Service Life Evaluation of Corrugated HDPE Pipe

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Outline

- Definition of design service life
- Discussion of the failure criteria for service life of corrugated HDPE pipes
- Service life protocol
  - Design / Installation requirements
  - Material requirements
- Validation of service life model on full-scale pipe tests
- Conclusions

Design Service Life

Definition: The period of service of a culvert without a need for major repairs.

For Metal (CMP): Normally the period of years from installation until deterioration reaches the point of either perforation of any point on the culvert or some specified percent of metal loss.

For Concrete (RCP): Typically the period in years from installation until reinforcing steel is exposed, or a crack signifying severe distress develops.

For Plastic: Service life may be considered at an end when excessive cracking, perforation or deflection has occurred.

NOTE: It is important to recognize that culverts are not assumed to be at or near the point of collapse at the end of their design service life. Rather it is the period of little or no rehabilitative maintenance.

*(from AASHTO Volume XIV Highway Drainage Guidelines for Culvert Inspection and rehabilitation 1999 ISBN I-56051-128-1)

Failure Modes to Consider for Service Life of Corrugated HDPE Pipe

- Structural performance limits
  - Wall buckling, deflection, etc.
  - Controlled by profile design, installation, design methodology, and post-installation inspection
- Material degradation / cracking
  - Stage I, II or III
  - Controlled by materials and installation (limit tensile stresses)
- Other system performance limits – joints, connections, etc.

What's considered a failure?

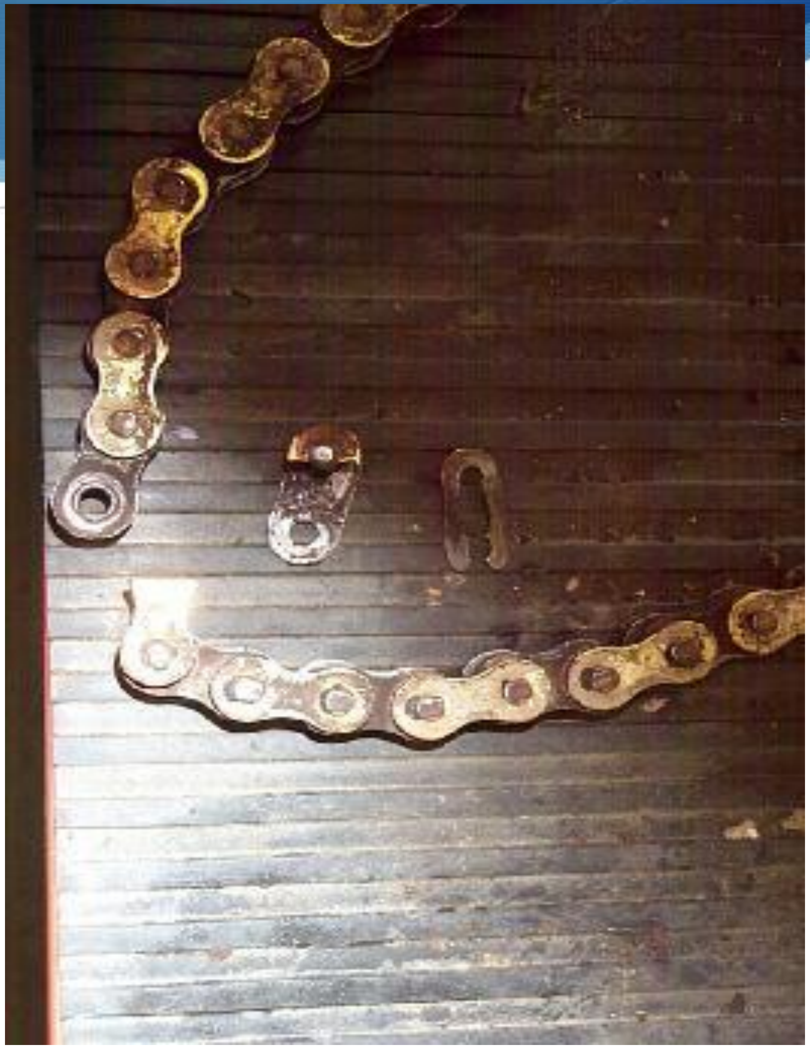
- Joint leakage?
- Installation issues?
- Backfill or compaction issues?

Figure 1.24 –Picture of Interstate 70 Sinkhole
Courtesy of Colorado Department of Transportation


ROAD CLOSED

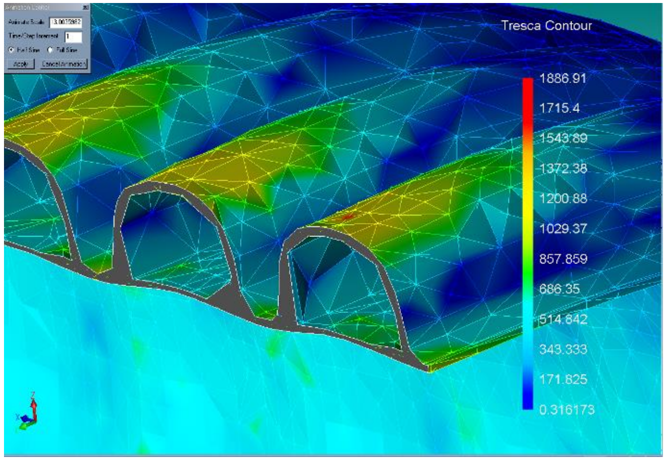
Failure Criteria for Service or Design Life

- Your piping system is only as good as its weakest link!



100-Yr. Service Life Considerations (Florida DOT Methodology)

- Structural design / installation considerations
  - Stress in pipe wall governed by installation conditions
  - Limit deflection and control with post-installation inspection
- Material considerations
  - Cracking due to Stage II (SCG) and Stage III (Oxidation / UV) failures



Determination of the Service Loads on Corrugated HDPE Pipe

- Buried corrugated HDPE pipe for gravity flow (low pressure) applications experiences live loads (traffic) and dead (earth)

- Deep fills subject the pipe to higher compressive stresses, while shallow fills and high deflections result in higher tensile stresses and strains

Stress in Pipe Wall – AASHTO LRFD Section 12

$$\sigma = \frac{P}{A} \pm \frac{Mc}{I}$$

σ = stress in pipe wall, psi
P = hoop thrust in pipe wall, lb/in
A = wall area, in^2/in
M = moment in pipe wall, lb-in/in
c = distance from extreme fiber in pipe wall to centroidal axis, in
I = moment of inertia of pipe wall, in^4/in

Stress in Pipe Wall – AASHTO LRFD Section 12

$$\sigma = \frac{P}{A} \pm \frac{Mc}{I}$$

Hoop Compression Stress (soil load)

Bending Stress (deflection)

Worst-Case Loading Condition for Cracking

- Goal for determining worst-case service condition for cracking: Minimize compressive stress while maximizing tensile stress
  - HDPE more prone to tensile failure than compressive
  - Worst-case condition = Low cover (low compressive stress), Max deflection (high bending stress)

Worst-Case Loading Condition for Cracking

- Worst-case service condition for cracking:
  - Minimize compressive stress / strain while maximizing tensile stress / strain
  - HDPE more prone to tensile failure than compressive
  - Worst-case condition = Low cover (low compressive stress), Max deflection (high bending stress)

0

Hoop Thrust Strain (Compression):

$$\varepsilon_t = 0.5 W_{sp} VAF / EA$$

Bending Strain (Tension):

$$\varepsilon_B = D_f(\Delta_b / D)(c / R)$$

Calculating Stress in the Pipe Wall

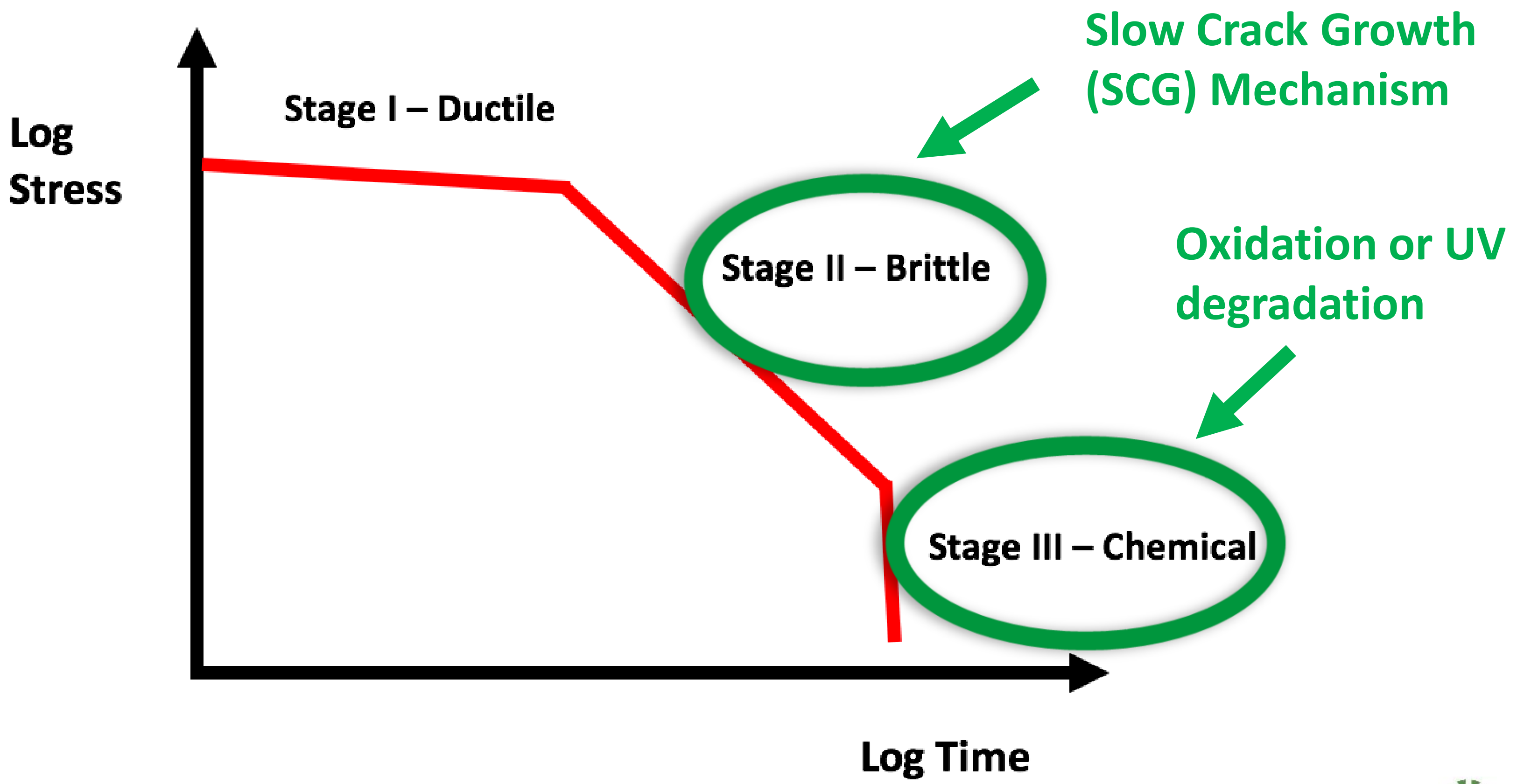
$$\varepsilon_B = D_f (\Delta_b / D)(c / R) = \underline{1.6\%}$$

$$\sigma = \varepsilon * E = 0.016 * 138 = \underline{2.2\ MPa\ (320\ psi)}$$

Conservatively, apply 1.5 factor for a factored stress of around 3.4 Mpa (500 psi)

ε_B =	Bending strain in pipe wall	Δ/D =	Vertical deflection = 5%
σ =	Stress in pipe wall	c_{out} =	Distance from centroid to extreme fiber of pipe wall
E =	Long-term modulus of elasticity = 20,000 psi (138 Mpa)	R =	Centroidal radius of pipe
D_f =	Shape factor = 4 for typical installations	c_{out}/R =	0.08 for typical corrugated HDPE pipe

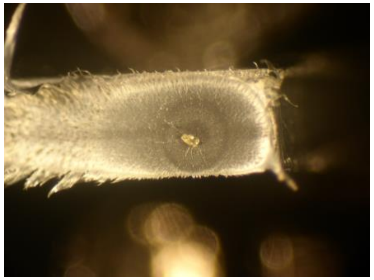
PE Failure Modes



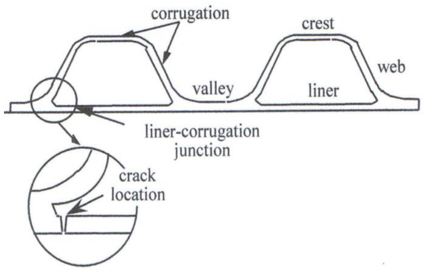
Stress Crack Tests

- Notched Constant Ligament Stress (NCLS) test – ASTM F2136

- Un-notched Constant Ligament Stress (UCLS) test – ASTM F3181 (for pipes containing recycled content)



- Junction Test (FDOT) – Qualification test



NCLS Test – ASTM F2136

- Index test that involves notching test specimens and placing them in a solution of water and Igepal @ 50 deg. C under a constant stress (600 psi) until stage II failure is observed
- M 294 requirements:
  - 18 hours on liner or
  - 24 hours on plaque
- CSA 182 requirements:
  - 24 hours on plaque
  - 400 hours for spiral pipe

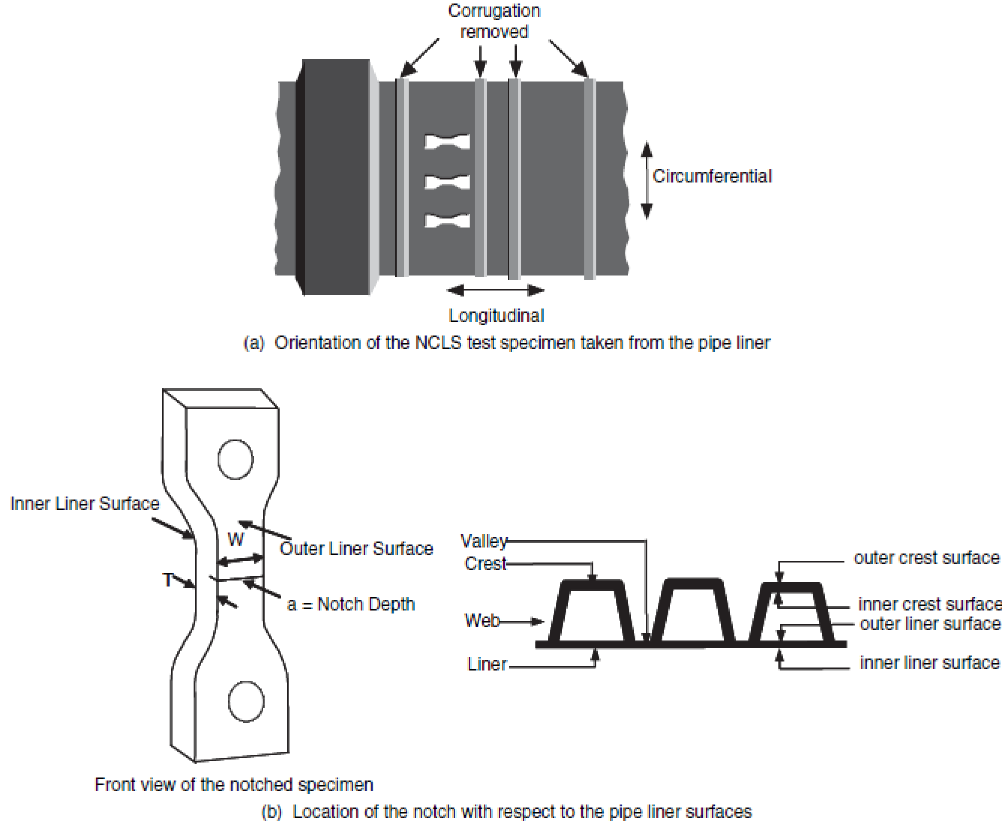


Figure F-1. NCLS test specimens from pipe liner.

UCLS Test – ASTM F3181

ASTM INTERNATIONAL

Designation: F3181 – 16

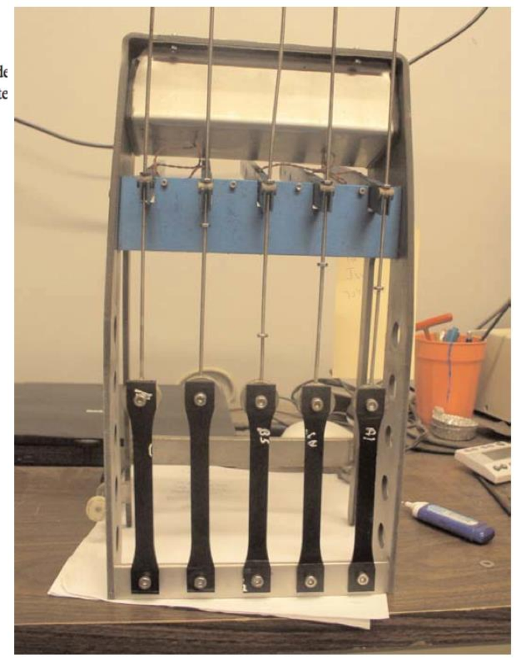
Standard Test Method for The Un-notched, Constant Ligament Stress Crack Test (UCLS) for HDPE Materials Containing Post- Consumer Recycled HDPE[1]

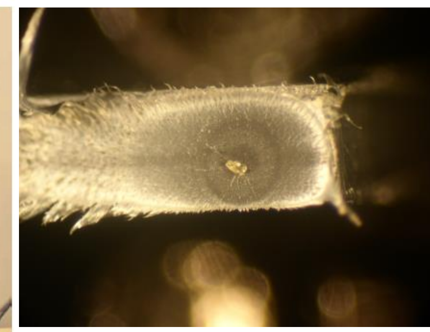
This standard is issued under the fixed designation F3181; the number immediately following the de
original adoption or, in the case of revision, the year of last revision. A number in parentheses indicate
superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

- Designed to evaluate crack initiation and propagation for pipes containing recycled materials

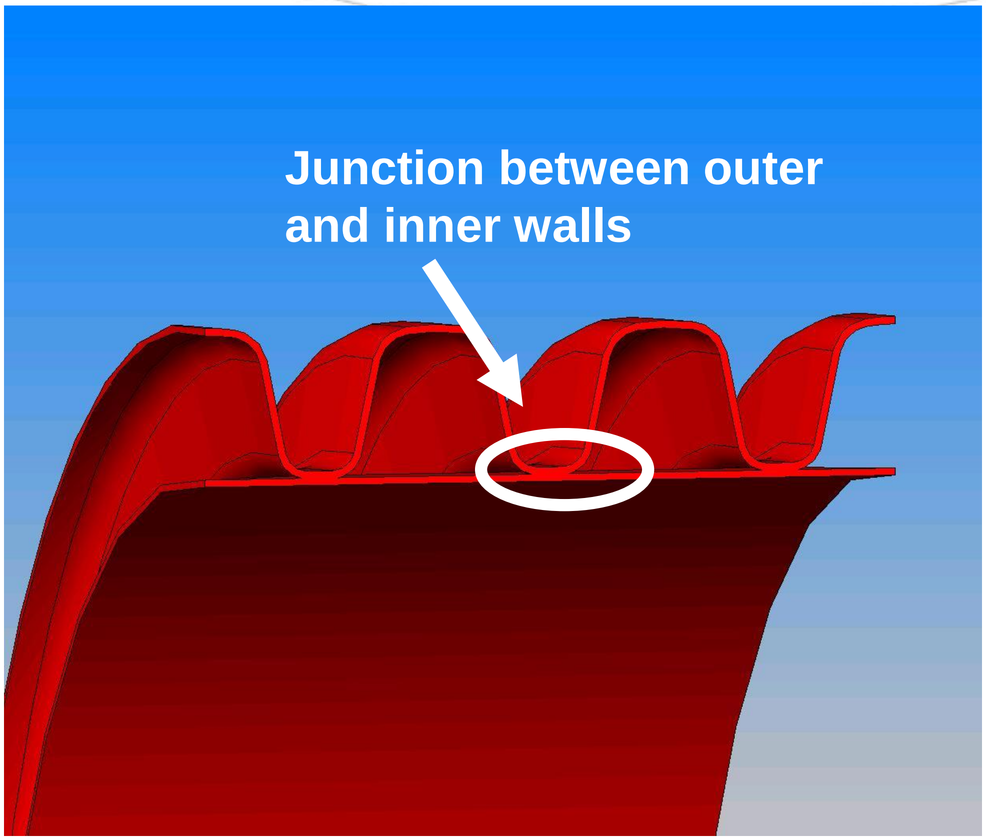
- Used for service life prediction

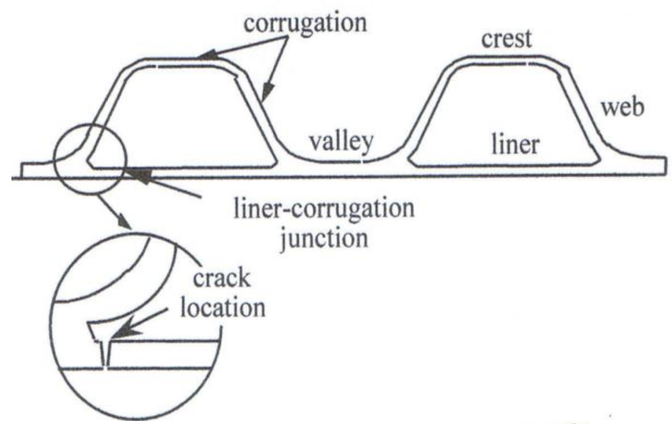
- Conducted in DI water at elevated temperatures (80 deg. C, 650 psi stress)

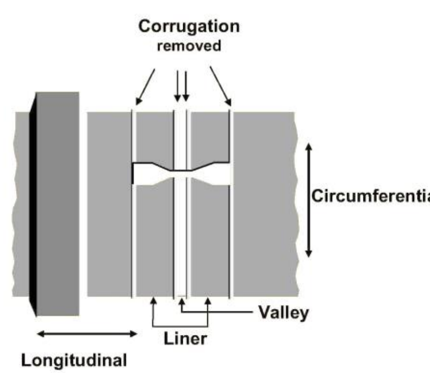




Junction Test (FDOT)







Methodology for Evaluating the Material's Resistance to Stage II Failure

- Conduct constant stress testing on specimens taken from the pipe wall in water at multiple elevated temperature / stress conditions
- Apply the Rate Process Method (RPM) or Popelar Shift Method (PSM) to shift data from test temperature and stress to service temperature and stress
- Same methodology used in pressure pipe industry, but test specimens and criteria are different

Example: Predicting Service Life Relative to Stage II Brittle Cracking (SCG) for Pipes Manufactured with Recycled Content (NCHRP Project 4-39, Pluimer)

- Conduct UCLS test in water at at least 3 different temperature / stress conditions (E.G. 80 deg. C / 650 psi; 80 deg. C / 450 psi; 70 deg. C / 650 psi)
- Use Popelar Shift Method (PSM) or Rate Process Method (RPM) to shift data from test temperature and stress to service temperature and stress:

Popelar Shift Method:

Stress Shift Factor = $e^{0.0116(T2-T1)}$

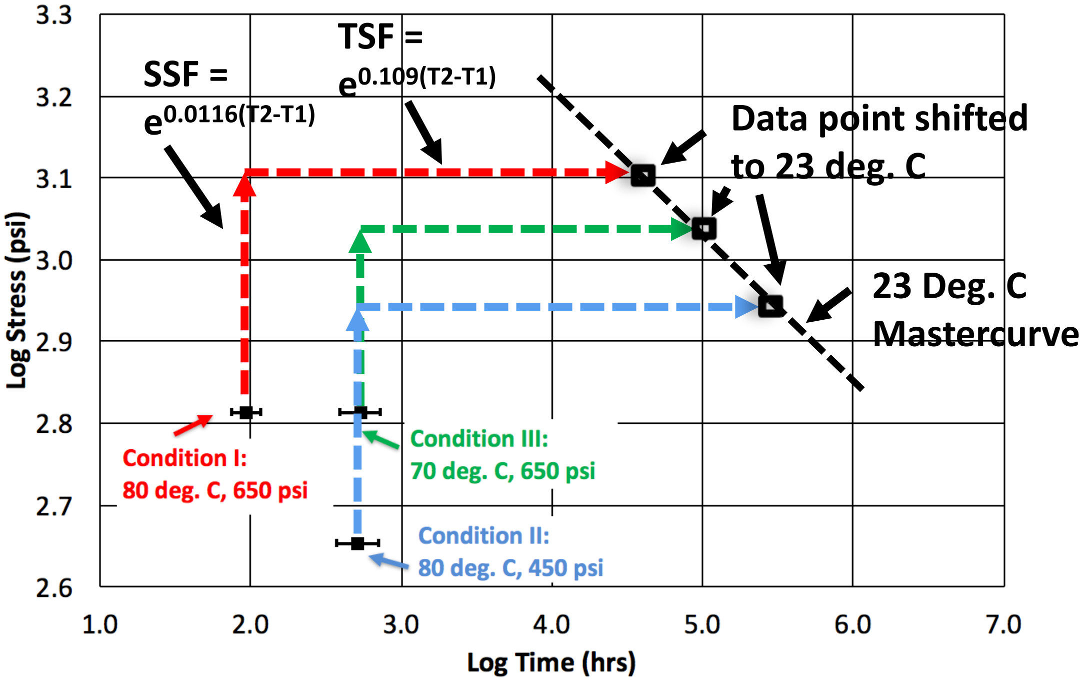
Time Shift Factor = $e^{0.109(T2-T1)}$

Rate Process Method:

$$\log t = A + \frac{B}{T} + \frac{C \log S}{T}$$

Illustration of Service Life Prediction

Pipe 4 – 49% PCR – UCLS Data shifted to 23 deg. C

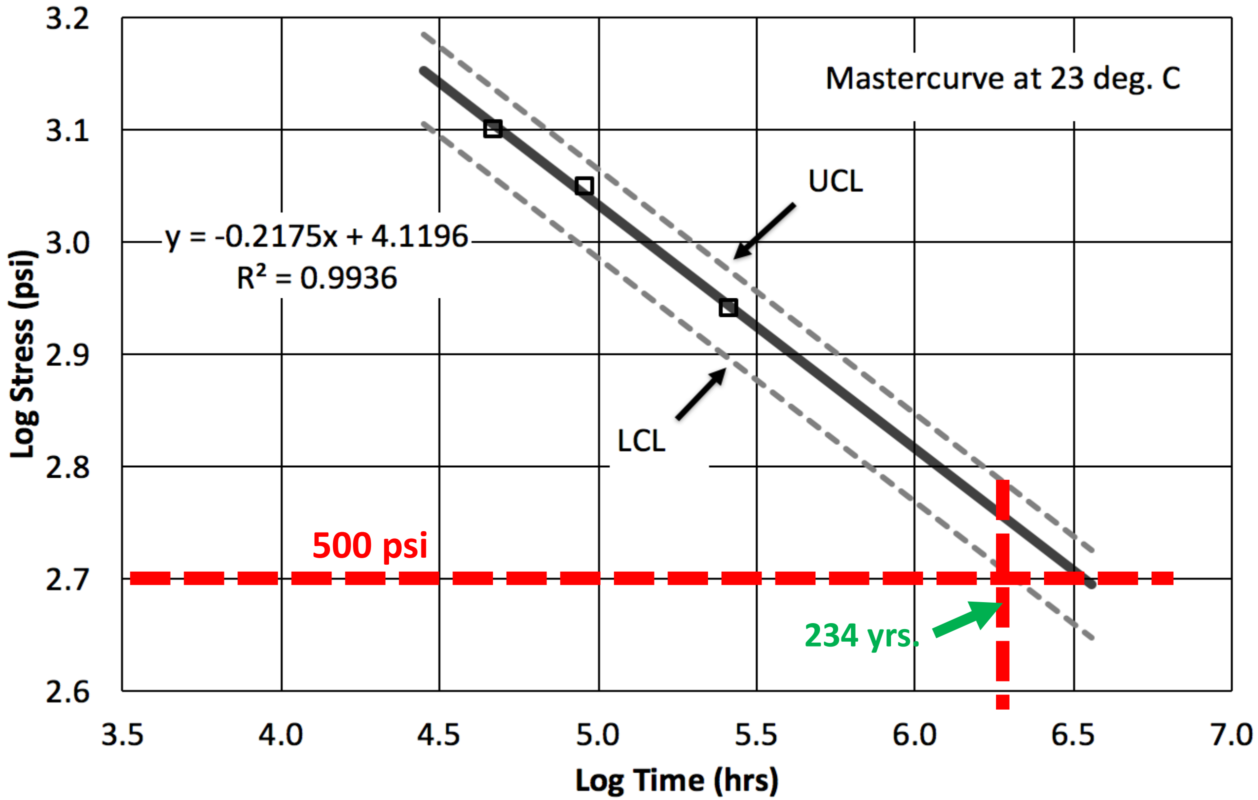


- Demonstration of bi-directional shifting using Popelar Shift Factors
- Shift elevated-temperature data to service temperature

Source: NCHRP Report 870, Pluimer, Sprague.

Illustration of Service Life Prediction

Pipe 4 – 49% PCR – UCLS Data Shifted to 23 deg. C



Source: NCHRP Report 870, Pluimer, Sprague.

Illustration of Service Life Prediction

Pipe 4 – 49% PCR – UCLS Data Shifted to 18 deg. C

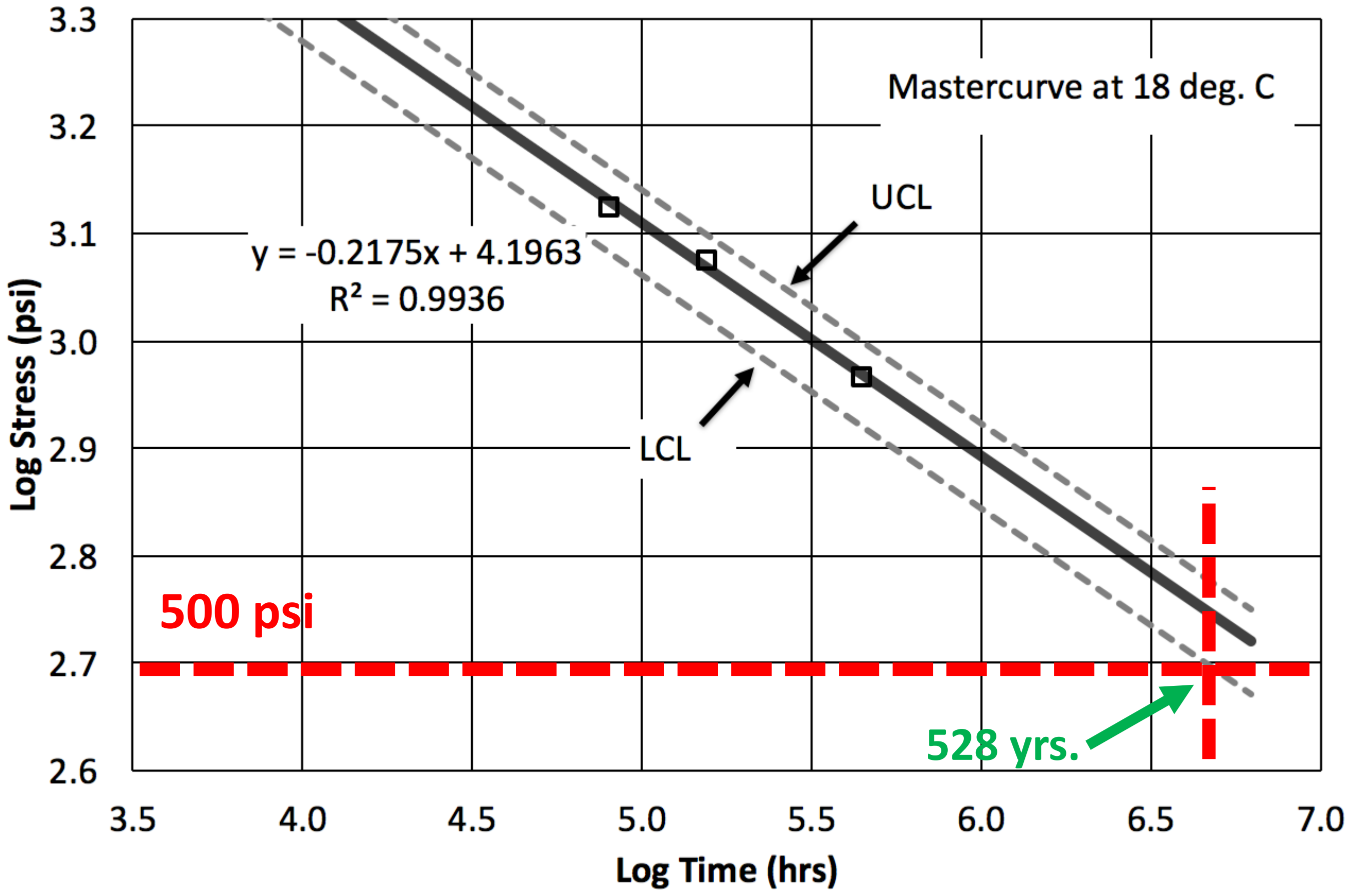
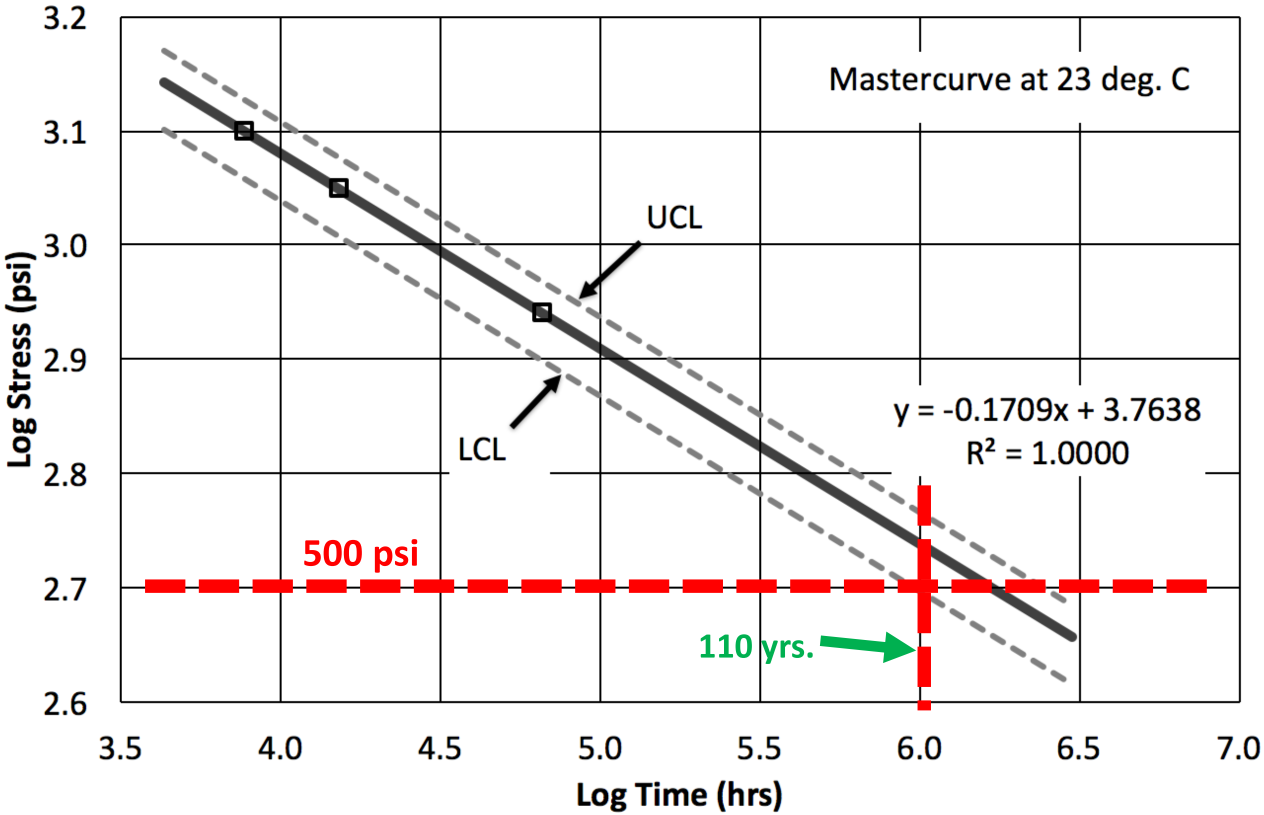


Illustration of Service Life Prediction

Pipe 3 – 98% PCR Pipe – UCLS Data Shifted to 23 deg. C



Source: NCHRP Report 870, Pluimer, Sprague.

Service Life Prediction @ 23 deg. C, 500 psi Stress, Relative to Stage II Cracking

Pipe	Mfctr.	Description	PCR	Predicted Service Life
Pipe 1	A	30 in. M294 pipe	0%	> 250 yrs.
Pipe 2	A	30 in. F2648 pipe	49%	> 250 yrs.
Pipe 3	A	30 in. Custom pipe	98%	110 yrs.
Pipe 4	A	30 in. F2648 pipe	49%	234 yrs.
Pipe 5	A	30 in. M294 pipe	0%	> 250 yrs.
Pipe 6	B	30 in. Custom pipe	98%	45 yrs.
Pipe 7	B	30 in. Custom pipe	98%	31 yrs.
Pipe 8	C	30 in. F2648 pipe	59%	> 250 yrs.
Pipe 9	C	30 in. F2648 pipe	54%	> 250 yrs.

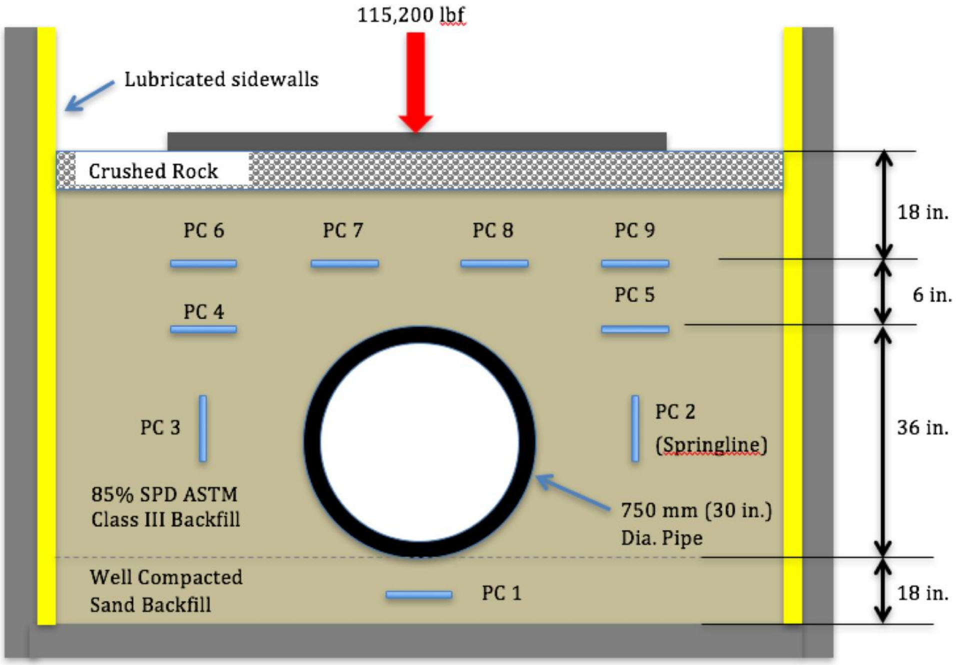
Source: NCHRP Report 870, Pluimer, Sprague.

Model Validation – NCHRP Project 4-39

- In NCHRP Project 4-39, the model was validated by accelerated testing on full-scale pipes
- Required producing pipe with blends of materials that were designed to fail within a year so that the model could be validated in a reasonable timeframe

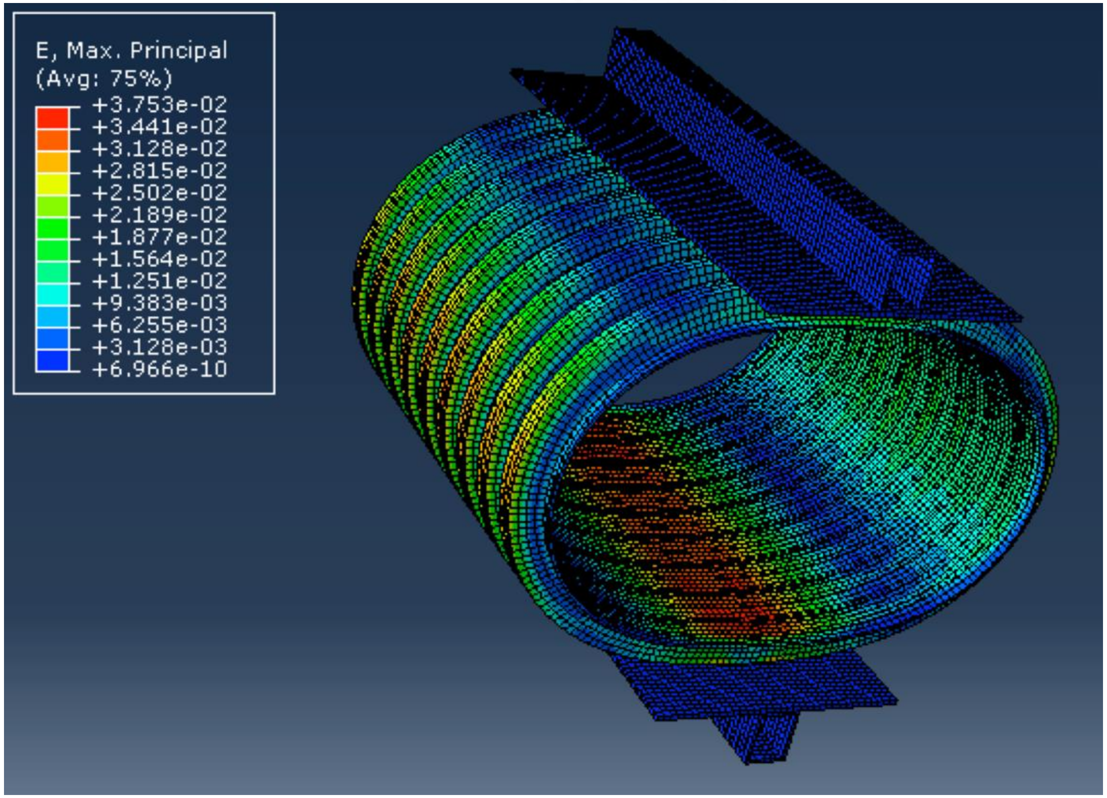
Source: NCHRP Report 870, Pluimer, Sprague.

Simulated Field Test – NCHRP Project 4-39



Source: NCHRP Report 870, Pluimer, Sprague.

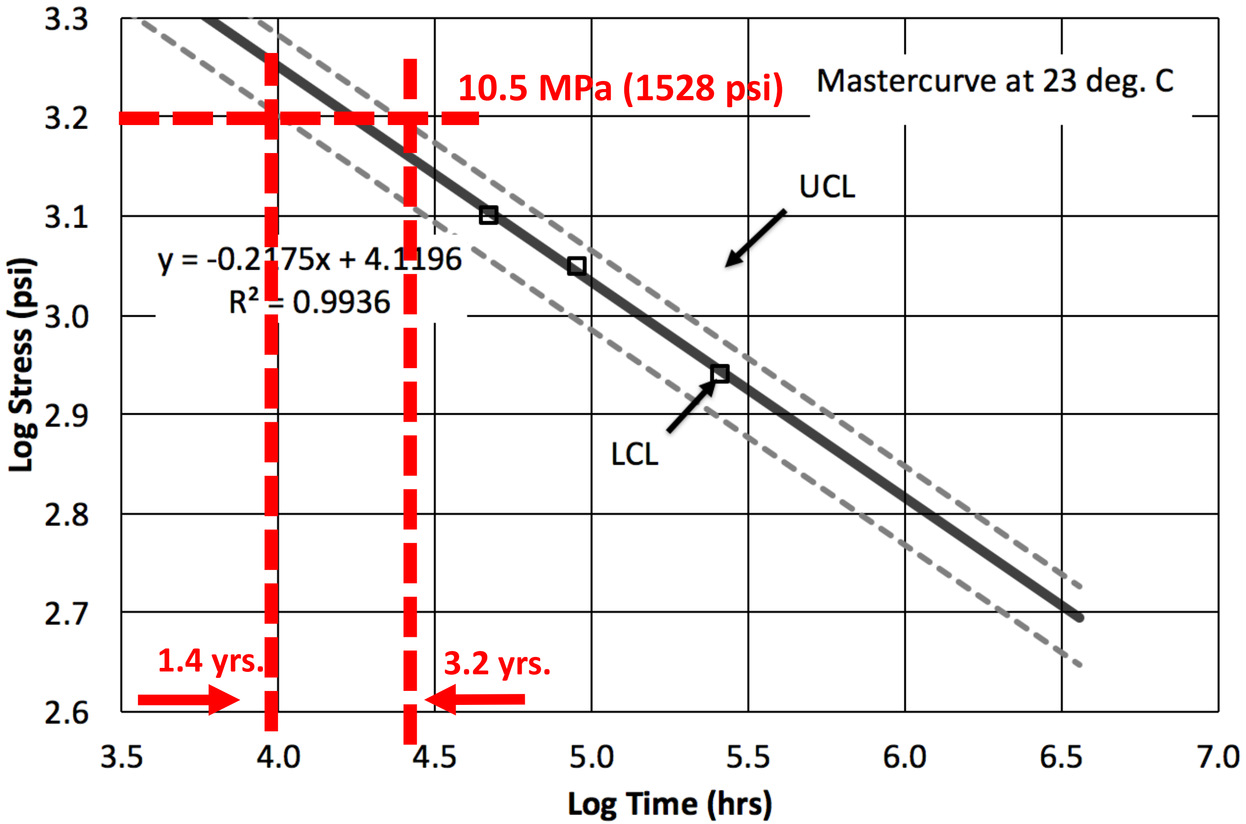
FEA Analysis – NCHRP Project 4-39



Source: NCHRP Report 870, Pluimer, Sprague.

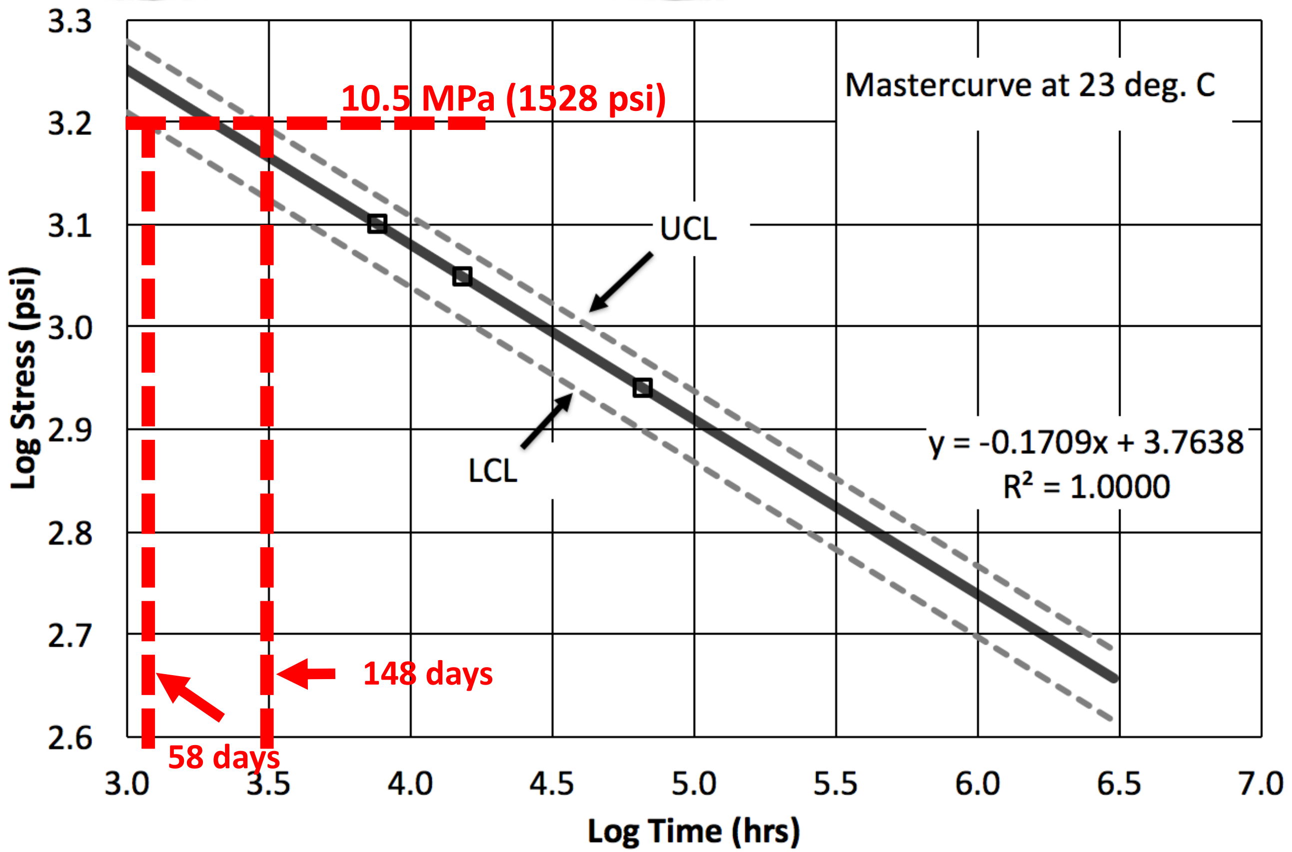
- Peak local strain at 20% deflection = 3.75%
- Peak tensile strain in simulated field test on buried pipes = 3.5%
- Average peak stress under these conditions ~ 10.5 MPa (1528 psi)

Illustration of Service Life Prediction Pipe 4 – 49% PCR – UCLS Data Shifted to 23 deg. C



Source: NCHRP Report 870, Pluimer, Sprague.

Illustration of Service Life Prediction Pipe 3 – 98% PCR Pipe – UCLS Data Shifted to 23 deg. C



Source: NCHRP Report 870, Pluimer, Sprague.

Full Scale Pipe Validation Testing in Accelerated Loading Conditions

Pipe	Description	PCR	Predicted Time to Cracking	Actual Time to First Cracking
Pipe 1	30 in. M294 pipe	0%	> 2 yrs.	> 1 yr. - No cracks
Pipe 2	30 in. F2648 pipe	49%	> 2 yrs.	> 1 yr. - No cracks
Pipe 3	30 in. Custom pipe	98%	58 – 148 days	101 days
Pipe 4	30 in. F2648 pipe	49%	1.4 – 3.1 yrs.	> 1 yr. - No cracks
Pipe 5	30 in. M294 pipe	0%	> 2 yrs.	> 1 yr. - No cracks
Pipe 6	30 in. Custom pipe	98%	71 – 220 days	185 days
Pipe 7	30 in. Custom pipe	98%	73 – 172 days	185 days
Pipe 8	30 in. F2648 pipe	54%	203 - 578 days	> 306 d - No cracks
Pipe 9	30 in. F2648 pipe	59%	139 – 357 days	300 days

Source: NCHRP Report 870, Pluimer, Sprague.

Cracking in Pipe 3 – 98% PCR Pipe

Source: NCHRP Report 870, Pluimer, Sprague.

Highlights of Service Life Prediction Method

- Every pipe that was predicted to crack developed cracks within the predicted timeframe, both for the parallel plate test and the simulated field test
- None of the pipes that were not predicted to crack developed cracks
- Based on these test results, the service life prediction model based on the UCLS test was validated
- The UCLS test provides the basis for a true performance-based specification for pipes manufactured with recycled materials
- *Note: The validation tests are extreme tests and are not typical of actual installations; Additionally, the pipes were formulated with blends of materials designed to crack within a reasonable timeframe*

Standard Recommended Practice for Service Life Determination

Standard Recommended Practice for

Service Life Determination of Corrugated HDPE Pipes Manufactured with Recycled Materials

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AASHTO Designation: M xxx-yy[1]

Technical Section: No., Name

Release: Group n (Month yyyy)

AASHTO

American Association of State Highway and Transportation Officials
444 North Capitol Street N.W., Suite 249
Washington, D.C. 20001

- Details procedure for determining the service life of corrugated HDPE pipes manufactured with recycled materials
- Provides equations to determine the minimum UCLS requirements to ensure service life at given conditions
- Balloted in October 2018, passed 48-0
- Published June 2019

Determining Minimum UCLS

$$t_T = {10^C}/{SF_t}$$

where

$$C = \left[\frac{\log(SF_\sigma * \sigma_T) - \log(\sigma_{SVC})}{m}\right] + \log(t_{SVC})$$

t_T = time to failure @ test cond., hrs.
m = slope of brittle curve
SF_σ = Stress shift factor
SF_t = Time shift factor

t_{SVC} = service life, hrs.
σ_{SVC} = design stress at service cond., psi
σ_T = stress at UCLS test condition, psi

Source: PhD Dissertation, Pluimer

Adjust for 95% Confidence

$$LCL_{95\%} = t_T = \bar{X}_{95\%} - t_{(n-1)}\left(COV * \bar{X}_{95\%} / \sqrt{n}\right)$$

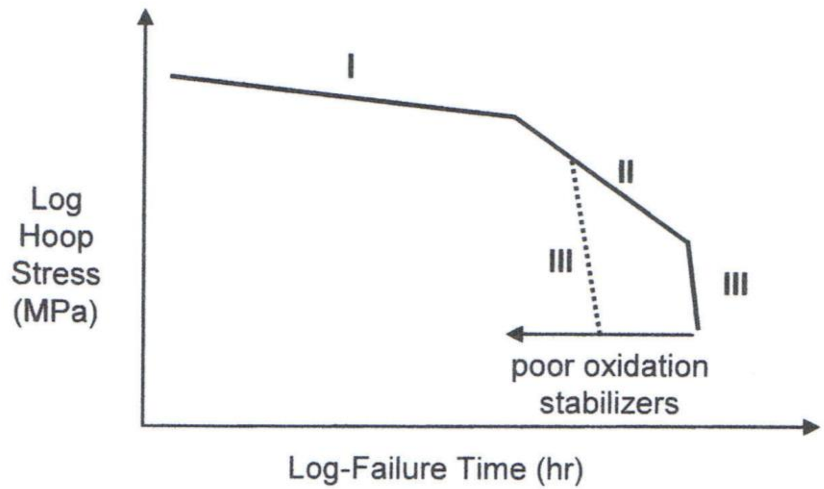
$$\bar{X}_{95\%} = \frac{t_T}{\left[1-\left(t_{(n-1)}*COV / \sqrt{n}\right)\right]}$$

X_{95} = Minimum UCLS test requirement
t_T = time to failure @ test cond., hrs.
t_{n-1} = t-statistic for 95% CI = 2.132
COV = Maximum coefficient of variation = 0.5
n = number of test specimens = 5

Source: PhD Dissertation, Pluimer

Ensuring Resistance to Stage III Failure

- To ensure Stage III failures do not occur in the piping system throughout the 100-year design life, antioxidants are added to the material formulation
- A 20-minute OIT test is required for pipes manufactured with recycled content
- Thermal stability test required for standard pipes manufactured with virgin materials
- Carbon black added to prevent UV degradation



A lack of antioxidants will shift Stage III failures to the left, potentially limiting the service life (McGrath and Hsuan, 2005)

Resources / References

- **Hsuan, Y. G. and McGrath, T. J.** *Protocol for Predicting Long-term Service of Corrugated High Density Polyethylene Pipes.* s.l. : Florida Department of Transportation, 2005. http://www.dot.state.fl.us/statematerialsoffice/laboratory/corrosion/hdpe/20050729_report.pdf

- **Pluimer, Michael.** Evaluation of Corrugated HDPE Pipes Manufactured with Recycled Content in Commuter Rail Applications. *Dissertation.* Villanova, PA : Proquest , 2016.

- **Pluimer, Michael; Sprague, Joel.** NCHRP Report 870: Field Performance of Corrugated HDPE Pipes Manufactured with Recycled Materials. National Academy of Sciences, Washington, DC. 2018.

- **Pluimer, Michael.** A Service Life Assessment of Corrugated HDPE Drainage Pipes. *Journal of ASTM International.* Conshohocken, PA 2011.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No one outsmarts a Fox.
Questions?