Analysis of the Heating of Proppants in a 'Pusher' Furnace

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Introduction

- Proppants use is increasing due to widespread use in the oil and gas extraction industry
- The proppants are designed to be conveyed with the carrier fluid and support the openings
- To achieve the high strength, and larger facture piece, a post heat treatment processes is often required.
- The uniformity of the temperature as well as the time at temperature can affect the final distribution of material properties.

Properties of Proppant Powder Beds

- Proppants typically are designed for a narrow range in particles size.
- Final proppant mixtures of selected particles size mixtures are typical
- Koseski* provided extensive research on the effects mechanical properties of glass ceramics with different time-temperature-transformation
  - Heat treatment of the andesite glass-ceramic proppants to form a controlled crystallization / devitrification which affect the material strength and size of fracture particles if the material fails
  - Residence time at temperature directly affected mechanical properties
  - Distribution of residence time within a bed of material would produce a range of material properties
  - KEY feature: this material can be "Over-Cooked"

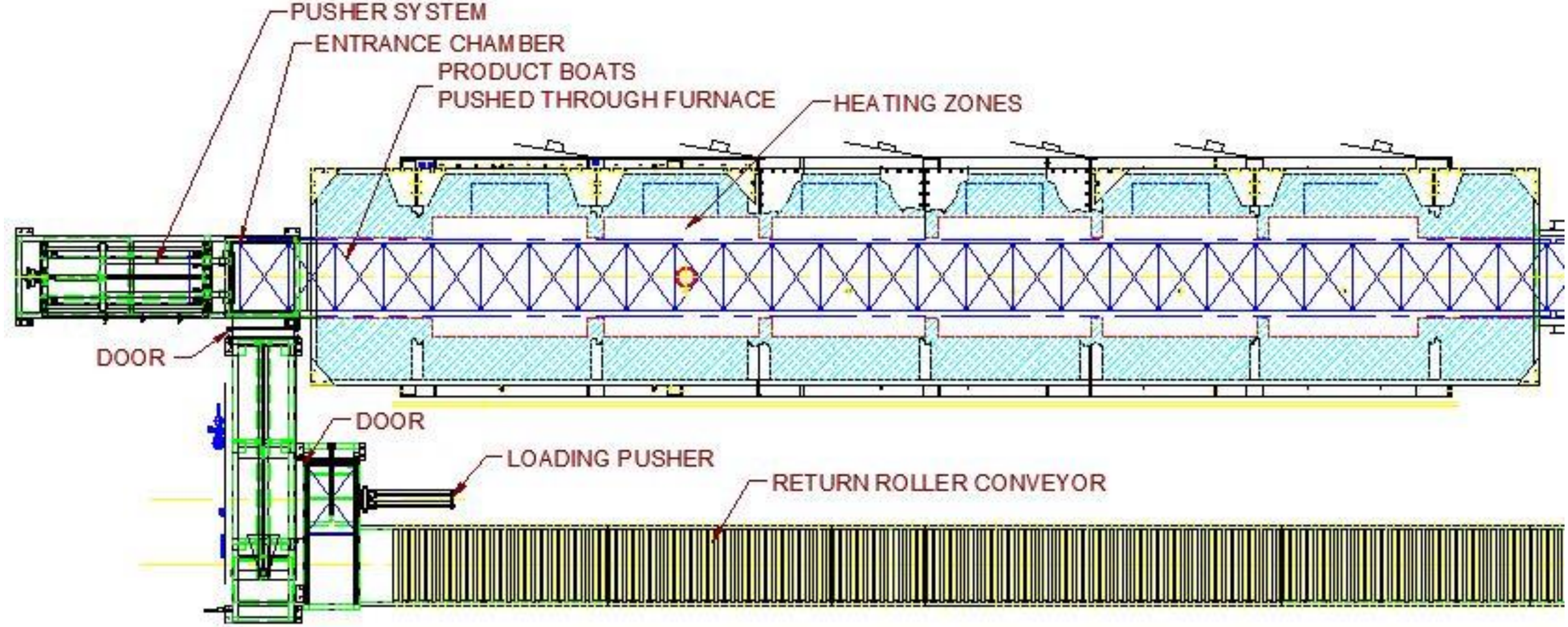
* Koseski "Manipulation of microstructure, phase evolution and mechanical properties by devitrification of andesite for use as proppant" PhD Dissertation. State College, PA, 2008.

Goals of Analysis

- Goals of heating of glass – ceramic proppants powders in a pusher furnace
  - Estimation of range of powder bed properties
    - Predicted with minimal known properties
  - Predict range of time to temperature for
    - Differing bed geometries
    - Range of powder density and particle sizes

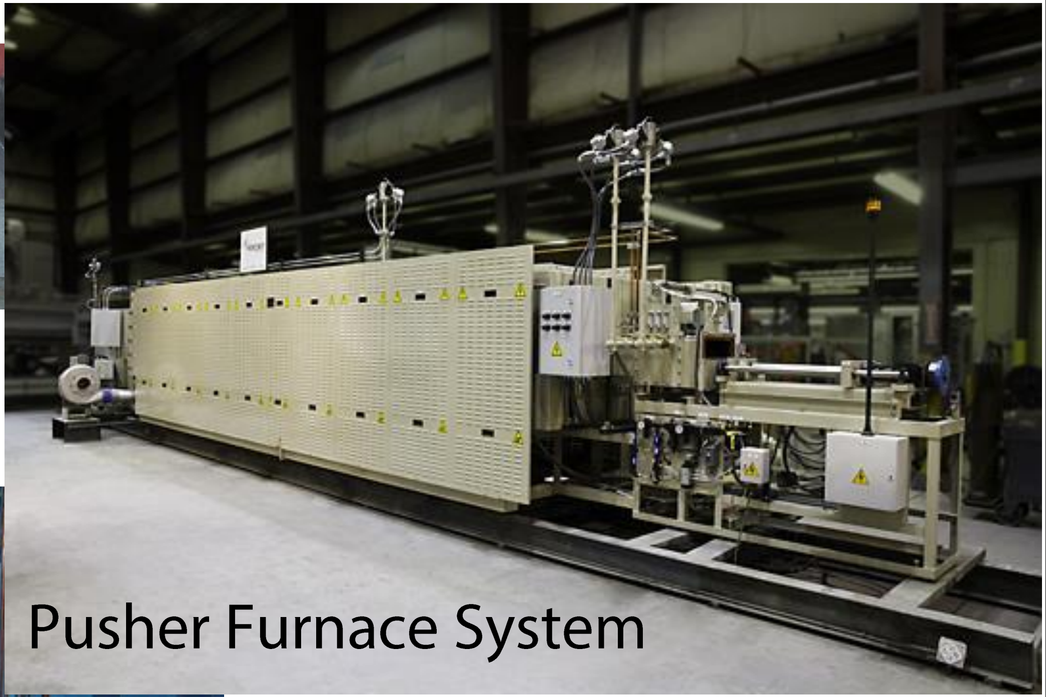
What is a "Pusher" Furnace?

A "pusher" furnace is a continuous furnace in which product containers (boats) are transported through the furnace by pushing the boats .

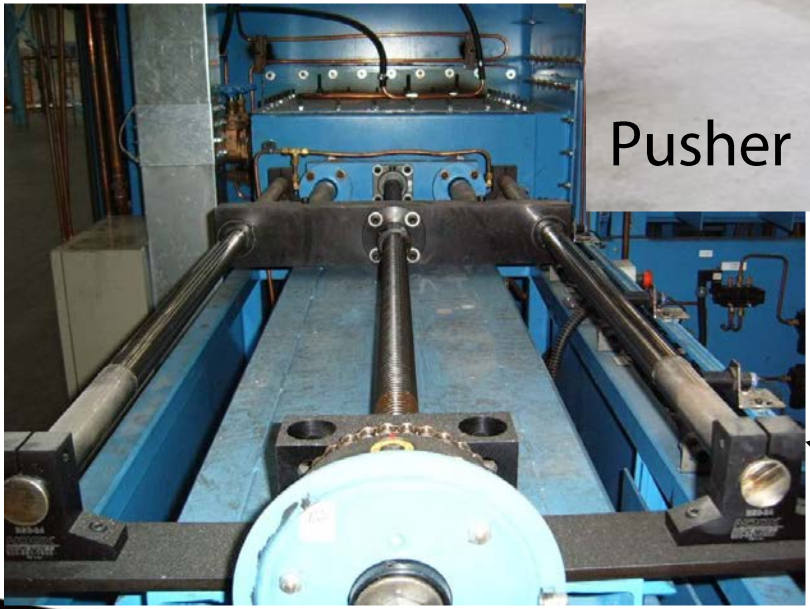


What is a "Pusher" Furnace?

Product Boats



Pusher Furnace System



Main Pusher

Model of Thermal Conductivity of Powder

- The equations presented in Sih-Barlow were used for the thermal conductivity prediction.
- Model considered for spherical particles.
- Significant affect of gas properties and particles sizes on conductivity

$$\frac{k}{k_g} = \left(1 - \sqrt{1-\varepsilon}\right)\left(1 + \frac{\varepsilon k_R}{k_g}\right) +$$

Free Fluid

Reduced Model for spherical particles

$$\sqrt{1-\varepsilon}\left[\frac{2}{1-\frac{k_g}{k_s}}\left(\frac{1}{\left(1-\frac{k_g}{k_s}\right)}\ln\frac{k_g}{k_s} - 1\right) + \frac{k_R}{k_g}\right]$$

Core Heat Transfer

$k_R = 4F d_p \sigma T^3$ (k_R conductivity by thermal radiation)
d_p = Particle diameter
k = Effective thermal conductivity of the powder bed
k_g = Thermal conductivity of the gas phase
k_s = Thermal conductivity of the solid phase
ε = Porosity of the powder bed

How to Apply Model with Limited Material Data

- There is some minimal set of parameters required
- These include:
  - Bulk density
  - Particle composition
  - Particle size
  - Pure component properties (specific heat, density, conductivity)

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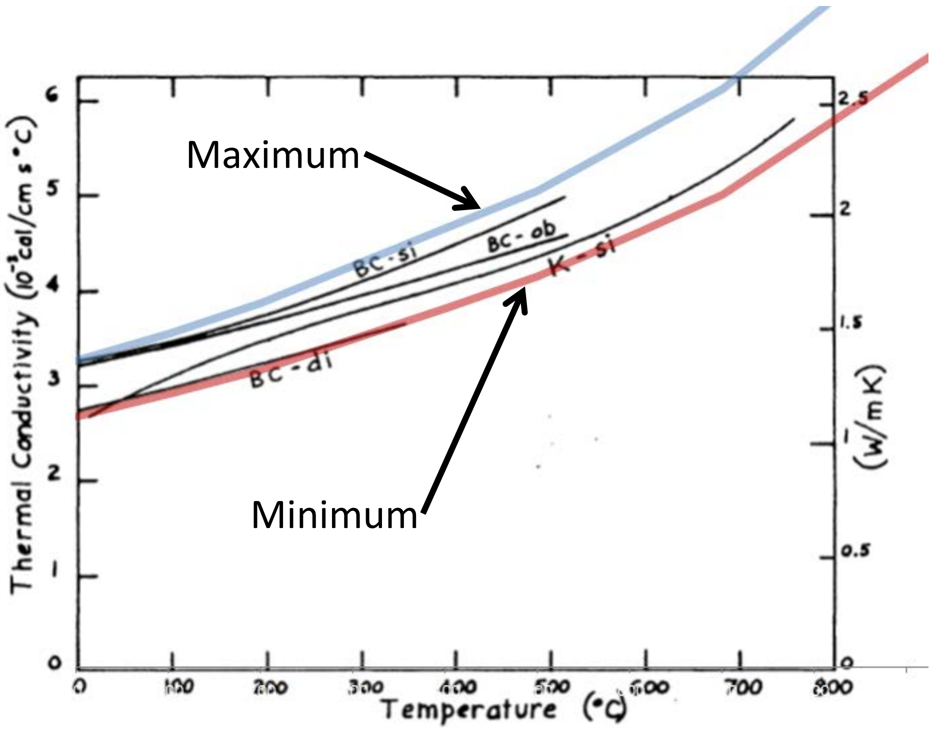
Properties of Andesite Glass-Ceramic Proppants Powder

- The particle size range and porosity of the bed are important factors in the calculations for thermal conductivity and thermal diffusivity
- Particle sizes range from 100 to 2400 μm
- Particle density of 2.5 g/cc used for all calculations
- Porosity for spheres within a poured bed is ~0.4

Thermal Conductivity of Andesite Glass-Ceramic

- Thermal conductivity for Andesite Glass is dependent on the specific composition of the glass.
- The curves from "THERMAL PROPERTIES OF ROCKS" By Robertson is used to bound a range of thermal conductivities of the material
- The range of material properties are used to create a high / low range of predicted bed properties

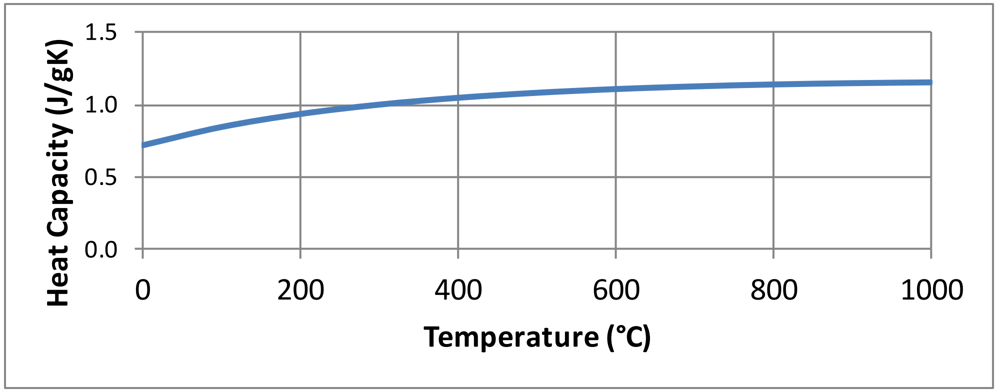


Specific Heat of Andesite Glass

- Neuville* provides a methodology and useful coefficients for calculating the specific heats of andesite glass. The formula is given below
- $C_p = a + bT + cT^{-2} + dT^{-0.5} \quad \left(\frac{J}{gfw\ K}\right)$

a	b	c	d
140.3	-0.014	637000	-1594

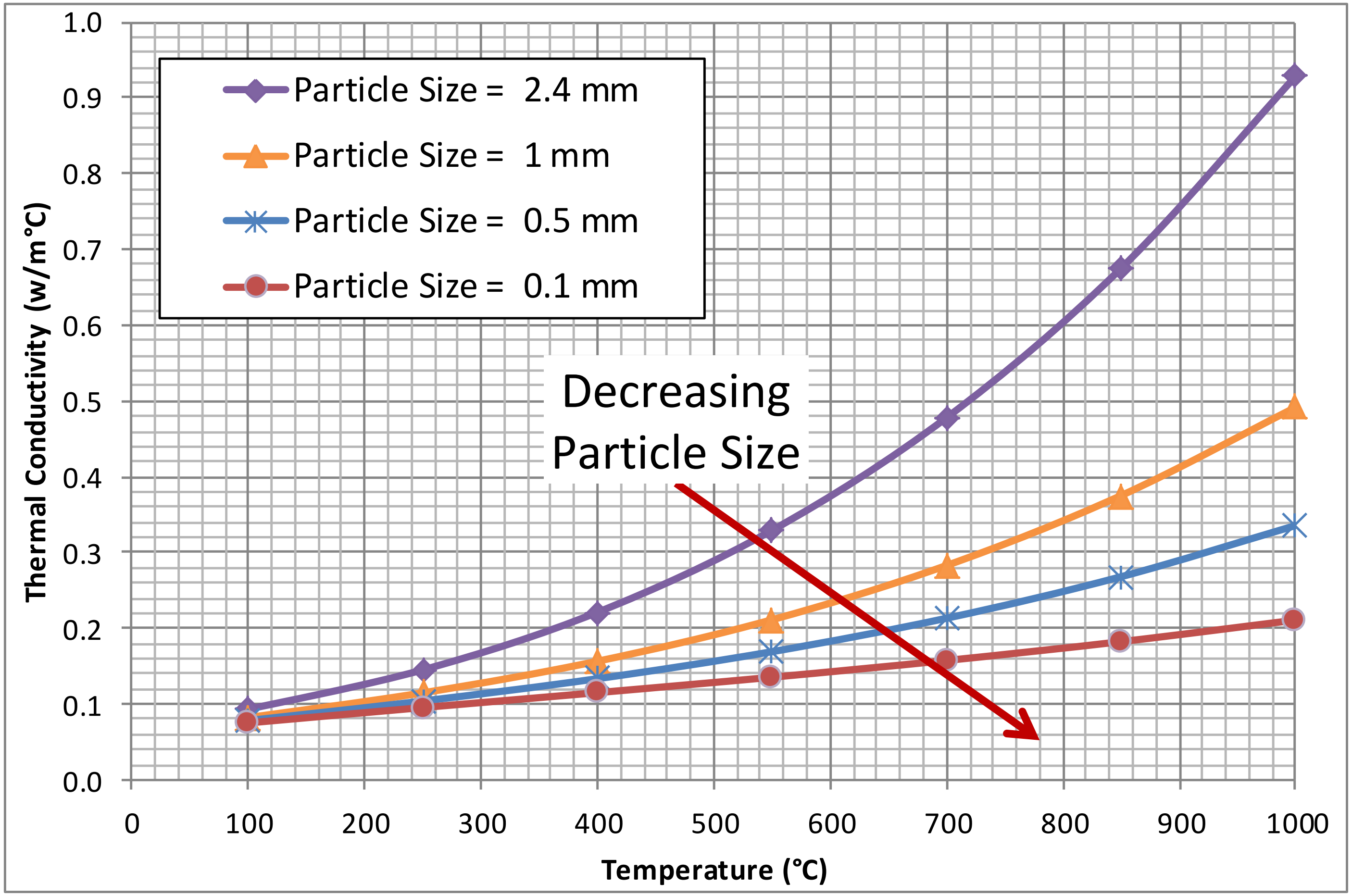
- gfw = 67.5 g/mole for Andesite Glass



* Neuville - Thermodynamic and rheological properties of rhyolite and andesite melts,1993

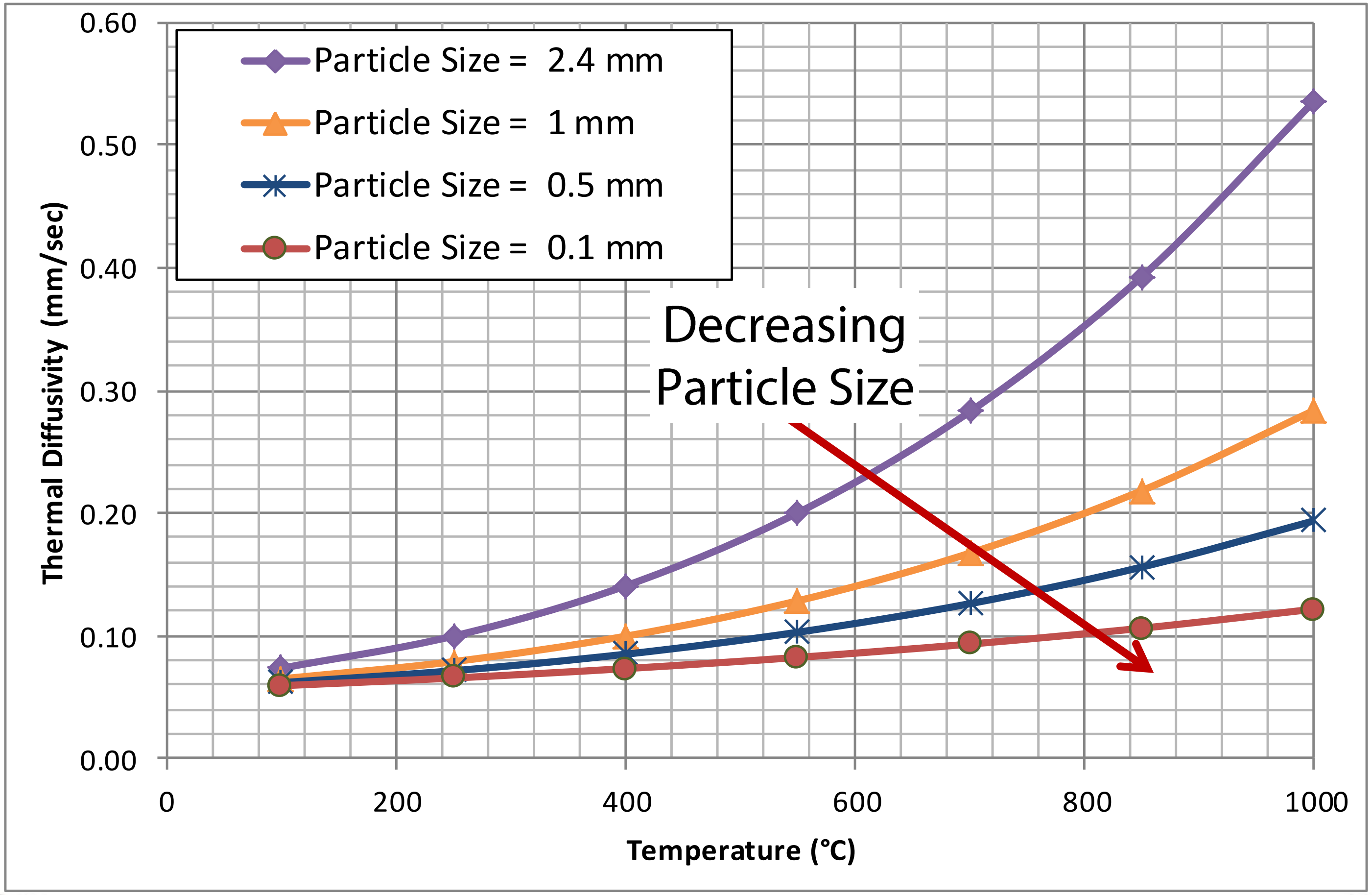
Thermal Conductivity Predictions for Proppant Bed

Thermal Conductivity a strong function of particle size and temperature



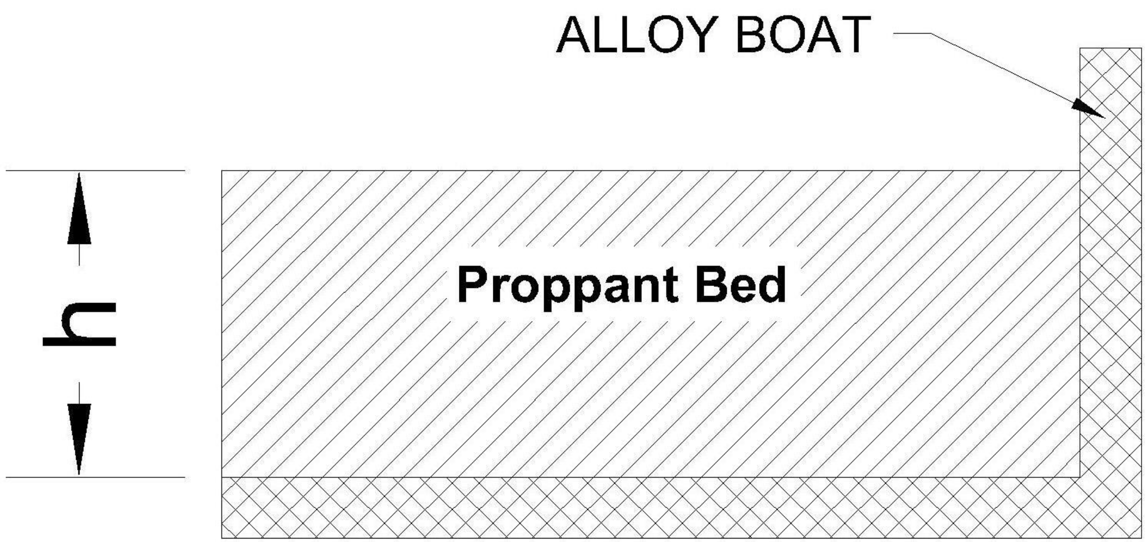
$\alpha = k_s/\rho C_p$
Powder Bed Thermal Diffusivity Predictions

- Minor variations of thermal diffusivity with the variations in thermal conductivity



Pusher Furnace Powder Bed Configurations

- Rectangular bed geometries selected
- Alloy considered for boat material
- Symmetric boundary condition in at center of boat



Target Temperature Uniformity
Selected Parameters

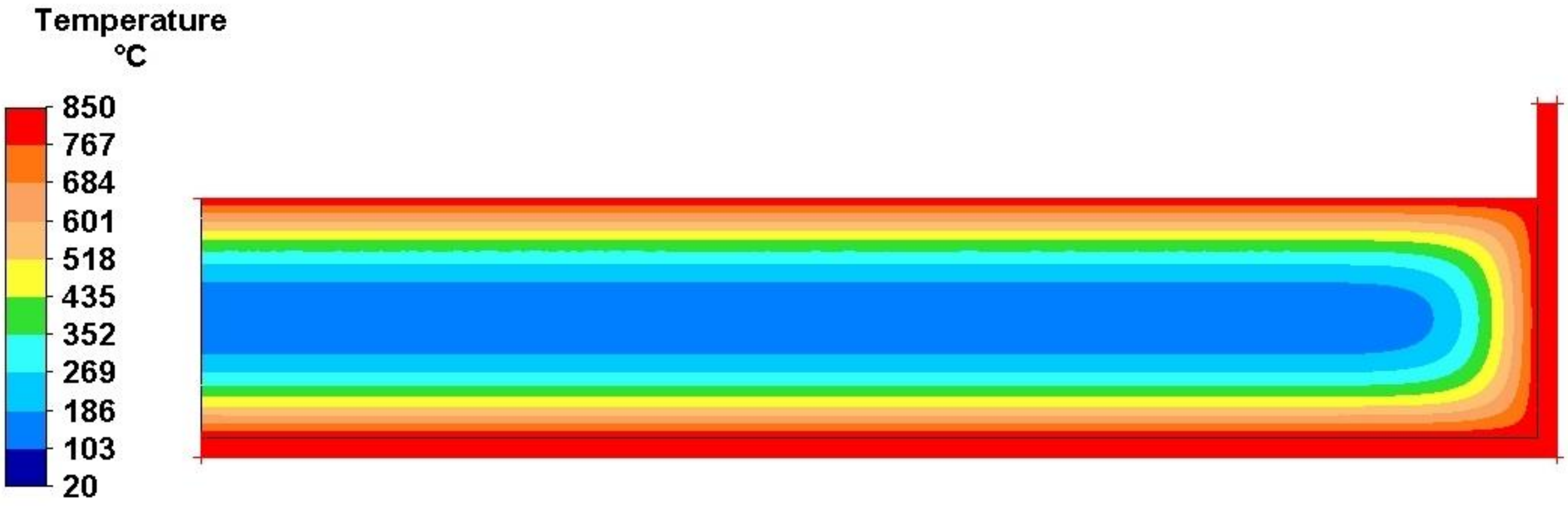
- Koseski* provided extensive research on the effects mechanical properties of andesite glass-ceramics proppants to define an optimal time - temperature window

Temperature	Hold Time
850°C	0.1 hr to 1 hr
900°C	0.1 hr to < 1hr
950°C	0.1 hr

- Bed material will have a distribution of time temperature.
- 850°C selected for analysis
- Boundary Condition Ramp to 850°C set at 10 minutes
- Bed depths: 25 mm and 50 mm

Results of Pusher Furnace Bed

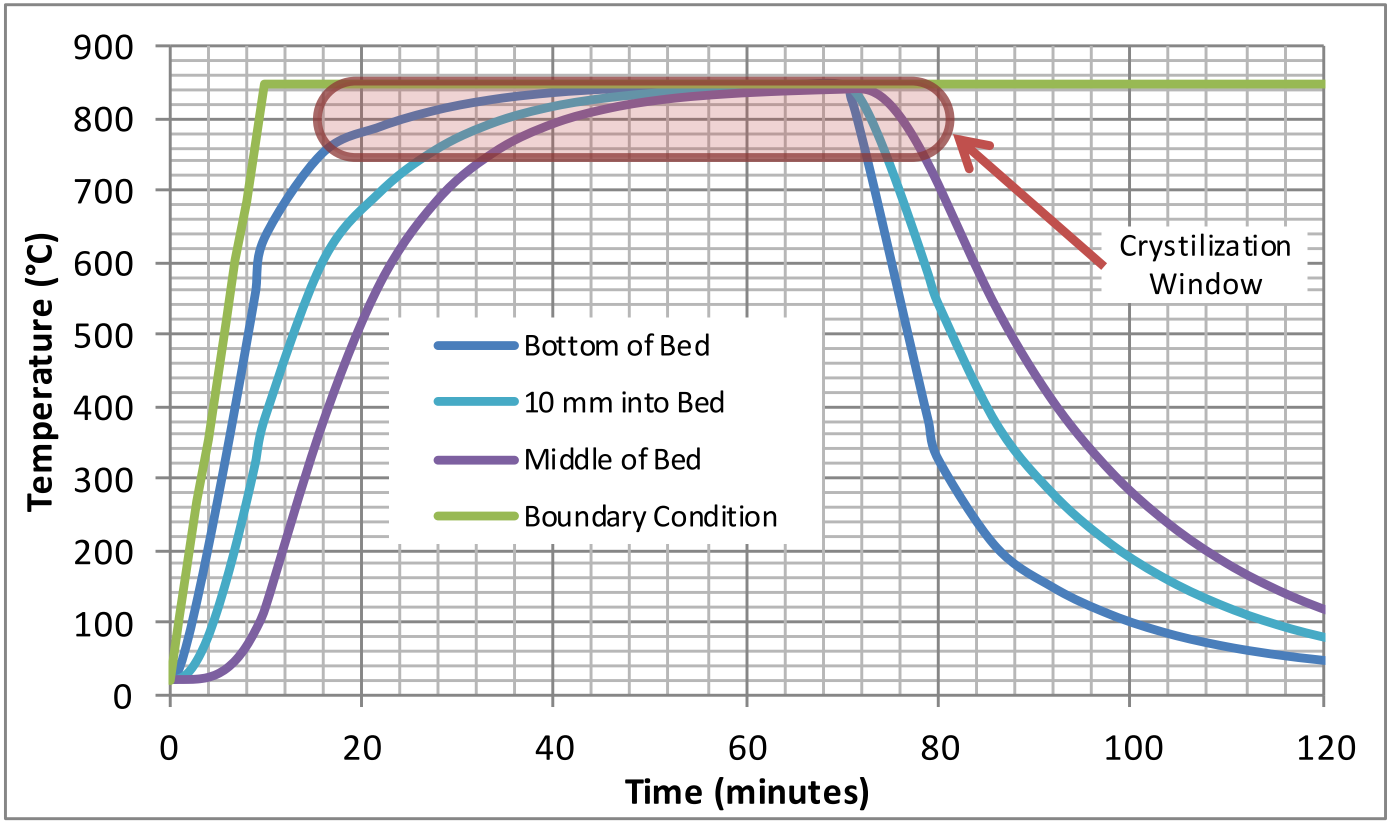
- Alloy boat is highly conductive – reaches process temperature quickly
- Powder bed is insulating and requires more time for the center to reach temperature



0.1 mm Diameter Proppant
Rectangular Bed with 25mm Bed Depth

Crystallization rate significant between 750 and 850°C

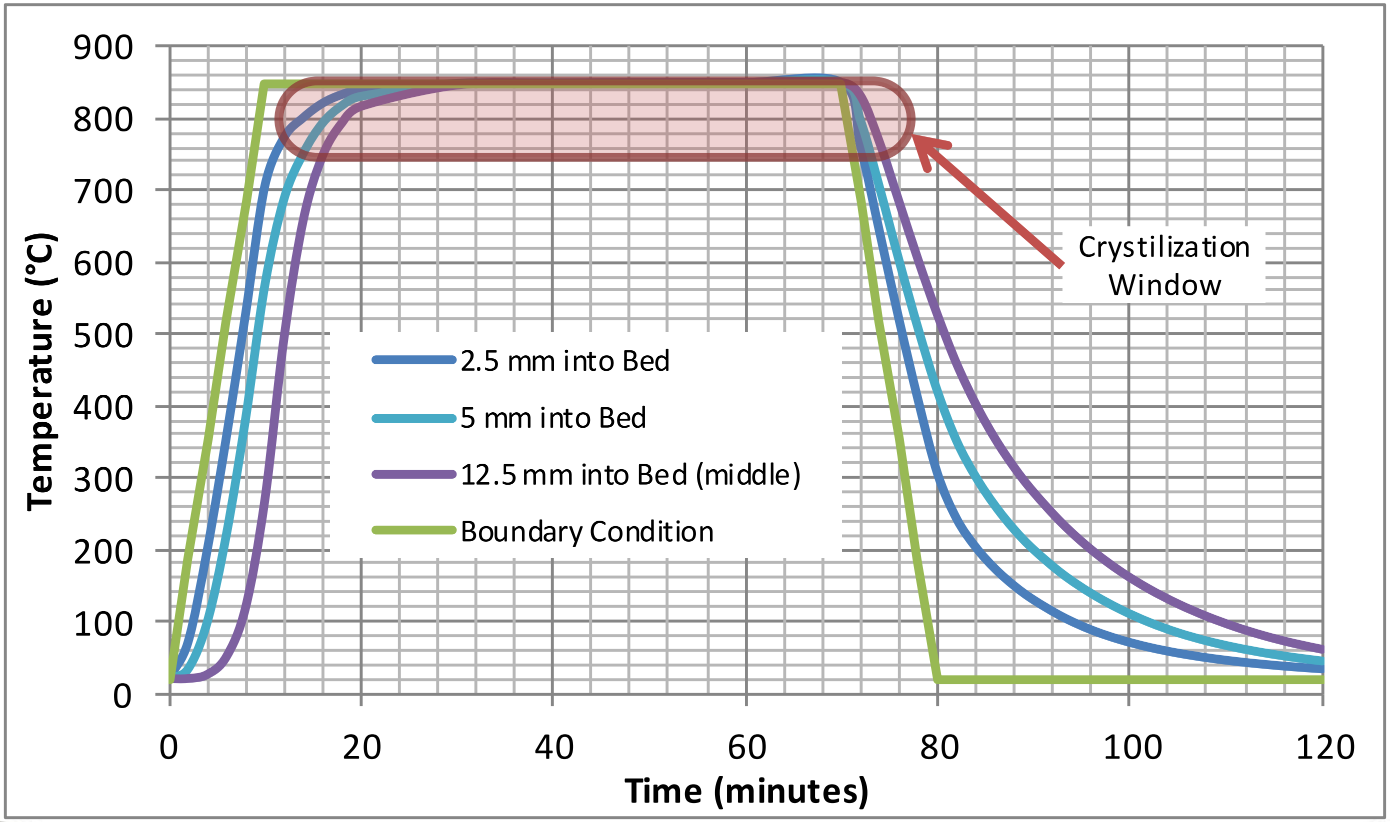
Longest Time above 750°C	62 min
Shortest Time above 750°C	44 min



2.4 mm Diameter Proppant Rectangular Bed with 25mm Bed Depth

Crystallization rate significant between 750 and 850°C

Longest Time above 750°C	60 min
Shortest Time above 750°C	58 min



Rectangular Bed with 25 and 50 mm Bed Depth

- Residence time between 750 and 850°C
- 25 mm bed depth provides between 5 and 15 minute variation between the different particle size beds
- 50 mm bed center did not reach 750C for 0.1 and 0.5 mm particles.
- Large time variation for 50 mm bed for 1 and 2 mm particles

Min / Max Residence Time Above 750°C				
	25 mm Bed Depth		50 mm Bed Depth	
Particle Size	Minimum Time	Maximum Time	Minimum Time	Maximum Time
0.1 mm	43	62	0*	62
0.5 mm	48	62	0*	62
1.0 mm	51	62	10	62
2.4 mm	57	62	35	62

* Center Did not reach 750°C

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Results for Rectangular Configuration

- Bed depth is controlling parameter
- Limit of bed depth for minimal variations in proppant time at temperature distribution.
- Smaller process time window required shallower bed
- The lower conductivity beds require more time to temperature
- Increasing width while managing the bed height can optimize the throughput

Conclusions

- Model predictions provided time to temperature design ranges
  - Predict usable bed depths to meet process windows
- Minimal material properties can be used
  - To predict bed properties
  - To estimate process design parameters

Thank you for your time!

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