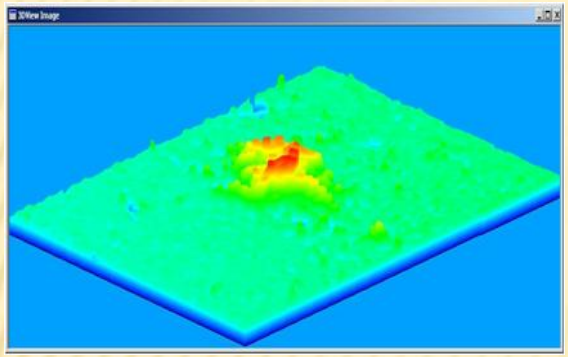
# Evaluation of Aluminum Pit Corrosion in Oak Ridge Research Reactor Pool



Ping-Rey Jang, Zhiling Long, Walter P. Okhuysen, Rangaswami Arunkumar, Jeffrey S. Lindner, and David L. Monts

Institute for Clean Energy Technology (ICET)
Mississippi State University

August 25, 2009

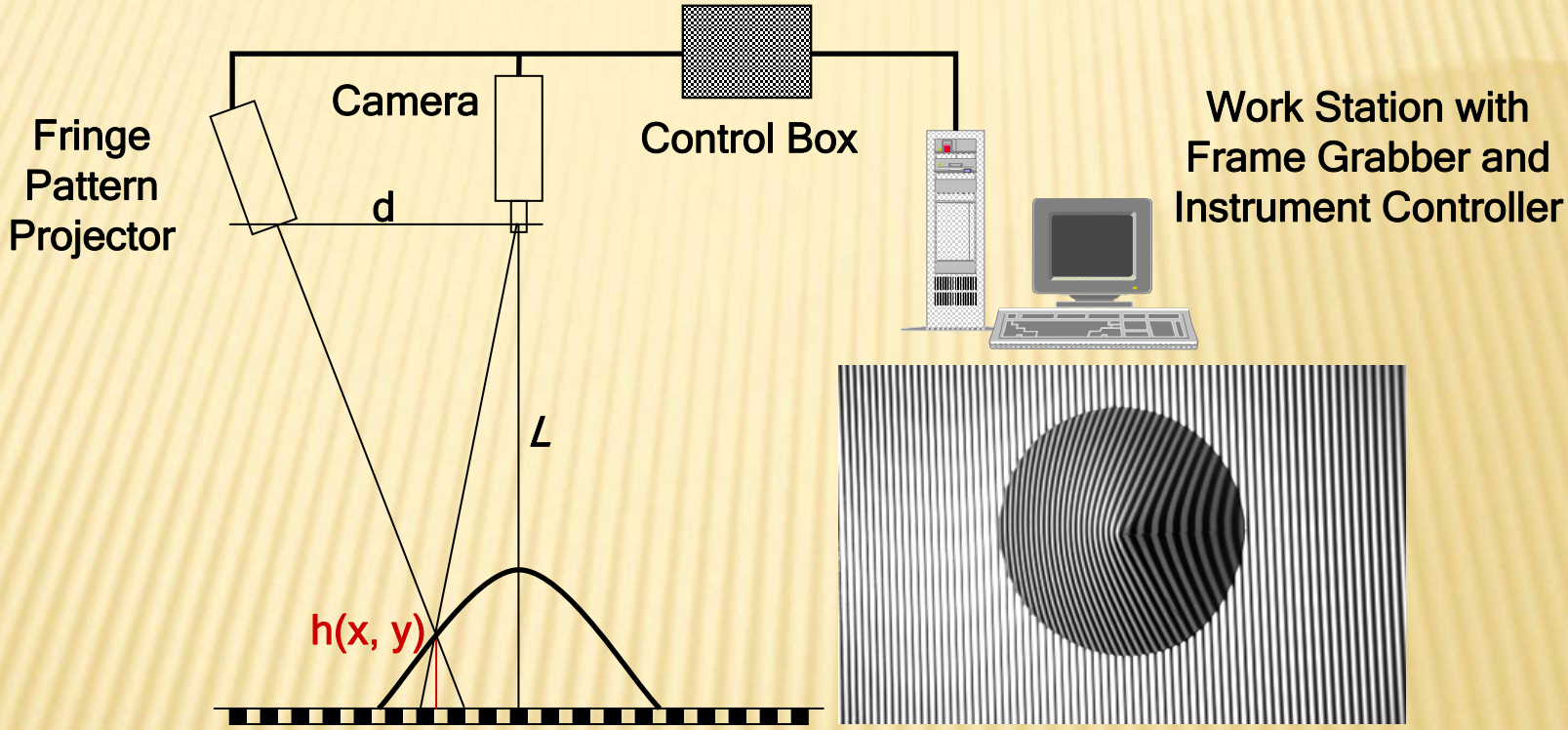
# Outline

- Purpose
- Fourier Transform Profilometry (FTP)
- Simulated FTP Measurements
- ICET Effort for Oak Ridge Research Reactor Pool
- Current FTP Effort for Hanford Waste Tanks
- Potential Applications
- Questions

# Purpose

The purpose was to characterize corrosion of the Oak Ridge Research Reactor (ORRR) pool to determine if corrosion has penetrated the aluminum liner. The results enabled ORNL to better plan for the decontamination and demolition of ORRR as part of the Oak Ridge cleanup program.

# Principle of Fourier Transform Profilometry (FTP) Technology

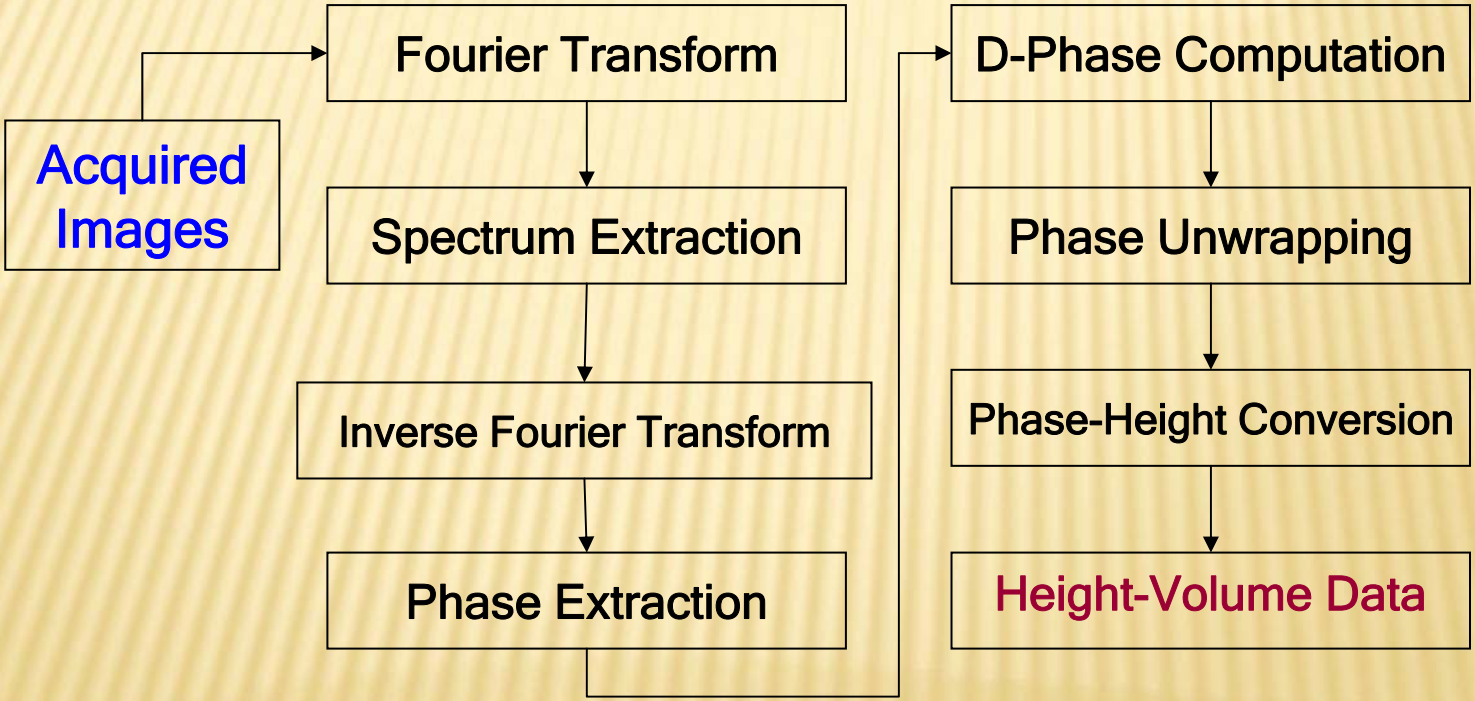



$$h(x, y) = \frac{L\Delta\Phi(x, y)}{\Delta\Phi(x, y) - 2\pi f_0 d}$$

Where:
h = height
$\Delta\Phi$ = phase variation
$f_0$ = fundamental frequency

# FTP Process Flow Chart

Fourier Transform Profilometry (FTP) - A 3-D shape measurement technique. Projecting a fringe pattern upon target surface and observing its deformation from a different view angle.



# FTP Imaging Acquisition/Analysis Software

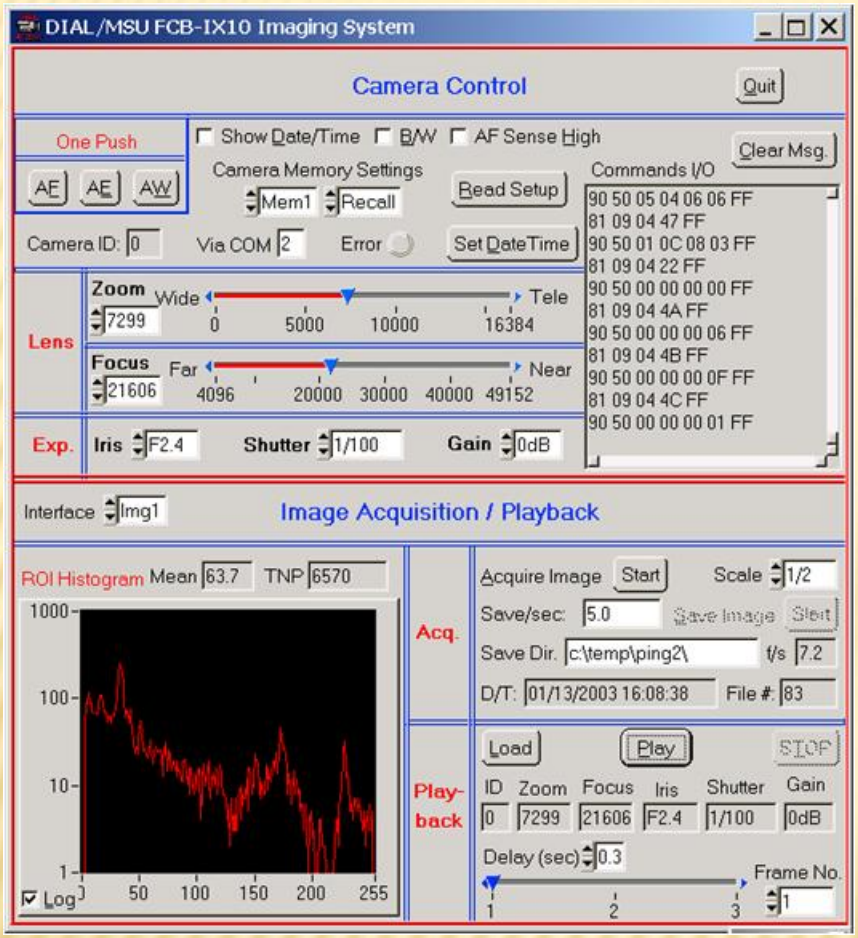



Image Acquisition

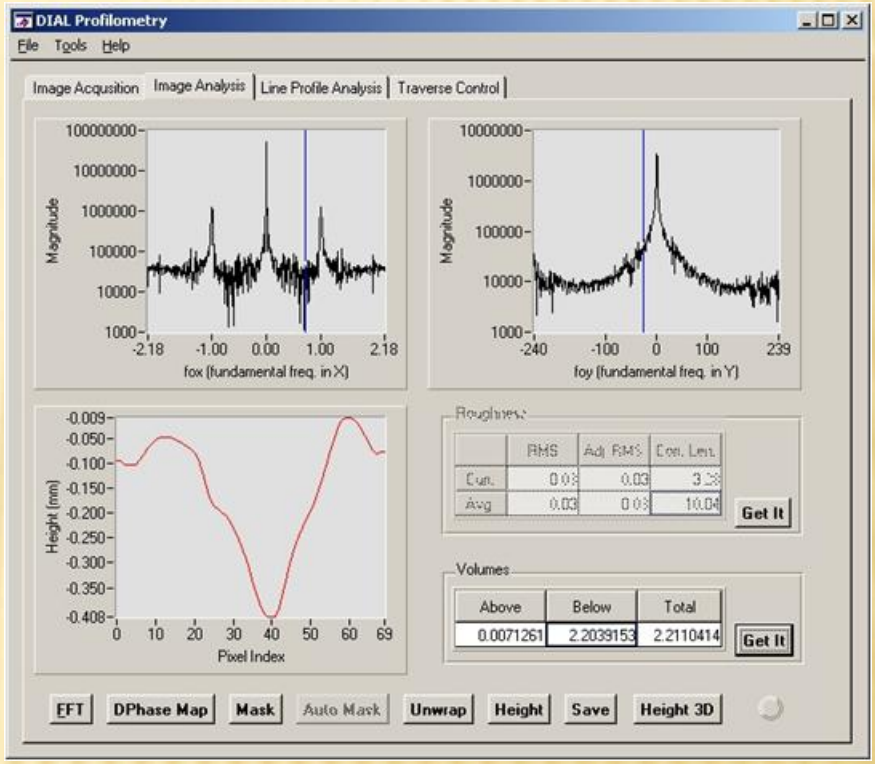
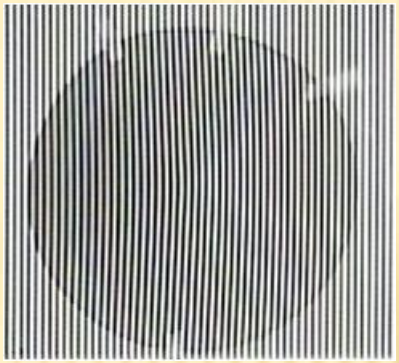


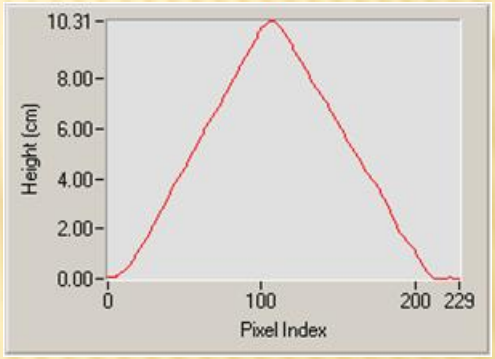

Image Analysis

# Typical Measurement Results under Simulated Conditions

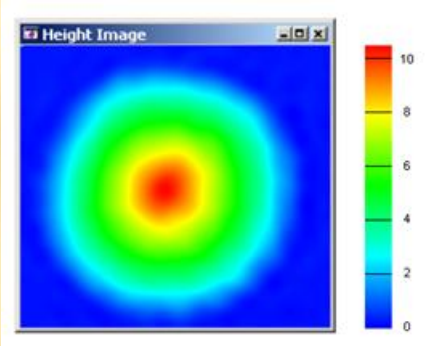
- Distance between camera and target: 455.3 cm (~15')
- Distance between camera and projector: 21.0 cm (~8")
- Ronchi filter: 250 Lines/Inch
- Target: paper cone with base diameter Φ = 26.7 cm (~10.5") and peak height = 10.4 cm (~4")



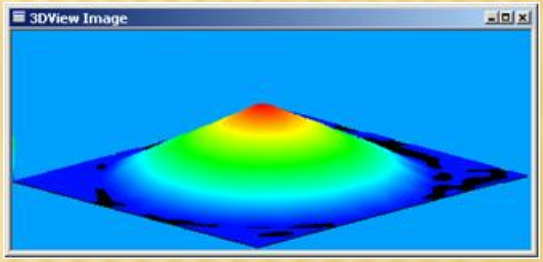
Target




Reconstructed 1D Profile



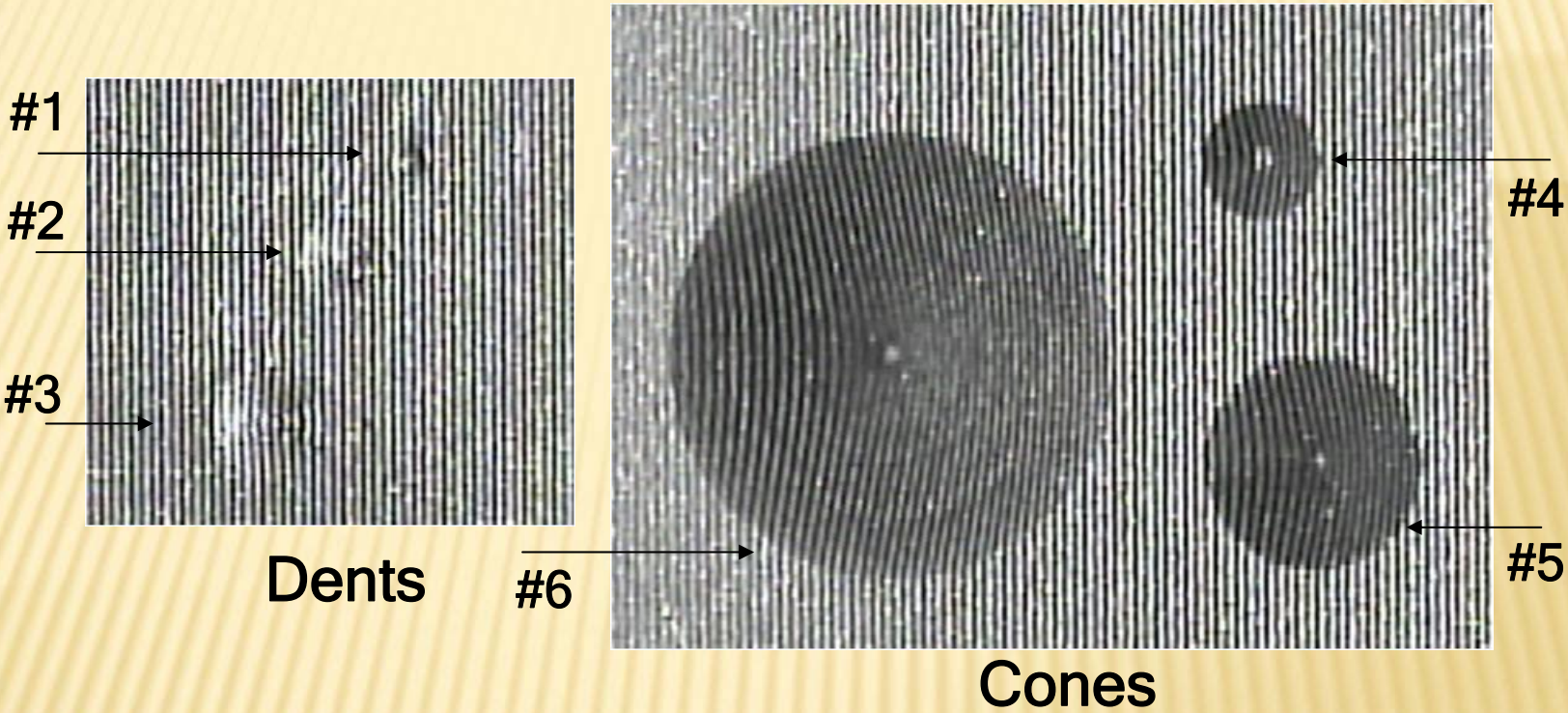

Reconstructed 2D Profile




Reconstructed 3D Profile

| | Target | Measured | Error |
|---|---|---|---|
| Peak Height (cm) | 10.4 | 10.31 | 0.9% |
| Volume ($cm^3$) | 1941.00 | 1962.73 | 1.1% |

# ORRR Simulation Measurements – Targets



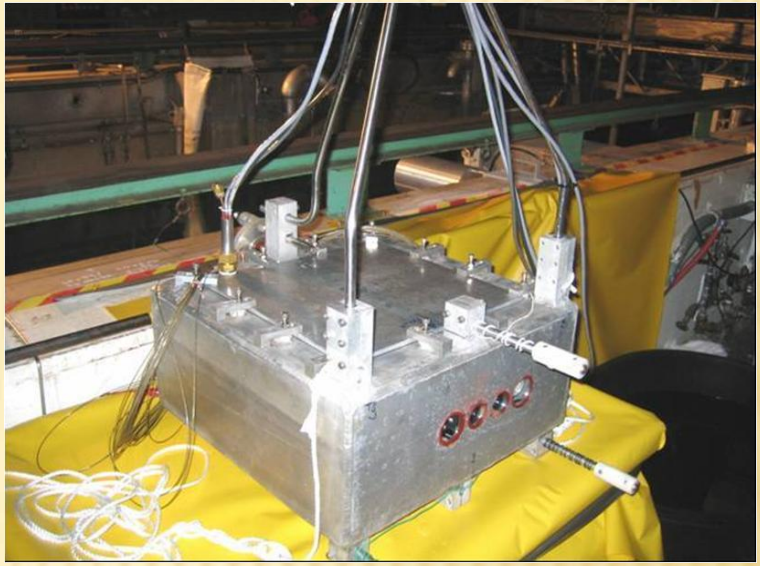

- Targets were small cone-shaped dents on an aluminum plate and aluminum cones placed on the plate.
  - Base diameters for dents: 1-3 mm; for cones: 3-12 mm.
  - Maximum depths/heights: 0.2-0.6 mm for dents; 1.5-6 mm for cones.

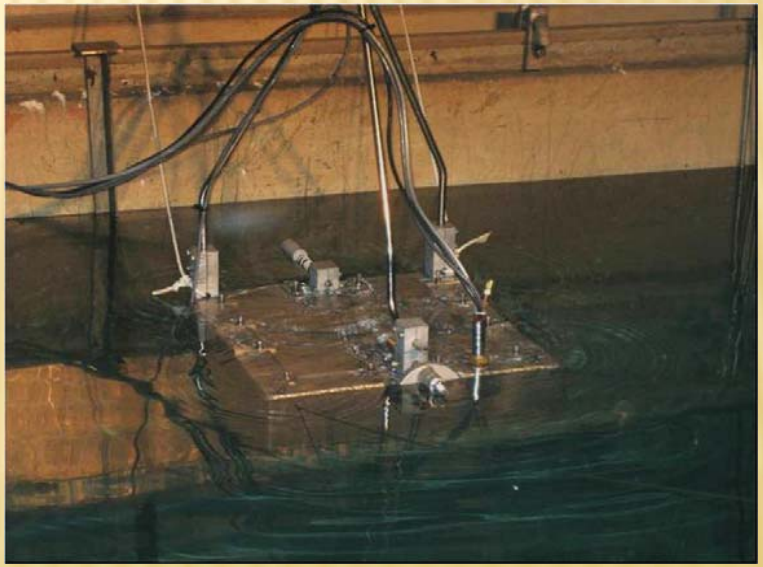
# Measurement Results
# - Maximum Depths/Heights in Water

| Target | Truth Data* (mm) | Measured (mm) | Error (mm) | Percentage Error (%) |
|---|---|---|---|---|
| #1 dent | -0.231 | -0.226 | 0.005 | -2.2 |
| #2 dent | -0.490 | -0.392 | 0.098 | -20.0 |
| #3 dent | -0.578 | -0.552 | 0.026 | -4.5 |
| #4 cone | 1.524 | 1.449 | -0.075 | -4.9 |
| #5 cone | 2.921 | 2.841 | -0.08 | -2.7 |
| #6 cone | 6.274 | 5.461 | -0.813 | -13.0 |

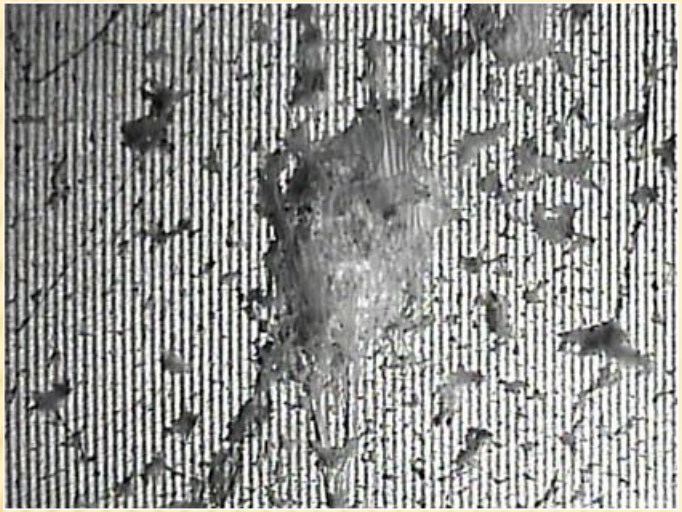
* Need verification and validation, especially for the dents.

# Deployment into ORRR Pool

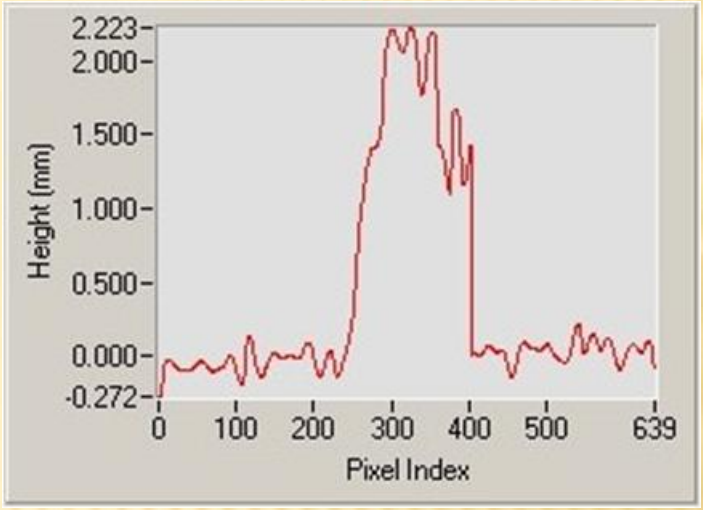




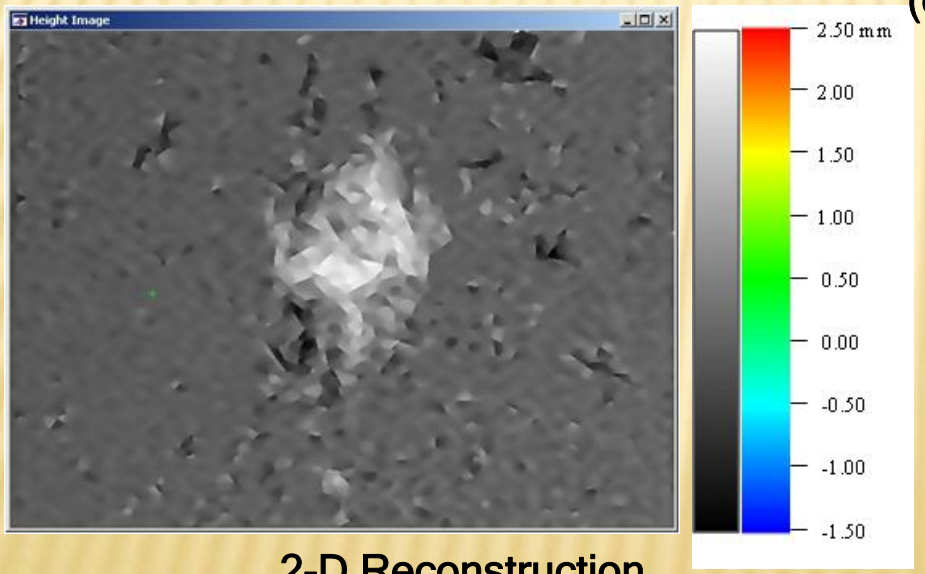
# Corrosion Target Measurement – Before Brushing



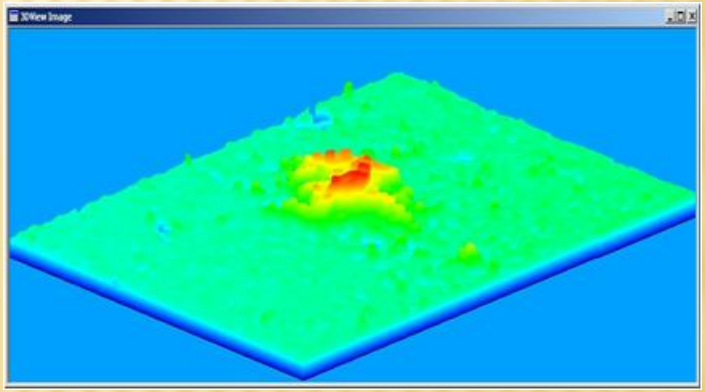
Original Image of Pit Corrosion




1-D Reconstruction
(cross section along a horizontal pixel line)



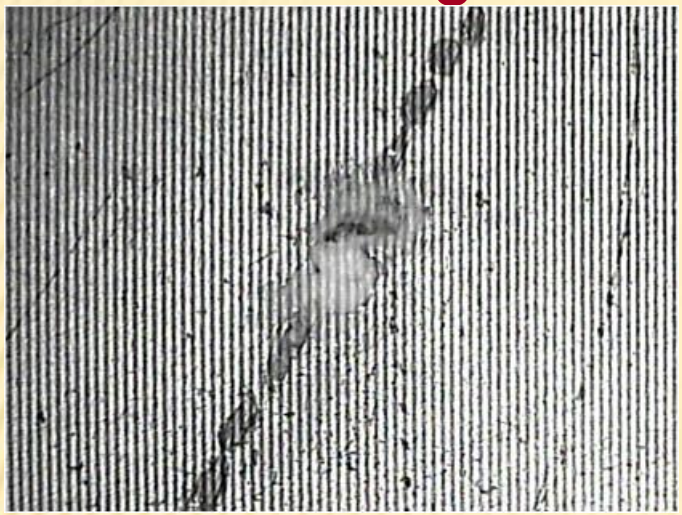

2-D Reconstruction



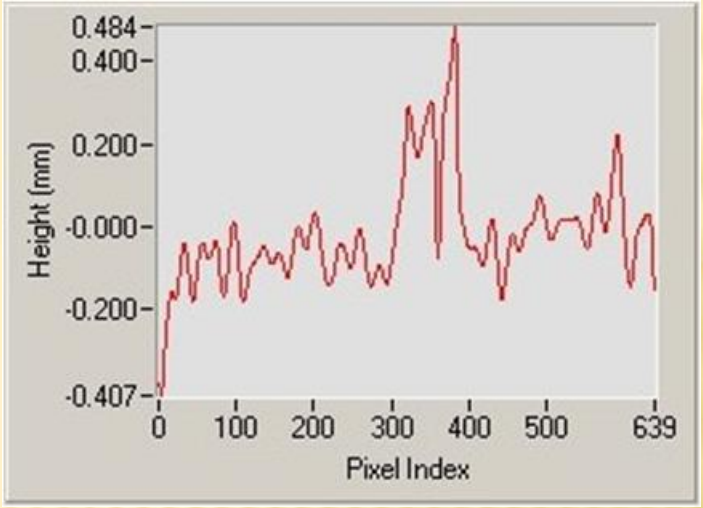
3-D Reconstruction

**Measured volume: 129.85 $mm^3$**

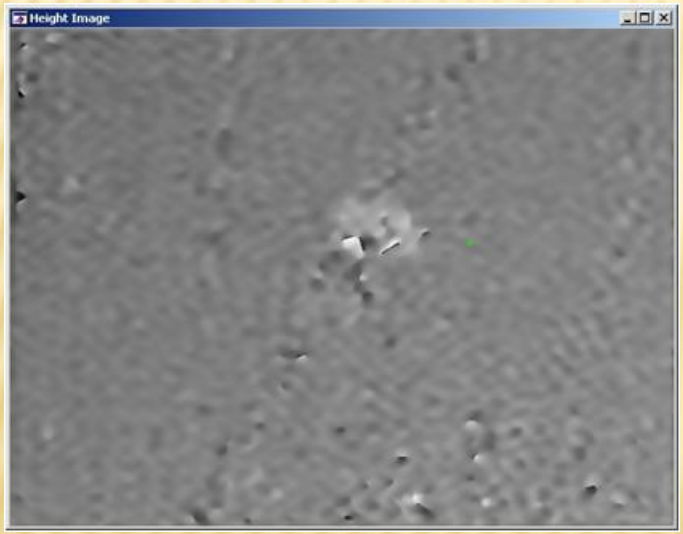
# Corrosion Target Measurement – After Brushing

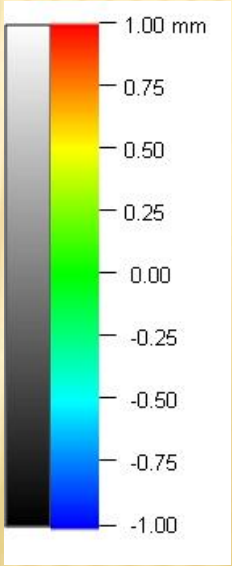


Original Image

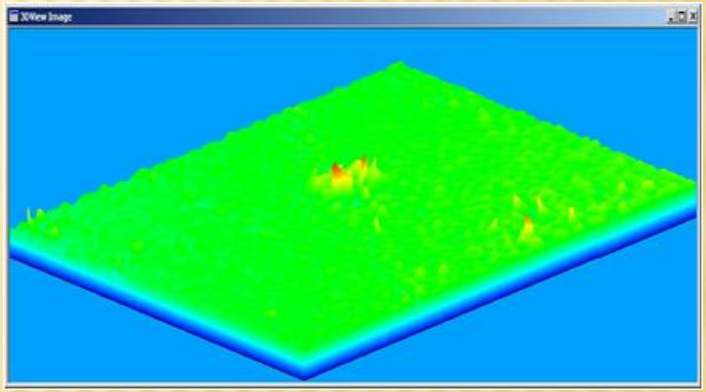



1-D Reconstruction
(cross section along a horizontal pixel line)




2-D Reconstruction



3-D Reconstruction

**Measured volume: 20.41 $mm^3$**

# Preliminary Results
# Correction of Measured Volumes

| | Before Brushing | After Brushing |
|---|---|---|
| Measured Volume ($mm^3$) | 129.85 | 20.41 |
| Correction Factor | 1.086 | 1.086 |
| Corrected Volume ($mm^3$) | 141.02 | 22.17 |

- This target is located on the South Wall, 6.9 m (22' 7“) away from the East Wall, and 0.235 m (9 1/4“) below the water surface. Images were acquired on December 9, 2005 at 11:35 a.m.
- The correction of water refraction distortion was done by multiplying the correction factor by the measured volume.

# Summary of Thermodynamic Modeling Results

In order to inhibit aluminum pit corrosion in ORRR pool:

- Maintain aqueous $O_2$ concentrations below about 0.015 g/kg $H_20$
- Maintain $Cl^-$ concentrations below about 0.005 g (NaCl equivalent)/kg $H_2O$
- Maintain pH as close to 7 as possible
- Maintain water temperature of at least 25°C

# Comparison of Experimental Results with Corrosion Calculations

- Collected over a 3.71 x 2.78 $cm^2$ area, the 141 $mm^3$ corrected volume corresponds to a total volume of aluminum involved of $4.40 \times 10^{-2}$ $cm^3$ and, thus, an <u>average</u> depth of $4.3 \times 10^{-3}$ cm.

- The facility has been in operation for 49 years. Consequently the average corrosion rate would be $8.7 \times 10^{-4}$ mm/yr.

- This result is consistent with the corrosion rate predicted by the model ~ $5.62 \times 10^{-4}$ mm/yr.

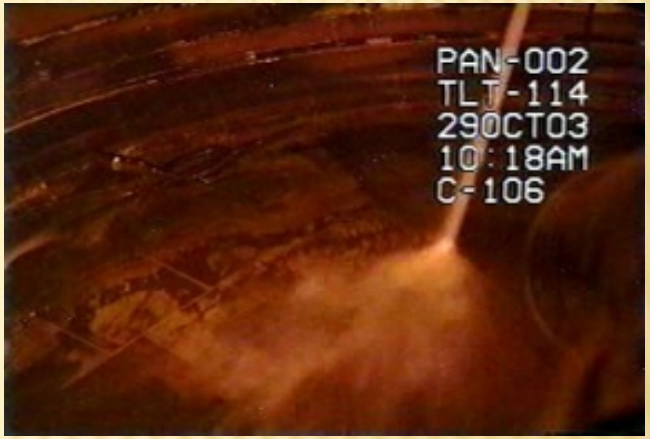
- Differences may arise from varying chemical compositions and local temperatures over the operational period of the facility and from the conservative assumption that pitting is uniform over the entire corrosion area investigated.

# Conclusions for ORRR Measurements

- Successfully deployed the submergible FTP measurement system and obtained measurements of some typical pit corrosion areas.
- The FTP analysis successfully reconstructed 3-D profiles of the corrosion on the surface of the pool wall.
- With correction applied to raw data, successfully measured volumes of the corrosion areas on the surface of the pool wall.

# Current FTP Effort for Hanford Waste Tanks – Residual Waste Volume Determination

C-202

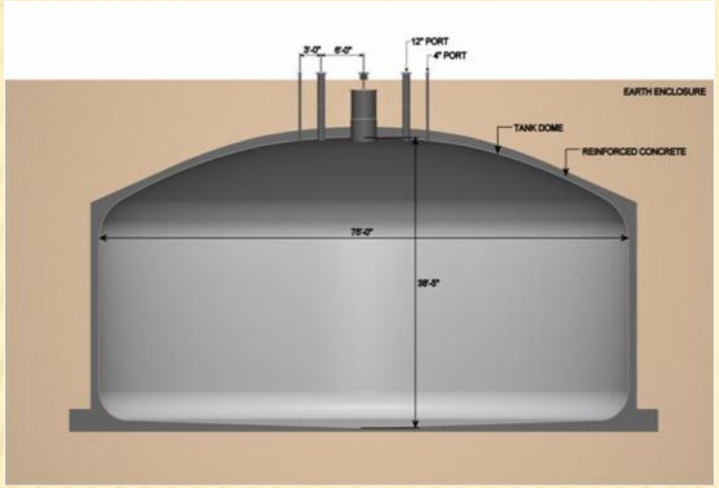


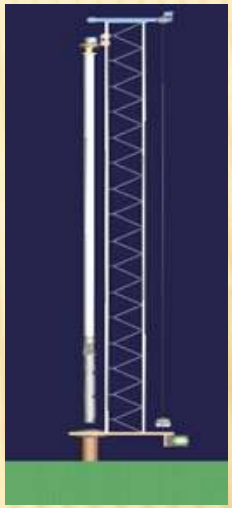

C-106

CH2MHILL
Hanford Group, Inc.

Improved tools for residual waste volume determination are expected to provide site operators and regulators with verifiable information that can be used in determination of closure timelines.

# Maximum Observation Distance : 53 ft at 62° 25 ft Above



## Design Goals for In-Tank FTP Probe Inspection System

- Must be deployable through 4" ID riser.
- Insertion depths of 9 to 30 ft.
- Ability to pan 360 º and to tilt 120°.
- Illumination must be provided.
- Deployment by 2 technicians wearing protective garment & heavy gloves w/o use of "crane."
- Max. riser loads of 500 lb axial & 250 ft-lb bending moment.
- Operator lifting limitation of 40 lbs will require breakdown into subassemblies.

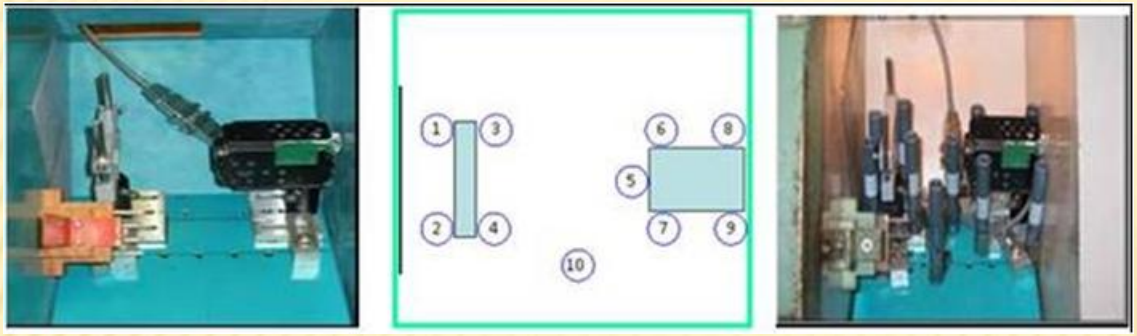
# FTP Results at Maximum Tank Distance

S3 S4 S6

| Target | True Volume ($cm^3$) | Measured Volume ($cm^3$) | Absolute Error ($cm^3$) | Relative Error (%) |
|---|---|---|---|---|
| S3 | 1954 ± 10 | 2057 | +103 | +5.3 |
| S3 | 1954 ± 10 | 2039 | +85 | +4.4 |
| S3 | 1954 ± 10 | 2085 | +131 | +6.7 |
| S3 | 1954 ± 10 | 2105 | +151 | +7.7 |
| S4 | 1071 ± 6 | 1089 | +18 | +1.7 |
| S4 | 1071 ± 6 | 1129 | +58 | +5.4 |
| S4 | 1071 ± 6 | 1081 | +10 | +0.9 |
| S4 | 1071 ± 6 | 1087 | +16 | +1.5 |
| S6 | 647 ± 4 | 683 | +36 | +5.6 |
| S6 | 647 ± 4 | 686 | +39 | +6.0 |
| S6 | 647 ± 4 | 695 | +48 | +7.4 |
| S6 | 647 ± 4 | 711 | +64 | +9.9 |

Average Relative Error +5.2 %

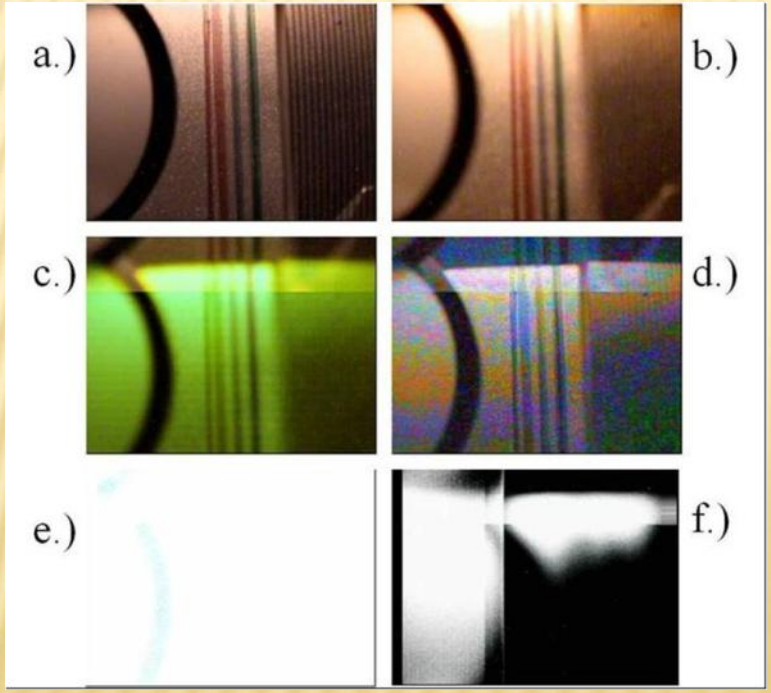
# Effect of Gamma Radiation on Camera Performance




| Location | R/hour |
|---|---|
| 1 | 54 |
| 2 | 60 |
| 3 | 34.5 |
| 4 | 32.7 |
| 5 | 21.6 |
| 6 | 12.6 |
| 7 | 15 |
| 8 | 12 |
| 9 | 12 |
| 10 | 3 |

Beginning

182nd hour




193rd hour

197th hour

198th hour

207th hour

# FTP Height Resolution

The resolution $\Delta h_p$ of FTP measurements is defined as the height (depth) that a single pixel in an acquired image can resolve.

$$\Delta h_p = \frac{L_0 \Delta\Phi_p}{[\Delta\Phi_p - 2\pi d f_0]}$$

where

$$\Delta\Phi_p = \frac{2\pi n_{line}}{x_{pixel}}$$

$L_0$ = camera-to-plane distance
$d$ = camera-to-projector distance
$f_0$ = fundamental frequency of observed fringe pattern on plane
$\Delta\Phi_p$ = phase shift that a single pixel in acquired image can resolve
$n_{line}$ = total number of fringe lines in image
$x_{pixel}$ = horizontal image dimension (in pixels)

# FTP Height Resolution

| Ronchi Filter (lines/inch) | Camera-to-Plane $L_0$ (cm) | Camera-to-Projector (cm) | $f_0$ (lines/cm) | $\Delta h_p$ (cm) |
|---|---|---|---|---|
| 300 | 1615.6 | 46.1 | 0.75 | 2.64 |
| 300 | 1616.2 | 33.4 | 0.75 | 3.65 |
| 300 | 1615.2 | 21.8 | 0.75 | 5.60 |
| 300 | 760.5 | 21.8 | 1.59 | 3.46 |
| 200 | 652.4 | 21.6 | 1.23 | 1.13 |
| 200 | 434.8 | 21.6 | 1.86 | 1.00 |
| 200 | 232.6 | 21.6 | 3.48 | 0.49 |
| 250 | 16.7 | 6.0 | 19.27 | 0.02 |

FTP system capable of sub-mm height resolution from several feet away even with low-resolution camera.

# Potential NDE Applications

- Non-contact characterization of tank interior corrosion
  - Capability of FTP technique has already been demonstrated.
  - Capable of sub-mm resolution from moderate distances.
  - Cost of FTP system (without deployment mechanisms, but including computer) about $5-7K.

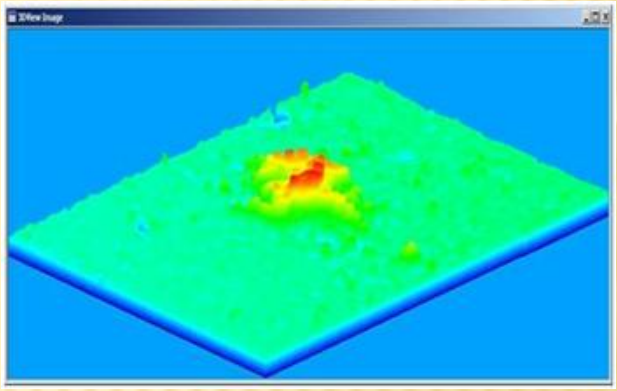
- Coupled with thermodynamic modeling, quantitative imaging results would enable more comprehensive characterization of tank integrity.

# Acknowledgments

We wish to thank Paula Kirk (ORNL), John Ettien and Darrell Dillinger (Bechtel Jacobs Company LLC), and Eric Sliger (Washington Group) for their assistance in the ORRR effort.

The ICET portion of this effort was funded by the U.S. Department of Energy's Office of Environmental Management through Cooperative Agreement DE-FC26-98FT-40395.

# Questions ?



## Contact Information:

Dr. David L. Monts
Institute for Clean Energy Technology (ICET)
Mississippi State University
Phone: (662) 325-7389
E-mail: Monts@ICET.MsState.Edu