Project Kickoff Call

Slow Crack Growth Evaluation Of Vintage Polyethylene Pipes

Gas Technology Institute

Project Manager: Andrew Hammerschmidt

Principal Investigator: Ernest Lever
Co-Investigators: Yongming Liu, Yiming Deng

Contract Number: DTPH5615T00007

Project Objective

- 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.

Project Objective - Continued

- 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.

Task 1 - Technical Advisory Panel

- Members
  - James G. Collins, Manager Pipeline Integrity, Duke Energy
  - Ryan Truair, Engineering Manager System Integrity, NW Natural
  - Andrew Benedict, President, Opvantek
- GTI will also seek additional members from pipeline operators and risk modeling professionals
- The committee will be consulted in real time as the project progresses, will be presented with interim reports and/or presentations, and will advise regarding various aspects
- Questions that they will help address
  - What constitutes a catastrophic event?
  - Would it depend only on the magnitude of the external event (e.g. earthquake or terror attack), or also on the receptor (e.g. isolated transmission pipeline as opposed to a strategically located utility)?
  - How mature or developed does an “approach” need to be in order to be considered?

Scope of Work

The program is made up of three separate, but closely coordinated projects:

1. GTI – Development of fitness for service calculations, Bayesian network and decision support tool, and guidelines for short-term pressure testing of vintage plastic pipelines.
2. University of Colorado, Denver – Development of endoscopic multi-spectral structured light scanning tools and data reduction algorithms.
3. Arizona State University – Development of Bayesian maximum entropy feature recognition algorithms and data reduction algorithms

Task 1 - Probabilistic Decision Support System Design (GTI)

- Review existing models pertaining to:
  - SCG of vintage polyethylene materials,
  - material behavior of polyethylene materials,
  - evolution of stress in gas distribution pipeline configurations,
  - fitness for service calculations, calculation of threat interactions in gas distribution pipeline systems,
  - determination of probability of failure in gas distribution pipeline systems, and
- determination of consequences in gas distribution pipeline systems.

- Develop ontologies to describe the knowledge represented in:
  - Models reviewed above,
  - regulatory requirements,
  - standards related to gas distribution pipelines.

Task 1 - Probabilistic Decision Support System Design (GTI)

- Identify data sources for:
  - historic data,
  - SME pertaining to factors impacting the performance of vintage plastic gas distribution pipelines,
  - methods for accessing gas distribution pipelines, and
  - published data structures relevant to this program.
- Define the data communication procedures and protocols for the various components of the decision support system.
- Design system architecture including:
  - Database, models,
  - Bayesian networks,
  - data entry methods,
  - simulation tools,
  - insights interface.

Task 2 - Probabilistic Decision Support System Development (GTI)

- Develop Bayesian Network Models:
  - Causal network,
  - SME network,
  - Historic data network, and
  - Inspection reports network.
- Develop Smart Forms:
  - Keyhole data gathering,
  - first response,
  - audit – these forms will guide the operator through the relevant data gathering stages and ensure only valid and relevant data is fed directly into the appropriate models.

Task 2 - Probabilistic Decision Support System Development (GTI)

- Develop Pressure Test Guidelines based on:
  - Rate RPM Testing,
  - Parametric FEM modeling, and a
  - Database of stress concentrations for known configurations to be compiled.

- A comprehensive test and deployment stage will test the decision support system components and their interaction with the structured light scanning methods to be developed in Tasks 3 and 4.

Task 3 - Structured Light Scanning Method Development (UCD)

- After a comprehensive literature review an initial design of the multispectral sensing prototype will be undertaken.
- Numerical simulation and sensor optimization will drive the development of damage detection algorithms used in the prototype.
- A data reduction framework and image reconstruction algorithms will be developed.

Task 4 - Bayesian Methods Development (ASU)

- This task will research imaging analysis and feature extraction methods needed to develop Bayesian classifiers needed to extract useful parametric data from the structured light scanning data stream.
- A reliability based maintenance framework and a dynamic Bayesian network for diagnosis/prognosis will be developed

Task 5 – Project management

- This task captures project management:
  - monthly progress reports,
  - quarterly reports,
  - DOT project review meetings,
  - final report,
  - publishing of papers and presentation.
- This task will cover the coordination of a combined group meeting every four months alternating between GTI, UCD and ASU facilities to:
  - share knowledge,
  - identify and resolve technical and program issues

Task 6 – Project Initiation Activities (GTI)

- This task will cover project initiation and the establishing of a Technical Advisory Committee (TAC).
- GTI will reach out to the most relevant stakeholders in government, academia, and industry to obtain SME feedback, comments, and guidance in major tasks.
- The committee will be comprised of PHMSA and other relevant regulators, liquid and gas pipeline operators, standard-developing organizations, and notable SME.
- TAC will involve with GTI in finalizing the scope of work and will be consulted as the project progress.
- GTI will periodically communicate with TAC and provide interim reports.

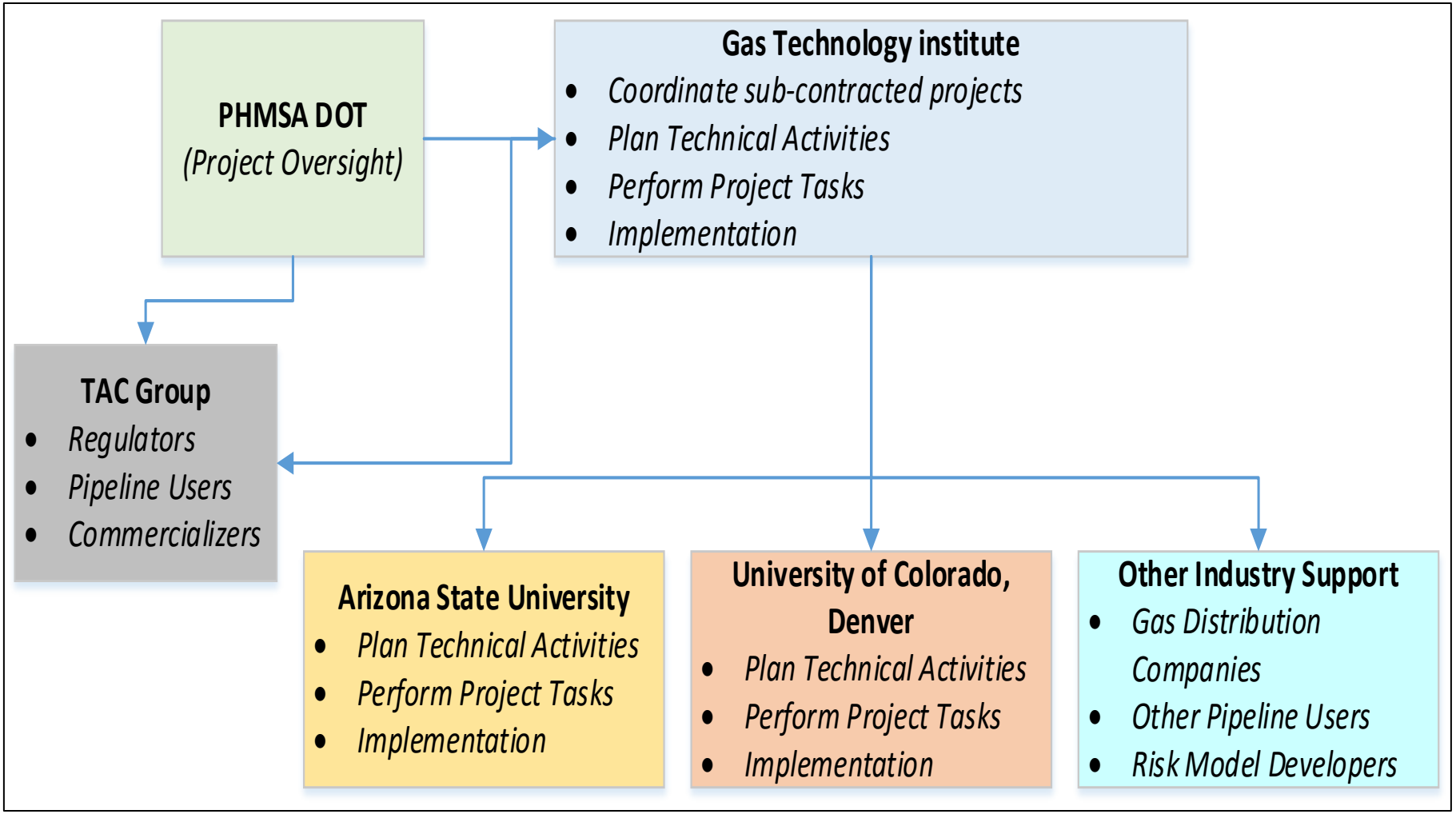
Project Tasks and Deliverables

Task		Task Description	2015		2016				2017		
			Sep.	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3
1		**Probabilistic Decision Support System Design**									
	1.1	Review of Existing models	D1								
	1.2	Develop Ontologies		D1							
	1.3	Design System Architecture		D1							
2		**Probabilistic Decision Support System Development**									
	2.1	Develop Bayesian Network Models		D1	D2						
	2.2	Develop Smart Forms			D2	D3	D4				
	2.3	Develop Pressure Test Guidelines			D2	D3					
	2.4	Test and Deploy				D3	D4	D5			
	2.5	Ongoing System Integration and Testing					D4	D5	D6	D7	D8
5		**Program Management**		R1	R2	R3	R4	R5	R6	R7	P, F
6		**Form Technical Advisory Committee**	D1								

Project Tasks and Deliverables - Continued

Task		Task Description	2015		2016				2017		
			Sep.	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3
3		**UCD Structured Light Scanning Method Development**									
	3.1	Literature Review	D3								
	3.2	Initial Design of Multispectral Sensing Prototype				D3	D4	D5	D6		
	3.3	Numerical Simulation and Sensor Optimization				D3					
	3.4	Develop Detection Algorithms				D3					
	3.5	Develop Prototype				D3				D7	D8
	3.6	Develop Data Reduction Framework								D7	
	3.7	Develop Image Reconstruction Algorithms								D7	
	3.8	Quarterly Reports, Final Report and Paper Submission		R1	R2	R3	R4	R5	R6	R7	P, F
4		**ASU Bayesian Methods Development**									
	4.1	Research Imaging Analysis and Feature Extraction		D1	D2	D3					
	4.2	Develop Bayesian Classifiers			D2	D3	D4	D5			
	4.3	Develop Reliability Based Maintenance Framework					D4	D5	D6	D7	
	4.4	Develop Dynamic Bayesian Network for Diagnosis/Prognosis							D6	D7	D8
	4.5	Quarterly Reports, Final Report and Paper Submission		R1	R2	R3	R4	R5	R6	R7	P, F

Project Layout



Technical Advisory Panel

- Michael J. Faulkenberry,
Director, Natural Gas, Avista
- James G. Collins,
Manager, Pipeline Integrity, Duke Energy
- Edward Newton,
Research & Materials Manager, Southern California Gas
- Andrew Benedict,
President, Opvantek
- Aaron Forster,
Materials Research Engineer,
Polymeric Materials Group, NIST

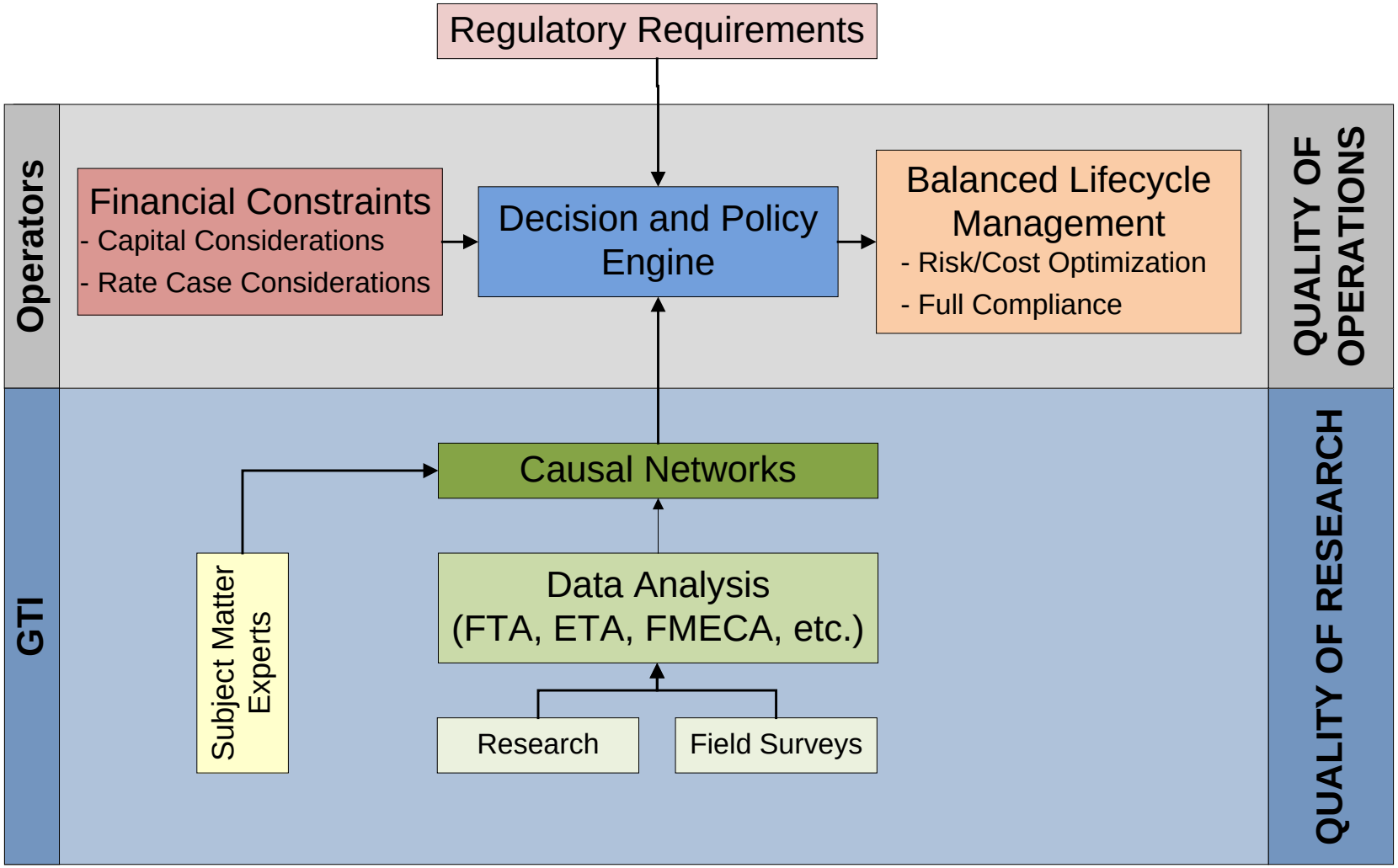
Technical Advisory Panel

- The Technical Advisory Panel will be invited to the first joint project meeting to be held mid-January 2016 at Arizona State University
- A detailed technical rationale will be presented to them and their feedback will be solicited
- Group project meetings will be held every four months alternating between ASU (January), CDU (May) and GTI (September)
- The Technical Advisory Panel will be invited to attend each meeting in person or via webinar

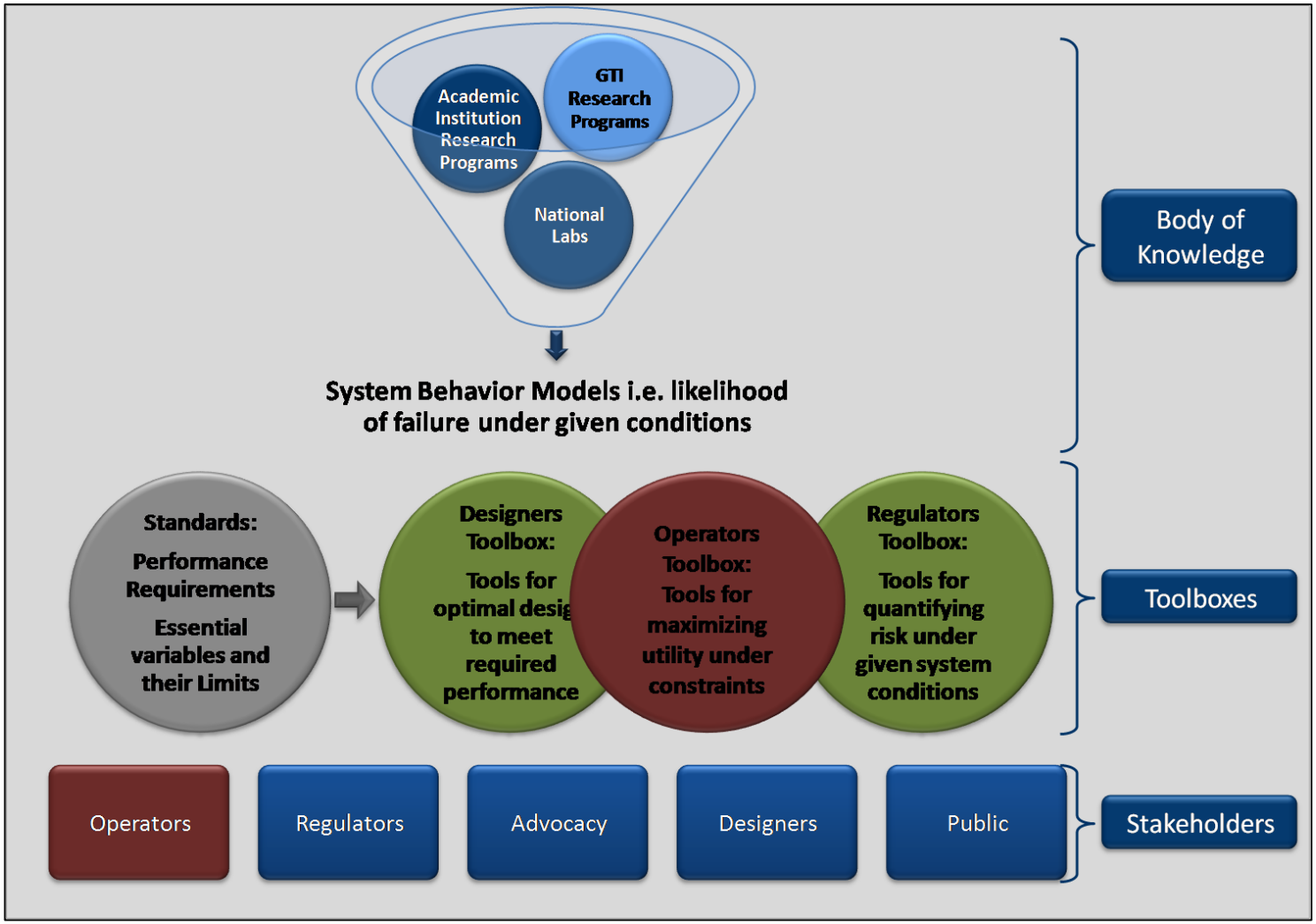
Background Slides

- Review of work since contract was signed
- Group discussion
- Questions

Decision/Policy Optimization for Balanced Lifecycle Management

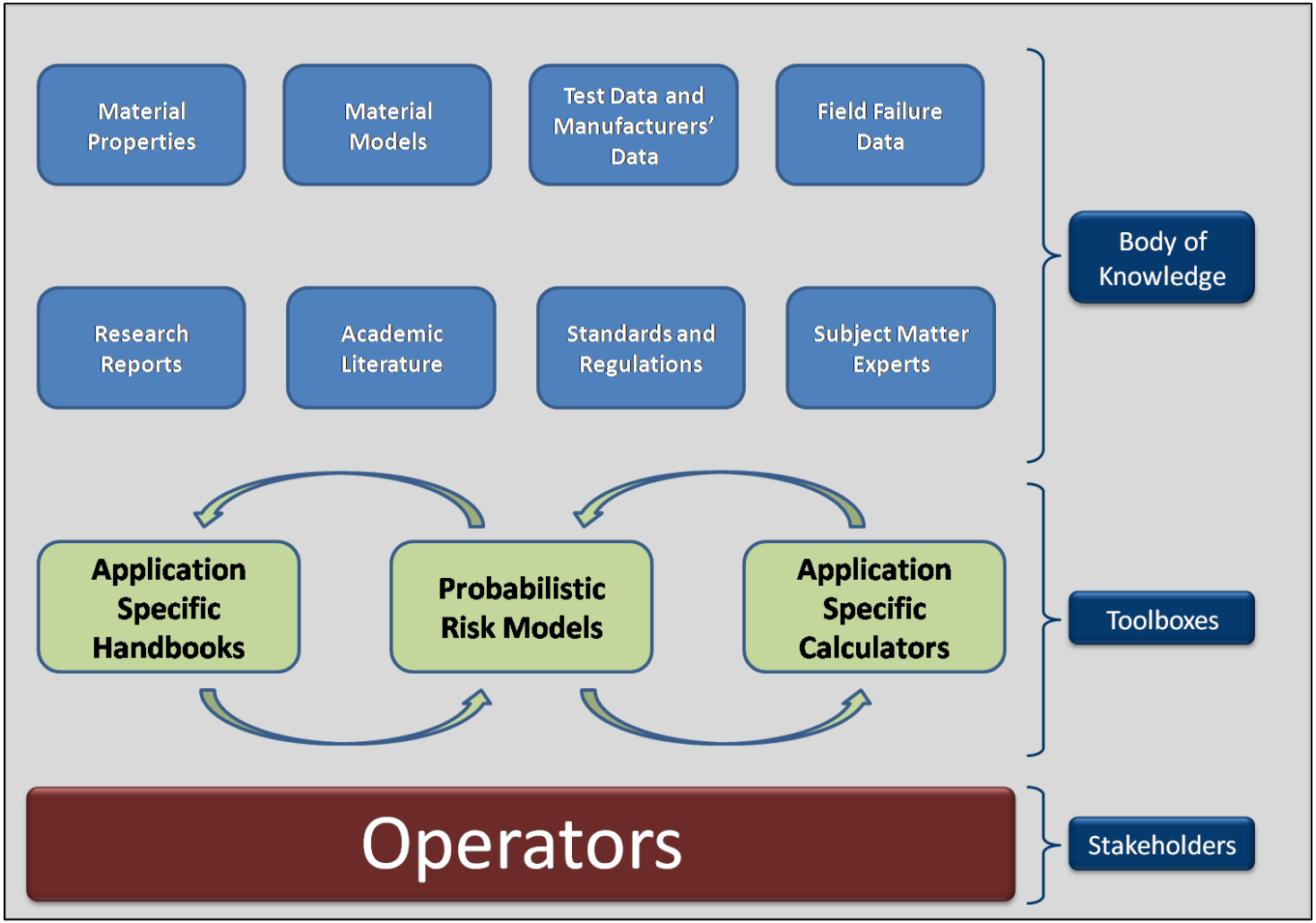


Coordinated Research and Development



Operator Specific Deliverables

Body of Knowledge and Toolboxes



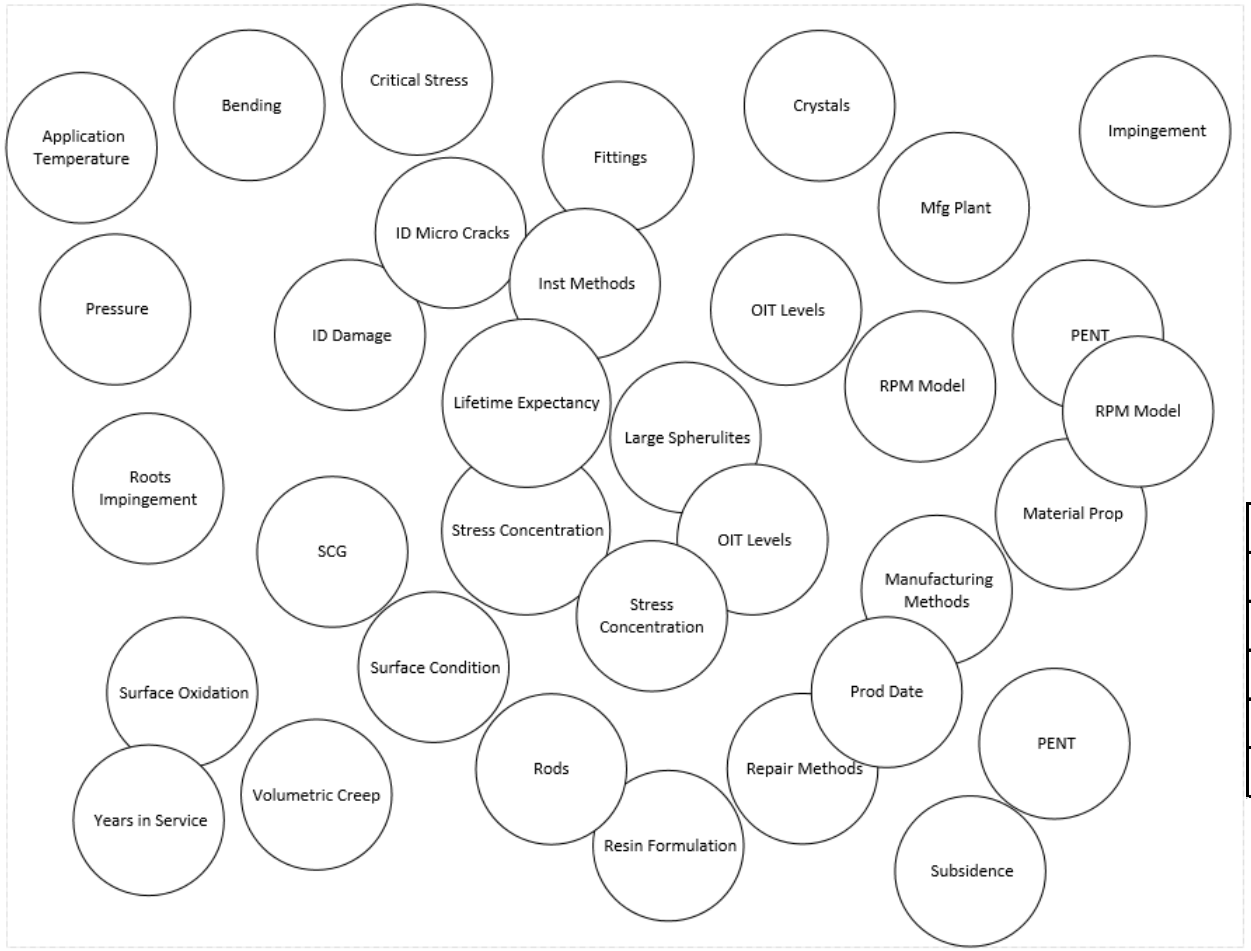
Project: Understanding Threat Interactions

> **Background**
- Many pipeline incidents are the result of multiple, interacting causes, not a single threat.
- Individual threats can each be at “acceptable” levels but when overlaid result in a significant threat to the pipeline or even a failure.

> **Approach**
- Identify threat combinations to address and control,
- Develop a method to calculate threat interaction levels and severity, and
- Provide a method to continuously monitor threat interactions and flag concerns at trigger points.

> **Benefits**
- Operators will be able to adequately identify combinations of threats and their associated risk.
- Reduction of an operator’s risk and enhancement of compliance with Subpart O regulations.

Factors in Aldyl A Risk Assessment



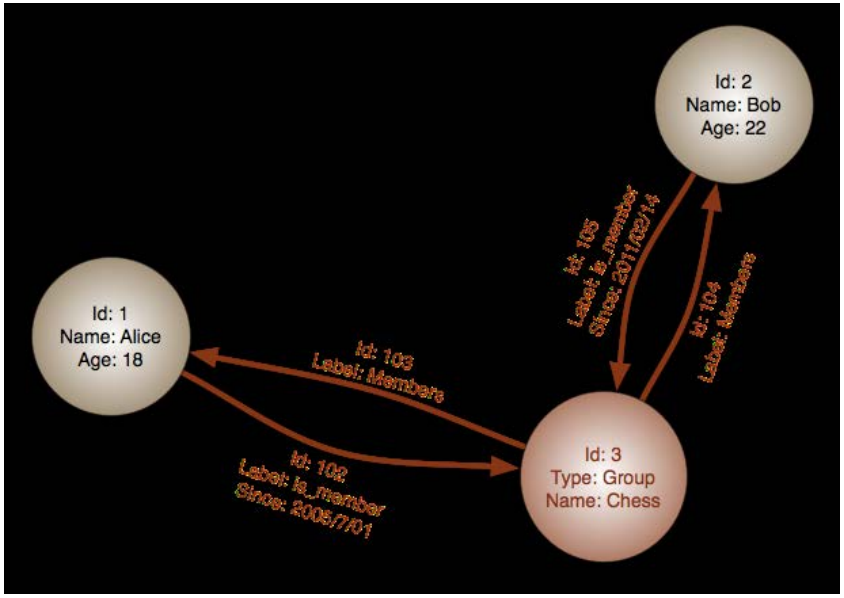
n=32

2^32=4,294,967,296

Interacting Factors	Combinations
2	496
3	4960
4	35960
5	201376
Sum	242792

Semantics, Ontologies, Graphs (From Wikipedia)

Semantics (from Ancient Greek: σημαντικός *sēmantikós*, "significant")[1][2] is the study of meaning. It focuses on the relation between *signifiers*, like words, phrases, signs, and symbols, and what they stand for, their denotation



The term *ontology* has its origin in philosophy and has been applied in many different ways. The word element *onto-* comes from the Greek *ὤν*, *ὄντος*, ("being", "that which is"), present participle of the verb *εἰμί* ("be"). The core meaning within computer science is a model for describing the world that consists of a set of types, properties, and relationship types. There is also generally an expectation that the features of the model in an ontology should closely resemble the real world (related to the object).[3]

Semantic Formulation in Mathematica

```
scgMap =
 Graph[{"Prod Date" ↦ "Manufacturing Methods", "Mfg Plant" ↦ "Manufacturing Methods",
   "Manufacturing Methods" ↦ "Crystals", "Manufacturing Methods" ↦ "Large Spherulites",
   "Manufacturing Methods" ↦ "Rods", "Rods" ↦ "Surface Condition",
   "Crystals" ↦ "Surface Condition", "Manufacturing Methods" ↦ "Surface Oxidation",
   "Large Spherulites" ↦ "Surface Condition", "Surface Oxidation" ↦ "Surface Condition",
   "Surface Oxidation" ↦ "ID Micro Cracks", "ID Micro Cracks" ↦ "Stress Concentration",
   "Material Prop" ↦ "PENT", "Repair Methods" ↦ "ID Damage",
   "Repair Methods" ↦ "Impingement", "Repair Methods" ↦ "Bending",
   "Repair Methods" ↦ "Subsidence", "Manufacturing Methods" ↦ "ID Damage",
   "ID Damage" ↦ "Stress Concentration", "Critical Stress" ↦ "SCG",
   "Pressure" ↦ "Critical Stress", "Bending" ↦ "Stress Concentration",
   "Stress Concentration" ↦ "Critical Stress", "Impingement" ↦ "Bending",
   "Fittings" ↦ "Bending", "Inst Methods" ↦ "Impingement", "Inst Methods" ↦ "Subsidence",
   "Inst Methods" ↦ "Bending", "Subsidence" → "Impingement", "Subsidence" → "Bending",
   "PENT" ↦ "Critical Stress", "Roots" → "Impingement",
   "Material Prop" ↦ "Stress Concentration", "Resin Formulation" ↦ "Material Prop",
   "Material Prop" ↦ "ID Micro Cracks", "Pressure" ↦ "Volumetric Creep",
   "Years in Service" ↦ "Volumetric Creep", "Volumetric Creep" ↦ "ID Micro Cracks",
   "ID Micro Cracks" ↦ "Surface Condition", "Surface Condition" ↦ "RPM Model",
   "Material Prop" ↦ "RPM Model", "Pressure" ↦ "RPM Model",
   "Stress Concentration" ↦ "RPM Model", "Manufacturing Methods" ↦ "OIT Levels",
   "Resin Formulation" ↦ "OIT Levels", "Years in Service" ↦ "OIT Levels",
   "OIT Levels" ↦ "Surface Condition", "Application Temperature" ↦ "RPM Model",
   "RPM Model" ↦ "Lifetime Expectancy"}, VertexLabels → "Name",
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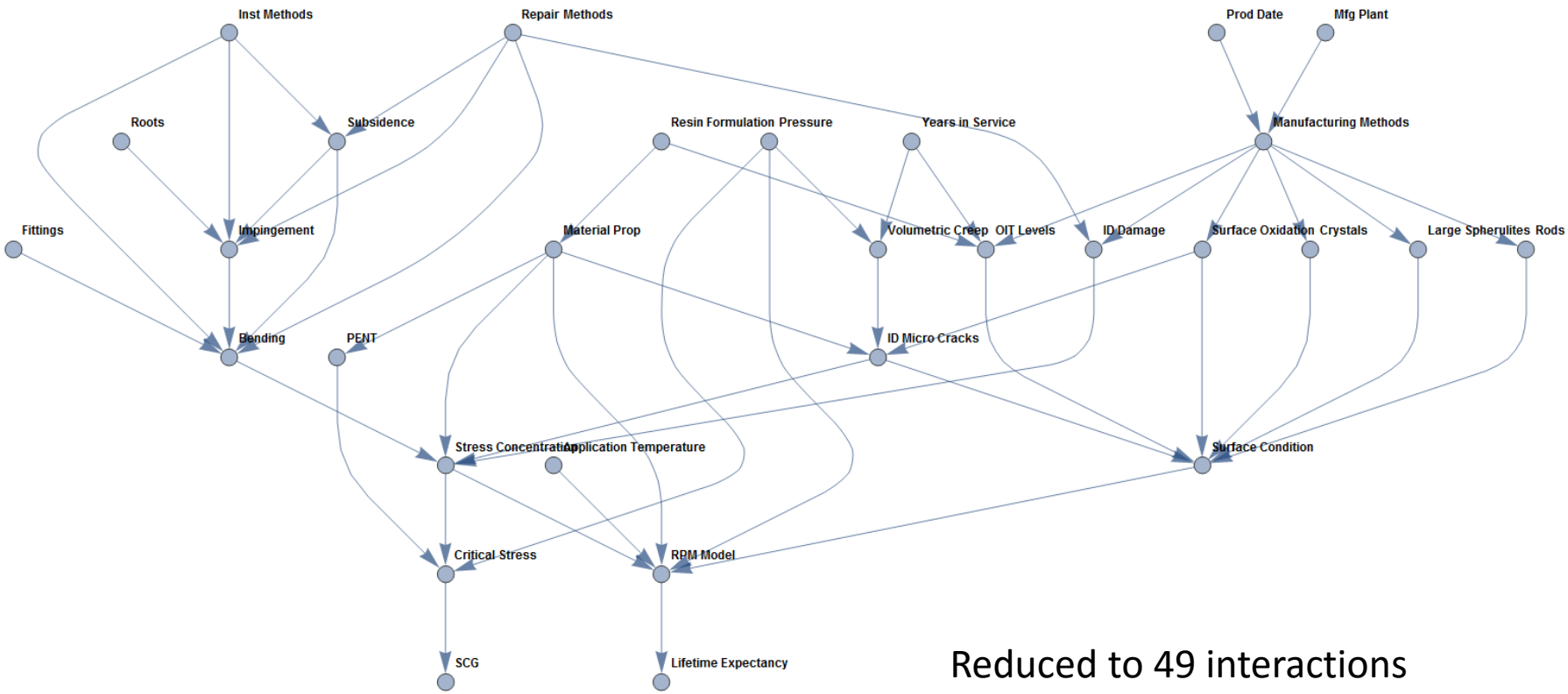
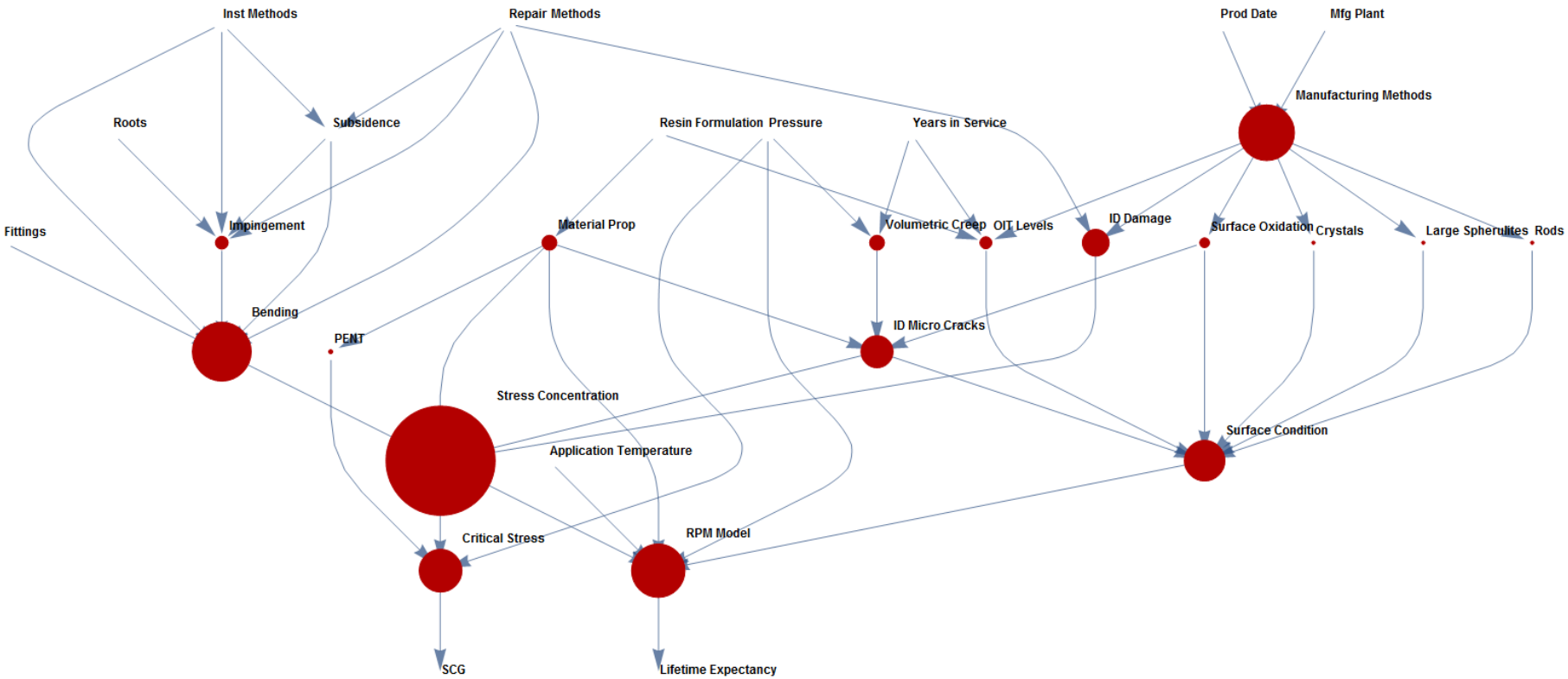
Graph of Aldyl A Risk Model – The Aldyl A Gas Pipeline Risk Ontology

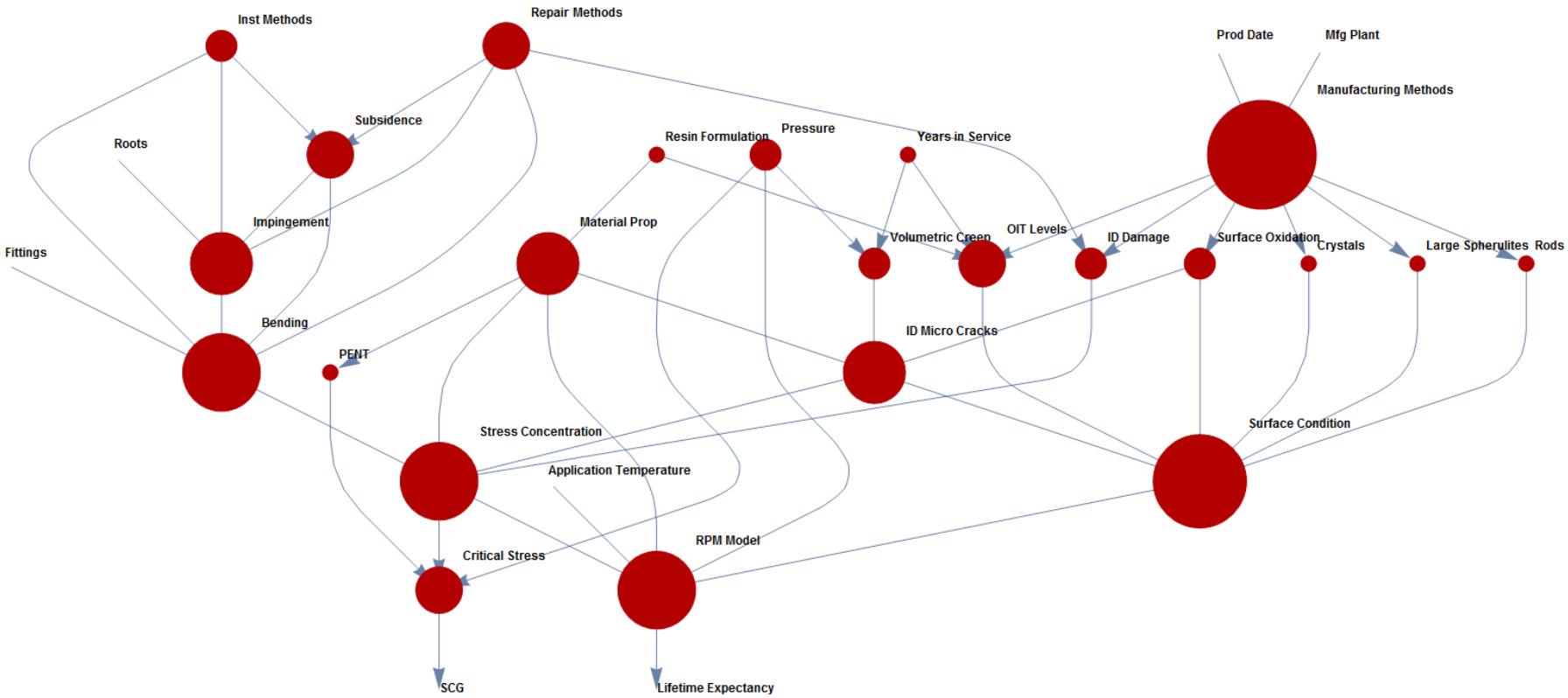


Reduced to 49 interactions
EdgeCount[scgMap]=49

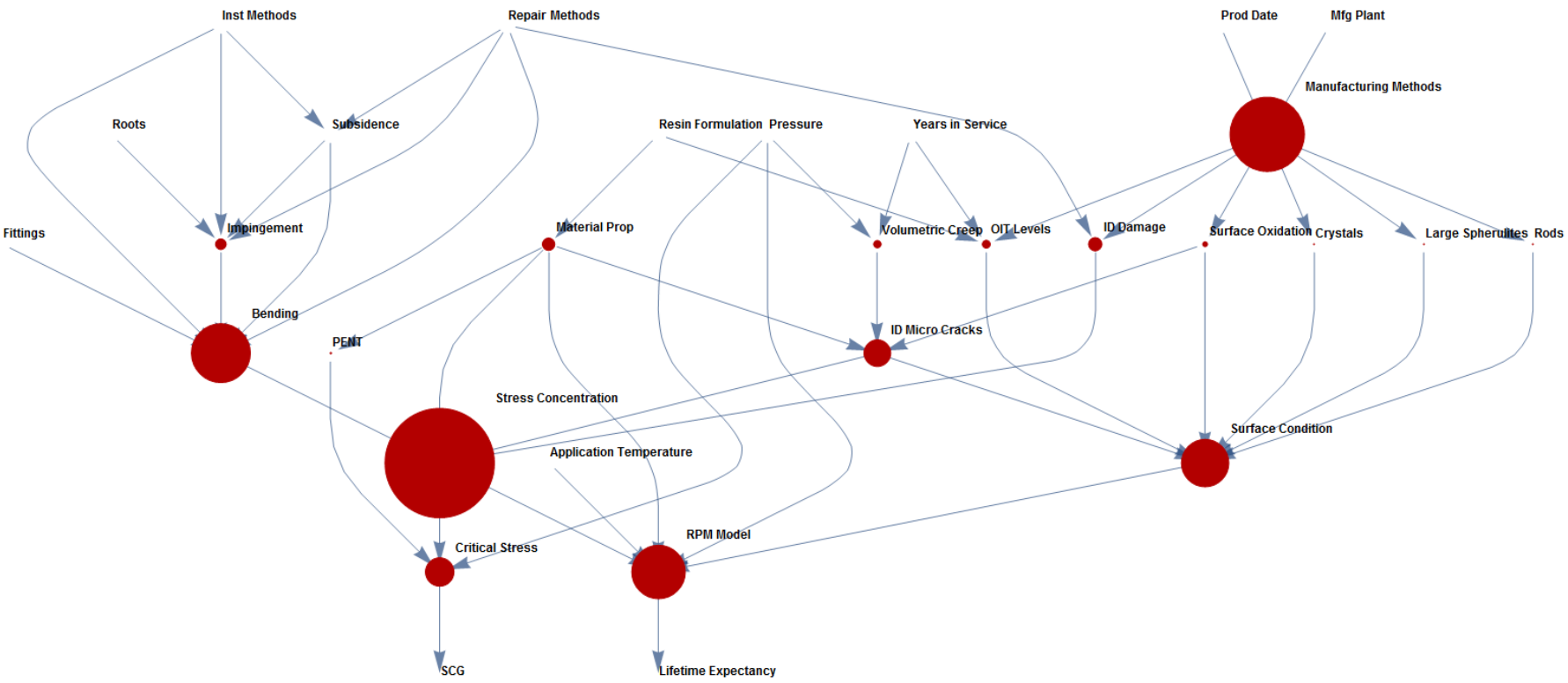
Betweeness Centrality (BC)



Degree Centrality (DC)



Composite Ranking (DC*BC)



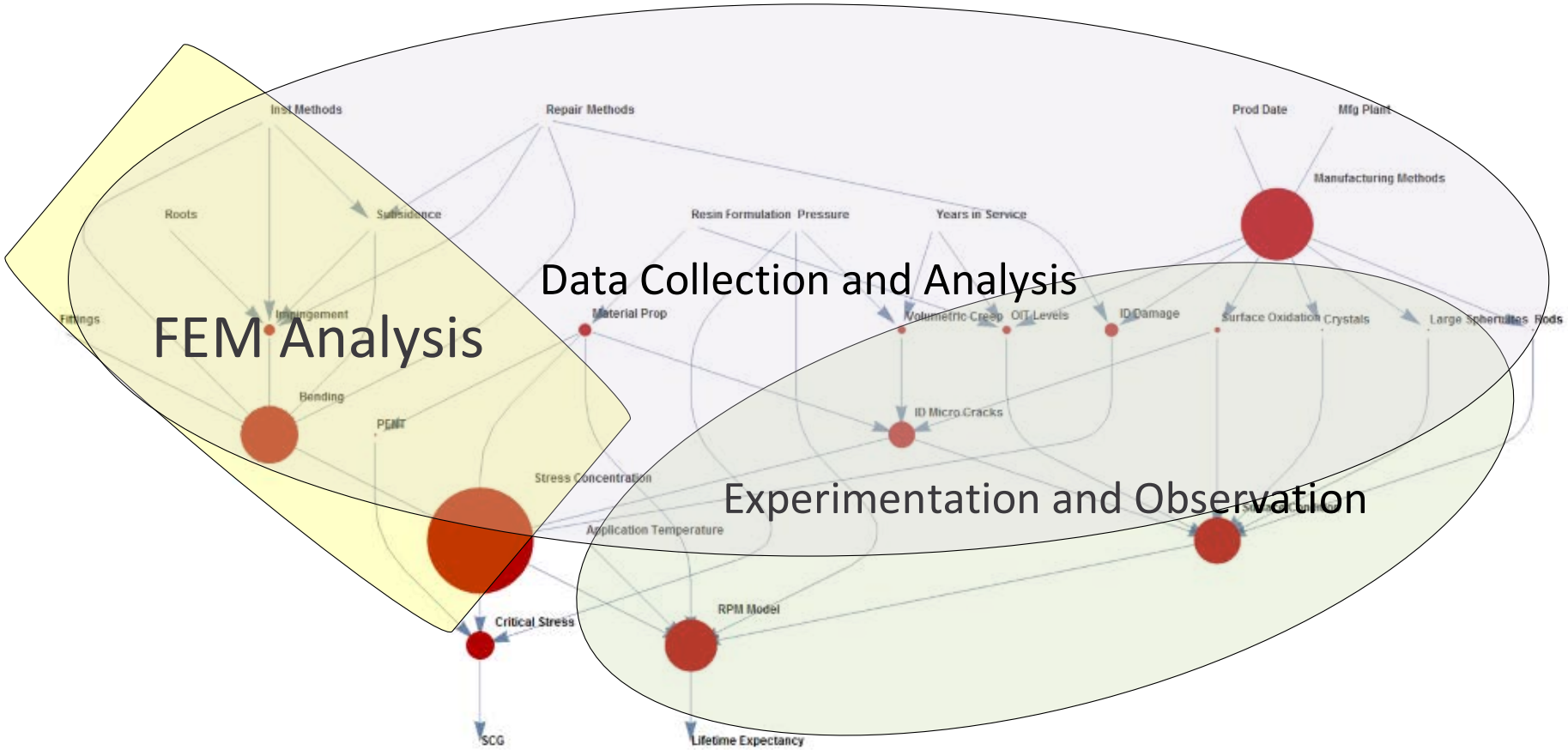
Betweeness, Degree and Composite Ranking

Stress Concentration	51.
Bending	27.5
Manufacturing Methods	26.
RPM Model	25.
Critical Stress	20.
Surface Condition	19.
ID Micro Cracks	15.
ID Damage	12.5
Volumetric Creep	7.
Material Prop	7.
Impingement	6.
OIT Levels	5.6
Surface Oxidation	4.6
PENT	2.
Rods	1.6
Large Spherulites	1.6
Crystals	1.6
Years in Service	0.
Subsidence	0.
SCG	0.
Roots	0.
Resin Formulation	0.
Repair Methods	0.
Prod Date	0.
Pressure	0.
Mfg Plant	0.
Lifetime Expectancy	0.
Inst Methods	0.
Fittings	0.
Application Temperature	0.

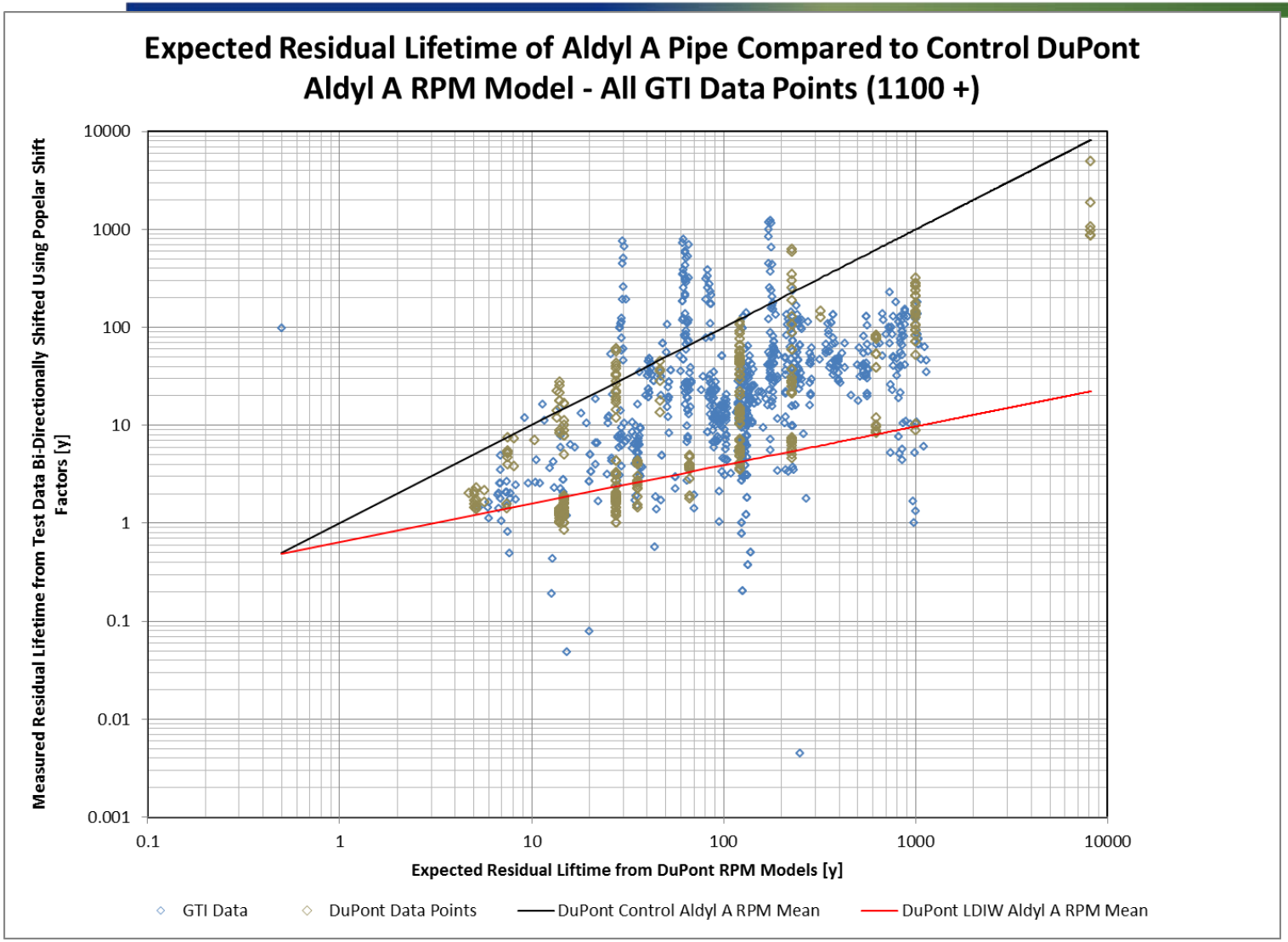
Manufacturing Methods	8
Surface Condition	7
Stress Concentration	6
RPM Model	6
Bending	6
Material Prop	5
Impingement	5
ID Micro Cracks	5
Subsidence	4
Repair Methods	4
OIT Levels	4
Critical Stress	4
Volumetric Creep	3
Surface Oxidation	3
Pressure	3
Inst Methods	3
ID Damage	3
Years in Service	2
Rods	2
Resin Formulation	2
PENT	2
Large Spherulites	2
Crystals	2
SCG	1
Roots	1
Prod Date	1
Mfg Plant	1
Lifetime Expectancy	1
Fittings	1
Application Temperature	1

Stress Concentration	306.
Manufacturing Methods	208.
Bending	165.
RPM Model	150.
Surface Condition	133.
Critical Stress	80.
ID Micro Cracks	75.
ID Damage	37.5
Material Prop	35.
Impingement	30.
OIT Levels	22.4
Volumetric Creep	21.
Surface Oxidation	13.8
PENT	4.
Rods	3.2
Large Spherulites	3.2
Crystals	3.2
Years in Service	0.
Subsidence	0.
SCG	0.
Roots	0.
Resin Formulation	0.
Repair Methods	0.
Prod Date	0.
Pressure	0.
Mfg Plant	0.
Lifetime Expectancy	0.
Inst Methods	0.
Fittings	0.
Application Temperature	0.

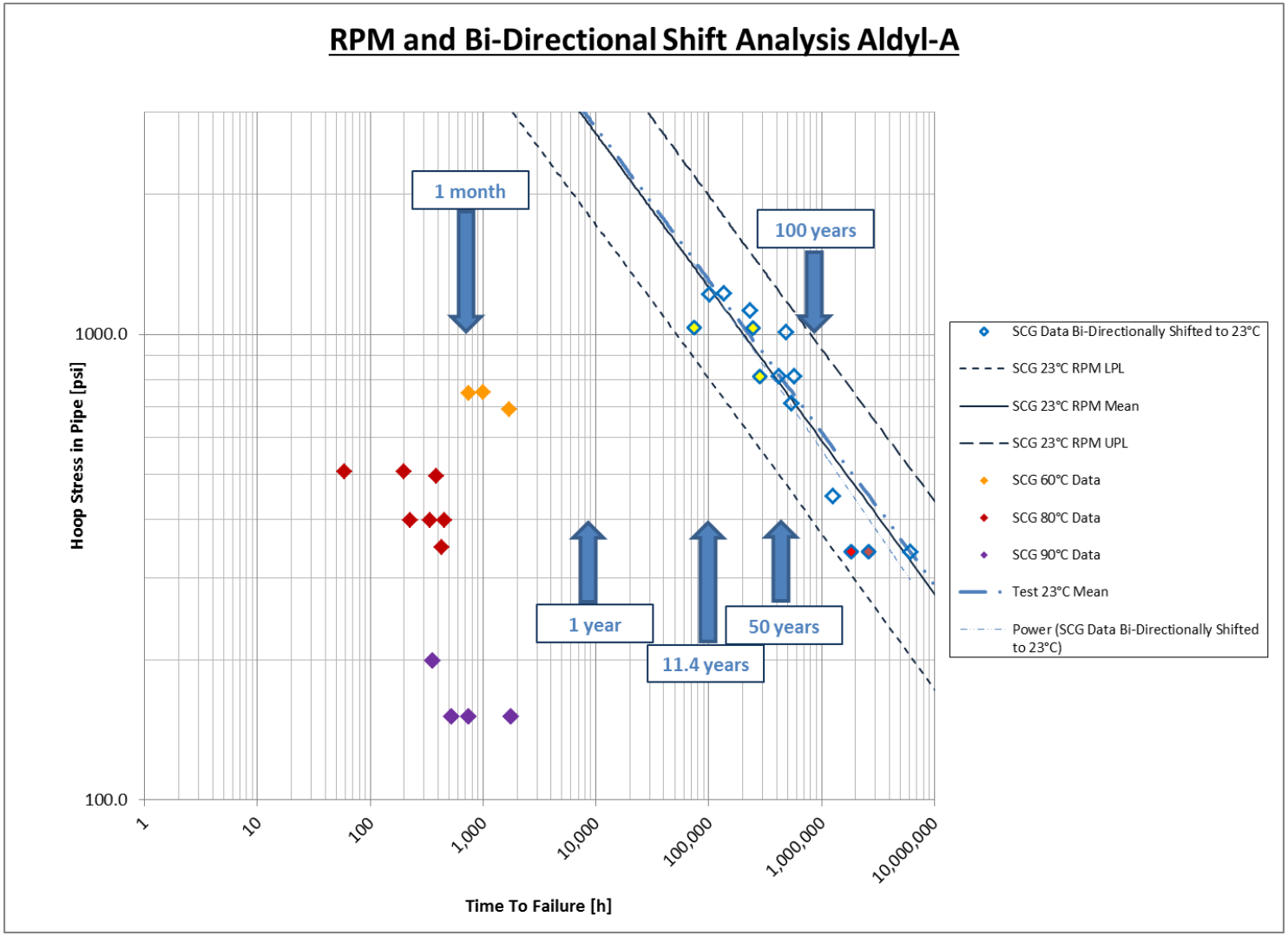
How to attach numbers to the network



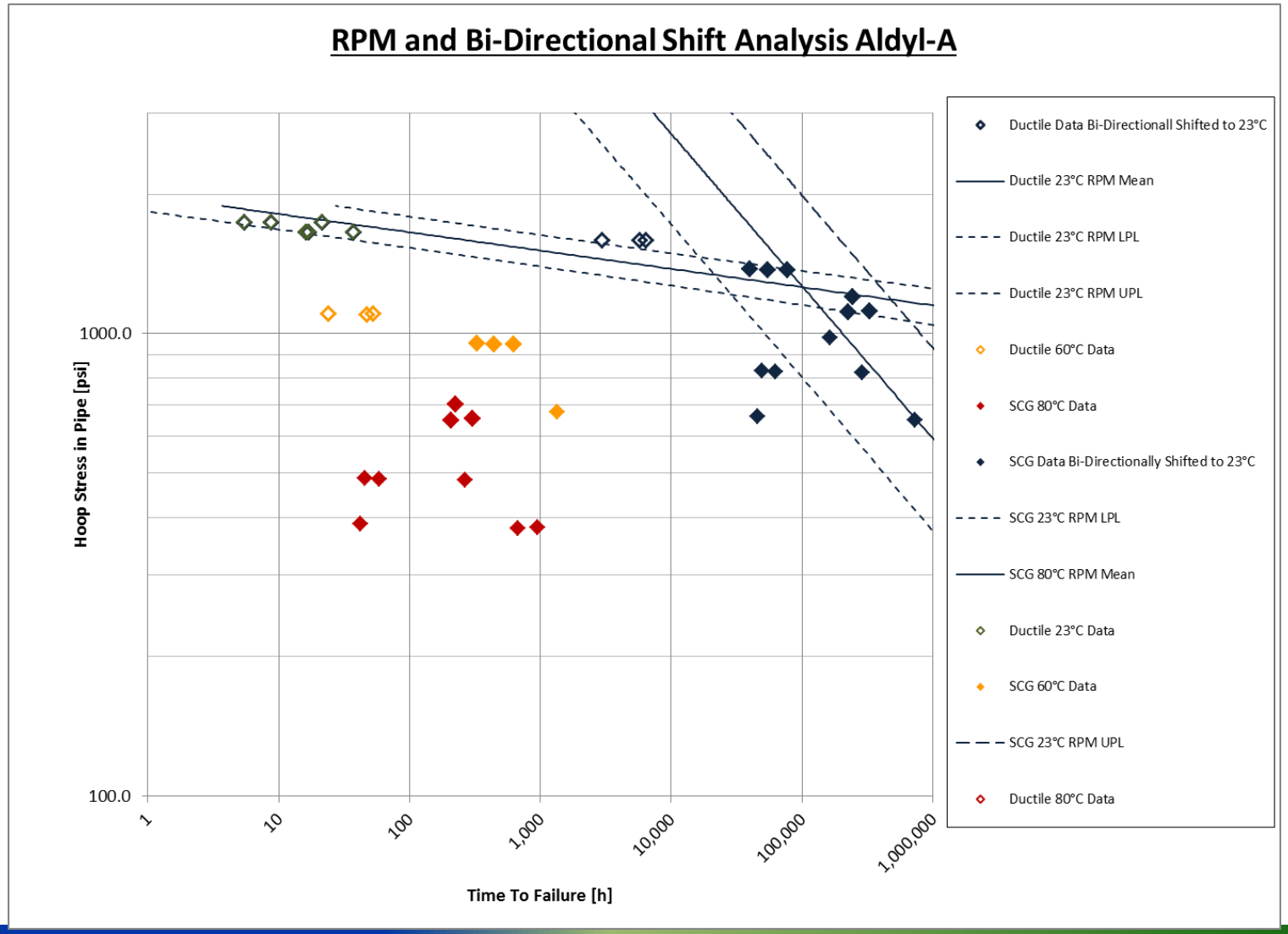
10 Years of Aldyl A Data Collection



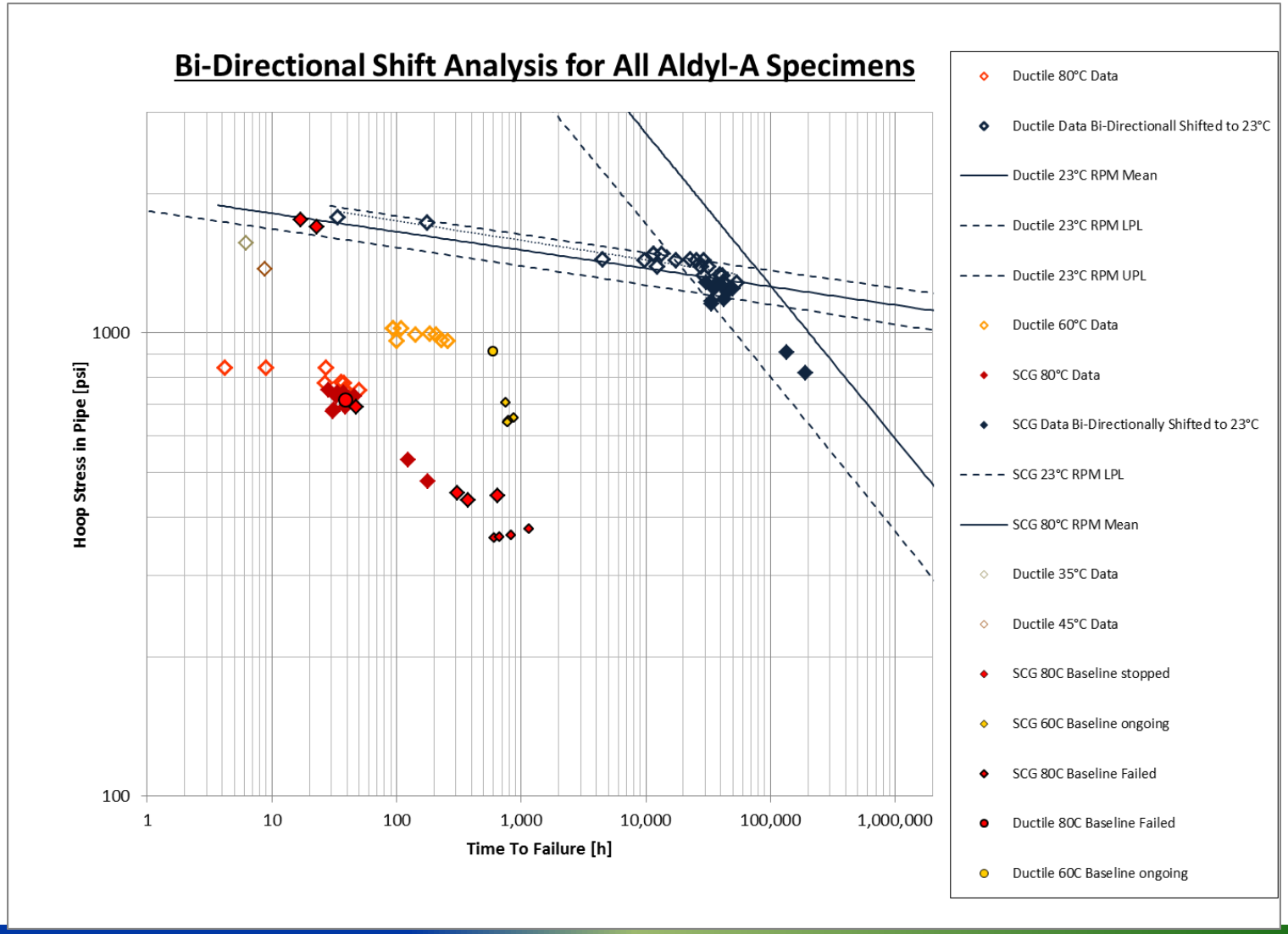
Utility A


RPM and Bi-Directional Shift Analysis Aldyl-A
1 month
100 years
1 year
11.4 years
50 years
1000.0
100.0
Hoop Stress in Pipe [psi]
1
10
100
1,000
10,000
100,000
1,000,000
10,000,000
Time To Failure [h]
SCG Data Bi-Directionally Shifted to 23°C
SCG 23°C RPM LPL
SCG 23°C RPM Mean
SCG 23°C RPM UPL
SCG 60°C Data
SCG 80°C Data
SCG 90°C Data
Test 23°C Mean
Power (SCG Data Bi-Directionally Shifted to 23°C)

Utility B


RPM and Bi-Directional Shift Analysis Aldyl-A
Hoop Stress in Pipe [psi]
1000.0
100.0
1
10
100
1,000
10,000
100,000
1,000,000
Time To Failure [h]
Ductile Data Bi-Directionall Shifted to 23°C
Ductile 23°C RPM Mean
Ductile 23°C RPM LPL
Ductile 23°C RPM UPL
Ductile 60°C Data
SCG 80°C Data
SCG Data Bi-Directionally Shifted to 23°C
SCG 23°C RPM LPL
SCG 80°C RPM Mean
Ductile 23°C Data
SCG 60°C Data
SCG 23°C RPM UPL
Ductile 80°C Data

Aldyl A – 40 years of service, ID surface condition eliminated

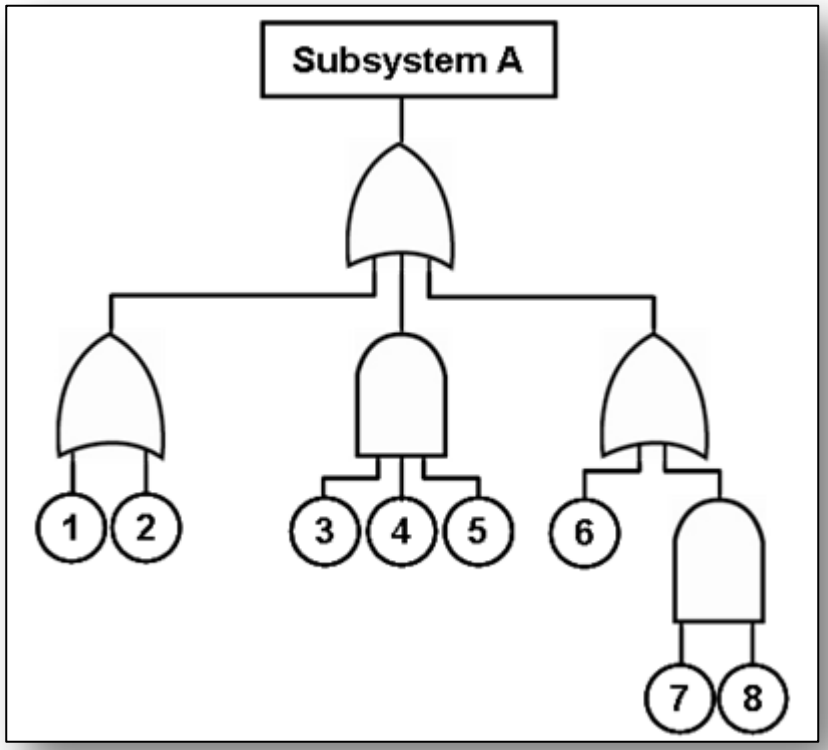


System Response → Fault & Event Trees

Can incorporate unlimited levels of interactions and include probabilities of events (from SMEs)

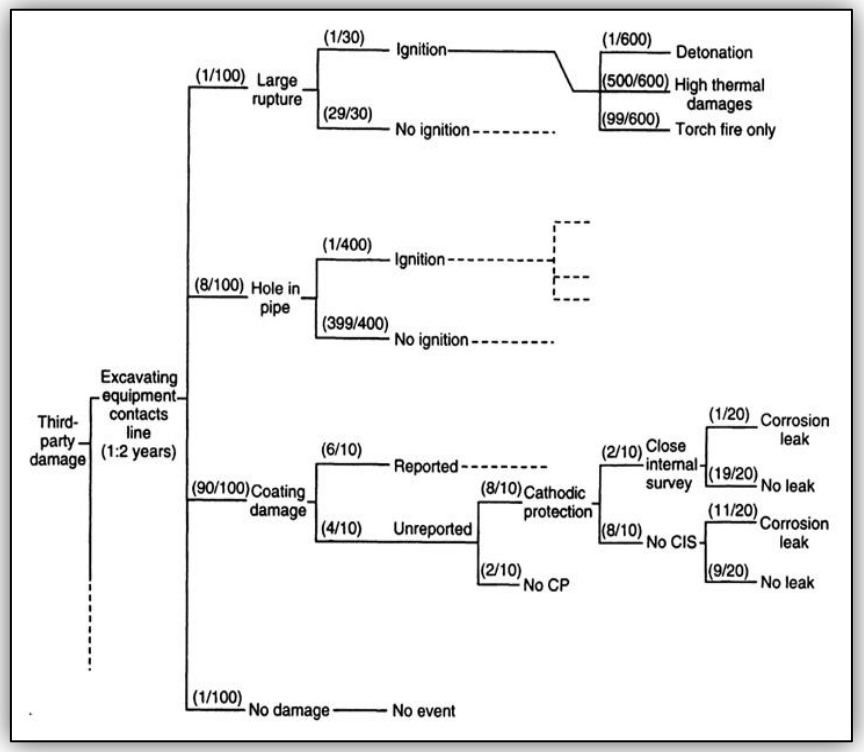
Fault Tree Analysis

Bottom up approach of sequential combinations of faults that will result in a failure.

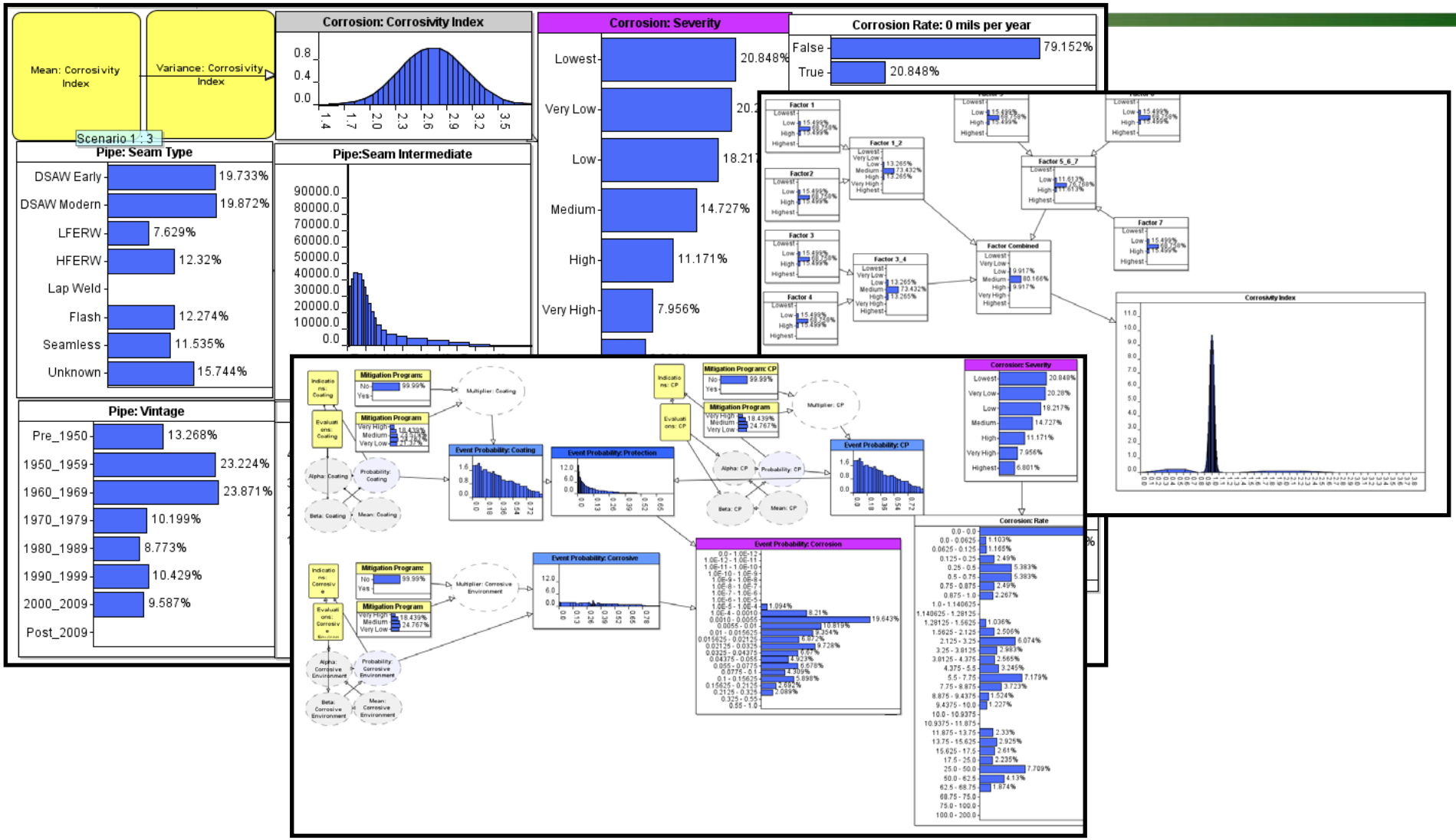


Event Tree Analysis

Probability/likelihood of events occurring and impact on consequence.



Probabilistic Models



Methodology: Rate Process Method (RPM)

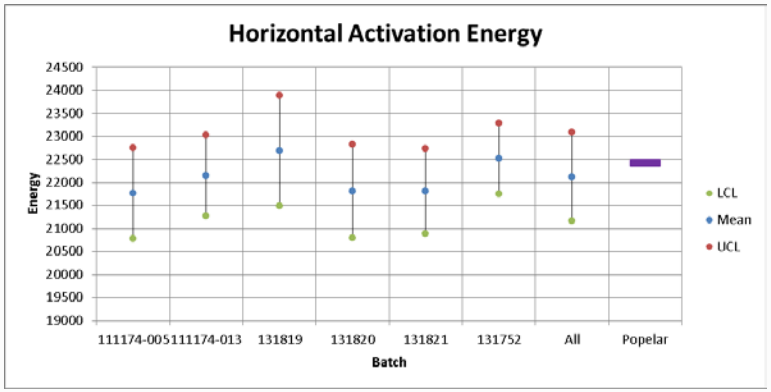
- Extensive historic hydrostatic test data covering all vintages has been assembled
- RPM models were generated for these historic data sets for reference

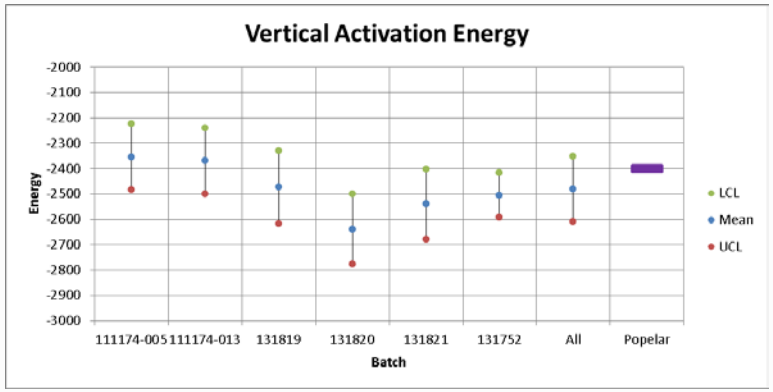
Parameters	C_1	C_2	C_3	C_4	R^2	Adjusted R^2
Value	-48.76	20,356	10.81	-4,671	0.92	0.91
Standard Error	6.01	2,102	2.07	724		

- This study is based on a set of 105 slow crack growth failures in pipe that were not associated with fittings or other known stress risers.
- The pipes were all extracted from a gas distribution system in 2010-2011
- They had been in service since 1972, 1973 and 1974.
- The pipes were tested at 70°C, 80°C and 90°C with failure times ranging from 10 hours to 5000 hours.

Methodology: Bi-Directional Shift Factors

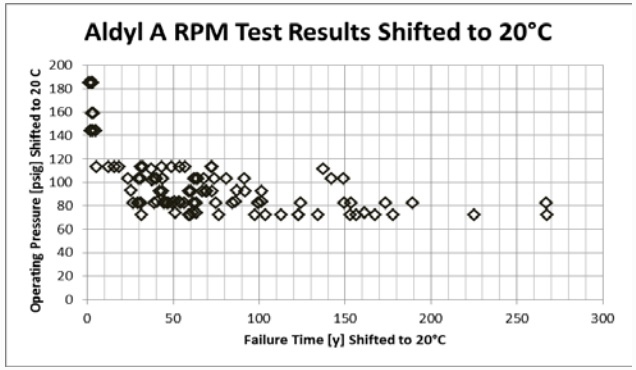
- We can only attach meaning to the results of hydrostatic testing if we compare them to reference data.
- The approach taken in this analysis was to develop the bi-directional shift factors for each batch of pipe tested using DTMA and rheological principles
- Extract the horizontal and vertical shift factors for the pipe in question.
- The method used was an extension of the method described by Mavridis and Shroff

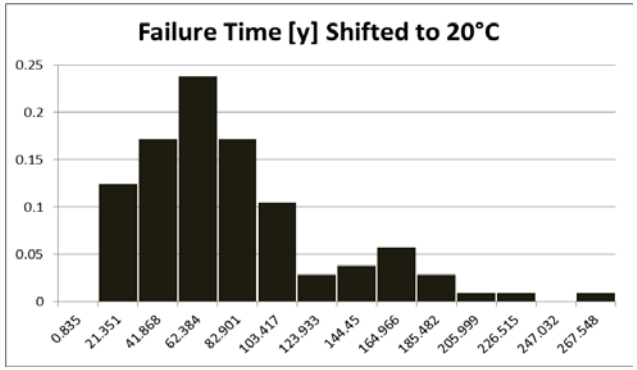




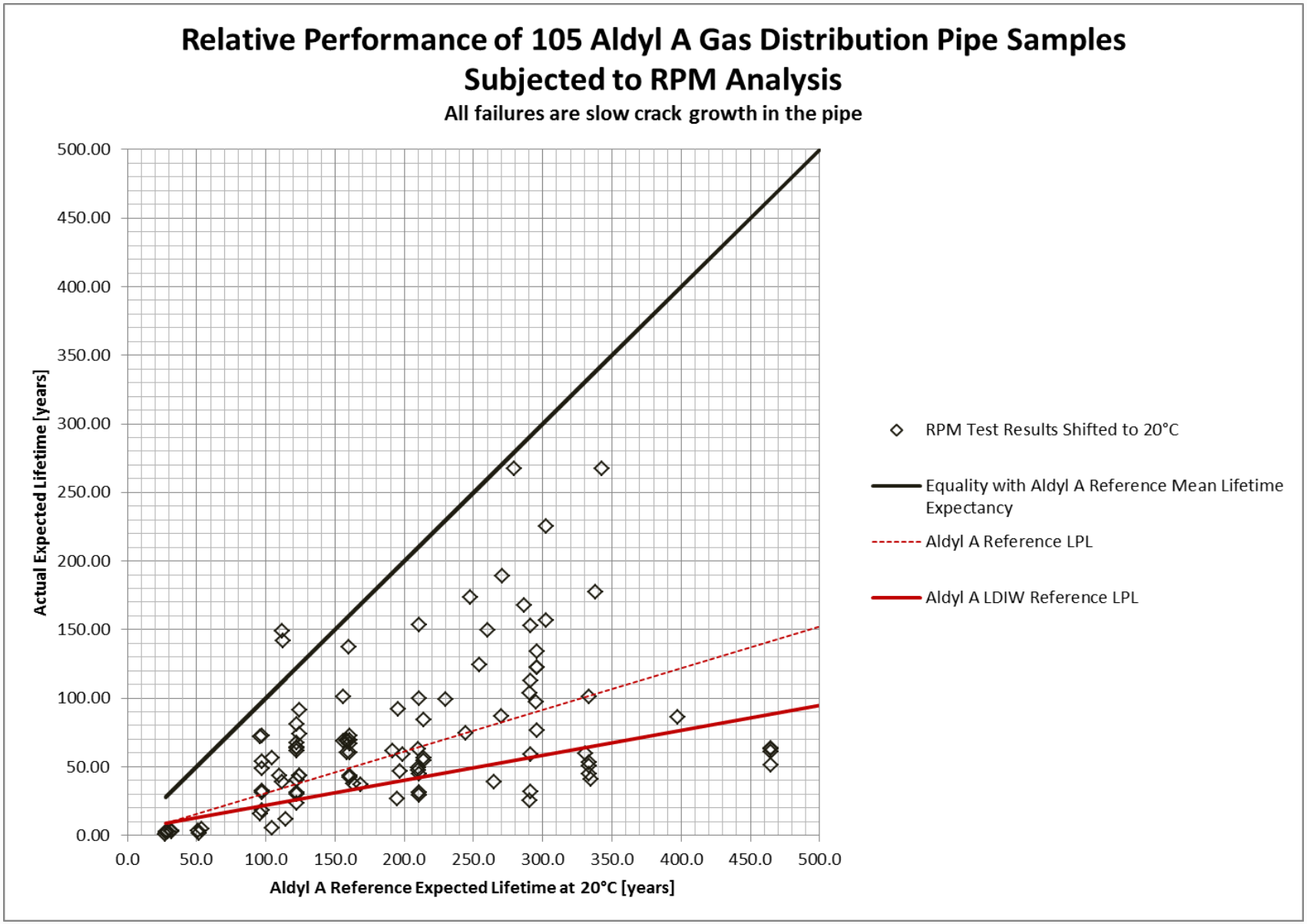
Methodology: Shift Results to Reference Temperature

- The 105 hydrostatic test results were shifted to 20°C
- The shifted failure times and equivalent operating pressures are shown in the plot below
- The distribution of expected failure times at 20°C is shown below





- The bi-directionally shifted test results cannot be used on their own to express an opinion about the relative risk ranking of the sampled pipes.
- It is essential to compare the shifted results to the reference data sets.

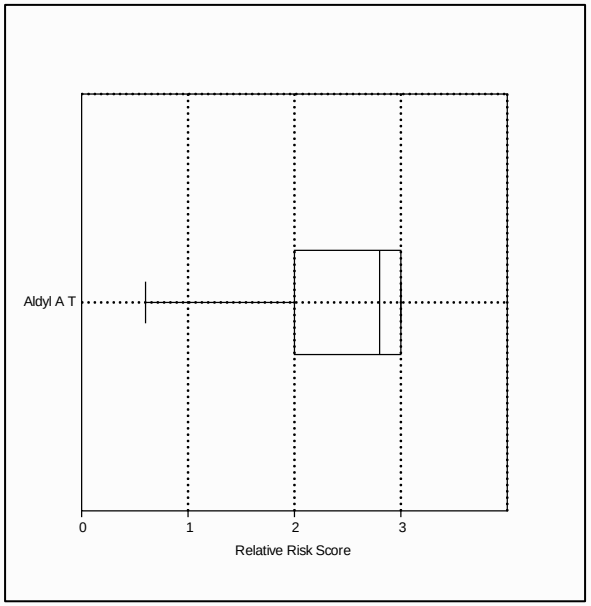

Relative Performance of 105 Aldyl A Gas Distribution Pipe Samples Subjected to RPM Analysis
All failures are slow crack growth in the pipe
Actual Expected Lifetime [years]
500.00
450.00
400.00
350.00
300.00
250.00
200.00
150.00
100.00
50.00
0.00
0.0
50.0
100.0
150.0
200.0
250.0
300.0
350.0
400.0
450.0
500.0
Aldyl A Reference Expected Lifetime at 20°C [years]
RPM Test Results Shifted to 20°C
Equality with Aldyl A Reference Mean Lifetime Expectancy
Aldyl A Reference LPL
Aldyl A LDIW Reference LPL

Methodology: Develop Relative Risk Score

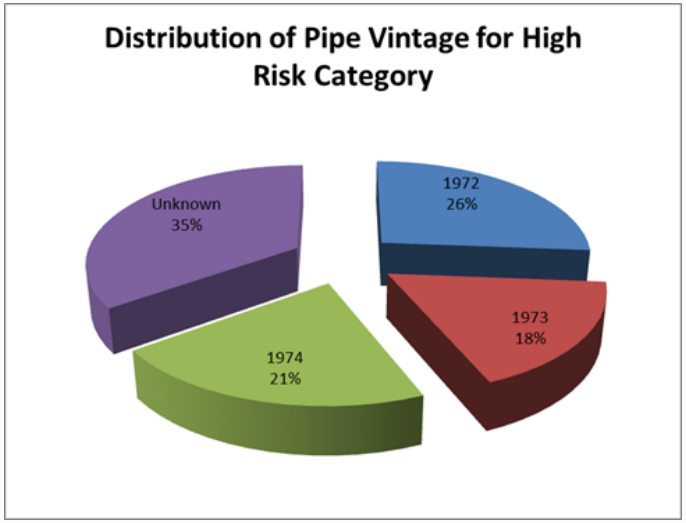
- The shifted test results are ranked relative to the RPM model results and assigned a relative risk score

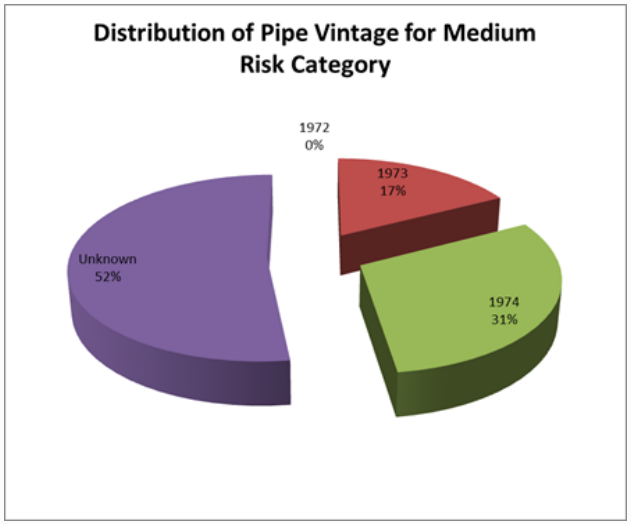
RISK CATEGORY	ORDINAL RANKING	CRITERION
High Risk	3	Performance < LPL of LDIW reference model
Medium Risk	2	Performance < LPL of **non** LDIW reference model
Low Risk	1	Performance > Mean of **non** LDIW reference model

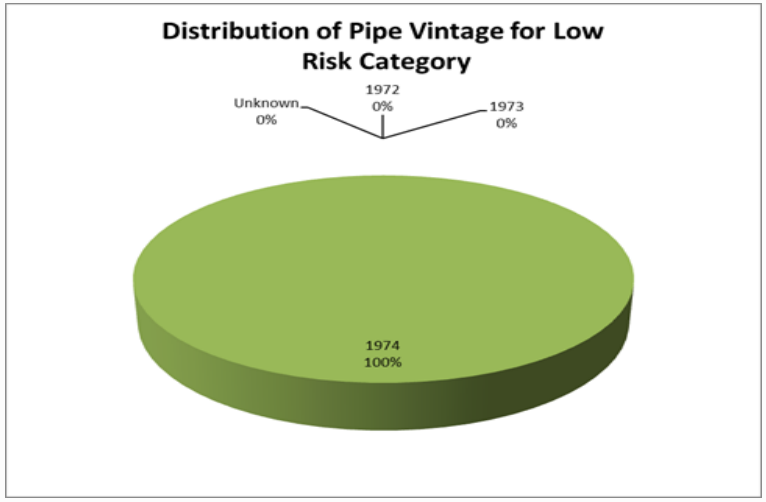
- The majority of the sampled pipe has a relatively high risk ranking
- The expected lifetimes of the pipes is well below those predicted by the RPM models of pipe tested in the 1970's
- Depletion of the stabilizer package over 40 years of service is a major factor



Pipe Risk vs Pipe Vintage

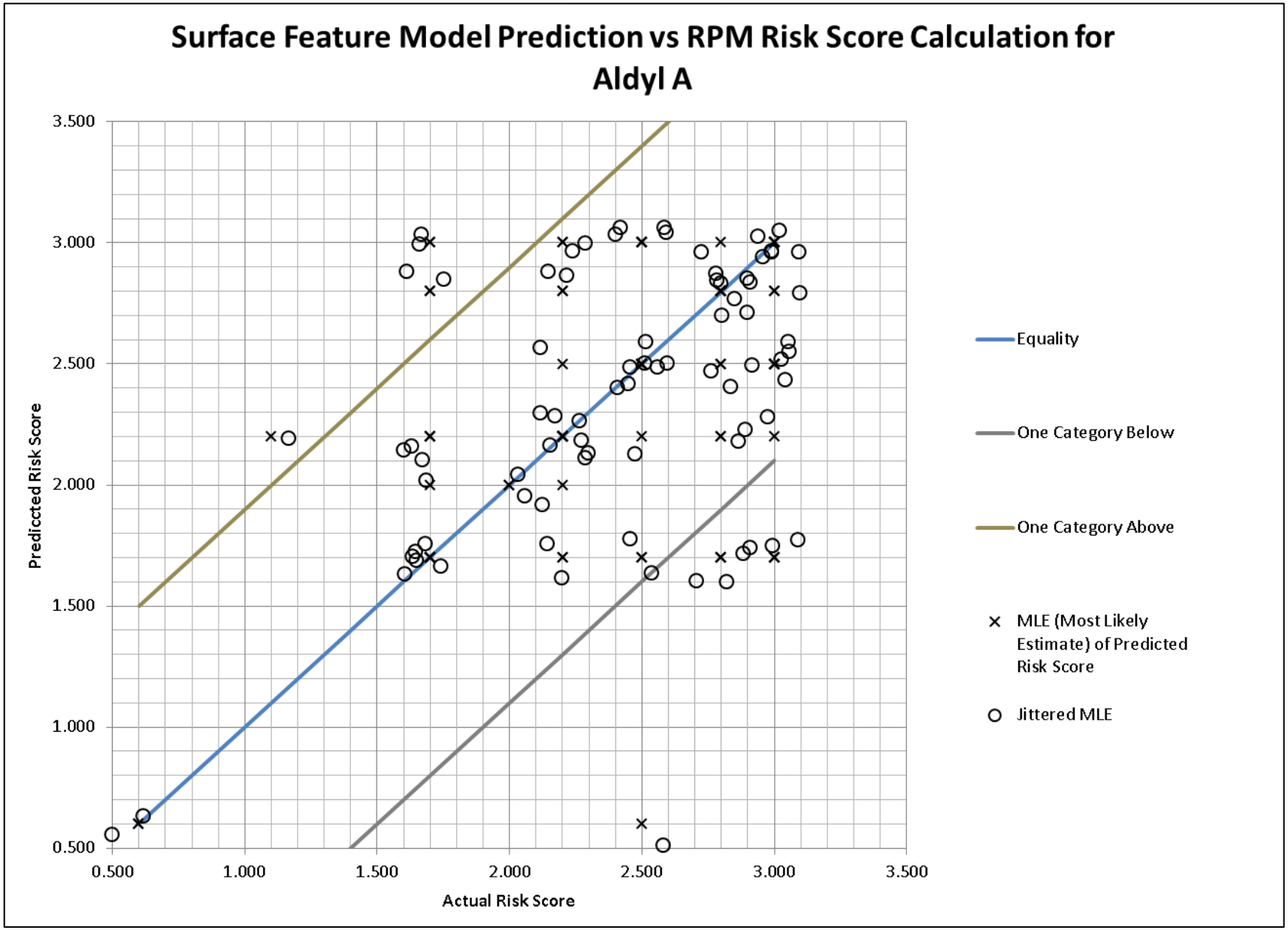






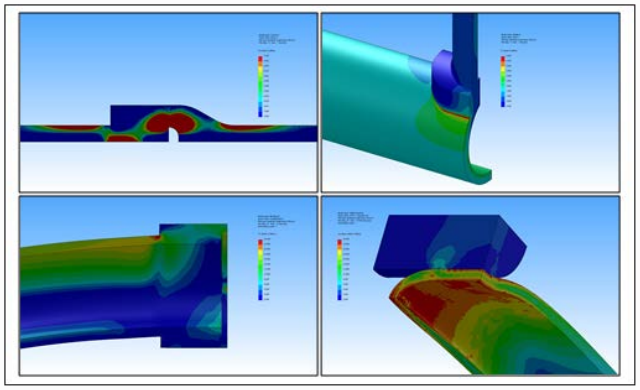
Methodology: Correlating Performance to Condition of Inner Pipe Wall

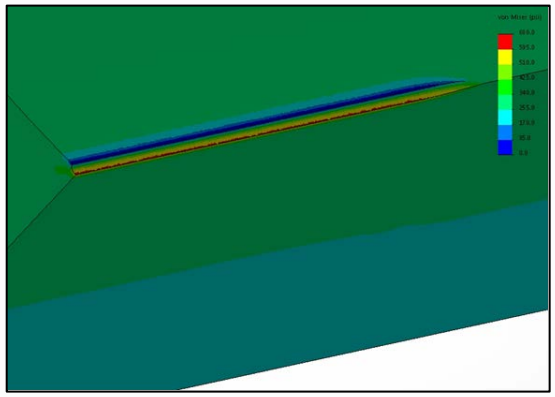
- The bulk material properties of the pipe as measured by tensile, compression and DTMA indicate that broadly speaking the Aldyl A does not degrade over time.
- There is evidence of a significant reduction in OIT from mid-wall to the inner wall.
- None of the 105 pipe samples had any indications of surface embrittlement due to significant oxidation of the inner wall
- A total of 73 pipe samples had a complete data set that includes SEM analysis, CPLM analysis, OIT and FTIR analysis.
- The SEM characterization of the inner wall yields several surface features of interest, all related to the organization of the spherulitic structure.
- Two of these features, together with OIT values and the spherulite size measured by CPLM were found to be promising in predicting the risk rank score

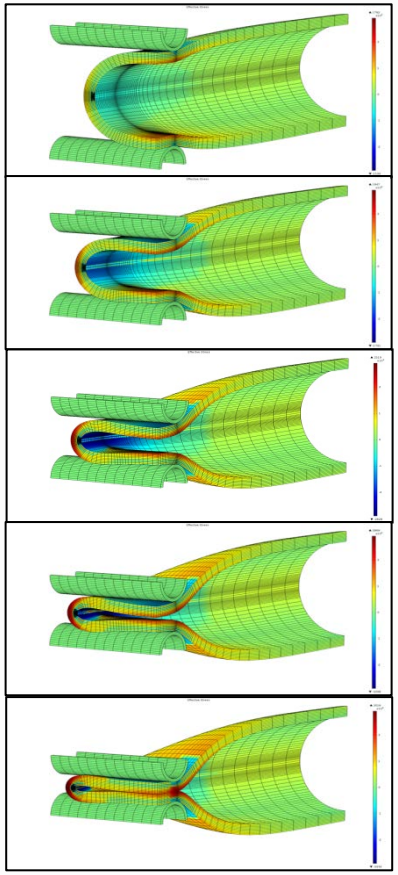

Surface Feature Model Prediction vs RPM Risk Score Calculation for Aldyl A
Predicted Risk Score
Actual Risk Score
3.500
3.000
2.500
2.000
1.500
1.000
0.500
0.500
1.000
1.500
2.000
2.500
3.000
3.500
Equality
One Category Below
One Category Above
MLE (Most Likely Estimate) of Predicted Risk Score
Jittered MLE

Methodology: Finite Element Method

- Application stresses are determined in order to:
  - Assess the likelihood of introducing damage through short term loading such as squeeze-off
  - Determine the stress concentration factors for various geometries or likely damage configurations







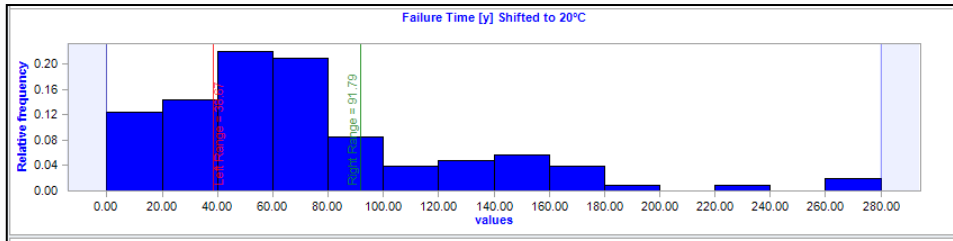
How to Tie Risk Ranking and FEM Together

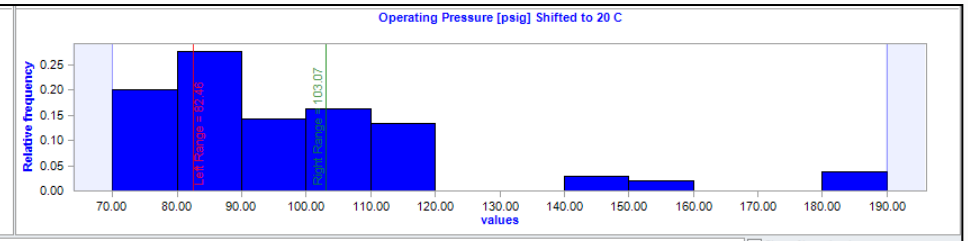
- 26% of the pipe is evaluated High risk and 5% of the pipe will have a lifetime expectancy at 20°C of less than 38 years at an operating pressure of less than 82 psig
  - If the pipeline operating pressure is 60 psig the maximum allowable stress intensification is 82/60=1.37
  - Most common stress intensifications in pipelines are higher than this

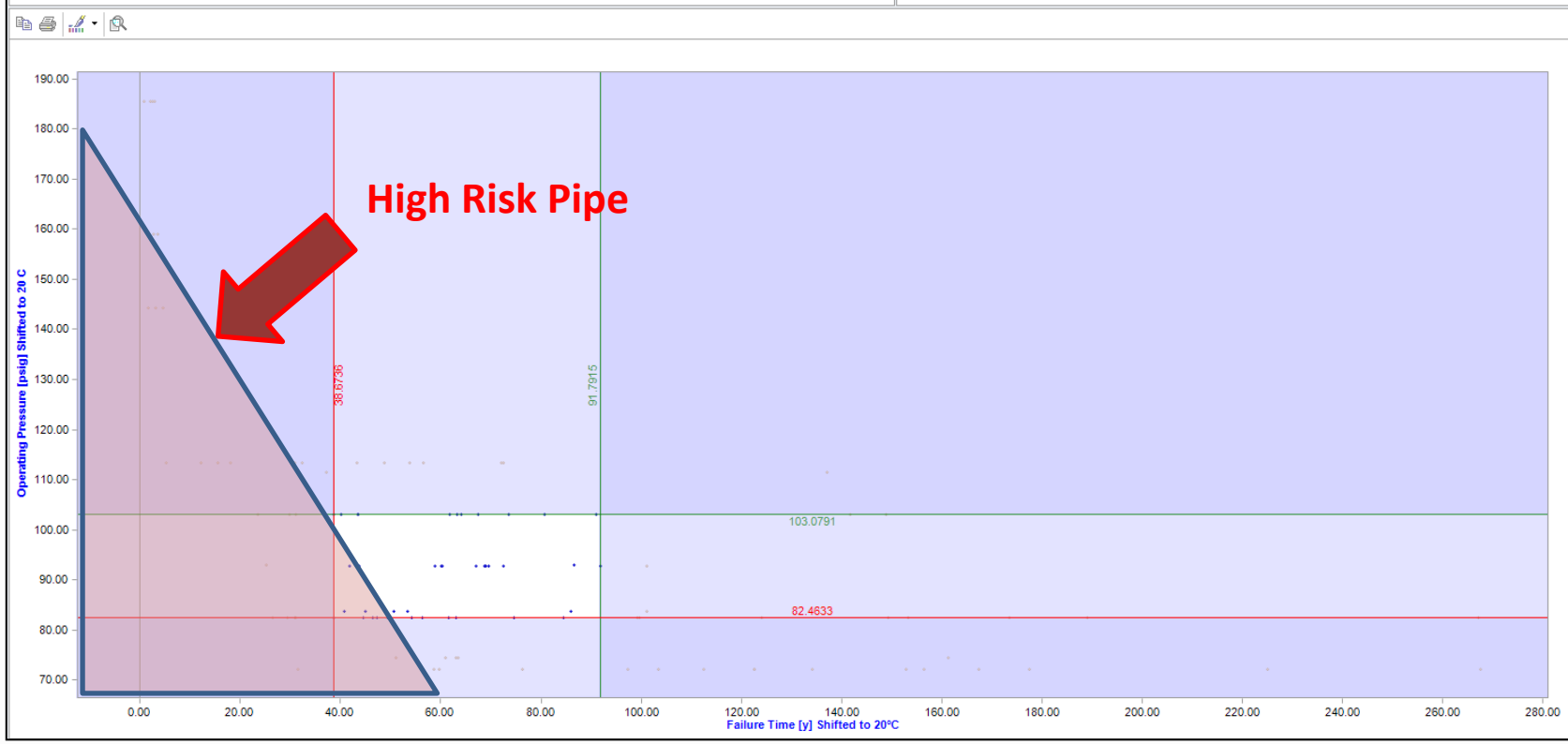
> **Expect slow crack growth failures in these pipes**

Pipe or Fitting Configuration (All with 60 psig Internal Pressure, SDR11)	Stress Intensification Factor
Socket Coupling – Coupling Edge	1.25
Saddle Tee	2.7
Socket Coupling – Coupling Center	1.8 – 2.9
Pipe with Bend Radius of 100 Pipe Diameters	3.0
Pipe with Bend Radius of 80 Pipe Diameters	3.6
Pipe with Bend Radius of 50 Pipe Diameters	4.7
Socket Coupling with Bend Radius of 100 Pipe Diameters	4.8
Socket Coupling with Bend Radius of 80 Pipe Diameters	5.8
Socket Coupling with Bend Radius of 50 Pipe Diameters	7.5
Squeeze-Off	8.5 – 10.5

Multivariate View of Risk Ranking





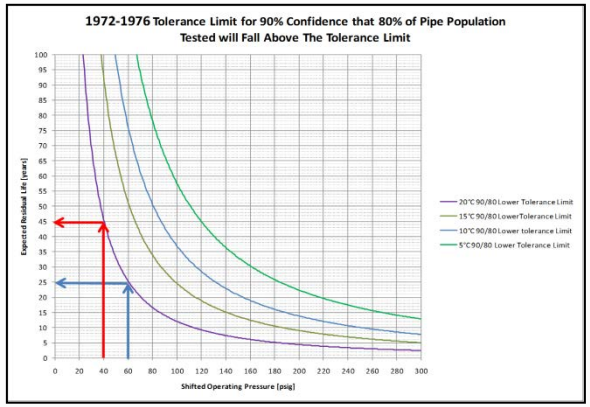


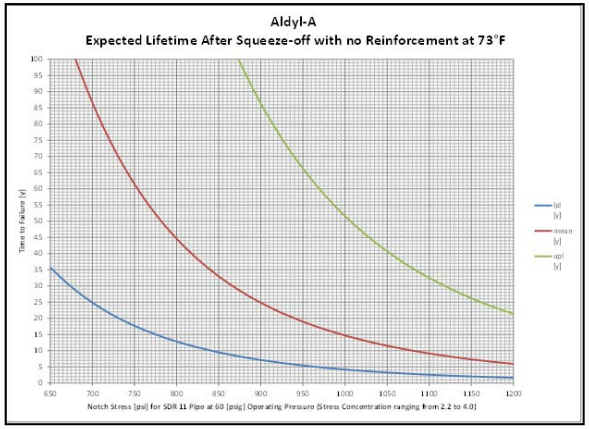
Show filtered only

	Failure Tin	Operating
Location		
Mean	72.0133	96.6272
Spread		
St. dev.	54.5128	25.6923
Variance	2971.648	660.0963
CofV	0.7570	0.2659
Shape		
Skewness	1.3758	1.9206
Kurtosis	5.2516	7.0430
Markers		
LowerX	38.6736	82.4633
UpperX	91.7915	103.0791
LowerP	0.2500	0.2500
UpperP	0.7500	0.7500
X Spread:	53.1180	20.6158
P Spread:	0.5000	0.5000
Percentile		
1%	0.8355	72.1554
3%	2.0273	72.1554
5%	2.5650	72.1554
10%	5.2202	72.1554
15%	25.2534	72.1554
20%	31.0171	74.3917
25%	37.6778	82.4633
30%	41.8460	82.4633
35%	44.9319	82.4633
40%	50.5504	82.4633
45%	56.2532	83.6906
50%	60.2967	92.7712
55%	63.1548	92.7712
60%	67.5623	92.7712
65%	72.0773	103.0791
70%	80.7905	103.0791
75%	91.7915	103.0791
80%	101.1778	111.5875
85%	134.1295	113.3871
90%	152.8409	113.3871
95%	173.4902	159.0639
97%	189.0323	185.5425
99%	267.1218	185.5425

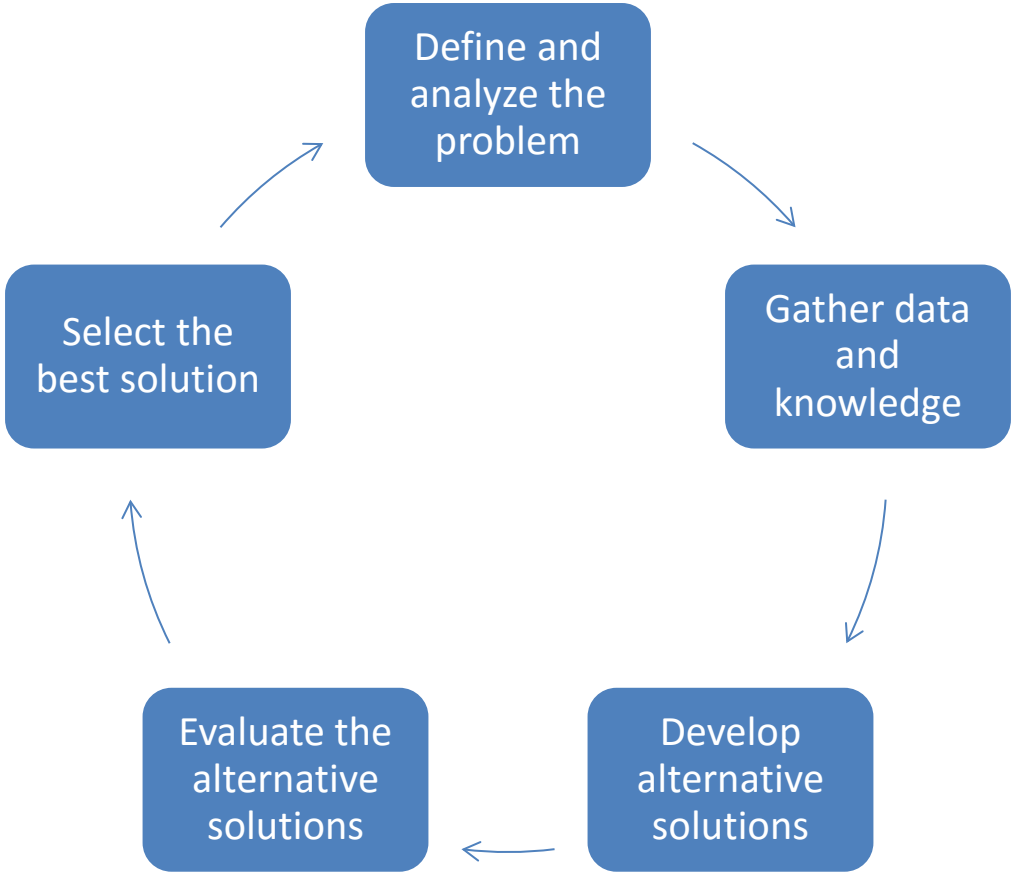
Combining FEM and RPM

- Detailed knowledge of the true stress states in the field application allow specific performance curves to be developed
- These specific performance curves enable operators to develop the appropriate mitigation strategy for their application



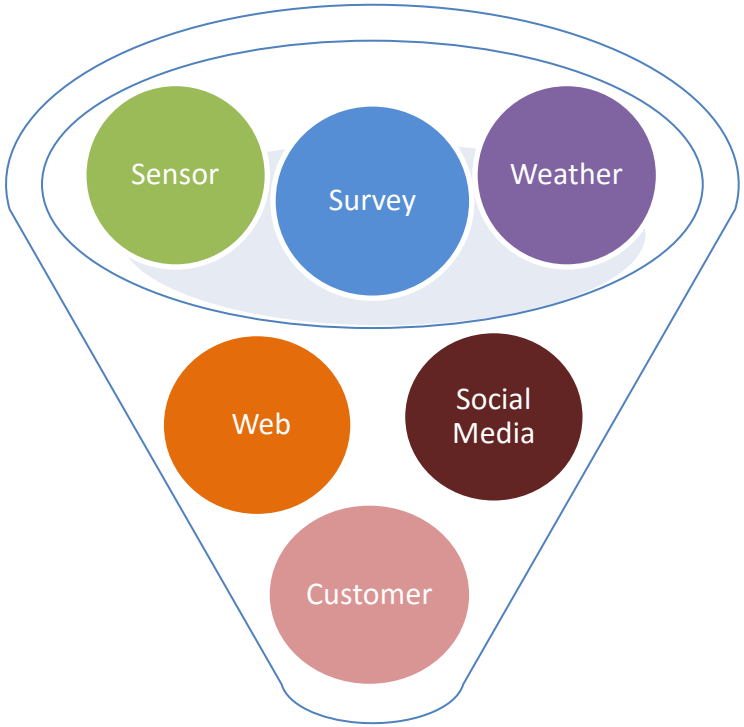


Decision making process



Challenges:
Presence of heterogeneous and dispersed data
Representation of knowledge
Identification of the best solution

Heterogeneous and dispersed data



Big data

Types of data:

- Structured (SQL)
- Unstructured (NoSQL, Graph DB)

Database System:

- NoSQL and Graph databases are not tied to a particular data schema. Therefore, they offer a robust database technology to store big data of any kind.

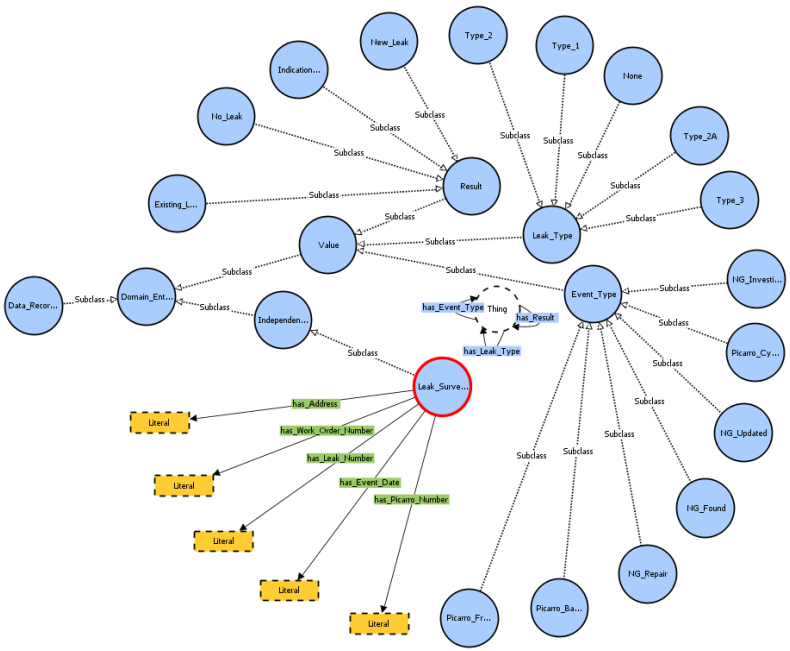
Representation of Knowledge

Subject Matter Expertise

+

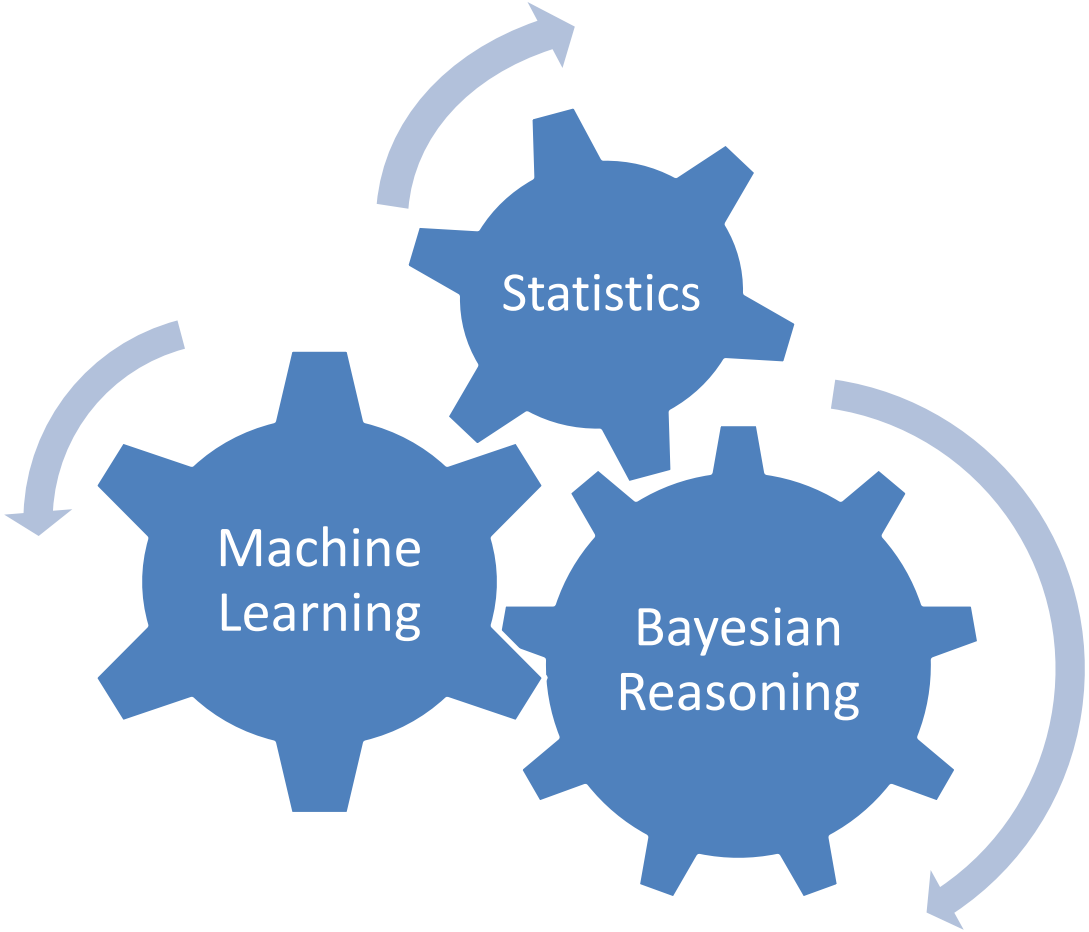
Historical observation

→ Knowledge

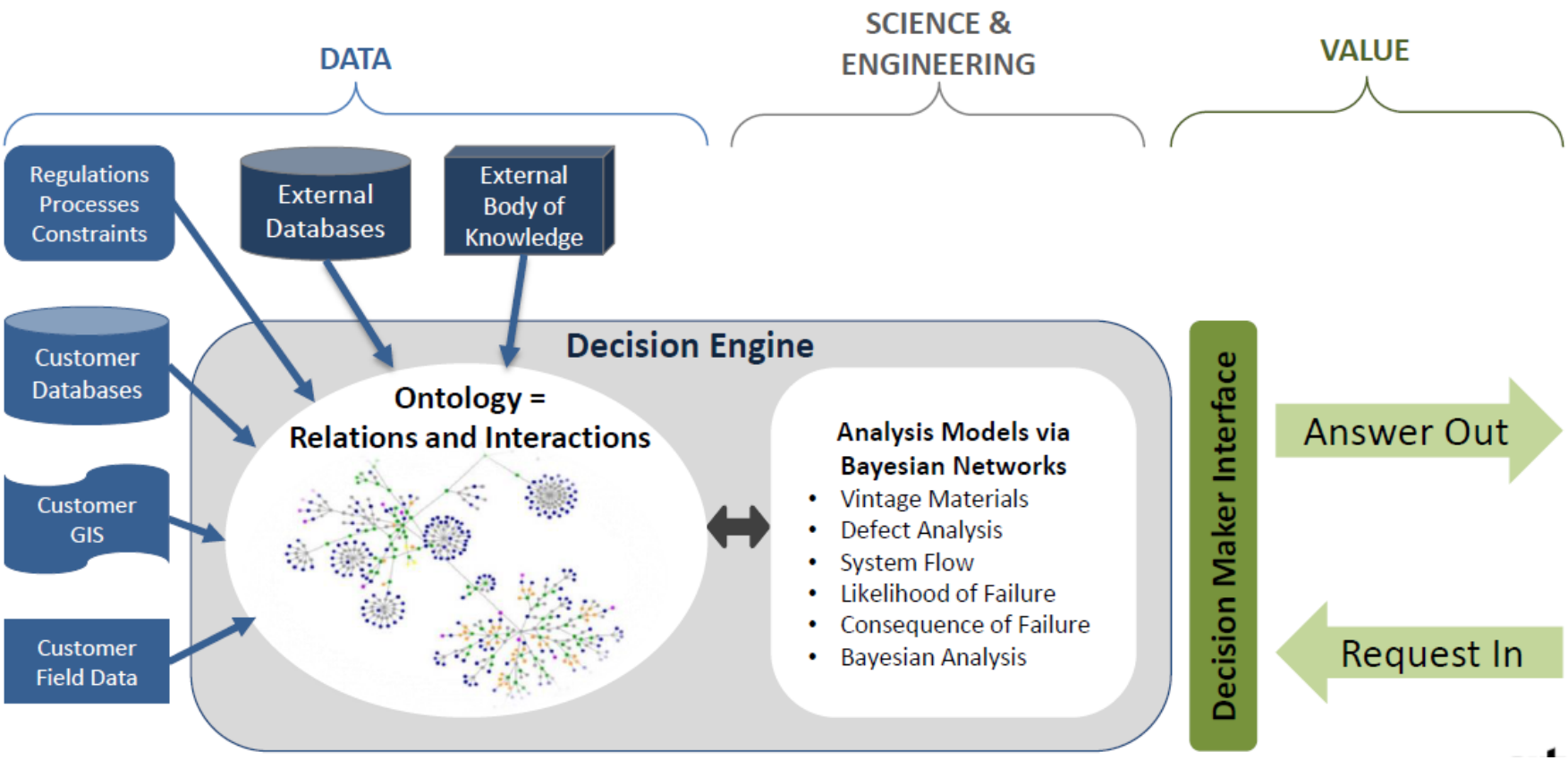


Ontology: knowledge as a graph

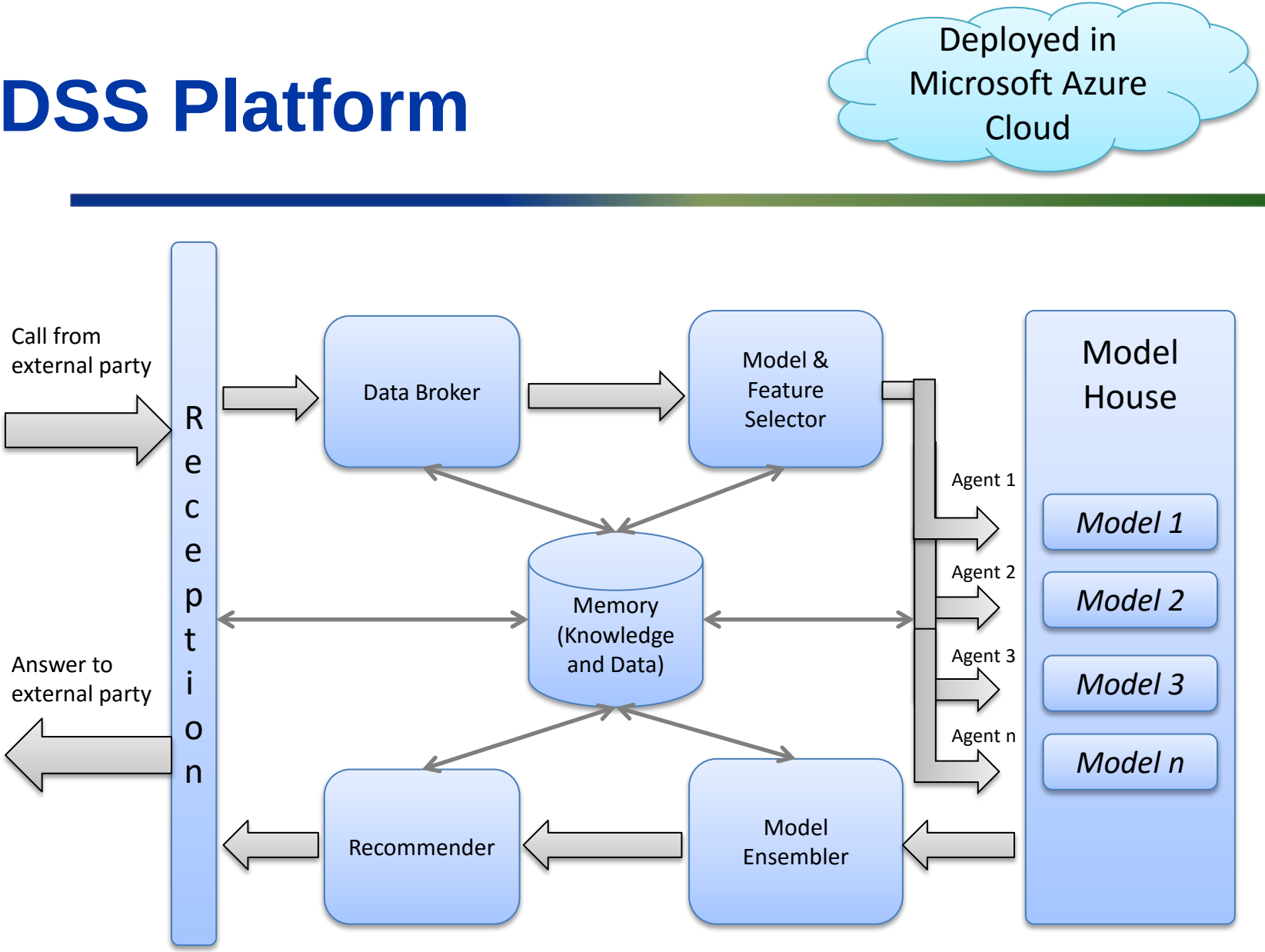
Identification of the best solution



EDSS Concept

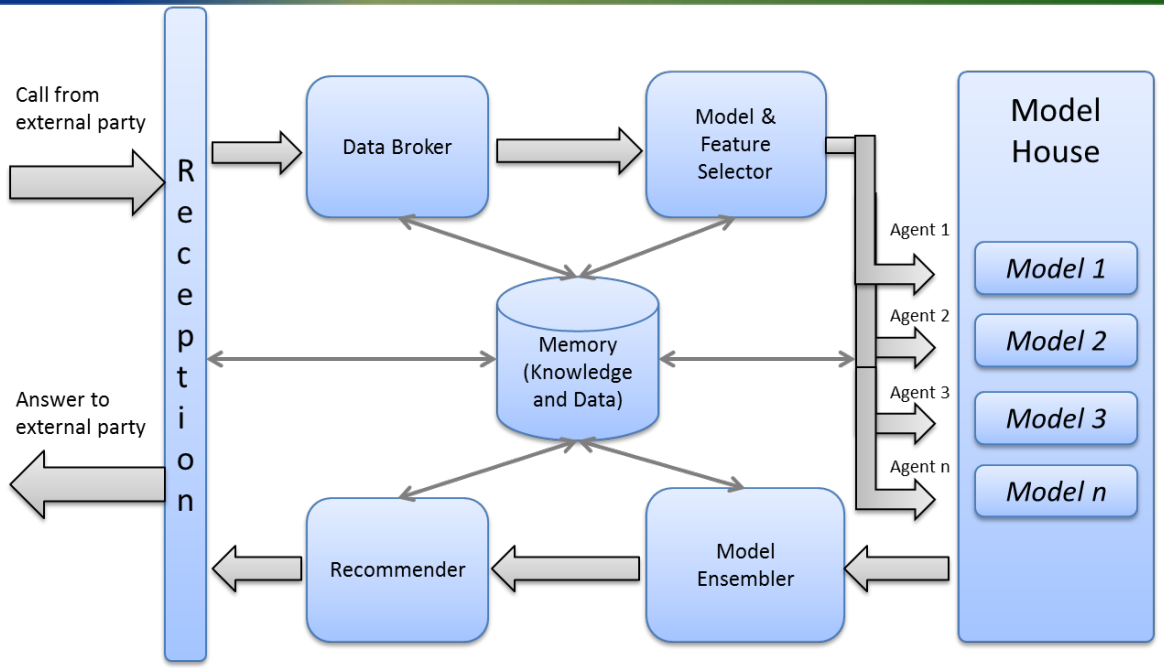


EDSS Platform



EDSS Platform

- Software-as-a-Service (SaaS) architecture
- Open-source technologies mostly licensed under Apache 2.0
- Models built with JAVA, R, and Python languages



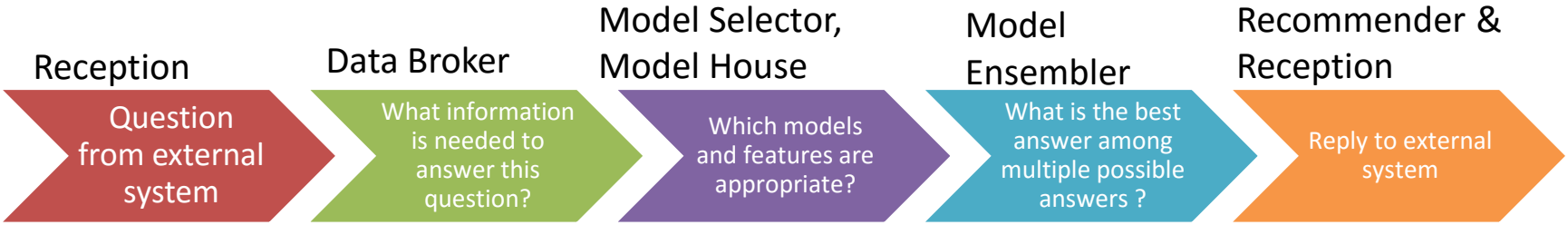


Figure: Decision making process in EDSS

EDSS: Reception

- ISO 19464 AMQP complaint
- Interacts with external party
  - Receives query (question)
  - Receives data
  - Sends solution
- Validates and parses query and/or data
- Logs information in memory

EDSS: Data Broker

- Fetch data from memory that are relevant to the question
- Prepares data by cleaning and pruning
- Logs information into memory

EDSS: Model and Feature Selector

- Selects single or multiple models based on
  - knowledge from ontology that resides in memory
  - query
  - data
- Selects important and appropriate features from data by performing statistical tests

EDSS: Agents

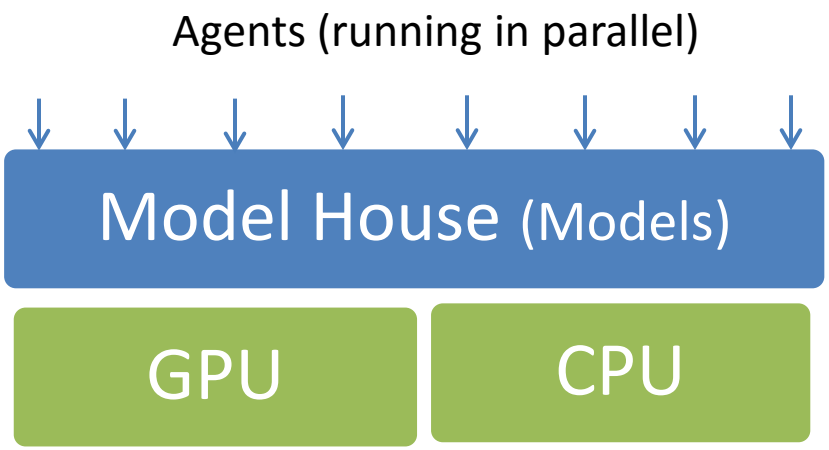
- Each model has its own dedicated agent. These agents execute models asynchronously in parallel.
- Prepares data in specific format for the selected model
- Pulls parameter values for models from memory, if required

EDSS: Models

- A model is a statistical or machine learning procedure that gives solution to a problem.
- Examples of models: Bayesian network, Neural network, Support vector machine, Random Forest, Decision tree, Naïve Bayes, etc.

EDSS: Model House

- Collection of models.
- Provides scalable and distributed cloud computing power to models per requirement.
  - Powers *simple mathematical models* to *intense image processing models*.



EDSS: Model Ensemble

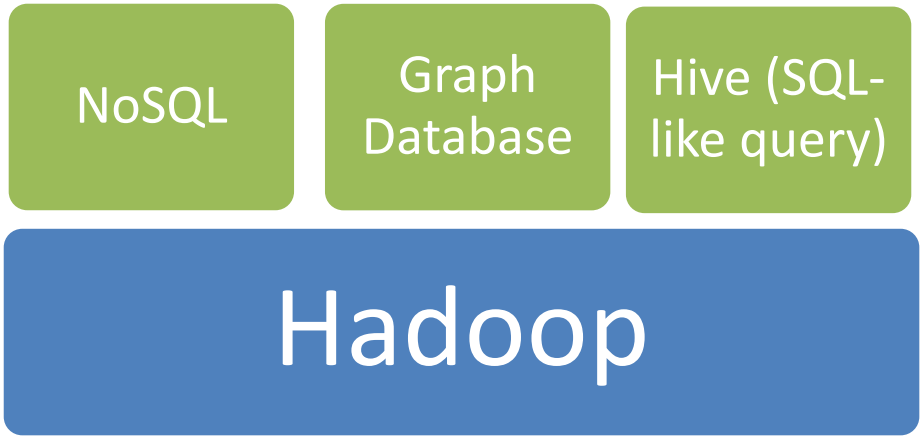
- Loads ensemble strategy stored in Memory DB
- Decides the best solution from the results of multiple models
- Write the result to Memory DB

EDSS: Recommender

- Recommends answer to external party
- Logs these recommendations in memory

EDSS: Memory

- Semantic Big Data Repository



Technologies

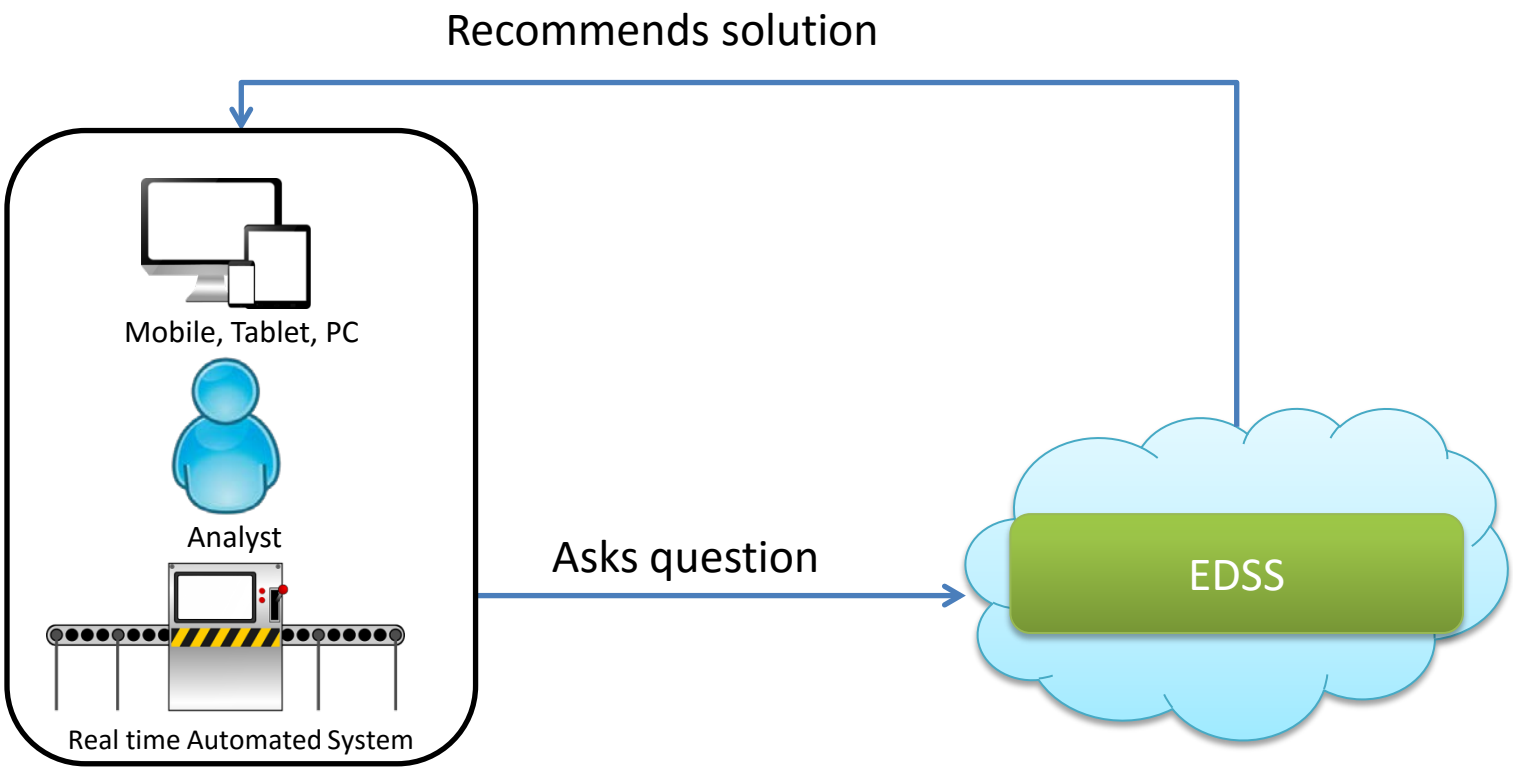
NoSQL: MongoDB, Couchbase, Cassandra

Graph DB: Titan

EDSS Features: Summary

- Cloud based
- Scalable
- Real-time processing
- Plug-and-play models
- Ontology-based knowledge representation
- Support for heterogeneous and dispersed big data

Use Case I: Question & Answer mode



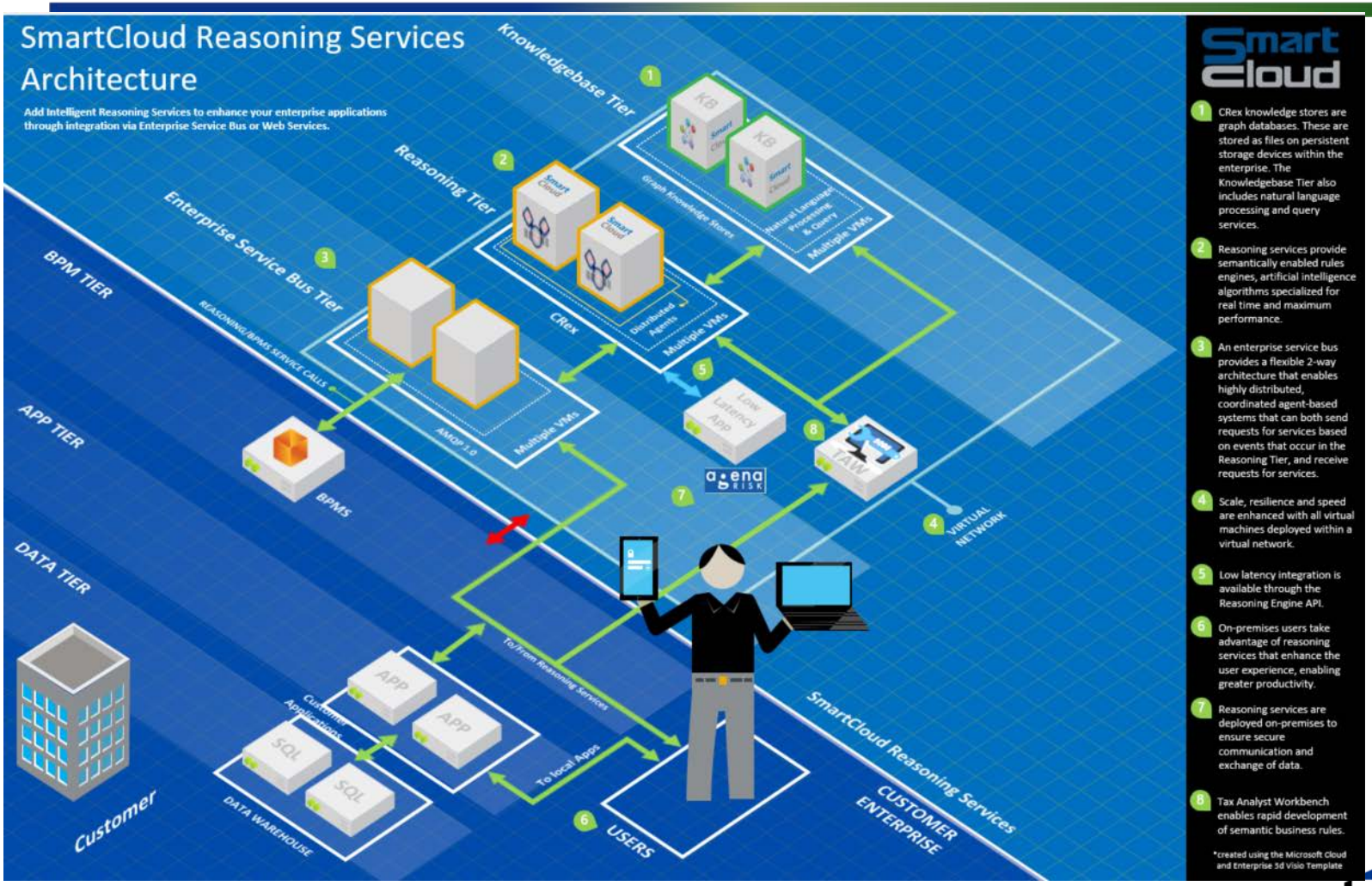
3rd party systems (e.g., SmartCloud, Inc)

Use Case II: Real time monitoring mode

Sensors deployed in the field

Web/Mobile/Tablet based Dashboard

EDSS Integration into Enterprise Systems



Bayesian/maximum entropy network-based damage identification

Arizona State University

Institutional PI: Yongming Liu

Students: Yuhao Wang, Rylie Rodes

Outline

- Background
- Technical approach and tasks
- Challenges and recent activities
- Schedule and deliverables
- Conclusions and future work

Background

- Challenge in pipeline damage diagnosis/prognosis and risk management
- Fast and automated identification, classification, and quantification of various types of damage
- Uncertainty quantification and reduction for accurate analysis and decision-making

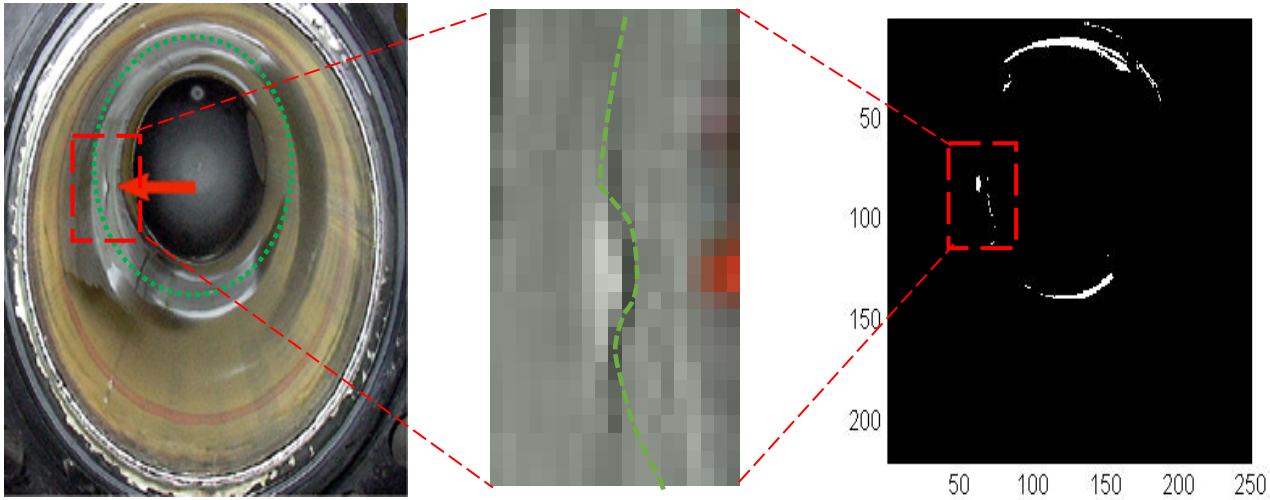
Project objectives:

- Develop an automatic damage precursor identification methodology using Bayesian/maximum entropy network
- Develop a reliability-based maintenance scheduling optimization framework for plastic pipeline systems

Technical approach and tasks

- Research Imaging Analysis and Feature Extraction
- Bayesian network classifier development
- Reliability-based maintenance scheduling
- Dynamic Bayesian network for diagnosis/prognosis

Structured light-based imaging analysis



Schematic illustration of imaging analysis with structure light scanning a) raw image with inner wall damage; b) lighting ring profile at the damage site; c) structure light image assisted feature identification; (raw image obtained from http://www.swri.org/3pubs/ttoday/fall02/smartpig.htm)

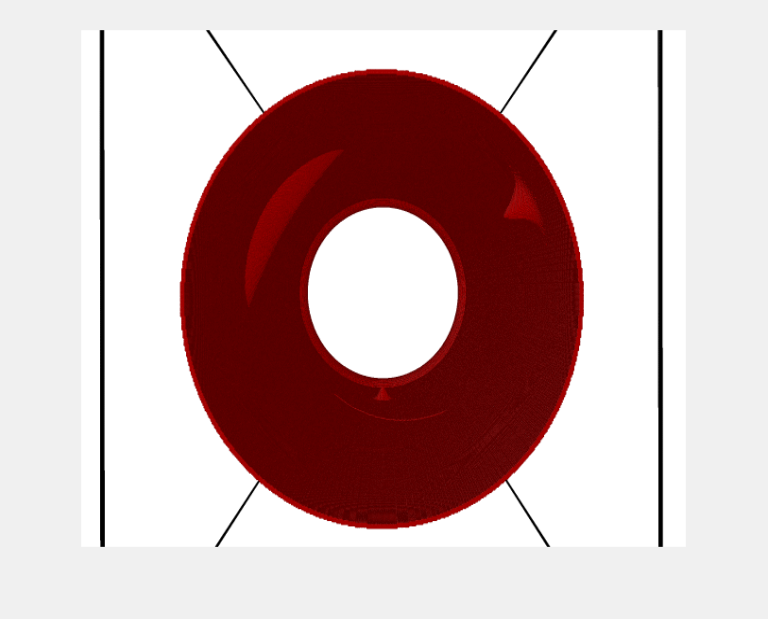
- Inner pipe imaging using structured light and 3D reconstruction (CU-Denver)
- Post imaging analysis for damage feature extraction (ASU)

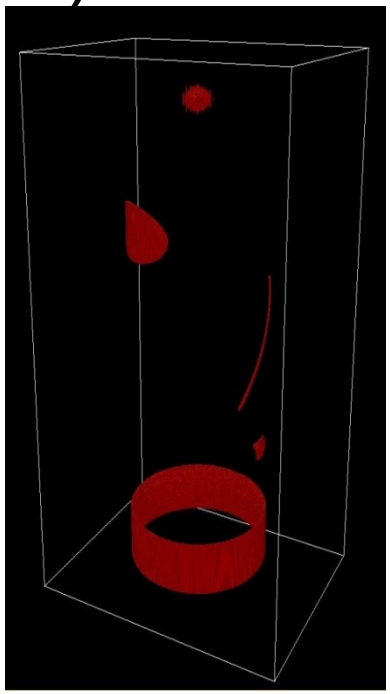
Image processing - 1

- Noise reduction
  - Hardware and software for imaging stabilization and noise filtering
- Background subtraction
  - Use structural element to create background image
  - Subtract the background from the original image
- Edge detection
  - An operator finds curves that follows a path of rapid change in image intensity

Image processing - 2

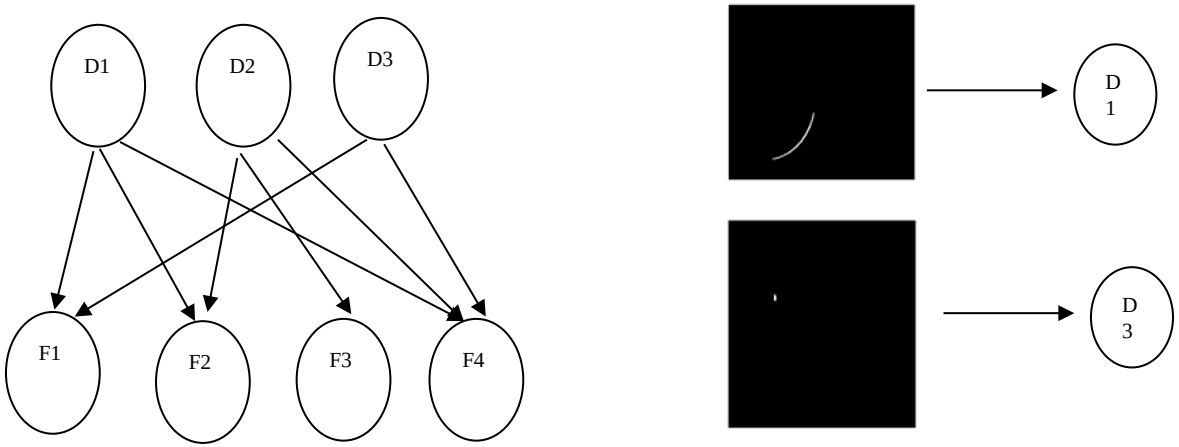
- Numerical simulation is done to demonstrate the algorithm development (ongoing work with CU-Denver for experimental imaging results)





Bayesian Network Classification - 1

- The features extracted from the image used for Bayesian network classification
- A network will be developed that can best describe the relationships between classes and features.



Schematic illustration of Bayesian network for damage precursor classification a) Bayes net for damage types and image features; b) feature classification with most probable damage types;

Bayesian Network Classification - 2

- Given a data set, build a classifier that can correctly predict the class of new objects.
- Classification is done by calculating the posterior for each class:

$$c^* = h_{NB}(\mathbf{a}) = \arg\max_{j=1\ldots m} P(c_j) \prod_{i=1}^{n} P(A_i = a_i | c_j)$$

- Different algorithm
  - Naïve Bayes (NB)
  - Tree Augmented Naïve Bayes (TAN)
  - Others

[1]Friedman, N., Geiger, D., & Goldszmidt, M. (1997). Bayesian Network Classifiers. *Machine Learning*, *29*, 131–163. http://doi.org/10.1023/A:1007465528199

[2]Gladys Castillo. Bayesian Networks Classifiers PPT Slide. University of Aveiro

Bayesian Network Classification - 3

- Generalized Bayesian Network based on the maximum entropy theory [1]
- Posterior is given by:

$$p(\theta) \propto \mu(\theta)\mu(x'|\theta)e^{\beta \cdot g(\theta)}$$

- where $\mu(\theta)$ is the prior, $\mu(x'|\theta)$ is the likelihood function and $e^{\beta \cdot g(\theta)}$ is the exponential term introduced by constraint. When $e^{\beta \cdot g(\theta)} = 0$, the equation is identical to the simple Bayes Theorem.

[1] Guan, X., & Jha, R. (n.d.). Probabilistic fatigue damage prognosis using maximum entropy approach. *Joutnal of intelligent manufacturing, 23(2*), 1–19.

Reliability-based maintenance scheduling

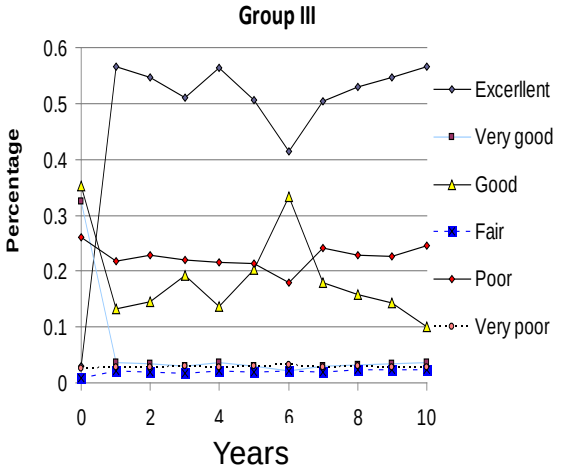
- Identified damage level can used to estimate the reliability/risk of aging pipelines
- Optimization of maintenance scheduling with reliability and budget constraints
- Decision making for type of repair and amount of repair to maximum the pipeline performance and minimize failure rate

conditionstate	1	2	3	4	5	6
do_nothing	0	0	0	0	0	0
repair	0	400	600	800	1600	1800
replacement	0	0	1600	1600	3000	3000

Cost function in optimization

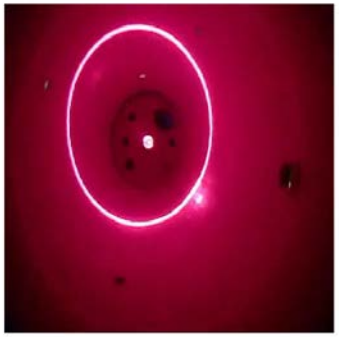
Reliability Constraint

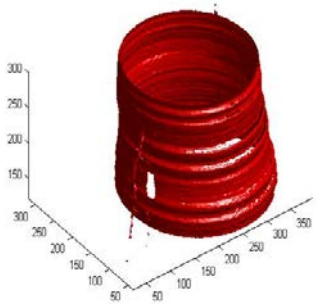
Budget Constraint



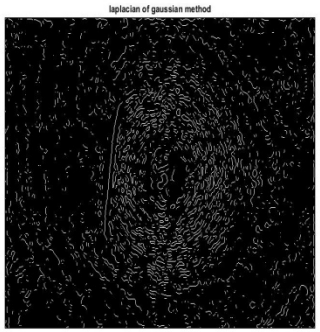
Optimized maintenance

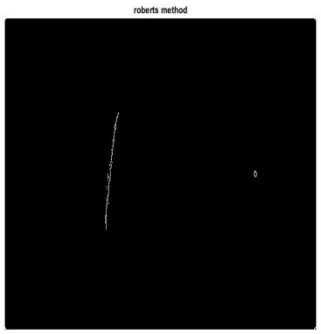
Challenges – imaging noise





Preliminary imaging results (CU Denver)



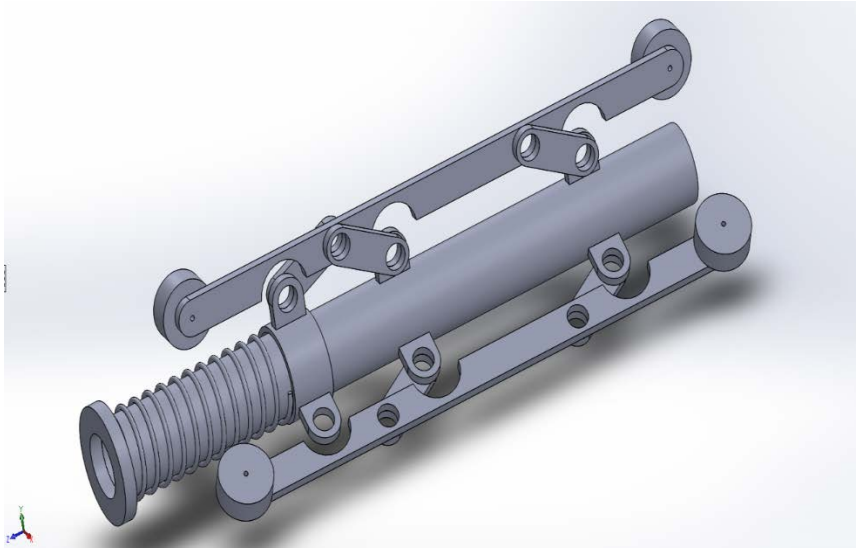


Different edge detection methods with noisy images (slit damage)

- Imaging quality is critical for the reconstruction and feature extraction
- Imaging hardware should be stabilized to reduce the shock-induced imaging noise
- Filtering should also be used to remove the imaging noise, especially for high frequency components

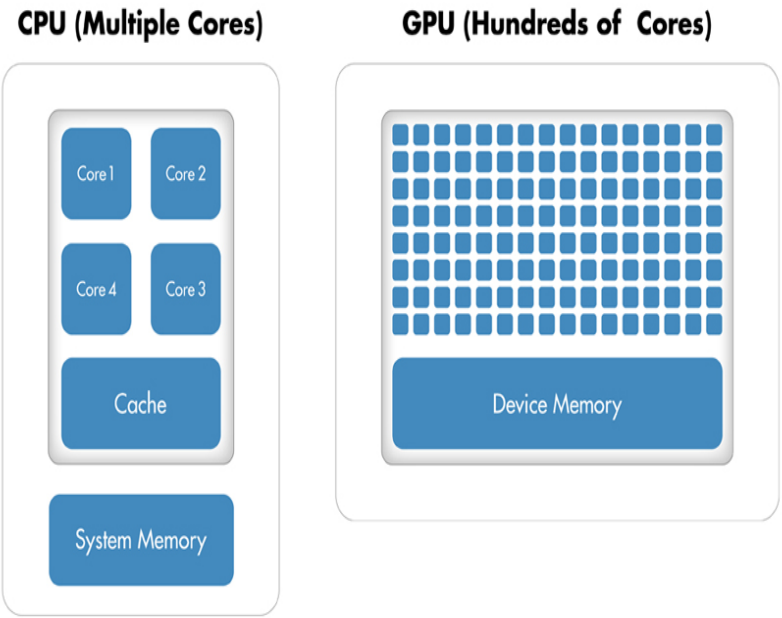
Imaging stabilizer

- Prototype design with spring-loaded shock absorber
- Miniature size and for 2 inch pipe
- Manufacturing using 3D printing



Challenges – high performance computing GPU programming

- Extremely computational expensive for large number of imaging analysis and processing
- GPU computing is investigated for massive parallel array of integer and floating-point processors and high-speed memory
- Pros:
  - Can achieve better performance with highly parallelized computing.
- Cons:
  - Size of the memory and the transfer speed between system memory and device memory.



Schedule and deliverables

Task		Task Description	2015		2016				2017		
			Sep.	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3
4		**ASU Bayesian Methods Development**									
	4.1	Research Imaging Analysis and Feature Extraction		D1	D2	D3					
	4.2	Develop Bayesian Classifiers			D2	D3	D4	D5			
	4.3	Develop Reliability Based Maintenance Framework					D4	D5	D6	D7	
	4.4	Develop Dynamic Bayesian Network for Diagnosis/Prognosis							D6	D7	D8
	4.5	Quarterly Reports, Final Report and Paper Submission		R1	R2	R3	R4	R5	R6	R7	P, F

Conclusions and future work

- Imaging analysis for feature extraction using simulated data
- Various noise reduction technique are investigated
- Classification using Bayesian network
- High performance computing for imaging analysis

Miniature and multispectral endoscopic sensing of inner vintage plastic pipe wall damage

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Dept. of Electrical Engineering
University of Colorado Denver

December 4, 2015

Lab of EM and Acoust imaging & Prog (LEAP)

Outline

- Background and objectives
- Technical approach and tasks
- Challenges and recent activities
- Schedule and deliverables
- Conclusion and future work

Background and Motivation

- Accurate detection, identification and classification of current vintage pipeline inner wall damage precursor are of critical importance
  - Limited success in sensing and characterizing the long lengths of deteriorating plastic pipelines with high probability of detection (POD)
  - State-of-the-art NDE: direct visual/optical, ultrasonic, liquid-coupled acoustic, LiDAR, laser topography, etc.
- Capability of the currently available technologies that can be **miniaturized** and **integrated** into smaller CTS size pipes for a fast scan is questionable and needs a systematic assessment

R&D Objectives

- Develop miniaturized and multispectral endoscopic sensors for insertion into vintage plastic gas distribution pipes down to $\frac{1}{2}$" to 1" CTS size with high sensitivity and specificity premature failure damage detection
- Develop a structured data dimensionality reduction framework that can be integrated with a real-time single mechanical scanning platform with the ability to efficiently scan long lengths of pipeline
- Tool demonstration in laboratory or controlled field environment to demonstrate the feasibility of an automated inspection and decision support system incorporating fully autonomous guidance (collaborative work with GTI and ASU)

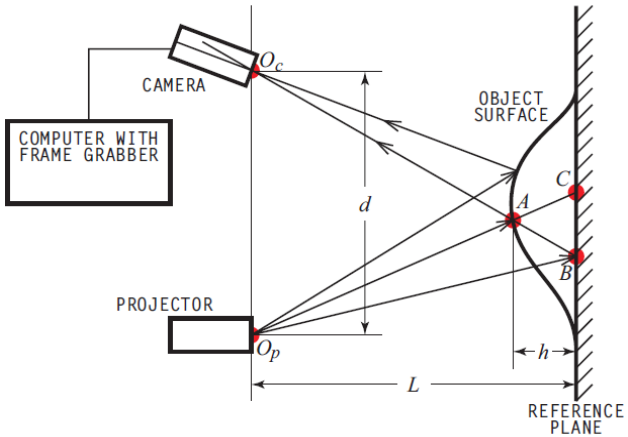
Technical Approach and Tasks

- Critical Defects and Damage Library
- Multispectral Sensing Prototype Design
- Numerical Simulation and Sensor Optimization
- Damage Detection and POD studies
- Miniaturized Sensor Development
- Structured and Multispectral Data Reduction Framework
- 3D Image Reconstruction

Task 1: Multispectral Sensing Prototype

- Structured light
  - 3-D shape acquisition technique that extract the 3d data from the deformations that occur in the projected patterns
  - The depth h is extracted from the intersection between camera and projector rays

$$h = \frac{BC \cdot (L/d)}{1 + BC/d}$$



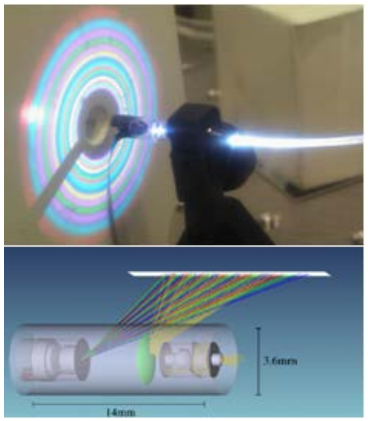
Where, the phase-shifting:

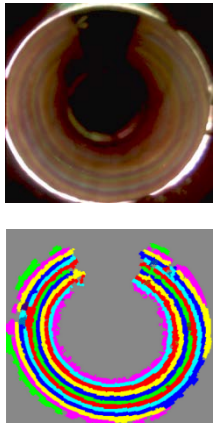
$$BC = \beta(\phi_c - \phi_b)$$

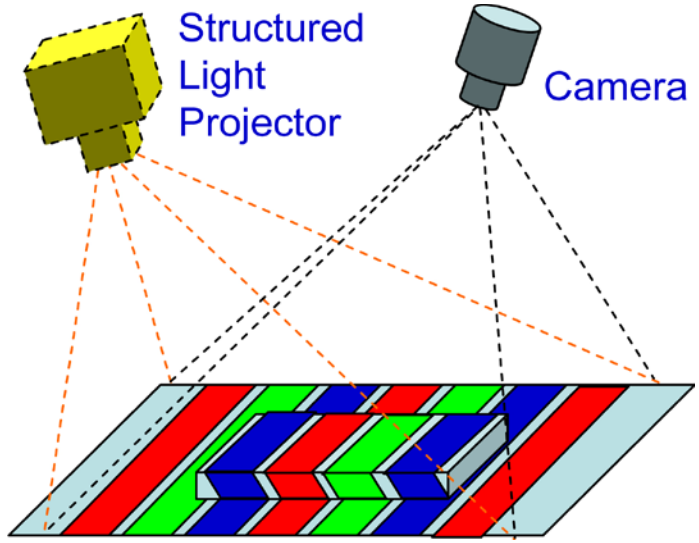
Guan C., Hassebrook, L. G., and Lau, D. L., Composite structured light pattern for three-dimensional video, Optics Express, **11**(5): p. 406-417, **2003**.

Multispectral Sensing Prototype

- Proposed colored pattern design
  - use a gray coded or colored patterns that have **unique sequences** in order to solve the location of the reconstructed 3D point





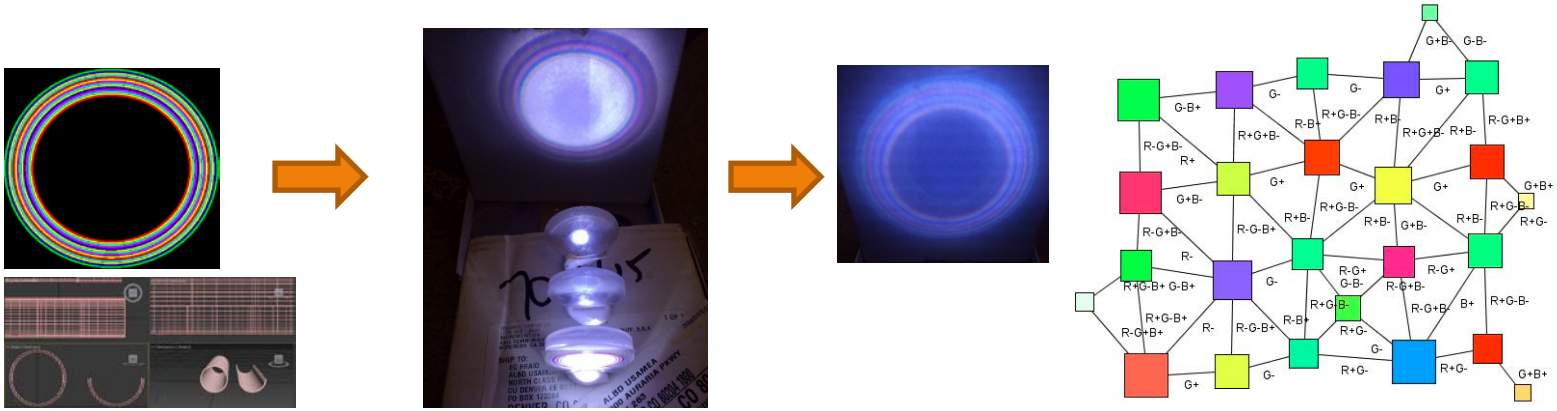


Schmalz, C., et al., An endoscopic 3D scanner based on structured light. Medical Image Analysis, **16**(5): p. 1063-1072, **2012**.

Jason Geng, "Structured-light 3D surface imaging: a tutorial," Adv. Opt. Photon. **3,** 128-160, **2011**
https://www.osapublishing.org/aop/abstract.cfm?uri=aop-3-2-128

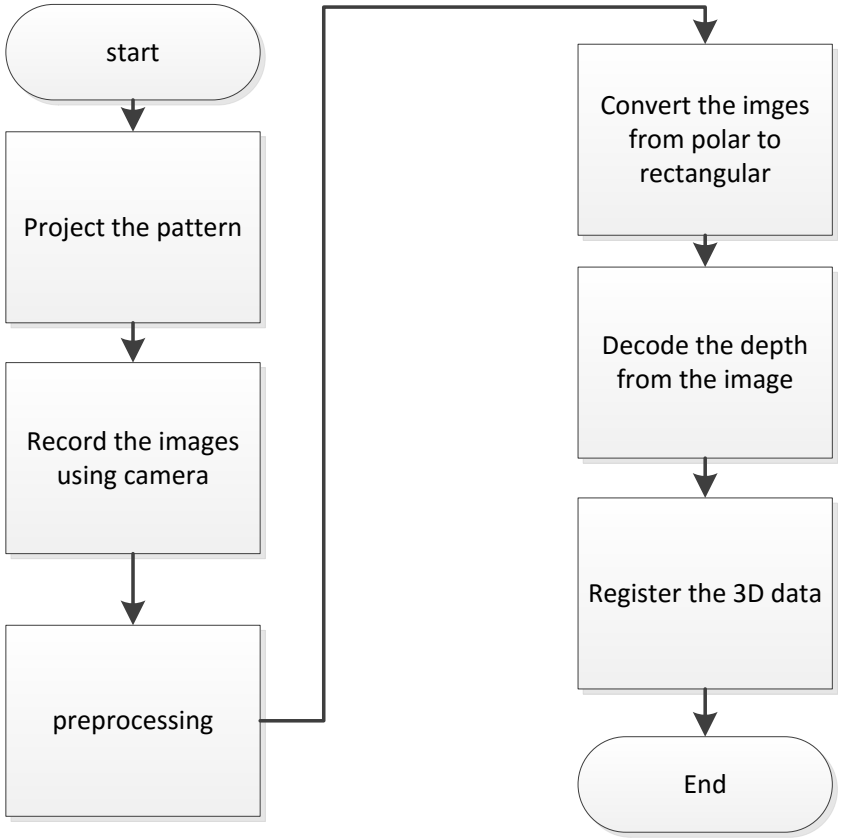
Region Adjacency Graph (RAG) based decoding

- Correspondence Problem: Find the accurate position of the stripes (Schmalz, 2012)
- Proposed method: A region adjacency graphs are created for both of the projected and imaged pattern(after watersheding) and the search for the right edge is achieved depending on the uniqueness of the projected sequences



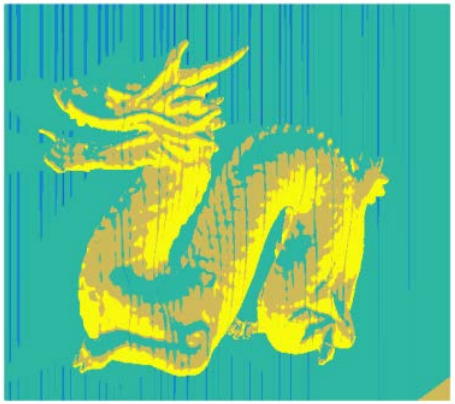
Overall Schematic

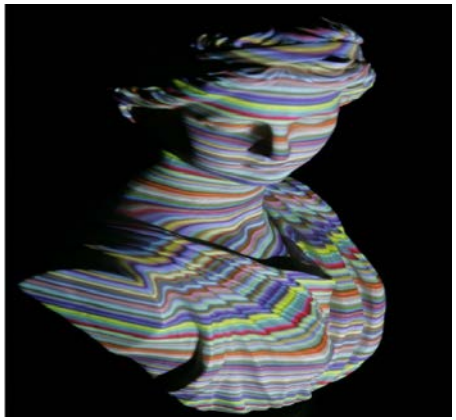
- Multispectral Sensing Flow chart



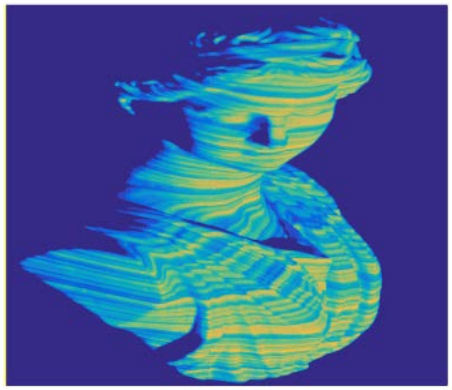
Simulation: Preliminary Results

- 3D Reconstruction





Original data:
http://www.dh.aist.go.jp/~shun/research/dlp/fig/structured.jpg



CU 3D recon results

Task 2: Structured Data Dimensionality Reduction

- Task 2 focuses on reducing the high dimensional structured light data obtained in Task 1 and extracting vintage pipeline inner wall damage-sensitive features that will be integrated with following research tasks using advanced image processing toolset
  - Supervised local fisher discriminant analysis (LFDA) and unsupervised locality preserving projection (LPP) based dimensionality reduction of multispectral data
  - Development of discrete wavelet transform based feature extraction and signature classification algorithms

Structured Data Processing

- Let $x_i \in R^d, (i = 1, 2, \ldots, n)$ be *d*-dimensional samples and $y_i \in \{1, 2, \ldots, c\}$ be associated class labels, where *n* is the number of samples and *c* is the number of classes.
- Let *X* be the matrix of all samples acquired in Task 1:

$$X = (x_1 \mid x_2 \mid \ldots \mid x_n)$$

- Let $z_i \in R^r, (1 \leq r \leq d)$ be low-dimensional representations of x_i, where *r* is the reduced dimension, i.e., the dimension of the extracted inner wall damage feature space

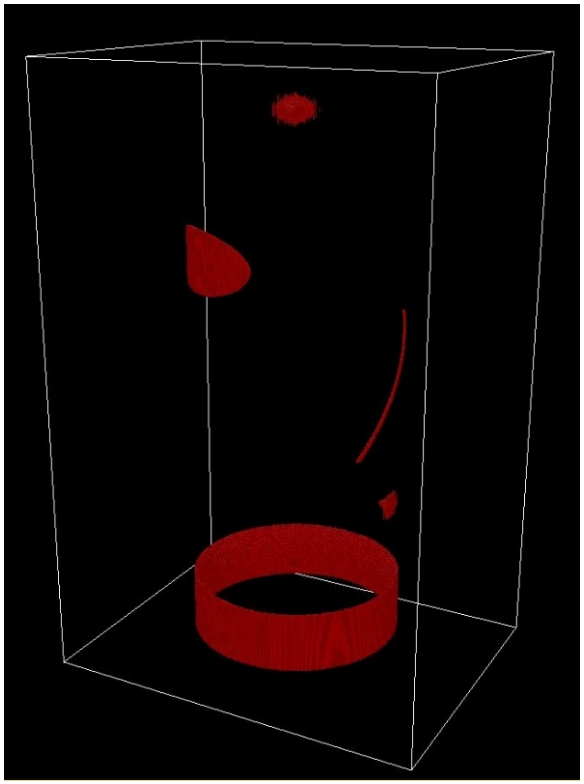
$$z_i = T^{\dagger} x_i$$

- For the proposed research, we start with linear dimensionality reduction above and extend to non-linear mapping

Q1 Activities and Challenges

- CU LEAP Lab customized pipe samples

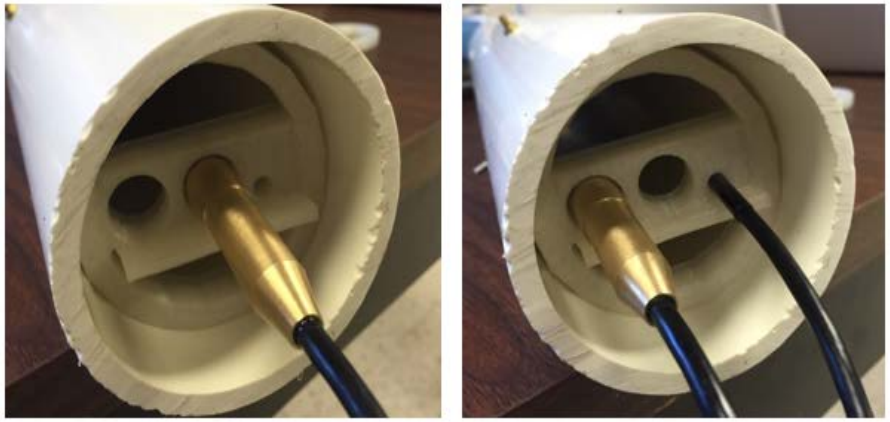
CU-Denver



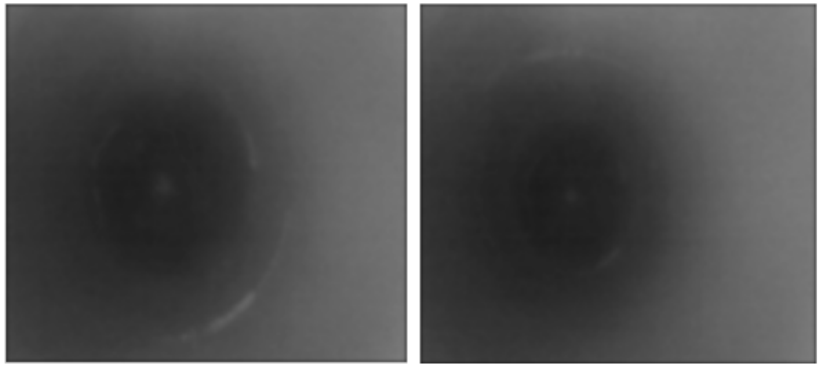
ASU

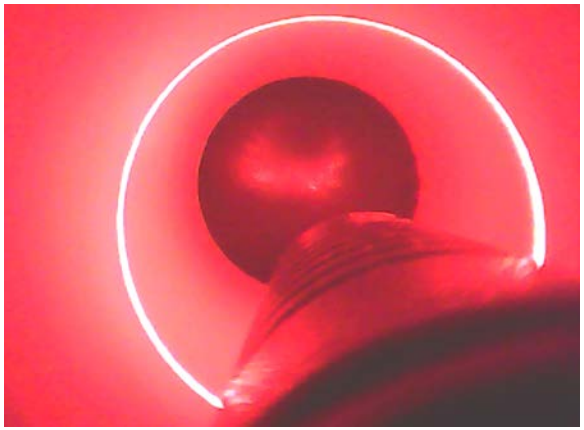
Initial Optical setup and Raw Data

- LED and Single color laser sources

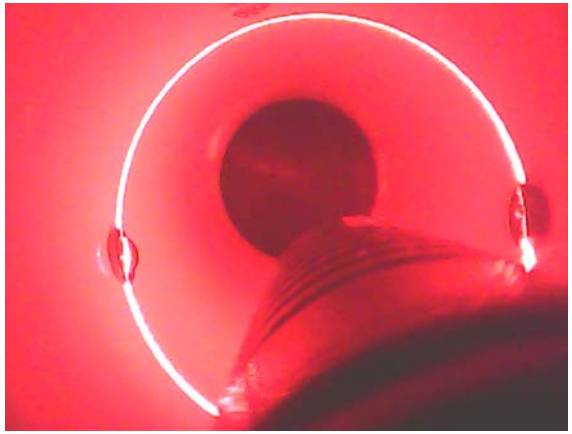


Low contrast and SNR





No damage

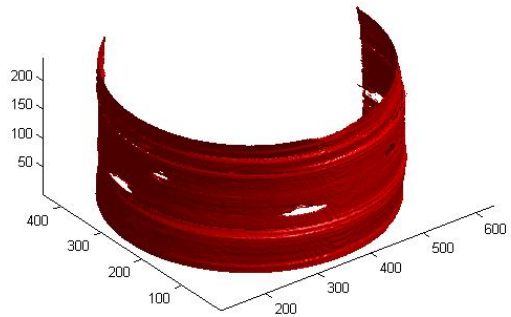


w/ damage

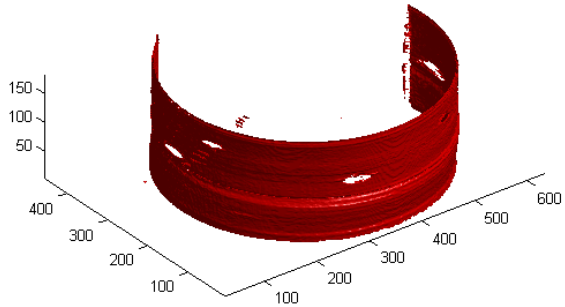
Three-dimensional Reconstruction

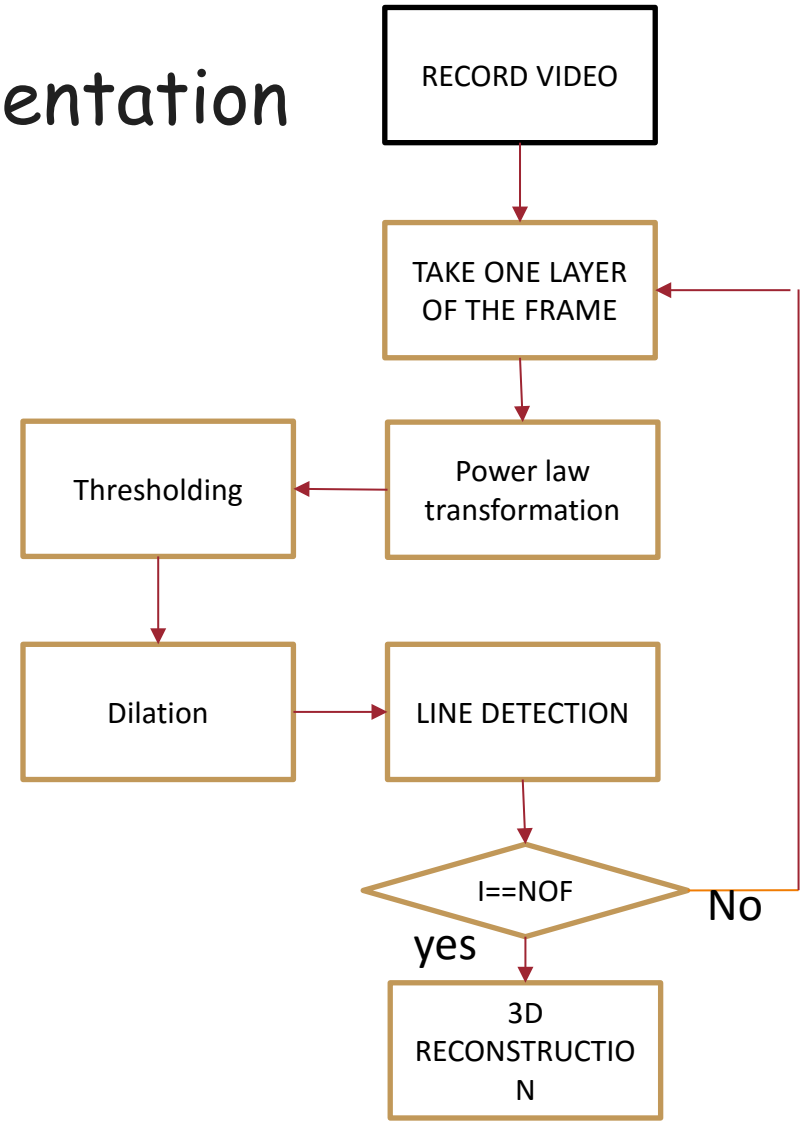
- Off-line MATLAB Implementation

Imaging #1



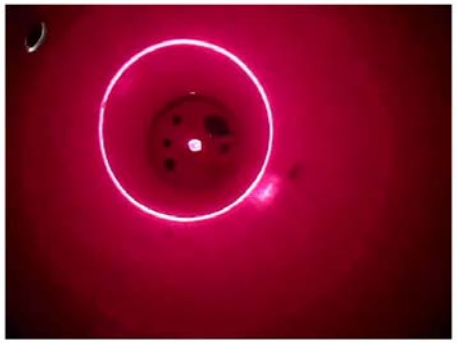
Imaging #2

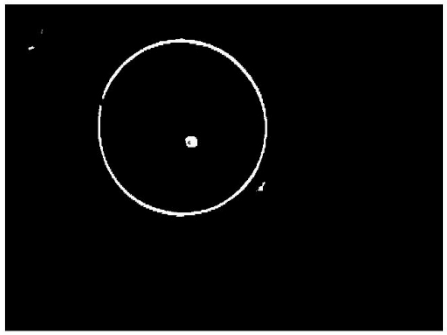




Challenges and Opportunities

- Multispectral source and camera alignment
- Noise suppression and filtering
- Material-, color-, damage- dependence reflections
- Automated sensor calibration
- Critical damage and image features correlation





Schedule and deliverables

Task		Task Description	2015		2016				2017		
			Sep.	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3
3		**UCD Structured Light Scanning Method Development**									
	3.1	Literature Review	D3								
	3.2	Initial Design of Multispectral Sensing Prototype				D3		D5			
	3.3	Numerical Simulation and Sensor Optimization				D3					
	3.4	Develop Detection Algorithms				D3					
	3.5	Develop Prototype				D3				D7	D8
	3.6	Develop Data Reduction Framework								D7	
	3.7	Develop Image Reconstruction Algorithms								D7	
	3.8	Quarterly Reports, Final Report and Paper Submission		R1	R2	R3	R4	R5	R6	R7	P, F

Conclusion and Future Work

- Preliminary and Quarter 1 work demonstrated the feasibility and promising performance of the proposed endoscopic sensing
- System Optimization and Miniaturization
- High performance computing assisted (near) real-time imaging and image analysis
- Prototyping and System Integration with Bayesian framework