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EFFECTS OF MATERIAL PROPERTIES, DESIGN AND CONSTRUCTION ON CORROSION CONTROL AND CONDITION ASSESSMENT OF WATER INFRASTRUCTURE

Steven Fox, P.E.
Vice President

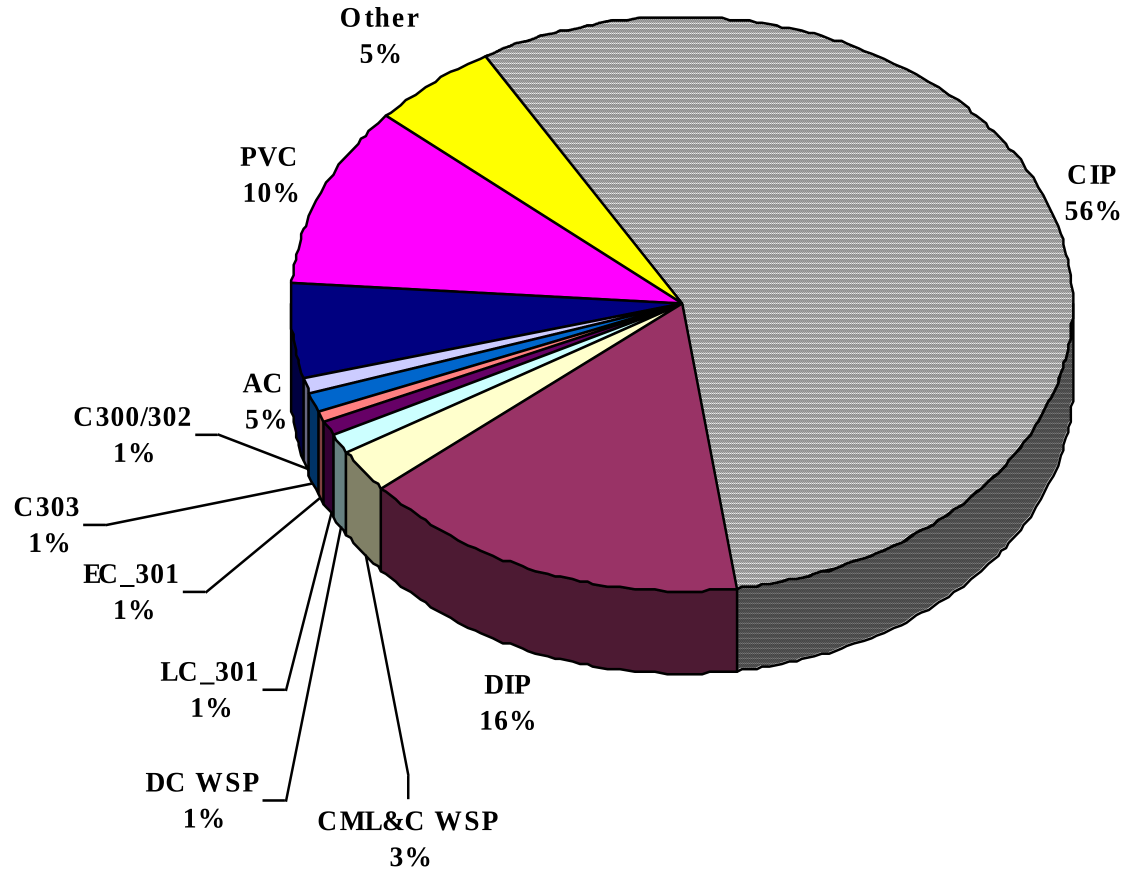
HDR | SCHIFF

“Market Driver” for Corrosion Control and Condition Assessment is Entropy

“Business” is Guaranteed by a Fundamental Law of Nature:

$$\Delta S_{universe} \geq 0$$

Most Municipalities have a wide Variety of Pipeline Materials



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Definition of Corrosion

- **Corrosion is the deterioration of a substance or its properties as a result of an undesirable reaction with the environment.**

- NACE International

It is irreversible and degenerative and related to the Second Law Thermodynamics

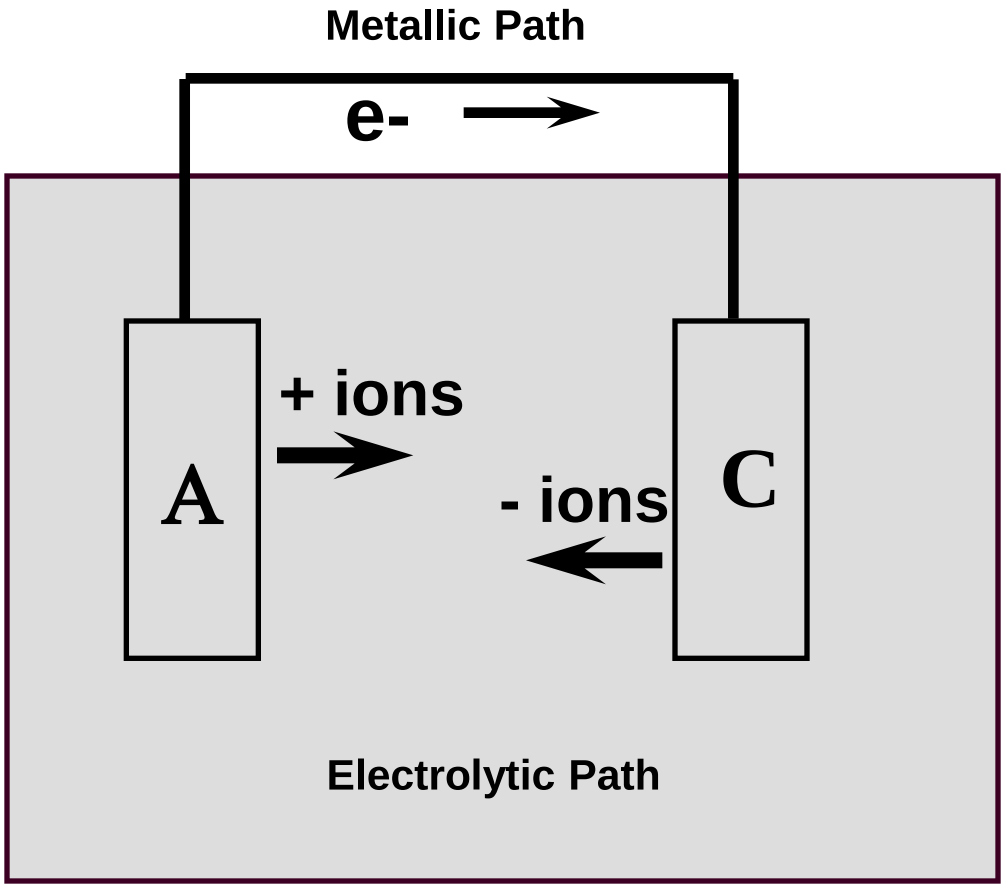
"Energy spontaneously tends to flow only from being concentrated in one place to becoming diffused or dispersed and spread out."

Fundamentally Everything You Need to Know About Corrosion

- **4 Parts of a Corrosion Cell**
  - Anode => Action (location where corrosion takes place)
    - Oxidation Half-Reaction
  - Cathode (no corrosion)
    - Reduction Half-Reaction
  - Electrolyte (Soil, Water, Moisture, etc.)
  - Electrical Connection between anode and cathode (wire, metal wall, etc.)

Electrochemical corrosion can be stopped by eliminating any one of the 4 components

Electrochemical Corrosion Cell



Concepts of the Four Basic Methods Corrosion Control

- Material Selection/Design Details
  - Choose materials compatible with environment.
  - Do not create corrosion cell through design/construction details.
- Corrosion Inhibitors
  - Alter the environment adjacent to metal to passivate and protect metal.
  - Concrete or mortar on steel are inhibitors

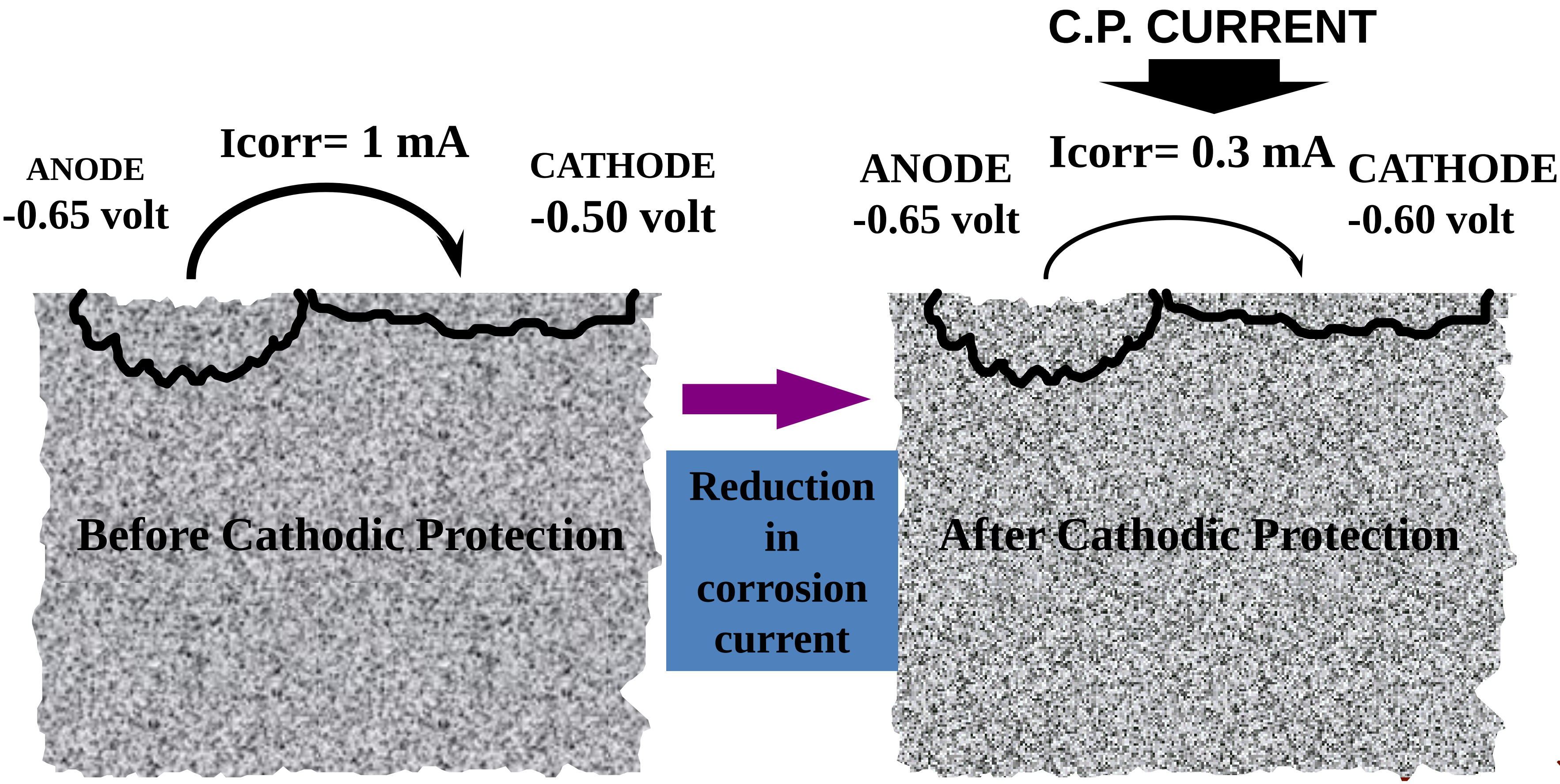
Concepts of the Four Basic Methods Corrosion Control (continued)

- Cathodic Protection
  - Electrochemically alter the surface condition of the metal to move the anodic reactions elsewhere.
- Coatings (exterior) and Linings (interior)
  - Provides a barrier between the electrolyte and protected the metal. Usually dielectric material that prevents electron and ionic current flow.

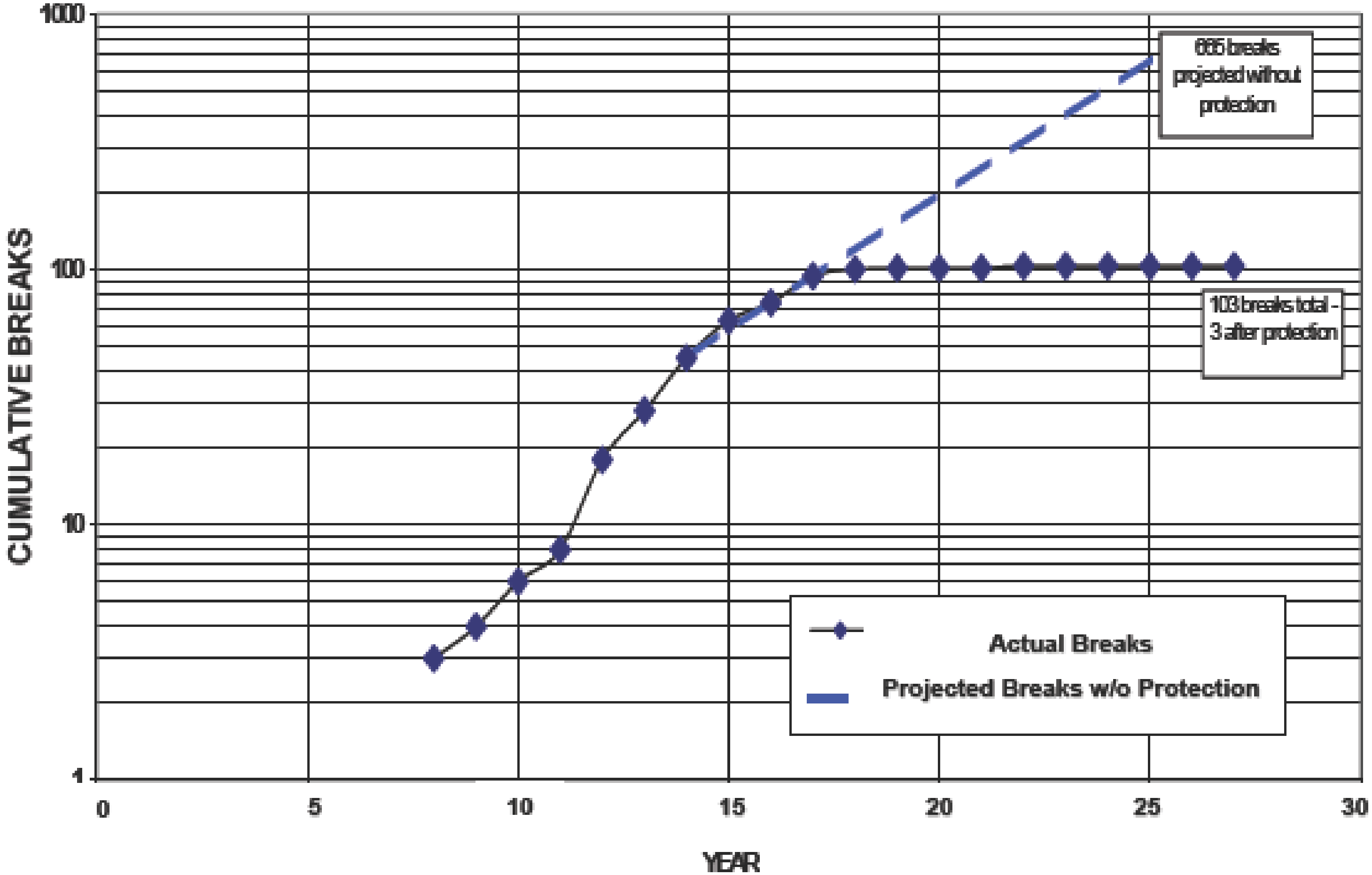
Coatings and Cathodic Protection Work Together

- Cathodic protection can be applied without coatings.
- Coatings should not be used without cathodic protection.
- Cathodic protection effectively protects defects in the coating.

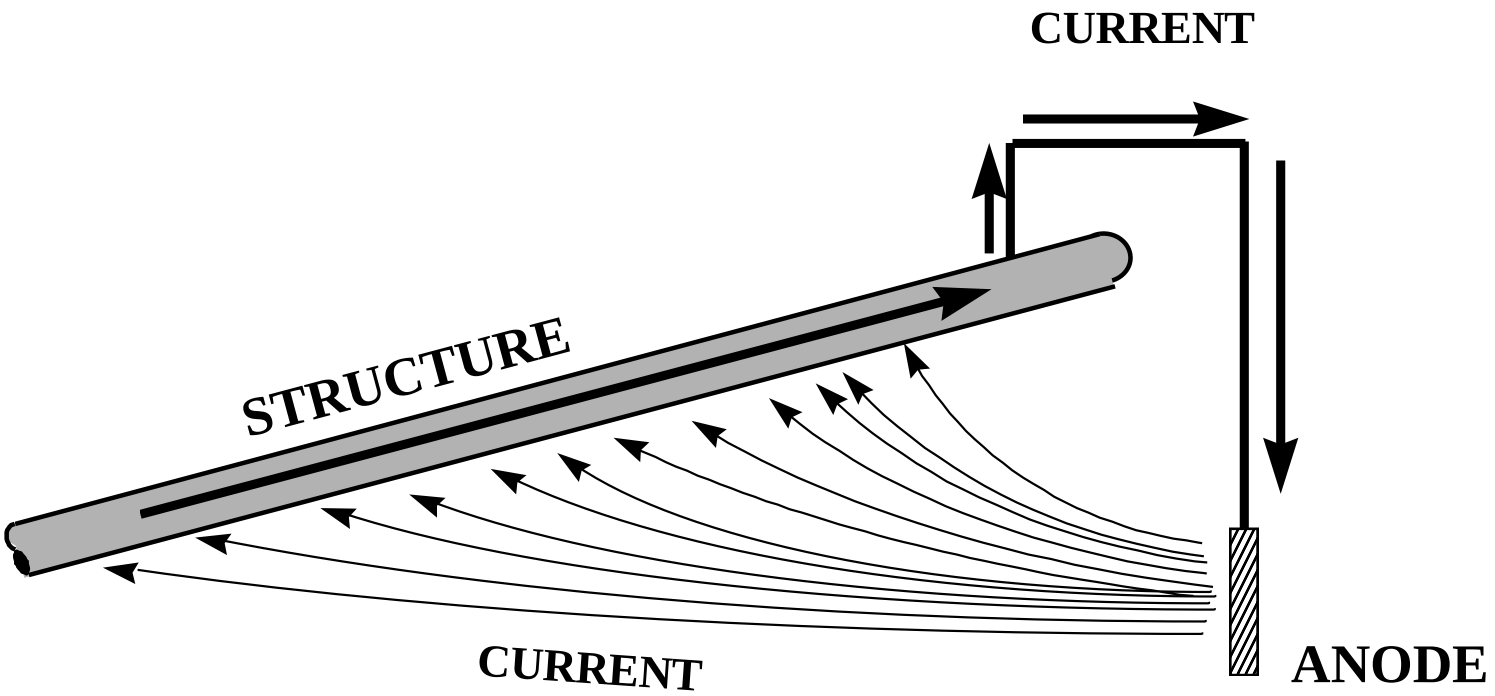
Effect of Cathodic Protection is to Reduce Driving Force for Current Flow



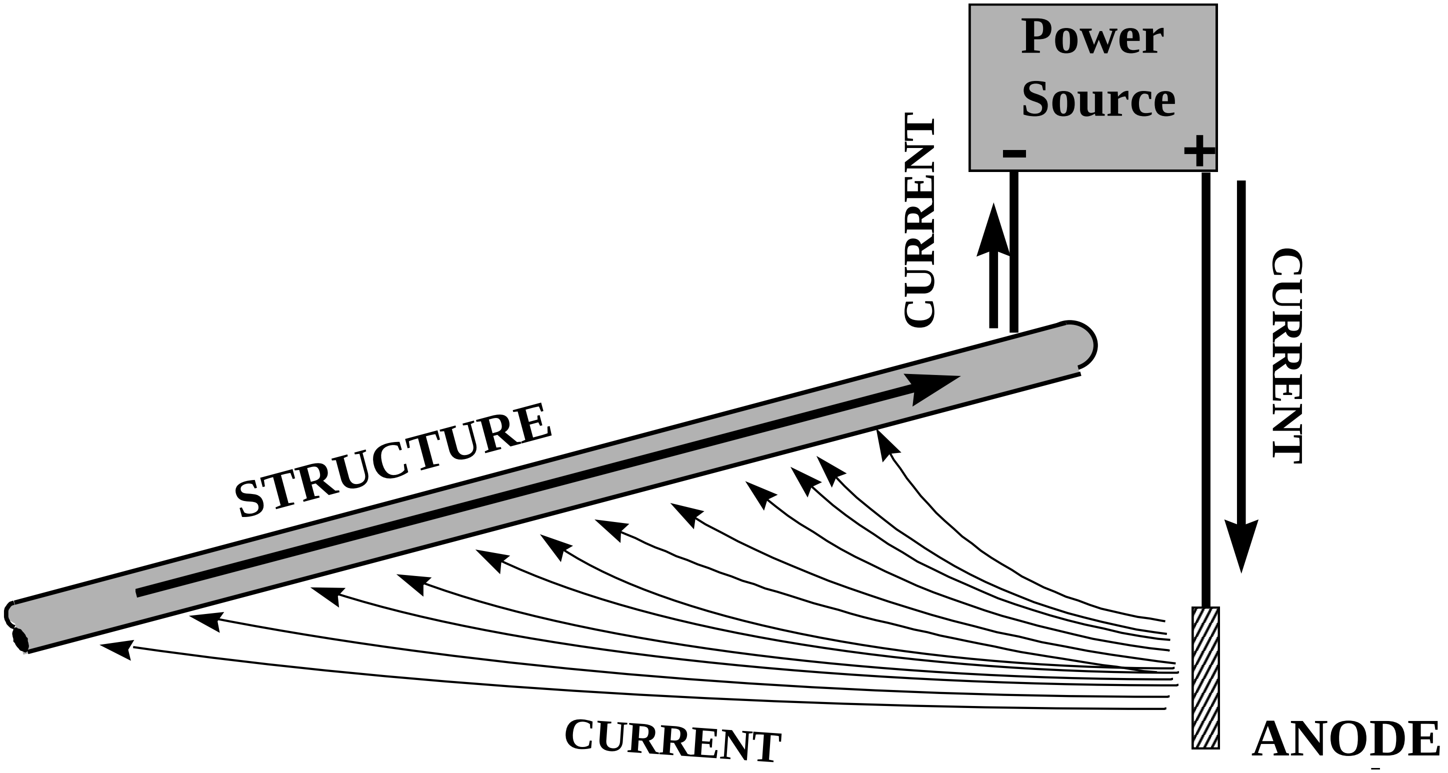
Cathodic Protection Stops Leaks.



Galvanic Anode Cathodic Protection System



Impressed Current Cathodic Protection



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$$ are Directly Proportional to Current Capacity (Amps).

- Life Cycle Costs = Construction + Operation
- Initial/Construction costs ~ Amps
- Operating/Maintenance Costs ~ Amps
- Anything and everything you do to reduce current requirement saves $$$.

CP Current Requirements for Water & Wastewater Industry Piping

Pipe Material	*Coating System*	*Current Requirement (ma/sf)*
Steel/Iron	***None***	***1 to 3***
Steel	***AWWA C205***	***0.1 to 0.5***
Steel/Iron	***Dielectric Coating AWWA C214, 217, 222***	***0.0006 to 0.040***
Ductile Iron with PE	***AWWA C105***	***0.020 to 0.1***

Cathodic Protection is not always the answer
PCCP failure caused by hydrogen embrittlement

- High strength prestressing wires are sensitive to cathodic hydrogen embrittlement.

DESIGN AND CONSTRUCTION

Material Selection

- Only works at the design stage.
- Must characterize the environment (#1)
- Choosing materials which are most compatible with the environment and cost constraints
  - High alloy materials may not be available in quantities and time frame needed

What Defines Corrosive Soil - Resistivity

- Traditional indicator of corrosivity.
- Determining factors:
  - Soluble salt content
  - Solubilities
  - Moisture content – Fluctuating ground water?
- >10,000 ohm-cm – Mildly Corrosive
- 10,000 to 2,000 – Moderately Corrosive
- 2,000 to 1,000 – Corrosive
- <1,000 – Severely Corrosive

What Defines Corrosive Soil - pH

- Hydrogen ion concentration
  - -log[H^+] (pH of 4.0 = 10^{-4} moles H^+ per liter)
- Not an indicator of buffering
- If less than 5.0 to 5.5, total acidity should be performed.
- Elevated pH generally beneficial, but must be completely uniform.

What Defines Corrosive Soil - Chloride

- Threat to reinforced concrete when greater than 400 ppm.
  - Previously 350 ppm
  - For prestressed pipe in arid conditions – 150 ppm
- Permeates concrete and overcomes corrosion inhibiting effects of high pH on reinforcing steel, pipe walls, pre-stressing wires, etc.

What Defines Corrosive Soil - Sulfate

- Sulfate attacks concrete directly.
- 1,000 mg/kg to 2,000 mg/kg = Moderate
- 2,000 mg/kg to 20,000 mg/kg = Severe
- >20,000 mg/kg = Very Severe

What Defines Corrosive Soil - Other

- NH_4^+ and NO_3^{1-} are deleterious to copper.
- Sulfide/Redox
  - Sulfate reducing bacteria
  - Anaerobic conditions
  - Black/gray fine grained soils
  - Aggressive to both copper and ferrous metals.

Corrosion Inhibitors

- Mortar/cement is the most common inhibitor for steel in the world.
- Admixtures can improve resistance of encased steel, particularly to chloride
  - Prior to Fabrication
  - Low Cost
- Uniform inhibitor distribution is critical

Coatings

- Applicable to service environment and construction methods.
- Are specifications complete and up to date?
  - Provisions for third party inspection

- **Poor surface preparation is the most frequent cause of premature coatings failure.**
- **Surface preparation is the most expensive operation of a painting project (> 60%).**

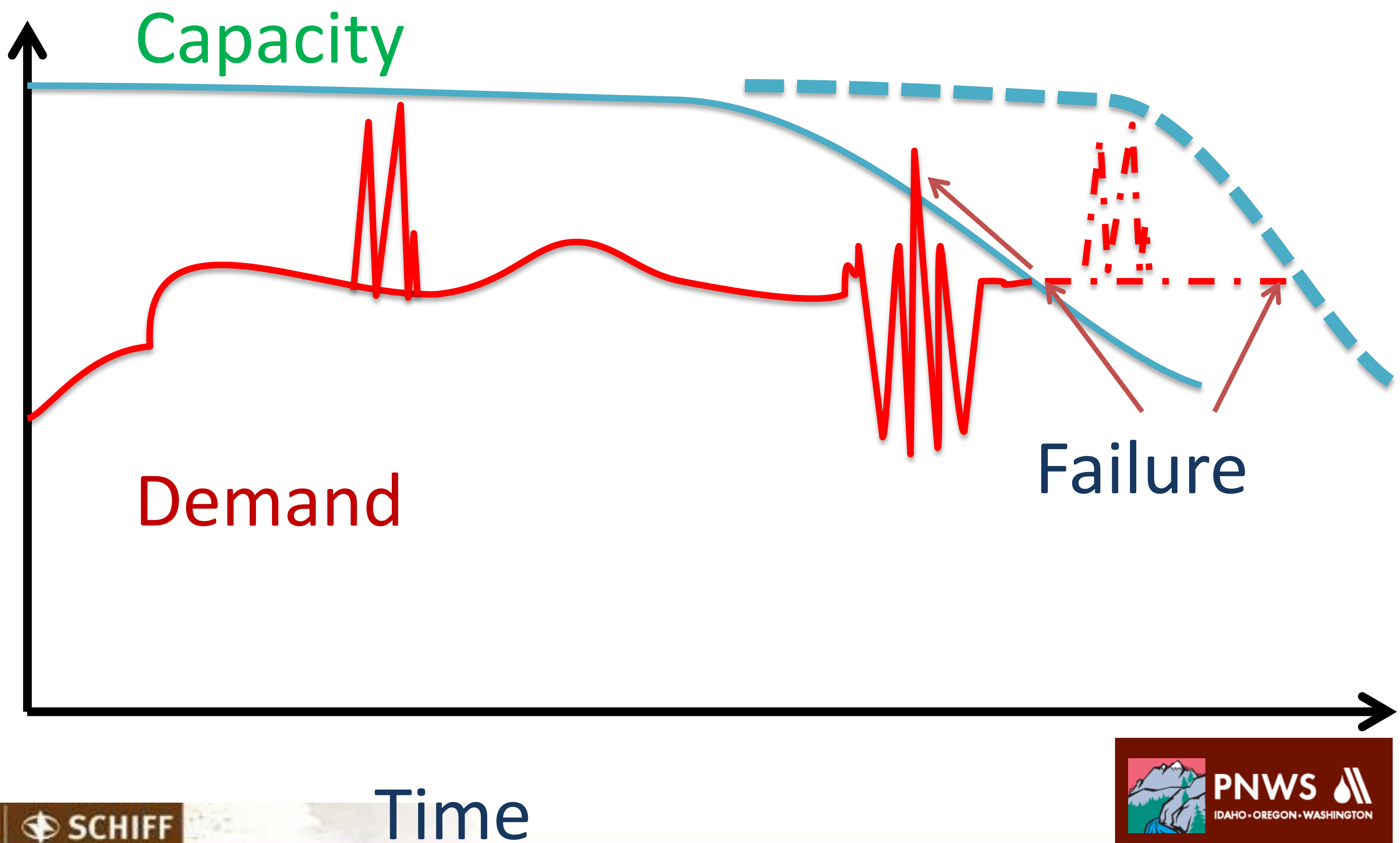
What about the future?

- Enough access points to adequately monitor
  - Internal
  - External
  - Accommodate technology

- Ready for the application of cathodic protection
  - Electrical continuity
  - Test stations

CONDITION ASSESSMENT AND ASSET LIFE EXTENSION

Fundamentally, Engineered Systems Fail When Demand Exceeds Capacity



Material Capacity changes are due to only three time dependent degradation mechanisms

- Creep
  - Not an issue for metallic pipes at ambient temperatures
- Fatigue
  - Cyclic loading with stresses approaching yield
- Corrosion
  - Electrochemical deterioration

Condition Assessment is a Multi-disciplinary Engineering "Art"

- Determining and documenting the physical state of infrastructure at a point in time
- Improve operations and maintenance of the structures
- Prioritization of improvements in a Capital Improvement Plan

A Balanced Approach Uses Data the Utility has Already Paid For

- Historical data have already been paid for
- Technology as appropriate: available, feasible, applicable and within budget constraints
- Each technology or approach has a limitation

Use all the data to analyze and produce the condition information

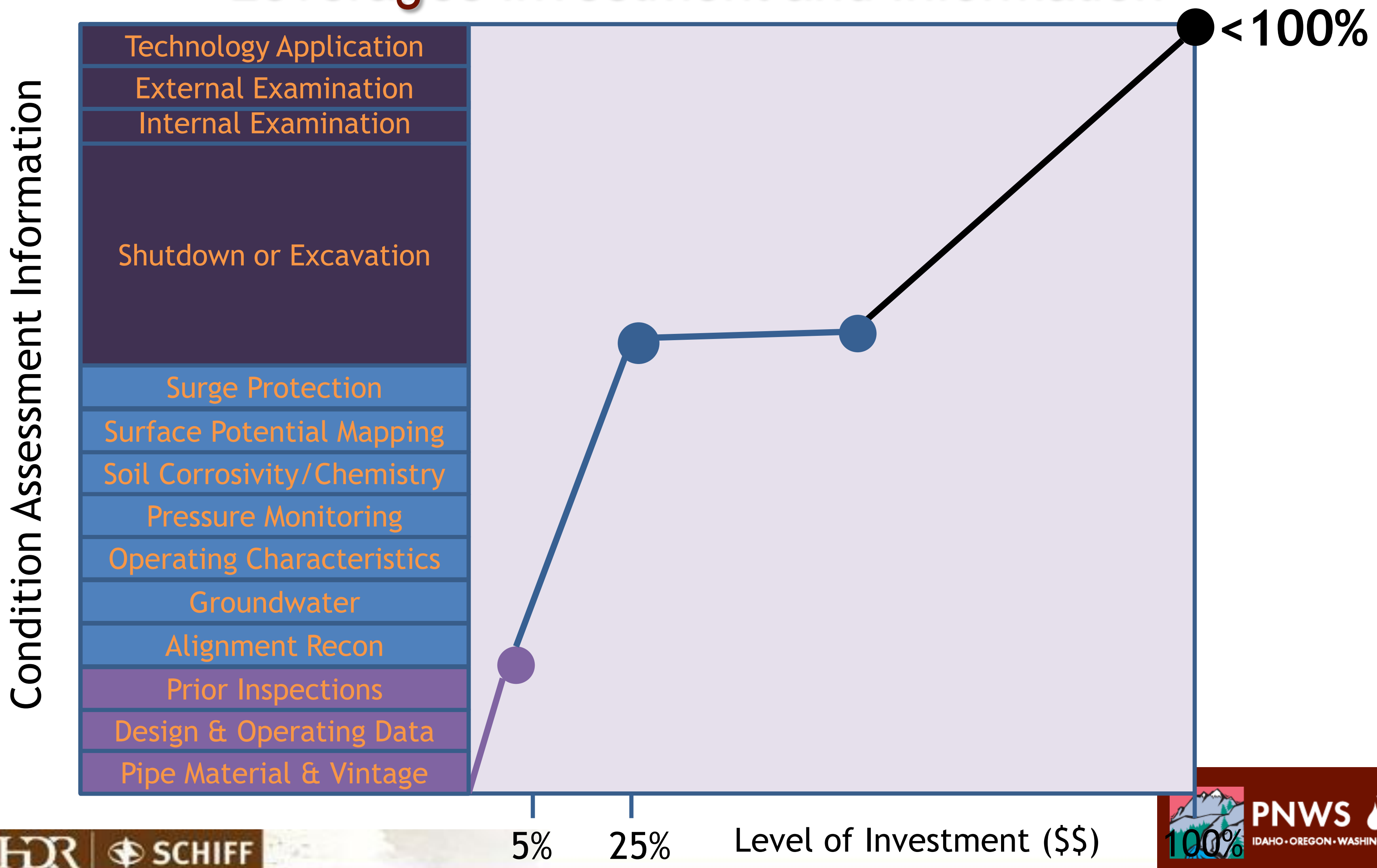
Technology is only one club in the Condition Assessment Golf Bag

- Imagine trying to play an entire round of golf with a 7-iron.
  - You can do it but you don't score well.
  - Generally, you need a driver and a putter.
- Technology provides data, not information.
- Understanding turns data into information.

Goal of Condition Assessment is to Turn Data into Actionable Information

Project Planning	Initial Assessment	Field Inspection	Engineering Analysis	Renewal Information
Inventory Data	Criticality Data	Technology Data	Life Extension Analysis	Rehabilitation

Phased Approach to Condition Assessment Leverages Investment and Information



In the Summer of 2009, Blow Out Pipe breaks in the City of LA Increased

Political pressures led to the formation of a "Blue Ribbon Committee" to Investigate

Table 1-1. List of experts who participated in analysis and their primary role.

Name and Affiliation	Primary Role
Jean-Pierre Bardet, Professor Chair, Sonny Astani Department of Civil and Environmental Engineering Director, Center on Megacities University of Southern California	• Assemble and lead the team of experts • Supervise the overall evaluation and peer review work • Assist on all aspects of the work described below. • Report to the Steering Committee
Tat Fu Postdoctoral Fellow Sonny Astani Department of Civil and Environmental Engineering, University of Southern California	• Perform statistical analysis and GIS analysis
Thomas D. O'Rourke Thomas R. Briggs Professor of Engineering School of Civil and Environmental Engineering Cornell University	• Perform engineering review and evaluation of the pipeline system • Provide engineering evaluation of the LADWP large, geographically distributed water supply systems and underground construction technologies.
Michael C. Palmer, PH.D., P.E. Instructor/Research Associate School of Civil and Environmental Engineering Cornell University	
E. John List, Ph.D., P.E. Principal Consultant Flow Science Incorporated	• Investigate the effect of transient pressures in water distribution system • Supervise deployment of sensors for measuring transients • Interpret sensor reading
R. Scott Foster, P.E. Vice President Flow Science Incorporated	
Graham E.C. Bell, Ph.D., P.E. Schiff Associates	• Examine the effects of external corrosion and metal fatigue • Provide additional data sets from other cities
Donald Ballantyne Senior Consultant MMI Engineering	• Provide and analyze data sets on water pipeline breaks from Seattle
Richard G. Little, Director Keston Institute for Public Finance and Infrastructure Policy, University of Southern California	• Analyze assets management
Andrea Donnellan QuakeSim Principal Investigator Jet Propulsion Laboratory (JPL)	• Conduct remote sensing pilot study

Leaks and Blowouts were clustered.

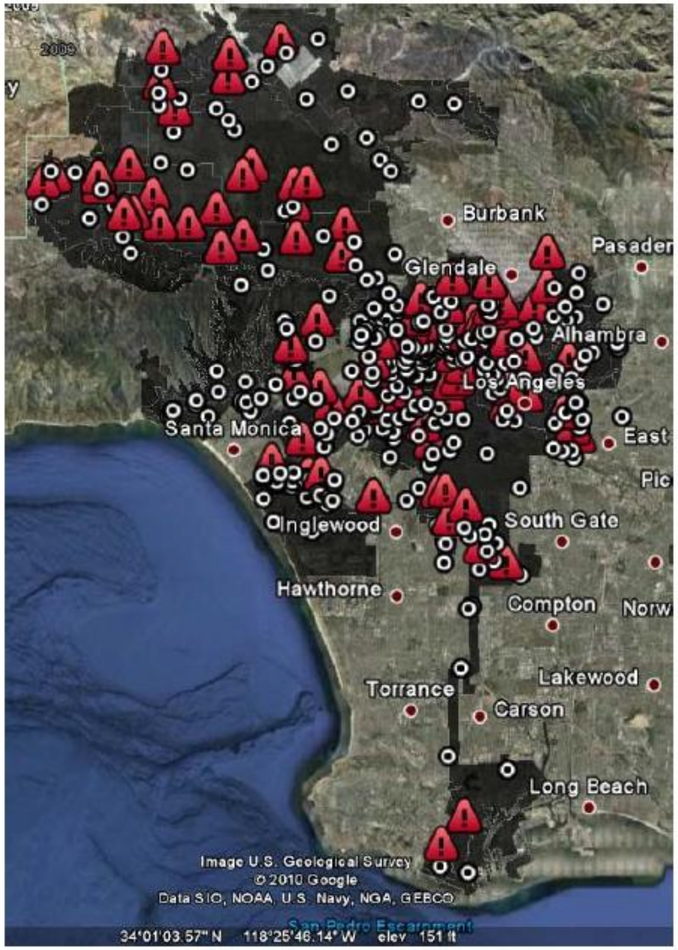


Figure 2-11. Location of LADWP water pipeline breaks (circles) and blowouts (triangles) in Summer 2009 (July, August and September).

Internal radial pressure surges and increases lead to longitudinal crack propagation

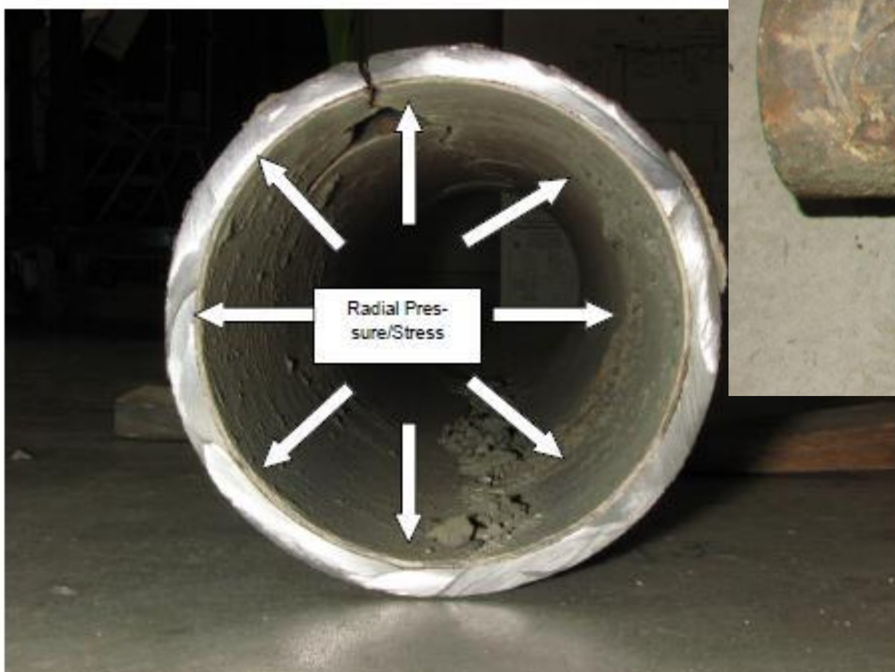
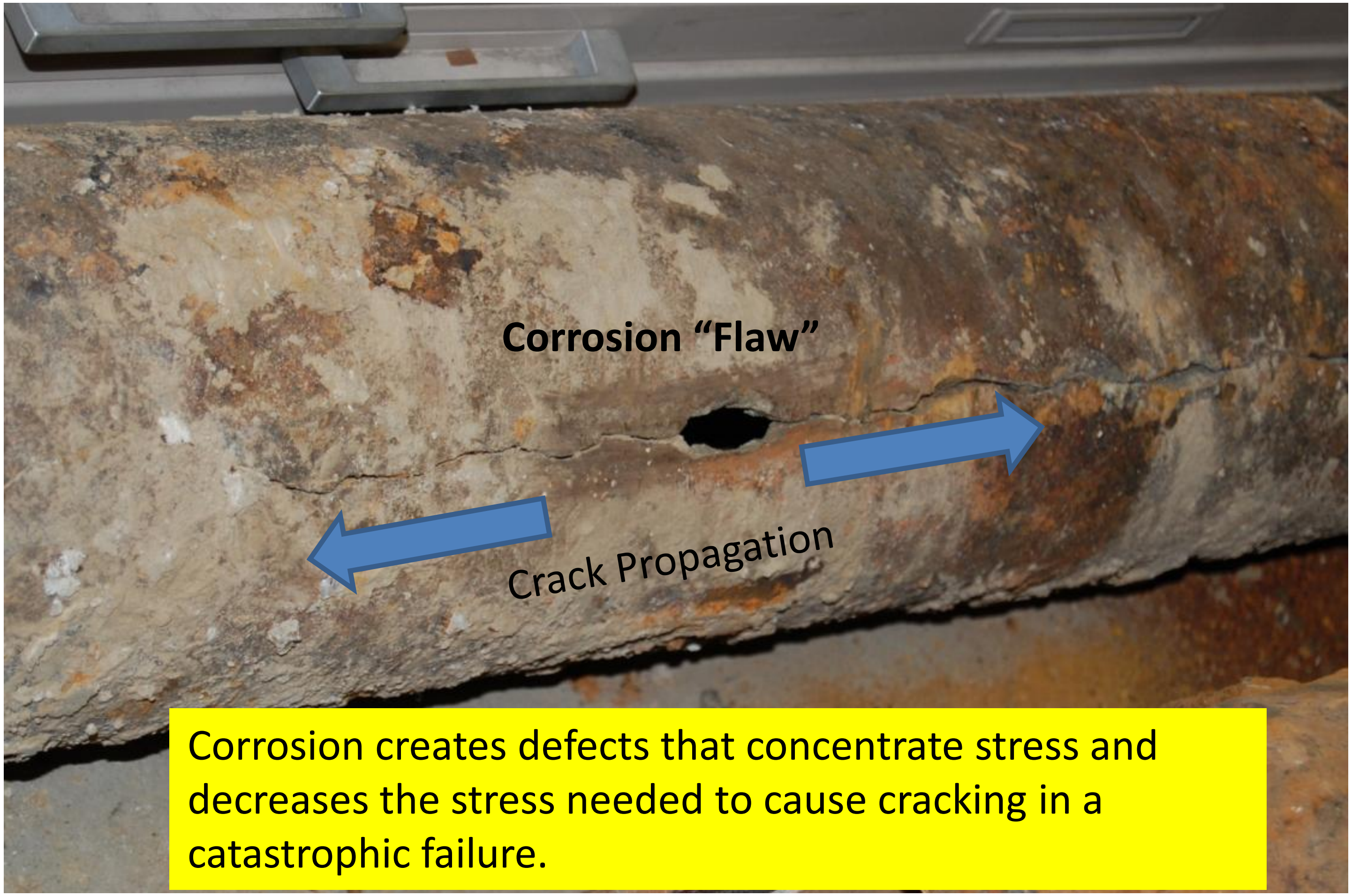


Figure 3-5. Axial View of cast ironlongitudinal break at Corbin Avenue and Kittridge Street

Cast Iron is more likely to catastrophically break due to crack propagation due to surge.



Similarly, beam loading leads to radial crack propagation.

Figure 3-3. "Circular Break" (Circumferential Crack Propagation) due to beam loading at 12212 Hartsook Street (Figure 2-2)

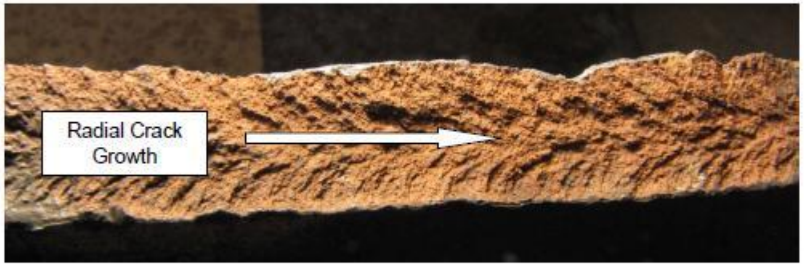
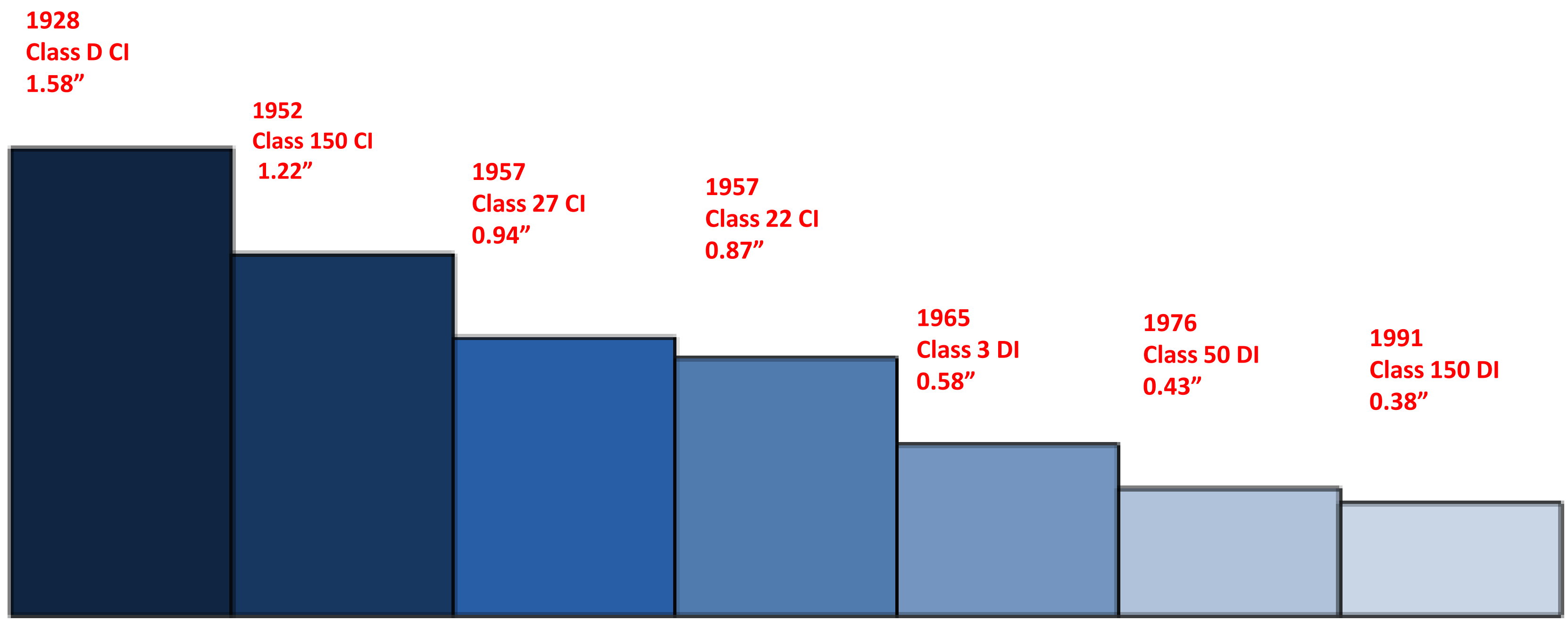


Figure 3-4. Failure morphology along edge of rapid circumferential crack propagation due to beam loading from circular blowout at 12212 Hartsook Street.

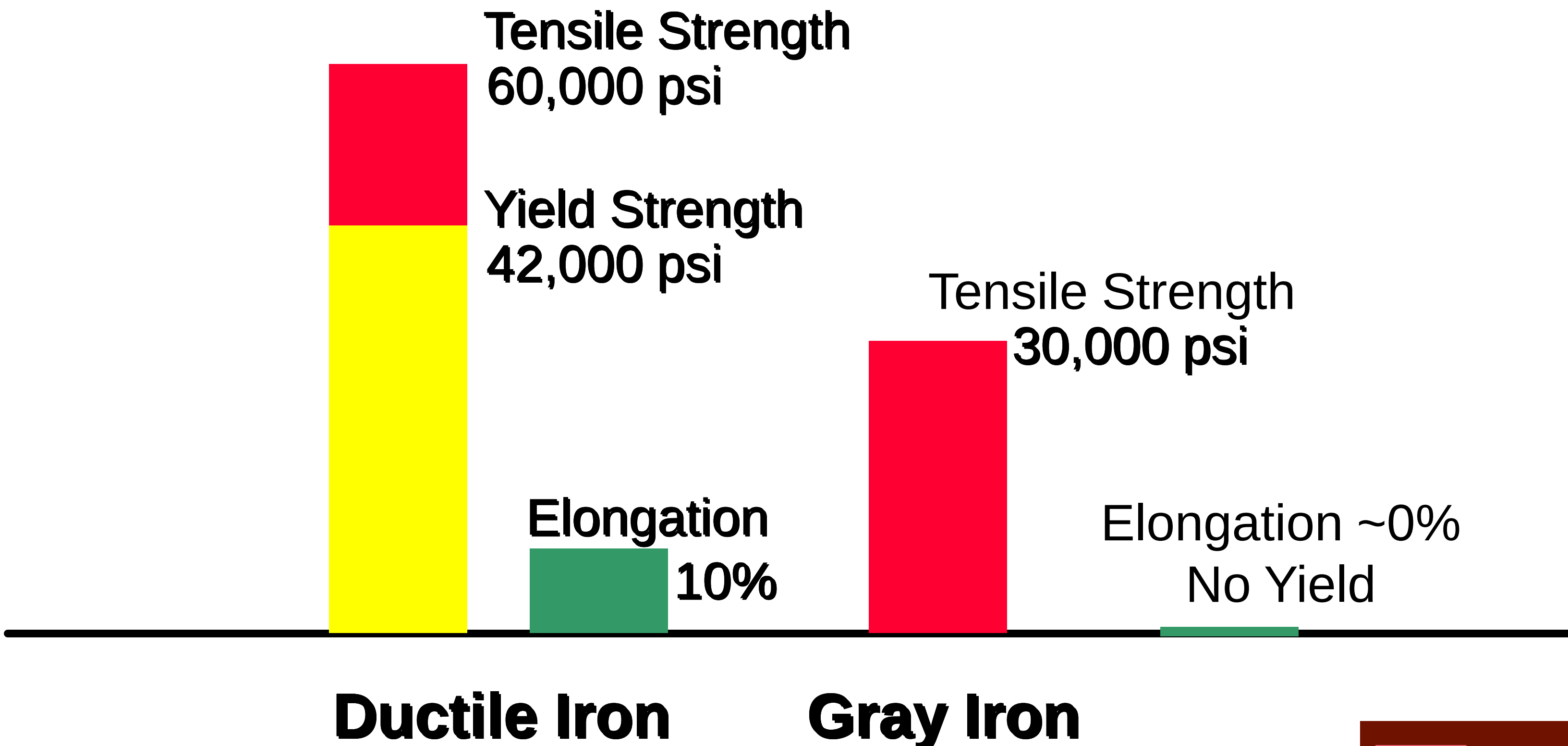
Iron pipe thickness have changed over time, so pipe age is not necessarily a good predictor of failure

EXAMPLE FOR MINIMUM WALL 36-INCH IRON PIPE



More material means more corrosion allowance.

Ductile v. Cast Iron Mechanical Properties



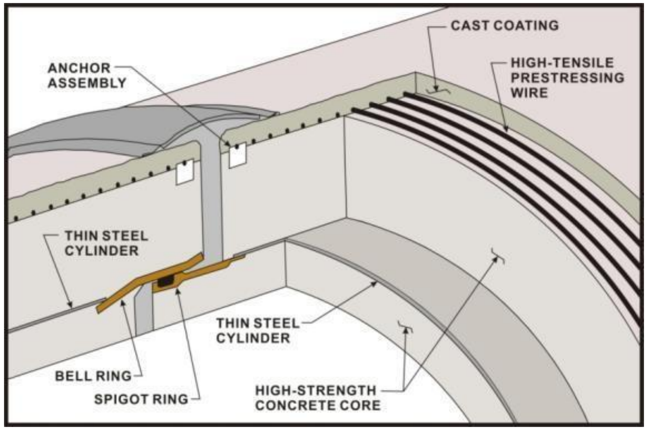
Long story short, the problem and solution was public policy

- In early 2009, LADWP institutes watering restrictions (every other day)
- 2009, cast iron blow outs increased dramatically.
- Root cause was that operational change due to water restrictions resulted in cyclic fatigue of aging brittle pipe material (cast iron) which leads to failures.
- 2010, even addresses water on even days, odd addresses water on odd days.
- Pipe breaks reduced back to previous levels.

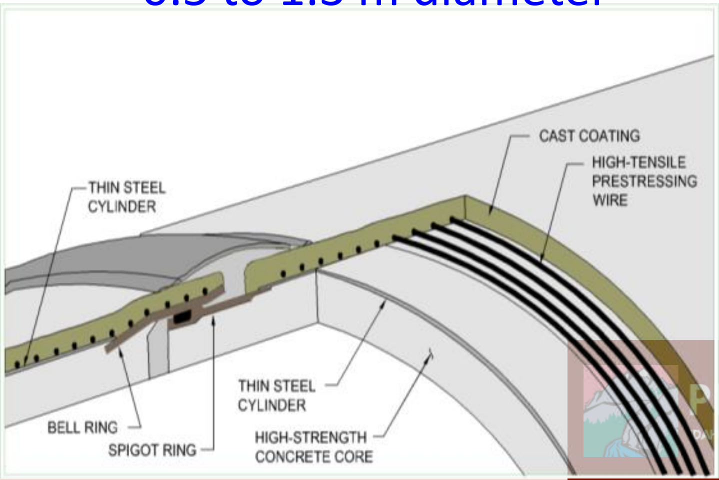
PCCP is a Complex Pipe Material.

- Composite pipe product
  - Internal mortar or concrete lining
  - Steel Cylinder
  - Concrete Core(s)
  - High Strength Prestressed Wires
  - Exterior Mortar Coating
- 1942 “War Pipe” substitute high strength steel and concrete for steel
- 18 to 250-inch diameter
- Up to 350 psi pressures

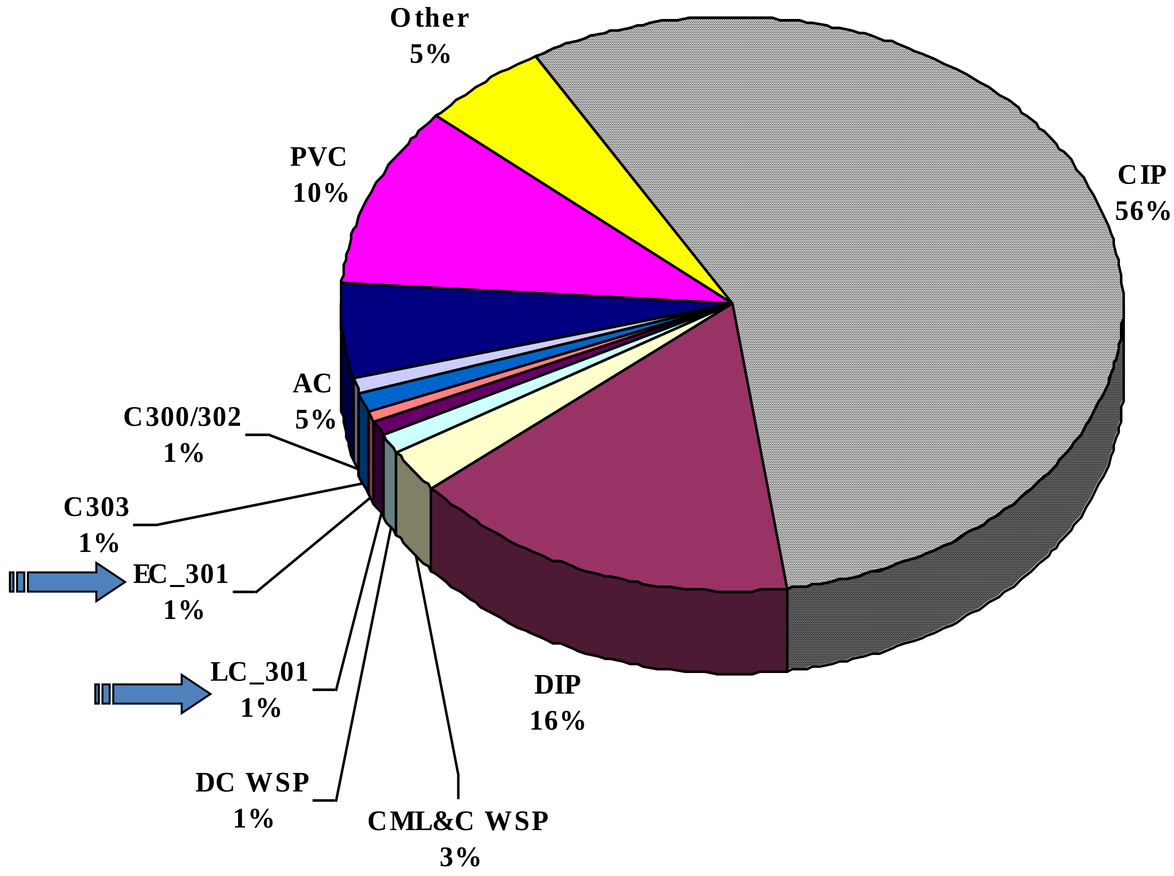
Early EC-PCCP Section
1.5 m to 6.5 m diameter



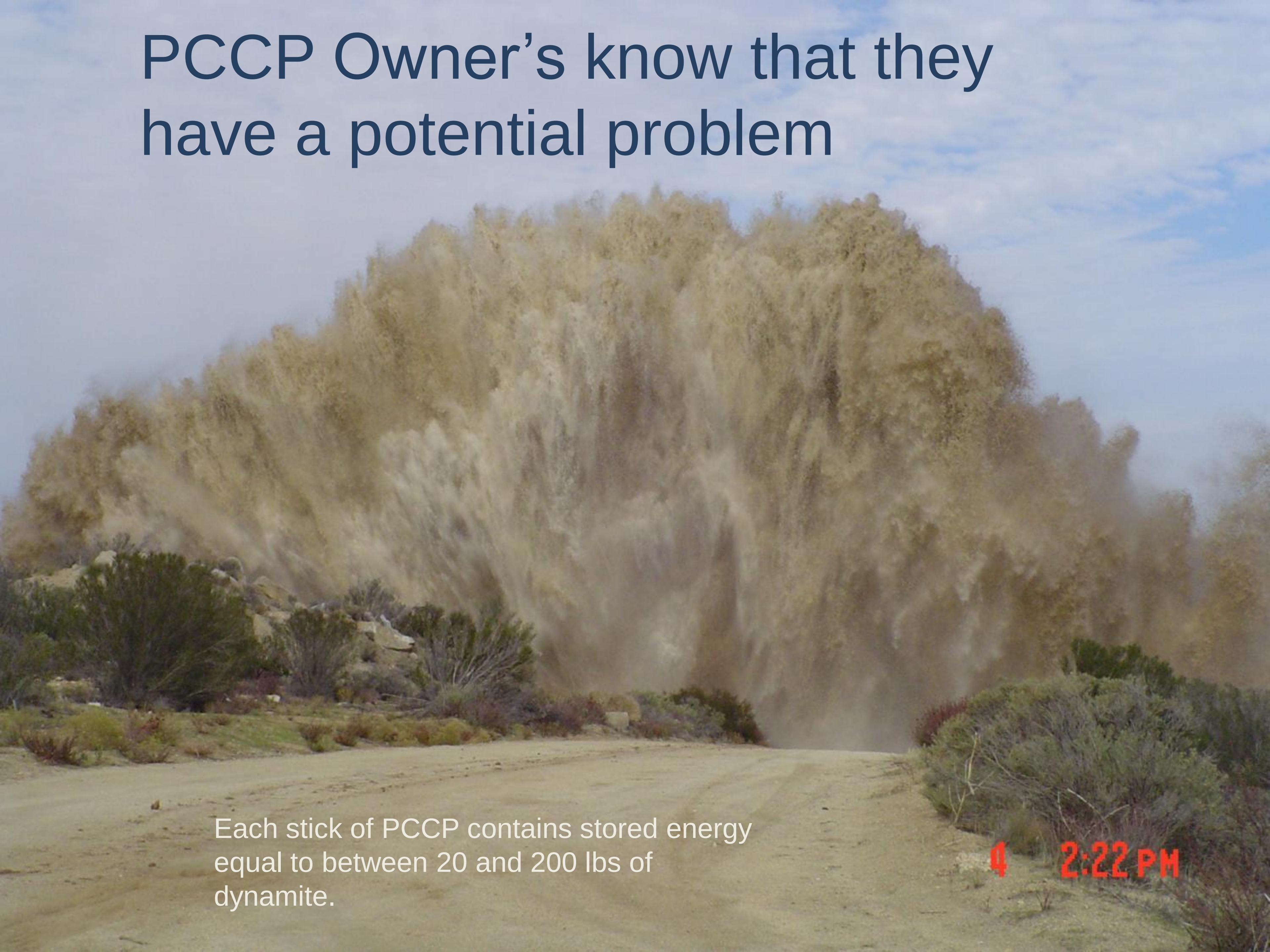
Early LC-PCCP Section
0.5 to 1.3 m diameter



PCCP is a Small Part of Pipeline Material Distribution



PCCP Owner's know that they have a potential problem

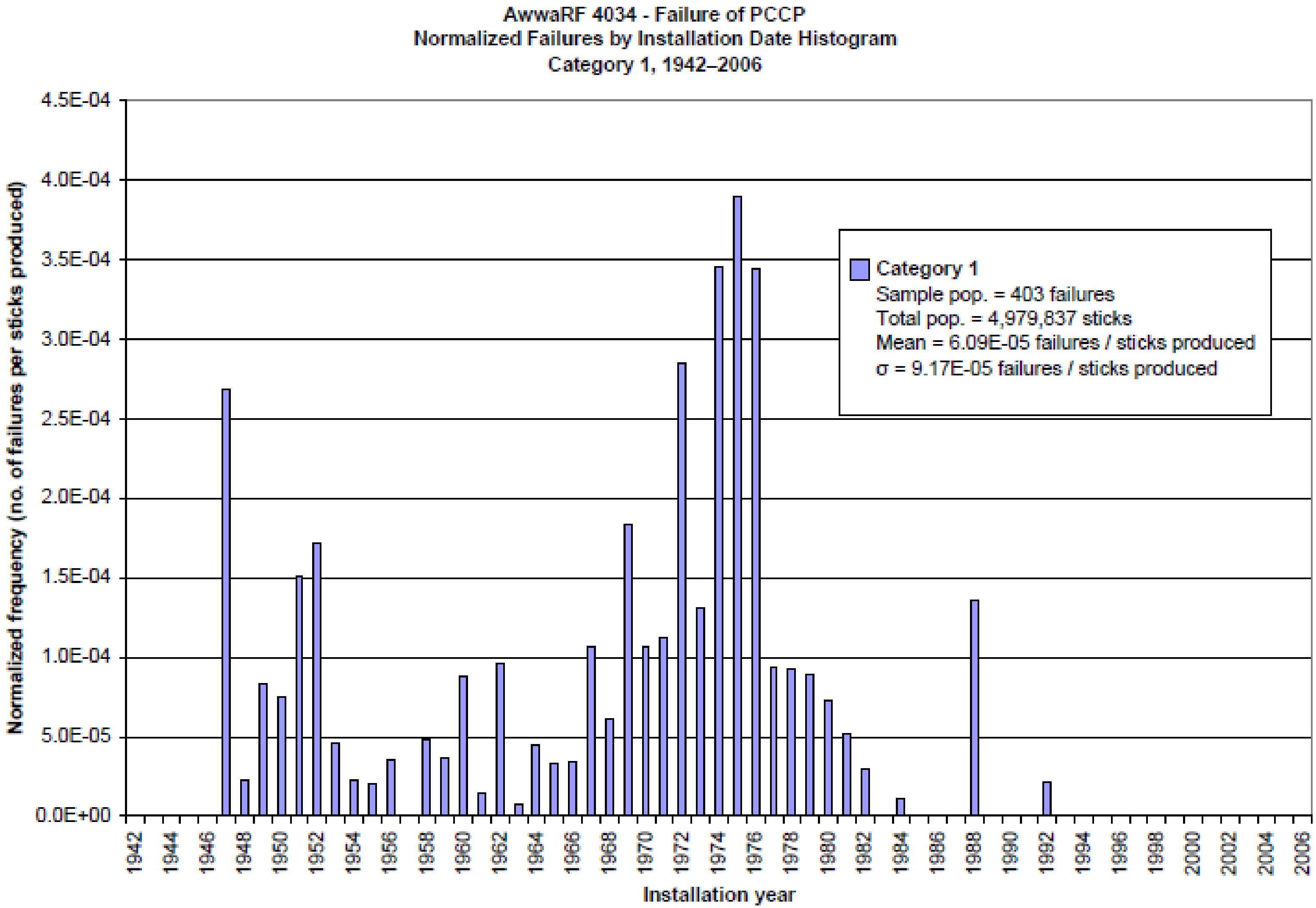


Each stick of PCCP contains stored energy equal to between 20 and 200 lbs of dynamite.

PCCP Standards Changed Overtime

- 7B.2-T (1949)
- AWWA
  - C301-52 First Ed.
  - C301-55 (tentative)
  - C301-58 (Second. Ed.)
  - C301-64
  - C301-72
  - C301-79
  - C301-84
  - C301-92 & C304-92
  - C301-99 & C304-92
  - C301-07 & C304-07

For PCCP, Based on its Era of Design Initial Estimate of Risk Can Be Made



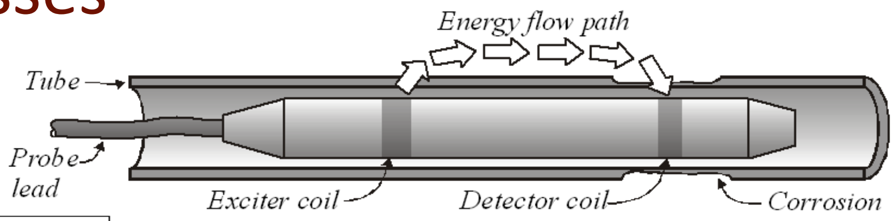
Direct Condition Assessment of Pipelines Using Different Technologies

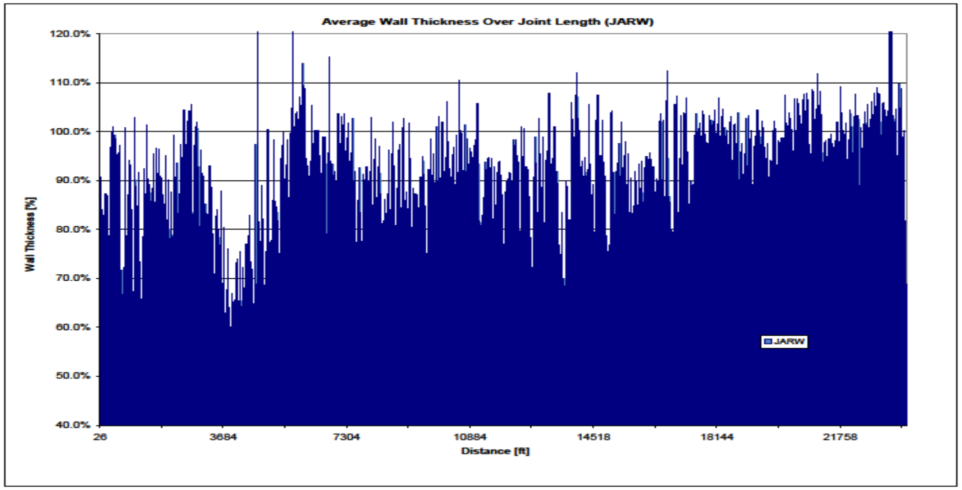
Controlled Destructive Exam

In-Pipe Non-Destructive Exam

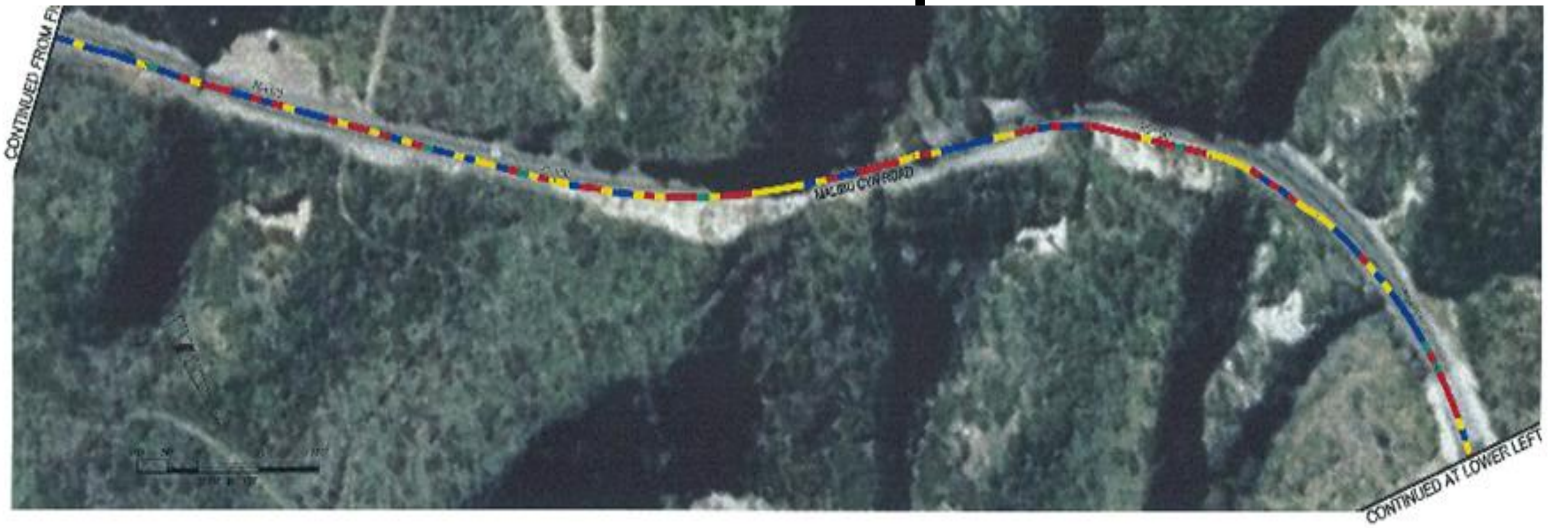
Remote Field Electromagnetic Technology Non-Destructive Direct Method.

- Provides an end-to-end, 360º evaluation
  - Pit size, depth, and location
  - General corrosion losses



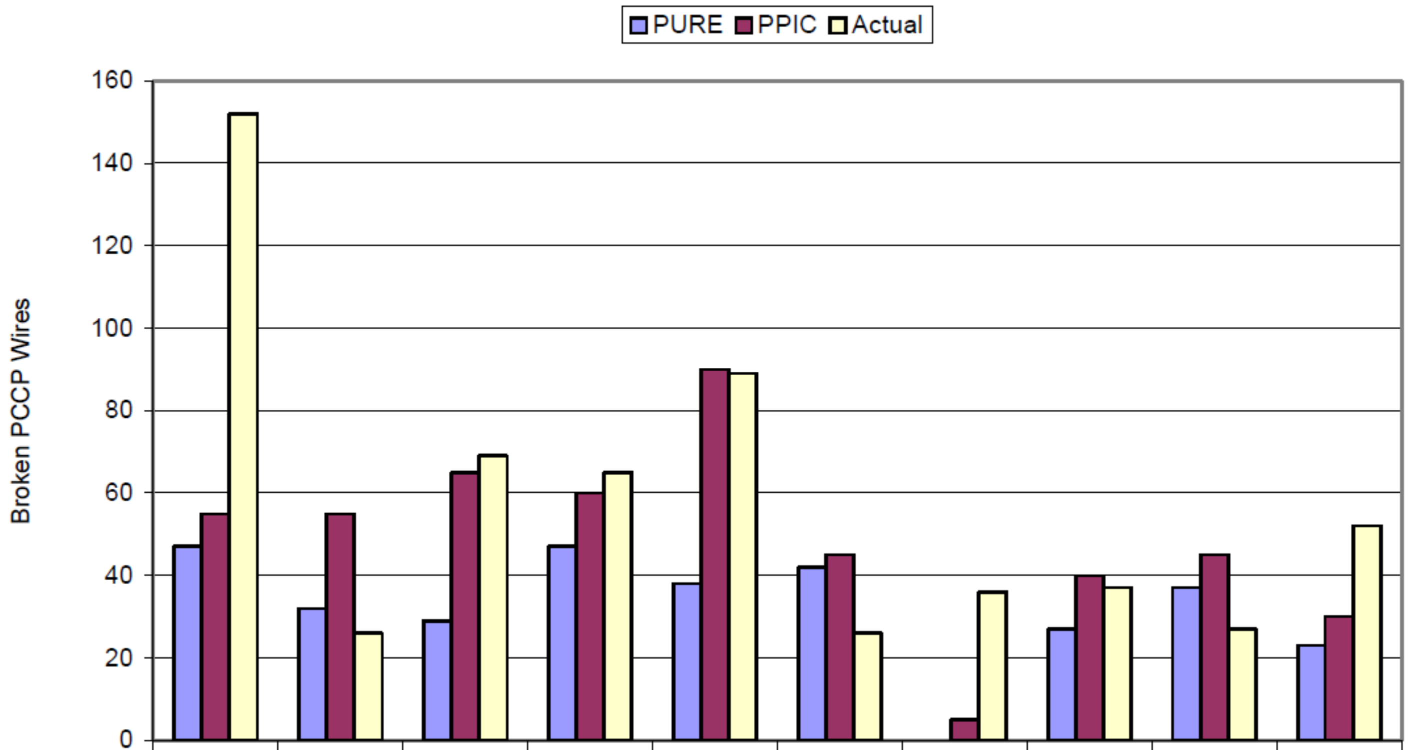


Not All Pipe is Bad!



Not all damage will be found by technology

False Positive and Negatives are Possible with All Techniques



	MK 1430	MK 913	MK 914	MK 729	MK 725	MK 720	MK 719	MK 718	MK 715	MK 714
PURE	47	32	29	47	38	42	0	27	37	23
PPIC	55	55	65	60	90	45	5	40	45	30
Actual	152	26	69	65	89	26	36	37	27	52

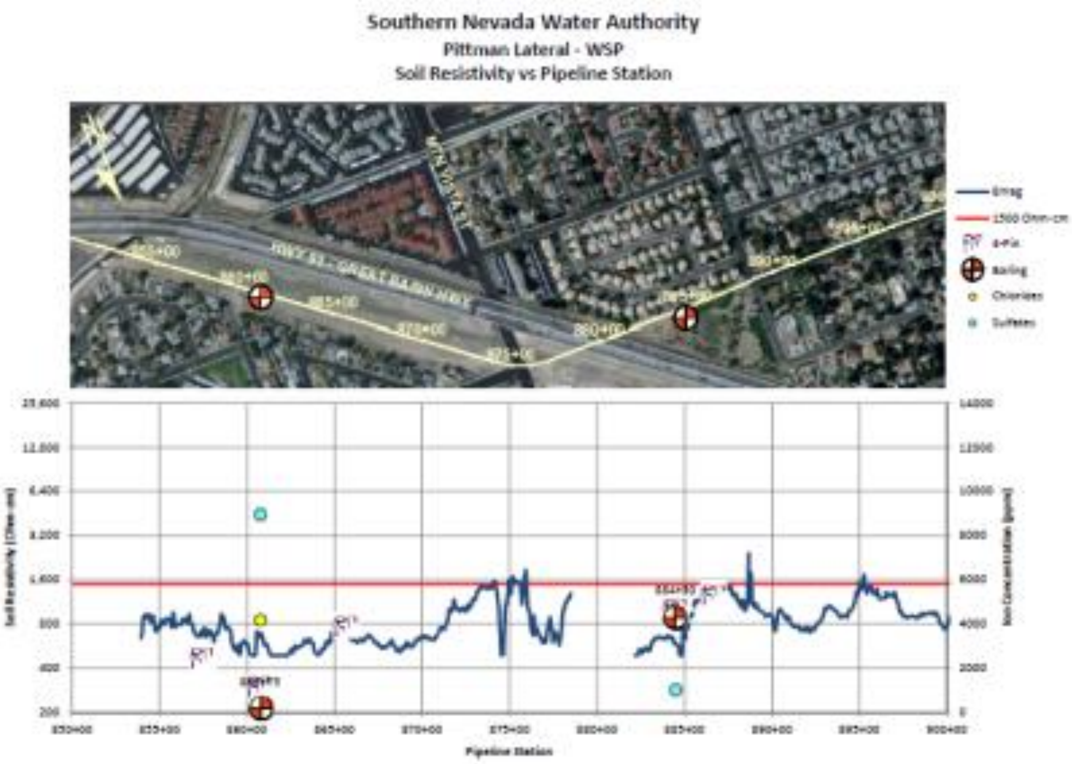
Pipe Number

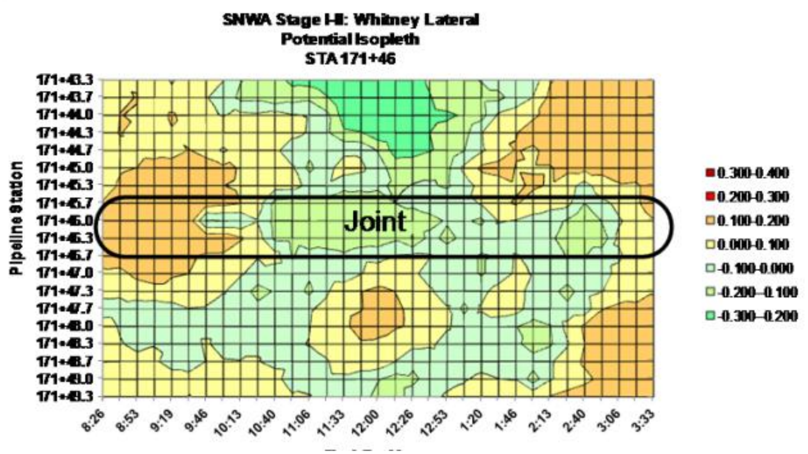
Multiple Techniques Improves Condition Assessment

Over-the-Line Corrosion Survey

External Corrosion Direct Assessment

Multiple Techniques Complement Each Other



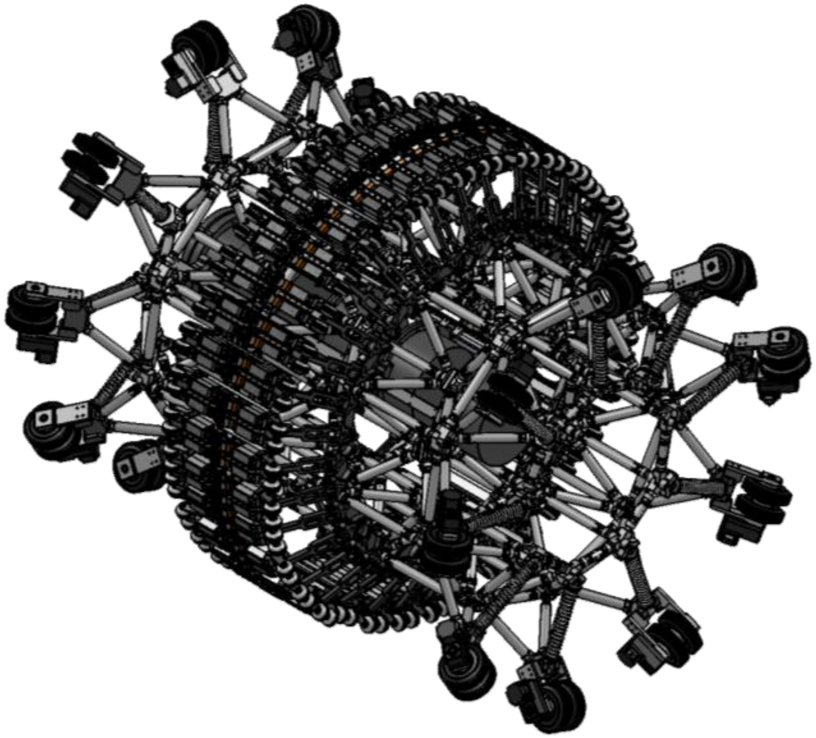


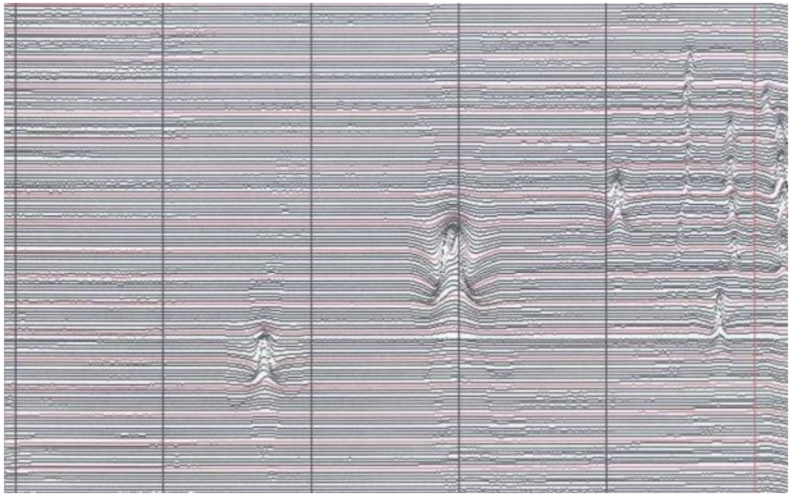
RFT Equipment for wet, live deployment

Large diameter tools suitable for steel water pipe have been developed.

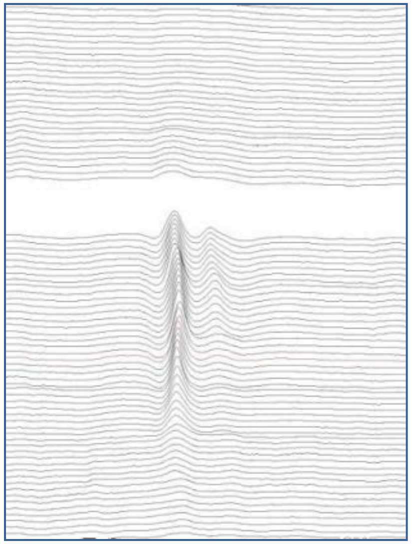
Pure MFL TOOL

Pipeline Inspection



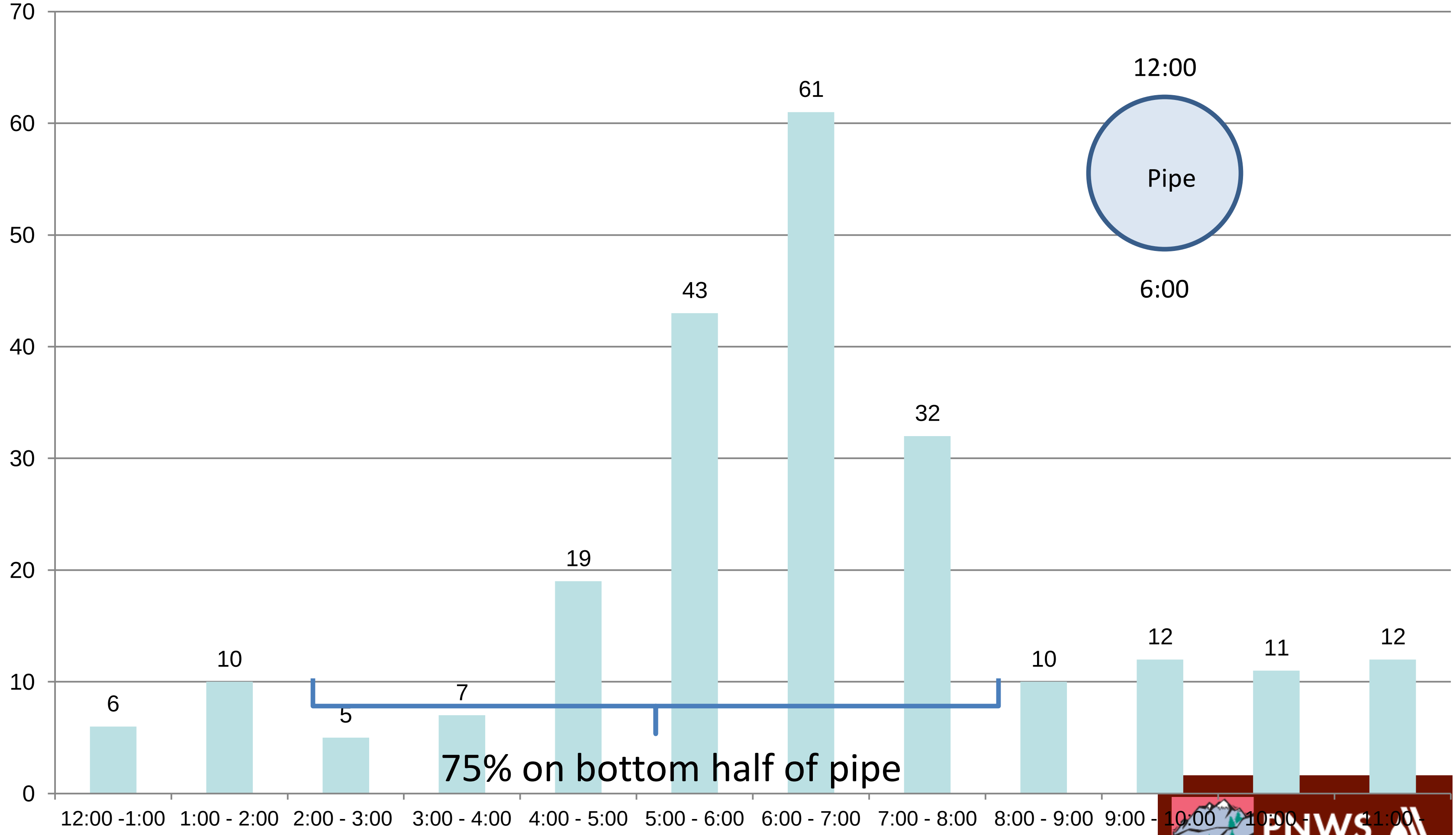


MFL Finds Hidden Metal Loss



Pit depth 70 percent through pipe wall. No other method indicated damage or corrosion

Location of corrosion damage was consistent with experience and intuition.



Technology cannot replace the human element.

- Technology can only narrow down where to "look" and "feel" by Direct Assessment (DA).
- If it looks bad, it probably is bad.
- If it feels thin, it probably is thin.
- Don't let technology replace millions of years of instincts.

Closing Shots and Thoughts

- There are four ways to control corrosion
  - Material Selection and Design
  - Corrosion Inhibitors and Monitoring
  - Coatings and Linings
  - Cathodic Protection
- Technology is a powerful and expensive tool that needs to be used wisely
- There is no substitute for laying eyes and hands on the structure.

Water vs. Wastewater: External Corrosion

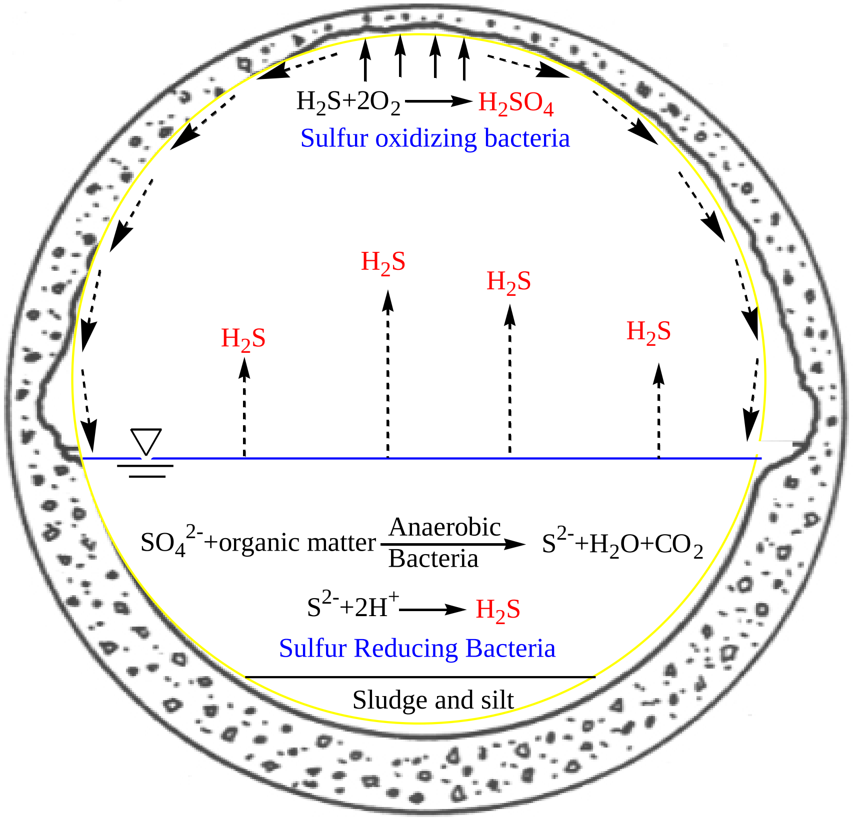
- Mechanisms are identical
- Corrosion Control for Exterior is Identical
- Materials, Design and Construction Practices
  - Similar.....
  - But Wastewater construction does not typically account for the eventual need for cathodic protection
    - Electrical Continuity of Pipelines and Structures
    - Electrical Isolation for Appurtenances

Water vs. Wastewater:
Internal Corrosion

- Not the Same At All.
- Corrosion Rates for wastewater can be extremely high.
- More often internal corrosion leads to problems
- This is one reason why external corrosion is ignored.

Internal Corrosion of Wastewater Systems

- Dominated by Formation of Sulfuric Acid



DIP for Force Main
Gas Pocket Corrosion

Internal Corrosion for Wastewater is Approached by 3 of 4 Corrosion Control Methods

- Material Selection/**Design Details**
  - Elimination of Gas Pockets
- Corrosion Inhibitors
  - Various Chemicals
- Linings
  - Polyethylene
  - Ceramic Epoxy

Mechanical capacity of cast iron changes over time due to growth of flaws

3. Material Analysis and Results

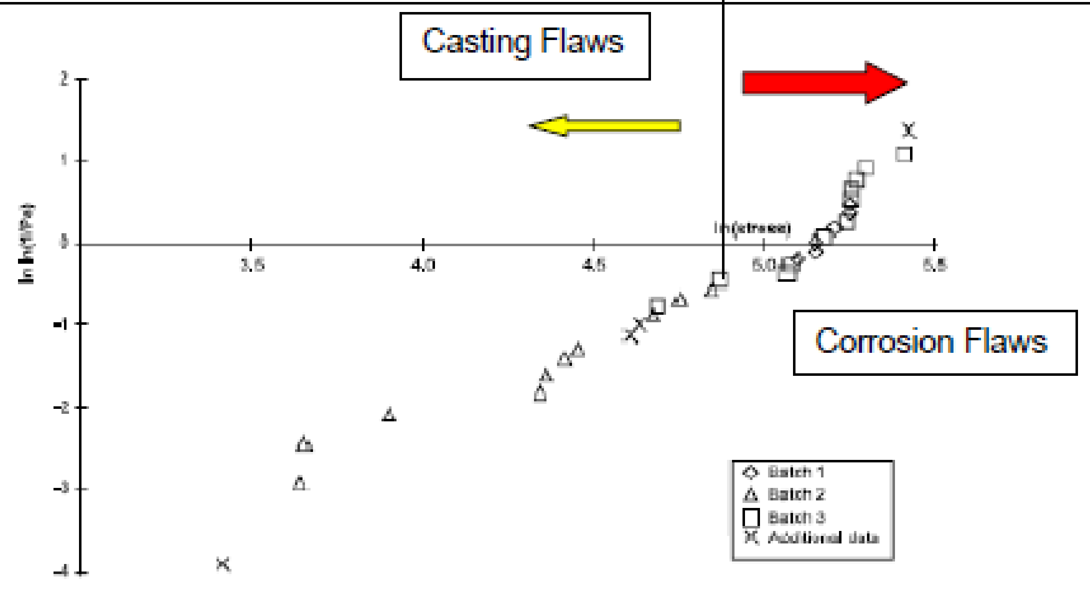


Fig. 6. Combined Weibull plot for fractured pipe samples.

Figure 3-10. Bimodal distribution of failure of historical service CI Pipe (Atkinson, et al. 2002)

Unless corrosion is controlled, flaw size will eventually lead to crack growth at normal operating conditions