U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

Clean. Reliable. Nuclear.

Pulsed Thermal Tomography Nondestructive Examination of Additively Manufactured Reactor Materials and Components

Advanced Methods in Manufacturing Annual Webinar

December 17-18, 2019

Alexander Heifetz

Argonne National Laboratory

Project Overview

- ## Goal and Objective
  - Develop pulsed thermal tomography (PTT) for in-service nondestructive evaluation (NDE) of additively manufactured (AM) metallic components
- ## Participants

Name	Affiliation
J.G. Sun, Thomas Elmer, Sasan Bakhtiari, Brian Saboriendo, Peter Kozak	Argonne National Laboratory
Dmitry Shribak	Argonne National Laboratory; The University of Chicago
Tiffany Liu	Argonne National Laboratory; Berkeley University of California
Xin Zhang, Jafar Saniie	Argonne National Laboratory; Illinois Institute of Technology
Bill Cleary	Westinghouse
Boris Khaykovich	Massachusetts Institute of Technology Nuclear Reactor Laboratory

Overview

- Overview of AM and NDE with PTT

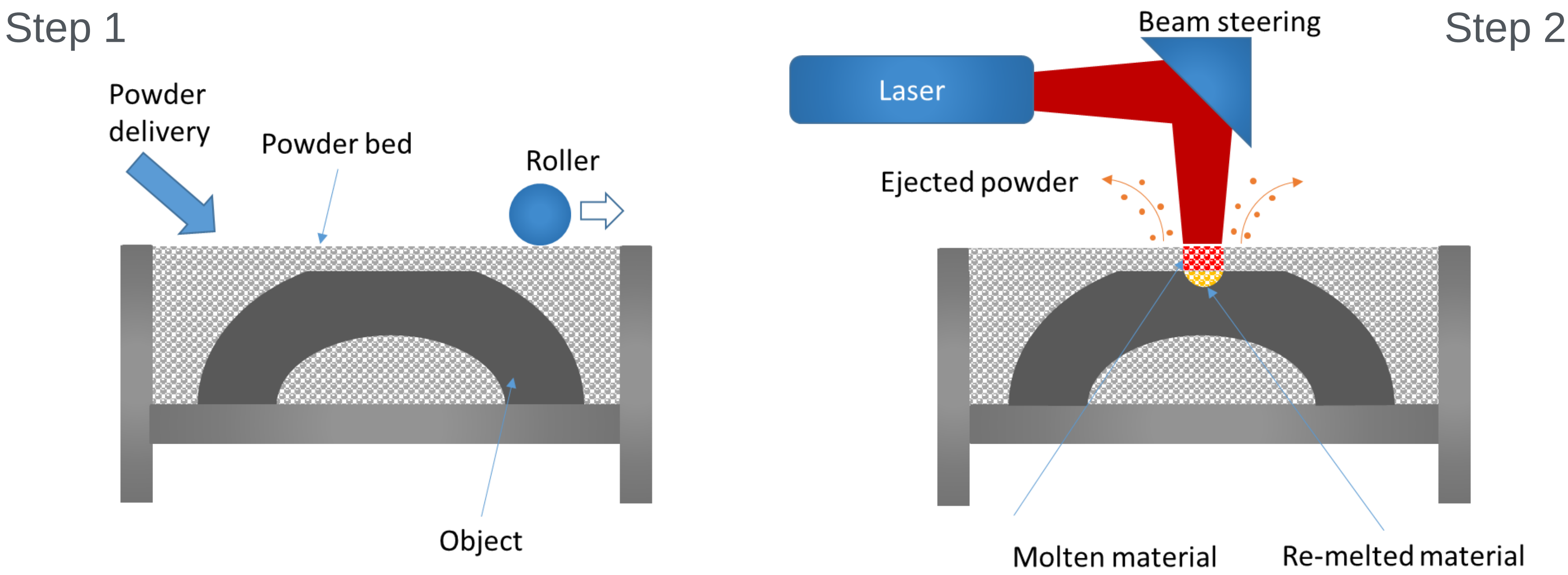
Overview

- Integration of AM into nuclear
  - Replacement of aging parts
  - Reduction of new construction cost
  - Rapid prototyping of reactor design (e.g. TCR)
- AM fabrication can introduce random flaws
  - Selective laser melting (SLM) used for AM of IN & SS
  - Typical flaws consist of porosity regions
- Need capability for NDE of AM metals
  - During and post-manufacturing
  - In-service NDE of parts
  - **Addressing by PTT**

L-R: the original, obsolete impeller; the 3D-printed prototype; the resulting 3D-printed replacement part [Image: Siemens Slovenia NPP]

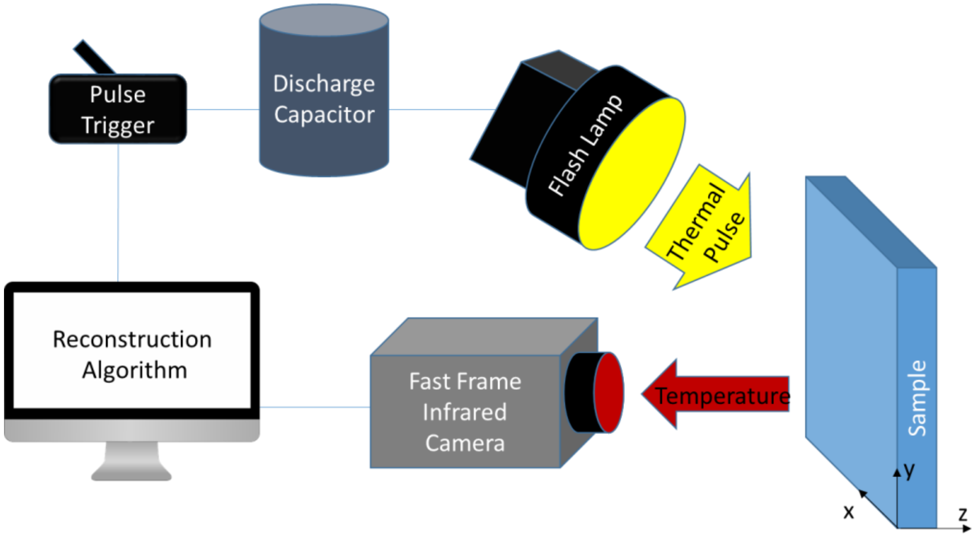
Overview of SLM

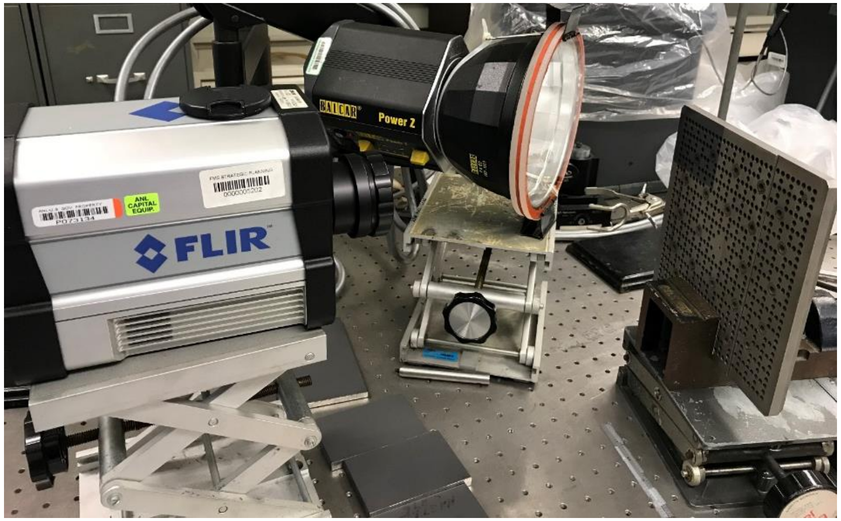
- Porosity can be introduced into AM parts due to
  - Incomplete melting of powder particles
  - Insufficient overlapping of melt pools
  - Powder ejection and splattering because of thermal gradients



NDE Approach

- Operating principle of pulsed thermal tomography (PTT)
  - Apply pulse of thermal energy to material surface with flash lamp
  - Record surface temperature transients T(x,y,t) with IR camera
  - Reconstruct 3-D thermal effusivity from measurements





Advantages of PTT

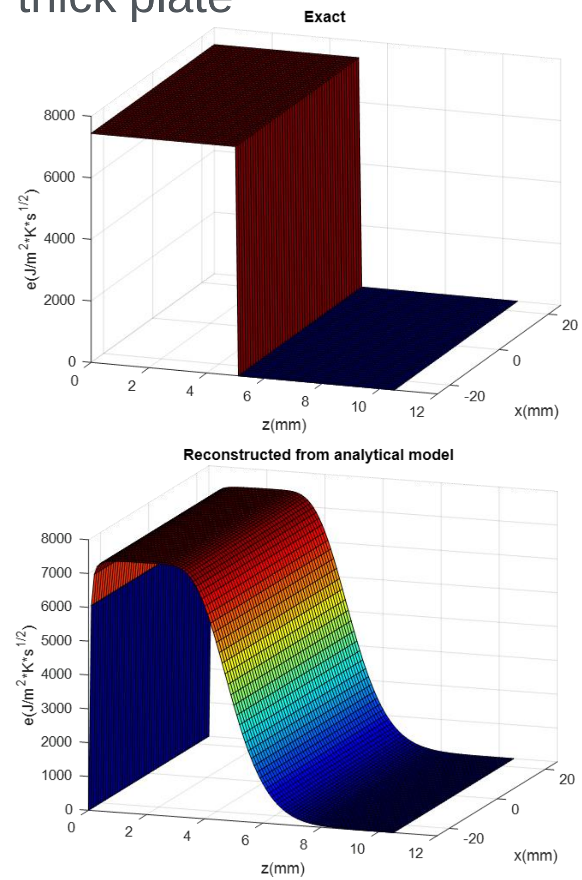
	X-Ray/Neutron CT	Ultrasonic	Pulsed Thermal Tomography
Non-contact	Yes	No	Yes
Compact	No	Yes	Yes
2-D Imaging	Yes	No	Yes
One-sided	No	Yes	Yes

PTT Effusivity Reconstruction Algorithm

- Reconstruction based on 1-D model of heat transfer $\boxed{\dfrac{\partial T}{\partial t} = \alpha \dfrac{\partial^2 T}{\partial z^2}}$
  - α is thermal diffusivity $\alpha = k/\rho c$
  - ρ is the density, c is the specific heat, k is the thermal conductivity
- Effusivity is a measure how material exchanges thermal energy with its surroundings $\boxed{e = (\rho c k)^{1/2}}$
- Characteristic relationship between depth and time is $\boxed{z = (\pi \alpha t)^{1/2}}$
- Reconstruction of spatial effusivity from analytic solution for semi-infinite medium

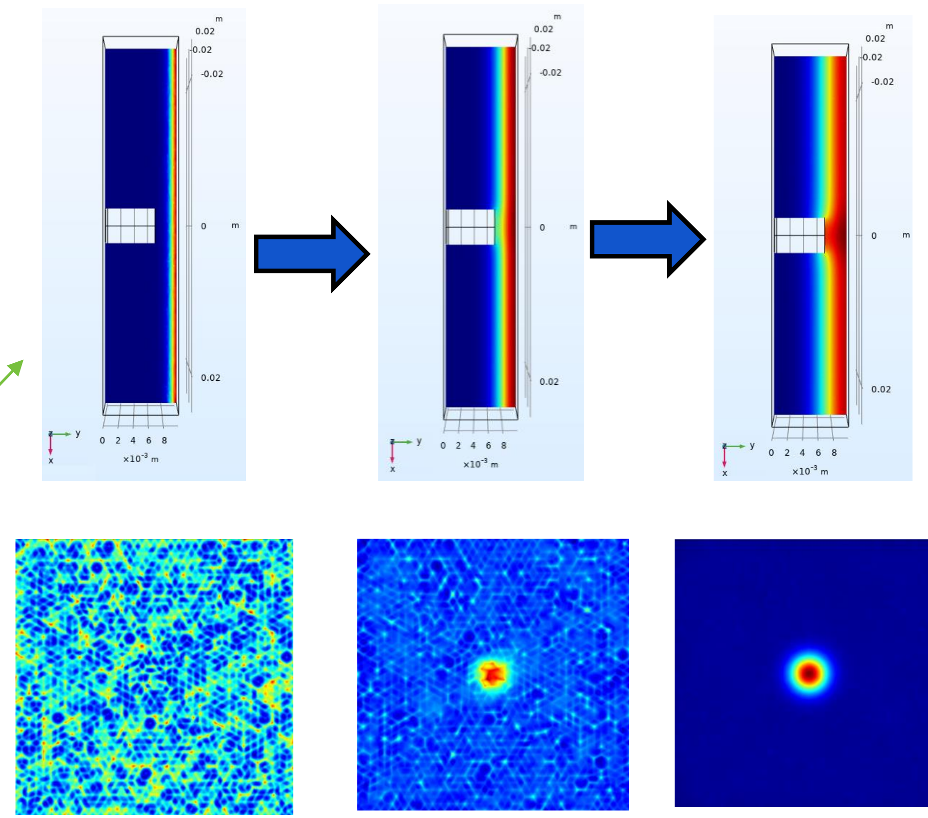
$$\boxed{e(z) = z \frac{2Q}{\pi \sqrt{\alpha}} \frac{d}{dt} \left(\frac{1}{T(t)} \right) \Bigg|_{t = z^2/\pi\alpha}}$$

Example: effusivity reconstruction for a 5mm-thick plate



Principle of Internal Defect Detection with PTT

- Temperature “hot spots” can be observed on the material surface above the flaw
- Demonstrate with COMSOL computer simulations
  - Time evolution of heat transfer through metallic plate
  - Appearance of localized “hot spot” on the plate front surface



Results

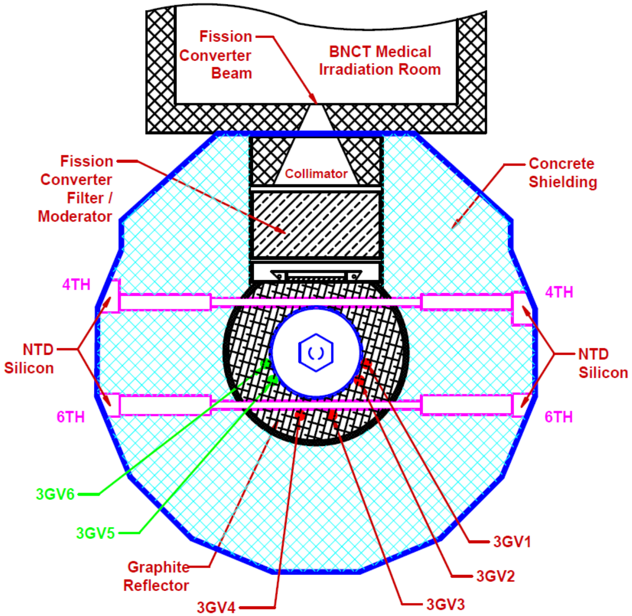
- PTT Imaging of Imprinted Internal Defects

Develop Compact PTT System for In-Situ NDE

- High-end cameras
  - Size ~ 12”x6”x6”
  - 100Hz to KHz frame rate
  - Cooled photon counting detection (20mK NETD sensitivity)
- Compact cameras
  - Size ~ 2”x2”x4”
    - Fits into 3GV port at MIT NRL
  - <60Hz frame rate
  - Uncooled microbolometer detection (50mK NETD sensitivity)

FLIR X8501
SC4000

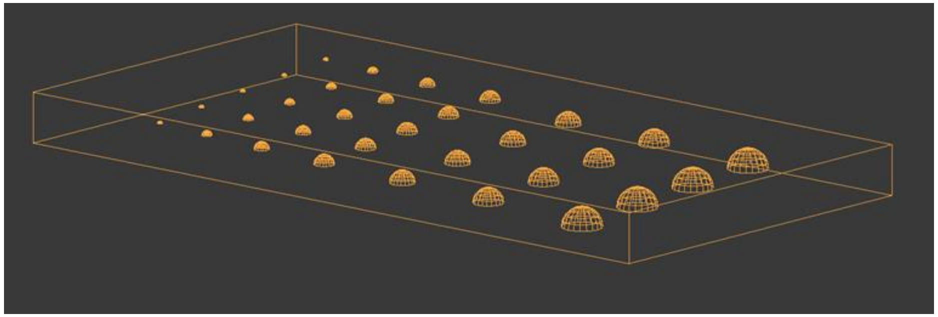
FLIR A65

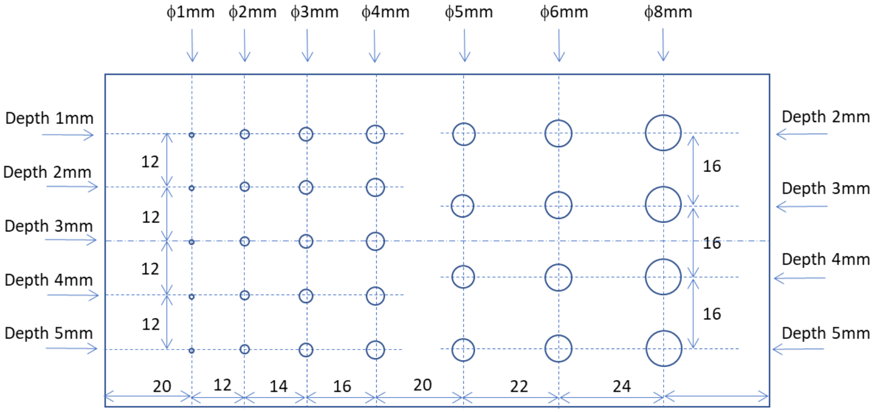


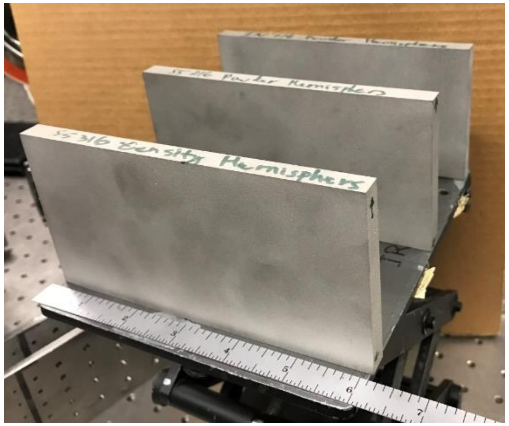
MIT (3GV) 3”ID vertical irradiation thimbles

AM Specimens with Imprinted Defects

- Designed 10mm-thick SS316 and IN718 specimens with hemispherical low-density internal defects



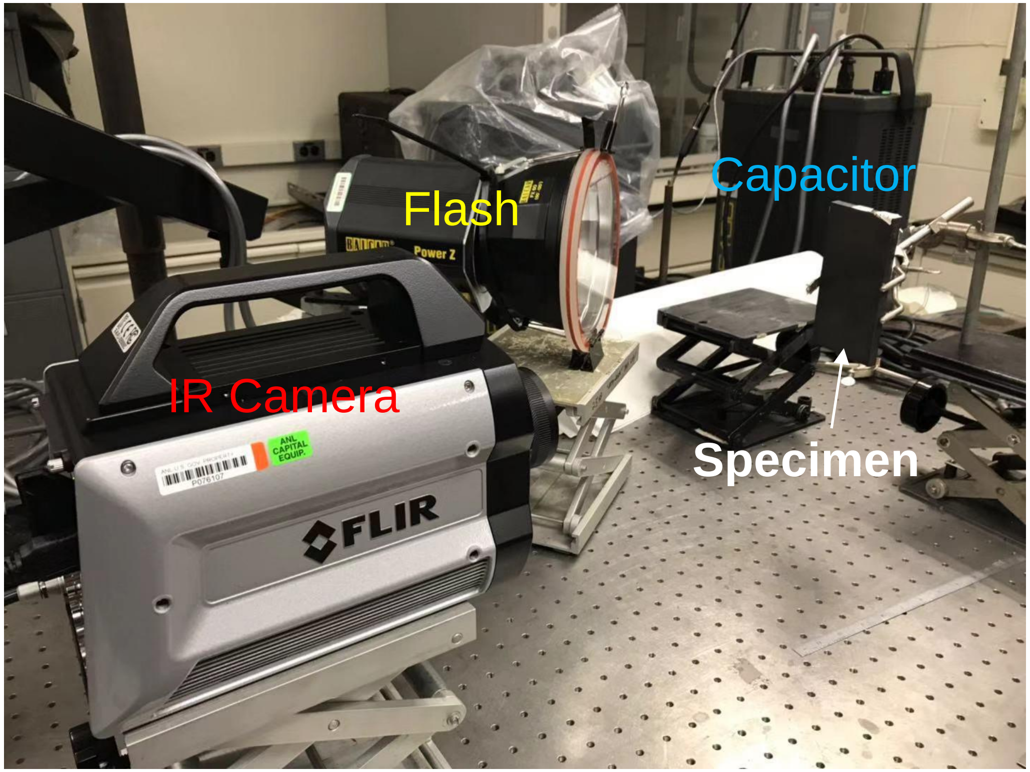




Fabricated by GPI

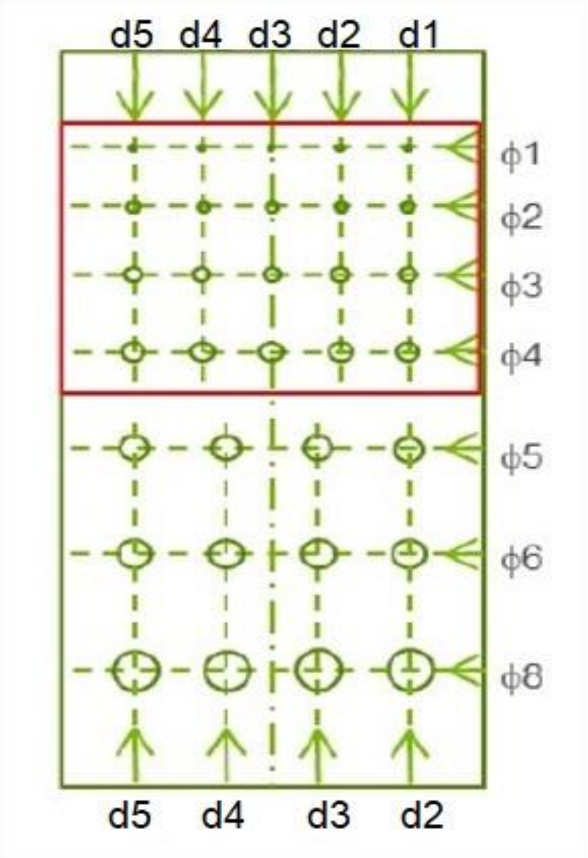
Imaging of AM Specimens with X8501sc

- Flash lamp pulse
  - Delivers 6400J/2ms
- Imaging camera
  - FLIR X8501sc
    - 3-5µm
    - 20mK NETD sensitivity
    - Operated at 216Hz with 768x520pixels window
  - 8s to scan through 10mm plate

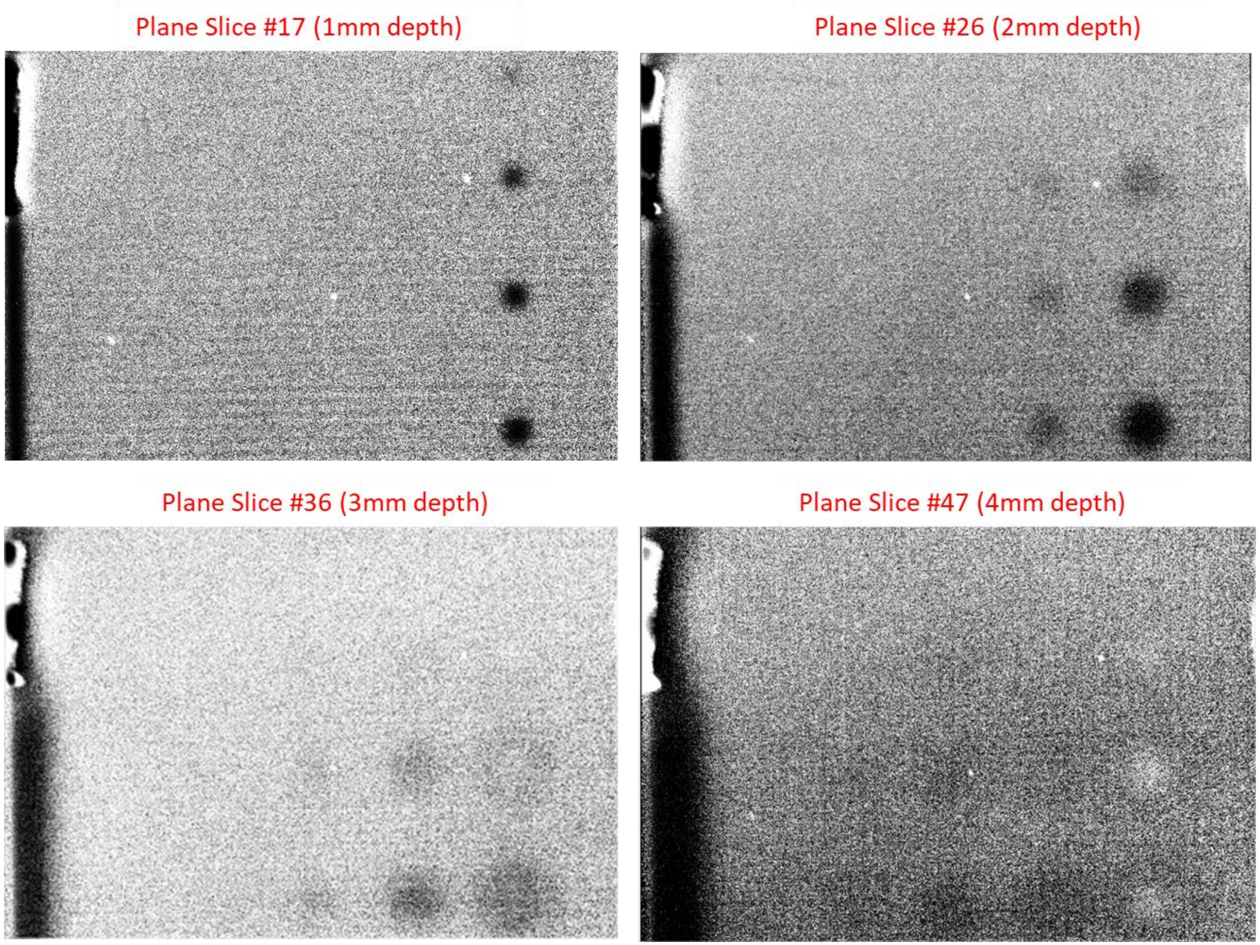


Imaging Small Holes in IN718 with X8501sc

Imaged area

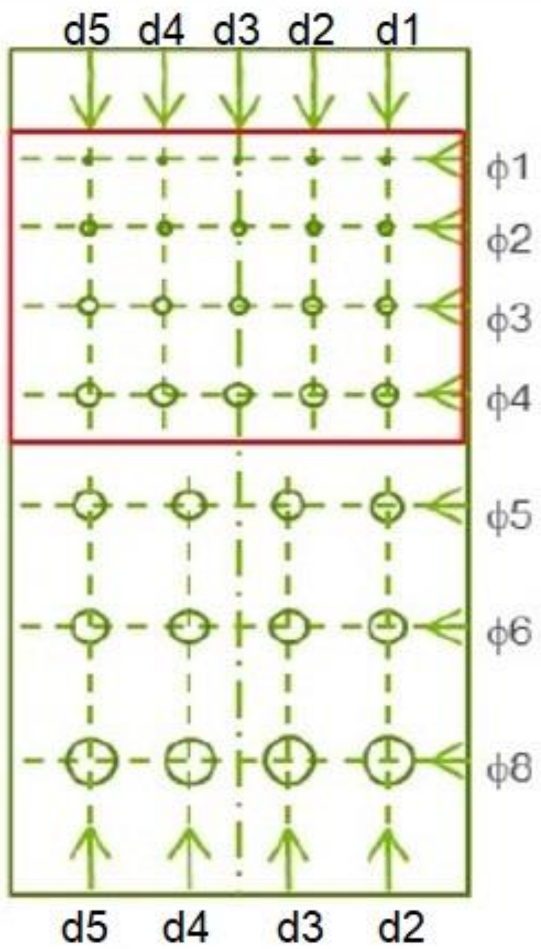


PTT Reconstructions



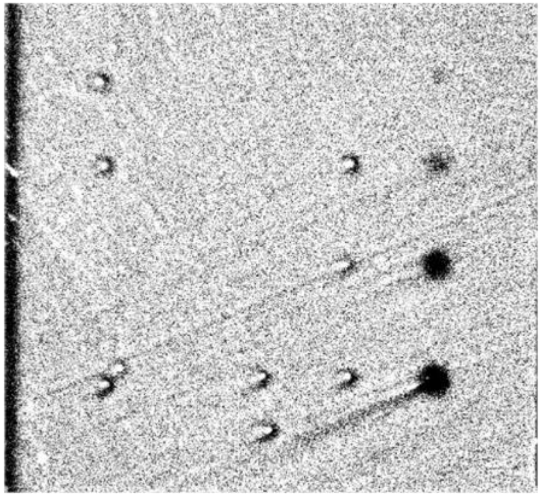
Imaging Small Holes in SS316 with X8501sc

Imaged area

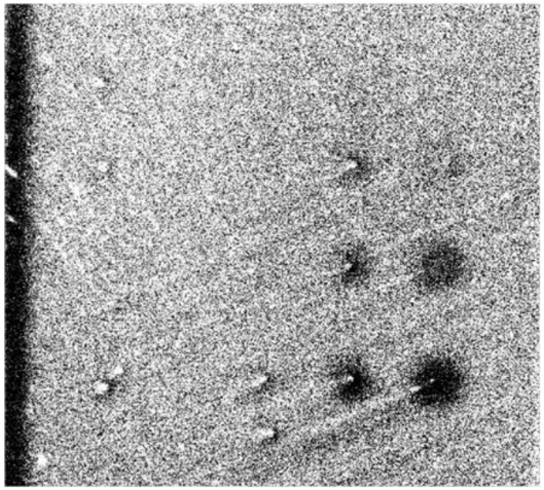


PTT Reconstructions

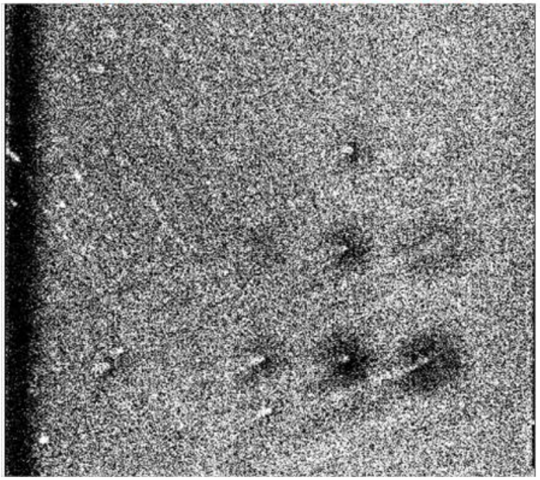
Plane Slice #15 (1mm depth)



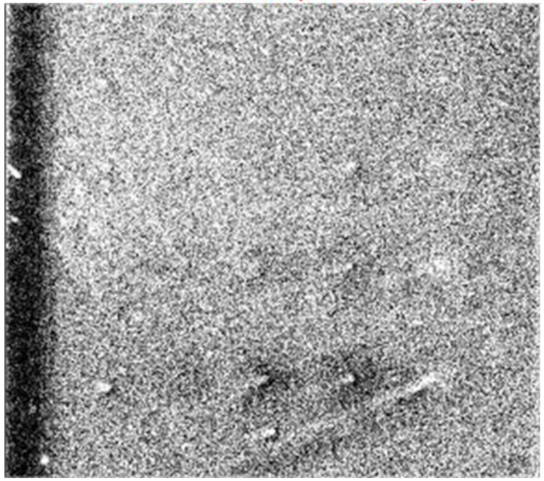
Plane Slice #22 (2mm depth)



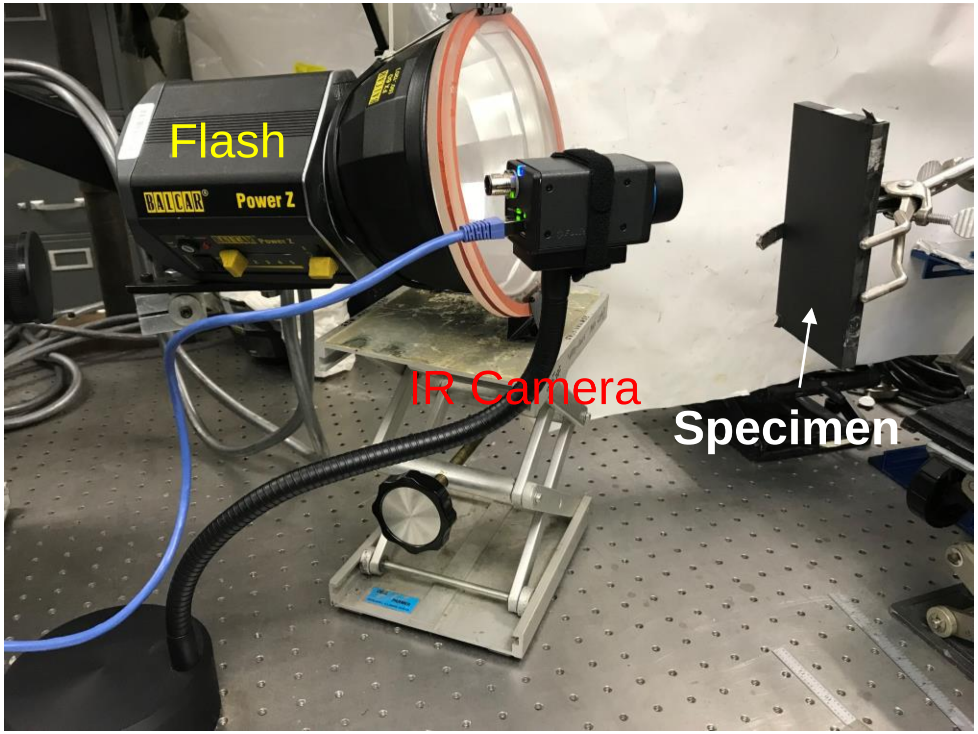
Plane Slice #26 (3mm depth)



Plane Slice #40 (4mm depth)

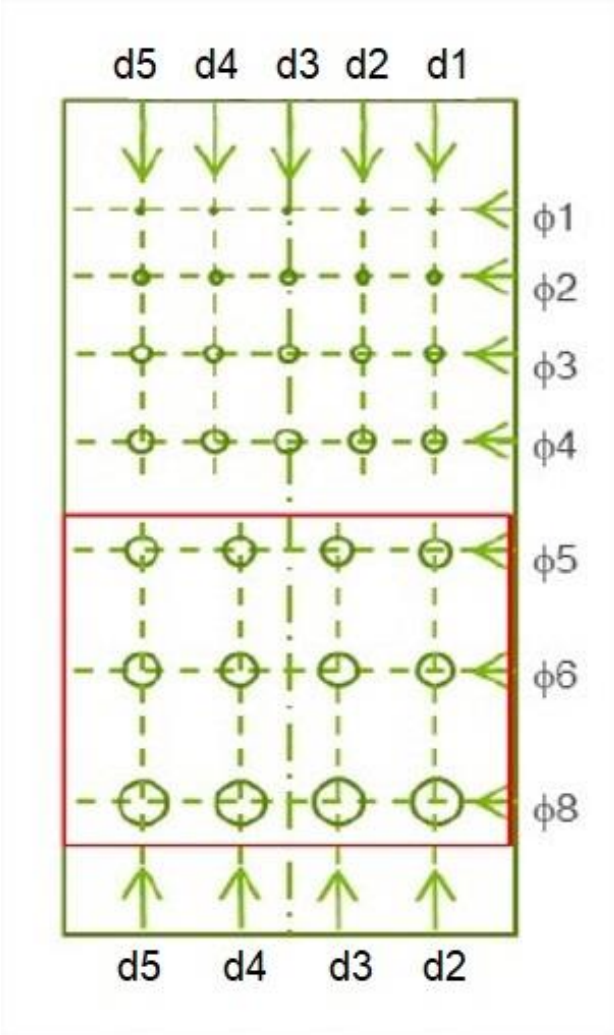


- Flash lamp pulse
  - Delivers 6400J/2ms
- Imaging camera
  - FLIR A65

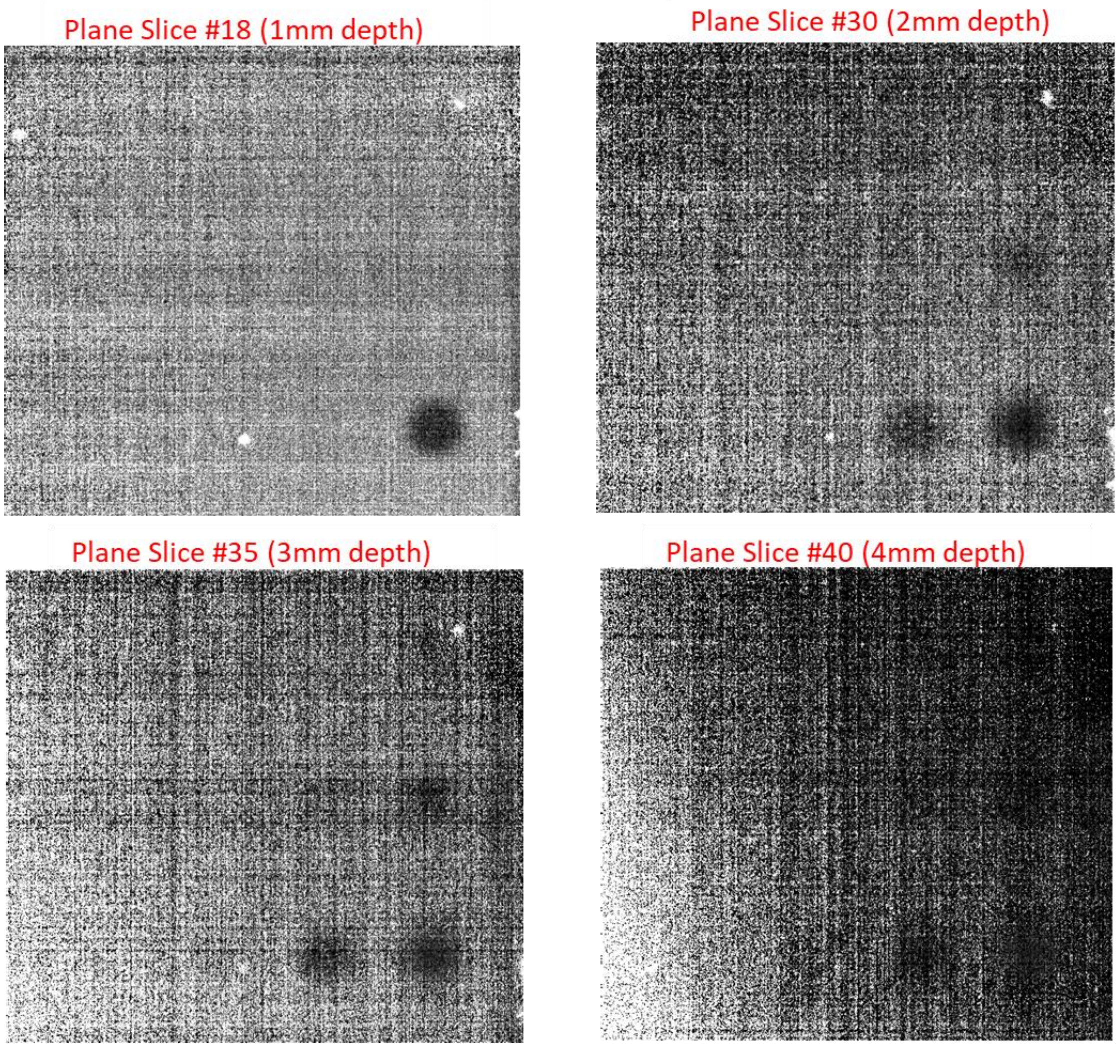


Imaging Large Holes in SS316 with A65

Imaged area



PTT Reconstructions

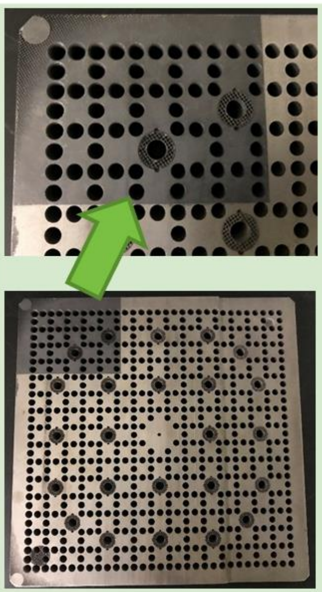
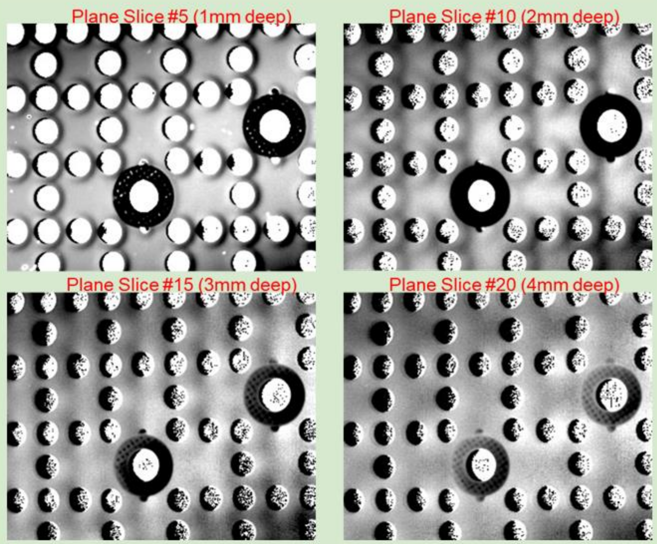
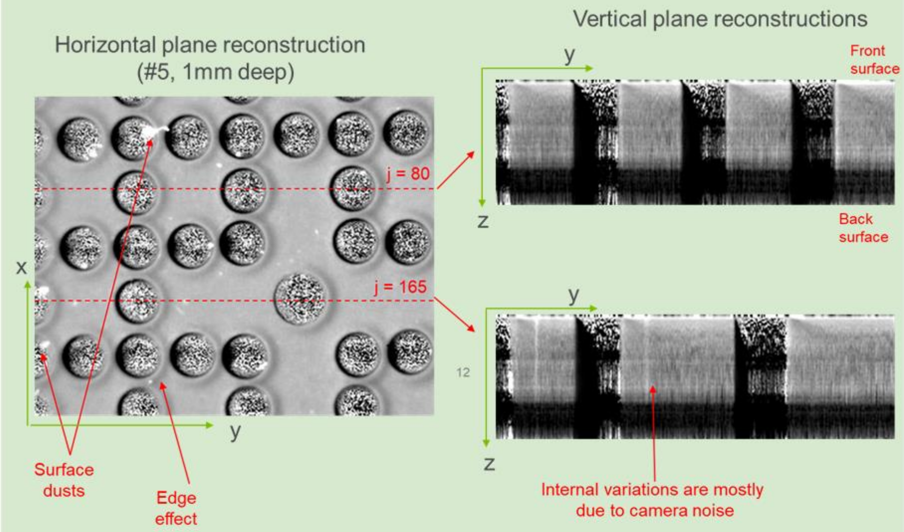


Results

- PTT Imaging of AM Structure

Imaging of AM IN718 Nozzle Plate

- 8in x 8in x 2/3in (17mm) Westinghouse plate,
- Imaging time 21s to scan through

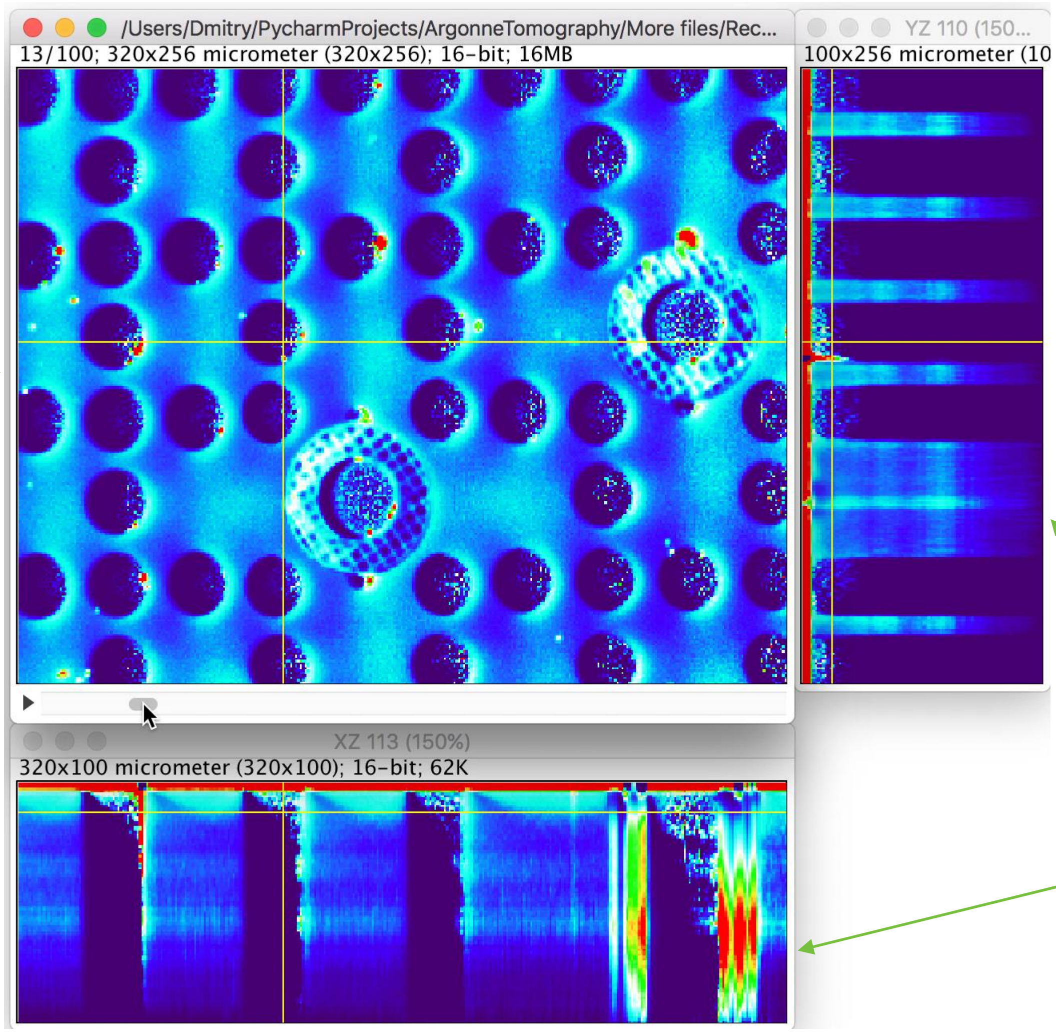
Photograph	Parallel Plane Slices	Cross-section Plane Slices
		

Nozzle Plate 3D Imaging with ImageJ

XY plane

YZ plane

Parallel plane cross-section reconstructions



XZ plane

Vertical plane cross-section reconstructions

Accomplishments

- Publications/Presentations
  – A. Heifetz, J.G. Sun, D. Shribak, T. Liu, T.W. Elmer, P. Kozak, S. Bakhtiari, B. Khaykovich, W. Cleary, “Pulsed thermal tomography nondestructive evaluation of additively manufactured reactor structural materials,” ***Transactions of the American Nuclear Society***, Vol. 121, 589-591, 2019
    - Presented at the ANS Winter Meeting,, Washington, D.C. November 17-21, 2019
  – A. Heifetz, “Pulsed Thermal Tomography Nondestructive Evaluation of Additively Manufactured Reactor Structural Materials,” invited talk, ***Purdue University Nuclear Engineering Weekly Seminar***, April 17, 2019
  – A. Heifetz, “Pulsed Thermal Tomography Nondestructive Evaluation of Reactor Structural Materials,” presented at ***MIT Nuclear Reactor Laboratory Seminar***, December 18, 2018.

Technology Impact

- *Advances the state of the art for nuclear application*
  - *Provides capability to perform NDE of nuclear-grade AM structures*
- *Supports the DOE-NE research mission*
  - *Supports integration of additive manufacturing into nuclear energy*
- *Impacts the nuclear industry*
  - *Helps to reduce manufacturing and maintenance costs*
- *Will be commercialized*
  - *Invention Disclosure at ANL has been filed by A. Heifetz, T.W. Elmer, and S. Bakhtiari in October 2019*

Conclusion

- *Demonstrated detection of calibrated flaws in AM SS316 and IN718 specimens*
  - *Porosity regions with 1mm diameter located 1mm below plate surface were detected*
- *Contact Information*
  - *aheifetz@anl.gov*
  - *630-252-4429*

Clean. Reliable. Nuclear.