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Development of a Testing and Analysis Framework for Validation of Rehabilitating Pipe-in-Pipe Technologies

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1. ABSTRACT

Aging natural gas pipeline infrastructure needs rehabilitation, and trenchless, pipe-in-pipe (PIP) technologies offer a versatile solution. For example, legacy cast/wrought iron pipes have been subject to elevated incident rates for decades (www.phmsa.dot.gov). In an effort to accelerate innovation, the United States (U.S.) Department of Energy (DOE) has invested in a recently initiated, 3-year research program focused on pipeline "REPAIR". To establish industry adoption of new technologies, a robust framework to evaluate and validate systems under in-service loading conditions is required. This paper introduces the approach taken by the Testing and Analysis team to develop a framework that confirms a 50-year design life for the PIP technologies. Testing protocols involve a comprehensive literature review, performance criteria, and relevant load cases and failure modes of PIP technologies. We use numerical and analytical modelling to investigate failure modes and severe conditions, thus informing testing protocols. In this paper, we discuss analytical frameworks and proposed model validation methods. We further discuss plans for test geometries (e.g., circumferentially cracked host pipe) and protocols (e.g., cyclic/dynamic traffic loading) to apply relevant load cases and probe failure modes in service. Modifications and enhancements are investigated in light of the insights gained from review and modelling. The testing and analysis framework for validating service life performance of trenchless PIP repair methods is intended to accelerate the development and adoption of new and safe repair technologies in the gas industry, as well as other critical lifeline systems.

2. INTRODUCTION

In 2020, legacy cast/wrought iron pipes accounted for almost 20,000 miles of main gas distribution lines (US DOT Pipeline and Hazardous Materials Safety Administration, 2021). While these legacy pipes do not constitute a large percentage of the total main gas distribution lines, (ca. 2.2% in average over 2010 to 2020), they account for roughly 8% of incidents in the same time frame. An incident is defined in Title 49 of the Code of Federal Regulations Parts 191 (USOFR (US Office of the Federal Register), 2021); the definition notes consequences of an event that would designate it an incident: fatality or injury requiring hospitalization, property damage over a certain cost, gas release over a certain volume, an emergency shutdown. The definition also permits other events without the listed consequences to be deemed incidents(USOFR (US Office of the Federal Register), 2021). Cast/wrought iron pipes are also associated with roughly 30% of incidents involving a fatality (US DOT Pipeline and Hazardous Materials Safety Administration, 2021). Given the investment, research, potential cost savings, and application of technologies to rehabilitate various lifeline systems (Allouche et al., 2014; Lu et al., 2020; Zhao and Rajani, 2002), the U.S. DOE is supporting a 3-year multi-million dollar project, **R**apid **E**ncapsulation of **P**ipelines **A**voiding **I**ntensive **R**eplacement (REPAIR). This program is intended to foster new products and engineering insight, with the ultimate aim to speed industry adoption of suitable technologies in gas distribution lines.

The main objective of REPAIR is to construct a new pipe inside of existing, incident-prone host pipe using robotic application techniques. The new pipe-in-pipe (PIP) structures must meet certain service-life and cost requirements. REPAIR involves various Technology Development teams (focused on material and system development and installation), Pipeline Mapping teams, and the Testing and Analysis team. REPAIR also engages a Testing and Technical Specifications Panel (TTSP), consisting of regulatory agencies and utility representatives, to advise and guide practical application and industry acceptance (Lewnard, 2021). The Testing and Analysis team is producing a framework to both establish and evaluate the required performance objectives of these PIP technologies over a 50-year service life. The ultimate goal of the Testing and Analysis team is to develop a set of standards reflecting typical service loads over a 50-year time frame for initial product validation.

The development of the design of the testing and analysis framework is the subject of this paper. Background concerning PIP behavior and previous PIP evaluation frameworks is described. Important ramifications of this existing work are noted, and then initial testing methods are outlined. This includes discussions of specimen geometries, testing protocols, and performance metrics. A brief overview of modelling to inform test methods is discussed. It is noted that much of the relevant literature is focused on internal pipe linings/liners, as opposed to PIP rehabilitation which is targeting a fully structural repair system.

3. REPAIR PIP PERFORMANCE OBJECTIVES

In REPAIR, the overarching requirement is that the PIP technologies maintain structural capacity, delivery, and natural gas containment. The program, in considering the scenarios that could compromise these requirements, defined a set of general high-level performance objectives (POs) for consideration in new technology validation. These POs were expanded by the Testing and Analysis team. This set is composed of primary POs for a base-level of industry acceptance. Table 1 presents these with example sources and potential failure modes.

It is noted the POs are not fully independent and have some overlap (e.g., **PO8** could be considered a sub-objective in the other POs, and **PO2** and **PO3** have overlap). There is considerable literature investigating rehabilitating PIP systems, which relates to these performance objectives. This literature often concerns or examines Cured in Place Liners (CIPL) or Cured in Place Pipe (CIPP) linings, the most common of pipe lining rehabilitation methods (Najafi, 2016), or Spray Applied Pipe Linings/Liners (SAPL). These POs and related literature are briefly discussed in the following sections.

PO1. Cyclic in-service surface loads

Cyclic surface loads, often due to overhead traffic, is a loading condition that can impose deformations related to **PO2** and **PO3**; in REPAIR, pipe deflection (**PO2**) is more likely the dominant deformation mode (see **PO2** and **PO3** text). Traffic loads are cyclic in nature, and thus present the potential for fatigue damage/failure. The separation of

PO1 from the others is meant to highlight the need of the repair PIPs to demonstrate adequate performance under fatigue loading over their service lives. A few authors have considered the response of CIPL systems (Jeon et al., 2004; Stewart et al., 2015) and SAPL systems (Ha et al., 2016) under repetitive lateral loading. Jeon et al. (2004) and Stewart et al. (2015) subject lined systems with full circumferential cracks or joints, to a number of bending cycles with displacements based on the expected traffic load over a 50-year service life. A reduction of stiffness of the system, which they note is most likely a result of debonding, is observed, but failure is not observed (Jeon et al., 2004; Stewart et al., 2015). Ha et al. (2016) find similar behavior with a SAPL lined system with a full circumferential crack under 10^5 bending cycles.

Table 1. REPAIR Performance Objectives

No.	**Performance Objectives**	**Example Sources**	**Potential Failure Modes**
PO1.	Cyclic in-service surface loads	Overhead traffic	Fatigue failure in bending
PO2.	Deflection (lateral deformation)	Adjacent excavation, surface loads, subsidence, frost heave, undermining	Failure due to bending & axial stresses, buckling, cross-section ovalization
PO3.	Cross-section stiffness (ovalization)	External pressure, surface load, deflection (bending) of the pipeline	Ring collapse & excessive/adverse ovalization
PO4.	Axial deformation (axial displacement)	Thermal Loading (expansion/contraction) seasonal temperature changes	Stress limit failure due to axial stresses, buckling, pinching, fracture of the PIP, detachment from host at termination point
PO5.	Circumferential (hoop) stress	Internal pressure, pressure fluctuations	Burst - failure due to tensile stress, stretch of material leading to loss of containment
PO6.	Puncture/impact	Rock impingement, host pipe fracture, contact by excavation equipment or other construction/external damage	Puncture, reduction in pressure capacity
PO7.	Compatibility with current and future gas compositions	Internal natural gas	Chemical degradation, excessive permeation
PO8.	Debonding at PIP/host pipe interface*	Differences in thermal expansion, mechanical loads	Gas back-tracking, loss of containment and delivery compromised, potential ring collapse
PO9.	Service connections	Abandoned and/or in-service connections	Failure due to stress concentrations, potential for differential movements may cause failure at connections, leakage at the service line connections and PIP end joints

* Bonding to the host pipe is not required of internal PIP repairs, see discussion of **PO8** below

PO2. Deflection (lateral deformation)

A PIP must be able to accommodate deflection (lateral deformation) in longitudinal bending, which could be imposed by a number of phenomena, e.g., overhead loads, subsidence, frost heave, and nearby excavation. The level of deflection experienced in such cases will in part depend on the stiffness of the PIP and size and nature of discontinuities in the host pipe. A number of authors have found that lined systems are quite capable of undergoing large vertical and corresponding angular displacements (upwards of 6°) at joints or full circumferential cracks in the host pipe under bending prior to failure (Allouche et al., 2012; Ha et al., 2016; O'Rourke et al., 2021). Often, experimental bending tests are part of a larger program that considers a number of additional load cases, e.g. axial loading and transverse shear (Allouche et al., 2012; Ha et al., 2016; Jeon et al., 2004; O'Rourke et al., 2021; Stewart et al., 2015).

PO3. Cross-section stiffness (ovalization)

This PO refers to a PIP's ability to resist ring collapse and transverse cross-sectional deformation. There has been considerable work on hydrostatic buckling (generally elastic) of a flexible internal liner in a rigid host pipe (Boot, 1997; El-Sawy and Moore, 1998; Li et al., 2019; Madryas and Szot, 2003; Omara et al., 1997; Straughan et al., 1995). Hydrostatic buckling is an extreme case, leading to failure by nearly instantaneous collapse. It may be caused by ground water leakage into the host pipe, subjecting the inner pipe to hydrostatic pressure (Li et al., 2012). Glock's expression (Glock, 1977) for the critical pressure on a tube in a rigid cavity has been found to agree both with experimental (Omara et al., 1997) and numerical results, when other factors (e.g., defects) are limited (El-Sawy and Moore, 1998; Li et al., 2019; Vasilikis and Karamanos, 2009). Considerations of elastic hydrostatic buckling appear to be the vast majority of work related to rehabilitating PIP systems and **PO3**, but some works have considered plastic hydrostatic buckling (Montel, 1960; Vasilikis and Karamanos, 2009) and ovalization of large diameter rigid pipes with SAPLs due to overhead loads (Najafi et al., 2021; Tehrani, 2020). Ovalization can also occur during PIP bending (Hilberink et al., 2011; Vasilikis and Karamanos, 2012). Cross-section ovalization of the repair PIP, as a result of longitudinal pipeline bending, may be the predominant cause of ovalization, given the relatively low D/t ratios of the liner systems and small section (diameter) and the rigidity of the outer pipes. Given potentially stiff PIPs, ring failure of the REPAIR PIPs may be governed by local maximum stress criteria within the ring (typical of rigid pipes), opposed to buckling instabilities (typical of flexible tubes).

PO4. Axial deformation (axial displacement)

Axial deformation of lined pipe systems, i.e., elongation/compression along the axial direction (long axis) of the pipe system, has been investigated by many authors (Allouche et al., 2012; Argyrou et al., 2018; Focke et al., 2011; Jeon et al., 2004; Moore, 2021; O'Rourke et al., 2021; Stewart et al., 2015; Zhong et al., 2017). Often there is a focus on joints or full circumferential cracks in the host pipe of both CIPL and CIPP linings (Allouche et al., 2012; Argyrou et al., 2018; Jeon et al., 2004; O'Rourke et al., 2021; Stewart et al., 2015; Zhong et al., 2017). Several researchers have considered axial deformation from seismic ground motion (Argyrou et al., 2018; Zhong et al., 2017). Axial pipeline deformation is also caused by thermal fluctuations (Jeon et al., 2004; Stewart et al., 2015). Axial deformations may result in: host pipe/liner debonding (Allouche et al., 2012; Argyrou et al., 2018), liner rupture under tension (Argyrou et al., 2018), and liner pinching in compression (Argyrou et al., 2018; Zhong et al., 2017). Internal pressure has an important effect on these responses, e.g., increasing internal pressure reduces the debonding tendency (Argyrou et al., 2018; Moore, 2021; Zhong et al., 2017).

PO5. Circumferential (hoop) stress

This PO refers to a PIP's ability to accommodate internal pressure without loss of containment or rupture. Many authors have studied pipe liners' behavior and failure under internal pressure experimentally and numerically (Adebola et al., 2021; Allouche et al., 2005; Brown et al., 2020, 2014; Ha et al., 2016; He and Kenny, 2019; Jaganathan et al., 2007; Knight et al., 2019). Several researchers attempted to capture the interactions between liner and host pipe (Adebola et al., 2021; Allouche et al., 2005; Brown et al., 2020, 2014; Ha et al., 2016; He and Kenny, 2019; Jaganathan et al., 2007). Numerous studies consider the effect of gaps and holes in the host pipe (Adebola et al., 2021; Allouche et al., 2005; Brown et al., 2020, 2014; Ha et al., 2016; He and Kenny, 2019; Jaganathan et al., 2007); many compare the response of the PIP at different diameter holes with those noted in ASTM F1216 – 16 and ASTM F2207 – 06 (Adebola et al., 2021; ASTM Committee F17, 2016a, 2019; Brown et al., 2020; He and Kenny, 2019). An important finding from some of this work is that the stress developed in the lining at large holes under internal pressure is higher than that developed in the unconfined lining under the same internal pressure, as a result of bending into the hole in the host pipe (Adebola et al., 2021; Allouche et al., 2005; Brown et al., 2020). With REPAIR targeting fully structural systems (substantially stiffer than many existing systems), this effect may be less prevalent.

PO6. Puncture/impact

There seems to be an absence of literature about the puncture of CIPL, CIPP, or SAPL lined systems. Indeed, with rigid host pipes, this would seem to be an unlikely failure mode. However, the potential for puncture of a PIP by fragments of the host pipe undergoing brittle fracture or the puncture by foreign objects in an area of extreme host pipe deterioration, warrant investigation.

PO7. Compatibility with current and future gas compositions

This PO reflects the need for PIP systems to handle current and future gas composition without chemical degradation or loss of containment (from permeation). With the future plans of using natural gas-hydrogen mix in the existing gas infrastructure, it is intended that systems developed in REPAIR have the capacity to handle these blends. Hydrogen embrittlement issues could be expected in some metallic repair PIP systems, while high permeation may occur in the polymer-based repair PIP systems (Birkitt et al., 2021). Standards enumerate various tests for exposure and property requirements of lining material after exposure to demonstrate chemical resistance (ASTM Committee F17, 2018, 2016a, 2019).

PO8. Debonding at the PIP/host pipe interface

To avoid gas backtracking between the internal repair and host pipe at service line connections and end joints, sufficient bonding between the PIP and host pipe is required. Bonding to the host pipe, other than at service connections and end joints, is not a requirement of the REPAIR systems. In fact, failures may be avoided under certain load cases more easily with no bonding between the PIP and host pipe, as demonstrated by Kozman (2020), and some level of PIP debonding from the host pipe reduces stresses and strains induced in the lining at circumferential cracks or separations in the host pipe (Netravali et al., 2000; O'Rourke et al., 2021). In the case of an unbonded system, the termination points must prevent full detachment and the associated potential for gas back-tracking (representing failure). In the case of a system that debonds under loading, the termination points again must be sufficient to avoid full detachment and ideally the debonding is local in nature to avoid gas back-tracking.

PO9. Service connections

These features are present in host pipes in the field. They present a variety of installation challenges (Das et al., 2016) and they can also act mechanically as stress concentrators. Much work has considered internal pressure of lined systems with holes in the host pipe (see **PO5**) and lined tee geometries (Allouche et al., 2005; Jaganathan et al., 2007) which are somewhat representative of abandoned service connections. The effect of these characteristics in external loading is less examined, and more studies of internal pipe – open connections behavior appear needed.

Additional Performance Considerations

There are several additional POs for the systems in REPAIR that are not directly considered by the Testing and Analysis Team. Seismic loading and other extreme demands from natural or manmade disasters, in general, are not considered in REPAIR. However, it is hoped some insight into the response of the PIPs can be gained from this work under such demands. The PIP material requirements for extremes in operating temperature (e.g., exposed pipe at a bridge crossing or pipe in proximity to a buried steam line) are not addressed by the Testing and Analysis team's program (as opposed to the more typical minimum and maximum operating temperatures). Service connections will be addressed in part by the Testing and Analysis Team; however, the related and broader aspects, such as bends, tees, and valves are not directly considered. The impact of PIP installation on existing components of the pipelines, e.g., materials (gaskets, lead, jute, sealants) in the cast iron joints, is not considered, nor is the PIPs' ability to permit the creation of new service lines. While these POs may be important to consider in certain circumstances, they are identified as critical secondary considerations that are beyond the initial scope of the Testing and Analysis Team's serviceability focus.

4. EXISTING PIP EVALUATION FRAMEWORKS

There are various standards and norms relevant to PIP technologies. Many of the relevant documents consider internal pipe linings/liners opposed to fully-structural internal pipes (PIPs). One useful classification system is American Water Works Association's (AWWA's) "Structural Classification of Pressure Pipe Linings" (2019), which gives four classes of linings from Class I, non-structural, to Class IV, fully structural. The REPAIR project is targeting fully structural systems, but for gas delivery. Lining products suitable for gas pipelines exist on the market (Lu et al., 2020).

There are several ASTM documents related to PIP technologies. In the context of the REPAIR project, ASTM F2207 – 06 (2019) is the most immediately relevant, as it concerns the rehabilitation of metallic gas pipes with CIPP lining. This standard entails several macroscale tests of such liners installed in metallic host pipe segments, including sustained pressure, bending, and tension tests. The specimens include full circumferential gaps of exposed liner, 1 to 2-inch (in.) (25 to 50 mm) wide, between two host pipe segments and a defect, e.g. a 4 in. (100 mm) diameter hole in 12 in. (300 mm) or lager diameter host pipe lined with a "medium pressure liner", but this document explicitly does not consider a lining system that is structurally independent from the host-pipe and requires that loading (excluding external and internal loads acting locally at discontinuities) is handled by the host pipe (ASTM Committee F17, 2019). ASTM F2207 – 06 (2019) also has a lengthy annex discussing the use of coupon level testing with reduced full-scale pipe specimen testing and mathematical models describing the mechanics to understand failure due to internal pressure of the liner considering holes in the host pipe. ASTM F1743 – 17 (2018) and F1216 – 16 (2016a) are standard practices that document CIPP installation procedures and note some test methods and flexural property requirements (and tensile strength in case of pressure pipes) as cured and after chemical exposure. ASTM F1216 – 16 also features some design considerations and equations, which are relevant for both of these standards (ASTM Committee F17, 2018; 2016a). Many authors have noted various issues with some of these design considerations (Adebola et al., 2021; Knight et al., 2019; Kozman, 2020; Najafi et al., 2021; Omara et al., 2000). ASTM D5813 – 04 (2018) is a standard specification describing CIPP systems for gravity flow systems. The document outlines a simple classification system not unlike AWWA's and defines some minimum requirements. The standards ASTM F3182 – 16 (2016b) and ASTM A849 – 15 (2021) concern SAPLs for potable water and drainage and sewer steel pipes, respectively.

Many researchers have investigated linings with respect to test methods and standards (Adebola et al., 2021; Brown et al., 2020; He and Kenny, 2019; Omara et al., 2000, 1997), and some have developed their own design and/or performance validation frameworks. Jeon et al. (2004) examine two cured in place pipe lining systems in cast iron host pipe under repetitive loads. The authors subject specimens with a full circumferential gaps between host pipe segments, spanned only by the liners, to cyclic axial loading, to simulate thermal effects, and cyclic bending, to simulate traffic and excavation events, that the systems would experience over their service life (Jeon et al., 2004). Stewart et al. (2015) take a similar approach in investigating cured in placed lining, investigating lined joints in cast iron host pipe. Generally, the material mechanical properties of the liner are not greatly changed by field aging or mechanical aging protocol (cyclic tests) in the study (Stewart et al., 2015). A framework for determining the displacements to be applied during cyclic loading is described in these studies; however, zero stiffness of the liner is assumed (Jeon et al., 2004; Stewart et al., 2015). These works adapt the approach first developed by O'Rourke et al. (1996) to assess the performance of anaerobic sealants used in joints of legacy cast-iron pipes. The assumption of zero liner stiffness is not applicable in the REPAIR project, and testing frameworks will need to address the internal repair pipe stiffness. Najafi et al. (2021) in a very recent report develop design equations and performance parameters for large diameter pipes (i.e., conduits) lined with SAPL considering overhead loads. Knight et al. (2019) examine and discuss extending the hydrostatic design basis method to CIPP to obtain long-term burst strengths for better design.

5. REPAIR TESTING AND ANALYSIS EVALUATION FRAMEWORK

The Testing and Analysis team's approach is similar to that of Jeon et al. (2004) and Stewart et al. (2015) considering external loading. Specimens are prepared of both steel and legacy cast iron host pipe. A suitable chemical aging treatment for the internal surfaces of the steel pipe, similar to that of Giacometti and Jadani (2019), is developed to mimic surface bonding characteristics of the legacy cast iron pipe. Steel specimens consist of two 60 in. (1500 mm) segments of host pipe, placed and lined such that there is a full circumferential segment of exposed liner representing a crack. The crack widths are determined from the input of the TTSP, finite element analyses and physical experiments on systems of known materials. Current plans are to consider crack widths of 0.5 in. (12.7 mm), corresponding to a joint opening displacement in cast iron systems noted by the TTSP, and a 6 in. (152.4 mm) crack, reflecting a severe case of local deterioration of the host pipe post repair. The team is also considering smaller cracks, as initial FE models have shown small cracks to give rise to higher axial stresses in bending and such cracks may capture host pipe contact across the crack and potential failure possibilities. Legacy cast iron specimens will be similar, but with the possibility of featuring a weak joint opposed to a crack. Steel host pipe segments will also feature holes, possibly inclusive of a service connection, which are also being determined from existing standards and TTSP feedback, in order to examine **PO9**.

Specimens will first be tested in four-point bending; a schematic of the bending test setup is shown in Figure 1. Approximately 500,000 bending cycles will be applied to the specimens, simulating overhead traffic load (**PO1**) displacements applied to an unsupported section of PIP within a fully circumferentially cracked host pipe or weak host pipe joint. After these cycles, a single larger displacement cycle will be applied to the pipe to simulate an undermining or nearby excavation event, considering **PO2**, which in turn will be followed by more traffic-based cycles. All of these displacements are influenced by the stiffness of the PIP and width of the circumferential crack, in addition to the typical parameters (applied load, depth of burial, soil support, and stiffness of the host pipe). These displacements will be determined with 1D FE models, which are supported by full 3D models and validated by existing experimental results. In tandem, simplified analytical expressions are developed, which will be used to facilitate determination of appropriate displacements based on stiffness of the PIP and width of the circumferential crack. Monitoring of the deformation with strain gauges, displacement transducers, and/or digital image correlation (DIC) during the flexural testing will be done to consider **PO3** (in bending) and **PO8**.

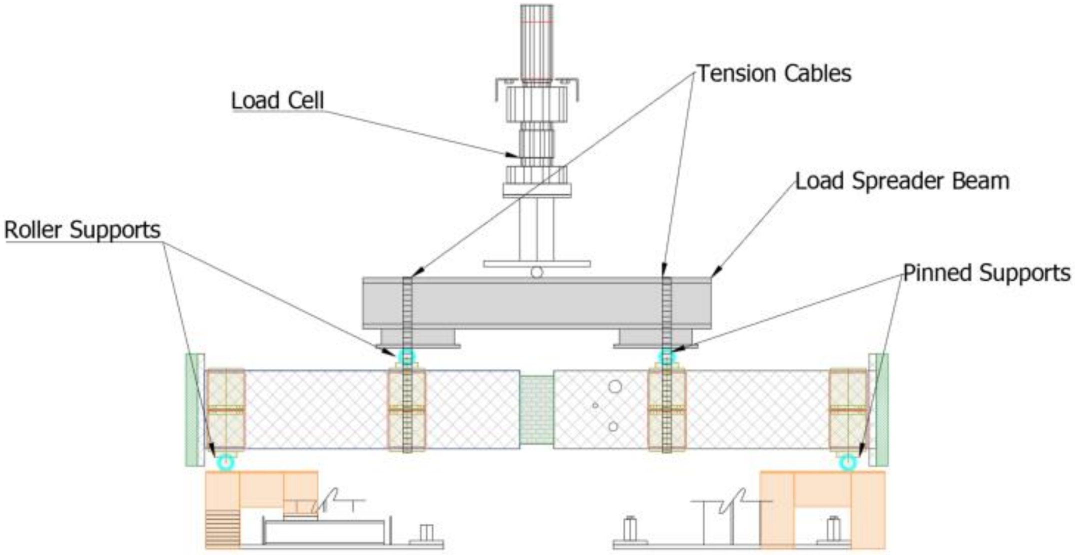

Figure 1. Schematic of a Typical Four-Point Bending Test Setup for Steel Specimen (AutoDesk® AutoCAD®).

Axial loading cycles will also be applied to the specimens to impose displacements that simulate the stresses developed in the system, in particular in the PIP at the crack, due to the annual thermal fluctuation experienced by buried pipelines. Using previous work (Stewart et al., 2015) and feedback from the TTSP, a temperature change, ΔT = 50°F (27.8°C) was selected. Fifty axial cycles will be applied to simulate the 50-year service life. The applied displacements will be determined with FE and analytical modelling, to account for the various aspects of the systems, inclusive of the nature of the bonding. After successful cyclic testing, specimens will be pulled to failure. The axial testing will evaluate both **PO4** and **PO8**. Both bending and axial loading will be performed on specimens pressurized with 60 psi (414 kPa) water.

Short-term burst pressure of the PIPs will be determined in hydrostatic pressure tests on steel pipes. An approximately 18 to 24 in. middle section of specimen will be removed after the application of the PIP. This allows for an unconfined PIP section to be tested. A schematic diagram of the test specimen is shown in Figure 2.

The length of the unconfined section of PIP in the specimen, as well as the end conditions with respect to axial movement (free, constrained, fixed) were analyzed with FE models. Long-term cyclic internal pressure testing will also be carried out, as well as puncture tests followed by applied internal pressure. These tests will be used to evaluate **PO5** and **PO6**. Permeation testing will be performed on the repair materials to consider **PO7**.

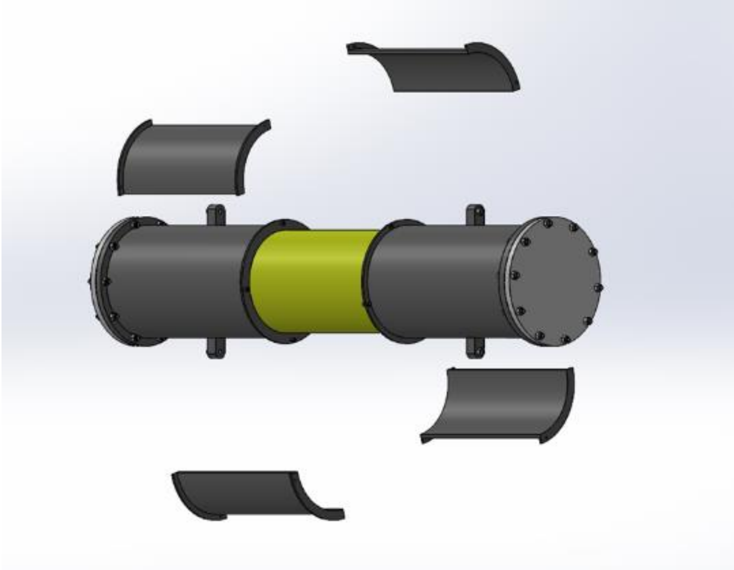

Figure 2. Internal Pressure Testing Specimen, showing the middle PIP unconfined section (DS SolidWorks®).

6. CONCLUSIONS

The REPAIR project is a multi-team, multi-institutional endeavor, supported by the U.S. DOE, with the aim of speeding the design and application of PIPs to reinforce the incident-prone bare steel and cast-iron pipe in U.S. gas distribution systems. Nine high-level primary performance objectives for the repair systems are explained in this paper. There has been considerable research published about hydrostatic buckling of flexible tubes in rigid pipes, lining behavior at host pipe discontinuities, and lined pipeline deformation with assumptions of zero stiffness liners. In the REPAIR project, there is the potential for very stiff pipe repair systems given the performance objectives, and the testing and analysis methods must take this into consideration. The Testing and Analysis team will apply cyclic bending and axial loads to repair lined pipe specimens with full circumferential cracks between the host pipe segments to evaluate externally-based performance objectives. Internal pressure tests on repaired pipe specimens and permeation tests on repair materials will be performed to evaluate internally-based performance objectives. Known material testing is beginning, and tests of systems with the developed materials are scheduled for 2023. The goal is to build a comprehensive evaluation framework for new pipe repair technologies, which considers primary performance objectives and allows for the timely application of new repair technologies.

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