Competitive Academic Agreement Program

"Glass-Polymer Composite High Pressure Pipes and Joints Design, Manufacture & Characterize"

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Project Team

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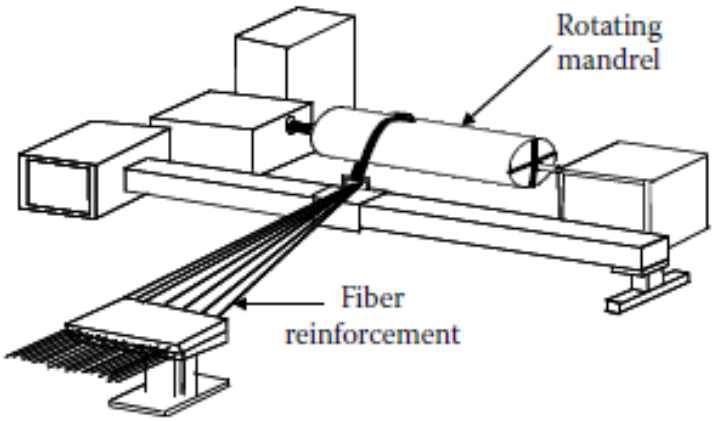
Research Objectives

- Develop GFRP pipes capable of resisting high burst pressures (up to 10,000 psi)
- Conduct burst testing of pipes for strength and failure modes
- Conduct burst testing of joints for strength and failure modes
- Burst pressure prediction through Classical Lamination Theory (CLT)
  - CLT for elastic prediction
  - Failure progression, failure criterion, failure prediction
- Investigate the detection of above pipes in buried state using Ground Penetrating Radar (GPR).
- Investigate the detection of buried pipe/gas leak using Mass Spectroscopy.

GFRP Pipe Manufacturing

- Fibers are wetted by running through a resin bath
- Wet fibers are wound around a mandrel
- Curing is activated by applying heat to the pipe
- Shrink wrap is wrapped around pipe to insure a void free surface



Glass Fiber Reinforced Polymer Pipe

- Corrosion resistance, soil interaction, pH, Moisture
- Resistance to hydrogen embrittlement
- Less electrical conductivity than steel
- Less thermal conductivity, fire resistance
- Higher strength to weight ratio than steel
- Better flexibility-differential settlement
- Potential for easier detectability

Research Methodology

- Hydrostatic burst pressure testing for strength
- CLT prediction- strength prediction
- Comparisons- Elastic, Failure Progression

Strength Determination

- 18 samples tested, regression analysis to determine long term hydrostatic pressure (LTHP)
- Determine hydrostatic design basis (HDB) from design tables
- Determine hydrostatic design pressure based on HBD and safety factors

Filament Wound Butt Joints

- 2 of 10” OD FW pipes
- Wrapped with bidirectional fibers
- Gauges on wrap and pipe
- Failed near 1,000 psi at the joint

FW Pipe Testing

- 3 of Thin Wall (0.45”)
  - 3,000 psi
- 3 of Thick Wall (0.80”)
  - 2 x 5,200 psi
  - 1 x 4,000 psi
- 4 strain gauges
  - 2 hoop, 1 axial, 1 fiber angle

10” OD Filament Wound Samples

Thin Wall Results

Specimen	Burst Pressure (psi)	Hoop A Failure Strain (με)	Hoop B Failure strain (με)	Average Hoop Failure Strain (με)	Longitudinal Failure Strain (με)	Fiber Angle Failure Strain (με)	Time to Failure (min)
1	2,761	15,800	15,179	15,490	-13,425	7,219	12.8
2	2,969	16,622	17,919	17,270	-12,975	4,855	14.0
3	3,142	15,415	17,411	16,278	-19,475	4,085	20.9

Thin Wall Failure Modes

- Interlaminar Delamination of layers
- No Fiber breakage
  - Failure of resin
  - Debonding
  - Fiber separation
- Pipe would leak, lose pressure, seal itself

Thin Wall Failure Modes

Thick Wall Results

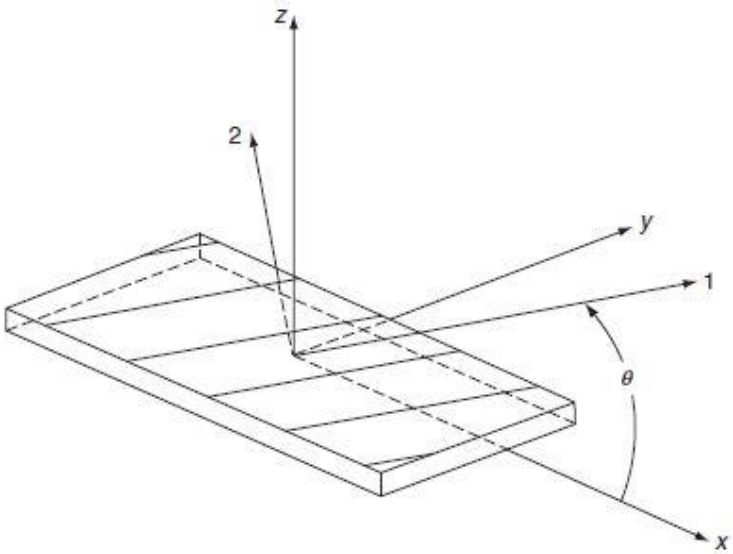
Specimen	Burst Pressure (psi)	Hoop A Failure Strain(με)	Hoop B Failure Strain(με)	Average Hoop Failure Strain (με)	Longitudinal Strain at Failure(με)	Fiber Angle Strain at Failure(με)	Time to Failure (min)
1	5,172	26,477	23,045	24,761	-37,543	-467	34
2	5,247	11,927	15,617	13,770	-18,938	1,623	25
3	4,024	14,816	13,889	14,352	-16,274	-1,505	11

Thick Wall Failure Modes

- Inconsistent Damage
- Interlaminar Delamination of layers
- No Fiber breakage
- Pipe would leak, lose pressure, seal itself

Failure Modes

Classical Lamination Theory

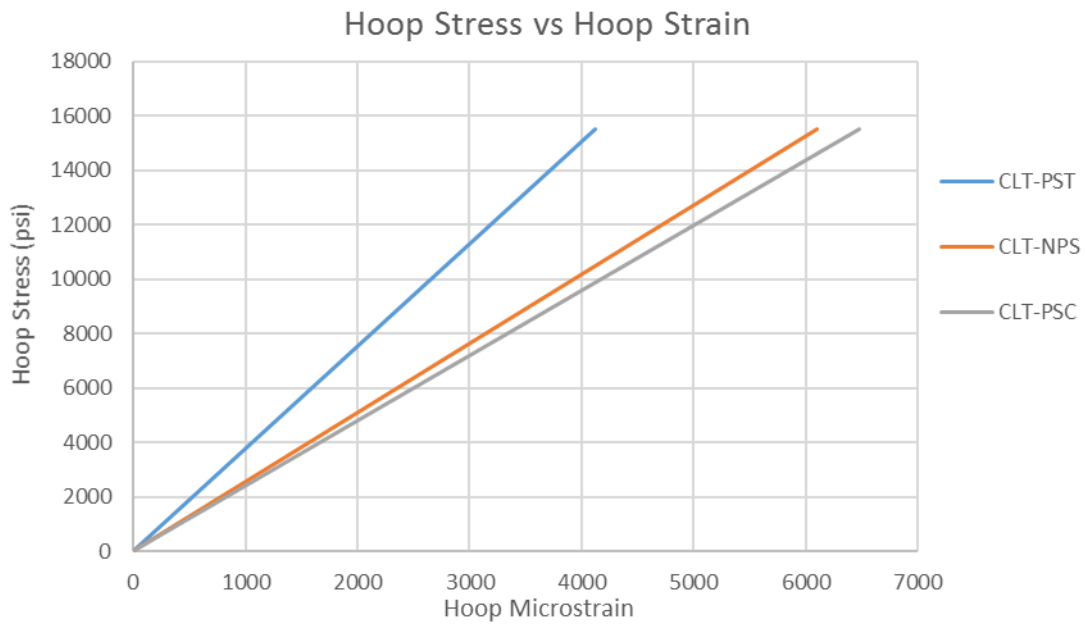


- Process through which fiber properties are transformed from fiber coordinates to global coordinates
- Assumes walls to be thin plate

Thin Wall Pipes

- Thin wall approximation R/t>10
- ⅜ Wall pipe
  - Thickness 0.45 inch, Radius 4.65 inch
  - 10<10.33<20
  - Thin Wall
- ¾ Wall Pipe
  - Thickness 0.8 inch, Radius 4.81 inch
  - 6.01<10<20
  - Thick Wall

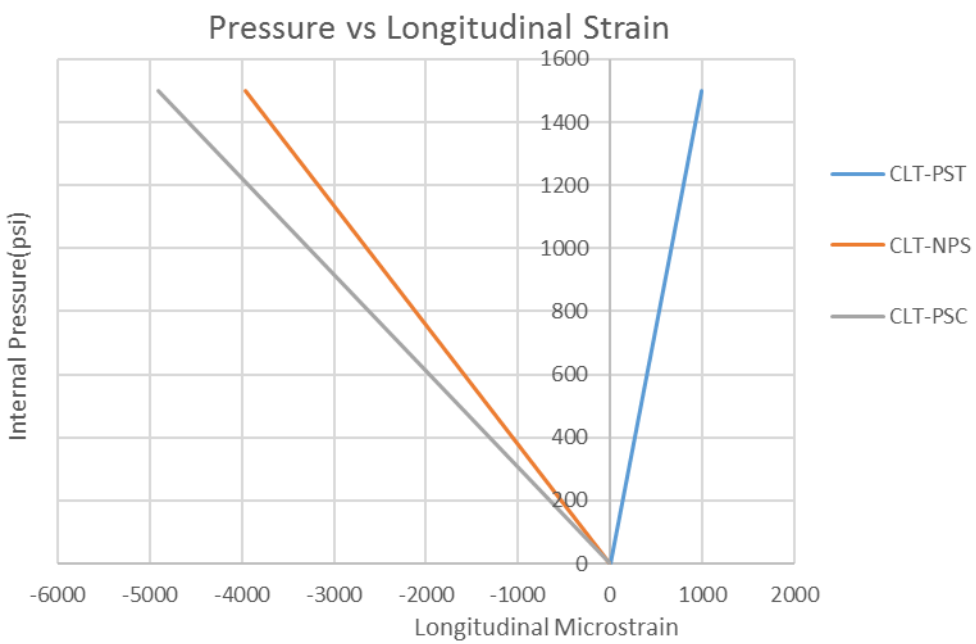
Thin Wall Hoop Stress/Strain Response



Prediction	Hoop Modulus (Msi)	Percent Difference
PST	3.76	+32.4
NPS	2.54	0
PSC	2.39	-5.91

- This is actually “apparent” modulus.
- True modulus never changes
- Predicted strains change
- Compared against approximated stresses

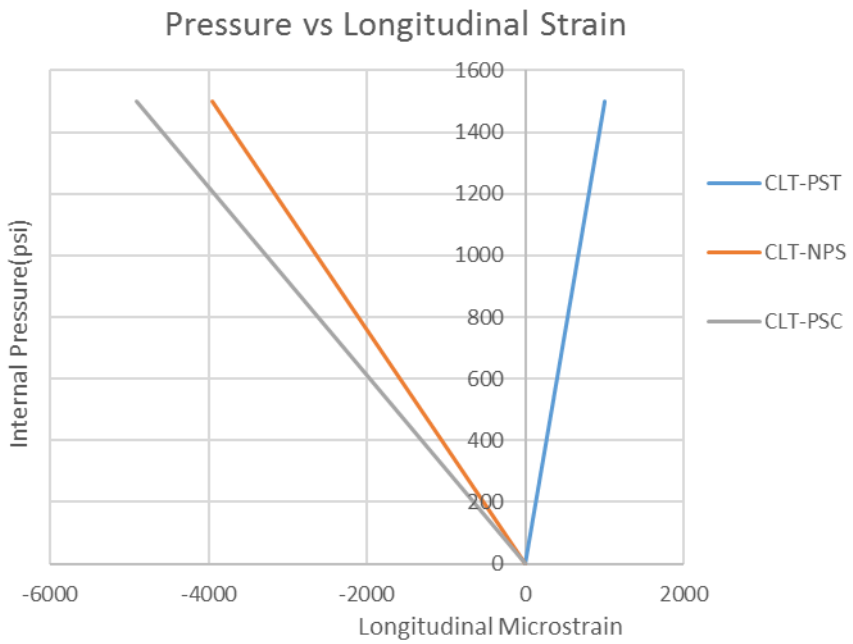
Thin Wall Longitudinal Pressure/Strain Response

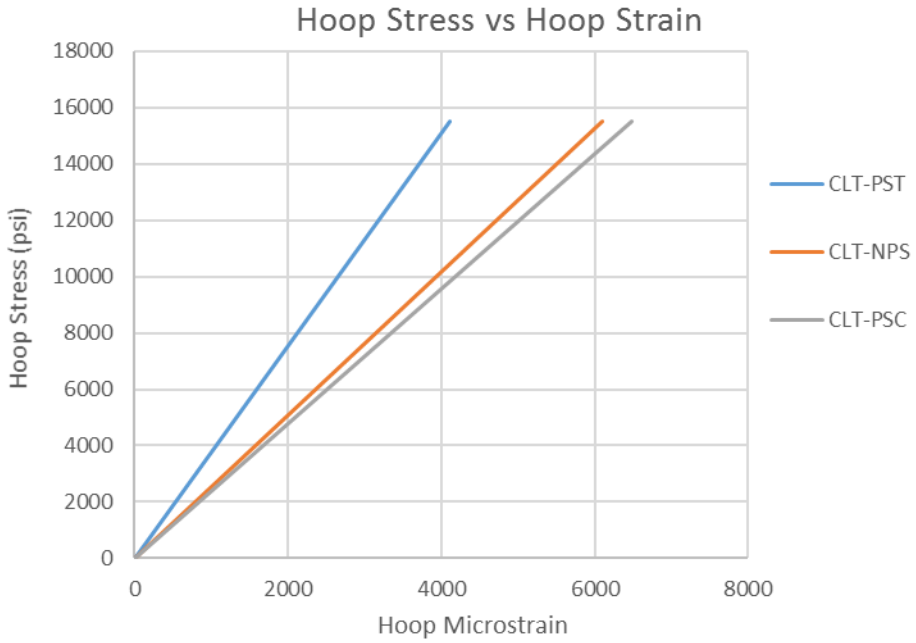


Prediction	Strain at 1,000 psi (με)	Percent Difference
PST	663	125
NPS	-2,637	0
PSC	-3,276	-19.5

- Hard to compare stress/strain when stress is not theoretically exerted for each model
- Pressure vs strain used instead

Plane Stress Scenario





Failure Progression

- CLT is the elastic prediction
- Failure progression based on failure criteria
  - Max Stress, Max Strain, Tsai-Wu, Tsai-Hill
  - Based on 5 strength properties of unidirectional lamina
- Stiffness degradation of failed plys
- Progresses till last ply failure

Hoop Stresses

Sample Name	Lame's Outer Hoop Stress (psi)	Lame's Inner Hoop Stress (psi)	Thin Wall Hoop Stress (psi)	Lame's Outer vs Thin Wall Difference	Lame's Inner vs Thin Wall Difference
3/4 Sample 1	30362	35534	32759	-7.3%	8.5%
3/4 Sample 2	30802	36049	33234	-7.3%	8.5%
3/4 Sample 3	23623	27647	25488	-7.3%	8.5%
3/8 Sample 1	27573	30352	28899	-4.6%	5.0%
3/8 Sample 2	29156	32125	30571	-4.6%	5.1%
3/8 Sample 3	30569	33711	32067	-4.7%	5.1%

Hoop Properties

Specimen	Average Hoop Modulus (Msi)	CLT-PSC Prediction (Msi)	Percent Error (%)	Lame's Outer Surface Hoop Modulus (Msi)	CLT-PSC Prediction (Msi)	Percent Error (%)
1	3.07	2.25	26.7	2.30	2.25	2.2
2	4.26	2.25	47.2	3.74	2.25	39.8
3	2.96	2.25	24.0	2.49	2.25	9.6

Concluding Observations

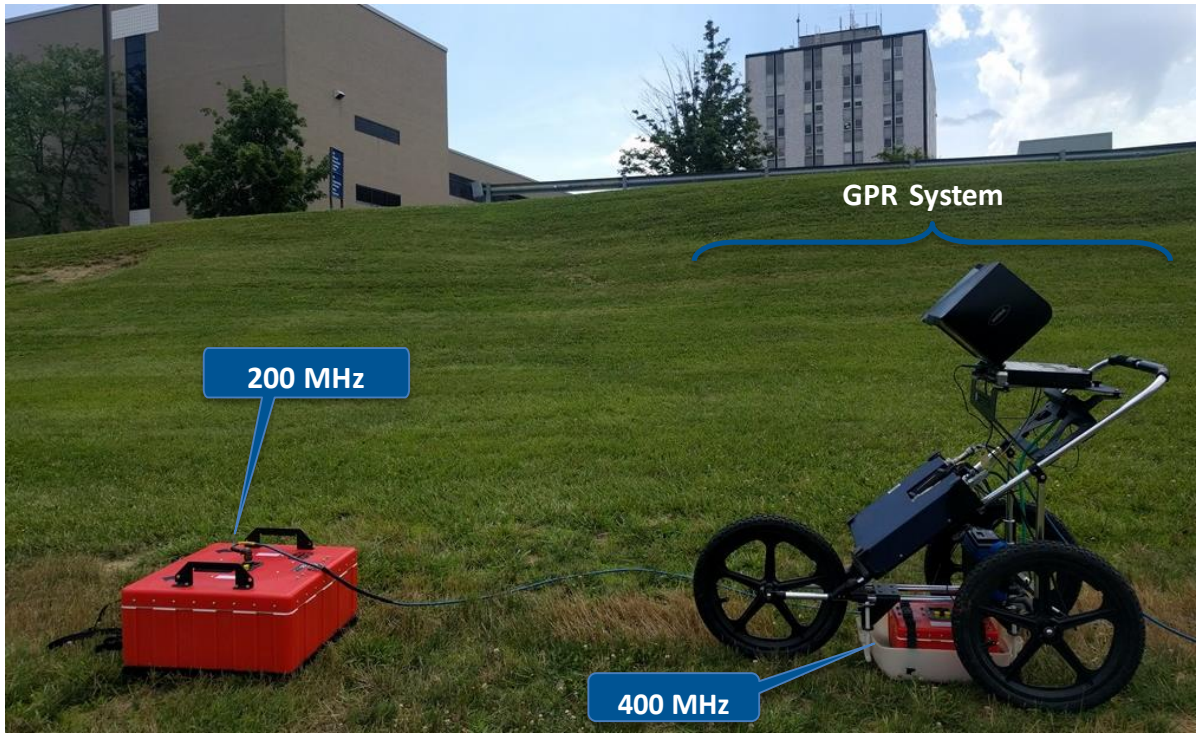
- Burst pressure testing to 5,200 psi
  - 3,000 psi for the thin wall specimens
- Burst pressure testing of joints near 1,000 psi
- CLT predict stress/strain behavior up to ≈ 30 percent ultimate stress
  - Failure predictions through CLT not yet produced
- Failure modes appear to be related to shear forces within the resin
  - Deboning of corrosion barrier layer
  - Fiber strain, debonding between fiber and resin, leakage
  - No fiber failure

GPR for Buried Pipe Detection

- Continuation of a previous study on locating buried non-metallic pipes using GPR.
- Previous Study:
  - ✓ Detectability of buried 12", 6", and 3" diameter PVC, GFRP, and CFRP pipes
  - ✓ Different external surface finishes and
  - ✓ Buried at different depths (up to 4 ft. of soil cover)
  - ✓ Investigated using GPR.
- Six pipe sections investigated in the current study (bigger diameter pipes at lower depths).

GPR Test Equipment

Manufacturer specifies maximum penetration depth as 30 ft. for 200 MHz (45 lb) and and 12 ft. for 400 MHz (11 lb)respectively



GPR equipment setup.

Two different antennae evaluated

200 MHz antenna with survey wheel.

Research Approach

Tasks to achieve the objective of the GPR test:

- Wrap a GFRP pipe with carbon fabric strip for easy detection.
- Create GFRP pipe with carbon nanoparticles overlay/coating.
- Wrap a PVC pipe with aluminum tape strip for easy detection.
- Compare with unwrapped GFRP pipe and steel pipe (control specimens).
- Investigate and compare the detectability of the above pipes (buried) using GPR.

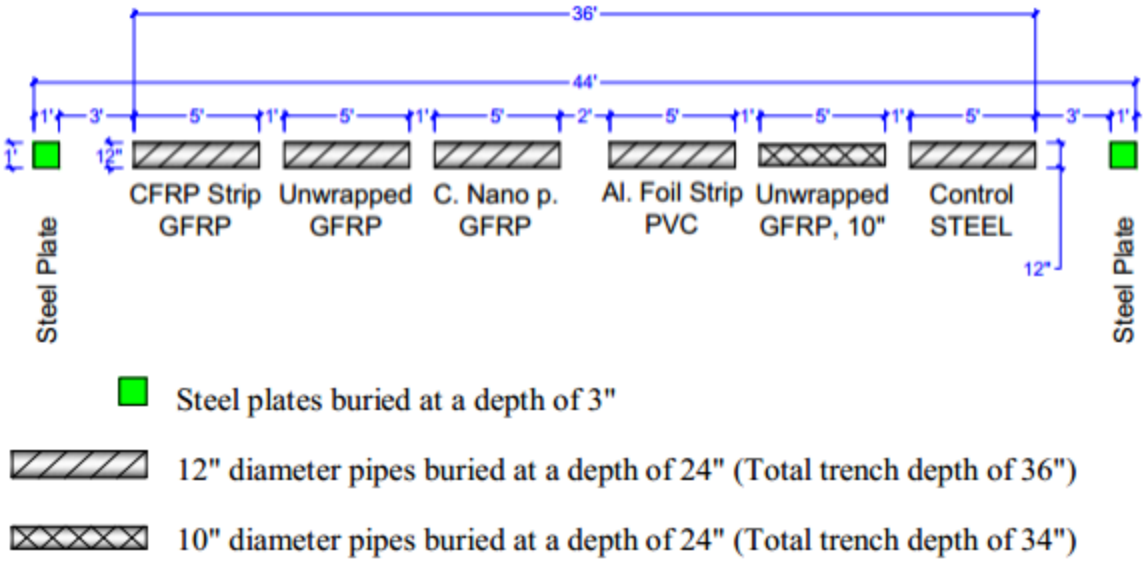
Pipe Samples

12" diameter GFRP with carbon fabric strip, and
12" diameter GFRP with carbon nanoparticle overlay

12" diameter PVC with aluminum strip, and
12" diameter steel control

Pipe Samples (continued)

All pipe samples buried at 2 ft. depth



Pipe layout for GPR testing.

Pipe samples being buried.

Decagon Sensors

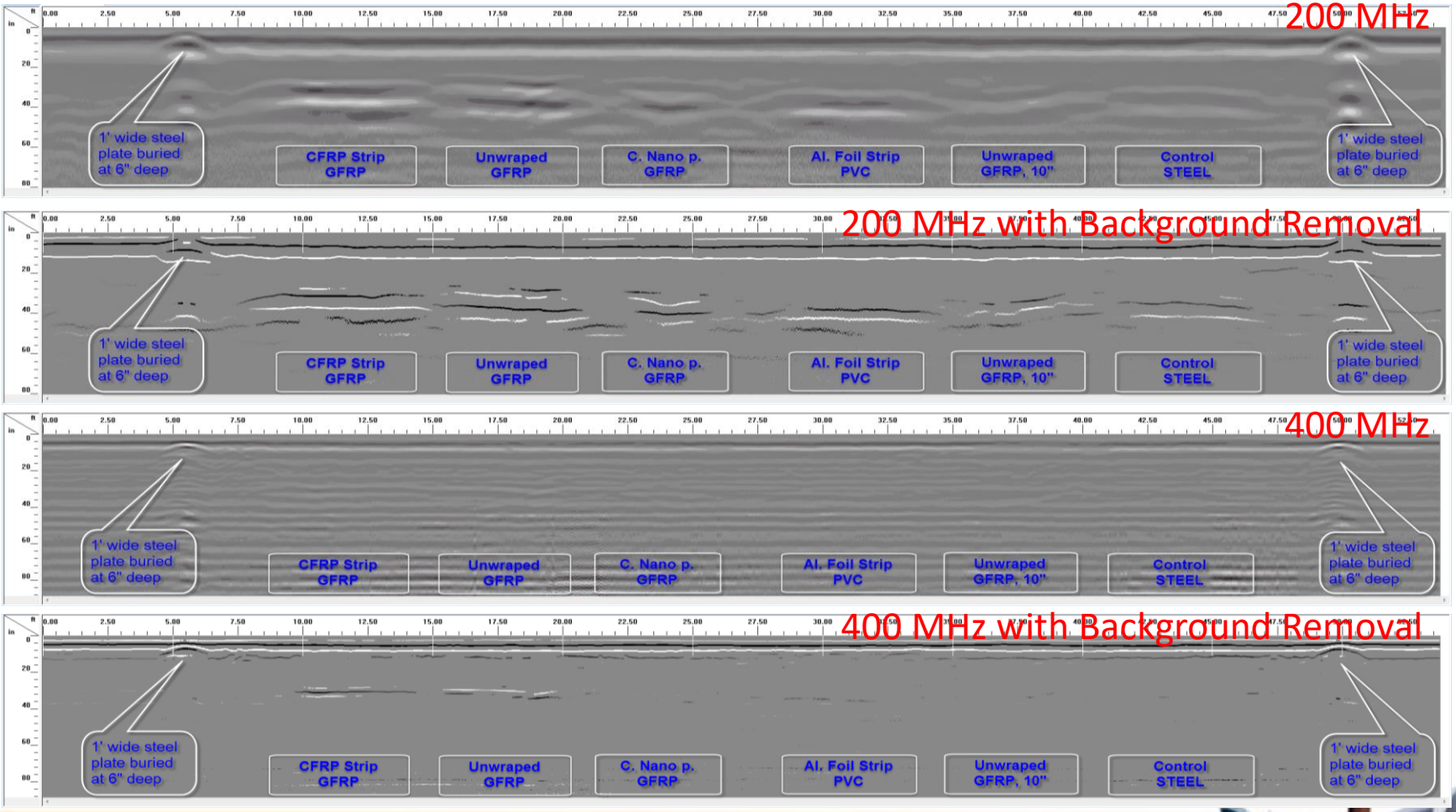
Used for measuring dielectric constant of soil.

Soil moisture and resistivity sensor.

Data logger.

GPR Results

200 MHz antenna works significantly better than 400 MHz antenna



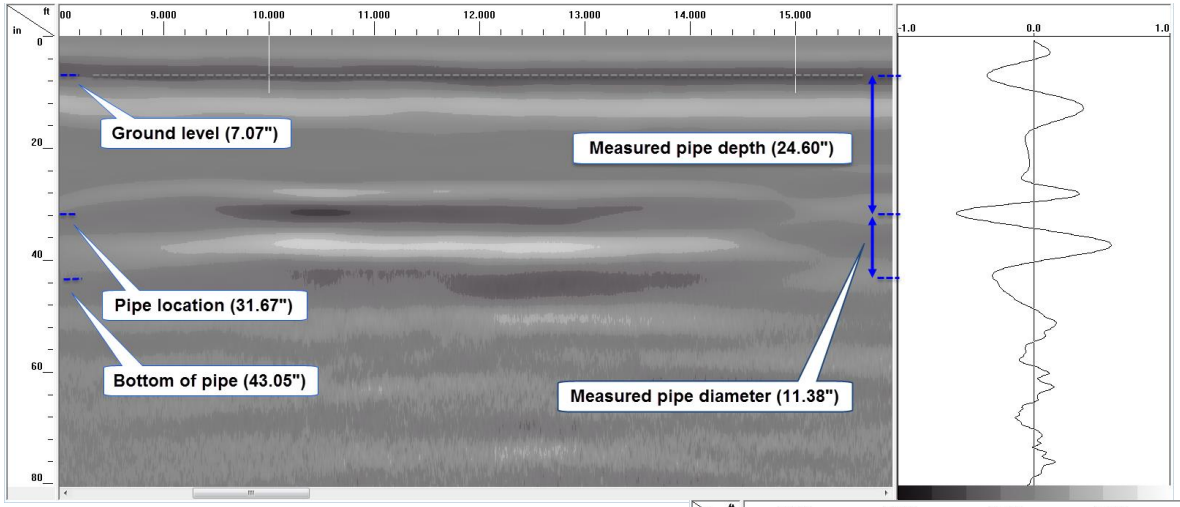
GPR Results (continued)

i. 200 MHz radar antenna was able to locate all the pipes buried at 2 ft. depth.

ii. It also produced significantly better result compared to 400 MHz radar antenna for buried pipe detection.

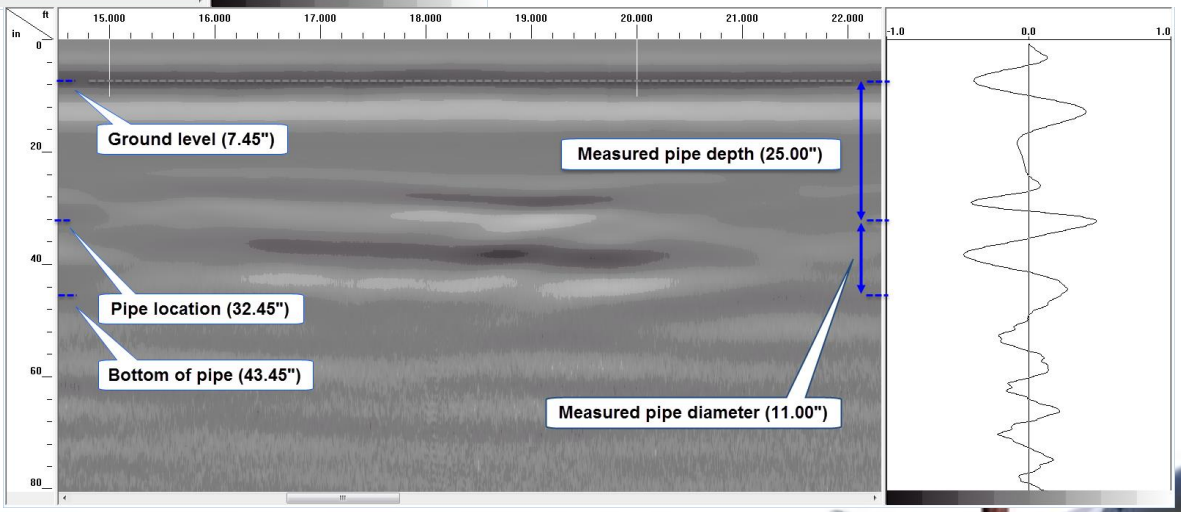
iii. 400 MHz GPR antenna was unable to detect some of the pipes buried at 2 ft., even after applying various data processing techniques.

GPR Results (continued) – 200 MHz

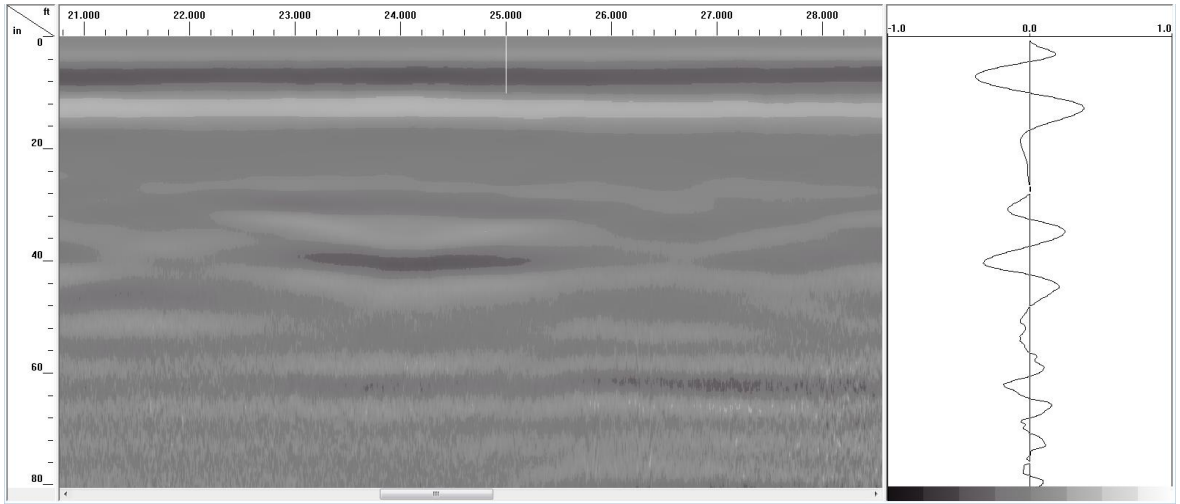


Longitudinal GPR scan over CFRP Strip 12" GFRP pipe.

Longitudinal GPR scan over unwrapped 12" GFRP pipe.

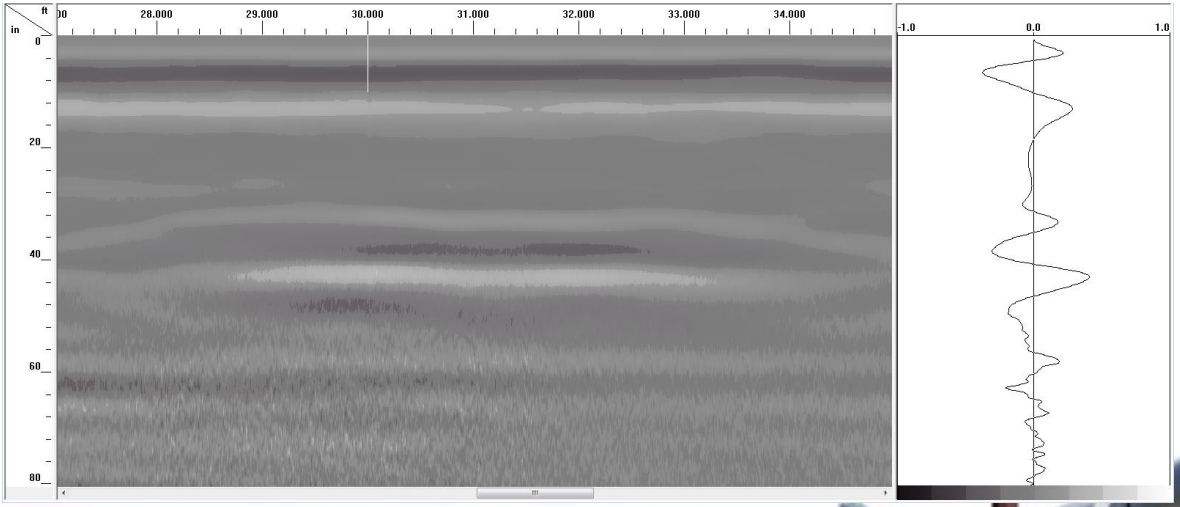


GPR Results (continued) – 200 MHz

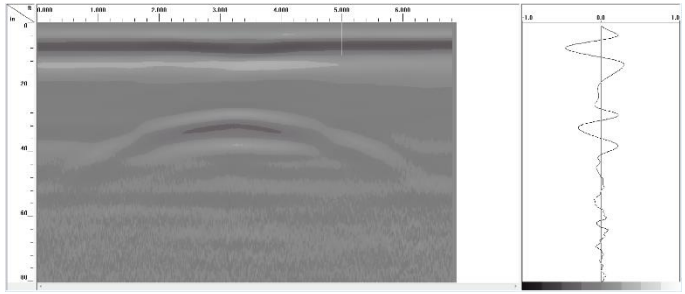


Longitudinal GPR scan over C. Nano p 12" GFRP pipe.

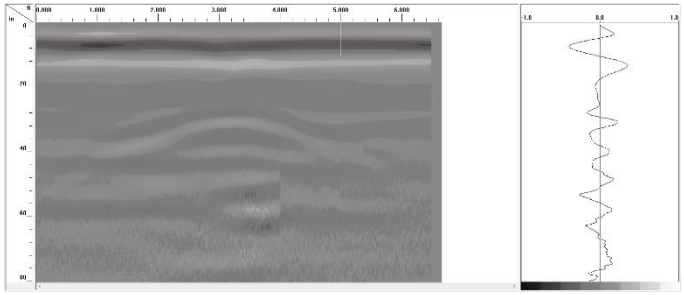
Longitudinal GPR scan over Al. Foil Strip 12" PVC pipe.



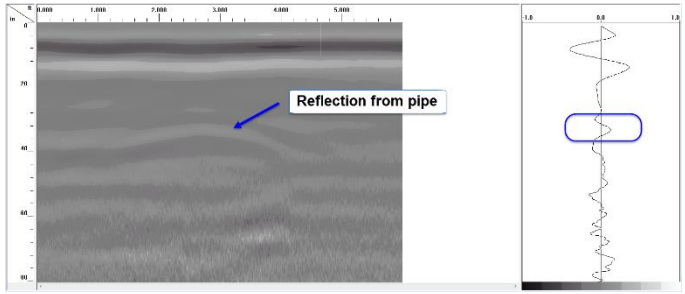
GPR Results (continued) – 200 MHz



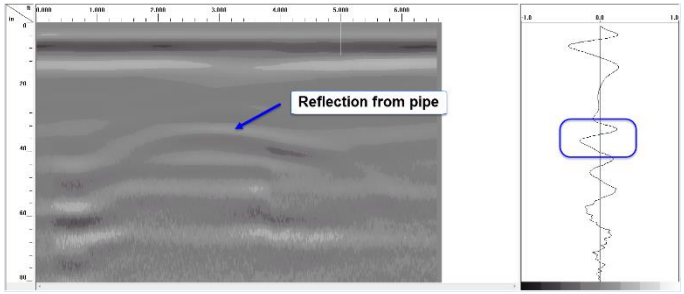
(a) 12" GFRP pipe wrapped CFRP fabric



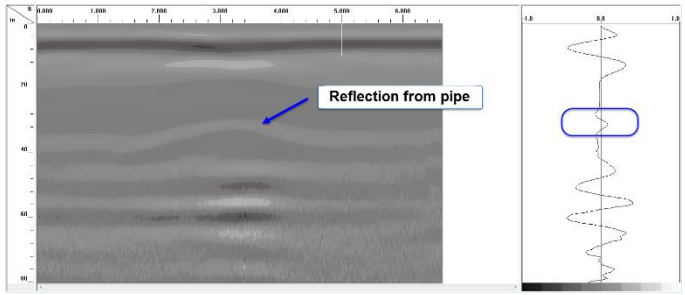
(b) Unwrapped 12" GFRP pipe



(c) 12" GFRP pipe with carbon nanoparticle overlay



(d) 12" PVC pipe wrapped with Aluminum foil strip



(e) Unwrapped GFRP pipe (10" diameter)

Transverse scan over some of the pipes using 200 MHz GPR antenna

GPR Results Summary

i. It is possible (but difficult) to detect buried non-metallic pipes without any modification to pipe surface up to 2ft. Depth using GPR.

ii. Use of carbon fabric or aluminum foil on the surface of non-metallic pipes significantly improves detectability of the buried pipes using GPR.

iii. Carbon fabric strip produces stronger signal reflections compared to aluminum foil strip.

GPR Results Summary

iv. An earlier study found that, buried non-metallic pipes are difficult to detect using GPR beyond 2 ft. depth; however, the addition of CFRP and aluminum foil overlays made it possible to detect these pipes at deeper depths beyond 2 ft. in the earlier study

v. Carbon nanoparticle coating did not provide any noticeable benefit in terms of improving detectability of buried pipes in this study.

vi. 200 MHz antenna (45 lb) was found to be much more effective compared to 400 MHz (11 lb) antenna.

Introduction – Gas Leak Detection

- The goals of this section are:
  - Construct a laboratory simulation of a buried underground leaking pipe
  - Develop a leak model to estimate leak size by measuring pressure loss and leak rate
  - Validate the ability to detect an underground gas leak at the surface
  - Estimate the diffusion of gas through the soil as a function of the leak rate and soil depth

Experimental Set-Up

- A 1.5 feet wide by 5 feet long by 5 feet high wooden box was used
- 18 or 36 inches of soil with a 1:1:2 mixture of sand, gravel, and top soil (porosity ≈ 0.4)
- Argon flowed through a 2-inch PVC test pipe simulating a buried leaking pipe
- PVC test pipe was placed in an 8-inch aluminum sheath to allow replacement
- This set-up mimics an underground leaking pipe

Figure 1: Exterior of Assembled Box

Experimental Set-Up – Leaking Pipe

- Pressure was measured with a pressure transducer inside the pipe
- A 0.0135 inch diameter hole was drilled in the center of PVC
- On-line mass spec was used to measure Ar concentration

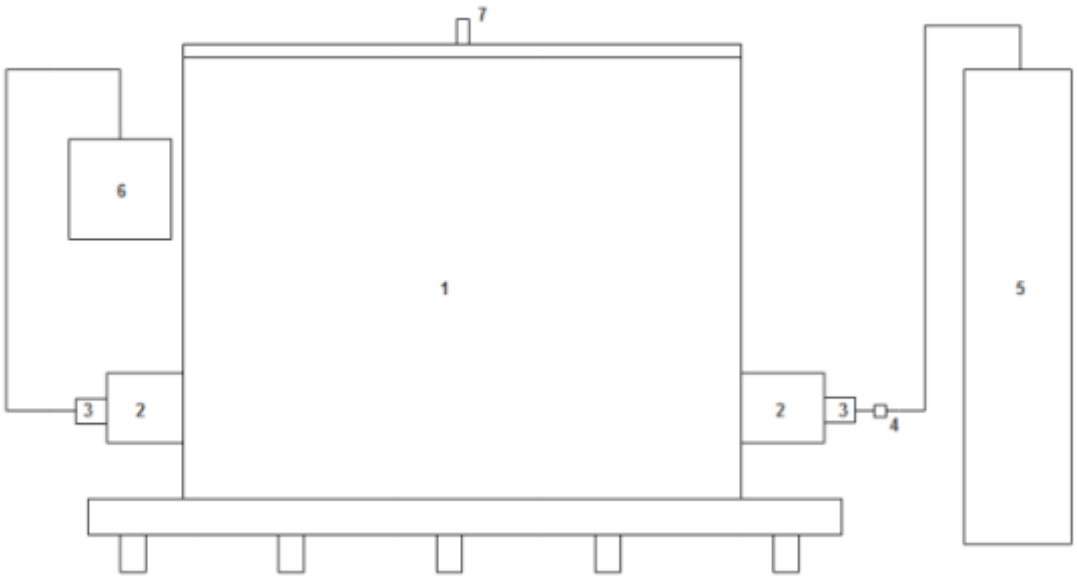


Diagram Key
1 -Test Apparatus
2 - Aluminum Pipe
3 - Test Pipe
4 - Gas Valve
5 - Ar Tank
6 - Pressure Transducer
7 - Mass Spec Probe

Figure 2: Testing Apparatus Schematic Side View

Leak Modeling

- The flow leaving the PVC pipe is choked and modeled as

$$\dot{m}(t) = C_0 A P(t) \sqrt{\frac{\gamma g_c M}{R T_0} \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}}$$

- All parameters except pressure and mass flow are constant
- Using the ideal gas law, the internal pressure can be modeled as a function of time

$$\ln\left(\frac{P(t)}{P_0}\right) = -kt$$

- If the size of leak and pressure are known, the leak rate can be calculated; or if the pressure and leak rate are known, the size of the leak can be predicted
- *k* remained within 5% between iterations of the experimental data

Choked Flow Model

- Pressure shown in legend is initial pressure
- Higher pressure results in a higher mass flowrate
- *k* value fits multiple initial pressures
- Choked flow assumption is valid for a leaking pipeline

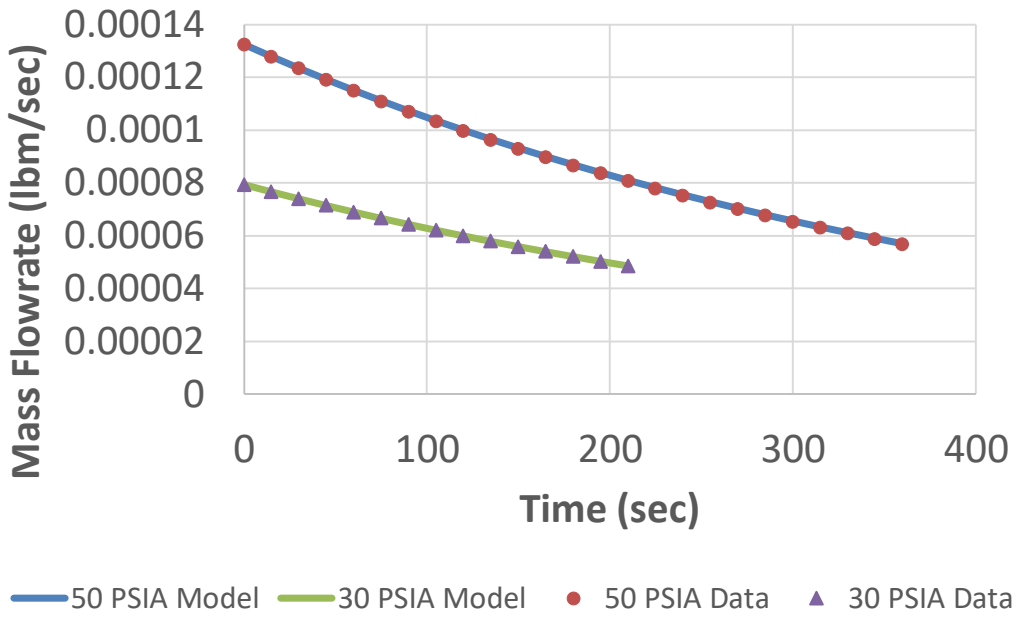


Figure 3: Modeled Choked Flow and Experimental Choked Flow as a Function of Time

Gas Detection Results

- Flow controller provided a steady flowrate into the soil from buried leaking pipe
- Over time Ar diffuses through the soil and out the surface
- The mass spectrometer was able to detect the gas emerging from the soil down to ppm
- Measured Ar concentration vs. time

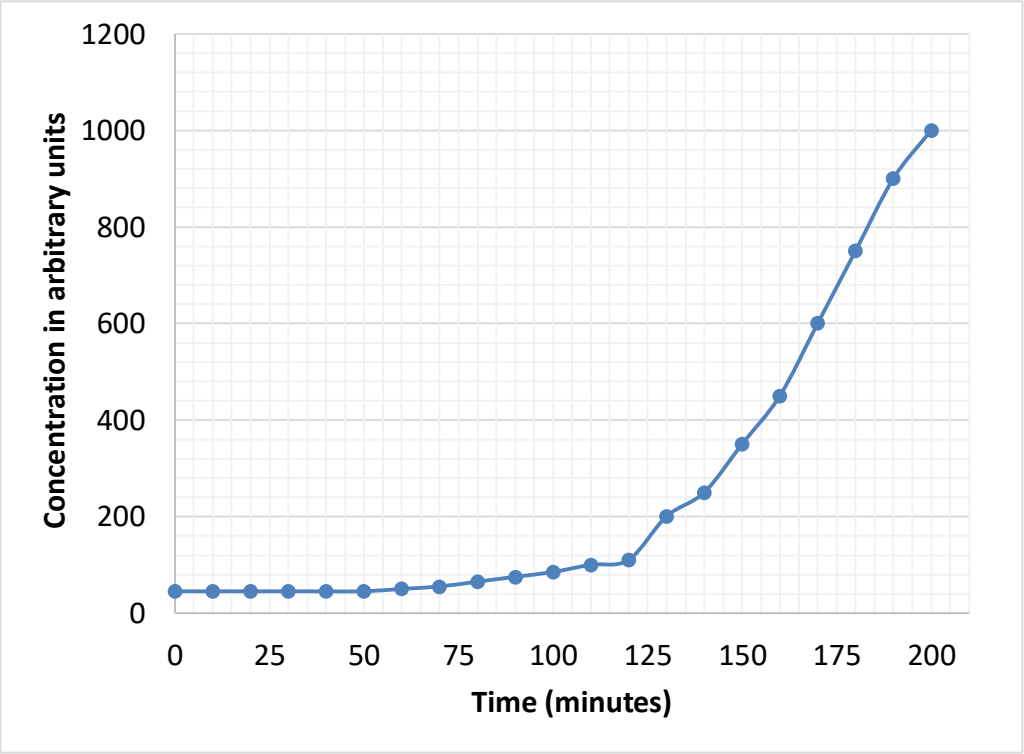


Figure 4: Concentration of Ar as a Function of Time at Soil Surface

Diffusion Studies

- A constant argon flowrate was passed through the bed
  - Flow varied between 1.5 and 2.0 liters/minute
  - Both 18 and 36 inch bed depths were tested
  - Soil porosity ≈ 0.4
- The transient Ar concentration at the soil surface was detected and normalized

$$Nomalized\ Concentration = \frac{c(t)-c_i}{c_f-c_i}$$

- The complementary error function provided an accurate description of the 1-D transient diffusion of Ar penetration through the soil

$$Fitted\ Normalized\ Concentration = 1 - \mathrm{erf}(\frac{H^2}{4Dt_s})$$

- Sum of squares was used to minimize difference between the experimental and normalized concentrations for fitting *Conc vs. t* and finding D for each flowrate and soil depth

Normalized Concentration Results

- The fitted data produced characteristic "s" shape of the error function
- Normalized concentration reached steady state
- Similar results were displayed across all trials

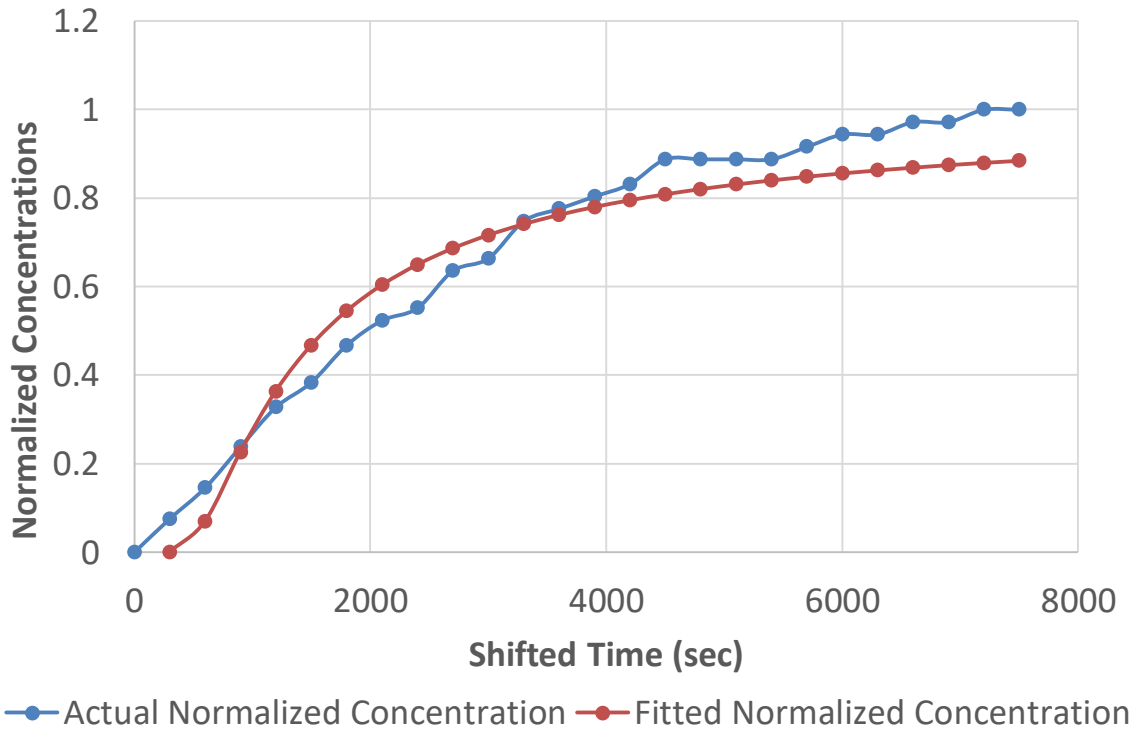


Figure 5: 1.75 L/min Argon Flowrate with 18-Inch Soil Depth

Diffusion Studies Continued

- Literature suggests diffusivity is a function of flowrate

$$D = D_o + AV^n$$

- Sum of squares was used to fit parameters *A* and *n*
- Some sources suggest n should have a value of 1

Table 1: Fitted Parameters for Minimization of Sum of Squares

Function Parameter	Value
D_o	0.06
A	0.347
n	1.26

Table 2: Minimized Sum of Squares with Parameter n Fixed at 1.00

Function Parameter	Value
D_o	0.06
A	0.403
n	1.00

Diffusion Model

- *n* corresponds to the exponent on flowrate from the previous equation
- Models agree with each other beneath 2.5 L/min
- As flowrate approaches 3.0 L/min models deviate
- Both models fit the experimental diffusivity well over range of data

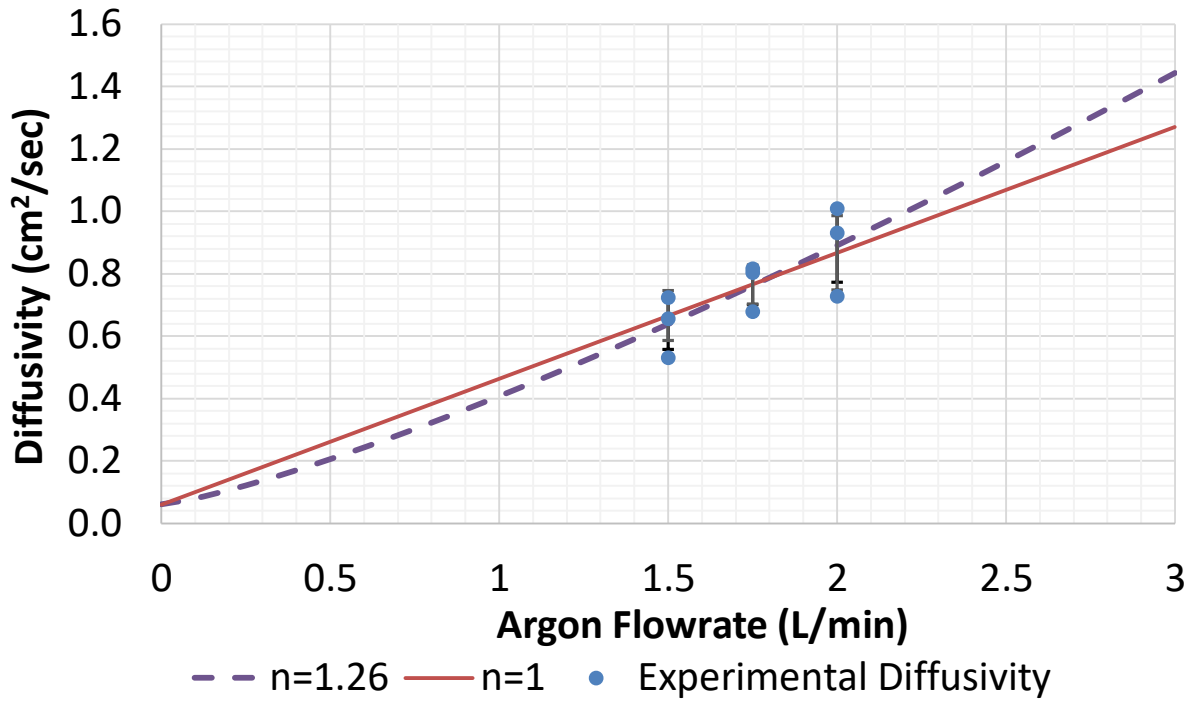


Figure 6: Diffusivity as a Function of Argon Flowrate

Conclusions – Gas Leak Detection

- A laboratory model of a leaking underground pipe was constructed; argon was a surrogate for methane
- A transient choked-flow model allowed the leak rate or size of leak to be predicted
- An on-line mass spectrometer at the soil surface detected leaking gas from pipeline underground down to few ppm
- Transient diffusion model fit convective diffusion of argon in a porous soil bed as function of gas flow rate and soil depth
- Experimental diffusivity of argon as a function of flowrate was modeled and agreed with the literature

Future Work

- Produce failure predictions through CLT
- Further testing with higher D/t ratio-test fiber failure
  - Test fiber strengths, determine failure modes
- Perform free-end burst tests
- Investigate S-glass pipes
- Continued development of high strength joints
- Continue evaluation of buried pipe detection using ground sensory technologies (GPR)
- Continue investigation on Gas Leak Detection

Project Reporting

- Final Report and student posters are available from:

https://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=721

THANK YOU!