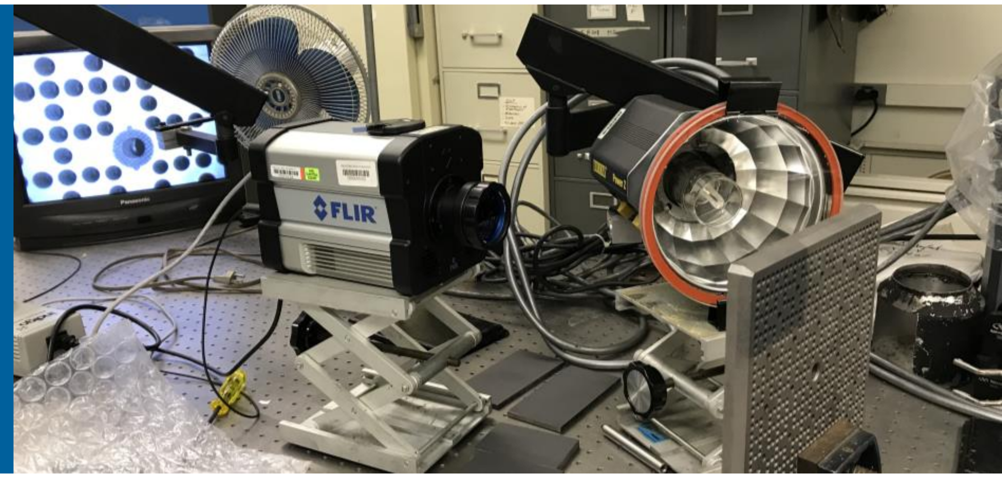
ADVANCED METHODS FOR MANUFACTURING ANNUAL PROGRAM REVIEW

PULSED THERMAL TOMOGRAPHY NONDESTRUCTIVE EVALUATION



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December 5, 2018, ORNL

OUTLINE

- Overview
- Objectives
- Approach
- Findings
- Future plans
- Expected applicability to commercial nuclear power

OVERVIEW, OBJECTIVES, APPROACH

OVERVIEW

- NEET AMM Project started in October 2018
  - 3 years duration
- Develop pulsed thermal tomography (PTT) for in-service non-destructive examination (NDE) of AM metallic components
- Project centered at ANL with MIT Reactor and Westinghouse collaborators

Development	Validation	Specimens
ANL	MIT Reactor	Westinghouse
MIT		GPI Industries

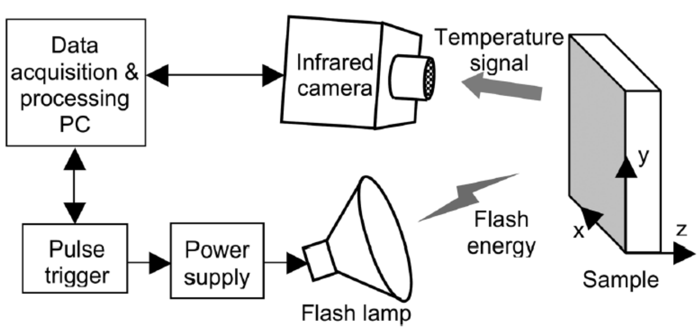
OBJECTIVES

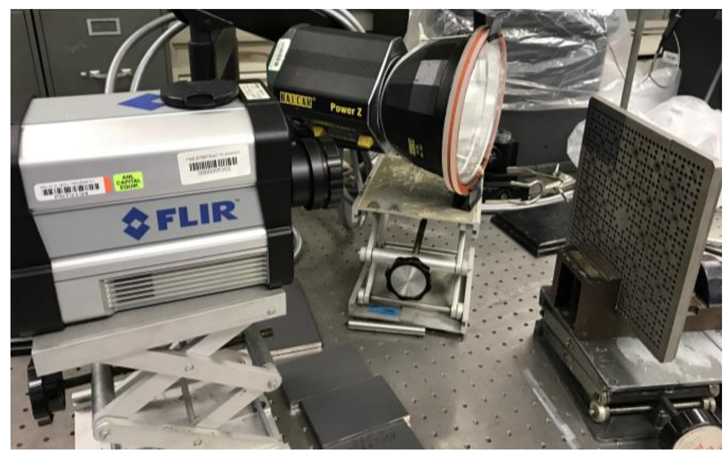
- Develop low-cost pulsed thermal tomography (PTT) system for in-service NDE of AM stainless steel and Inconel materials and components
  - Transition from laboratory system based on high-end camera to low-cost system based on compact camera
  - Compact IR camera is less expensive alternative to imaging IR fiber bundle
- Validation studies to be performed at MIT Reactor
  - Design new PTT system subject to spatial constraint of MITR
  - Demonstrate performance at MITR

APPROACH

Principle of PTT operation

- Apply a pulse of thermal energy to surface with flash lamp
  - Balcar ASYM 6400 source delivers 6400J/2ms
- Record surface temperature transients T(x,y,t) with IR camera
  - FLIR SC 4000 IR camera 3-5µm with 420fps 320x256 pixels array





Existing PTT system

APPROACH

Example: image flat bottom holes (indentations) in hastelloy plate

Pattern of indentations

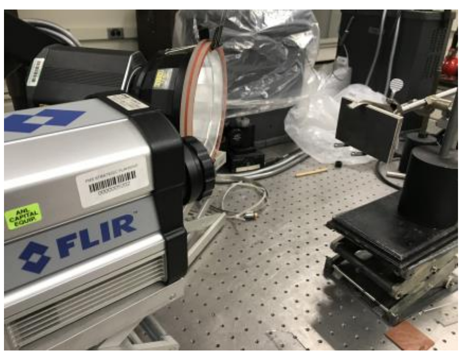
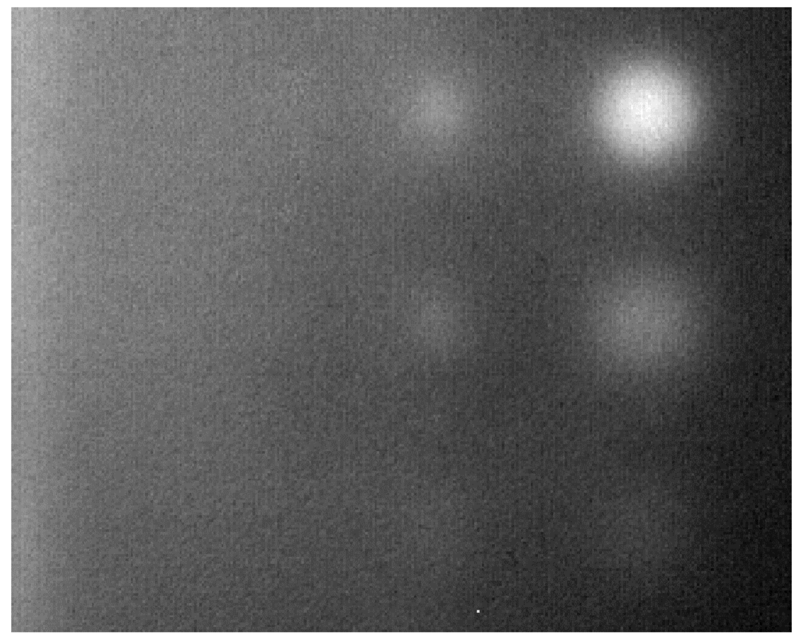


Image from flat side

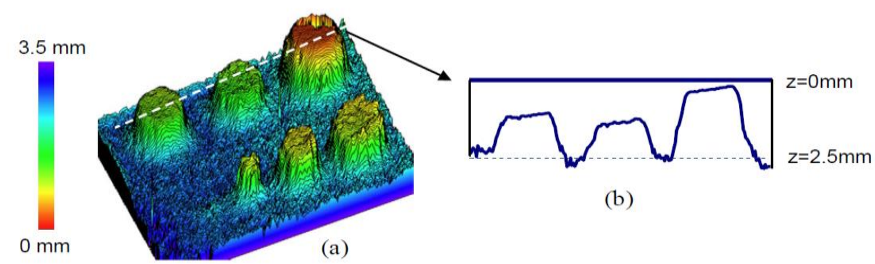
Surface Temperature



APPROACH

Principle of PTT operation

- Internal thermal resistance changes local surface temperature T(x,y,t) time decay
- Relate time t to depth z using established model of heat diffusion in 1-D
  - e.g. for constant diffusivity $z = (\pi \alpha t)^{1/2}$
  - Depth estimation requires knowledge of diffusivity α
- Obtain 3-D reconstruction (spatial and depth) of material effusivity $e = (\rho c k)^{1/2}$
  - ρ is the density, c is the specific heat, k is the thermal conductivity

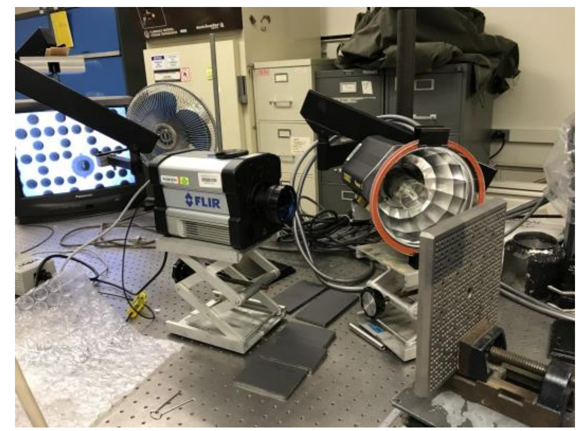


Examples of 3-D reconstruction of ceramic matrix composite plate with holes (3) Surface elevation plot and (b) Vertical slice of predicted depth map.

APPROACH

Technical merits of PTT for in-service applications

- Non-contact
  – Current laboratory system operates at standoff distance of one foot
- One sided measurements
- Can be made compact and low-cost
  – LWIR (7μm to 14μm) small form factor cameras are commercially available
- Fast operation
  – Typical laboratory scans take ~10s
- Use ANL algorithm for 3-D effusivity reconstruction

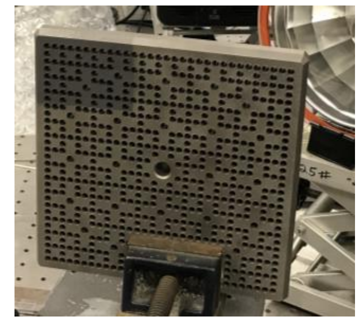


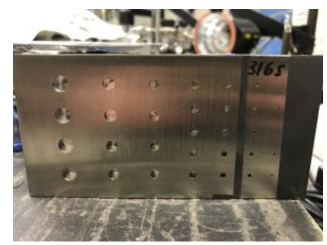
FINDINGS

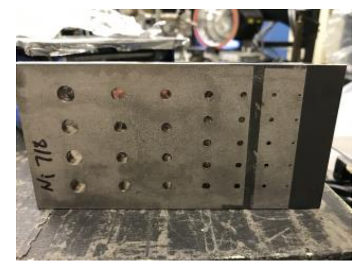
FINDINGS

Summary to-date

- Evaluating capability in tomographic imaging of stainless steel and Inconel metallic samples
  - AM Westinghouse nozzle plate
  - Flat bottom hole stainless steel Inconel and hastelloy plates
  - Explored data visualization options
- Designing low-cost compact system for in-service NDE
  - Working with FLIR to identify technology options
  - Coordinating with MITR to develop system requirements



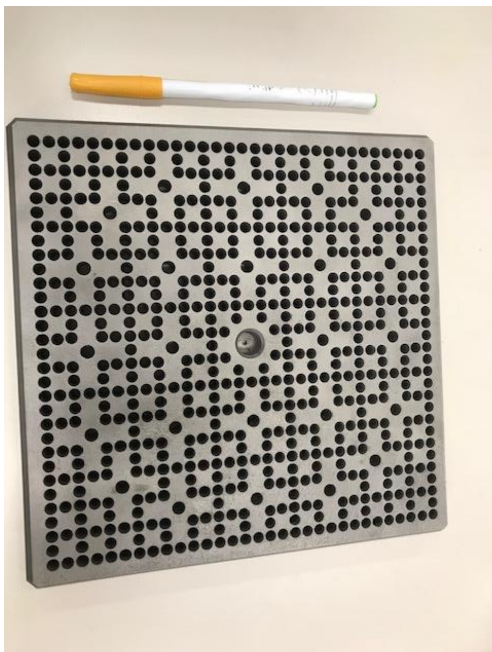




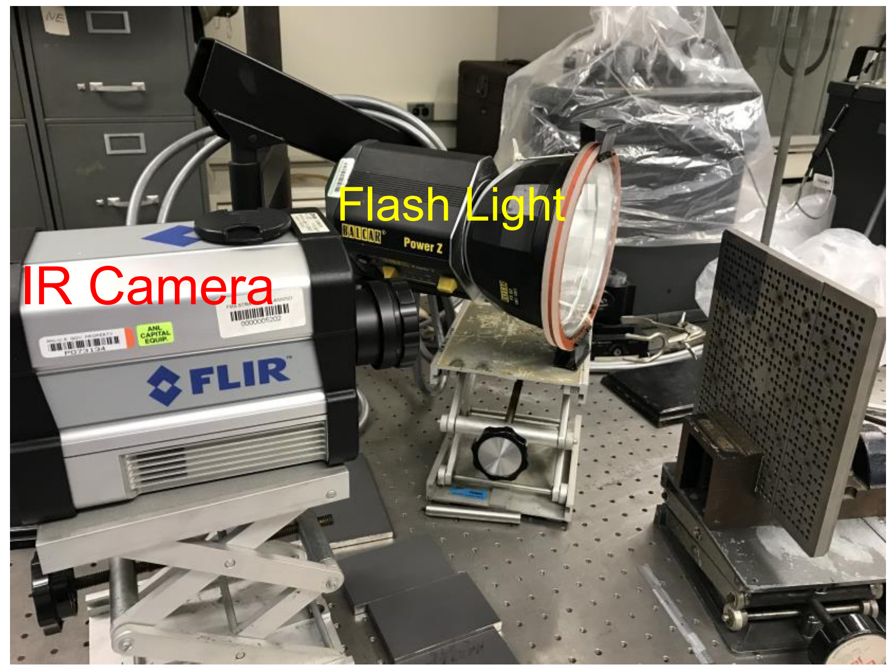
FINDINGS

Imaging of Westinghouse AM nozzle plate

- Inconel 718 nozzle plate (8”x8”x3/4”)



Pulsed Thermal Tomography Setup

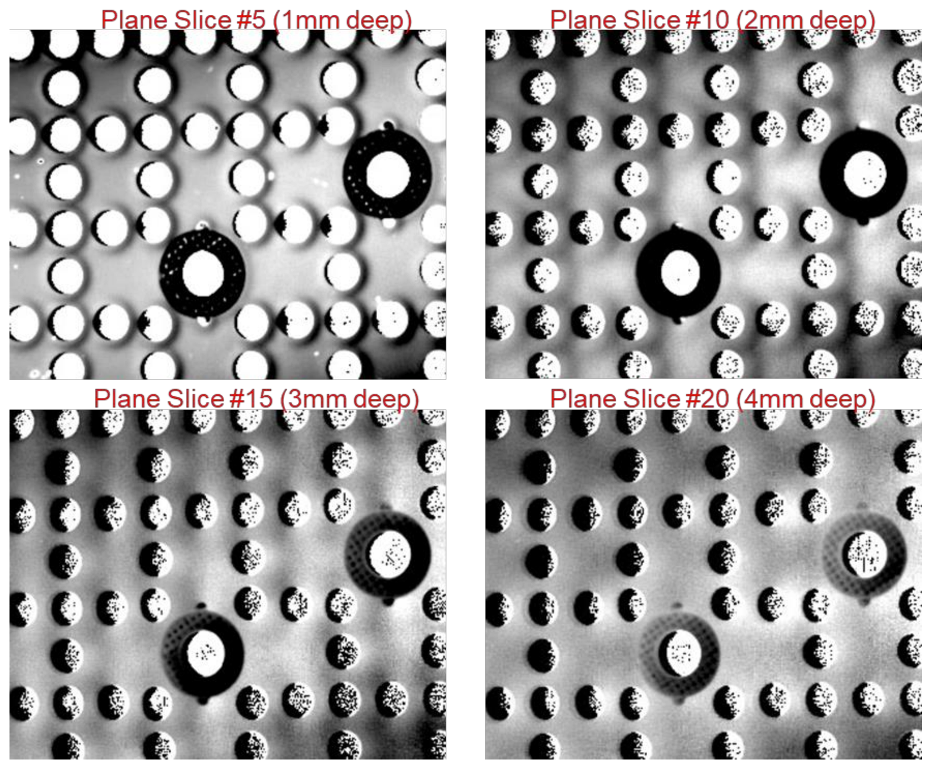


FINDINGS

Westinghouse AM Inconel 718 nozzle plate

- 3-D reconstructions

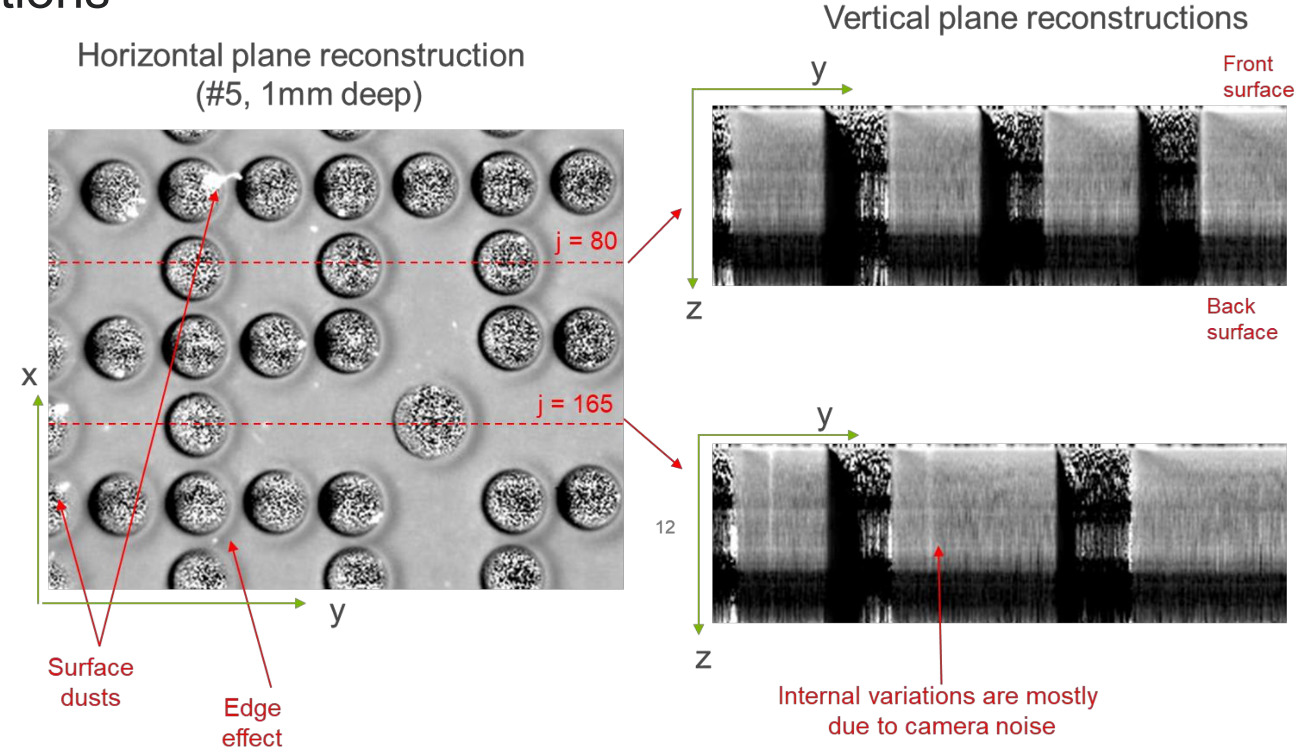
Thickness L=17mm
Test duration t_{test} = 20.93s,
Thermal diffusivity α = 6.25 mm^2/s,
Optical depth $D = (\pi * \alpha * t_{test})^{1/2}$ = 20.3mm



FINDINGS

Westinghouse AM Inconel nozzle plate

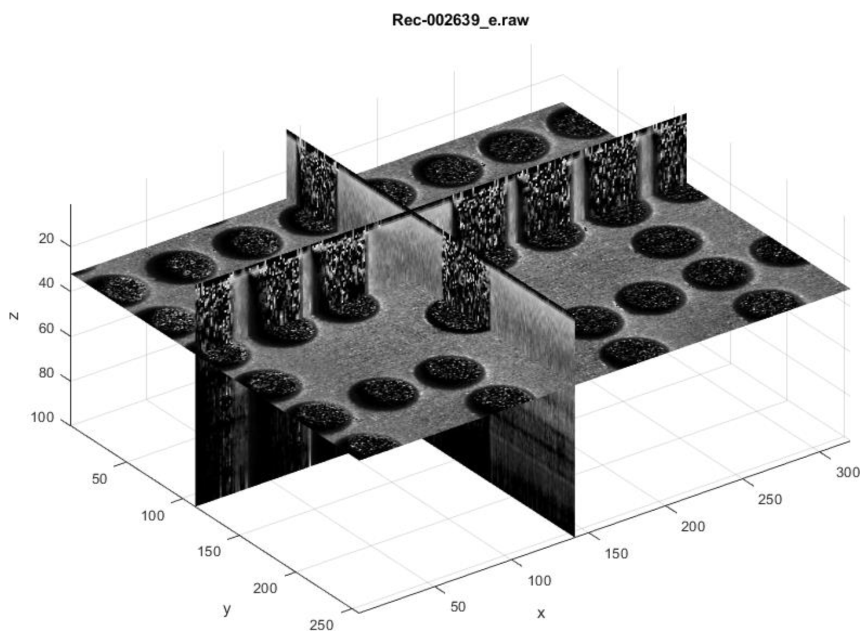
- 3-D reconstructions

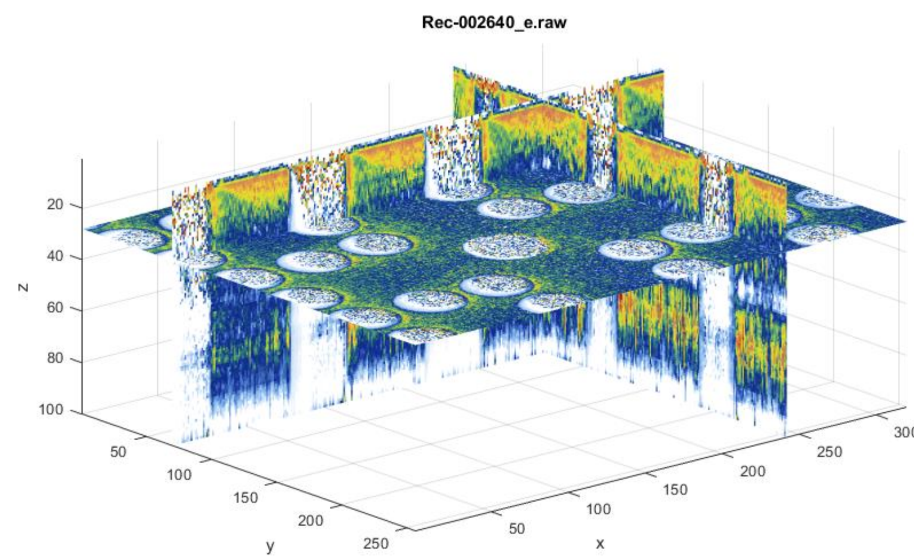


FINDINGS

Imaging of Westinghouse AM IN718 nozzle plate

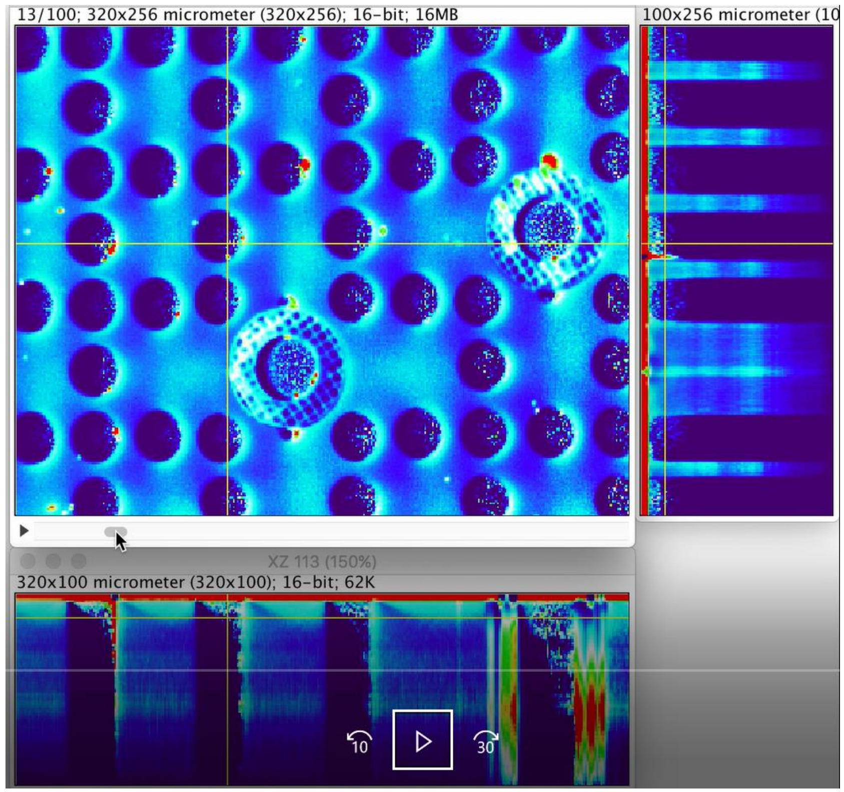
- 3-D reconstructions and data visualizations with MATLAB





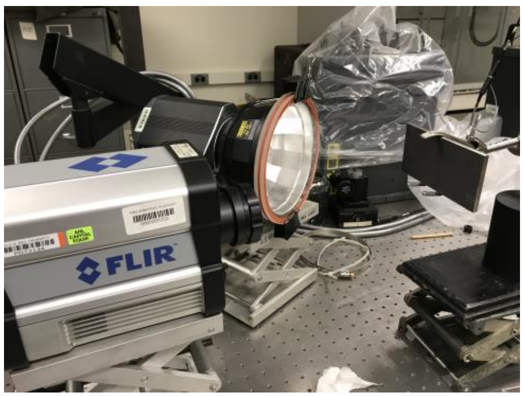
FINDINGS

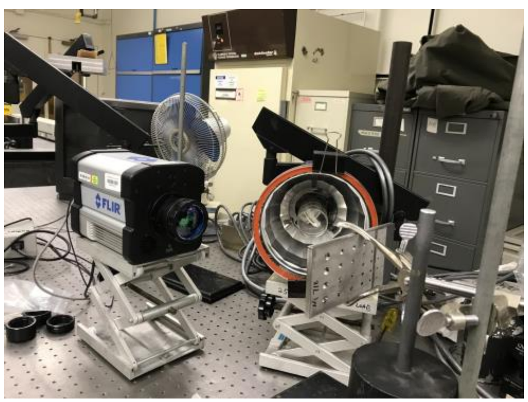
Westinghouse AM IN718 nozzle plate 3-D imaging with ImageJ



FINDINGS

Imaging of flat bottom holes (indentations) in SS316 and IN718 plates

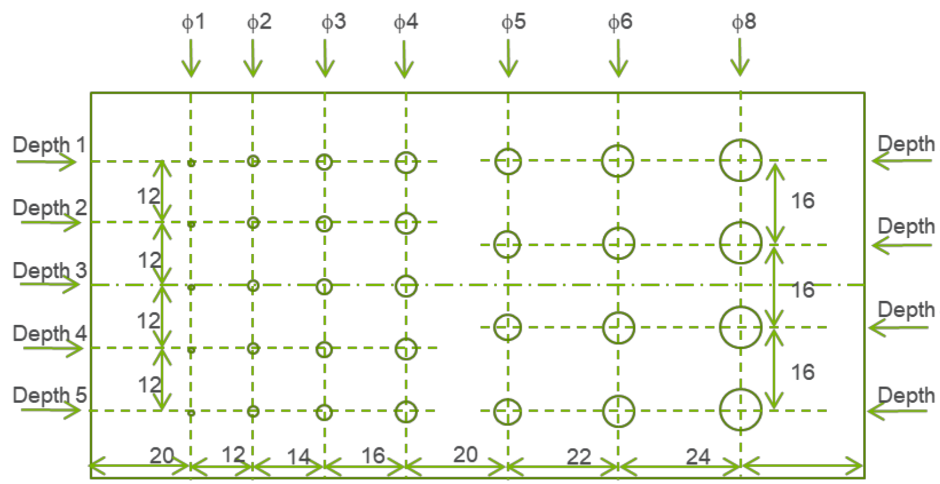




Imaging from flat side

Note: depth is measured from undrilled flat surface

All dimensions in mm

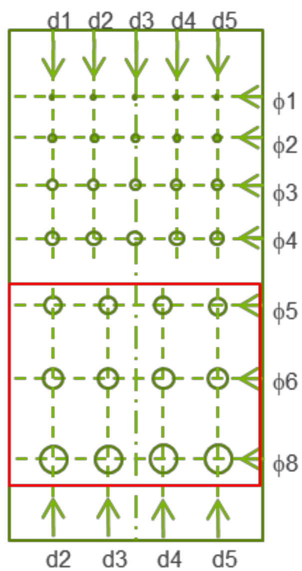


Materials: SS316 and N718

FINDINGS

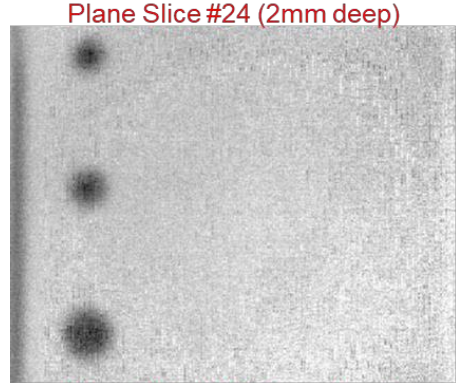
Imaging flat bottom holes in SS316 plate

- Imaged area

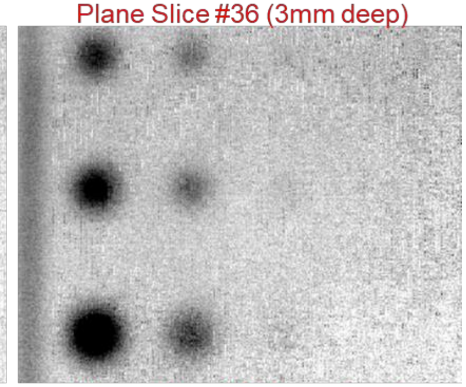


Thickness L=6.22mm
Test duration t_{test} = 5.89s
Estimated diffusivity α = 3.72 mm^2/s
Imaging depth D= $(\pi * \alpha * t_{test})^{1/2}$ = 8.3mm

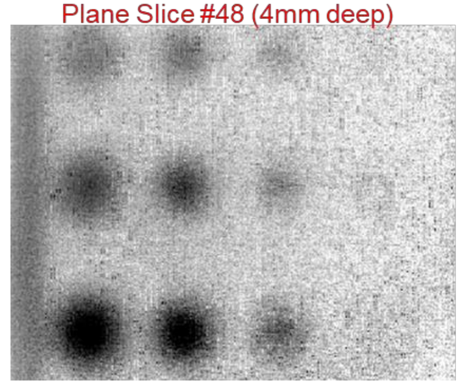
Plane Slice #24 (2mm deep)



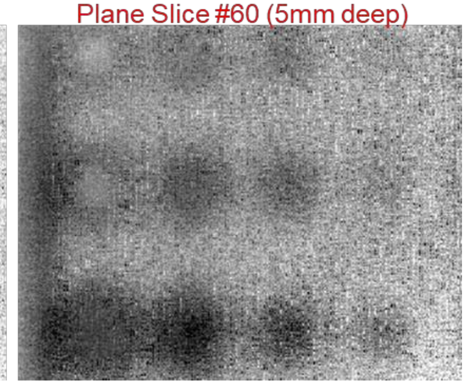
Plane Slice #36 (3mm deep)



Plane Slice #48 (4mm deep)



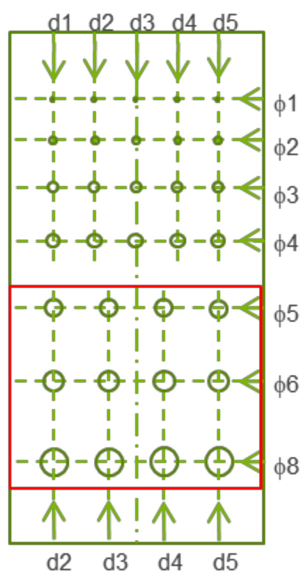
Plane Slice #60 (5mm deep)

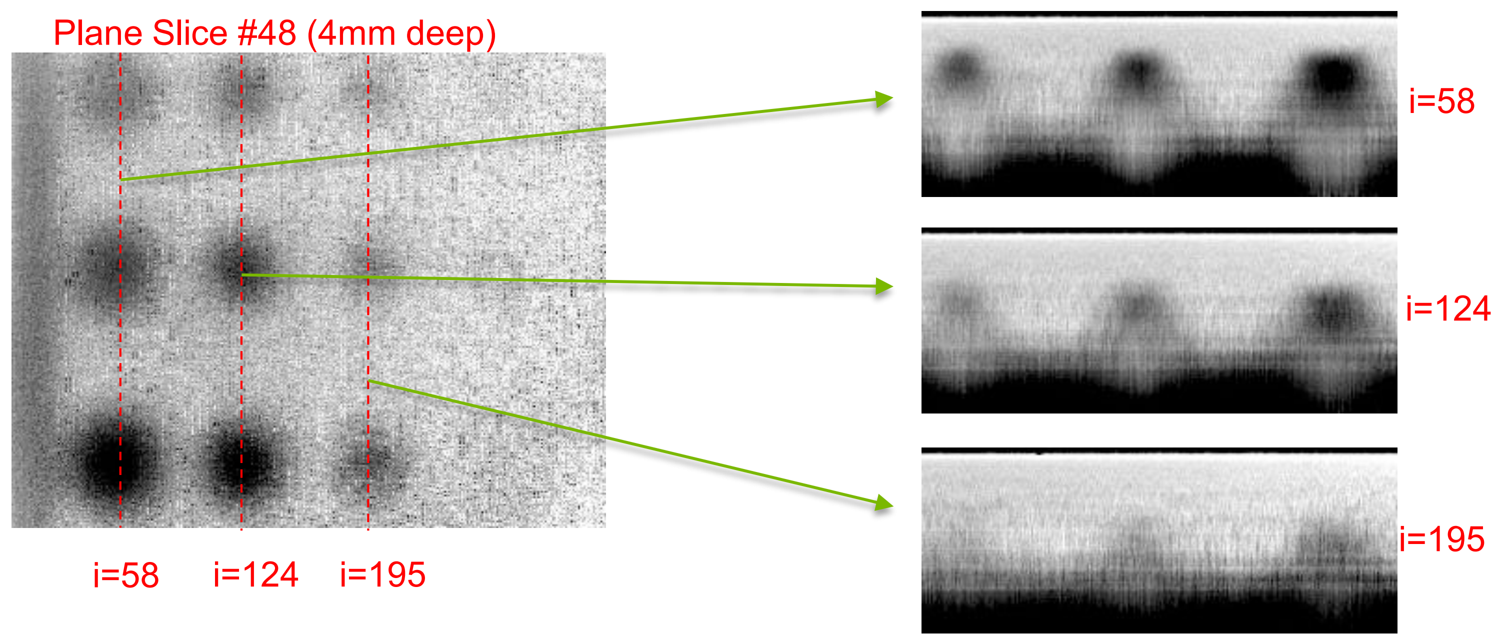


FINDINGS

Imaging flat bottom holes in SS316 plate

- Cross-section images

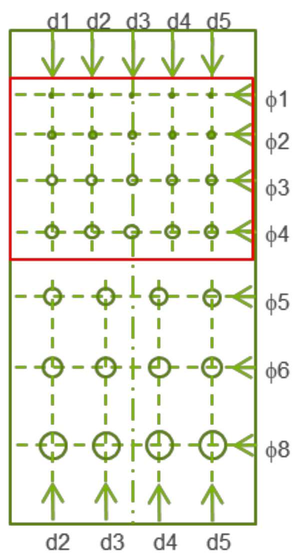




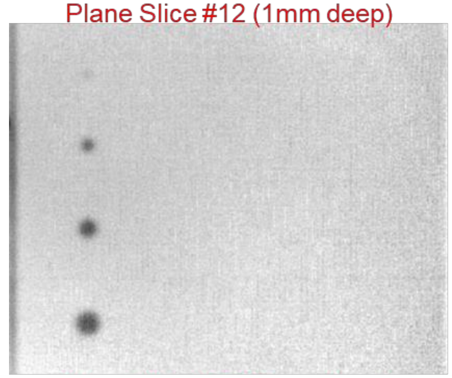
FINDINGS

Imaging flat bottom holes SS316 plate

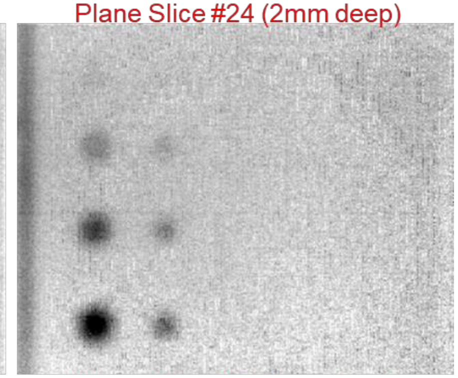
- Imaged area



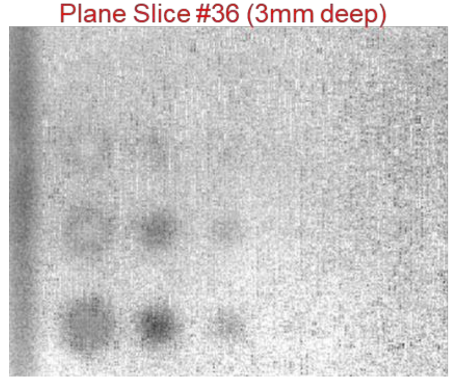
Plane Slice #12 (1mm deep)



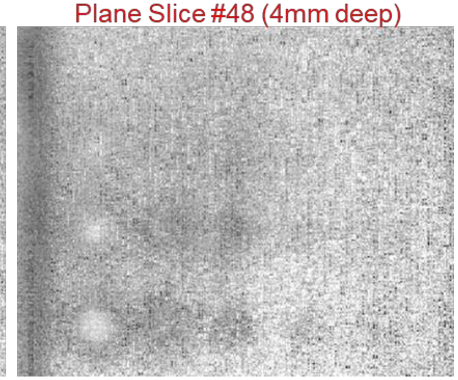
Plane Slice #24 (2mm deep)



Plane Slice #36 (3mm deep)

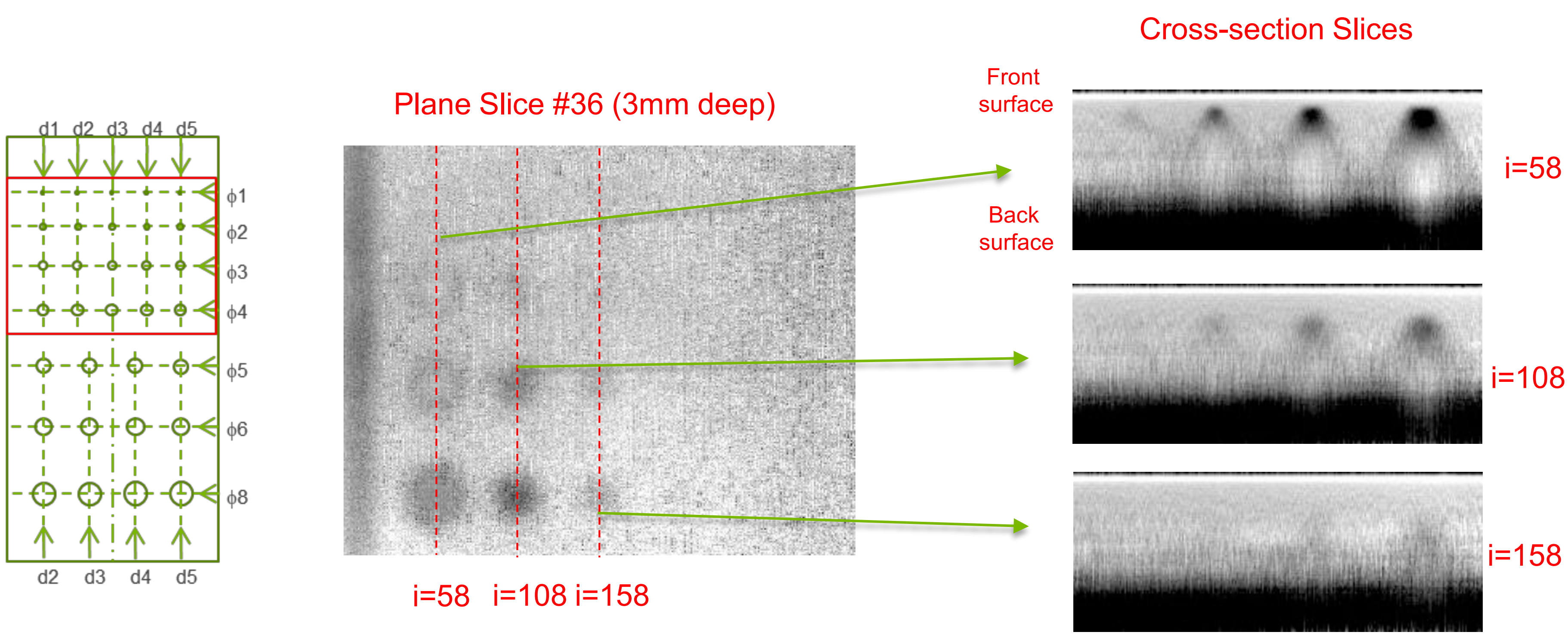


Plane Slice #48 (4mm deep)



FINDINGS

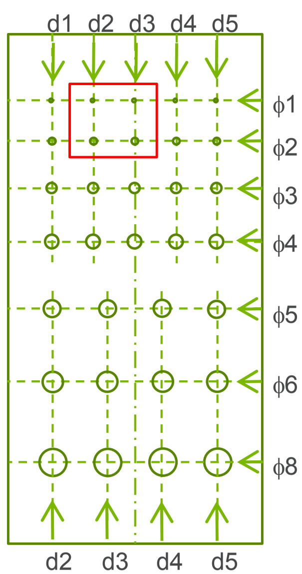
Imaging flat bottom holes in SS316 plate

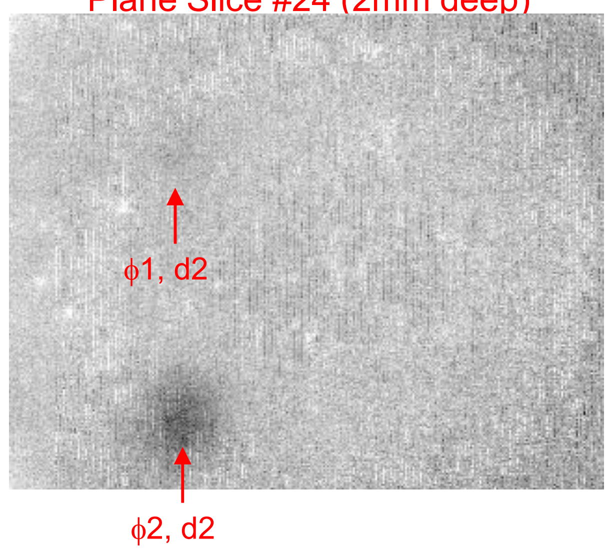


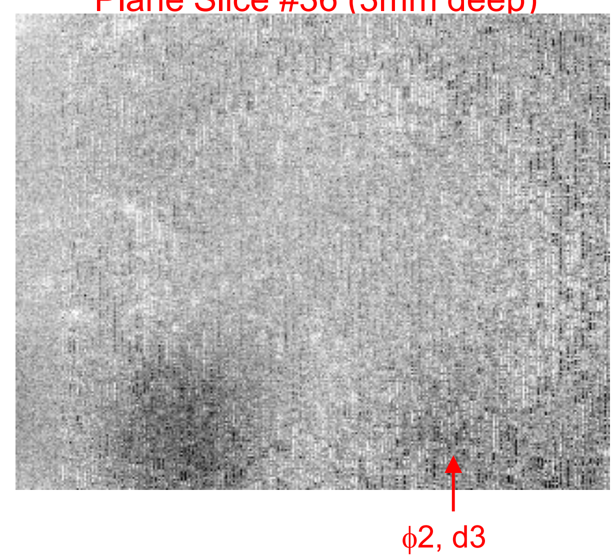
FINDINGS

Imaging flat bottom holes SS316 plate

- Imaged area



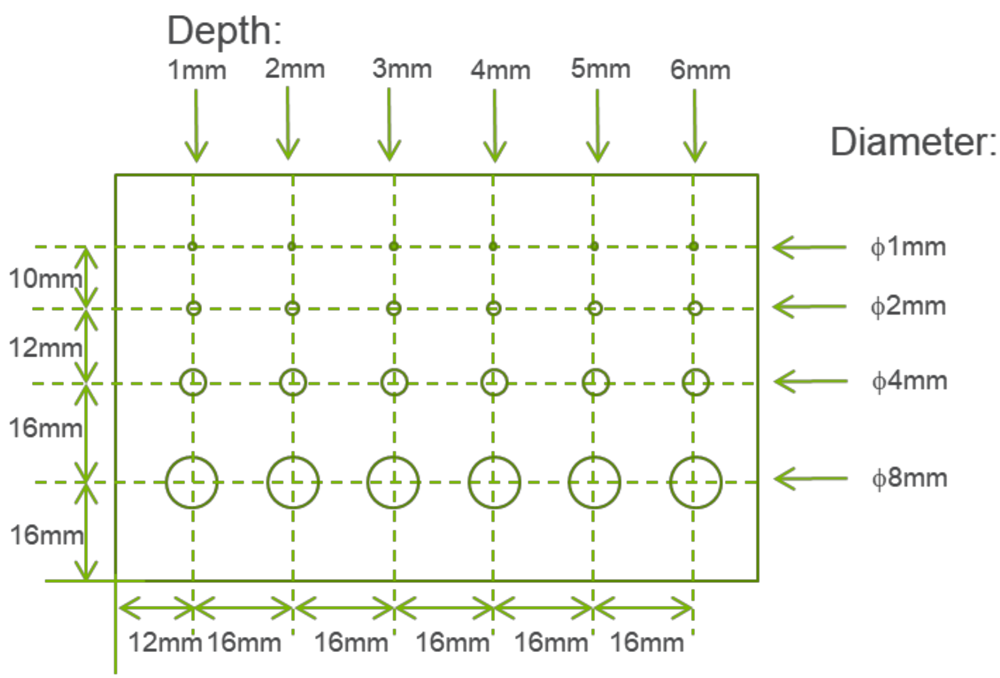


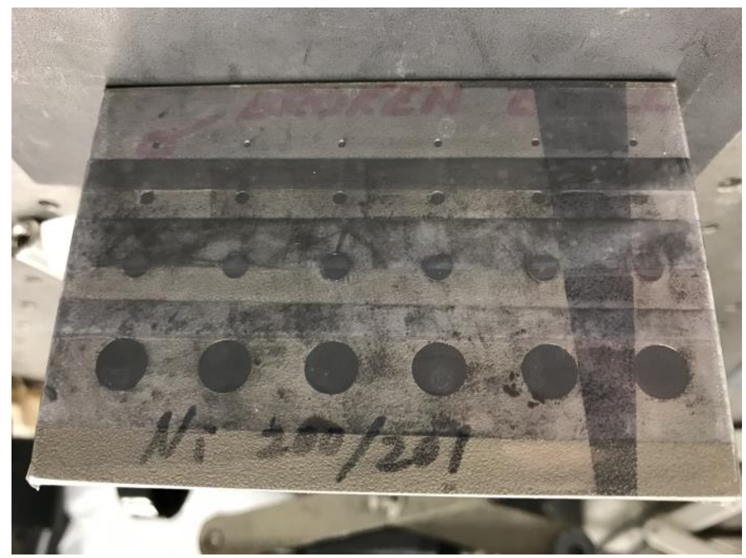


FINDINGS

Preliminary evaluation of porosity detection with PTT

- Filled holes in Ni200 plate with Ni200 50µm powder to simulate porosity

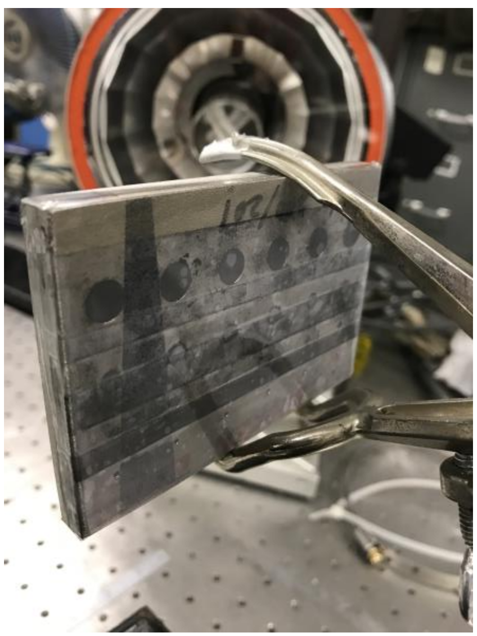


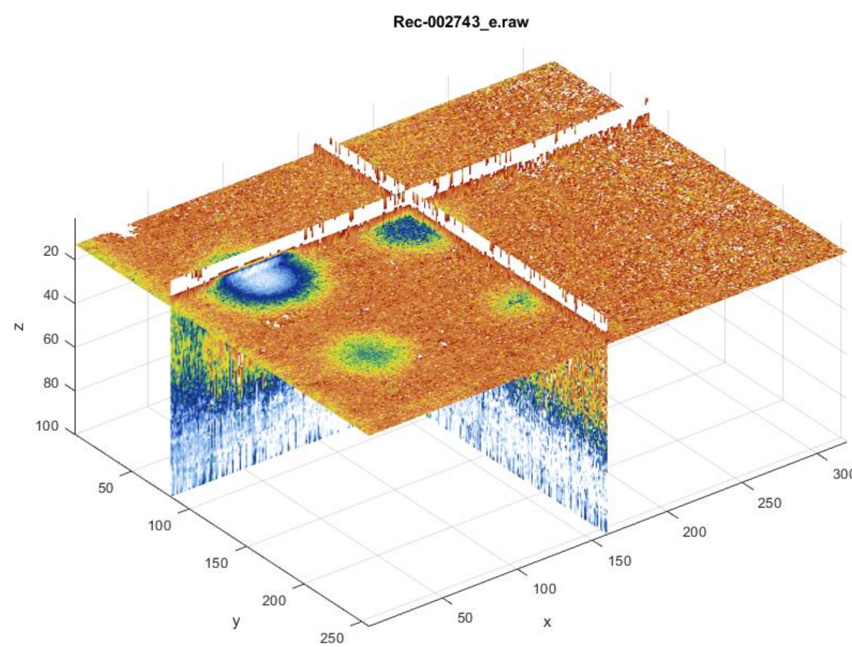


FINDINGS

Imaging of Ni200 plate with flat bottom holes filled with Ni powder

- 3-D reconstruction qualitative results

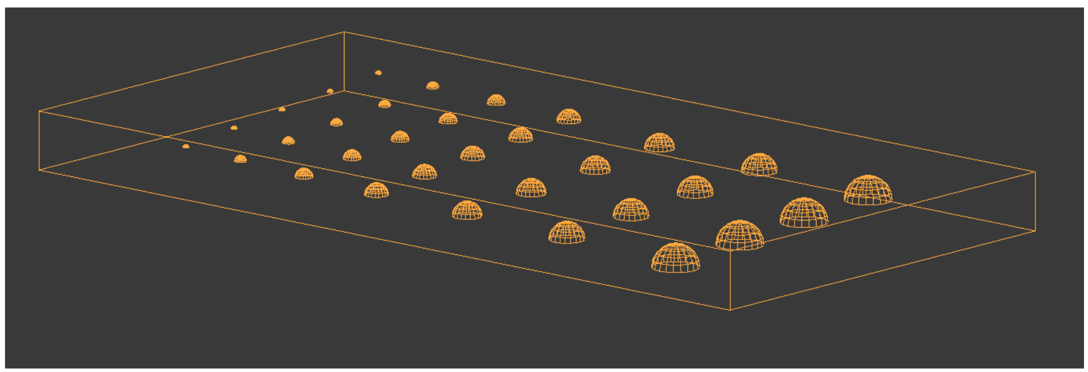




PLANS FOR FY19

Damage detection calibration

- Evaluate PTT system performance in detection of porosity regions
- Working with GPI to develop AM stainless steel and Inconel specimens with porosity inclusions



PLANS FOR FY19

Challenges of PTT with small cameras

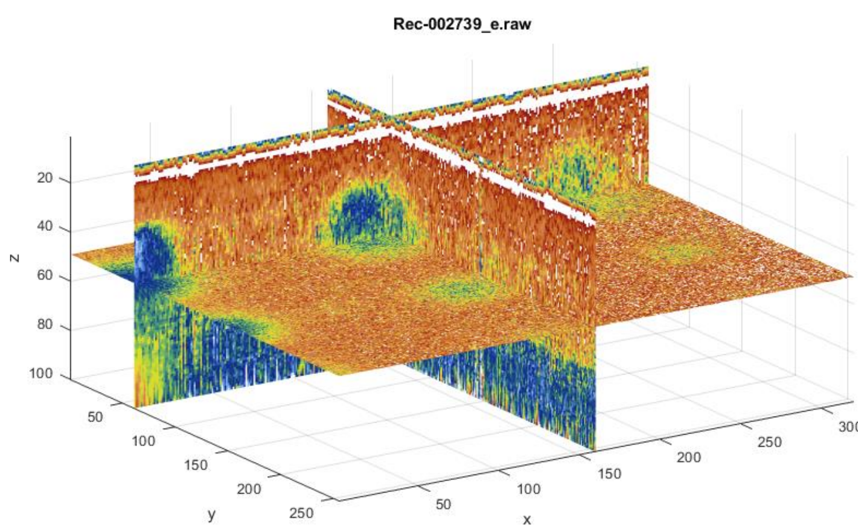
- High-end cameras
  - 100Hz to KHz frame rate
  - Cooled photon counting detection

- Compact cameras ~2”x2”x4” and smaller
  - Uncooled microbolomer detector
  - Frame rate <60Hz

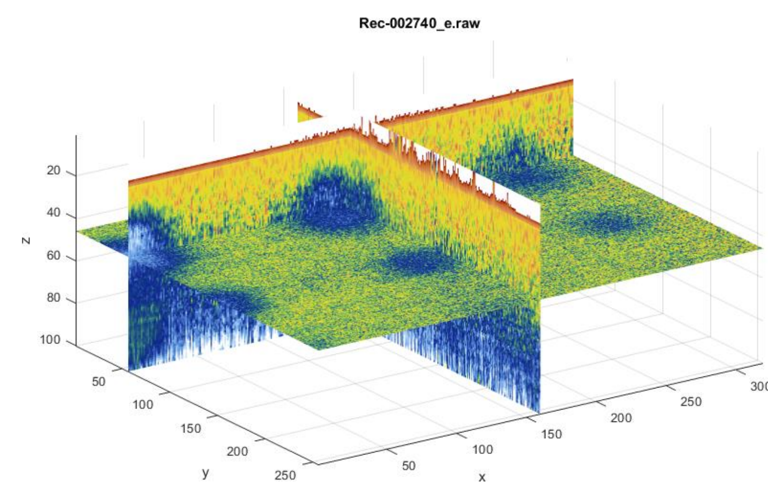
FINDINGS

Preliminary evaluation of PTT imaging at low frame rate

- Comparison of SS316 flat bottom holes reconstruction with 200Hz and 60Hz scans



200Hz

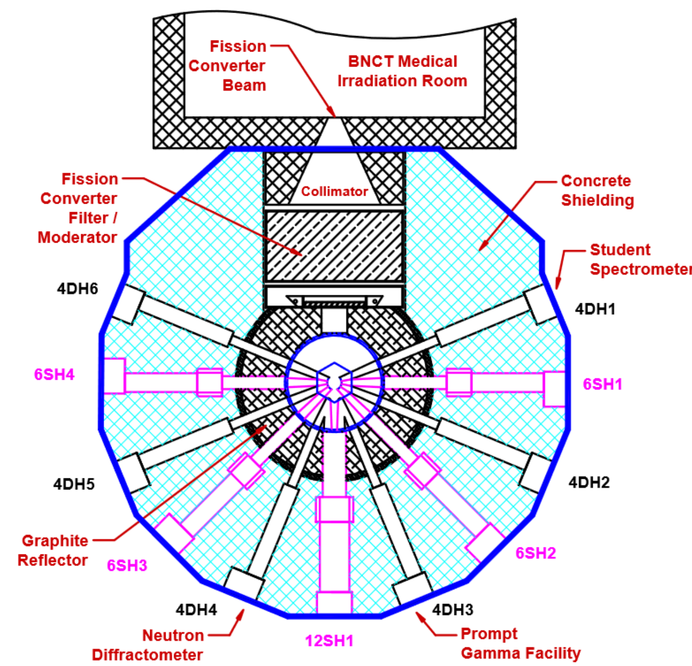


60Hz

PLANS FOR FY19

Design in-service NDE system

- Working with MITR to identify best penetration tunnels for validation experiments
  - Identify size limitations for compact thermal camera
  - AM parts will be inserted into MITR for imaging with compact PTT



Cutaway of MITR showing radial beam ports

SUMMARY

U.S. DEPARTMENT OF ENERGY

Argonne National Laboratory is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC.

Argonne NATIONAL LABORATORY

SUMMARY

- Demonstrated capability of tomographic imaging of stainless steel and Inconel specimens
  - Westinghouse AM nozzle plate
  - Flat bottom hole stainless steel and Inconel plates
  - Plan to submit preliminary results to QNDE and ASME conferences
- Plan to development of low-cost system for NDE
  - Evaluation studies will be conducted with compact thermal camera
  - Coordinating validation studies with MIT Nuclear Reactor

EXPECTED APPLICABILITY TO COMMERCIAL NUCLEAR POWER

- Deliver low-cost system for in-service NDE of reactor components
  - Demonstrate performance in research reactor environment
- Plan to discuss ASME codes at relevant meetings

QUESTIONS?