were just around the corner, historically marked by higher seasonal temperatures and an increased water demand. The remaining few weeks were spent performing visual and sounding inspections, removing 60 degraded mortar joints and repointing them, and recording stenciled pipe specification data from each stick of pipe in the 96-inch, 84-inch, 78-inch and 66-inch pipelines, essentially, the backbone of the transmission line system (Fig. 4, Fig. 5, Fig. 6).

Fig. 7 New Manhole

Fig. 8 Godwin Pump

Fig. 9 Pointing Joints

Fig. 10 Lining Cylinder

YEAR TWO (2000) TRANSITIONING FROM REACTIVE TO PROACTIVE

One year after the failure and still fresh in the minds of the Water Department, the media and the impacted community, the Tucson team continued to proactively learn and apply preventive maintenance practices, and begin to prepare the water transmission line for manned entry, with safe ingress, egress and working in the pipeline for extended periods of time. Several manholes were installed over manways for accessing the pipeline at key locations (Figure 7). In addition, several manholes were installed at key dewatering locations for efficiently dewatering the transmission line, and a large Godwin pump on a trailer purchased for dewatering syphons (Figure 8). Additional proactive work performed during the first year following the failure included removing the mortar of 260 joints that had prematurely failed (Figure 9). The last major task to occur during the year 2000 outage included applying a cement mortar lining to the inside of a 96-inch steel cylinder that had replaced the failed 72-inch butterfly valve (Figure 10). Later in the year, Tucson staff attended its first PCCP User's Group Meeting in Goodyear, Arizona. Inspection techniques discussed included visual inspections, hammer testing, soil surveys, acoustic monitoring, echo impact and remote field eddy current unit. All methods are non-destructive and produce various degrees of accuracy, comparatively. The attendees, however, displayed an overwhelming interest in the "remote field eddy current" method. In fact, much of the discussion centered on the necessity to calibrate the eddy current equipment to test pipe diameters greater than 96-inch. The eddy current equipment had been calibrated for most pipe diameters larger than 54-inch and smaller than the 96-inch. Several participants among the group committed to joint funding the calibration and furthering the use and study of the "remote field eddy current method" due to the proven success and results of the equipment.

Fig. 11 PPIC RFEC/TC (Electromagnetic Survey)

Fig. 12 PPIC REC/TC (Electromagnetic Survey)

YEAR THREE (2001) EMPLOYING PREVENTIVE AND PREDICTIVE MAINTENANCE

Just two years following Tucson's 96-inch pipeline failure, the electromagnetic technology continued to gain popularity in the industry, promising to locate and approximate damaged and broken wires within the wall of the prestressed concrete cylinder pipe. This new technology, Remote Field Eddy Current Transformer Coupling (RFEC/TC), was soon deployed in the Tucson PCCP transmission line system, ultimately establishing Tucson's first baseline survey of broken wires that wrap the City's embedded cylinder 66-inch, 78-inch, 84-inch and 96-inch PCCP (Figure 11 and Figure 12). This new "tool" in Tucson's toolbox became an important part of Tucson's asset management program plans. Nine pipe segments were located with broken wires ranging from 5 wire breaks to 30 wire breaks.

YEAR FOUR (2002) ADVANCING PREVENTIVE AND PREDICTIVE MAINTENANCE STRATEGIES

During the fourth year of Tucson's PPP, nine agencies teamed up to support a game changing research project that would approximate the remaining useful life of PCCP containing broken or damaged wires. The study would lead to the widely adopted and used "risk curves" or "failure curves" often used in the industry today to predict remaining useful life of one stick of pipe (Figure 13). The team included Tucson Water, Metropolitan Water District of Southern California (Metropolitan), Palo Verde Nuclear Generating Station, Calleguas Municipal Water District, Central Arizona Project, Tarrant Regional Water District, San Diego County Water Authority, and Denver Water. The team entered into a contract with Simpson Gumpertz & Heger Inc (SGH) for a study on *"Predicting Strength of Prestressed Concrete Cylinder Pipe with Broken Prestressing Wires"*. The American Pressure Pipe Association had funded the cost of hydrostatic pressure testing of pipes with broken wires (Figure 14).

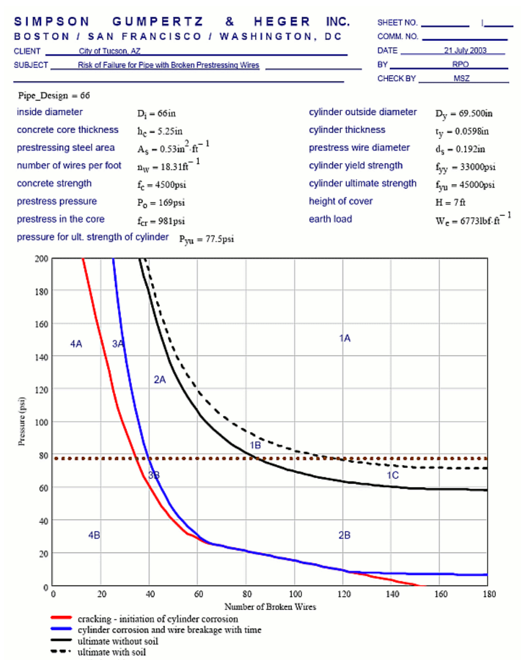

Fig. 13 SGH Risk Curve (Failure Curve)

YEAR FIVE (2003) REFINING PREVENTIVE AND PREDICTIVE MAINTENANCE STRATEGIES

In 2003 Tucson Water continued to expand its electromagnetic surveys to other PCCP within the water system, targeting a 54-inch diameter transmission line, vintage 1980. A relatively young pipeline at the time, Tucson was anxious to expand its asset management program, especially in areas where the transmission lines are within close approximation of residential areas, schools and major traffic routes. This transmission line, unlike most others in Tucson's

PCCP inventory, has access ports on the top, opposed to the springline of the pipe, making ingress and egress simpler.

Fig. 14 SGH PCCP FEM Agency Funded Study

Fig. 15 Pure Tech. 66” EM Survey

Fig. 16 Damaged Wires 66” PCCP

YEAR SIX (2004) INTEGRATING TECHNOLOGIES TO PREDICT AND PREVENT PIPE RUPTURES

In 2004 Tucson integrated and implemented several new asset management tools and technologies to predict and prevent catastrophic pipeline failure. The tools and technologies included hydrophone arrays, transient pressure monitors, pipeline risk management system, tendon repair methods for pipeline repair, and the much anticipated “risk” or “failure” curve. Of all these tools, the most awaited “tool” in the industry was the “risk curve” or “failure curve”, which was a byproduct of the recent study, *“Risk Analysis of Prestressed Concrete Cylinder*

Pipe with Broken Wires" (Zarghamee et al. 2003). As a participant in the study, Tucson received its first "risk curve" and was ready to apply this new tool to one of its monitored distressed pipes. The risk curve allowed Tucson to either intervene or continue to monitor distressed PCCP with broken wire regions. The transient pressure monitors allowed Tucson to measure the adverse effects of transients and surges on its PCCP inventory, especially areas of distressed pipe. In addition, Tucson had the transient events and knowledge control and could mitigate the damaging effects of pressure transients and surges. Equipped with a toolbox of tendons for repairing and rehabilitating distressed PCCP, transient pressure monitors (TP1 and TP3), and a GIS based pipeline risk management software system, Tucson began to pursue distressed pipe and proactively intervene when the risk of failure was determined too high. Beginning with a 66-inch PCCP with an estimated 30 broken wires based on Electromagnetic (EM) results, coupled with the risk curve produced by SGH, Tucson excavated and validated a damaged 66-inch embedded PCCP (Fig. 15). Upon excavation of the pipe, Tucson had located and validated the damaged pipe, caused by a third party drill rig many years earlier (Fig. 16). The repair method chosen was "tendon repair", a method of using 3/8" braded steel protected by a lubricant filled nylon sheath, installed in circumferential hoops, approximately 3" apart and coated with shotcrete (Fig. 17).

Fig. 17 66" Dia. Tendon Repair

Fig. 18 Hydrophone Installation

Fig. 19 AFO Installation

YEAR SEVEN (2005) USING ACOUSTIC FIBER OPTICS (AFO) AS INTERVENTION STRATEGY

During the seventh year of Tucson's asset management program for PCCP, acoustic fiber optics (AFO) technology was introduced to the North American industry (Fig. 19 and Fig. 20). This was another tremendous technological advancement to the industry and to Tucson's Pipeline Protection Program (PPP). The AFO permitted Tucson and other owners to monitor the health of its PCCP, and record any wire breaks that may occur in real time. Now, for the first time Tucson was able to combine nearly real-time wire break events, with the historical baseline of wire break events detected by EM, apply a risk curve for the particular design of PCCP, and start estimating the pipe's remaining useful life. With this important integration of technology, Tucson had all the right tools to manage its PCCP inventory. Tucson replaced its 2003 era hydrophone inventory with AFO (Figure 18).

Fig. 20 AFO Installation

YEARS EIGHT THRU THIRTEEN (2006-2011) TRUSTING IN TECHNOLOGY TO MANAGE RISK

With all of the industry best practice technologies in place, for the next several years Tucson continued to trust technologies to manage its PCCP inventory. The AFO system and transient monitoring system became the primary monitoring tools to avert pipeline failure, leading to 15 separate and distinct repairs on pipes ranging from 54-inches thru 96-inches in diameter. In 2010, Tucson applied its first Carbon Fiber Reinforced Polymer (CFRP) to rehab a 54-inch diameter PCCP, 20 foot in length. Tucson continues to use both tendon repair and carbon fiber repair for rehab and repair of its PCCP inventory.

YEAR FOURTEEN (2012) INVESTMENT IN TECHNOLOGY AND RETURN ON INVESTMENT

On August 17, 2012, 13 years following the catastrophic failure of the City's largest, most important water transmission line, Tucson Water experienced its biggest return on investment (ROI) since the implementation of its Pipeline Protection Program. Its single most important investment to date, acoustic fiber optics (AFO) for monitoring PCCP, alerted the City to 21 successive wire breaks over a 24-hour period, prompting the City to once again, shut down its largest most critical water transmission line (Fig. 21 and Fig. 22). However, this outage was without a catastrophic event that had previously cost the City approximately five million dollars in litigation and damage to infrastructure and private property. After promptly shutting the critical transmission line down, it was drained, inspected and the damaged area rehabbed with CFRP (Fig. 23)

Fig. 21 Internal Crack 96" PCCP

Fig. 22 Incipient Failure 96" PCCP

Fig. 23 Structural CFRP 96" Rehab

YEAR FIFTEEN AND SIXTEEN (2013 AND 2014) UPGRADING THE FIRST GENERATION AFO

Tucson Water's initial investment in acoustic fiber optics, considered the first generation of AFO, was approaching the end of its useful service life by 2013. Tucson decided not to delay the replacement and upgrade of this vitally important asset management tool and risk not having monitoring ability. In 2013 and 2014, Tucson replaced all of its acoustic fiber optic cables and computer data acquisition systems. From an owner's perspective, there's no better time to justify the expense of replacing such an important asset than when it's nearing the end of its service life, and just provided the biggest ROI since the implementation of the utility's asset management program.

YEAR SEVENTEEN THRU TWENTY (2015 THRU 2019) MAINTAINING INVESTMENTS AND STAYING THE COURSE

During the past five years, Tucson Water has continued to stay the course of its asset management program for PCCP and has begun to place more emphasis on valve reliability to ensure safe and reliable shutdowns of its transmission line systems. Butterfly valves that were problematic during the early years of the PPP have been refurbished with seat gasket replacements and refurbished actuators, making them safe and reliable. The vast majority of Tucson's PCCP inventory is performing well and considered "good pipe", while occasional segments displaying distress are monitored more closely. Tucson's reliance on technology and its approach to managing its PCCP inventory has resulted in a cost-effective program, employing just four fulltime employees.

CONCLUSION

In February of 1999, the City's largest potable water transmission line, a 96-inch diameter (4000 mm) prestressed concrete cylinder pipeline (PCCP) failed catastrophically, releasing a flood of water, mud, rock and debris, crashing into a neighborhood, knocking down block walls, trapping people in homes, floating vehicles out of driveways and causing extensive damage to private property and homes within the community. This one failure of a pipeline just 11 years old, cost the City approximately five-million dollars in private property damage, collateral damage and litigation, and forced the City to revert back to pumping native groundwater for months, until the transmission line was restored to service. Just weeks after the historic failure, the Maintenance Division, under the direction of Operations Superintendent, Britt Klein, began the infancy stages of an asset management program for concrete pressure pipelines, beginning with its largest most critical water transmission lines, Prestressed Concrete Cylinder Pipe (PCCP), diameters 48-inch, 54-inch, 66-inch, 72-inch, 84-inch and 96-inch. The details and steps taken over several years following the historic failure are bulleted below.

- Year 1999 Performed visual and sounding inspections, recorded stencil specs and pipe numbers from pipe walls, repaired 60 mortar joints, began installing manholes.
- Year 2000 Continued installing manholes, repaired 260 mortar joints, attended first PCCP User's Group Meeting.
- Year 2001 Performed Remote Field Eddy Current Transformer Coupling (RFEC/TC) Inspections and jointly funded the calibration of RFEC technology for 96-inch PCCP
- Year 2002 Jointly funded study *"Risk Analysis of Prestressed Concrete Cylinder Pipe with Broken Wires."*
- Year 2003 Tucson Water expands electromagnetic inspections to 54-inch diameter PCCP.
- Year 2004 Began installing hydrophone arrays, transient pressure monitors, pipeline risk management system, tendon repair methods for pipeline repair, and the much anticipated "risk" or "failure" curve for predicting incipient failure of PCCP.
- Year 2005 Began installing Acoustic Fiber Optics (AFO) systems in Tucson's PCCP.
- Year 2006 Continued the installation of AFO. Began validating EM predicted wire break regions.
- Year 2007 Continued the expansion of corrosion monitoring and impressed current systems on Tucson's concrete pressure pipe inventory.
- Years 2008-2011 Performed multiple interventions and rehabilitations of distressed pipe.
- Year 2012 Tucson realized largest ROI since program inception by averting 96-inch incipient failure adjacent residential community.
- Years 2013-2019 Tucson Water stays the course of monitoring its PCCP inventory with AFO being the most relied upon tool outside of good project management.

For more than 20 years following the City's largest, single most costly pipeline failure in its history, Tucson Water has been able to prevent a catastrophic failure (burst) of its single most important water transmission line, through the implementation of current technologies, best management practices, and good leadership. Twenty years later, Tucson continues to be a leader in the industry, and a model for best practice asset management.

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Balancing Present and Future Needs

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ABSTRACT

Accommodating future needs is an important consideration for a well-planned pipeline system because of the long-term lifecycles of the infrastructure. However, this process can also result in overdesign with respect to the present. Technology historians have identified several dynamics that are involved in the resolution of this tension between present and future needs. Using these dynamics, this paper proposes an analytical methodology to defensibly balance them. The goal of the approach is to set the vision for the pipeline infrastructure plan in a way that makes the best long-term use of available funding. To quantify this, present worth analysis is used to scrutinize preferred design approaches against other alternatives. The output seeks to identify hidden lifecycle costs from future needs that may warrant approach reconsideration. The methodology is applied to critique past decisions in the design of wastewater collection systems. In addition, it is presented as a viable tool to assist with sustainable decision-making.

INTRODUCTION

Pipeline networks play unique, yet crucial roles in sustainable development, as these are the primary vehicles for the transport of water, energy, and many other materials. Their effectiveness will determine our success at mitigating droughts, sea level rise, energy shortages, and other societal imperatives. Furthermore, they are often embedded at the deepest levels of the built environment and thus are expected to sustainably meet future needs beyond the immediate design context. Sustainability doesn't have one meaning, but the familiar 1987 United Nations definition illuminates a central insight:

> "Development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

Despite its insight, balancing present and future needs is often difficult to demonstrate concretely in decision making. Committing real, up-front funds to an uncertain future seems poorly compromised, but failing to plan offers no improvement. As a result, the pipeline engineer encounters a significant paradox while striving for sustainable design. However, resolving this paradox is coupled with a compelling opportunity to influence the broader whole of the engineering profession.

INFRASTRUCTURE DYNAMICS

Understanding the conflict between present and future needs may seem to require clairvoyant foresight, yet the paradox is often clarified remarkably in hindsight. Engineering historians, authors, and researchers have analyzed histories of diverse engineering systems to inform a set of general principles of historical change. These time-based principles are known as infrastructure