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Spatially Resolved Analysis of Material Response to Destructive Environments Utilizing Three-Dimensional Scans

SAND2018-????C

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Outline

- Introduction and motivation
- Experimental Setup: Solar Furnace
- Scanner Validation
- Experimental Data
- Conclusions

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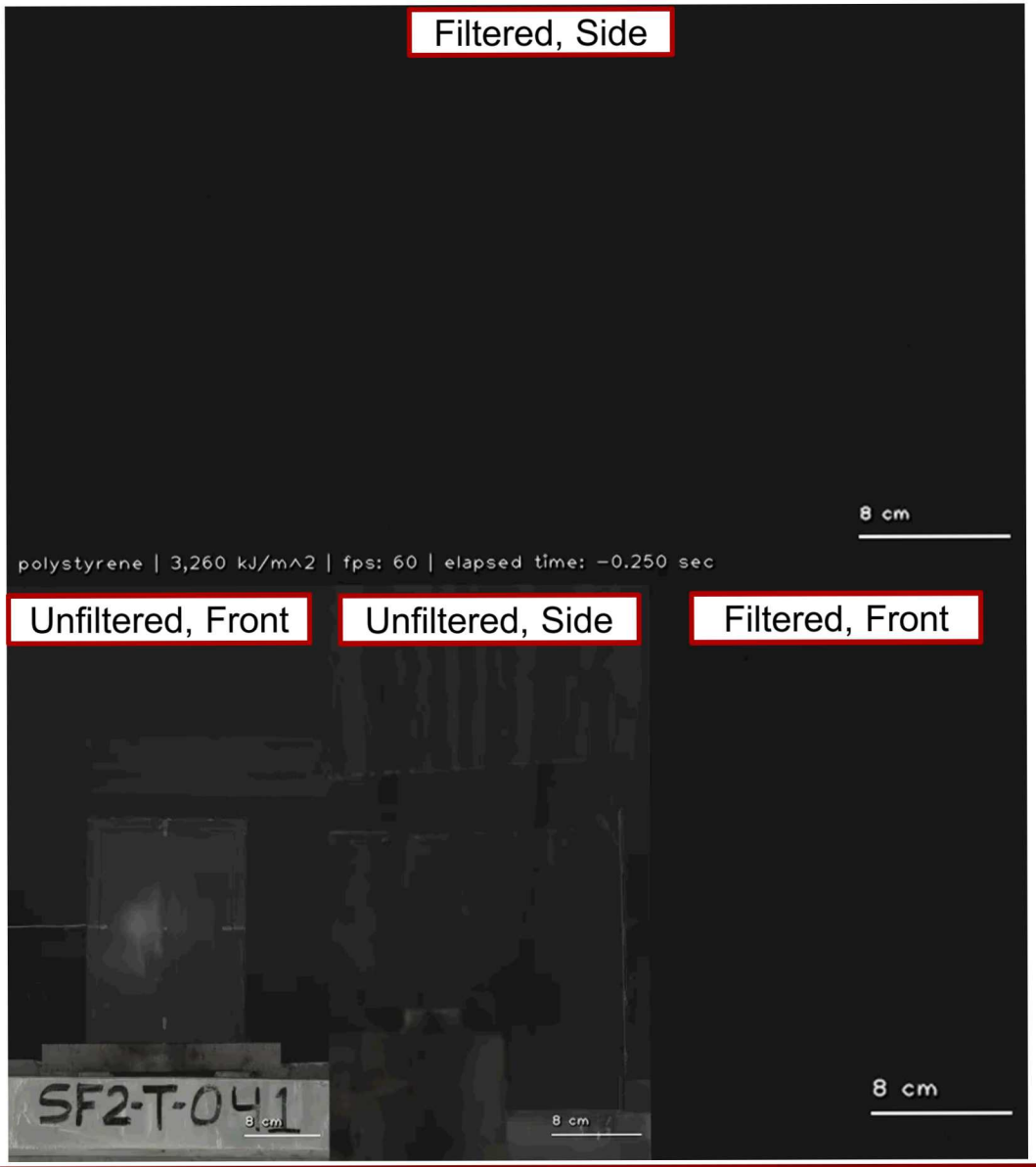
Introduction and Motivation

- A variety of sources can produce heat flux well beyond those typical of fire environments:
  - Directed Energy Weapons
  - Nuclear Weapons
  - Explosives
  - Propellants
- At extreme (~1 MW/m^2) heat flux, the incident energy dominates the surface energy balance
  - Radiation (~100 kW/m^2) and convection (~10 kW/m^2) are relatively small even when the surface reaches ignition temperatures (≈ 600 °C)
- **Objective:** Improve modeling tools by **characterizing the surface topology** of samples after exposure to intense thermal irradiation.

Response to Extreme Irradiation

- Under extreme irradiation (~0.1 – 1 MW/m^2), a material can:
  - Pyrolyze strongly as the surface recedes
    - The material chemically decomposes, producing combustible gases.
  - Ignite by a variety of mechanisms:
    - Transient Flaming
    - Sustained Flaming
    - Sustained Smoldering
  - As well as other responses:
    - Melt, spall, char, exfoliate, etc.

Example: Polystyrene



Material:
High-Impact Polystyrene
3.2 mm thick

Exposure:
3.26 MJ/m^2

Ignition Data:
Sustained Flaming
Ign. time: 0.85 s
Pyr. time: 0.38 s

Programmatic Objectives

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- This study is part of a wider program, **focusing on pyrolysis and ignition** at extreme radiative heat flux.
  - **Experimental** data at small and large scale
    - Solar Furnace (≈10 cm spot)
    - Solar Tower (≈1 m spot)
  - **Simple ignition models** (e.g., empirical correlations) that can predict material response to a given environment.
  - **High-fidelity computational models** that capture the complex physics and accurately predict pyrolysis and ignition.
- These advancements will produce **ignition models** spanning a wide range of **environments** and **materials**.

Motivation for Surface Recession

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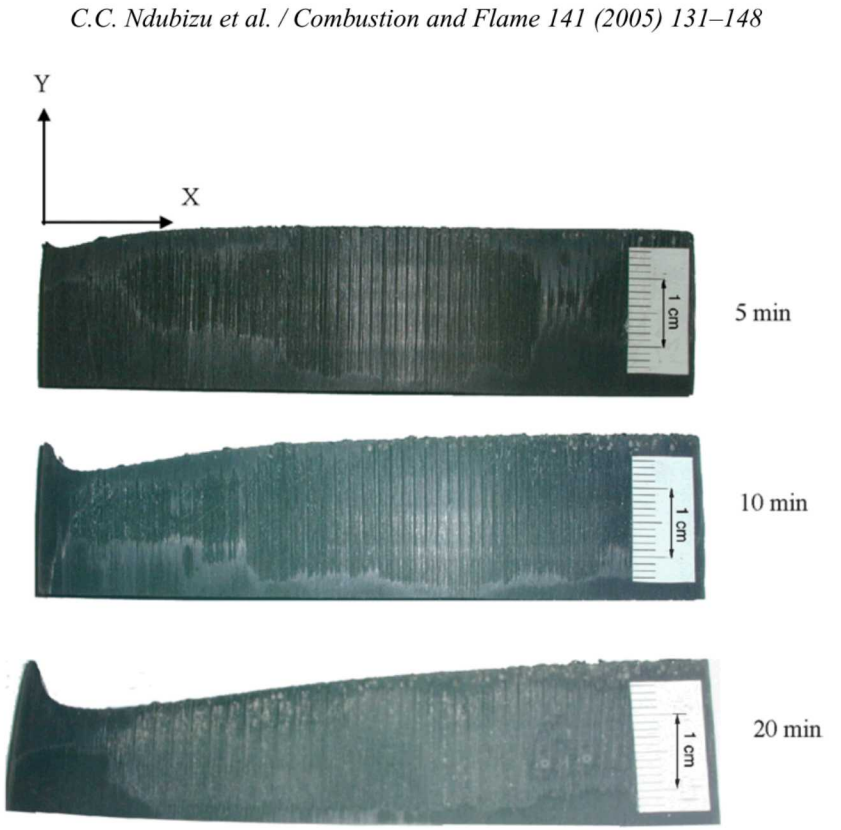
- Example of surface recession: Wood

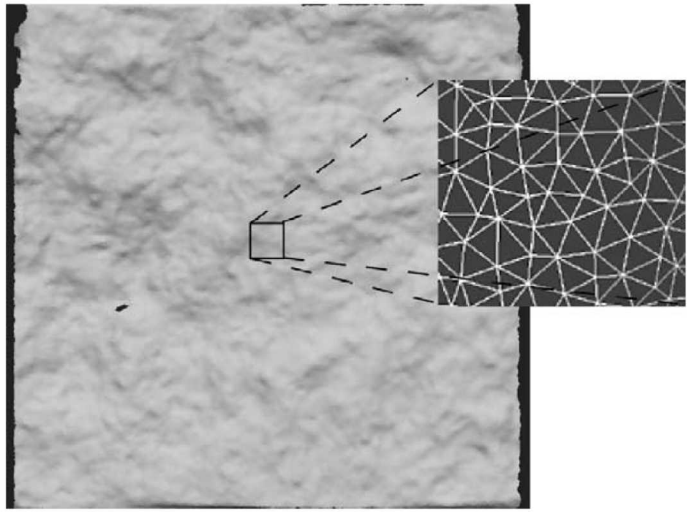
Motivation for 3D Scanning

- Quantifying the surface recession
  - Data collection
  - CFD boundary condition
  - Model validation
- Two methods are common:
  - Localized char/crater depth
    - A probe measures depth relative to original surface height.
  - Sample cross sections
    - Material is cut on a plane normal to the surface, thickness is measured.
- 3D Scanning may be superior?



3D Scanning

- 3D Scanners are sometimes used in related problem areas:

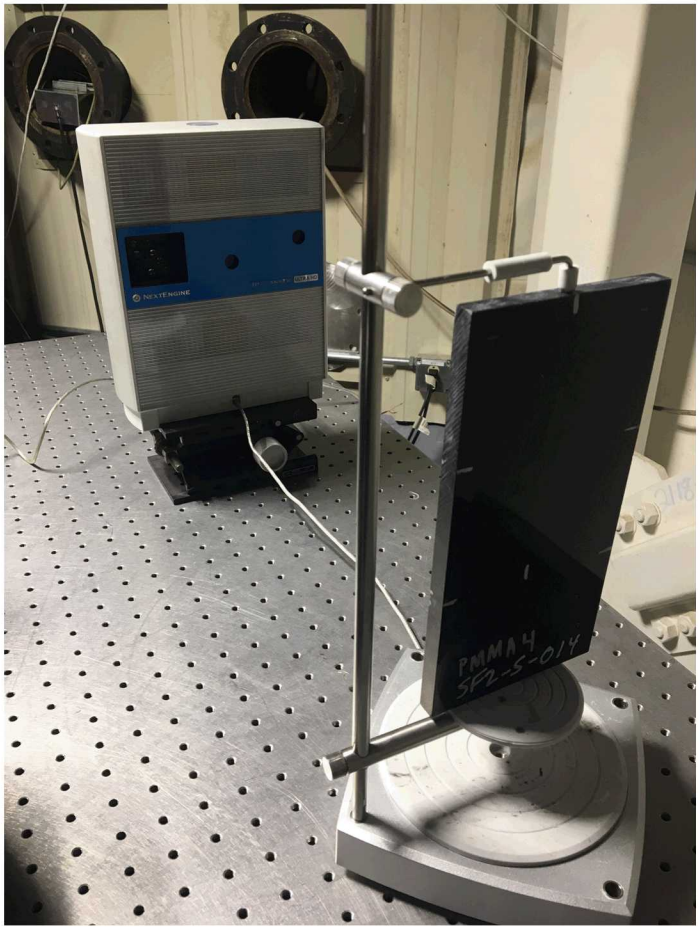


Grasselli, G. et al., Int. J Rock Mech. Mining S., (39) 2002

- But their use for destructive thermal environments is not common.

Commercial 3D Scanners

- Commercial 3D scanners are affordable (~$1000) and make the technology widely available.
  - Scans sample surface with 650 nm lasers
  - Records data with two image sensors.
- Common for medical and design applications.
- Not validated for scientific measurements.
  - Advertised accuracy: 0.13 mm (0.005”)
- This study will **validate** the scanner and **demonstrate** its capabilities.



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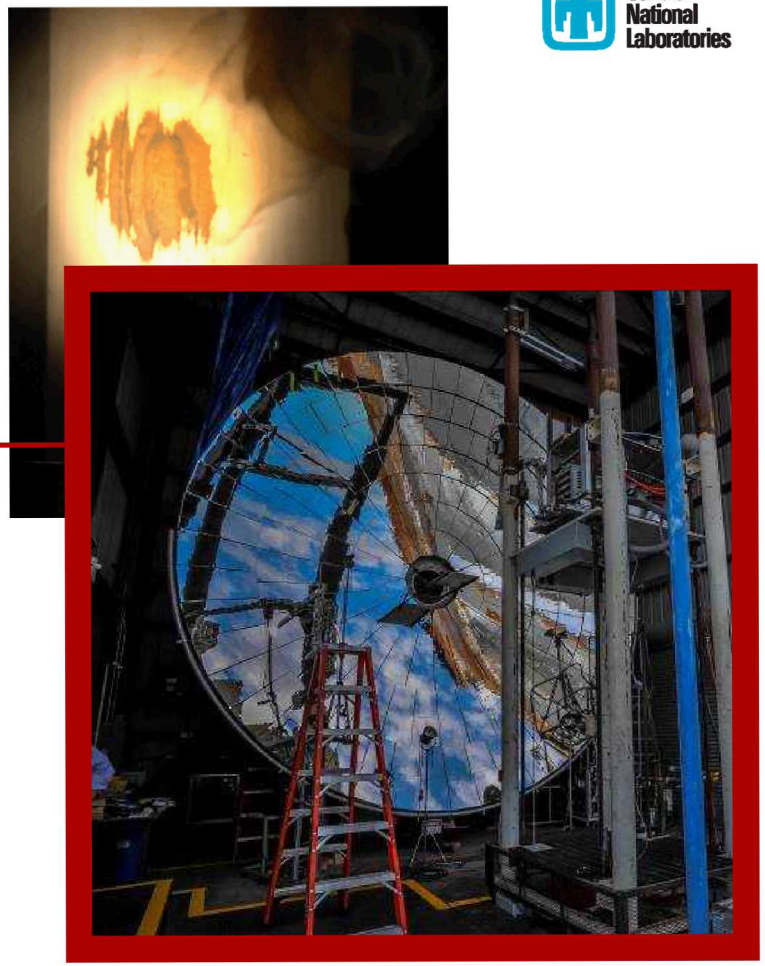
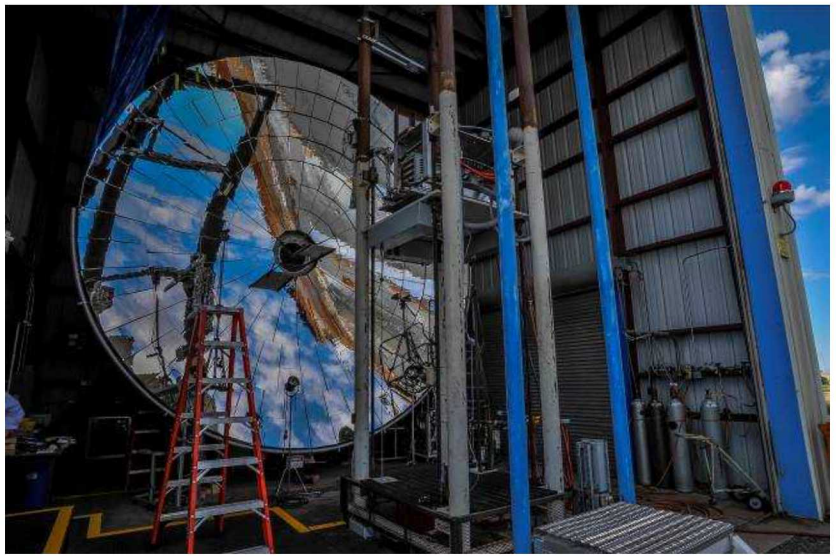


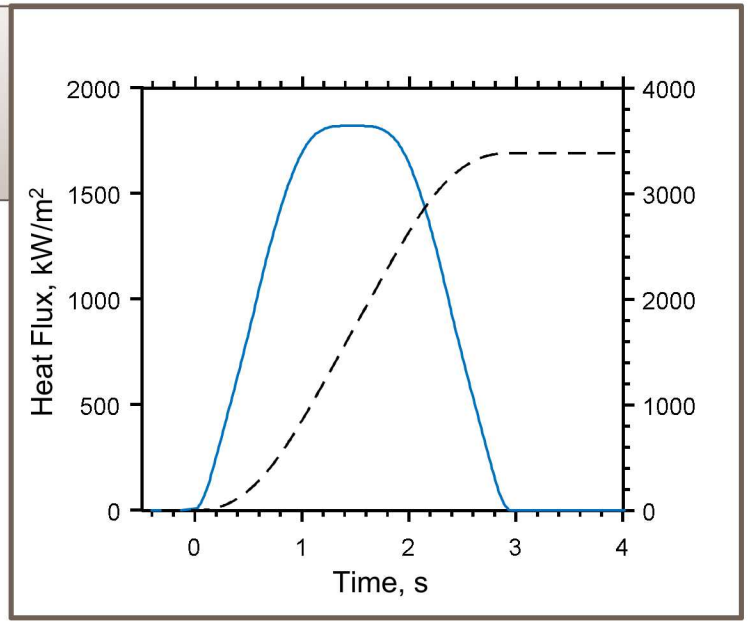
Solar Furnace



- Heliostat tracks sun
- Parabolic dish focuses light
- Attenuator controls temporal flux profile
- 3-axis table positions sample/instrumentation
- Generates heat flux of up to 6 MW/m^2 on a ≈8 cm spot

Instrumentation

- Radiometer and heat-flux gauge quantify flux/fluence
- Cameras capture material response
- Photographs taken before and after
- Mass recorded before and after
- 3D Scans after



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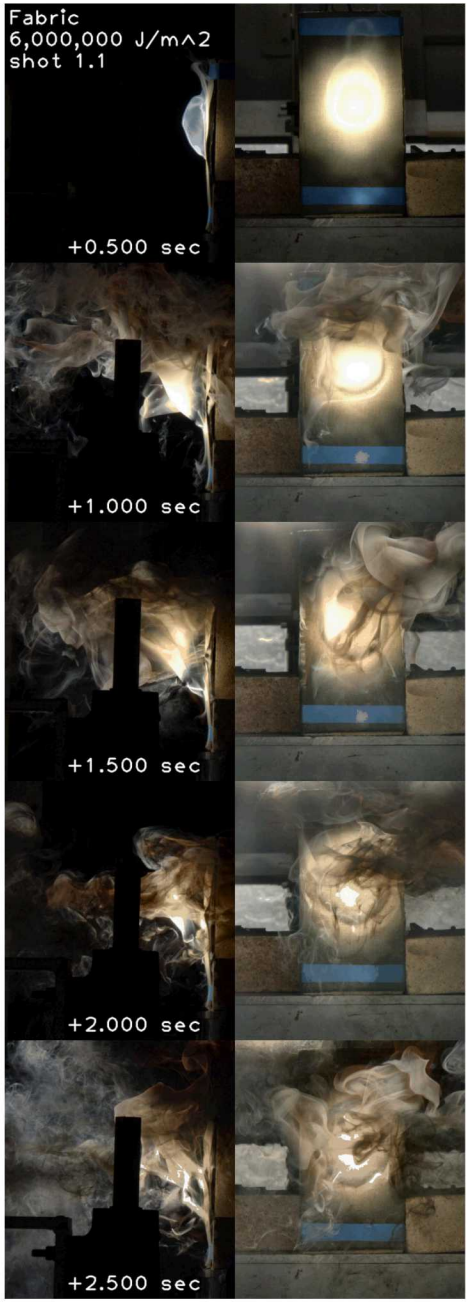

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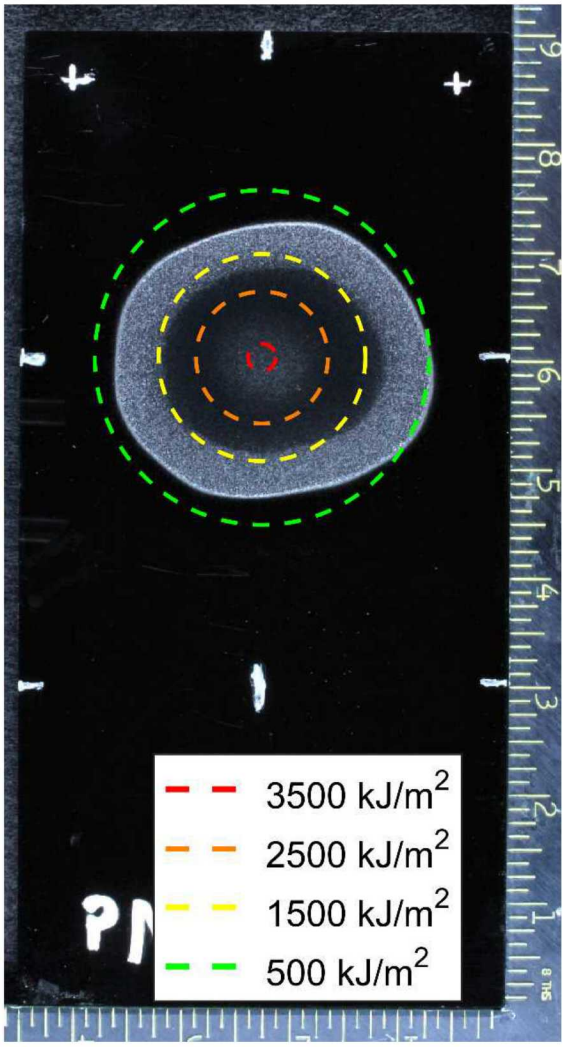

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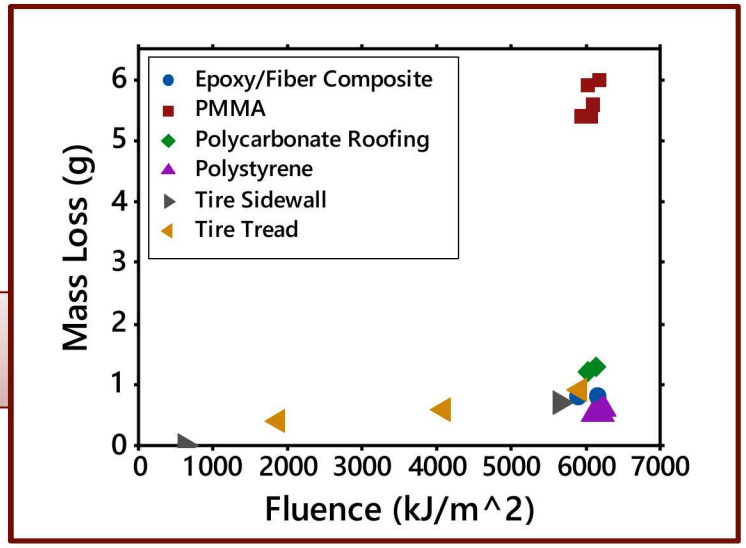

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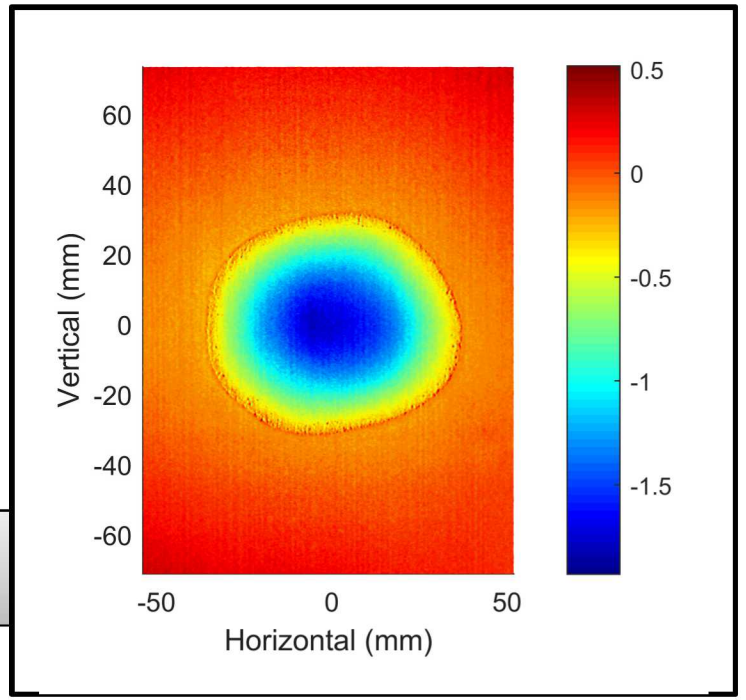
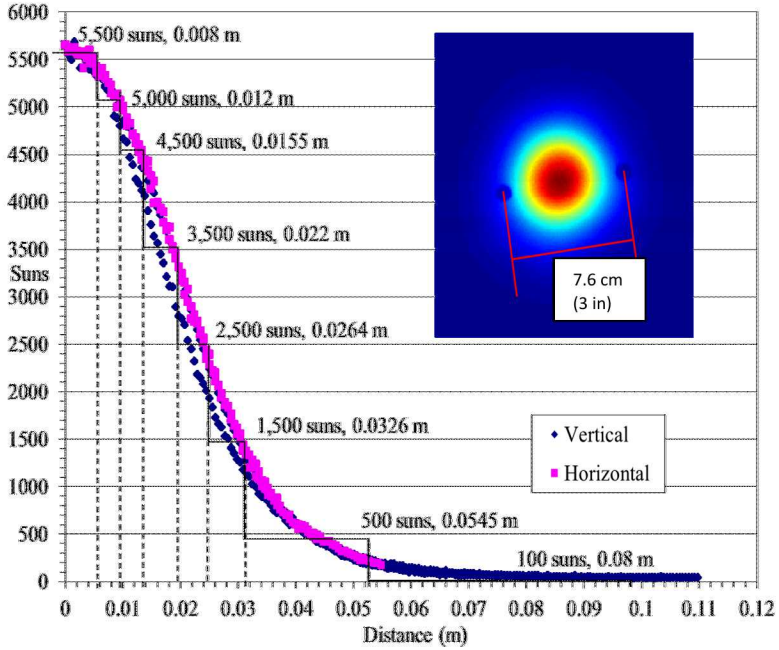


Heat Flux: Spatial Profile

$$q''(t,r) = \frac{q_o''(t)}{1 + \exp\left(C\left(\frac{R_0}{R_1}r\right)^D - B\right)}$$

$B = 6.662$
$C = 27.7$
$D = 0.401$
$R_0/R_1 = 1.34$
r is radius in meters

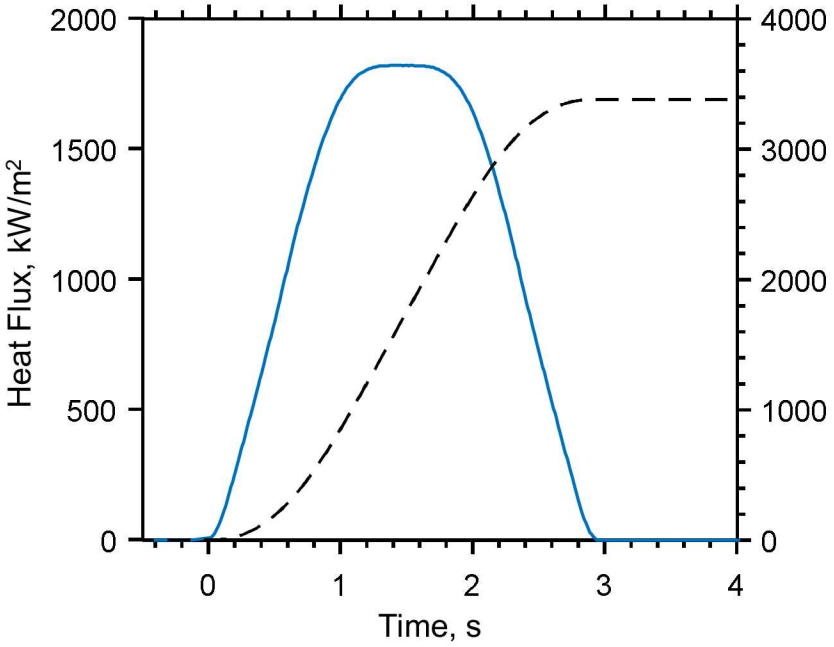


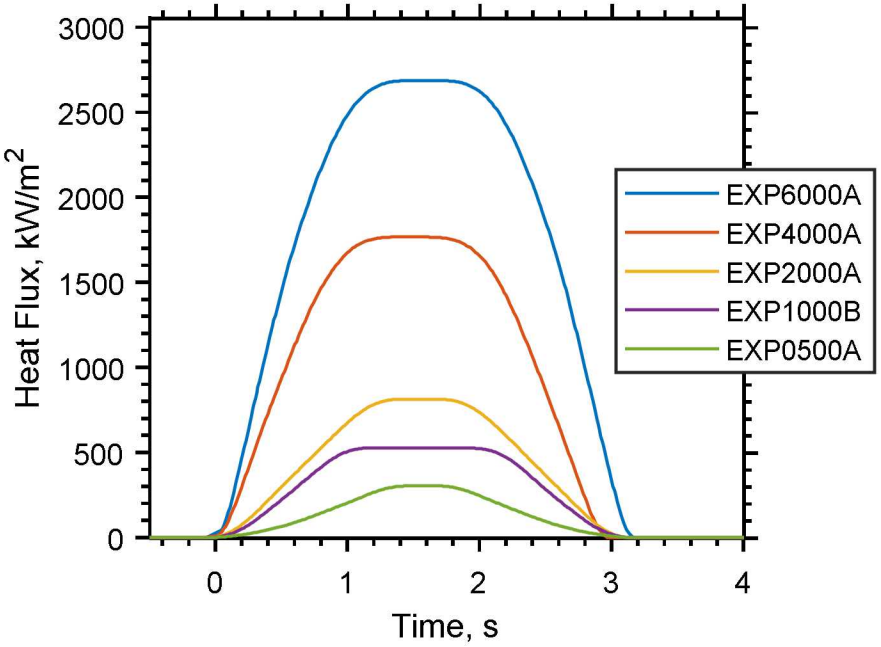
- Spatial distribution of beam has been characterized:

  Ho, C. K. et.al., Proc. Int. Conf. on Energy Sustain. 4 (2010) 1-9.

- Spot diameter is roughly 8 cm

Heat Flux: Temporal Profile





- Exposure profiles with varying nominal fluence (0.2–6 MJ/m^2)
- Ramp and plateau durations are matched
- Pulse is closest to a square-wave, limited by attenuator speed

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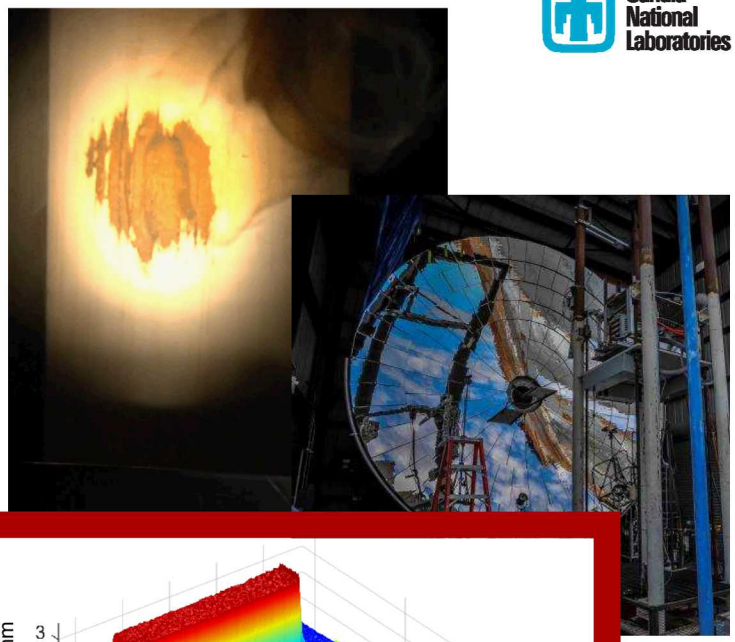
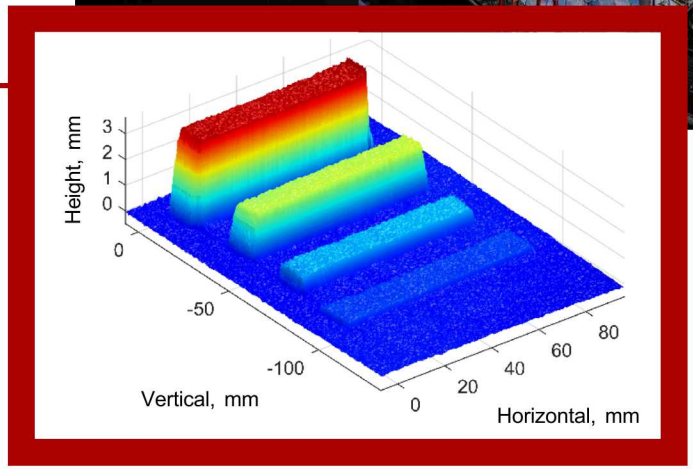
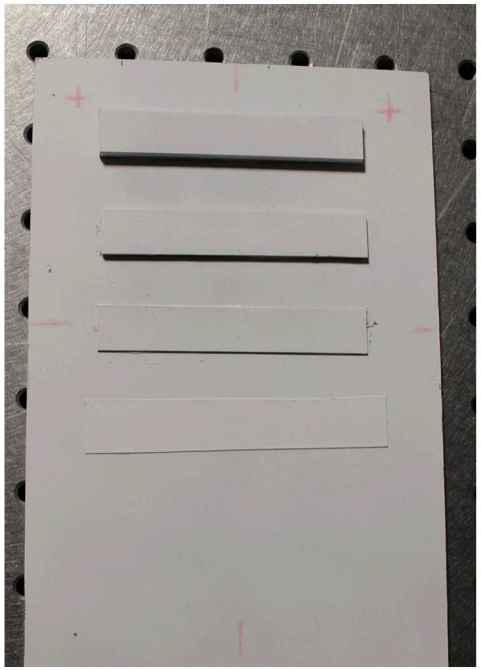




3D Scanner Test Plan

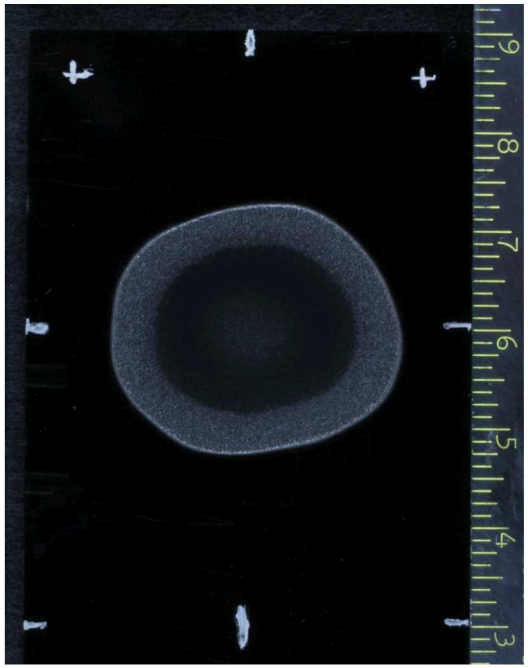
- The presented results consist of three types of samples:

Validation Sample



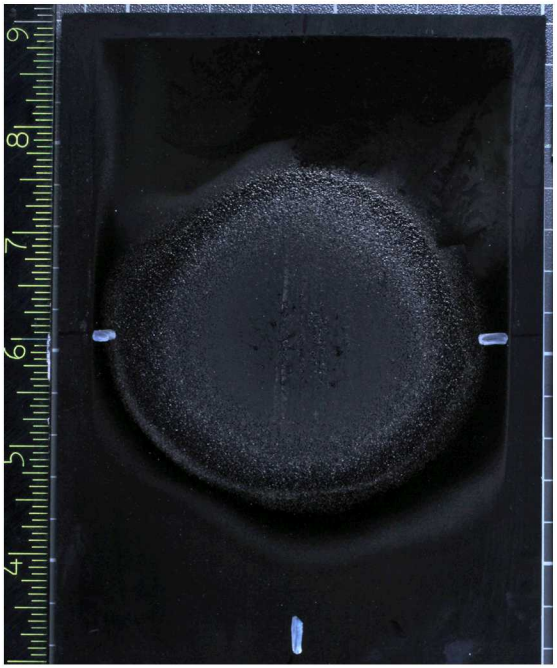
- Known features
- Evaluate accuracy

PMMA



- Deep crater
- Minimal distortion

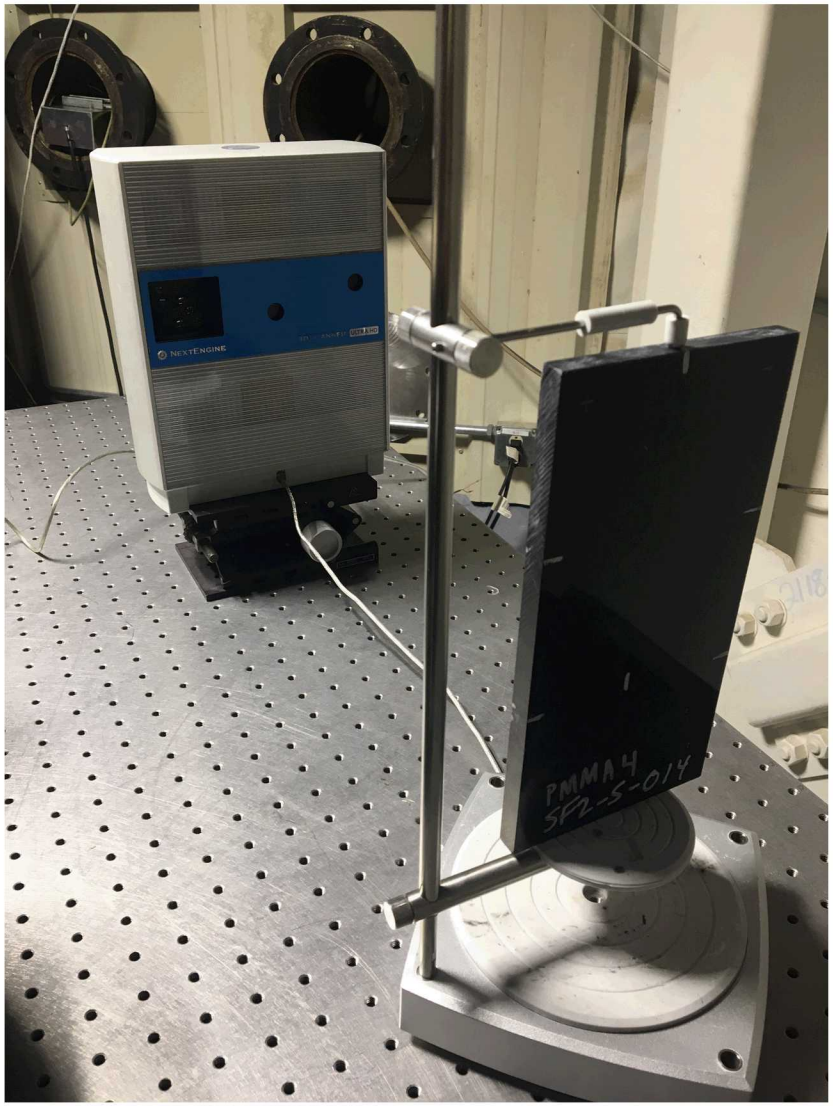
Polystyrene



- Shallow crater
- Large distortion

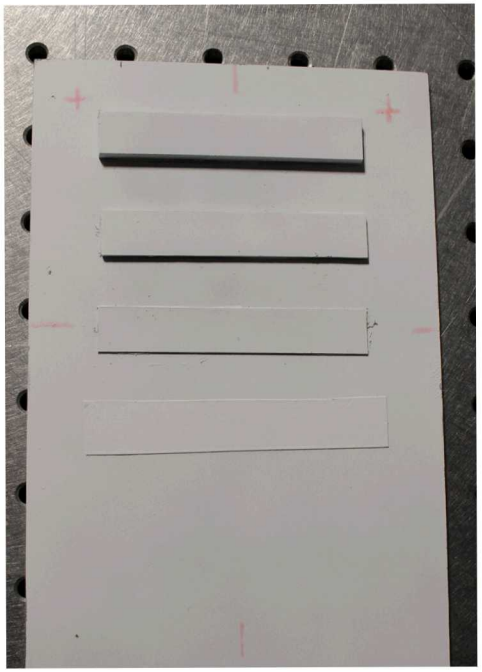
3D Scanning

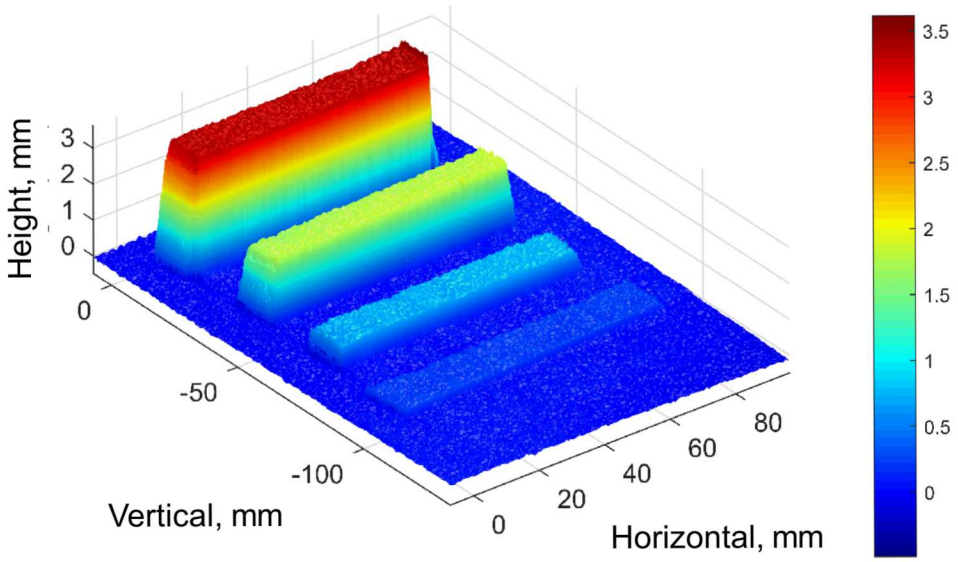
- 3D Scanning Procedure:
  - Coat samples with white, diffuse (matte) coating
    - Magnaflux Spotcheck SKD-S2
  - Draw alignment marks on front and back surfaces
  - Perform 3D scans from three angles (normal and ±36 °C) on **front** and **back** surfaces
  - Merge and process scans in manufacturer software (ScanStudio HD)



Validation Scan

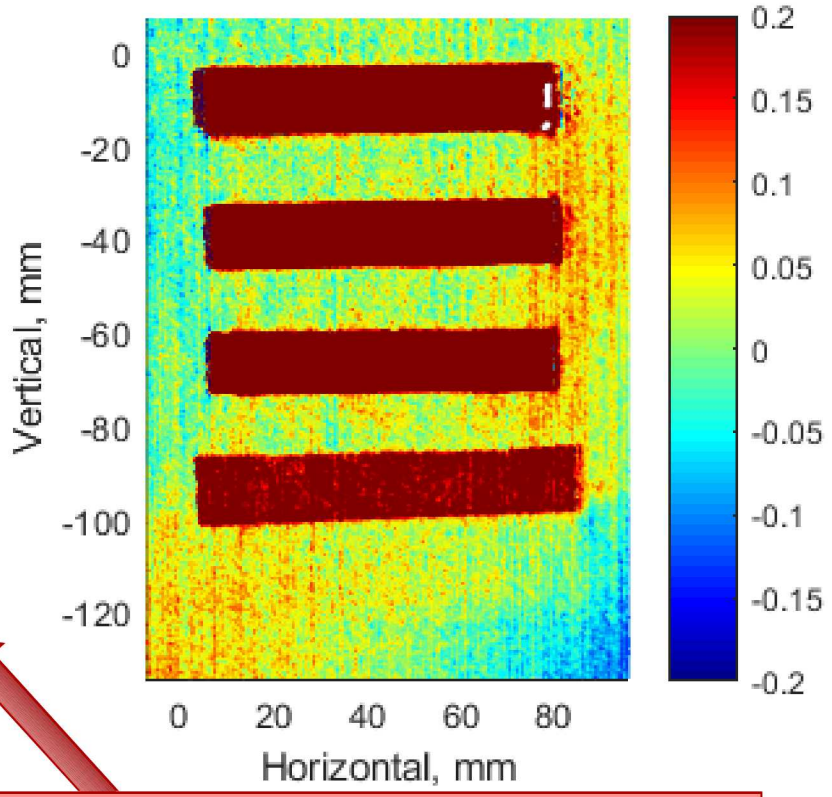
- Validate scanner
  - Flat panel with steps of known thickness (3.26, 1.66, 0.56, 0.17 mm)
  - Compare surface reconstruction to known profile





Scanner Noise

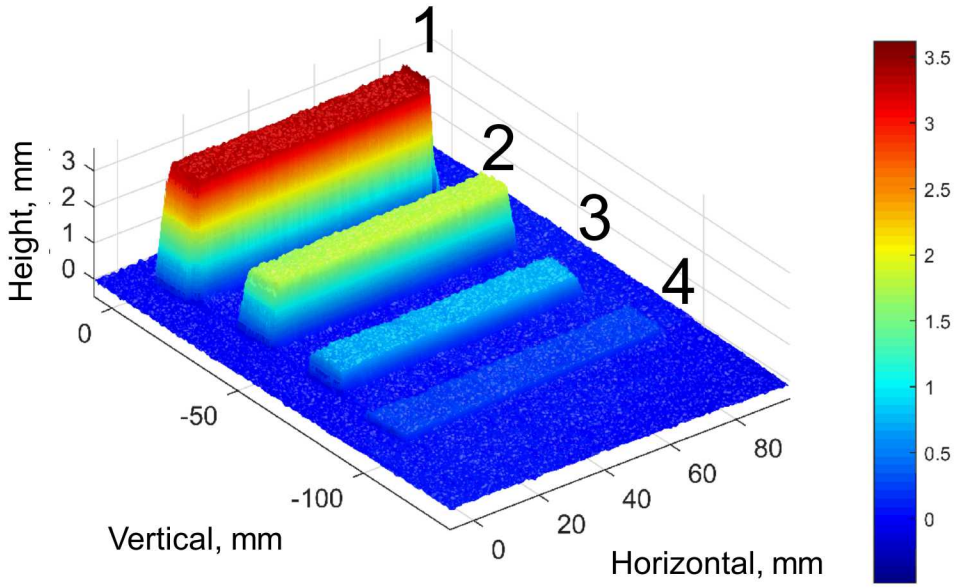
- First, examine height of flat base plane (ignore steps).
- Faulty variations (~0.1 mm) on flat surface, including:
  - Vertical Striations
    - Variation: ~0.1 mm
  - Random variations (noise)
    - Noise RMS: 0.025 mm
    - Normally distributed
  - Variations over ~10 cm lengths
    - -0.03 to +0.07 mm



First two effects are eliminated when averaging over ~1 cm^2 areas.

Scanner Accuracy

- Evaluating accuracy of known step heights
  - ≈0.1 mm accuracy for most features
  - Very thin features may have better accuracy.



Step	Act. Height (mm)	Scan. Height (mm)	Meas. Error (mm)	Percent Error (%)
1	3.26	3.35	.09	3.8
2	1.66	1.73	.07	4.4
3	0.56	0.65	.09	16.0
4	0.17	0.18	.01	4.8

Scanner Validation

- Based on the previous slides:
  - Scanner signal contains noise and vertical striations.
    - Removed by averaging over 1 cm^2 area.
  - Profile varies ($\pm$0.05 mm) over moderate distances (~10 cm)
    - Likely to affect accuracy of the measurements
  - Surface features on the order of 1 mm are accurate to $\pm$0.1 mm
  - Surface features on the order of 0.1 mm may have better accuracy

- Conclusions:
  - Base measurements on averaged areas (~1 cm^2) when possible
  - Advertised accuracy ($\pm$0.13 mm) is consistent with our results.

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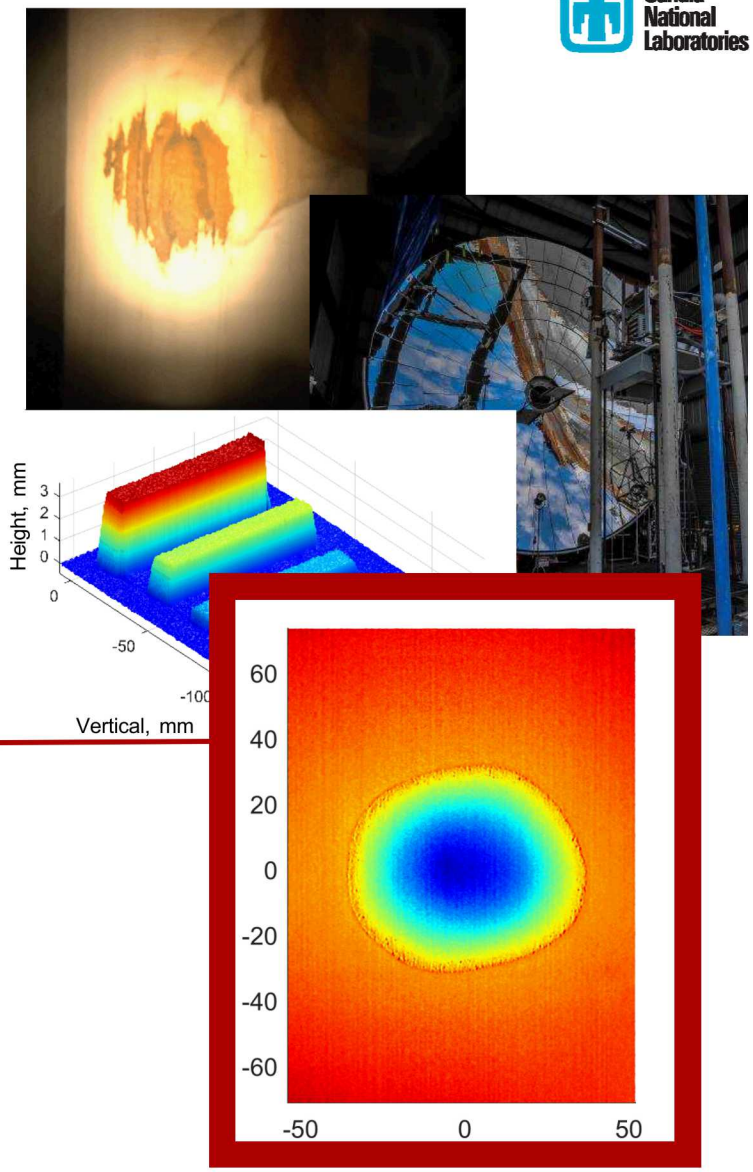
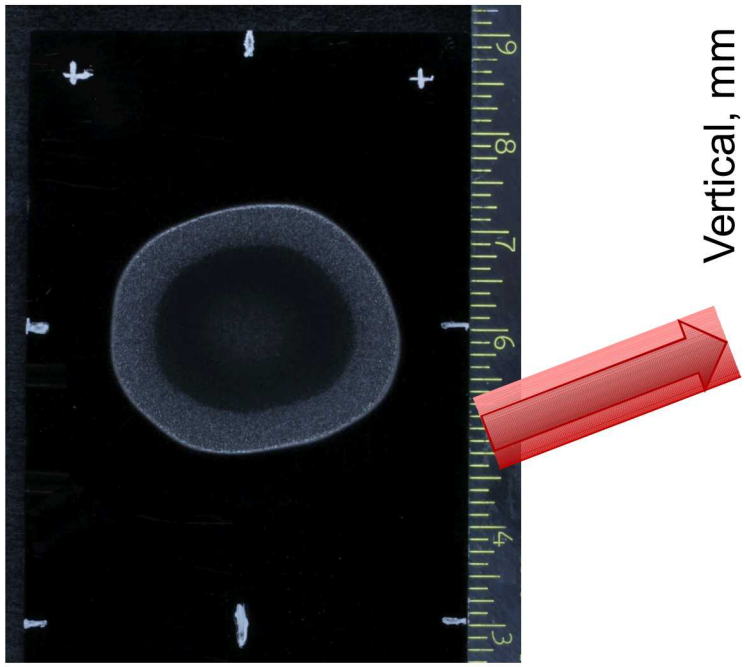
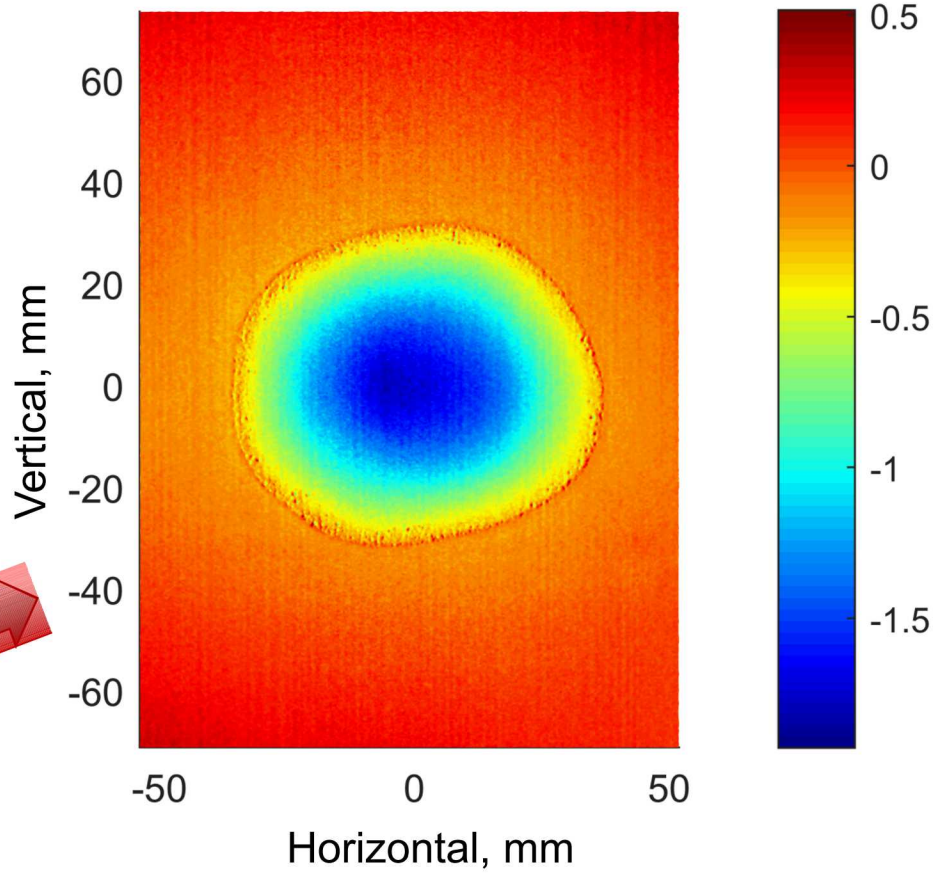


PMMA (≈3.6 MJ/m²)

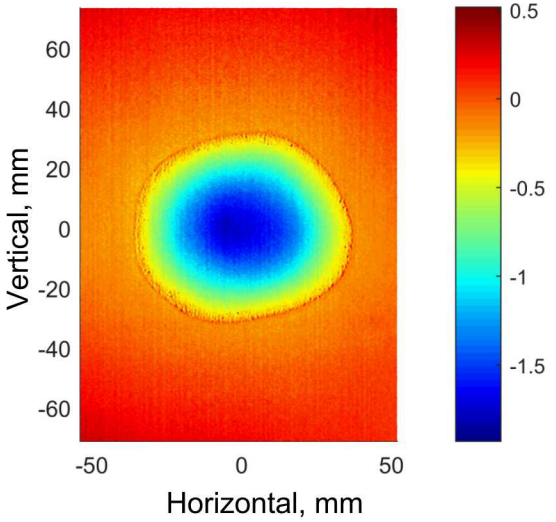
- PMMA samples were ideal for 3D scanning
  - Negligible charring/swelling
  - Deep crater (≈2 mm)
  - Minimal distortion
    - Front scan only





PMMA

- Compare surface/volume displacement to mass loss
  - Scanner overestimates mass loss by ≈10%
  - Potentially affected by concavity

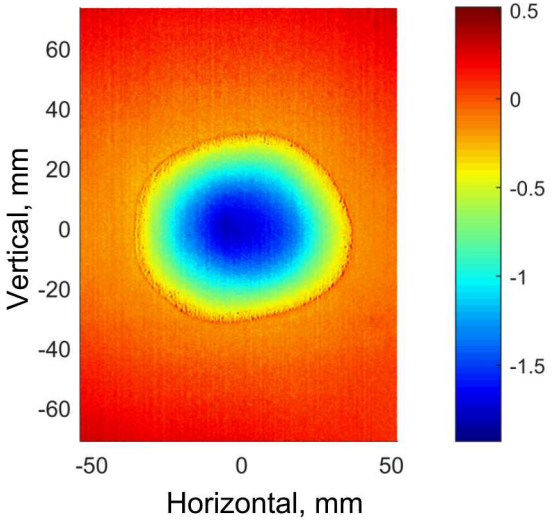


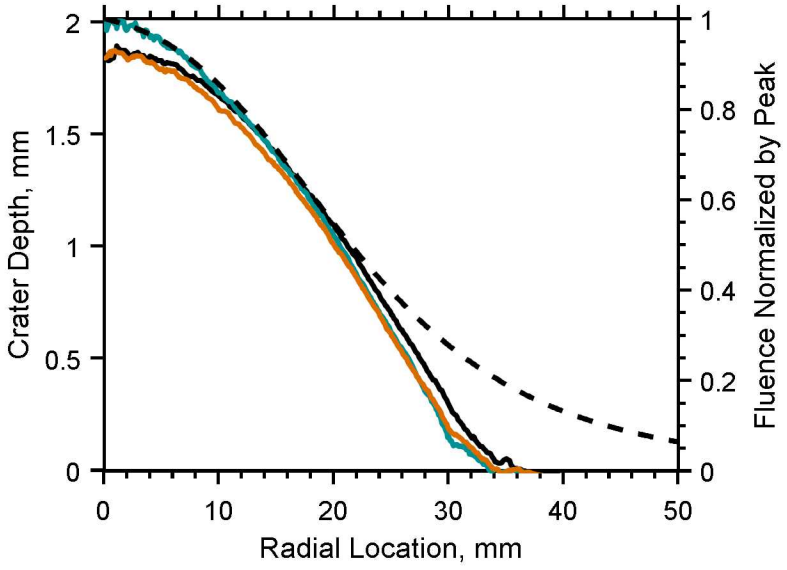
Sample	Exp. Fluence $kJ\,m^{-2}$	Act. Mass Loss (g)	Scan. Mass Loss (g)	Meas. Error (g)	Percent Error (%)
1	3780	2.70	3.07	0.37	13.5
2	3490	2.55	2.86	0.31	12.2
3	3430	2.55	2.79	0.24	9.4

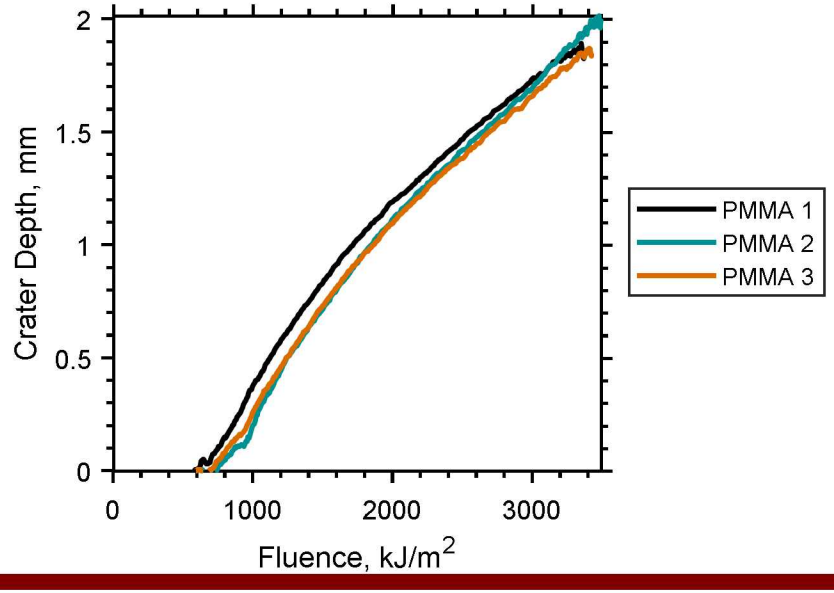
$$m'' = \rho \Delta z$$

PMMA

- Compare surface profile to local exposure fluence
  - Linear correlation above 2,000 kJ/m^2
  - Crater rim at ≈ 30 mm and ≈1,000 kJ/m^2

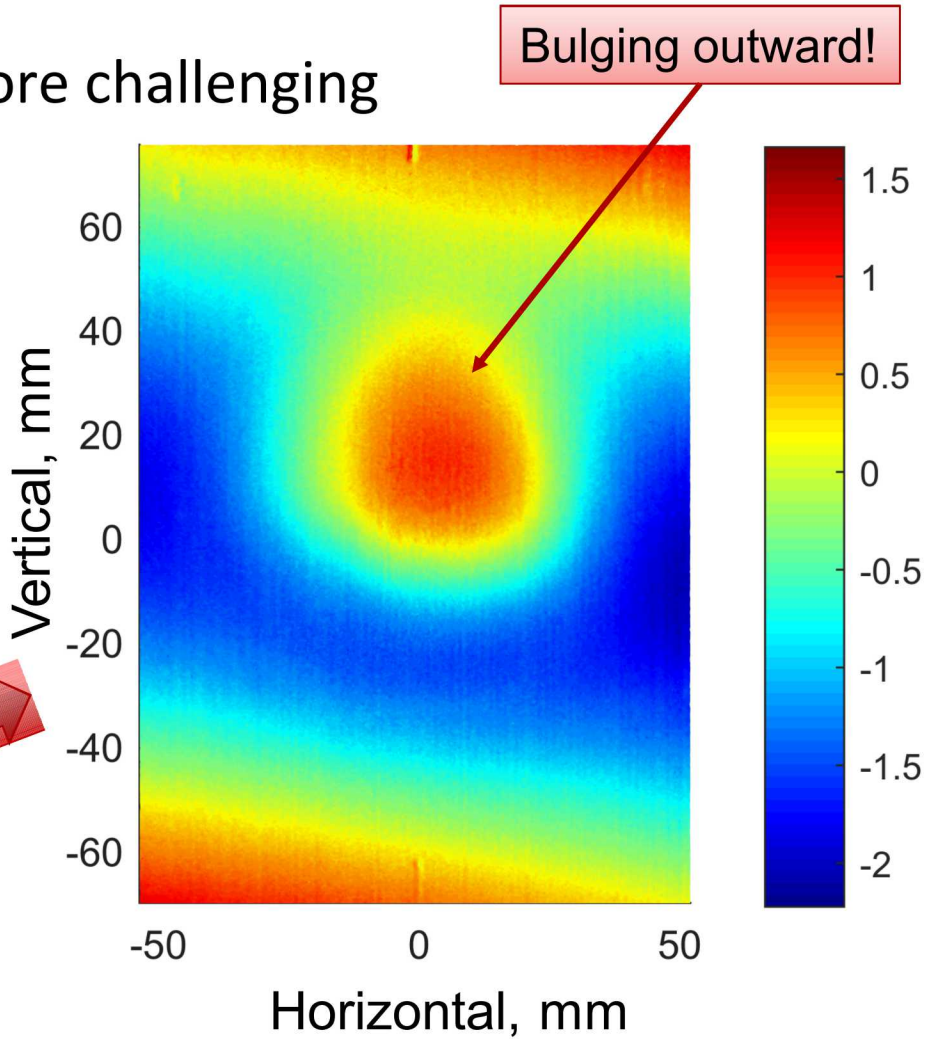






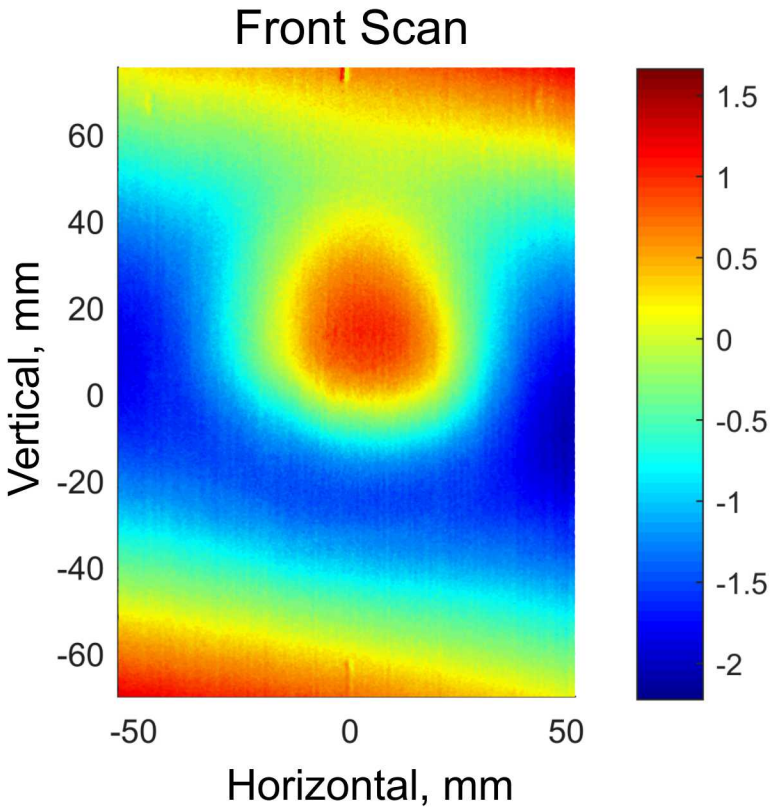
Polystyrene (≈3.2 MJ/m^2)

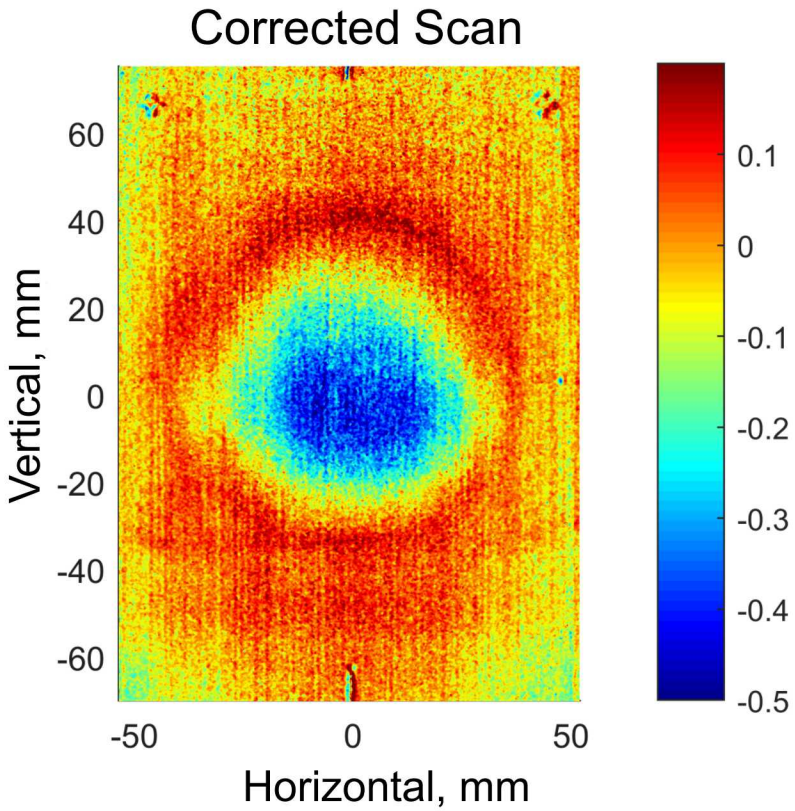
- Polystyrene samples were more challenging
  - Evidence of charring/swelling
  - Shallow crater (≈0.5 mm)
  - Significant Distortion (≈4 mm)



Polystyrene

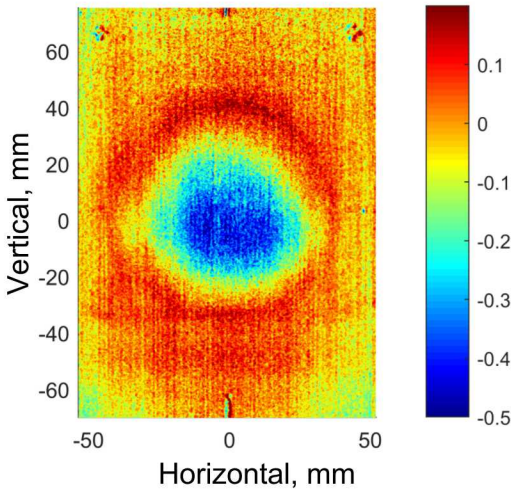
- Warping of material hides most of the relevant data!
- Use back-side scan to correct for warping.





Polystyrene

- Compare surface/volume displacement to mass loss
  - Scanner underestimates mass loss by ≈40%
  - Potentially affected by swelling

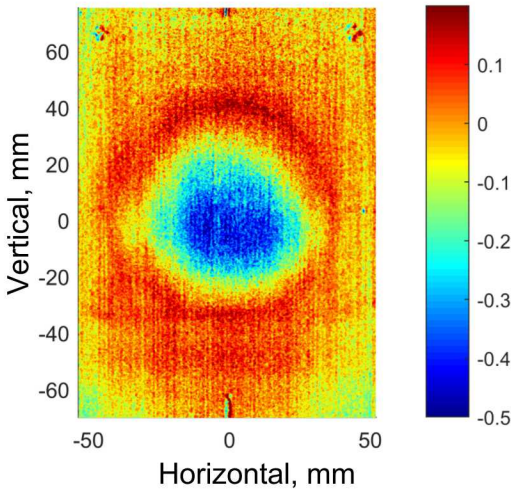


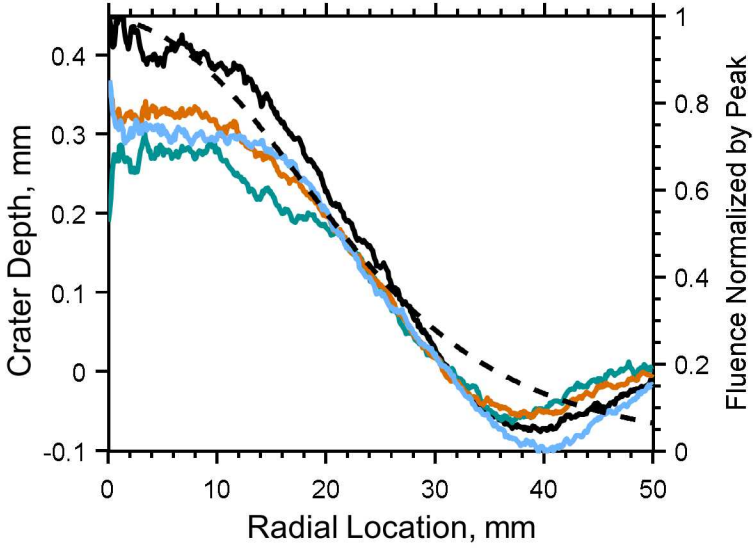
Sample	Exp. Fluence $kJ\,m^{-2}$	Act. Mass Loss (g)	Scan. Mass Loss (g)	Meas. Error (g)	Percent Error (%)
1	3110	0.81	0.61	-0.20	-24.2
2	2990	0.78	0.42	-0.36	-46.6
3	3030	0.92	0.47	-0.45	-48.5
4	3320	0.89	0.50	-0.39	-44.0

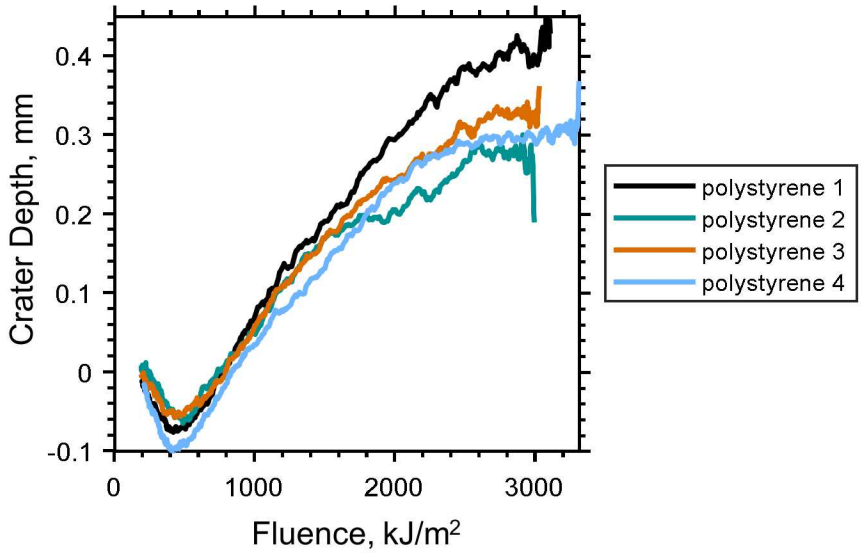
$$m'' = \rho \Delta z$$

Polystyrene

- Compare surface profile to local exposure fluence
  - Crater depth nonlinear with fluence at center (plateau)
  - Rim (swelling?) at edge of crater







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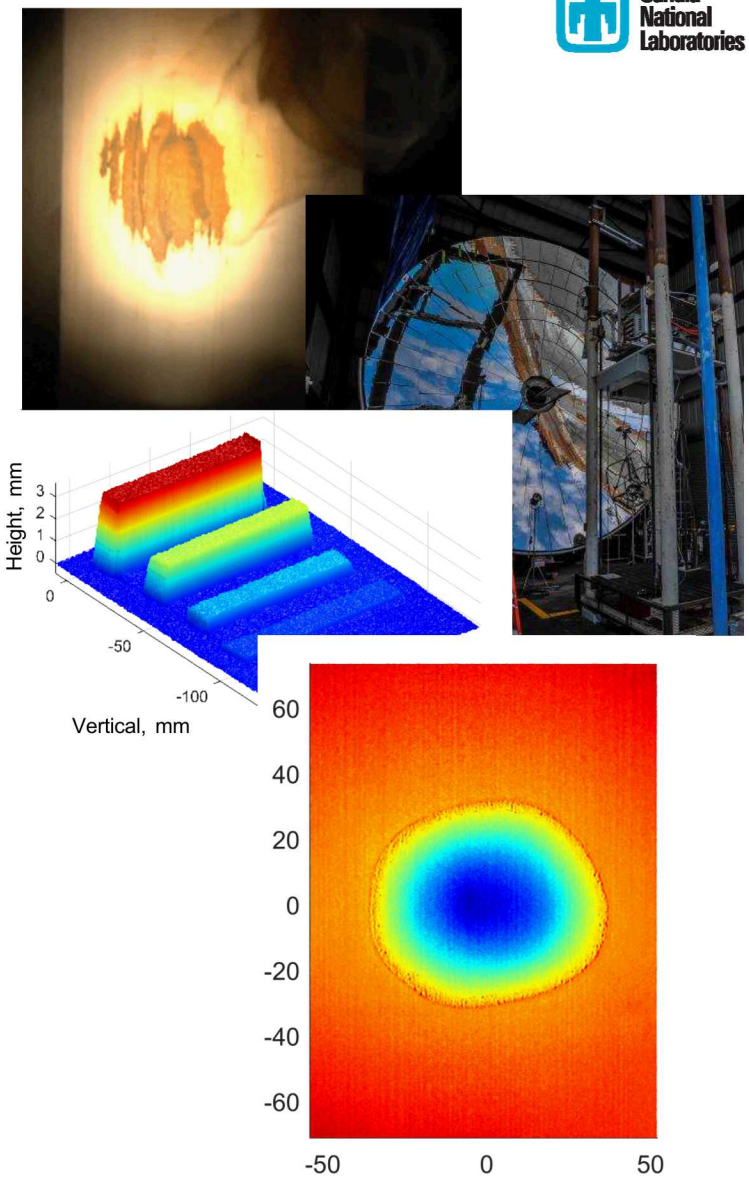

Conclusions

- Scanner is affected by color variations, cannot resolve reflective surfaces
  - Coating the samples is recommended (if color varies)
- The advertised accuracy (± 0.13 mm) is reasonable.
  - Accuracy likely depends on sample geometry and various scanner settings. Validation scans are recommended for future studies.
- The scanner provides useful data.
  - Evaluate surface displacement.
  - Correlate to other variables.
  - Compare to model predictions.

Acknowledgements

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