the Energy to Lead

DTPH5615T00007
Project 643

Slow Crack Growth Evaluation of Vintage Polyethylene Pipes

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Project Debrief Webinar

November 1st 2017

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Public Concern Over Vintage Plastic Pipe in Gas Distribution Systems

As early as 1982 , the industry was made aware of the vulnerability of pre-1973 Aldyl A pipe to premature failures due to brittle-like cracking (slit or fracture due to SCG). In 1986, squeeze-off was identified as a factor increasing the risk of SCG failures. Several significant incidents related to SCG failures in vintage plastic pipe prompted the NTSB to issue a special investigative report in April 1998 . **The report pointed out the deficiencies in the ASTM methods for rating plastic piping. The general pressure based design approach may have also over-rated the strength and resistance of plastic pipe to brittle-like cracking**. PHMSA issued a series of safety advisories related to plastic pipe and fittings (ADB-99-01, ADB-99-02), 2002 (ADB-02-07) and 2007 (ADB-07-01).

In 2011, two gas incidents occurred in rapid succession in California; Cupertino (August 31, 2011) and Roseville (September 27, 2011). This led the California Public Utilities Commission (CPUC) on March 14, 2012 to identify early vintage Aldyl A pipes as a major potential hazard affecting gas pipeline safety .

Slow Crack Growth Evaluation of Vintage Polyethylene Pipes: Objective

Project structured to address NTSB concerns about design methodologies for plastic pipe and the various PHMSA Safety Alerts

Slow Crack Growth Evaluation of Vintage Polyethylene Pipes

Main Objective

Develop an integrated set of quantitative tools that will provide a structured approach to reducing operational risk in vintage plastic distribution systems susceptible to Slow Crack Growth failures. The tools will provide a probabilistic estimate of the remaining effective lifetime of individual segments of vintage plastic pipe and a yes/no determination of whether a short-term pressure test is capable of validating the maximum defect size in the system.

Public Abstract

This collaborative program will provide an integrated set of quantitative tools that will provide a structured approach to reducing operational risk in vintage plastic distribution systems susceptible to Slow Crack Growth failures. A novel endoscopic structured light scanning tool will be developed and prototyped for internal inspection of small diameter plastic pipe. The data generated by the tool will be properly reduced to essential parameters to be synthesized with additional available system information including external conditions, inspection and leak records, historic data, and subject matter expertise into a fitness for service evaluation. This assessment will include a probabilistic estimate of the remaining effective lifetime of individual segments of vintage plastic pipe and a yes/no determination of whether a short-term pressure test is capable of validating the maximum defect size in the system. The Bayesian network methods employed are ideally suited to evaluating interacting threats, investigating root causes, and predicting the effect of mitigation strategies based on conditional probabilities calculated from available data.

FINAL REPORT

DTPH5615T00007 Prj643 Final v2

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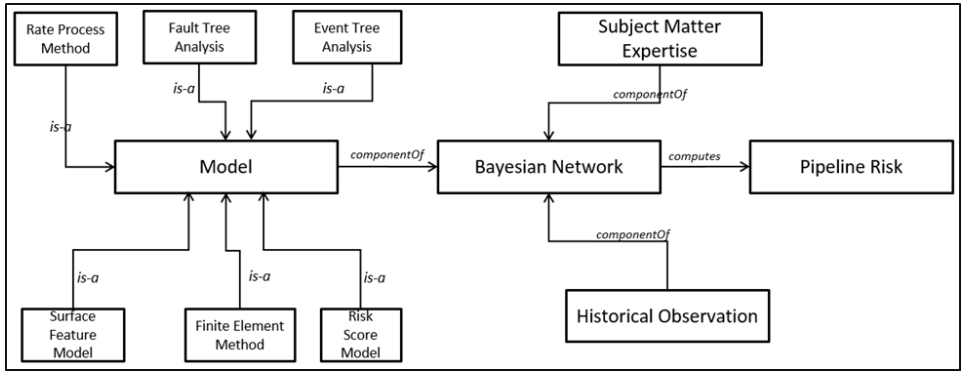
Objective: Integrated Set of Quantitative Tools 1

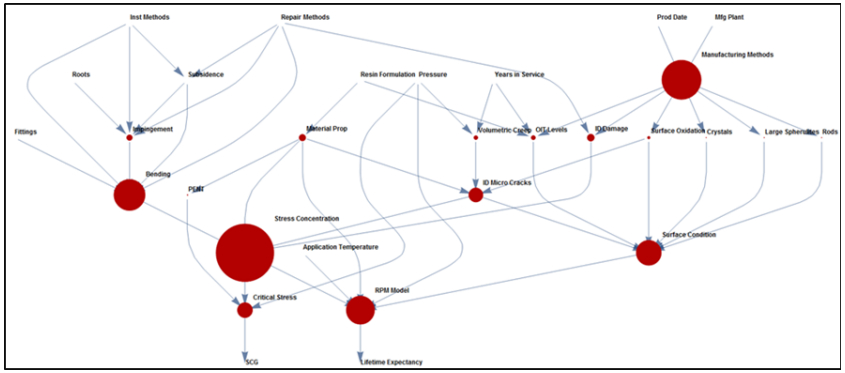
Provide a structured approach to evaluating the latent risk in vintage polyethylene pipes, such as Aldyl-A, that are common in gas distribution systems:

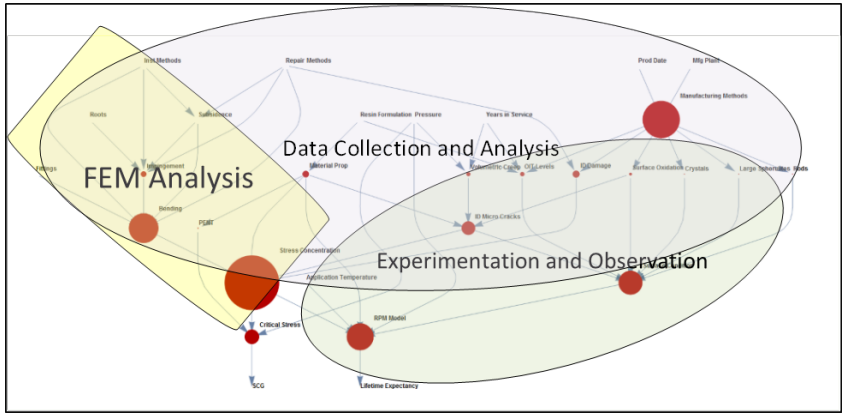
> Hybrid causal Bayesian network that:

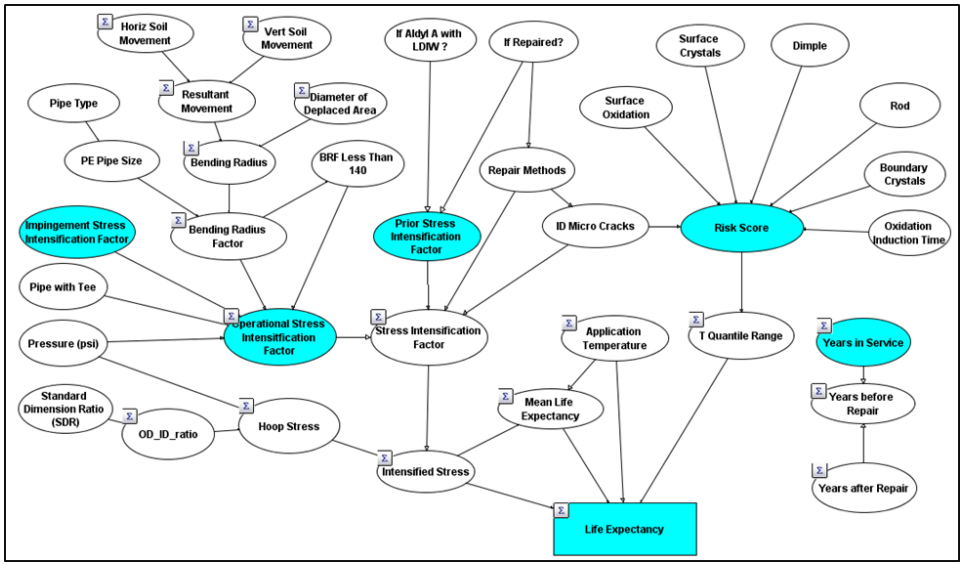
- Allows the synthesis of subject matter expertise with well understood physical causation pathways to failure
- Logical structures inherently integrate disparate data sources into a coherent framework for decision support
- Readily updated as new information becomes available.

Constructing the Bayesian Network

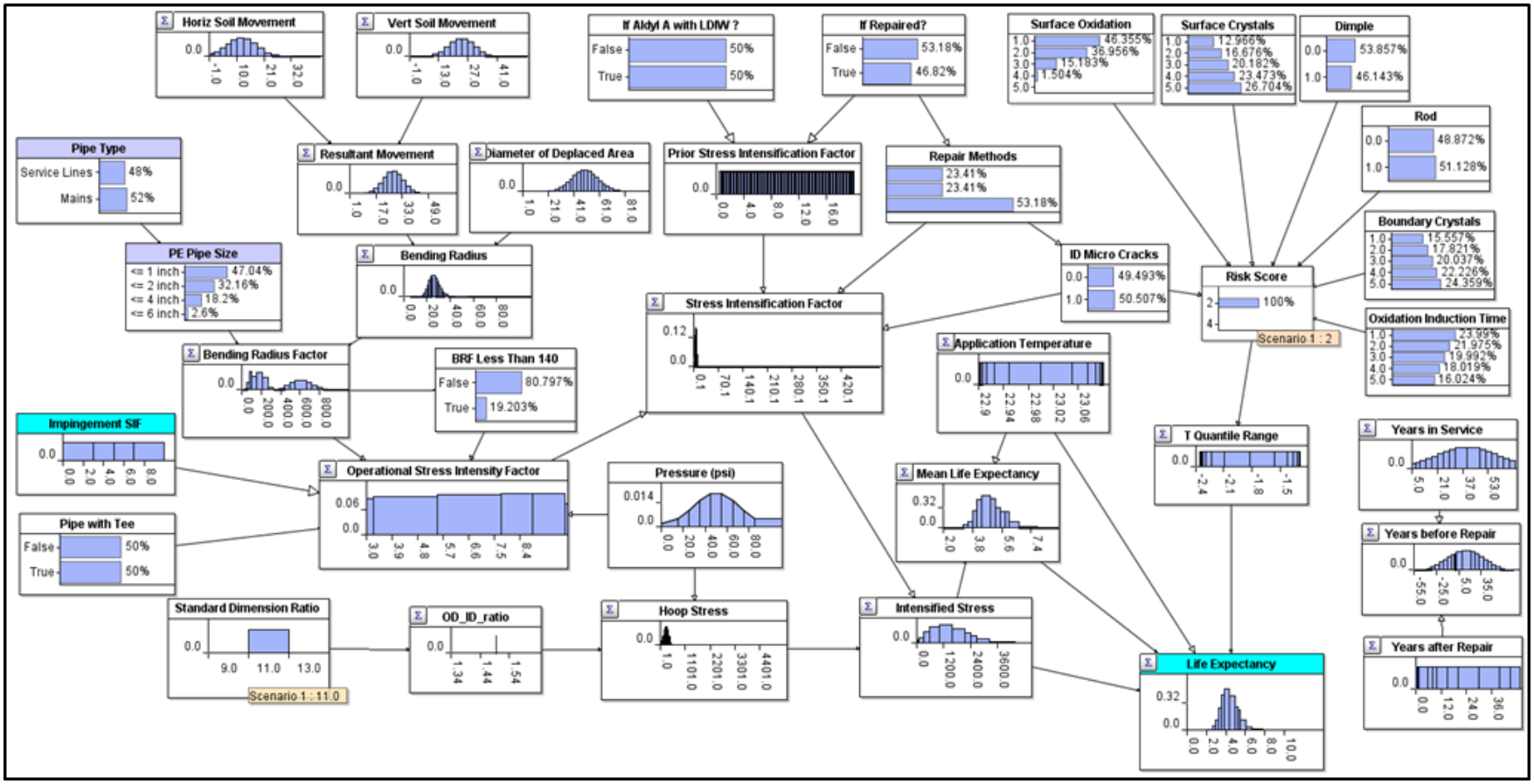








Probabilistic Model for Lifetime Expectancy

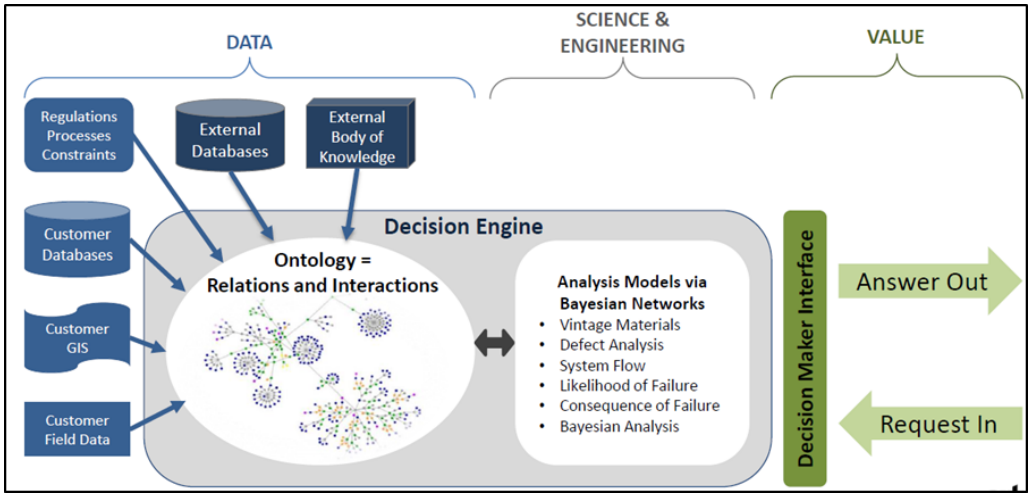


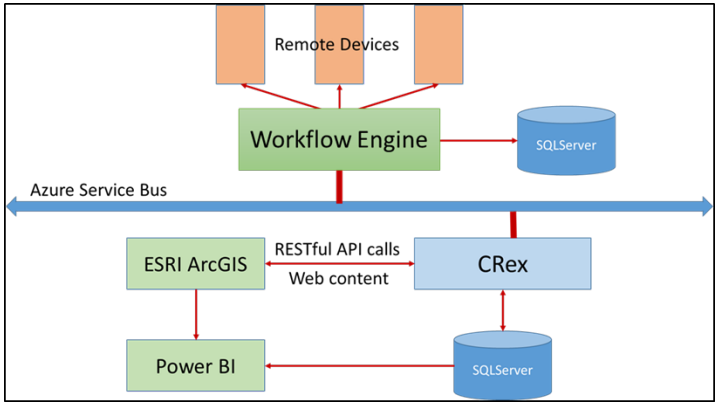
Objective: Integrated Set of Quantitative Tools 2

From the outset, the project was structured around developing software agents that are modular and can be integrated into any decision support framework.

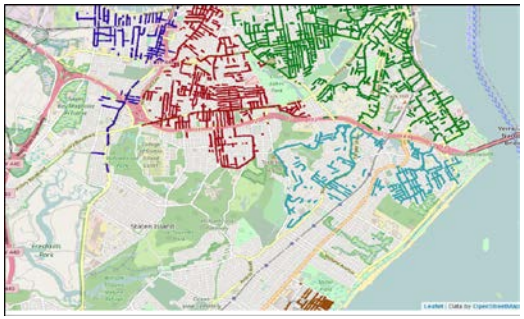
- The framework chosen in this project was a commercially available Artificial Intelligence (AI) platform that has built in ability to deal with any given business logic.
  - The Bayesian networks developed in this project were successfully integrated into the AI framework
  - Used to assess risk dynamically on a synthetic geographical dataset with over 7,000 data elements

Integrated Analysis Tools





Probability of Failure within 5 years	Number of Segments	Percent of Segments	Cumulative %	Average Years in Service	Linear Feet	Replacement Cost	Cumulative Replacement Cost
90%+	183	2.38%	2.38%	51.8	12,426	$2,795,756	$2,795,756
80-90%	975	12.66%	15.03%	44.1	82,997	$18,674,363	$21,470,118
70-80%	985	12.79%	27.82%	44.0	81,316	$18,296,065	$39,766,183
60-70%	993	12.89%	40.71%	44.1	88,431	$19,896,967	$59,663,150
50-60%	398	5.17%	45.88%	40.4	31,286	$7,039,312	$66,702,463
40-50%	218	2.83%	48.71%	44.1	16,707	$3,759,120	$70,461,583
30-40%	64	0.83%	49.54%	43.9	4,141	$931,670	$71,393,253
20-30%	1,162	15.09%	64.62%	45.3	121,652	$27,371,634	$98,764,887
10-20%	1,494	19.40%	84.02%	37.0	131,774	$29,649,092	$128,413,979
<10%	1,262	16.38%	100.40%	40.7	123,825	$27,860,680	$156,274,660



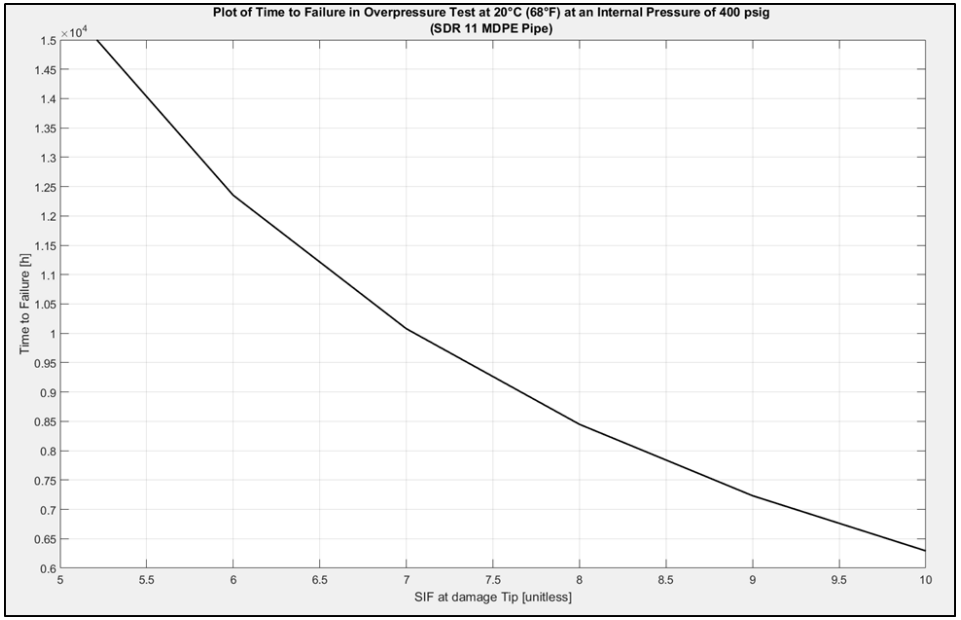
Objective: Fitness for service approach that can support replacement prioritization

- A Stress Intensification Factor (SIF) based approach was developed for fitness for purpose determination
- Two decision support approaches were developed:
  - Reliability based maintenance models based on a fracture mechanics damage propagation approach
  - Bayesian network approach that integrates pipeline configuration, loading conditions and material models was used to predict expected lifetime for pipeline segments.
  - Both approaches were validated against historic data sets and shown to be equally effective.
- The material models were used to show that there is no effective pressure test approach to support pipeline replacement prioritization for polyethylene pipe.
  - The lifetime expectancy of components given the available data inputs into the detailed material models developed in this project is the only viable option for enhancing decisions aimed at ensuring system integrity

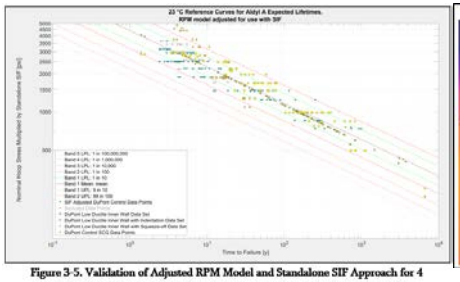
SIF, Damage Propagation, Short-Term Pressure Test

Table 3-2. Adjusted SIF for use with Adjusted RPM Model

Adjusted SIF for SCG Failure: Logistic Distribution Parameters for use with adjusted RPM model given in Table 3-1	Standalone SIF		Relative to baseline pipe SIF	
	Mu	sigma	Mu	sigma
Pipe Quality Tier 1 SCG – Baseline SIF	1.016	0.061	1.016	0.061
Use standalone SIF value for single SIF. Develop composite SIF by adding SIF referenced to baseline using Equation 2-5 for each independent SIF component acting on pipe component to the baseline SIF				
Pipe Quality Tier 2 SCG	1.117	0.067	0.461	0.028
Pipe Quality Tier 3 Severe Grooves SCG	1.524	0.091	1.136	0.068
Pipe Quality Tier 4 LDIW SCG	2.936	0.176	2.755	0.165
LDIW Squeeze-off SCG	3.401	0.204	3.246	0.195
LDIW Impingement SCG	4.367	0.262	4.247	0.255



1. Determine vertical shift factors by aligning control ductile data to RPM mean line
2. Determine horizontal shift factors by aligning control SCG data to RPM mean line
3. Shift all data sets to reference temperature of 73.4°F using adjusted shift factors
4. Calculate intercepts for lines of slope equal to control ductile model that pass through all control ductile points
5. Calculate nominal ductile SIF by dividing actual shifted hoop stress by mean stress calculated from model
6. Calculate adjSIF ductile relative to the worst performing point – the point with smallest intercept calculated above
7. SIF3=3*SIFadj to peg worst point to FEM SIF for pipe with sharp scoring from extrusion process that asymptotically tends to 3
8. Calculate instantaneous ductile yield stress from RPM model adjusted to pass through best performing data point
9. Calculate nominal SCG SIF by dividing actual shifted time by mean time calculated from control SCG model
10. Calculate adjSIF SCG relative to the best performing SCG data point
11. Adjust the mean of the SCG adjSIF distribution to be equal to the mean of the ductile adjSIF distribution by adding the difference between means
12. Multiply the shifted hoop stress the adjSIF and divide the result by the ductile yield to identify points with immediate damage propagation
13. Use the points with immediate damage propagation to fit a propagation time as a function of SIF and Hoop Stress (near and far field stress)
14. Use the points without immediate damage propagation to fit a crack initiation time as a function of near and far field stress model
15. Use the propagation time model to identify what circumstances can be identified in a short term over pressure test



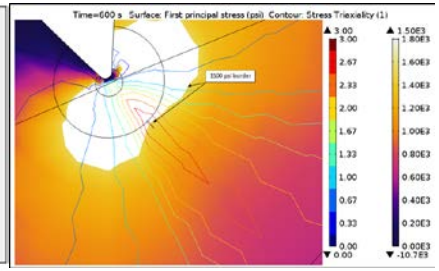
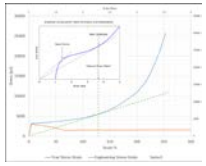
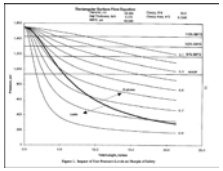
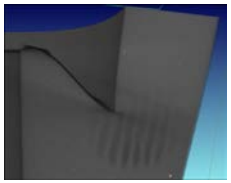


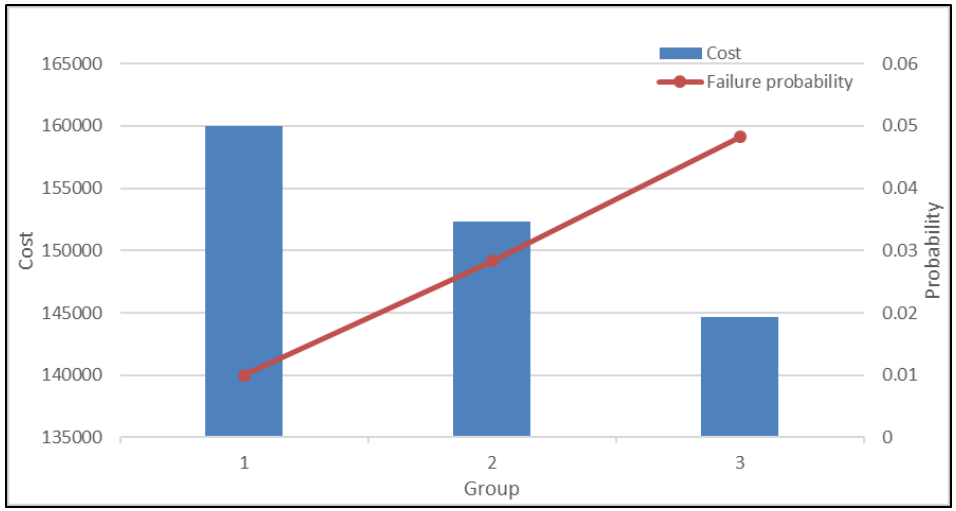
Figure 3-5. Validation of Adjusted RPM Model and Standalone SIF Approach for 4 Independent Datasets with Different Intrinsic Defects and Loading Conditions

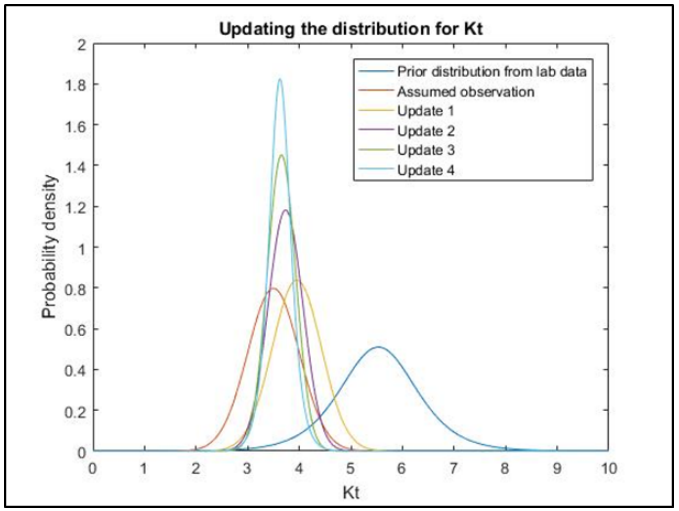


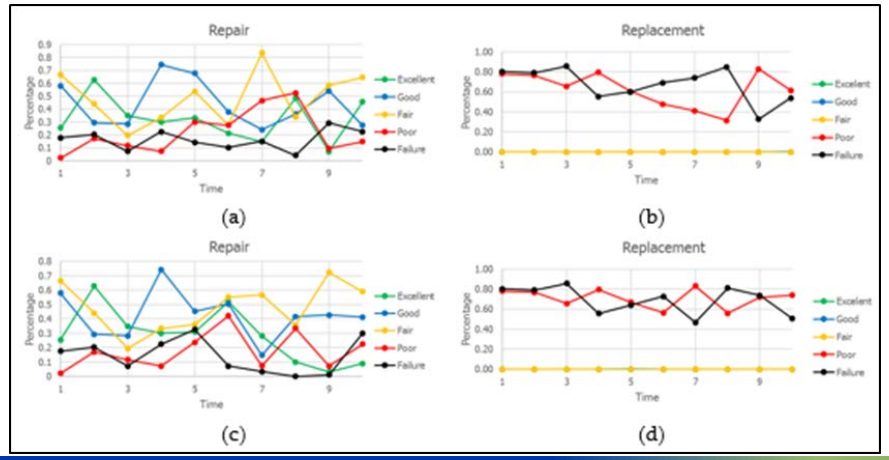


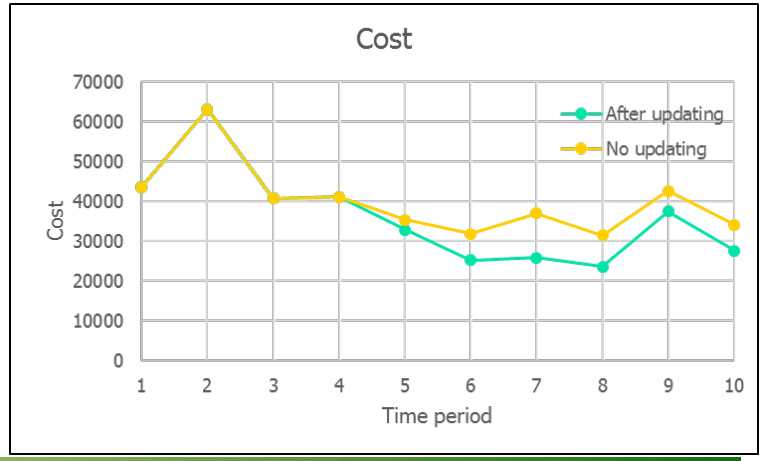


Reliability Based Maintenance Optimization





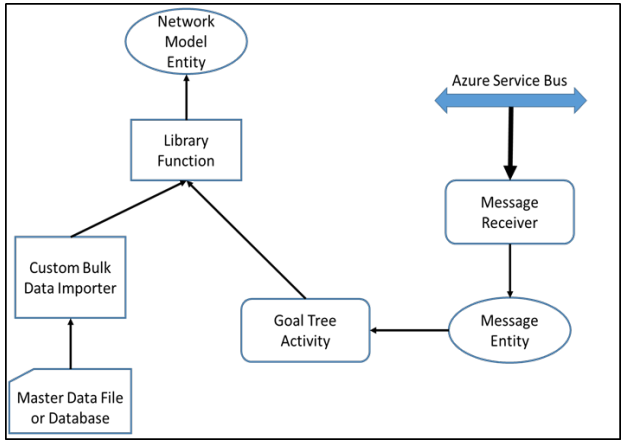


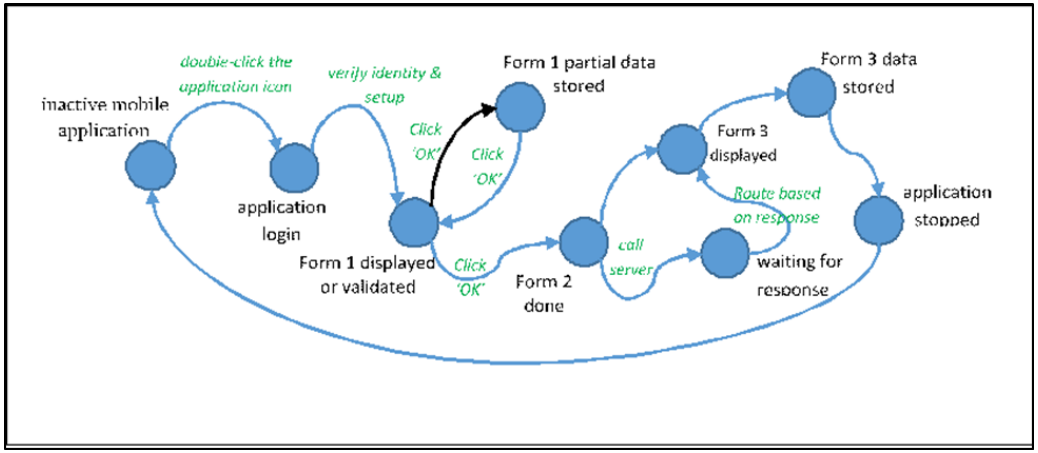


Objective: Utilize data from multiple sources such as in ditch condition assessment and leak records

- Intelligent data entry forms were developed and integrated into the AI framework to capture disparate data and route the data to the relevant models.
- Bayesian updating of the model output, after this data was input via the forms, was demonstrated

Intelligent Data-Entry Forms





Use Case: Field Collection Activities

Pre-Conditions	Step	Outcomes
From Cognitive Data Collection Use Case Field collection activity selected	1 **Collect Data for Page 1**	Required data collected
Page 1 data collected	2 **Collect Data for Page 2**	Required data collected
Page 2 data collected	3 **Collect Data for Page 3**	Required data collected
...	4 **Collect Data for ...**	Required data collected
All required data has been collected Technician initiates save and upload	5 **Data Saved to Local Device**	Data saved on local device: Geo-location Timestamp Collected data **To Cognitive Data Collection Use Case** Report data collection completed
Field collection data saved locally Connection established to remote server	6 **Upload Report to Remote Server**	Report saved on remote server

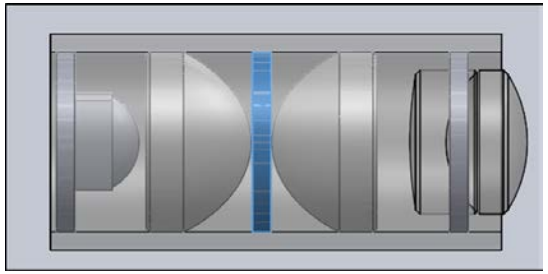
Use Case: Workflow Management

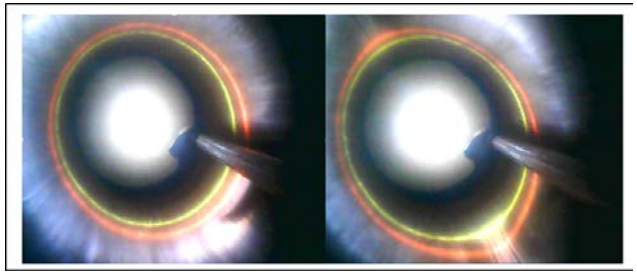
Pre-Conditions	Step	Outcomes
Link established to host server	1 **Open Application**	Application authentication screen appears
Configuration Developer enters identifying credentials	2 **User Authentication**	User ID, organization, and role has been validated for Configuration Developer access
Authorized Configuration Developer Business modelling tools	3 **Design and Test Workflow**	Tested new or updated data collection workflow
Tested workflow update Approval for deployment	4 **Schedule Workflow Updates**	Workflow updates ready to be pushed to mobile devices
Connected mobile device One or more workflow updates available	5 **Deploy Workflow**	Workflow updated on mobile device, deployed on subsequent data collections

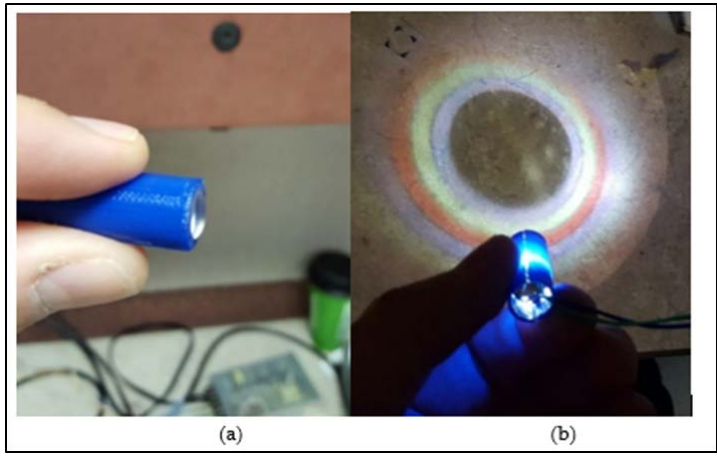
Objective: provide a means to access the pipe in a congested urban environment

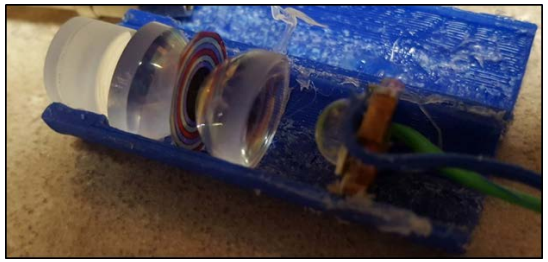
- Several variants of prototype endoscopic structured-light cameras were developed to measure pipe geometry from inside the pipe
- The cameras developed are small enough to insert into 1” IPS diameter tubing and are suitable for integration into existing keyhole methods for accessing pipelines in congested urban environments
- The project demonstrated that these cameras can identify several common geometric features consistent with pipeline anomalies known to introduce significant stress risers that drive pipeline failure via Slow Crack Growth (SCG)
- Feature recognition and data reduction methods were developed for the massive amounts of data acquired by the endoscopic tool

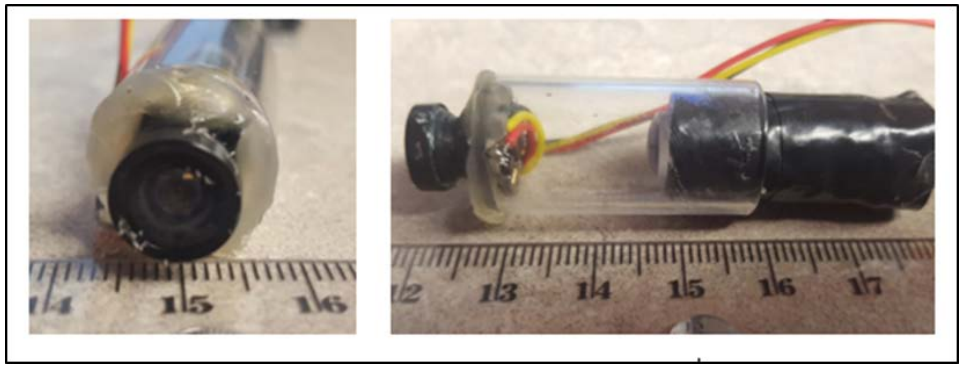
Miniaturized Scanning Device

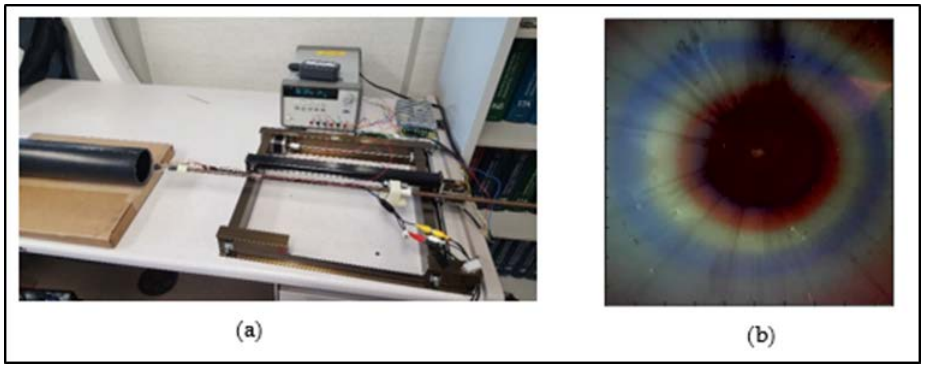




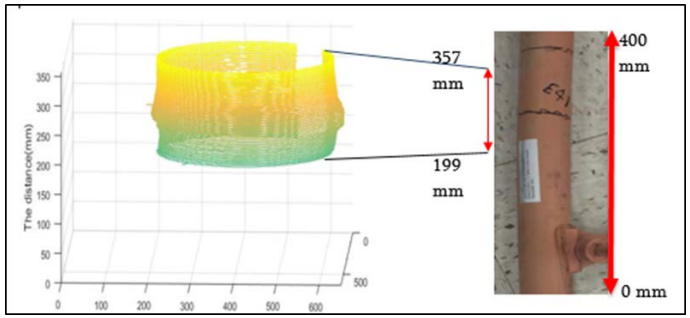


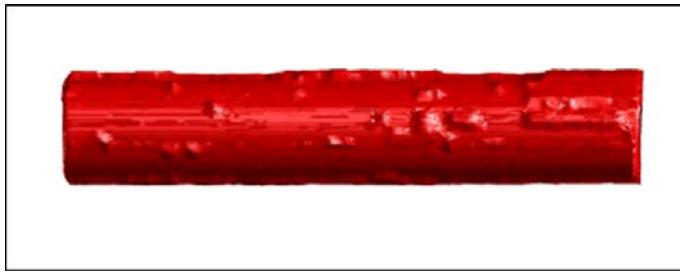


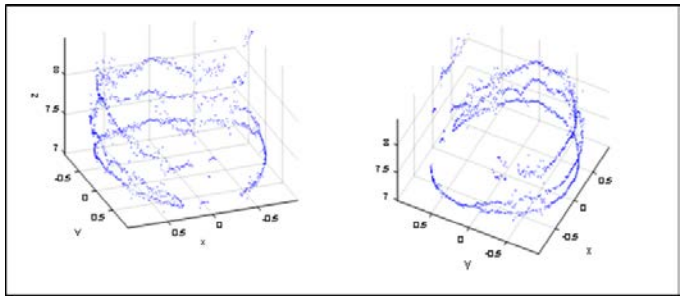


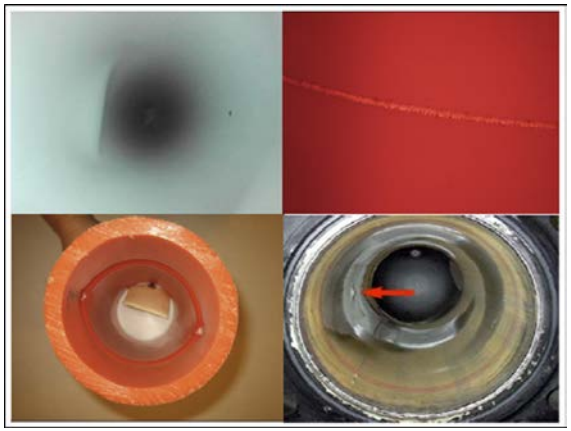


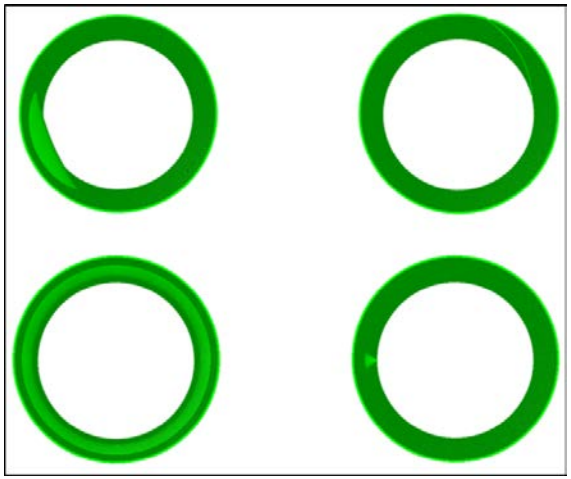
Reconstruction of Pipe Damage from Scans

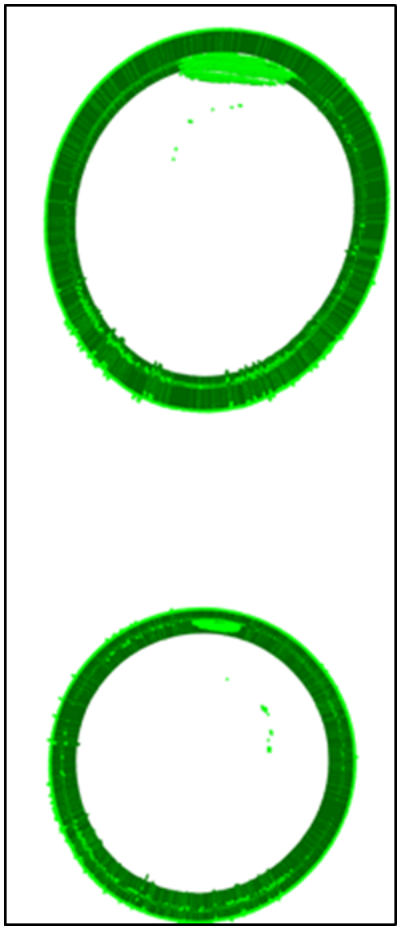








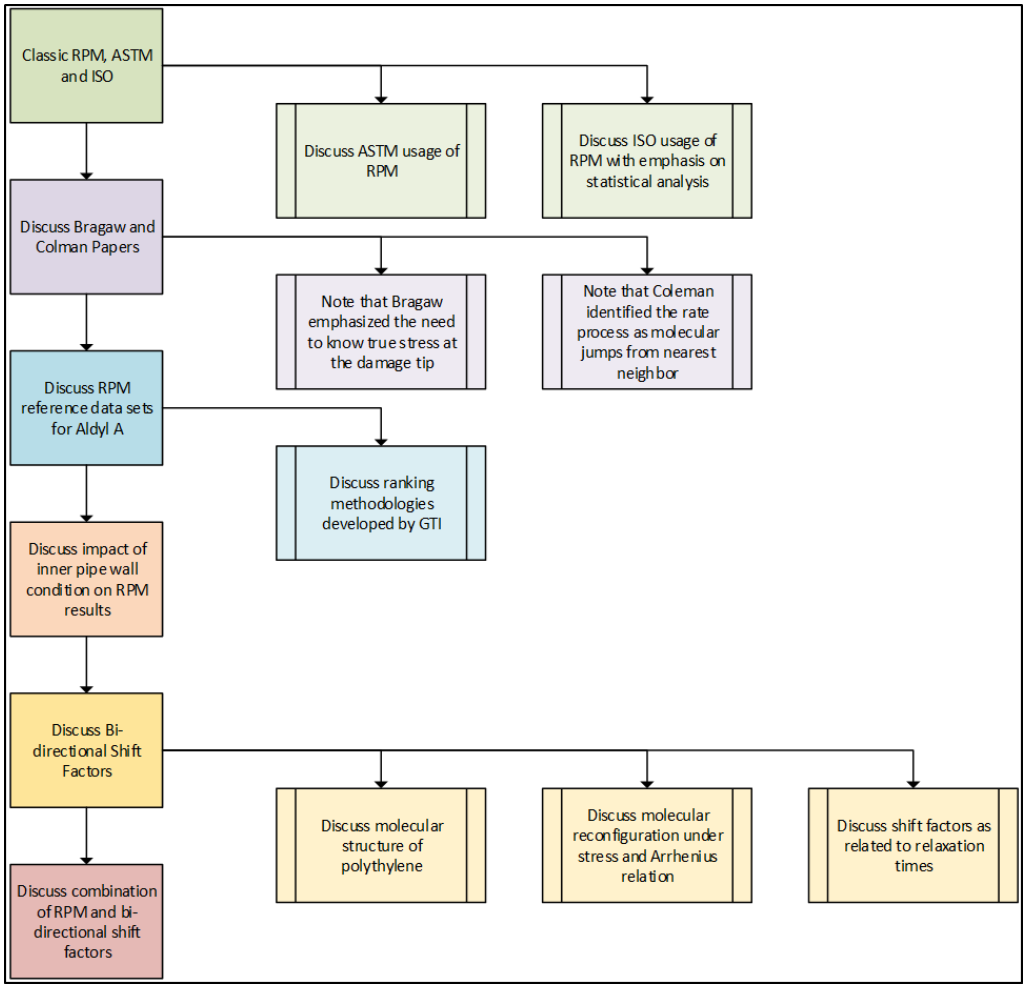


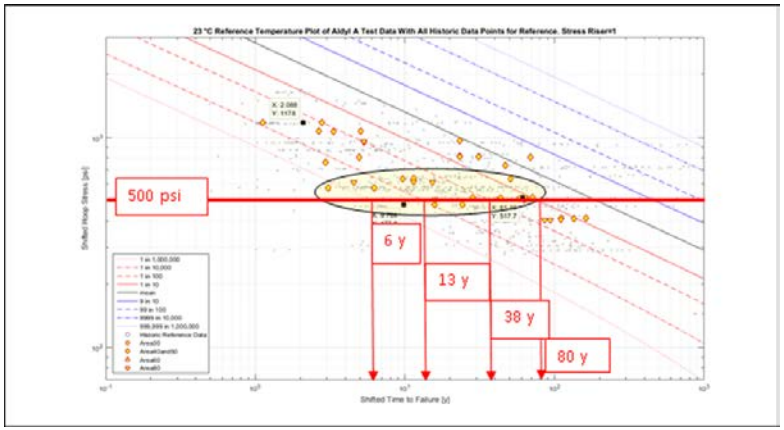


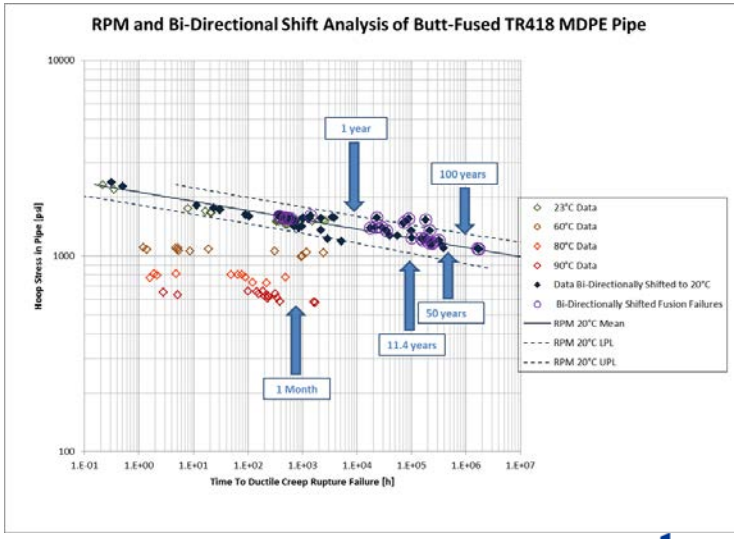
Final Report Sections 1-2 and Deliverables

Report Section	Topics Covered and Deliverables
Section 1: Rate Process Models (RPM) for Aldyl-A Piping Systems	**Topics:** 1. Rate Process Method a. Ranking methods b. Impact of inner wall surface on RPM 2. Polyethylene structure and molecular motion 3. Bi-directional shift factors
	Deliverables: 1. Reference RPM model for Aldyl A 2. Model for correlating surface condition to RPM ranking 3. Validated bi-directional shift factors for Aldyl A and other polyethylene materials
Section 2: Stress Intensification Factors (SIF) for Aldyl-A Piping Systems	**Topics:** 1. Failure mechanism of polyethylene 2. Variance of stress in polyethylene pipes 3. What is a SIF
	Deliverables: 1. SIF for various polyethylene piping configurations 2. Probability distributions for SIF in polyethylene piping systems with a quantification of uncertainty for the mean 3. Method for combining multiple SIF in a coherent manner

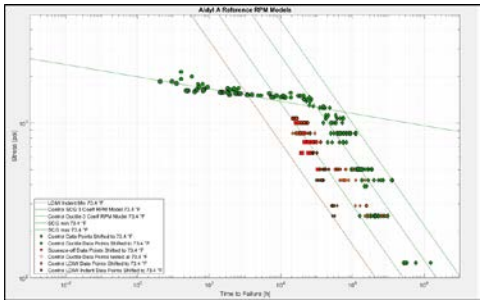
Section 1 – RPM, Master Curves

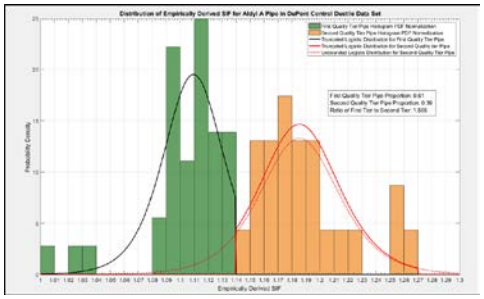


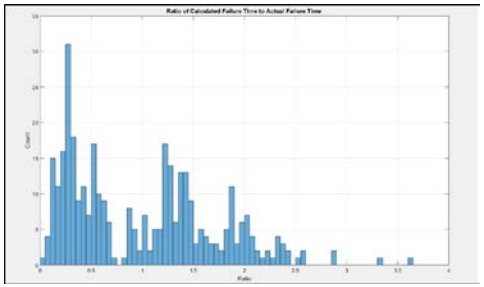


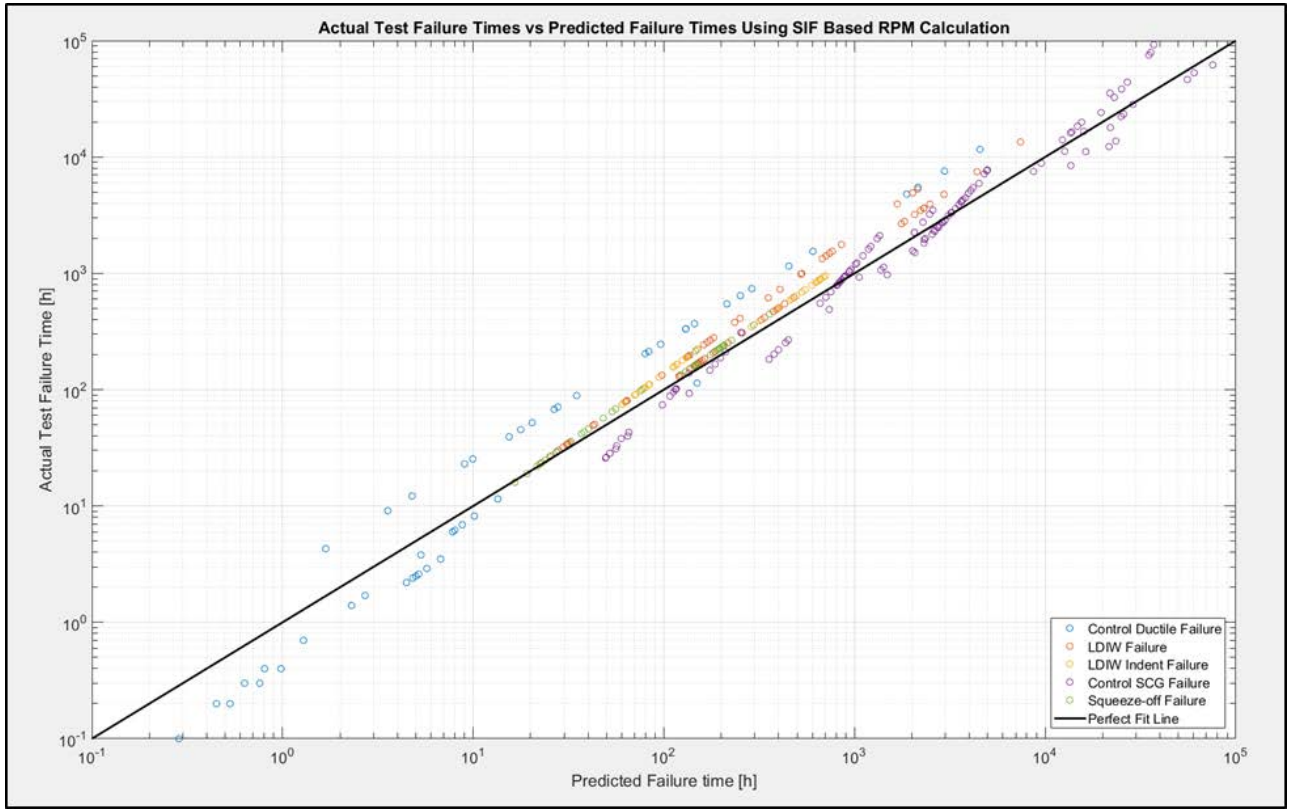


Section 2, SIF – Reducing Uncertainty in Data Analysis





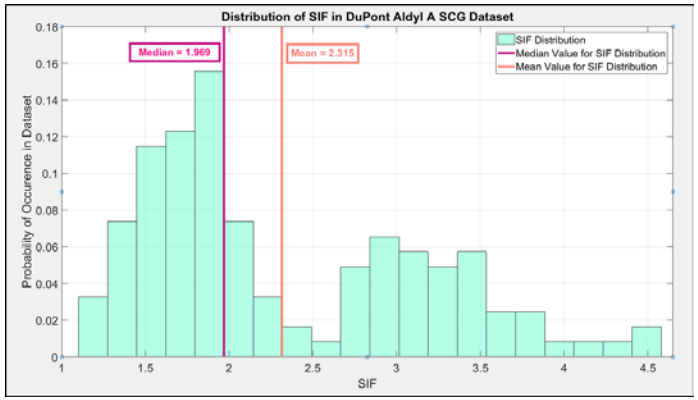


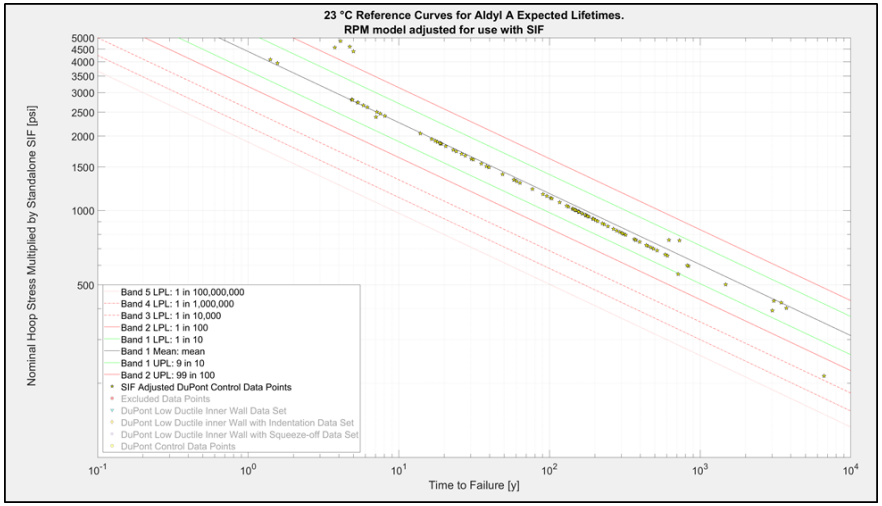


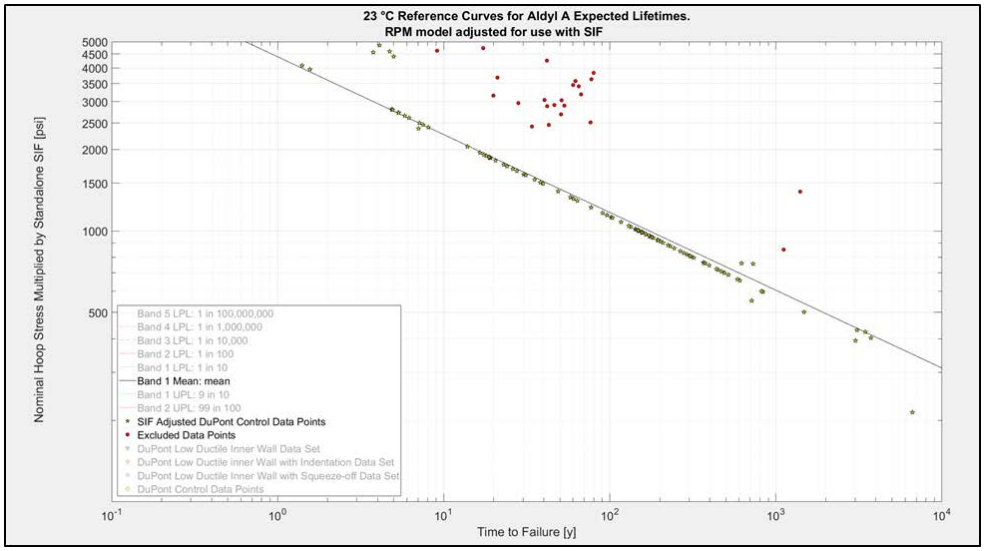
Final Report Sections 3,4 and Deliverables

Report Section	Topics Covered and Deliverables
Section 3: Adjusted RPM Models for Use with Aldyl-A SIF	**Topics:** 1. Need to adjust the control RPM model to account for distribution of SIF included in the dataset 2. Need to calibrate standard SIF distributions for use with the adjusted RPM model 3. Validation of the adjusted RPM model and calibrated SIF **Deliverables:** 1. Universal model for SCG failure mode of Aldyl A pipe 2. Calibrated SIF for known pipe conditions 3. Validation of model and SIF over four independent reference datasets
Section 4: Bayesian Network Model for Aldyl-A Lifetime Expectancy Systems	**Topics:** 1. Causal mechanisms for generating stress fields in Aldyl A pipe 2. Methodology for addressing interacting causal factors 3. Calibration of Bayesian network to reference datasets **Deliverables:** 1. Comprehensive expert system for Aldyl A piping systems that addresses all interactions 2. Calibrated and validated Bayesian network for predicting lifetime expectancy of Aldyl A piping segments

Section 3, Adjusting RPM Models for Use with SIF







Adjusted SIF for SCG Failure: Logistic Distribution Parameters for use with adjusted RPM model given in **Table 3-1**	Standalone SIF		Relative to baseline pipe SIF	
	Mu	sigma	Mu	sigma
Pipe Quality Tier 1 SCG – Baseline SIF	1.016	0.061	1.016	0.061
Use standalone SIF value for single SIF. Develop composite SIF by adding SIF referenced to baseline using **Equation 2-5** for each independent SIF component acting on pipe component to the baseline SIF				
Pipe Quality Tier 2 SCG	1.117	0.067	0.461	0.028
Pipe Quality Tier 3 Severe Grooves SCG	1.524	0.091	1.136	0.068
Pipe Quality Tier 4 LDIW SCG	2.936	0.176	2.755	0.165
LDIW Squeeze-off SCG	3.401	0.204	3.246	0.195
LDIW Impingement SCG	4.367	0.262	4.247	0.255

Final Report Sections 5-8 and Deliverables

Report Section	Topics Covered and Deliverables
Section 5: Structured Light Method for Internal Inspection of Aldyl-A Pipe	**Topics:** 1. Development of endoscopic structured light tool for internal inspection of gas distribution pipe 2. Algorithms for detecting and categorizing internal pipeline defects and geometry 3. Motion detection and distance measurement 4. Data reduction techniques **Deliverables:** 1. Working prototype of endoscopic structured light tool for internal inspection of gas distribution pipe 2. Algorithms for damage detection and classification 3. Data reduction methods
Section 6: Damage Detection from Optical Imaging, Creep-Crack Growth Prediction, and Condition-based Maintenance Framework for Aldyl-A Pipes	**Topics:** 1. Image reconstruction and damage classification 2. Bayesian maximum entropy network 3. Creep crack growth prediction 4. Maintenance frameworks **Deliverables:** 1. Algorithms for image reconstruction 2. Working Bayesian maximum entropy network 3. Validated creep crack growth model for lifetime prediction for Aldyl A pipe segments 4. Framework for optimizing maintenance of Aldyl A piping systems i.e. repair/replace balance

Report Section	Topics Covered and Deliverables
Section 7: Enterprise Decision Support System (EDSS) Framework	**Topics:** 1. Semantics of decision support framework for Aldyl A piping systems 2. Probabilistic decision support framework 3. Data entry 4. Simulation 5. Insights 6. Query 7. Communication **Deliverables:** 1. Functioning enterprise decision support framework that incorporates the Bayesian network developed in section 4 2. Smart forms for data entry 3. Insights and analytics framework 4. Data reporting framework
Section 8: Feasibility of Using a Short-Term Pressure Test to Determine Fitness for Service in the Context of Slow Crack Growth Systems	**Topics:** 1. Historic usage of short-term pressure tests in determining fitness for service of gas transmission pipe 2. Applicability to plastic gas distribution pipe 3. Localized damage propagation in plastic pipe **Deliverables:** 1. Conclusion that short-term testing is not a viable fitness for service test for plastic gas distribution pipe 2. Explanation of reasons why the method is not viable

Final Report Sections 9,10 and Deliverables

Report Section	Topics Covered and Deliverables
Section 9: Summary and Recommendations	**Topics:** Summarizes technical achievements and recommends utilizing the methods developed in the project to transition to probabilistic, reliability based risk assessment methods. Recommends establishing a Joint Industry Program (JIP) to develop guideline for this transition. Recommends that the JIP oversee the commercialization and deployment of the structures light scanning tool that can be integrated into existing keyhole technologies
Section 10: Recommendations for Future Work	**Topics:** Lists future work effort in three areas: 1. Fitness for Service 2. Decision Support Systems 3. Sensing Damage via Internal Inspection The future work efforts are designed to enhance the methods developed, address potential weaknesses in the approaches and further integrate disparate efforts that all contribute to system risk and integrity.

Questions?

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