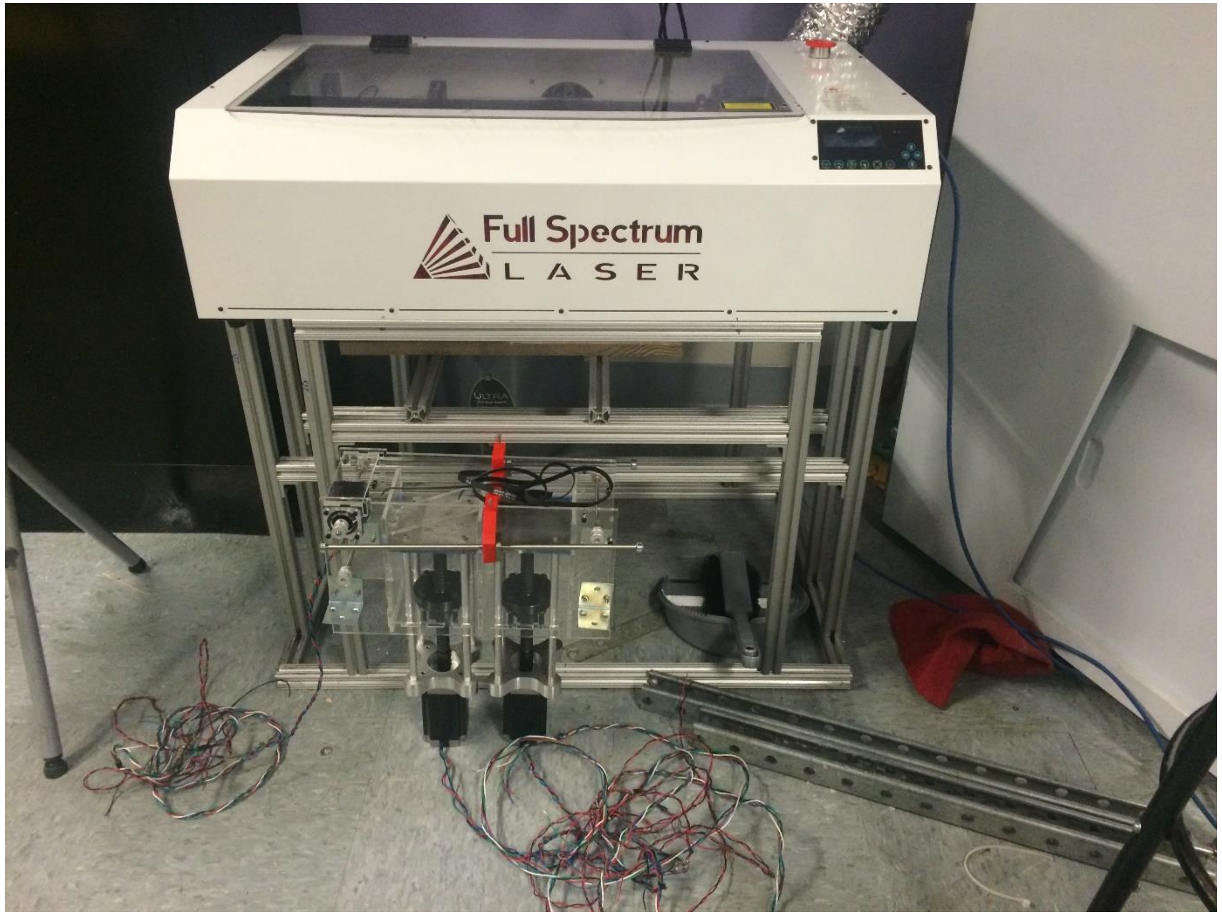


Test Readiness Review (TRR)

Cameron Brown, Max Feldman,
Tony Lima, Caleb Lipscomb,
Erick Chewakin, Nick Lindholm,
Jon Sobol, Ryan Niedzinski

Solid Propellant Additive Manufacturing (SPAM)

Agenda

Overview → Cameron

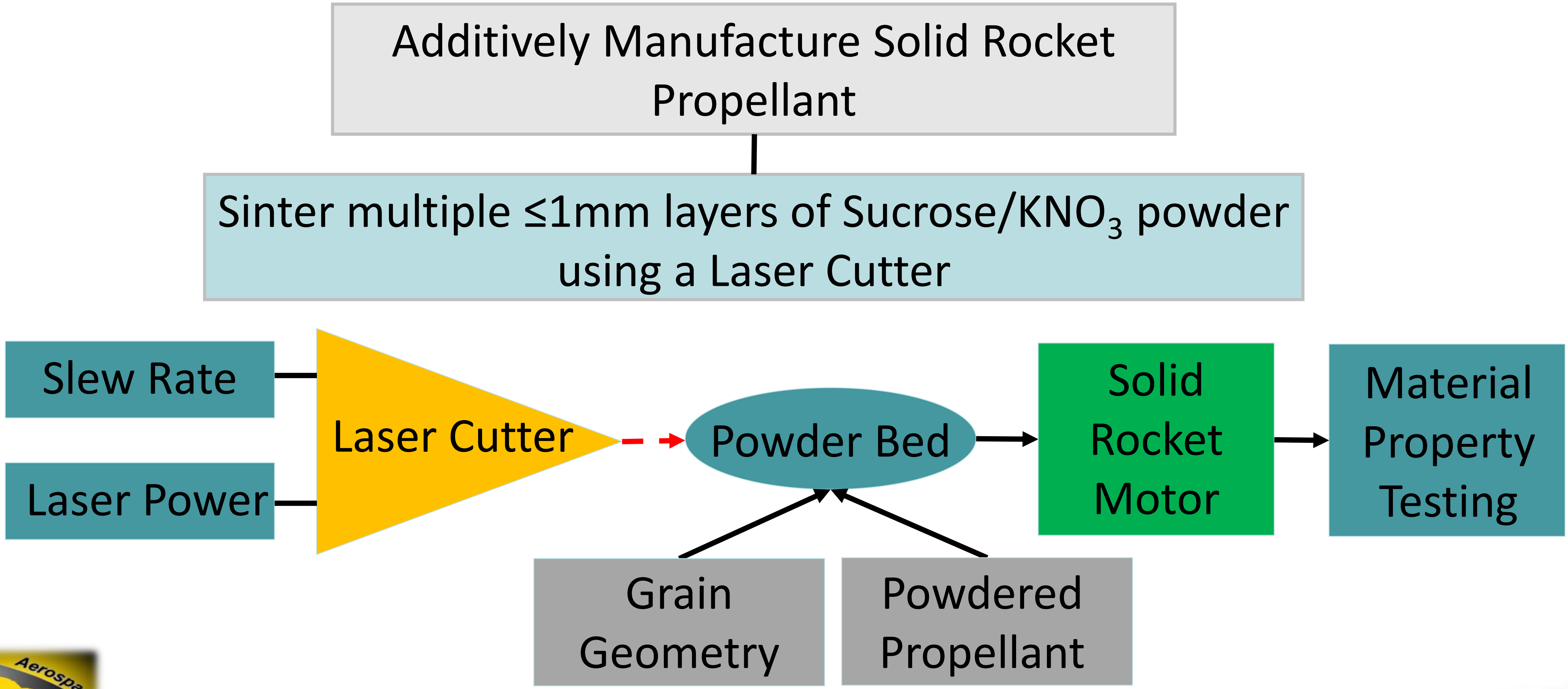
Testing:

- **Laser Sintering** → Tony
- **Powder Bed** → Nick
- **Material Properties** → Erick

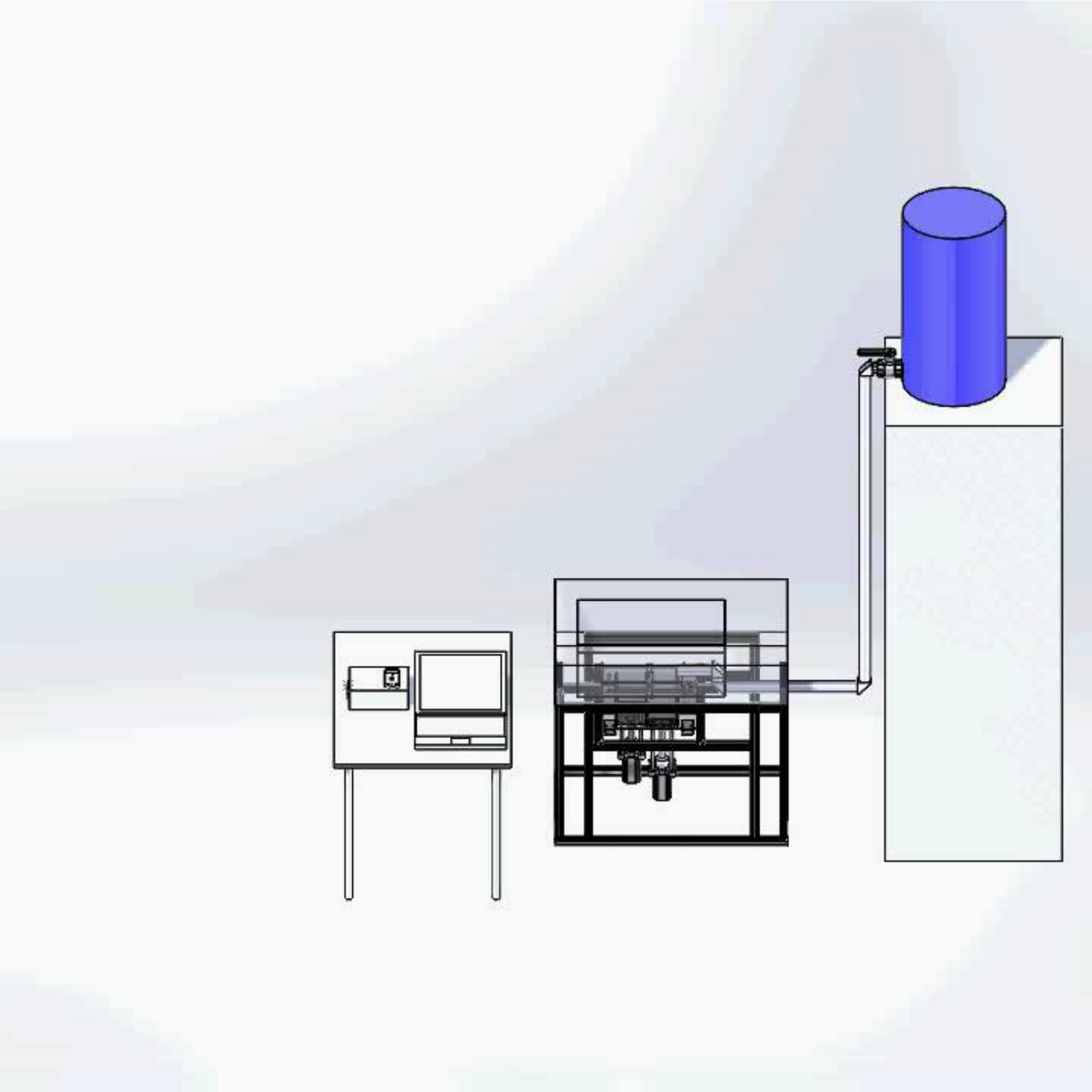
Summary → Erick

Project Overview

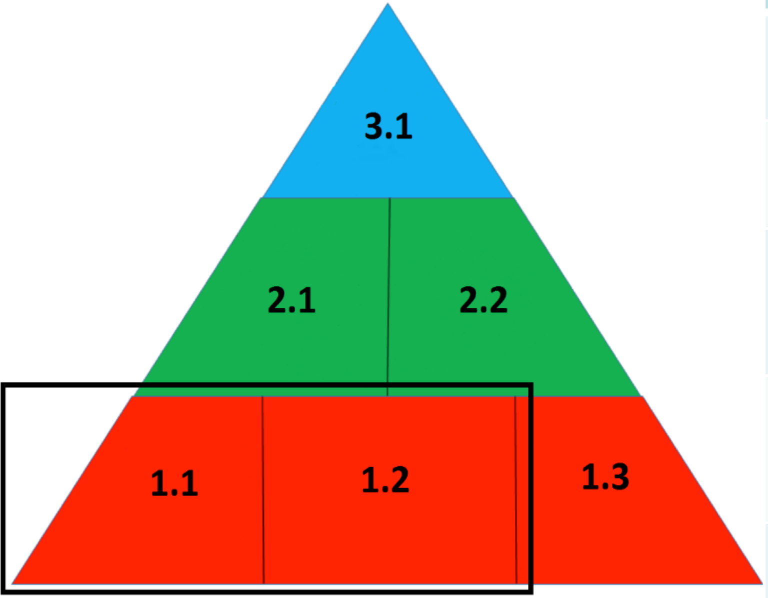
Project Purpose



Concept of Operations

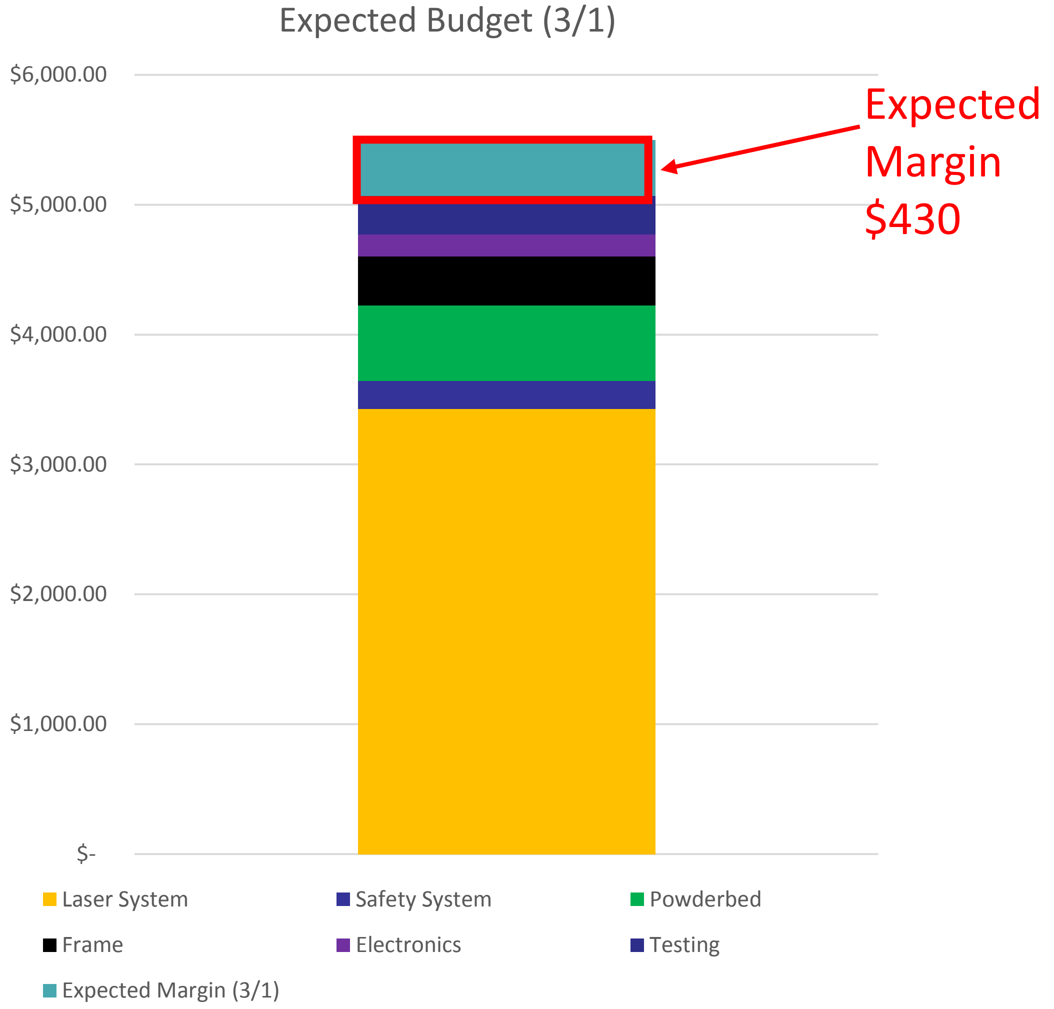


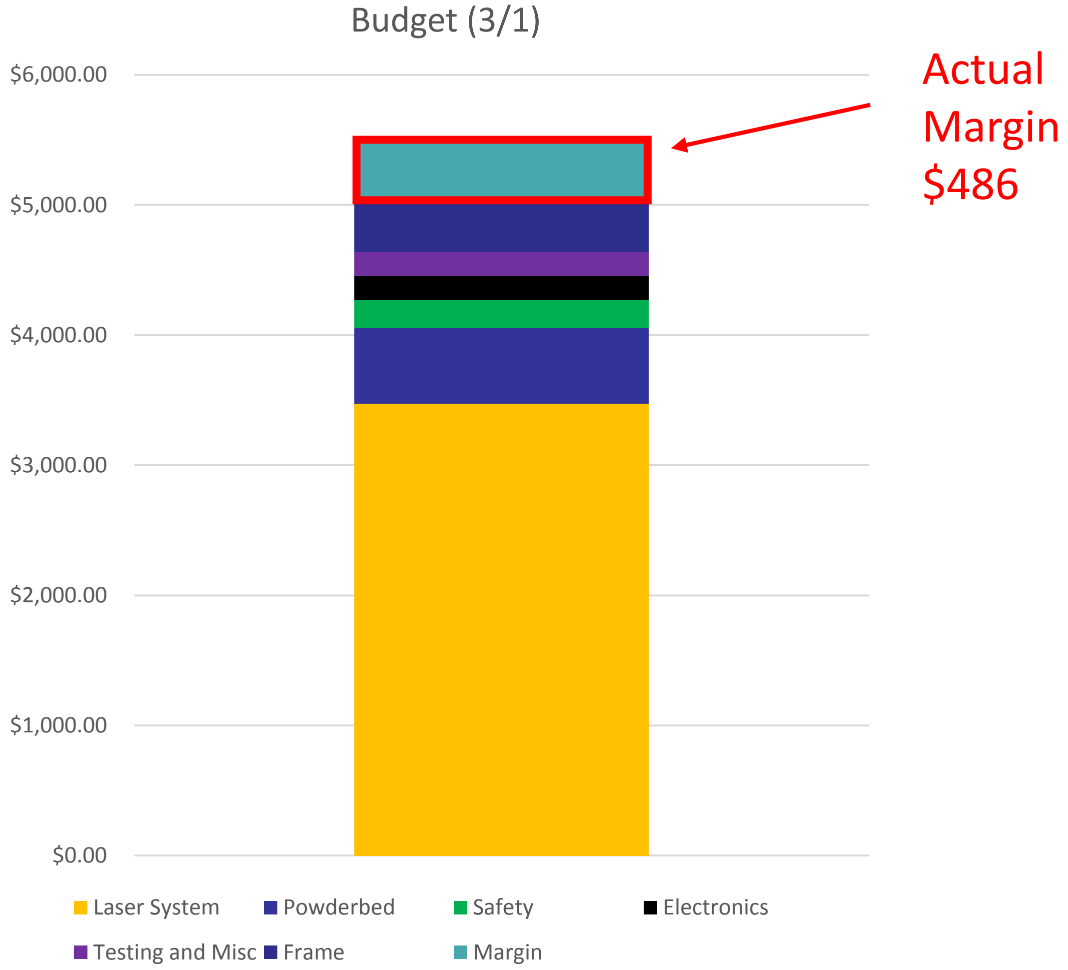
Levels of Success



Level	Description	Achieved	Completion Date
1.1	Design 3D Printing System for Sucrose-KNO3	Yes	11/10/15
1.2	Characterize a Thermal Model for Propellant	Yes	1/30/16
1.3	Use Analogous Method to form Solid Propellant	No	3/10/16
2.1	Compare Material Properties (Casted vs Printed)	No	4/1/16
2.2	Print a Solid Rocket Motor Cylinder	No	3/23/16
3.1	Manufacture and Test 5 Different Grain Shapes	No	4/8/16

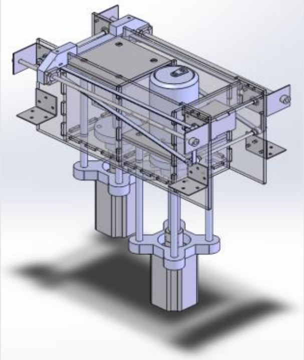
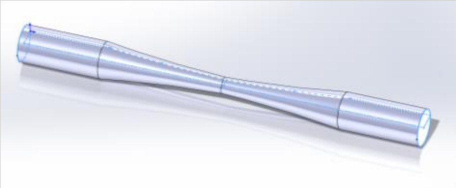
Financial Status





Overview | Laser Testing | Powder Bed Testing | Material Testing

Critical Testing Elements

CPE	Description		Planned Completion Date
1) Laser Sintering Sucrose and KNO3		• Verify Thermal Model and Laser Energy Control	**March 28th**
2) Powder Bed Component Integration		• Component Integration and Tolerance Verification • Full Powder Bed Cycle Test	**March 16th**
3) Material Property Testing		• Validate Material Properties Between Casted and Printed Motors	**April 7th**

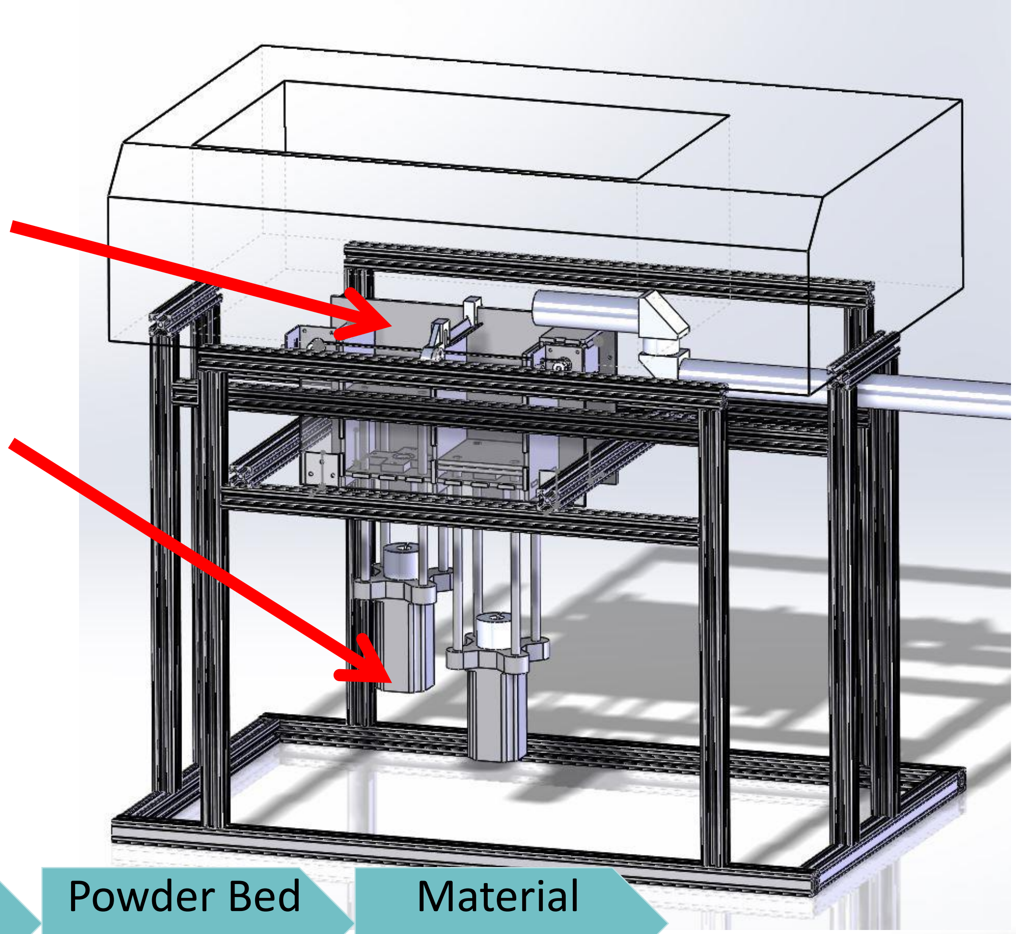
Design Changes

Design Changes: Ventilation

Problem: Laser Cutter Filled with Fine Particulate During Testing

Safe Engineering Solution:

- Powdered propellant mixture atomized into enclosure here
- Side wall and additional fans for ventilation installed
- Safely remove particulate faster than build up



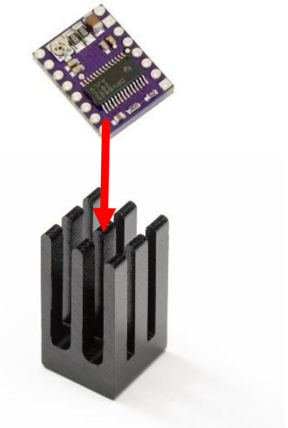
Design Changes: Driver Heat

Problem: Motor Drivers Overheat Due to High Wattage Input

Impact: Behind Schedule on Electrical Component Testing

Learned: Need higher amp rated drivers (2000% more expensive)

Or modify existing drivers for better heat dissipation

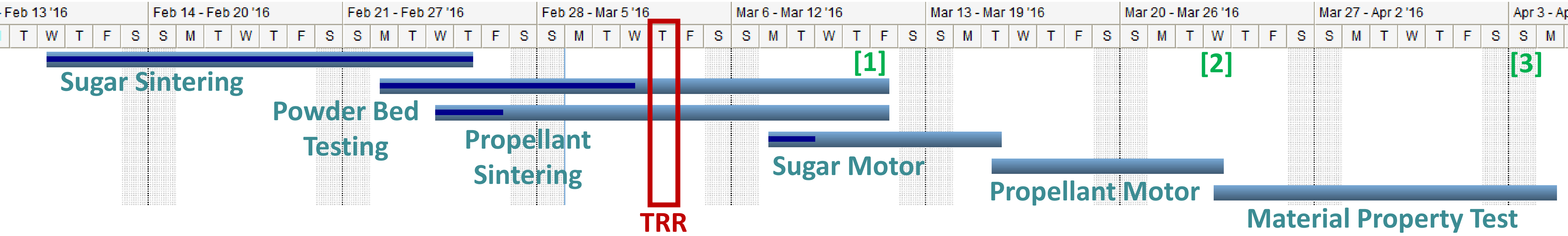


Solution:

- Calculated wattage and required heat removal
- Purchased applicable heatsinks
- Solution verified by 3/4/16 (One Week Behind Schedule)

Testing

Testing Schedule



Summary:

- Behind schedule by 1 Week due to unexpected obstacles
- [1] <u>Level 1 Success:</u> scheduled for 3/10/16
- [2] <u>Level 2 Success:</u> scheduled for 3/23/16
- [3] <u>Level 3 Success:</u> scheduled for 4/4/16

Sugar Sintering Test: Overview

Test Purpose: Validate Sugar Thermal Model

Requirement	Description
1.3	Laser raises propellant temperature to 185°C

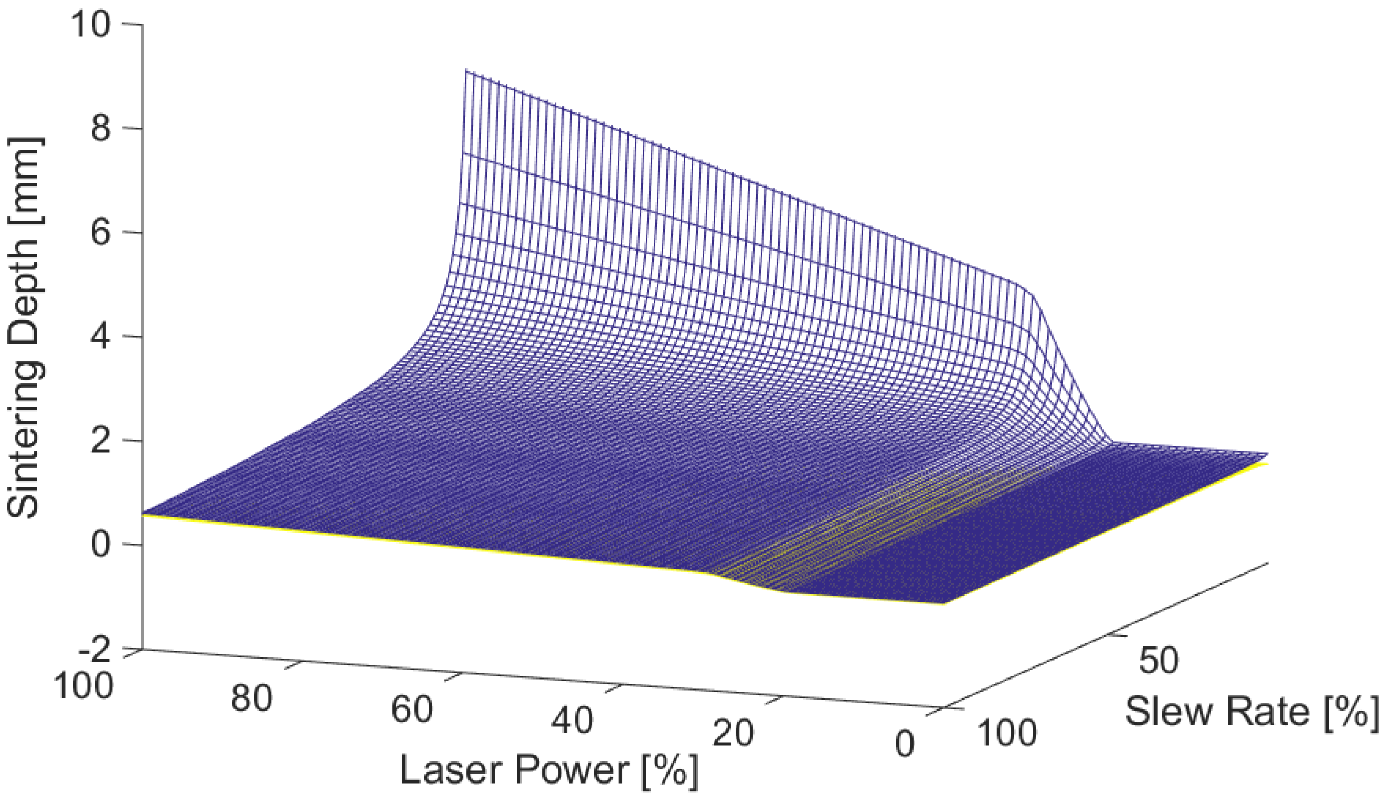
Test Procedure:

- Sinter small samples of sucrose at varying power and slew rates
- Record sintering depths with calipers
- Compare to model predictions

Expected Results:

- Exponential increase between 10% and 1% slew rate
- Not sensitive to Power

Predicted Sintering Depths [mm] by Control Parameters



Overview | Laser Testing | Powder Bed Testing | Material Testing

Sugar Sintering Test: Results

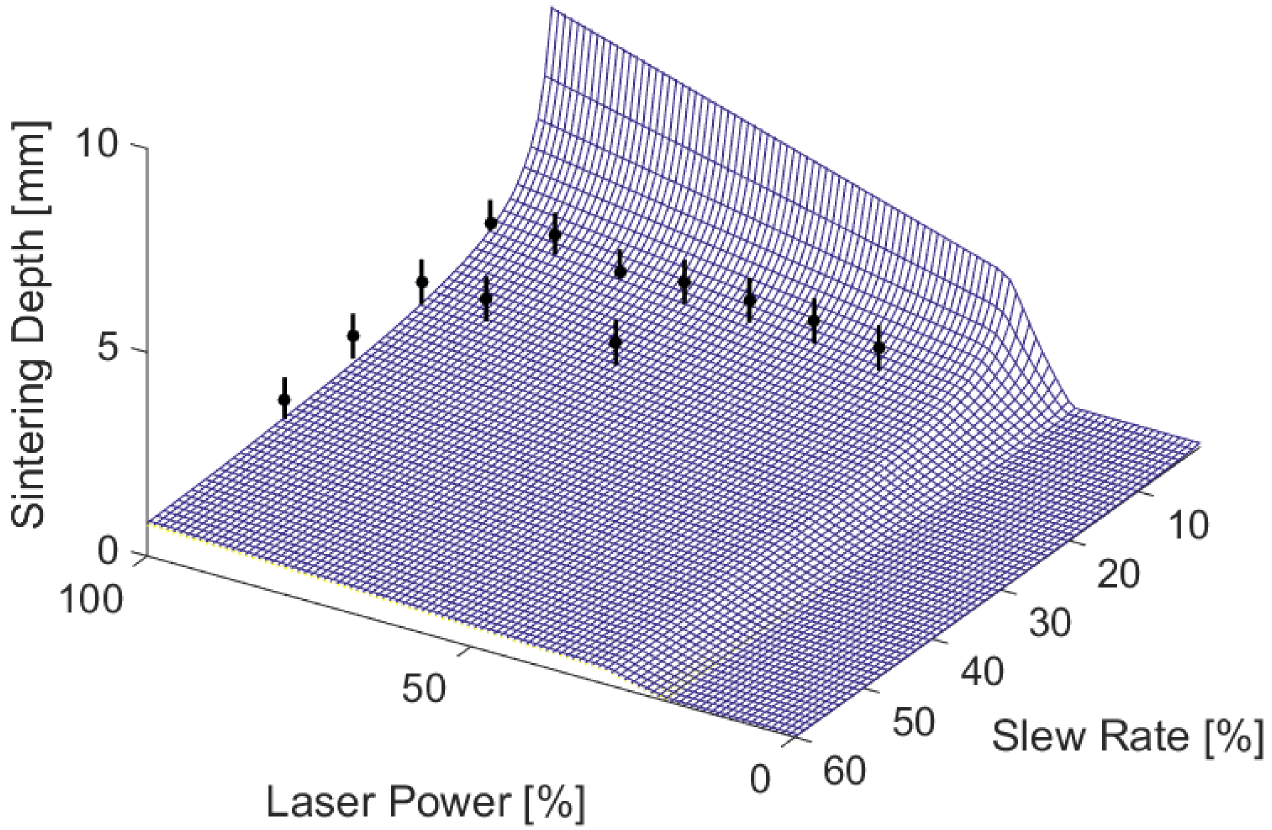
Results:

- Most samples thicker than predicted
  - Likely caused by size of sugar granules
- Minimum Sintering Depth
- Inaccurate (>1 Std) at Power < 5%
  - Caused by heat conduction

Future Analysis:

- Test goodness of fit (X^2)
- Update model with minimum thickness
- Re-test goodness of fit

Predicted Vs. Measured Sintering Depths [mm]

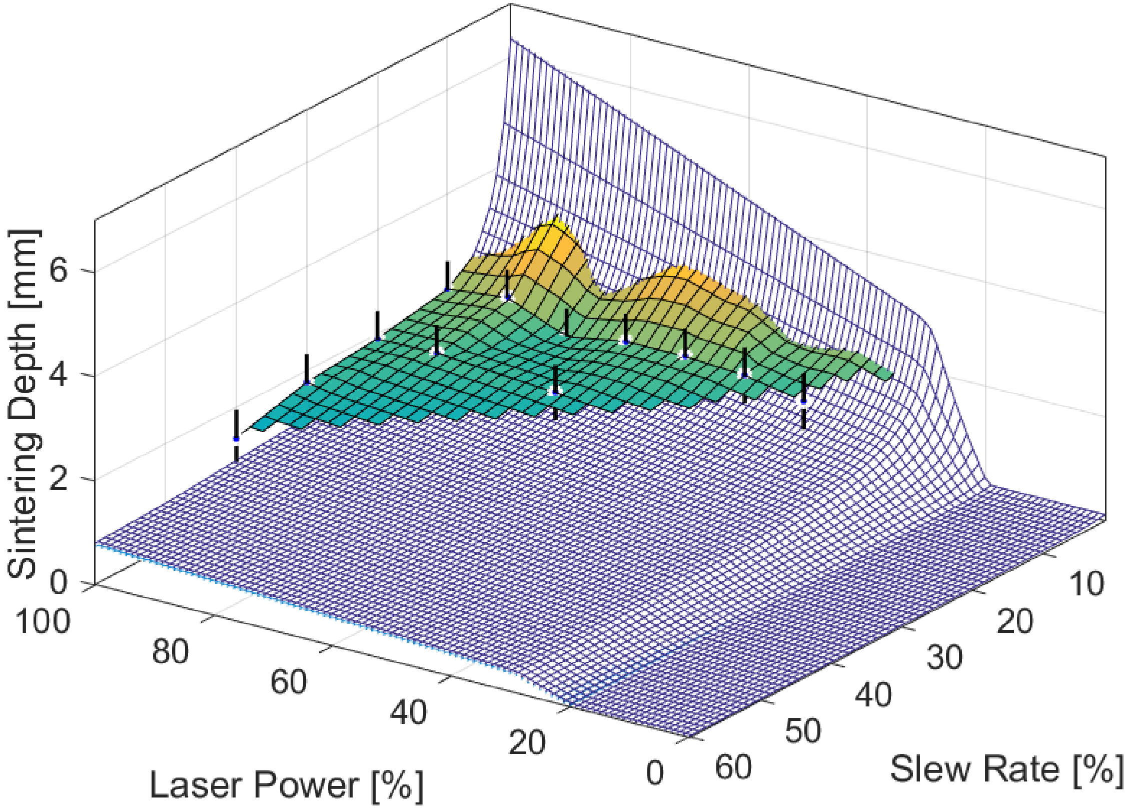


Overview | Laser Testing | Powder Bed Testing | Material Testing

Sugar Sintering Test: Results

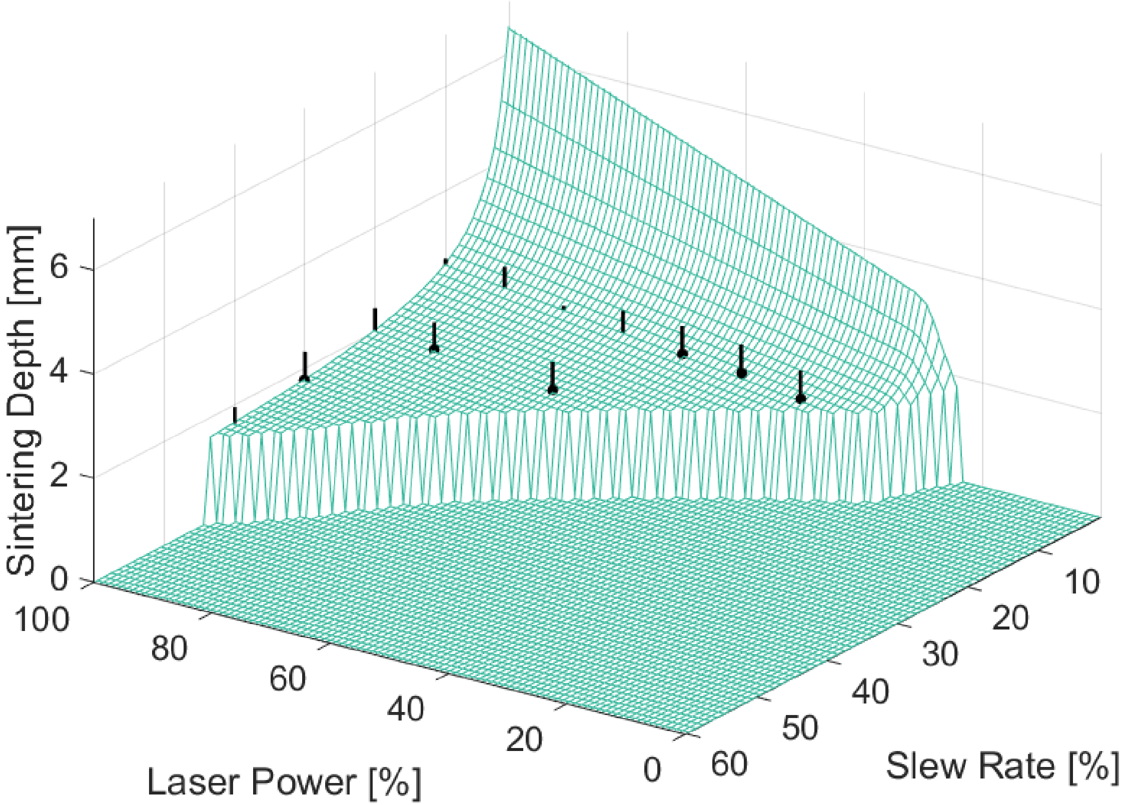
- First Model: $X^2_{red} = 9.05$

Predicted vs Measured Sintering Depths (Old)



- Adjusted Model: $X^2_{red} = 1.00$

Predicted vs Measured Sintering Depths (Updated)



Propellant Sintering Test: Overview

Test Purpose: Validate Propellant Thermal Model

Requirement	Description
1.3	Laser raises propellant temperature to 185°C

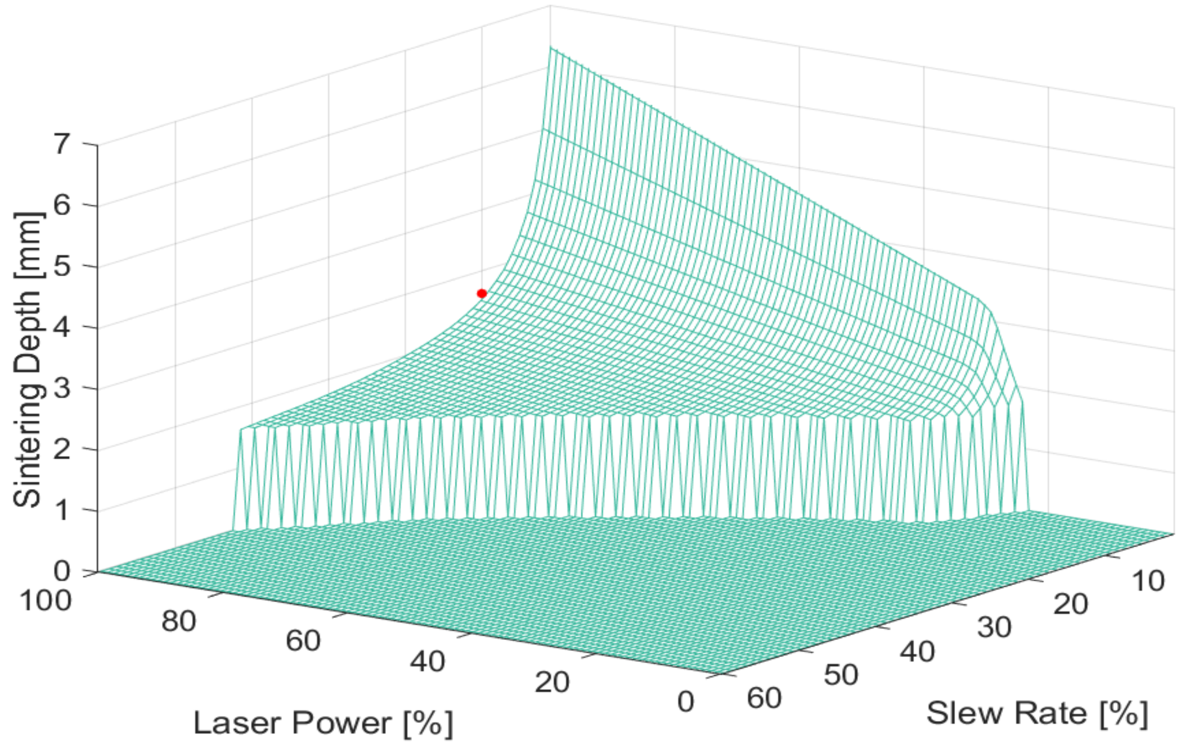
Test Procedure: (Same as Previous Test)

- Sinter small samples of propellant at varying power and slew rates
- Record sintering depths with calipers
- Compare to model predictions

Expected Results:

- Sintering depths should not change by more than 1 mm
- Average of 2 mm sintering depths at 10% slew rate

Predicted Propellant Sintering Depths [mm]



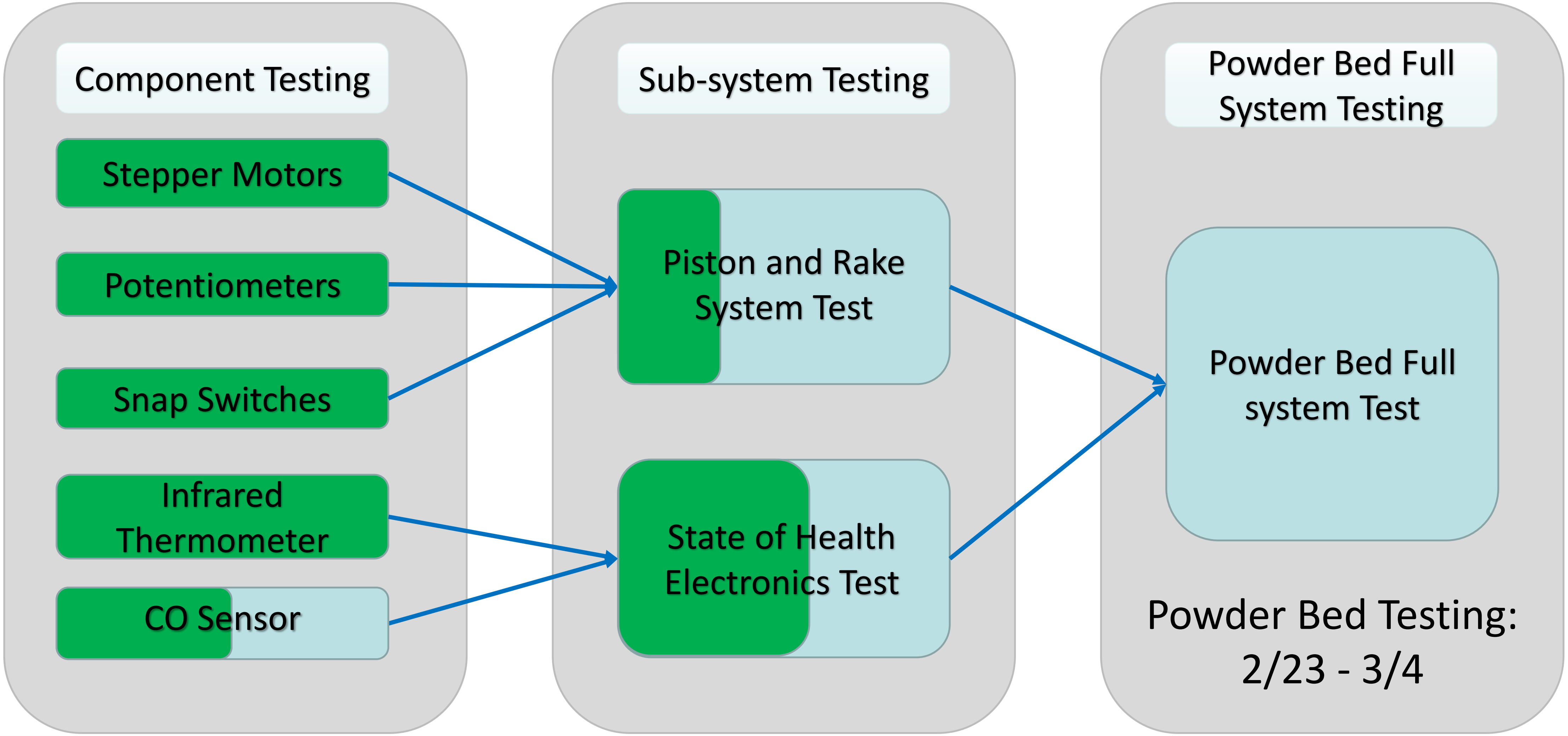
This Test Will Accomplish Level 1 Success (3/10/16)

Overview | Laser Testing | Powder Bed Testing | Material Testing

Laser Sintering Test Summary

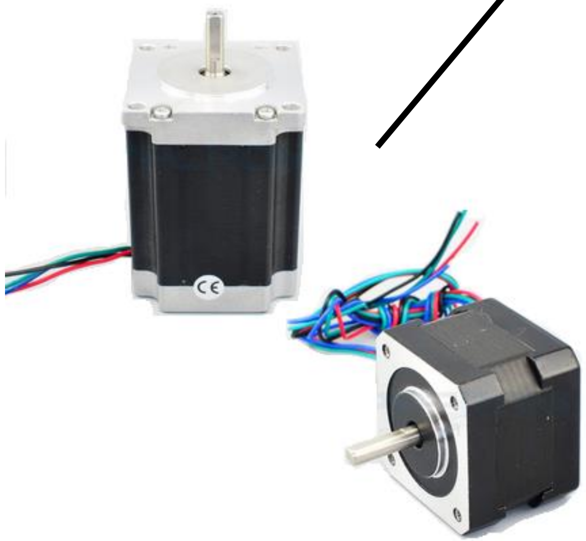
Test	Status (% Complete)	Total Required Testing Hours	Expected Completion Date
Sugar Sintering Test	100 %	10	2/16
Propellant Sintering	10 %	10	3/10
Sucrose Motor Print	20 %	5	3/15
Full Motor Printing	0 %	15	3/28

Powder Bed Testing Flow

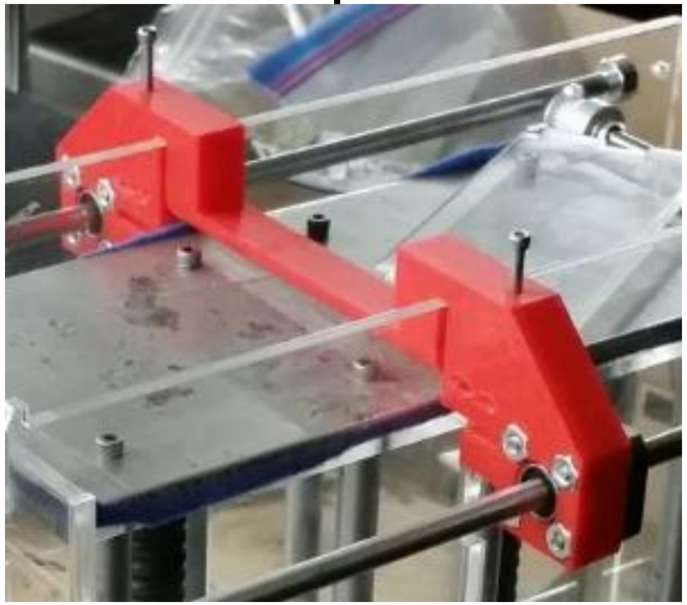


Powder Bed Integration Tests

Full System Integration Tests



Piston Motor/Driver Tests



Rake Pull/Binding Tests

Piston Tests

Powder Bed Tests: Motor/Driver

Test Purpose:

- Confirm motors meet Required Tolerances

Test Procedure:

- Command known number of steps.
- Measure resultant motion and torque

Expected Results:

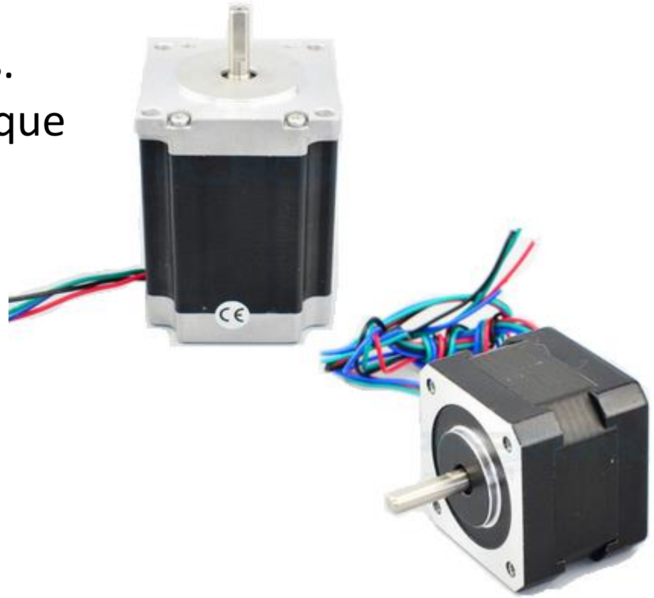
- Motors operate within specs

Problem:

- Drivers overheat during operation

Solution:

- Attach heat sinks to drivers



Motor	Expected Torque (N*m)	Expected Accuracy (deg/step)
NEMA-23 (Piston Motor 1)	2.4	1.8 (deg/step)
NEMA-23 (Piston Motor 2)	2.4	1.8 (deg/step)
NEMA-17 (Rake Motor)	0.43	1.8 (deg/step)

Table: Expected Motor Specifications

Rake Neutral Friction Test

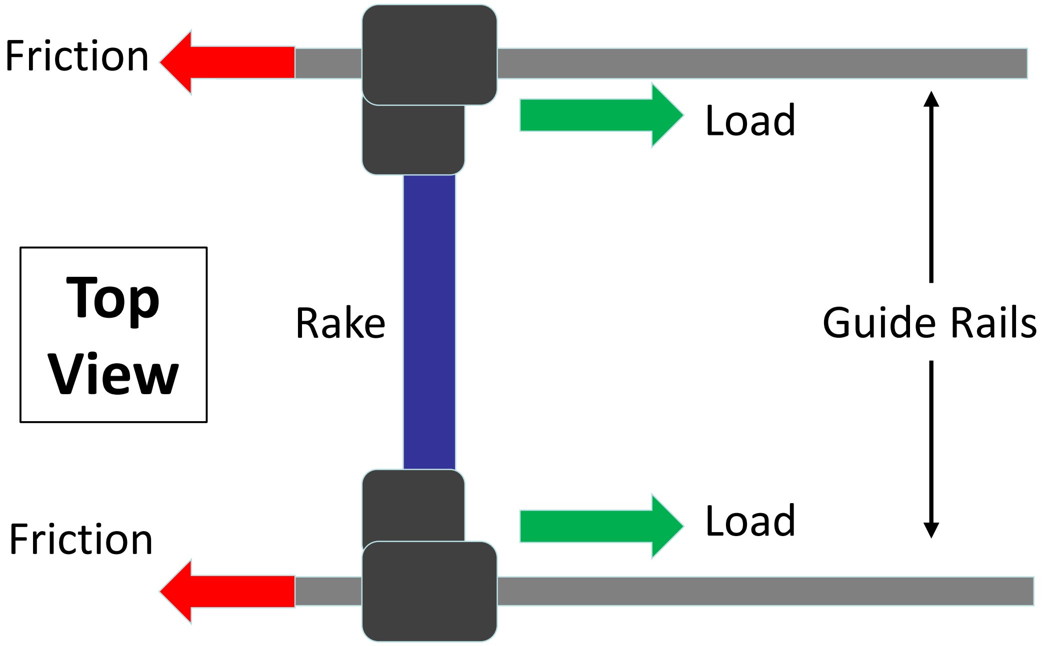
Test Purpose:

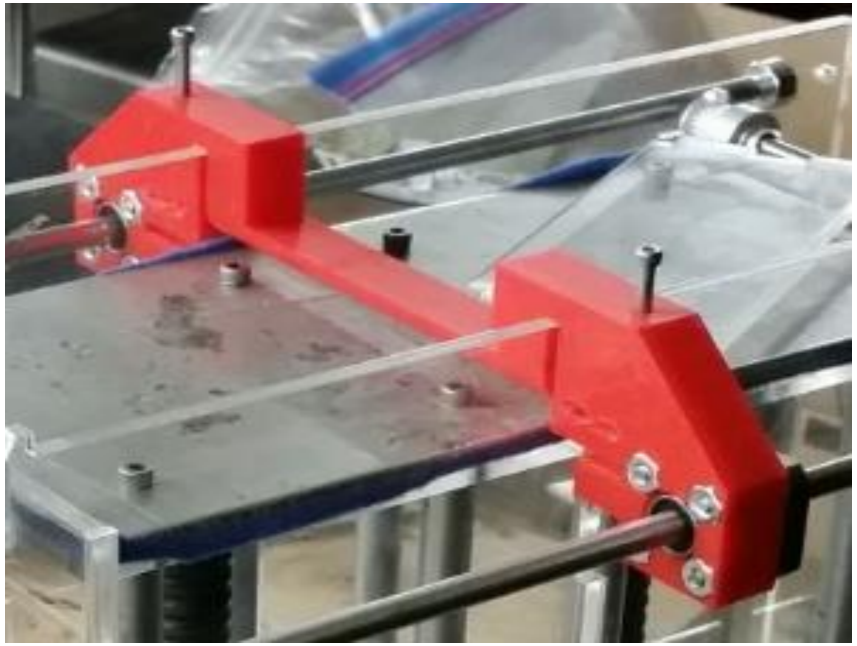
- Can the motor move the rake and a layer of powder?
- What is the friction force in the assembly?

Expected Results:

- The rake increases the expected load on the motor by less than a factor of 2

Requirement	Description
2.4.3	Rake shall deliver propellant to the print area





Manufactured Rake (Red)

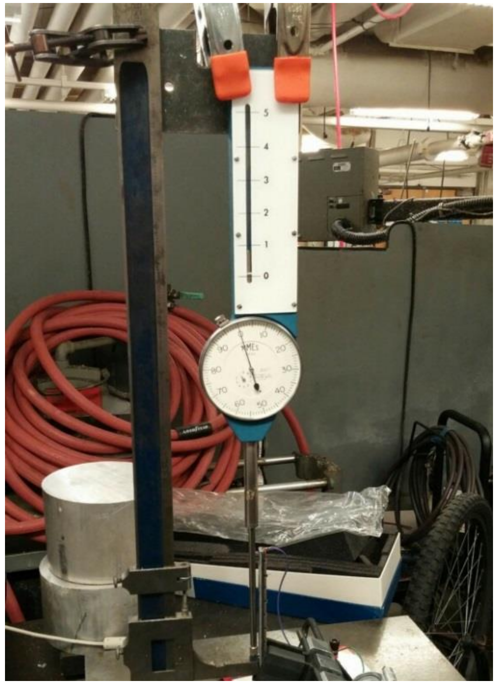
Powder Bed Integration: Lifts

Test Purpose:
Confirm pistons are controlled and move as expected

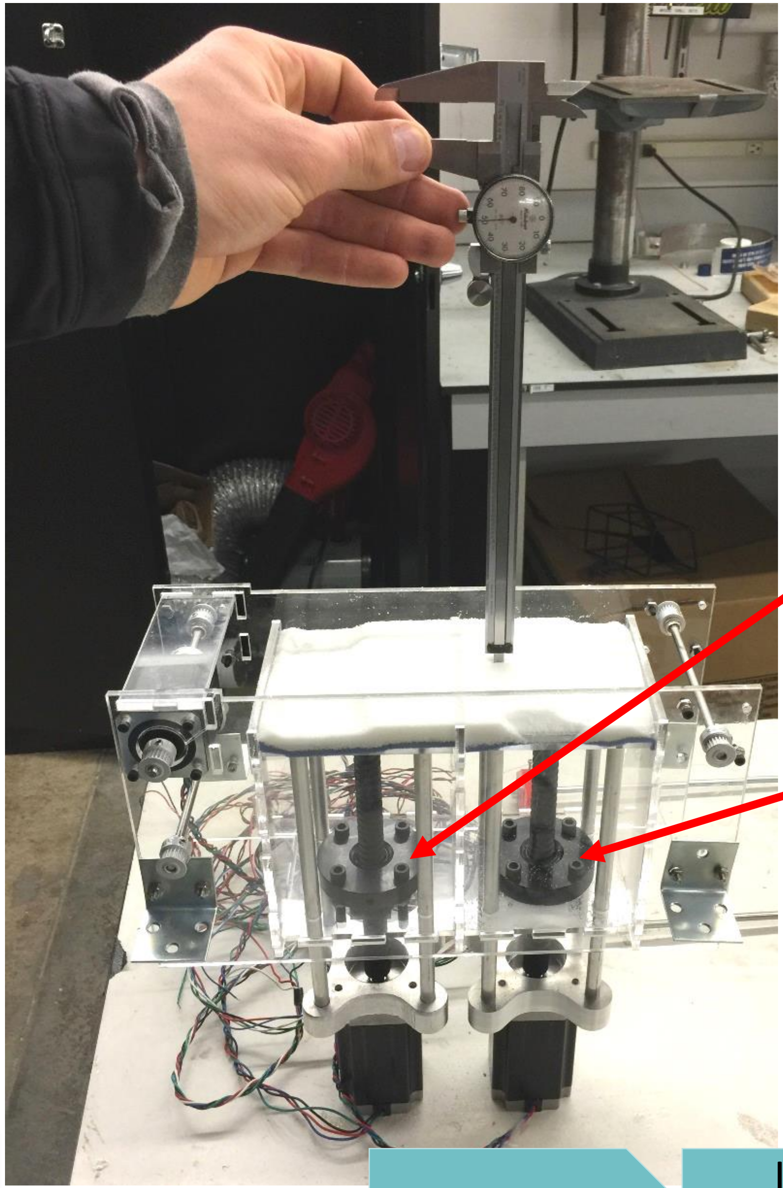
Requirement Verified	Description
2.1.2	The Powder Bed shall move 1.0+0.3mm.
2.4.2.2	Pistons displace 2.5kg of propellant
2.4.2.3	Pistons move 2.85" vertically

Expected Results:
1.8 degrees per step => 0.02 mm vertical movement

Dial Micrometer:
Used to verify predicted lift tolerance.
Accuracy: 0.001" = 0.0254mm



Piston Lift Assembly:
Measure height increase for each motor step



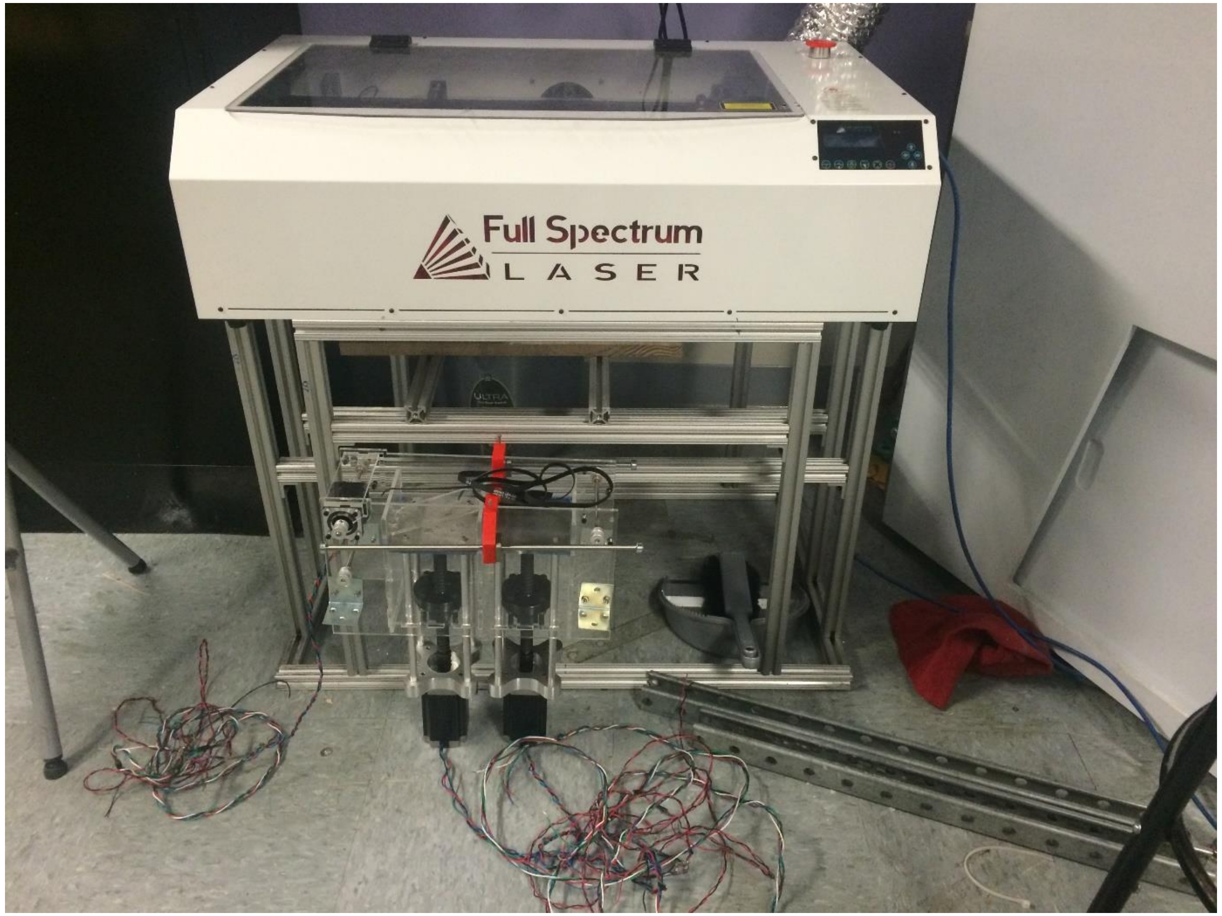
Layer Tolerance Test

- **2.4.1.1**: Reservoir vertical movement to an accuracy of 2 mm ±1 mm
- **2.4.2.1**: Sintering area vertical movement to an accuracy of 2 mm ±1 mm

Powder Bed System Integration Test

Test Purpose: Verify Powder Bed Requirements

Requirement Verified	Description
1.4	Layers of propellant 2.0±1.0 mm
2.4	Autonomously deliver unsintered material to manufacturing area.
2.4.1/2.4.2	Piston controlled chambers shall hold unsintered powder and the completed motor.
2.4.3	A Rake shall autonomously deliver unsintered powder.
2.4.5	Each cycle shall take no more than five minutes.



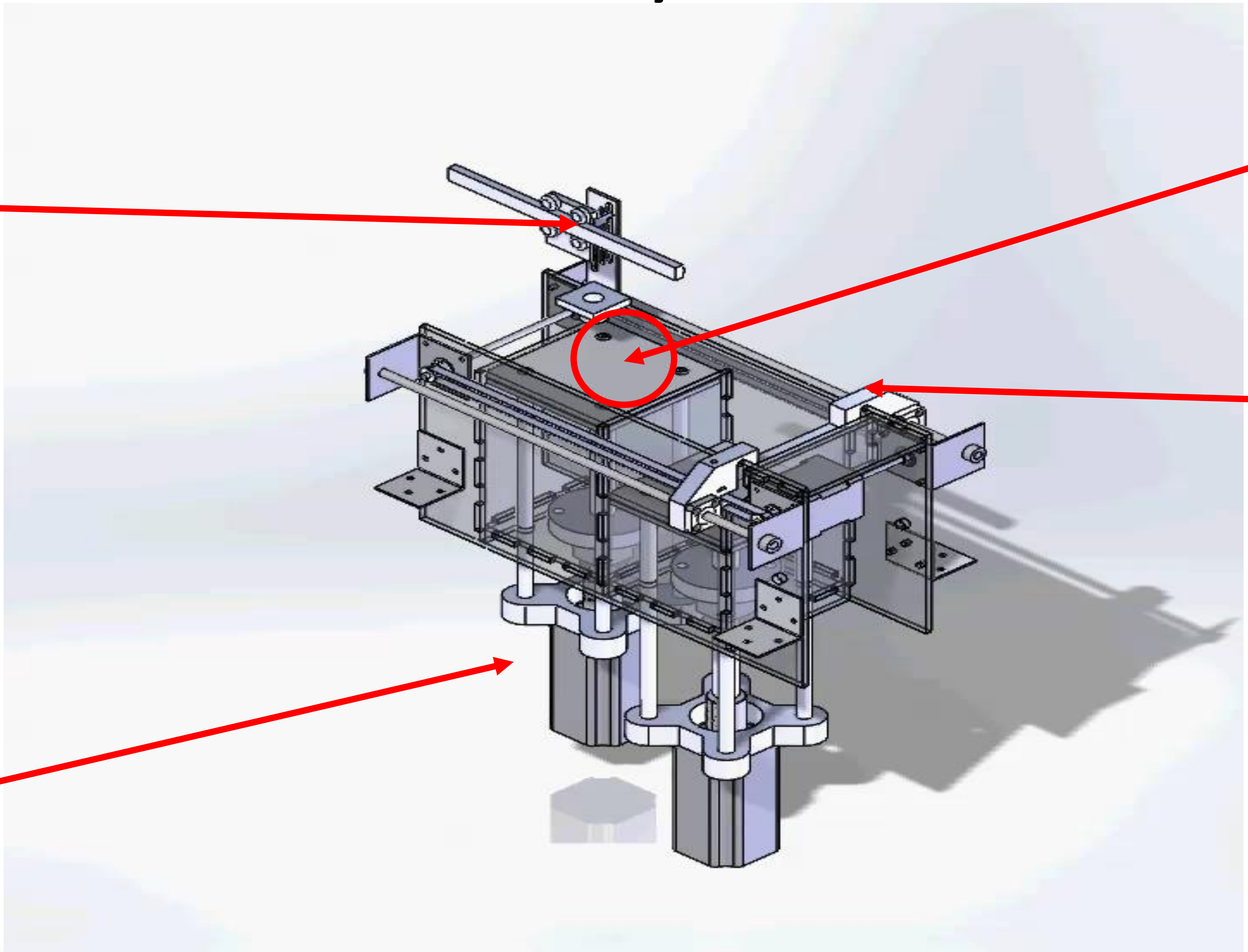
Powder Bed Full Cycle Test: Overview

Dial Micrometer measures sintered depth

Sintering region

Rake sweeps propellant to sintering region

Pistons move 1mm+/-.3mm of propellant to sintering region



Powder Bed Testing Summary

Test	Status (% Complete)	Total Required Testing Hours	Expected Completion Date
Functional Component Testing	90%	10	3/4
Frictional Testing	10%	5	3/4
Lift Tolerance	25%	5	3/8
Rake Tolerance	0%	5	3/8
Full Cycle Test	0%	15	3/10

Material Properties Testing

Test Purpose:

- How does the printed propellant differ from cast propellant?
- Any differences that would indicate that printing is not a viable SRM manufacturing method?

Requirement Verified	Description
DR 3.1	Compare selected material properties of printed and cast propellants
DR 1.2	Printed layers bond

Subtests:

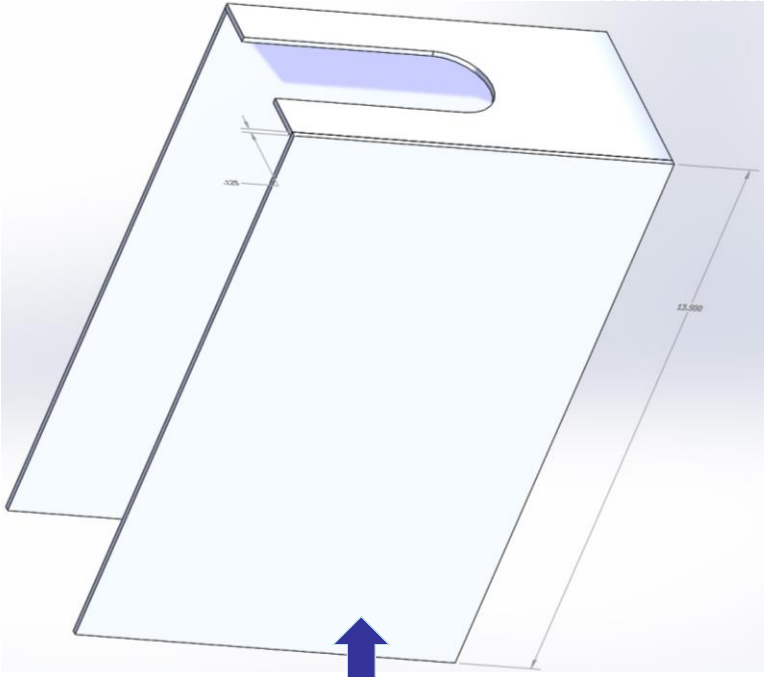
- Density
- Tensile Strength
- Crush Strength

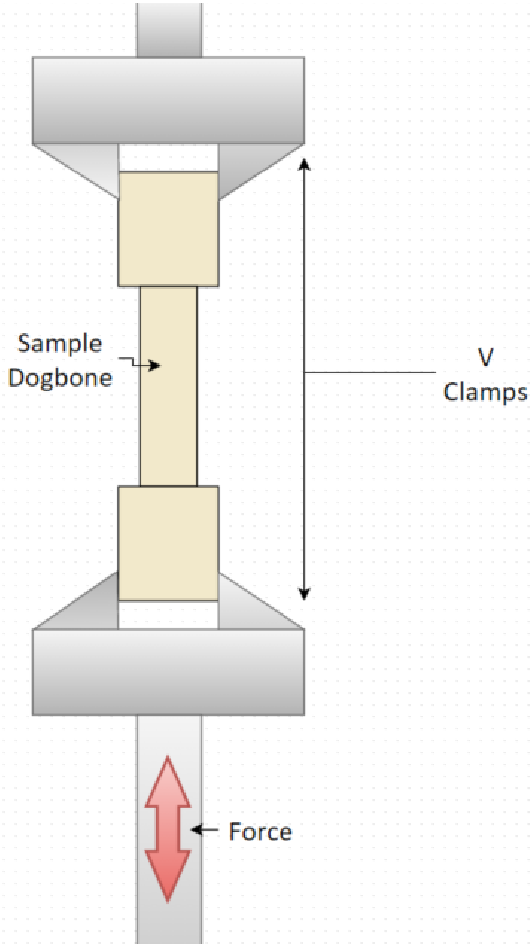
Expected Results:

- Printed propellant will be weaker, and less dense

Material Properties: Strength

- Tensile strength, crush strength
- Differences between printed and cast propellant? Is printing viable?
- Deformation measured via camera
- Max stress of 24 Mpa
  - Ignition from thermoelastic effects at 72 MPa
  - 271 lbf for our sample with Safety factor of 2.4
- Debris fully contained for EH & S disposal





Material Testing Summary

Test	Status (% Complete)	Total Required Testing Hours	Expected Completion Date
Material Properties	0%	25	3/30
Instron	0%	25	4/07

Material Testing Plan:

- Material testing cannot begin until propellant has been successfully sintered and shaped
- Scheduled to test from 3/23/16 to 4/7/16

SPAM Status Summary

- Behind on Testing Schedule
  - Still Within Margin

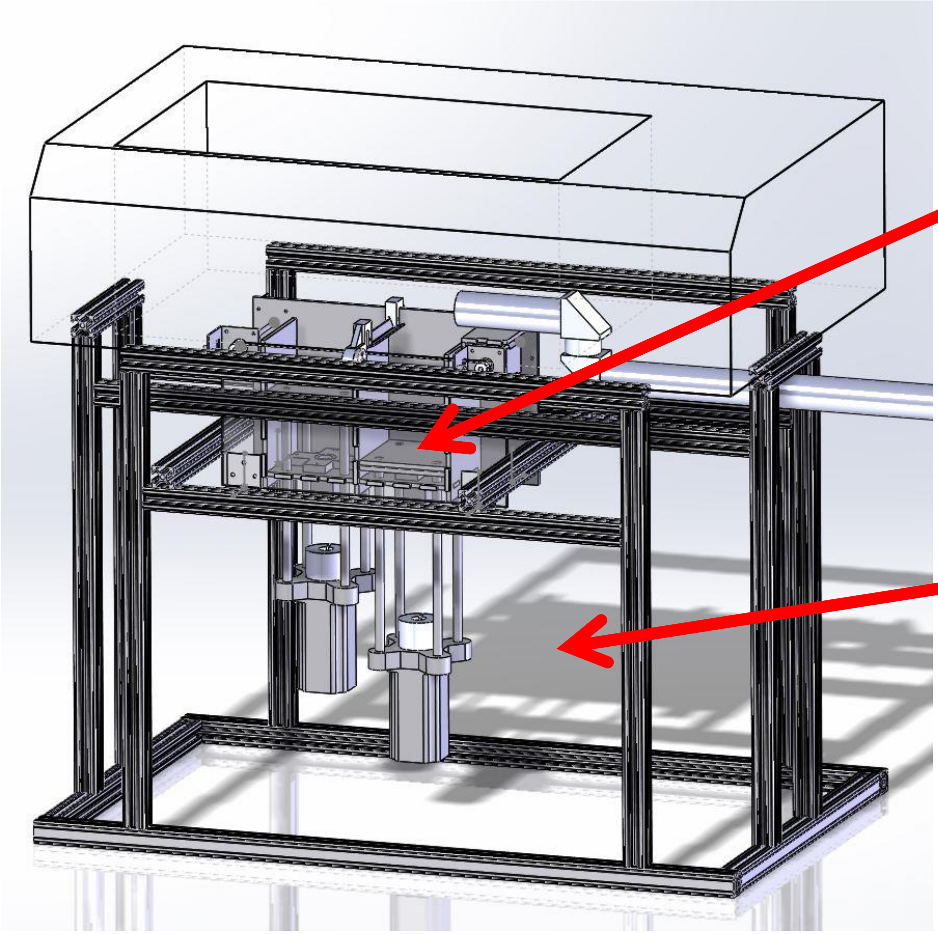
Level of Success	Description	% Complete	Deadline
1	Test Propellant Sintering	90%	3/10/16
2	Printed Material Testing	20%	3/23/16
3	Compare Multiple Grain Patterns	0%	4/7/16

Questions?

Backup Slides

Ventilation Changes (Back-up)

Design Changes: Ventilation

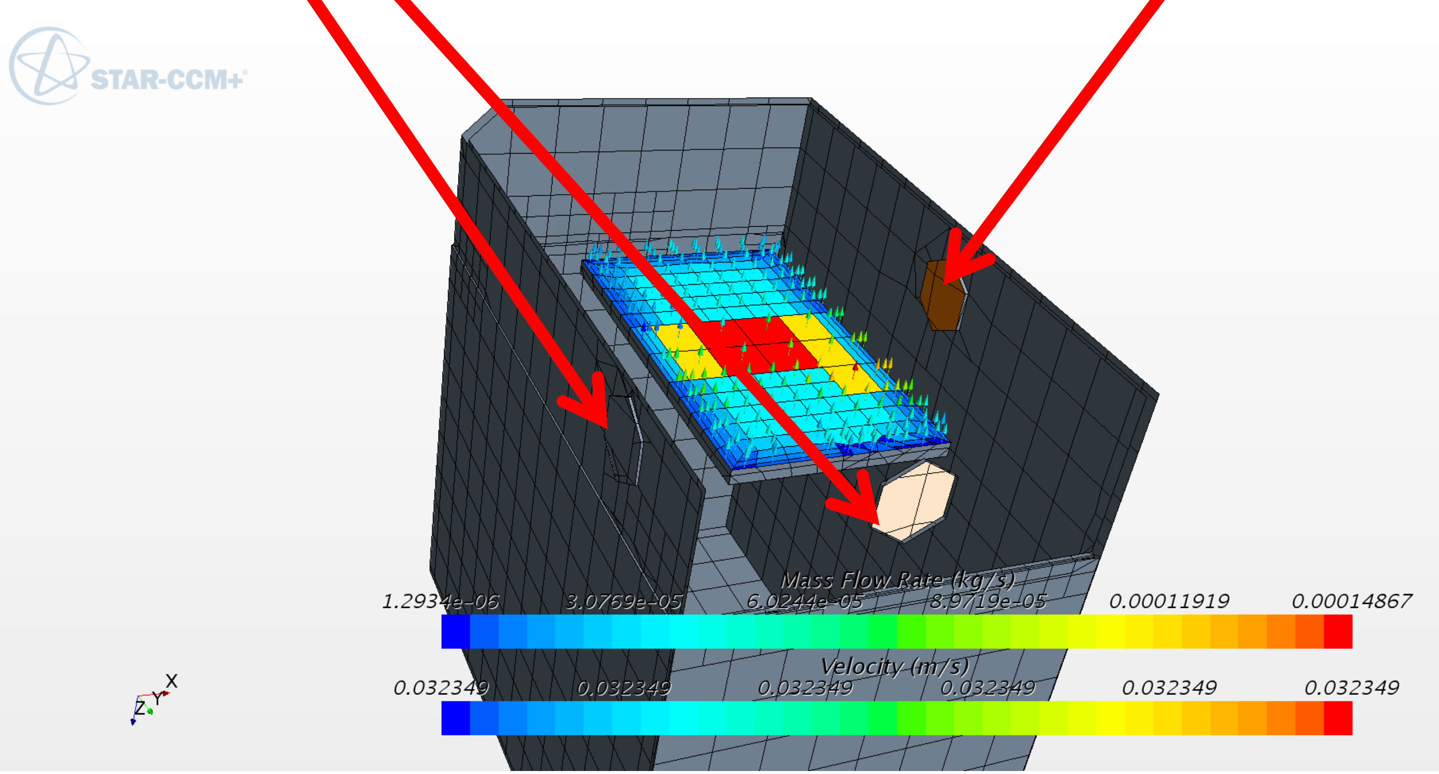


Fumes from Sucrose-KNO3 mix are hazardous in large quantities

Side wall and additional fans for ventilation must be installed

Design Changes: Ventilation

Component	Condition
Fan 1	$\dot{m} = .090\ kg/s$ (600 CFM)
Fan 2	$\dot{m} = .057\ kg/s$ (400 CFM)
Outlet Duct	Zero Pressure Outlet



Powder Bed Additional Tests
(Back-up)

Powder Bed Component Tests: Acrylic 'Snap' Test

Test Purpose:
Characterize acrylic fit and bonding options for stability, strength, and ease of manufacturing.

Test Procedure:
- Laser cut patterns for matching peg-hole and peg-small hole.
- Assemble with glue/epoxy and write observations.

Results:
- Matching peg-hole + epoxy hold but require effort to hold in place while curing.
- Peg-small hole snaps together without need for epoxy.

Facilities/Tools:
- Laser cutter
- Epoxy

Problem:
- Peg-small hole method used for Acrylic Body but results could not be replicated (pegs would not fit into holes)

Solution:
- Backup acrylic used to cut matching peg-hole body.

Requirement Verified	Description
None	The acrylic body is not part of the functional requirements.

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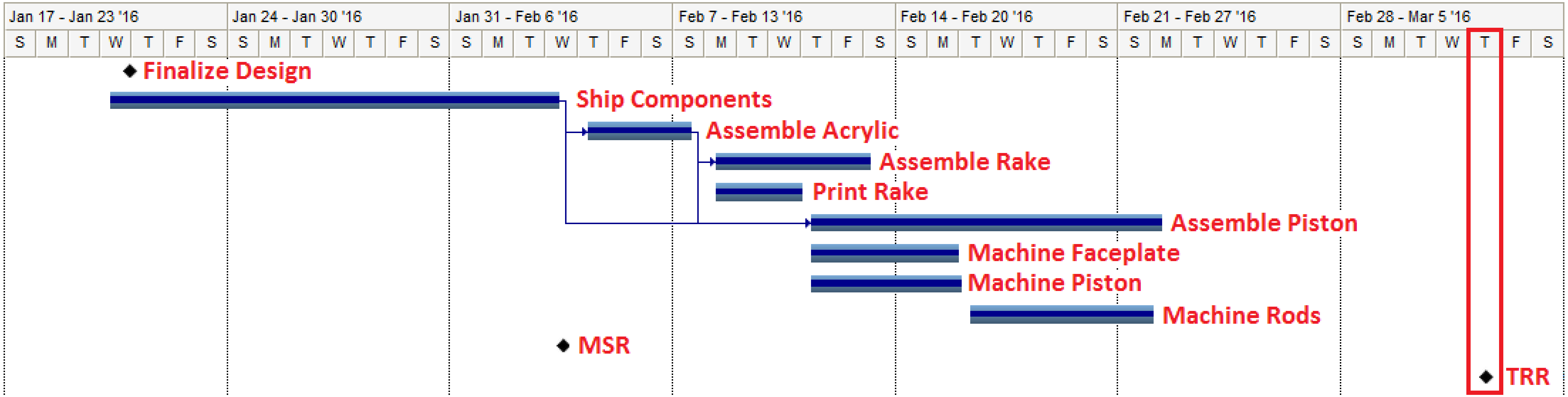
Powder Bed Manufacturing Schedule



Problem: Completed 1 week behind schedule
Impact: Integration testing is on a tighter schedule
Level 1 success still expected to occur on March 10th

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All Tests Schedule
(Back-up)

REMAKE THIS CHEWBACCA Testing Schedule