The single largest barrier or gap to acceptance of this technology is the absence of design engineering guidelines and consequently robust regulatory approval. Most deployments thus far have been done on a case-to-case basis. There's also an unfounded concern about the robustness of composite pipe compared to the legacy steel pipe infrastructure.
De-Risking	• Developing robust design, construction, and quality guidelines • additional testing and analysis to bolster the confidence and reliability of composite pipe • Incorporation of monitoring and sensing technology to obtain real time indication of the system health • Clear articulation of residual risk and its management • Obtaining regulatory approval
Application	The technology is currently developed to work stand-alone and in specific cases may be considered for liner applications on existing steel pipe.
Impact	• Increase safe operation with embedded sensors • Favorable techno-economics-ability to retrofit and produce construction costs • Improved efficiency in construction and human exposure
TRL	6-7
CRI	1-2
Vendors	Various

Table A-1b: Thermoplastic Composite Pipe-Bonded

Technology	Thermoplastics composite pipe-bonded
Summary	This is a technology for manufacture of composite pipe that incorporates an inner layer, reinforcement, and an outer layer. These three discrete layers are bonded to each other. A variety of inner liners are currently in the market- HDPE, PEEK, PA, PPS and PVDF to address a variety of environments. The reinforcement is mostly carbon fiber or aramid to provide hoop stress and other load carrying resistance depending on the type and orientation of the winding. The outer layer generally consists of a thermoplastic material primarily to combat wear.
Size	Various
Pressure	Various
Tech. Gaps	As with unbonded composites, the single largest barrier or gap to acceptance of this technology is the absence of design engineering guidelines and consequently robust regulatory approval. Most deployments thus far have been done on a case-to-case basis. There's also an unfounded concern about the robustness of composite pipe compared to the legacy steel pipe infrastructure.
De-Risking Opportunity	• developing robust design, construction, and quality guidelines • additional testing and analysis to bolster the confidence and reliability of composite pipe • Methods to assess health and residual life • incorporation of monitoring and sensing technology to obtain real time indication of the system health • clear articulation of residual risk and its management • obtaining regulatory approval
Application	the technology is currently developed to work stand alone and in specific cases may be considered for liner applications on existing steel pipe.
Impact	• increase safe operation with embedded sensors • favorable techno-economics-ability to retrofit and produce construction costs • improved efficiency in construction and human exposure
TRL	6-7
CRL	1-2
Vendors	Various

Table A-1c: Composite repairs and crack arrestors

Technology	Composite repairs and crack arrestor technology
Summary	Composite repairs and crack arrestor technology are included in the same section because, in most cases both employ similar technology. Both approaches employ a composite sleeve to reduce the local hoop stress by providing additional reinforcement. In the case of a crack arrestor, the intent is to reduce the driving force around a growing crack so that it arrests in the vicinity of the crack origin. Significant work has been carried out and composite repairs and crack arrestors through various joint industry projects. Composite repair sleeves are widely used in industry. Crack arrested technology, despite the theoretical demonstration and limited testing, has been deployed in very specific applications like ethylene and CO2 lines
Size	Various
Pressure	Various
Tech. Gaps	• Design guidelines • Life estimation guidelines • Confidence in solutions • Regulatory approval protocols
De-Risking	• Consolidate existing body of knowledge to define design and validation guidelines • Identify additional subscale and full-scale testing to validate the science • Since it encompasses the whole industry, this may be a fertile ground for joint industry projects
Application	• Pipeline rehabilitation • Pipeline re purposing • Supercritical CO2
Impact	• Safe operations • significant techno-economic benefits in Capex and Opex
TRL	8
CRL	2
Vendors	Various

Table A-1d: Connectors

Technology	Connectors
Summary	Connectors present a very difficult technology. On one hand, it's a key component for reliable operation of NTP. It is also a significant contributor to the reported failures-statistically a large percentage of failures can be attributed to those emanating from connectors. However, connector design is proprietary technology- hence only limited data exists in the public domain.
Size	Various
Pressure	Various
Tech. Gaps	• Design and installation guidelines • Quality assurance guidelines • Competence of understanding of the failure modes and effects • Health monitoring
De-Risking	• As an industry, we must be working very closely with the connector manufacturers to address the technology gaps listed above • Incorporate health sensing and leaks sensing/monitoring in the connector • It's also essential to do it so to obtain regulatory approval of the non-traditional pipe as a system.
Application	Non-traditional pipe application
Impact	• Construction efficiency • Cost optimization
TRL	7-8
CRL	1-2
Vendors	Various

Table A-1e: Fiber Optics

Technology	Fiber Optics (as a system)
Summary	Fiber optic technology for structural health monitoring, measuring temperature, pressure and strain is a mature technology and has been deployed in specific areas for pipeline integrity. It enables real-time measurement of strain and temperature. Combining high spatial resolution, strain, and temperature resolution and accuracy. long lengths in the range of 10s of kilometers can be interrogated using fiber optic techniques. Many systems work on BODTA and BODTR modes enabling sensing even if there is a break in the cable.
Tech. Gaps	• Fiber optics is most valuable when used as a system in conjunction with existing structural components like pipelines. This requires that adequate technology exists for installing fiber optics in key right-of-way either along the pipe or inside • Some non-traditional pipe composite pipe manufacturers have incorporated fiber optic during manufacturing. However, the protocols around monitoring, sensing and structural health are not explicitly developed for operators to confidently use it. The includes Testing of non-traditional pipes with embedded fiber optics as a system for structural soundness and resistance in various environments. • Qualifying non-traditional pipe with embedded sensors like fiber optics will be a key enabler in rapid regulatory approval
De-Risking	• A well-articulated failure modes risk and risk management strategy needs to be developed • Supplemental testing and analysis to demonstrate the robustness of the fiber optic – component and system • Clear articulation of how fiber optic sensing enhances the structural health monitoring and integrity of the system must be developed for regulatory approval
Application	• Steel and composite pipelines • Damage detection • Leak detection
Impact	• Real time health monitoring of assets • Reliability and confidence in asset integrity
TRL	Component level 8/9 System level 4/5
CRL	1
Vendors	Various

Table A-1f: Passive Sensors

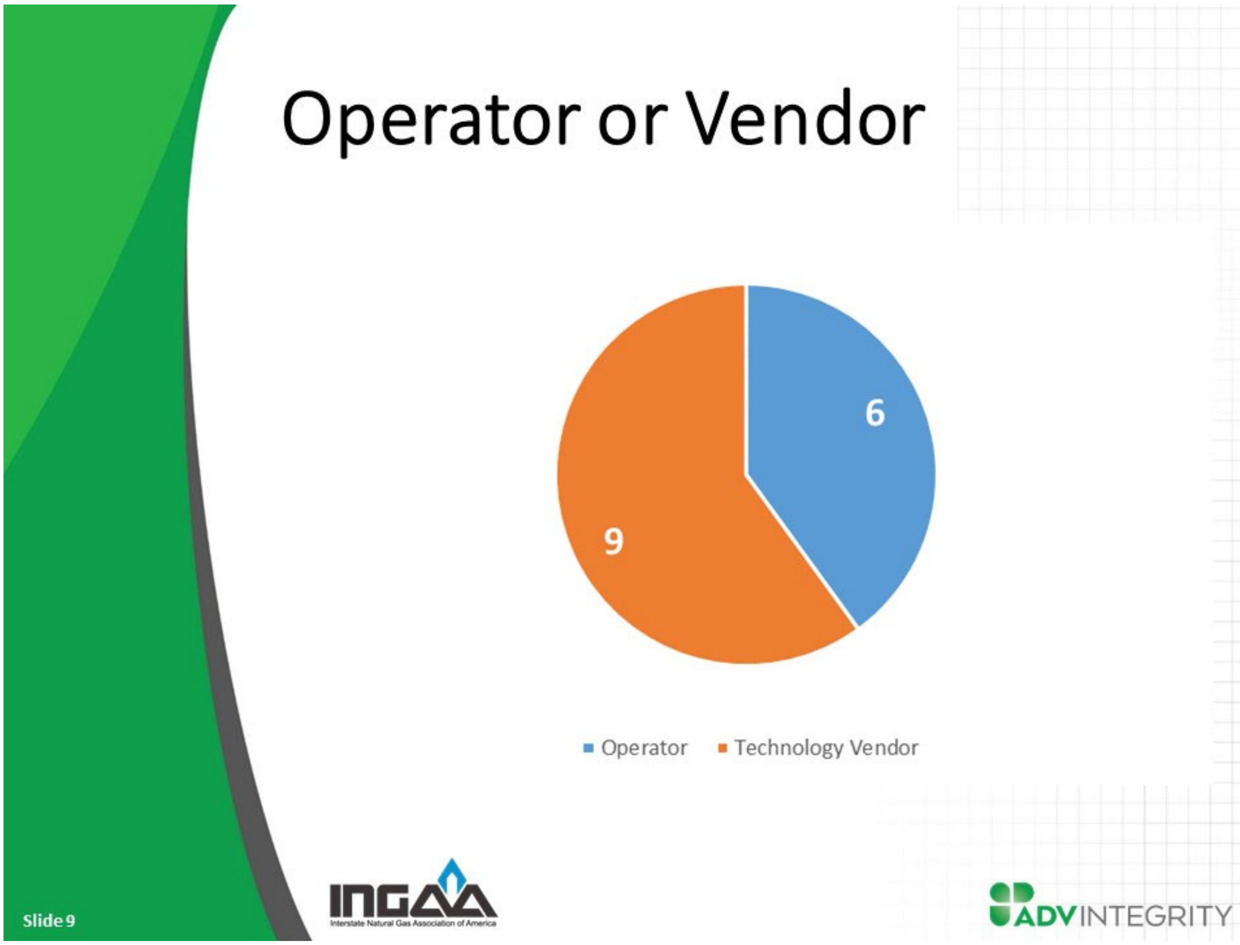
Technology	Passive sensor technologies
Summary	Passive sensor technology is increasingly becoming attractive; it's not necessary to have a power source to activate the sensors. These sensors fall into different categories-those based on nano wafers, RF and others based on passive antenna technology. Both rely on changes in the configuration of the sensor to detect the onset of damage - by detecting changes in • Persistence, • Changes in surface acoustic waves velocity and attenuation • Changes in electromagnetic resonance. • They're deployed as actual components or more recently as spray on nanocomposites. • These are relatively inexpensive devices • Must be deployed near the potential damage location
Tech. Gaps	• Technology is not tested/qualified for sensitivity and robustness • Limited industrial application demonstrated so far • Component level technology – system level development • Clearly articulate the risk management capability of the technology
De-Risking	• Technology available- must be qualified for sensitivity and robustness • Technology must be incorporated in a structural component and system level validation and qualification must be carried out • System level solution must be submitted for regulatory approval
Application	Temperature, Pressure, Strain, Chemical Species, Corrosion, cracking
Impact	structural health monitoring low-cost sensors can measure a wide variety of parameters with one sensor
TRL	Component: 3/4
CRL	0
Vendors	https://predyct.io/predyct-platform-iot-and-cloud/#iot www.kla.com

Table A-1g: Acoustic Emission and Ultrasonics

Technology	Acoustic emission & Ultrasonics
Summary	Although both techniques rely on sound for sensing, monitoring and inspection, there is a fundamental difference between how these techniques work. • Acoustic emission is generally employed as a sensing and monitoring tool. It relies on sound emanated from defects that when they are growing, or subject to transients like pressure. This sound can be captured using suitable electronics and triangulation can be utilized to pinpoint the location of potential defects. Therefore, Acoustic emission can be either an inspection tool OR monitoring and sensing tool. • Ultrasonics on the other hand inject ultrasound into the component of interest and analyzes the signal bouncing back from internal defects or velocity changes to detect and size defects. Generally, ultrasonics are used as an inspection tool for both non-metallic composites and steel pipelines.
Tech. Gaps	• Ultrasonics and acoustic emission are mature techniques for inspection and monitoring of metallic infrastructure. • For non-metallics like composites, the technique has been demonstrated to be able to inspect and monitor defects - however large-scale commercial implementation is limited • The absence of standards and guidelines supported by testing and qualification, is one of the predominant reasons for lack of wider acceptance.
De-Risking	• Additional testing both at component and system level incorporating non-metallics will significantly improve the confidence of using that technique at a wider scale. • Standards and guidelines must be developed like how these techniques are currently being employed to inspect and monitor steel infrastructure. • This is a good opportunity for a joint industry effort incorporating technology providers, operators, engineering companies and regulators.
Application	• Composite pipe monitoring • Ability to sense failures in composite pipes - especially reinforcement wires and disbonding • Ability to detect the onset of damage
Impact	• Reliability • License to operate • Cost optimization
TRL	TRL-3/4 for Composites
CRL	1
Vendors	Various

APPENDIX 2: INDUSTRY SURVEY

A questionnaire pertaining to the NTP application and challenges, was circulated to all INGAA members and technology companies invited by ADV Integrity, Inc. Copied below are the questions and answers that were submitted, which included 6 operators and 9 technology companies.




Responses from Technology Vendors
Slide 10


Product Name
• Composite Repair Technologies
• Belzona
• CSNRI Atlas Wrap
• OmegaWrap™
• TEAM FCR Composite Repair
• Spoolable Pipe Technology Companies
• Baker Hughes
• FlexSteel
• Smartpipe®
Slide 11
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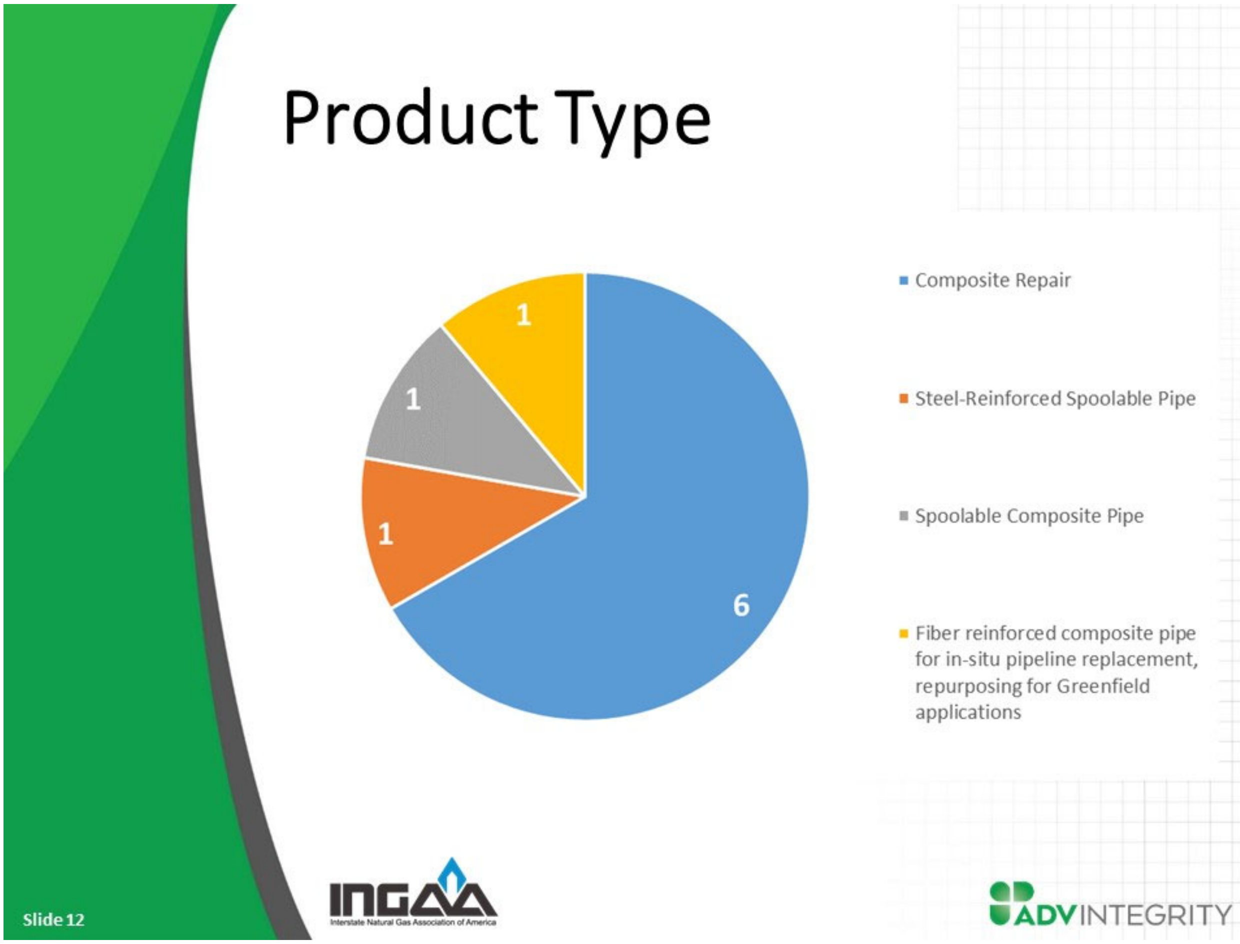
Product Type
1
1
1
6
Composite Repair
Steel-Reinforced Spoolable Pipe
Spoolable Composite Pipe
Fiber reinforced composite pipe for in-situ pipeline replacement, repurposing for Greenfield applications
Slide 12
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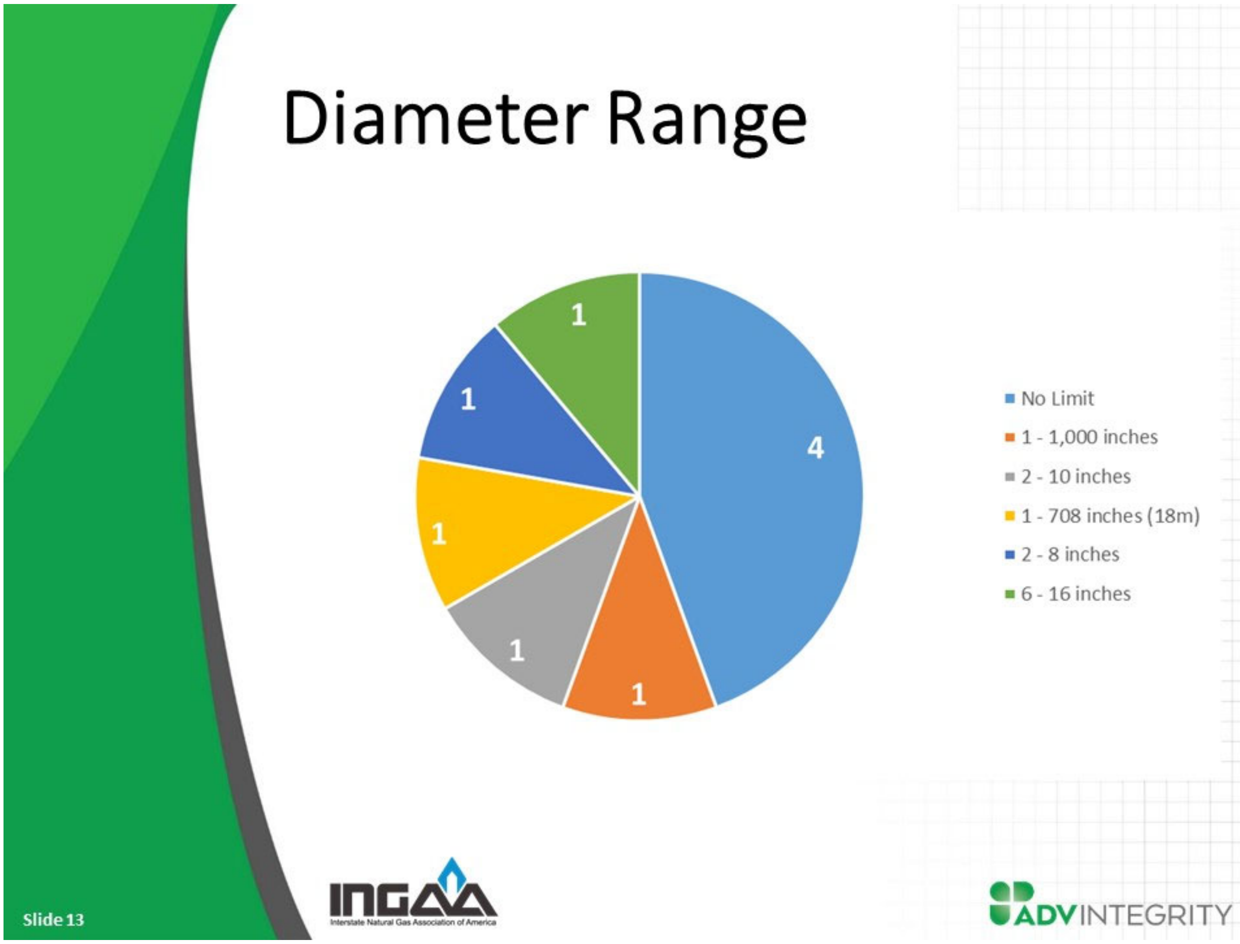
Diameter Range
4
1
1
1
1
1
No Limit
1 - 1,000 inches
2 - 10 inches
1 - 708 inches (18m)
2 - 8 inches
6 - 16 inches
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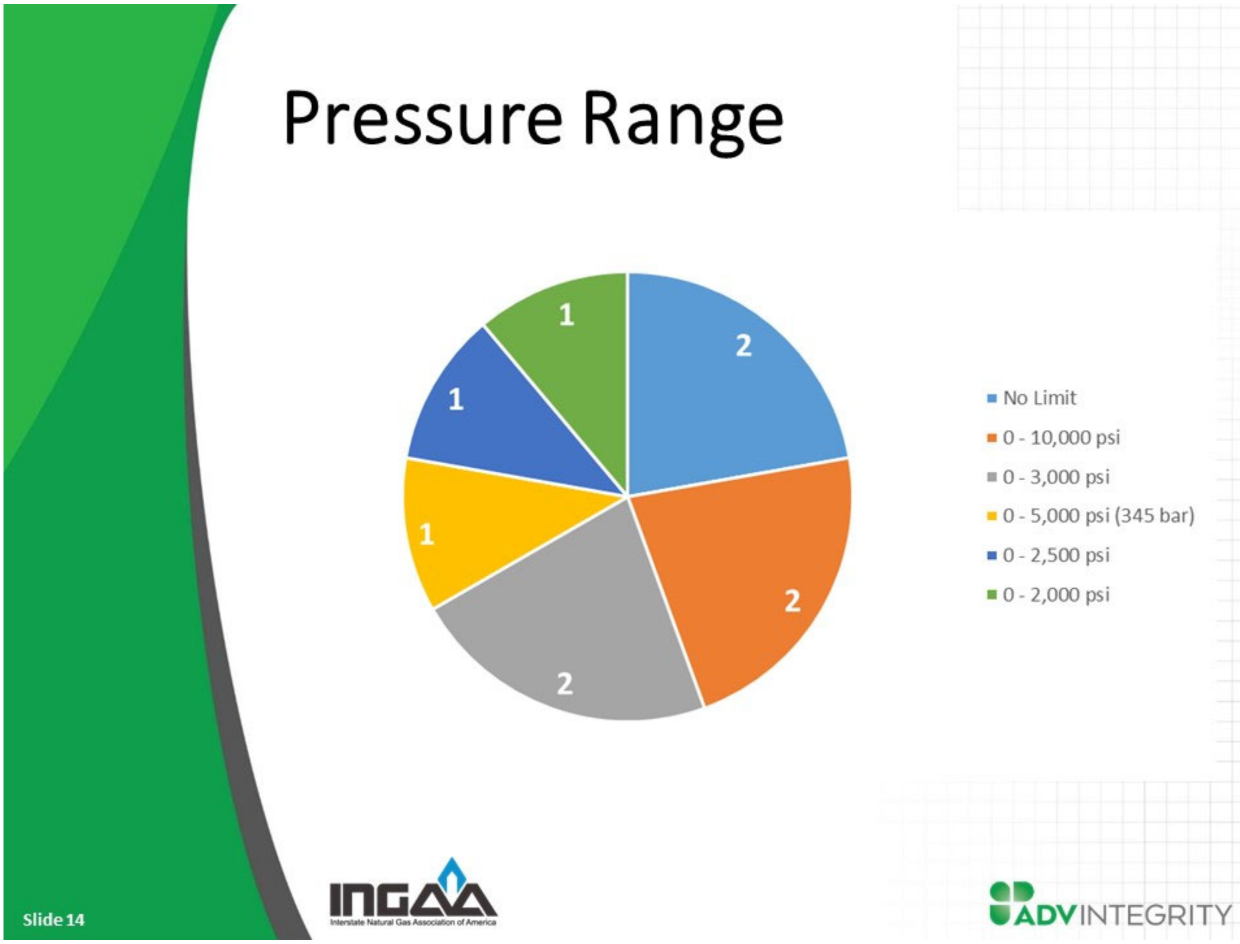
Pressure Range
2
2
2
1
1
1
No Limit
0 - 10,000 psi
0 - 3,000 psi
0 - 5,000 psi (345 bar)
0 - 2,500 psi
0 - 2,000 psi
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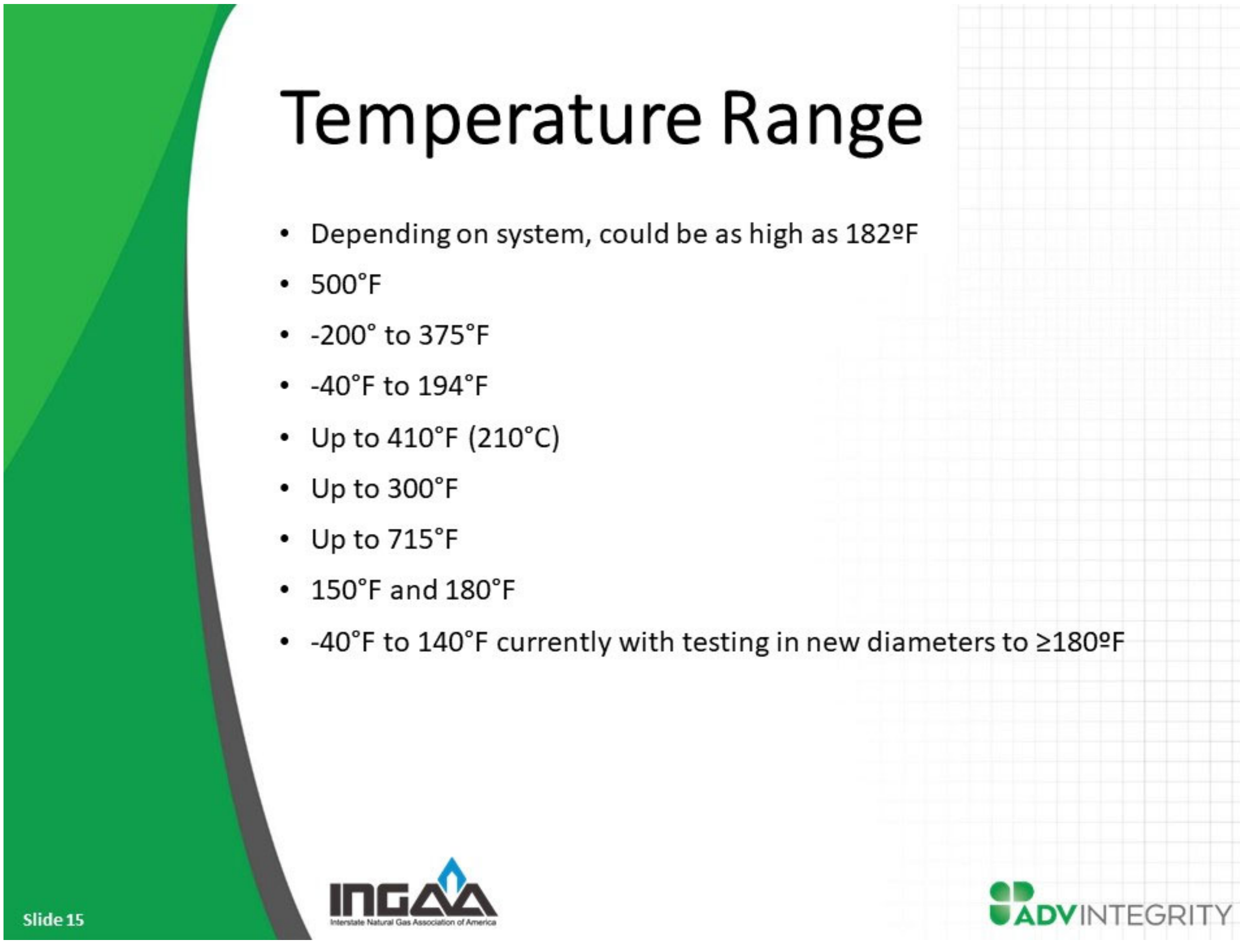
Temperature Range
• Depending on system, could be as high as 182ºF
• 500°F
• -200° to 375°F
• -40°F to 194°F
• Up to 410°F (210°C)
• Up to 300°F
• Up to 715°F
• 150°F and 180°F
• -40°F to 140°F currently with testing in new diameters to ≥180ºF
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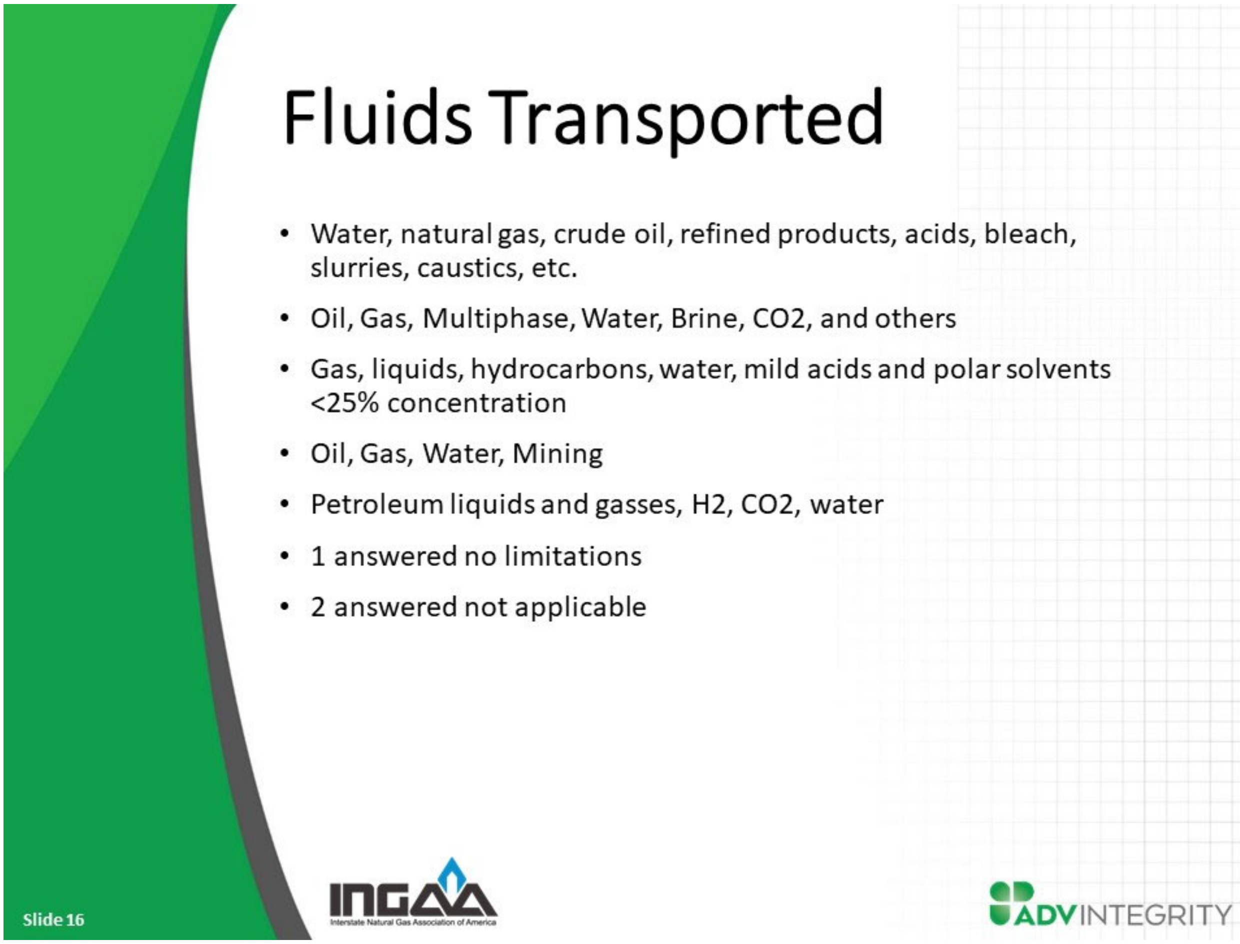
Fluids Transported
• Water, natural gas, crude oil, refined products, acids, bleach, slurries, caustics, etc.
• Oil, Gas, Multiphase, Water, Brine, CO2, and others
• Gas, liquids, hydrocarbons, water, mild acids and polar solvents <25% concentration
• Oil, Gas, Water, Mining
• Petroleum liquids and gasses, H2, CO2, water
• 1 answered no limitations
• 2 answered not applicable
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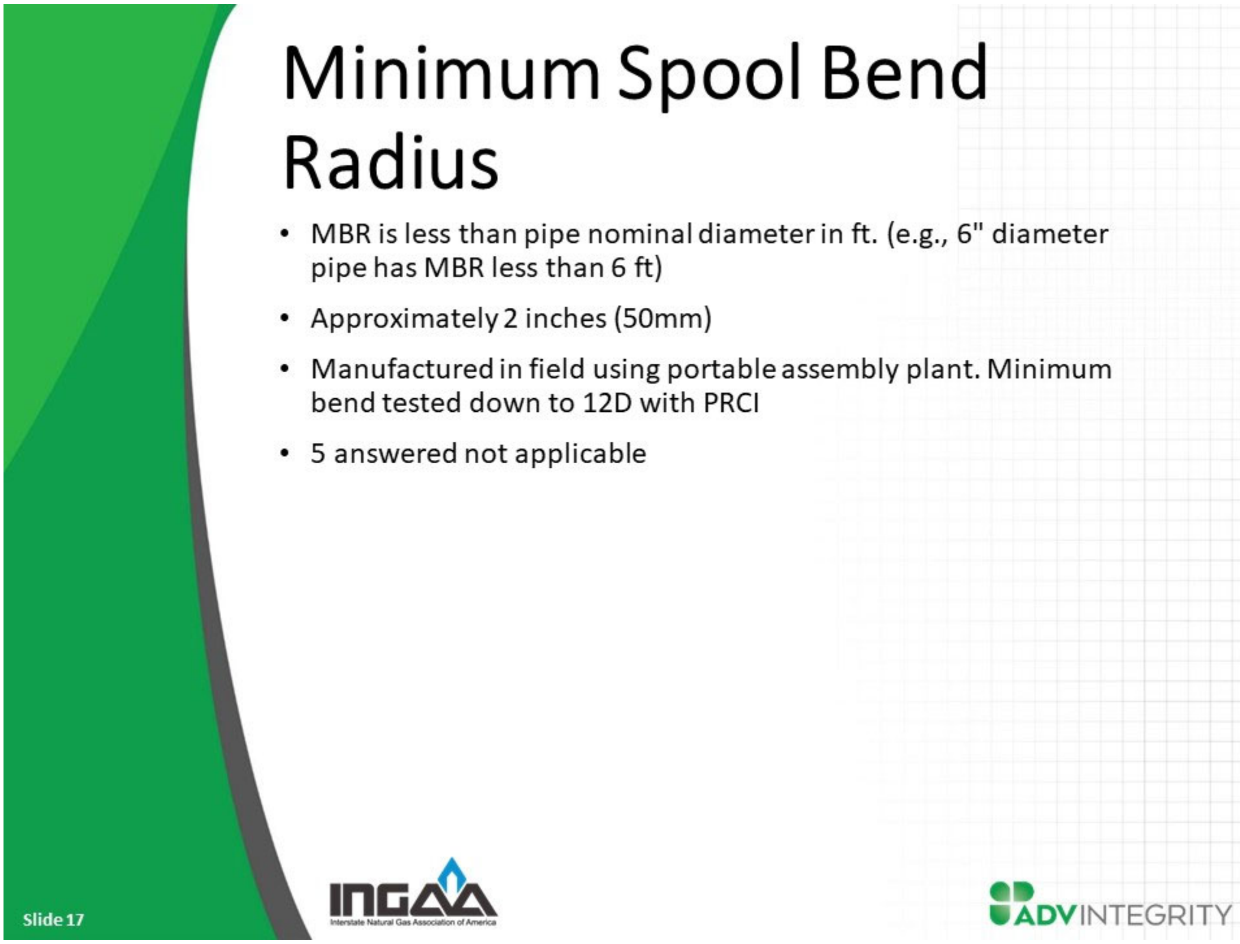
Minimum Spool Bend Radius
• MBR is less than pipe nominal diameter in ft. (e.g., 6" diameter pipe has MBR less than 6 ft)
• Approximately 2 inches (50mm)
• Manufactured in field using portable assembly plant. Minimum bend tested down to 12D with PRCI
• 5 answered not applicable
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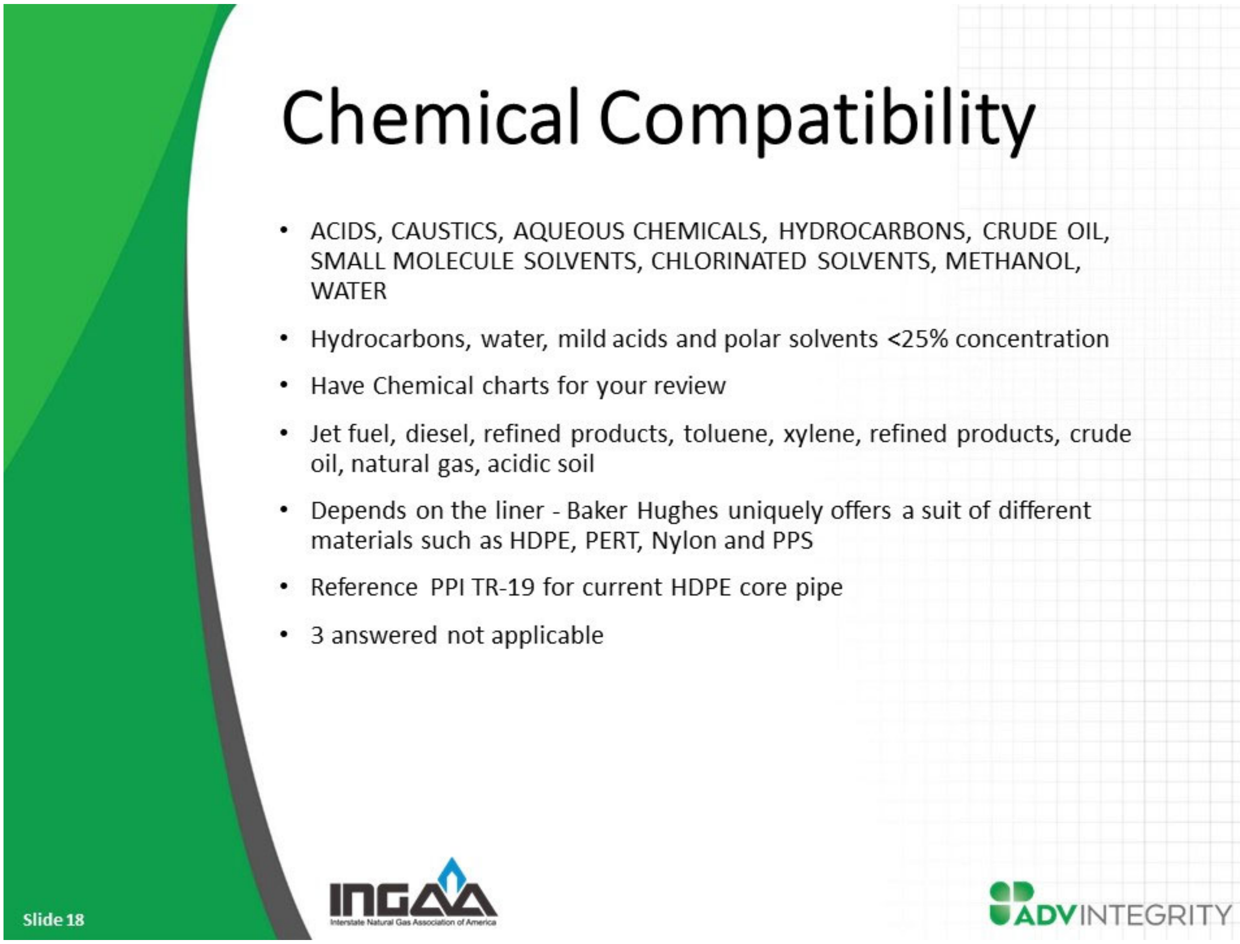
Chemical Compatibility
• ACIDS, CAUSTICS, AQUEOUS CHEMICALS, HYDROCARBONS, CRUDE OIL, SMALL MOLECULE SOLVENTS, CHLORINATED SOLVENTS, METHANOL, WATER
• Hydrocarbons, water, mild acids and polar solvents <25% concentration
• Have Chemical charts for your review
• Jet fuel, diesel, refined products, toluene, xylene, refined products, crude oil, natural gas, acidic soil
• Depends on the liner - Baker Hughes uniquely offers a suit of different materials such as HDPE, PERT, Nylon and PPS
• Reference PPI TR-19 for current HDPE core pipe
• 3 answered not applicable
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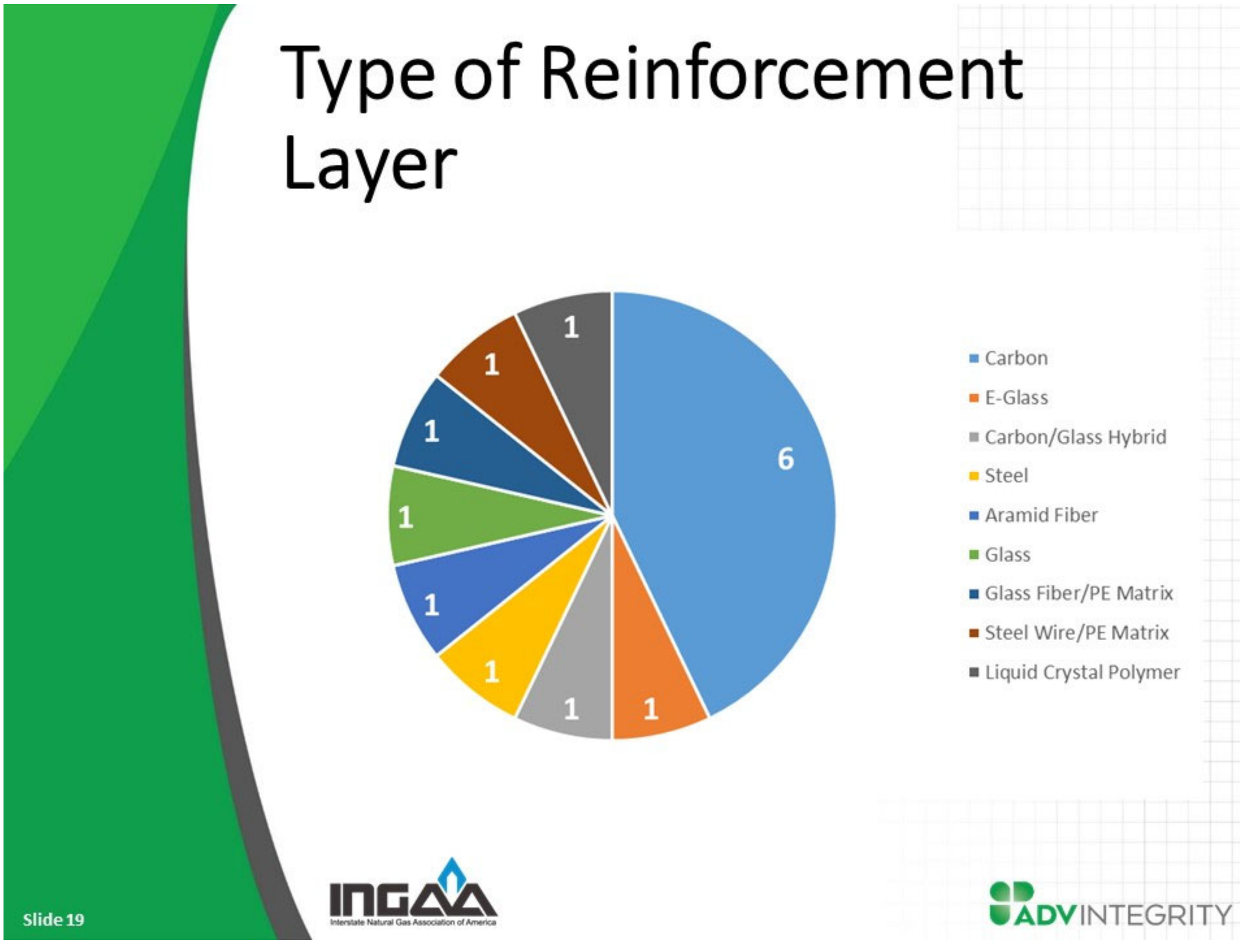
Type of Reinforcement Layer
6
1
1
1
1
1
1
1
1
Carbon
E-Glass
Carbon/Glass Hybrid
Steel
Aramid Fiber
Glass
Glass Fiber/PE Matrix
Steel Wire/PE Matrix
Liquid Crystal Polymer
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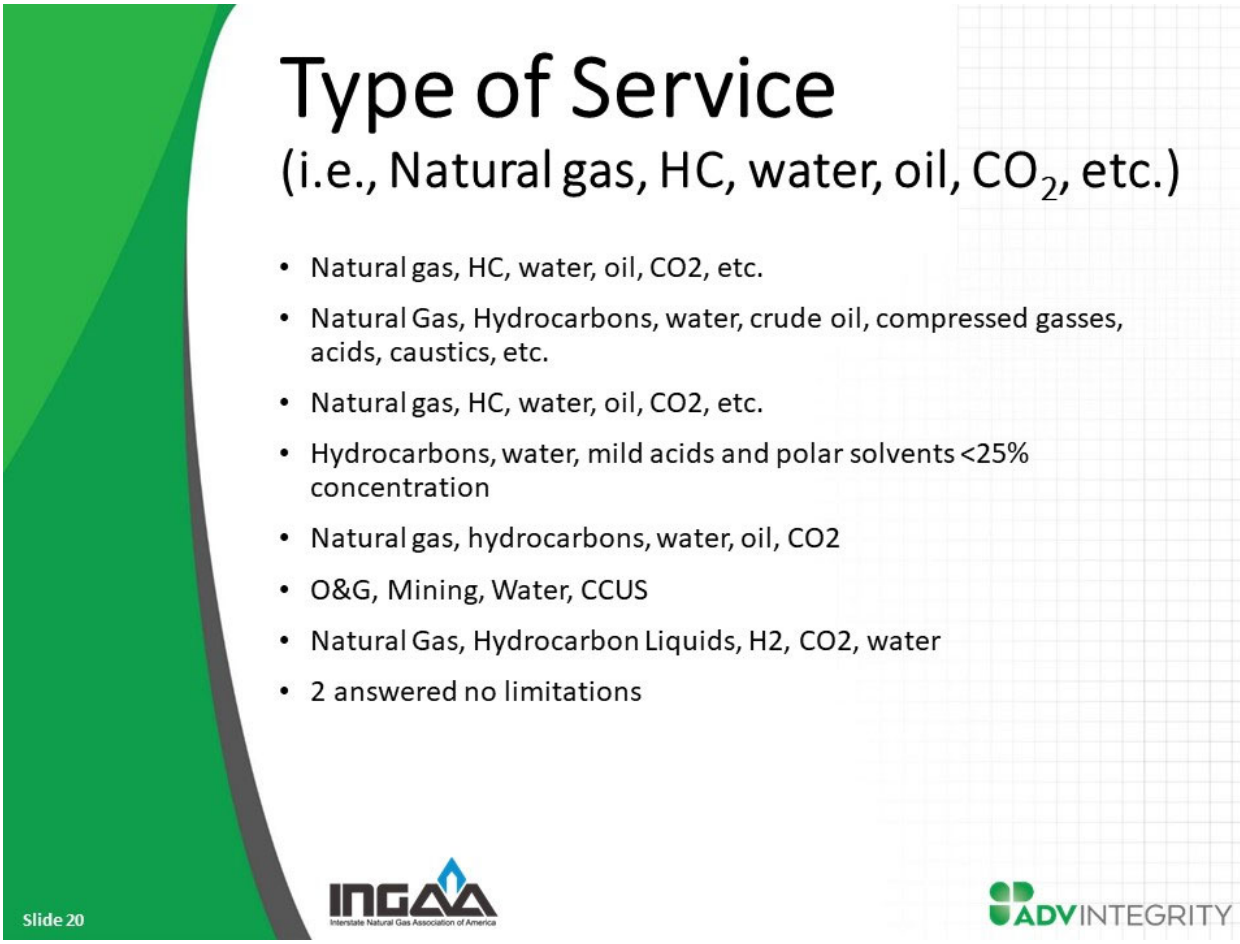
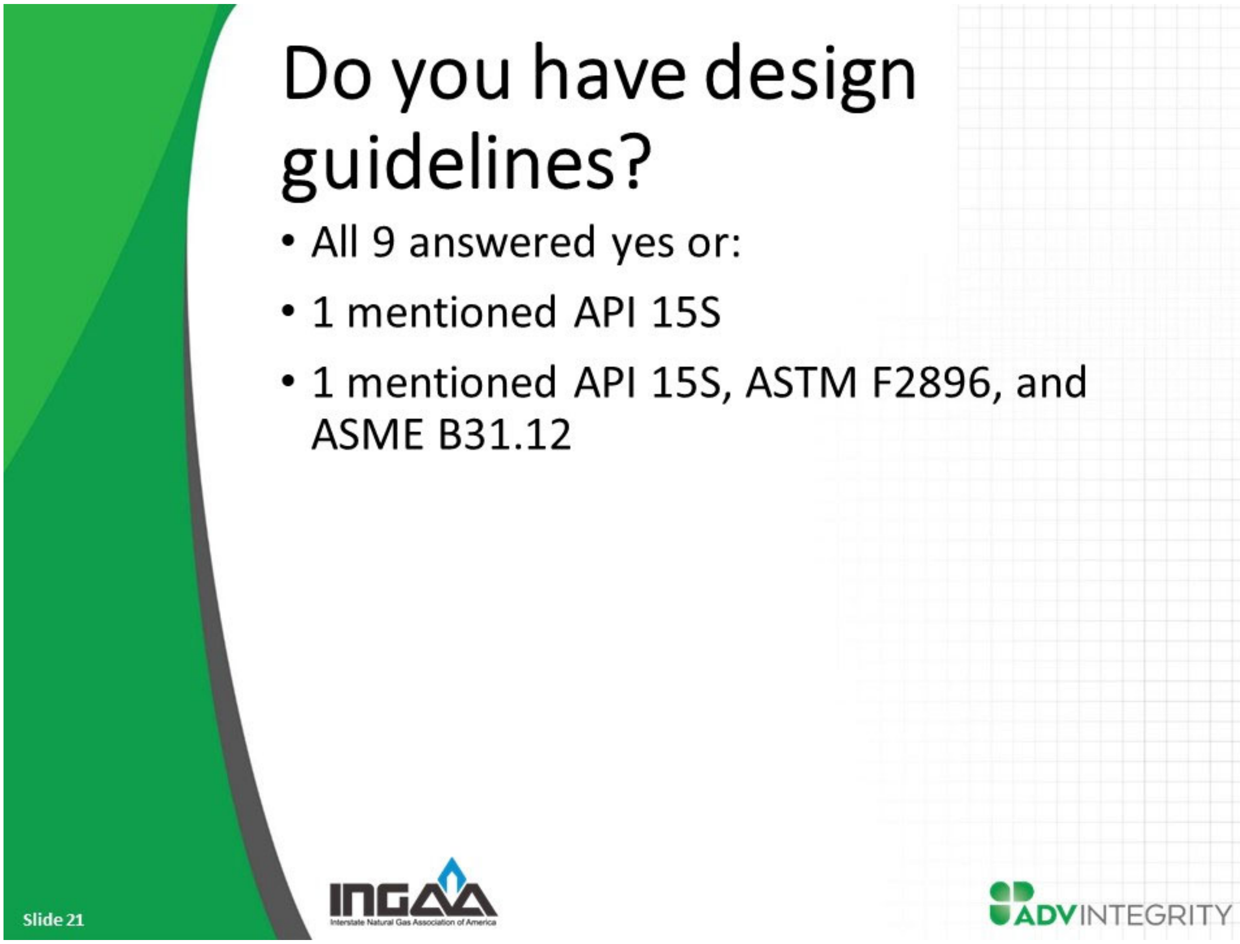

Type of Service
(i.e., Natural gas, HC, water, oil, CO_2, etc.)
• Natural gas, HC, water, oil, CO2, etc.
• Natural Gas, Hydrocarbons, water, crude oil, compressed gasses, acids, caustics, etc.
• Natural gas, HC, water, oil, CO2, etc.
• Hydrocarbons, water, mild acids and polar solvents <25% concentration
• Natural gas, hydrocarbons, water, oil, CO2
• O&G, Mining, Water, CCUS
• Natural Gas, Hydrocarbon Liquids, H2, CO2, water
• 2 answered no limitations
Slide 20
Interstate Natural Gas Association of America
ADVINTEGRITY


Do you have design guidelines?
• All 9 answered yes or:
• 1 mentioned API 15S
• 1 mentioned API 15S, ASTM F2896, and ASME B31.12
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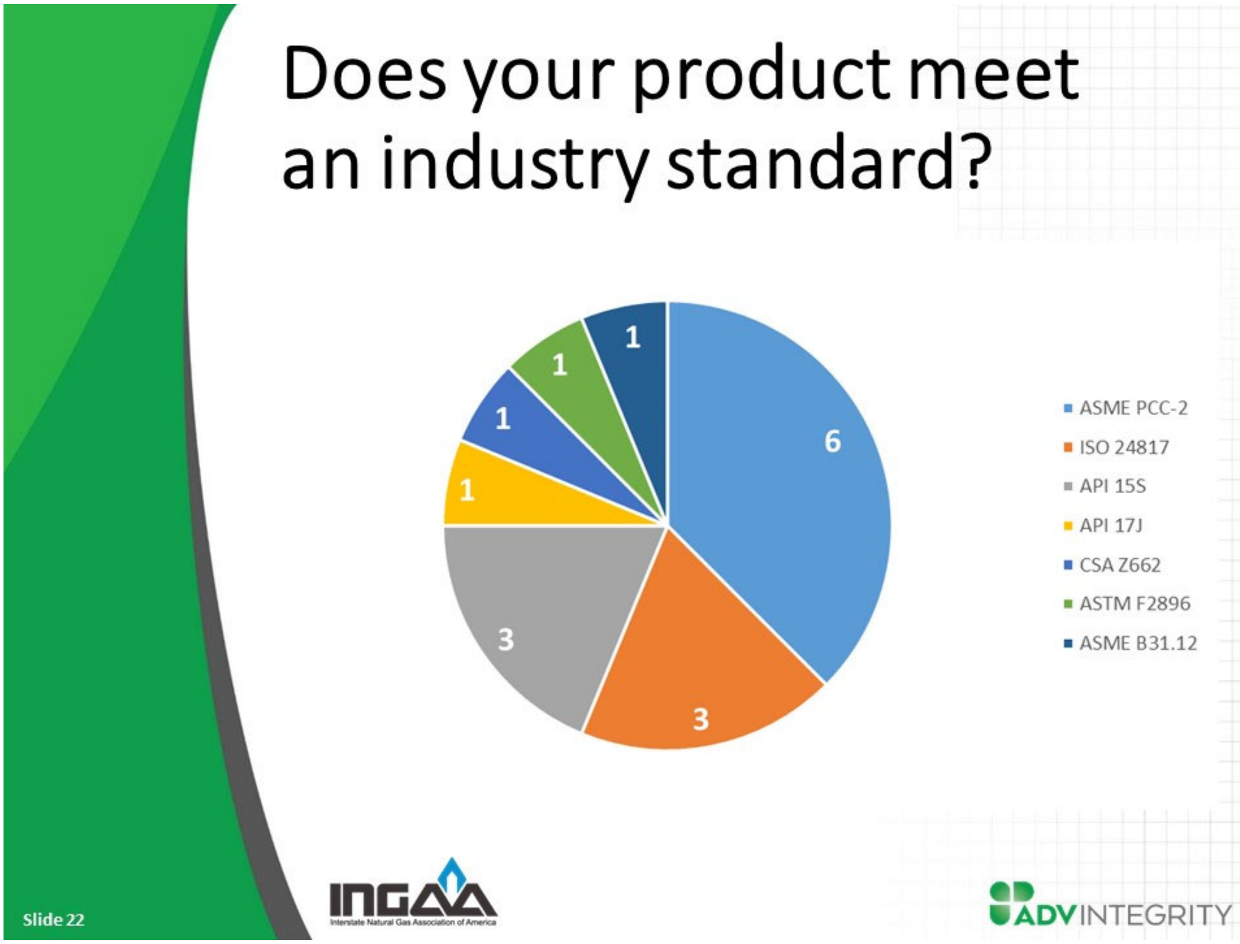
Does your product meet an industry standard?
6
3
3
1
1
1
1
ASME PCC-2
ISO 24817
API 15S
API 17J
CSA Z662
ASTM F2896
ASME B31.12
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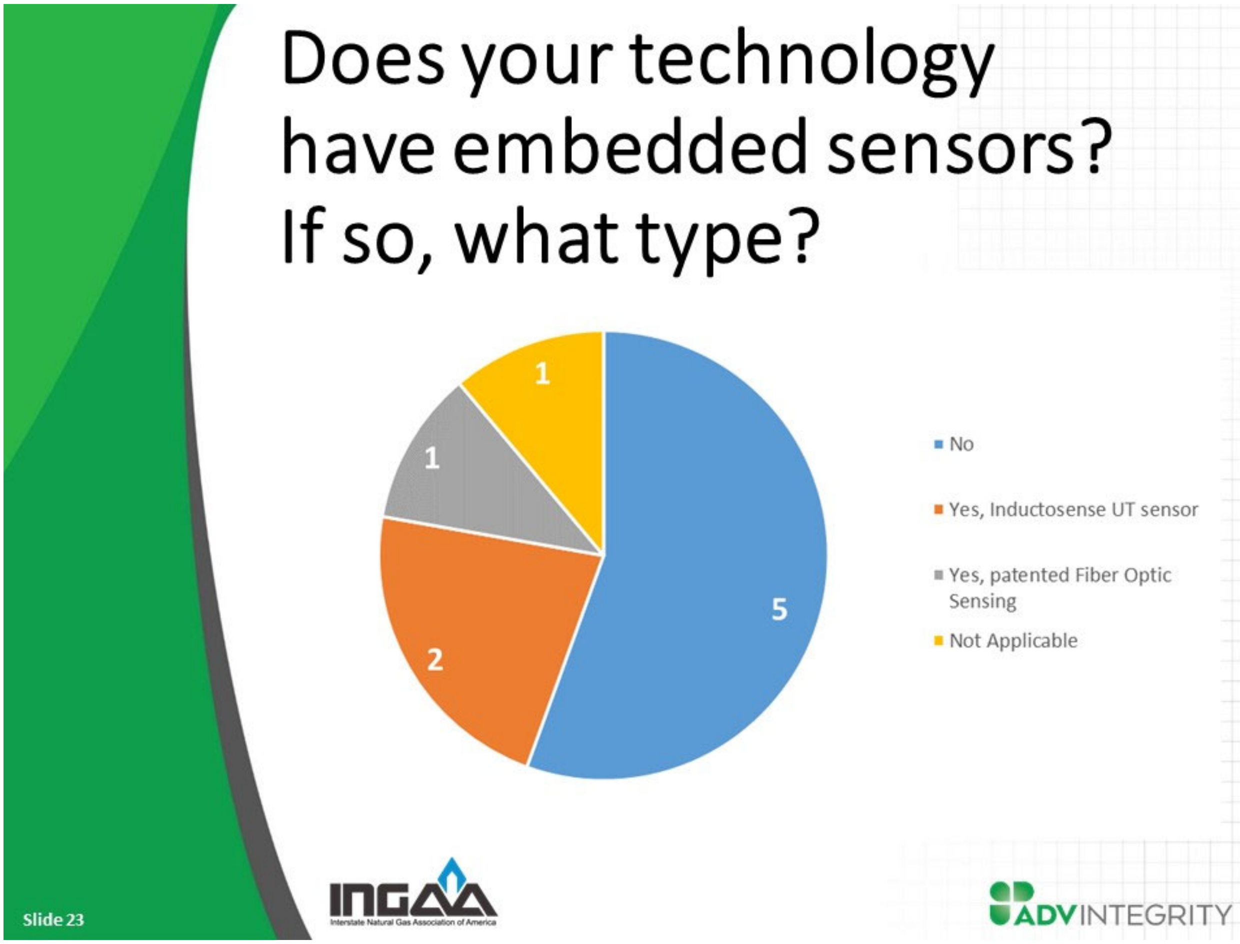
Does your technology have embedded sensors? If so, what type?
1
1
2
5
No
Yes, Inductosense UT sensor
Yes, patented Fiber Optic Sensing
Not Applicable
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Typical barriers for acceptance (1 of 2)

- Sufficient testing data. Insufficient resources at Operating company to conduct review process (i.e., "We just don't have the time"). Adoption by other operators (i.e., "We don't want to be the first" or "Our company hasn't started using composites yet").
- Acceptability for repairs of crack type damage
- Lack of understanding of composite repairs, we are not the typical solution used at that plant/facility, lack of a local, qualified contractor to perform the installation, fear of required surface preparation (causing more damage to the pipe)
- Regulatory
- Education of operators on how the technology should and particularly on how it should NOT be used.
- “Through wall on 200psi+ pipeline thru PHMSA guidelinesBSEE for numerous repairs offshore GoM"

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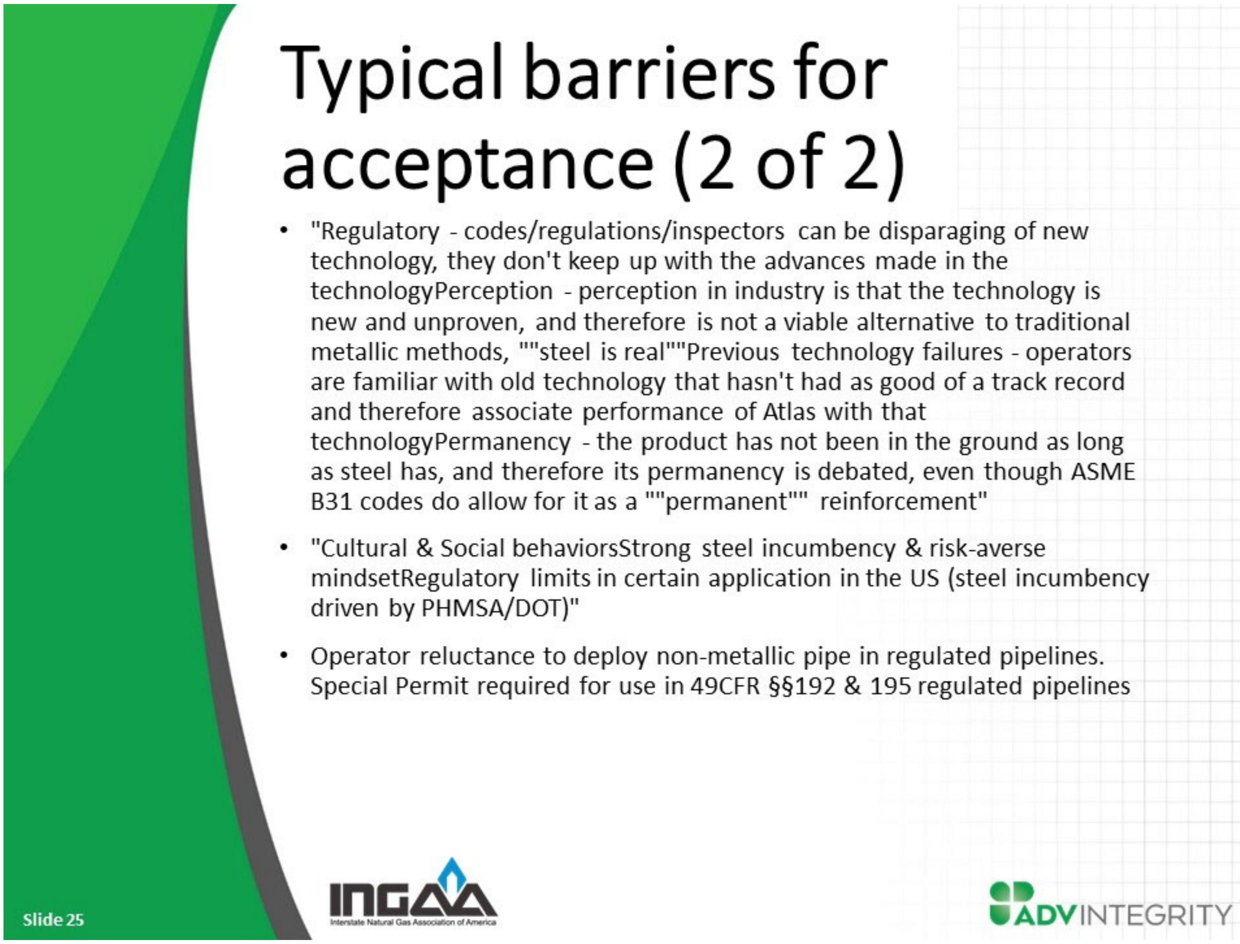
Typical barriers for acceptance (2 of 2)
• "Regulatory - codes/regulations/inspectors can be disparaging of new technology, they don't keep up with the advances made in the technologyPerception - perception in industry is that the technology is new and unproven, and therefore is not a viable alternative to traditional metallic methods, ""steel is real""Previous technology failures - operators are familiar with old technology that hasn't had as good of a track record and therefore associate performance of Atlas with that technologyPermanency - the product has not been in the ground as long as steel has, and therefore its permanency is debated, even though ASME B31 codes do allow for it as a ""permanent"" reinforcement"
• "Cultural & Social behaviorsStrong steel incumbency & risk-averse mindsetRegulatory limits in certain application in the US (steel incumbency driven by PHMSA/DOT)"
• Operator reluctance to deploy non-metallic pipe in regulated pipelines. Special Permit required for use in 49CFR §§192 & 195 regulated pipelines
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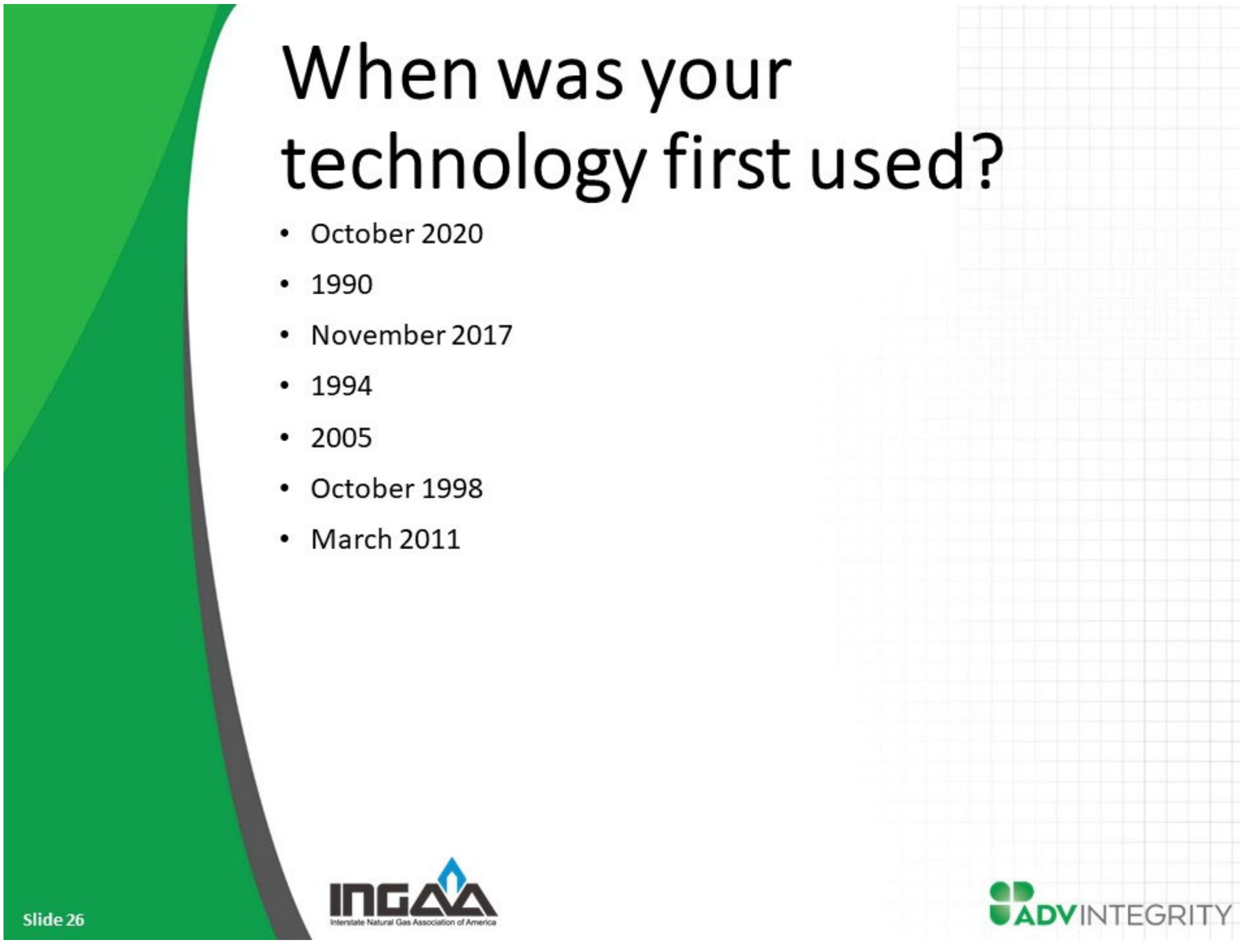
When was your technology first used?
• October 2020
• 1990
• November 2017
• 1994
• 2005
• October 1998
• March 2011
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Field experience (1 of 2)
TEAM have engineered and installed composite repairs to a wide variety of equipment and damage mechanisms. In addition to being a cost effective and compliant provider of standard composite repair solutions, TEAM also specialize in highly complex repairs requiring additional analysis such as repairs to cracking damage or where external loading is present.
"We are very involved in the installation of our products, although we are not an application company. We typically conduct a training session for any new contractors that we are working with and require a technical specialist onsite for their first few projects to ensure they are installing the system correctly. Some noteworthy projects include:1. 16,000 linear feet of externally repaired pipes in New York city2. Roughly 1,200 linear feet of vertical, compressed gas piping, crossing a major bridge in New York with several active leaks and severe corrosion.3. External reinforcement of refined products pipelines ranging from 30 - 46 inches in diameter including Jet fuel, Diesel and Gasoline."
1000s of successful projects over the past 20 years
Too extensive to list in detail. Gas and liquid pipelines. Pipework through-out plants and refineries. Cooling water systems in nuclear plants. Coke gas systems in steel works. Critical systems in nuclear reprocessing plants. Nuclear submarines. Storage tanks. Separator vessels. Deck plating. Ship decks. Passenger Trains. Vent lines and towers. Flare lines. Natural Gas Transmission and Distribution. Corrosion, dents, cracks, structural reinforcement. Midstream pipelines (gas and liquid). Well heads. FPSOs and other offshore applications.
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Field experience (1 of 2)
Provide technical assistance, turnkey services, training, and designs for installers of the products. Occidental, Shell, Exxon, Enterprise, Chevron, Valero are some of the major clients utilizing Belzona for projects on a daily basis. Numerous other smaller clients use us in GoM and downstream. Do not go after the pipeline industry at this time.
"Atlas is a carbon fiber and epoxy composite repair that has been combined with the BlackDiamond line, which was first used in the late 1990's. It has been used globally around the world with increasing adoption levels every year. Installation has been simplified and is very repeatable and reliable in the field due to using simple installation methods and providing belt and suspenders techniques such as adding in a liquid epoxy coating between the pipe and the carbon fiber wrap and compressing the wrap to the pipe with a compression film to help eliminate installation defects. Noteworthy projects include:-Reinforcement of 1500 vintage girth welds in Eastern Europe in 2017-Reinforcement of 50+ crack-like defects for a US gas operator in 2015 as the first crack reinforcement project-Reinforcement of 50+ vintage girth welds for a US gas operator to protect against failure during a landslide-Reinforcement of 300 meters of 42"" oil pipeline for an Asia pipeline operator in 2022-Reinforcement of 40 meters of a bulged 42"" pipeline for a Canadian gas pipeline operator in 2019-Reinforcement of over 100 wrinkle bends for a US gas operator from 2014-2022-Reinforcement of 20+ crack-like defects for a US gas operator in 2021-Many more"
Initial commercial projects carried out in regulated natural gas distribution in Texas and Illinois. Crude oil project in regulated commercial service and non-regulated water service in California.
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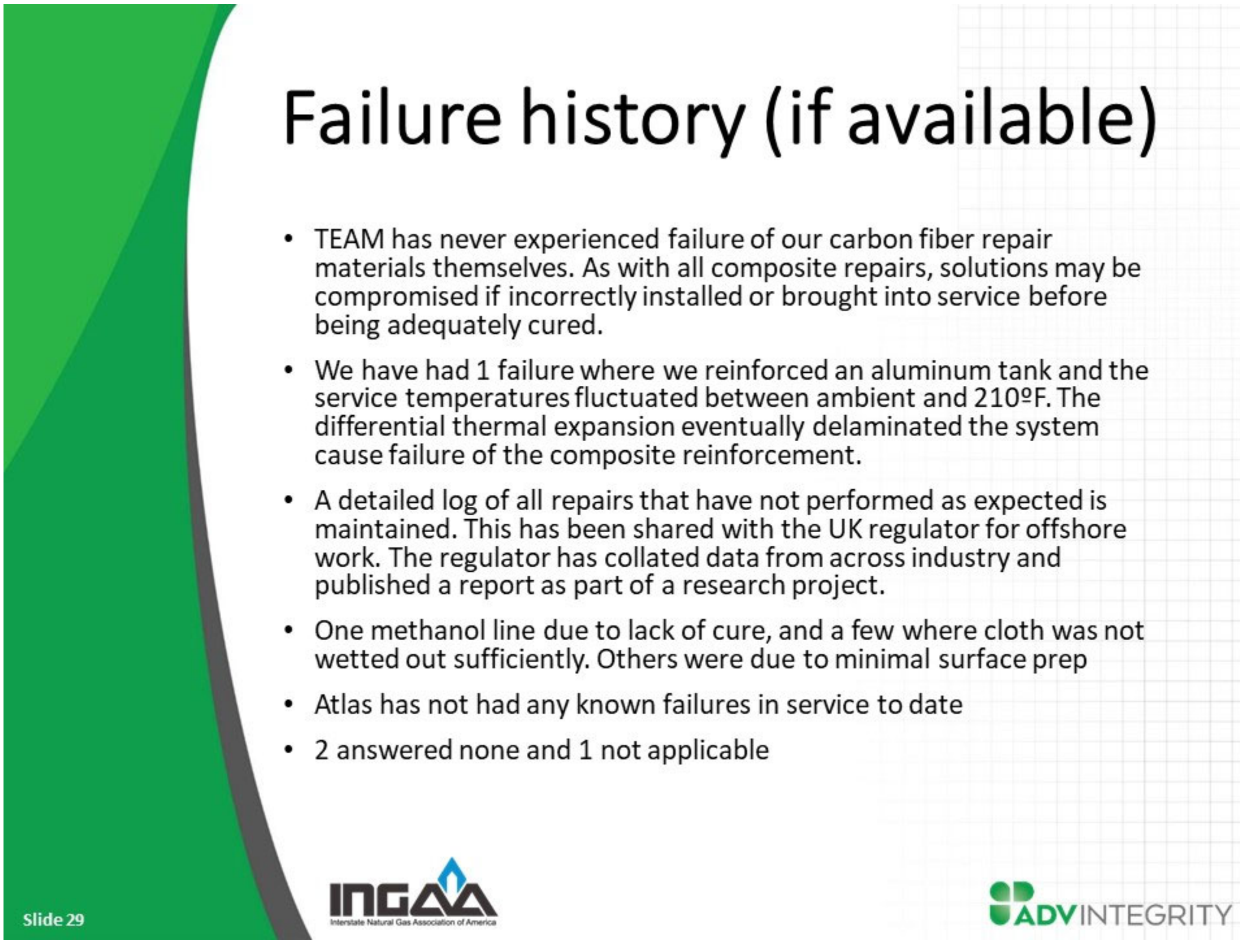
Failure history (if available)
• TEAM has never experienced failure of our carbon fiber repair materials themselves. As with all composite repairs, solutions may be compromised if incorrectly installed or brought into service before being adequately cured.
• We have had 1 failure where we reinforced an aluminum tank and the service temperatures fluctuated between ambient and 210ºF. The differential thermal expansion eventually delaminated the system cause failure of the composite reinforcement.
• A detailed log of all repairs that have not performed as expected is maintained. This has been shared with the UK regulator for offshore work. The regulator has collated data from across industry and published a report as part of a research project.
• One methanol line due to lack of cure, and a few where cloth was not wetted out sufficiently. Others were due to minimal surface prep
• Atlas has not had any known failures in service to date
• 2 answered none and 1 not applicable
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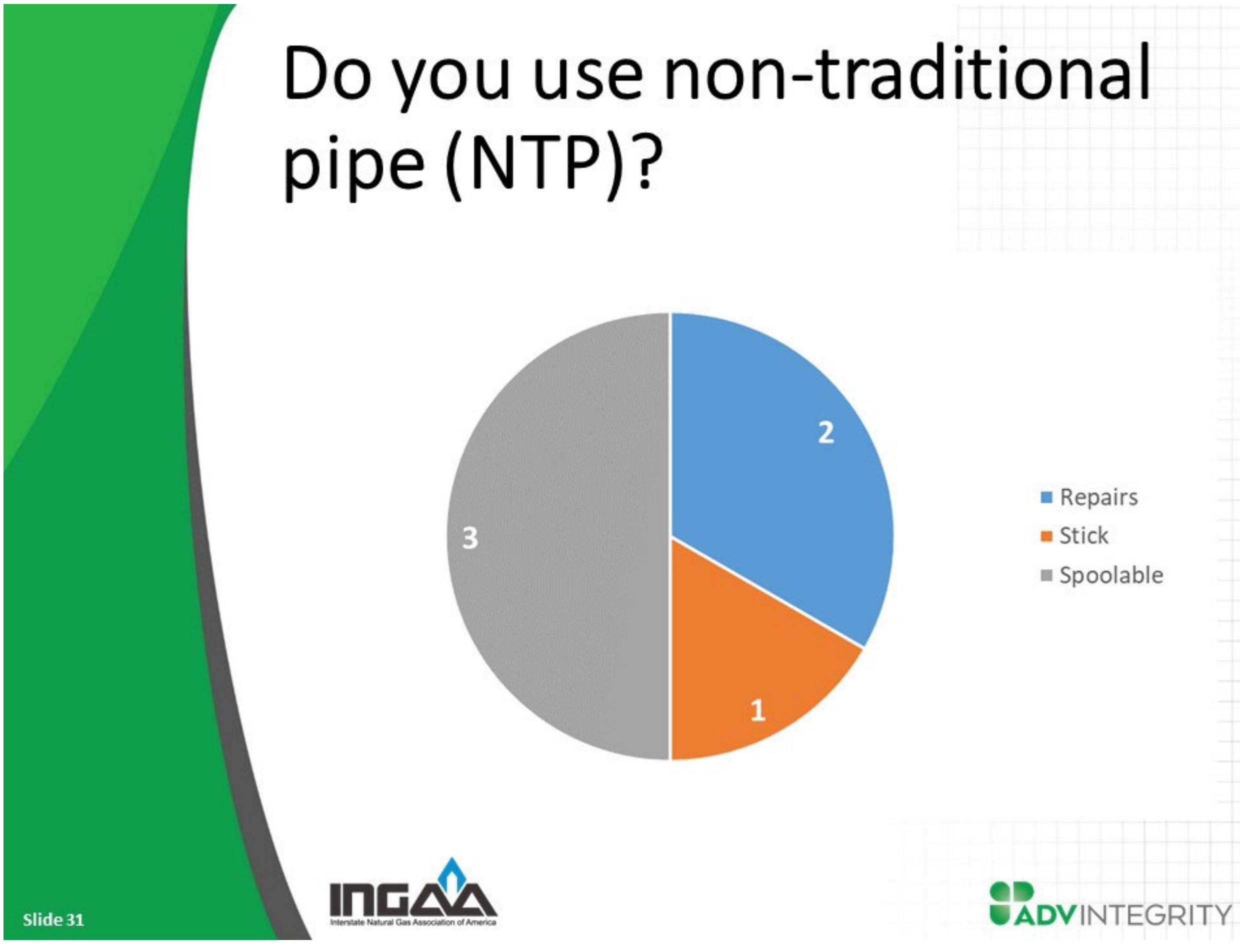
Answers from Operators
Slide 30


Do you use non-traditional pipe (NTP)?
2
1
3
Repairs
Stick
Spoolable
Slide 31
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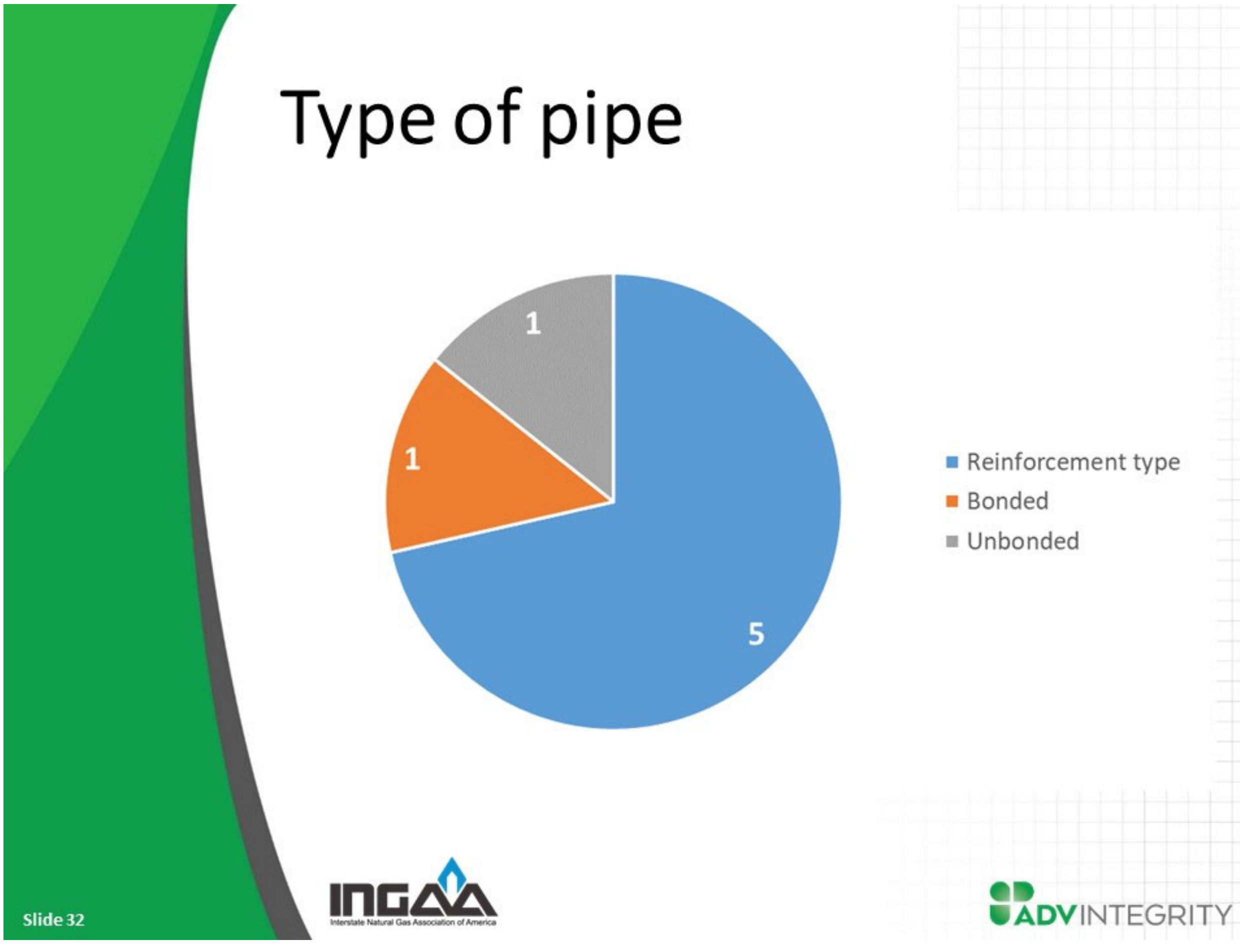
Type of pipe
1
1
5
Reinforcement type
Bonded
Unbonded
Slide 32
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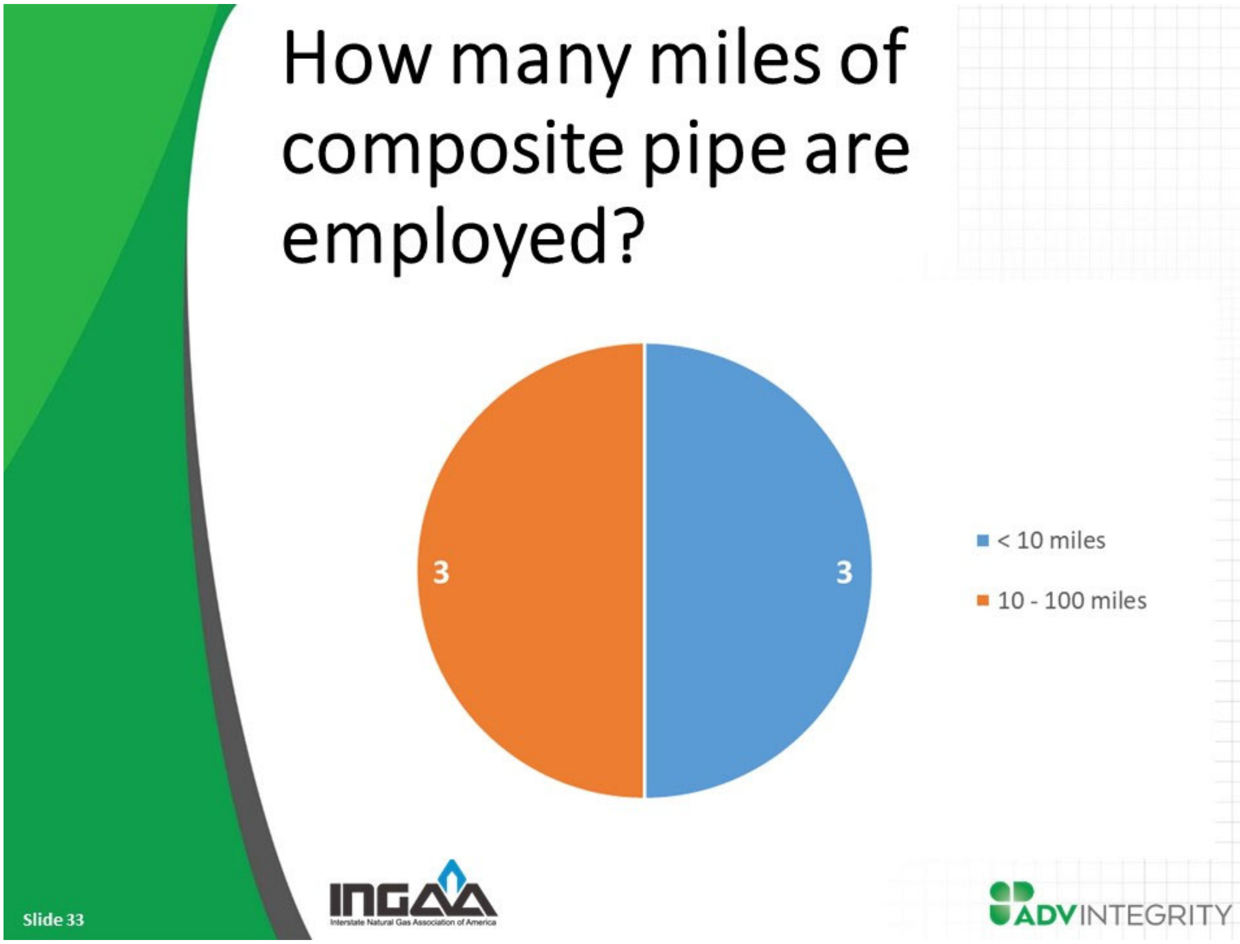
How many miles of composite pipe are employed?
3
3
< 10 miles
10 - 100 miles
Slide 33
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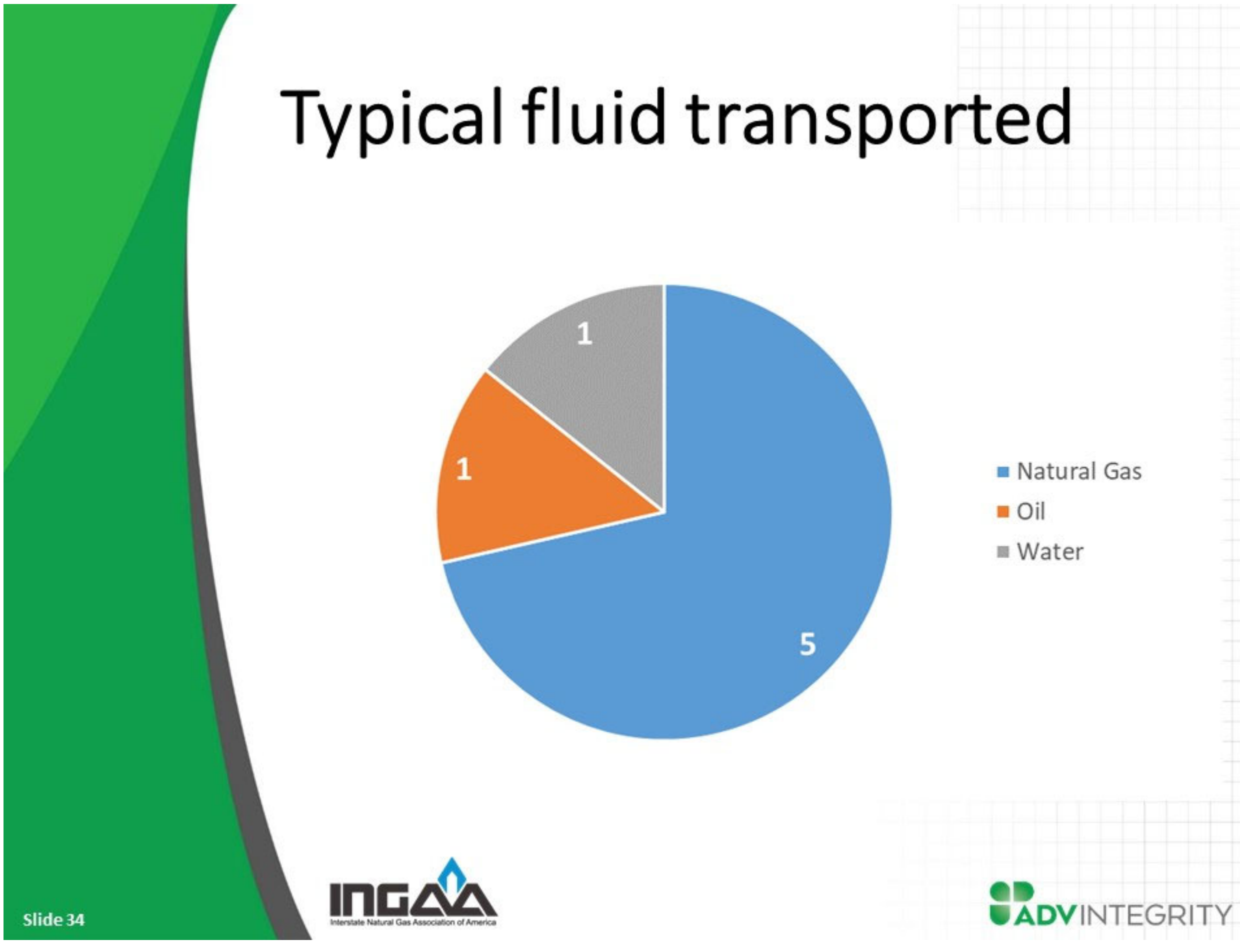
Typical fluid transported
1
1
5
Natural Gas
Oil
Water
Slide 34
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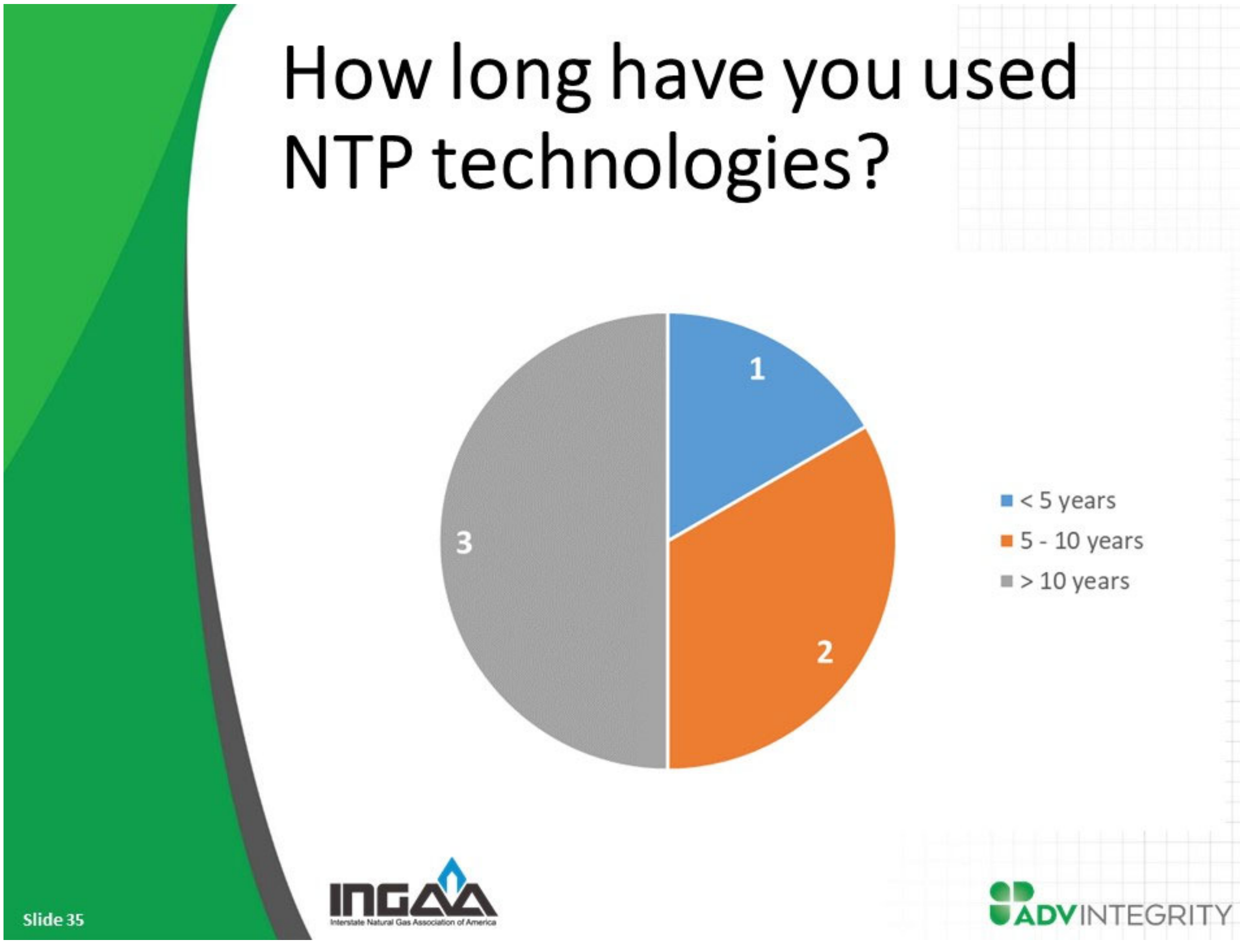
How long have you used NTP technologies?
1
2
3
< 5 years
5 - 10 years
> 10 years
Slide 35
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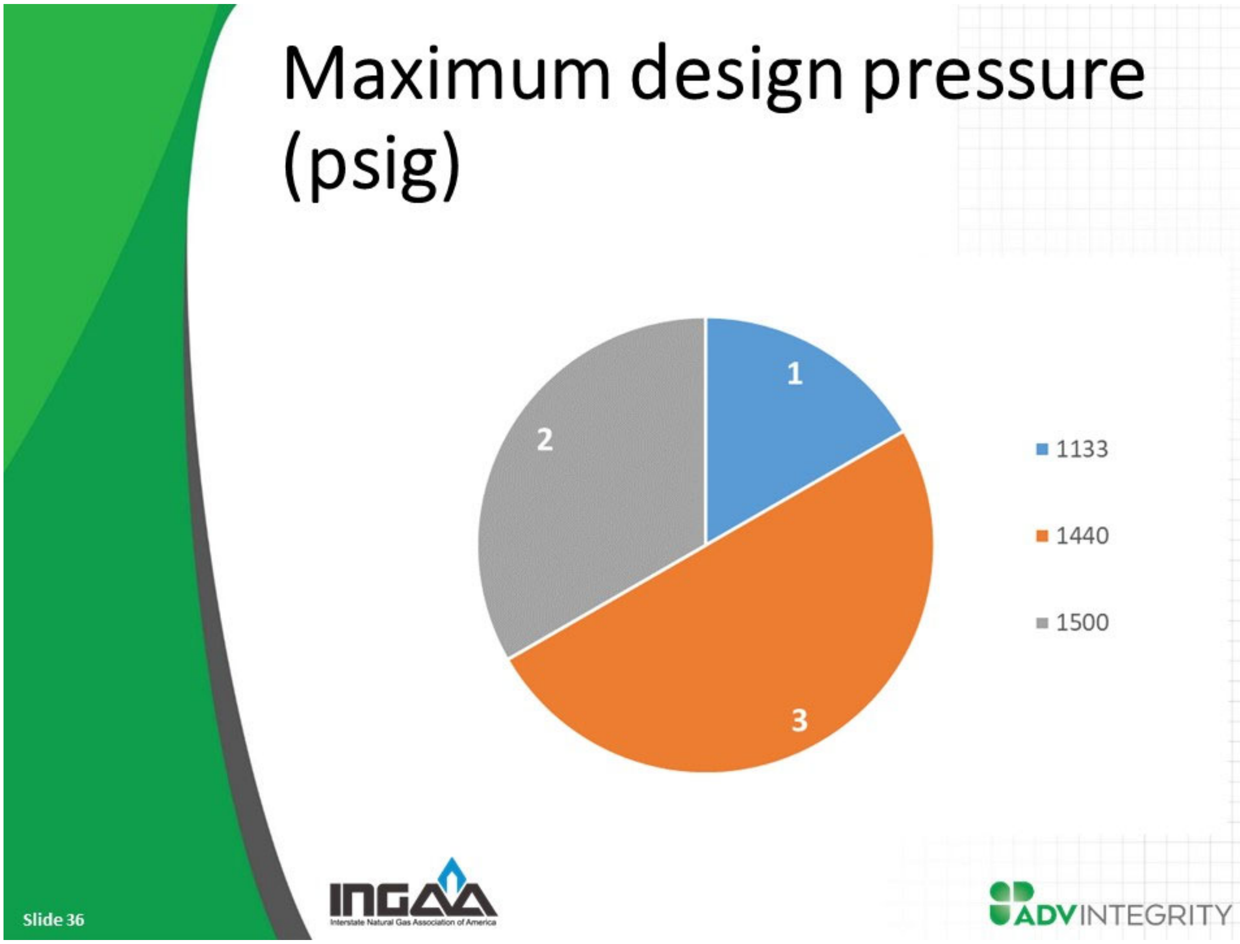
Maximum design pressure (psig)
1
2
3
1133
1440
1500
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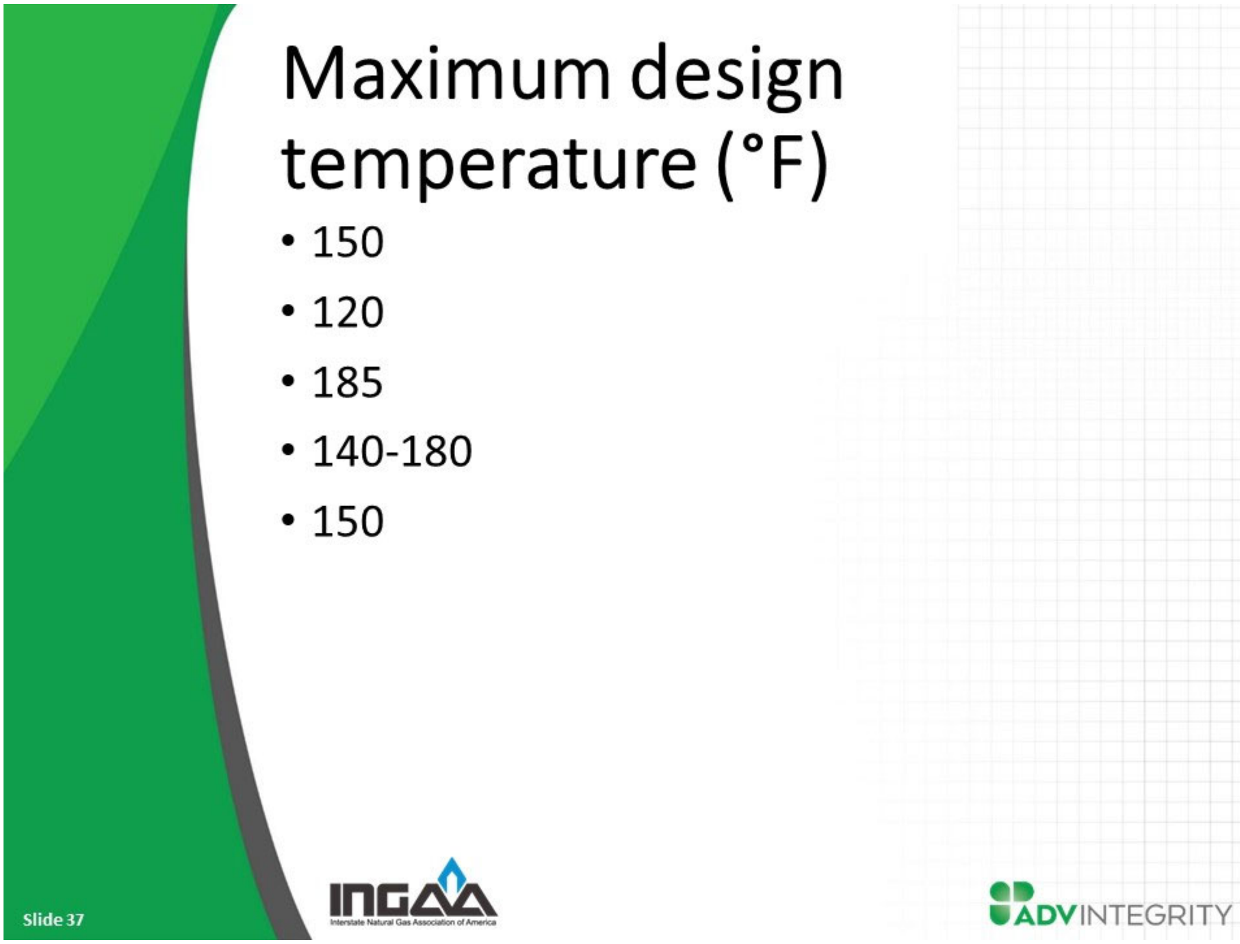
Maximum design temperature (°F)
• 150
• 120
• 185
• 140-180
• 150
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Identified reason for failure
• 1 answered Construction and Environmental (cold weather)
• 1 answered Lightning strike
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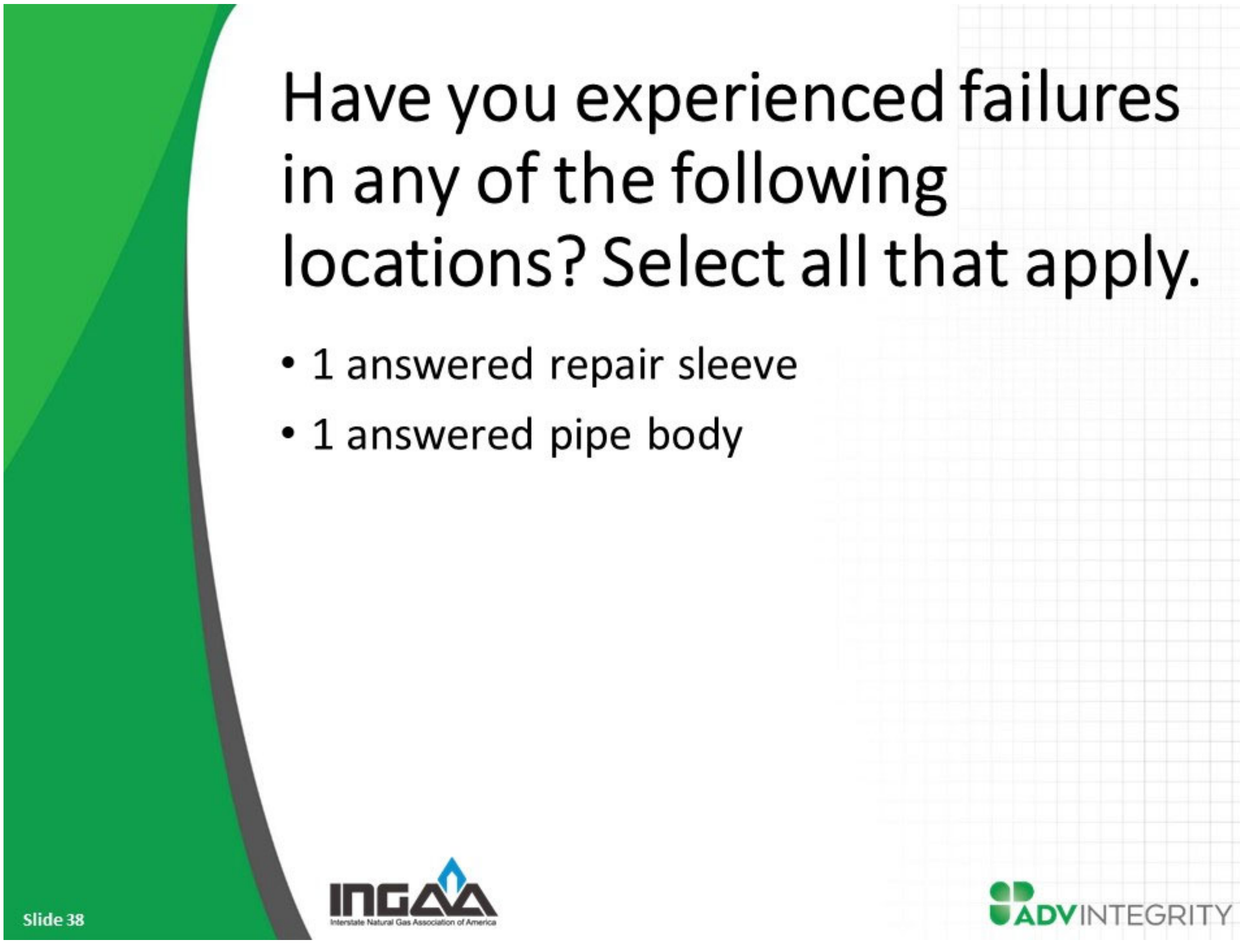
Have you experienced failures in any of the following locations? Select all that apply.
• 1 answered repair sleeve
• 1 answered pipe body
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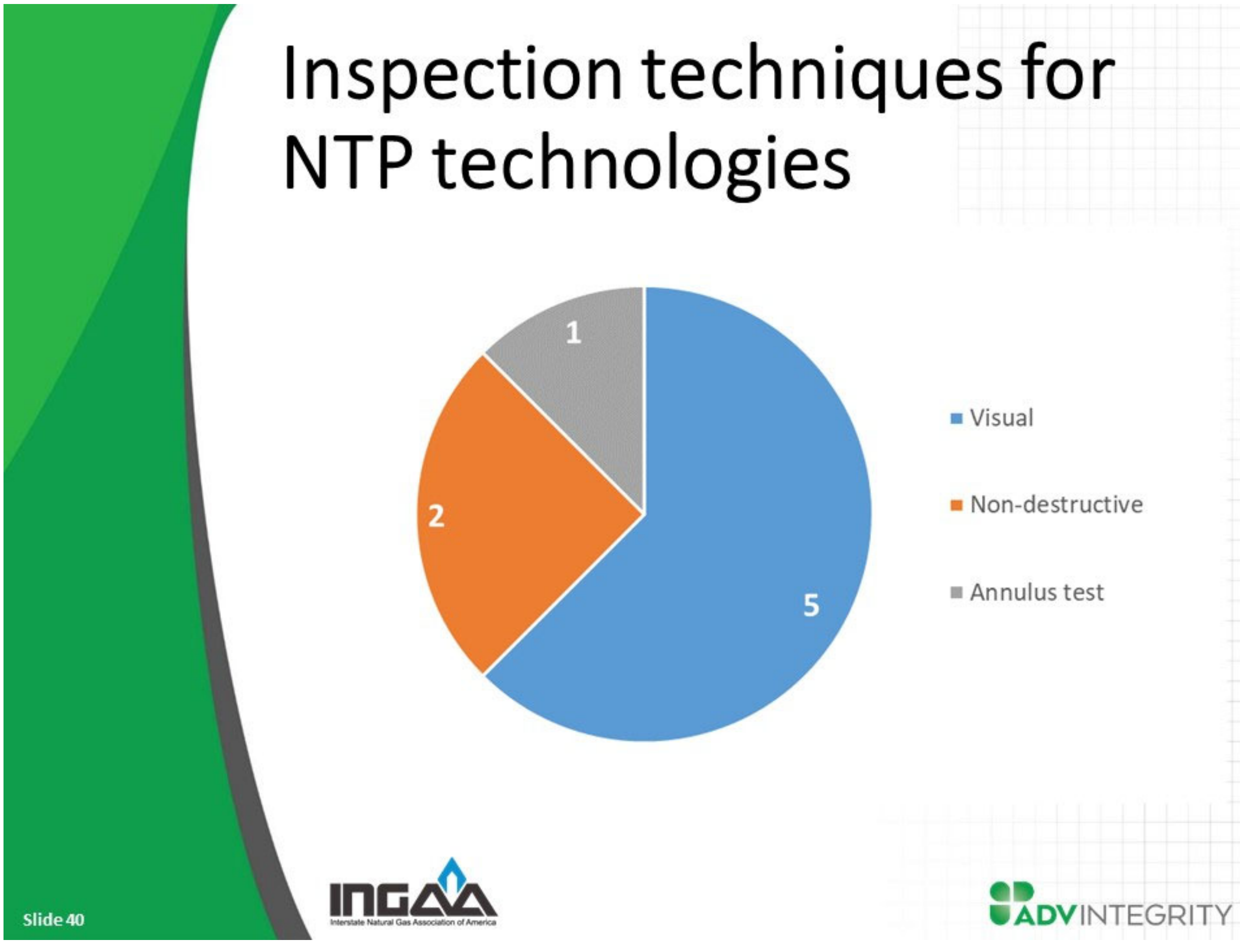
Inspection techniques for NTP technologies
1
2
5
Visual
Non-destructive
Annulus test
Slide 40
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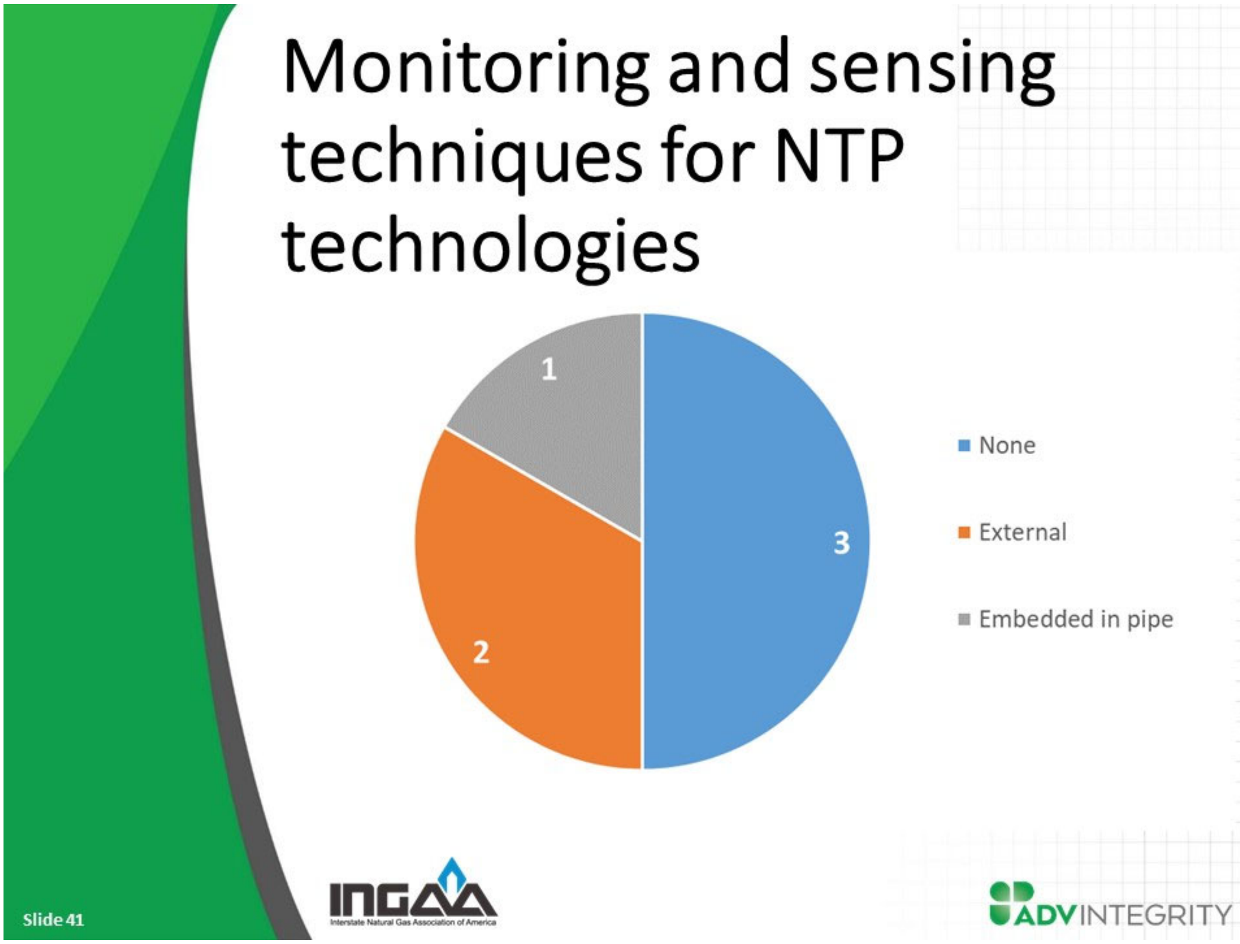
Monitoring and sensing techniques for NTP technologies
1
3
2
None
External
Embedded in pipe
Slide 41
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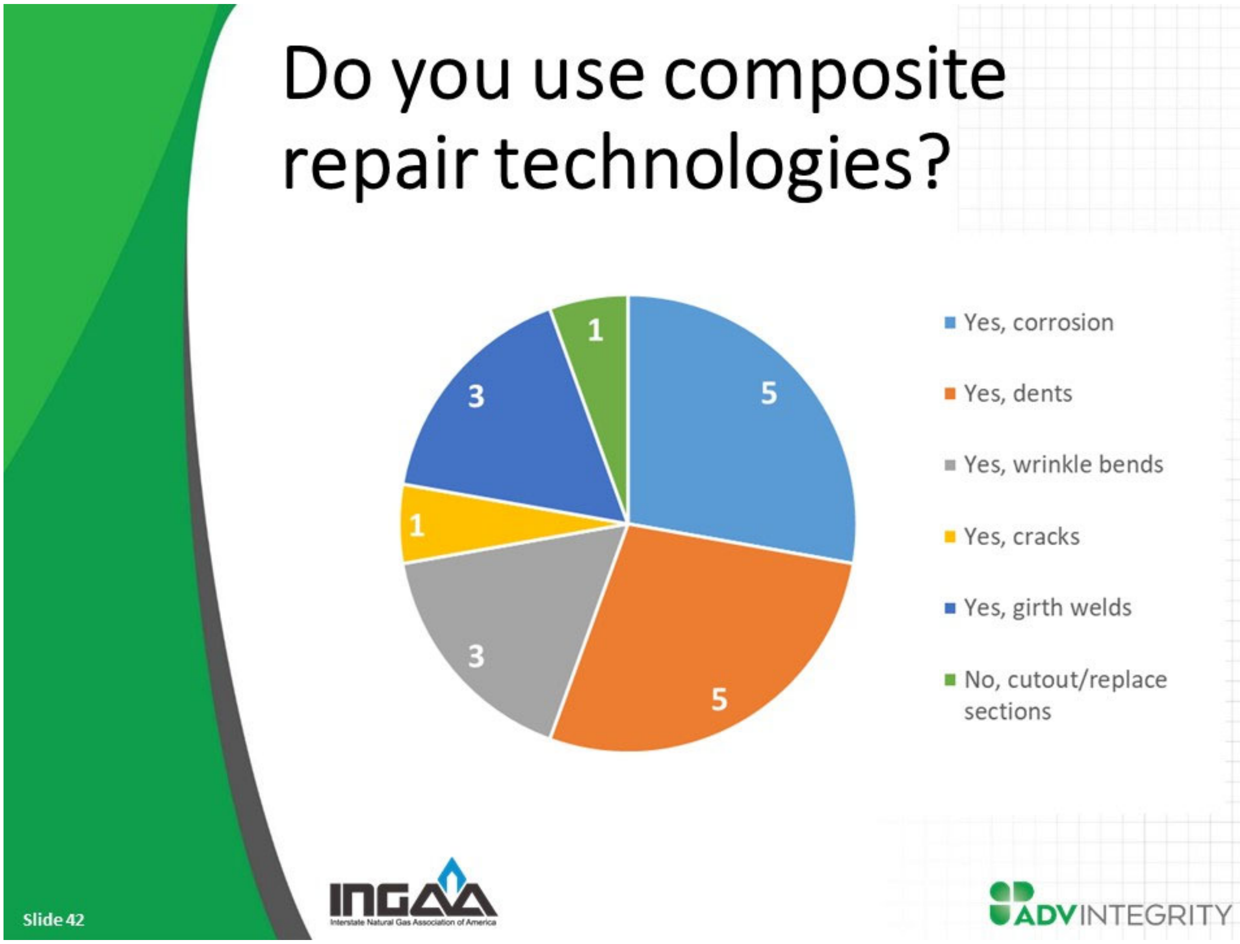
Do you use composite repair technologies?
5
5
3
1
3
1
Yes, corrosion
Yes, dents
Yes, wrinkle bends
Yes, cracks
Yes, girth welds
No, cutout/replace sections
Slide 42
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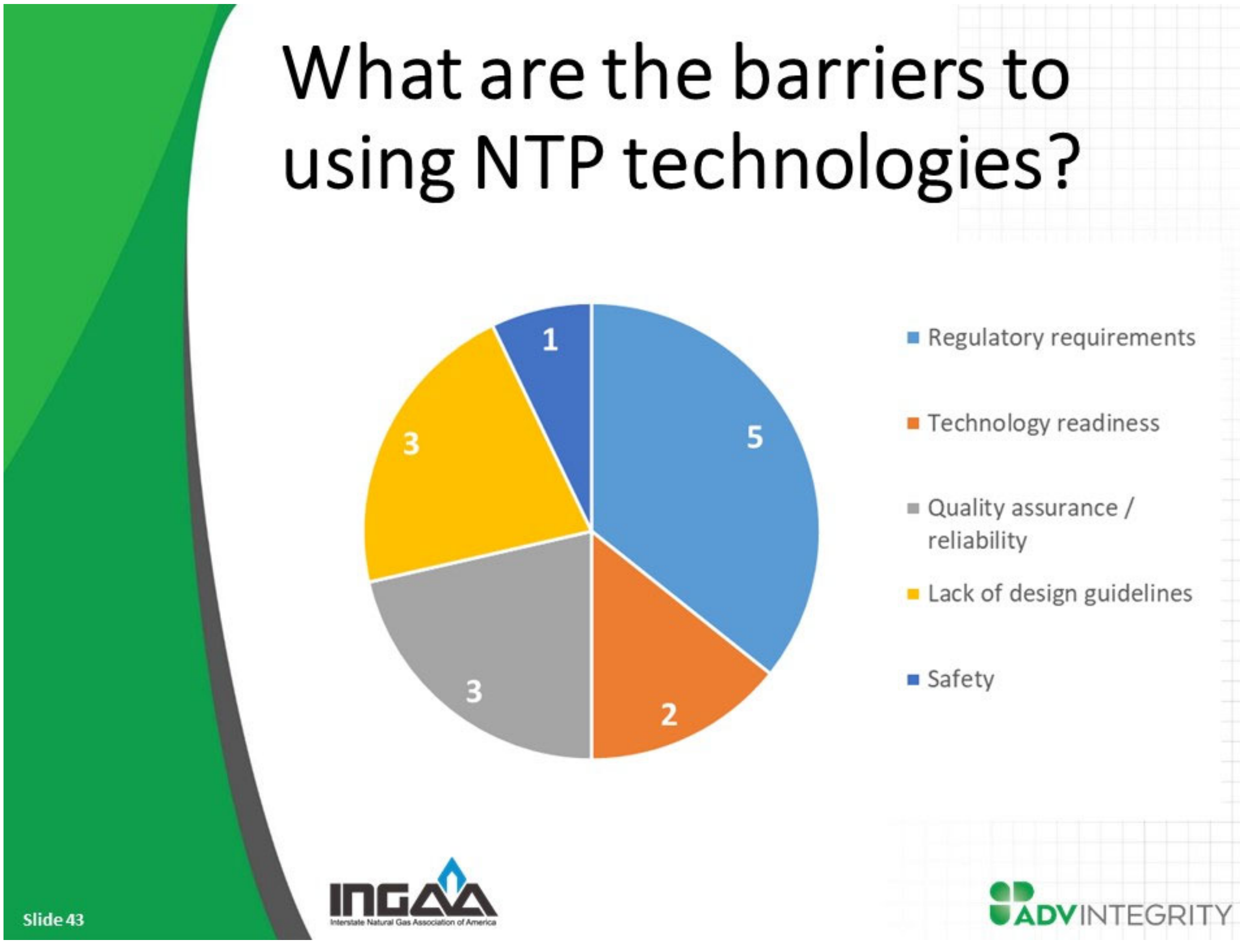
What are the barriers to using NTP technologies?
5
2
3
3
1
Regulatory requirements
Technology readiness
Quality assurance / reliability
Lack of design guidelines
Safety
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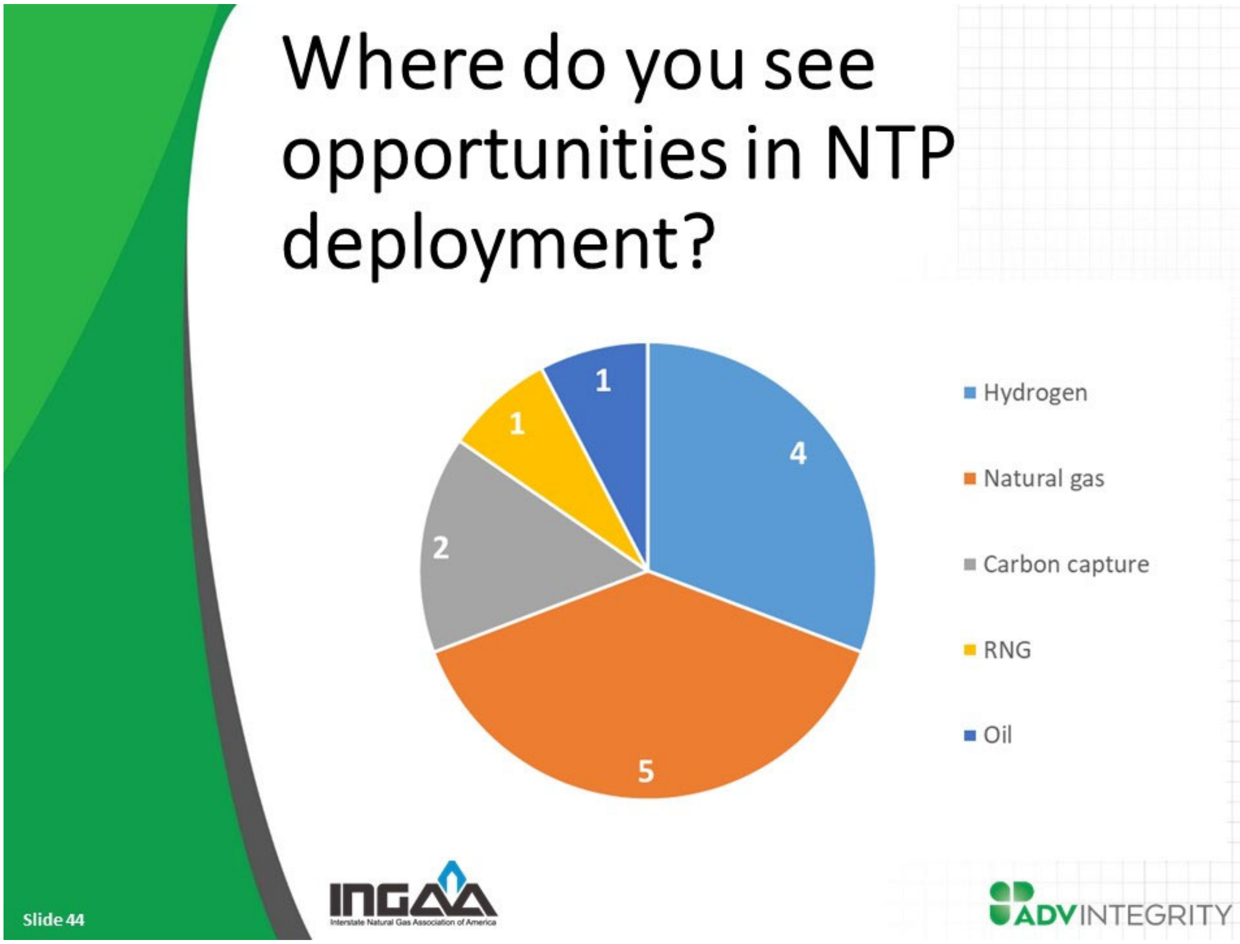
Slide 43


Where do you see opportunities in NTP deployment?
4
5
2
1
1
Hydrogen
Natural gas
Carbon capture
RNG
Oil
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High Level Survey Summary

- ❖ Composite repair
  - ❖ Composite repair technology is thus far a mature technology and is being employed by various operators.
  - ❖ Composite repair technology also has the regulatory nod.
- ❖ Inspection/Monitoring/Sensing
  - ❖ Limited I/M/S by operators
  - ❖ nontraditional pipe technology providers have only limited deployment of sensors embedded in their composite pipe products.
  - ❖ Sensing and monitoring are key to the successful and reliable acceptance and deployment of nontraditional pipes
- ❖ Regulatory acceptance is pointed out as a gap both by operators and technology providers.
- ❖ In addition to conventional Natural gas and water, operators see NTP opportunities in the emerging fields of energy transition-Hydrogen, Carbon capture, renewable natural gas etc.
- ❖ The survey also highlights some significant differences in operator and vendor perceptions on NTP – on barriers to acceptance.

Barriers – Operators view	Barriers- Technology Providers Views
• Regulatory barriers • Technology readiness • Quality assurance and reliability guidelines/practices • Lack of design guidelines	• Lack of resources at the operator level to test and approve products • "Not being the first to deploy" attitude • Perception and lack of awareness / limited confidence in NTP • Cultural and social barriers • Technology providers all felt that there are adequate design guidelines, and their product meets industry standards. • Technology readiness, QA, reliability was not perceived as barriers

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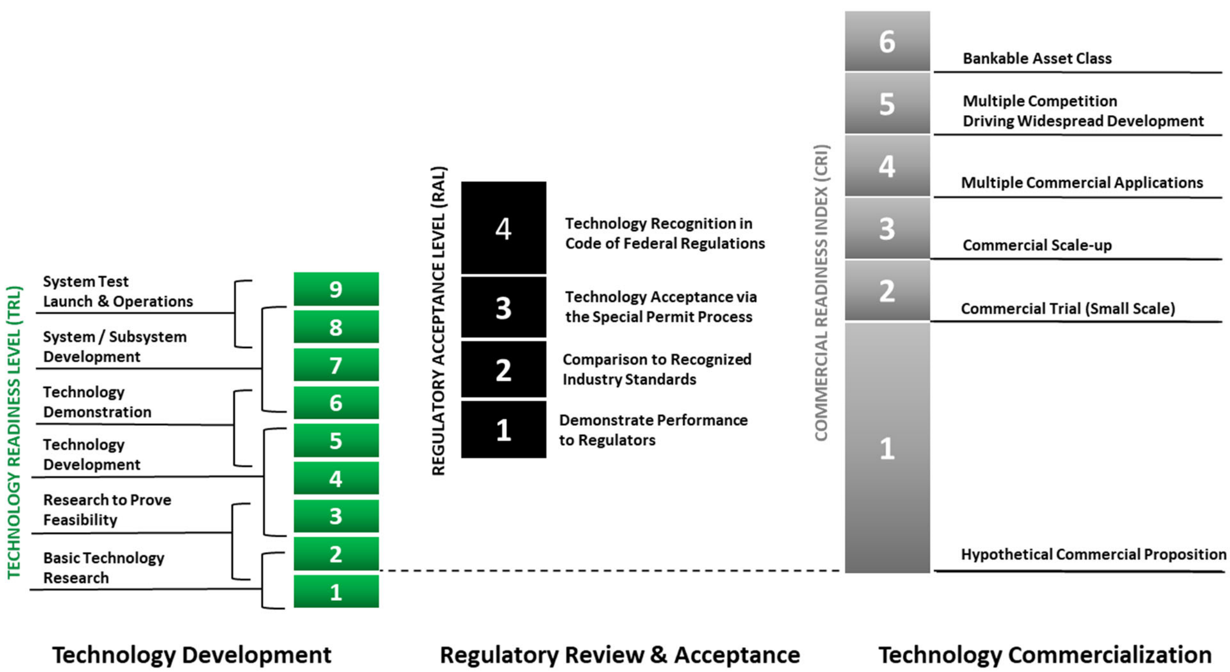
INGAA Interstate Natural Gas Association of America

ADVINTEGRITY

APPENDIX 3: TECHNICAL, REGULATORY, AND COMMERCIAL ASSESSMENT LEVELS

Throughout this report, the terms technology readiness level (TRL) and commercial readiness index (CRI) are used. Also included is a new concept introduced as the Regulatory Acceptance Level (RAL). As shown in this figure, there is an interdependency on the three assessment criteria and the diagram combines all three to demonstrates where commercial readiness starts with respect to the technology readiness level. For all the technologies discussed here, deployment depends heavily on a mature commercial readiness index.

Operators and technology companies must be cognizant of the need to keep regulators apprised of technology developments so that when ready to be deployed, regulators are in a position to support their deployment. The RALs provide a framework for when to engage regulators in the technology assessment process. In this scenario, regulators can become proponents of technology advancement and adoption to improve the inherent safety and integrity of today's high pressure pipeline system.



APPENDIX 4: SUMMARY OF RISK ASSESSMENTS

This appendix contains the detailed risk analysis and mitigation survey conducted for the various NTP segments. Individual risk analysis summaries are shown in the following appendix sections.

Table 4a: Composite Pipe - Failure Causes

Failure Causes	Design-mechanical, environment & geotech	Materials selection	QA/QC of pipe material	Construction guidelines	Installation guidelines	Construction QA	Post installation inspection& testing	Testing and acceptance criteria	Pipe qualification (Validation & Verification)	System testing	Operations
Material Defect	■	■	■								
Thermal stress-axial loading	■										
Ground movement	■						■	■	■	■	
Cyclic stress	■	■					■	■	■	■	
Resonance	■	■					■	■	■	■	
Overpressure	■	■						■	■	■	■
Liquid hammer	■	■						■	■	■	■
High velocity Erosion	■	■						■	■	■	■
Operational											■
Human factors Outside Force Damage (OFD)									■	■	■
Chemical incompatibility	■	■						■	■	■	
Improper installation	■			■	■	■	■				
Improper construction	■			■	■	■	■				

Table 4b: Composite Pipe-Connector Failure Causes

Failure Causes	Design-mechanical, environment & geotech	Materials selection	QA/QC of connector	Construction guidelines	Installation guidelines	Construction QA	Post installation inspection& testing	Testing and acceptance criteria of connected joint	Connector qualification (Validation & Verification)	System testing
Improper connection to pipe	■		■	■	■	■	■	■	■	■
Pipe & Connector-Thermal and mech property incompatibility	■	■						■	■	■
Stiffness difference	■	■								
Improper support	■									
Field connections made during inclement weather				■	■	■	■			
Connections not made per manufacturer spec			■							
Proper acceptance criteria not set	■	■					■	■	■	■
Corrosion	■	■								

Table 4c: Composites - Failure Modes

Failure mode	Design	Testing	Materials selection	Process control (manufacturing, QA)	Operational control
Ply failure	■	■			
Matrix cracking	■	■	■		
Delamination	■	■			
Permeability		■	■		■
Polymer fracture	■		■		
Plastic deformation	■		■		
Maximum deformation	■	■			■
Debonding			■	■	
Crazing			■		
Impact	■	■			■
Mechanical damage	■				■
Wear & Tear	■		■		■
Chemical degradation		■	■		■
Swelling		■			■
Leaching		■			■
RGD		■			■
UV		■			
Thermal softening/morphology	■	■	■		
Cyclic load/Life	■	■	■		■
Stress rupture	■	■	■		■

Table 4d: Risk Analysis – Composite Pipe and Connector

TCP-Cause	Before De-Risking					After De-Risking				
	Probability	Consequence	Risk score	Lack of Inspectability	RPN	Probability	Consequence	Risk score	Lack of Inspectability	RPN
Composite Pipe										
Material Defect	4	4	16	5	80	2	4	8	2	16
Thermal stress-axial loading	4	4	16	5	80	2	4	8	2	16
Ground movement	4	4	16	5	80	3	4	12	2	24
Cyclic stress	4	4	16	5	80	3	4	12	2	24
Resonance	3	3	9	5	45	3	3	9	2	18
Overpressure	4	4	16	5	80	2	4	8	2	16
Liquid hammer	4	4	16	5	80	3	4	12	3	36
High velocity Erosion	4	4	16	5	80	3	4	12	2	24
Operational	4	4	16	4	64	4	4	16	2	32
Human factors OFD	4	4	16	5	80	4	4	16	2	32
Chemical incompatibility	4	4	16	5	80	2	4	8	3	24
Improper installation	4	4	16	5	80	2	4	8	3	24
Improper construction	4	4	16	5	80	2	4	8	3	24
Composite Pipe Connector										
Improper connection to pipe	3	4	12	5	60	2	4	8	4	32
Pipe & Connector-Thermal and mech property incompatibility	3	4	12	5	60	2	4	8	4	32
Stiffness difference	3	4	12	5	60	2	4	8	4	32
Improper support	4	4	16	5	80	3	4	12	4	48
Field connections made during inclement weather	4	4	16	5	80	3	4	12	4	48
Connections not made per manufacturer spec	4	4	16	5	80	3	4	12	4	48
Proper acceptance criteria not set	4	4	16	5	80	3	4	12	4	48
Corrosion	3	4	12	5	60	2	4	8	4	32

NOTES & OBSERVATIONS:

1. Note the reduction in the RPNs after de-risking has taken place.
2. The “Lack of Inspectability” has the greatest contribution to reducing the risk associated with composite technology implementation.

Table 4e: Risk Analysis – Steel Pipe

Note that this table has been provided as a frame of reference relative to what would be expected for composite pipe technologies.

STEEL-Cause	Before De-Risking					After De-Risking				
	Probability	Consequence	Risk score	Lack of Inspectability	RPN	Probability	Consequence	Risk score	Lack of Inspectability	RPN
Corrosion	4	4	16	5	80	1	4	4	1	4
Environmental cracking	4	4	16	5	80	2	4	8	2	16
Hydrogen embrittlement	4	4	16	5	80	2	4	8	2	16
Corrosion and corrosion fatigue	4	4	16	5	80	2	4	8	2	16
Low temperature brittleness	3	4	12	5	60	2	4	8	4	32
Running ductile fracture	4	4	16	5	80	3	4	12	4	48
Weld failure due to quality, stress state and environment	4	4	16	5	80	3	4	12	2	24
Failure of fittings	4	4	16	5	80	3	4	12	3	36
Overload	4	4	16	5	80	2	4	8	3	24

Table 4f: Risk Analysis & Mitigation Composite Pipe and Connector

Composite Pipe Failure Cause	Before De-Risking					After De-Risking					Design-mechanical, environment & geotech	Materials selection & QA	QA/QC of pipe/ Connector material	Construction guidelines	Installation guidelines	Construction QA	Post installation inspection& testing	Testing and acceptance criteria	Pipe / Connector qualification (Validation & Verification)	System testing	Operations	Fluid Process control	Fluid spec control	Surveillance	Embedded sensors	Sensor QA+system QA
	Probability	Consequence	Risk score	Lack of Inspectability	RPN	Probability	Consequence	Risk score	Lack of Inspectability	RPN																
Composite Pipe																										
Material Defect	4	4	16	5	80	2	4	8	2	16	■	■	■	■	■	■	■	■	■	■			■			
Thermal stress-axial loading	4	4	16	5	80	2	4	8	2	16	■	■	■	■	■	■								■	■	■
Ground movement	4	4	16	5	80	3	4	12	2	24	■		■	■	■	■								■	■	■
Cyclic stress	4	4	16	5	80	3	4	12	2	24	■	■	■					■	■	■		■		■	■	■
Resonance	3	3	9	5	45	3	3	9	2	18	■		■					■	■	■		■		■	■	■
Overpressure	4	4	16	5	80	2	4	8	2	16	■	■	■					■	■	■		■		■	■	■
Liquid hammer	4	4	16	5	80	3	4	12	3	36	■	■	■					■	■	■		■		■	■	■
High velocity Erosion	4	4	16	5	80	3	4	12	2	24	■	■	■					■	■	■		■		■	■	■
Operational	4	4	16	4	64	4	4	16	2	32			■									■		■	■	■
Human factors OFD	4	4	16	5	80	4	4	16	2	32		■	■											■	■	■
Chemical incompatibility	4	4	16	5	80	2	4	8	3	24	■	■	■								■	■	■	■	■	■
Improper installation	4	4	16	5	80	2	4	8	3	24			■		■		■							■	■	■
Improper construction	4	4	16	5	80	2	4	8	3	24			■	■	■	■	■	■	■	■						
Composite Pipe Connector																										
Improper connection to pipe	3	4	12	5	60	2	4	8	4	32	■			■	■	■	■	■								
Pipe & Connector-Thermal and mech property incompatibility	3	4	12	5	60	2	4	8	4	32	■	■								■						
Stiffness difference	3	4	12	5	60	2	4	8	4	32	■	■								■						
Improper support	4	4	16	5	80	3	4	12	4	48	■			■	■	■	■									
Field connections made during inclement weather	4	4	16	5	80	3	4	12	4	48				■	■	■	■	■								
Connections not made per manufacturer spec	4	4	16	5	80	3	4	12	4	48	■		■	■	■	■	■	■								
Proper acceptance criteria not set	4	4	16	5	80	3	4	12	4	48			■	■	■	■	■	■	■	■						
Corrosion	3	4	12	5	60	2	4	8	4	32																

Table 4g: Risk Analysis & Mitigation Steel Pipe

Steel Pipe Failure Cause	Before De-Risking					After De-Risking					Corrosion control-fluid specs	Design including geotech + guidelines	Material selection	ECA, FFP design	Inhibition, scavenging	Process control	Crack arrestor	Reinforcement design	Construction QA	Surveillance & Monitoring	Repurposing protocols	System testing
	Probability	Consequence	Risk score	Lack of Inspectability	RPN	Probability	Consequence	Risk score	Lack of Inspectability	RPN												
Corrosion	4	4	16	5	80	1	4	4	1	4												
Environmental cracking	4	4	16	5	80	2	4	8	2	16												
Hydrogen embrittlement	4	4	16	5	80	2	4	8	2	16												
Corrosion and corrosion fatigue	4	4	16	5	80	2	4	8	2	16												
Low temperature brittleness	3	4	12	5	60	2	4	8	4	32												
Running ductile fracture	4	4	16	5	80	3	4	12	4	48												
Weld failure due to quality, stress state and environment	4	4	16	5	80	3	4	12	2	24												
Failure of fittings	4	4	16	5	80	3	4	12	3	36												
Overload	4	4	16	5	80	2	4	8	3	24												

Table 4h: Gaps Analysis-Composite pipe and connectors

Composite Pipe & Connectors	Published materials (Open literature)	Industry Standards	Design Guidelines (Industry, Vendor, Business)	Research Underway (Private)	Research (JIP)	Field/Practical experience & Failure data	Regulations	Risk management guidelines	Test data-component & system
Design & Loading									
Biaxial loading	Green	Yellow	Yellow		Yellow	Yellow	Red	Red	
Triaxial loading	Green	Yellow	Yellow		Yellow	Yellow	Red	Red	
Tortional loading	Green	Yellow	Yellow		Yellow	Yellow	Red	Red	
Cyclic stress	Green	Yellow	Yellow		Yellow	Yellow	Red	Red	
External load	Green	Yellow	Yellow		Yellow	Yellow	Red	Red	Yellow
Impact load	Green	Yellow	Yellow		Yellow	Yellow	Red	Red	Yellow
Collapse load	Green	Yellow	Yellow		Red	Yellow	Red	Red	Yellow
Thermal load	Green	Yellow	Yellow		Red	Yellow	Red	Red	Yellow
Pressure surge	Green	Yellow	Yellow		Red	Yellow	Red	Red	Yellow
Life prediction	Green	Yellow	Red		Red	Yellow	Red	Red	Red
Connector/End fitting	Red	Red	Yellow		Yellow	Yellow	Red	Red	Red
Annulus pressure management	Green	Yellow	Yellow		Yellow	Yellow	Red	Red	Red
Environmental resistance									
Component compatability to fluid (OG)	Green	Red	Red			Yellow	Red	Red	Yellow
Component compatability to fluid (Dense phase CO2, Hydrogen)	Yellow	Red	Red			Red	Red	Red	Yellow
System compatability (OG)	Yellow	Red	Red			Yellow	Red	Red	Yellow
System compatabiilty (CO2, Hydrogen)	Yellow	Red	Red			Red	Red	Red	Red
Life cycle-Environment + Stress (OG)	Yellow	Red	Red			Red	Red	Red	Red
Lifecycle - Environment + Stress (Dense phase CO2, Hydrogen)	Red	Red	Red			Red	Red	Red	Red
Sensing & Monitoring									
Monitoring & Sensing technology	Yellow	Red	Red			Yellow	Red	Red	Yellow
Embeded monitoring system	Red	Red	Red			Red	Red	Red	Red
External monitoring system	Red	Red	Red			Red	Red	Red	Red
Construction, QA, Inspection									
Manufacturing procedure	Yellow	Yellow	Yellow			Yellow	Red	Red	
Manufacturing QA	Red	Yellow	Yellow			Yellow	Red	Red	
Inspec tion tools and techniques	Yellow	Red	Yellow			Yellow	Red	Red	
QA & testing for the pipe system (with sensors)	Red	Red	Red			Red	Red	Red	
Construction/Installation damage mitigation	Red	Red	Red			Yellow	Red	Red	
Construction/Installation QA	Red	Red	Red			Yellow	Red	Red	
Post installation									
Repair practices	Green	Yellow	Yellow			Green	Red	Red	Yellow
Retrofitting/tapping pra ctice	Yellow	Yellow	Yellow			Yellow	Red	Red	
Pre-commissioning tests	Red	Yellow	Yellow			Yellow	Red	Red	Red
Assessment									
Full scale testing	Red	Red	Yellow			Yellow	Red	Red	Red
Sub-scale testing	Yellow	Red	Yellow			Yellow	Red	Red	Yellow
Fitness for service	Red	Red	Red			Yellow	Red	Red	Red
Residual life estimation	Red	Red	Red			Yellow	Red	Red	Red

Color-coding:

Green	Extensive work completed; confidence in performance
Yellow	Some work already done; Additional work required
Red	Very little work done, Significant work required
	Non-colored cells indicate insufficient data available to make an assessment

Table 4i: Gaps Analysis-Crack Arrestor and Repair Sleeves

Crack Arrestors	Published materials (Open literature)	Industry Standards	Design Guidelines (Industry, Vendor, Business)	Research Underway (Private)	Research (JIP)	Field/Practical experience & Failure data	Regulations	Risk management guidelines	Published materials (Open literature)	Industry Standards	Design Guidelines (Industry, Vendor, Business)	Research Underway (Private)	Research (JIP)	Field/Practical experience & Failure data	Regulations	Risk management guidelines	Test data-component & system	Lifecycle cost data
Crack Arrestor - Design & Loading																		
Stress analysis																		
Spacing and thickness desisgn																		
Crack arrestor materials selection																		
Fracture propagation resistance																		
Life prediction																		
Construction, QA, Inspection																		
Manufacturing procedure			?															
Manufacturing QA			?															
Inspection tools and techniques			?															
Construction/Installation damage mitigation			?															
Construction/Installation QA			?															
Post installation																		
Pre-commissioning tests																		
Assessment																		
Full scale testing																		
Fitness for service																		
Residual life estimation																		
Periodic inspection, tools, frequency, acceptance criteria																		

Color-coding:

Green	Extensive work completed; confidence in performance
Yellow	Some work already done; Additional work required
Red	Very little work done, Significant work required
White	Non-colored cells indicate insufficient data available to make an assessment

Composite Repairs	Published materials (Open literature)	Industry Standards	Design Guidelines (Industry, Vendor, Business)	Research Underway (Private)	Research (JIP)	Field/Practical experience & Failure data	Prescriptive Regulations	Risk management guidelines
Design & Loading								
Stress analysis	Yellow	Red	Yellow	Green	Green	Yellow	Red	Red
Length and thickness design	Yellow	Red	Yellow	Green	Green	Yellow	Red	Red
Repair materials selection	Yellow	Red	Yellow	Green	Green	Yellow	Red	Red
Hoop stress repair	Yellow	Red	Yellow	Green	Green	Yellow	Red	Red
Girth weld repair (bending/geotech loads)	Yellow	Red	Yellow	Green	Green	Yellow	Red	Red
Combined loads	Red	Red	Yellow	Green	Green	Yellow	Red	Red
Fracture propagation resistance	Red	Red	Yellow	Yellow	Yellow	Yellow	Red	Red
Life prediction	Yellow	Red	Red	Yellow	Yellow	Yellow	Red	Red
Construction, QA, Inspection								
Manufacturing procedure	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Red	Red
Manufacturing QA	Red	Yellow	Yellow	Yellow	Yellow	Yellow	Red	Red
Inspection tools and techniques	Yellow	Red	Yellow	Yellow	Yellow	Yellow	Red	Red
Construction/Installation damage mitigation	Red	Red	Yellow	Yellow	Yellow	Yellow	Red	Red
Construction/Installation QA	Red	Red	Yellow	Yellow	Yellow	Yellow	Red	Red
Post installation								
Pre-commissioning tests	Red	Red	Yellow	Yellow	Yellow	Yellow	Red	Red
Assessment								
Full scale testing	Yellow	Red	Yellow	Green	Green	Yellow	Red	Red
Fitness for service	Red	Red	Red	Yellow	Yellow	Yellow	Red	Red
Residual life estimation	Red	Red	Red	Yellow	Yellow	Yellow	Red	Red
Periodic inspection, tools, frequency, acceptance criteria	Red	Red	Red	Yellow	Yellow	Yellow	Red	Red

Color-coding:

Green	Extensive work completed; confidence in performance
Yellow	Some work already done; Additional work required
Red	Very little work done, Significant work required
	Non-colored cells indicate insufficient data available to make an assessment

Table 4j: Gaps analysis-Consolidated List

Component/System	Risk	Ability to Implement Gaps in Knowledge, Experience	Design, Guidelines	Published info	Standards and Regulations	Environmental resistance	Mature monitoring and sensing	Construction & Installation practices, guidelines QA	Validation, Verification, Testing protocols, info-Component & System	Lifecycle estimation	Research (Internal)	Research JIP
Composite Pipe	Human factors, OFD											
Composite Pipe	Operational / process control											
Composite Pipe	Transient loads (Fluid hammer, surge, cyclic loads..)											
Composite Pipe	Construction & Installation related failures											
Composite Pipe	Fluid incompatibility											
Composite Pipe	Geotechnical load uncertainty											
Composite Pipe	Reinforcement failure											
Composite Pipe	Sensor availability/failure											
Connectors	Construction & Installation related failures											
Crack Arrestor	Design, QA, Mfg.											
	Installation											
	Assessment											
Repair	Design, QA, Mfg.											
	Installation											
	Assessment											
Steel	Running fracture											
Steel	Low temperature brittle fracture											
Steel	Overload failure-girth welds											

Color-coding:

	Extensive work completed; confidence in performance
	Some work already done; Additional work required
	Very little work done, Significant work required
	Non-colored cells indicate insufficient data available to make an assessment

APPENDIX 5: RISK MATRIX AND RISK PRIORITIZATION

-

Contained in this appendix is background information on the elements associated with conducting a risk analysis. Provided in the tables below are the ratings associated with likelihood and consequence. The numerical values presented below were used in the risk tables included in Appendix 4.

Likelihood Rating	Definition
Very Low	Mean Time Before Failure (MTBF) > 30 years Failure not foreseeable under normal operating conditions within the remaining life of the asset
Low	Mean Time Before Failure (MTBF) > 10 years but < 30 years Failure possible within life of asset, based on knowledge of construction materials and service conditions
Medium	Mean Time Before Failure (MTBF) > 5 years but < 10 years Failure probable within life of asset, based on knowledge of construction materials and service conditions
High	Mean Time Before Failure (MTBF) < 5 years High probability of failure within life of asset, based on knowledge of construction materials and service conditions
Very High	Mean Time Before Failure (MTBF) < 2 years Very high probability of failure within life of asset, based on knowledge of construction materials and service conditions

Likelihood of Failure Assessment Criteria

Putting the Consequence and Likelihood tables together gives us a Risk Matrix. The following is typical:

	Consequences				
Likelihood	Negligible	Marginal	Moderate	Critical	Catastrophic
Very High	MEDIUM (5)	MEDIUM (6)	HIGH (7)	HIGH (8)	HIGH (9)
High	LOW (4)	MEDIUM (5)	MEDIUM (6)	HIGH (7)	HIGH (8)
Medium	LOW (3)	LOW (4)	MEDIUM (5)	MEDIUM (6)	HIGH (7)
Low	LOW (2)	LOW (3)	LOW (4)	MEDIUM (5)	MEDIUM (6)
Very Low	LOW (1)	LOW (2)	LOW (3)	LOW (4)	MEDIUM (5)

Consequence Rating	Safety (S)	Environment (E)	Production (P)	Business (B)
Very Low (Negligible)	No injury to personnel	No Harmful release or environmental consequence	Minimal loss of production / drilling operations	Slight equipment damage, repair cost or increase in OPEX (<$1,000) No impact on plan
Low (Marginal)	Slight injury resulting in First Aid Case	Minor release/contained spill localized and contained within site boundaries	Minor downtime or less than 6 hrs total loss of production / drilling or total production loss exceeding 1,000 boe	Minor system damage, repair cost or increase in OPEX ($1,000<$10,000) impact on plan, delay <1 month
Medium (Moderate)	Minor personnel injury impact or illness. Affects work performance	Moderate release of harmful substances with possible widespread effect Increased flaring	Moderate downtime or 0.25 -1 days total loss of production / drilling or total production loss exceeding 5,000 boe	Moderate system damage, repair cost or increase in OPEX ($10,000<$100,000) Impact on plan, delay <1 month
High (Critical)	Severe personnel injury or disability. Degraded function of Safety Critical Equipment	Uncontained release of hazardous substance Breach of flaring limits	Major downtime or 1-10 days total loss of production / drilling or total production loss exceeding 25,000 boe	Major system damage or increase in OPEX (>$100k< $1,000,000) Impacts plan, delay 1 month < 3months
Very High (Catastrophic)	Fatality(s) Loss of function of Safety Critical Equipment	Large uncontained release of hazardous substance Prosecution for breach of flaring limits	Extended downtime or more than 10 days total loss of production / drilling or total production loss exceeding 100,000 boe	Extensive damage, repair costs or increase in OPEX (>$1,000,000) Impacts plan, delay >3 months

Detection (D) [edit]

The means or method by which a failure is detected, isolate failure *modes* (e.g. No direct system effect, while a redunda a critical length). It should be made clear how the failure mo latency period may be entered.

Rating	Meaning
1	Certain – fault will be caught on test –
2	Almost certain
3	High
4	Moderate
5	Low
6	Fault is undetected by operators or maintainers