SHRP2 SOLUTIONS
STRATEGIC HIGHWAY RESEARCH PROGRAM

Nondestructive Tunnel Liner Evaluation

Using Ground Penetrating Radar, Infrared Thermography and High Resolution Imaging

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U.S. Department of Transportation
Federal Highway Administration

AMERICAN ASSOCIATION OF STATE HIGHWAY AND TRANSPORTATION OFFICIALS
AASHTO

Tunnel Evaluation

Using GPR - IRT - HRI Technology

Evaluation of Tunnel Liners Presents a Challenging Problem

- ➢ Tunnels are in the constant presence of moisture, and over time can experience:
- • Deterioration of liner & corrosion of reinforcement,
- • Voids behind liner & water flow thru liner

- ➢ Evaluation & maintenance is difficult due to:
- • Limited access & high usage,
- • Accessible from one side only
- • Presence of tile face masking underlying problems
- • Difficulties in physical access to conduct inspections

- ➢ Manual and destructive methods exist, but are difficult, labor intensive, require closures and are expensive

What is needed is a better, more cost effective non-destructive method

SHRP2 R06G Proposed NDT Solution

- Ground Penetrating Radar
- Infrared Thermography, and
- High Resolution Video Imaging

Penetradar Corporation

- IRIS GPR
- IRT Systems
- HRI Systems
- Vehicle Inspection Systems
- R&D – SHRP, NASA, NVESD

Technical Services












SHRP2 R06G Focused on Existing NDT Technologies Previously Used in Other Applications

- Infrared Thermography
- Ground Penetrating Radar
- High Resolution Imaging

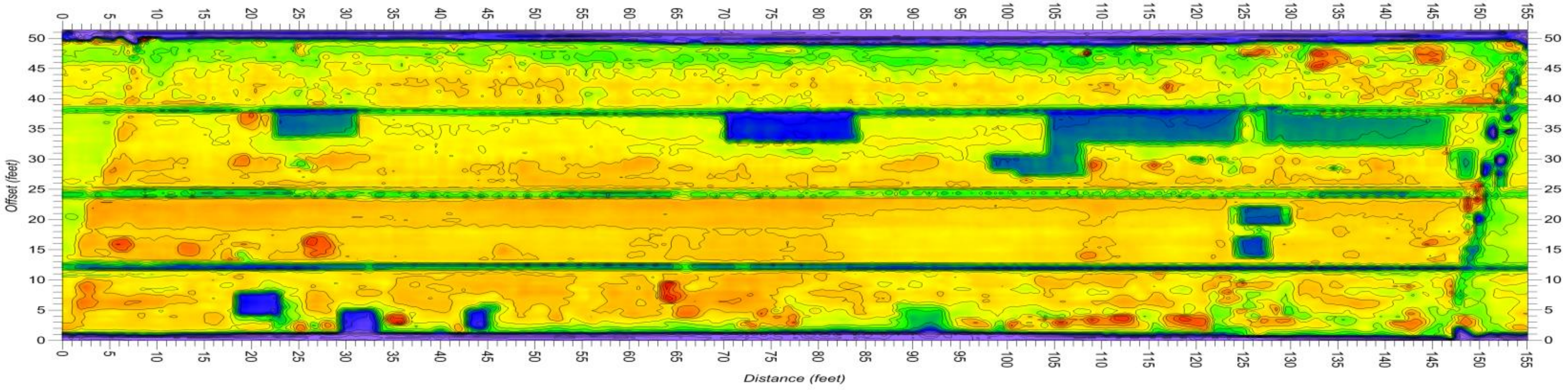
High-Speed Infrared Thermography

- Infrared Camera
  - 640 x 480 resolution
  - 0.1 degree C resolution
  - 30 Hz scan rate
  - Radiometric data

- Data Collected in a Continuous Swath

- Results are converted from forward-view to plan-view.

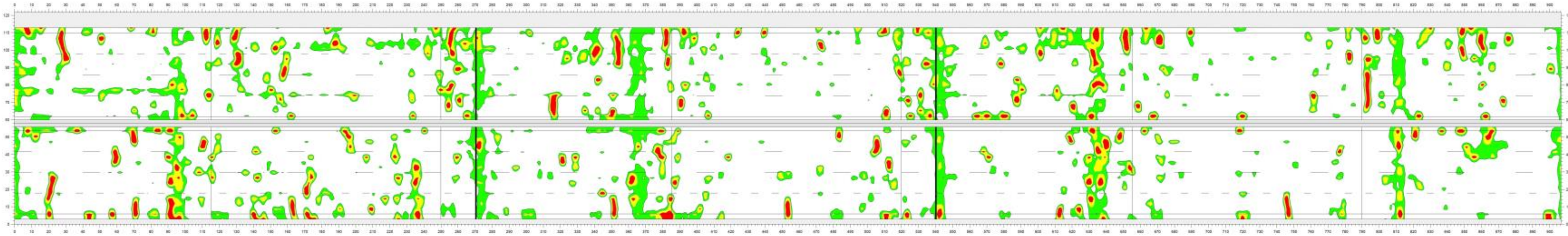
IRT bridge deck evaluation shown below. Delaminations shown as “red” areas



High-Speed Ground Penetrating Radar

- GPR
  - Non-contacting antennas (500MHz to 2.5GHz)
  - 100 Hz scan rate (or greater)
  - 4 Antenna array
- Data Collected as Individual Scans
- Results are assembled into a plan-view map.

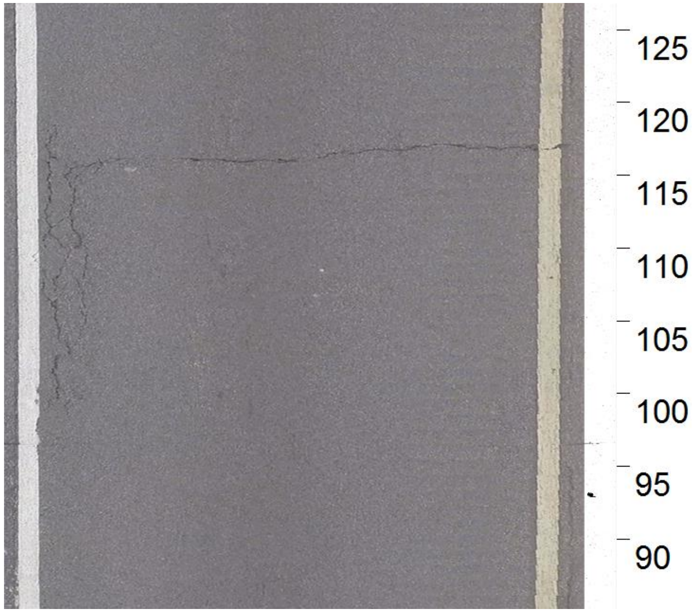
GPR bridge deck evaluation. Probable areas of delamination shown as green-yellow-red



High Resolution Imaging

- High Resolution Video Camera
  - 4k optical resolution (3840 x 2160 pixel = 8.3M pixel)
  - 120Hz scan rate

- High speed image recording (50MPH)
  - Collected in forward-view
  - Converted to plan-view (top-view)



Tunnel Liner Evaluation

Advantages of GPR and IRT for Evaluation of Tunnels

- Non-Destructive
- Non-Contacting
- Fast (10-15MPH) Inspection Speed
- Not affected by Surface Material (or Presence of Tile) - GPR

Tunnel Liner Evaluation

USES OF NDT IN TUNNEL EVALUATION

- Liner Thickness & Depth of Reinforcement
- Delamination of the Concrete Liner
- Voids Between the Liner and Base
- Water Flow Through and Behind the Liner
- Detection of Cracks

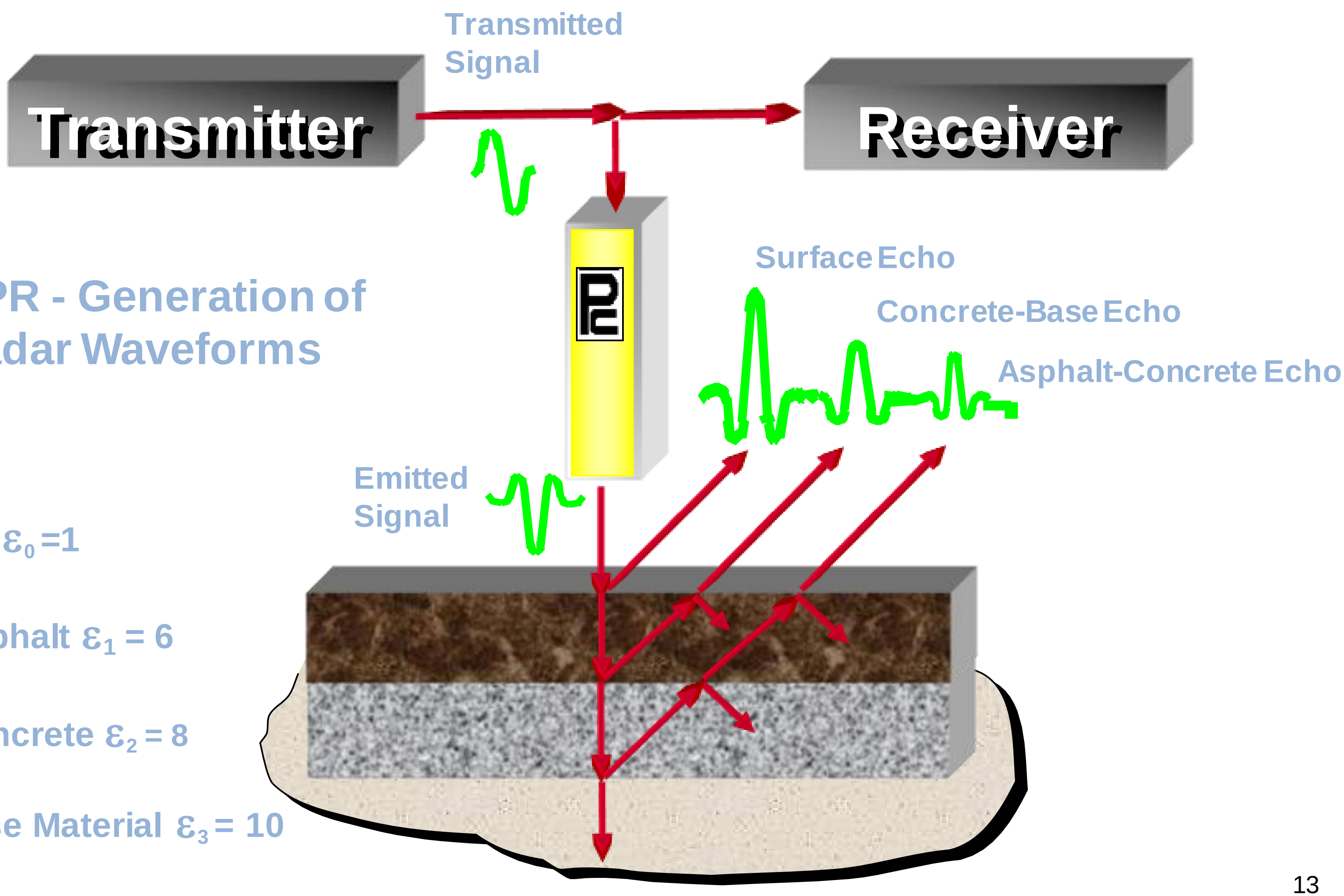
Tunnel Liner Evaluation

Theory

- GPR Layer Thickness
- GPR Void Detection
- GPR Detection of Moisture Within and Behind Liner
- GPR Detection of Deterioration of Concrete Liner
- IRT Detection of Concrete Cracks & Water Flow

Tunnel Liner Evaluation

GPR - Generation of Radar Waveforms



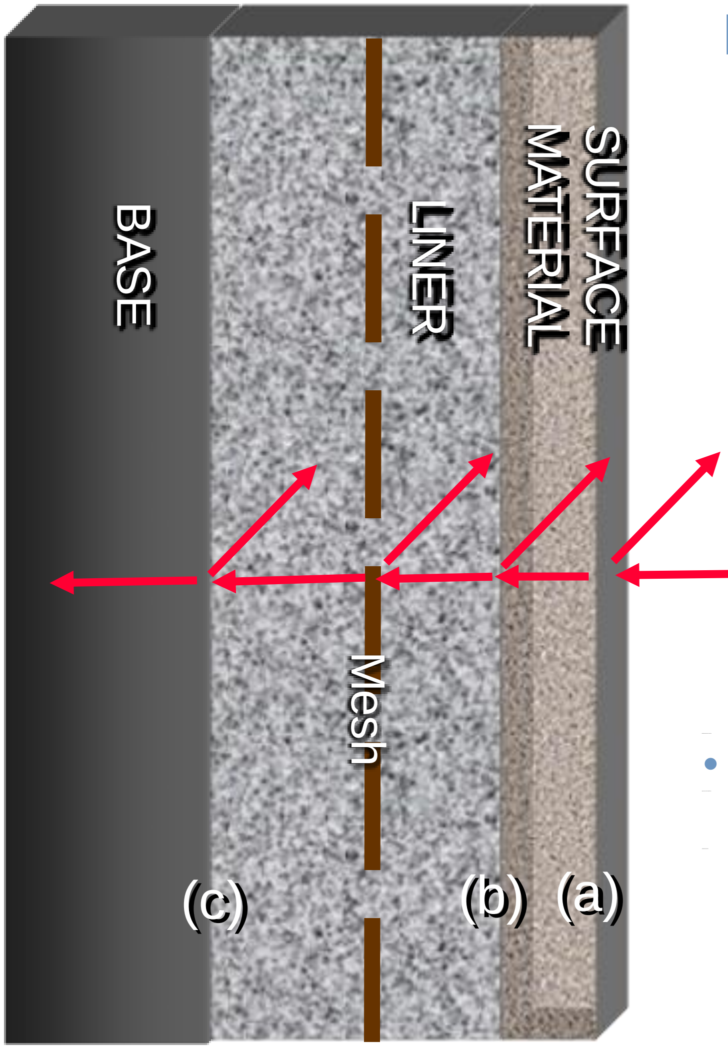
Air $\varepsilon_0 = 1$

Asphalt $\varepsilon_1 = 6$

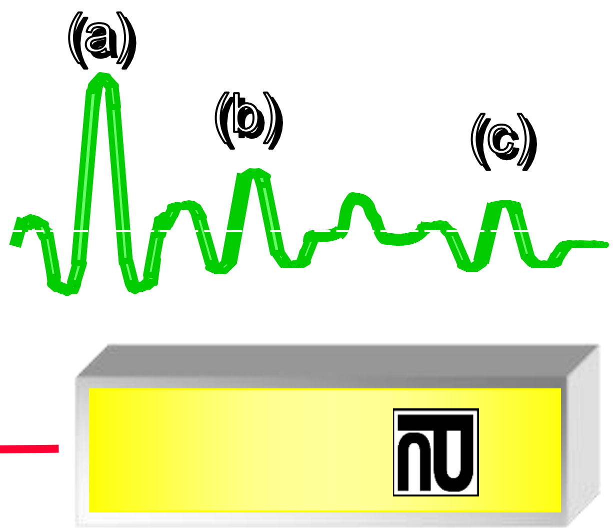
Concrete $\varepsilon_2 = 8$

Base Material $\varepsilon_3 = 10$

Tunnel Liner Evaluation - GPR



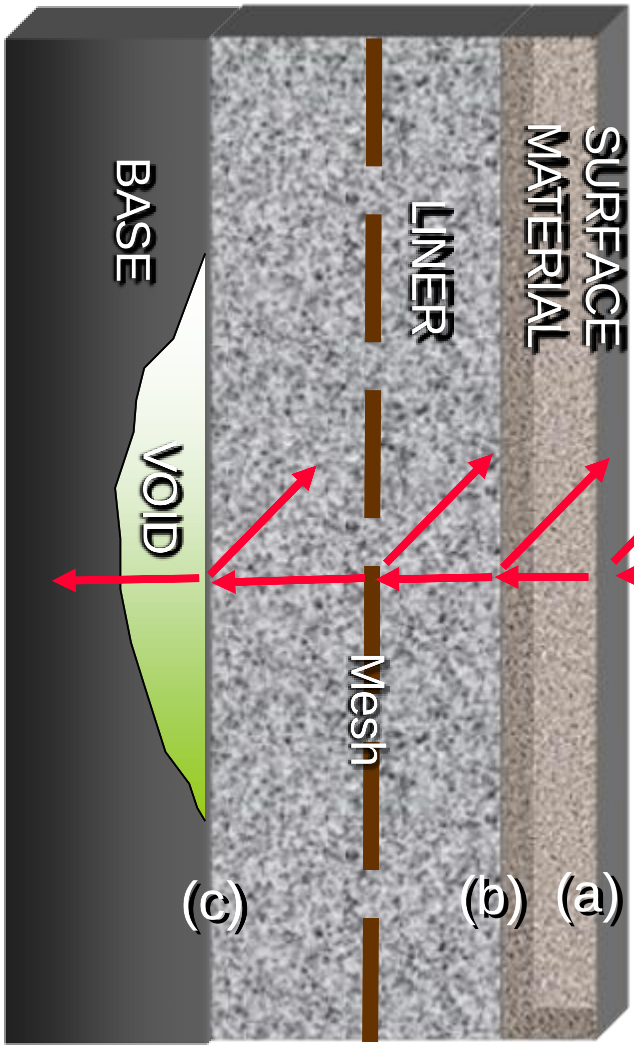
LINER THICKNESS MEASUREMENT



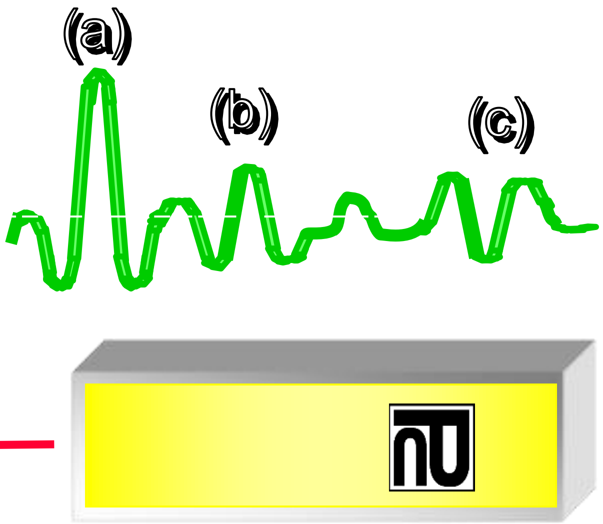
- GPR Measurement of Layer Thickness (X) Based on Transit Time of Radar Wave (T) and Radar Wave Velocity (V)

$$X = V * T$$

Tunnel Liner Evaluation - GPR

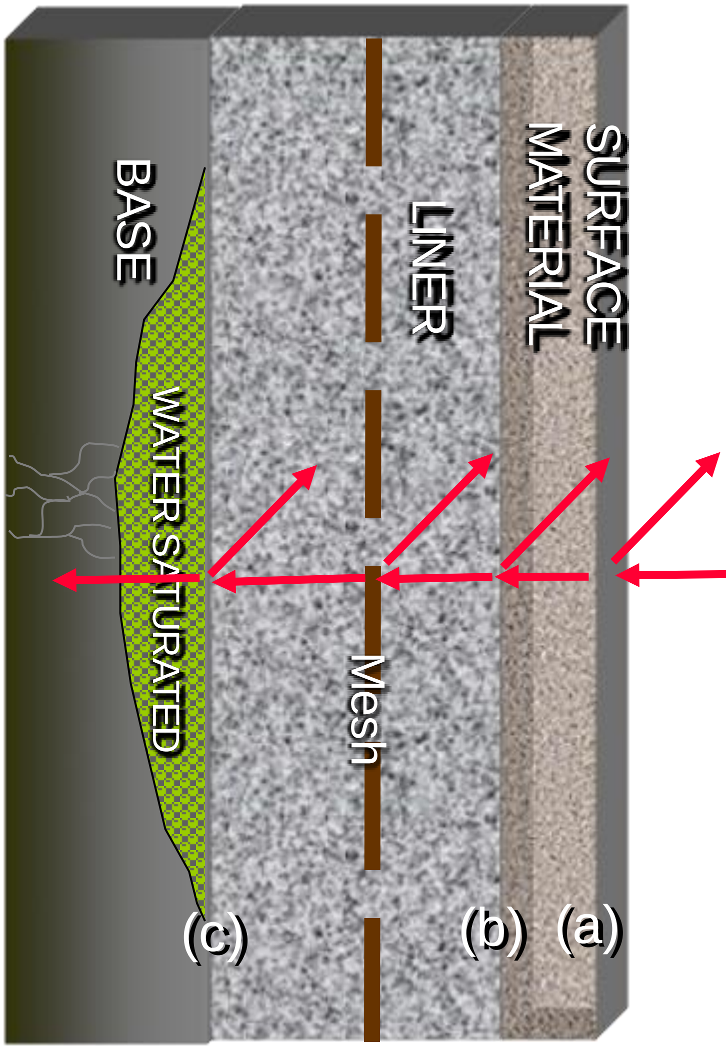


VOID DETECTION

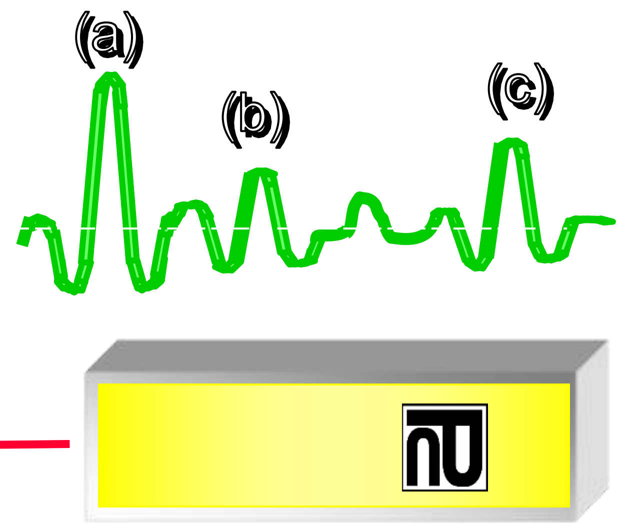


- GPR Detection of Voids Behind Tunnel Liner Based on Polarity of Signal from Back of the Liner
- Could be Air or Water-Filled

Tunnel Liner Evaluation - GPR

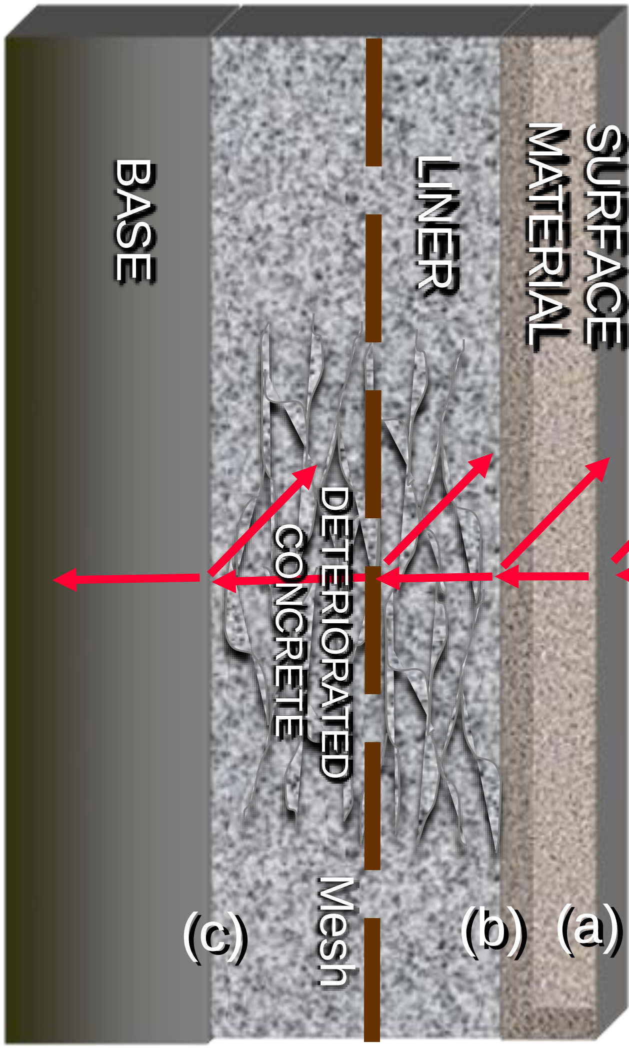


MOISTURE DETECTION

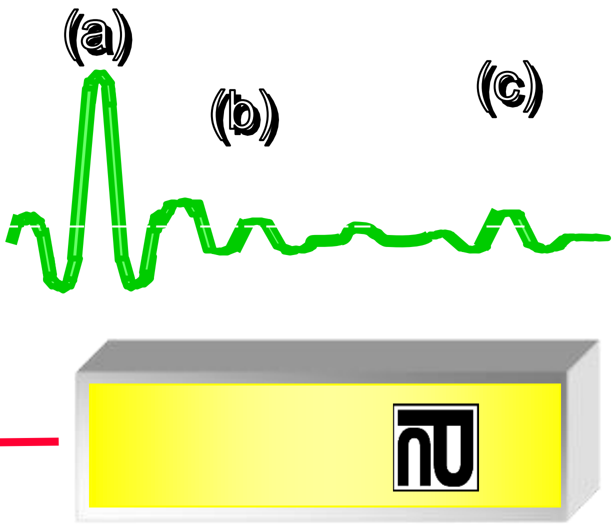


GPR Detection of Moisture in Liner or Base by Measuring the Reflection Coefficient (ρ) or Dielectric Constant (ε) of Material

Tunnel Liner Evaluation - GPR

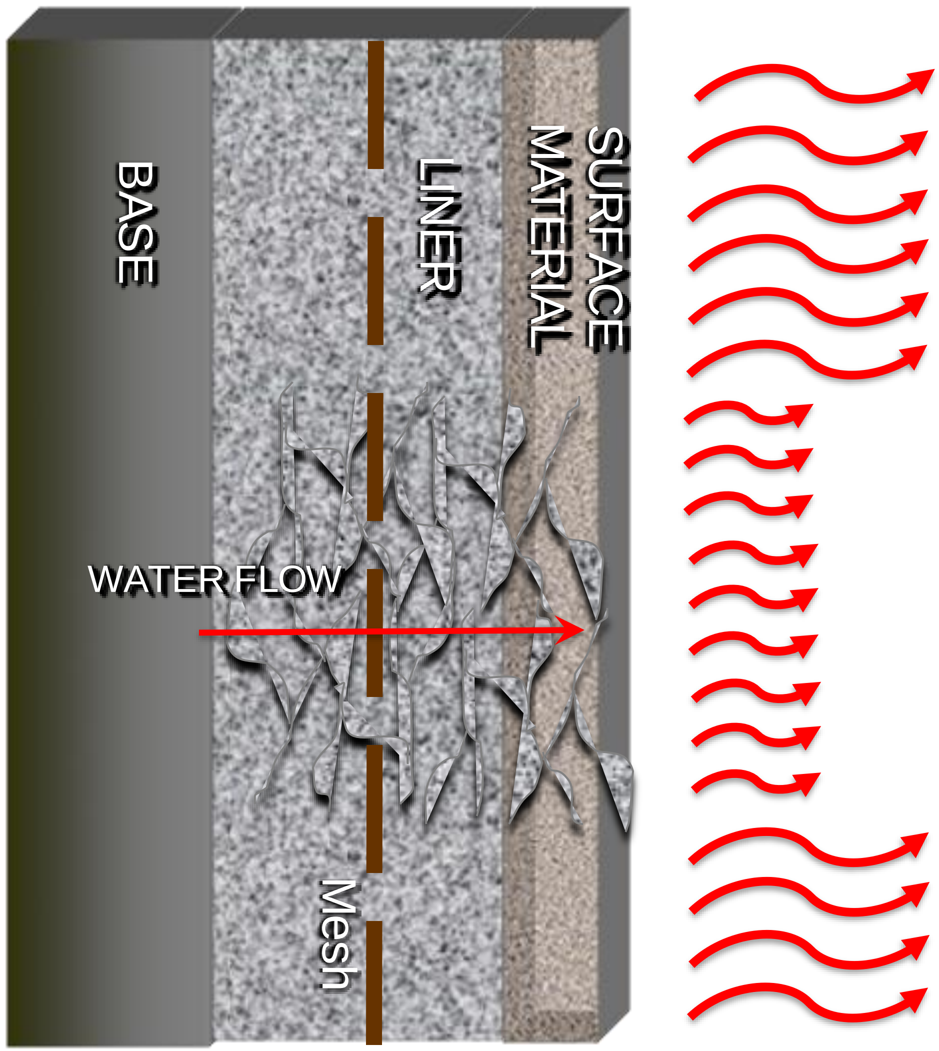


CONCRETE DETERIORATION



- GPR Detection of Deteriorated Concrete is Based on Measurement of Signal Attenuation in the Material

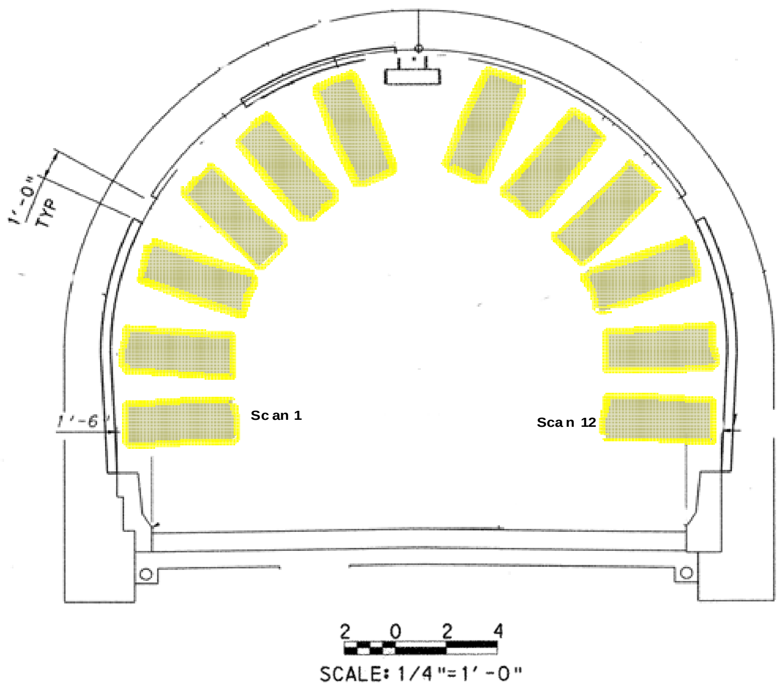
Tunnel Liner Evaluation - IRT



CONCRETE DETERIORATION, CRACKS AND WATER FLOW

- IRT DETECTS CRACKS AND WATER FLOW BASED ON TEMPERATURE DIFFERENTIAL

Tunnel Liner Evaluation



INSPECTION METHOD

- GPR - Longitudinal Scans are made in all Clock Positions Along Length of Tunnel – 3 Ft apart
- IRT & HRI – Longitudinal Scans are made along the length of the tunnel. Left & Right Wall & Ceiling
- Speed 10-15MPH

Tunnel Liner Evaluation

GPR Data Collection

GPR System used for Inspection of Roadway Tunnels

- **Penetradar GPR Shown in Liberty Tunnel, Pittsburgh, PA**

Tunnel Liner Evaluation

GPR Data Collection

GPR System used for Inspection of Roadway Tunnels

- **Penetradar's GPR Shown in Liberty Tunnel in Pittsburgh, PA**

45 second video
[click image to start/stop]

Tunnel Liner Evaluation

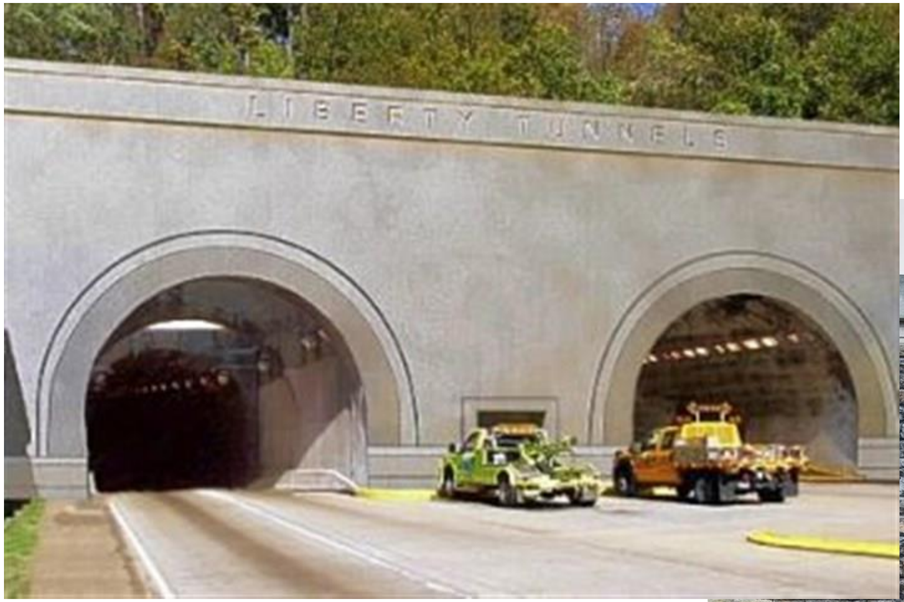
GPR Data Collection

Hyrail GPR System used for Inspection of Rail Tunnels

- **Penetradar's GPR System Shown in DART Tunnel**

Tunnel Liner Evaluation

NON-DESTRUCTIVE INSPECTION OF LIBERTY AND ARMSTRONG TUNNELS



Tunnel Liner Evaluation

NON-DESTRUCTIVE INSPECTION OF LIBERTY AND ARMSTRONG TUNNELS (September 22 – 25, 2015)

Methods used:

Ground Penetrating Radar
Infrared Thermography
High Resolution Imaging

Objectives:

GPR
Detect Delamination/Deterioration – shallow delamination
Voids & Areas of High Moisture Behind Liner
Areas of Moisture in Liner

IRT
Areas of Water Flow & Surface Moisture
Cracks
Debonded Tiles

HRI
Visual documentation
Used for comparison with GPR and IRT

Tunnel Liner Evaluation

Liberty Tunnel NDT Inspection

- GPR, IRT and HRI
  - Approx. 177,000 sq. ft. inspected in one evening (over 1 mile length)
- Shallow delamination of liner
  - Detected with GPR in 4.1% of area inspected, overall
  - In test area GPR detected 11.9% and sounding detected 7.2%
  - In test area GPR detected 73.2% of delaminations that were detected with sounding
  - In test area GPR detected 90.2% of sound areas that were detected with sounding
- Water-filled voids and moisture behind liner
  - Was detected with GPR in 13.2% of area, overall
- Air-filled voids behind liner
  - Was detected with GPR in 6.5% of area, overall
- IRT did not produce usable information

Tunnel Liner Evaluation

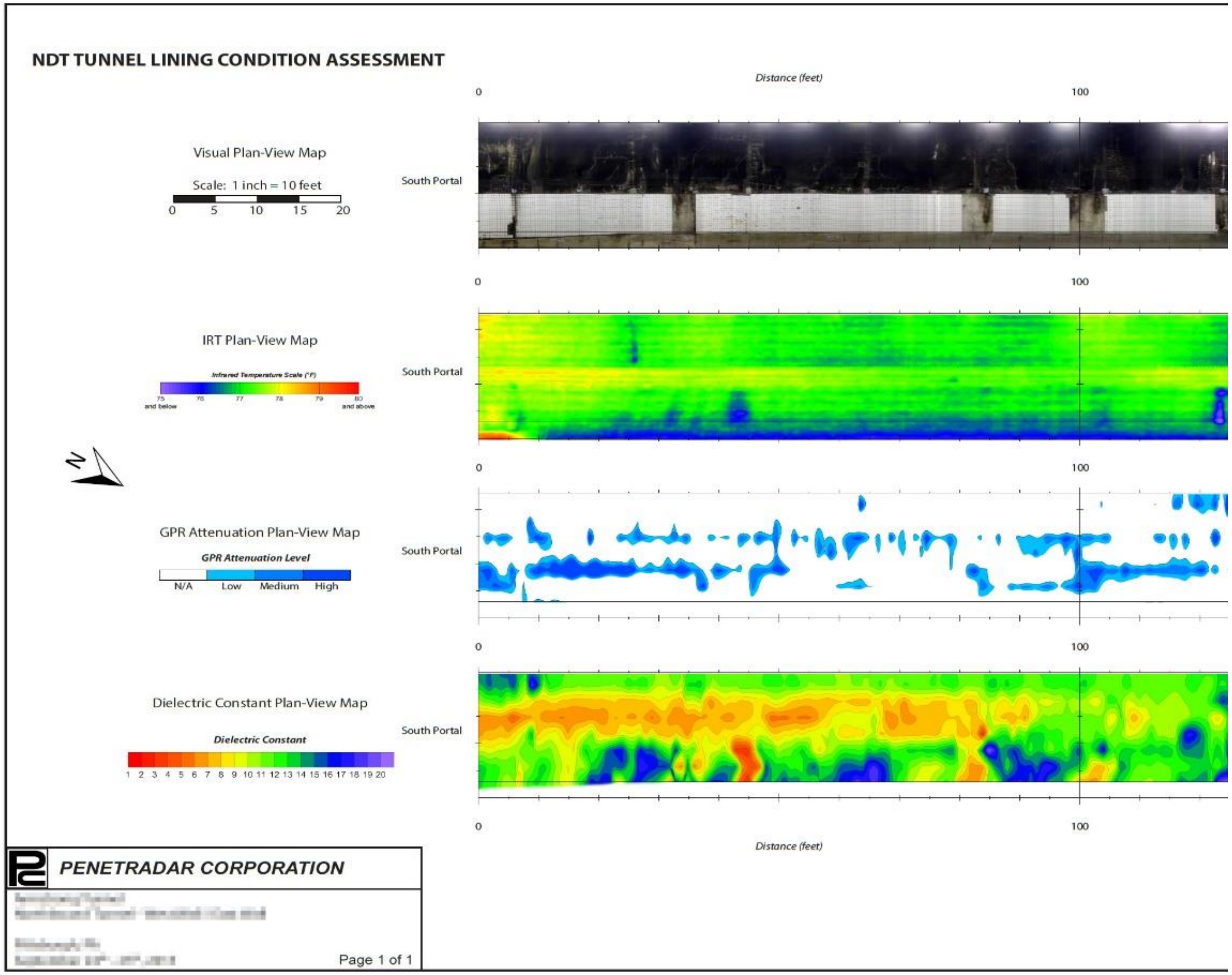
Armstrong Tunnel NDT Inspection

- GPR, IRT and HRI
  - Approx. 57,000 square feet of wall area inspected in one evening

- Deterioration of concrete liner
  - Measurement of GPR signal attenuation per ASTM D6087-03
  - Medium or high signal attenuation detected in 14.4% of wall area
  - Low signal attenuation detected in 10.9% of wall area

- Moisture in concrete liner
  - Was detected with GPR by measurement of dielectric constant
  - High moisture (10+%) detected in 14.1% of wall area
  - Medium moisture (2% - 10%) detected in 73.4% of wall area
  - Low moisture (<2%) detected in 12.5% of wall area

Tunnel Liner Evaluation



Armstrong Tunnel

High Resolution Image

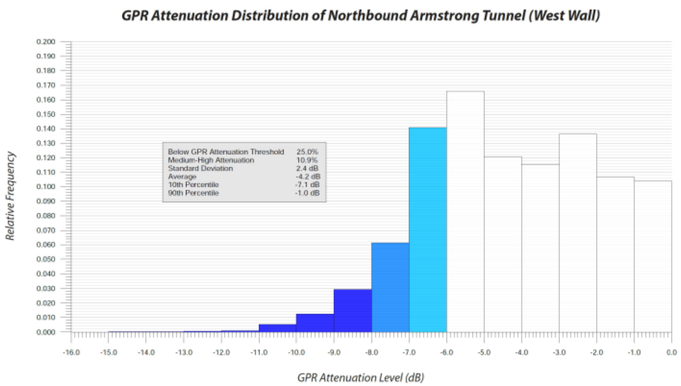
IRT Thermal Image

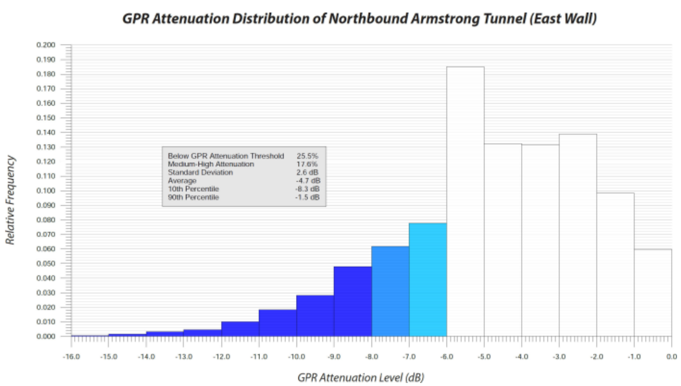
GPR Attenuation

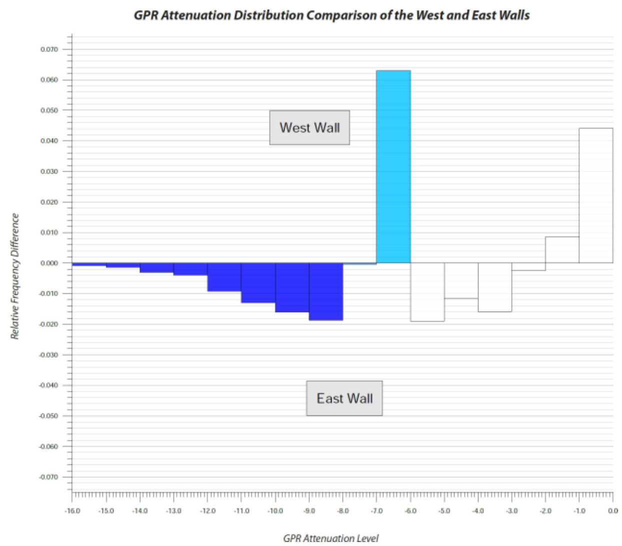
GPR Dielectric Constant

Tunnel Liner Evaluation

Armstrong Tunnel GPR Attenuation Distribution





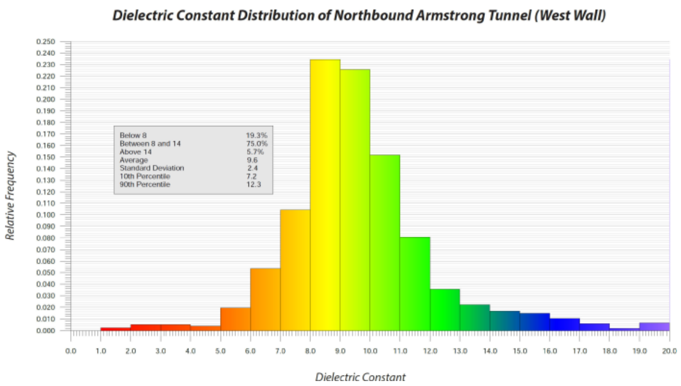


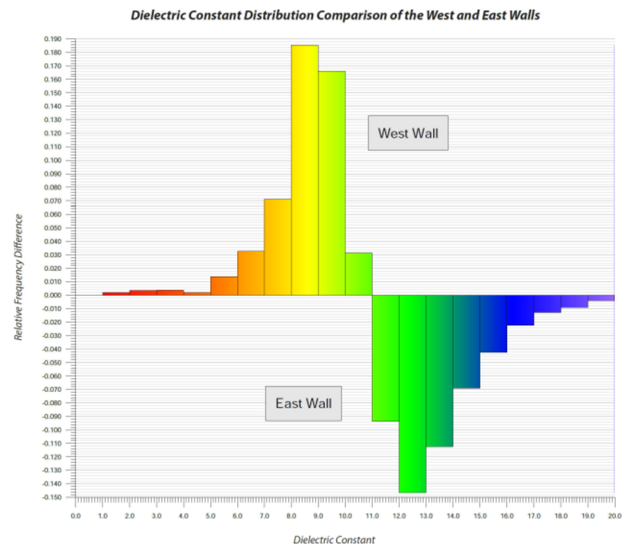
- West Wall Attenuation: 25.0% Total
- East Wall Attenuation : 25.5 % Total

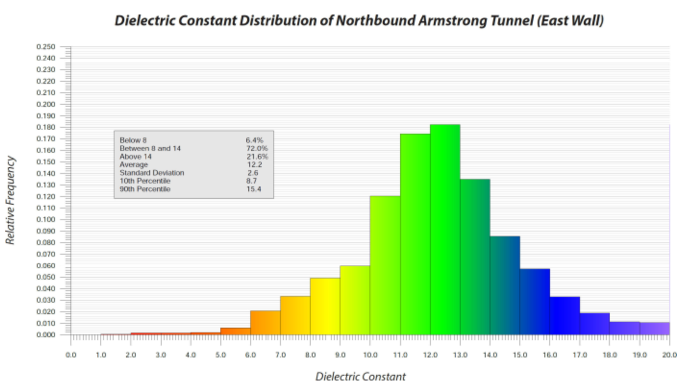
- East Wall contained higher levels of attenuation
  - Suggest east wall to be in generally worse physical condition

Tunnel Liner Evaluation

Armstrong Tunnel Dielectric Constant (ε_r) Distribution





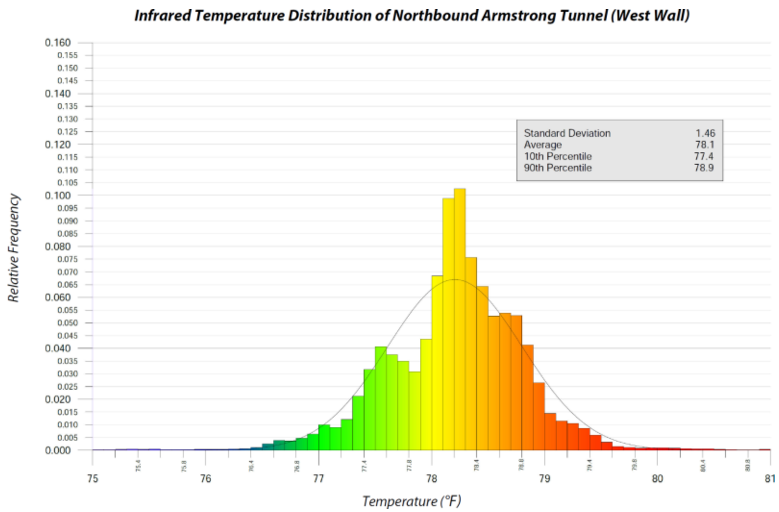


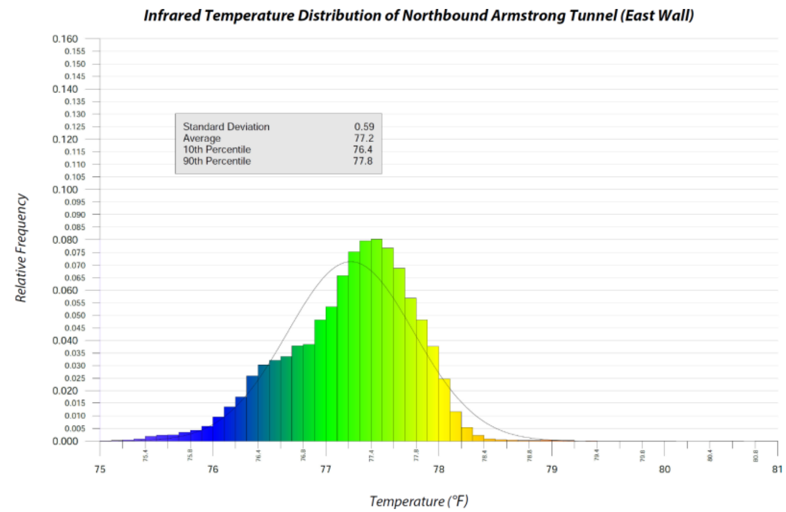
- West Wall Average ε_r : 9.6 (~ 4% moisture content)
- East Wall Average ε_r : 12.2 (~ 8% moisture content)

- East Wall was calculated to have almost twice the moisture content as the West Wall.

Tunnel Liner Evaluation

Armstrong Tunnel Infrared Temperature Distribution





- West Wall Average Temperature: 78.1° F
- East Wall Average Temperature: 77.2° F

- Difference in temperature could be due to:
  - Construction of tunnel and area behind each wall
  - Result of higher moisture content conducting heat

Conclusions and Recommendations

- Methods defined by SHRP2 R06G for tunnel evaluation were shown to be feasible in practice
  - Equipment specifications have been identified
  - Procedures have been developed & demonstrated
  - Methods of analysis of data have been suggested
- Additional Field Testing with Additional Ground Truth
  - with emphasis on determining reliability of NDT relative to various types of defects and identification of appropriate method of data analysis
- Each Tunnel to be Evaluated Based on its Specific Design
  - Need to better define the technique and analysis methods to achieve optimal results based on design, age and general condition
- Development of Standards – ASTM & AASHTO

THANK YOU

Tunnel Evaluation

Using GPR - IRT - HRI Technology

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