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CONDITION ASSESSMENT AND REHAB: A HOLISTIC APPROACH

David E. Russell, President, PICA Corporation, 4909 75 Ave., Edmonton, AB, T6B2S3, Canada and
Clint Jones, Senior Product Developer, 3M Infrastructure Protection Division, 3M Center, Building 223-02-S-24, St. Paul, MN 55144-1000 and
Ryan Rogers, Market Development Manager, 3M Infrastructure Protection Division, 3M Center, Building 223-02-S-24, St. Paul, MN 55144-1000

Abstract

Current practice for North American Municipalities is to repair pipelines when they leak and to replace them when leakage rates become intolerable. Some larger organizations employ desktop studies which include leakage rates, pipe age, soil resistivity, coupon testing and other criteria to decide when pipelines should be replaced or rehabilitated. These methodologies can inadvertently lead to unnecessary costs resulting from the wholesale replacement of pipelines that are still in reasonably good structural condition, as well as undesirable social disruptions from unneeded open excavations and interrupted water service. It has been reported that 96% of pipelines are still in good working condition [v]; therefore, focusing on the repair or rehabilitation of just 4% of our aging pipelines would result in the most efficient use of municipality resources.

3M Infrastructure Protection and PICA: Pipeline Inspection and Condition Assessment Corp., have teamed up to offer a cost-effective solution to achieve this goal.

This paper discusses the rational for proactive *Direct Condition Assessment* of potable water mains followed by *selective lining*, using 3M's polyurea liner, to extend the life of pipelines. This innovative approach allows for the establishment of a proactive, comprehensive rehabilitation program.

BACKGROUND

Budgets for pipe replacement in North America, for potable water pipe, allow the replacement of typically less than 1% of the installed length per annum. At the same time, our aging infrastructure is failing at an accelerated rate, leading to inaccurate projections for maintenance budgets, and less money available for replacement. A study done by Utah State University concludes that $1trillion is needed for pipe replacement over the next two decades [vi].

The cost of replacing pipelines varies widely, depending on pipe size and location within city streets; however, *Direct Condition Assessment (DCA)* can often be accomplished for less than 5% of replacement cost. It follows; therefore, that asset managers would benefit from a thorough DCA before incurring the wholesale cost of replacement. This hypothesis is only true if there are no other compelling reasons for replacing a pipeline (increasing C-factor, increasing overall volume to an area, re-paving a major artery etc.). For pipelines that are simply aging and leak frequency is increasing, the benefits of DCA and selective lining present a compelling cost-benefit argument.

WHAT IS DCA?

Direct Condition Assessment (DCA) is the process of determining the remaining structural wall thickness of a pipe. To accomplish this measurement in a meaningful way, the full circumference of the pipe should be interrogated with high-resolution sensors. By doing this, even small diameter local degradation can be detected and quantified.

Carbon steel, cast-iron and ductile-iron pipes corrode in local cells, when external corrosion protection breaks down, allowing ground water to contact the pipe. Electric current flowing between the pipe and soil is a galvanic cell which essentially reduces the metal to its oxide. In the case of cast and ductile-iron the corrosion is known as graphitization. As the iron is reduced, a matrix of graphite is left behind. The graphite still has some structural strength, until it reaches a critical size when an event such as frost heave, water hammer, earthquake or traffic vibrations can cause the graphite plug to pop out and water to leak.

Detecting these areas of graphitization creates a thickness profile of the pipe section and allows an asset manager to rank the pipe according to its remaining life. Knowing the exact location and severity of the local corrosion pits provides an opportunity to proactively repair them (external clamp or surgical replacement), or to choose a rehabilitation technique such as a liner.

Fig-1: typical corrosion cells in cast-iron pipe

There is only one class of inspection tool that can provide the precision to detect small, deep local pits: *In-Line Inspection Tools* (ILI tools). ILI Tools are sent through the pipe, after moderate cleaning and bore-proofing, with water pressure. Long lengths of pipe can be inspected in “free swimming” mode, or shorter lengths in “tethered” mode. In either case, the pipe must be excavated and taken out of service for a short period of time. The pipe is cut into and a *launcher or launch barrel* is installed. The Tool is introduced into the pipe through this launcher

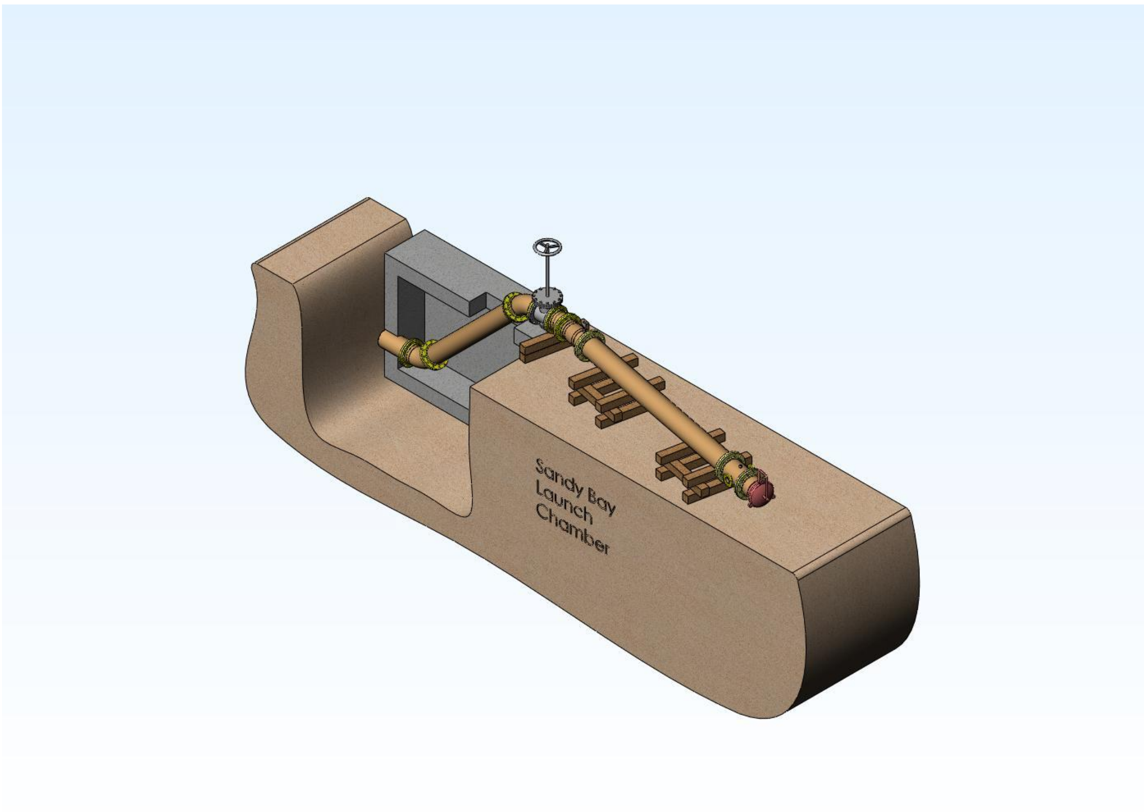

Fig-2: Typical launcher or Receiver for ILI Tool

The ILI Tools can employ one of several kinds of Non-Destructive Test techniques such as:

- Magnetic Flux Leakage (MFL)
- Ultra-sonic (U.T.)
- Remote Field (RFT)
- Sonar
- Laser
- CCTV

The last three of these techniques only provide information about the inside of the pipe. They do not measure remaining wall thickness.

Of the remaining three techniques, only Remote Field (RFT) has the ability to measure the remaining wall thickness in all three materials (steel, cast and ductile), in the presence of liners (cement mortar or P.E.) or internal scale and tubercles. The other two techniques (MFL and U.T.) require a relatively clean and smooth inner surface in order to couple their sensors to the pipe to measure remaining wall. **RFT Tools should; therefore, be the technology of choice for the DCA of water and waste water pipelines.**

Fig-3: Typical 16" pipe diameter RFT Tool (courtesy PICA Corp)

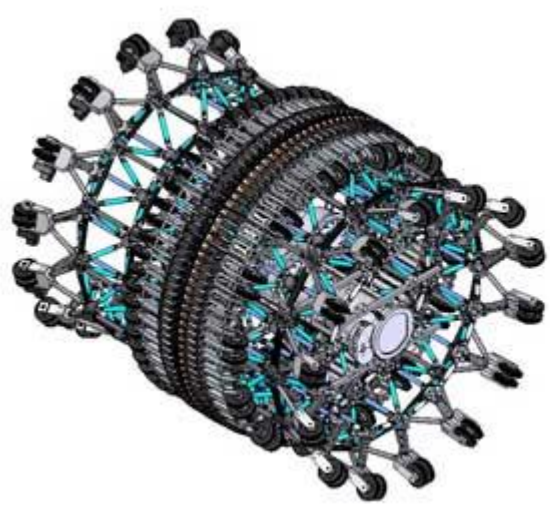

Fig-4: Typical MFL Tool (courtesy Pure Technologies)

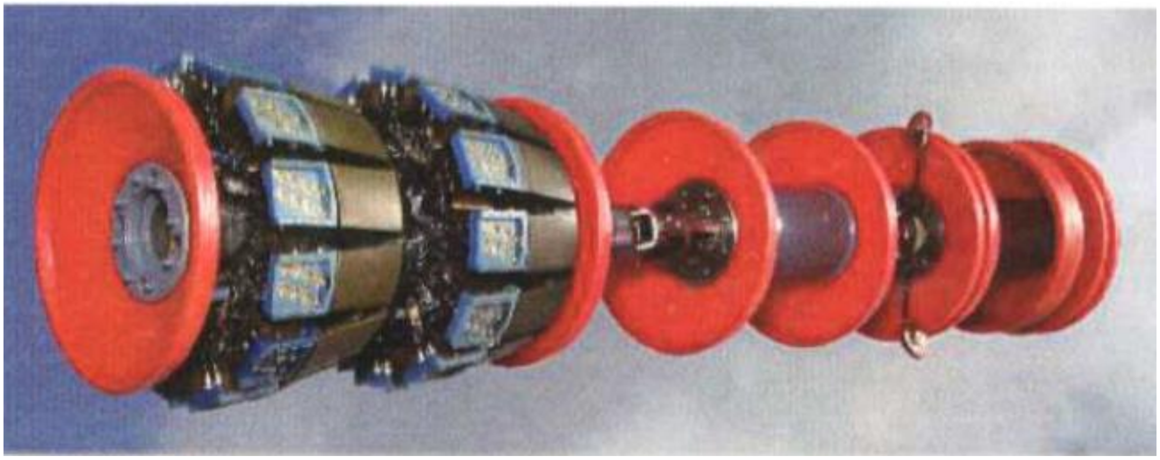

Fig-5: Typical Ultrasonic Tool (courtesy Weatherford Oilfield)

REHABILITATION OF PIPELINES BY SPRAY-ON LINERS

Like all infrastructure, the condition of potable water delivery infrastructure deteriorates gradually over time. Combinations of corrosion, soil movements, traffic loads, and operating pressures can eventually result in poor water quality, leakage problems, loss of pressure and more importantly, high maintenance costs. About 50% of the North American water delivery infrastructure systems were made with cast iron pipes installed prior to the 1950s. Now showing tuberculation, these systems typically have lower hydraulic capacity and increasing water quality problems[i] attributed to surrounding soil environment and the composition of water. Consequently, structural damage and leakage problems are common, particularly in older cast iron waterlines of large diameters.

Historical Perspective of Structural Spray Lining Products

In open-cut methods, an original method of infrastructure renewal involving trenching, backfilling, compaction and reinstatement of ground and pavement, nearly 70% of the total project cost[ii] can be attributed to the pre- and post-construction aspect of the renewal process, not to the renewal of the system itself with polyethylene or new ductile iron pipe. Additionally, social and environmental factors related to open-cut methods include adverse impacts on the community, businesses, and commuters due to air pollution, noise and dust, safety hazards and traffic disruptions.

Advancing technologies, environmental concerns and economic trends have resulted in the development of a variety of more efficient, sustainable, cost-effective methods for renewal of existing water pipe infrastructure. These advanced technologies included a variety of products called linings, which, instead of fully replacing existing pipe infrastructure, create new surfaces inside existing pipes.

During the 1990s, many applicators and contractors adopted structural spray lining products utilizing epoxy resin. Slow setting, the characteristics of these products requires a minimum 16-hour cure period and often results in 36 hours of service shutdown periods. Since then, next generation polyurea linings have become increasingly popular. Because polyurea spray lining is generally performed in conjunction with a trenchless technology application process, these products can provide considerable social and financial advantages compared to traditional open-cut methods and long cure time alternatives.

The choice of a renewal method for water delivery infrastructure is dependent on the physical conditions of the existing pipeline system. Length, size, type, pipe material, number of connections, hydrant locations and bends must be considered before the most appropriate renewal method is selected. The key elements for selection of a specific method for renewal of water pipes are:

- The nature of the problem or problems the water pipe is facing and the objectives for the renewal method
- The hydraulic and operating pressure requirements for the renewal method
- The pipe material, dimensions and features (bends, alignment, joints, history of previous repairs, depth, degree of corrosion) of the old water pipe
- The types and locations of valves, fittings and hydrants
- Length of time the water pipe can be out of service or bypassing requirements
- Other site and project specific factors
- Cost of the renewal method

Primary Failure Modes and Pipe Rehabilitation Classifications

There are three major categories of water main problems: water quality issues, leaks or flow issues, and structural issues. Water quality issues are typically the result of tuberculation buildup that becomes dislodged and manifests itself as brown or red water conditions at the end-user. Poor water flow, increasing system pump or pressure requirements, and leakage are typical symptoms in systems with heavy corrosive buildup and tuberculation which may simultaneous reduce hydraulic capacity of the affected line or system and adversely require increases in water pump pressures and increase system operational costs. Structural problems include internal and external pipe wall corrosion, erosion, metal graphitization, and may eventually translate into pinholes, cavities, voids, and transverse or longitudinal cracks. These structural issues may result in pipe failure and breaks or, under severe cases, significant infrastructure damage and cascading effects such as pipe bursts, sinkholes, and road damage. In conjunction with an appropriate condition assessment, polyurea linings may be suitable to address many of these potable water main problems.

Linings used for renewal of drinking water pipes can be classified into four AWWA classifications (Non Structural I, Semi-Structural II, Semi-Structural III, and Structural IV) and into four BS EN ISO 11295:2010 classifications (Non Structural D, Semi-Structural C, Semi-Structural B, and Structural A). The lining classification is based on the performance of the lined pipe when subjected to internal pressure, external loads and on the capability of the lining to survive specific host pipe failure modes. Tables 1 and 2 show these lining classifications.

Table 1- AWWA Structural Classification of Lining Systems[iii]

System Class	Non Structural Class I	Semi-Structural		Structural Class IV
		Class II	Class III	
Corrosion Protection	Yes	Yes	Yes	Yes
Gap Spanning Capability	No	Yes	Yes	Yes
Inherent Ring Stiffness	No (Depends on Adhesion)	No (Depends on Adhesion)	Yes (Self Support)	Yes (Self Support)
Survives Internally Induced Burst Failures of Host Pipe and	No	No	No	Yes

Table 2- **BS EN ISO 11295:2010** Structural Classification of Lining Systems[iv]

System Class	Non Structural Class I	Semi-Structural		Structural Class IV
		Class II	Class III	
Corrosion Protection	Yes	Yes	Yes	Yes
Gap Spanning Capability	No	Yes	Yes	Yes
Inherent Ring Stiffness	No (Depends on Adhesion)	No (Depends on Adhesion)	Yes (Self Support)	Yes (Self Support)
Survives Internally Induced Burst Failures of Host Pipe	No	No	No	Yes

Structural spray linings are becoming a popular and cost effective alternative to open cut renewal methods where existing pipe is replaced with polyethylene pipe. Spray linings, including epoxy, acrylic and polyurethane coatings applied in situ, are increasingly being designed to repair existing pipe infrastructure by spanning gaps and discontinuities without full replacement. This lining must be able to withstand short-term loads, such as groundwater rise, surcharge pressure or drop in internal fluid pressure (vacuum pressure), and long-term loads such as embankment loads, soil, groundwater and operational loads (water pressure).

Polyurea Spin Cast Spray Lining or Spray in Place Pipe (SIPP)

Acknowledging the drawbacks associated with epoxy resins and unsaturated polyesters, several companies, including 3M, have developed rapid-setting in-situ applied polymeric products for drinking water pipe rehabilitation. Many of these formulations are high build and are applied to the internal pipe surface using a highly controlled, centrifugal spin-cast application process. The end result is a high build, inert, corrosion resistant lined system that has renewed the internal surface of the infrastructure.

Polyurea linings generally have sufficient integrity to withstand the full pipe operating pressure when installed at the appropriate lining caliper thickness based on specific manufacturer material properties, pipe operating requirements, pipe condition, pipe diameter, bury depth, target design life, safety factor and host material substrate type.

Design Considerations

One advantage of high build polyurea lining solutions is the ability to vary the applied liner thickness caliper in order to achieve specific liner performance targets. To accomplish this, engineering design equations may be used. The variables in the equations are often times known but there is educated guesswork involved, especially when Direct Condition Assessment is not a part of the design process. More definitive data that is collected up front about the pipe to be rehabilitated can improve confidence in the assumptions being used to specify the liner thickness and thereby reduce the chance for premature failure of the liner. Table 3 outlines some of the common design variables when considering liner caliper thickness.

Table 3: Input Variables for Liner Caliper Thickness

Pipe Diameter
Pipe Bury Depth
Pipe Substrate Material
Lining Type ● Structural Lining ● Barrier Coating Only (water quality lining)
Pipe Condition ● Partially deteriorated gravity pipe ● Partially deteriorated pressure pipe ● Fully deteriorated pressure pipe ● Fully deteriorated gravity pipe

For Structural Linings Only:

- System Operating Pressure
- Support of Live & Soil Loads (host pipe or liner)
- Post Lining Corrosion Hole Size [1" (25mm) or 2" (50mm)]
- Desired Design Life (20, 30, 40, 50 yrs)
- Desired Safety Factor (1, 1.5, 2)
- Location of Water Table (above or below pipe invert)

DIRECT CONDITION ASSESSMENT AND LINER THICKNESS SELECTION

Direct Condition Assessment can be utilized to identify remaining wall thickness of the host pipe, the presence of through holes or voids and provide the specifying engineer with a missing piece of the input data to determine the most appropriate design assumptions to determine the ideal polyurea spray lining caliper. Four of the most common engineering equations for various pipe type conditions are described below. Direct Condition Assessment may be used to help select which case is most appropriate and this in turn can provide some confidence of the appropriate lining caliper thickness to specify. Each equation is described in some detail below. The ultimate decision on liner caliper thickness rests with the specifying engineer based on the specific variables and assumptions that are most appropriate for any given scenario. Direct Condition Assessment is most useful in determining whether a pipe falls under the *fully* or *partially* deteriorated design condition. It also can provide insight into the dimension of anticipated through hole corrosion voids.

Partially Deteriorated Gravity Pipe Condition

In this case, the pipe may have displaced joints, cracks or corrosion. The original host pipe is assumed to carry or support all of the soil and live loads throughout the anticipated remaining lifetime of the lined pipe. In this scenario, the liner is only specified at a thickness necessary to support the hydrostatic pressure due to external leaking. The location of the water table relative to the invert of the pipe is relevant in this equation (ie. water table above or below the pipe). In addition, where no hydrostatic pressure is present (water table below the pipe) a suitable SDR may be chosen between 45 and 100, depending on the expected transient vacuum conditions that the pipe will experience and the desired design life. For an SDR of 100, the equation used to determine lining caliper is $t = D/100$. The adhesion of the liner to the host pipe, hole spanning capability of the liner are not considered in the calculation nor are vacuum loads. The ovality distortion of the host pipe is assumed to be $< 10\%$.

t = liner thickness
D = pipe diameter
C = ovality factor
E_L = 50 year estimated flexural modulus
P_{ext} = hydrostatic pressure
v = Poisson's ratio
K = enhancement factor

$$t = \frac{D}{\left(\frac{2\,K\,C\,E_L}{P_{ext}\,N\,(1-v^2)}\right)^{\frac{1}{3}} + 1}$$

Fig-6: Partially Deteriorated Gravity Pipe Calculation

Partially Deteriorated Pressure Pipe Calculation

In this case, the pipe may have displaced joints, cracks or corrosion. Again, the host pipe is assumed to support all soil and live loads throughout the anticipated remaining lifetime of the lined pipe. The liner in this case is expected to support the hydrostatic pressure due to leaking and support internal pressure at the hole spans. The hole spans are holes which may form in the host pipe at some point after the liner is installed and the bending stress around the hole created by the internal pressure pushing against the liner is what dictates the liner design thickness. The results of this case are typically compared against the partially deteriorated gravity liner thickness and the more conservative liner thickness (ie. thicker liner) would typically be selected.

t = liner thickness
D_O = pipe diameter
D_h = 2" hole in pipe
S_L = long term flexural strength
P_i = normal pipe pressure
N = safety factor

$$t = \frac{D_O}{\left(\frac{5.33}{\mathrm{P_i}}\left(\frac{D_O}{D_h}\right)^2 \frac{\mathrm{S_L}}{\mathrm{N}}\right)^{\frac{1}{2}} + 1}$$

Fig-7: Partially Deteriorated Pressure Pipe Calculation

Fully Deteriorated Pressure Pipe Calculation

In this scenario the liner thickness is specific to assume the liner will support all soil and live loads throughout the lifetime of the lining. The fully deteriorated gravity pipe equation should be reviewed and the most conservative number is selected when compared to the fully deteriorated pressure pipe calculation. For longer design life values, the pressure pipe condition tends to be the more conservative calculation when compared to the gravity pipe condition. Vacuum loads are not considered in this equation.

t = liner thickness
D = pipe diameter
S_{tL} = long term tensile strength
P_i = normal pipe pressure
N = safety factor

$$t = \frac{D}{\left(\frac{2\,S_{tL}}{P_i\,N}\right) + 1}$$

Flex strength based thickness for fully deteriorated, pressure pipes

Fig-8: Fully Deteriorated Pressure Pipe Calculation

Fully Deteriorated Gravity Pipe Calculation

In this final scenario, the liner thickness is specific to assume that the liner will support all internal and external pressures including soil, hydrostatic and live loads in addition to internal operating pressure. Negative (vacuum) pressure events, adhesion of the liner to the host pipe, hole spanning capability are not considered in this equation and ovality distortion of the host pipe is assumed to be < 10%.

t = liner thickness
D_O = pipe diameter
P_t = total external pressure
N = safety factor
E_L = long term flex modulus
C = ovality factor

R_W = water buoyancy factor
B' = coefficient of elastic support
E' = elastic support from soil
H_S = height of soil
H_W' = height of water

$$t = 0.721 D_O \left(\frac{\left(\frac{NP_t}{C}\right)^2}{E_L R_W B' E'} \right)^{\frac{1}{3}}$$

$$P_t = P'_W + P_S + P_L$$

$$R_W = 1 - 0.33\left(\frac{H_W}{H_S}\right) \geq 0.67$$

$$B' = \frac{1}{(1 + 4e^{-0.065 H_S})}$$

Flex Modulus/Buckling based thickness for fully deteriorated, gravity pipes

Fig-9: Fully Deteriorated Gravity Pipe Calculation

CONCLUSION

The benefits of direct condition assessment and engineered lining solution, offer the asset manager the opportunity to extend the life of aging pipelines at a fraction of the cost of open-cut replacement. The resultant product offers a range of improvements over the existing pipe which include:

1. Improved water quality
2. Improved throughput (hydraulic capacity)
3. Life extension (deferment of the cost of replacement for a considerable length of time, possibly equal to the expected life of a replacement pipe)
4. Complete knowledge of pipe condition before lining and ability to monitor the condition through subsequent DCA inspections (works through the liner)
5. Elimination of leakage (in and out) at joints
6. Ability, through the prior DCA, to use the *right* liner thickness

Further information about this approach can be obtained through any of the authors, 3M or PICA Corp.

References

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[V] *A game Plan for Aging Water Infrastructure (2010), Journal AWWA, 102:4*

[vi] *Water Main Break Rates in the USA and Canada (2012). Utah State Buried Structures Laboratory, S. Folkman, PhD.*