Characterization and Fitness-for-Service of Corroded Cast Iron Pipe

DOT Contract DTPH56-15-T-00006
Final Project WebEx

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Executive Summary

- This WebEx summarizes the 200-page project final report which provides a Cast Iron (CI) Fitness-For-Service (FFS) model, calculator, and method for operators to characterize and grade graphitic corrosion defects on cast iron natural gas pipe.
- These deliverables will help operators make monitoring and repair decisions, as well as prioritize their replacement program; leading to improved safety and supply stability.

Project Final Report

- The final report page numbers are referenced on each slide of this presentation to provide the reader the location of more detailed information.
- All the reference/citations for the WebEx material, tables, and plots can be found in the final report.
- The final report is located on the DOT/PHMSA Research Page: https://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=641

Acknowledgements

- GTI thanks the project sponsor, the Pipeline and Hazardous Materials and Safety Administration, for its financial and program support.
- We also thank the industry members of the project Technical Advisory Panel for their outstanding technical guidance during this effort.
- DOT Project Manager: Chris McLaren.
- GTI Project Team: Daniel Ersoy, Oren Lever, Khalid Farrag, Brian Miller, and Kristine Wiley.

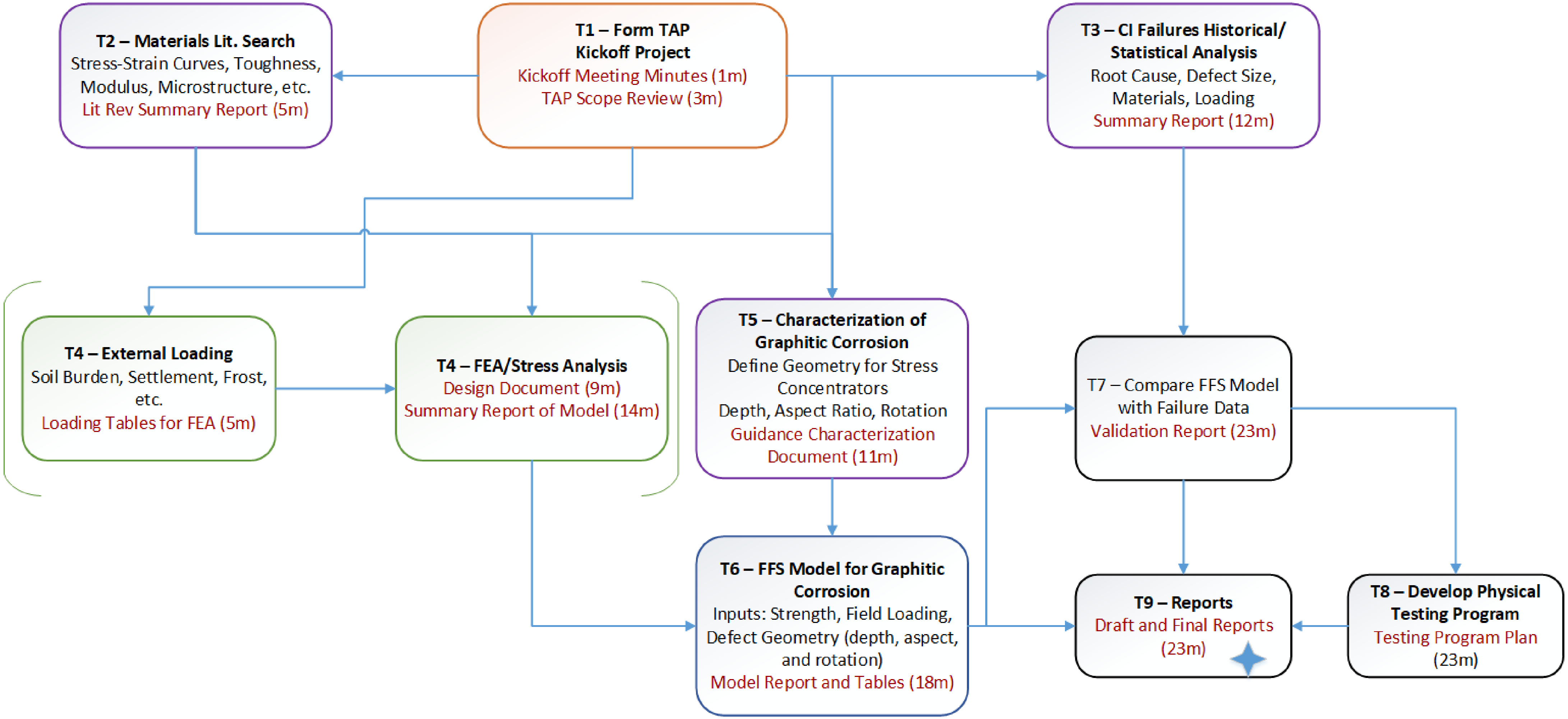
Introduction

- Cast iron piping was installed over a period spanning more than 100 years, leading to a great variability in the material properties. Different manufacturing processes, chemistries, and designs have led to a wide range of material characteristics and performance levels.
- When operators assess their cast iron piping systems and find corrosion, especially graphitic corrosion, they are often left without sound engineering guidance if the corrosion, and resulting wall loss, are an integrity threat or allowable within the design and operational restrictions of the installation.

Approach

- Operators need FFS guidance for cast iron piping that can be consulted when graphitic corrosion defects and wall loss are identified in cast iron piping systems.
- FFS guidance in the form of a remaining factor of safety for cast iron assets provides a go/no-go decision for immediate threat mitigation.
- It will also provide validated engineering guidance to identify and prioritize highest risk piping for replacement programs.

Project Structure

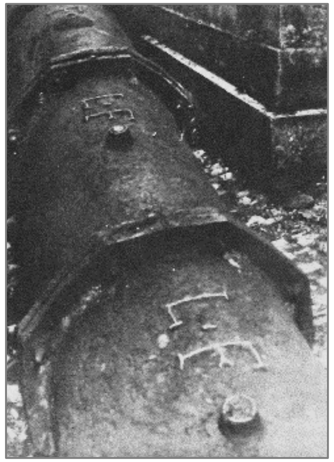


Literature Search

- As part of this project a detailed literature search on cast iron materials was conducted.
- The report summarizes the history, use, composition, microstructure, mechanical properties, metallurgy, and corrosion characteristics of gray cast iron in general and cast iron used for natural gas distribution systems.
- The review included a detailed explanation of graphitic corrosion of gray cast irons and the effect of graphitic corrosion on residual pipe strength.
- A set of field testing and sampling considerations was developed; including a table of standards and methods to obtain mechanical, physical, and chemical properties from in-service pipelines.

Cast Iron History and Graphitic Corrosion
Literature Search

History (p. 7)

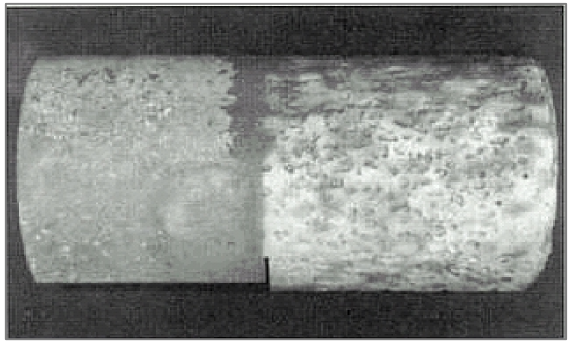


Natural Gas Use (p. 8)

Congested Areas (p. 9)

Field Graphitic Corrosion (pp. 10-11)

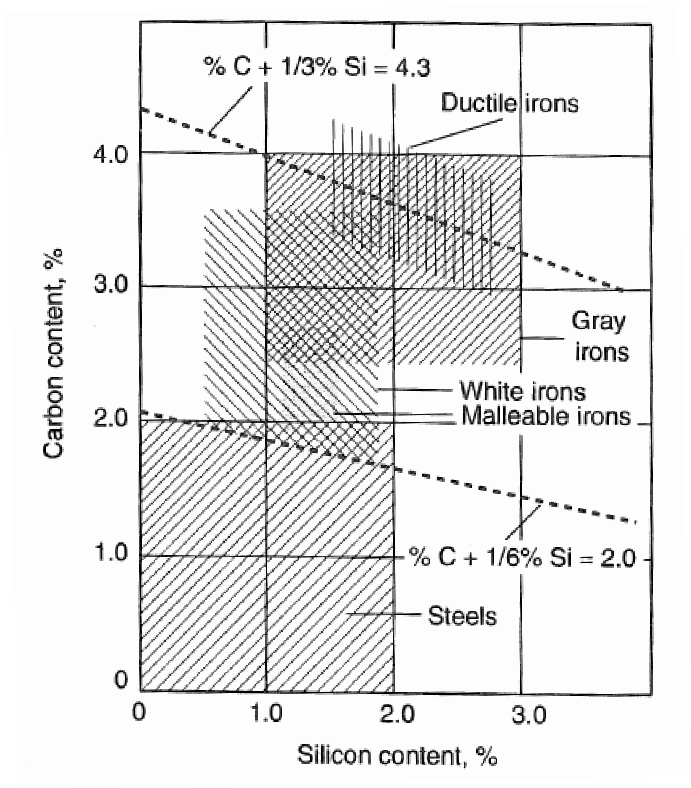
Pre- and Post-Grit Blasting (p. 10)



Cast Iron General Groupings

Literature Search

Carbon & Si for Steel and CI Materials (p. 12)



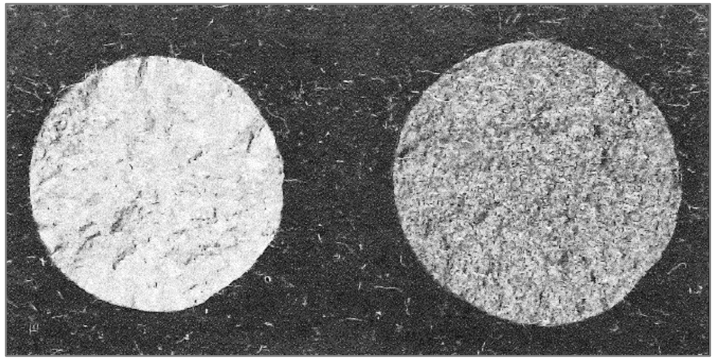
CI Groupings (p. 13)

Main Cast Iron Groupings

The main groups of cast irons are:

1. **Gray cast iron**
2. White cast iron
3. Malleable iron
4. Ductile (nodular) iron
5. Alloy cast iron

Gray vs. White Fracture (p. 13)



Grouping and Categorizations (pp. 25-26)

- By tensile strength "Class" in ksi (ASTM A48)
- By dominant section thickness
- By broad alloy classes

Related Properties with Class (pp. 14-15)

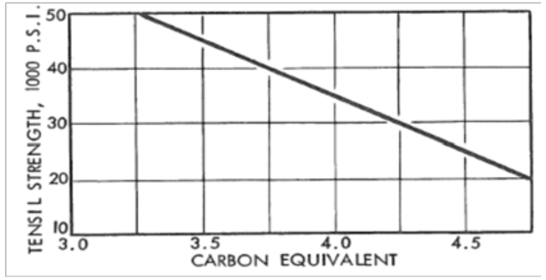
- As class goes up these go up: strength, fine finish ability, modulus, wear resistance
- As class goes up these go down: Machinability, thermal shock resistance, damping, ability to cast thin sections

Metallurgy – Composition of Gray Iron
Literature Search

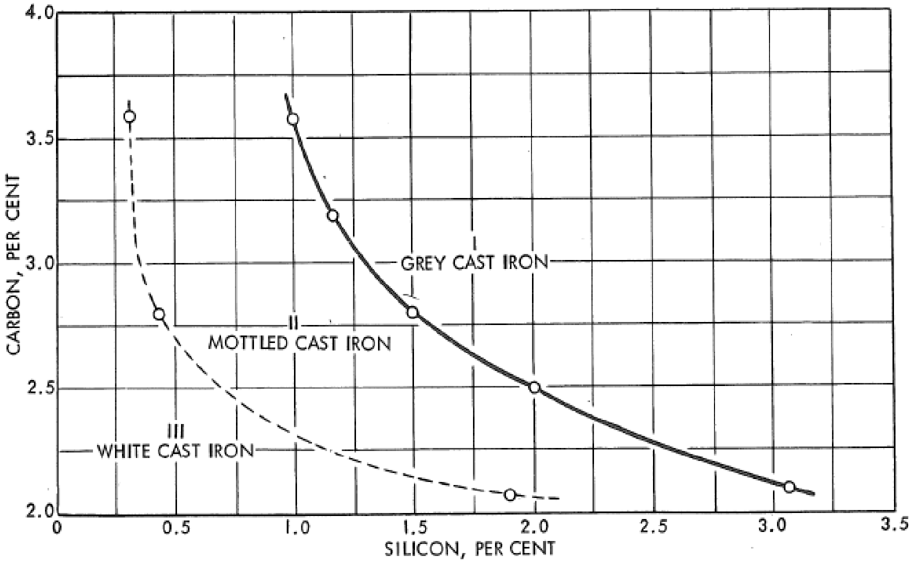
Carbon Equivalent, C.E. (p. 20)

C.E. = T.C. + (Si + P)/3
T.C. = Total Carbon

C.E. vs. Tensile Strength (p. 20)



Composition Limits for CIs (p. 21)



Composition for Commercial Gray Iron (p. 29)

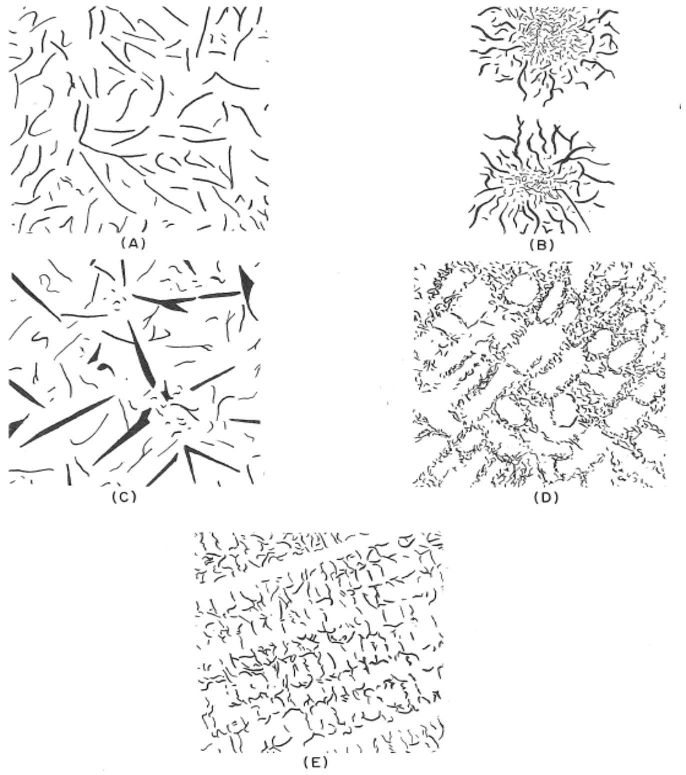
Type of iron	Total carbon, %	Silicon, %
Class 20	3.40-3.60	2.30-2.50
Class 30	3.10-3.30	2.10-2.30
Class 40	2.95-3.15	1.70-2.00
Class 50	2.70-3.00	1.70-2.00
Class 60	2.50-2.85	1.90-2.10

ASTM A48 class	Carbon equivalent	Composition, %				
		C	Si	Mn	P	S
20B	4.5	3.1-3.4	2.5-2.8	0.5-0.7	0.9	0.15
55B	3.6	≤3.1	1.4-1.6	0.6-0.75	0.1	0.12

Gray Cast Iron Microstructure

Literature Search

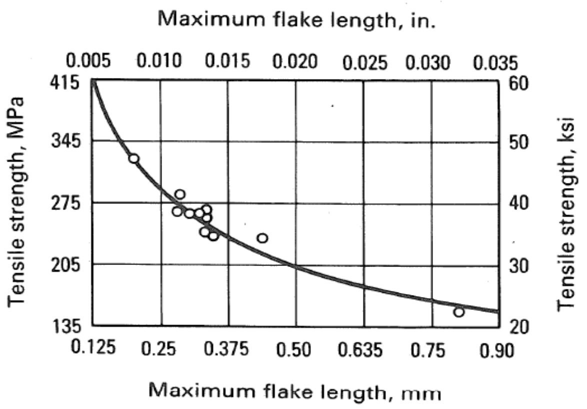
ASTM Graphite Flake Types (p. 16)



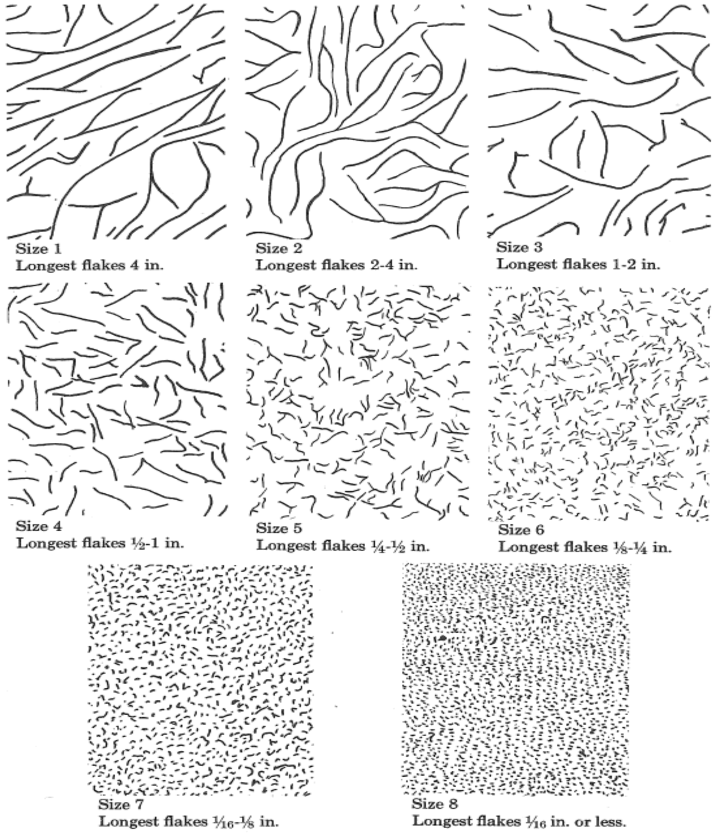
Steps to Examine (p. 15)

- Sanding
- Polishing
- Microscopy for flake types
- Etched
- Microscopy for structure

Flake Length v. Strength (p. 31)



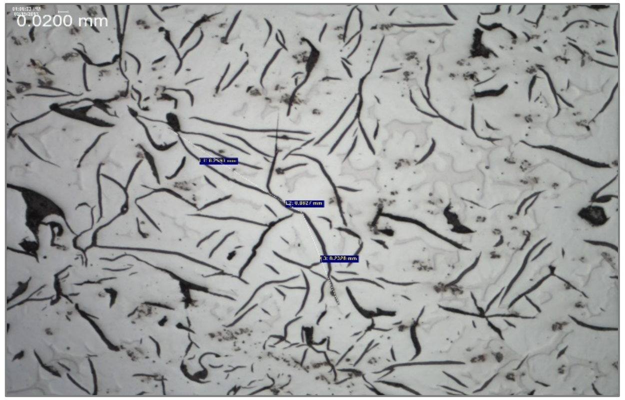
ASTM Flake Size (p. 17)



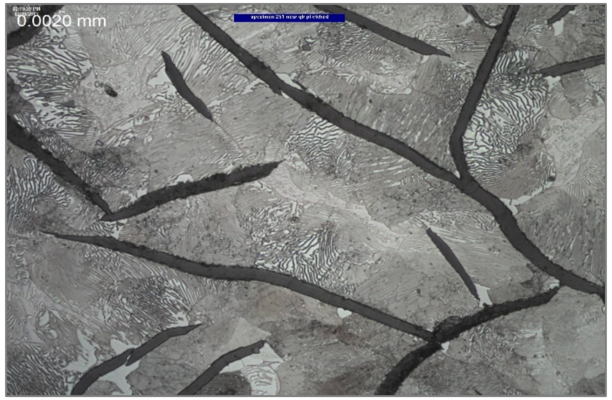
Gray Cast Iron Microstructure

Literature Search

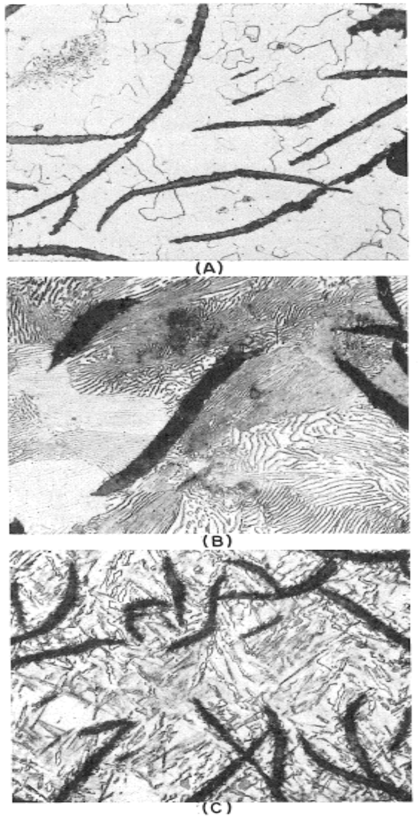
Unetched Gray (p. 18)



Etched Gray (p. 18)



Gray CI Matrix with Ferrite, Pearlite, and Acicular Ferrite (p. 15)



Common Gray Phase Mechanicals (p. 34)

Phase	Tensile strength, MPa (ksi)	Elongation, %	Hardness, HB
Ferrite	272-290 (39.5-42)	61	75
Pearlite	862 (125)	10	200
Cementite	...	...	550

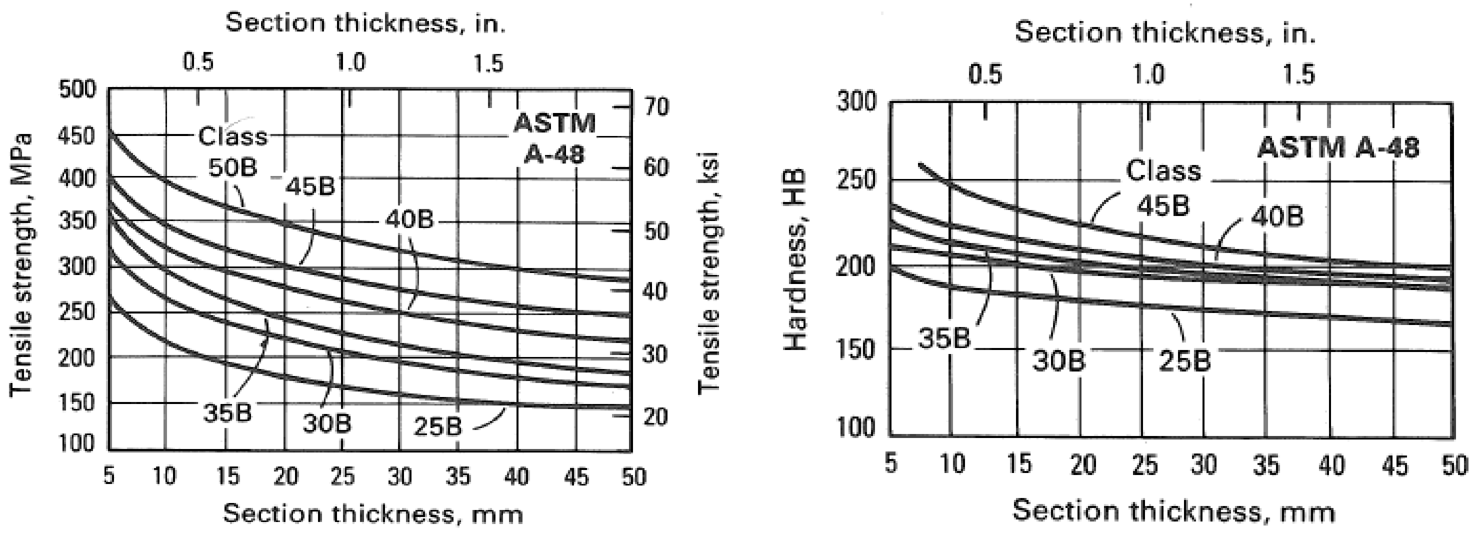
Hardness Ranges for Structure Combinations (p. 35)

Microstructure	Hardness, HB
Ferrite + graphite	110-140
Pearlite + graphite	200-260
Pearlite + graphite + massive carbides	300-450
Bainite + graphite	260-350
Tempered martensite + graphite	350-550
Austenite + graphite	140-160

Metallurgy – Thickness and Cooling Rates of Gray Iron

Literature Search

Wall Thickness Effect on Tensile and Hardness (p. 24)



Effect of Cooling Rate on Microstructure and Properties (p. 22)

COOLING RATE	MICROSTRUCTURE *	REMARKS	BHN
FAST	P + C (WHITE IRON)	EXTREMELY HARD AND BRITTLE	325-500
MODERATELY FAST	P + C + G (MOTTLED IRON)	GREATEST STRENGTH, HARD TO MACHINE	250
MODERATE	P + G	BEST HIGH TEST IRONS; CLOSE GRAINED	200
MODERATELY SLOW	P + G + F	FAIR STRENGTH, EASY MACHINING, FAIR FINISH	150
SLOW	F + G	LOW STRENGTH, OPEN GRAINED MACHINES SOFT	100

* P = PEARLITE C = CEMENITE G = GRAPHITE F = FERRITE

Mechanical Properties Gray Cast Iron

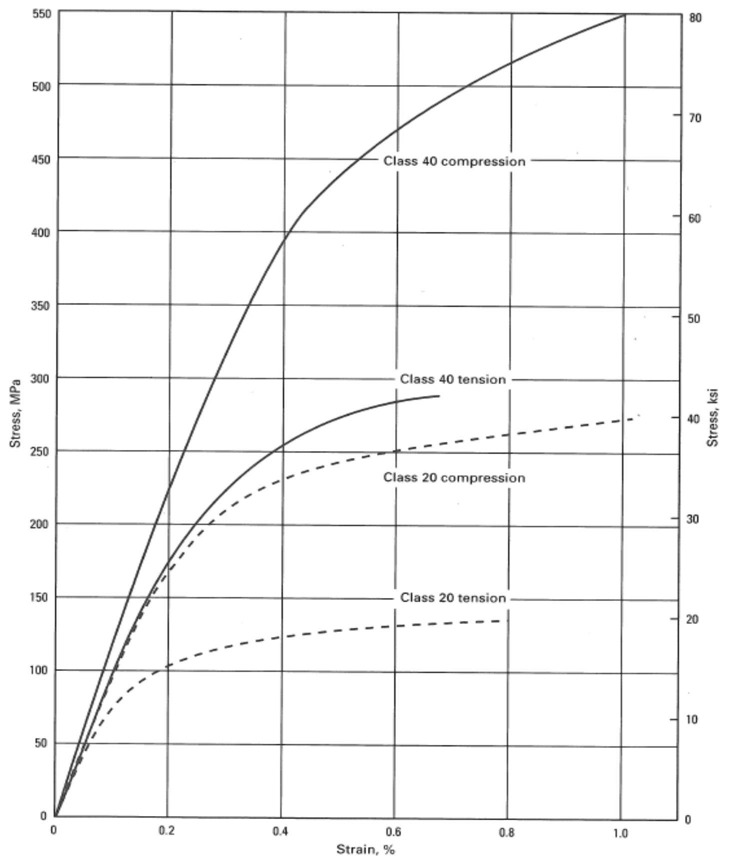
Literature Search

Typical Mechanical Properties As-Cast Gray Iron Test Bars (p. 38)

ASTM A48 class	Tensile strength MPa	Tensile strength ksi	Torsional shear strength MPa	Torsional shear strength ksi	Compressive strength MPa	Compressive strength ksi
20	152	22	179	26	572	83
25	179	26	220	32	669	97
30	214	31	276	40	752	109
35	252	36.5	334	48.5	855	124
40	293	42.5	393	57	965	140
50	362	52.5	503	73	1130	164
60	431	62.5	610	88.5	1293	187.5

ASTM A48 class	Reversed bending fatigue limit MPa	Reversed bending fatigue limit ksi	Transverse load on test bar B kN	Transverse load on test bar B lbf	Hardness, HB
20	69	10	8.23	1850	156
25	79	11.5	9.67	2175	174
30	97	14	11.23	2525	210
35	110	16	12.68	2850	212
40	128	18.5	14.12	3175	235
50	148	21.5	16.01	3600	262
60	169	24.5	16.46	3700	302

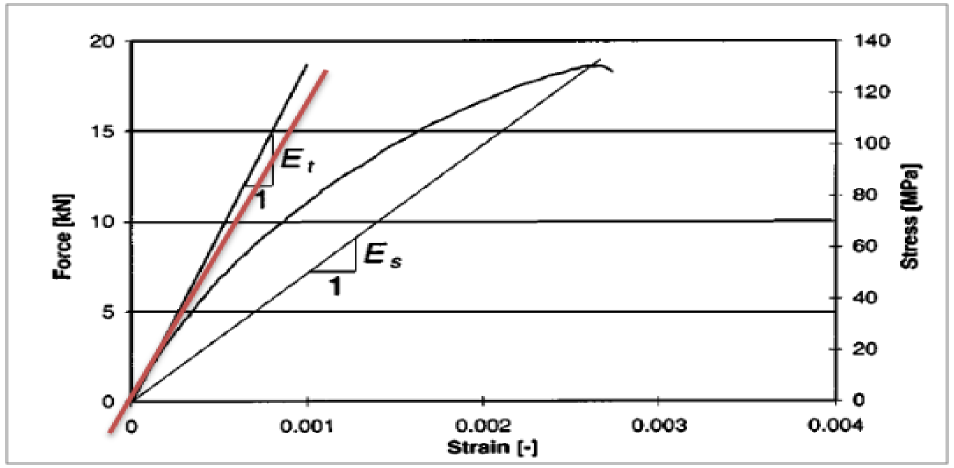
Stress-Strain Curves (p. 39)



Modulus of Elasticity and Hardness v. Tensile Gray Irons

Literature Search

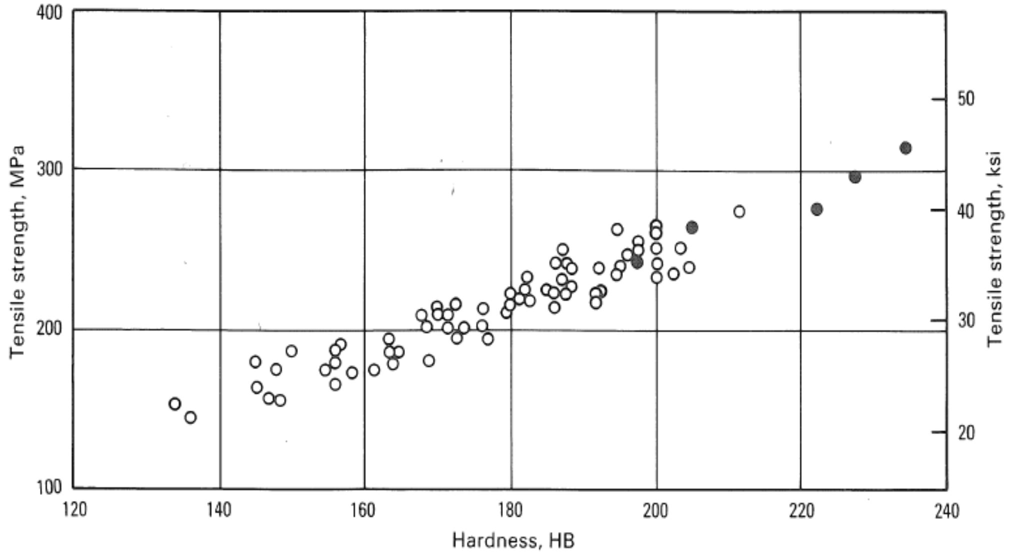
Tangent and Secant Modulus (p. 40)



Modulus of Elasticity of As-Cast Gray Iron (p. 41)

ASTM A 48 class	Tensile modulus GPa	Tensile modulus 10^6 psi	Torsional modulus GPa	Torsional modulus 10^6 psi
20	66-97	9.6-14.0	27-39	3.9-5.6
25	79-102	11.5-14.8	32-41	4.6-6.0
30	90-113	13.0-16.4	36-45	5.2-6.6
35	100-119	14.5-17.2	40-48	5.8-6.9
40	110-138	16.0-20.0	44-54	6.4-7.8
50	130-157	18.8-22.8	50-55	7.2-8.0
60	141-162	20.4-23.5	54-59	7.8-8.5

Hardness v. Tensile Gray Iron (p. 42)



Casting Method v. Structure and Strength

Literature Search

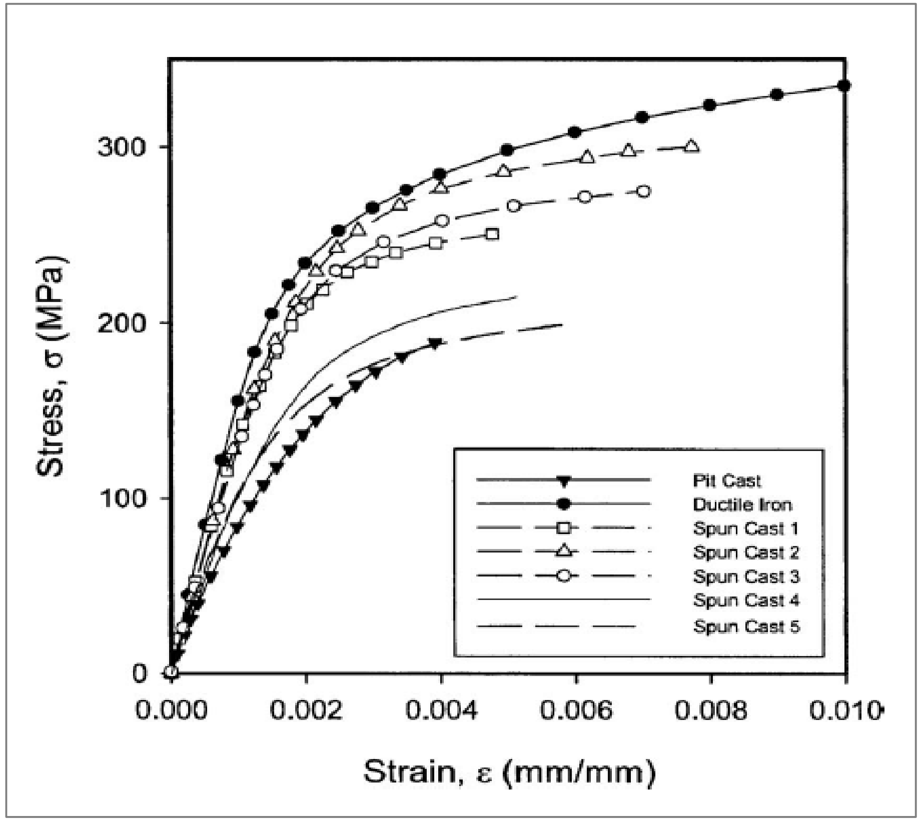
ASTM Flake Type/Size v. Casting Method (p. 43)

Sample	ASTM flake type[a] Inner surface	Center	Outer surface	ASTM flake size[b] Inner surface	Center	Outer surface
Pit cast	C	C	C	4	4	4
Spun Cast 1	A	D	D	6	8	7
Spun Cast 2	C	D	D	5	7	8
Spun Cast 3	C	D	D	5	8	8
Spun Cast 4	C	C–D	D	4	5–8	8
Spun Cast 5	C	C–D	D	4	5–8	8

[a]In ASTM A 247 the flake type indicates how the graphite flakes are distributed in the metal matrix. Type A indicates uniformly distributed, apparently randomly oriented flakes; Type C indicates randomly oriented flakes of widely varying sizes and Type D a very fine pattern of flakes surrounding areas without graphite.

[b]In ASTM A 247 the sizes refer to a range of values as measured at 100× magnification that vary geometrically from 1 to 128 mm. Size 3 corresponds to approximately 16–32 mm at this magnification, Size 4 to 8–16 mm, Size 5 to 4–8 mm, Size 6 to 2–4 mm, Size 7 to 1–2 mm, and Size 8 to 0–1 mm.

Tensile Stress-Strain Relation v. Casting Type (p. 44)



Exhumed Gray Cast Iron Pipe Mechanical Properties

Literature Search

Comparison of Mechanical Properties of Gray Cast Iron Pipes (p. 46)

Type of cast iron	Reference	Age of pipes	Tensile strength (MPa)	Compressive strength[c] (MPa)	Modulus of rupture (MPa)	Secant elastic modulus (MPa)	Fracture toughness (MPa $\sqrt{m}$)
Pit	Rajani et al. (2000)	64–115 years	33–267	n/a	132–378	38,000–168,000	5.7–13.7
Pit & spun	Conlin and Baker (1991)	Out of service pipes	137–212	n/a	n/a	n/a	10.5–15.6
Pit & spun	**This study (2002)[a]**	**50–124 years[b]**	**47–297**	**519–1,047**	**164–349**	**23,000–150,000**	n/a
Spun	Yamamoto et al. (1983)	22–79 years	100–150	n/a	20–250	n/a	n/a
Spun	Caproco Corrosion (1985)	22–28 years	70–217	n/a	n/a	n/a	n/a
Spun	Ma and Yamada (1994)	21–32 years	40–320	n/a	120–320	n/a	n/a
Spun	Rajani et al. (2000)	22–61 years	135–305	n/a	194–445	43,000–159,000	10.3–15.4

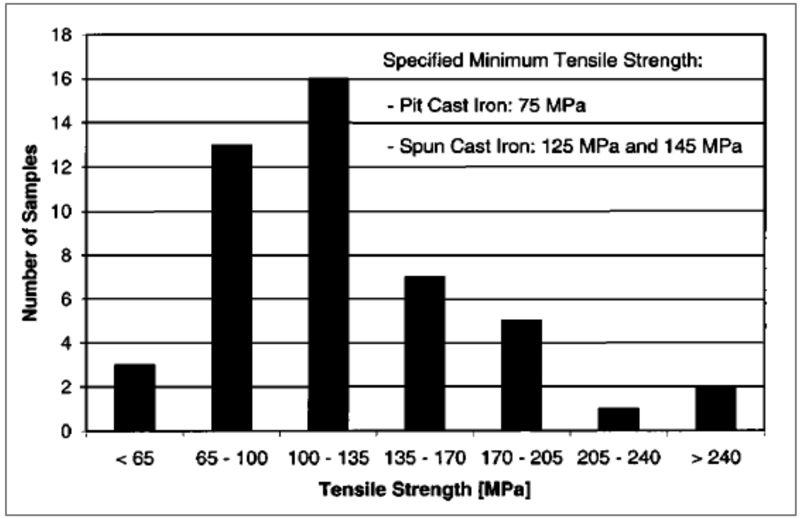
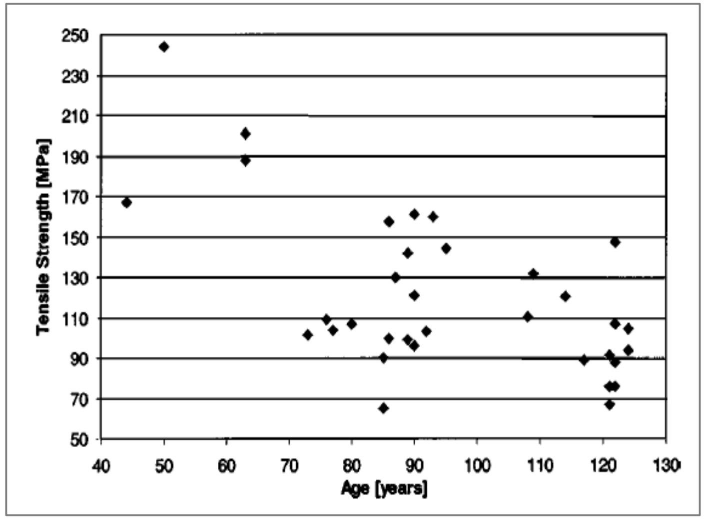
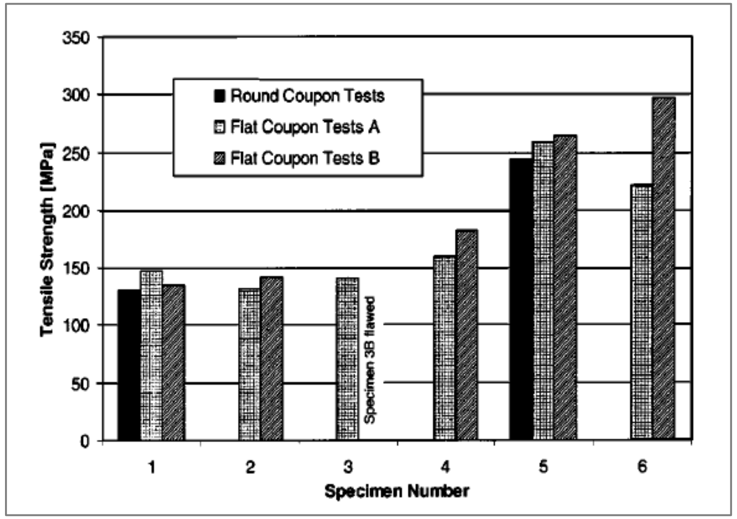
[a]Please refer to the "Test Results" section.

[b]Where data were available.

[c]Ultimate strength (as opposed to yield strength). (1 m=3.281 ft, 1 MPa=0.145 ksi.)

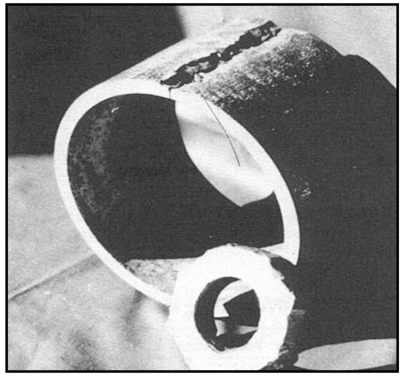
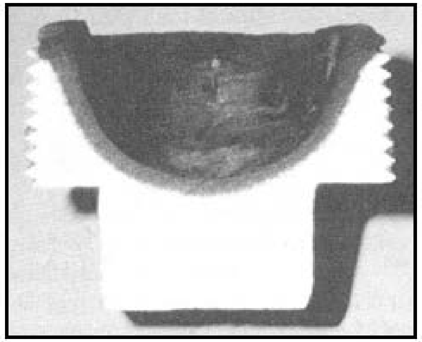
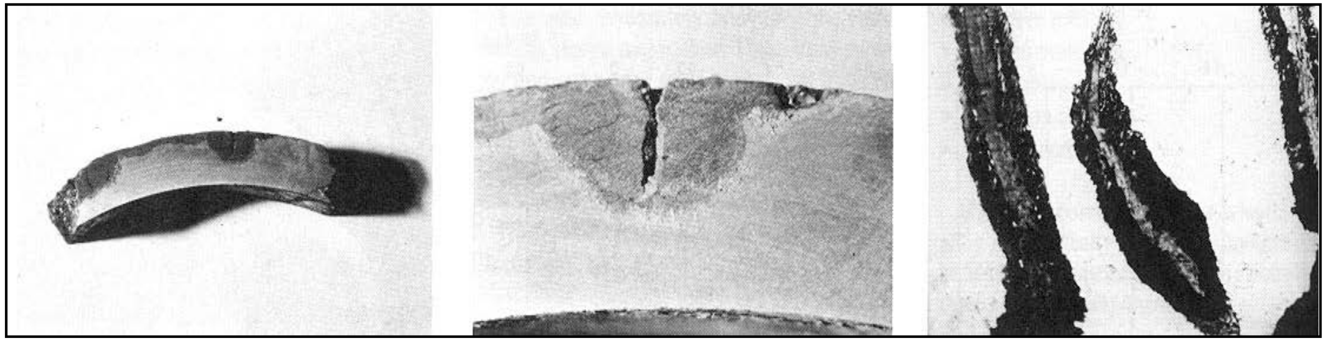
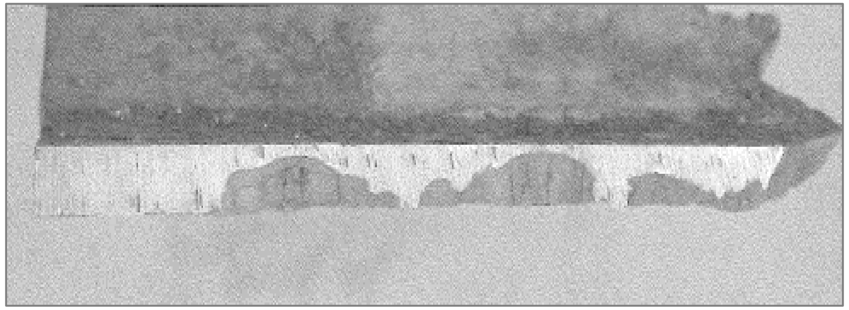
Exhumed Pipe Strength with Corrosion and Other Defects

Literature Search

Tensile Strength Distribution with Defects (p. 47)	Tensile Strength v. Age of Gray Iron with Defects Pipe (p. 47)	Tensile Strength with No Defects (p. 48)
		

Graphitic Corrosion

Literature Search

<table>
<tr><td>Cast Iron Elbow (p. 50)
</td><td>8-in. Gray Iron Pipe (p. 51)
</td><td>Gray Iron Pipe Plug (p. 52)
</td></tr>
<tr><td colspan="2">Same 8-in. Pipe Close-up of Corrosion and De-alloyed Flake Region (p. 52)
</td><td>Cast Iron Water Main (p. 52)
</td></tr>
</table>

Graphitic Corrosion

Literature Search

Cast Iron Gas Main (p. 53)

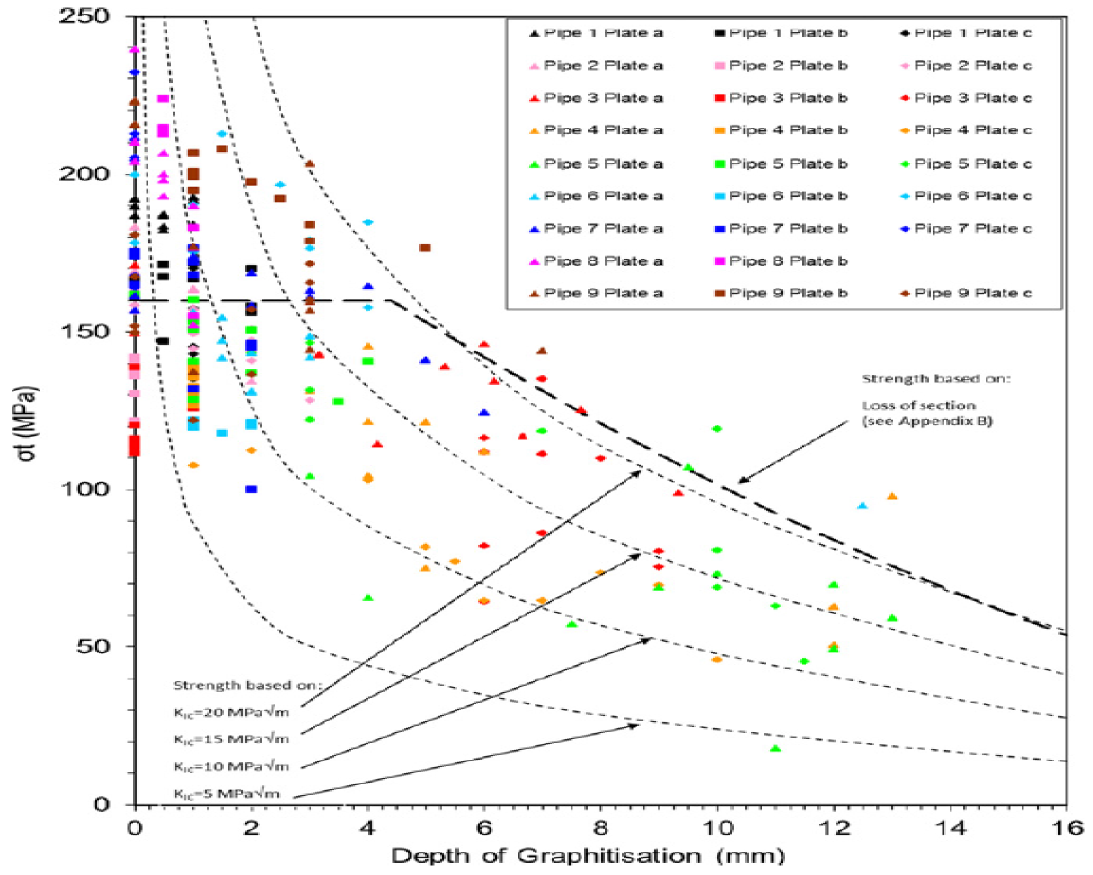
Gas Main Near Joint (p. 53)

De-alloyed Region Around Flakes (p. 54)

Effect of Corrosion on Residual Pipe Strength

Literature Search

Strength v. Depth of Graphitic Corrosion (p. 63)



Review of Cast Iron Failure Incidents, Load/Stress Analysis, and Design Codes

- Developed a summary of cast iron failure incidents, as well as associated loads and stresses on cast iron pipes due to external loads and environmental conditions.
- This included a review of the parameters affecting cast iron corrosion and an analysis of the loads and stresses which the cast iron pipes are subjected to in the field.
- Additionally, performed a review and summary of design codes for cast iron pipes.

“Class” by Pressure and Typical Sizes of CI Pipes

Cast Iron Failure Assessment

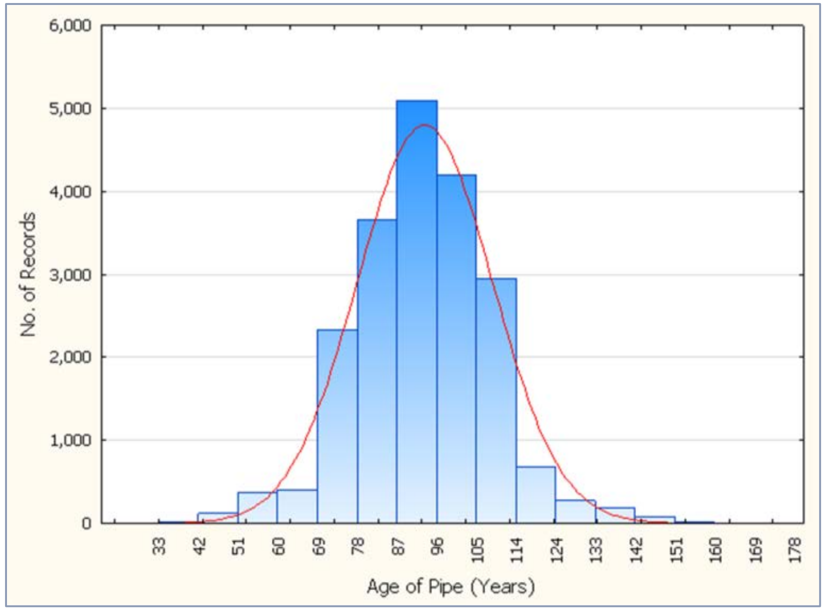
Pipe Sizes for Class 150 Cast Iron Pipes (p. 67)

Nominal size	CENTRIFUGALLY CAST PIPE ANSI A21.6 • ANSI A21.8 AWWA C106 • AWWA C108			PIT CAST PIPE ANSI A21.2 AWWA C102		
	O.D.	I.D.	THICKNESS	O.D.	I.D.	THICKNESS
CLASS 150 • 150 PSI • 346 FT. HD.						
3"	3.96	3.32	.32	3.80	3.06	.37
4"	4.80	4.10	.35	4.80	4.00	.40
6"	6.90	6.14	.38	6.90	6.04	.43
8"	9.05	8.23	.41	9.05	8.13	.46
10"	11.10	10.22	.44	11.10	10.02	.54
12"	13.20	12.24	.48	13.20	12.04	.58
14"	15.65	14.63	.51	15.65	14.39	.63
16"	17.80	16.72	.54	17.80	16.44	.68
18"	19.92	18.76	.58	19.92	18.46	.73
20"	22.06	20.82	.62	22.06	20.40	.83
24"	26.32	24.86	.73	26.32	24.46	.93
30"	32.00	30.30	.85	32.40	30.20	1.10
36"	38.30	36.42	.94	38.70	36.26	1.22
42"	44.50	42.40	1.05	45.10	42.40	1.35
48"	50.80	48.52	1.14	51.40	48.44	1.48
54"	-	-	-	57.80	54.54	1.63
60"	-	-	-	64.20	60.42	1.89

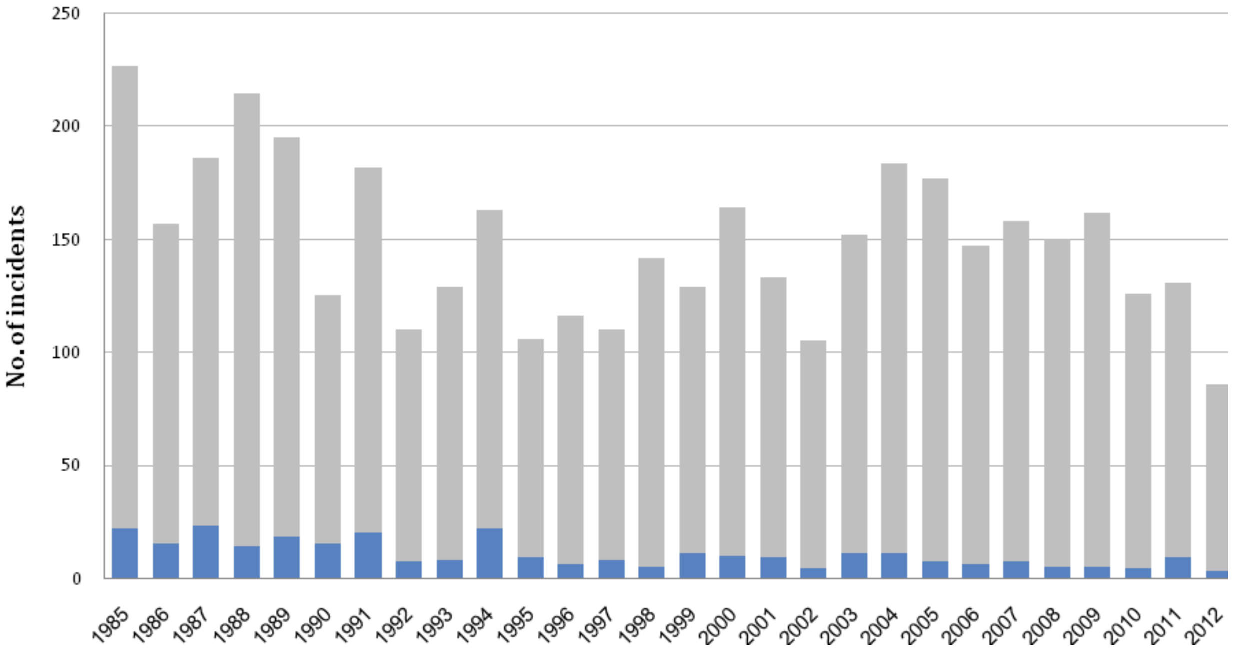
Cast Iron Age Distribution and Percent of Incidents

Cast Iron Failure Assessment

CI Age in Gas Distribution System (p. 66)



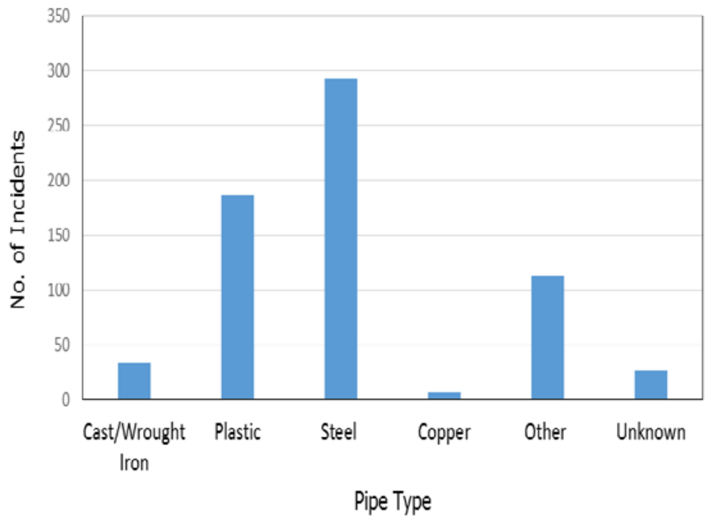
Total Incidents vs. Cast Iron Incidents Since 1985 (p. 68)



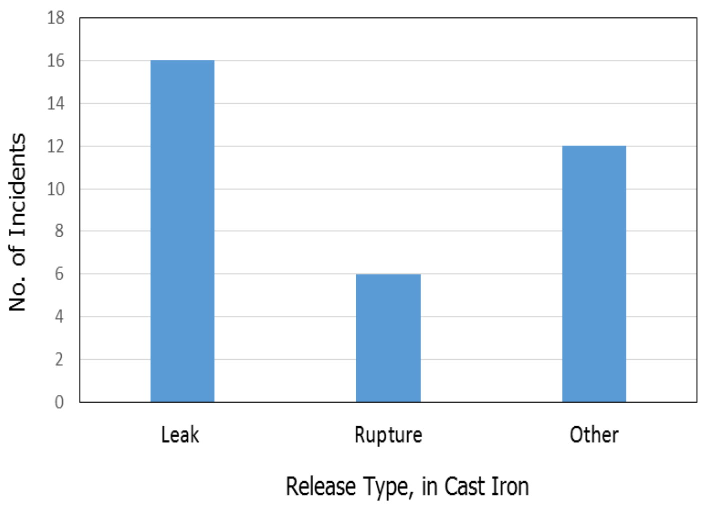
PHMSA 2010 – 2015 Significant Incident Analysis

Cast Iron Failure Assessment

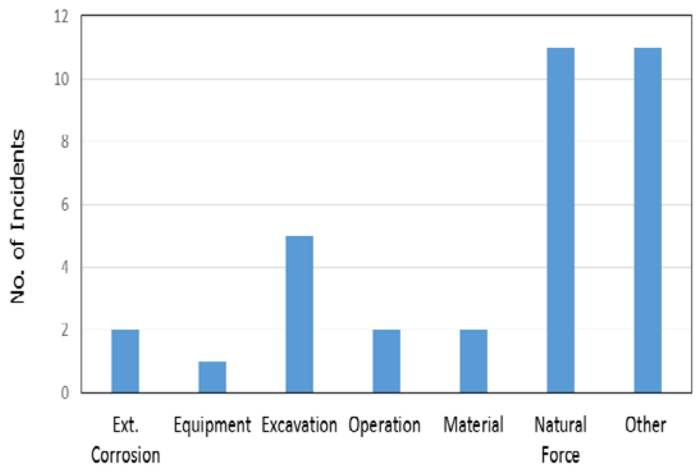
Material Type (p. 72)



Cast Iron 34 Failures - Type (p. 72)

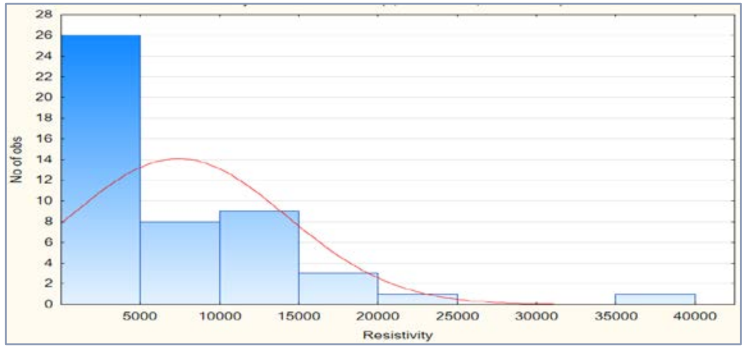
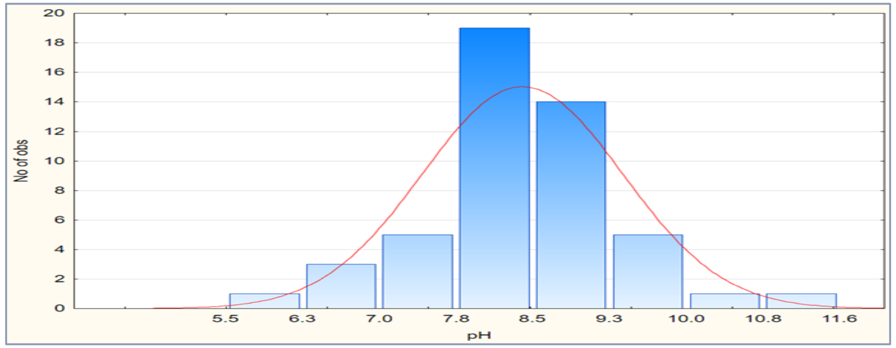
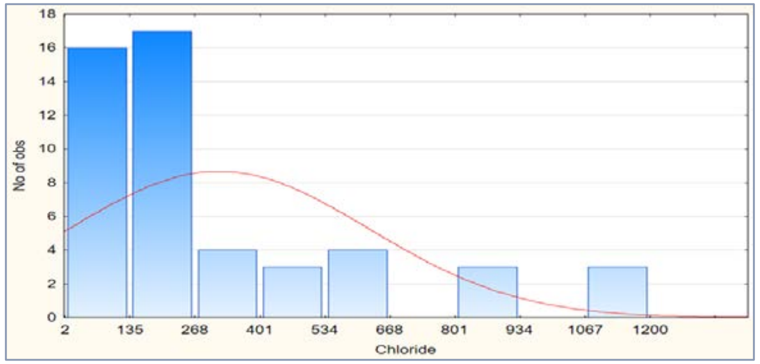
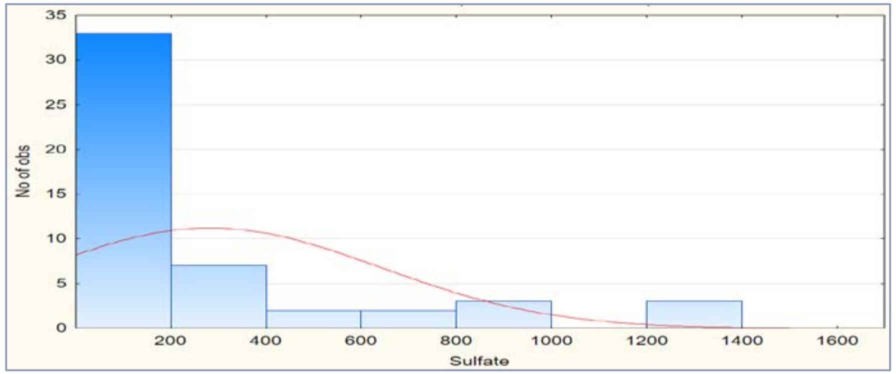


Cast Iron 2 Corrosion Failures (p. 73)



Northeast Utility Analysis of Corrosion and Soil Samples

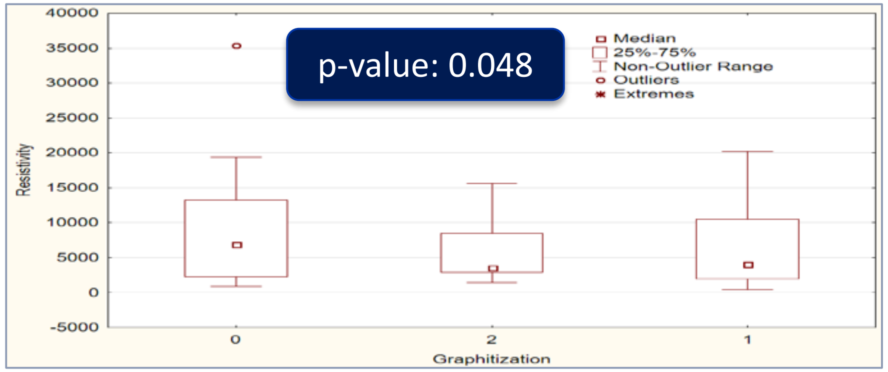
Cast Iron Failure Assessment - Distributions

Soil resistivity measurements in the samples (p. 74)	pH measurements in the samples (p. 75)
	
Chloride measurements in the samples (p. 75)	Sulfate measurements in the samples (p. 76)
	

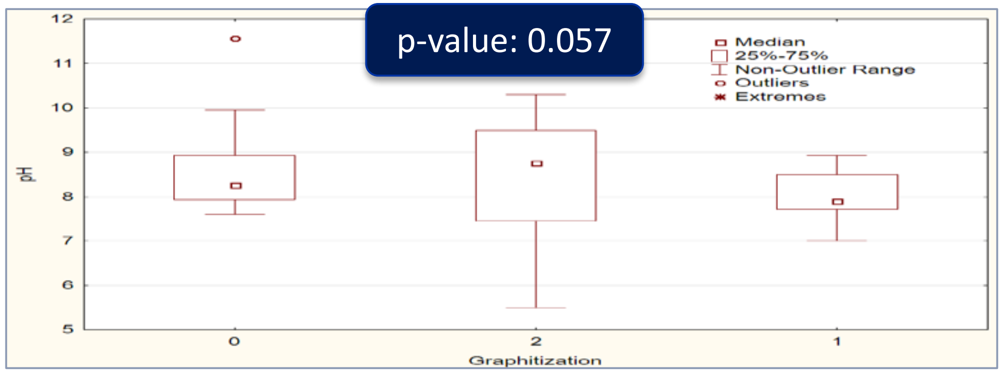
Northeast Utility Analysis of Corrosion and Soil Samples

Cast Iron Failure Assessment – Comparison of Means and ANOVA

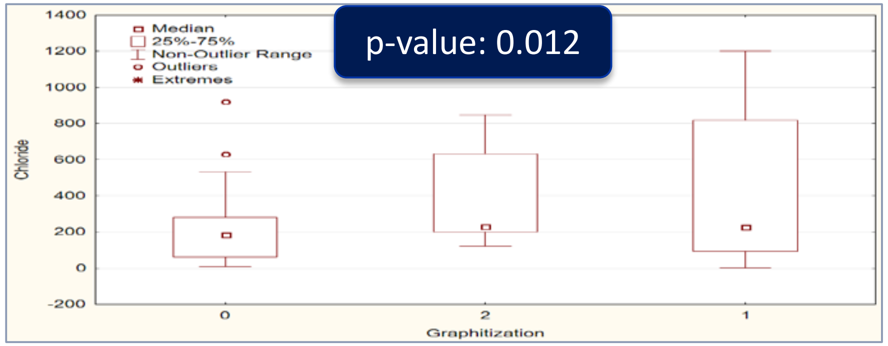
Graphitic Corrosion Levels v. Soil Resistivity (p. 77)



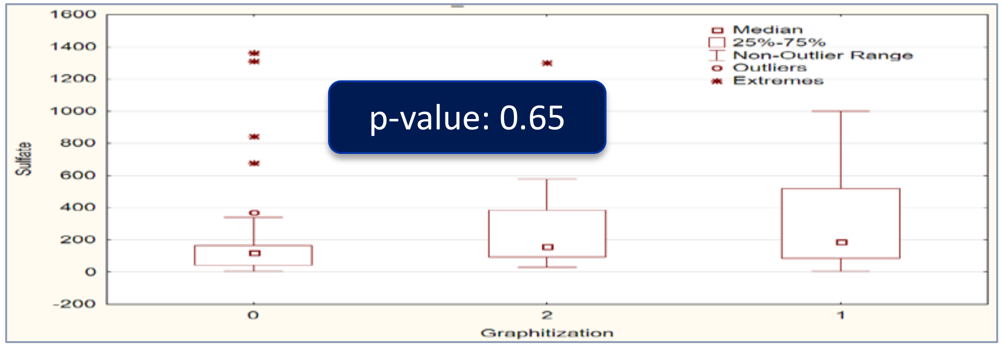
Graphitic Corrosion Levels v. pH (p. 77)



Graphitic Corrosion Levels v. Chlorides (p. 78)



Graphitic Corrosion Levels v. Sulfate (p. 78)



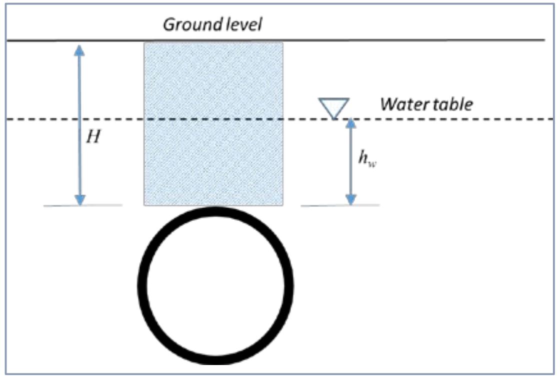
Pipe Stresses Under Internal and External Loads

Cast Iron Failure Assessment

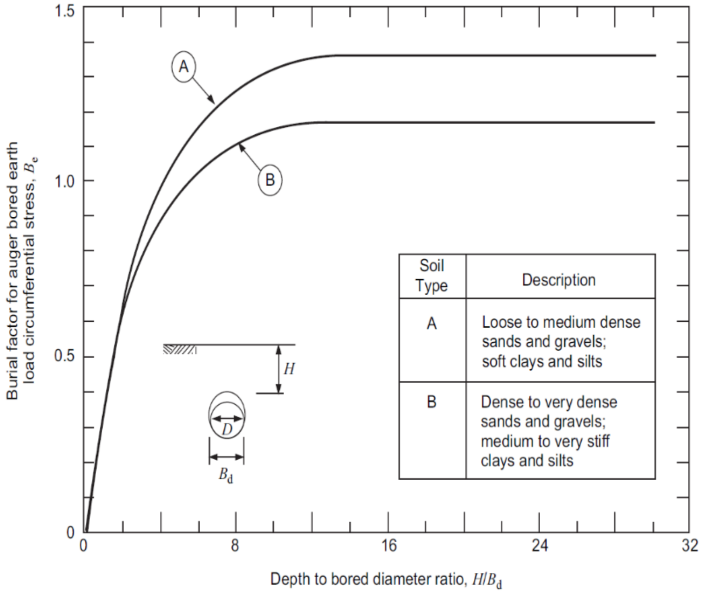
Sources of loads (p. 80)

- Overburden earth load and traffic loads
- Internal pressure
- Shrink/swell of soil and frost heave
- Loss of ground support/undermine
- Dynamic loads from earthquakes/ blasting
- Temperature induced loads

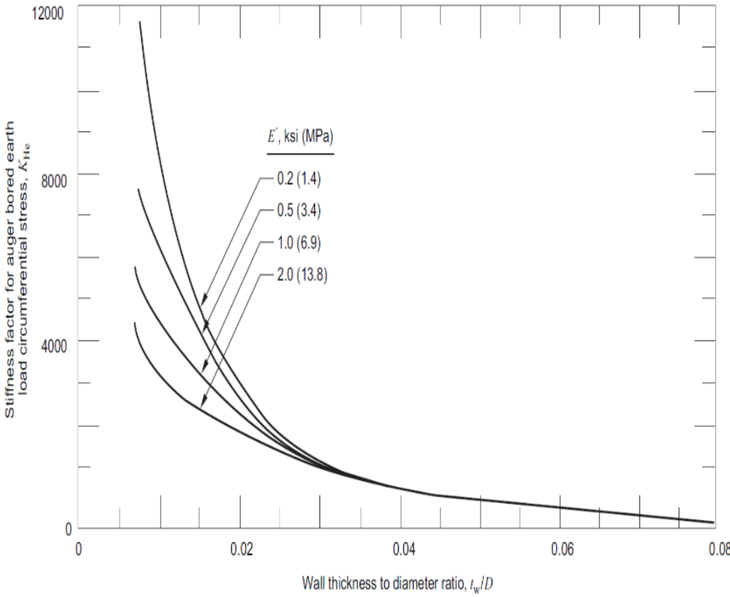
Soil Prism Above Pipe (p. 81)



Burial Factor v. Depth to Bored Diameter Ratio (p. 83)



Burial (Stiffness) Factor v. Wall Thickness-to-Diameter Ration (p. 82)



Dynamic, Pressure, Uplift and Temperature Based Loading

Cast Iron Failure Assessment

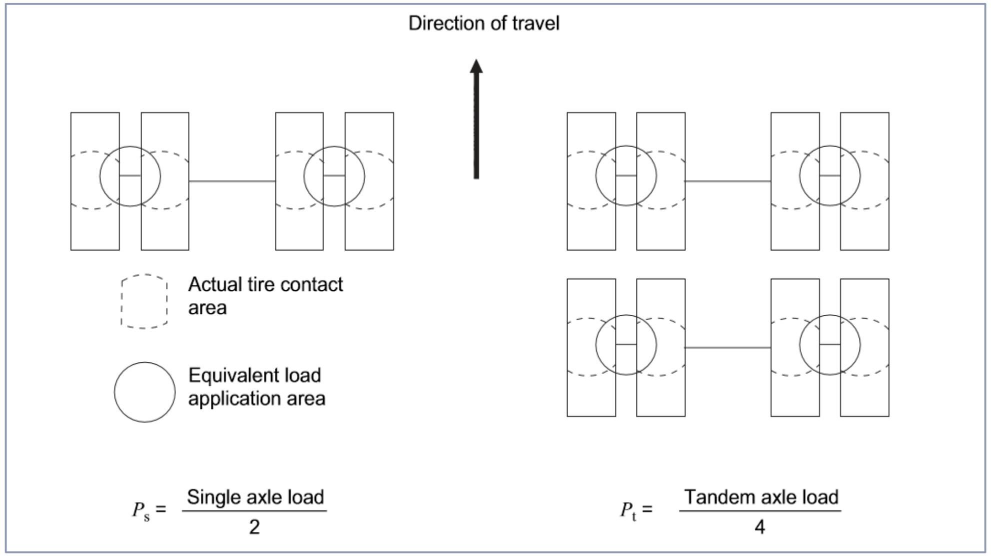
Live Loads with Depth of Cover (p. 85)

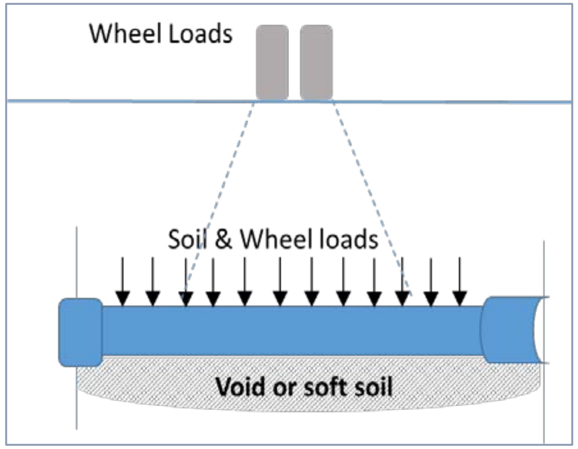
Live load transferred to pipe, lb/in²			
Height of cover, ft	Highway H20*	Railway E80†	Airport‡
1	12.50	--	--
2	5.56	26.39	13.14
3	4.17	23.61	12.28
4	2.78	18.40	11.27
5	1.74	16.67	10.09
6	1.39	15.63	8.79
7	1.22	12.15	7.85
8	0.69	11.11	6.93
10	§	7.64	6.09
12	§	5.56	4.76

Pressure, Uplift, and Temp Loads (p. 85-87)

- $S_{i\,(Barlow)} \leq F.E.T.SMYS$
- $F_b = W_w - [\,W_p + (\gamma_s\, h_s - \gamma_w\, h_w)D]$
- $\sigma_b = \frac{F_b\, L^2}{10\, Z}$
- $\sigma_t = E\,\alpha\,(T_2 - T_1)$

Traffic Loads - Including Bending (p. 84 and 87)





Review of Design Codes for Cast Iron Pipes

Cast Iron Failure Assessment

§ 192.275 Cast iron pipe: sealing, clamps, gasket, threaded joints, brazing

§ 192.369 Service lines: Connections to cast iron or ductile iron mains

§ 192.373 Service lines: Cast iron and ductile iron

§ 192.489 Remedial measures: Cast iron and ductile iron pipelines

§ 192.557 Uprating

§ 192.621 Maximum allowable operating pressure: High-pressure distribution systems

§ 192.753 Caulked bell and spigot joints

§ 192.755 Protecting cast-iron pipelines

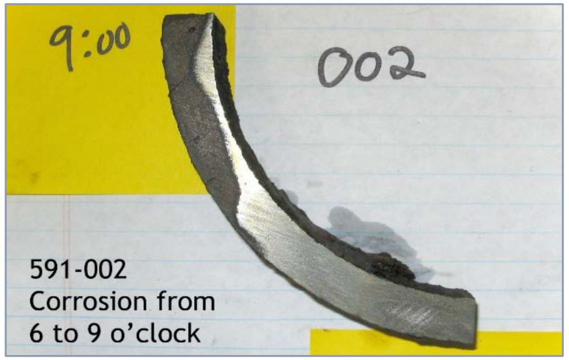
Field Measurement Method for Cast Iron Corrosion

- A method for measurement of graphitic corrosion in the field was developed with detailed guidance on measurement of corrosion defects to be used as part of the FFS model input.
- This included a general set of guidelines for operator to characterize the type and severity of graphitic corrosion on a cast iron pipeline in the field.
- This will allow the operator to consistently and reliably develop part of the input data needed to run the FFS cast iron model.

Measurement Tools

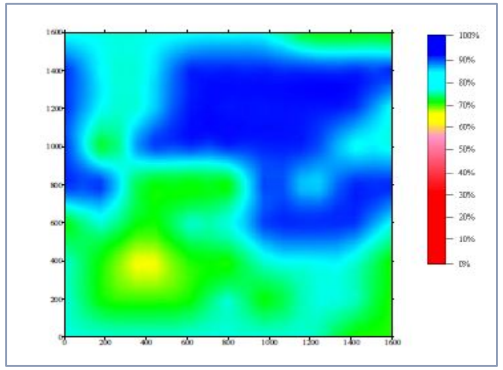
Characterization of Graphitic Corrosion Severity

Corrosion Profile (p. 92)



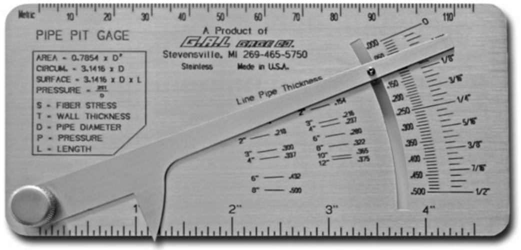
Preferred Bridging Pit Gauge (p. 93)

BEM Scan (p. 95)

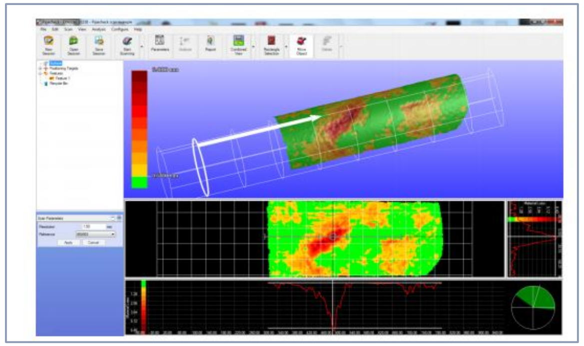


Severe Pitting (p. 92)

Not Preferred Basic Pit Gauge (p. 93)



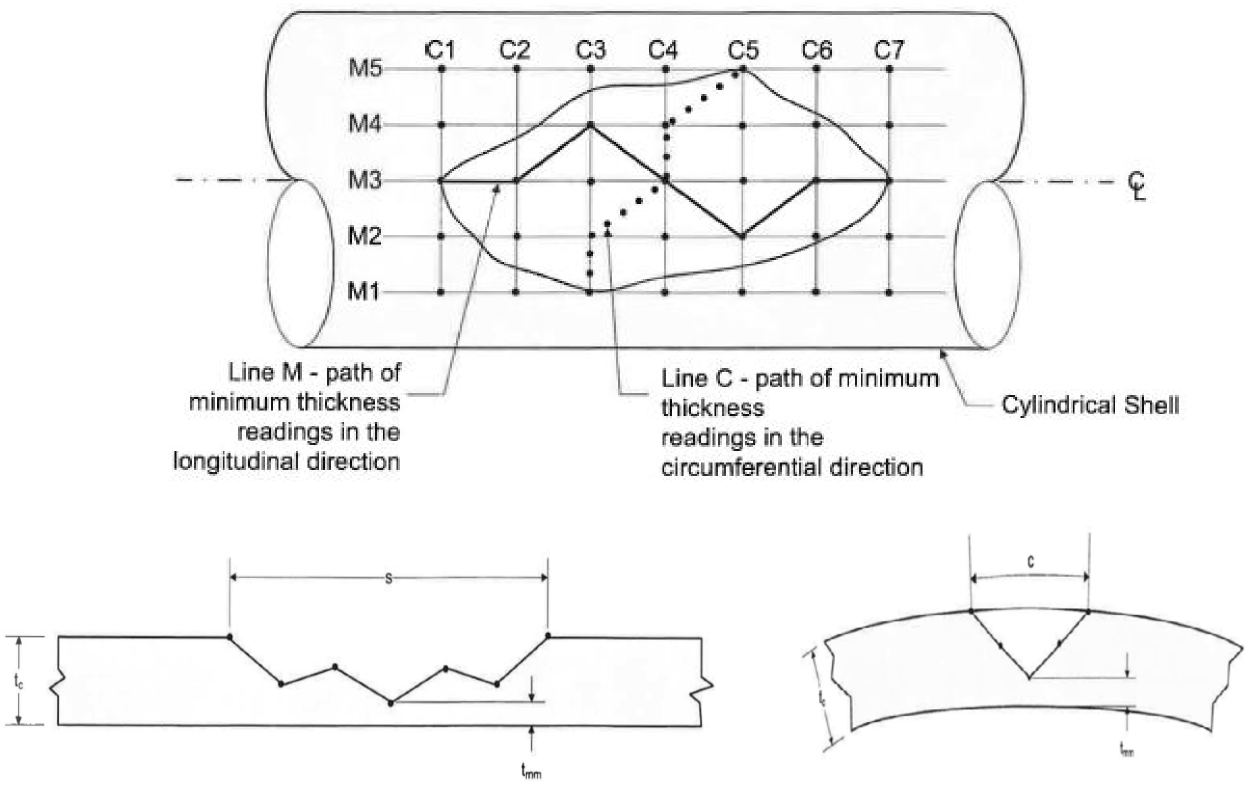
Laser Scan (p. 95)



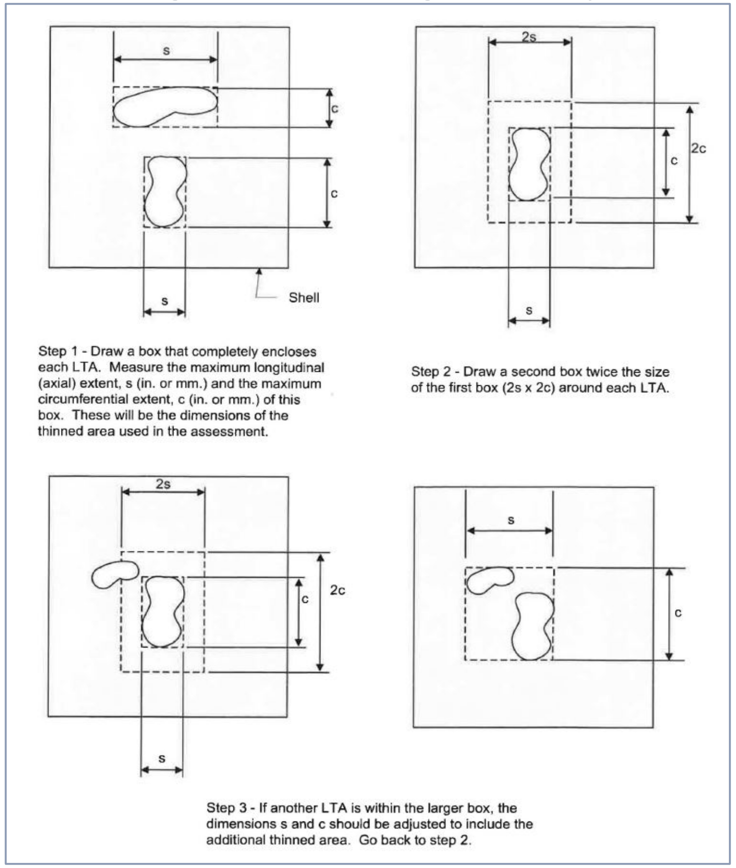
Measurement Method - Modified API 579-1/ASME FFS-1 Part 4

Characterization of Graphitic Corrosion Severity

Inspection Planes and Critical Thickness Profiles (Long./Circum.) (p. 99)



Combining and Resizing Flaws (p. 100)



CI FFS Model Development Using Finite Element Analysis, Design of Experiments, & Statistical Regression

- A CI FFS model for graphitic corrosion defects was developed using Finite Element Analysis, Design of Experiments, and Statistical Regression.
- The model can be used to determine the critical defect size and characteristics that could lead to premature piping failure.

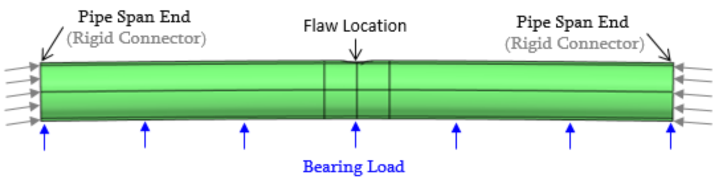
Overview, Boundaries, and Geometries

Finite Element Analysis (FEA) Model and Statistical Analysis

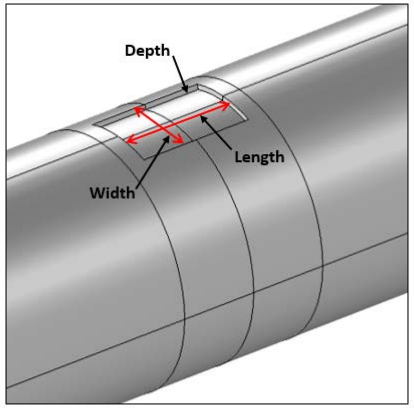
Overview (p. 102)

- Nonlinear, 3D finite element model
- Design of Experiments (DoE)
- Response Surface Method (RSM)
- Utilized 97.5% conservative upper prediction limit (UPL)
- Programmed into Excel calculator

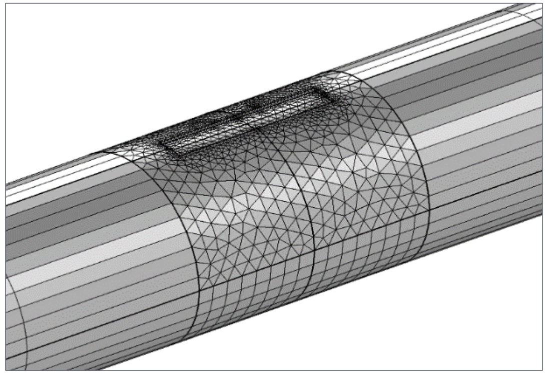
FE Boundary Conditions (p. 104)

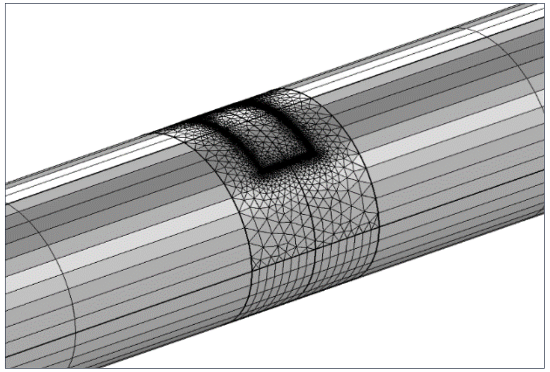


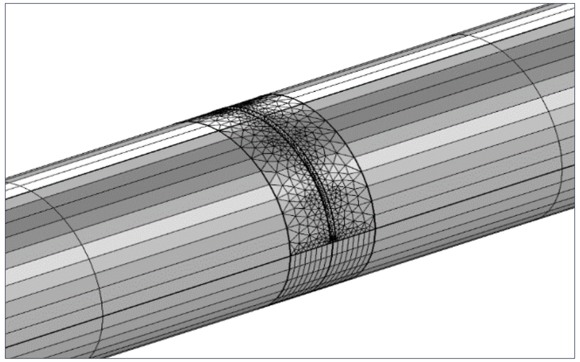
Flaw Geometry (p. 105)



A Few Examples of Corrosion Defect and Meshes (pp. 107-110)



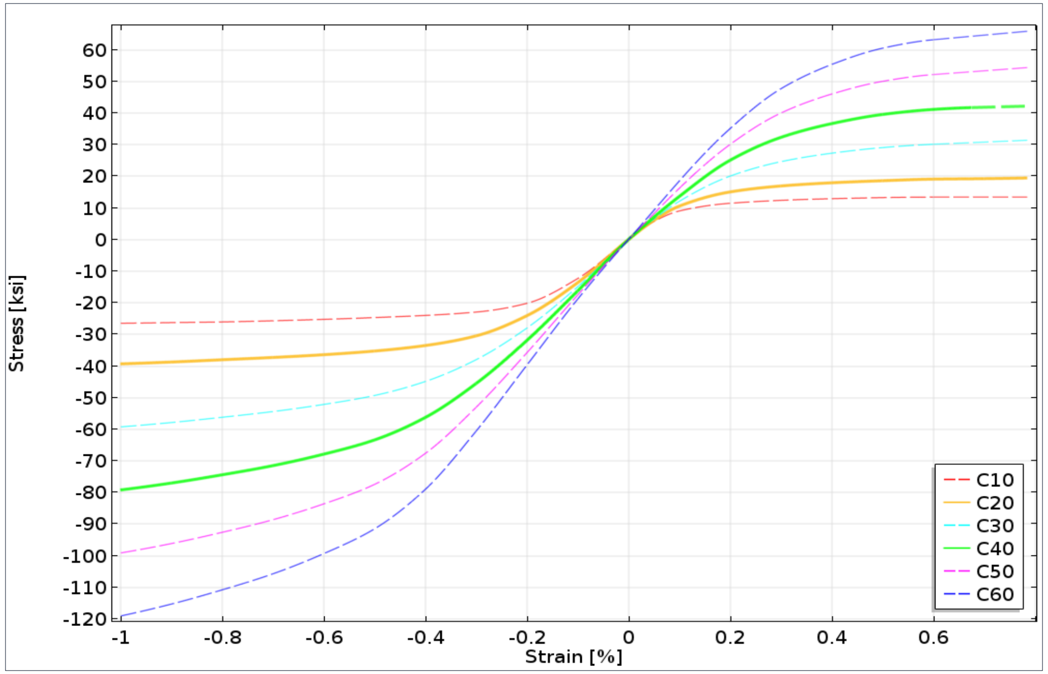




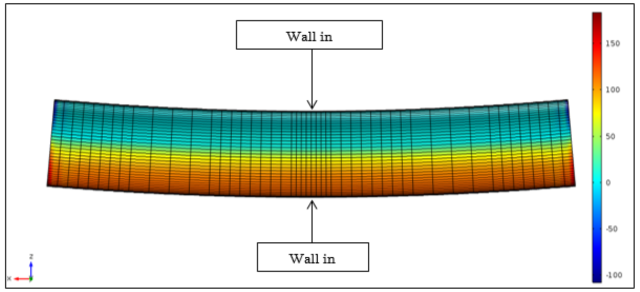
Material Properties for Modeling

Finite Element Analysis (FEA) Model and Statistical Analysis

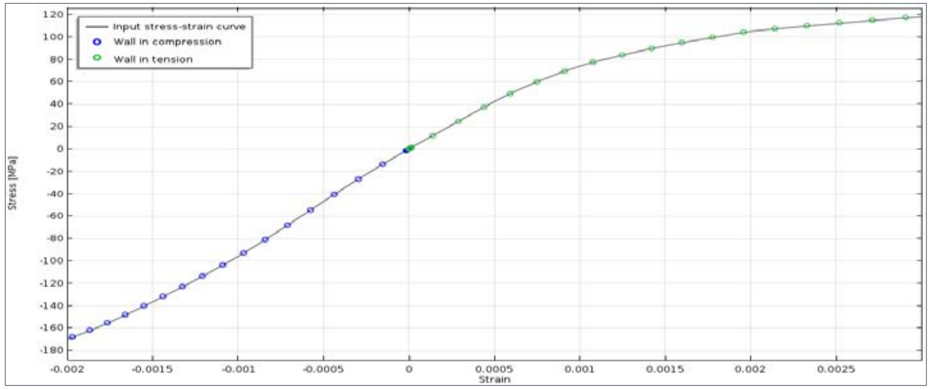
True Stress-Strain Classes 10 to 60 (p. 113)



Simple Bending (p. 112)



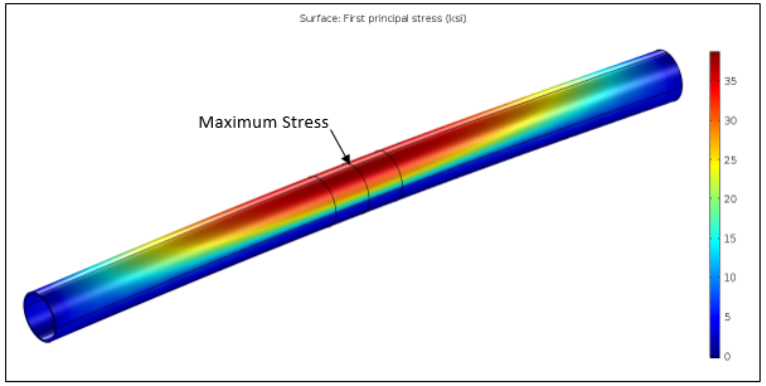
Simulation Stresses (p. 112)



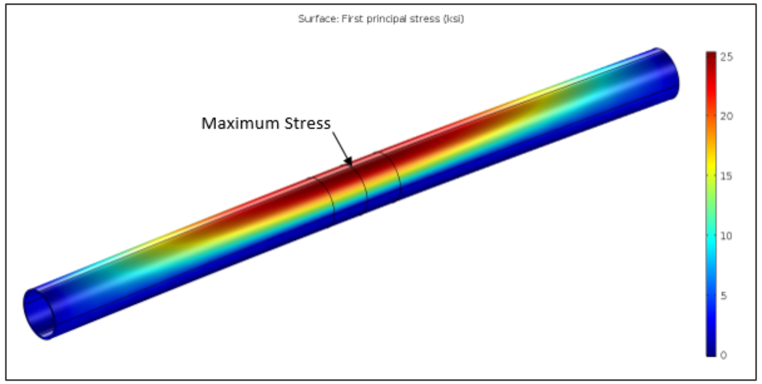
Stresses Under Different Loading Conditions – No Defect

Finite Element Analysis (FEA) Model and Statistical Analysis

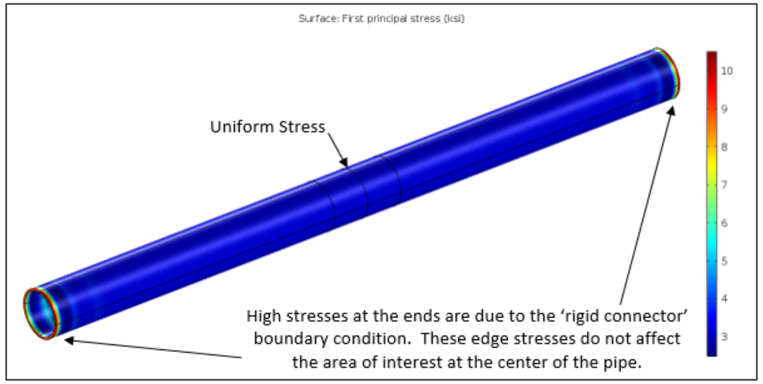
Bending with no axial restraint
(p. 114)



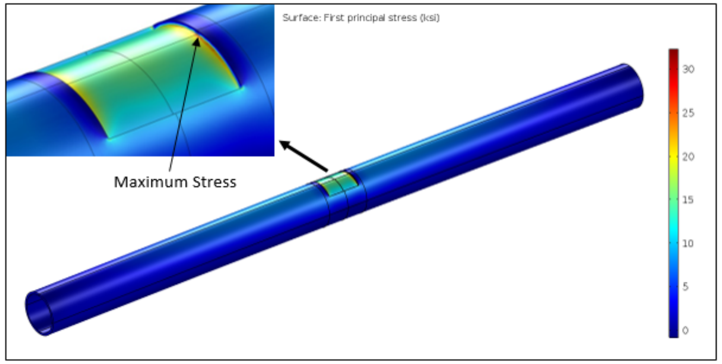
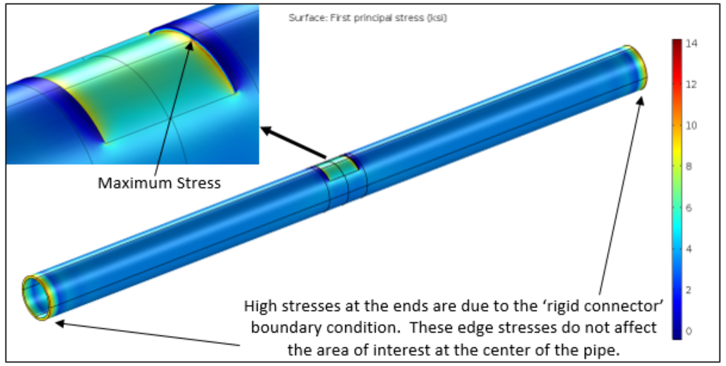
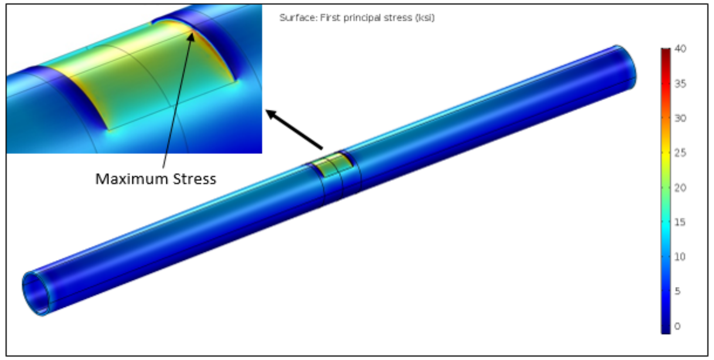
Bending with axial restraint
(p. 115)



Thermal contraction with no bending
(p. 115)



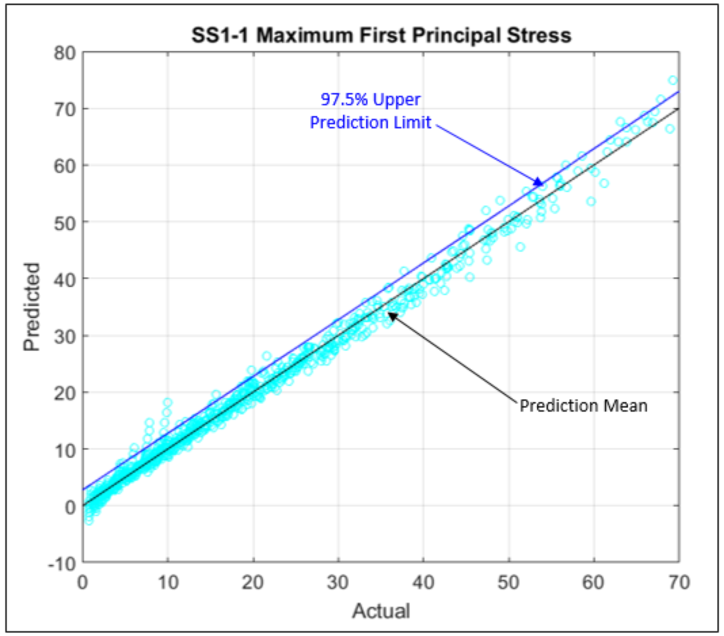
Stresses Under Different Loading Conditions – With Defect
Finite Element Analysis (FEA) Model and Statistical Analysis

Pipe with wall loss and bending (p. 114)	Pipe with wall loss and thermal contraction, no bending (p. 115)	Pipe with wall loss under bending, with thermal contraction (p. 115)
		

Response Surface Predicted vs. FEA Actuals – No Flaw

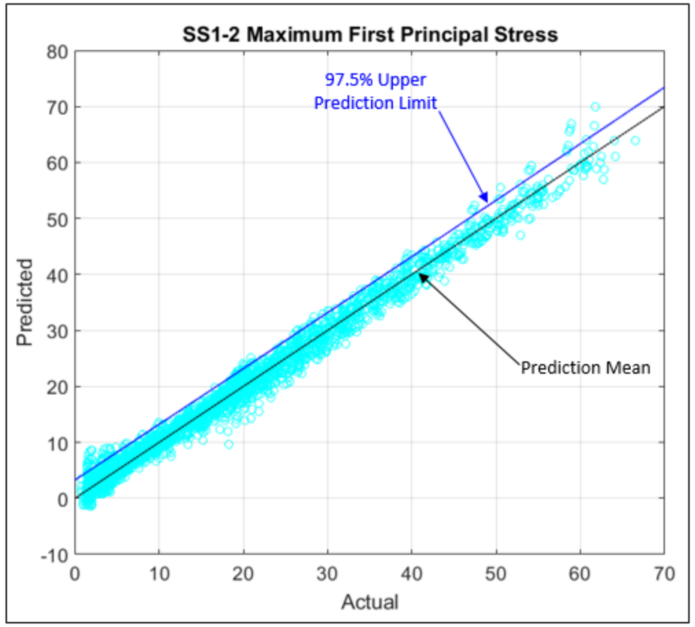
Finite Element Analysis (FEA) Model and Statistical Analysis

Response Surface
No flaw, axially free end (p. 119)



$R^2 = 0.9917$

Response Surface
No flaw, restrained ends (p. 123)



$R^2 = 0.9868$

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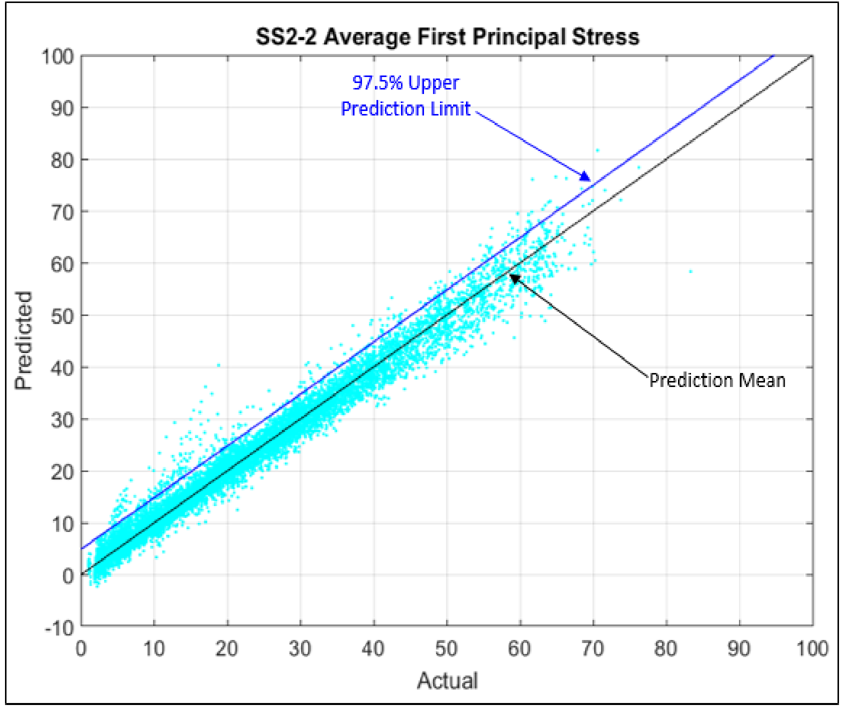
Response Surface Predicted vs. FEA Actuals – Flaw

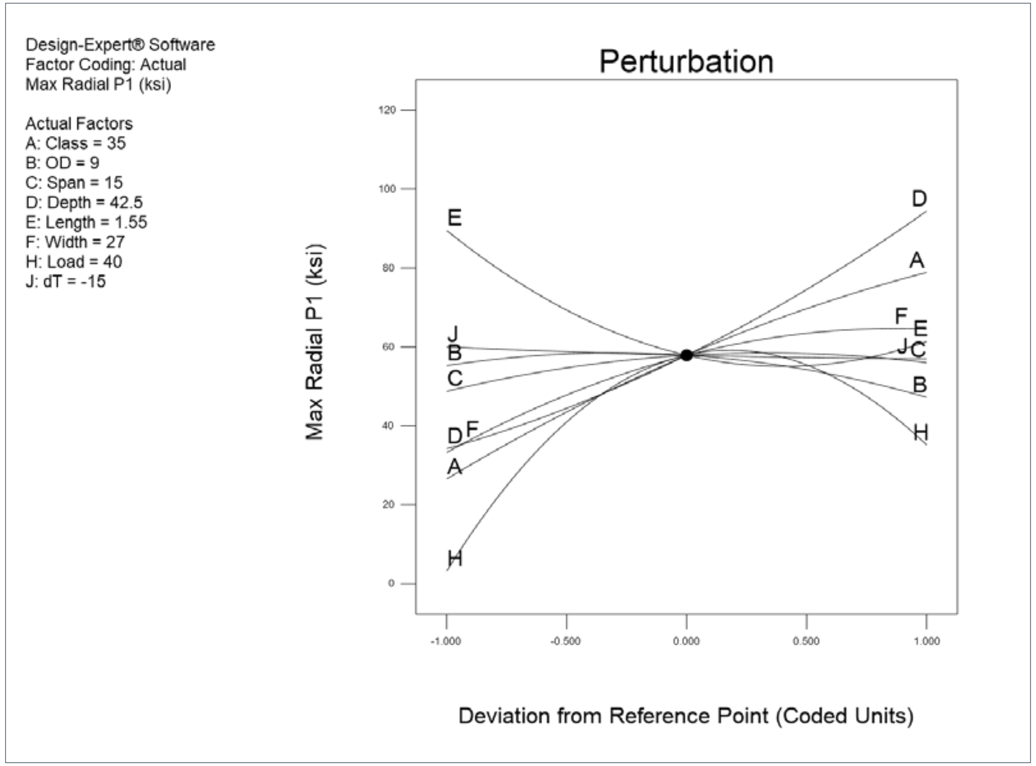
Finite Element Analysis (FEA) Model and Statistical Analysis

Response Surface
With flaw, restrained ends (p. 133)



R2 = 0.9725

Perturbation Diagram
Pipe with flaw and axially restrained ends (p. 134)



Excel Based Calculator and Training Manual

> The results of the model were incorporated into an Excel-based, end-user calculator.

> A user's training manual was developed with a set of examples to facilitate implementation of the FFS model with the end user (Appendix B)

> Examples of the calculator use will be shown in the next section that summarizes model first-pass validation with field failure data.

First-Pass Validation of CI FFS Model with Field Failure Data and Uncertainty Analysis/Effects of Input Variation

- A first-pass validation of the FFS model was completed through the analysis of select cast iron field failures.
- The failure data was compared against the FFS model results under the same parameters.
- Analyzed the effect of input uncertainty on the model results.
- This was done through Monte Carlo simulations that allowed the inclusion of measurement uncertainty for input variables such as diameter, thickness, material strength, corrosion defect geometry, etc.

Case 1 – Corrosion Effects

First Pass Validation of Model with Field Failure Data

Incident Data (p. 141)

Pipe Characteristics	
Pipe material	NA
Pipe diameter (inch)	6
Internal Pressure (psi)	5
Crossing	No
Depth of Cover (inch)	54
Installation year	1928
Location	Class 3
Incident	
City, State	Detroit, MI
Incident Year	Oct 2011
Damage Width	2 holes at bottom of pipes about 4 inch diam.
Damage Length	
Cause	External Graphitic Localized Corrosion
Consequences	Pipe rupture, fatality, release of gas

Model Output (p. 142)

Inputs:

Pipe Dimensions

Parameter	Units	Description	Value	Minimum	Maximum
class	ksi	Material class (tensile strength)	40	10	60
D	in	Pipe outer diameter	6	4.8	13.2
span	ft	Pipe span	12	12	18
t	in	Pipe wall thickness (if known)		*<-- If a value is entered h*	
t.pred	in	Pipe wall thickness predicted by OD	0.413		

Corrosion Flaw Dimensions

Parameter	Units	Description	Value	Minimum	Maximum
flaw.d	in	Maximum corrosion flaw depth	0.33	0.021	0.330
flaw.l	in	Maximum corrosion flaw length (along pipe axis)	4	0.157	4.723
flaw.w	in	Maximum corrosion flaw width (around circumference)	4	0.942	9.236

Operating Conditions

Parameter	Units	Description	Value	Minimum
P	psig	Pressure	5	0
T.max	°F	Maximum buried operating temperature	75	
T.min	°F	Minimum buried operating temperature	55	

Soil and Traffic Loads

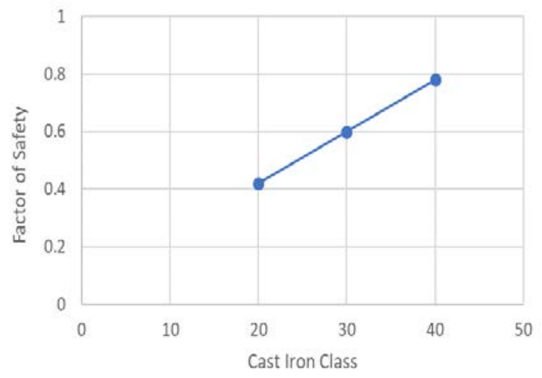
Parameter	Units	Description	Value	
soil.type		Soil type	Gravel/Base	
soil.weight	pcf	Soil wet weight per cubic foot	153	
soil.weight.user	pcf	Soil weight per cubic foot, user defined		*<-- If a value is entered h*
soil.depth	ft	Soil depth	4.5	
traffic.type		Traffic type (road,rail,none)	None	

Outputs:

Pipe stresses with corrosion defect

Parameter	Units	Description	Value
UTS	ksi	Material class (tensile strength)	40
P1.max	ksi	Maximum resolved tensile stress	56.9
SF.corroded	ratio	Tensile strength safety factor	0.70

Change of F.S. with Pipe Class (p. 142)



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Case 2 – Corrosion and Crossing Effects

First Pass Validation of Model with Field Failure Data

Incident Data (p. 143)

Pipe Characteristics	
Pipe material	ASA A21.1
Pipe diameter (inch)	12
Internal Pressure, MOP (psi)	25
Crossing	No
Depth of Cover (inch)	48
Installation year	1961
Location	Class 3
Incident Characteristics	
City, State	Saint Louis, MO
Incident Year	2012
Damage Width (inch)	2.5
Damage Length (inch)	6.5
Cause	External Graphitic Localized Corrosion
Consequences	Shut down, ignition, evacuation, no explosion

Model Output (p. 144)

Inputs:

Pipe Dimensions

Parameter	Units	Description	Value	Minimum	Maximum
class	ksi	Material class (tensile strength)	20	10	60
D	in	Pipe outer diameter	12	4.8	13.2
span	ft	Pipe span	12	12	18
t	in	Pipe wall thickness (if known)		*<-- If a value is entered h*	
t.pred	in	Pipe wall thickness predicted by OD	0.513		

Corrosion Flaw Dimensions

Parameter	Units	Description	Value	Minimum	Maximum
flaw.d	in	Maximum corrosion flaw depth	0.5	0.026	0.411
flaw.l	in	Maximum corrosion flaw length (along pipe axis)	2.5	0.248	7.446
flaw.w	in	Maximum corrosion flaw width (around circumference)	6.5	1.885	18.473

Operating Conditions

Parameter	Units	Description	Value	Minimum
P	psig	Pressure	25	0
T.max	°F	Maximum buried operating temperature	75	
T.min	°F	Minimum buried operating temperature	55	

Soil and Traffic Loads

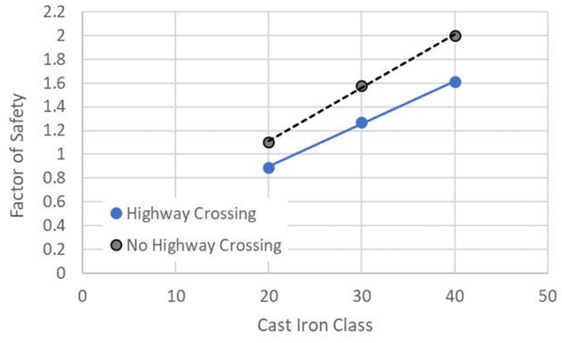
Parameter	Units	Description	Value	
soil.type		Soil type	Gravel/Base	
soil.weight	pcf	Soil wet weight per cubic foot	153	
soil.weight.user	pcf	Soil weight per cubic foot, user defined		*<-- If a value is entered h*
soil.depth	ft	Soil depth	4	
traffic.type		Traffic type (road,rail,none)	Highway	

Outputs:

Pipe stresses with corrosion defect

Parameter	Units	Description	Value
UTS	ksi	Material class (tensile strength)	20
P1.max	ksi	Maximum resolved tensile stress	22.5
SF.corroded	ratio	Tensile strength safety factor	0.89

Change of F.S. with Pipe Class and Crossing Type (p. 144)



Case 5 – Frost Heave with Corrosion Effects

First Pass Validation of Model with Field Failure Data

Incident Data (p. 149)

Pipe Characteristics	
Pipe material	NA
Pipe diameter (inch)	4
Internal Pressure, MOP (psi)	5
Crossing	No
Depth of Cover (inch)	48
Installation year	1930
Location	Class 3
Incident Characteristics	
City, State	Detroit, MI
Incident Year	March 2011
Damage Width (inch)	NA
Damage Length (inch)	NA
Cause	Circumferential crack due to frost heave
Consequences	Explosion

Model Output (p. 150)

Inputs:

Pipe Dimensions

Parameter	Units	Description	Value	Minimum	Maximum	
class	ksi	Material class (tensile strength)	20	10	60	
D	in	Pipe outer diameter	4	4.8	13.2	
span	ft	Pipe span	12	12	18	
t	in	Pipe wall thickness (if known)				*<-- If a value is entered h*
t.pred	in	Pipe wall thickness predicted by OD	0.401			

Corrosion Flaw Dimensions

Parameter	Units	Description	Value	Minimum	Maximum
flaw.d	in	Maximum corrosion flaw depth	0	0.020	0.320
flaw.l	in	Maximum corrosion flaw length (along pipe axis)	0	0.127	3.797
flaw.w	in	Maximum corrosion flaw width (around circumference)	0	0.628	6.158

Operating Conditions

Parameter	Units	Description	Value	Minimum
P	psig	Pressure	35	0
T.max	°F	Maximum buried operating temperature	75	
T.min	°F	Minimum buried operating temperature	25	

Soil and Traffic Loads

Parameter	Units	Description	Value	
soil.type		Soil type	Sand/Silt	
soil.weight	pcf	Soil wet weight per cubic foot	127	
soil.weight.user	pcf	Soil weight per cubic foot, user defined		*<-- If a value is entered h*
soil.depth	ft	Soil depth	3	
traffic.type		Traffic type (road,rail,none)	Highway	

Outputs:

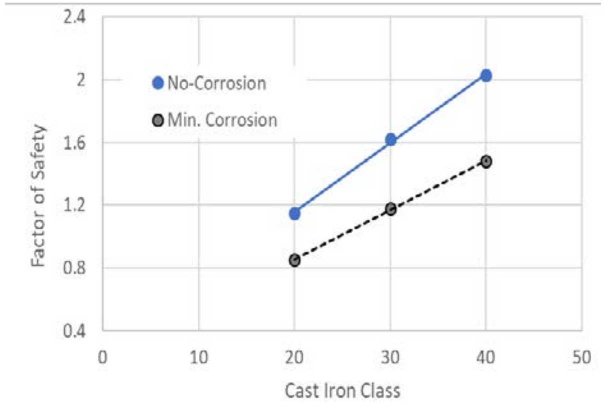
Pipe stresses with corrosion defect

Parameter	Units	Description	Value
UTS	ksi	Material class (tensile strength)	20
P1.max	ksi	Maximum resolved tensile stress	23.6
SF.corroded	ratio	Tensile strength safety factor	0.85

Pipe stresses with no defect

Parameter	Units	Description	Value
UTS	ksi	Material class (tensile strength)	20
P1.max.flawless	ksi	Maximum resolved radial stress, without flaw	17.4
SF.flawless	ratio	Tensile strength safety factor of flawless pipe	1.15
P.hoop	ksi	Hoop stress due to internal pressure (Barlow's Formula)	0.17

Change of F.S. with Pipe Class and Corrosion Severity (p. 151)



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Effect of Input Uncertainty on Model Output

First Pass Validation of Model with Field Failure Data

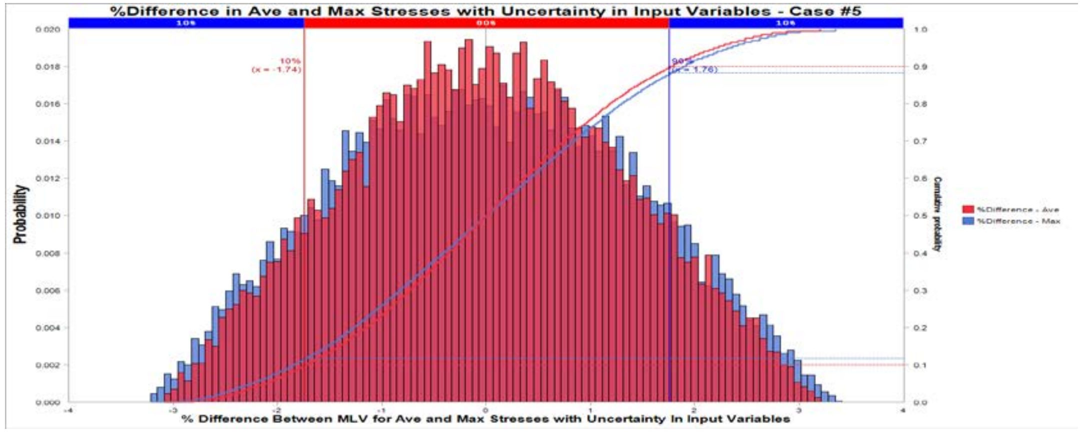
Input Variable Uncertainty Bounds (p. 153)

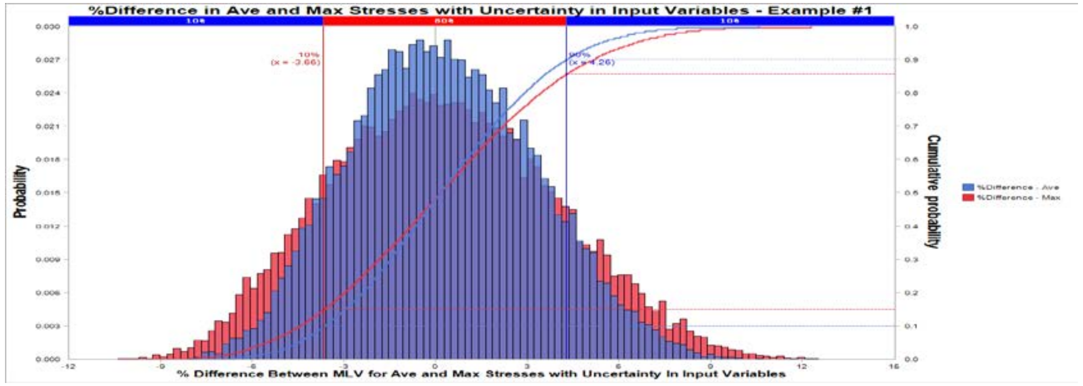
Input Variable	Units	Min/Max Bounds of Measurement
Pipe Tensile Strength (Class)	KSI	+/- 10%
Pipe Outer Diameter (OD)	Inches	+/- 1%
Flaw Depth (Flaw D)	Inches	+/- 5%
Flaw Length (Flaw L)	Inches	+/- 5%
Flaw Width (Flaw W)	Inches	+/- 5%
Burial Depth (Soil D)	Feet	+/- 10%

Summary of Simulation Results (p. 154)

Simulation Name	Class (ksi)	OD (in)	Span (ft)	Flaw D (in)	Flaw L (in)	Flaw W (in)	Soil Dep (ft)	%Diff Ave UPL	%Diff Max UPL	Factor of Safety (F.S.)
Failure Case #1	40	6	12	0.33	4.0	4.0	4.5	3.95%	3.60%	0.70
Failure Case #5	20	4	12	0.020	0.127	0.628	3	1.76%	1.88%	0.85
Example #1	30	10	18	0.25	4	8	6	4.26%	5.13%	1.06
Example #2	20	6	12	0.05	1	4	6	4.38%	5.15%	1.17
Example #3	50	8	18	0.2	1	5	6	4.26%	4.03%	1.14

Case #5 and Example #1 MC Simulation Results





Comprehensive, Testing-Based Validation Program

Subtitle

- The report summarizes the basis and specific recommendations for a comprehensive, testing-based validation program for the developed FFS model.
- The program considers and lists gray iron materials testing specifications, consensus standards for mechanical testing, currently available (new) gray cast iron materials, vintage piping samples to consider, and how many testing replicates are recommended for each material type.

Gray Iron Test Specifications (p. 159)

Physical Testing Validation Program Concept

Specification	Year	Class	UTS	Modulus of Rupture	Comments
AWWA Cast Iron Pipe Specification	1908	NA	20 ksi	NA	UTS by tensile bar
ASA A21.1 Cast Iron Pit Cast Pipe	1939	NA	11 ksi	40 ksi	UTS by burst test
ASA A21.7 Cast Iron Centrifugally Cast Pipe	1952	NA	18 ksi	40 ksi	UTS by burst test
ANSI/AWWA C101 Thickness Design of Cast Iron Pipe	1957	NA	21 ksi	45 ksi	Specimens Machined from Cast test Bars
ASTM A74 Standard Specification for Cast Iron Soil Pipe and Fittings	2016	NA	21 ksi	NA	
ASTM A48 Standard Specification for Gray Iron Castings	2016	class 20	20 ksi	NA	
		class 25	25 ksi		
		class 30	30 ksi		
		class 35	35 ksi		
		class 40	40 ksi		
		class 45	45 ksi		
		class 50	50 ksi		
		class 55	55 ksi		
		class 60	60 ksi		

Gray Iron Mechanical Tests (p. 160)

Physical Testing Validation Program Concept

Standards Organization	Test Type	Specification	Test Specimen approx dimensions	Comments	
ASTM	Compression Test	E-9 Standard Test Methods of Compression Testing	1" x 0.5"dia.	Standard ASTM compression test of machined cylindrical specimens, demanding requirements for test fixturing, specimen preparation.	
ANSI-AWWA	Talbot Strip Test of Modulus of Rupture	ANSI C106 Gray Iron Pipe Centrifugally Cast Pipe	10.5" x 0.5" x pipe wall thickness longitudinal from pipe specimen, parallel machined sides	4 point bend test, 10" between supports, loads applied at two points 3.33" in from supports.	Modulus of Rupture $R = Wl/td^2$ where W is the breaking load, *l* is the span between supports, t is the wall thickness and d is the machined width.
ANSI-AWWA	Pipe Ring Test for Modulus of Rupture	ANSI C106 Gray Iron Pipe Centrifugally Cast Pipe	for pipe ≤ 12" ring length = 1/2 the nominal dia., for pipe sizes ≥ 14", 10.5" ring length	3 edge ring compression test, U-channel in bottom hardwood block, single top hardwood block. This test is designed to produce longitudinal cracks.	$R = 0.954(W(d+t)/bt^2)$ where R is modulus of rupture, W is the breaking load, d is the inside diameter, t= thickness and b= ring length.
ASTM	Bend Test	A438 Standard Test Method for Transverse Testing Of Gray Cast Iron	15" x 1" round bar	3 point bend test with tables that allow estimates of UTS based on the breaking load of a test bar.	
ASTM	Tensile Test	A74 Standard Specification for Cast Iron Soil Pipe and Fittings , ASTM A48 and E8	4" long, 0.5" dia. in gauge length	Standard tensile test per ASTM A48 and E8m, specimen machined from cast bar.	
N/A	Strip Flexure Test	4 point bend test	120mm x 10mm x WT strip samples	Bend test used by Belmonte et al . 2008 to produce failure strength data and Weibull modulus. N = 10-15/pipe.	
N/A	Longitudinal Bend test	4 point bend test	1.4 m pipe specimen	Pipe bend test used by Seica *et al* 2004 to produce circumferential failures.	

New Production Gray Iron Materials (p. 161)
Physical Testing Validation Program Concept

Configuration	Manufacturer	Product	UTS spec	ASTM A247 Flake type	ASTM A247 Flake size	Matrix	Comments
Bars and Machined Tubes	Dura-Bar	G2	40 ksi min	A and D	4-6	pearlite, with ferrite/pearlite rim	This grade also produced in trepanned tubes, e.g. 7" OD with 5" ID
	Dura-Bar	G2S	40 ksi min	A and D	4-6	pearlite, rim 80% pearlite	This grade also produced in trepanned tubes, e.g. 7" OD with 5" ID
	Dura-Bar	G2P	40 ksi min	A and D	4-6	pearlite, rim 80% pearlite	
	Dura-Bar	G2A	40 ksi min	D	6-8	pearlite	
	Dura-Bar	G1A	25 ksi min	D	6-8	ferrite	Dura-Bar states that this grade is not a stock item but "can be ordered in volume quantities"
New Pipe	Charlotte Pipe	ASTM A74 Cast Iron Soil Pipe	21 ksi min	unspecified	unspecified	unspecified	(n.b. per the mfr's literature the pipes are spun cast, therefore the actual tensile is probably closer to the range of 30 to 40ksi than to 21ksi, see Makar & McDonald 2007)
Pipe Fittings	Charlotte Pipe	ASTM A74 Cast Iron Soil Pipe	21 ksi min	unspecified	unspecified	unspecified	(n.b. per the mfr's literature fittings are cast in static molds this should create a coarser graphite structure and lower UTS than spun cast pipe)

Planned Testing Matrix (p. 163)

Physical Testing Validation Program Concept

Material	TEST REPLICATES							
	Form	A48/E8 Tensile	E9 Compression	ASTM A247 Microstructure	4 point bend of longitudinal strip	4 point bend of pipe	3 point ring bearing	Hydrostatic Pressure Test
Vintage Pit Cast Iron Pipe	pipe 1	3	3	1	5	1	1	
	pipe 2	3	3	1	5	1	1	
	pipe 3	3	3	1				1
Vintage Spun Cast Iron Pipe	pipe 4	3	3	1	5	1	1	
	pipe 5	3	3	1	5	1	1	
	pipe 6	3	3	1				1
2018 A74 spun cast soil pipe (new production)	as received	5	5	1	15	3	3	1
	w. artificial defects				15	3	3	
2018 A74 static cast soil pipe fitting (new production)	as received	5	5	1	15	3	3	
	w. artificial defects				15	3	3	

Appendix Sections

Appendix A – Contains a Field Testing and Sampling Process

Appendix B – Contains a Training Manual for the FFS Excel-Based Calculator

Recommendations / Follow On Work

The Technical Advisory Panel (TAP) suggested:

- Expand the applicability of the calculator solution to include larger diameter pipe, 20 inch and larger, which several of them are currently using.
- Provide a full geo-spatial implementation example showing the solution applied to a cast iron network with rankings for an accelerated mains replacement program.

Based on these suggestions, the project team will augment the FFS solution for the larger diameter cast iron pipes from 14 to 48 inches and provide a geo-spatial example of the FFS solution applied to a pipe network.

These additional features will be distributed by an addendum report and revised calculator by December 31, 2018.

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