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 cost effective and non-destructive method

Tunnel Evaluation

Using GPR - IRT - HRI Technology

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












Tunnel Evaluation

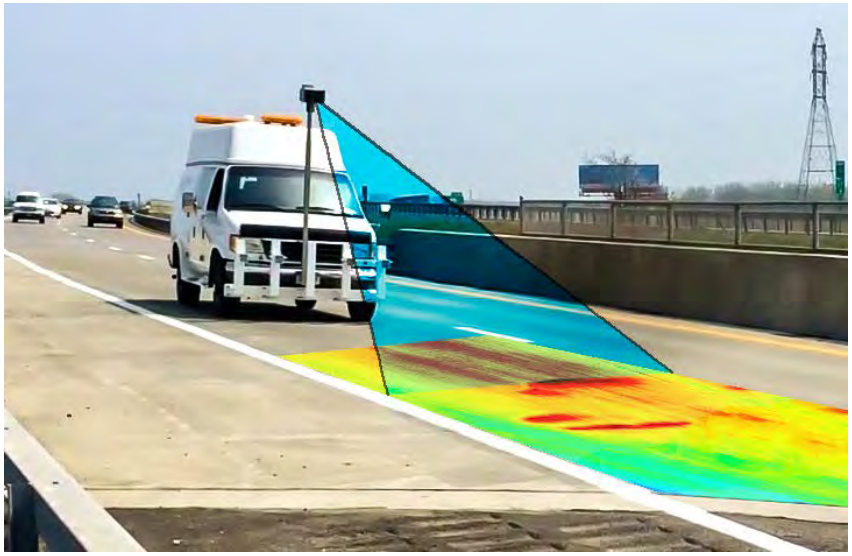
Using GPR - IRT - HRI Technology

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

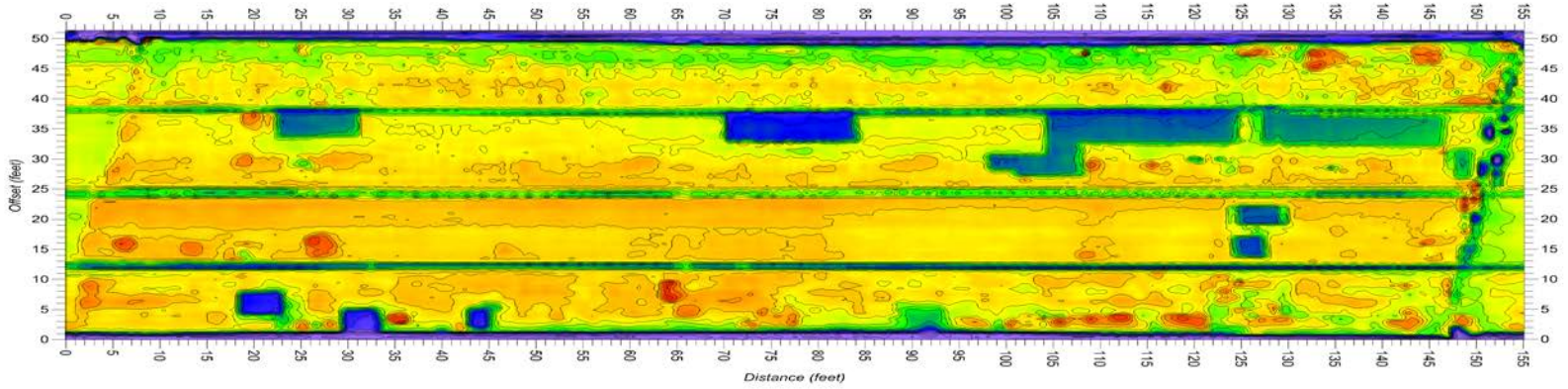
- Infrared Thermography
- Ground Penetrating Radar
- High Resolution Imaging

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.



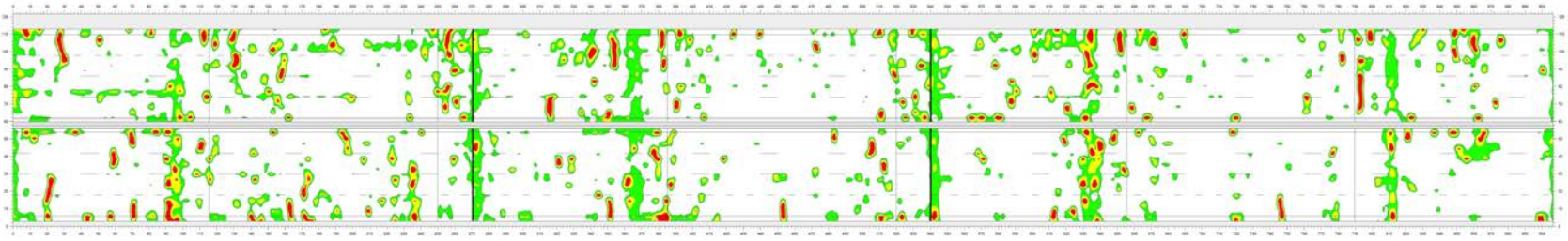
IRT bridge deck evaluation shown below.
Delaminations shown as “red” areas



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.

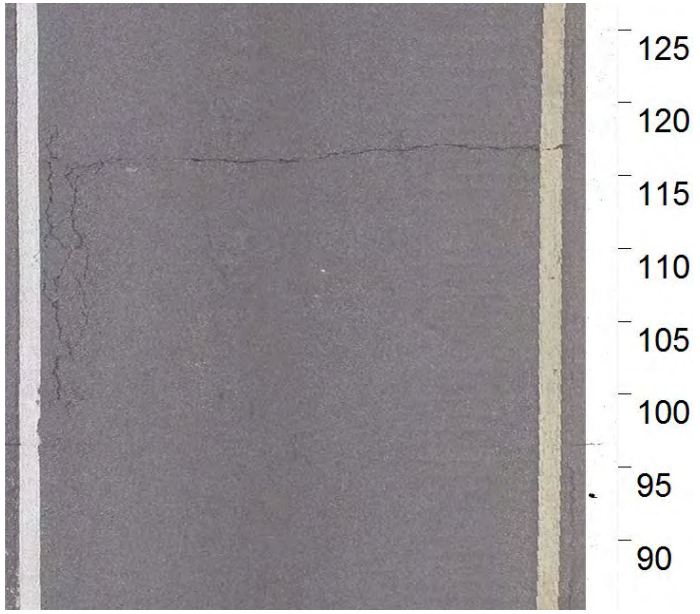
GPR bridge deck evaluation. Probable areas of delamination shown as green-yellow-red



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

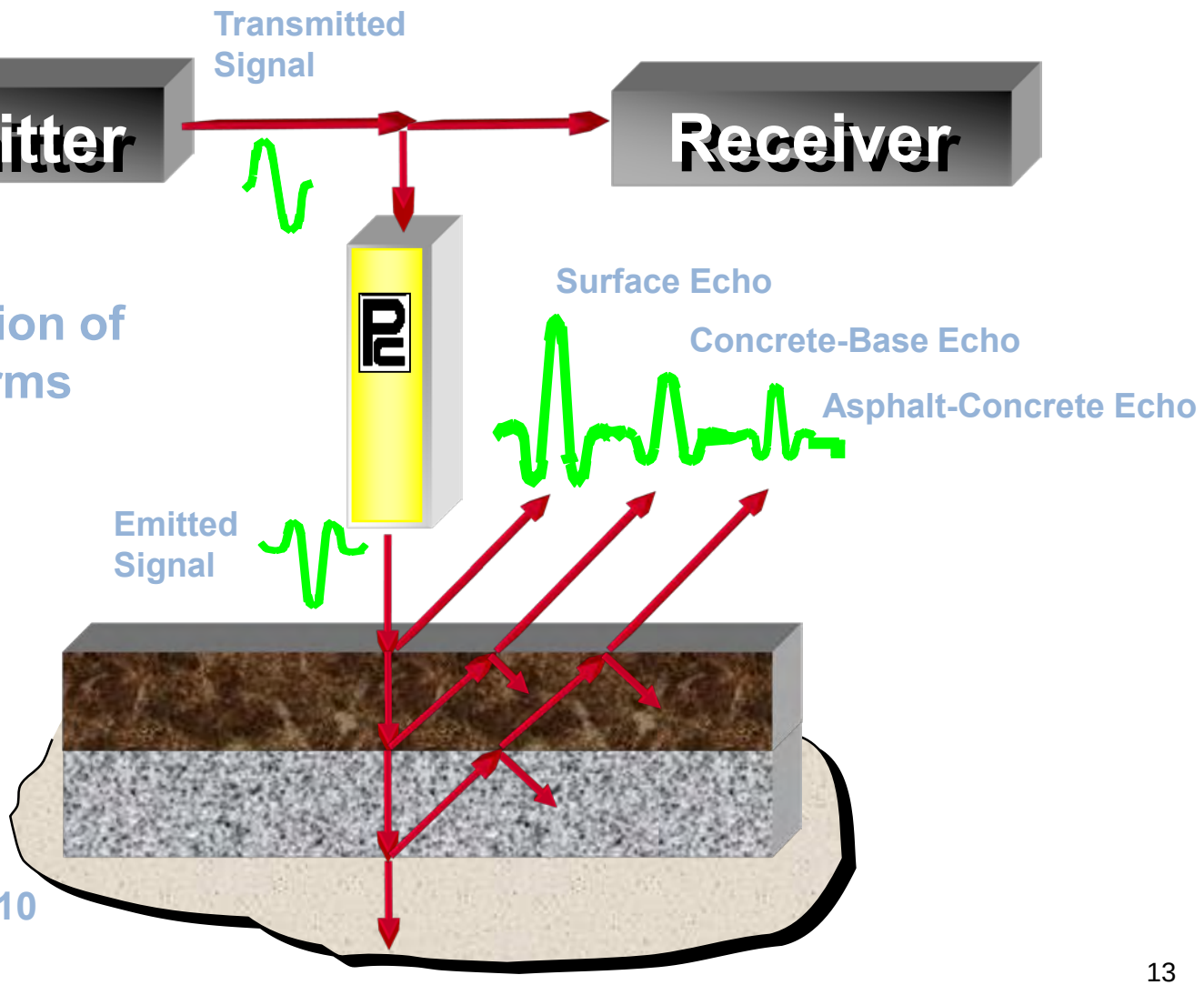
- Liner Thickness & Depth of Reinforcement
- Delamination of the Concrete Liner
- Voids Between the Liner and Base
- Water Flow Through and Behind the Liner
- Detection of Cracks

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

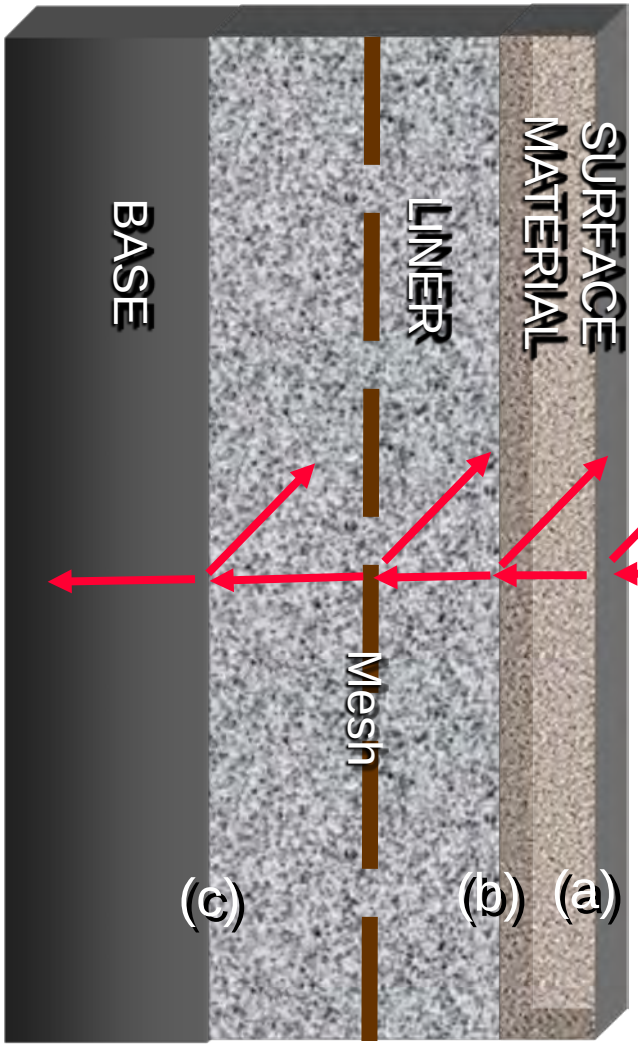
Air $\varepsilon_0 = 1$

Asphalt $\varepsilon_1 = 6$

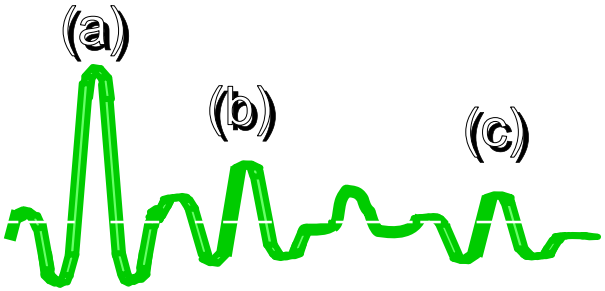
Concrete $\varepsilon_2 = 8$

Base Material $\varepsilon_3 = 10$

Tunnel Liner Evaluation - GPR



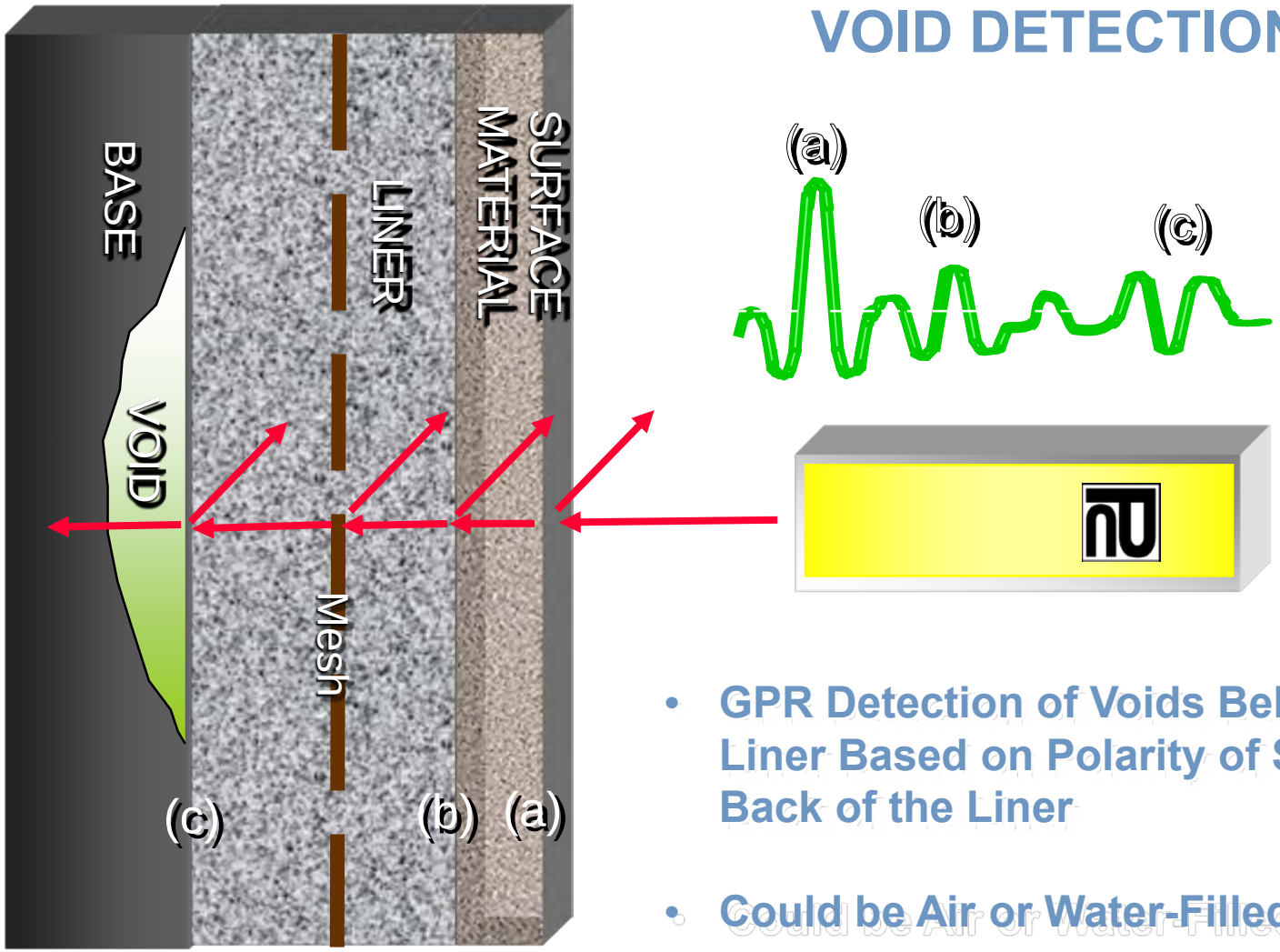
LINER THICKNESS MEASUREMENT



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

$$X = V * T$$

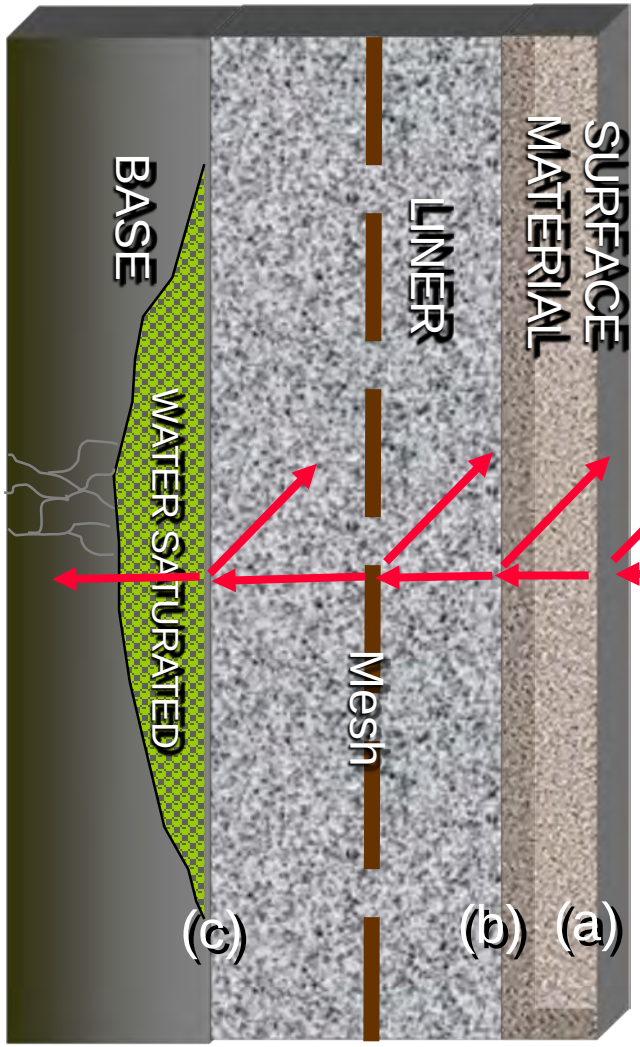
Tunnel Liner Evaluation - GPR



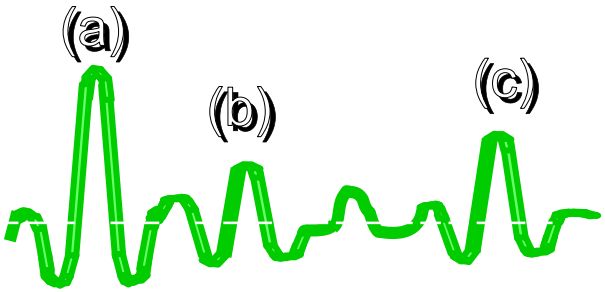
VOID DETECTION

- 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

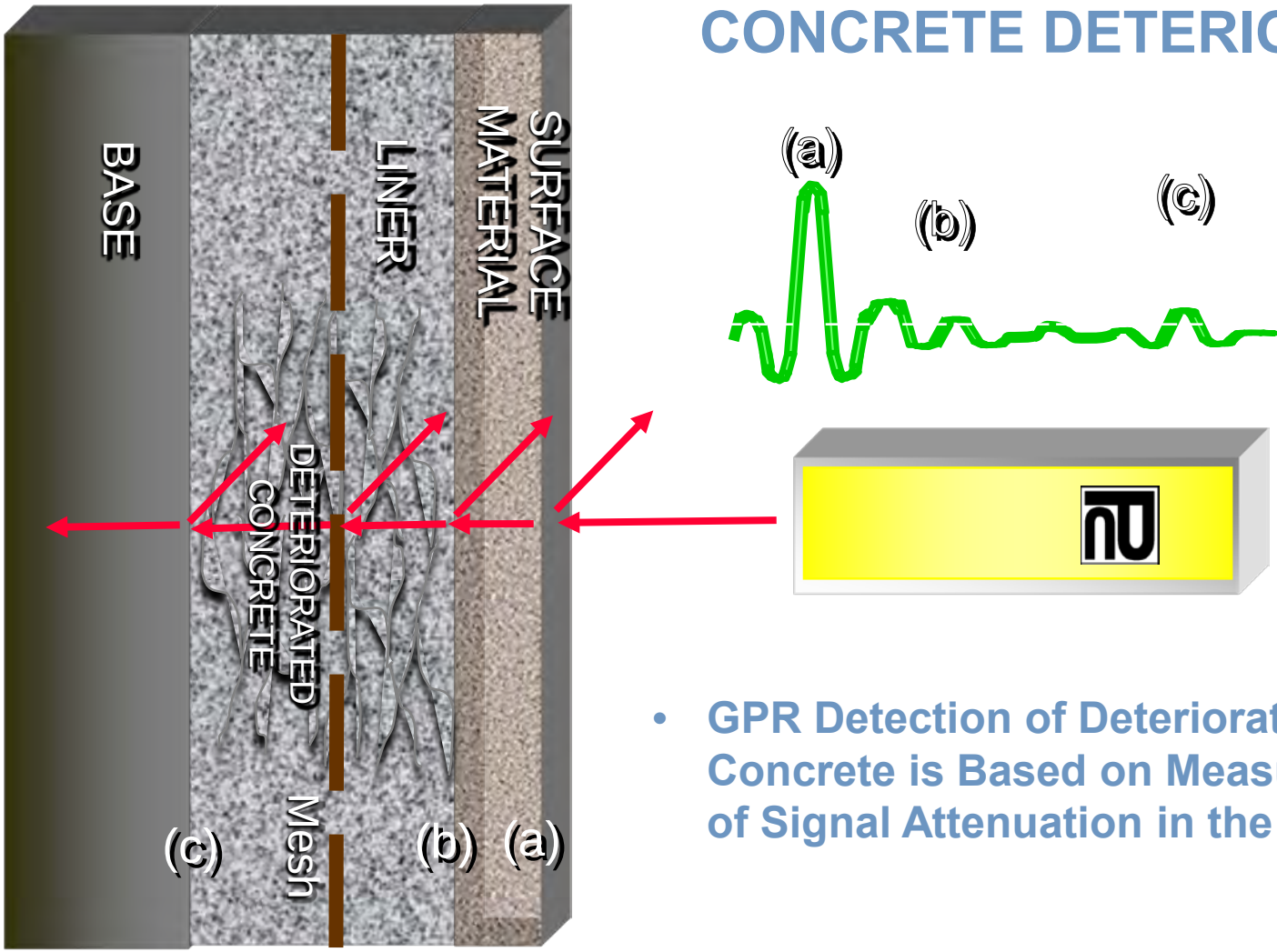


MOISTURE DETECTION



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

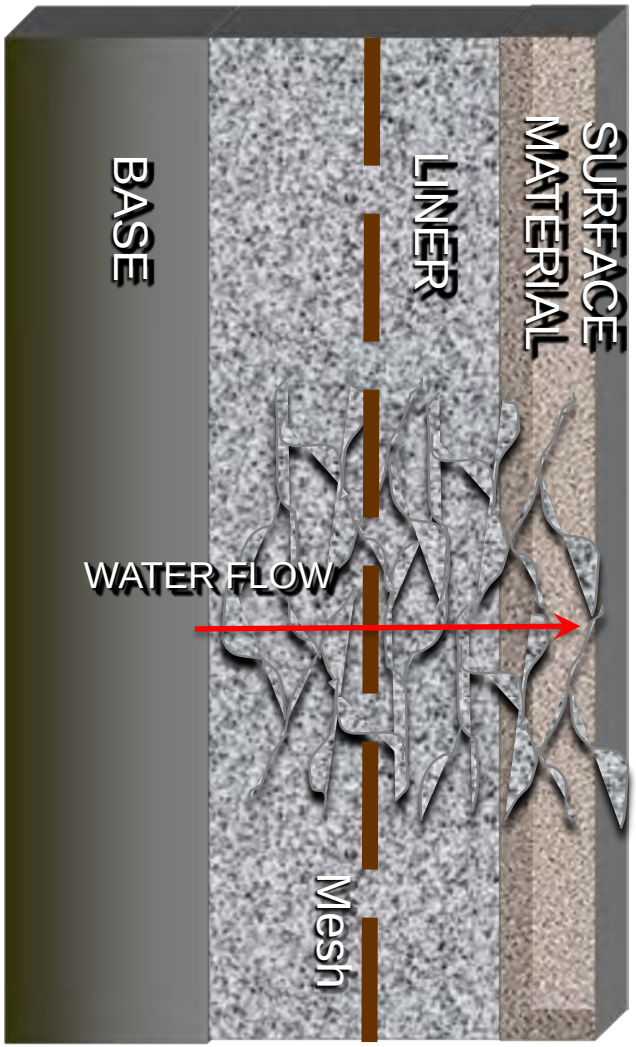
Tunnel Liner Evaluation - GPR

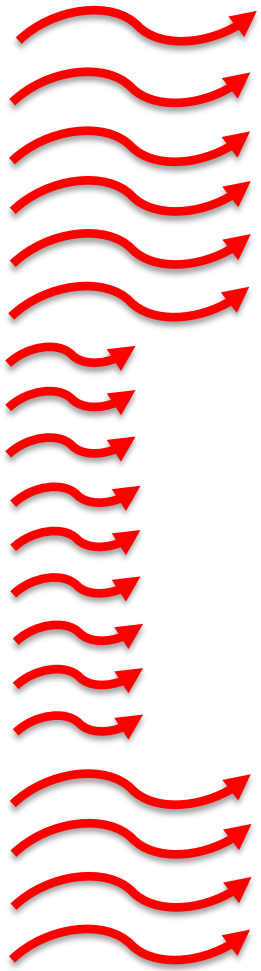


CONCRETE DETERIORATION

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

Tunnel Liner Evaluation - IRT

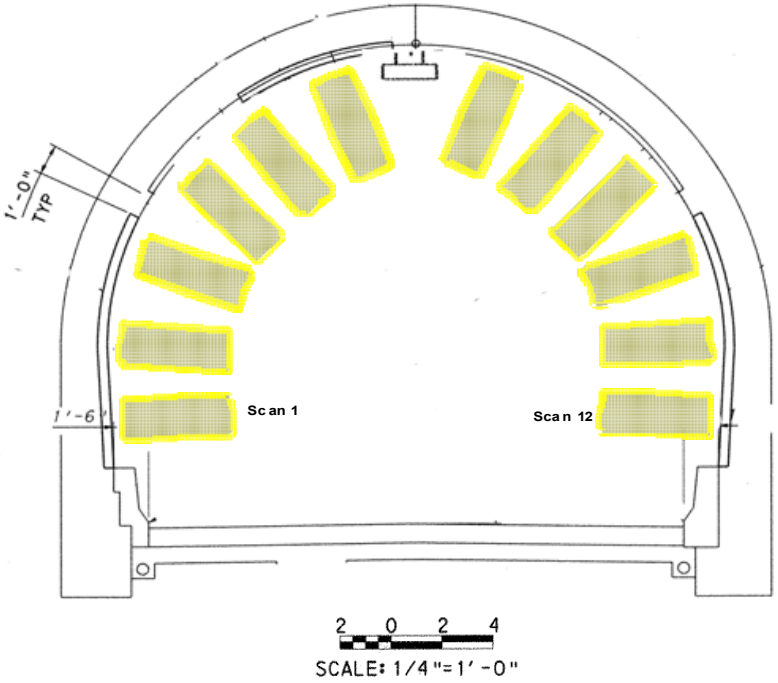




CONCRETE DETERIORATION, CRACKS AND WATER FLOW

- 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

PR System used for
spection of Roadway
unnels

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

45 second video
[click image to start/stop]

Tunnel Liner Evaluation

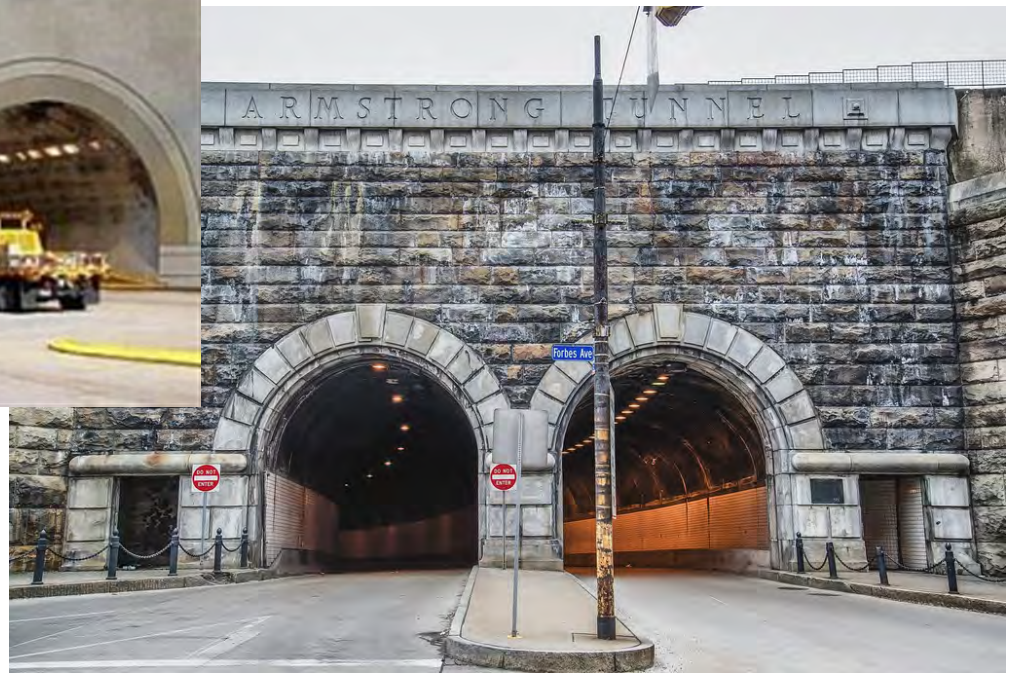
GPR Data Collection

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

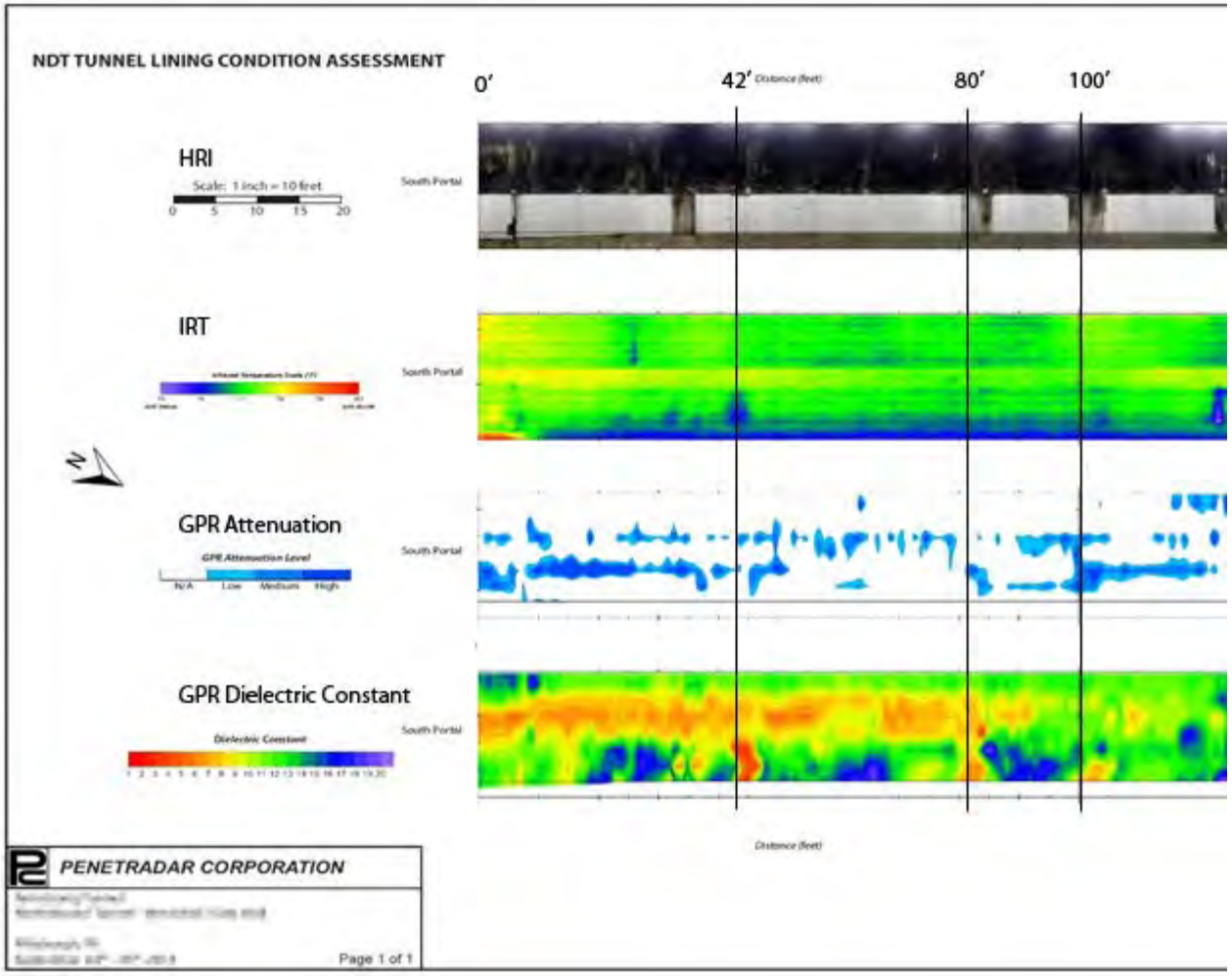
Armstrong Tunnel NDT Inspection

- 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

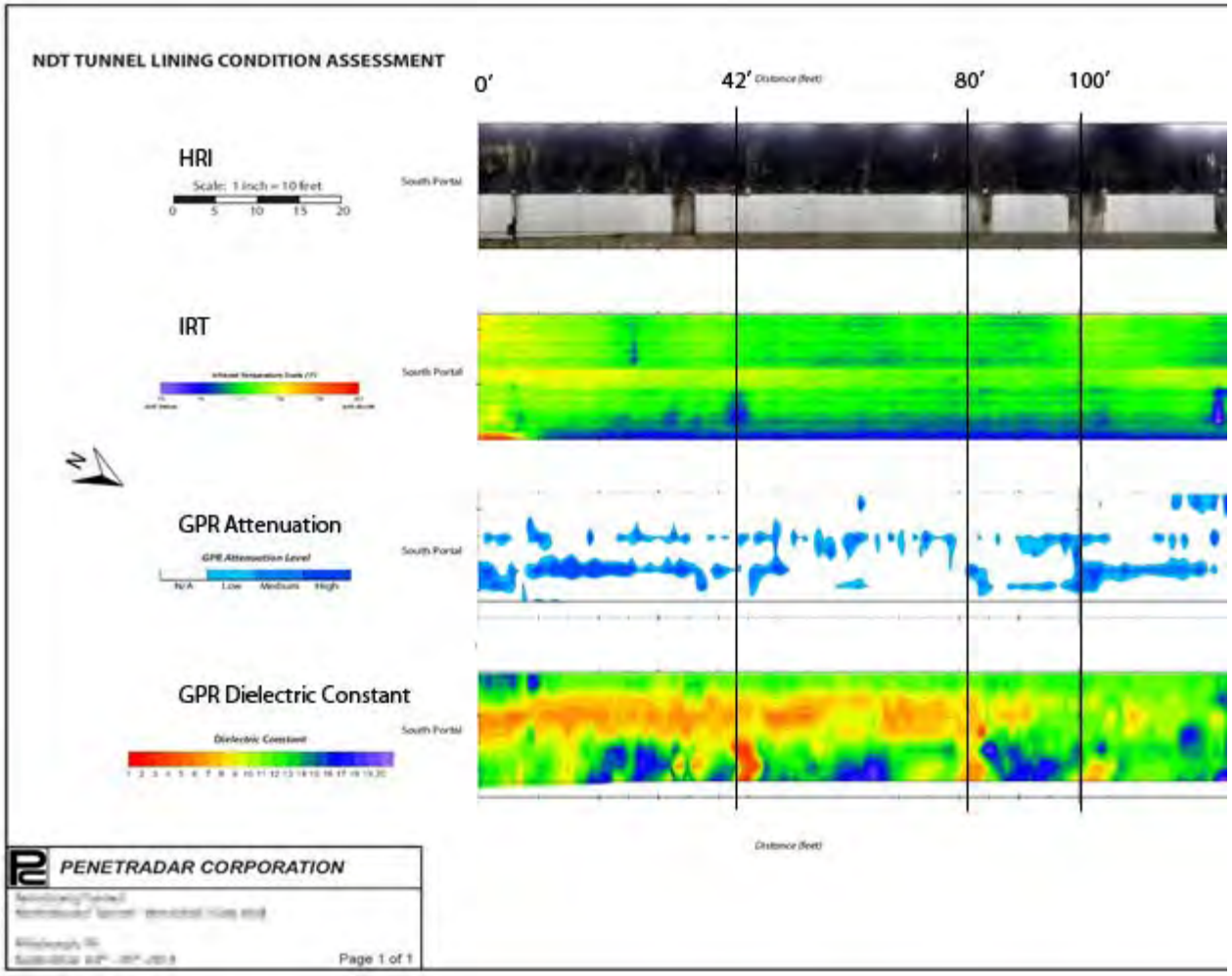
High Resolution Image

IRT Thermal Image

GPR Attenuation

GPR Dielectric Constant

Tunnel Liner Evaluation

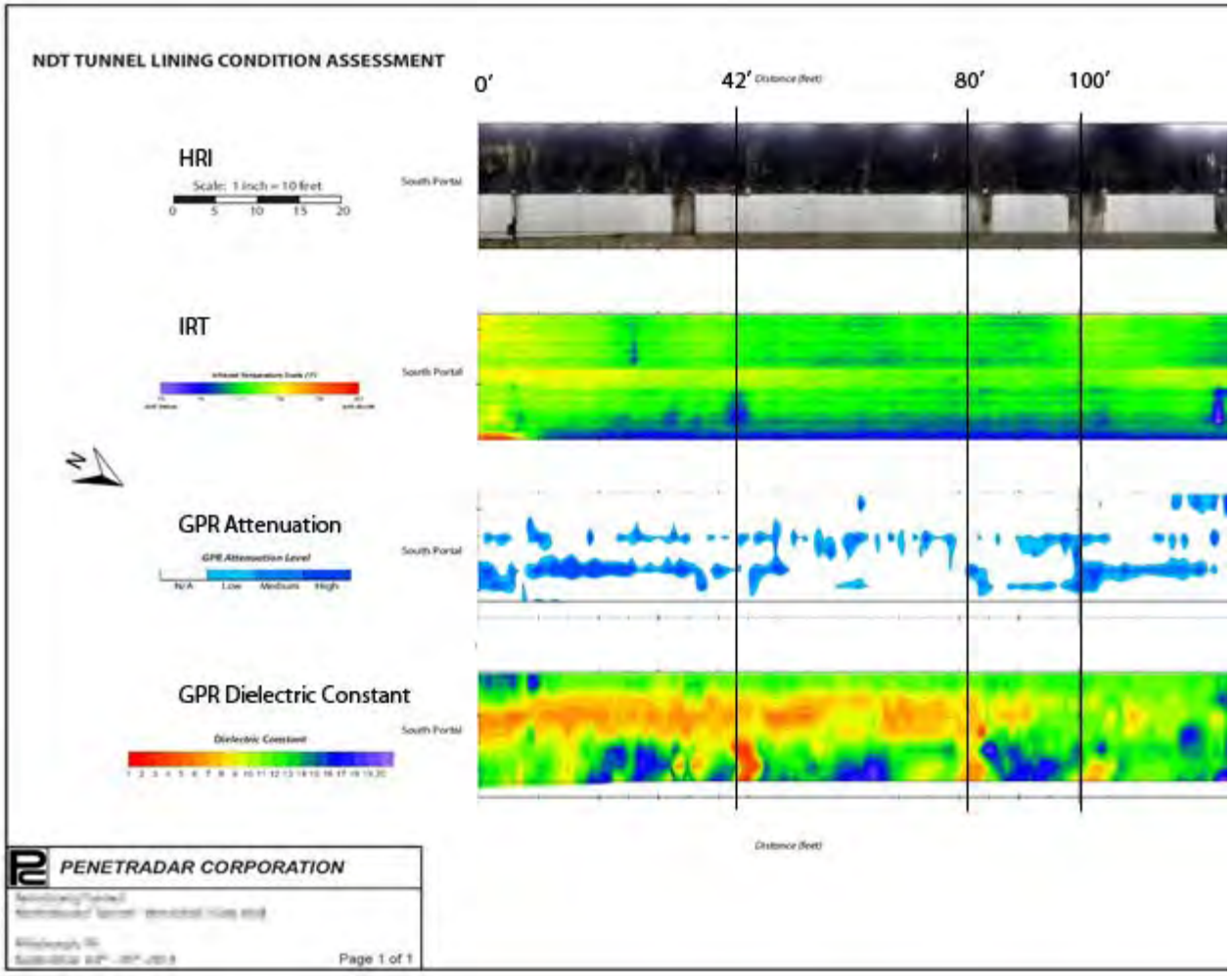


Armstrong Tunnel

Possible Debonded Tile at 42 ft

HRI – No Defect
IRT – Low Temp
GPR Attenuation – Low
GPR Dielectric - Low

Tunnel Liner Evaluation

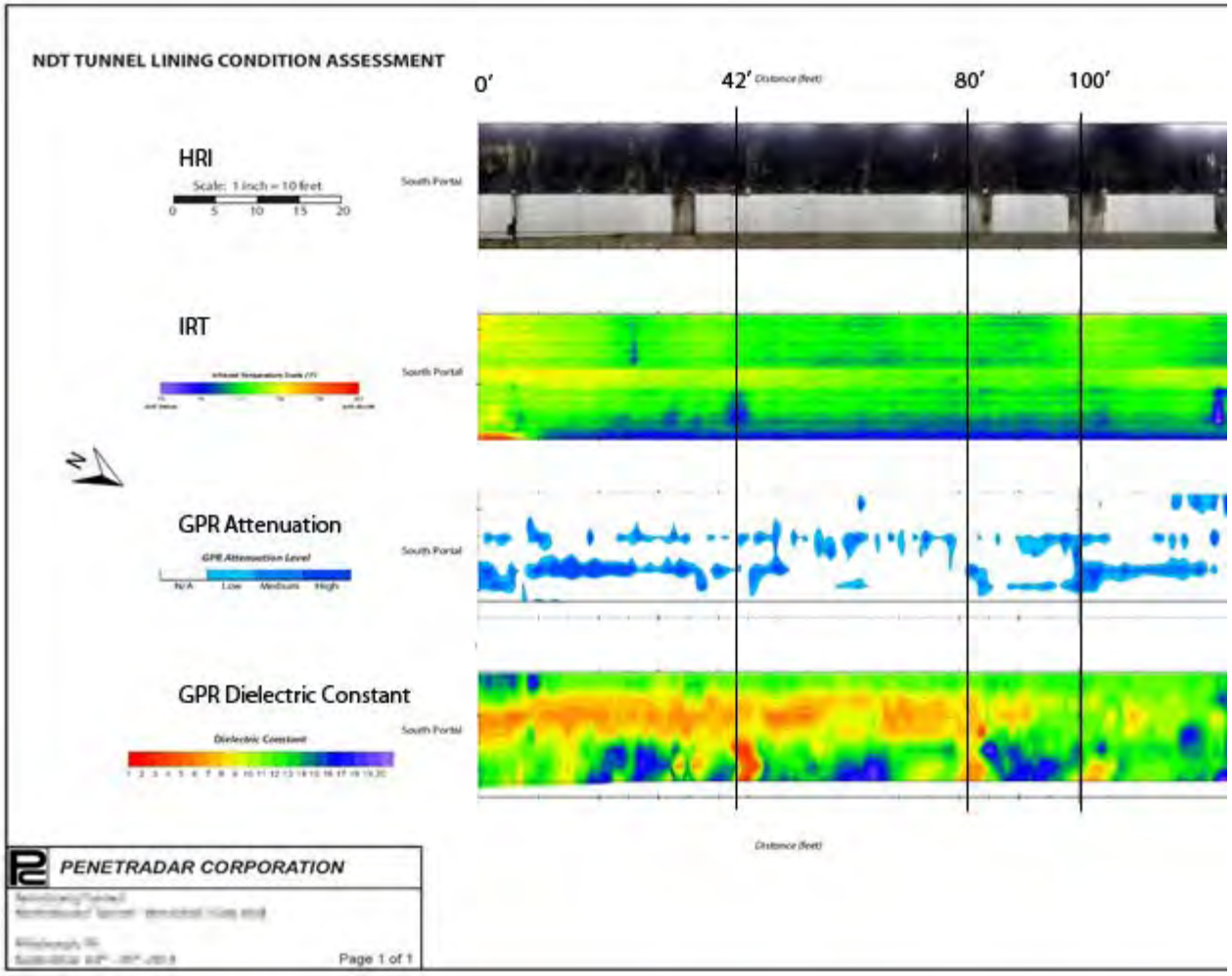


Armstrong Tunnel

Possible Deterioration at 80 ft

HRI – Missing Tile
IRT – No Temp Variation
GPR Attenuation – High
GPR Dielectric - Low

Tunnel Liner Evaluation



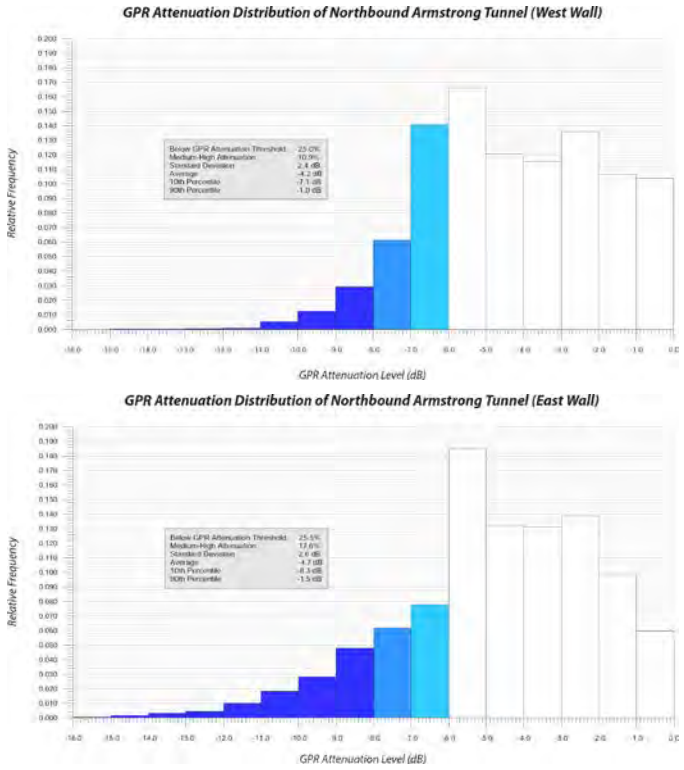
Armstrong Tunnel

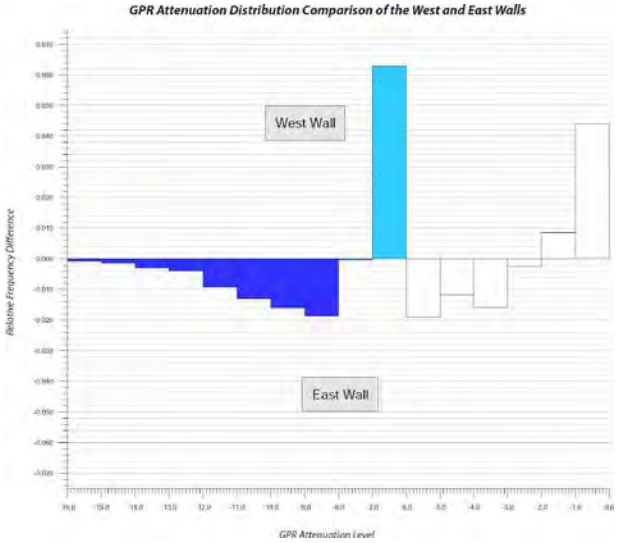
Possible Deterioration at 100 ft

HRI – Missing Tiles
IRT – No Temp Variation
GPR Attenuation – High
GPR Dielectric – Low

Tunnel Liner Evaluation

Armstrong Tunnel GPR Attenuation Distribution



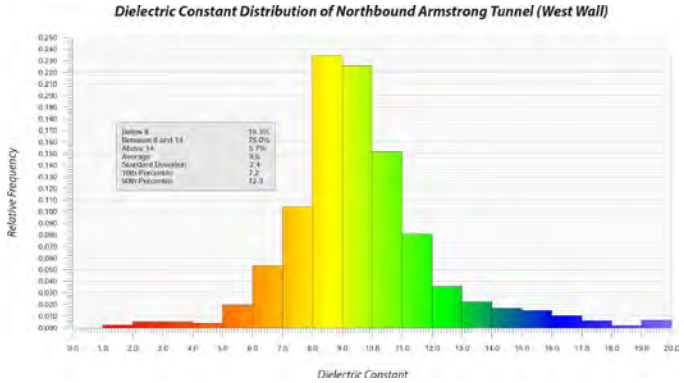


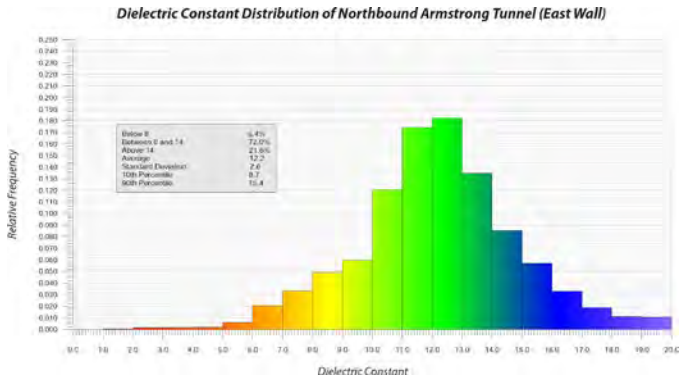
- West Wall Attenuation: 25.0% Total
- East Wall Attenuation : 25.5 % Total

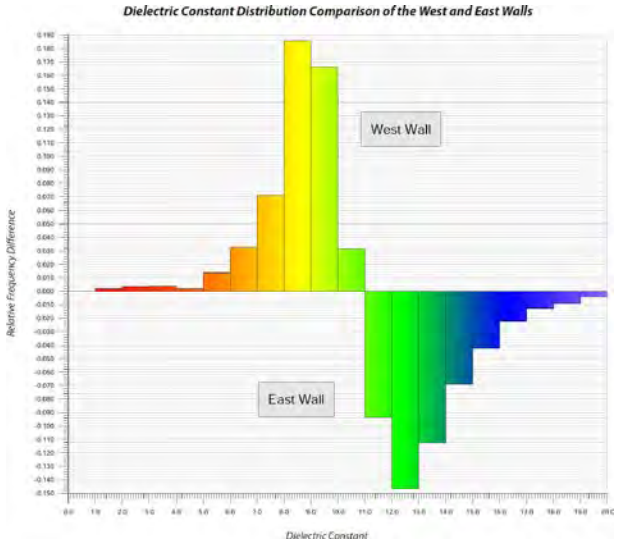
- East Wall contained higher levels of attenuation
  - Suggest east wall to be in generally worse physical condition

Tunnel Liner Evaluation

Armstrong Tunnel Dielectric Constant (ε_r) Distribution





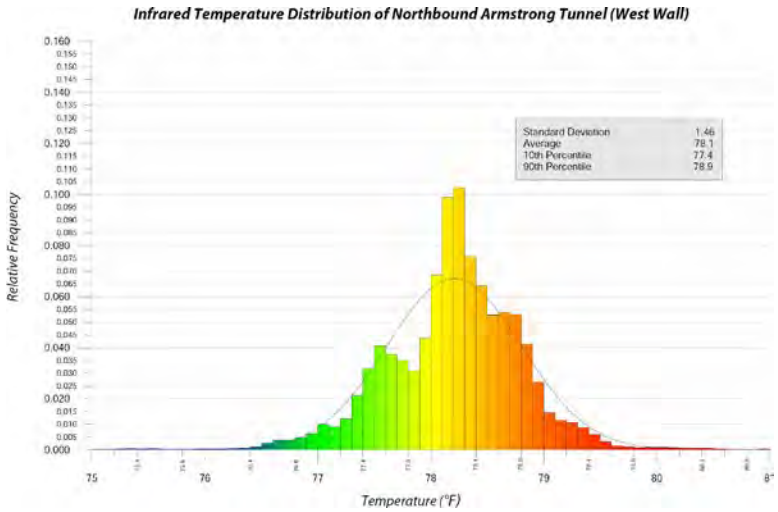


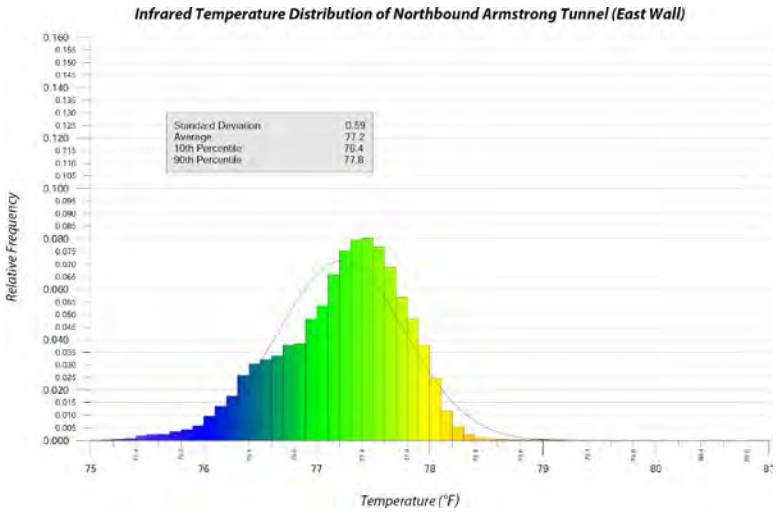
- West Wall Average ε_r : 9.6 (~ 4% moisture content)
- East Wall Average ε_r : 12.2 (~ 8% moisture content)

- 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

Tunnel Liner Evaluation

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
  - Methods of analysis are tunnel specific
  - Combination of technologies should be used
- Good correspondence between NDT and ground truth
- Need to develop Standards – ASTM & AASHTO

Tunnel Evaluation

Using GPR - IRT - HRI Technology

Tunnel Evaluation

Using GPR - IRT - HRI Technology

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