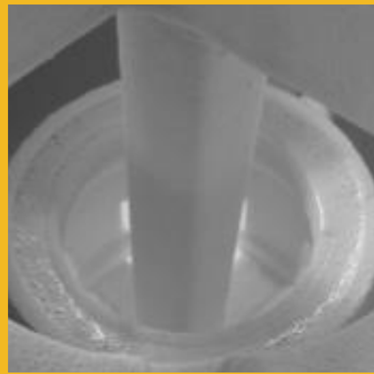




How Process Variables Impact Ceramic Shell Properties and Performance

Dave Berta, Casey Wolfe and Mike Hendricks

Ransom & Randolph

Maumee, Ohio, USA

R&R DENTSPLY

Investing with Innovation™

Agenda

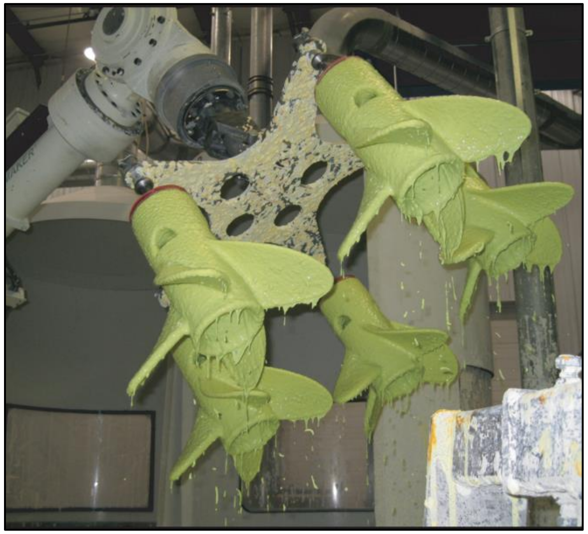
- **Background**
  - Shell system evolution
  - Shell building equipment evolution
- **Purpose of Paper**
- **Design of Experiment (DOE)**
  - Overview
  - Input Variables
  - Output Variables
  - DOE Setup
- **Results and Discussion**
- **Conclusions**
- **Acknowledgements**

Background

- **Shell System Evolution**
  - Alcohol based gave way to water based binder systems
  - Binders and systems specifically for primary and backup applications
  - Polymers
    - Speed up shell drying
    - Increase adhesion
    - Increase green strength
  - Fibers
    - Increase build rate
    - Improve slurry retention on edges
    - Strengthen shells
    - Reduce number of coats required

Background

- **Robot System Evolution**
  - Robot systems have been part of the process from early days
  - Hardware technology of robotic systems has had little evolution – state of the art for some time
  - Evolution has been in the programming of the robots
    - Unique dipping and draining techniques
    - Can be unique per each dip
  - Shell building is a function of the program vs the actual robot.



Purpose of Paper

The purpose of this paper is to utilize a Design of Experiment (DOE) approach to determine what the effects of certain controllable shell building process variables have on the shell properties.

Design Of Experiment
Overview

- DOE Definition – An effort to explain the variation of information under *conditions* that are hypothesized to reflect the variation of *observations*.

- Input Variables – (*conditions*)
  - Viscosity
  - Dwell Time
  - Draining Technique
- Output Variables – (*observations*)
  - Shell Strength
  - Edge Thickness
  - Hot Permeability
  - Round Thickness
  - Spalling Load

Design of Experiment
Input Variables - Viscosity

- Measure of a fluid's resistance to flow
- Quantifies the thickness or thinness of a fluid
- Universally standard test in the industry and well documented
- Viscosity targets are unique for each foundry depending on process, part geometry and experience

Design of Experiment
Input Variables – Dwell Time

- **Defined as the time the shell is in the slurry before removal for draining**
- **Shells will absorb some liquid when dipped (ceramic sponge)**
  - Longer dwell
    - More liquid absorbed from slurry
    - Draining slurry is more uniform in rheology
  - Shorter dwell
    - More liquid is absorbed from the slurry layer being drained
    - Draining slurry can change in rheology as liquid is absorbed by shell
- **Dwell time has a greater impact on backup coats (thicker sponge) than primary coats**

Design of Experiment

Input Variables – Draining Technique

- Purpose of draining is to remove excess slurry from the part, ensure cluster is evenly coated to accept a consistent layer of stucco
- Draining is a combination of manipulation of the cluster and time
- Estimated that over 50% of the slurry that is on a cluster when it exits the slurry tank has to drain off back into the tank
- It will take longer for slurry to drain off of a part in motion than a stagnant part
- Consider a stagnant drain – a "GUSH" – before manipulation of the cluster

Design of Experiment
Output Variables

- These are all well defined, documented and discussed in previous ICI technical papers and not discussed in great detail in presentation
  - Shell Strength
    - MOR
    - AFL (Load Bearing Capacity)
    - Thickness
  - Edge Thickness

Figure 1 – Wax

Figure 2 – Cut Sample

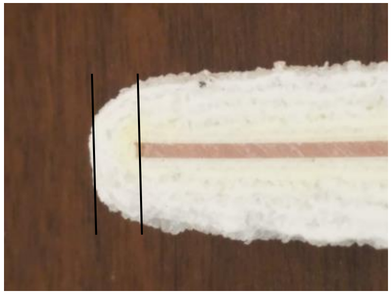


Figure 3 – Edge Measurement

  - Hot Permeability
  - Round Thickness – Permeability ball thickness
    - Better represent production parts
    - 3D vs 2D
  - Spalling Load – Intercoat adhesion measurement

Design of Experiment
DOE Setup

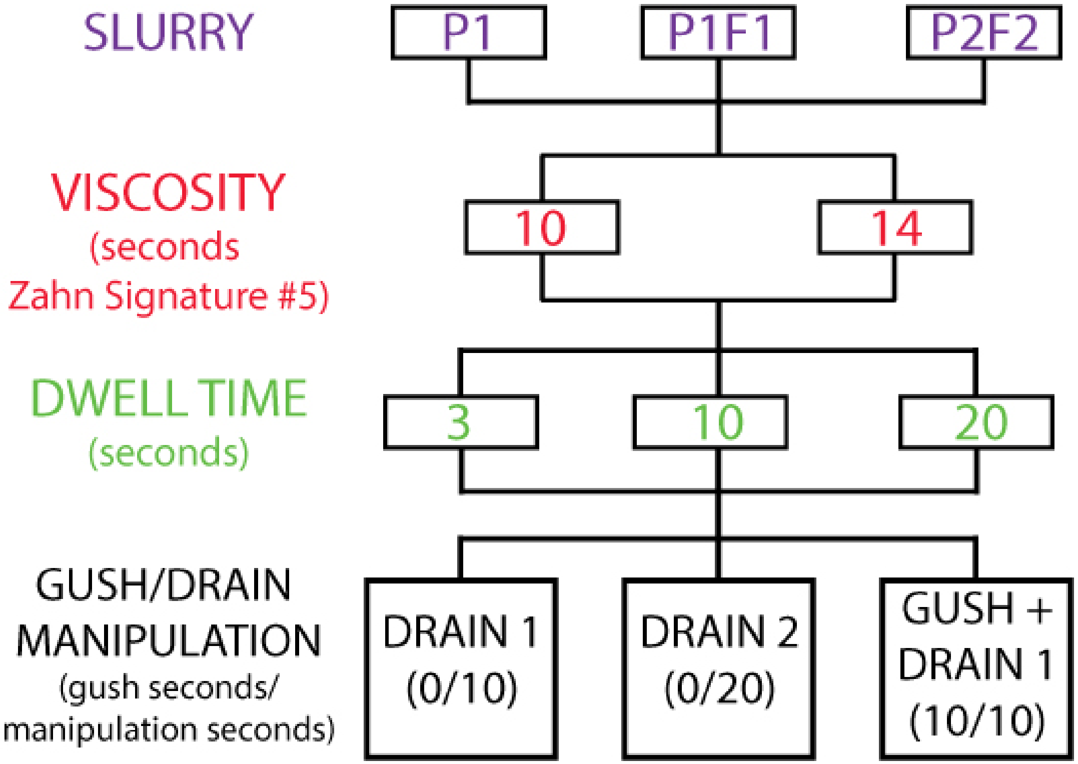
- **Three controlled input variables**
  - Viscosity – 2 levels
  - Dwell time – 3 levels
  - Draining technique – 3 levels
- **Systems tested**

Slurry ID	Binder Component	Refractory
P1	Polymer 1	140 mesh fused silica
P1F1	Polymer 1 with Fiber 1	140 mesh fused silica
P2F2	Polymer 2 with Fiber 2	140 mesh fused silica

Design of Experiment

DOE Setup

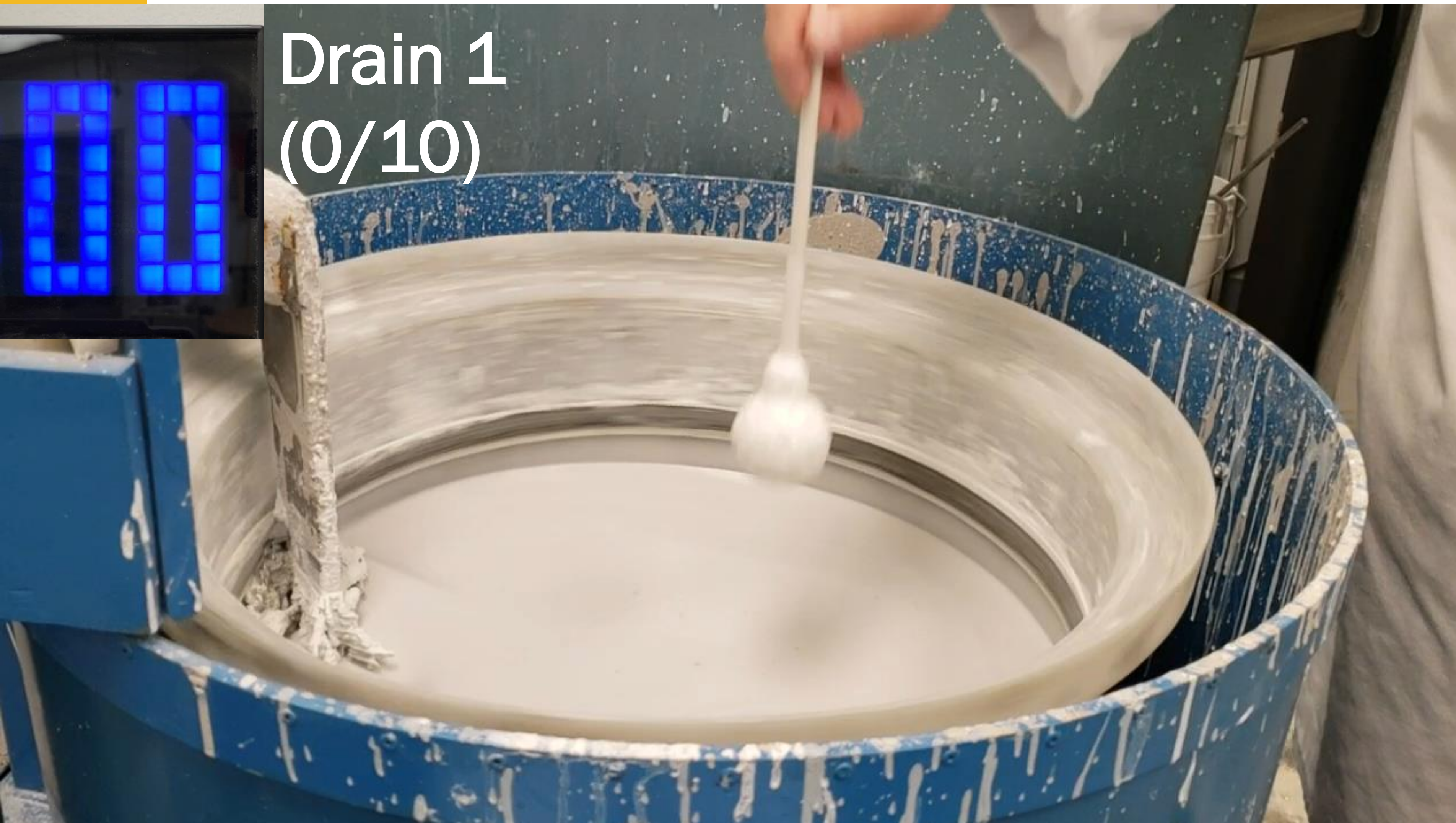
- Used DOE Software to set up testing combinations
- Samples were built using a total of 54 separate combinations of parameters
- The actual 54 combinations are listed in Appendix 1



Design of Experiment
Draining Technique Videos

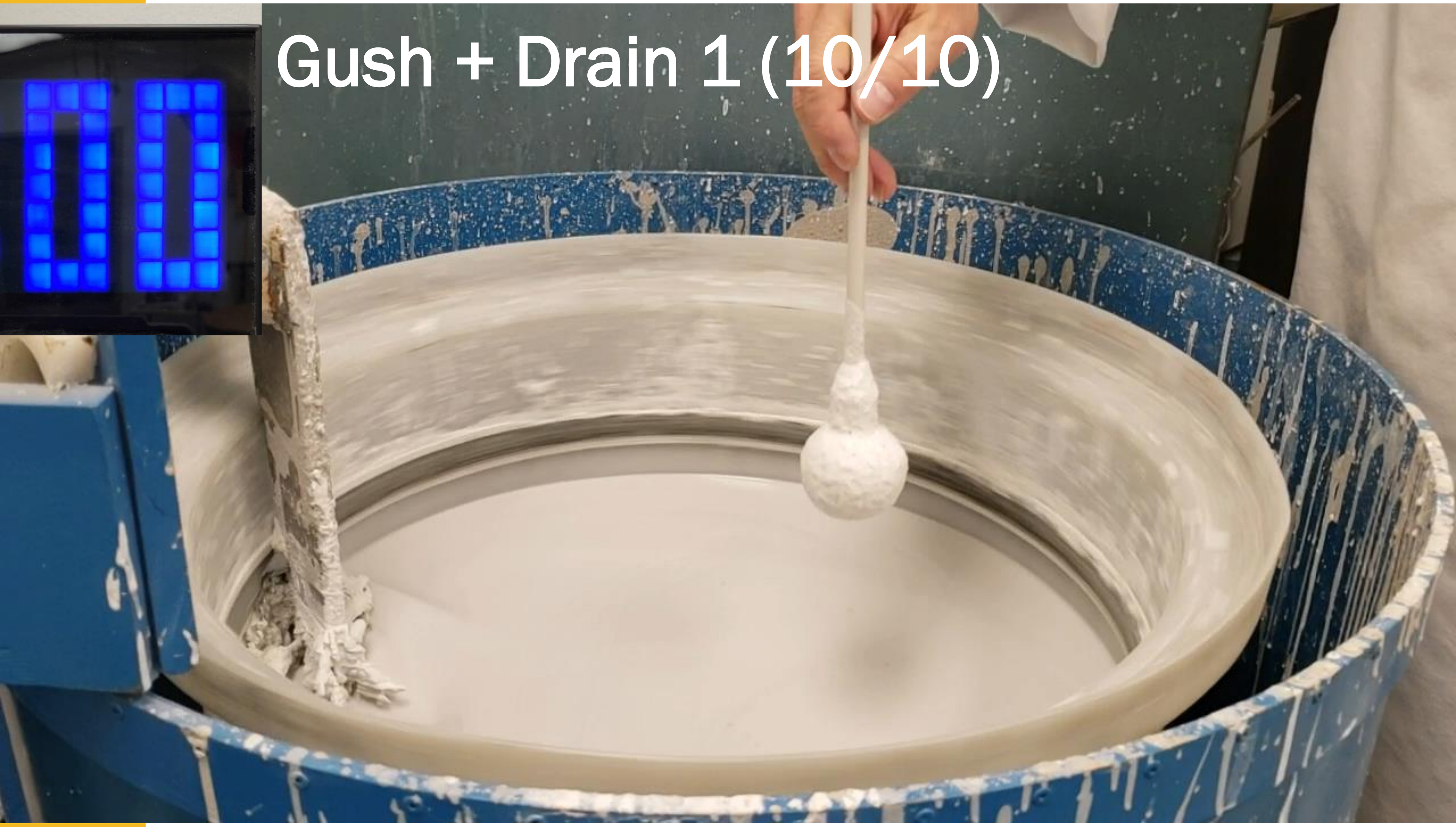
- **Three videos**
  - Permeability balls being dipped
  - 10 Second Dwell Time

- **Drain Techniques**
  - Video 1
  - Video 2
  - Video 3


Drain 1
(0/10)

Drain 2 (0/20)

Gush + Drain 1 (10/10)



Results

Significant Factors Affecting Design Outputs

Factor	MOR (green)	AFL (green)	Thickness (flat)	Thickness (round)	Permeability (hot)	Spalling Load	Edge build (top)	Edge build (bottom)
Backup System	X	X	X	X	X		X	
Viscosity								
Dwell Time		X	X	X			X	
Draining Technique				X				X

X denotes that the Factor has an impact on Output Variable

Results
Backup System

Factor	MOR (green)	AFL (green)	Thickness (flat)	Thickness (round)	Permeability (hot)	Spalling Load	Edge build (top)	Edge build (bottom)
Backup System	X	X	X	X	X		X	

- A change in the backup system produced significant effect on most output variables
- Confirms previous studies that showed that shell systems are designed to maximize shell properties
- This paper is more focused on process variables effects so will not discuss in detail here

Results
Viscosity

Factor	MOR (green)	AFL (green)	Thickness (flat)	Thickness (round)	Permeability (hot)	Spalling Load	Edge build (top)	Edge build (bottom)
Viscosity								

- The 4 second change in viscosities chosen (10 & 14/Zahn 5) did not significantly impact the output variables
- Somewhat surprising result as viscosity is such a key control parameter in the industry
- Could be due to forgiveness of the shell system
- More work could be done to see how large of a viscosity change would make an impact on shell properties

Results

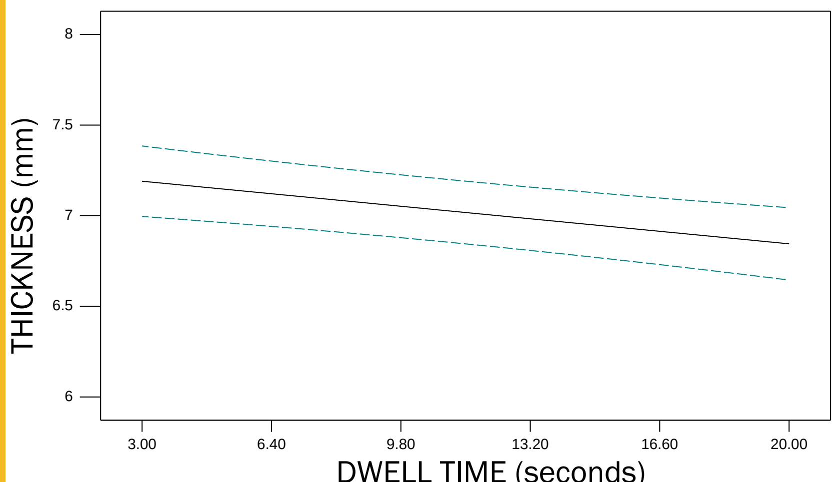
Dwell time & Draining Techniques

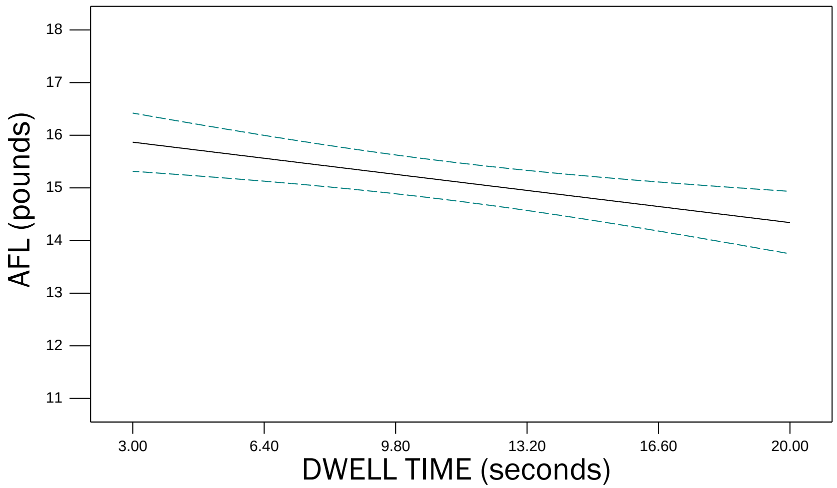
Factor	MOR (green)	AFL (green)	Thickness (flat)	Thickness (round)	Permeability (hot)	Spalling Load	Edge build (top)	Edge build (bottom)
Dwell Time		X	X	X			X	
Draining Technique				X				X

- These input factors do impact the output variables
- Purpose of paper was to look at the effects that controllable process variables had on the shell
- Explore these in more detail

RESULTS
DWELL TIME IMPACT ON THICKNESS AND AFL

- **As dwell time increases, thickness decreases**
  - Confirms the ceramic sponge concept
- **Decrease in thickness, decreases AFL**

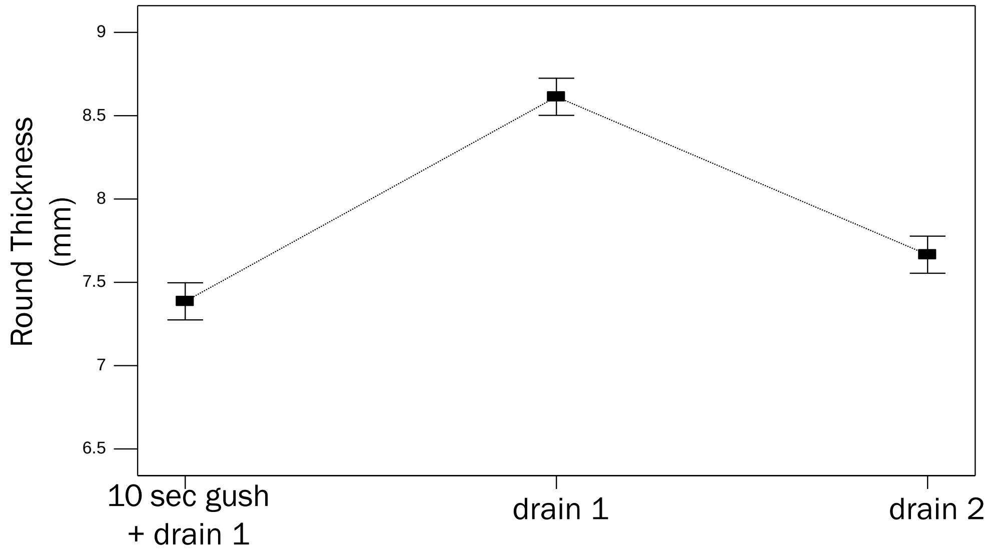




- **Practical Application**
  - Increase dwell time on parts prone to bridging
  - Increase in dwell time could eliminate the need for prewet on some parts

Results
Drain Technique Effect on Round Thickness

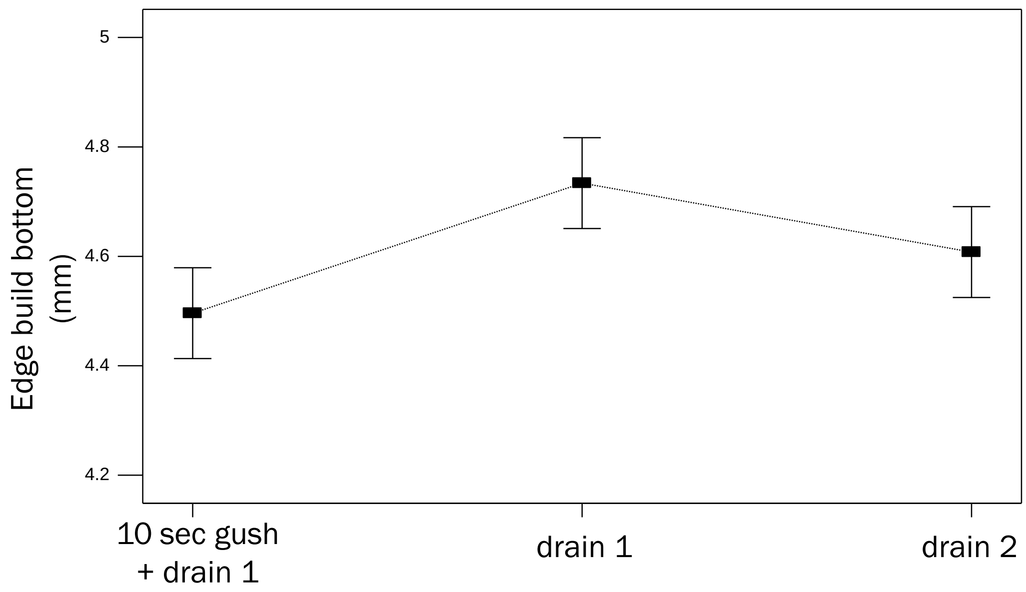
- Drain technique did not impact flat bar thickness
- Round part simulates actual production parts better (3D).
- Shorter drain – thicker
- Gush plus drain – thinner than just drain



- Practical Application
  - Adding a gush speeds cycle especially considering part complexity and multi tree clusters

Results
Drain Technique Effect on Edge Build

- Impact seen only on bottom edge
- Top thickness behaves similarly to the overall shell thickness
- Bottom thickness behaves similarly to the round part thickness
- Stagnant drain results in a thinner shell



Investing with Innovation™

RESULTS

- Foundries can develop individual dipping techniques to optimize shell build and properties
- Where bridging is a concern, implementing a longer dwell and a gush can impact shell build by producing a thinner coat
- Where edge cracking is an issue, a reduction in drain time and dwell time can increase the thickness
- Consider adding extended “gush” when dipping sealcoats to speed time and reduce slurry dripping as unstuccoed parts travel down the conveyor
- Overall dipping and draining cycle can be manipulated to impact throughput
- A longer dwell time and addition of a gush could save production time

Conclusions

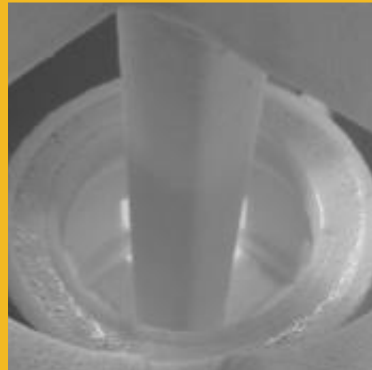
- Foundries can make a real impact on shell build by making simple changes to their dipping and draining techniques
- Different parts will require some experimentation to discover what works best for the foundry, parts being dipped, etc.
- Today's robots allow the user to program multiple configurations
- Investing in personnel training and establishing robot cycles specific to different part configurations would allow the foundry to optimize dip, drain & dwell patterns; allowing for more efficient production and improving shell casting performance

Future Work Opportunities

- **Results of this investigation were not groundbreaking**
  - Simple test pieces and limited manipulation capabilities
- **Results do indicate that more work could be done to truly understand the overall impact the process variables have on shell properties and performance**
- **Future work with a foundry could look at impact on actual production parts**
  - Shell build time
  - Dewax cracking
  - Shell weight
  - Knockout
  - Etc.
- **Could be an opportunity for future collaboration with an interested foundry**

Acknowledgements

- We would like to thank the following
  - Sam Jeffrey, R&R Product and Application Technician, for all of his work on setting up and testing samples
  - Alisa Rawski and Marti Hunyor in the R&R Marketing Group for their work on completion of the written paper and presentation


QUESTIONS?

Thank You!