Solid Propellant Additive Manufacturing

Printing Solid Rocket Motors

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Nick Lindholm, Caleb Lipscomb, Ryan Niedzinski, & Jon Sobol

Agenda

• Project Purpose and Objectives	->	Ryan
• Design Description	->	Jon
• Test Overview	->	Erick
• Test Results		
○ Powder Bed	->	Nick
○ Sintering Results	->	Caleb, Tony
• Systems Engineering	->	Max
• Project Management	->	Cameron

Project Purpose and Objectives

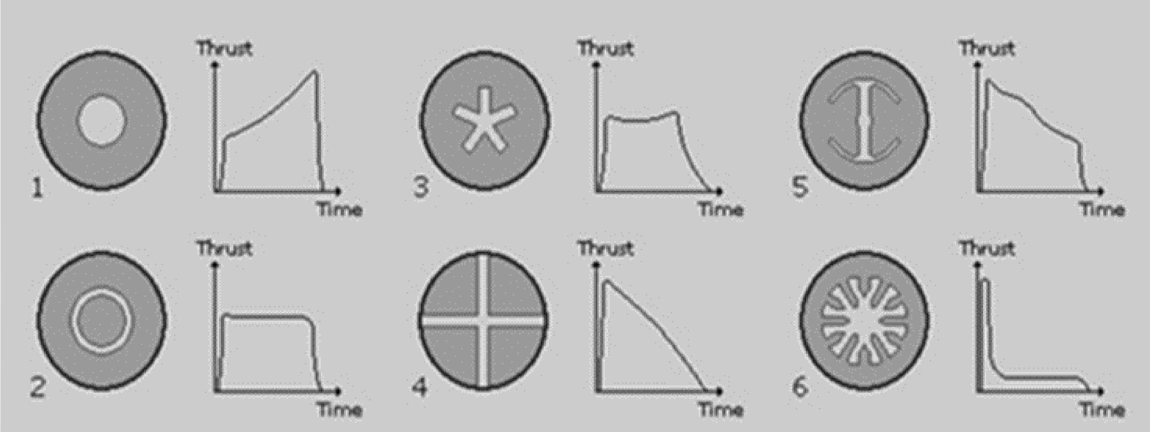
Project Statement

Design and integrate an additive manufacturing system such that it will print sucrose-potassium nitrate solid rocket propellant and compare the mechanical characteristics of the printed propellants to those manufactured by the traditional casting method.

Field of Application

Solid Rocket Motors

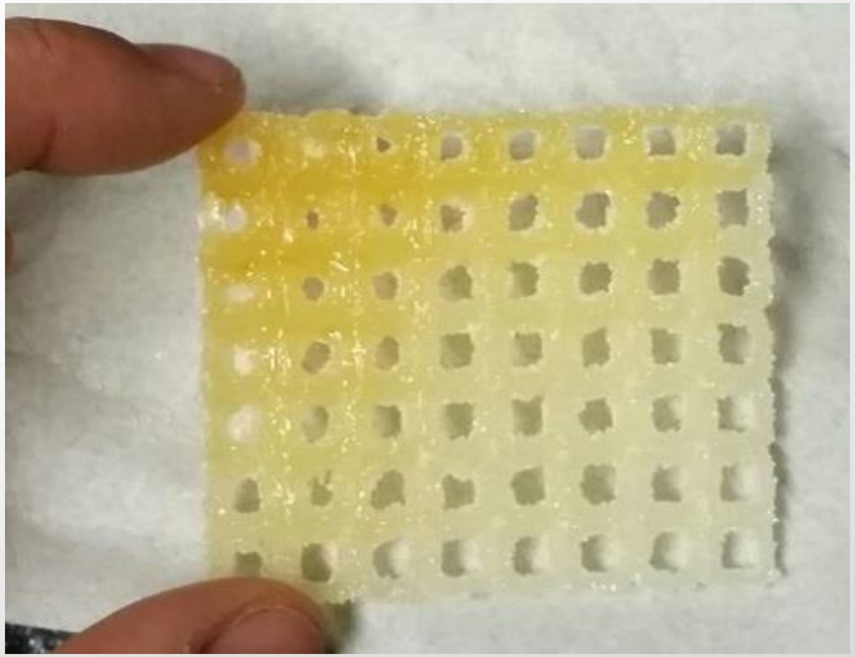
- Cylinders of solid rocket propellant (fuel + oxidizer) with different cross sectional grain shapes
- Grain shape determines thrust profile through available surface area to burn
    - Higher surface area -> Higher thrust
- Normally made by casting
    - Propellant cures in a cylindrical tube
    - Desired grain shape is bored through the middle



Example Grain Shapes and Thrust Profiles[1]

Casting vs. Additive Manufacturing

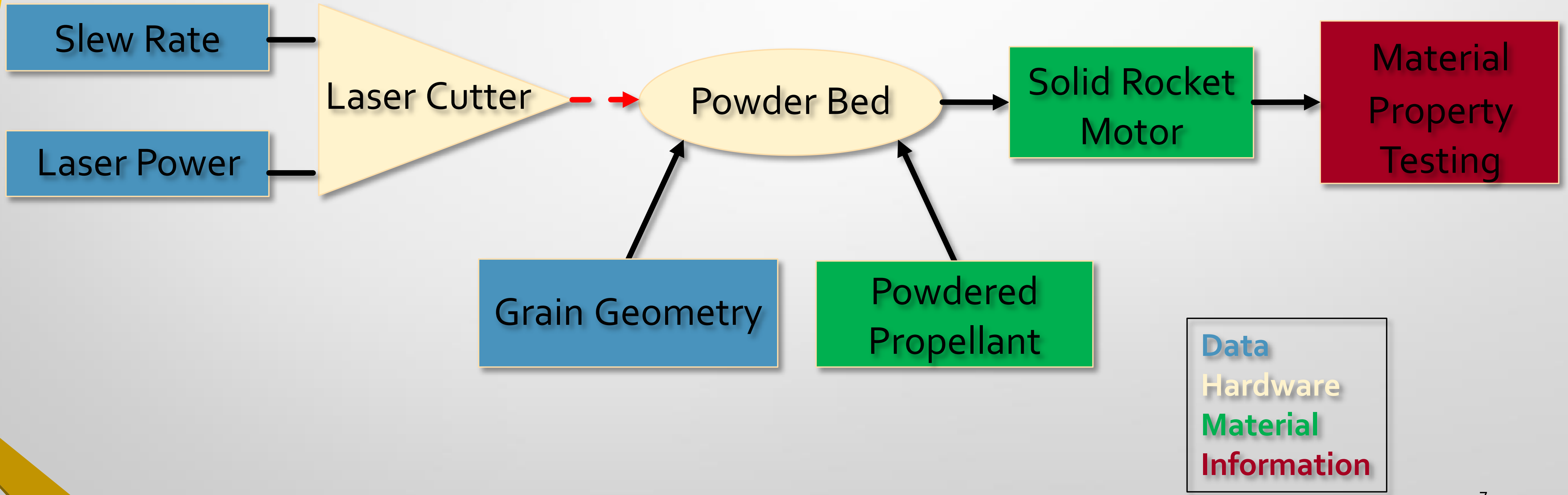
- Problems with Traditional Casting:
  - Limited number of grain shapes
  - Air bubbles in cast
  - Nonuniform setting
- Impact of 3D Printing on SRM Manufacturing:
  - Produce complex grain shapes and new thrust profiles
  - No need to manufacture a different cast for each design
  - Consistent material properties in each layer



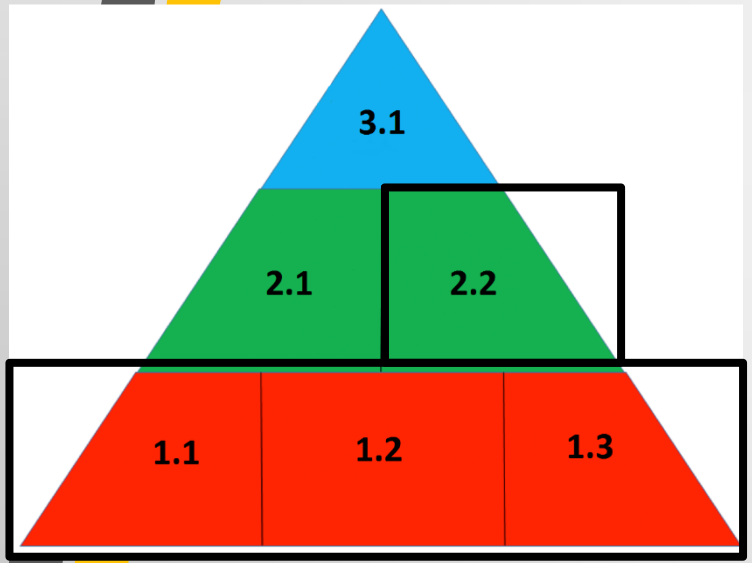
Example complex shape produced from SLS printing

Project Concept of Operations

Sinter multiple layers of Sucrose/KNO_3 powder using SLS



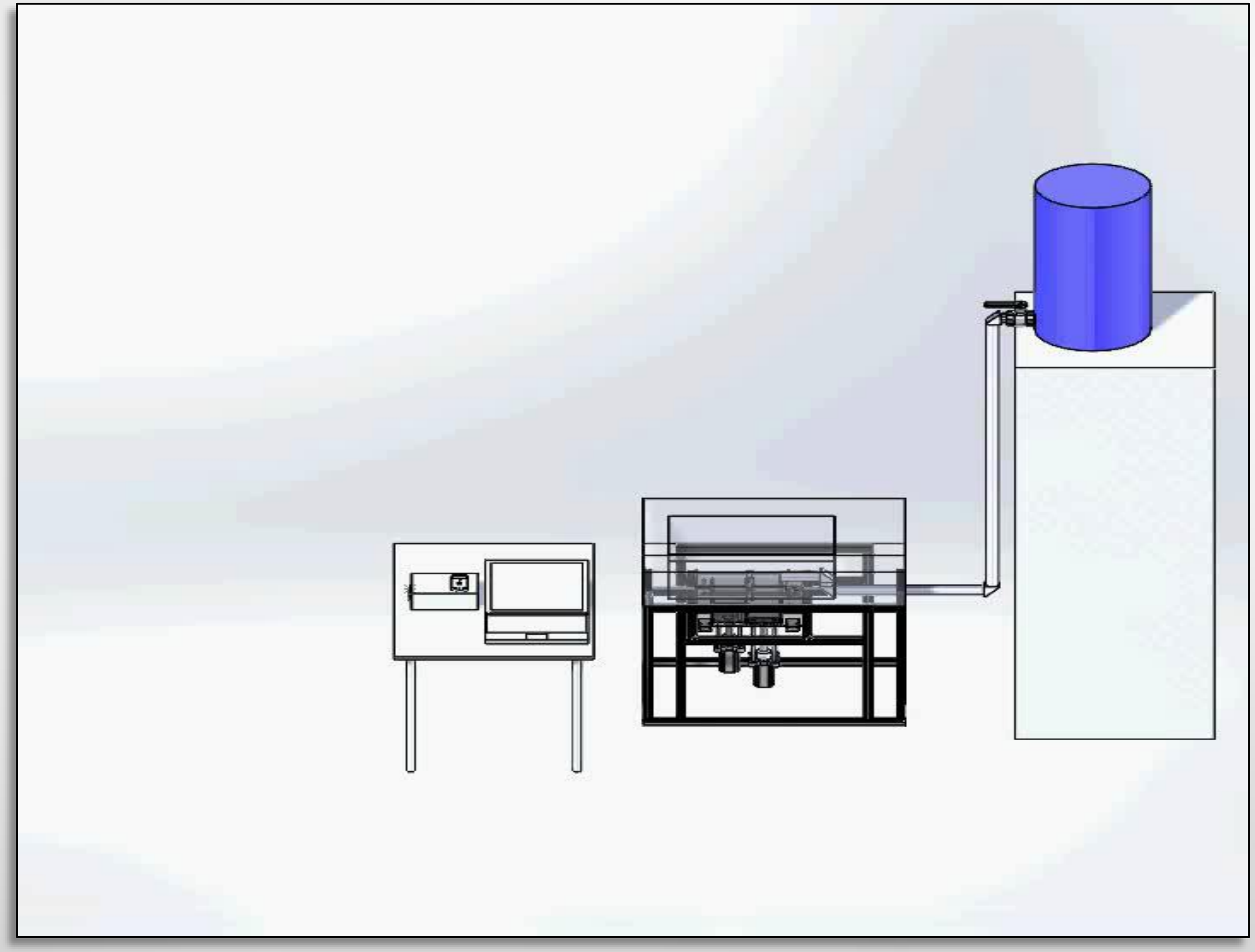
Levels of Success



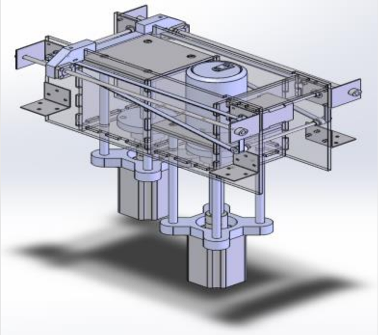
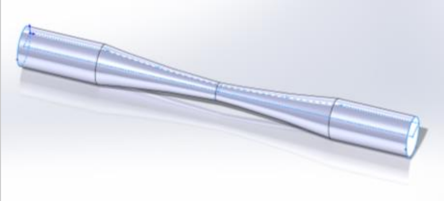
Level	Description	Status
1.1	Design 3D Printing System for Sucrose-KNO_3	Achieved
1.2	Characterize a Thermal Model for Propellant	Achieved
1.3	Use Analogous Method to form Solid Propellant	Achieved
2.1	Compare Material Properties (Casted vs Printed)	Not Achieved
2.2	Print a Solid Rocket Motor Cylinder	Achieved
3.1	Manufacture 5 Different Grain Shapes	Not Achieved

Design Description

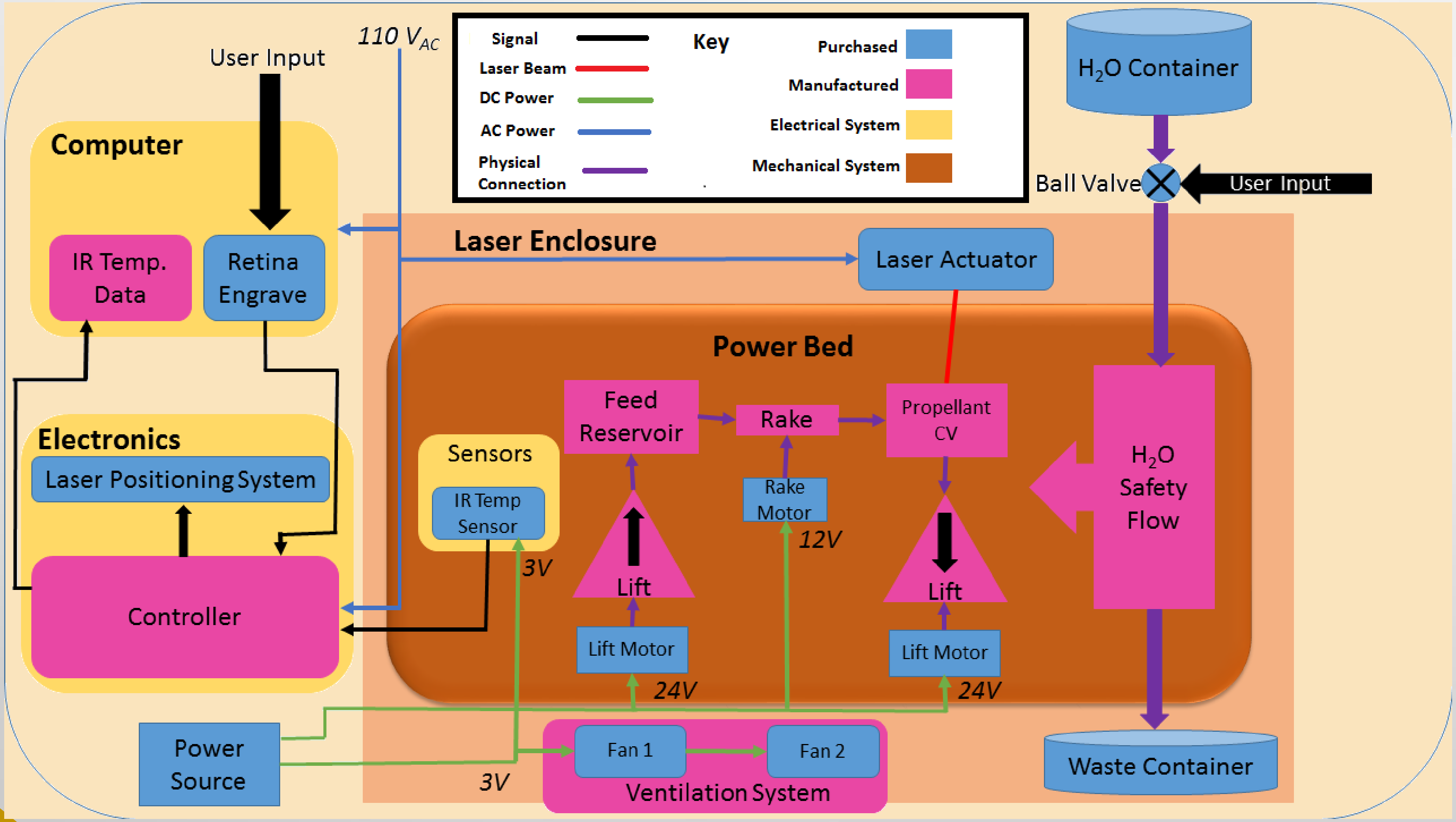
Design Overview



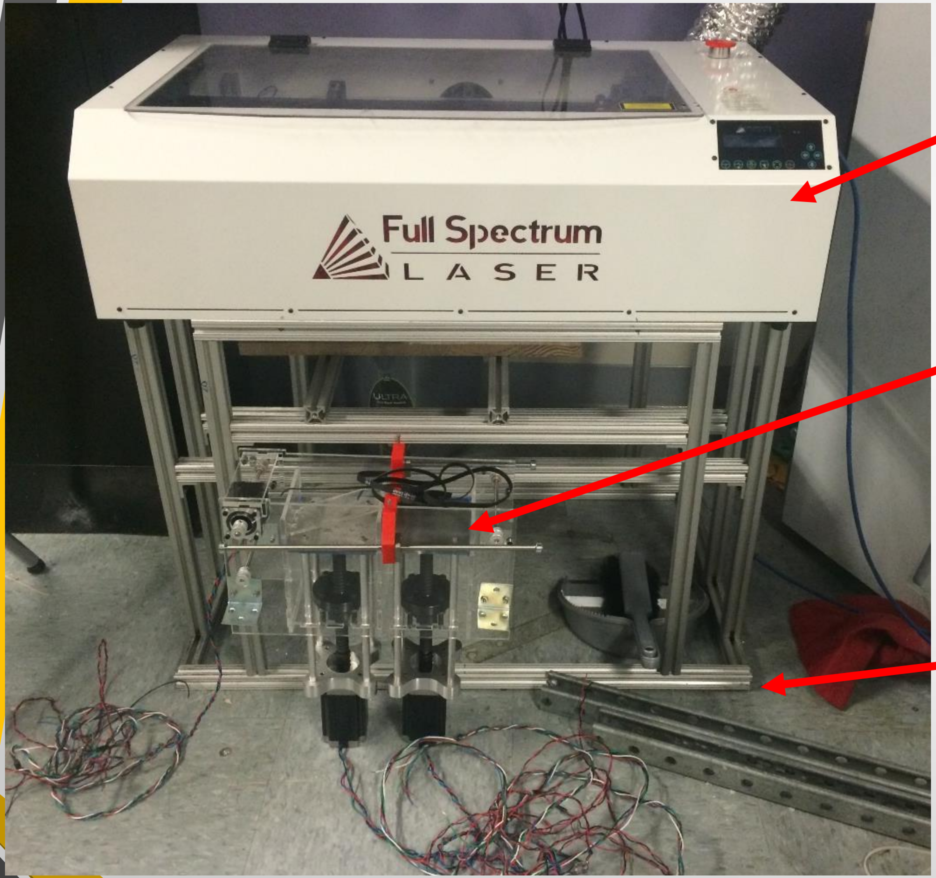
Critical Project Elements

CPE	Description	
Laser Sintering Sucrose and KNO3		• Verify Thermal Model and Laser Energy Control
Powder Bed		• Component Integration and Tolerance Verification • Full Powder Bed Cycle Test
Material Property Testing		• Validate Material Properties Between Casted and Printed Motors

Functional Block Diagram



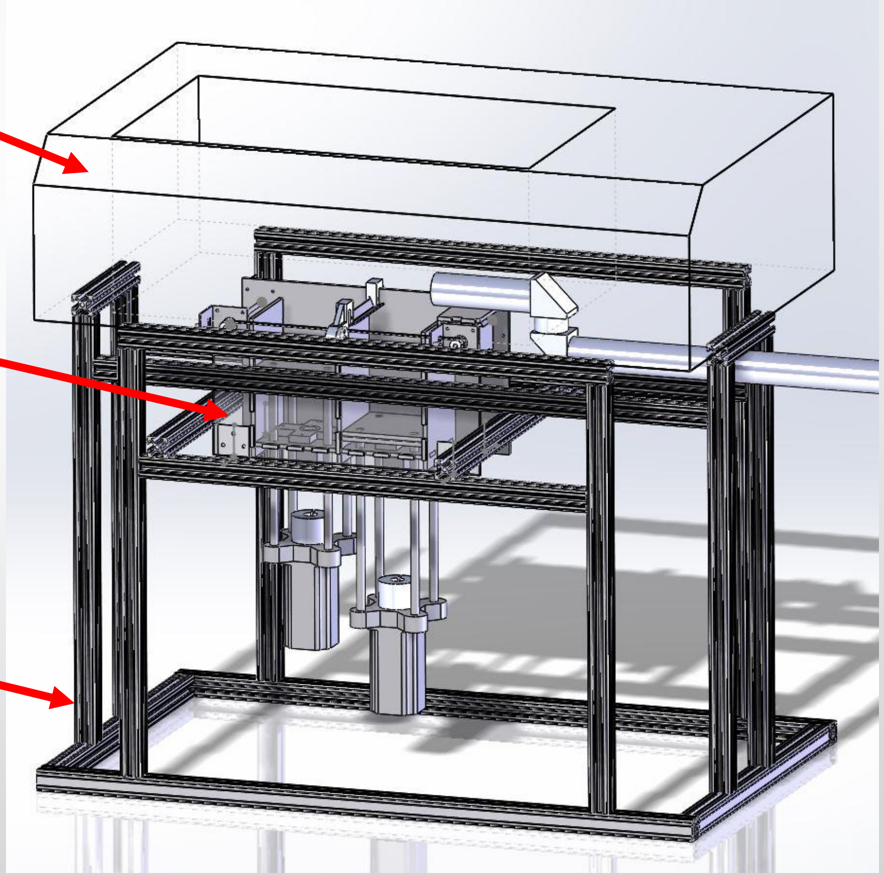
SLS Printer Components



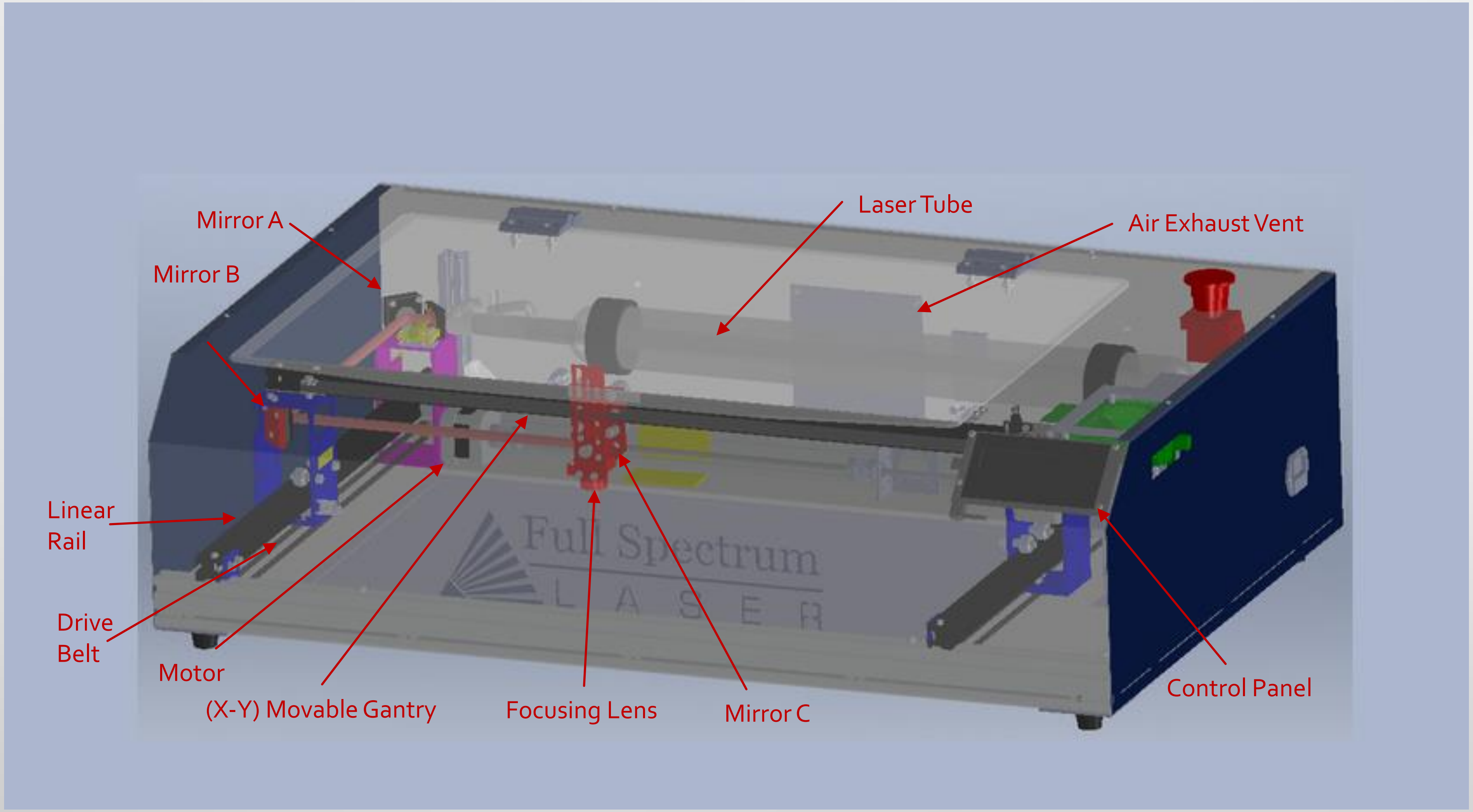
Laser cutter

Powder bed system

Aluminum frame

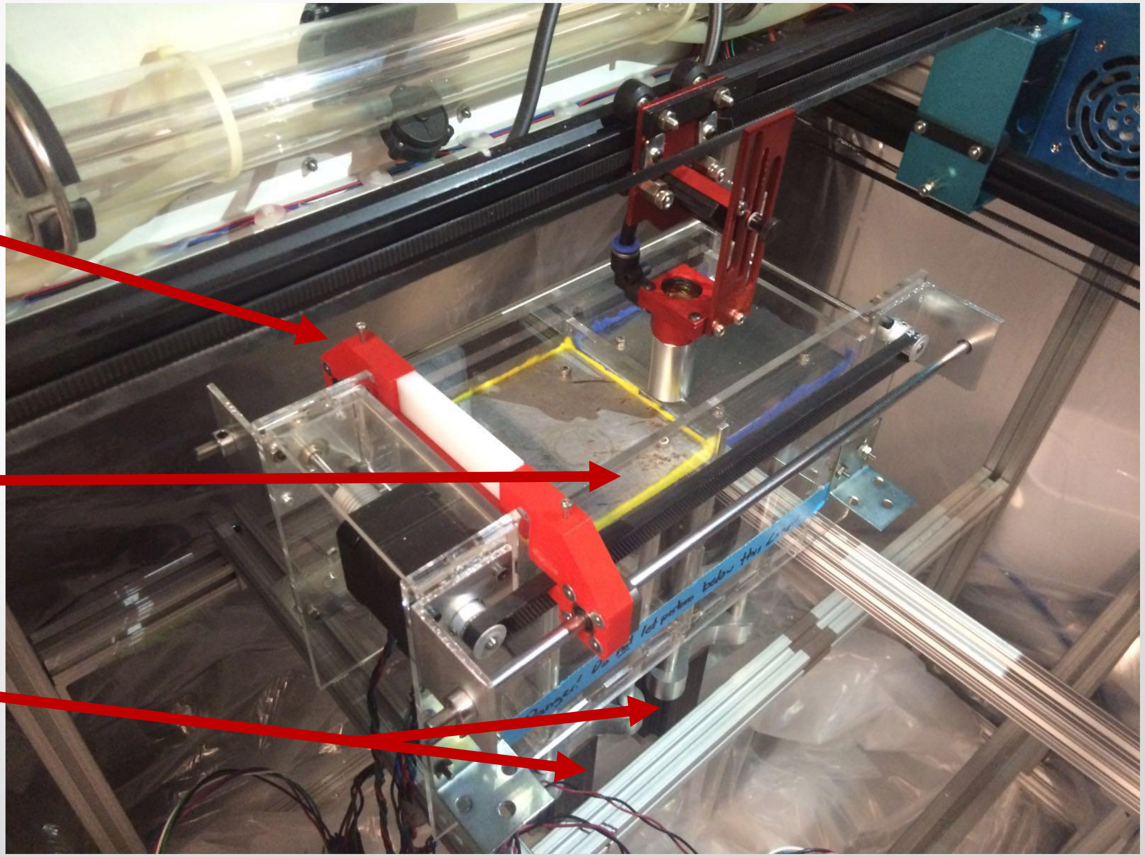


Laser Cutter

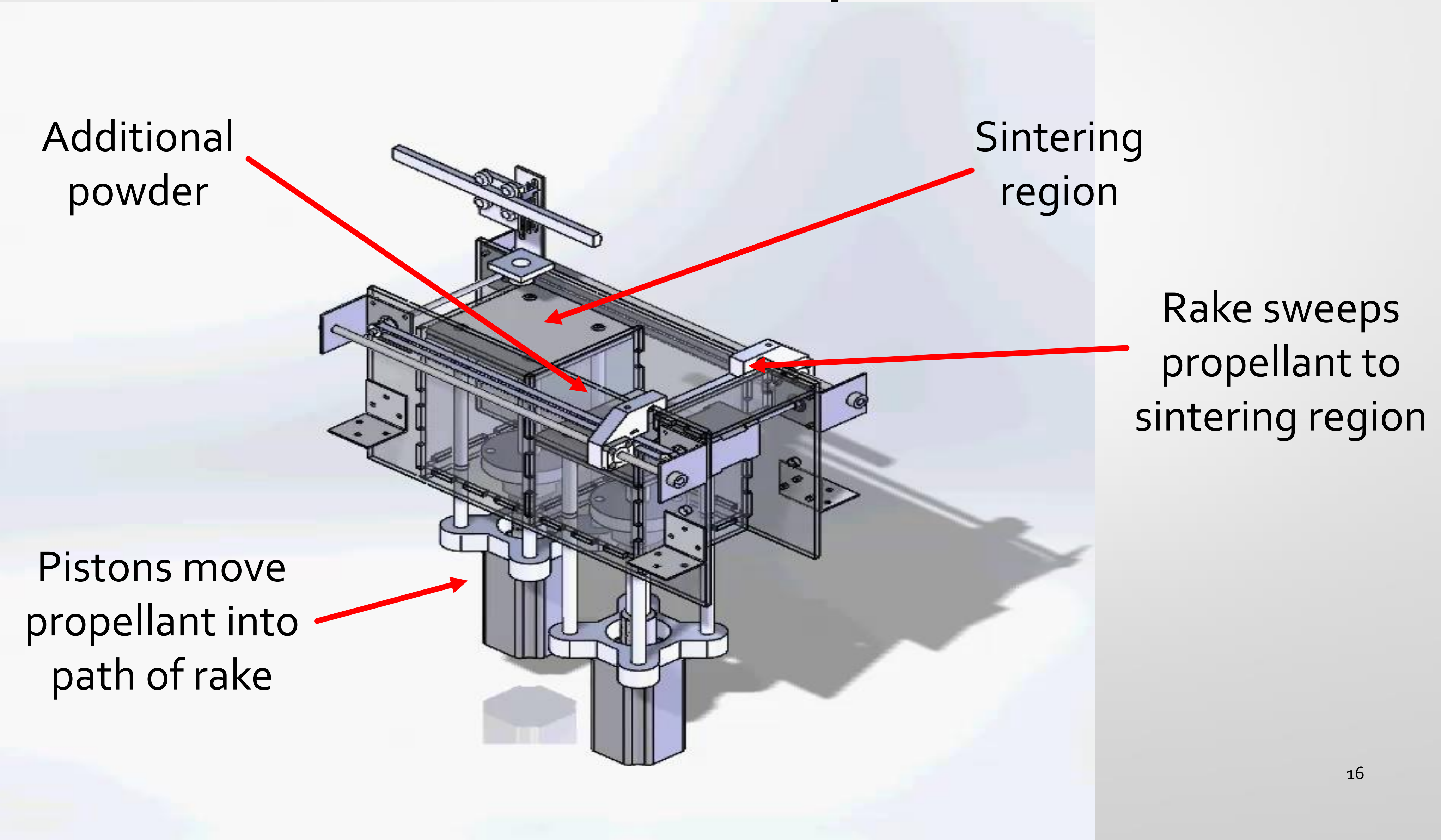


Powder Bed Design

- Acrylic Body
- Rake System
  - Stepper motor and plastic wedge flatten powder and move it to the sintering region
- Gutter System
  - Acrylic body designed to direct water and powder away from the electronics
- Pistons
  - Stepper motors provide vertical motion



Powder Bed Full Cycle



Design Changes Since TRR

- **Water Safety System – Not Implemented**
  →Outdoor testing location

- **Structural Testing of Motor – Non-feasible**
  →Highly brittle product
  →Control cracked during casting (cross-section too thin)

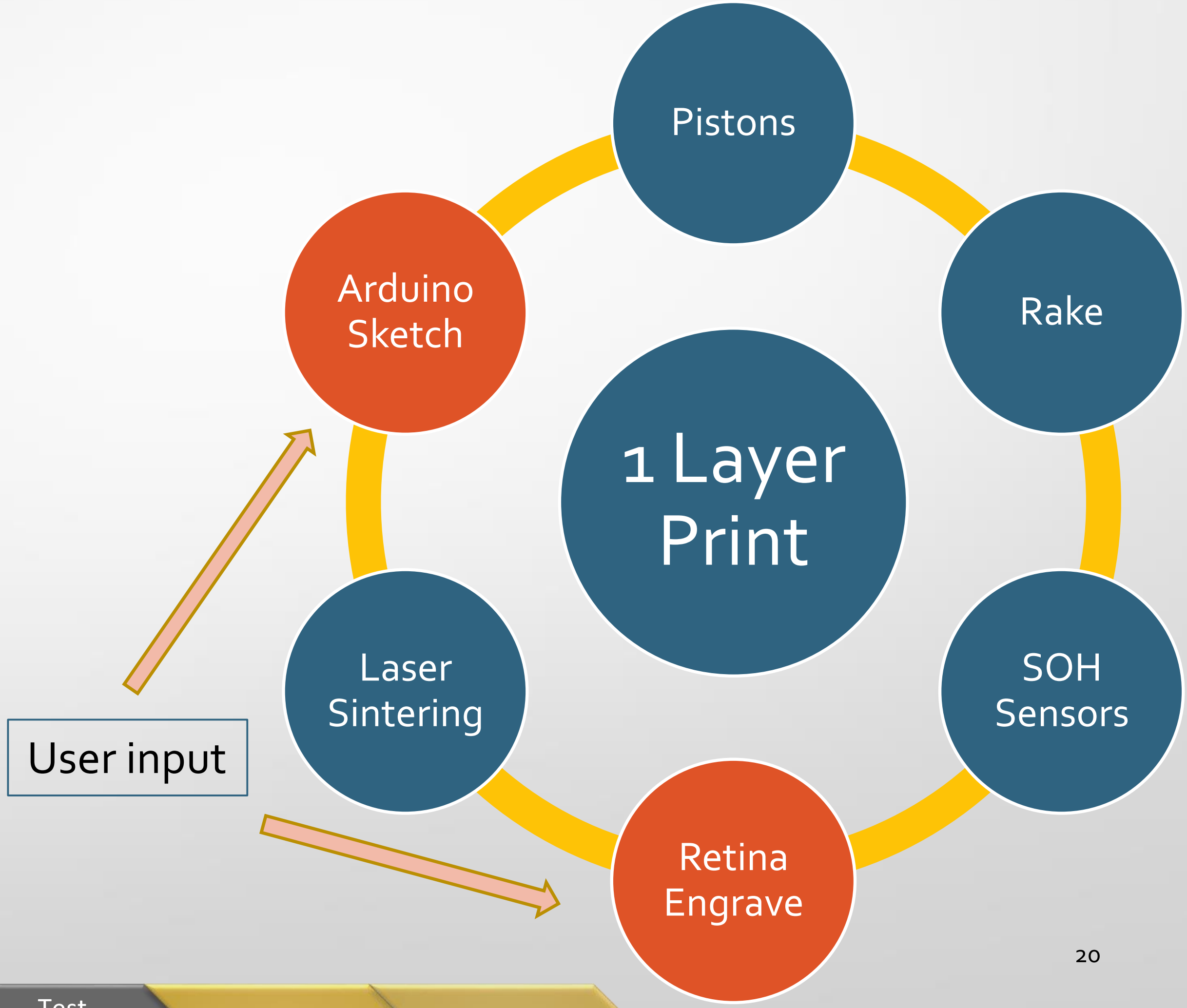
Test Overview

Functional Requirements Overview

Designation	Requirement Description	Verified
FR 1	The project shall produce a printer capable of automated 3D additive manufacturing.	Provisionally
FR 2	The rocket propellant shall be a solid composite propellant consisting of oxidizer and fuel.	Yes
FR 3	The printer shall have a mechanism to transport the mixed fuel and oxidizer to the manufacturing area.	Yes
FR 4	The printed propellant properties shall be compared to traditionally cast propellant material properties.	Provisionally
FR 5	Safety shall be the primary concern in every aspect of the project.	Yes

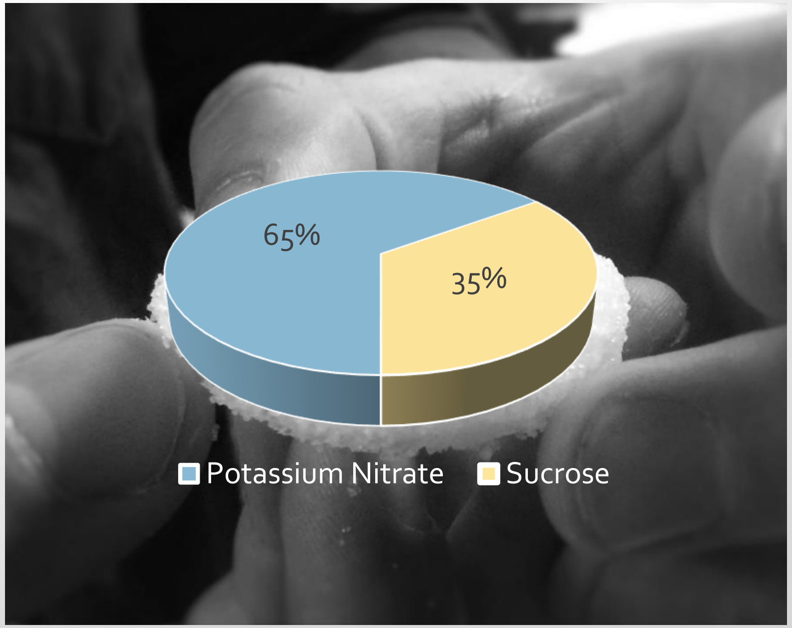
Requirements Fulfillment: FR 1

- The project shall produce a printer capable of automated 3D additive manufacturing.
  - Partially fulfilled
  - User intervention required at exchanges between powder bed and laser cutter



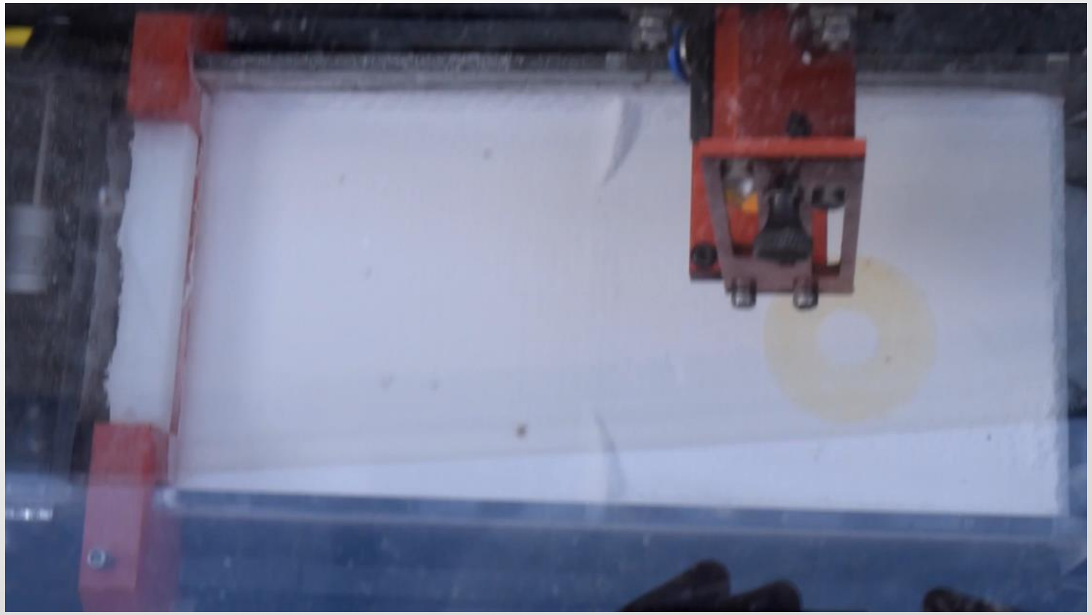
Requirements Fulfillment: FR 2

- The rocket propellant shall be a solid composite propellant consisting of oxidizer and fuel.
  - 35% Sucrose fuel : 65% Potassium Nitrate oxidizer
  - Same ratio as defined in requirements
  - Highest performing ratio (Naka, 2012)



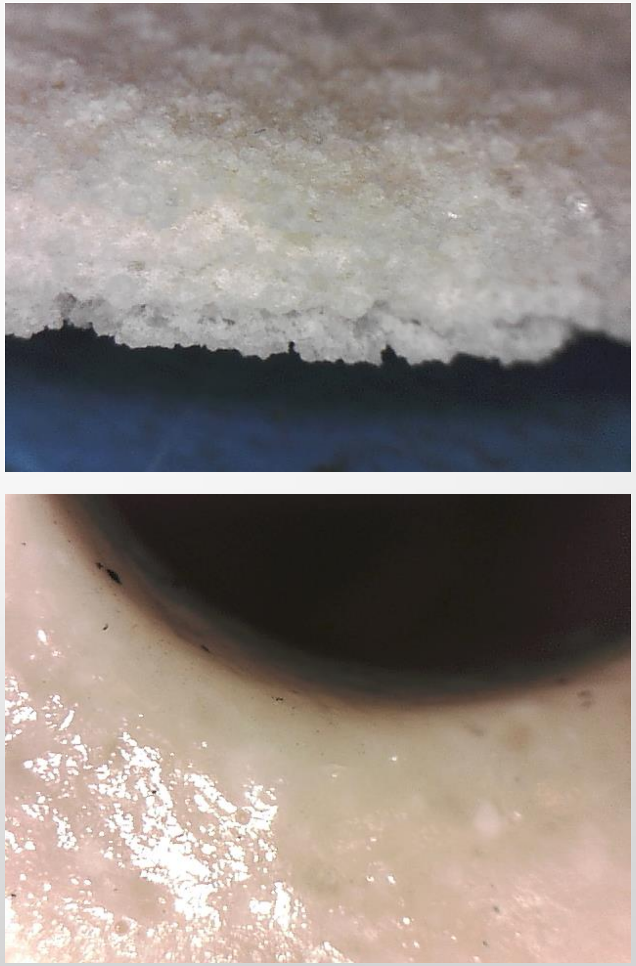
Requirements Fulfillment: FR 3

- The printer shall have a mechanism to transport the mixed fuel and oxidizer to the manufacturing area.
  - Layers of 1.98 ± 0.2mm exceed requirements
    - Original target 1 ± 0.3mm layer gives poor results
    - Translated to ± 0.3mm maximum error



Requirements Fulfillment: FR 4

- The printed propellant properties shall be compared to traditionally cast propellant material properties.
  - Printed propellant less dense, less homogeneous, more brittle
  - Tensile/Compression testing incomplete
    - Printing process too unstable to manufacture dogbones
    - Sample cast is too small for brittle propellant



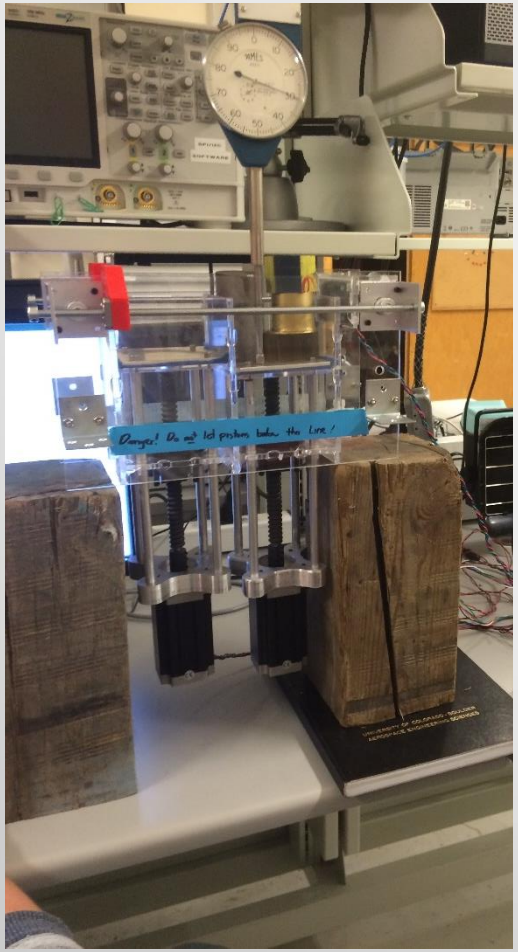
Printed (top) vs. Cast (bottom)

Requirements Fulfillment: FR 5

- Safety shall be the primary concern in every aspect of the project.
  - Water identified as only reliable extiguisher
  - Safe operational settings identified
    - Powder temp between 24°C and 200°C; margin of 200°C
  - Outdoor system test
  - <$20 in hardware damage; ignition events contained

Test Results: Powder Bed

Powder Bed Tolerance Testing



- Level powder bed to ensure uniform measuring surface
- Load pistons with expected mass (2.5kg)
- Dial micrometer (pictured) used for vertical measurements
- Perform tests:

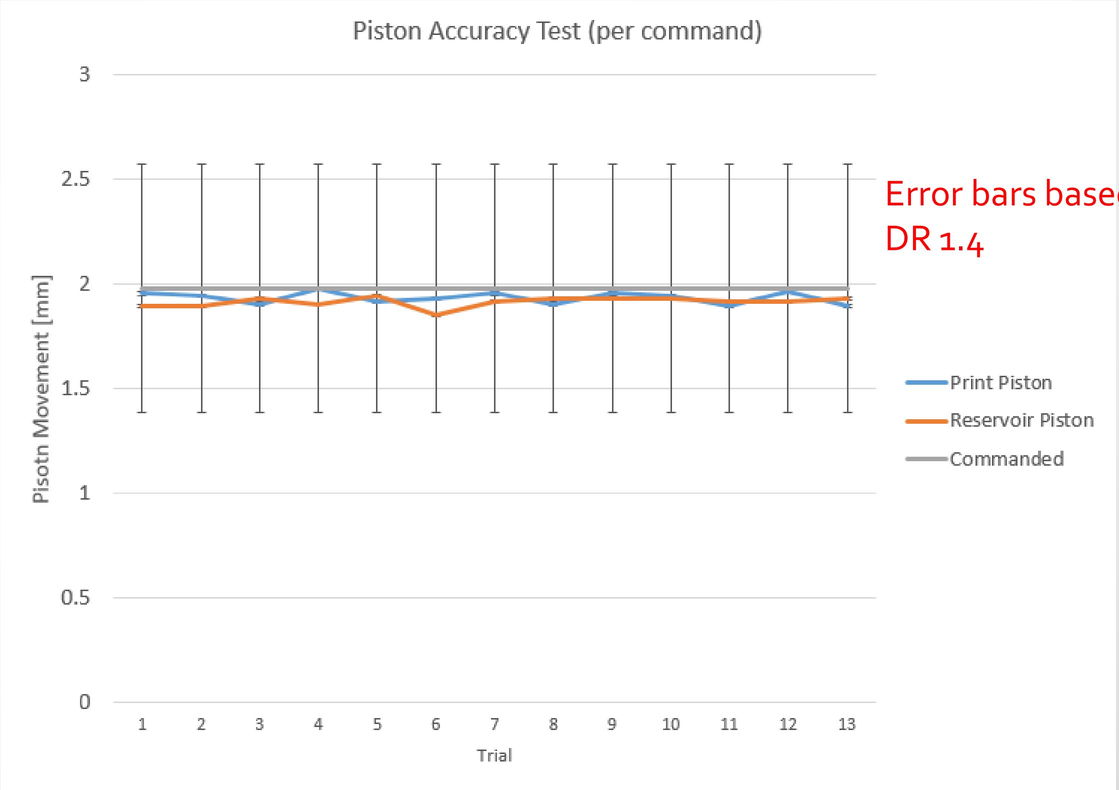
1. Record initial position
2. Command known number of steps
3. Record final position
4. Repeat steps 2 and 3 for all trials

Requirement ID	Description
1.4	Layers shall be 1±0.3mm

Powder Bed Tolerance Testing Results

Trial	Command [mm]	Actual [mm]	Error [%]
1	1.98	1.9558	-1.22
2	1.98	1.9431	-1.86
3	1.98	1.905	-3.79
4	1.98	1.9812	0.06
5	1.98	1.9177	-3.15
6	1.98	1.9304	-2.50
7	1.98	1.9558	-1.22
8	1.98	1.905	-3.79
9	1.98	1.9558	-1.22
10	1.98	1.9431	-1.86
11	1.98	1.8923	-4.43
…	…	…	…

*All distances are downward



Error bars based on DR 1.4

- 77 Steps/trial commanded
- Bias towards loss suggests steps are smaller or are being skipped
- Error is within 30% at all times

Powder Bed Tolerance Testing Results

Theoretical:

$$\Delta Z = 38.88\ steps/mm$$

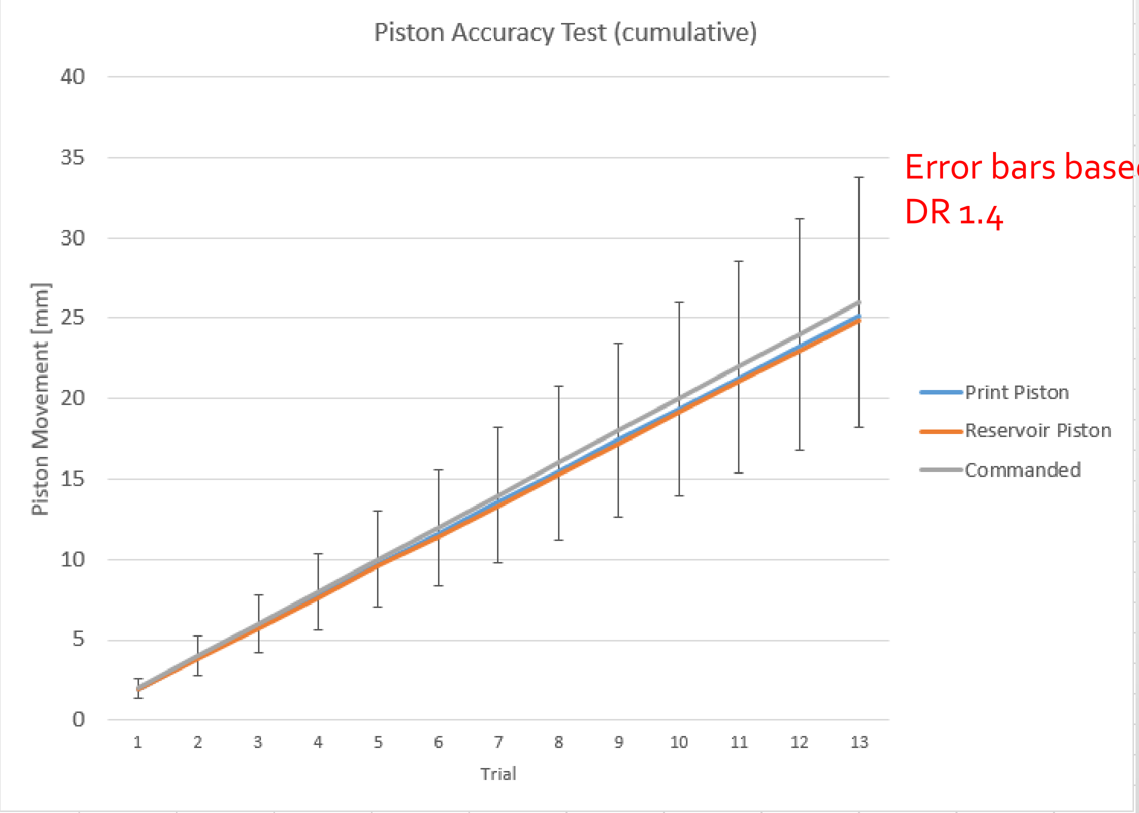
Actual (77 steps/trial):

$$\Delta Z_{avg} = 1.934\ mm/trial$$
$$= 39.81\ steps/mm$$

Even when under load pistons behave as expected

Actual height is less than commanded height by ~2%, well within the requirement of 30%

Thinner layers allow for sintering between layers



Error bars based on DR 1.4

Requirement ID	Description
1.4	Layers shall be 1±0.3mm

Test Results: Sintering Model

Sintering Model: Assumptions

- Laser sweeps out a rectangle of area as it moves
- Layer depth is variable
- All laser energy is deposited uniformly into the layer
- No heat loss to surroundings
  - Model limited to fast slew rates

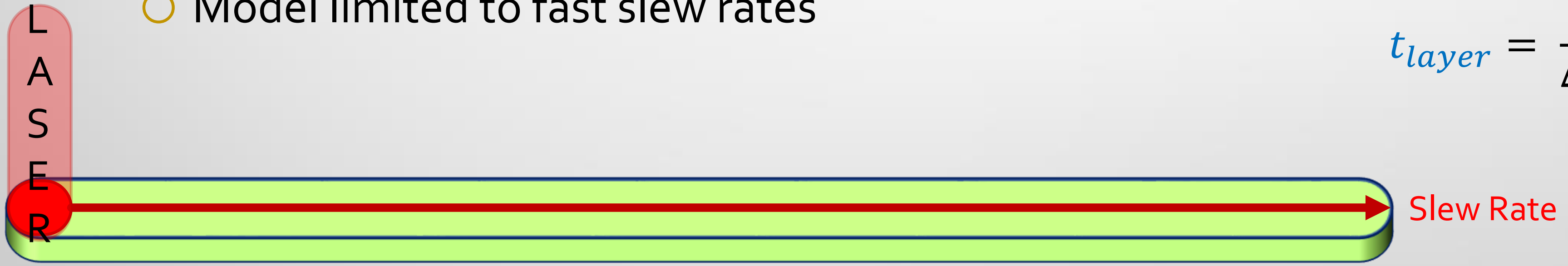
$$Q_{in} = C_p * m * \Delta T$$

$$Q_{in} = (1 - al) * Power * \Delta t$$

$$m = \dot{m} * \Delta t$$

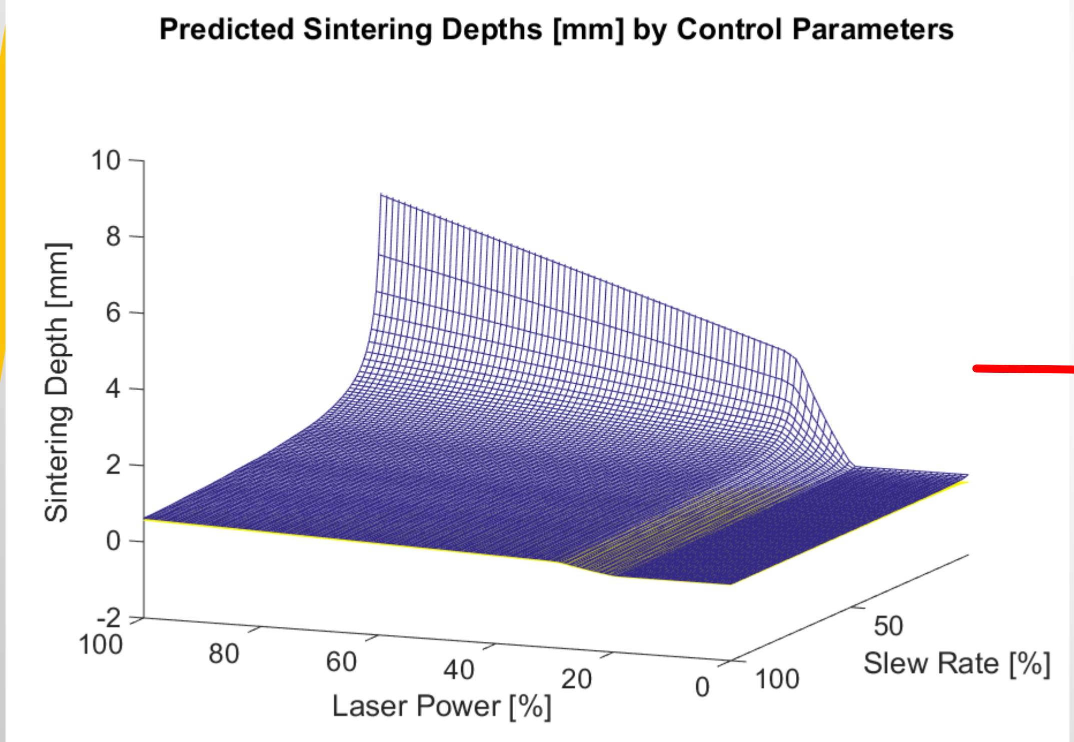
$$\dot{m} = t_{layer} * d_{laser} * r_{slew}$$

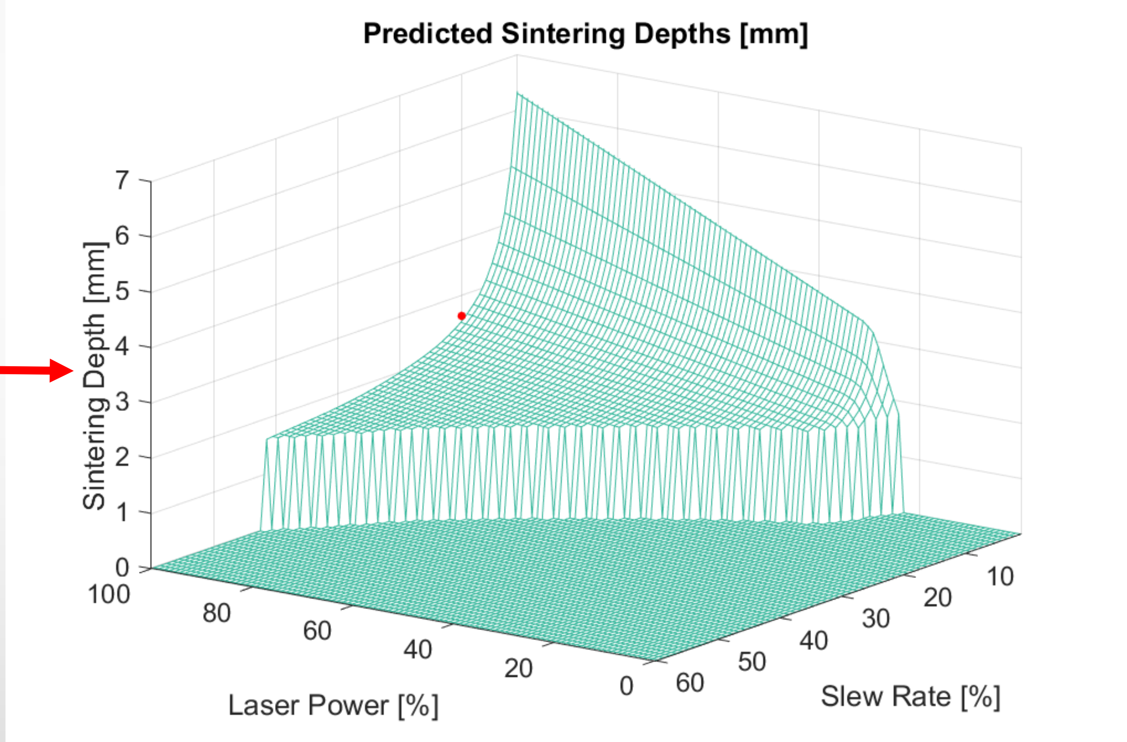
$$t_{layer} = \frac{(1 - al) * Power}{\Delta T * C_p * d_{laser} * r_{slew}}$$



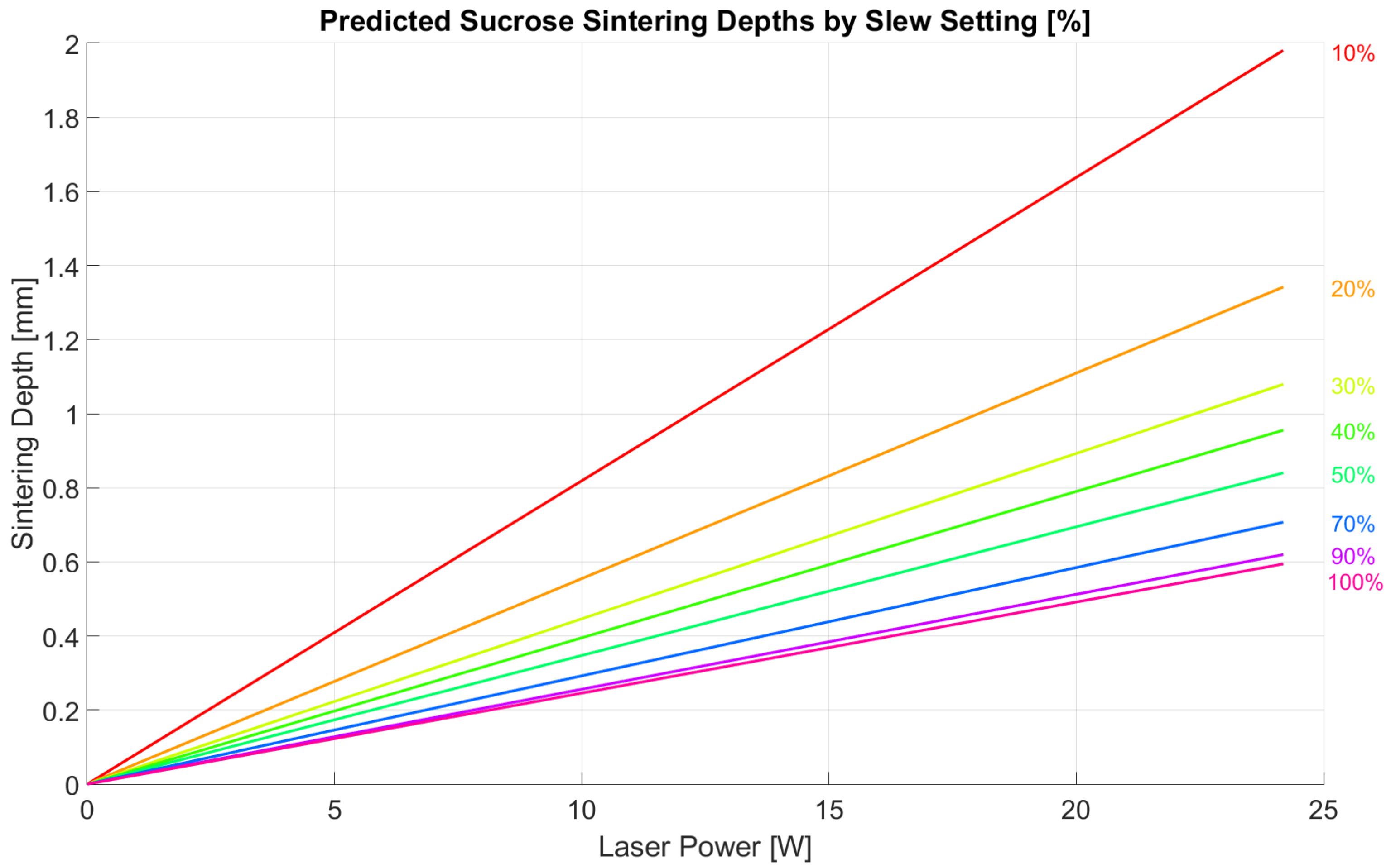
Propellant Layer that receives Laser energy

Sintering Model: Sucrose Predictions

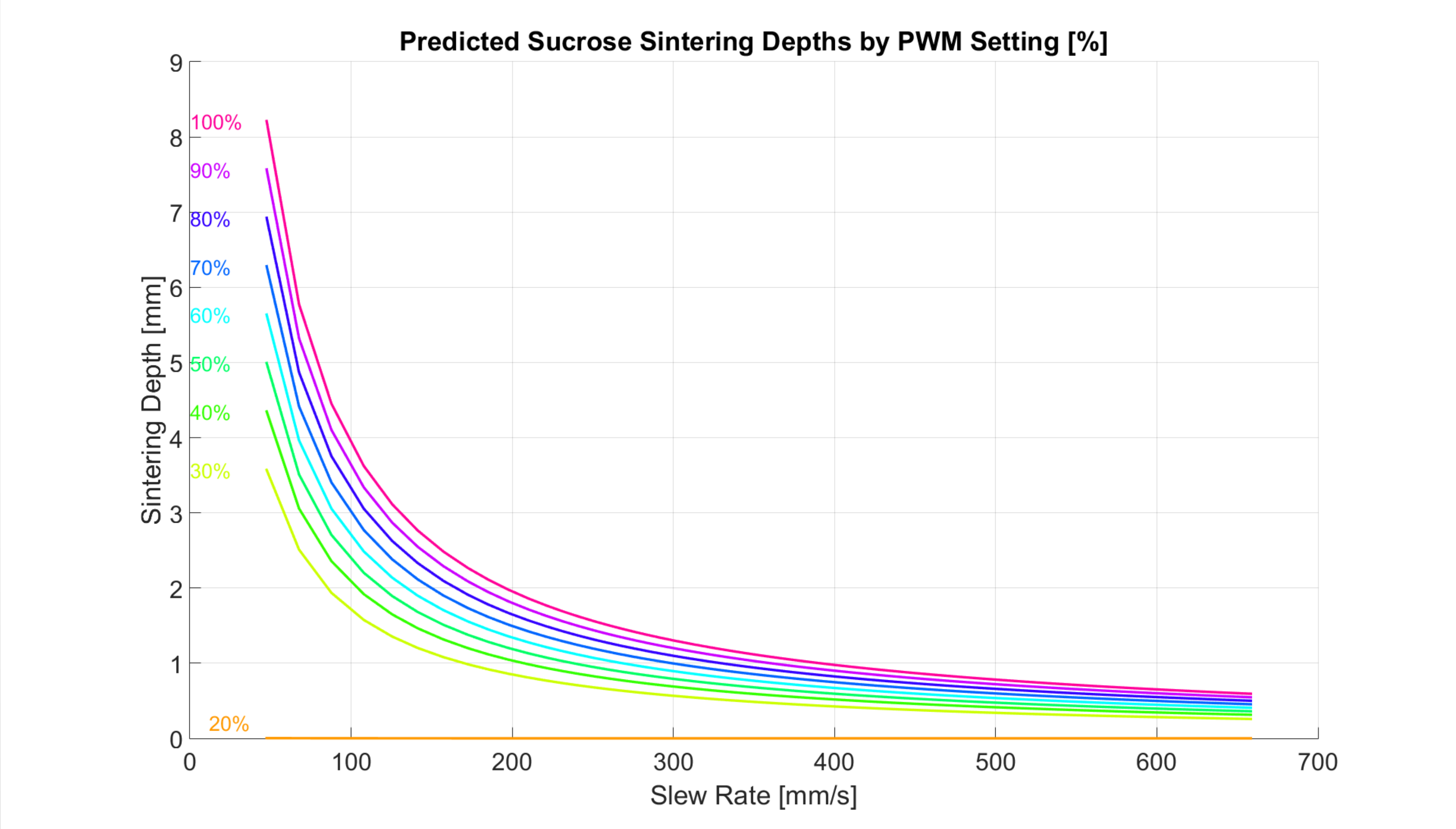




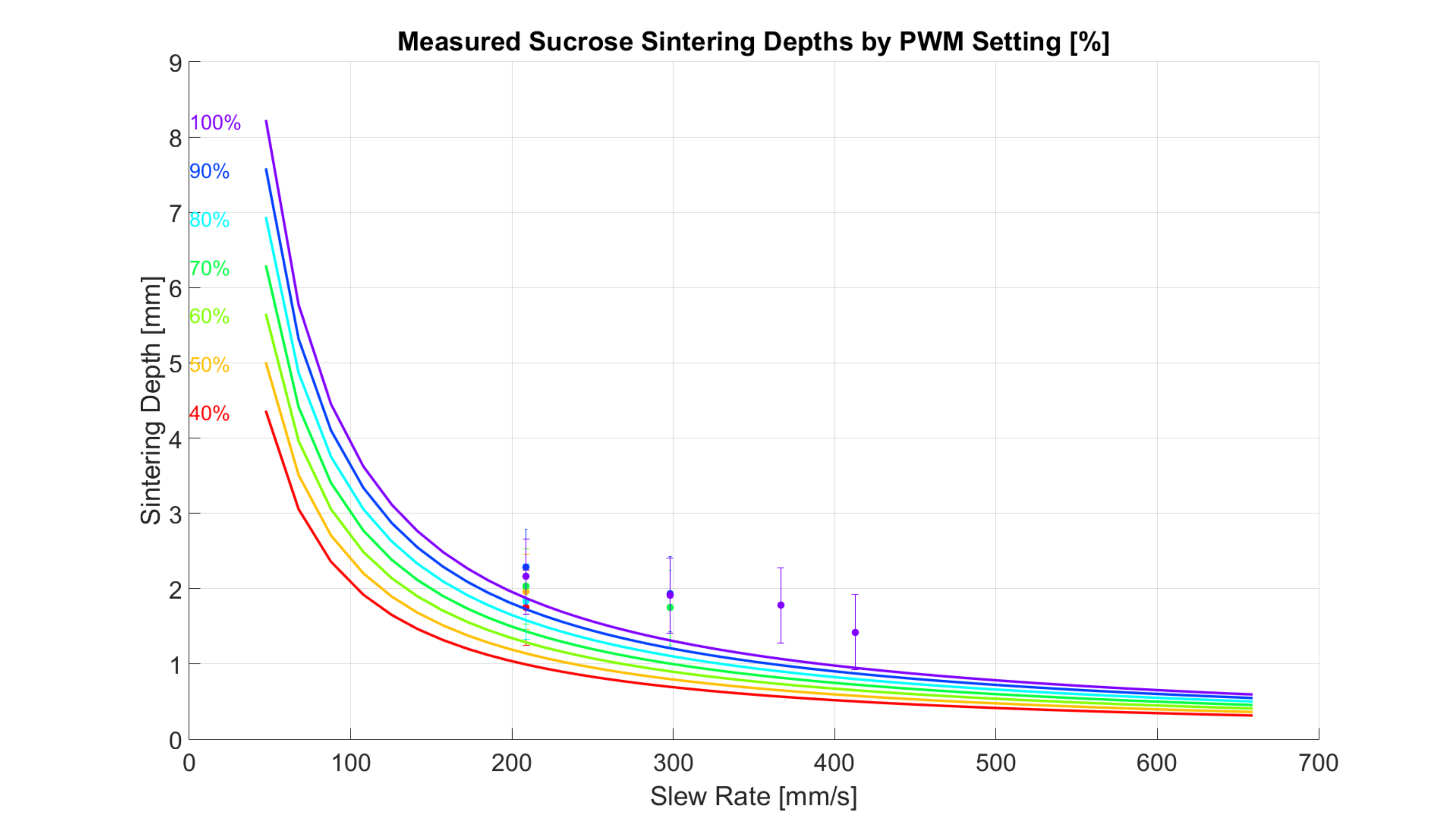
Sintering Model: Sucrose Predictions



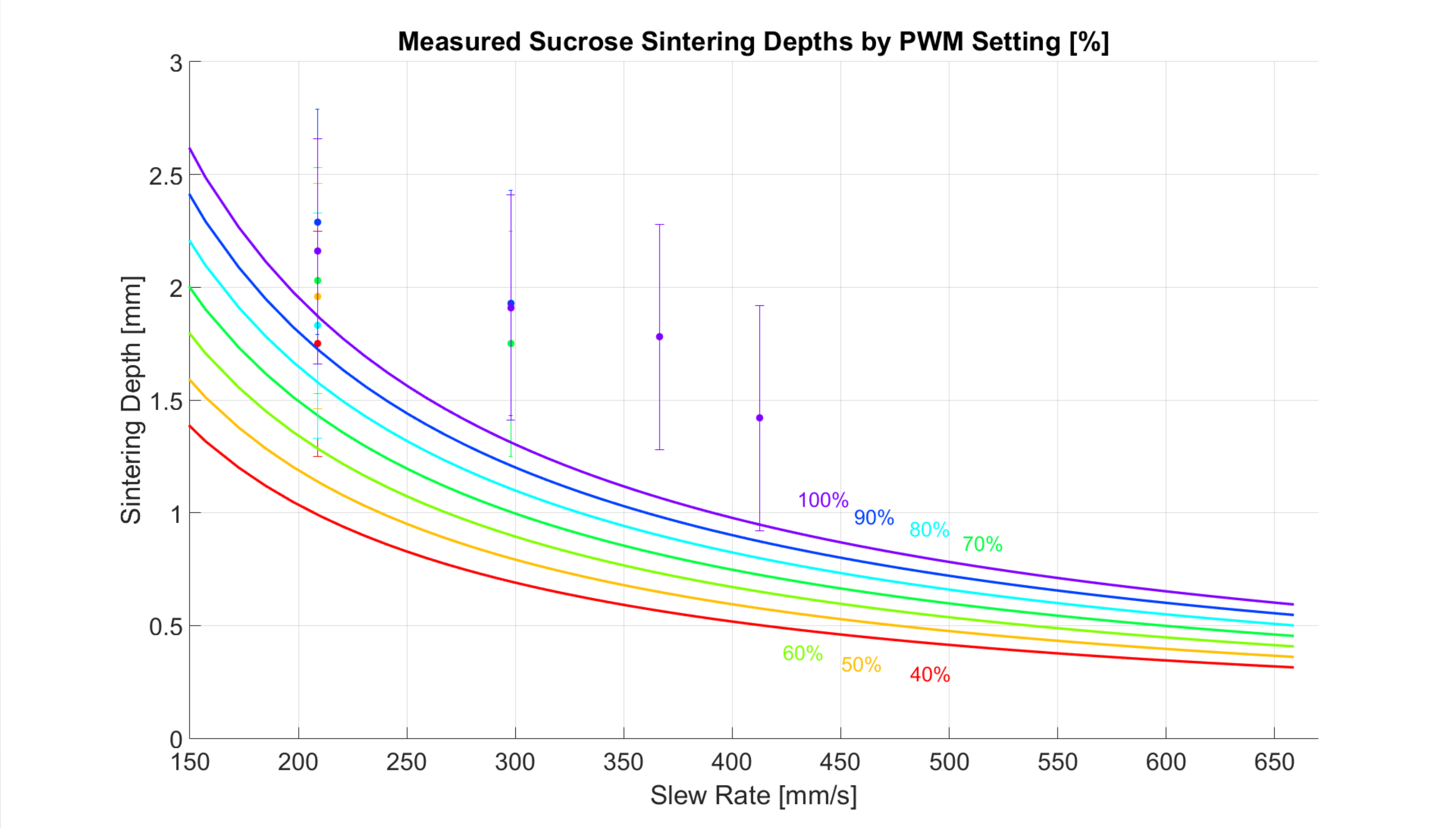
Sintering Model: Sucrose Predictions



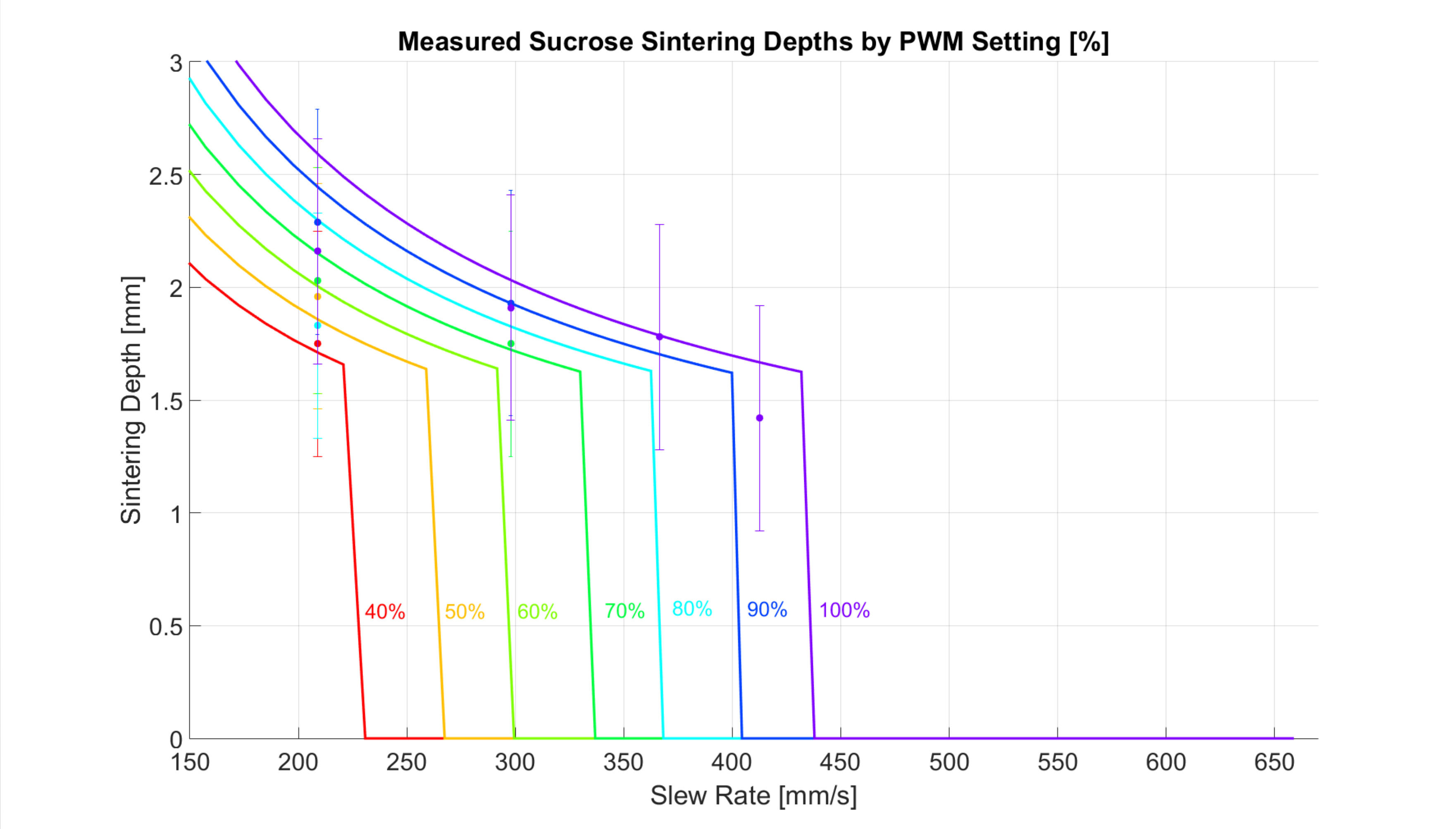
Sintering Model: Sucrose Measurements



Sintering Model: Sucrose Measurements

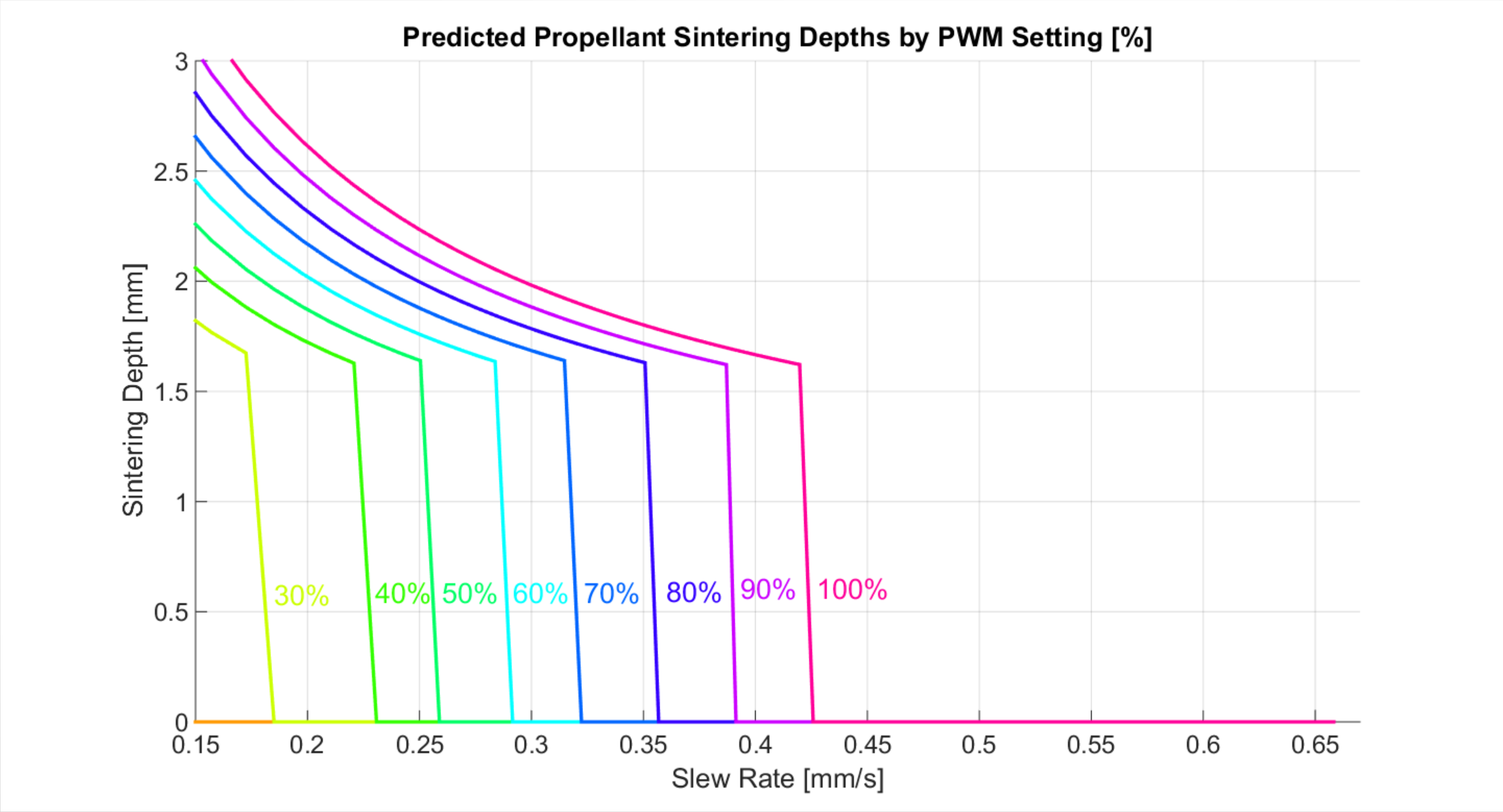


Sintering Model: Sucrose Measurements

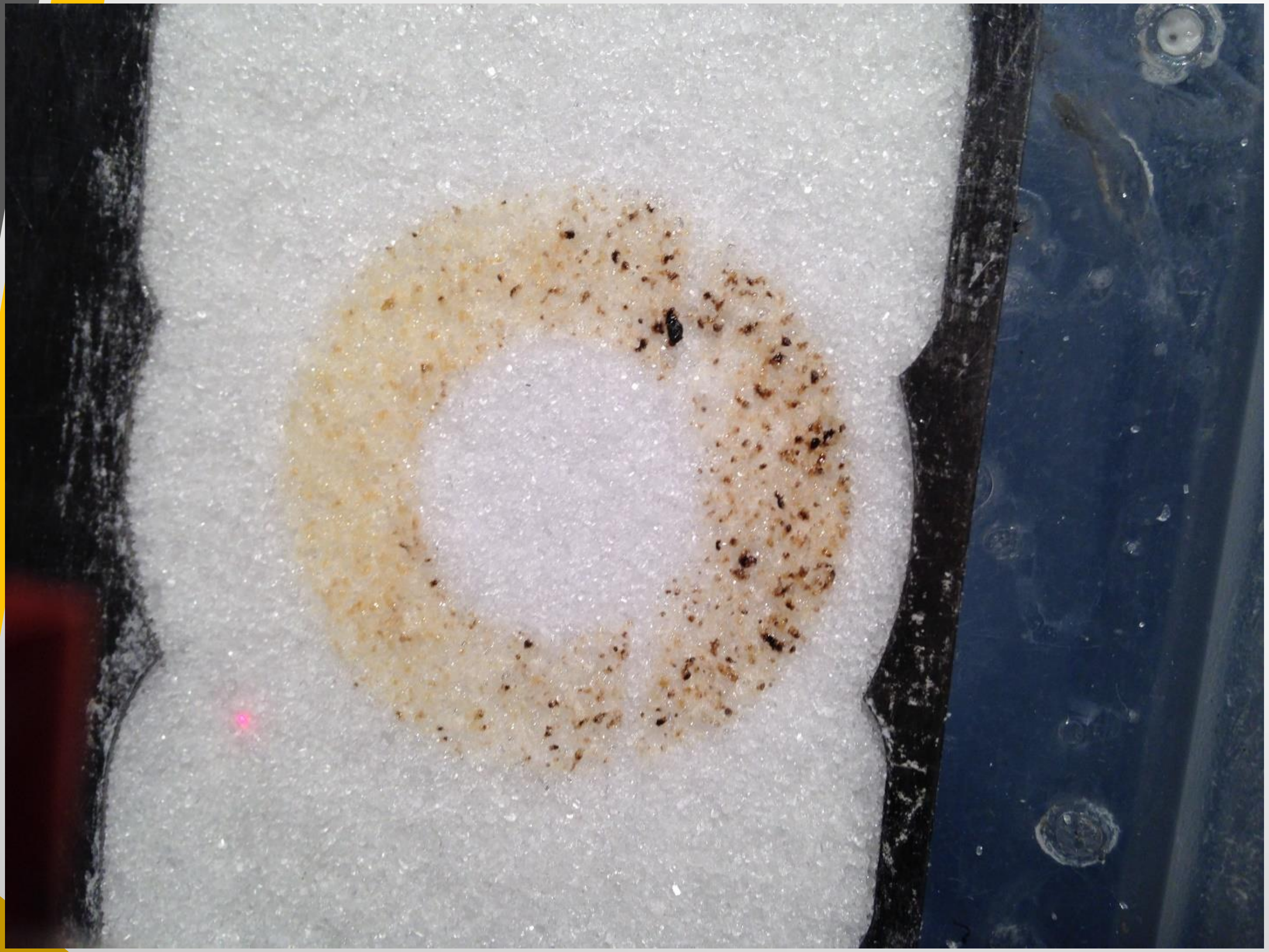


Purpose | Design Description | Test Overview & Results | Systems Engineering | Project Management

Sintering Model: Propellant Predictions

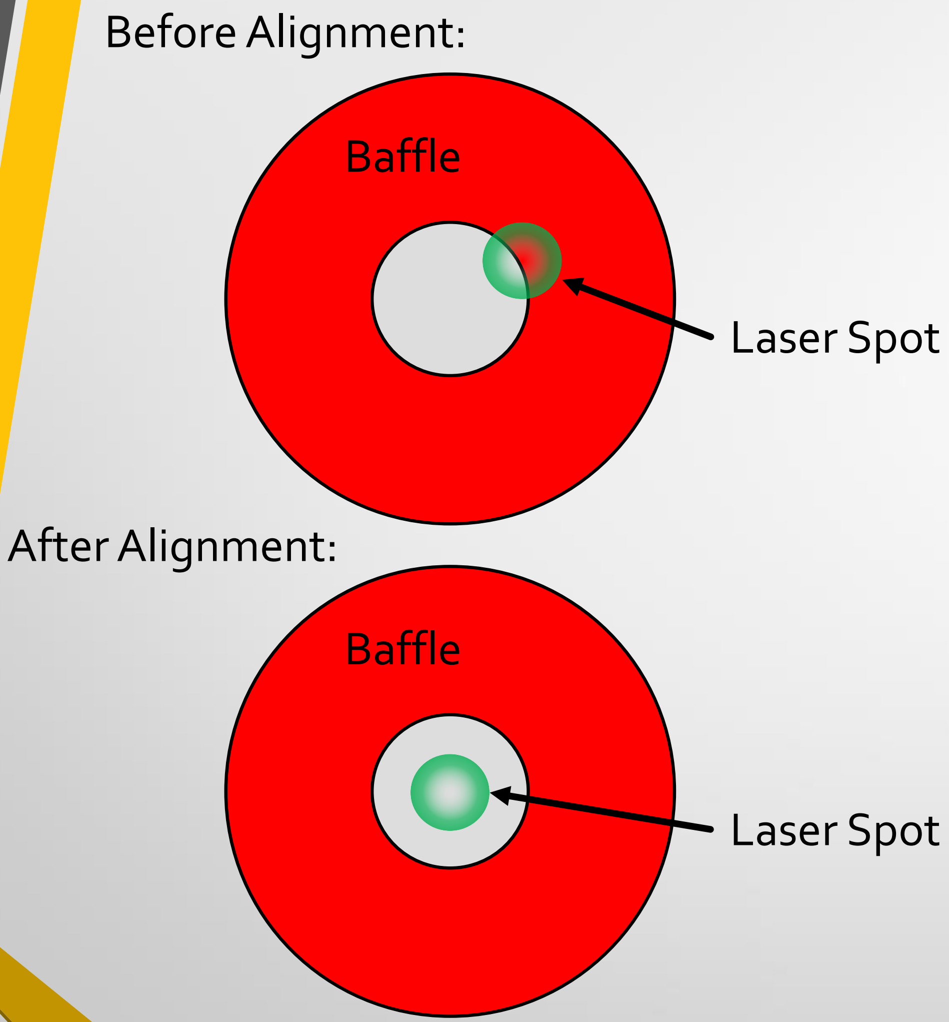


Sintering Model: Propellant Predicament



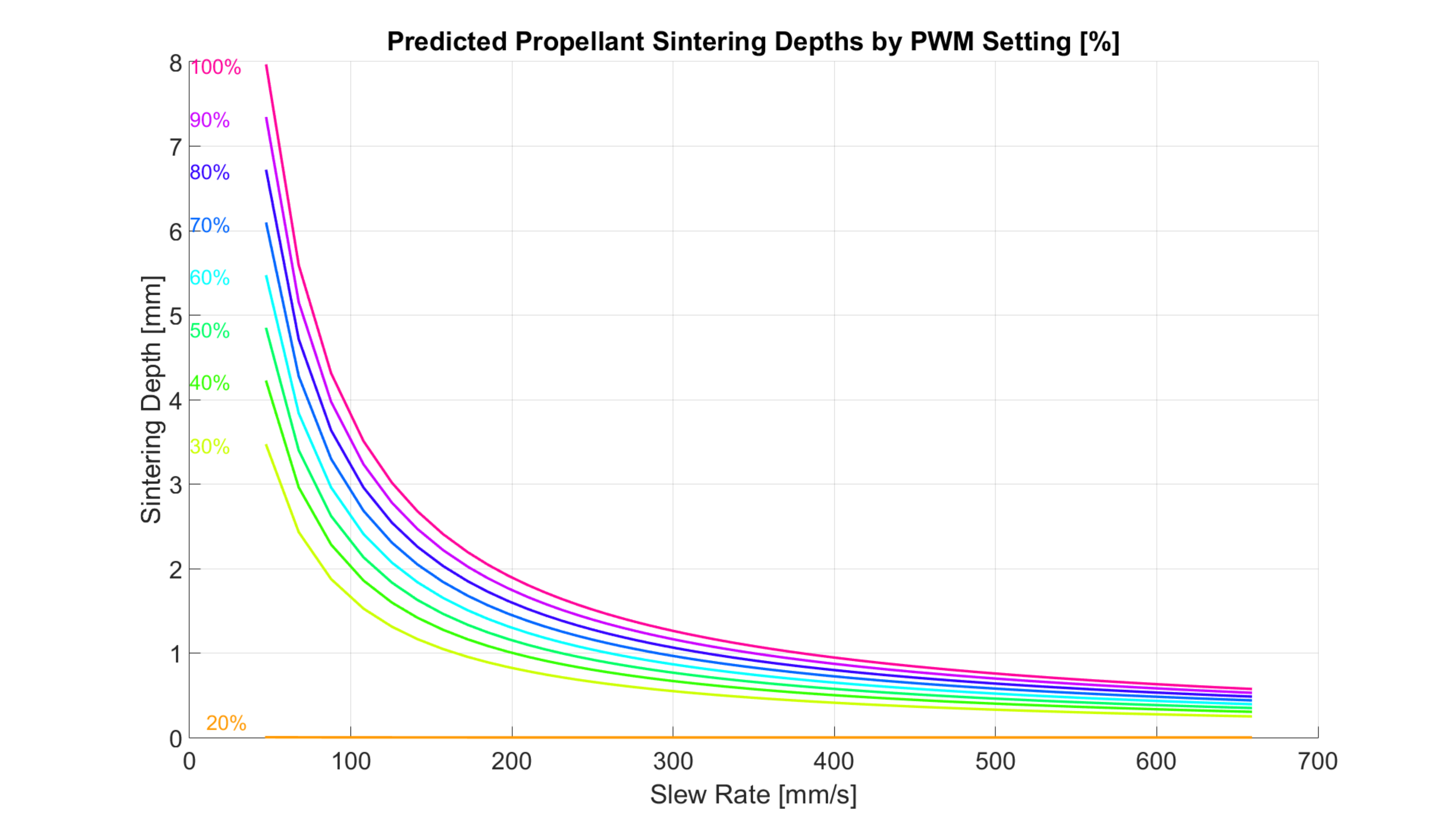
- Coarse KNO_3 and Sucrose showed regularly uneven sintering
- Black spots appeared randomly
- Ignition starts when black spots grow too large (get too hot)
- Caused by non-uniformity in fuel mixture due to poor mixing
- Switched to Fine Powder

Sintering Model: Mirror Alignment Issues

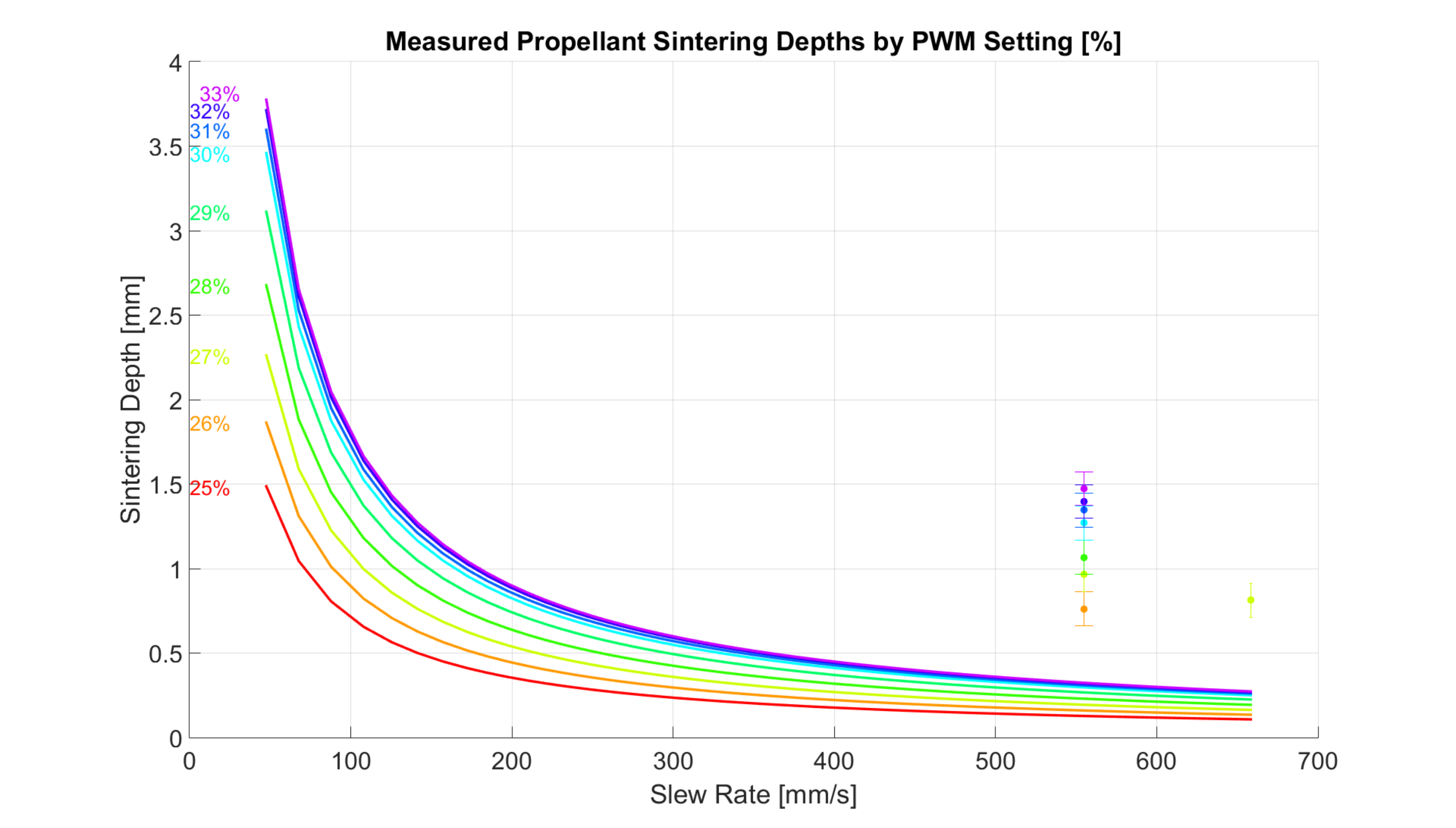


- Biggest Source of error in our measurements
- Laser Spot was obscured by baffle
- Resulted in lower power and different sintering behavior

Sintering Model: Propellant Predictions



Sintering Model: Propellant Measurements



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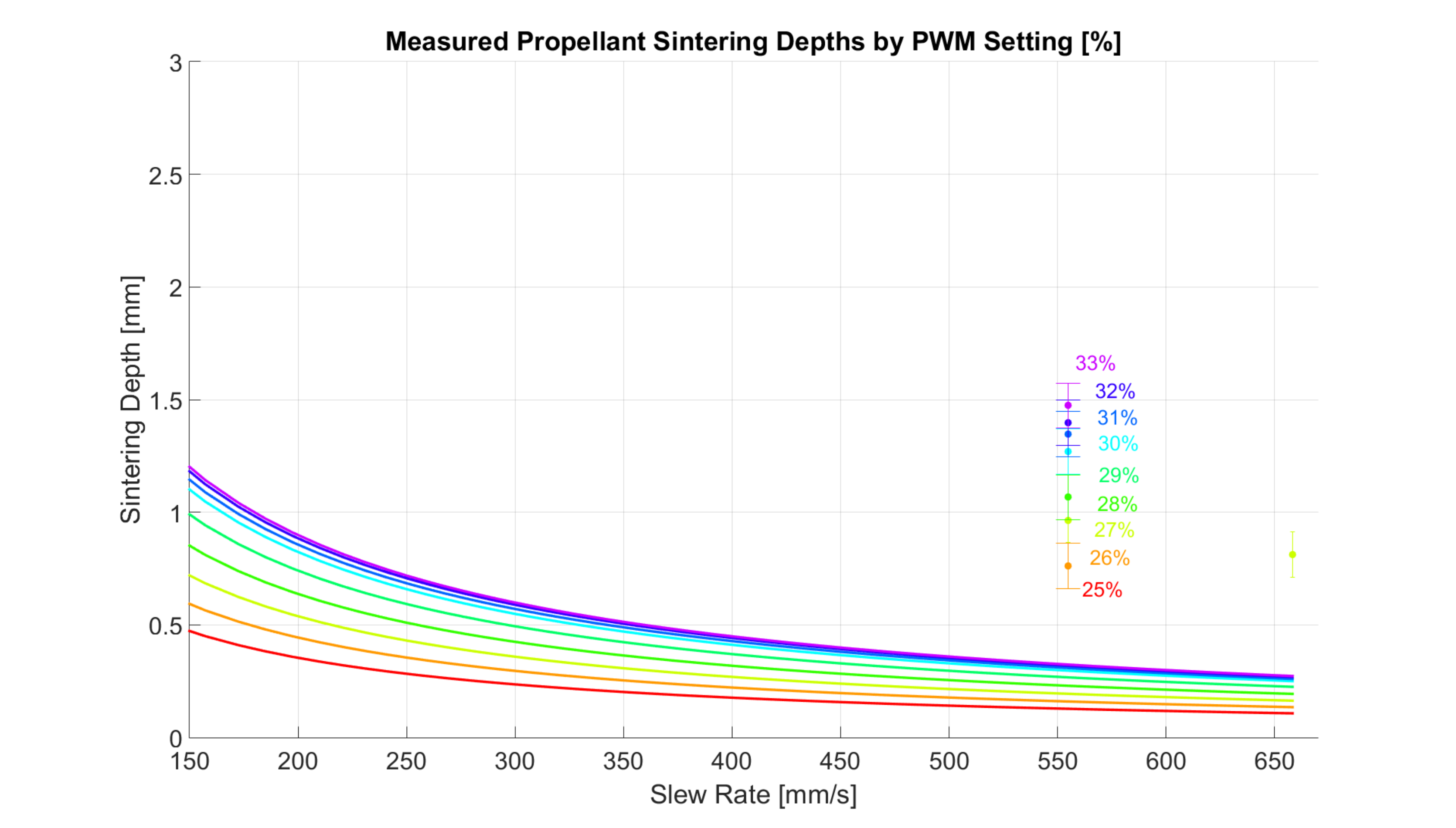
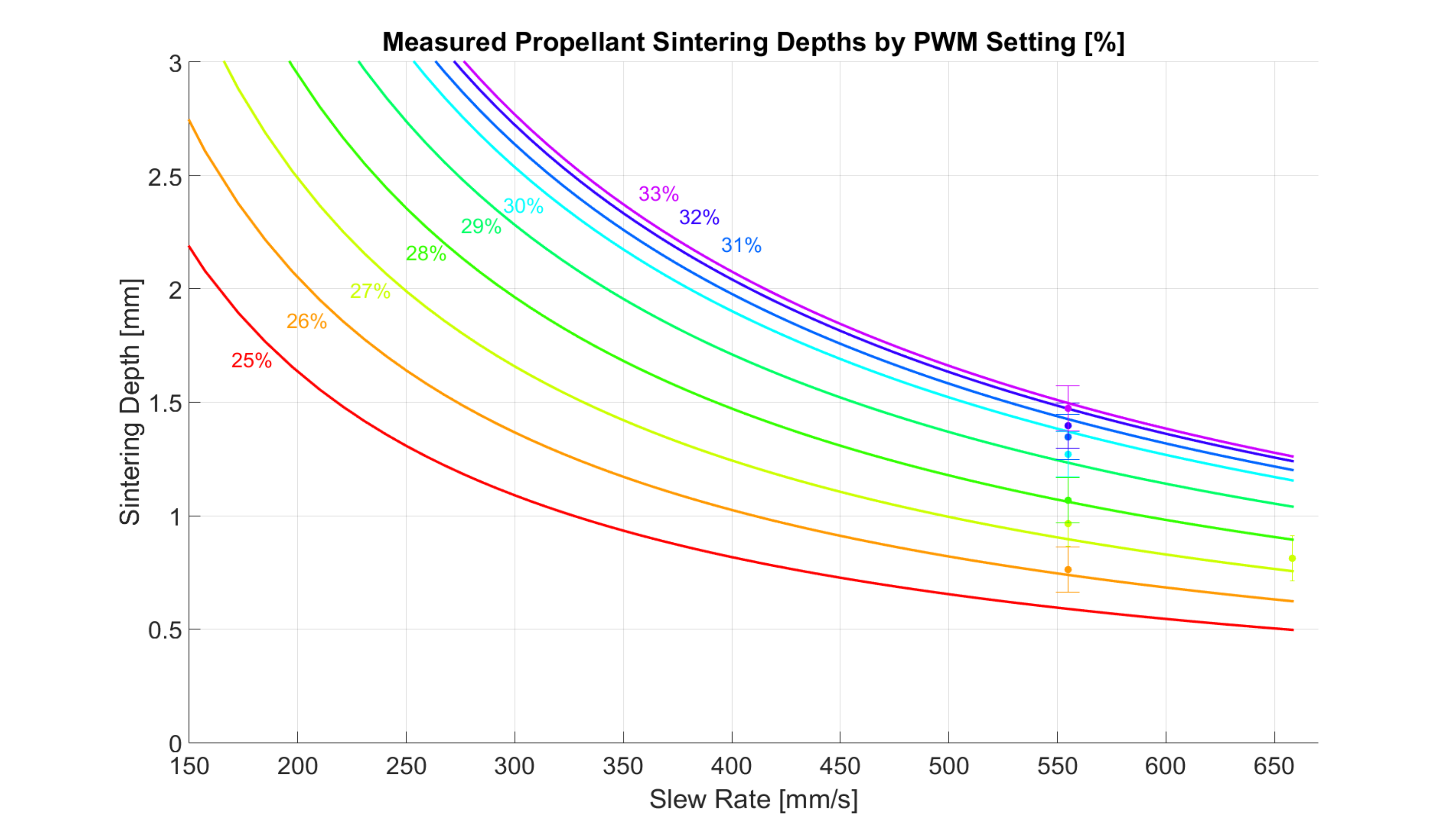


Sintering Model: Propellant Measurements



Propellant Heat Model: Optical Depth

- Optical Depth:
- $\tau = -\log T$, T = transmittance
- Sintering Depth:
- $d_{sint} = \frac{\tau}{A*\rho}$, A = absorptivity (A = 1-T)
- Sintering Depths:

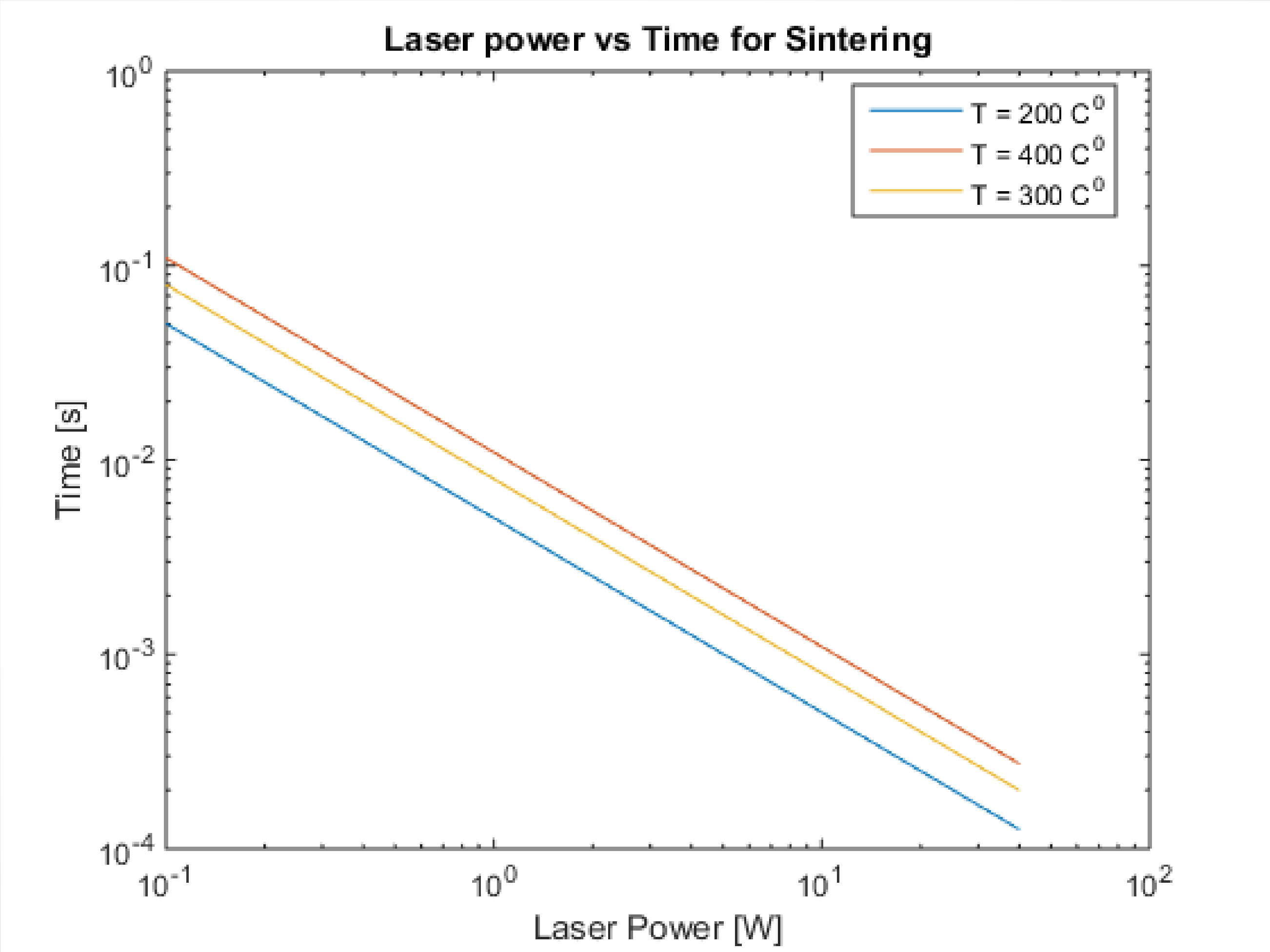
	Calculated	Measured
Sucrose	1.98 mm	2.3 +/- 0.35 mm
Propellant	1.61 mm	1.1 +/- 0.12 mm

Propellant Heat Model: Lumped Capacitance

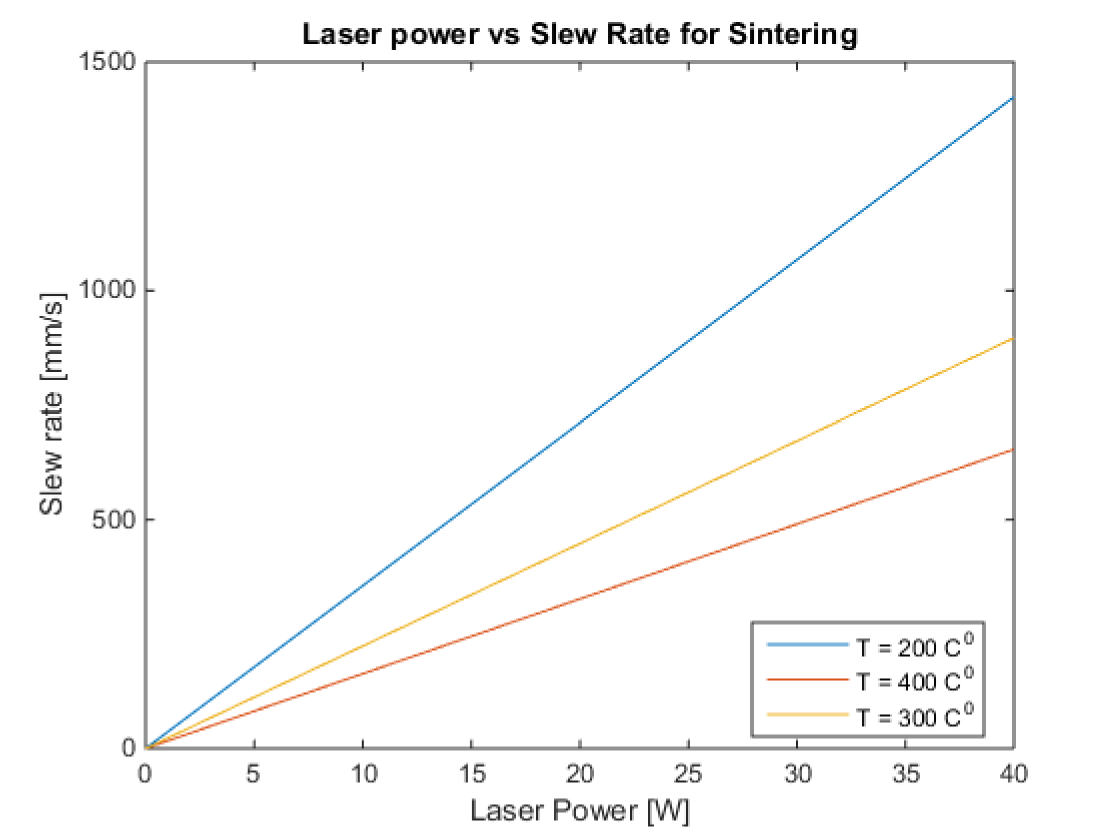
- Assume: All heat is absorbed uniformly at in a cylinder with radius of laser beam and depth of optical depth
- Equation: gives time over spot as a function of laser power
- $dt = \frac{\pi * r_{laser}^2 * d_{sint} * \rho * Cp * T}{A * P_{laser}}$
- Time over spot converted to slew rate:
- $slew\ rate = 2 * \frac{r_{laser}}{dt}$

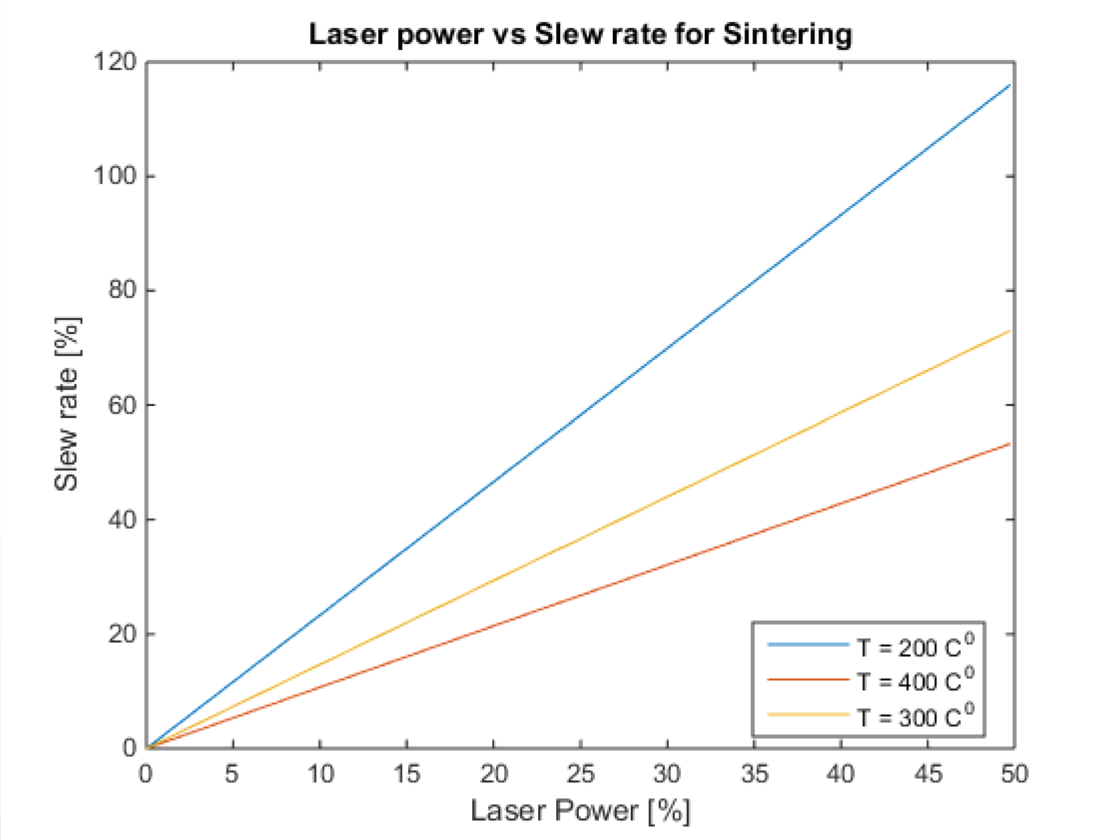
Propellant Thermal Model: Laser Cutter Settings

- Optical depth and surface temp are inputs
  - 200 C° lower bound
  - 300 C° upper bound
- Laser Power and Time over spot are outputs
- Time converted to slew rate



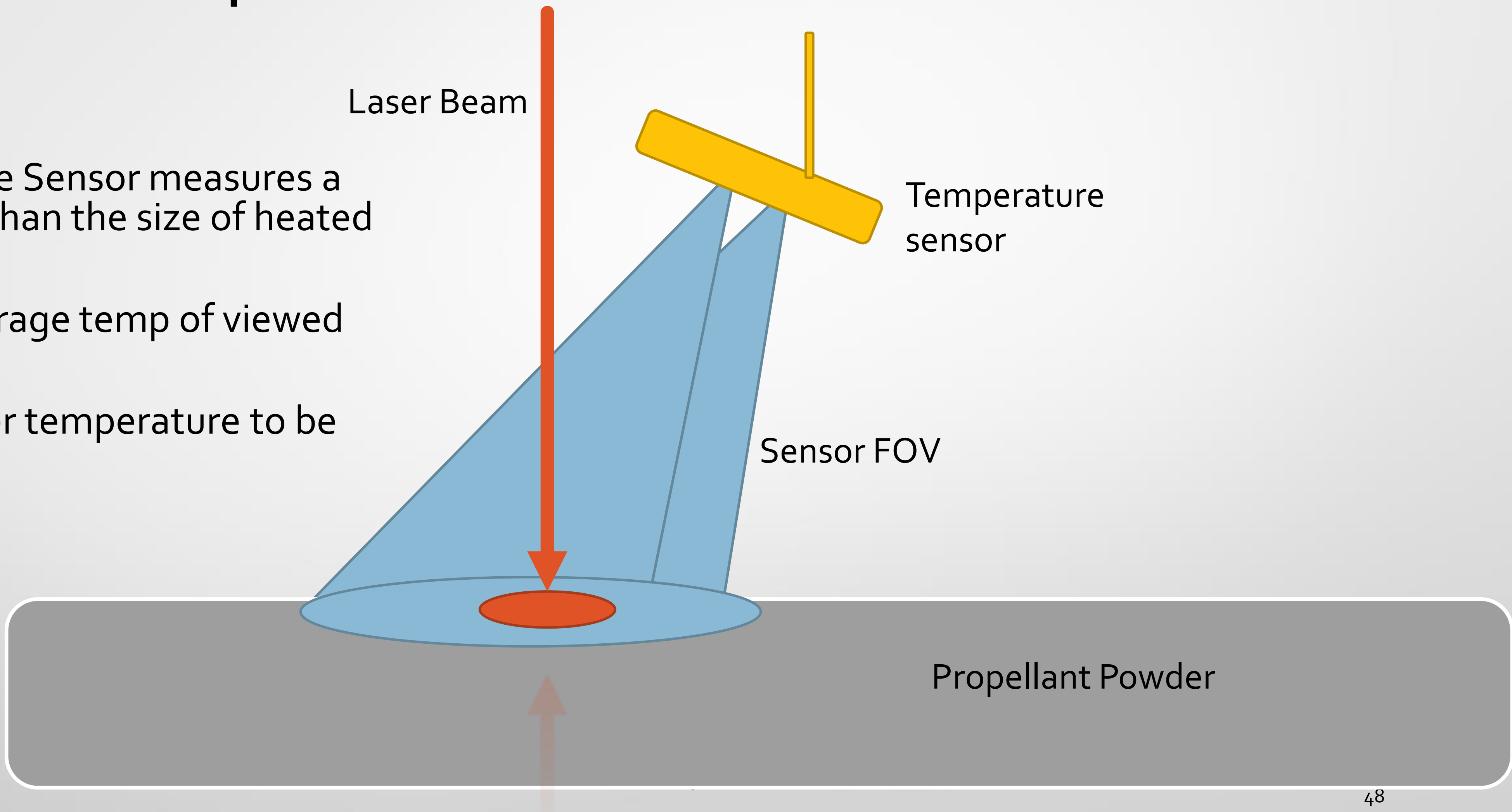
Propellant Thermal Model: Predictions



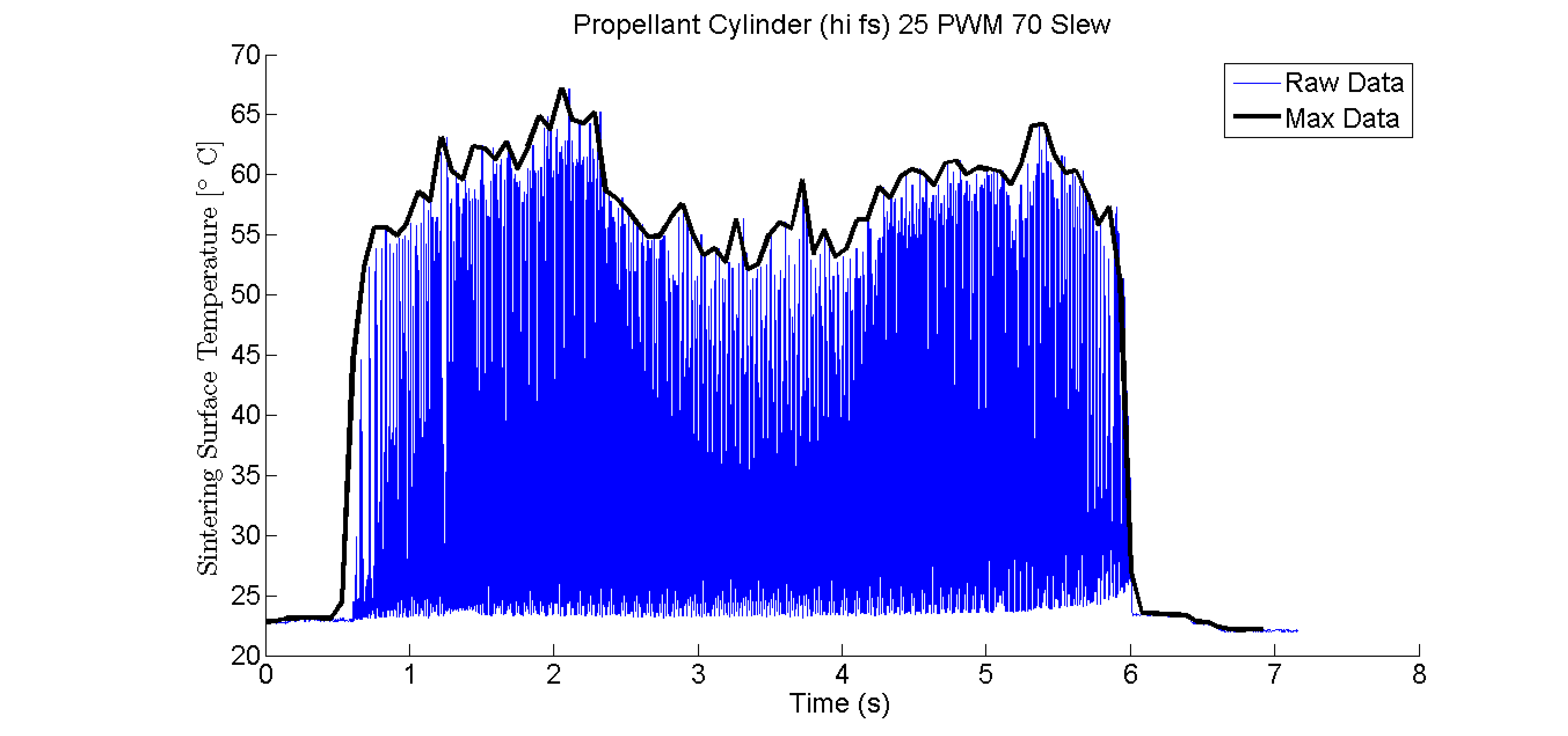


Sensor Operation and Model Validation

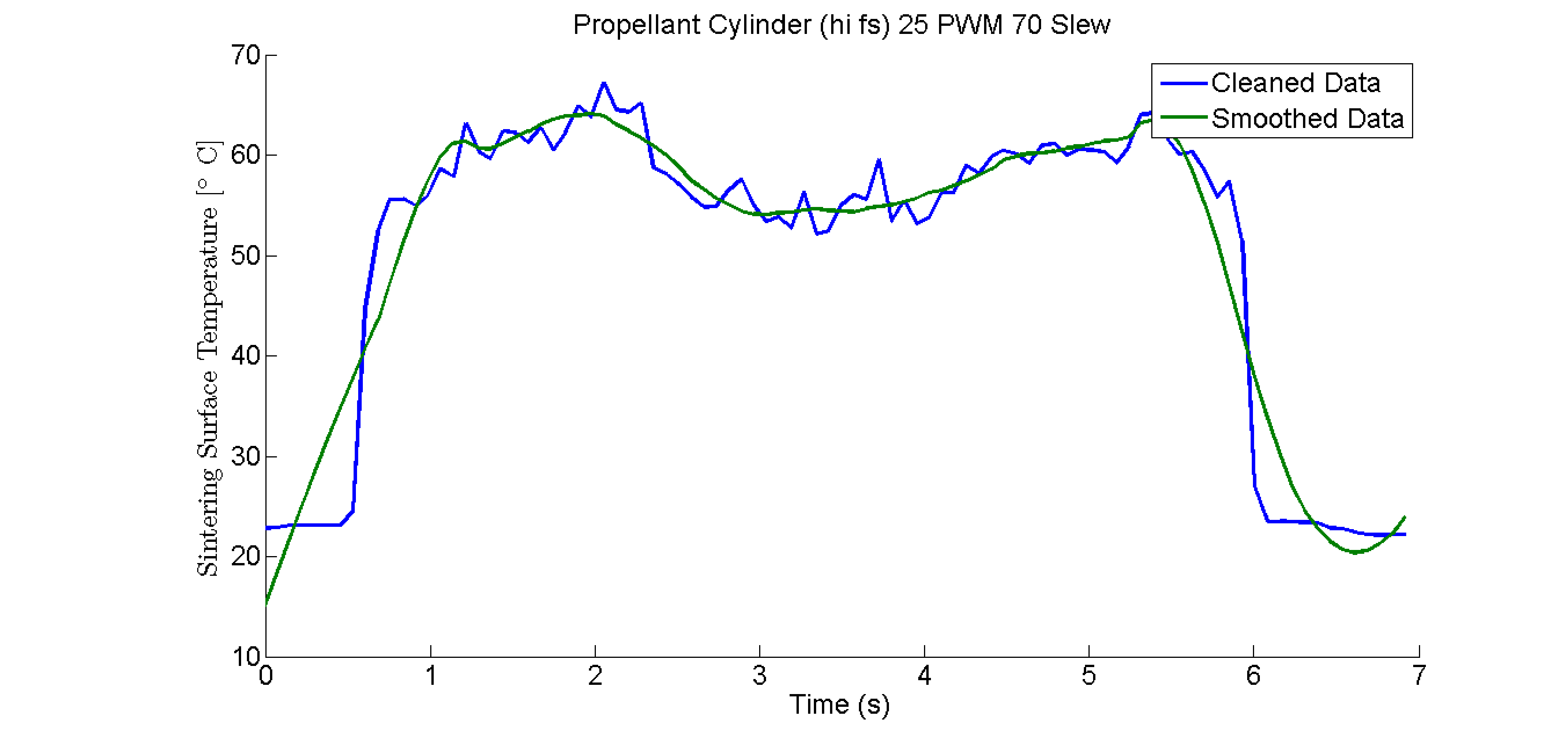
- Temperature Sensor measures a spot larger than the size of heated area
- Reports average temp of viewed area
- Causes lower temperature to be observed



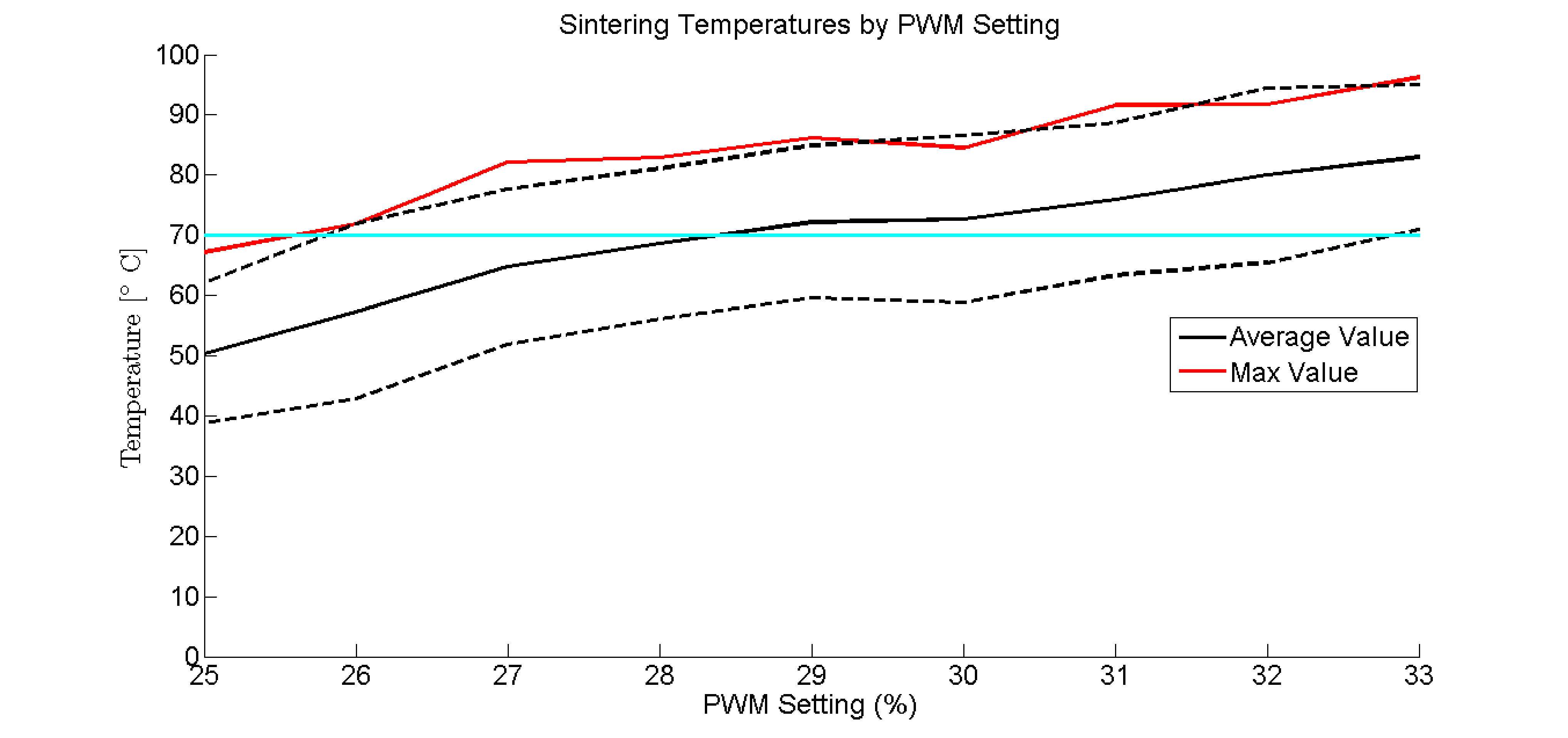
Sintering Model: Temp. Measurements



Sintering Model: Temp. Measurements



Sintering Model: Temp. Measurements



Propellant Test Results (Visual)

PWM: 25%
Slew: 70%

PWM: 26%
Slew: 70%

PWM: 27%
Slew: 70%

PWM: 28%
Slew: 70%

PWM: 29%
Slew: 70%

Increasing PWM

Material Properties: Microscopic Comparison

- Printed propellant less dense
- Both brittle, but casted is stronger

- Layers bonded, but obvious
  - Fracture occurs in shear along layers

Results Summary

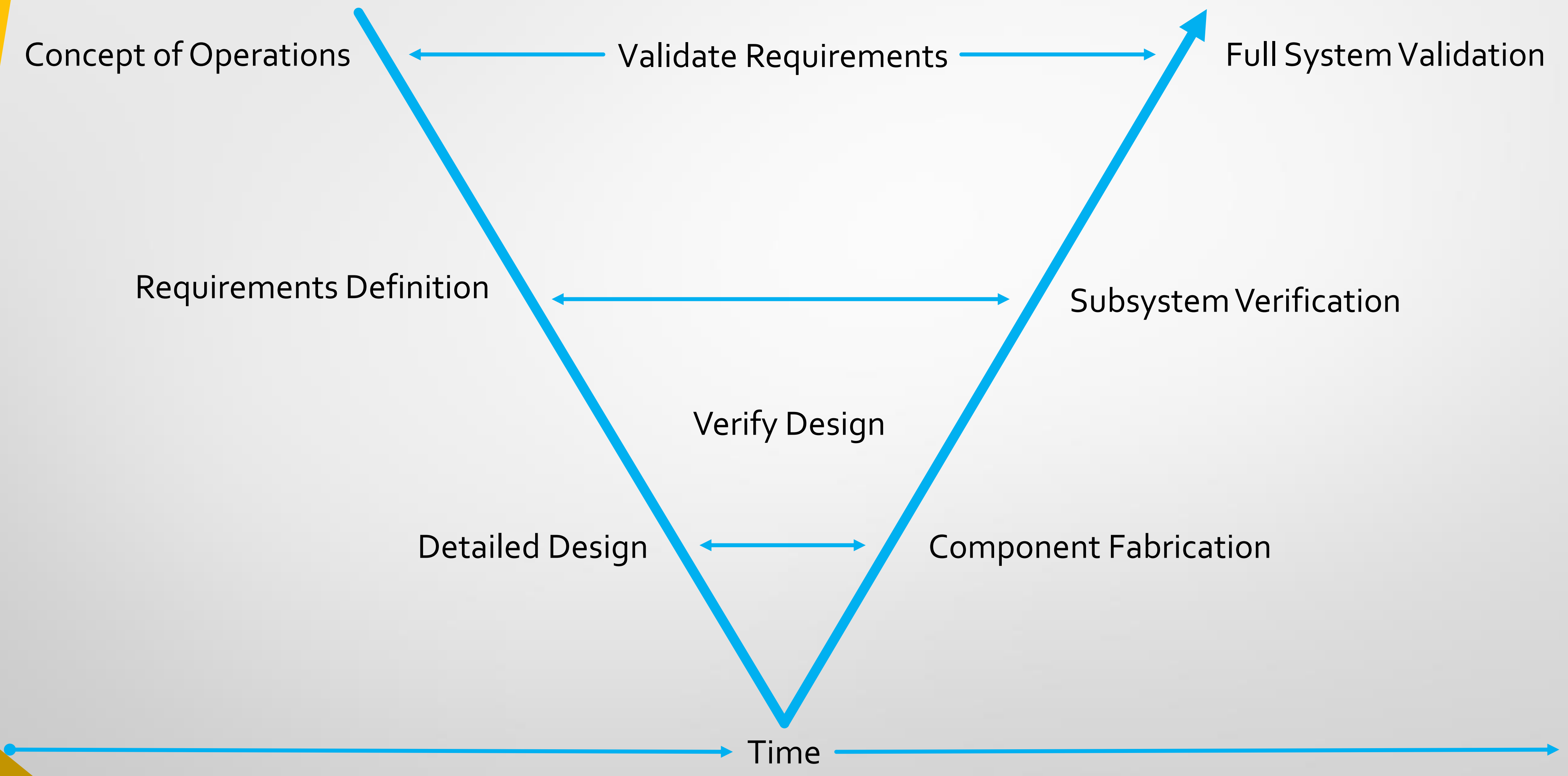
Proof of Concept – First ever 3D printed Solid Rocket Motor

Inert Sugar Print– Over 15 layers (~30mm) in star pattern printed during Symposium demo—2 hours to complete

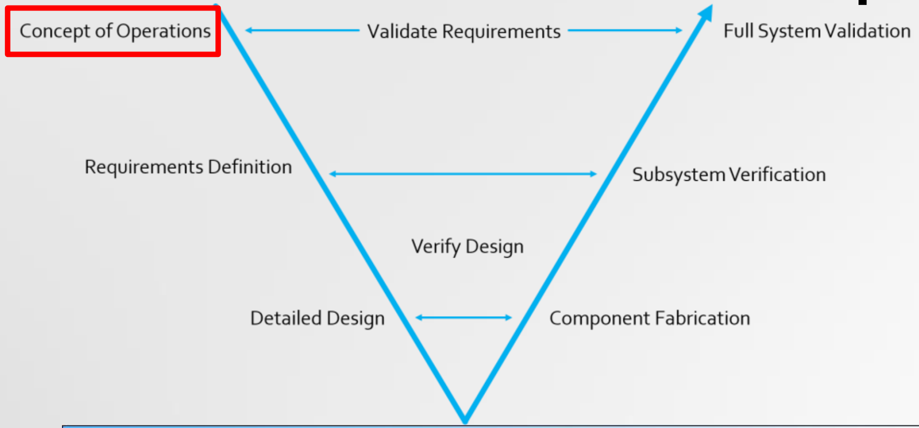
Material Comparison – printed propellant is lower quality than cast; still viable

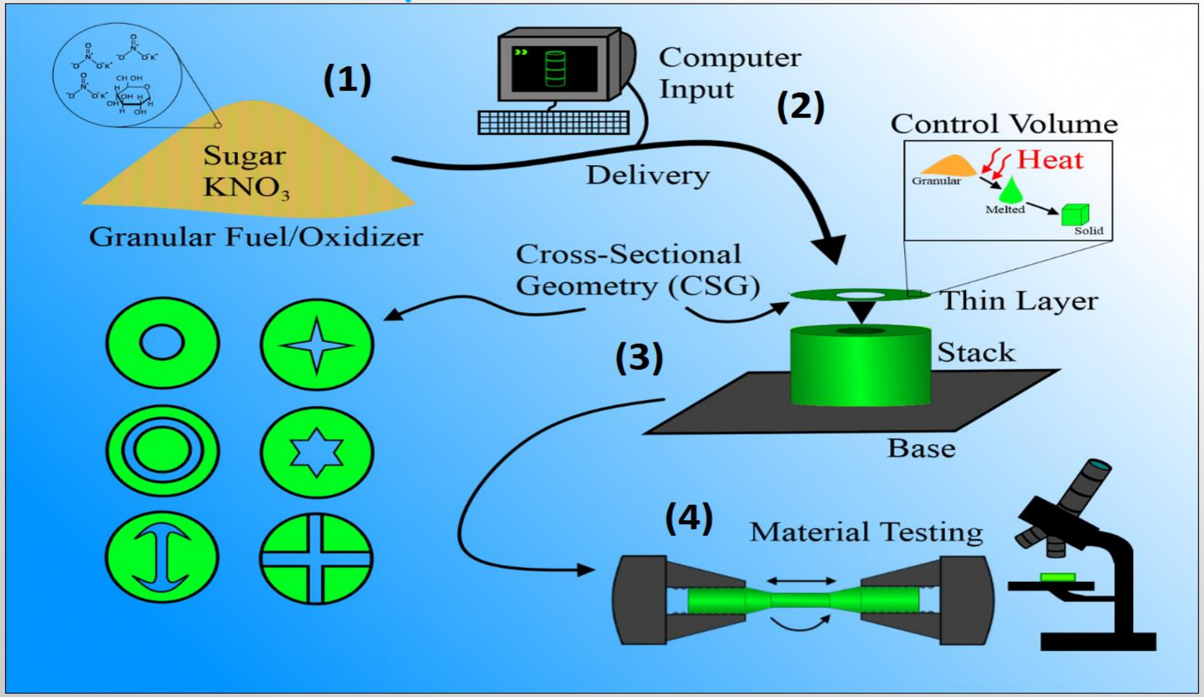
Systems Engineering

Systems Engineering Approach



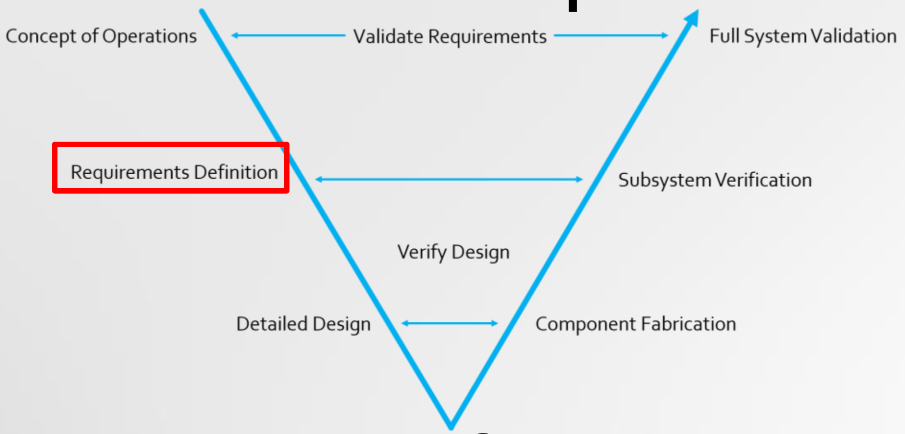
Concept of Operation





Major changes made early lead to a well defined system CONOPS with no major changes throughout the project

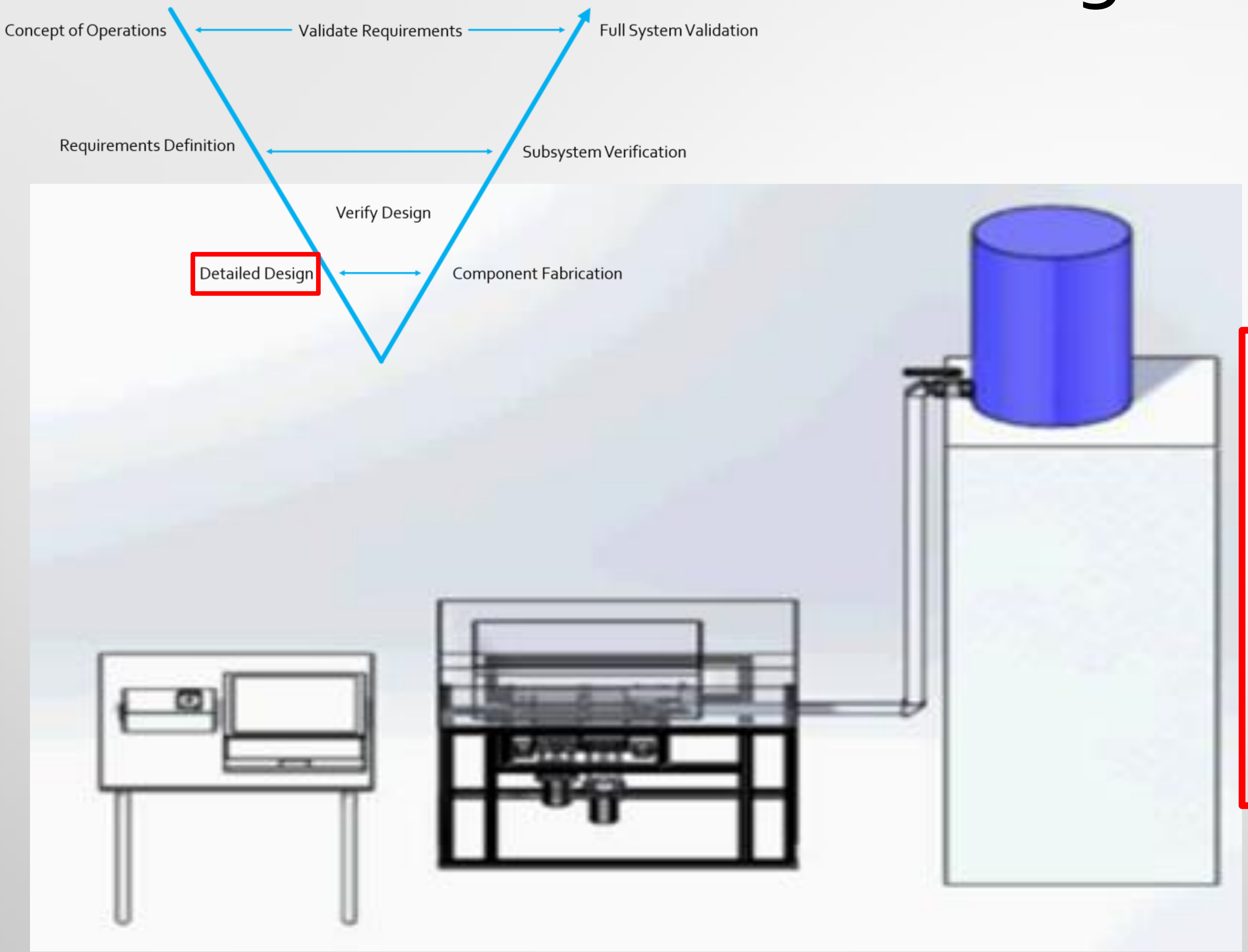
Requirements Definition



- FR 1: The manufacturing system shall be capable of manufacturing at least two layers of solid propellant
- FR 2: The manufacturing system shall be capable of automated additive manufacturing
- FR 3: The manufacturing system shall be verified through testing
- FR 4: The entire system shall be safe under normal operation

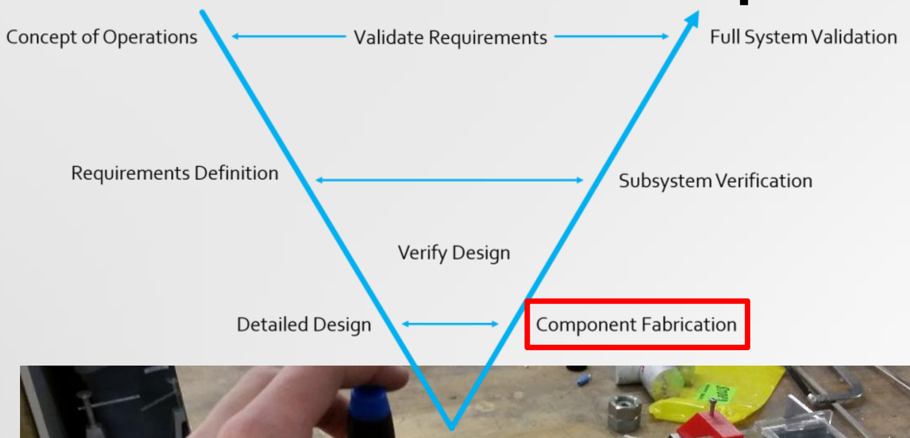
Clear and **continued communication** with SAS facilitated sound Functional Requirements throughout the project

Detailed Design



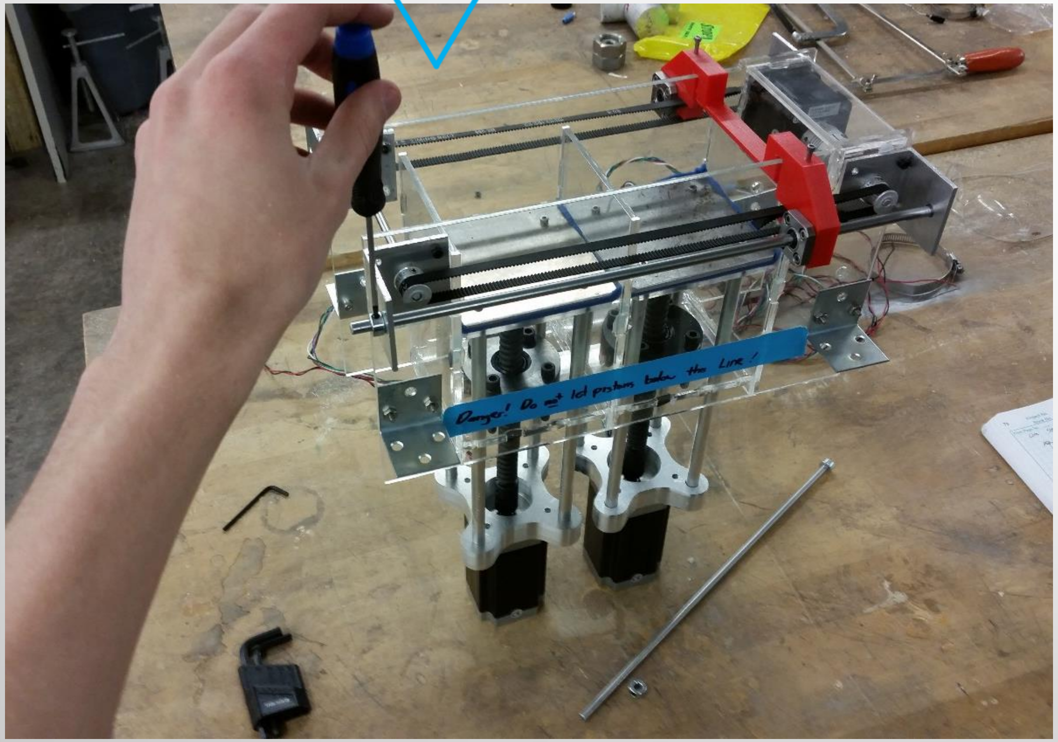
Changes Since CDR:
1. Safety system
2. Piston motion data acquisition
3. Propellant particle containment

Component Fabrication

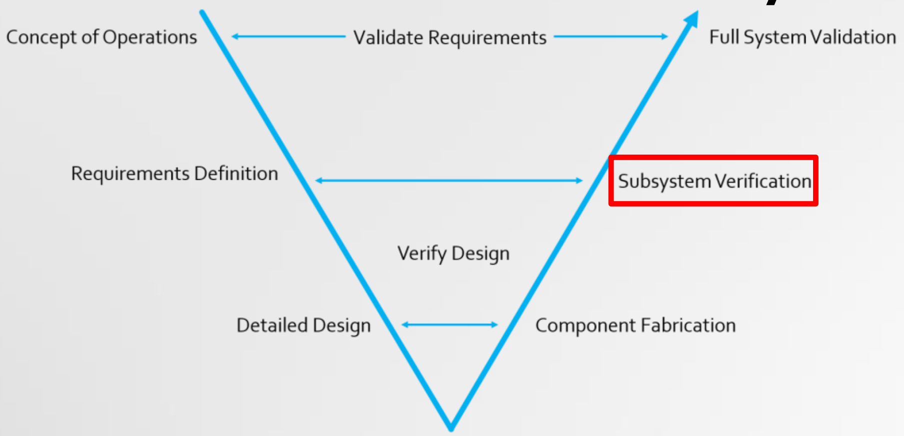


Fabrication Learning Curve:

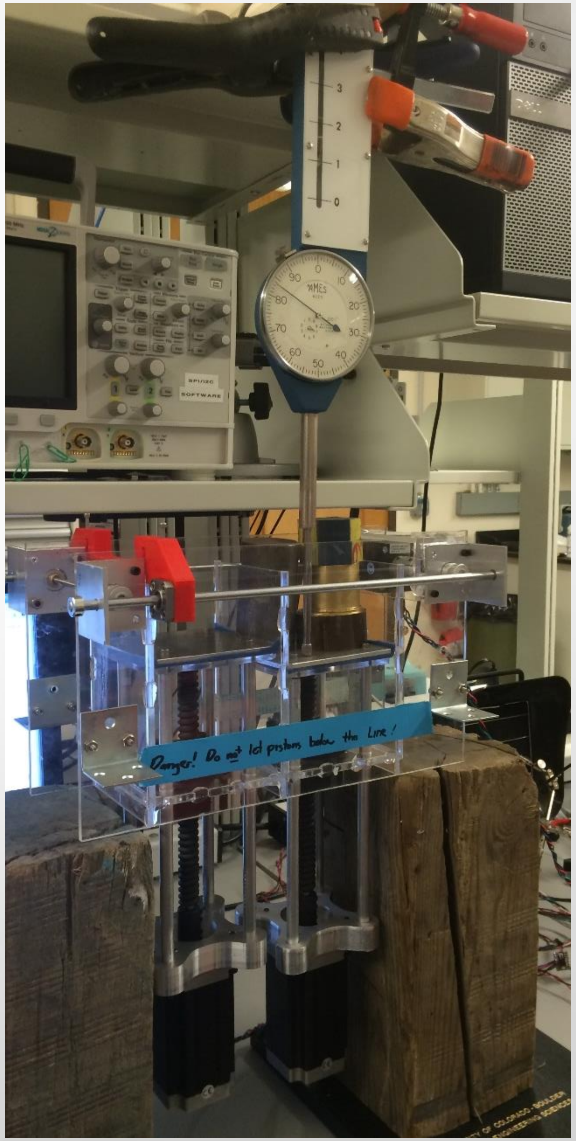
1. Acrylic tolerance issue
2. Bracket shipping time delays
3. Temperature sensor damages



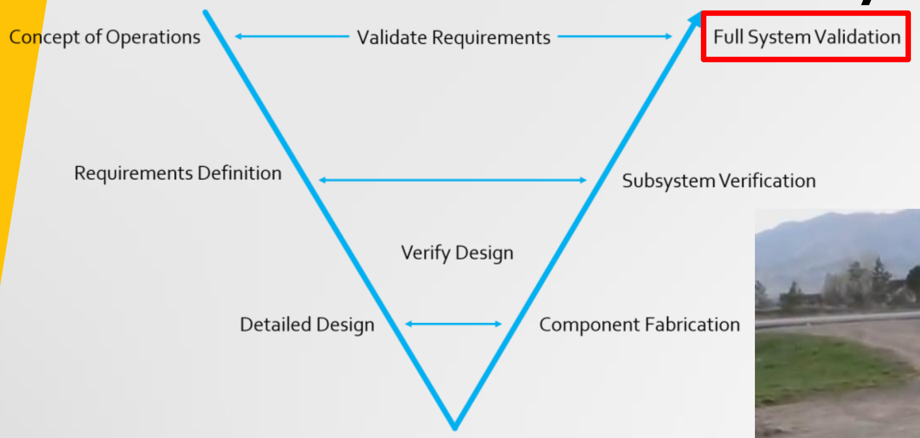
Subsystem Verification



1. Slew Rate Testing
2. CO_2 Power Output Testing
3. Powder Bed Testing
   - Rake Tests
   - Piston Tests



Full System Validation



Successful final print with more time the team would print additional motors

Project Management

Project Management

Approach

- More laid-back approach to try to reduce micromanaging
  - Main management focus was on meetings, client interaction, and communication between members
- Systems leads were designated, but team members tended to move to work on multiple systems as needed

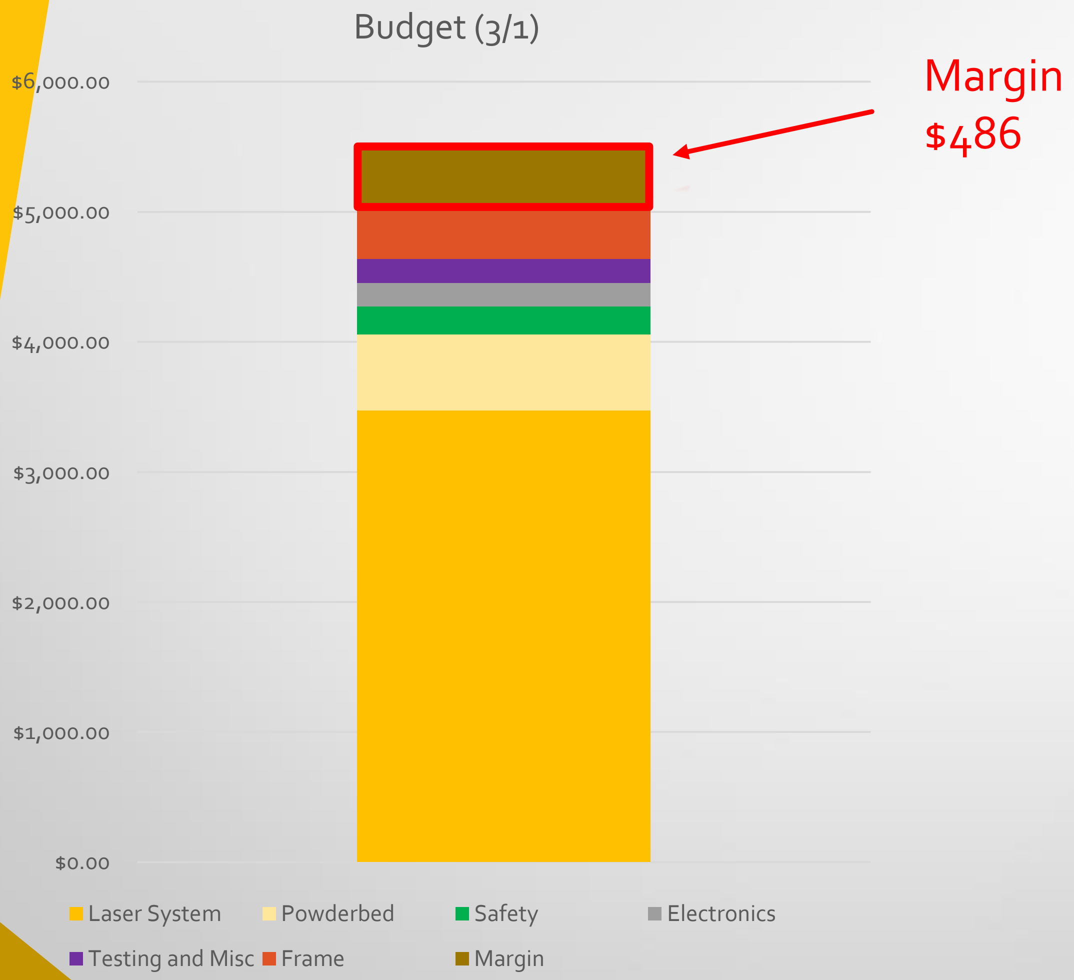
Successes

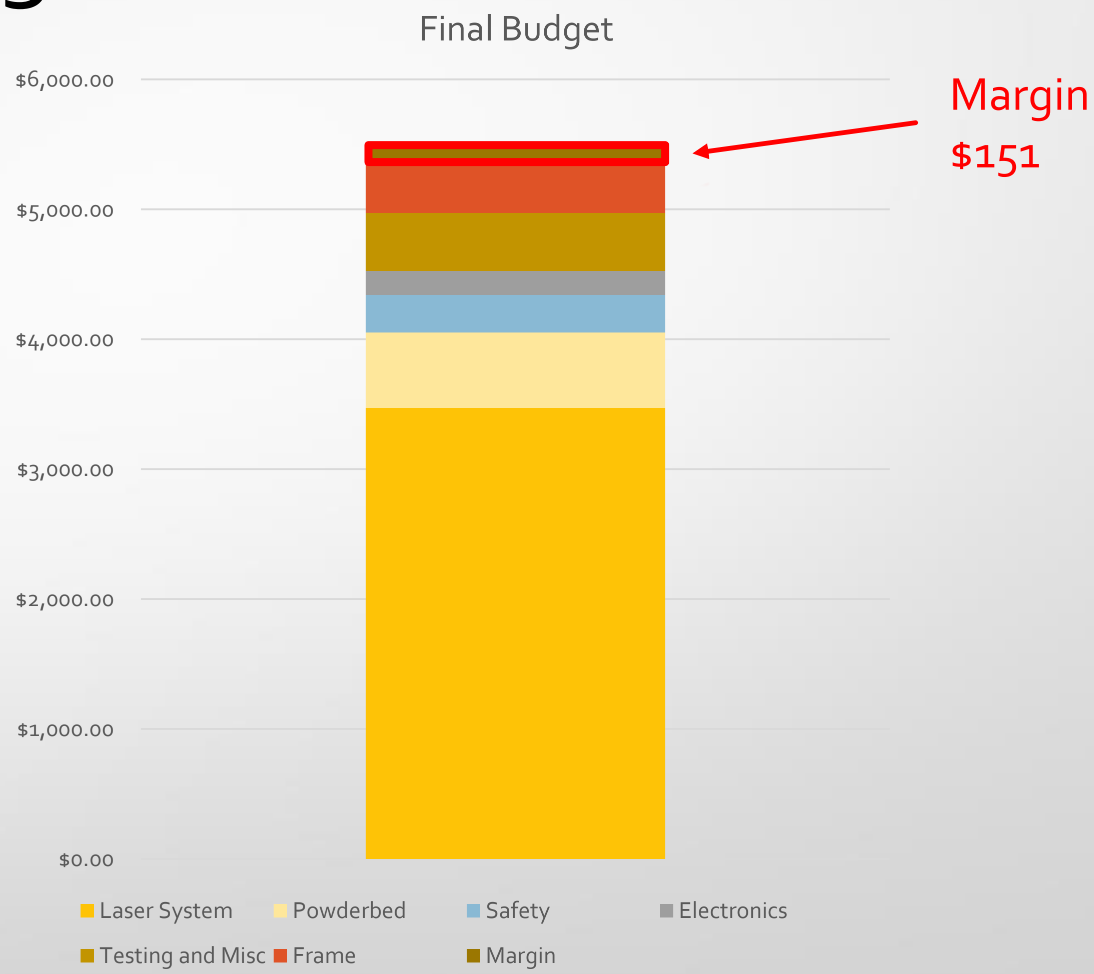
- Followed schedule fairly well
- Powder bed worked great/tolerances met
- 3D SRM was printed
- Happy customer/2nd gen project requested

Key Lessons Learned

- **Communication can make or break a project**
  - Action items help but only if they're utilized
  - The PM can help with communication, but it takes effort from the whole team
- **Tasks rarely get done on time, always plan with margin**
- **Its important to understand problems from other team members' perspectives**
- **Nature of the project held it back initially**
  - Research based
  - First-generation
  - Lack of direction/concept is new

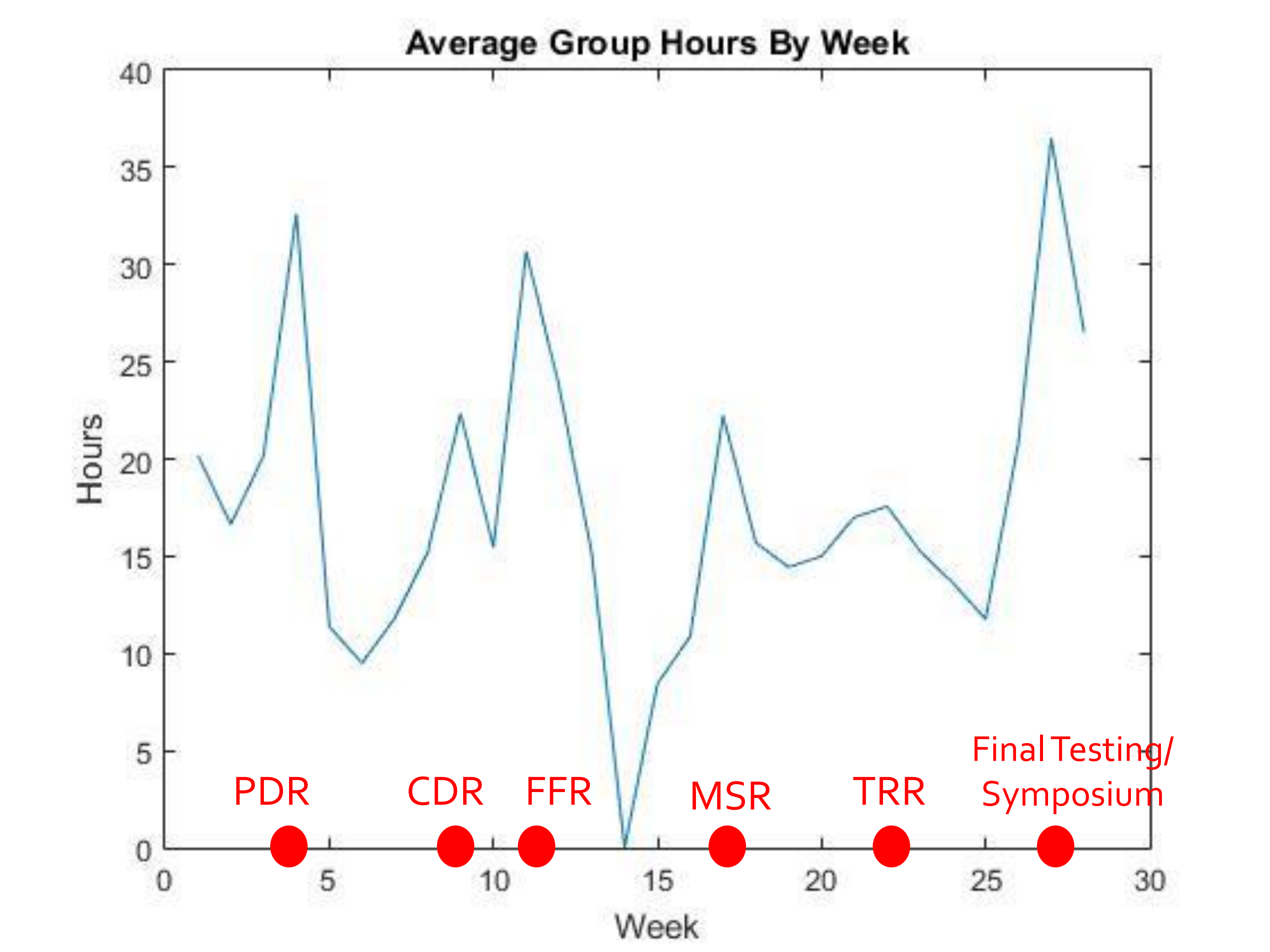
Budget





Purpose | Design Description | Test Overview & Results | Systems Engineering | Project Management

Industry Cost Analysis



Total Project Equivalent Cost	
Number of Team Members	8
Total Hours	3,925 (Actual)
Salary Estimate	$31.25/hour
Subtotal	$123,623
200% Overhead	$247,246
Material Cost	$5,350
Total Project Cost	**$252,600**

Acknowledgements

Team SPAM would like to thank everyone who made this project possible:

-Special Aerospace Services
-Dr. Ryan Starkey
-CU Boulder Aerospace PAB
-Ifuzion 3D Printing
-Andreas Bastian (OpenSLS)
-Richard Nakka Rocketry
-Frontier Astronautics

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Questions?

Back Up Slides

Powder Bed Tolerance Testing Results (BACKUP)

Print Piston Accuracy Test

trial	disp [mil]	disp [mm]	cumulat.	com [mm]	cumulat.	err [mm]	err [%]
1	77	1.9558	1.9558	1.98	1.98	-0.0242	-1.22222
2	76.5	1.9431	3.8989	1.98	3.96	-0.0369	-1.86364
3	75	1.905	5.8039	1.98	5.94	-0.075	-3.78788
4	78	1.9812	7.7851	1.98	7.92	0.0012	0.060606
5	75.5	1.9177	9.7028	1.98	9.9	-0.0623	-3.14646
6	76	1.9304	11.6332	1.98	11.88	-0.0496	-2.50505
7	77	1.9558	13.589	1.98	13.86	-0.0242	-1.22222
8	75	1.905	15.494	1.98	15.84	-0.075	-3.78788
9	77	1.9558	17.4498	1.98	17.82	-0.0242	-1.22222
10	76.5	1.9431	19.3929	1.98	19.8	-0.0369	-1.86364
11	74.5	1.8923	21.2852	1.98	21.78	-0.0877	-4.42929
12	77.5	1.9685	23.2537	1.98	23.76	-0.0115	-0.58081
13	74.5	1.8923	25.146	1.98	25.74	-0.0877	-4.42929
	MEAN	1.934308					

Print Piston Step Test

trial	disp [mil]	disp [mm]	cumulat.	com [mm]	cumulat.	err [mm]	err [%]
1	39	0.9906	0.9906	1	1	-0.0094	-0.94
2	-36	-0.9144	0.0762	-1	0	0.0856	-8.56
3	39	0.9906	1.0668	1	1	-0.0094	-0.94
4	-33	-0.8382	0.2286	-1	0	0.1618	-16.18
5	38	0.9652	1.1938	1	1	-0.0348	-3.48

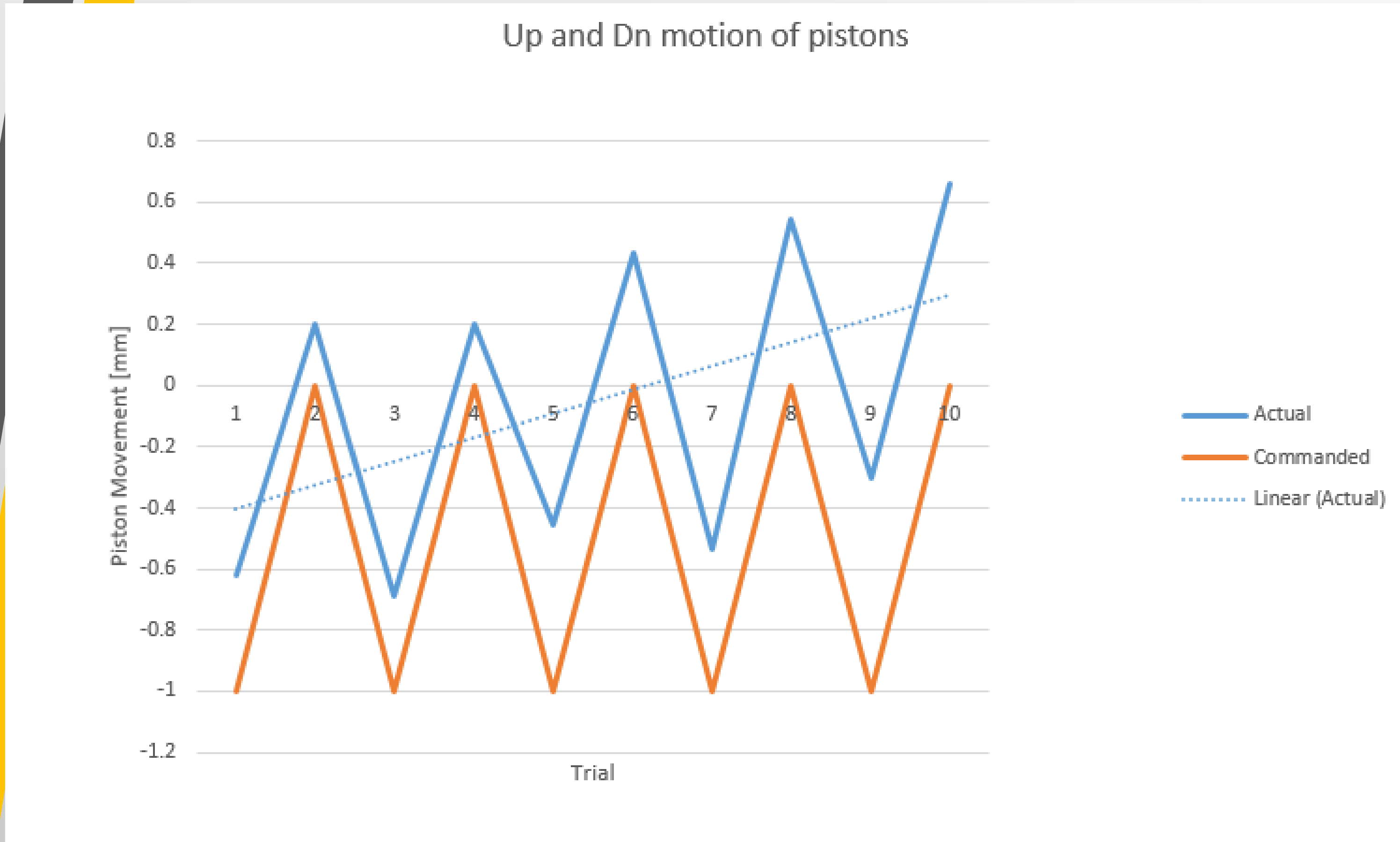
Reservoir Piston Accuracy Test

trial	disp [mil]	disp [mm]	cumulat.	com [mm]	cumulat.	err [mm]	err [%]
1	74.5	1.8923	1.8923	1.98	1.98	-0.0877	-4.42929
2	74.5	1.8923	3.7846	1.98	3.96	-0.0877	-4.42929
3	76	1.9304	5.715	1.98	5.94	-0.0496	-2.50505
4	75	1.905	7.62	1.98	7.92	-0.075	-3.78788
5	76.5	1.9431	9.5631	1.98	9.9	-0.0369	-1.86364
6	73	1.8542	11.4173	1.98	11.88	-0.1258	-6.35354
7	75.5	1.9177	13.335	1.98	13.86	-0.0623	-3.14646
8	76	1.9304	15.2654	1.98	15.84	-0.0496	-2.50505
9	76	1.9304	17.1958	1.98	17.82	-0.0496	-2.50505
10	76	1.9304	19.1262	1.98	19.8	-0.0496	-2.50505
11	75.5	1.9177	21.0439	1.98	21.78	-0.0623	-3.14646
12	75.5	1.9177	22.9616	1.98	23.76	-0.0623	-3.14646
13	76	1.9304	24.892	1.98	25.74	-0.0496	-2.50505
	MEAN	1.914769					

Reservoir Piston Step Test

trial	disp [mil]	disp [mm]	cumulat.	com [mm]	cumulat.	err [mm]	err [%]
1	-24.5	-0.6223	-0.6223	-1	-1	0.3777	-37.77
2	32.5	0.8255	0.2032	1	0	-0.1745	-17.45
3	-35	-0.889	-0.6858	-1	-1	0.111	-11.1
4	35	0.889	0.2032	1	0	-0.111	-11.1
5	-26	-0.6604	-0.4572	-1	-1	0.3396	-33.96
6	35	0.889	0.4318	1	0	-0.111	-11.1
7	-38	-0.9652	-0.5334	-1	-1	0.0348	-3.48
8	42.5	1.0795	0.5461	1	0	0.0795	7.95
9	-33.5	-0.8509	-0.3048	-1	-1	0.1491	-14.91
10	38	0.9652	0.6604	1	0	-0.0348	-3.48

Powder Bed Tolerance Testing Results (BACKUP)



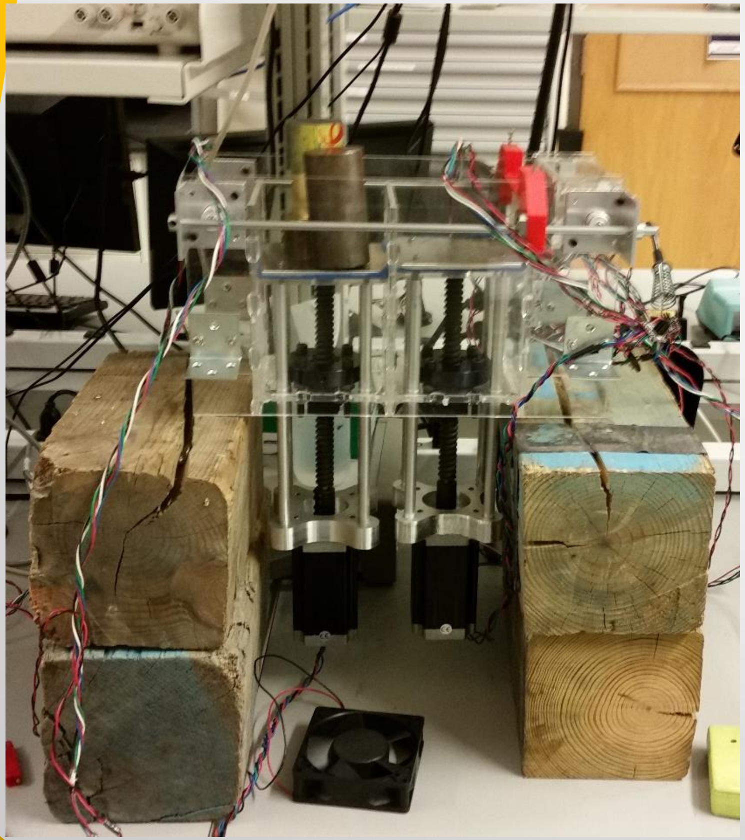
*Positive down, negative up

Slow increase of actual position relative to commanded position suggests the system has a harder time moving up than down

Relative error can be as high as 37%

The system does not rely on up and down motion, only continuous motion in one direction (see main slides for results)

Requirement 2.4.1.2/2.4.2.2: Pistons shall support 2.5kg + own weight (BACKUP)

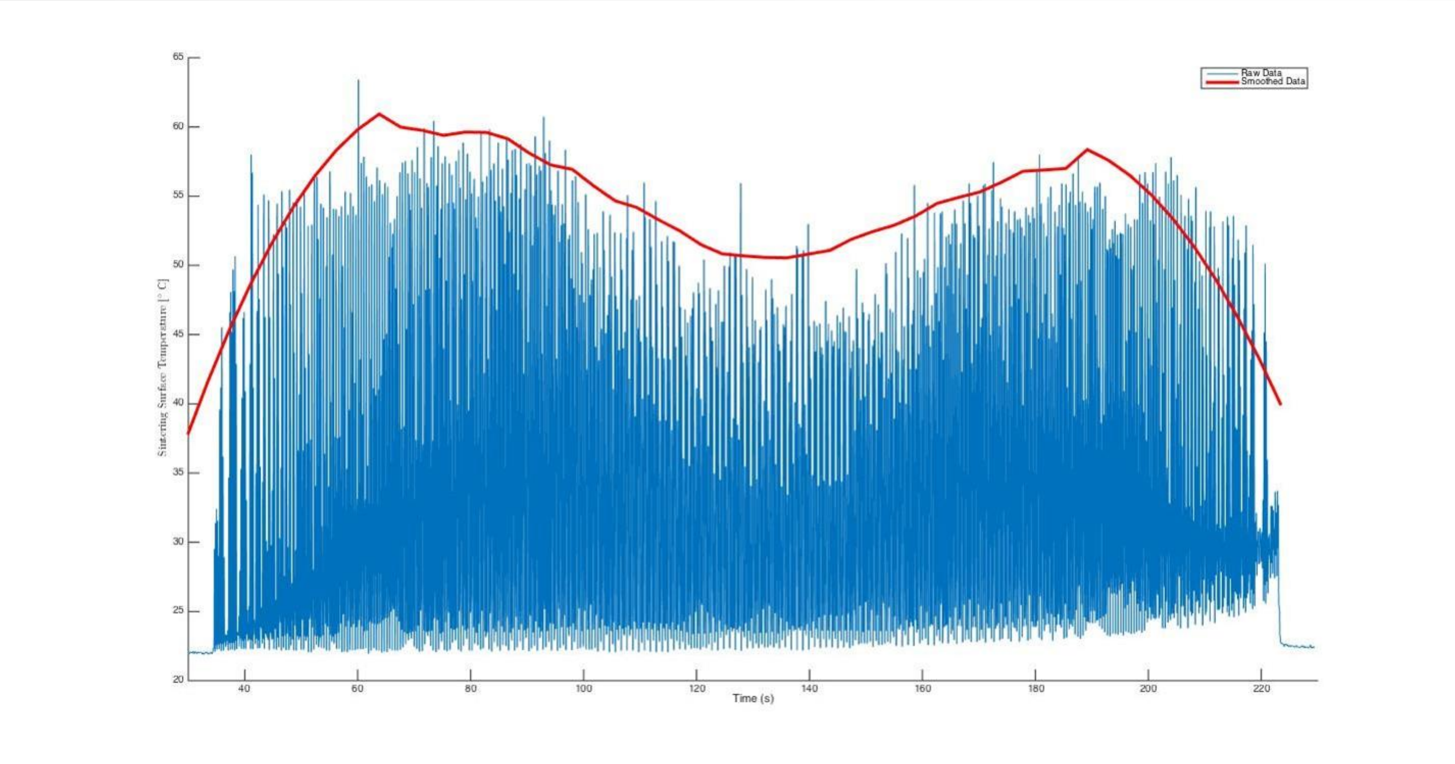


- Scrap metal taken from machine shop and massed:

Description	MASS (kg)
Hexagonal steel	0.47
Short round copper	0.62
Tall round copper	1.02
Round brass	0.45
TOTAL	2.56

- Empirical evidence shows pistons support the load and can lift without difficulty

Requirement 2.4.5: Each cycle shall take less than 5 minutes (BACKUP)



Nominal engrave job:
~195 second

5 min = 300 sec

Time left = 300 – 195 = 105

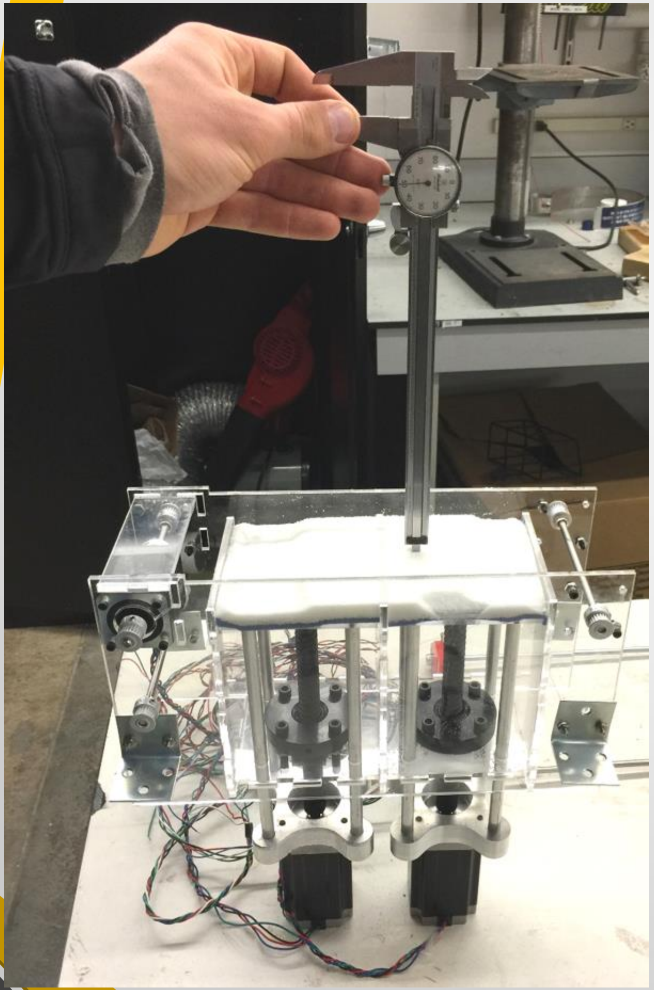
Nominal PB cycle << 105 sec

Depends heavily on geometry and cutter DPI but is generally less than 5 min

Requirement 2.4.1.4: Reservoir shall deliver 150% of powder needed (BACKUP)

150% by volume.
Volume is driven by vertical motion of the pistons.
Software has a variable that controls how much more vertical distance the reservoir covers.
For most prints this is set at 1.3 (130%) but there is no limitation on how large this value can be.
This value can be fully controlled by the user.

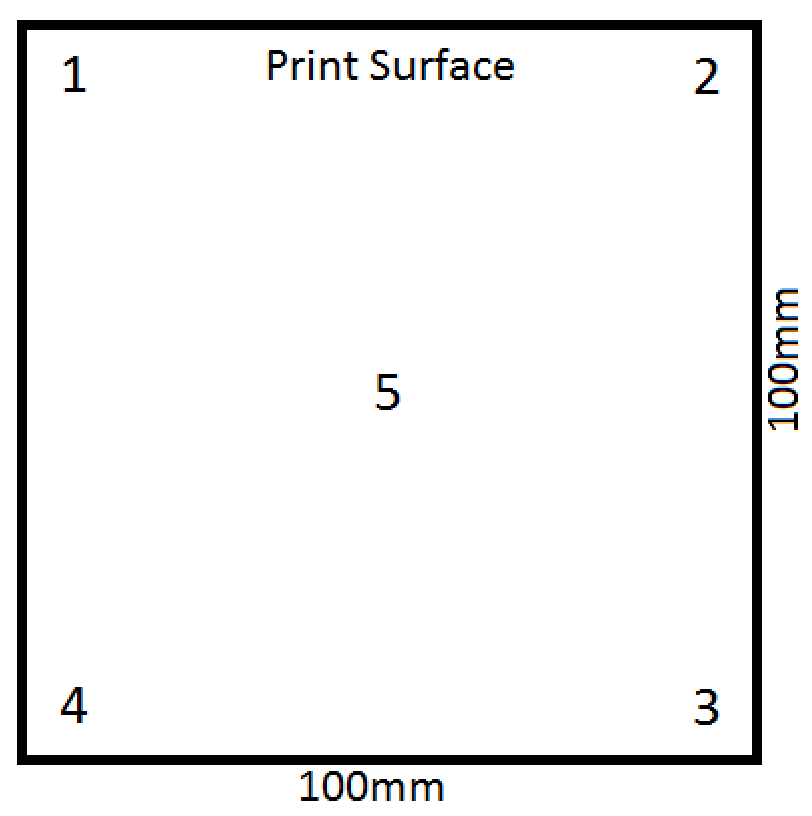
Rake Tolerance Testing



1. Level pistons and place in a known position
2. Fill both pistons with powder
3. Run a powder bed cycle
4. Measure layer depth at corners and center

Requirement ID	Description
3.7	Rake performance shall be characterized through depth measurements

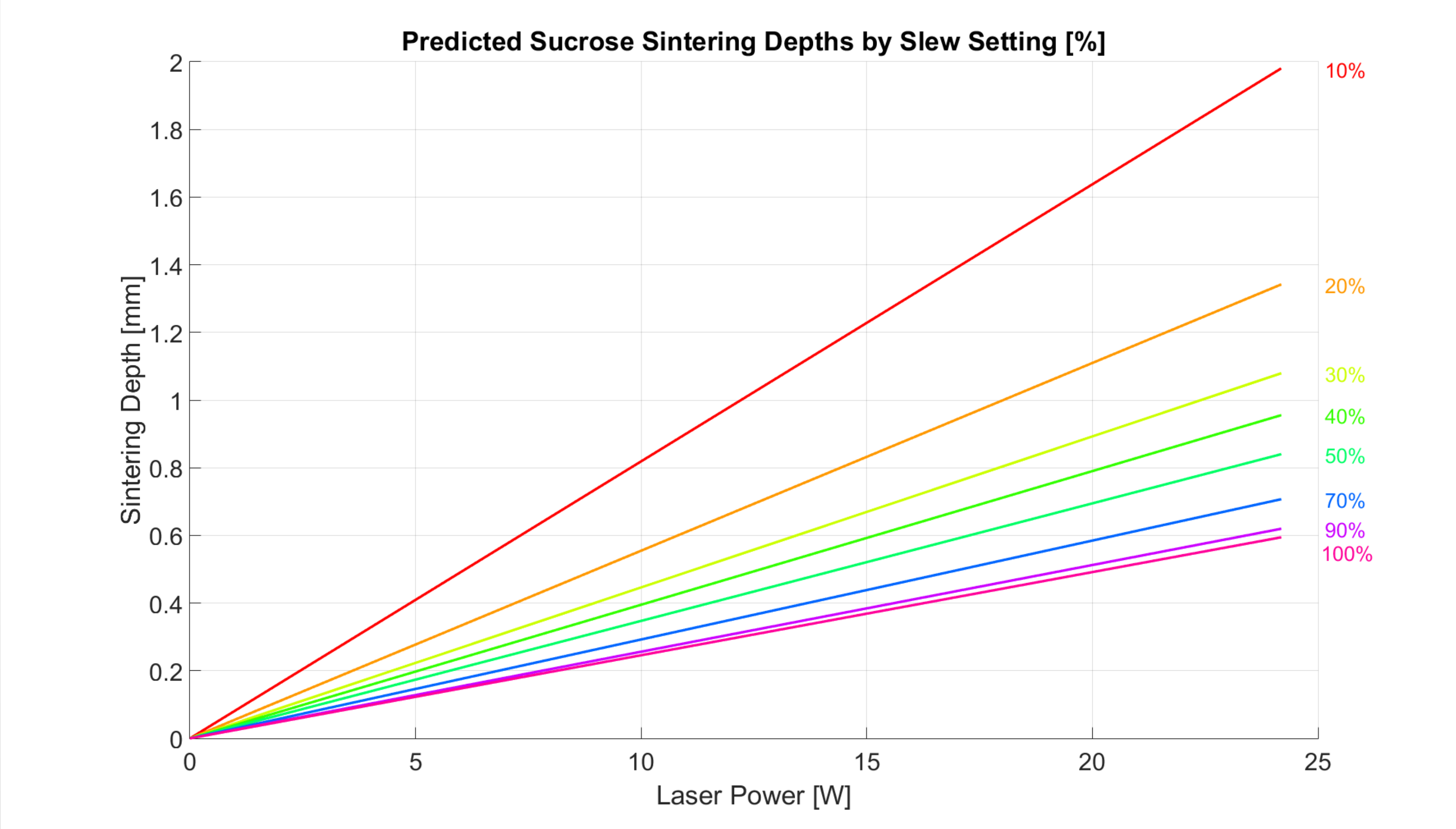
Rake Tolerance Testing Results



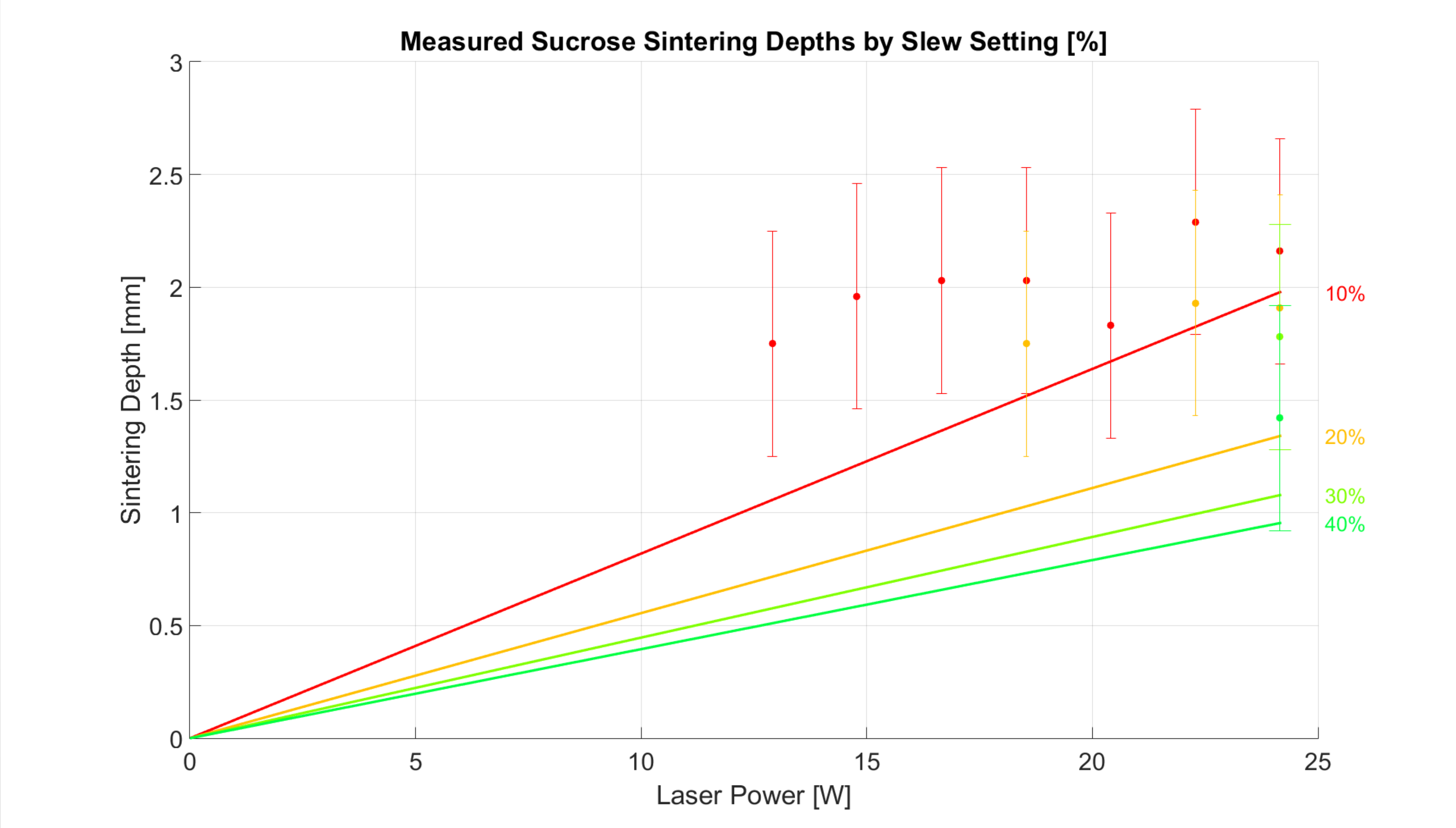
Trial	1 [in]	2 [in]	3 [in]	4 [in]	5 [in]
BASE					
1 (ΔZ)					
2 (ΔZ)					
3 (ΔZ)					
4 (ΔZ)					

Data biases towards…
This implies…
This affects us like…

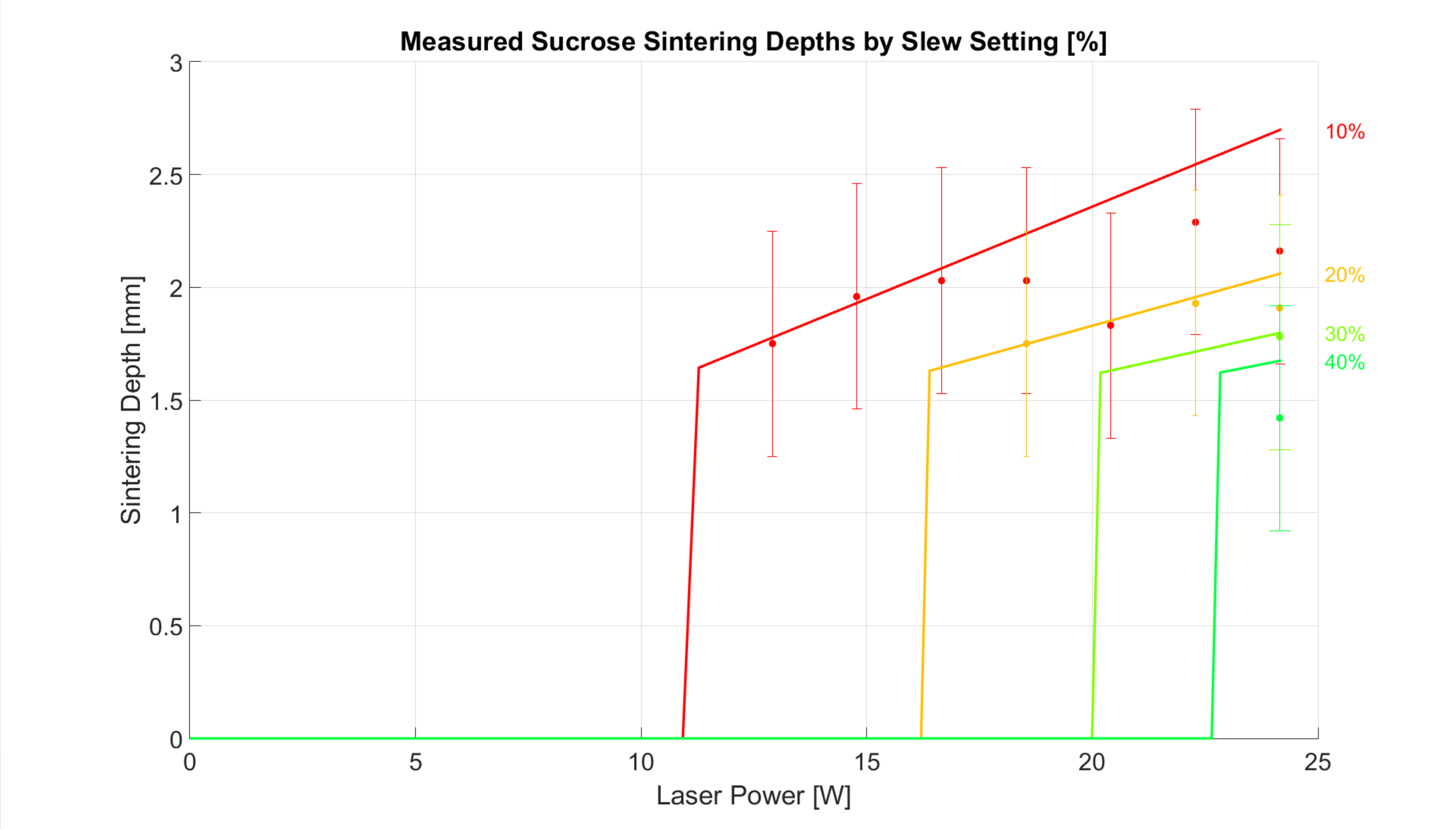
Sintering Model: Sucrose Predictions



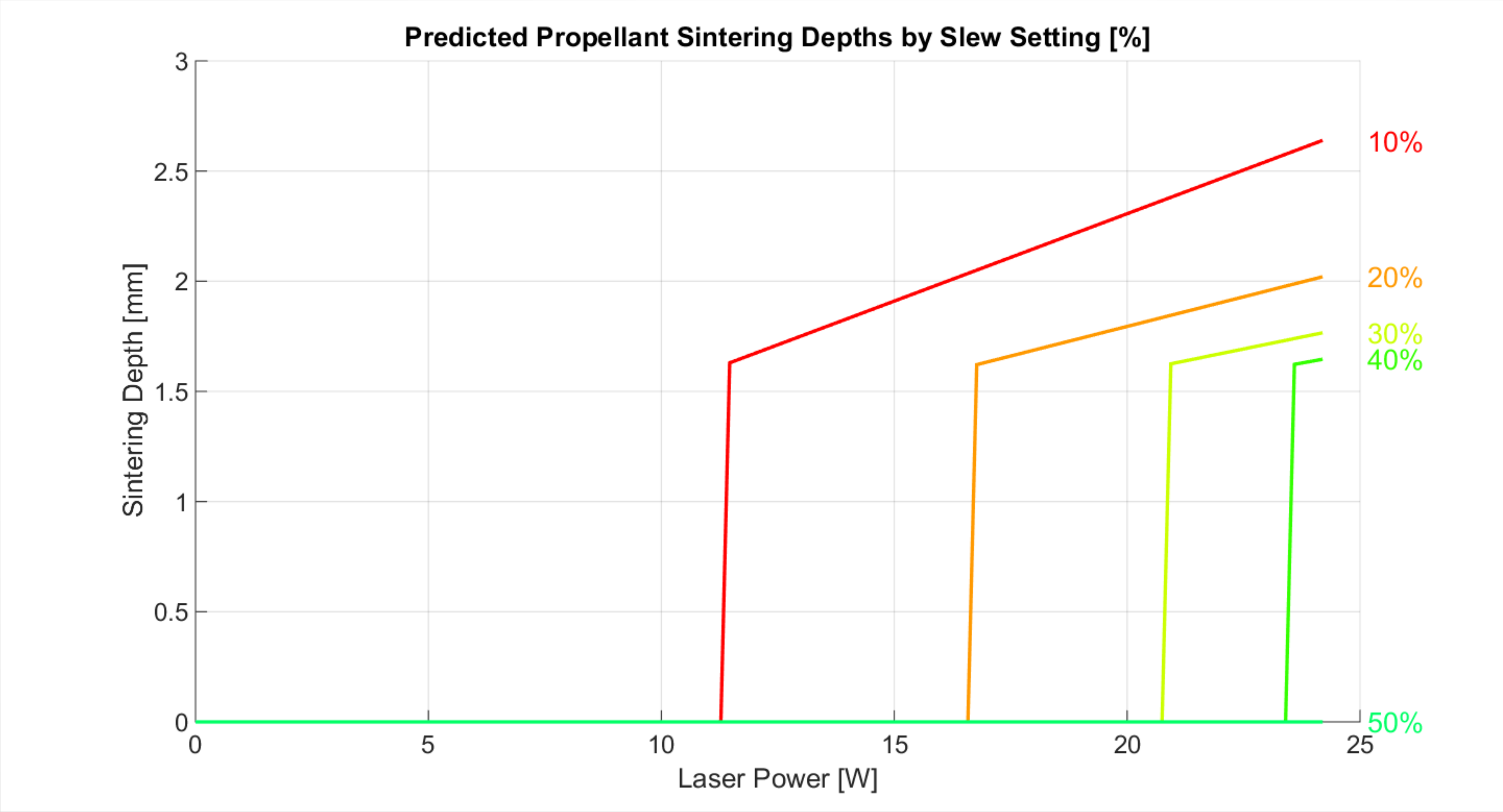
Sintering Model: Sucrose Measurements



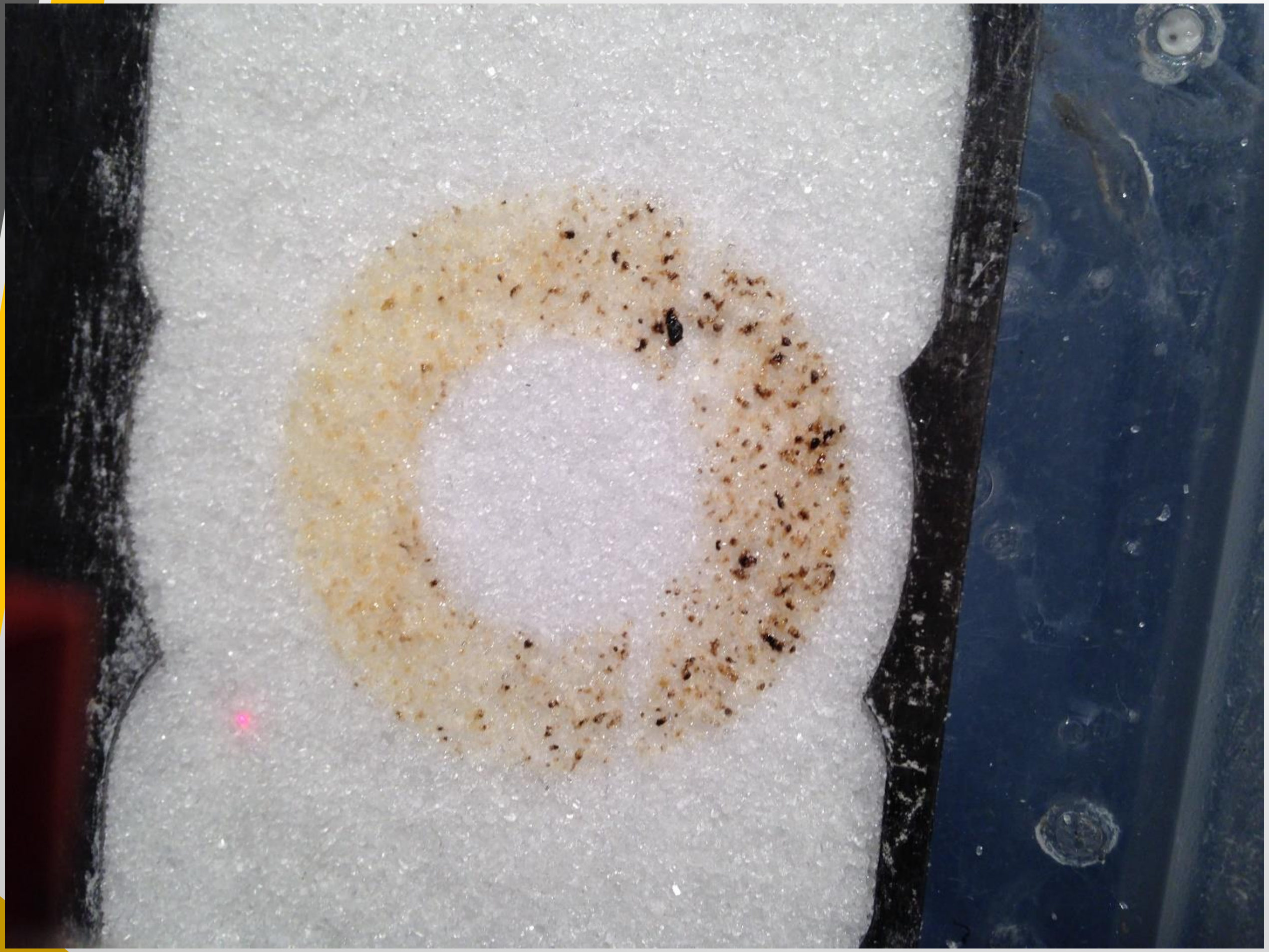
Sintering Model: Sucrose Measurements



Sintering Model: Propellant Predictions



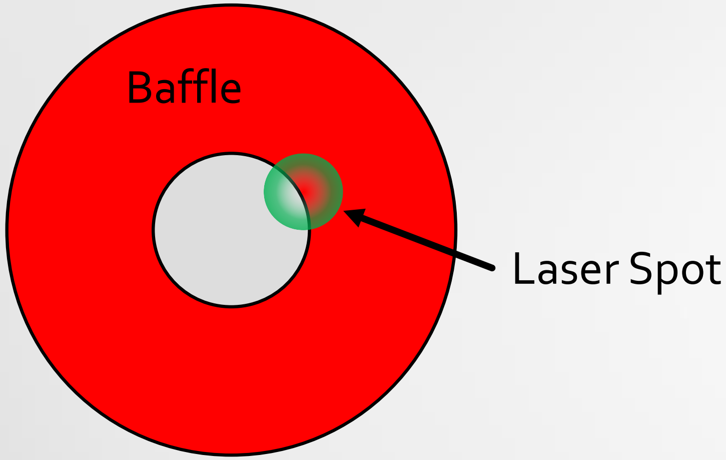
Sintering Model: Propellant Predicament



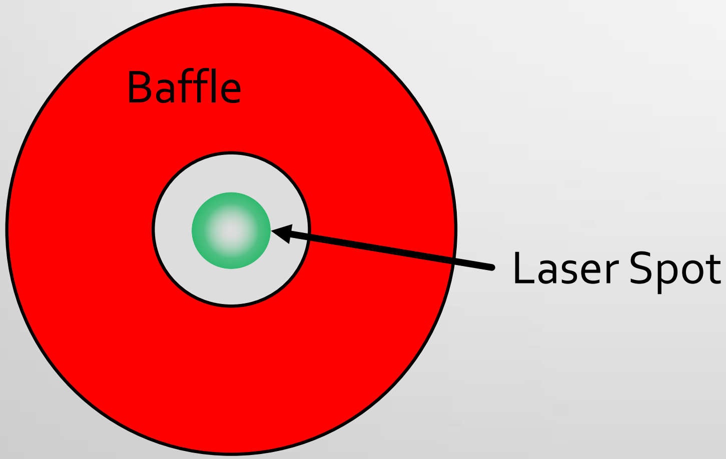
- Coarse KNO_3 and Sucrose showed regularly uneven sintering
- Black spots appeared randomly
- Ignition starts when black spots grow too large (get too hot)
- Caused by non-uniformity in fuel mixture due to poor mixing
- Switched to Fine Powder

Sintering Model: Mirror Alignment Issues

Before Alignment:

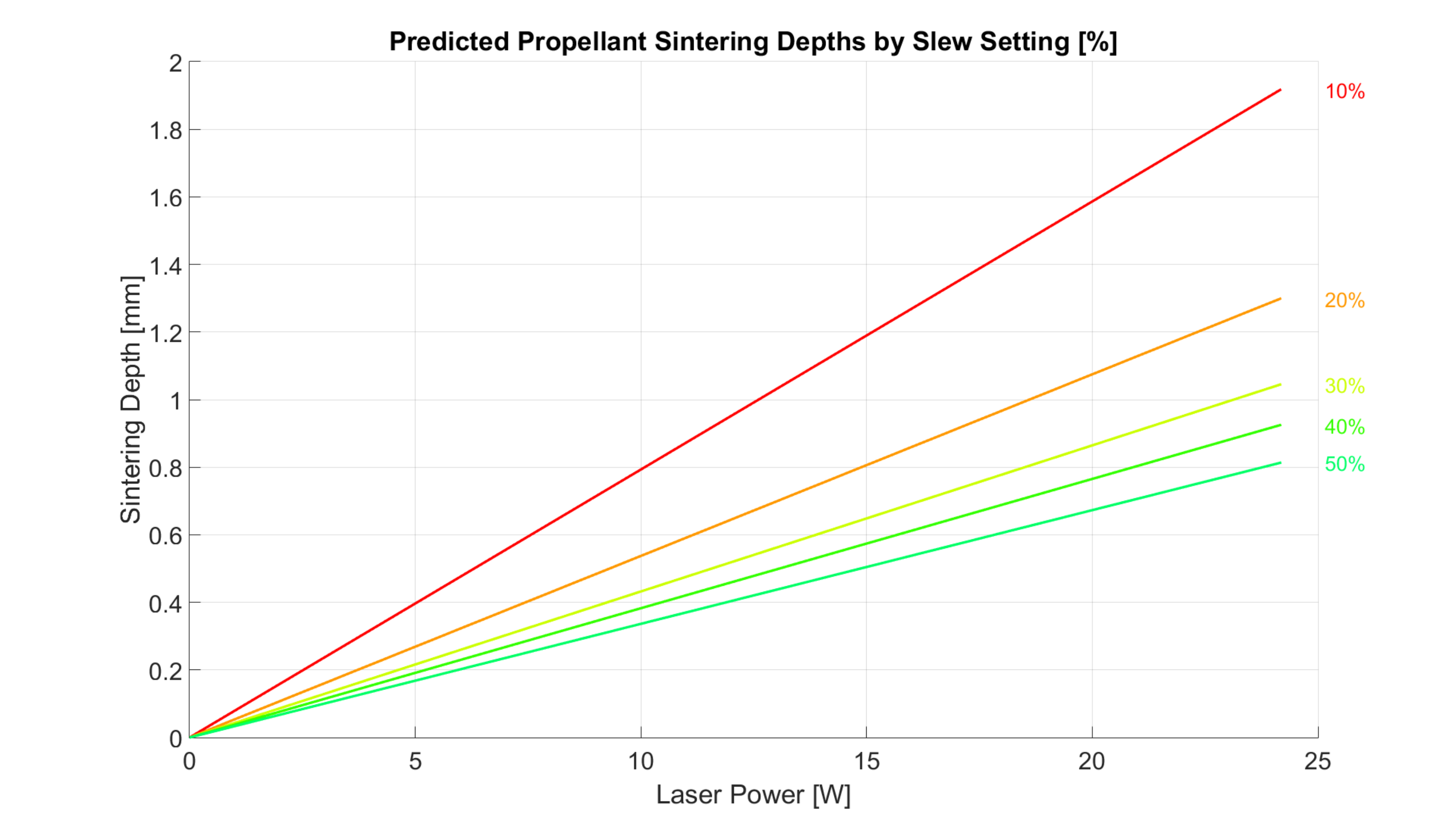


After Alignment:

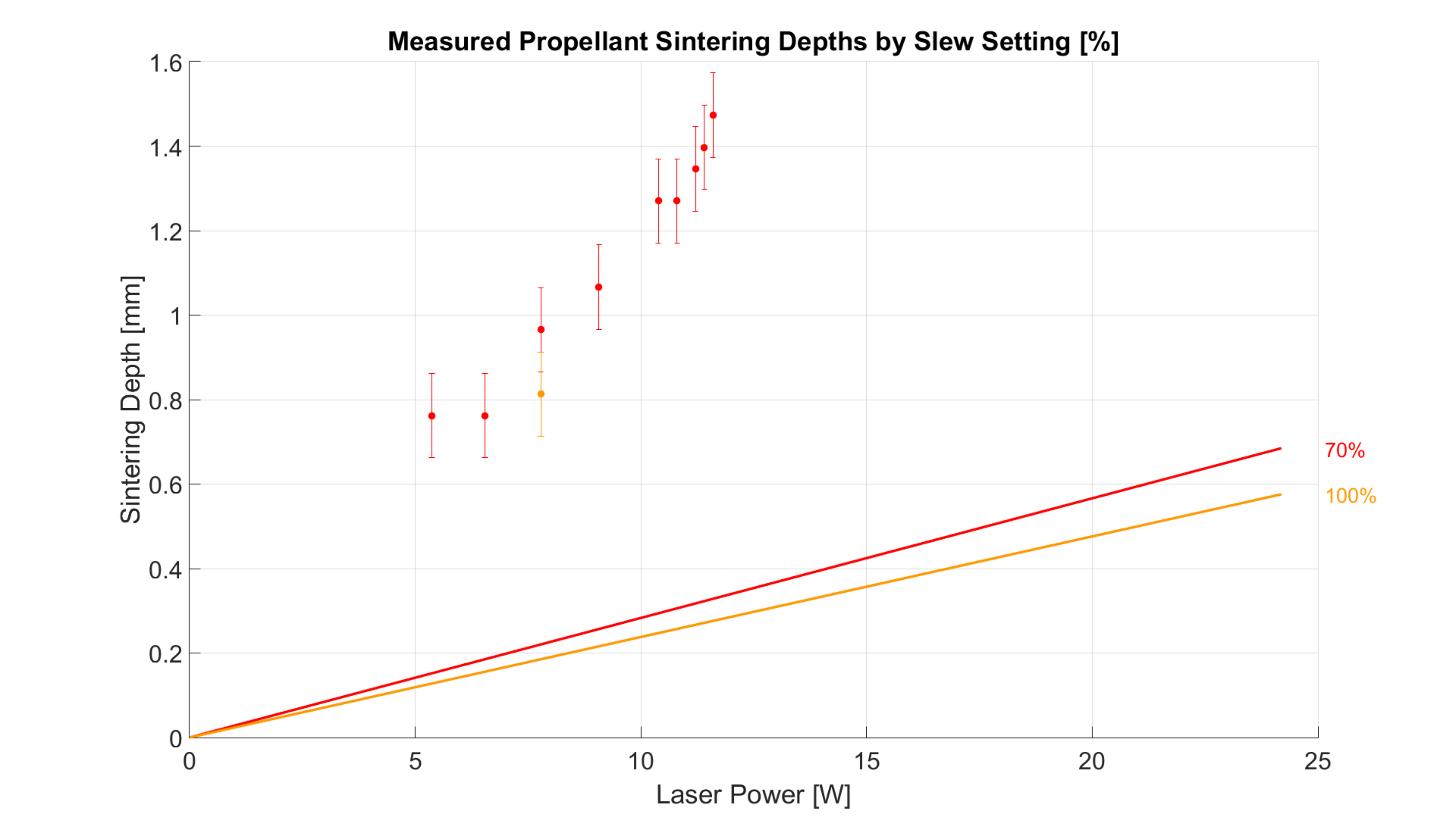


- Biggest Source of error in our measurements
- Laser Spot was obscured by baffle
- Resulted in lower power and different sintering behavior

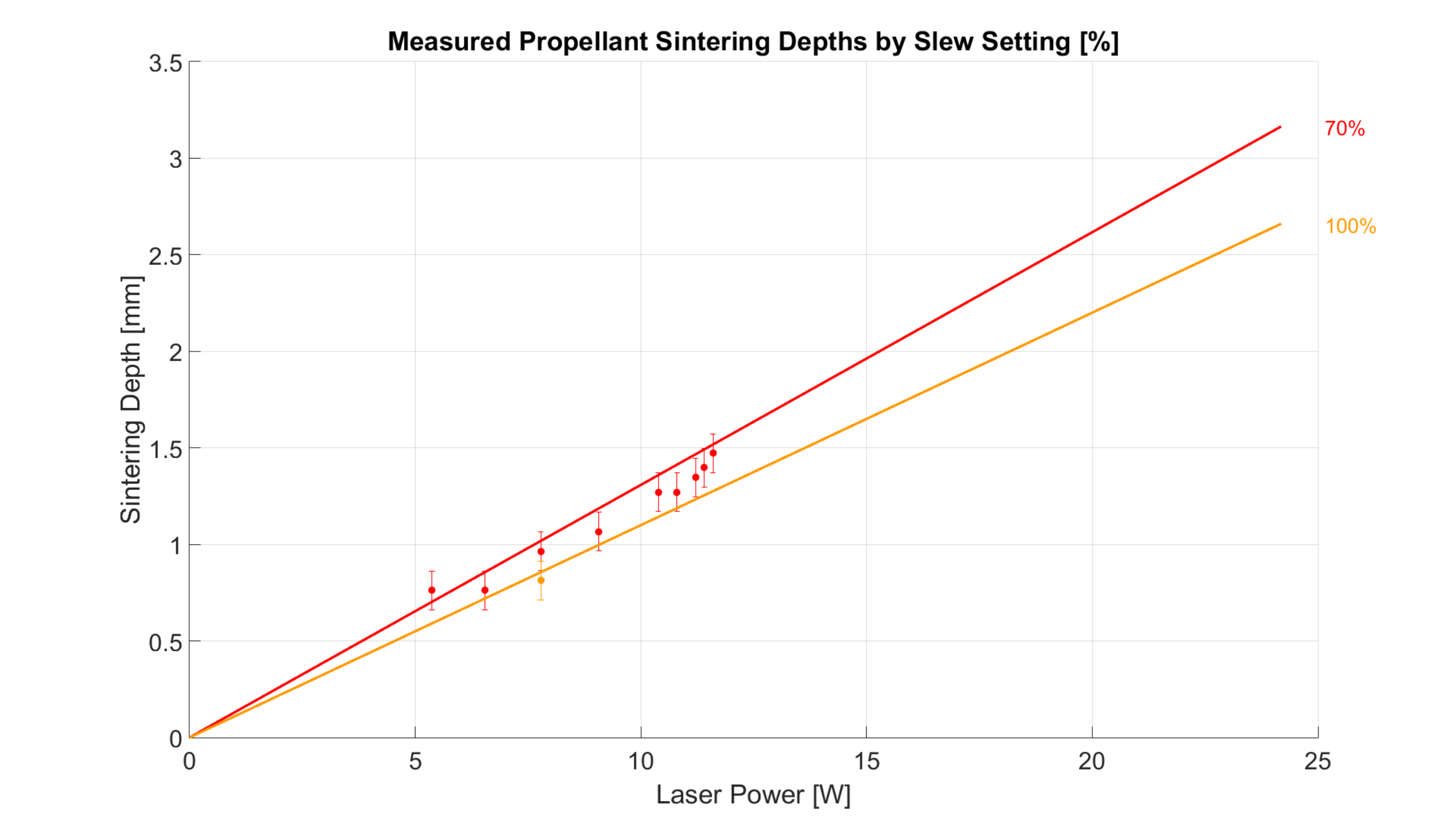
Sintering Model: Propellant Predictions



Sintering Model: Propellant Measurements



Sintering Model: Propellant Measurements



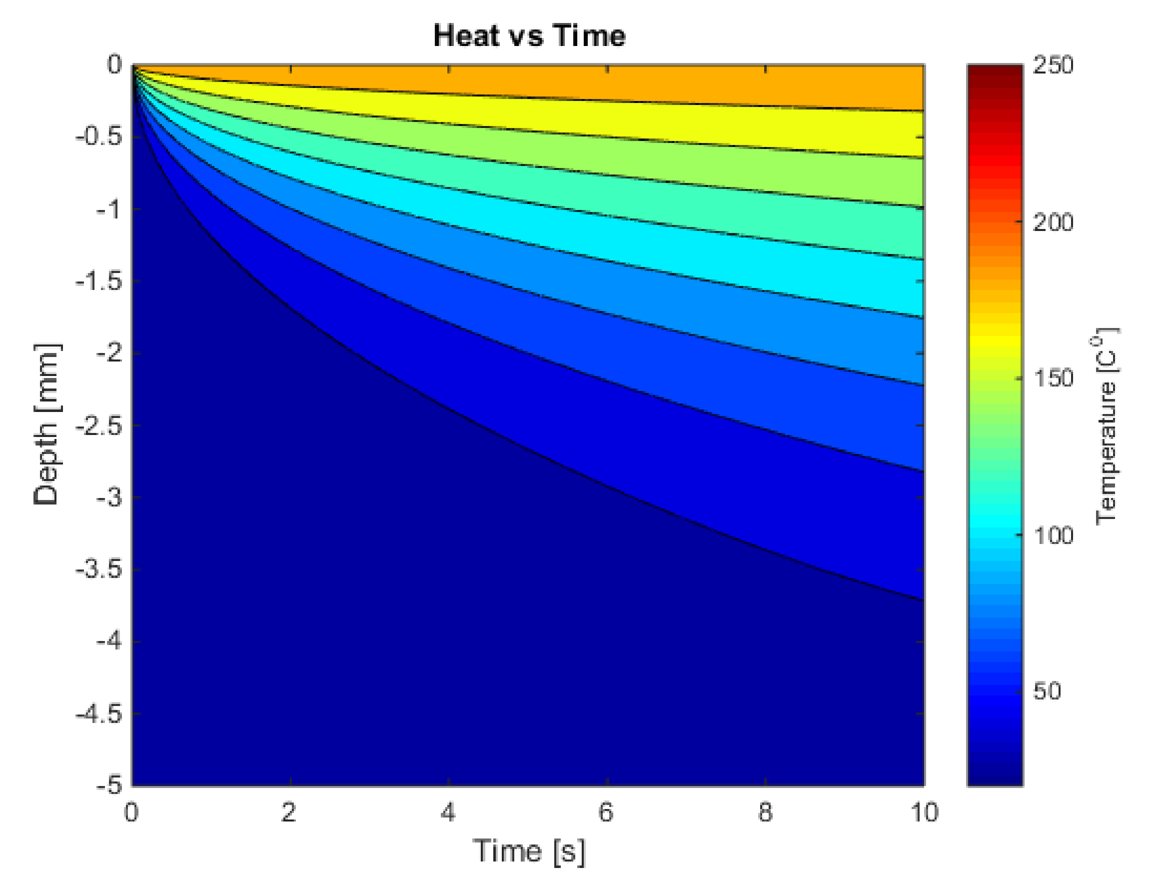
Updated Propellant Conduction Model

- Numerically solve 1D transient heat transfer equation
- $\frac{\partial T}{\partial t} = \kappa \frac{\partial^2 T}{\partial x^2}$ where $\kappa = \frac{k}{\rho c}$
- c = heat capacity, ρ is density, k is thermal conductivity, and κ is thermal diffusivity.
- Numerically solve by combining midpoint method and Euler's method:
- $\left.\frac{\partial T}{\partial t}\right|_{i,j} = \frac{T_{i,j+1} - T_{i,j}}{\Delta t}$, $\left.\frac{\partial^2 T}{\partial x^2}\right|_{i,j} = \frac{T_{i+1,j} - 2T_{i,j} + T_{i-1,j}}{(\Delta x)^2}$
- $T_{i,j+1} = \kappa * \frac{\Delta t}{(\Delta x)^2} * \left[\left(T_{i+1,j} - 2T_{i,j} + T_{i-1,j}\right) + T_{i,j}\right]$

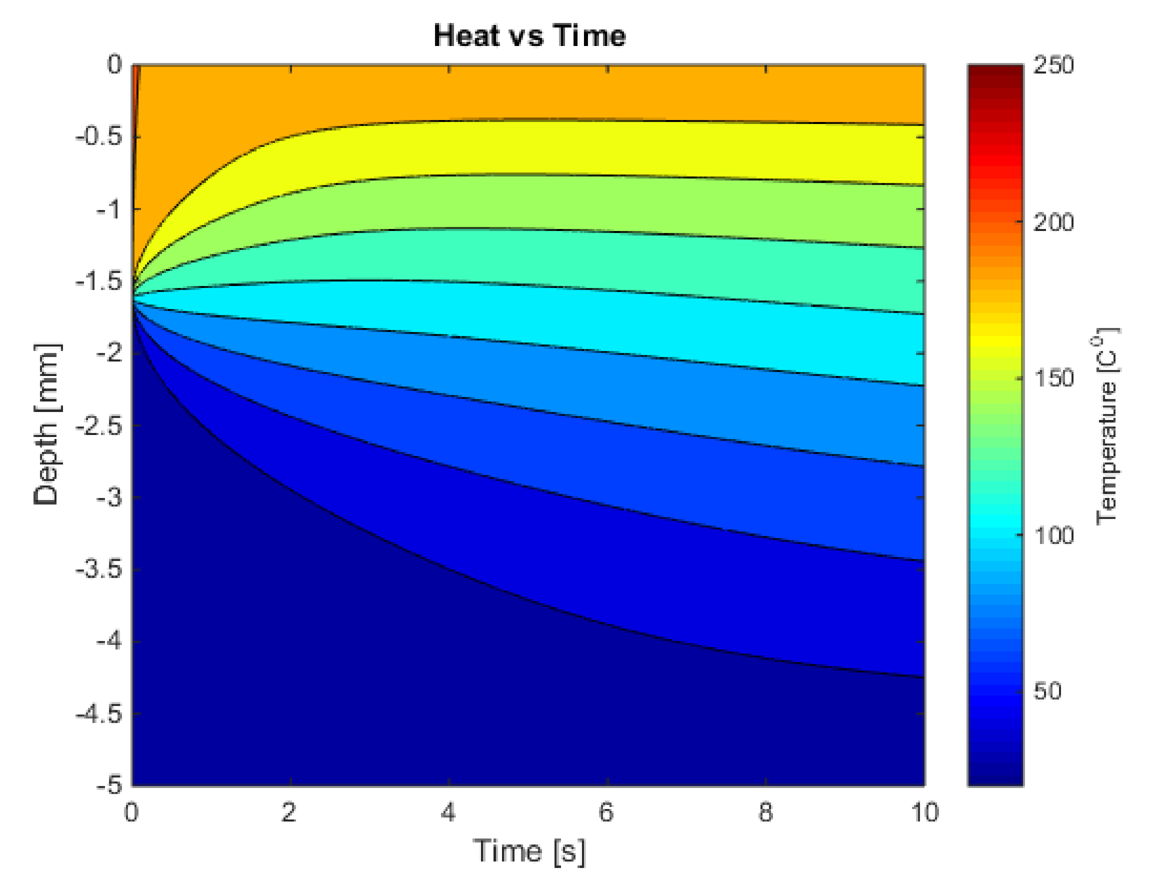
Updated Propellant Conduction Model

- Values used for a 35% Sucrose, 65% KNO_3 (by mass) propellant :
  - c = 1046.5 J/(kg*K)
  - ρ = 1927.4 kg/m^3
  - k = 0.5020
  - κ = 2.4888*10^{-7}
  - Powder bed length: 5 mm
  - IC: Room temp and Optical Depth @ sintering temp
  - BC: Room temp and sintering temp

Propellant Heat Transfer Model: Results



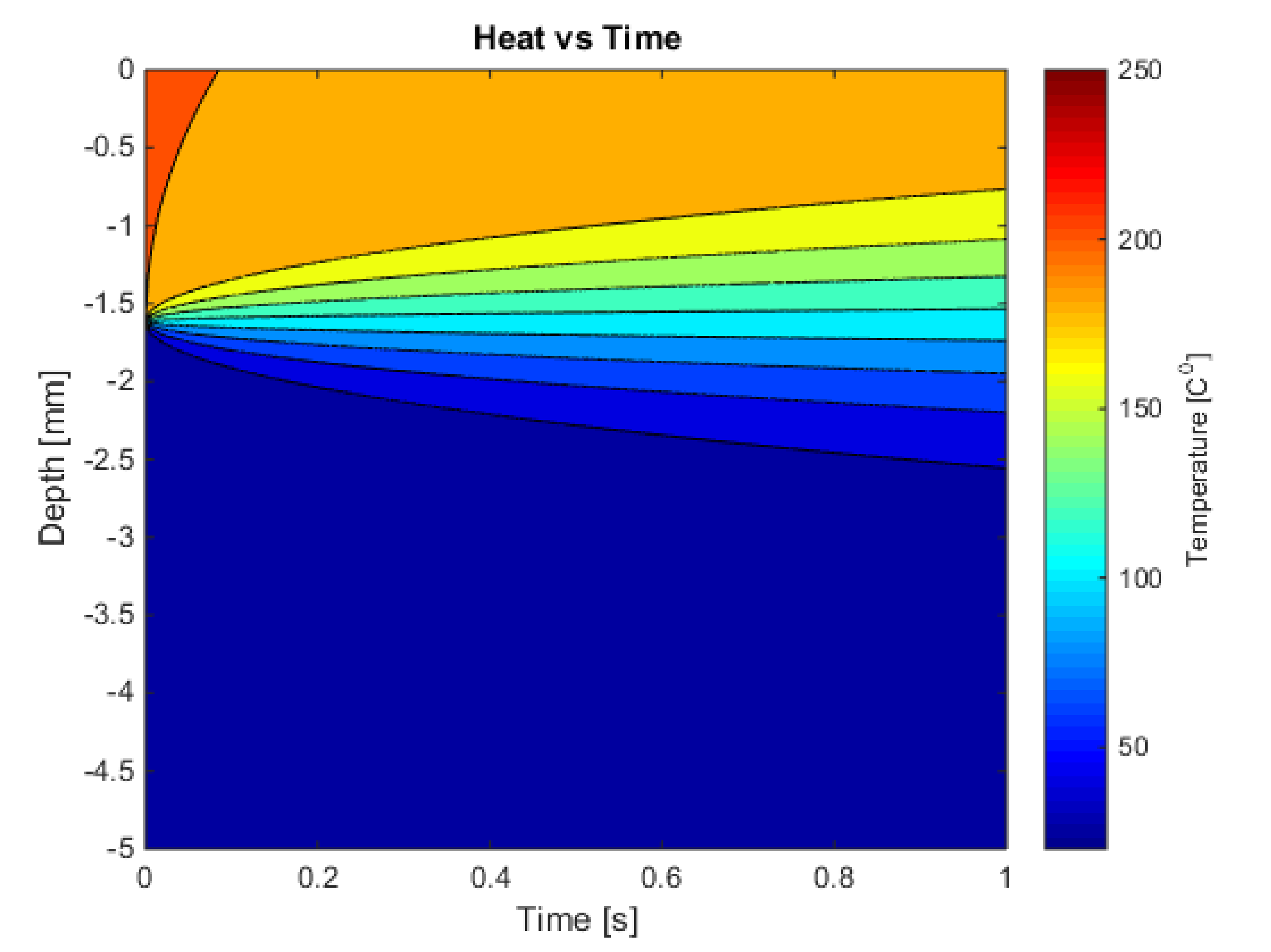
- BC: Top layer @ 200 C⁰
  Bottom layer at 24 C⁰



- Optical Depth Starts at 200 C⁰

Propellant Heat Transfer Model: Results

- Heat conduction negligible
- Propellant is an insulator
- Optical depth determines layer depth
- Select Laser power/slew rate based on surface temp



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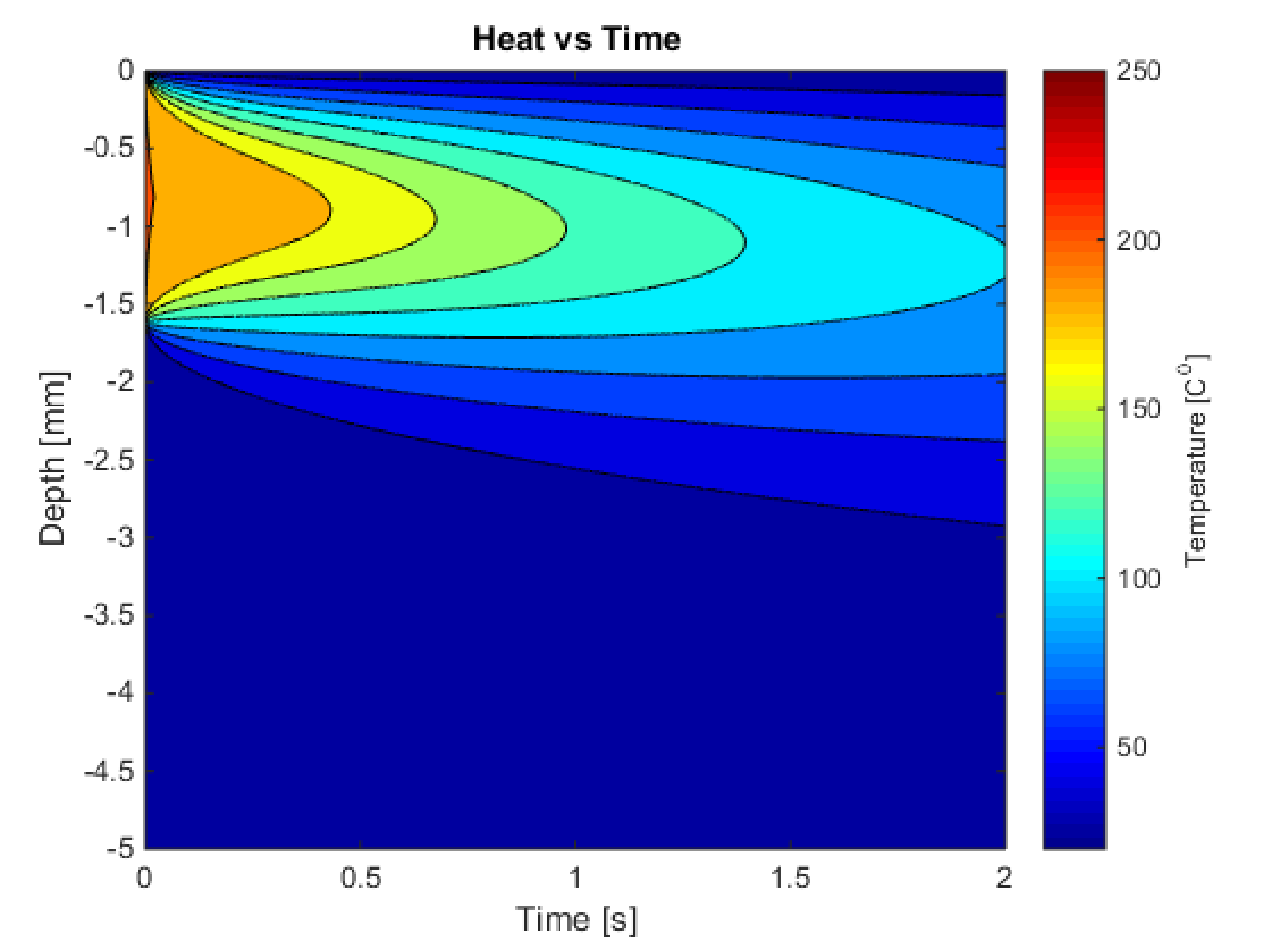

Propellant Heat Transfer Model: Results

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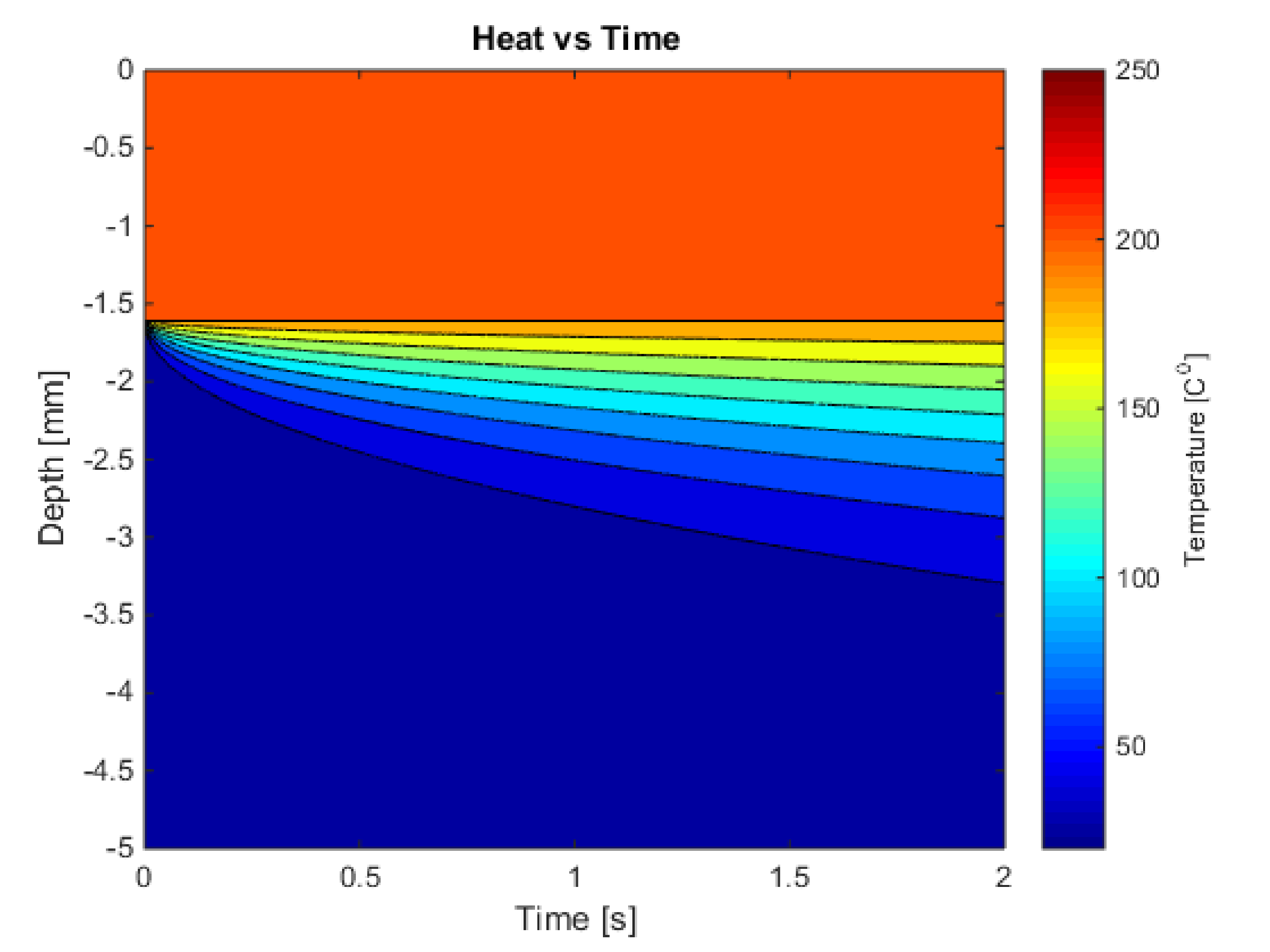


Propellant Heat Model: Optical Depth

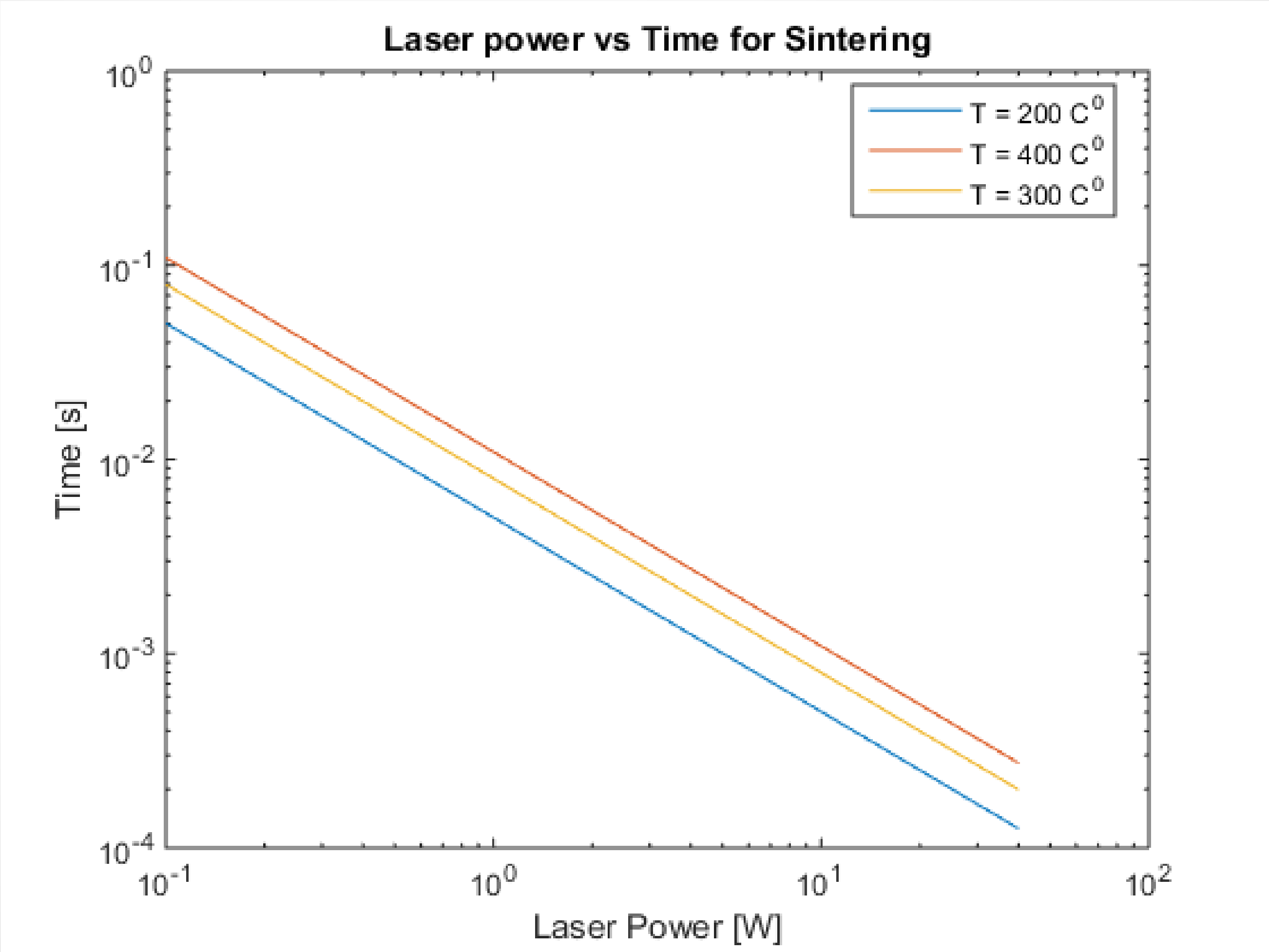
- Optical Depth:
- $\tau = -\log T$, T = transmittance
- Sintering Depth:
- $d_{sint} = \frac{\tau}{A*\rho}$, A = absorptivity (A = 1-T)
- Sintering Depths:
  - Sucrose: d_{sint} = 1.98 mm
  - Propellant (35% Sucrose, 65% KNO_3): d_{sint} = 1.61 mm

Propellant Heat Model: Lumped Capacitance

- Assume: All heat is absorbed uniformly at in a cylinder with radius of lase beam and depth of optical depth
- Equation: gives time over spot as a function of laser power
- $dt = \frac{\pi * r_{laser}^2 * d_{sint} * \rho * Cp * T}{A * P_{laser}}$
- Time over spot converted to slew rate:
- $slew\ rate = 2 * \frac{r_{laser}}{dt}$

Propellant Thermal Model: Laser Cutter Settings

- Optical depth and surface temp are inputs
  - 200 C° lower bound
  - 300 C° upper bound
- Laser Power and Time over spot are outputs
- Time converted to slew rate



Propellant Thermal Model: Laser Cutter Settings