

**Abstract:** Mercury Marine aims to optimize their reduced pressure test (RPT) procedure for their lost foam aluminum A356.2 casting line. The RPT is key to prevent hydrogen porosity in casts as it gives a quick estimation of dissolved hydrogen in the melt. X-Ray Micro CT was used to determine porosity volume fraction and pore sizes of 25" Hg, 27" Hg, 28" Hg, and 29" Hg vacuum pressure RPT samples. XCT data was compared to 2D metallographic analysis of vertically sectioned samples and Archimedes' Density calculations showing strong correlation. A proposed PowerBI dashboard was developed for Mercury Marine's operations to track RPT results to limit waste and monitor performance.

This work is sponsored by Mercury Marine in Fond du Lac, WI



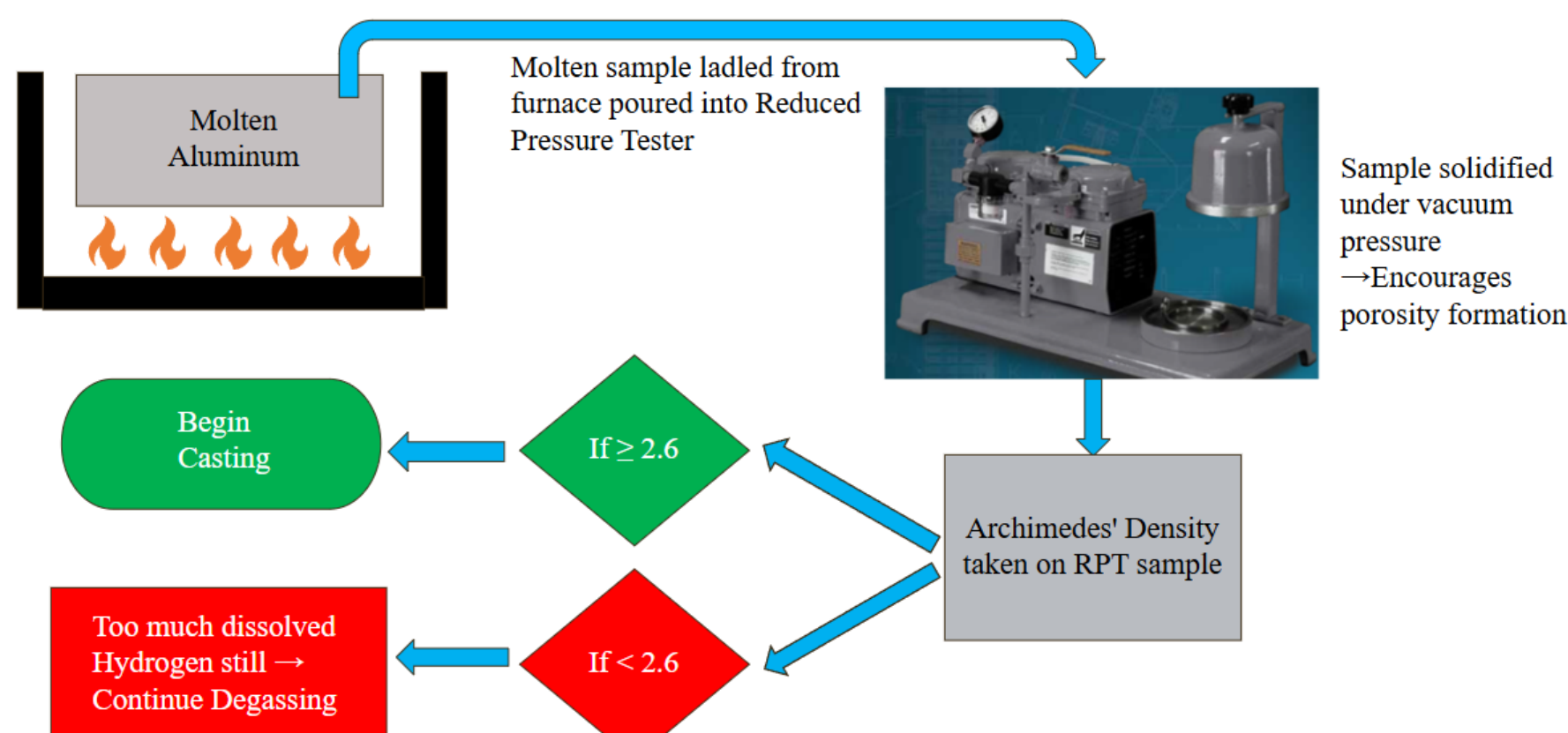
### Background

#### Motivation:

- Hydrogen has high solubility in liquid aluminum, but low solubility in solid aluminum leading to porosity in cast components.
- Pores negatively impact mechanical properties, specifically strength and fatigue resistance.
- Degassing with nitrogen is necessary to remove any dissolved hydrogen from the melt prior to casting to prevent defects.
- There are many uncontrollable variables from environmental (high humidity) to processing conditions (rotary speed, gas flow rate, etc.).
- Many manufacturers conduct Reduced Pressure Test (RPT) which exaggerates porosity formation and gives a specific gravity measurement to estimate the dissolved hydrogen content in the melt.

#### Problem Statement:

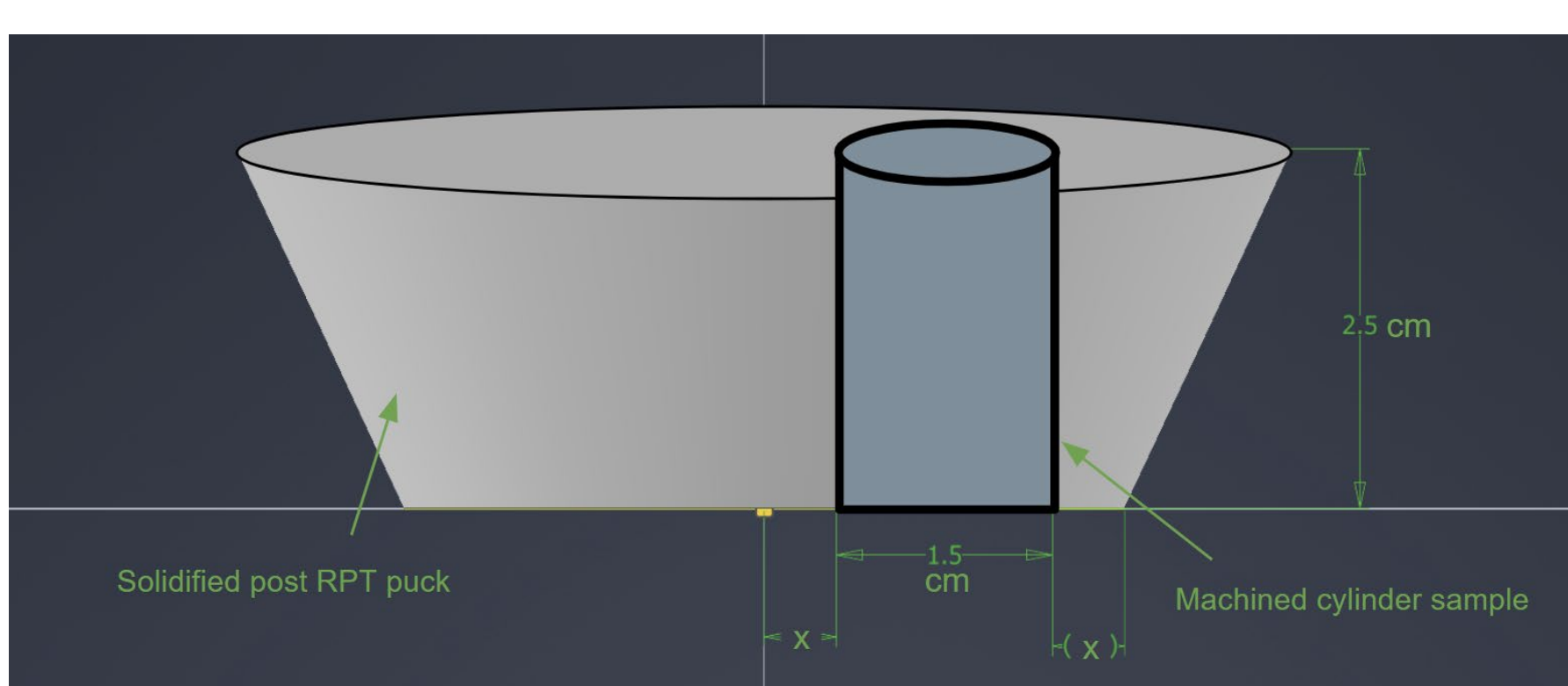
- Optimization of RPT parameters is crucial to ensure hydrogen content is low enough to prevent porosity issues.
- The foundry cannot waste batches due to false negatives or spend too much time on degassing cycles which wastes nitrogen.
- Mercury Marine requires a secondary quality control (QC) instrument to complement their existing QC feedback loop, shown below.



### Experimental Procedure

#### Initial preparation:

- A356.2 samples taken from Mercury Marine's lost foam investment casting line and reduced pressure tested at 25, 27, 28, and 29" Hg RPT vacuum pressure.
- Cylinders machined halfway between center and edge of RPT puck as illustrated below.

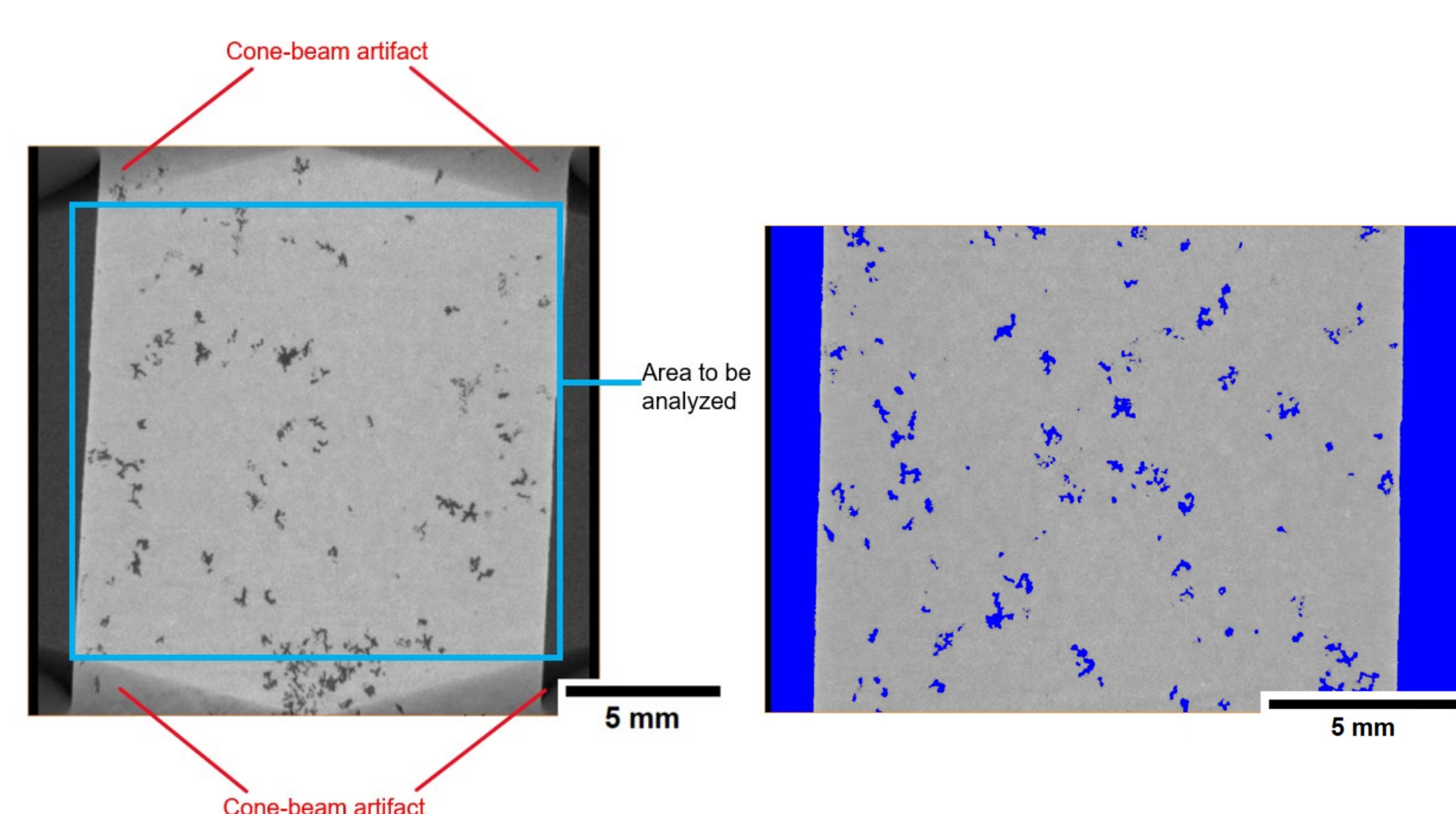


#### Metallography Procedure:

- Samples were sectioned parallel to the infiltration direction and polished to a final polish of 3 μm diamond paste.
- Porosity quantification was performed by applying a greyscale threshold to distinguish pore features from the surrounding matrix.

#### X-Ray Tomography Procedure:

- Full cylindrical samples were scanned at a voxel resolution of 18.1 μm and an X-ray source voltage of 80 kV at 100 W power.
- Three-dimensional image analysis was performed in Avizo 9, followed by the removal of artifacts and application of a greyscale threshold to isolate and quantify internal porosity, with the segmentation approach validated against representative cross-sections.

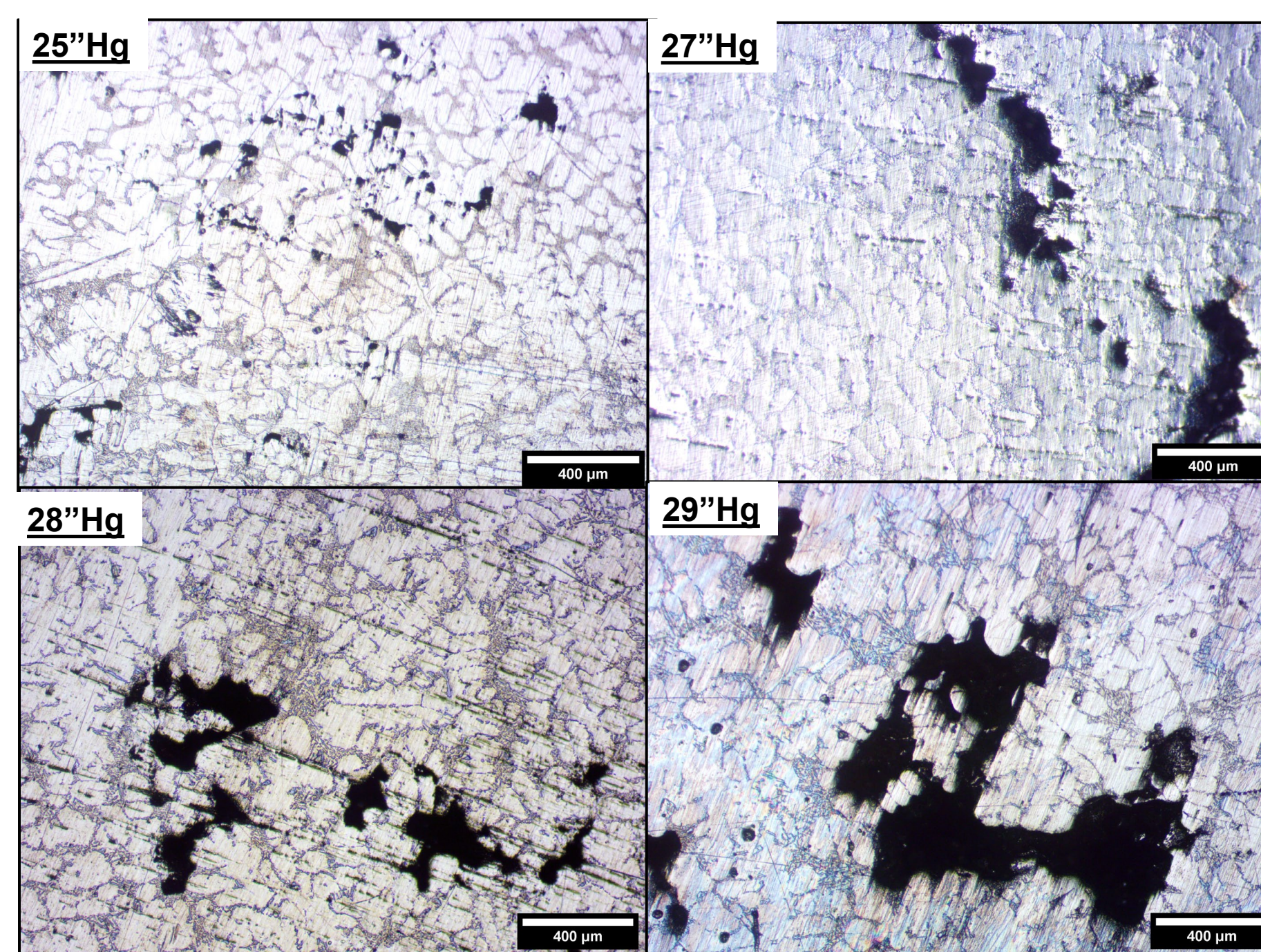


### Experimental Results

#### Optical Microscopy:

- The heat maps below indicate the pore area fractions of the 2D cross-sectioned samples. Partitions were sectioned to be of equal fractions of true sample dimensions, and 2 images were taken per section with image location chosen at random within the subsection bounds and without overlapping.

Pore Area Fraction (%) of Samples	25" Hg			27" Hg			28" Hg			29" Hg		
Top	1.0	0.8	0.4	0.5	3.6	1.2	9.3	5.0	5.3	3.9	4.8	10.6
Middle	1.3	1.2	2.3	0.1	2.6	1.4	2.7	3.2	2.7	1.0	3.4	12.2
Bottom	0.6	0.7	1.0	0.5	0.1	0.1	1.1	2.3	1.8	0.4	2.4	5.4

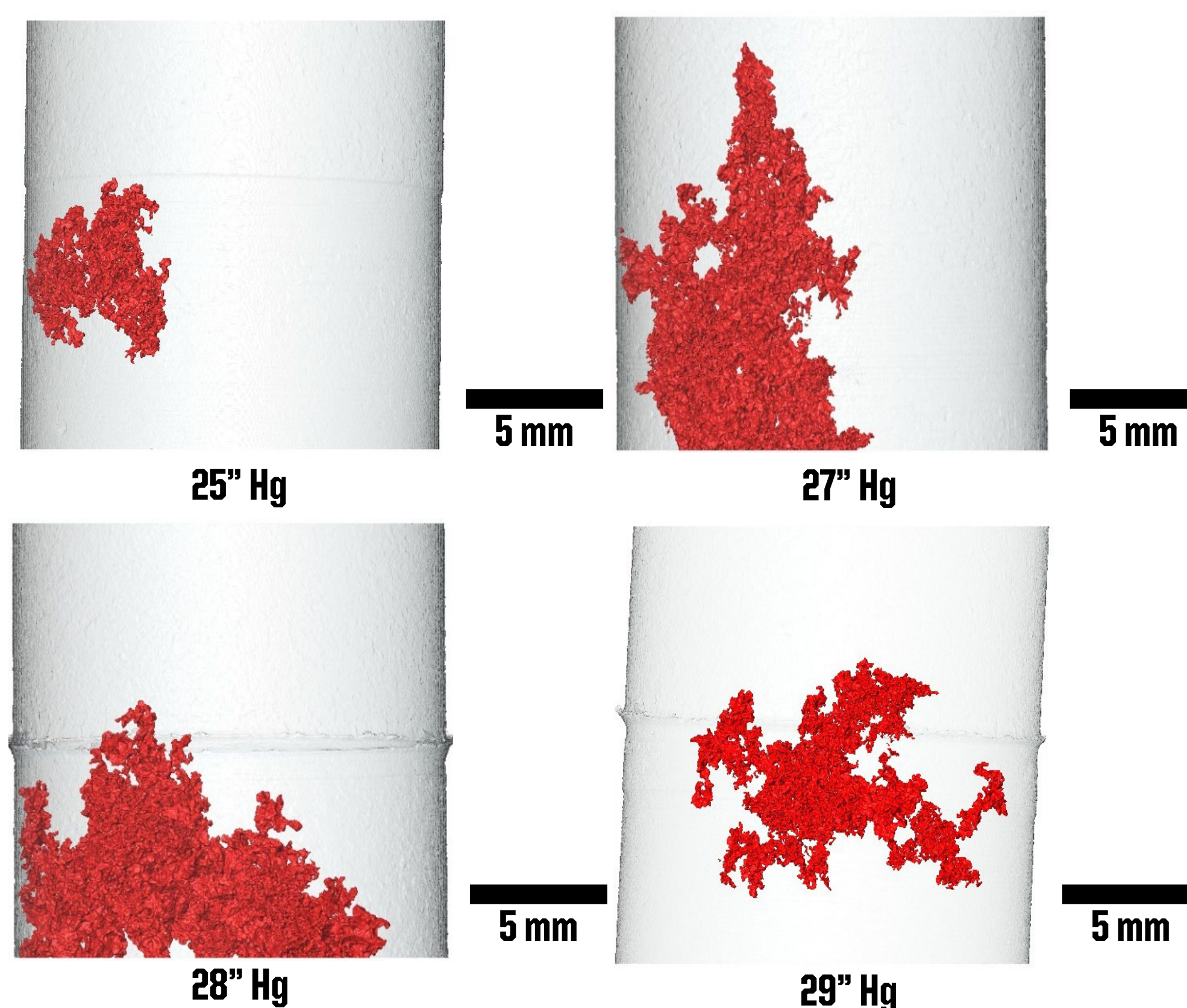


- Images Corresponding to Maximum Pore Area Fraction from Heat Map Imaging for each RPT Cross-Section.

#### X-Ray Tomography:

- XCT analysis of Pore Volume Fraction with calculated density using theoretical A356 density of 2.69 g/cm<sup>3</sup> [1] from XCT analysis compared to experimental Archimedes Density, shown in the table below.

	25" Hg	27" Hg	28" Hg	29" Hg
Pore Volume Fraction (%)	2.9	4.2	4.8	5.3
XCT-Derived Density (g/cm <sup>3</sup> )	2.61	2.58	2.56	2.55
Archimedes Density (g/cm <sup>3</sup> )	2.60	2.60	2.58	2.54

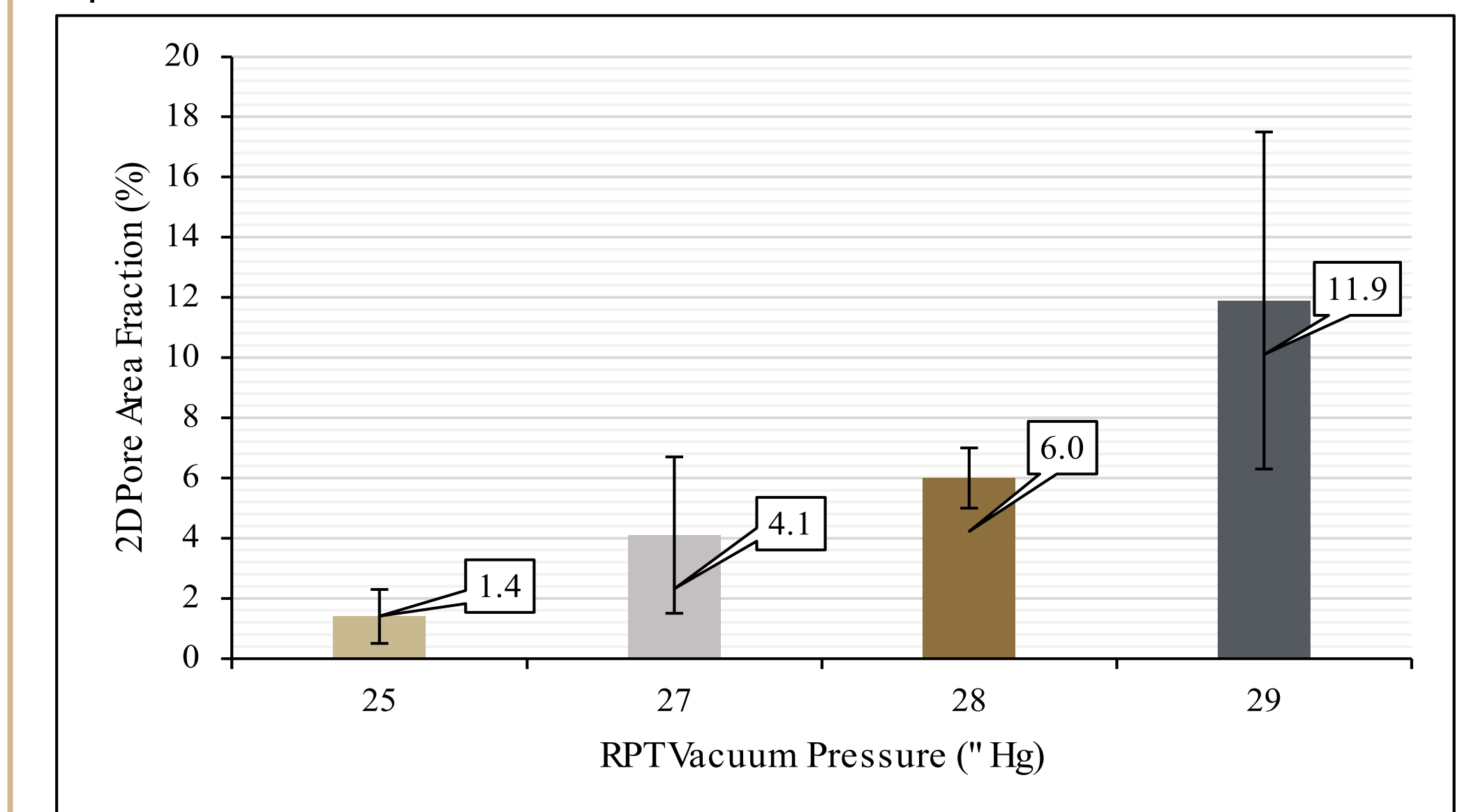


- XCT scans of samples under RPT vacuum pressures of 25", 27", 28", and 29" Hg respectively, with mapping of the largest pore in these samples shown in red.

### Conclusions & Recommendations

#### Conclusions:

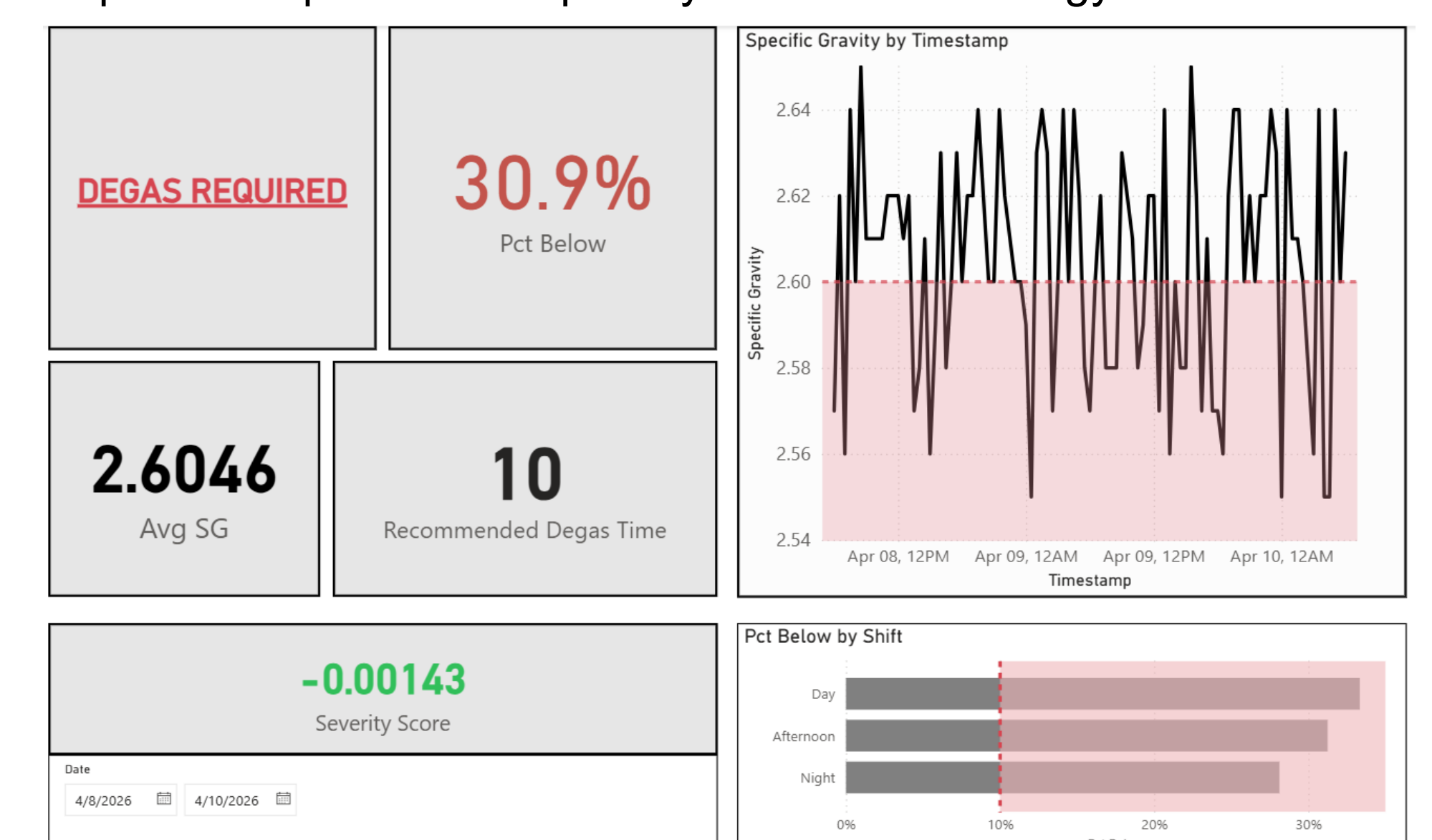
- Based on optical microscopy results, the average pore area fraction percentages for A356.2 samples under the four (4) RPT vacuum pressures were calculated and are shown below.



- Trends in our optical and XCT data show an increase in average pore area fraction and largest pore size with an increase in vacuum pressure, which is supported by literature [2].
- Additional XCT scans of samples' pore networks confirmed a homogenous distribution and structure of pores, asserting that porosity is likely governed by bulk hydrogen content rather than localized defects.
- While our data shows that an RPT pressure vacuum of 29" Hg does exaggerate porosity the most, utilizing this during an in-line test would result in a higher scrap percentage and too low of yield.

#### Recommendations and Final Deliverable

- It is our recommendation that Mercury Marine implement a variable RPT vacuum pressure of either 27" Hg or 28" Hg depending on part criticality. 27" Hg test pressure would be used on parts where larger defects can be tolerated to save on degassing material costs since sensitivity is lower (sample passed specific gravity check of 2.6). On structural/high-stress components, 28" Hg test pressure would be used for its higher hydrogen detection (experimental densities were less than 2.6 and had slightly higher pore area and volume)
- In addition, the team designed a PowerBI dashboard meant for operators to track shift-wide trends in post-RPT specific gravity values.
- This dashboard allows for an optimal degassing cycle time to be calculated which becomes especially helpful on high-humidity days or instances of increased rotor wear
- By adding a secondary QC instrument, this allows for faster decisions to be made regarding degassing cycle times and can lead to higher yields, as well as less porosity-driven delays in the plant's casting schedule.
- Future work includes increasing sample replication and further refining correlations between RPT results and casting porosity to improve the predictive capability of this methodology.



### Acknowledgements & References

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#### References

- Kulkarni, S.G., Meghni, J.V., & Lal, A. (2014). Effect of fly ash hybrid reinforcement on mechanical property and density of aluminum 356 alloy. *Procedia Materials Science*, 5, 746-754.
- Samuel AM, Samuel E, Songmene V, Samuel FH. A Review on Porosity Formation in Aluminum-Based Alloys. *Materials* (Basel).