Preserve and Protect – Using Risk to Assess and Manage Your Utility's Infrastructure

PNWS-AWWA Conference

May 4, 2011

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Workshop Agenda

- Introductions
- Objectives of this training, “roadmap”
- Review: ***Risk*** and other selected basic AM concepts
- What is “Remaining Asset Life” and why do we care?
  - Expanded “asset life” definitions
  - Role of asset life in asset management
- Putting it all together: How service level, physical, and economic life interact with ***risk*** to guide asset investment
  - Determining End of Service Level/Capacity Life
  - Determining End of Physical Life
  - Determining End of Economic Life

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Nature of this workshop

- This presentation is built upon the core structure presented in EPA's *Fundamentals of AM* (Tom's Bad Day) workshop.
- The focus of the workshop is as much on *methodology* as on concept – how basic AM practices (e.g. risk, condition, remaining life) can be refined and advanced to produce better decisions
- Many of the concepts and methodological approaches presented are at the "edge" of current AM practice in the water industry (although many are basic practice in other industries – and have been for some time).
- Not all methodologies are relevant to every organization; it is left to the practitioner to select and adapt those that are.

Real world strategic questions framing this training

- How do I determine *at what point in an asset's life cycle* I should adopt a capital re-investment (major repair, refurbish, or replace) strategy?
- How do I determine *which* investment strategy (capital versus O&M, which capital)?
- How can I determine when investment in (*additional) condition assessment* is warranted?

Advanced asset management thought is centered on a paradigm of *reliability*.

Real world operations level AM questions – pipe example

70 – 90% of the pipe we replace has physical life left!

- How well do we understand how pipes fail?
- Can we predict, with reasonable accuracy, *how many* pipe sections will fail in a given timeframe?
- Can we predict, with reasonable accuracy, *which* pipe sections will fail at a point in time?
- At what point is (*more*) condition assessment cost effective? How do we determine that?
- How do we determine which reinvestment option is best?
- *How do we determine when best to reinvest/renew?*

Objectives of this training

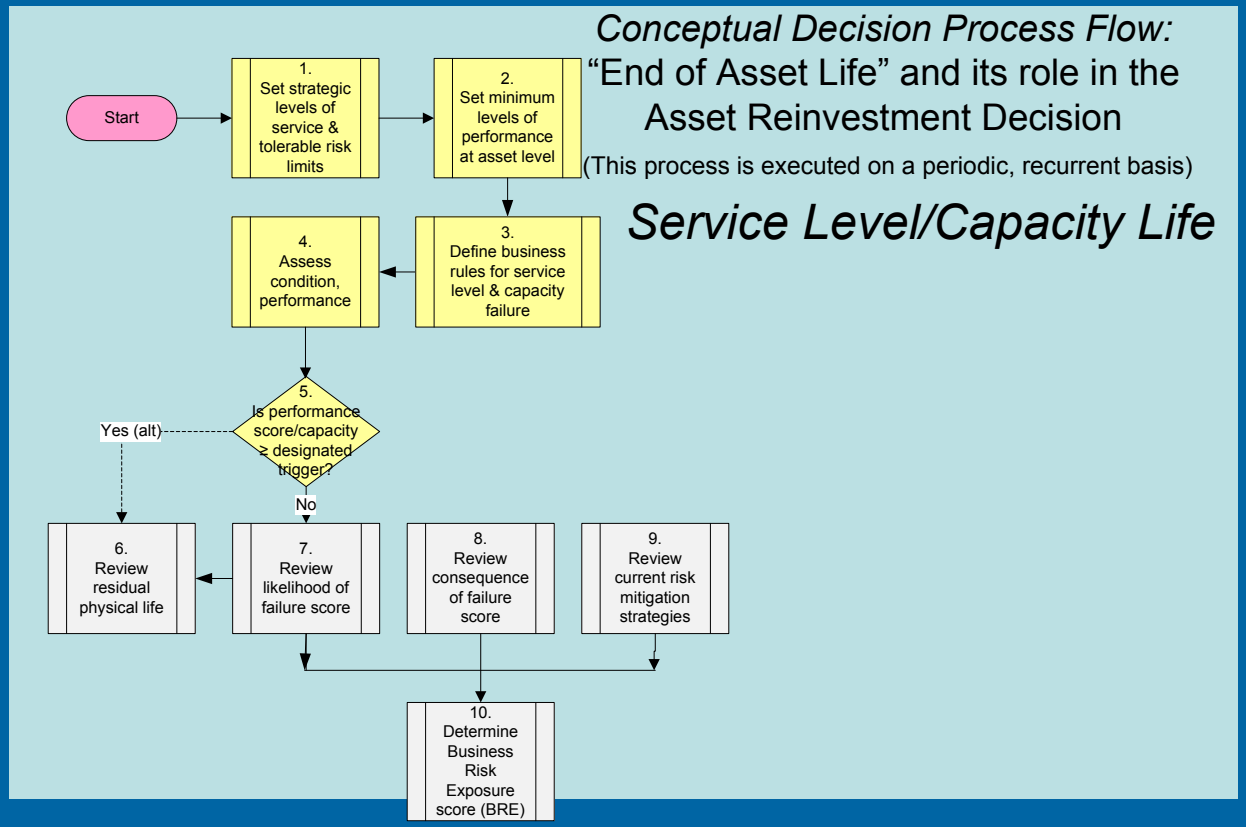
At the end of this training, a participant should be able to:

- Describe the distinction among and determine for an asset the end of:
  - Service Level/Capacity life
  - Physical life
  - Economic life
- Describe in general terms the “advanced state of the practice” in determining the “probability of failure” of an asset (including related condition assessment);
- With appropriate assistance, be able to develop conditional probabilities of failure and establish appropriate probability density functions for management strategy groups of assets
- Determine the consequences of failure in economic “triple bottom line” terms;

Fundamental “take home” message

- Reinvestment in America’s deteriorating legacy infrastructure poses substantial financial challenges to most utilities across the country.
- Cost effective re-investment in an asset requires an understanding of when that asset reaches its “end of life”.
- The end of life for an asset involves a systematic interaction among three “triggers”:
  - Service level/capacity life
  - Physical life
  - Economic life
- *Reinvestment is really a decision process where the practitioner systematically determines for a specific asset or class of assets which of the three triggers trips the reinvestment decision first and at what point in time.*

Risk Roadmap



Our roadmap: determining the "End of Service Level/Capacity Life"

Core references for this training

- David Marlow et al, *Remaining Asset Life: a State of the Art Review*; CSIRO/WERF (WERF SAM1R06d)
- John Moubray, *RCM II Reliability Centered Maintenance*, (Second Edition); Industrial Press Inc., 1997
- National Institute for Standards and Technology website (Engineering Statistics Handbook – Section 8: Reliability) http://www.itl.nist.gov/div898/handbook/apr/apr.htm
- *Optimized Decision Making Guidelines*, Edition 1; NZ NAMS Committee
- US EPA Aging Water Infrastructure website: http://www.epa.gov/awi/

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Review: Selected basic AM concepts

- AM Framework
  - “Views” of AM
  - 5 core questions
  - 10 step process to an AM Plan
- Level Of Service/asset performance standards
- Role of risk
- Decision-making

View 1: Definition - asset management

- *Management paradigm* and *body of management practices*
- Applied to the *entire portfolio* of infrastructure assets at all levels of the organization
- Seeking to *minimize total costs* of acquiring, operating, maintaining, and renewing assets…
- Within an environment of *limited resources*
- While *continuously delivering the service level levels* customers desire and regulators require
- At an acceptable level of *risk* to the organization

View 5: Five core questions

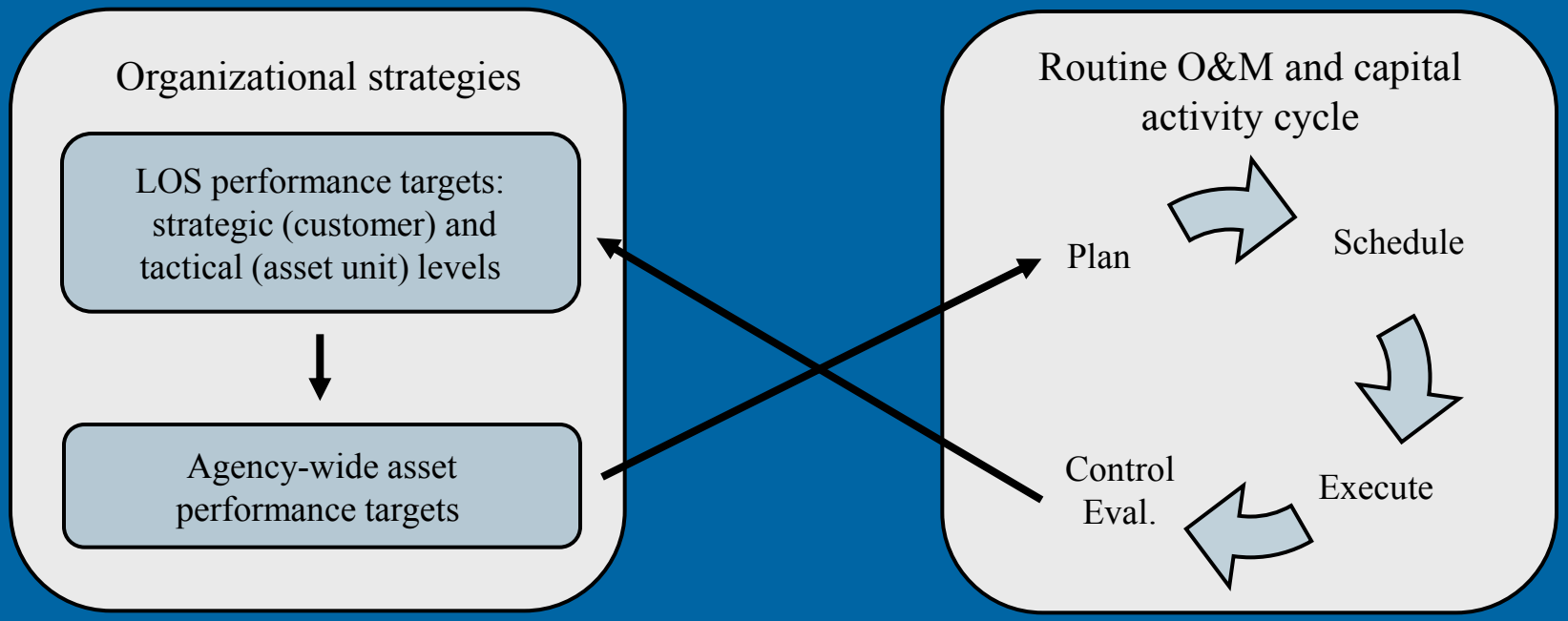
1. What is the current state of my assets?
   - What do I own?
   - Where is it?
   - What condition is it in? What is its performance?
   - What is its remaining useful life?
   - What is its remaining economic value?
2. What is my required level of service (LOS)?
   - What is the demand for my service levels by my stakeholders?
   - What do regulators require?
   - What is my actual performance?
3. Which assets are critical to sustained performance?
   - How does it fail? How can it fail?
   - What is the likelihood of failure?
   - What does it cost to repair?
   - What are the consequences of failure?
4. What are my best O&M and CIP investment strategies?
   - What alternative management options exist?
   - Which are the most feasible for my organization?
5. What is my best long-term funding strategy?

Integration of 5 core questions with 10-step process

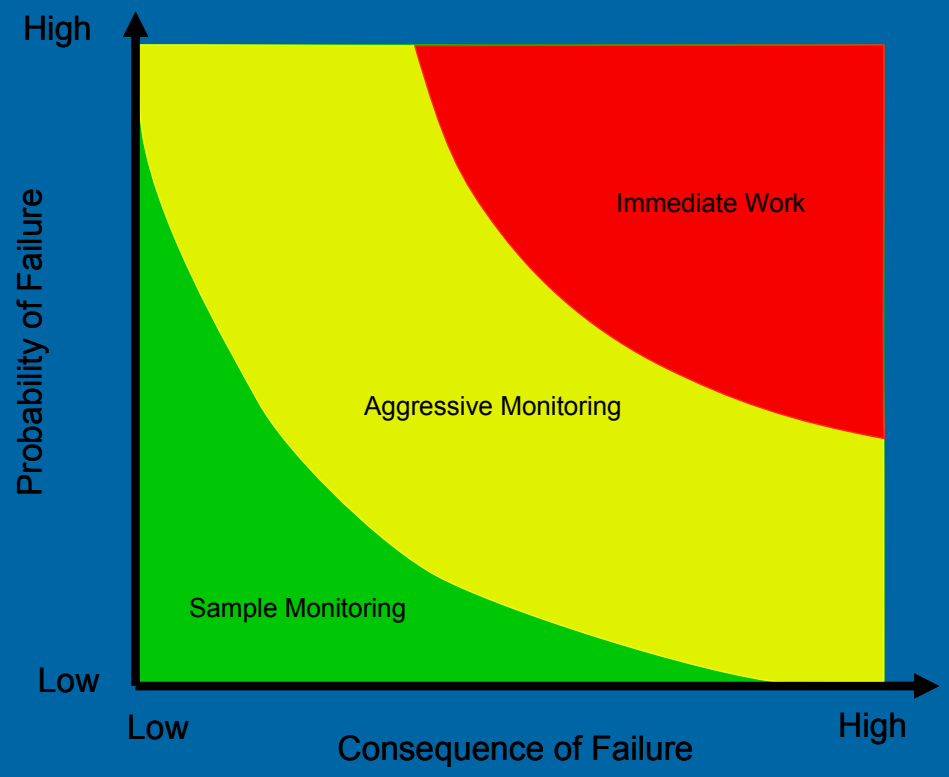
- What is the current state of our assets?
- What is my required Level Of Service?
- Which assets are critical to sustained performance?
- What are my best O&M and CIP Investment Strategies?
- What is my best long-term funding strategy?

Develop Asset Register → Failure Modes: •Capacity •Physical Mortality •Level of Service •Financial Efficiency → Determine Physical & Economic Residual Lives → Collect Historic Costs & Determine Current Replacement Cost → Set Current & Future Levels of Service → Establish Risk Ratings (Relative Criticality) → Develop Appropriate Maintenance & Operations Plans → Develop Appropriate CIP Program → Future Funding Strategy → Build the AMP

Alignment of O&M and capital investment activities with organizational Level of Service strategies



Determining significant failures – the role of “risk”



Business risk drives work program (O&M, CIP)

The Business Risk (“Criticality”) Metric

Current Risk Cost → **Business Risk Exposure (BRE)**

=

Costs of the Consequences Of Failure → **Consequence Of Failure (CoF)**

X

Probability Of Failure (PoF) → **Related to Condition, Reliability**

X

Redundancy Of Asset Function → **Factor: 0.0 to 1.0**

BRE = CoF X PoF X R

Example of risk table

Matrix of probability and consequence of failure

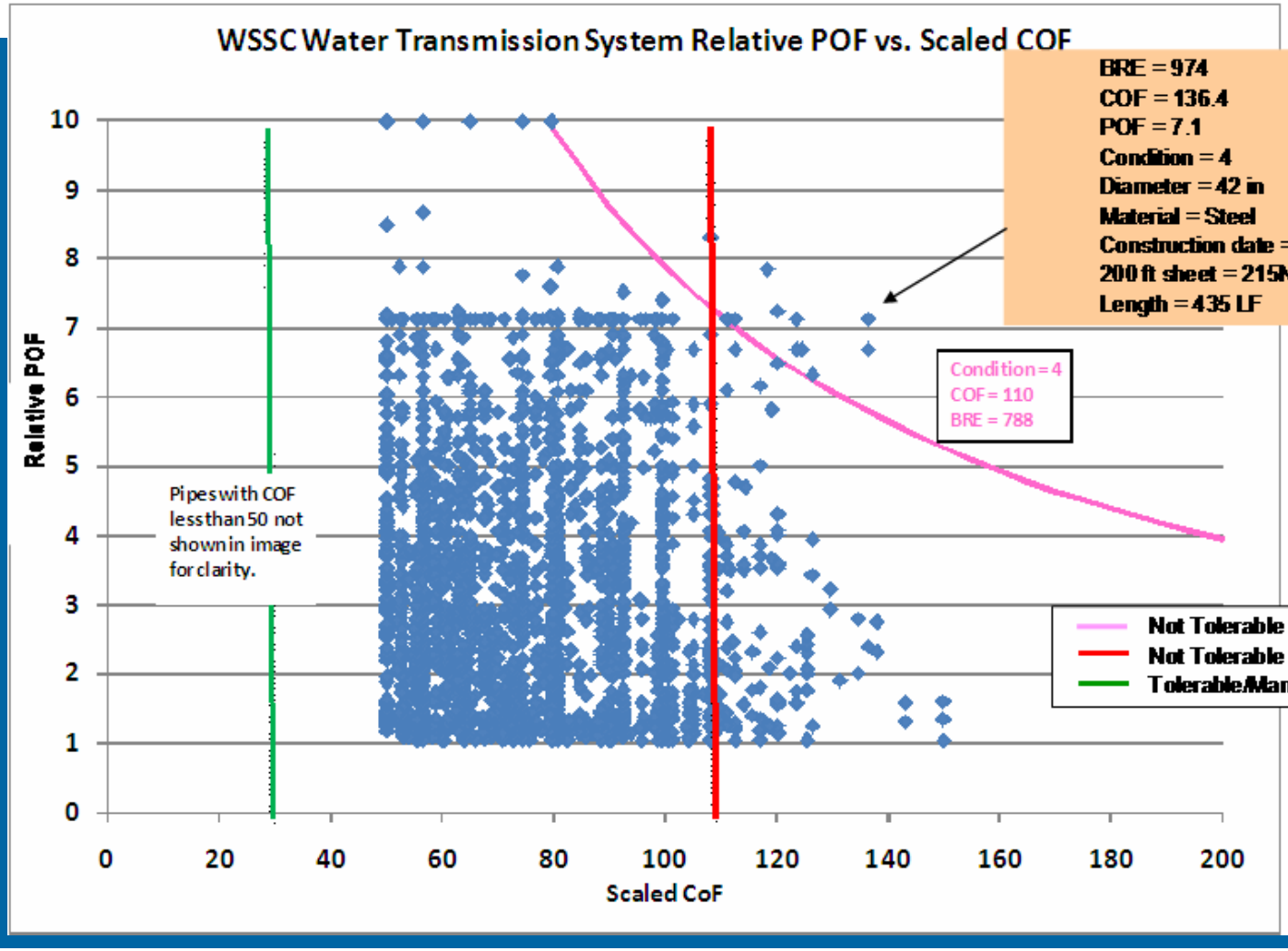
- Water Mains
  - CoF Factors:
    - LandUse (15)
    - Size (10)
    - Environment (10)
    - Traffic (5)
    - Pressure (10)
  - PoF Factors:
    - Install Year (5)
    - Rotten Mains List (1)

Probability of Failure						
	6	0	137	77	11	0
	5	10	2366	1357	284	0
	4	0	260	124	20	0
	3	13	742	350	137	0
	2	8	627	558	295	6
	1	5	1287	634	98	0
Total number of asset: 9406		10	20	30	40	50
		Consequence of Failure				

4%
54%
42%

Example: water transmission Tolerable Risk Limit

1.
Set strategic levels of service & tolerable risk limits



High BRE transmission pipeline - #974

1. Set strategic levels of service & tolerable risk limits

- Steel pipe installed with cathodic protection
- No work order history hence the condition is capped at 8 based on soil type and time spent under soil
- The high COF is due to
  - 360 customers
  - 51 hydrants would be out of service when this pipe breaks,
  - it is under or near a county road,
  - 47 feet to water bodies (environmentally sensitive area),
  - 51 feet to a building,
  - critical customer status due to the presence of 1 or more of : school, dialysis, nursing home, home machines

Let’s clarify terms

Ambiguous:

- “Risk” (may refer to probability of failure or risk x consequence)
- “Criticality” (often refers to consequence of failure but may refer to “risk” above)

Preferred:

- Probability of failure
- Consequence of failure
- *“Business risk exposure”*

It's about *investment!*

- The term "investment" embraces maintenance, operations, and capital outlay – whatever disbursement is necessary to sustain performance.
- Our focus is on improving our bottom line through better financial decision-making.
- We do that by systematically balancing
  - the perceived value to the utility (i.e., customers/stakeholders) of *avoiding the consequences of failure* (i.e., not intervening)

  with

  - the cost of investing (intervening) to prevent or delay failure.

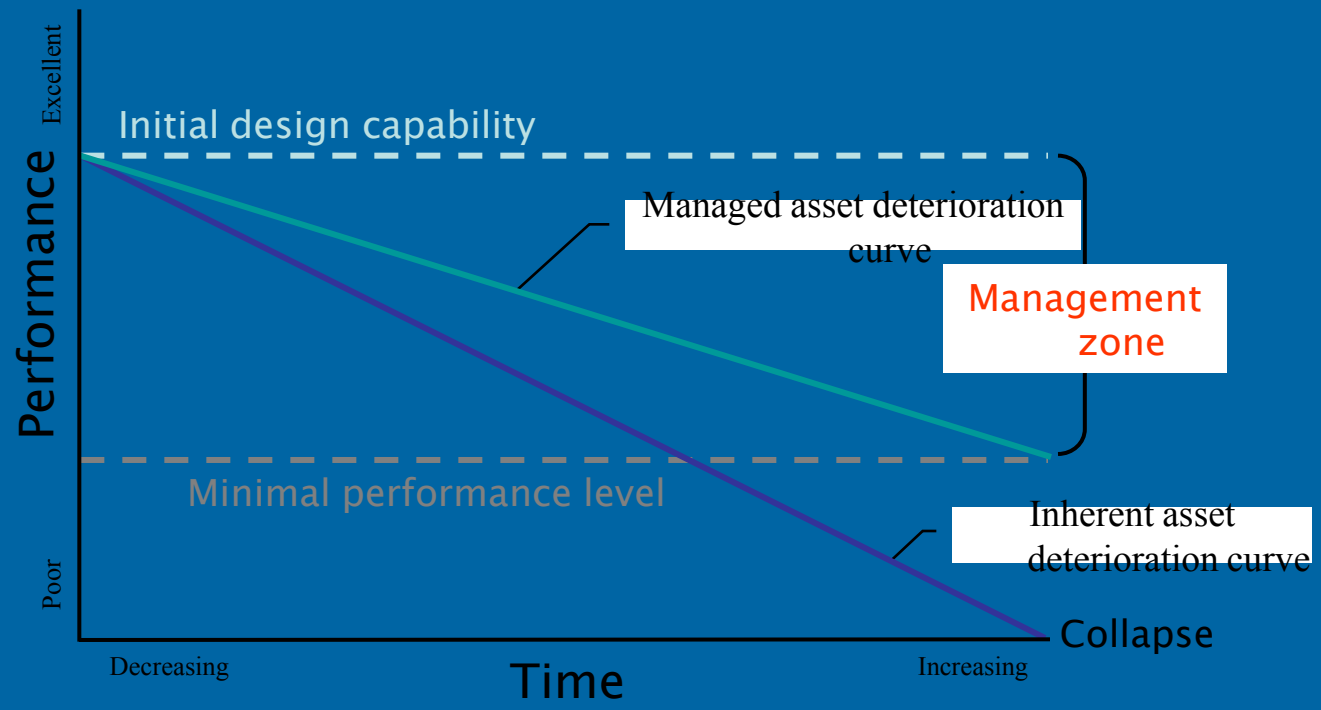
The AM core ideas – (r)evolutionary trends in AM thinking

- Performance based AM
  - Condition based
  - Reliability based
  - Operational outcomes based
- Risk based AM
  - Ordinal scale based (e.g. 1-10)
  - Full economic value
- Service Levels based AM

Finally: Convergence & Integration

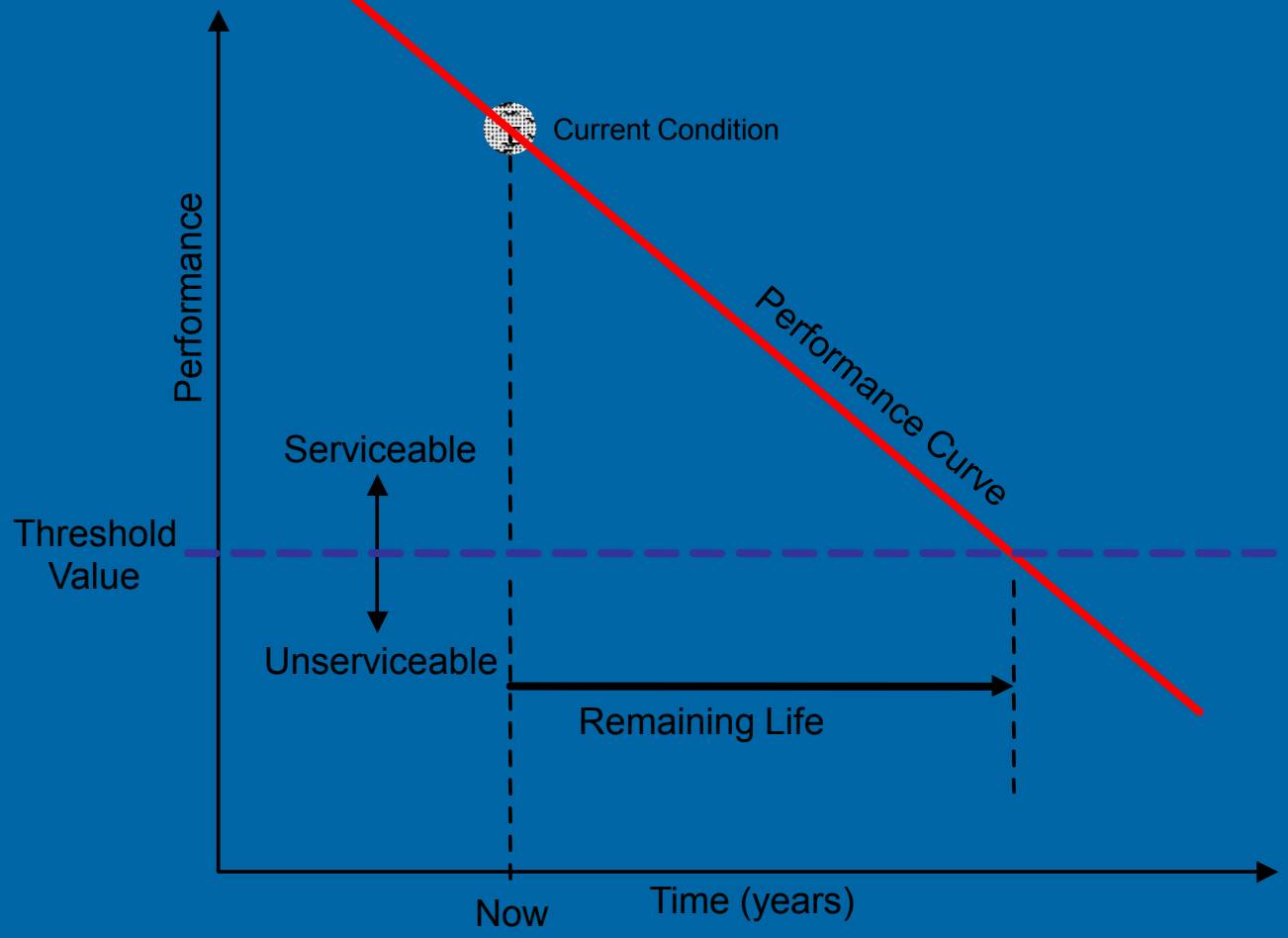
Understanding how our assets "fail"

Managing asset deterioration



"Failure is…the inability of any asset to do what users want it to do."
John Moubray

Determining Remaining Life



Definition: “effective asset life”

- “Effective asset life” is the lowest expected life for a selected asset given its operating environment where that life is derived from a determination of the most imminent trigger among the three asset life triggers (service level/capacity life, physical life, economic life).
- Example (remaining life):
  - service level/capacity life – 3 breaks, estimated 2 years to next break
  - Physical life – 30 years
  - Economic life – 10 years

Service level/Capacity life

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- Making the investment decision - and a very brief look at “true” optimization
- Applying what we have reviewed – a hands-on exercise

Recall: What do we mean by “remaining asset life”?

- *End of service level/capacity life* – when an asset can no longer do what we/our customers/stakeholders require it to do
- *End of physical life* – when an asset is physically non-functioning
- *End of economic life* – when an asset ceases to be the lowest cost alternative to satisfy a specified level of performance or service level

Review “Level of Service”: defining our “product”

1. Set strategic levels of service & tolerable risk limits

- What does your utility “sell”?
  - *Generation, transmission, treatment, and distribution of potable water*

- In what manner? (highest level “attributes” of customer service level)
  - Dependable service level/product
  - Environmentally responsible
  - Customer friendly
  - Affordable

What causes customer dissatisfaction ("outrage")? - *attributes* of **service level**

1. Set strategic levels of service & tolerable risk limits

- Service adequacy
  - Safety/health (standards, quality, pressure)
  - Quality (standards, taste, color, clarity, pressure)
- Reliability (frequency of outages)
- Availability/maintainability (duration of outages)
- Affordability/efficiency (price, equity, fiscal condition)
- Environmental impact
- Courtesy

Around which specific attributes is "outrage" reached in my community? For which assets or major processes? At what specific point?

Service Level Example

Community Outcome	Core Value	Activity Strategic Outcomes	Customer Levels of Service (CLOS)		Technical Levels of Service (TLOS)	
			Current Target (2008)	Proposed Target (2012)	Current Target (2008)	Proposed Target (2012)
Environmental						
Water sources are protected.	Water Quality	Protect water quality	Meet DOH requirements, and coordinate with local land use councils.	As per current	Well head program - time of travel zones are inspected biannually by staff looking for potential sources of contamination	As per current
The drinking water is safe.	Water Quality	Water quality is safe for drinking	75% of customers believe the drinking water is safe to drink 70% of customers believe the drinking water has a good taste	80% of customers believe the drinking water is safe to drink 75% of customers believe the drinking water has a good taste	Comply with 100% of DOH WAC 246.290 monitoring requirements. Maintain fluoride concentration between 0.8 – 1.3 mg/L in distribution system. Maintain pH concentration between 7.6 and 8.3 in distribution system.	As per current As per current As per current

Set up “end of *service level/capacity* life” business rules

4.
Define business rules for service level & capacity failure

- Relate strategic level LOS to operational level asset *performance* in measurable terms
- Identify “service life” assets: “cannot fail” and “low tolerable risk” assets (e.g. assets where failure of the asset leads directly to failure to sustain service levels/performance standards *and* which are of such high consequence of failure that they are deemed “cannot fail” or “low risk tolerance” assets)
- Set up “business rules” that operationalize LOS statements
  - Minimum condition score (i.e. “condition score no greater than 6”)
  - Maximum risk score (“BRE score not to exceed 64”)
  - Number of failures/unit of time (i.e. “no more than 3 breaks in five years and no more than 5 breaks over lifetime”)
- *Since end of service level/capacity life is defined by LOS / asset performance parameters, these business rules constitute “triggers” or “tripwires” for reaching the end of service level/capacity life!*

Determining End of Physical Life

A staged approach to condition assessment

3. Assess condition, performance

15% – 25% of assets

5% – 10% of assets

CAP 1– Basic
All assets

Desktop Review
Photo walkthrough
Delphi reviews

- Review asset performance
- Interview key staff
- Convene Delphi workshops
- Use age profiles
- Identify CAP 2 assets

CAP 2 – Intermediate
"At risk" assets

Desktop review combined with Delphi reviews, field inspections

- Use multi-aspect condition scale
- Identify CAP 3 assets (i.e., candidates for economically rationalized advanced inspection)

CAP 3 – Advanced
Critical / high cost assets

Specialist inspections/techniques

- Validate cost effectiveness of specialist inspections and techniques
- Execute and analyze results
- Take action as appropriate

Level 1 assessment score sheet – structural condition

3.
Assess
condition,
performance

Physical Condition Grade – Rating Guidelines	
1 Excellent	Asset is like new, fully operable, well maintained, and performs consistently at or above current standards. Little wear shown and no further action required.
3 Good	Asset is sound and well maintained but may be showing some signs of wear. Delivering full efficiency with little or no performance deterioration. Virtually all maintenance is planned preventive in nature. At worst, only minor repair might be needed in the near term.
5 Moderate	Asset is functionally sound, showing normal signs of wear relative to use and age. May have minor failures or diminished efficiency and some performance deterioration. Likely showing modest increased maintenance and/or operations costs. Minor to moderate refurbishment may be needed in the near term.
7 Poor	Asset functions but requires a sustained high level of maintenance to remain operational. Shows substantial wear and is likely to cause significant performance deterioration in the near term. Near term scheduled rehabilitation or replacement needed.
9 Very Poor	Very near end of physical life. Substantial on-going maintenance with short, recurrent maintenance intervals required to keep the asset operational. Unplanned corrective maintenance is common. Renewal (refurbishment or replacement) is expected in near term.
10 Failing	Effective life exceeded and/ or excessive maintenance cost incurred. A high risk of breakdown or imminent failure with serious impact on performance. No additional life expectancy; immediate replacement or rehabilitation needed.

Level 1 assessment score sheet – operational process condition

3. Assess condition, performance

Operational/Process Condition Grade – Rating Guidelines	
1 Excellent	Meets all Level of Service targets including all legal/regulatory requirements. Meets all design requirements – i.e. capacity exceeds maximum designed flow. Overall operational performance is excellent and meets all known expected intermediate term requirements.
3 Good	Meets all design and legal/regulatory requirements. May have minor risk under extreme conditions. Overall performance excellent and will likely meet expected future requirements
5 Moderate	Generally meets all design requirements, but can expect some failures in performance under normally expected conditions (i.e. Occasional operation of overflows, odor complaints, or design shortcomings). Current performance is acceptable to marginal but would likely not meet future additional requirements or increased demand.
7 Poor	Has expected performance failures under normally expected conditions in its operating environment (i.e. routine operation of overflows, persistent odor complaints, or capacity issues). Current performance is marginal and does not meet future additional requirements or increased demand.
9 Very Poor	Current performance unacceptable and does not meet criteria. Recurring and expected continued failures against performance standards.
10 Failing	Current performance unacceptable and does not meet criteria. Recurring and expected continued failures against performance standards.

A composite performance scoring structure

3.
Assess condition, performance

Element	Description					
SCORE	1	3	5	7	9	10
Physical Condition	Substantially exceeds current requirements	Exceeds current requirements	Meets current requirements but with room for improvement	Obvious concerns: cost/benefit questions	Inefficient; becoming ineffective, obsolete	Failing, not capable of sustaining required performance
Operational performance	Negligible attention required	Exceeds current requirements	Meets current requirements but with room for improvement	Obvious concerns: cost/benefit questions	Difficult to sustain performance	Failing, not capable of sustaining required performance
Reliability	As specified by manufacturer	Infrequent breakdown	Occasional breakdown	Periodic breakdown	Continuous recurrent breakdown	Virtually inoperable
Availability	Virtually always operational	Out of service only for very short periods	Out of service for moderate period; moderately difficult to return to service	Increasingly difficult to return to service; parts becoming a challenge	Extensive downtime duration; difficult to return to service; parts, difficult to acquire, rare skills required	Virtually impossible to return to service; parts no longer available; unavailable trained personnel
Maintainability	Preventive maintenance only; baseline monitoring	Largely PM, some minor repair	Increasing minor corrective maintenance required; shortening of monitoring intervals	Predictive and corrective maintenance becoming dominant; frequency of work orders increasing substantially	Work orders well above average for type of asset; recurrent minor repair; close monitoring required	Corrective maintenance is frequent with recurrent patterns of failure; asset must be virtually constantly monitored or "run to failure" response readied for implementation
% Physical life consumed	Almost new; up to 10% physical life consumed	Up to 30% physical life consumed	Up to 50% physical life consumed	Up to 70% physical life consumed	Up to 90% physical life consumed	Virtually consumed, imminent failure
SCORE	1	3	5	7	9	10

Level 3 performance assessment scoring sheet

3.
Assess
condition,
performance

Conventional Pumps

Included: Dry well & line shaft pumps Centrifugal pumps Vertical multi-stage booster pumps Screw pumps

	Aspect	Distress Mode	Rating 1	Rating 2	Rating 3	Rating 4	Rating 5
CONDITION ASSESSMENT							
A	**Structure Appearance**	Leakage	Appears as new.	Minimal moisture on seals/joints.	Water dripping from seals/joints.	Water pooling on floor	Water squirting/ running onto floor.
B		Shaft, Supports, Bearing Deterioration	Shaft & supports sound - no shaft distortion or deterioration evident.	Minor shaft/ support deterioration evident, no impact on the structural strength or function.	Shaft distortion or bearing/housing wear evident, little impact on structural integrity or function.	Shaft distortion or bearing/housing wear evident and has impacted on asset integrity or function.	Significant shaft distortion or bearing/housing wear evident, high probability of fracture or failure.
C	**Use**	Motor Hours Run*	< 10,000	> 10,000	> 50,000	> 100,000	> 200,000
D	**Symptoms**	Vibration / oscillation	No unusual vibration / oscillation detectable	Minor vibration / oscillation detected	Moderate vibration / oscillation	Considerable vibration / oscillation (wristwatch shakes)	Major vibration / oscillation
E		Temperature	No unusual temperature detected	Minimal heat from casing using hand	Heat detected by hand	Heat detected by hand is uncomfortable	Heat too high to assess by hand
F		Noise	No unusual noises detected.	Slight whine/rattle detected.	Moderate whine/rattle detected, easily heard over pump noise.	Loud whine/rattle.	Disturbingly loud operation/vibrations.

Notes: *Motor hours run and corresponding condition rating will depend on the type of pump and the application the pump is used for (i.e. thickened sludge conveyance versus influent wastewater).

3.
Assess condition, performance

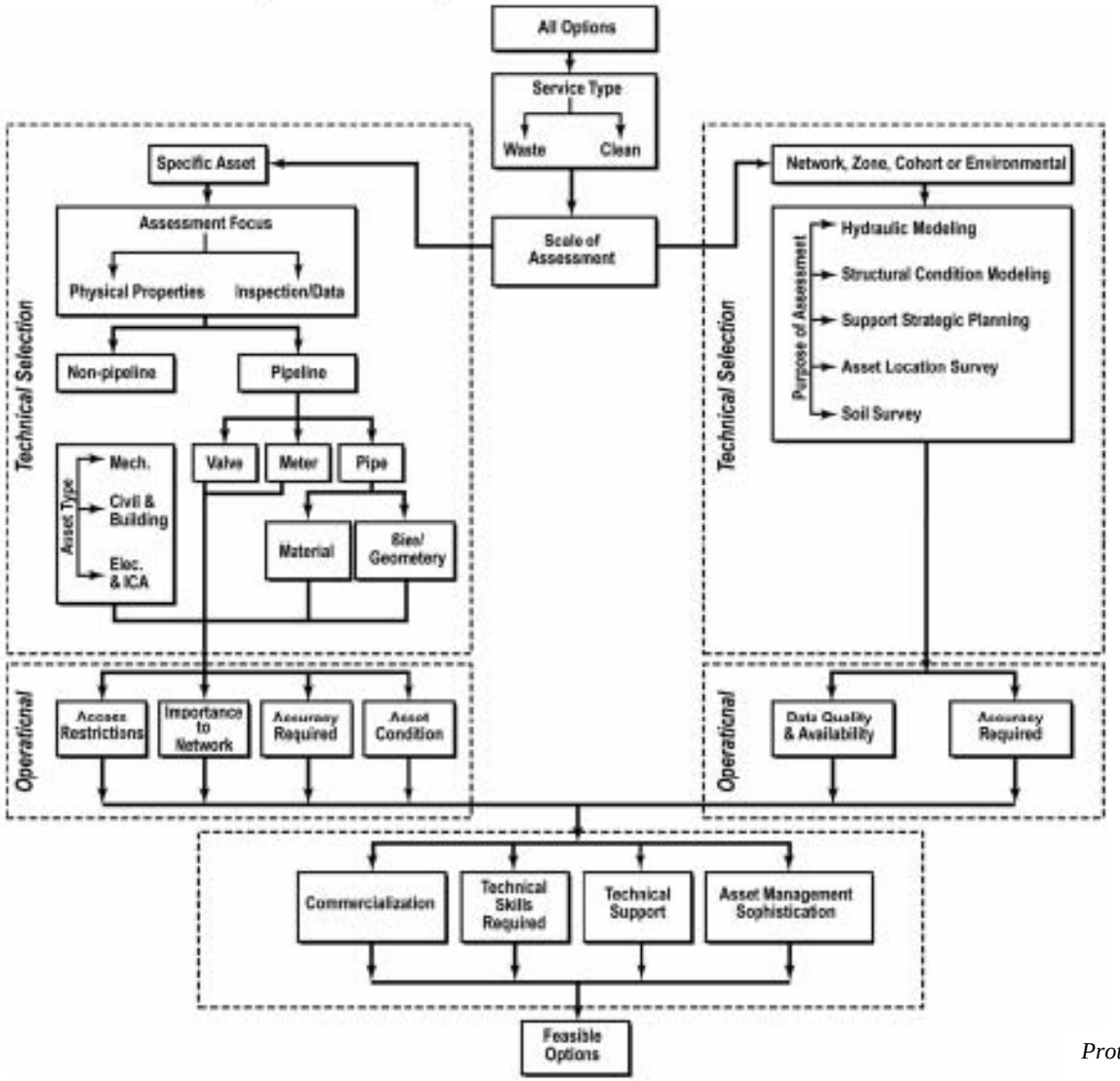

Figure 6-2 Conceptual overview of pathways in the tool selection Expert System.

Selecting a suitable condition assessment technique

Condition assessment technology is now remarkably robust

Protocols For Assessing Condition And Performance Of Water And Wastewater Assets; WERF Condition Assessment Protocols (CAP) Project (Project 03-CTS-20CO) (484 pages) December 2006

Emerging sewer inspection tools and technologies

3.
Assess
condition,
performance

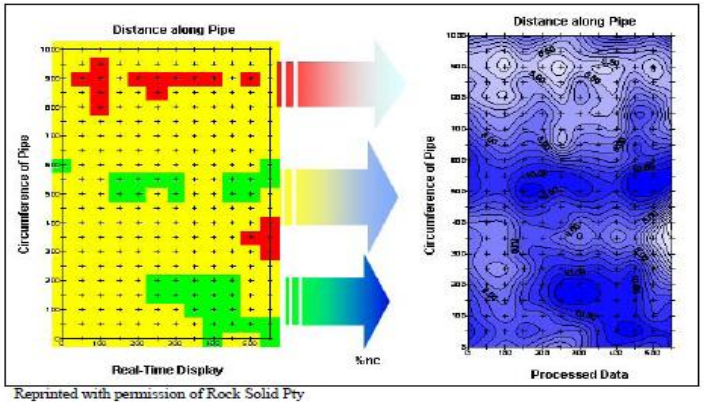

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Figure A-11. Post-Survey Data Processing, Analysis, and Plotting

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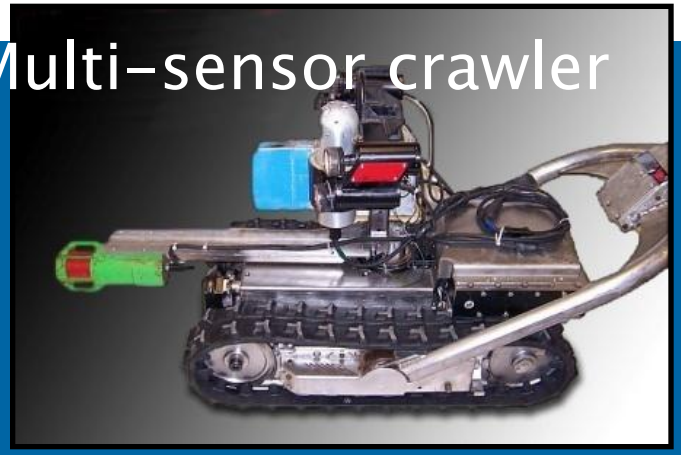
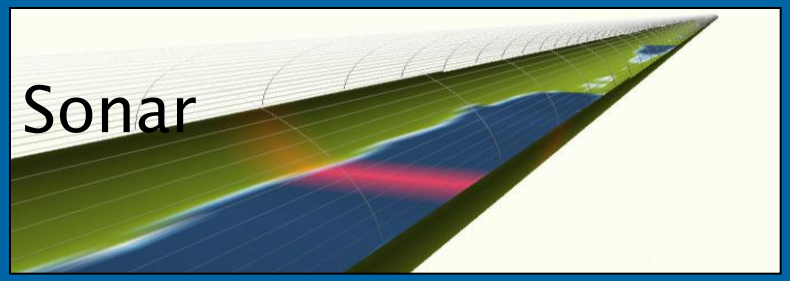
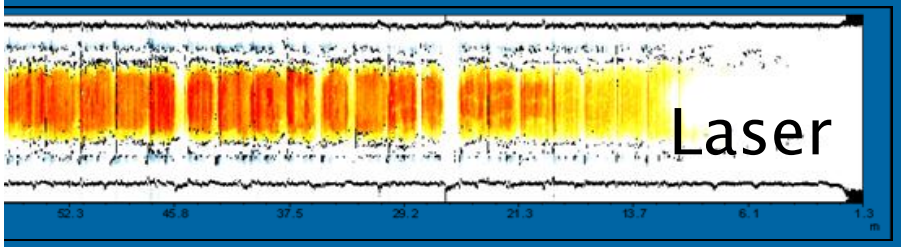
Figure A-12. A BEM Hand Held Tool Being Used to Scan a Gray Iron Pipe







“Take home” ideas

- Strategic service levels must be linked to asset performance standards to be effective
- “Cannot fail” and “low risk tolerance” assets should be systematically identified
- Business rules which determine for each critical asset what is an appropriate risk tolerance level trigger for that asset and at what level the trigger is tripped must be developed
- Asset status (database) must be periodically and systematically reviewed for trigger status (database must be current and accurate)

Where to go for state of practice in pipe condition assessment

- *Condition Assessment of Ferrous Water Transmission and Distribution Systems State of Technology Review Report* (111 pp, 3.22 MB) (EPA/600/R-09/055) June 2009
- *Condition Assessment of Wastewater Collection Systems - State of Technology Review Report (*74 pp, 1.05 MB) (EPA/600/R-09/049) May 2009
- *Protocols For Assessing Condition And Performance Of Water And Wastewater Assets*; WERF Condition Assessment Protocols (CAP) Project (Project 03-CTS-20CO) (484 pages) December 2006

State of practice in predicting “likelihood of failure”

7.
Review
likelihood of
failure score

- Determining the likelihood of failure is a core step in determining business risk
- Typically, we assume simple relationships among condition codes, likelihood of failure, and remaining asset life.
- In reality, nothing is simple about the relationships
- *What is the state of knowledge about predicting failure?*
  - *Role of “failure modes”*
  - *Statistical models*
  - *Concepts from reliability science*

What is a “failure mode”?

7.
Review
likelihood of
failure score

- A failure mode is a systematic series of sequential and interrelated causal steps that (can) lead to the failure of an asset.
- We recognize two distinct levels of failure modes:
  - Primary (strategic) level failure modes
  - Tactical/operational level failure modes

Review: 4 primary failure modes (strategic level)

7. Review likelihood of failure score

Failure Mode	*Definition*	*Tactical Aspects*	*Management Strategy*
Capacity	Volume of demand exceeds design capacity	Growth, system expansion	(Re)design
LOS	Functional requirements exceed design capability	Codes & permits: NPDES, CSOs, OSHA, noise, odor, life safety; service level, etc.	(Re)design
Mortality	Consumption of asset reduces performance below acceptable level	Physical deterioration due to age, usage (including operator error), acts of nature	O&M optimization, renewal
Efficiency	Operations costs exceed that of feasible alternatives	Pay-back period	Replace

Tactical/operational level failure modes

7. Review likelihood of failure score

- Tactical/operational level failure modes can derive from
  - the physical nature of the asset itself,
  - the environment within which it operates, and
  - the maintenance and operation of the asset
  - or the interaction of all of the above.
- Most assets can fail for dozens if not hundreds of reasons. The search is for *feasible and most likely* failure modes.
- A good tactical level failure mode statement has at least a noun and a verb (plus, ideally, an object) ("impeller jammed by foreign object").
- Our search is for that most likely or *"imminent"* failure mode that can be expected to drive a given asset to failure in its specific operating environment.

How failure modes relate to condition assessment

7. Review likelihood of failure score

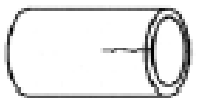
- At any given point in its life cycle, most assets have many operative failure modes and mechanics at work.
- While assessing condition to determine the state of the asset is very important to managing the asset, *irrelevant assessment is wasteful.*
- By understanding failure modes and identifying those that are most likely to drive a given asset to fail in its operating environment, we can
  - Focus our assessment on those attributes of the asset that provide the most telling “failure signatures” (what to monitor).
  - Select and apply those (rapidly improving) technologies that most directly measure the dominant failure modes (which technology(ies) to use to monitor).
  - Time the assessment most cost effectively (when to monitor)

Typical ferrous pipe failure modes

7. Review likelihood of failure score

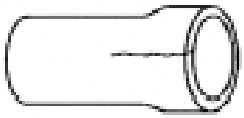
Circumferential break

- Bending stress from frost
- Bending stress from swelling clay
- Thermal contraction
- Longitudinal stress near valves and fittings



Longitudinal break

- Hoop stress from internal water pressure
- Ring stress from soil cover load
- Hoop stress from freezing water
- Ring stress from traffic load

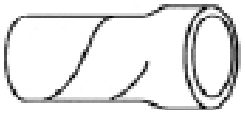


Split Bell

- Expansion of joint material (e.g. leadite)

Bell Shear

- "Over horning" spigot in bell
- Bending stress

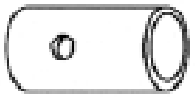


Spiral Break

- Combination of bending stress and hoop stress from internal water pressure

Rupture/Blowout

- Hoop stress from internal water pressure
- Corrosion of steel prestressing wires in CPP



Through Hole

- Corrosion pitting
- Casting flaws

Thomson, Condition Assessment of Ferrous Water Transmission and Distribution Systems STATE OF TECHNOLOGY

REVIEW REPORT; EPA/600/R-09/055, June 2009, www.epa.gov/ord; p 13

7. Review likelihood of failure score

Alternative view: pipe failure modes

Ductile Iron Wastewater Pipe Life Cycle			
Failure Causes			Brief Explanation
Design			
1	Poor Design		
		Coating	Not designed for a thick enough coating
		Connection	Connections not properly sized to fit pipe
		Vertical Connections	Connection types not properly selected
		Chemical Vulnerable Material	Materials vulnerable to sulphate attack and corrosion
		Trust Restraint	Thrust restraint poorly designed
		Corrosion Control	Corrosion control method not properly selected
		Thickness	Thickness not properly designed for specified internal and external loads
		Special Applications	Applications such as pipe on supports poorly designed
2	Poor Project Planning		
		Improper Connections	Poor connections at joint
		Under-Design for Load	Excessive crushing or ring stress
		Time Limited Design	Designed for a short age expectancy
		Poor Assumptions of Environment	Poor support design, seasonal shrinkage/swelling, and migration of fines into or along bedding
3	Dimensioning		
Manufacture			
4	Manufacturing Defects		
		Wall Thickness	Thickness can vary around the circumference of pipe while manufacturing
		Inclusions of Unintended Structures	Inclusion in metal which are unintended
		Surface Defects	Surface defects during manufacturing
		Cheap Composite Material	Materials with material that doesn't meet the standard
		Improper Connections	Poor connections at joint
5	Storage		
6	Observation and Quality Control		
Construction			
7	Transit		
		Coating Damage	Damage to coating while in transit, or loading and unloading
8	Human Error		
		Third Party Damage	Excavations occur near pipeline
9	Poor Workmanship		
		Improper Connections	Poor connections at joint
		Uneven Bedding	Poor backfill operations
		Poor Backfilling Material	Corrosive backfill material
		Impact Damage	Excessive crushing
		Lining Issues	Lining installed incorrectly or poorly
10	Observation and Quality Control		
Operation & Maintenance			

Sinha, *Development Of Protocols And Methods For Predicting The Remaining Economic Life Of Wastewater Pipe Infrastructure Assets*; WERF 06-SAM-1 CO, Phase 1 Report, p.130

Another view: pipe failure modes

7. Review likelihood of failure score

Table 1. Analysis of criteria for condition assessment

		Pipe Material	Failure Mode	CAUSE OF FAILURE AND PROPERTIES TO MONITOR			
				Internal (changes to pipe material, dimensions)		External (forces acting on pipe)	
				Cause	Corresponding Property	Cause	Corresponding Property
Identify Pipeline for Assessment; Classify Pipe Types in Pipeline	Water + Wastewater-pressure pipes	CI	Blown Section	Ext. corrosion +wall thinning	Wall thickness, pit depth, soil LPR, pH, resistivity	High transient pressure	Pressure profile on network
			Longitudinal Split	Ext. corrosion +wall thinning	Wall thickness, pit depth, soil LPR, pH, resistivity	High transient pressure,	Pressure profile on network
			Broken Back	Ext. corrosion +wall thinning	Wall thickness, pit depth, soil LPR, pH, resistivity	Soil movement, shrinkage	Soil reactivity, deflection load
		AC	Blown Section	Ext. + Int. deterioration. of wall	Core measurements, soil pH, water pH	High transient pressure	Pressure profile on network
			Longitudinal Split	Ext. + Int. deterioration. of wall	Core measurements, soil pH, water pH	High transient pressure	Pressure profile on network
			Broken Back	Ext. + Int. deterioration. of wall	Core measurements, soil pH, water pH	Soil movement, shrinkage	Soil reactivity, deflection load
		DI	Perforation	Ext. corrosion +wall thinning +damage to coating	Wall thickness, pit depth, soil LPR, pH, resistivity	High transient pressure	Pressure profile on network
		MS	Perforation	Ext. corrosion +wall thinning +damage to coating	Wall thickness, pit depth, soil LPR, pH, resistivity	High transient pressure	Pressure profile on network
		uPVC, PE, ABS	Longitudinal Split	Installation damage + processing defects	Fracture toughness, flaw size	High pressures, point loads, soil loads	Installation & Pressure profile, deflection
	Wastewater-non pressure pipes	CI	Perforation	Ext. + Int. corrosion +wall thinning	Wall thickness, pit depth, soil LPR, pH, resistivity, water pH	Not applicable	Not applicable
			Broken Back	Ext. + Int. corrosion +wall thinning	Wall thickness, pit depth, soil LPR, pH, resistivity, water pH	Soil movement, shrinkage	Soil reactivity, deflection load
			Collapse	Infiltration. through joints and perforations	Voids on wall, displaced and broken joints	Cavitation of soil	Soil moisture, reactivity, deflection load
		AC	Broken Back	Ext. + Int. deterioration. of wall	Core measurements, soil pH, water pH	Soil movement, shrinkage	Soil reactivity, deflection load
			Collapse	Infiltration. through joints and perforations	Voids on wall, displaced and broken joints	Cavitation of soil	Soil moisture, reactivity, deflection load
		VC	Perforation	Erosion of wall	Quality of w/water, pH	Not applicable	Not applicable
			Collapse	Infiltration through joints and perforations	Voids on wall, displaced and broken joints	Cavitation of soil	Soil moisture, reactivity, deflection load
		RC	Perforation	Erosion of wall	Quality of w/water, pH	Not applicable	Not applicable
			Collapse	Infiltration through joints and perforations	Voids on wall, displaced and broken joints	Cavitation of soil	Soil moisture, reactivity, deflection load
		MS	Perforation	Ext. + Int. corrosion +wall thinning, damage to coating	Wall thickness, pit depth, soil LPR, pH, resistivity, water pH	Not applicable	Not applicable
		uPVC, PE, ABS	Longitudinal Split	Installation damage + processing defects	Fracture toughness, diametrical deflection	Point Loads, soil loads	Installation level
			Buckling	High SDR	Examine exhumed pipe, flaw size	Negative pressures, Soil support	Network pressure profile, Installation level, compaction
		DI	Perforation	Ext. + Int. corrosion +wall thinning, damage to coating	Wall thickness, pit depth, soil LPR, pH, resistivity, water pH	Not applicable	Not applicable

Burns et al, *Condition Monitoring and its Role in Asset Management*, Pipes Wagga Wagga 2001, p 5

Overview: State of a Failure Prediction

7. Review likelihood of failure score

Data and Knowledge

- Failure history
- Condition
- Failure mode attributes
  - Asset intrinsic
  - Asset environmental
  - Asset operational

Analytic Methodologies

- "Heuristic" — Expert knowledge (Delphi process)
- Deterministic/Statistical — Physical (deterministic) or statistical ("known" distributions)
- Fuzzy logic — Uncertainty (unknown distributions)
- Learning models — Neural networks

Example: typical deterioration factors for ferrous pipe

7. Review likelihood of failure score

Three separate groups of factors that drive failure:

- Core or intrinsic factors
  - Steady, continuous deterioration mechanics related to engineering design and specification, material, manufacturing processes, manufacturer, construction/installation management, nature of conveyed water
- Environmental factors
  - Cyclical mechanisms such as temperature, soil moisture, soil chemistry, depth, soil type and aggressiveness, proximity to electrical fields
- Operational factors
  - O&M factors such as quality, nature and frequency of maintenance, nature and timing of renewal, level of applied protection (cathodic or wrapped), historic rate of failure

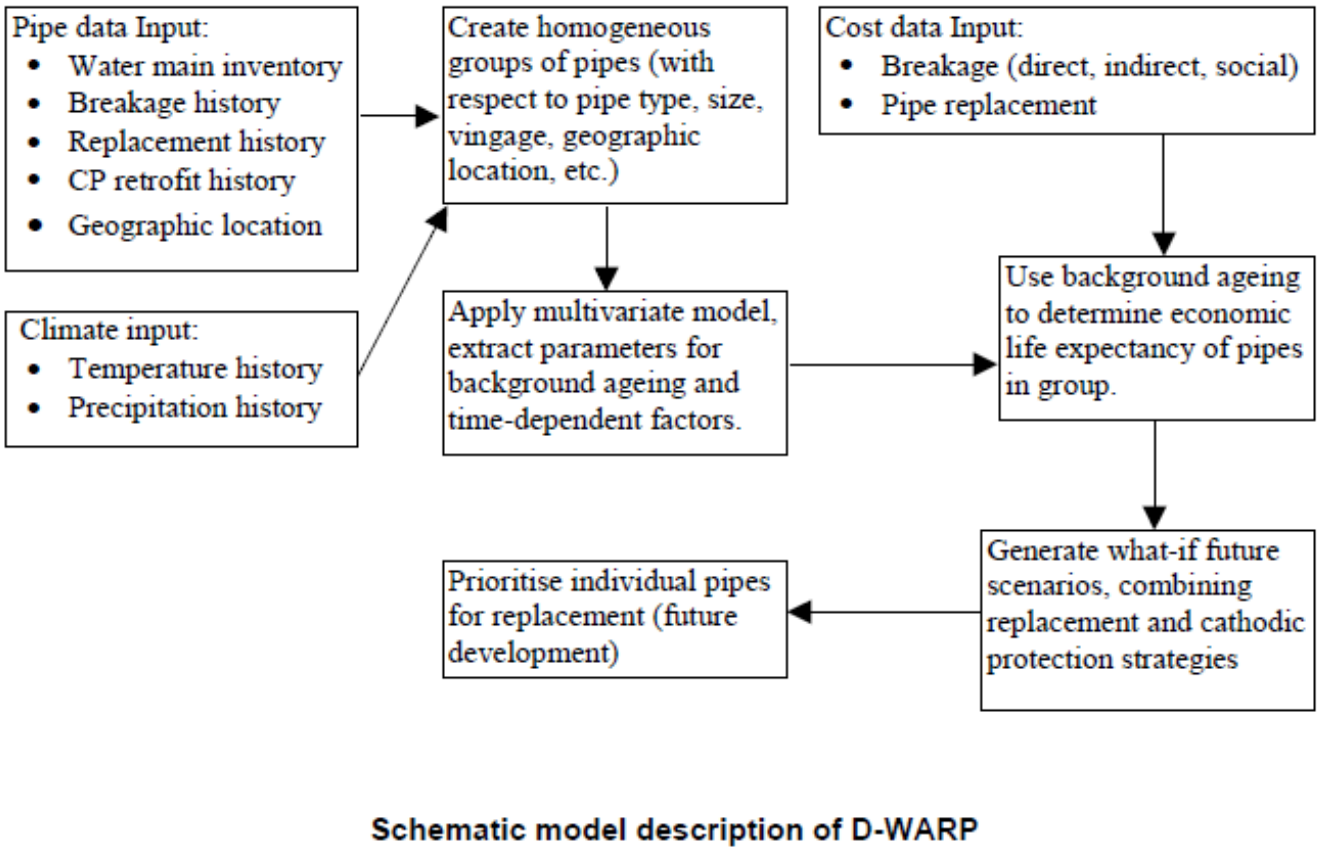
Enter: “management strategy groups” concept

7. Review likelihood of failure score

- Grouping of assets with similar renewal / behavioral patterns
- Purpose - to assist:
  - Assigning asset lives and decay curves
  - Calculating current replacement costs
  - Calculating risk
    - Consequence of failure
    - Probability/likelihood of failure
  - Developing life-cycle management plans
- Examples
  - Transmission Pipes, CIP, Built < 1920, in high pressure areas
  - Potable water pumps, ABC Co., 123 series, installed between1983 - 1989

Example: Advanced statistical predictive modeling structure

7. Review likelihood of failure score



Schematic model description of D-WARP

Page 1-3, D-WARP User's Manual, NRC-C

Attributes of failure modeling methodologies

7. Review likelihood of failure score

	Deterministic Approaches	Statistical Models – Failure Event Data	Statistical Models – Service Lifetime	Statistical Models – Cohort Survival	Statistical Methods – Ordinal Regression
Minimum AM sophistication	None	Basic	Basic	Initial stages	Initial stages
Data requirements	Low	Asset and failure data	Asset and failure data	Asset and condition data	Asset and condition data
Inclusion of expert opinion	None	Only in model construction	No	Only in model construction	Only in model construction
Treatment of economic risk factors	None	Yes, when packaged	Possible	Possible	No
Blackbox	No	No	No	No	No
Packaged	No	Packages available to facilitate analysis; packages for specific asset types available	Packages available to facilitate analysis	Packages available to facilitate analysis; packages for specific asset types available	Packages available to facilitate analysis
Population or single asset	Single asset	Population	Population	Population	Population
Scenario testing	Not explicitly	Yes when packaged	No	Yes when packaged	No

Marlow et al, "The State of the Art in Modeling Remaining Asset Life", *Remaining Asset Life: A State of the Art Review*, WERF, 2009, p.58 (WERF SAM1R06d)

Summary to this point

7. Review likelihood of failure score

(Assets in general, pipe more specifically)

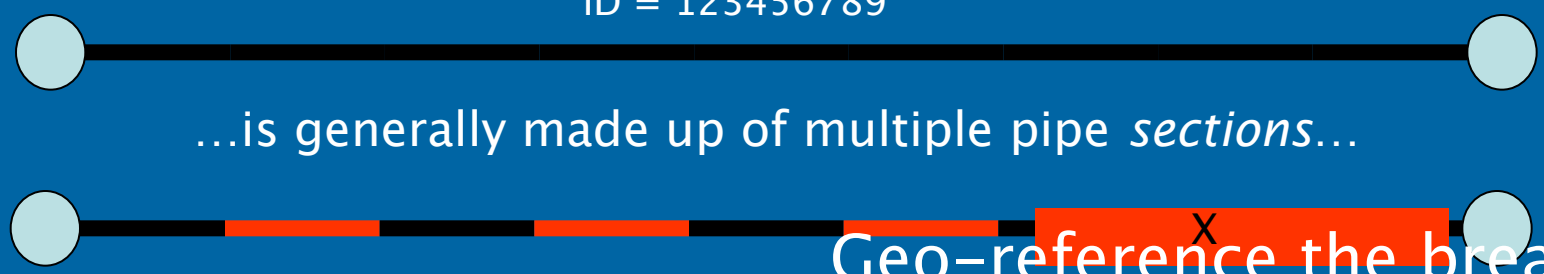
- Methodological approaches for more accurately predicting failures, especially for pipe, have been substantially refined over the past five to ten years
- Methodologies have been largely extracted from “operations research” with increasing distinction between “probability” and “likelihood” (uncertainty)
- Value added from the latest developments comes in two forms:
  - Improved accuracy in the prediction of failure *rates* for a given set of data
  - *Much better understanding of what drives failure!*
- However:
  - Predictions cannot be universal (that is, one set of curves for an asset class fits all utilities) since operating environments are unique to each utility – this still is not widely appreciated by many practitioners and researchers
  - Reliability sciences based methodologies seem to have been largely by-passed

But…!

7.
Review
likelihood of
failure score

A pipe *segment*…

ID = 123456789



…is generally made up of multiple pipe *sections*…

Geo-reference the break!!!

- Most of us keep what records we do at the pipe *segment* level (id = manhole to manhole).
- Pipe rarely *physically* fails as a segment; rather, specific *sections* fail.
- Each section has its own unique performance characteristics; one pipe's performance is generally independent of its neighbor's.

Imputation versus condition assessment

7.
Review
likelihood of
failure score

- Care must be taken not to over apply higher level analysis to specific assets
- Age and general attribute based failure modeling should best be limited to
  - strategic level analysis (pipe type and number by age cohort across system/network) and
  - A “first cut” identification of “problem assets”.
- *However, to effectively forecast failure at the **asset level** (that is, specifically **which** pipe section, which motor, etc.) it generally requires technologically-relevant condition assessment at the asset level.*

General notes on the state of predictive modeling of asset failure

7. Review likelihood of failure score

- A set of ***universal*** "deterioration curves" by asset class is and has been the ***"golden chalice"*** for many AM researchers for a number of years; extensive research has been and is underway here and abroad to derive such curves.
- However, given the number of unique factors that combine to drive failure for any given asset (a specific motor, a particular pipe section) *in its own operating environment*, it is highly unlikely that such universal curves can exist *at a level of accuracy that is useful at the operational level (the future lies in effective periodic or continuous monitoring/sensoring).*
- Key distinction:
  - *How **many** of this type of asset* (ductile iron pipe section, centrifugal motor) can be expected to fail at a specified age?
  - *When* can we expect ***this*** *specific asset* (pipe section, motor) to fail?

Less sophisticated approach: Identify “at risk” assets

7. Review likelihood of failure score

Conduct desktop search through database(s) for:

- High business risk exposure scores
- Very low remaining useful lives
- Poor condition scores or scores approaching designated minimum acceptable levels
- Poor performance scores
- Poor reliability scores
- No redundancy
- Imminent major failure mode of “capacity” or “level of service”
- “Problem assets” (high work order frequency/ maintenance time)

Simple alternative to formal predictive modeling

6. Review residual physical life

% of Physical Life Consumed	Performance Rating / POF
<10	1
20	2
30	3
40	4
50	5
60	6
70	7
80	8
90	9
At failure	10

PoF is probability of failure

Where performance is a composite score of such attributes as:

1. Condition
2. Operating performance
3. Reliability
4. Availability
5. Maintainability
6. Repair history

Recall: our composite performance scoring structure

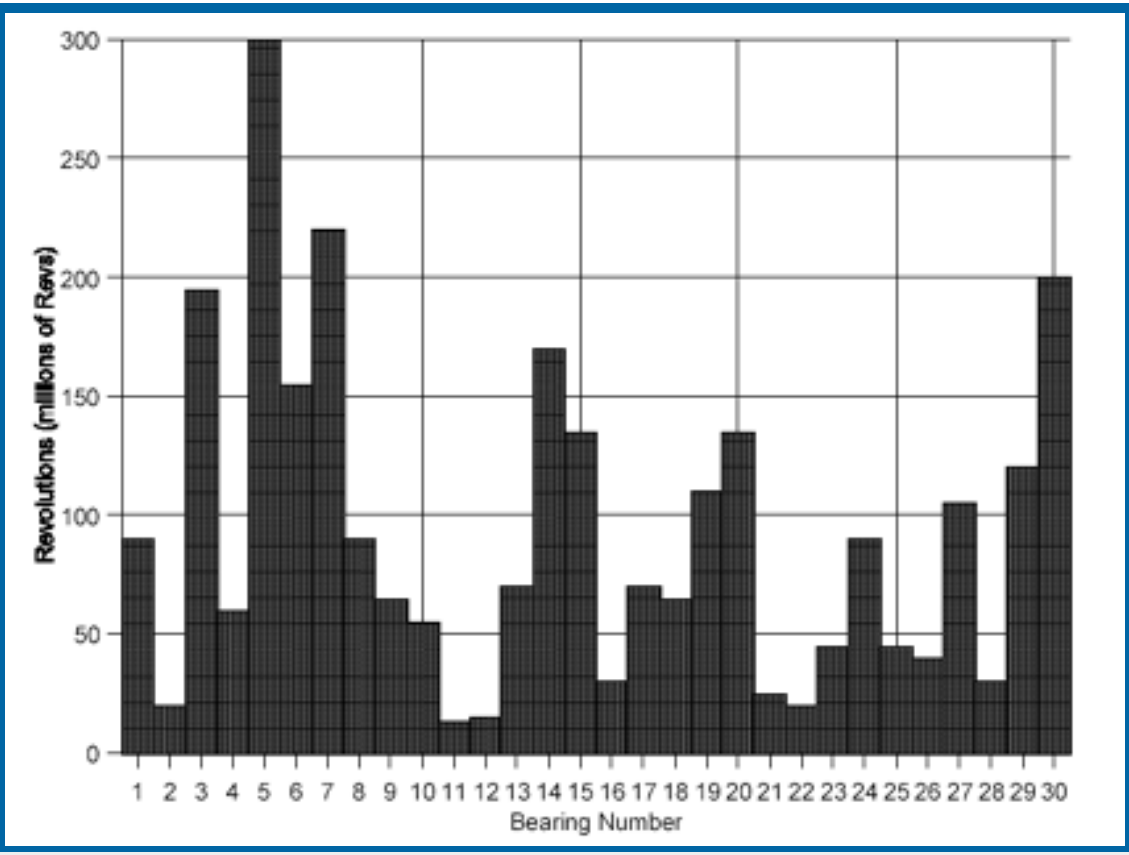
6. Review residual physical life

Element	Description					
SCORE	1	3	5	7	9	10
Physical Condition	Substantially exceeds current requirements	Exceeds current requirements	Meets current requirements but with room for improvement	Obvious concerns: cost/benefit questions	Inefficient; becoming ineffective, obsolete	Failing, not capable of sustaining required performance
Operational performance	Negligible attention required	Exceeds current requirements	Meets current requirements but with room for improvement	Obvious concerns: cost/benefit questions	Difficult to sustain performance	Failing, not capable of sustaining required performance
Reliability	As specified by manufacturer	Infrequent breakdown	Occasional breakdown	Periodic breakdown	Continuous recurrent breakdown	Virtually inoperable
Availability	Virtually always operational	Out of service only for very short periods	Out of service for moderate period; moderately difficult to return to service	Increasingly difficult to return to service; parts becoming a challenge	Extensive downtime duration; difficult to return to service; parts, difficult to acquire, rare skills required	Virtually impossible to return to service; parts no longer available; unavailable trained personnel
Maintainability	Preventive maintenance only; baseline monitoring	Largely PM, some minor repair	Increasing minor corrective maintenance required; shortening of monitoring intervals	Predictive and corrective maintenance becoming dominant; frequency of work orders increasing substantially	Work orders well above average for type of asset; recurrent minor repair; close monitoring required	Corrective maintenance is frequent with recurrent patterns of failure; asset must be virtually constantly monitored or "run to failure" response readied for implementation
% Physical life consumed	Almost new; up to 10% physical life consumed	Up to 30% physical life consumed	Up to 50% physical life consumed	Up to 70% physical life consumed	Up to 90% physical life consumed	Virtually consumed, imminent failure
SCORE	1	3	5	7	9	10

Here's a simple way to convert to remaining life

But: Can failure really be predicted?

6.
Review
residual
physical life



Bearing Life Scatter

(Ball and Roller Bearings: Theory, Design, & Application Eschmann, et al John Wiley & Sons. 1985)

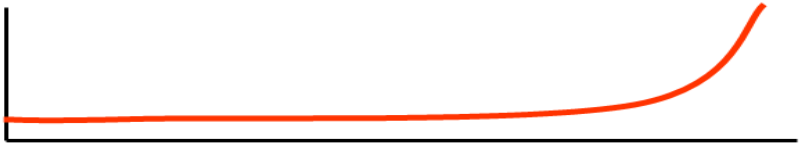
From Reliability Theory: The six classical failure curve patterns

6. Review residual physical life

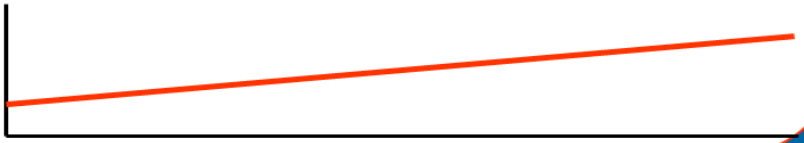
Age related

Pattern A: High initial incidence of failure followed by a constant or increasing conditional probability to "wear-out". (Composite of B and F)

Pattern B: Classic "wear-out", constant or increasing conditional probability to wear-out.



Pattern C: Gradual aging; wear out age is not identifiable.

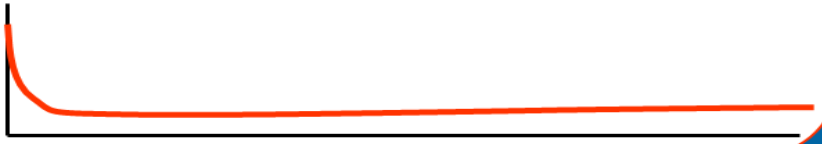


"Random"

Pattern D: Best new followed by increased but leveling conditional probability of failure.

Pattern E: Totally random; conditional probability equal at all ages.

Pattern F: "Infant mortality"; high initial rate followed by constant lower rate.

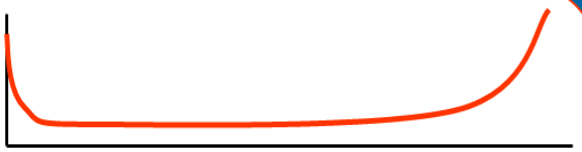


Failure curves relate to types of assets

6. Review residual physical life

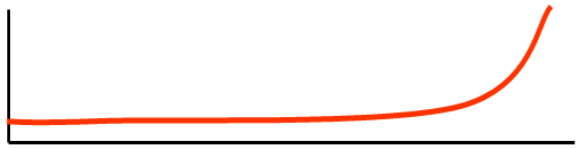
Age related

Pattern A: High initial incidence of failure followed by a constant or increasing conditional probability to "wear-out". (Composite of B and F)



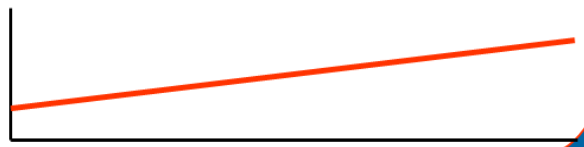
Complex mechanical equipment with high integration of complex parts, eg, gearboxes, transmissions, etc

Pattern B: Classic "wear-out", constant or increasing conditional probability to wear-out.



Mechanical equipment with a dominant age-related failure mode, eg, pumps, valves, piping (erosion)

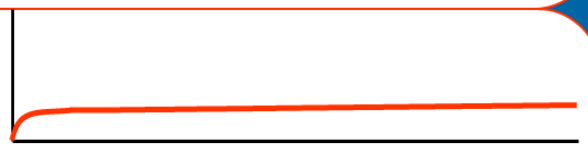
Pattern C: Gradual aging; wear out age is not identifiable.



Commonly, structural fatigue

"Random"

Pattern D: Best new followed by increased but leveling conditional probability of failure.

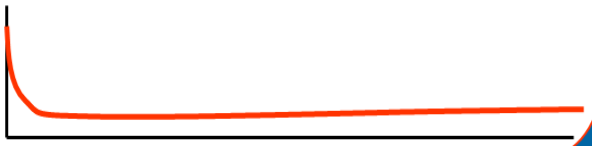


Commonly, structural fatigue

Pattern E: Totally random; conditional probability equal at all ages.

Complex electromechanical equipment without a dominant failure mode or equipment subject to excessive forces

Pattern F: "Infant mortality"; high initial rate followed by constant lower rate.

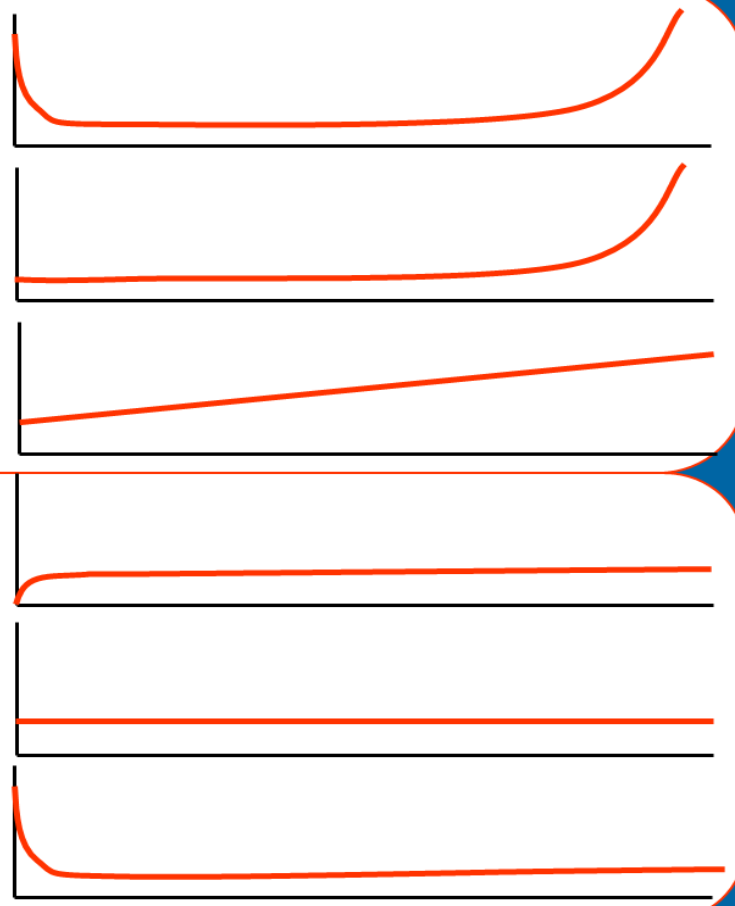


Electronic components such as computers and PLCs

Note that age related failures are a *substantial minority* in major studies!

6. Review residual physical life

		United Airlines 1968	US Navy 1983
Age related	Pattern A: High initial incidence of failure followed by a constant or increasing conditional probability to "wear-out". (Composite of B and F)	4%	3%
Age related	Pattern B: Classic "wear-out", constant or increasing conditional probability to wear-out.	2%	17%
Age related	Pattern C: Gradual aging; wear out age is not identifiable.	5%	3%
"Random"	Pattern D: Best new followed by increased but leveling conditional probability of failure.	7%	6%
"Random"	Pattern E: Totally random; conditional probability equal at all ages.	14%	42%
"Random"	Pattern F: "Infant mortality"; high initial rate followed by constant lower rate.	68%	29%



Establishing basic concepts in Reliability Science

6. Review residual physical life

- At a given point in time, a component or system is either functioning or it has failed; the component or system operating state changes with age and usage.
- **Reliability** - The probability that a functional unit will perform its required function for a specified period of time under stated (operating) conditions
- The likelihood that failures will occur varies over time according to an *expected probability function*
- Where the expected probability function is selected because
  - There is a physical argument that theoretically matches a failure mechanism to a *"life distribution model"*
  - A particular model has previously been used successfully for the same or a similar failure mechanism
  - A convenient model provides a good empirical fit to a set of failure data

Drilling deeper - basic terms and concepts

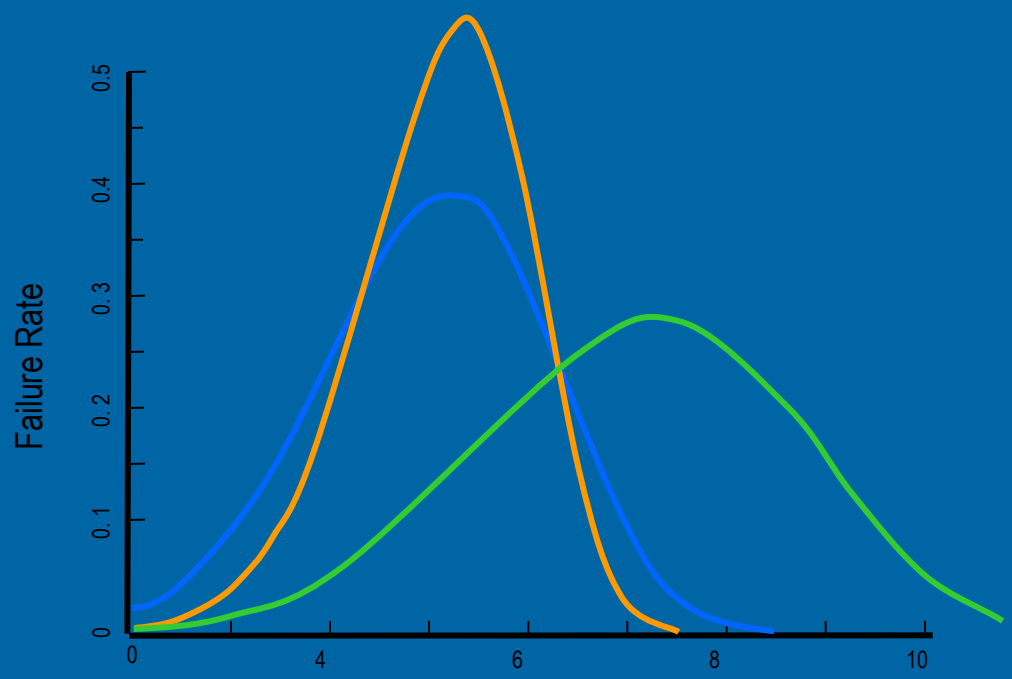
6. Review residual physical life

- **Reliability Given Time:** The probability that a product will operate successfully at a particular point in time. For example, “there is an 88% chance that the product will operate successfully after 3 years of operation.”
- **Probability of Failure Given Time:** The probability that a product will be failed at a particular point in time. Probability of failure is also known as "unreliability" and it is 1 minus the reliability. For example, there is a 12% chance that the product will be failed after 3 years of operation (and an 88% chance that it will operate successfully).
- **Mean Life:** The average time that the products in the population are expected to operate before failure. This metric is often referred to as mean time to failure (MTTF) or mean time before failure (MTBF).
- **Failure Rate:** The number of failures per unit time that can be expected to occur for the product. Warranty Time: The estimated time when the reliability will be equal to a specified goal. For example, the estimated time of operation is 4 years with a reliability of 90%.
- **B(X) Life:** The estimated time when the *probability of failure* will reach a specified point (X%). For example, if 90% of the products are expected to fail by 35 years of operation, then the B(90) life is 35 years.

http://www.weibull.com/basics/lifedata.htm

“Life data analysis” – the Weibull function for PoF

6. Review residual physical life



- In order to fit a statistical model to a life data set, the analyst estimates the parameters of the life distribution that will make the function most closely fit the data.
- The parameters control the scale, shape and location of the *pdf* function.
- For example, in the 2-parameter Weibull model, The shape parameter, β, defines the shape of the distribution and the scale parameter, ή,(eta) defines where the bulk of the distribution lies.

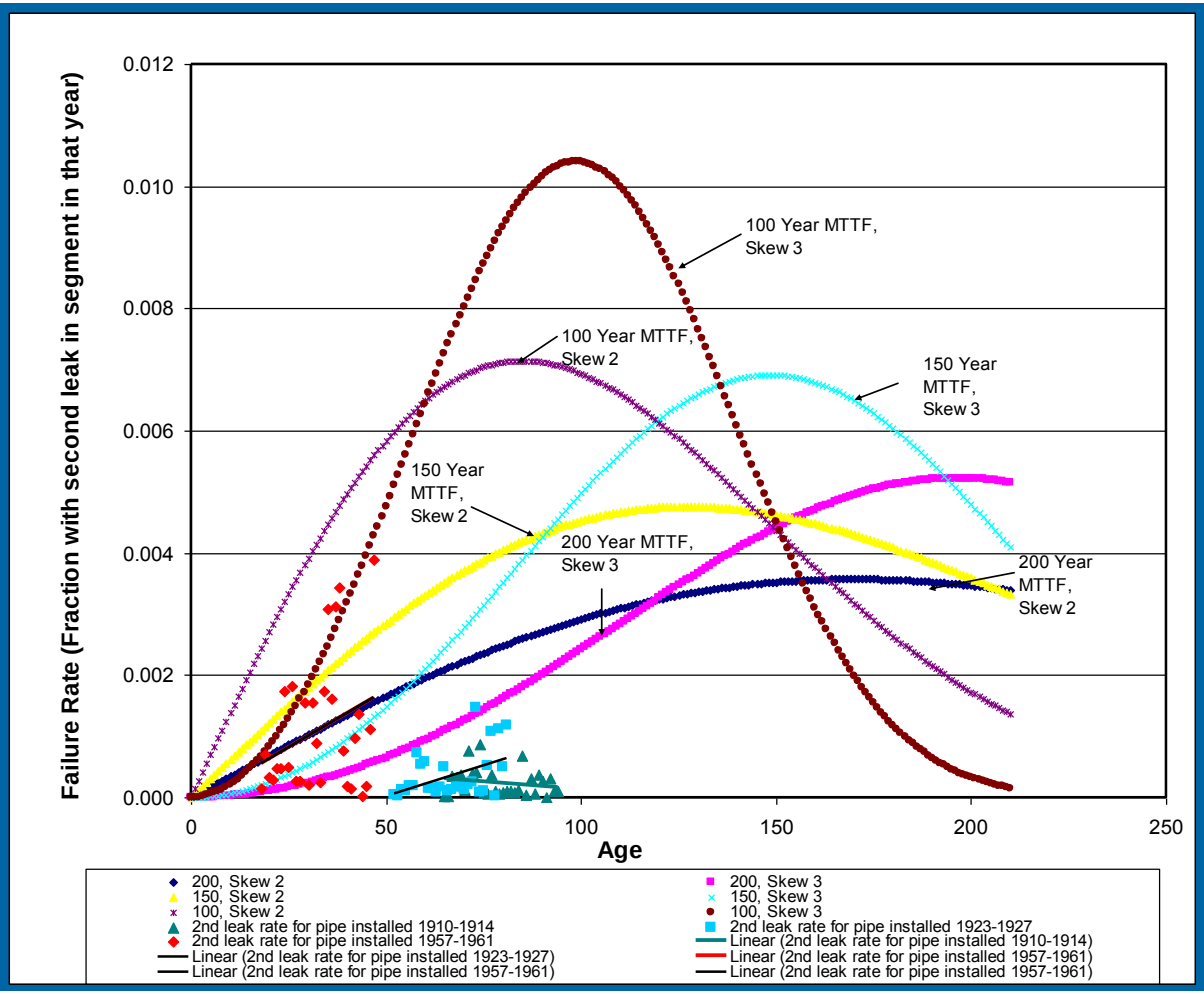
3-parameter model:

$$f(T) = \frac{\beta}{\eta}\left(\frac{T}{\eta}\right)^{\beta-1} e^{-\left(\frac{T}{\eta}\right)^{\beta}}$$

$$f(T) \geq 0,\ T \geq 0,\ \beta > 0,\ \eta > 0$$

Source: weibull.com, http://www.itl.nist.gov/div898/handbook/apr/section1/apr162.htm

Example: City of Portland (OR) Water



Insights from reliability toolbox: "survivor analysis"

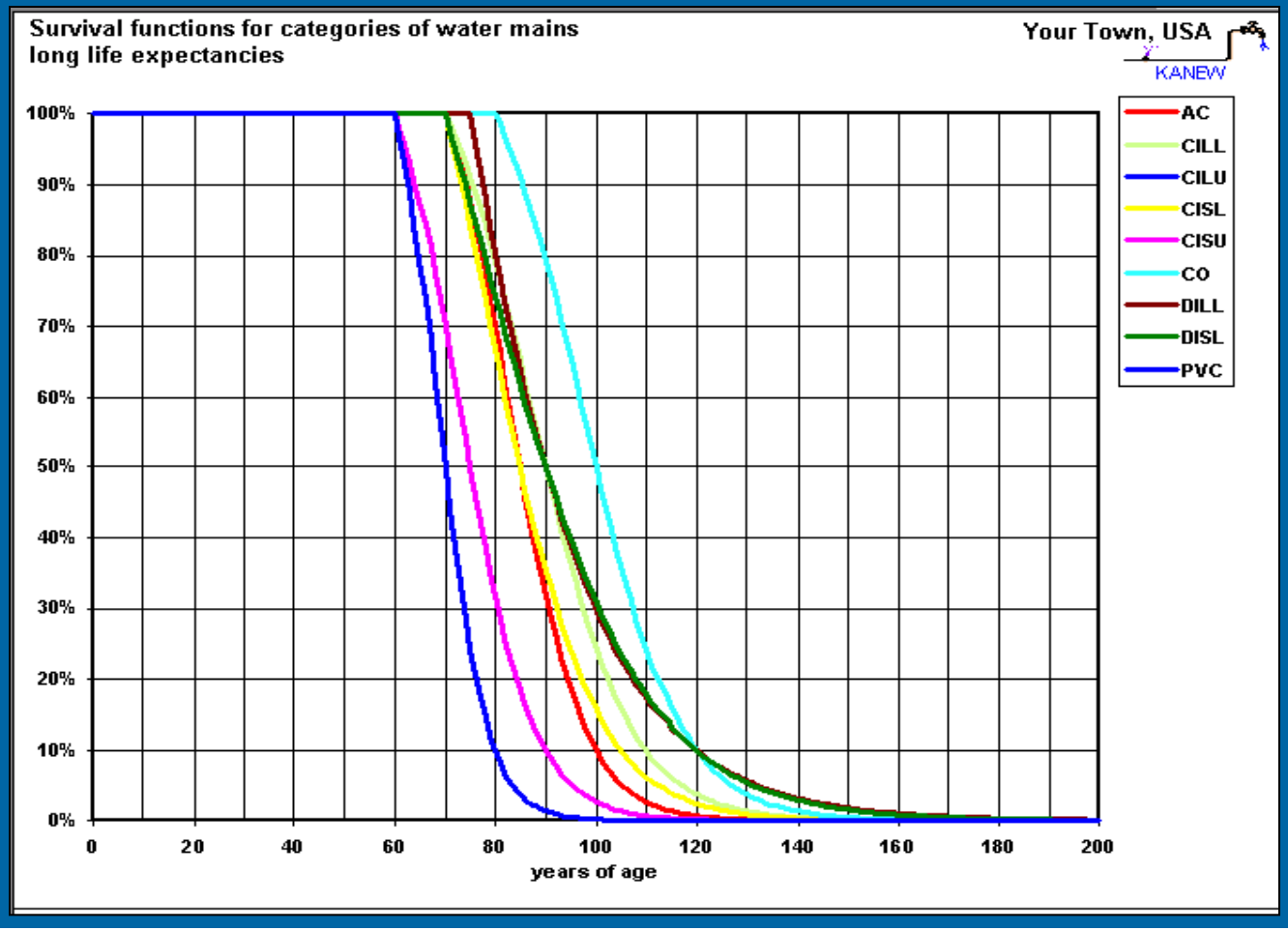
6. Review residual physical life

Survival analysis attempts to answer questions such as:

- What is the fraction of a population (eg, group of assets) which will survive past a certain defined point in time?
- Of those that survive to that point in time, at what rate can they be expected to fail in subsequent periods of time?

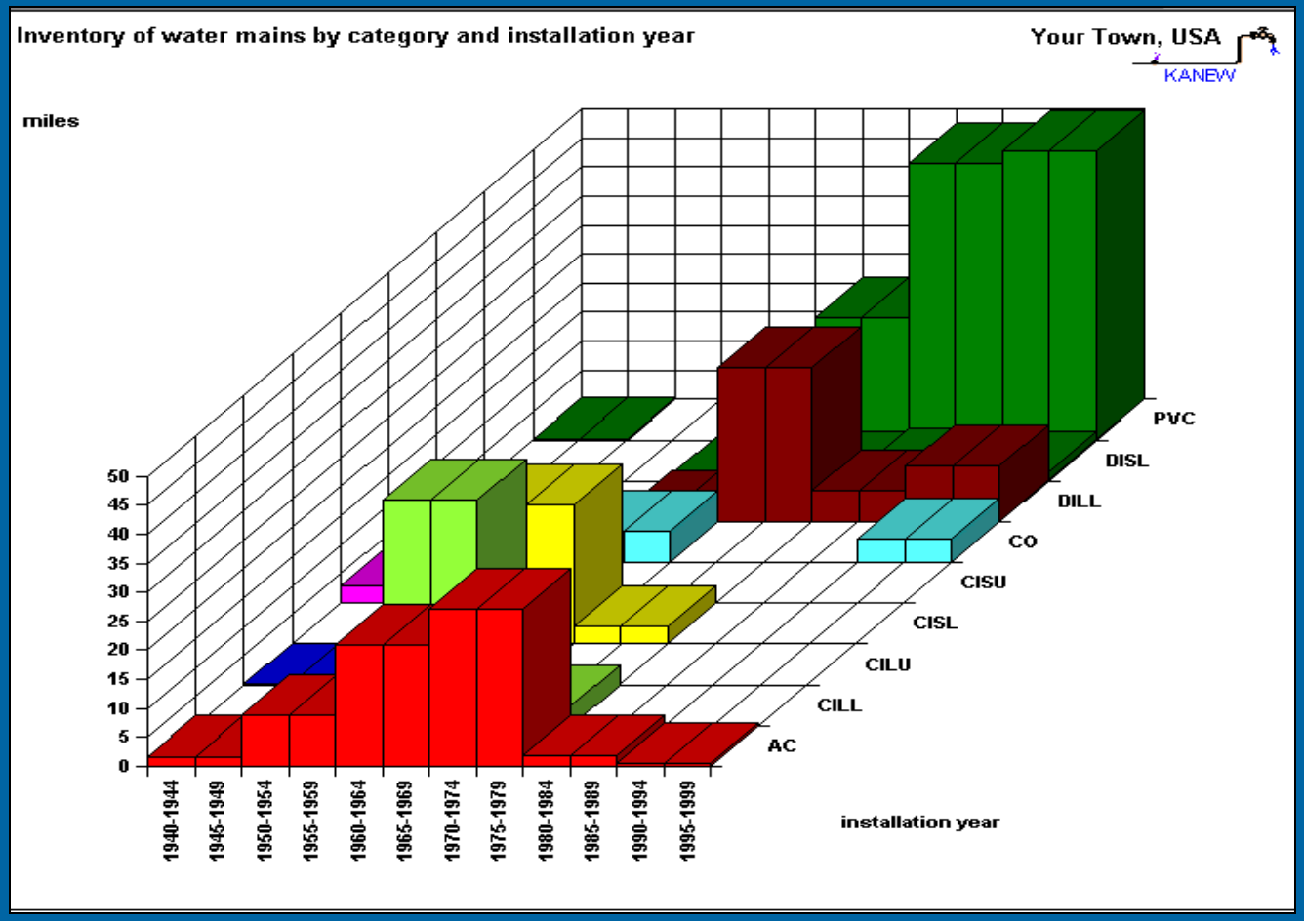
Example of survivor curves

6.
Review
residual
physical life



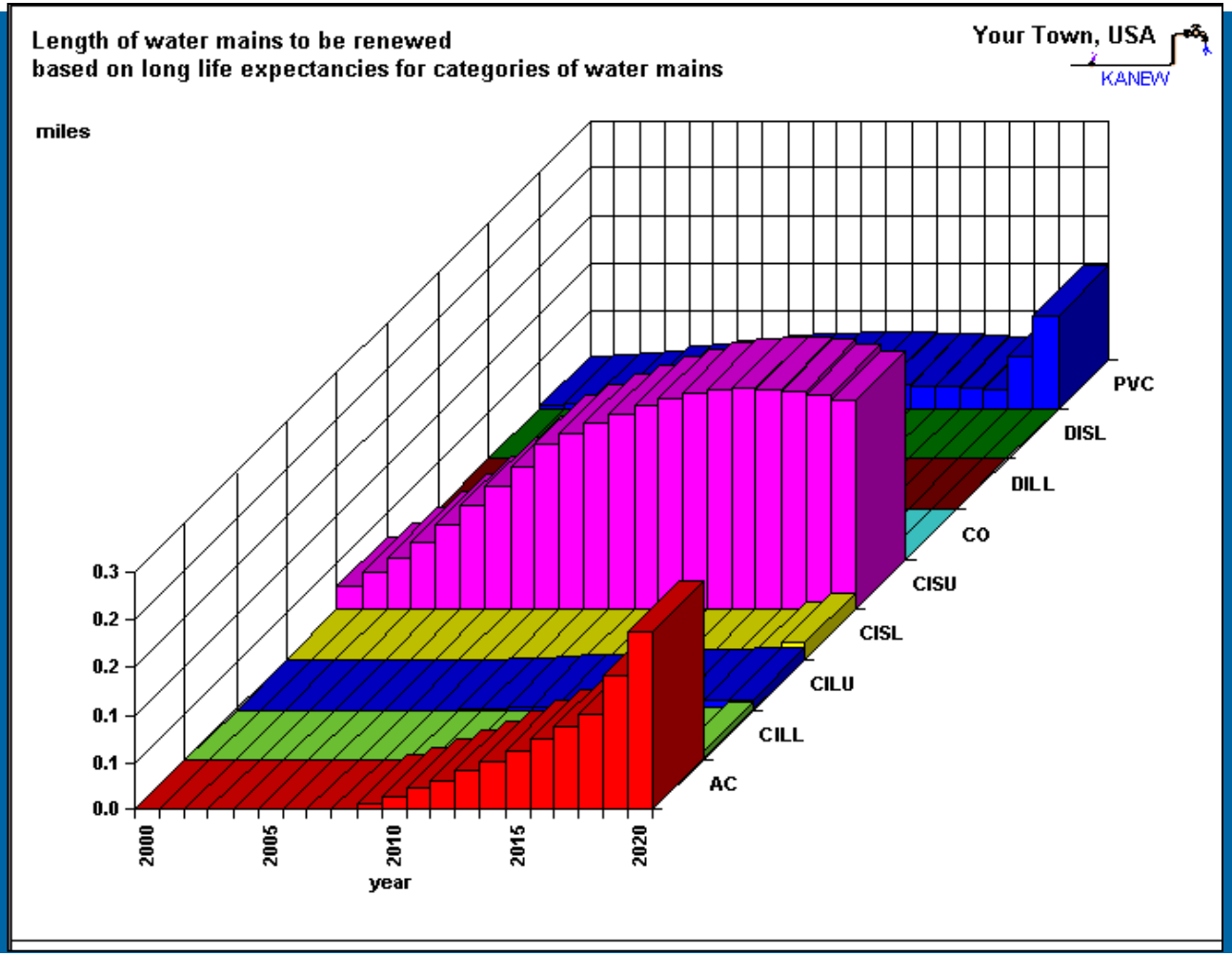
Example: Kanew – survivor functions for projecting pipe failure

6. Review residual physical life



Example: Kanew – projecting forward by pipe type

6. Review residual physical life



6.
Review
residual
physical life

So, what is our tactical level approach where failure at the asset level *cannot* be accurately predicted?

- Avoid/defer the consequences (significantly reduce the likelihood of functional failure - e.g. designate as “cannot fail” or “low risk tolerance”)
  - Replace just before significant increase in conditional probability (see: LOS business rules and conditional probability curves)
  - Add redundancy
  - Increase design specifications
  - Raise O&M standards; set narrower monitoring intervals
- Accept but manage the consequences
  - Develop reactive response plans that focus on consequence oriented risk mitigation strategies such as:
    - Containment/off-line storage
    - SCADA alarming
    - By-pass/pump around
    - Critical spares on site
    - Increase valve density

Reduced to core questions…

6. Review residual physical life

- Does the asset have a time or usage related wear-out pattern?
  - Yes:
    - Is the failure pattern reasonably discernable?, and
    - Can a set of tasks – a strategy - be developed that reduces the probability of failure to an acceptable level? and
    - Is the strategy with its associated required monitoring interval cost effective?
    - If so, establish a proactive intervention strategy
  - Otherwise:
    - Re-design/re-specify, replace at a “safe life limit”, and/or
    - “Run to failure” and manage the failure event and its consequences
    - Deploy appropriate condition assessment protocols/technologies

“Take home” ideas from this module

- Distinguish between:
  - *Strategic level: How **many*** assets can be expected to fail in a given time frame and at what cost (strategic funding)
  - *Tactical/operations level: **Which*** specific assets will fail in a given time frame (renewal program)
- Set up/determine/understand:
  - Management strategy groups
  - Relevant conditional failure curve associated with each management strategy group

Questions?

Deriving the CIP investment program – a best practice model

1. The strategic CIP "Business Plan"
   - What are we going to do and why?
   - What will it cost?
   - How will it be funded?
   - Life-cycle impact on LOS, rates, and financial condition

2. On time and on budget
   - Managing costs
   - Managing schedules and deliverables
   - Managing contracts and changes

3. Integration into the portfolio of assets
   - Registry
   - Start-up, shake-down, burn-in, commissioning
   - Manuals, spares, and service
   - Initiating the maintenance regimen

1
- Identification
- Validation
- Prioritization
- Financing

2
- Execution
- Control

3
- Handover

“Prioritization” rank-orders validated projects

A. Public Health/Safety, Mandated Program, BOC Irrevocable Commitment, Phase Completion

Points	Criteria
20	• Urgent to meet *emergency situations* to remedy or prevent a major health / safety hazard.
19	• Essential to remedy or prevent a major health / safety hazard; • Essential to comply with legally mandated programs and avoid penalty; • Essential to comply with irrevocable commitment by the BOC.
15	• Essential to complete a project phase, otherwise the system will not be operational.
6	• Very positive economic impact; • Ongoing support by BOC for *county grants match and outside agency grants*; • Project identified as highest priority by BOC or County Manager; • Potential hazard – deferral of project would increase significant level of hazard.
3	• Potential hazard – deferral of project would *not* increase significant level of hazard.
0	• Project does not apply to the aforementioned criteria.

B. Service Delivery, Fiscal Impact, Leverage

Points	Criteria
7	• The project creates revenues or identifies savings *in excess of the project cost* and is justified by a cost benefit analysis; • Implementation plans of the project are required prior to capital allocation and cost savings reduce the base operating budget.
6	• Project significantly improves service delivery which will substantially reduce *subsequent operating or capital costs*; • County funds are reimbursed by the federal or state government at a rate of 50% or greater.
5	• Project significantly improves service delivery and will be utilized by multiple departments with *little or no impact* on future operating or capital costs (less than $20,000 per year); • Essential operating capital to meet service growth and/or mandated programs.
4	• Project significantly improves service delivery with *little or no impact* on future operating or capital costs (less than $10,000 per year); • County funds are reimbursed by the federal or state government at a rate less than 50%.
3	• Project improves service delivery with *no impact* on future operating or capital costs (less than $10,000 per year) • Essential operating capital to meet service growth and / or mandated programs
2	• Project significantly improves service delivery with *moderate impact* on future operating or capital costs ($10,000 – $50,000 per year)
1	• Project significantly improves service delivery with *high impact* on future operating or capital costs (more than $50,000 per year)
0	• Project does not significantly improve service delivery; • Project balance available for annual program; • Project requires further study before consideration.

Example: Possible prioritization factors & weights

Factor	Weight
Public Health/Safety	15
Federal or State Mandated Program	15
Local Irrevocable Commitment	15
Business Risk Exposure	10
Service Delivery Impact	10
Fiscal Impact	10
Conformance with Plan / Policies; Phase Completion/	8
Efficiency Improvement	7
Leverage	6
Project Interdependence	4
Total Maximum Score	**100**

Supplement to prioritization factor weighting

"Risk"

No	Project description	Cost $M	B/C ratio	PBP yrs	CLR	BRE
256	South trunk renewal	4.2	2.42	2.5	**83**	**610**
102	Expand plant automation	6.5	2.35	3.5	**63**	**411**
16	Renew digester heaters	2.8	2.10	4.0	**74**	**219**
205	New CMMS	8.5	1.95	5.0	**69**	**712**
167	Office accommodation	4.7	1.35	6.2	**72**	**813**
150	Siphon renewals	2.6	1.30	7.2	**73**	**471**

Assume agency CIP limit of $25M

Capital or Maintenance ?

- Many capital projects can be deferred significantly by increased or better maintenance for some periods of time ;
- Always remember that if we defer capital we may need to increase maintenance budgets for the period of deferral or at least make a contingency allowance for it ;
- Action : Calculate this maintenance cost and include with the deferral recommendations to the CIP setting & budget sessions.

Questions?