Solid Propellant Additive Manufacturing

Preliminary Design Review

Customer:
Special Aerospace Services (SAS)

Advisor:
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Team Members

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Agenda

- Project Overview
  - Project Motivation
  - CONOPs
  - FBD
  - Baseline Design
- Evidence of Baseline Feasibility
  - Thermal Model
  - Safety Analysis
  - Powder Bed Design
  - Software and Component Integration
  - Structural Testing
- Status Summary

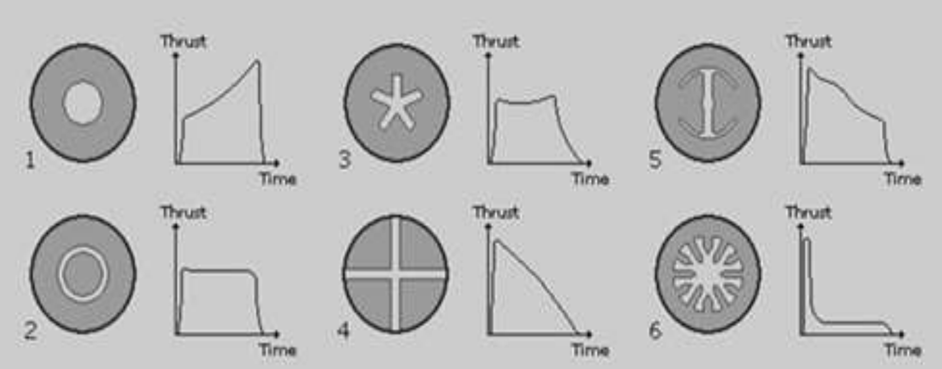
Definitions

- Grain - the cross-sectional geometry of solid propellant
- FDM - Fused Deposition Modeling
- SLS - Selective Laser Sintering
- Propellant Cake - a disk of solid rocket motor propellant
- SRM - Solid Rocket Motor
- SOH - State of Health
- PWM - Pulse Width Modulation

Project Overview

Motivation

- Traditional Casting Limitations:
  - Limited number of grain shapes
  - Air Bubbles in cast
  - Nonuniform setting



Example Grain Shapes and Thrust Profiles[1]

- 3D printing can improve the traditional casting method:
  - Produce complex grain shapes and new thrust profiles
  - Does not need to manufacture a different cast for each design

Solid Rocket Composite Propellant: Sucrose - KNO_3

Melting Points:

- Sucrose: ~186 ℃
- KNO3: ~333 ℃
- Propellant Auto-Ignition ~ 400 ℃

Propellant Composition:

- Fuel = Sucrose(35% by mass)
- Oxidizer = KNO3 (65% by mass)

Potassium Nitrate Powder[2]

Reason for choosing Sucrose-KNO3

- Safer than other solid rocket fuel (non-explosive)
- Easy to obtain
- Not restricted by the International Traffic in Arms Regulation (ITAR)

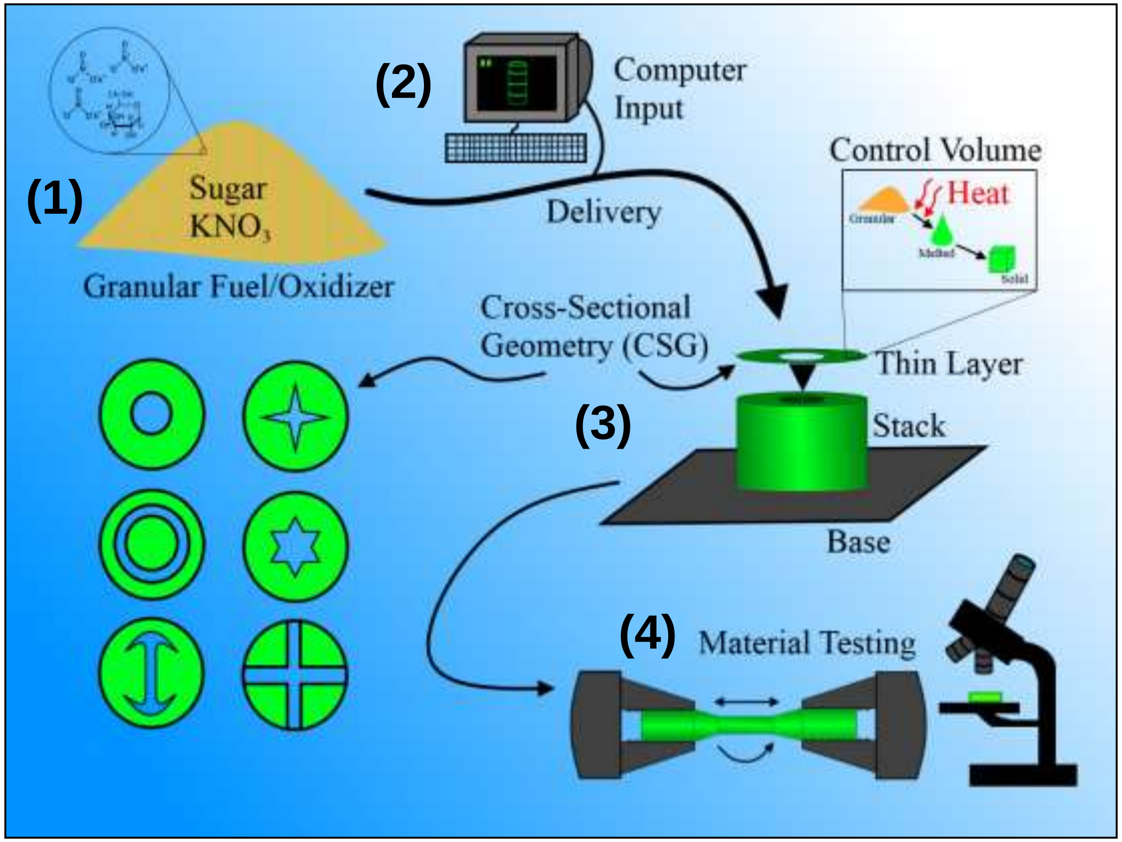
Sucrose Powder[3]

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.

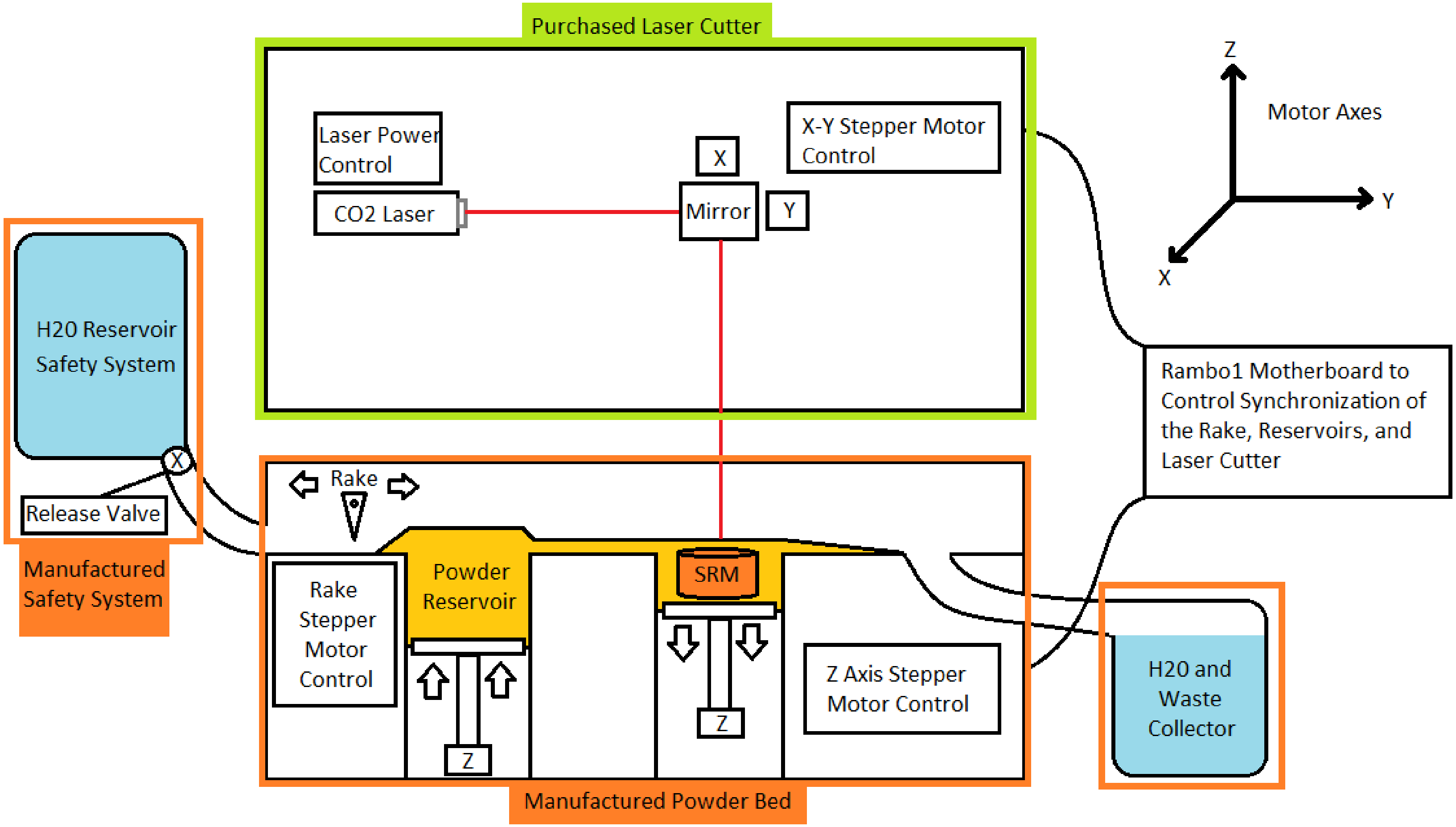
Full Project Concept of Operations

1) Mix KNO3 and sucrose for printing
2) Upload CAD file of desired grain shape to printer
3) Print desired cross section layer by layer
4) Remove finished motor from printer bed and conduct material testing



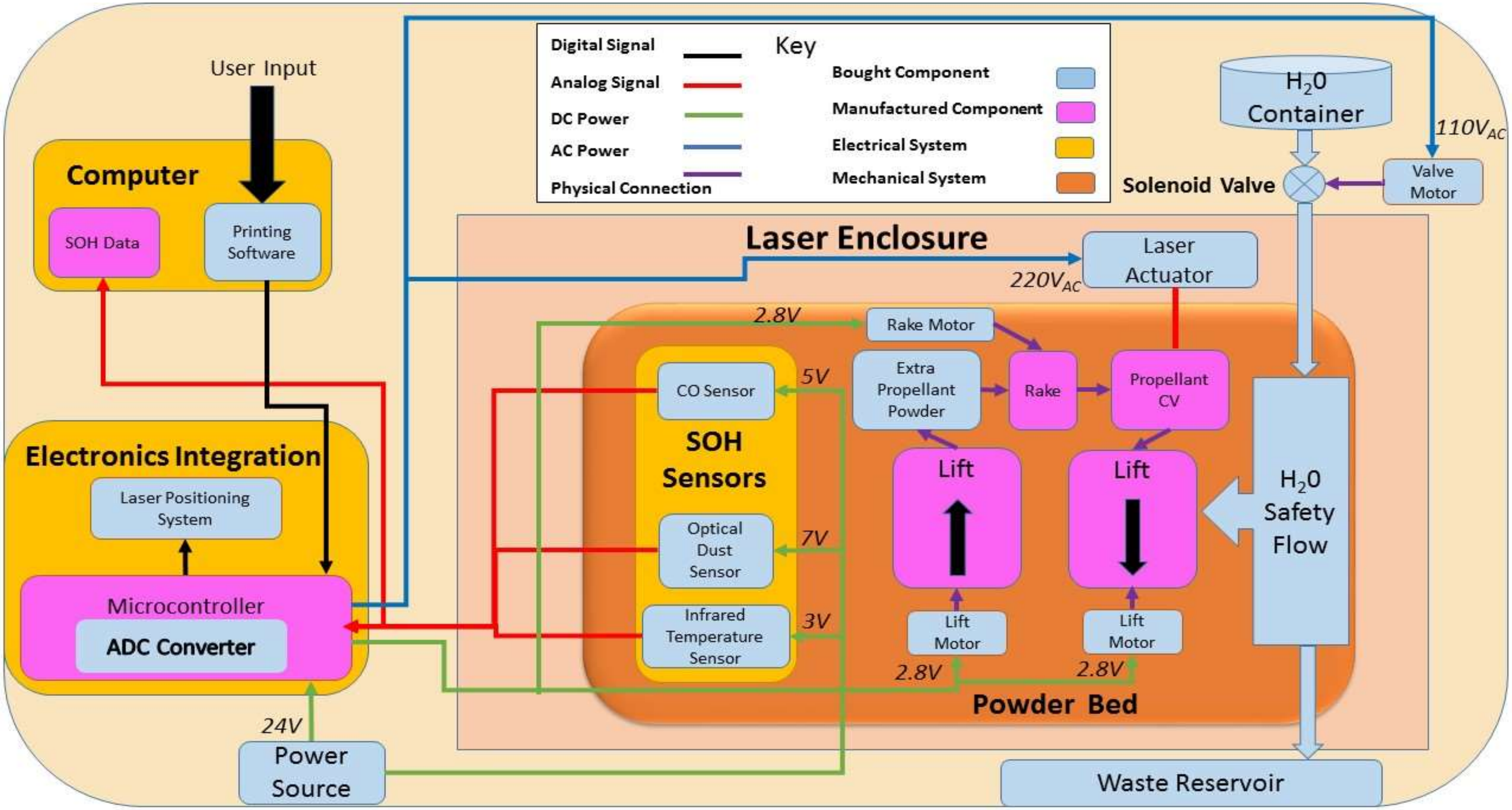
Project CONOPs Diagram

Printer Concept of Operations



Project Overview | Baseline Feasibility | Status Summary

System Functional Block Diagram



Key

Digital Signal —

Analog Signal —

DC Power —

AC Power —

Physical Connection —

Bought Component 🟦

Manufactured Component 🟪

Electrical System 🟨

Mechanical System 🟧

User Input

Computer

SOH Data

Printing Software

Electronics Integration

Laser Positioning System

Microcontroller

ADC Converter

24V

Power Source

H_20 Container

$110V_{AC}$

Valve Motor

Solenoid Valve

Laser Enclosure

Laser Actuator

$220V_{AC}$

2.8V

Rake Motor

Extra Propellant Powder

Rake

Propellant CV

CO Sensor

5V

SOH Sensors

Optical Dust Sensor

7V

Infrared Temperature Sensor

3V

Lift

Lift

Lift Motor

Lift Motor

2.8V

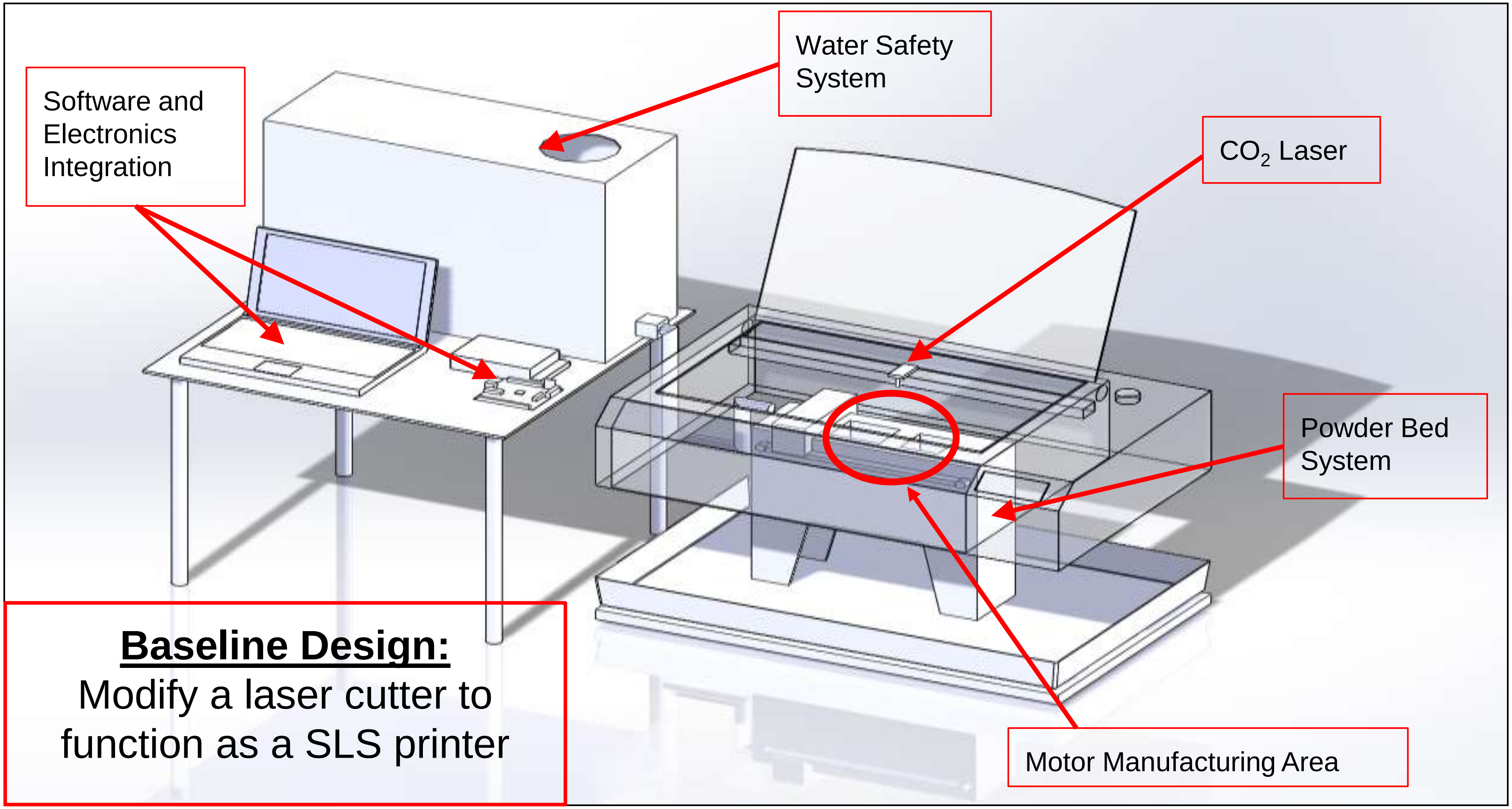
2.8V

H_20 Safety Flow

Powder Bed

Waste Reservoir

Baseline Design Overview



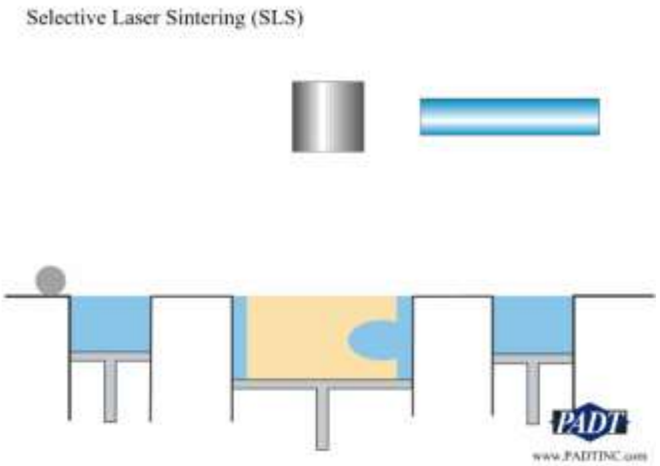
Baseline Design:
Modify a laser cutter to function as a SLS printer

What is Selective Laser Sintering?

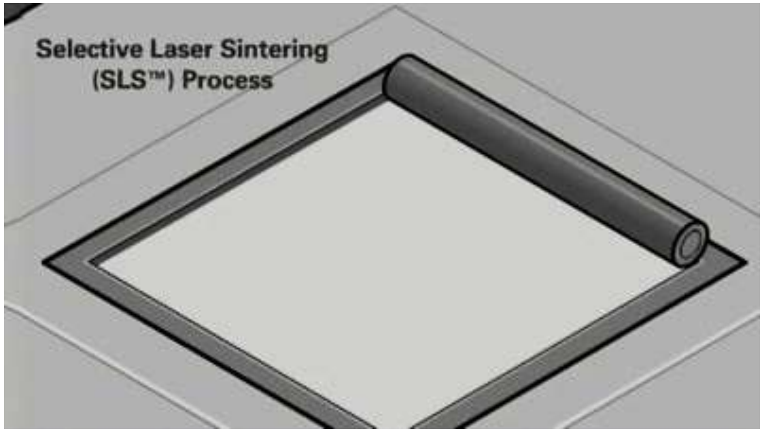
- Selective Laser Sintering (SLS) is a type of Additive Manufacturing which sinters/melts a powder with a laser

<u>SLS Operation:</u>

1. A CAD file is uploaded to the printer
2. The printer uses a CO_2 laser to heat a specified cross-sectional area of the powdered material
3. The heated material binds together forming a solid
4. The powder bed is then lowered by one layer thickness
5. A new layer of powder material is then swept on top of the previously fused layer



SLS Process (Profile View)[4]



SLS Process (Top View)[5]

Baseline Requirements

Functional Requirements

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

Design Requirements

Parent Functional Requirement	Design Requirements
FR 1	1.1: The printer shall have a functional 3D positioning system. 1.2: The printer shall be capable of manufacturing user-defined designs given a .step file input. 1.3: Each layer of manufactured material shall bond to the previous and following layer (when applicable).
FR 2	2.1: The fuel and oxidizer shall be mixed into a homogeneous mixture prior to manufacturing. 2.2: The fuel shall be composed of potassium nitrate and sucrose.

Design Requirements Contd.

Parent Functional Requirement	Design Requirements
FR 3	3.1: The printed layer of propellant shall be no more than 1.0 mm. 3.2: Each layer shall have a tolerance of ±30%.
FR 4	4.1: The following properties of additively manufactured propellant and cast propellant shall be measured: density, tensile strength, crush strength, and energy released during combustion.
FR 5	5.1: The energy released during combustion of the propellant shall be measured. 5.2: The chemical species created as reactants during combustion of the propellant shall be identified 5.3: The printer design shall include a fire-extinguishing safety system.

Design Requirements Contd.

Parent Functional Requirement	Design Requirements
FR 5	5.4: The project shall produce a thermodynamic model to predict temperature distribution of the propellant during manufacturing to within 10 C^0. 5.5: The 3D printer shall have a State of Health System capable of measuring the propellant temperature to within 5 C^0. 5.6: The State of Health System shall be capable of cutting off power to the laser if a propellent temperature of over 350 C^0 is detected 5.7: The State of Health System contain the following sensors for redundancy: Carbon Monoxide sensor, Temperature sensor, Optical Dust sensor.

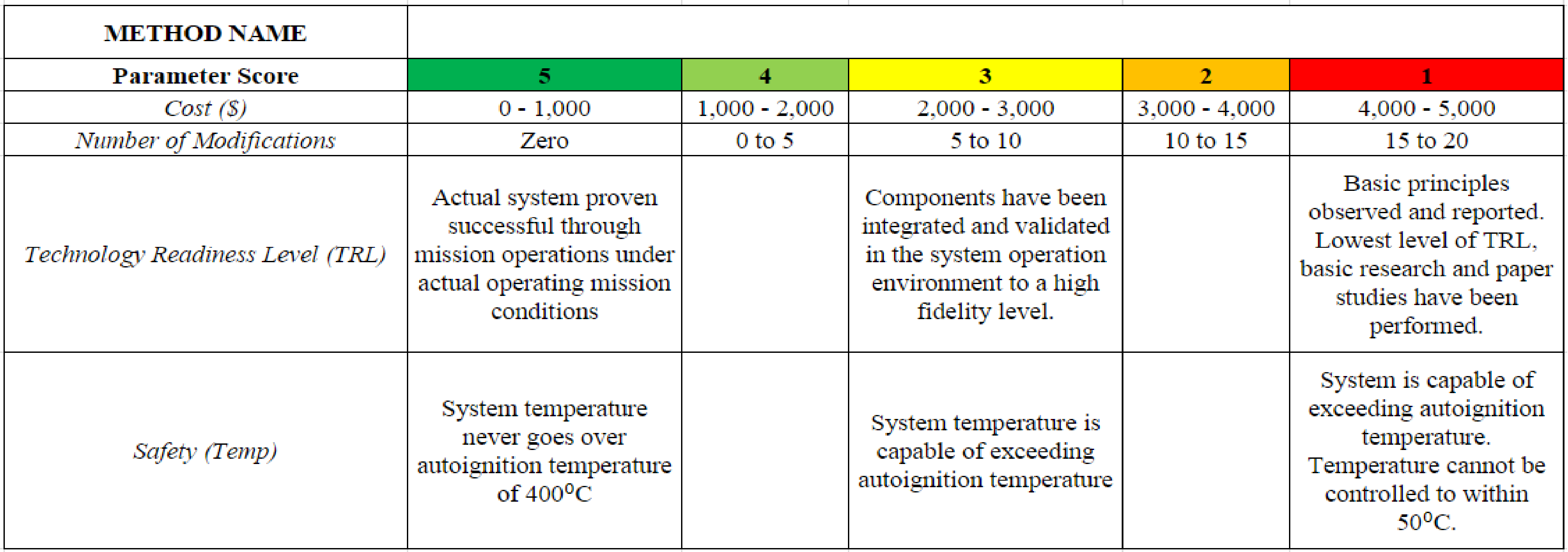
Critical Project Elements for SLS

Critical Project Element (CPE)	Description
CPE #1: Thermal Model	• Safety • Laser requirements
CPE #2: Safety Design	• Fire risk • Prevention
CPE #3: Powder Bed	• Layer thickness • Motor control
CPE #4: Software and Electronics Integration	• Electronics system design • Software integration
CPE #5: Material Testing	• Necessary tests • Machinery

Printing Method Trade Study

Methods compared in trade study

- Fused Deposition Modeling (FDM)
- Selective Laser Sintering (SLS)
- Stereolithography (SLA)



METHOD NAME					
Parameter Score	**5**	**4**	**3**	**2**	**1**
Cost ($)	0 - 1,000	1,000 - 2,000	2,000 - 3,000	3,000 - 4,000	4,000 - 5,000
Number of Modifications	Zero	0 to 5	5 to 10	10 to 15	15 to 20
Technology Readiness Level (TRL)	Actual system proven successful through mission operations under actual operating mission conditions		Components have been integrated and validated in the system operation environment to a high fidelity level.		Basic principles observed and reported. Lowest level of TRL, basic research and paper studies have been performed.
Safety (Temp)	System temperature never goes over autoignition temperature of 400°C		System temperature is capable of exceeding autoignition temperature		System is capable of exceeding autoignition temperature. Temperature cannot be controlled to within 50°C.

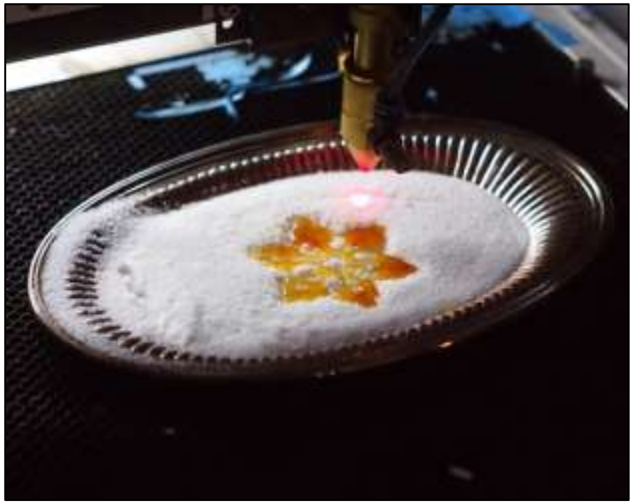
Trade Study Results

Winner: Selective Laser Sintering (SLS)

- TRL: Multiple demonstrations of feasibility with sugar as printed material
- Safety: Energy output of laser can be finely tuned to avoid combustion
- Modifications: Fewer modifications than standard FDM printers to convert a laser cutter

Functional Requirement:
FR 1: The project shall produce a 3D printer capable of automated additive manufacturing.


Maker Faire mascot sugar model[6]

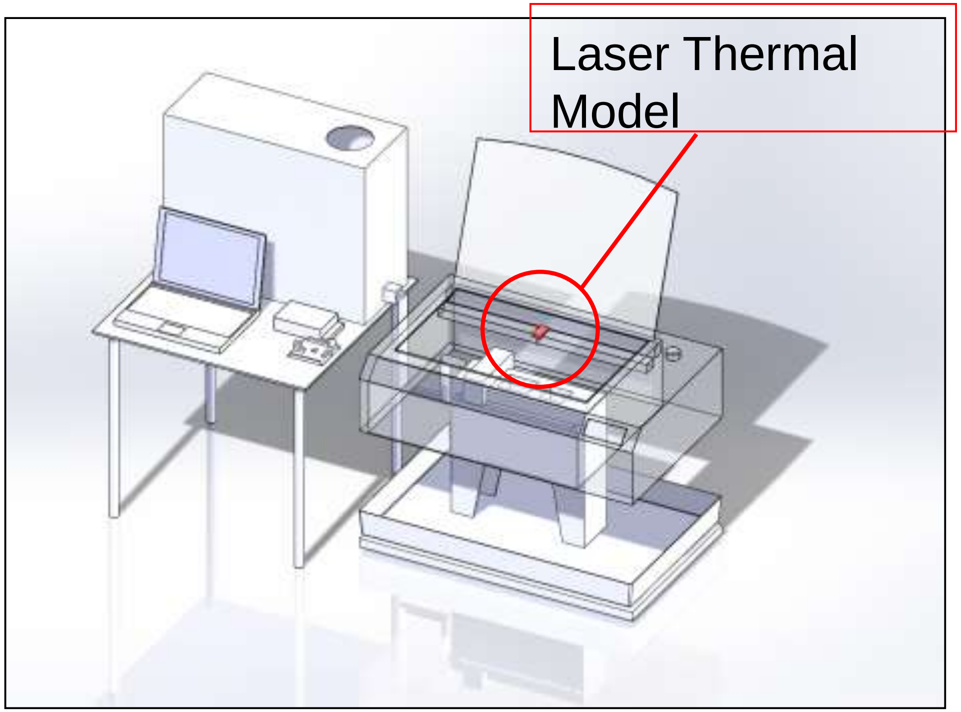

SLS printing pure sucrose[7]

CPE #1: Thermal Model

CPE #1: Thermal Model Design

- A thermal model is essential in determining the power and safety of the SLS printer
  - It ensures feasibility of the laser sintering complete layers of sucrose

  - It allows calculation of laser power restrictions and safety margins to prevent autoignition

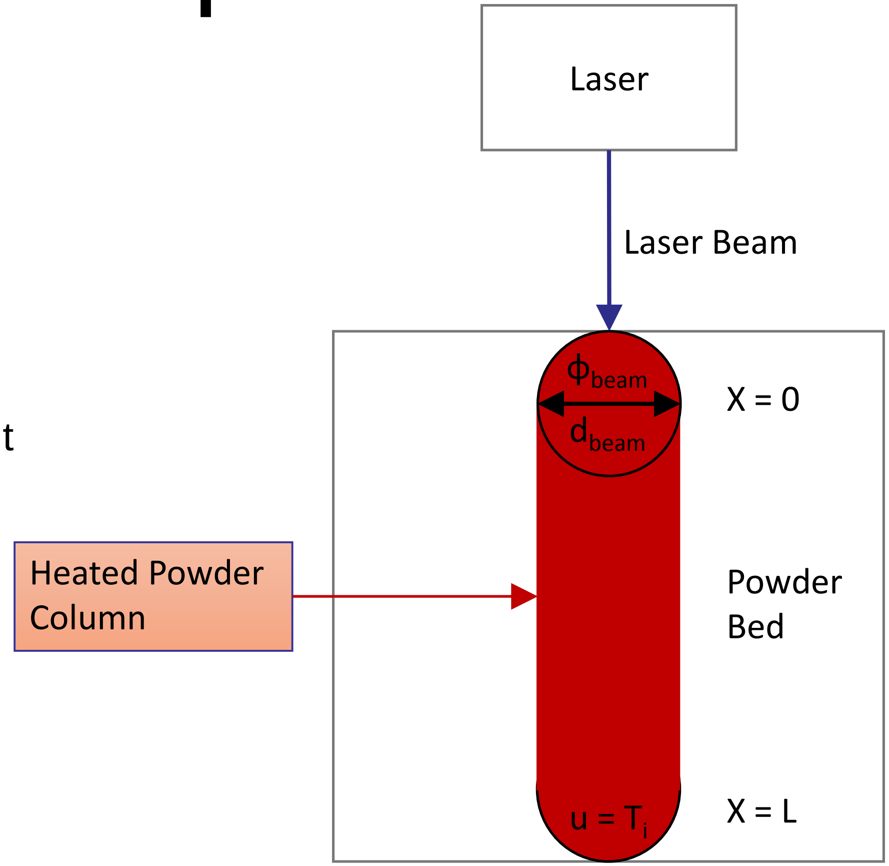


Laser Thermal Model

Baseline Design: Laser Location

CPE #1: Assumptions

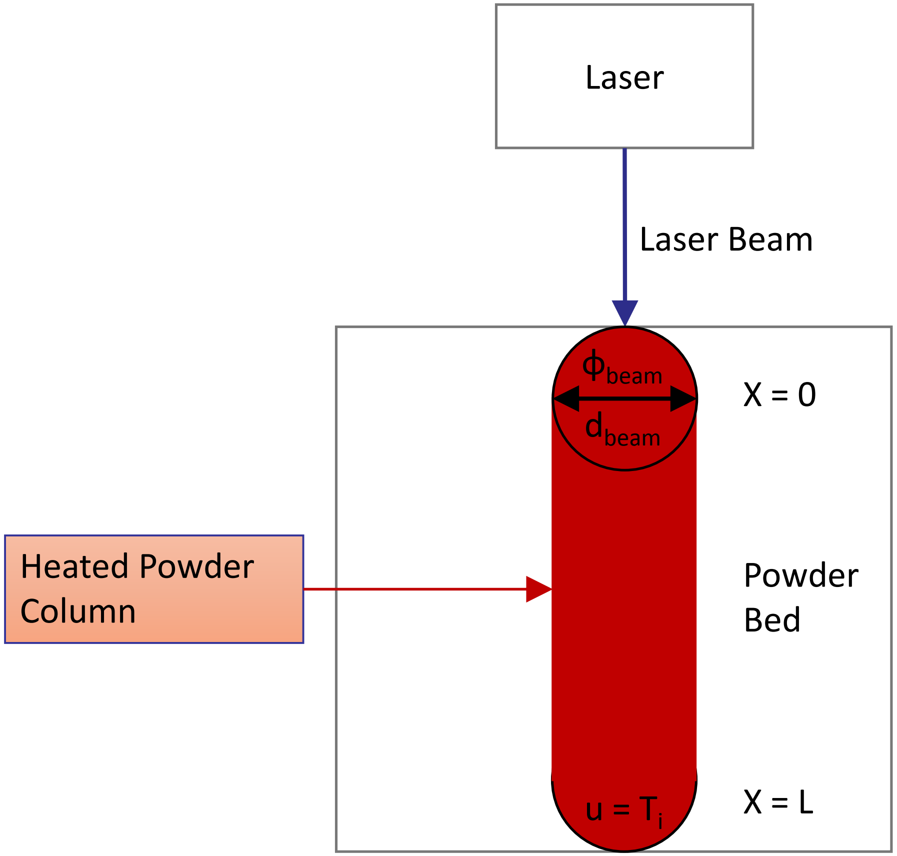
- Heat transfer modeled as a 1D rod
  - Only area in laser beam is heated (Diameter = beam width)
  - No heat is transferred to surrounding powder
- Reaches steady state instantaneously
  - Flux is assumed to be total energy per unit area of laser pulse
- Powder mixture is modeled as a solid
- Initial condition: uniform temperature throughout powder, T_i
- Boundary conditions:
  - Bottom of powder bed is forced to be T_i
  - Top of powder bed experiences constant heat flux, φ_{beam}



1D Heat Transfer Model

CPE #1: Values Used in Model

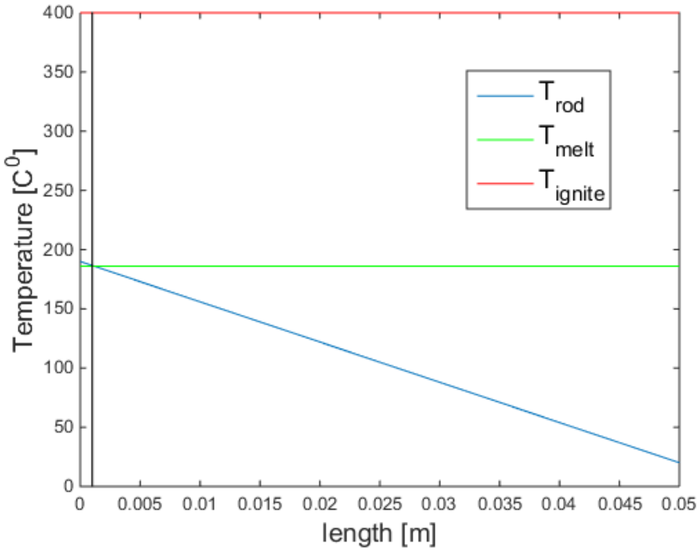
- d_{beam} = 0.1 mm
- Δt = 1 ms
- L = 0.05 m
- K_0 = 0.502 W/(m*k)
  - Weighted average by mass of K_0 of sucrose and KN03
  - 35% Sucrose, 65% $KN0_3$
  - K_0 for $KN0_3$ is 0.691 W/(m*K)
  - K_0 for Sucrose is 0.151 W/(m*K)
- T_i = 20 C^0 and 100 C^0
- φ_{beam} varies proportionally with P_{beam}
  - P_{beam} is a design parameter



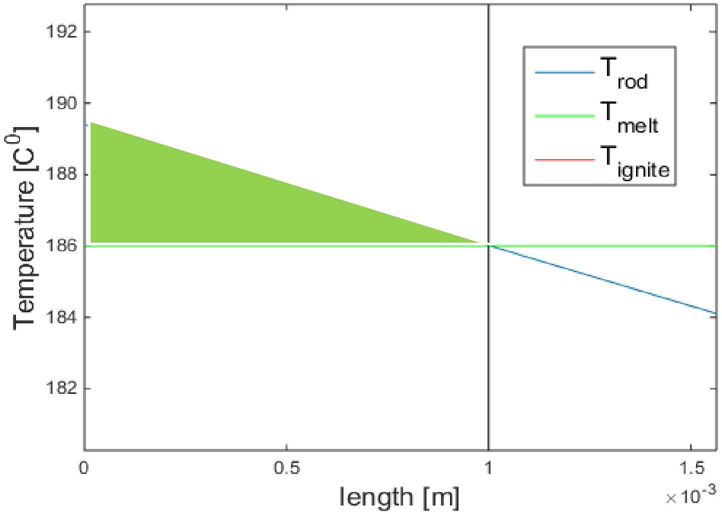
1D Heat Transfer Model

CPE #1: Results of Room Temp Powder Bed (20 C^0)

- P_{beam} = 13.4 mW
- φ_{beam} = 1.7 kJ/m^2
- Green region = molten propellant
- Take-away: **sintering without propellant ignition is feasible**



Powder Temperature



Molten region

CPE #1: Conclusions & Future Tasks

- Conclusions:
  - Achieve sintering with safety margin of about ~200^0 C
  - Need to reduce power of 40 W laser for safe sintering
  - Laser system viable for sintering
- Future Tasks:
  - Develop time dependent heat transfer model
  - Find more accurate value of K_0
  - Characterize reflectivity of Propellant powder
  - Create more accurate model of beam power
  - Develop model of heat transfer through a powder

Thermal Model Requirements Fulfillment

Functional Requirement:

FR 5: Safety shall be the primary concern in every aspect of the project.

Design Requirement:

DR 5.4: The project shall produce a thermodynamic model to predict temperature distribution of the propellant during manufacturing.

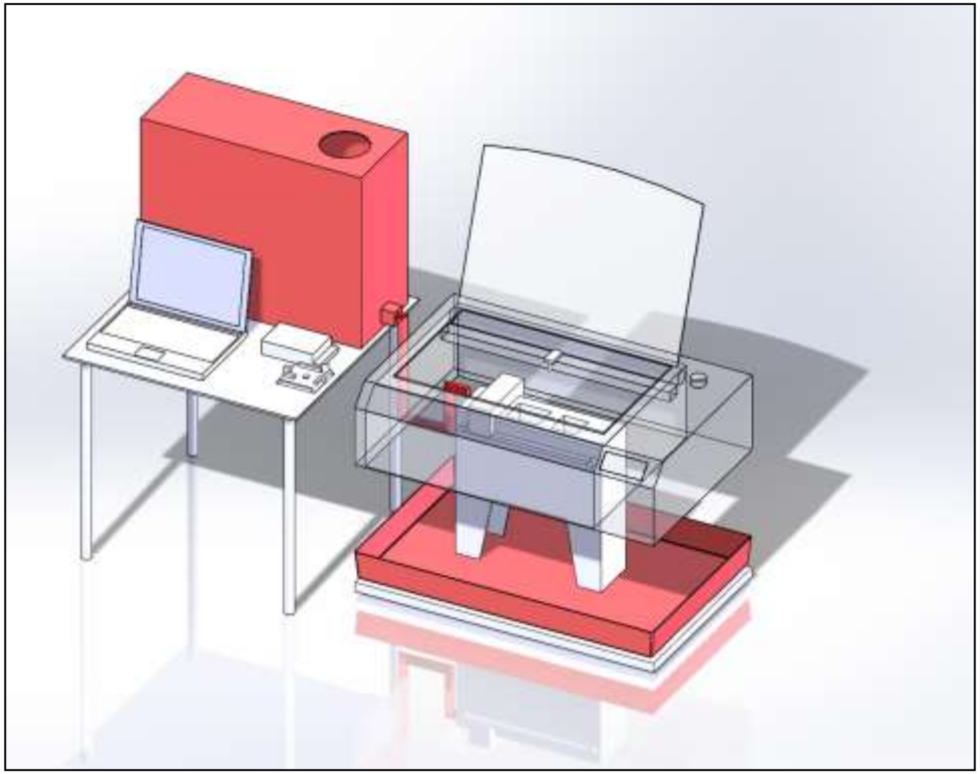
Baseline Design:

Complete the thermal model and implement power correction on laser output

CPE #2: Safety Design

CPE #2: Safety Design

- Team will have training in HazMat Disposal and Laser Safety
- Low Chance of Combustion (From Heat Model)
- "State of Health" System monitors Powder Bed
- Integrated Extinguishing Mechanism

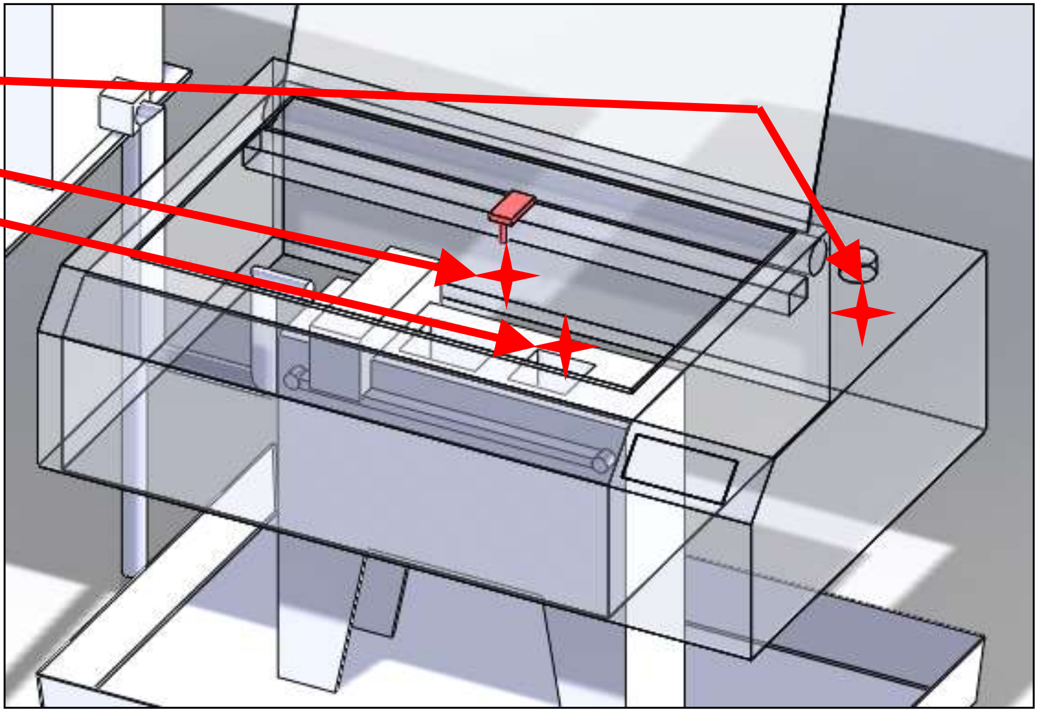


Baseline Design: Safety System

CPE #2: State of Health System

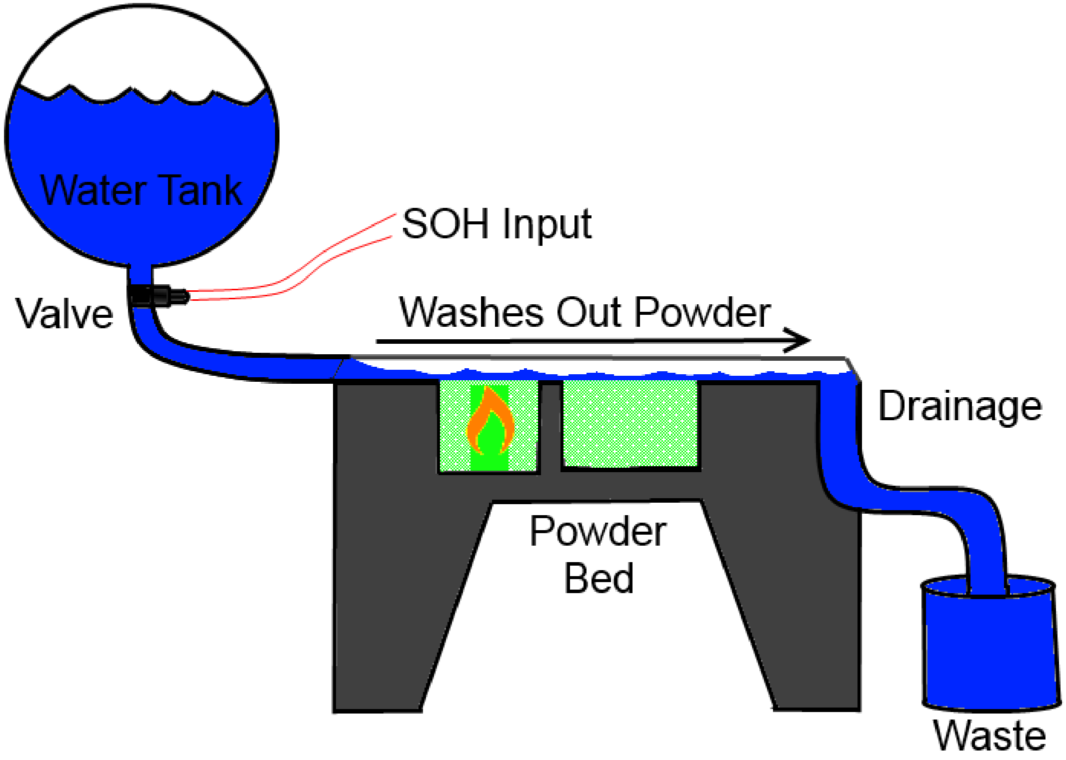
- Three Sensors:
  - -Optical Dust Sensor
  - -Infrared Thermometer
  - -Carbon Monoxide Sensor

- Emergency Response:
  - -Cut power to laser diode
  - Activate release valve for H2O reservoir



Baseline Design: SOH System Location

CPE #2: Water Safety System



Water Safety Concept of Operations

- Water dilutes powder and flushes into waste container
- Total Energy Release of Entire Powder Bed: **1.7 MJ**
- Required Volume of Water Reservoir for ΔT = 20°: **50 L**
- Container dimensions:
  - 0.62m x 0.39m x 0.22m
- Safety Factor: **2.4**

Safety Requirements Fulfillment

Functional Requirement:

FR 5: Safety shall be the primary concern in every aspect of the project.

Design Requirement:

DR 5.4: The project shall produce a thermodynamic model to predict temperature distribution of the propellant during manufacturing to within 10 C^0.

DR 5.5: The 3D printer shall have a State of Health System capable of measuring the propellant temperature to within 5 C^0.

DR 5.6: The State of Health System shall be capable of cutting off power to the laser if a propellant temperature of over 350 C^0 is detected

DR 5.7: The State of Health System contain the following sensors for redundancy: Carbon Monoxide sensor, Temperature sensor, Optical Dust sensor.

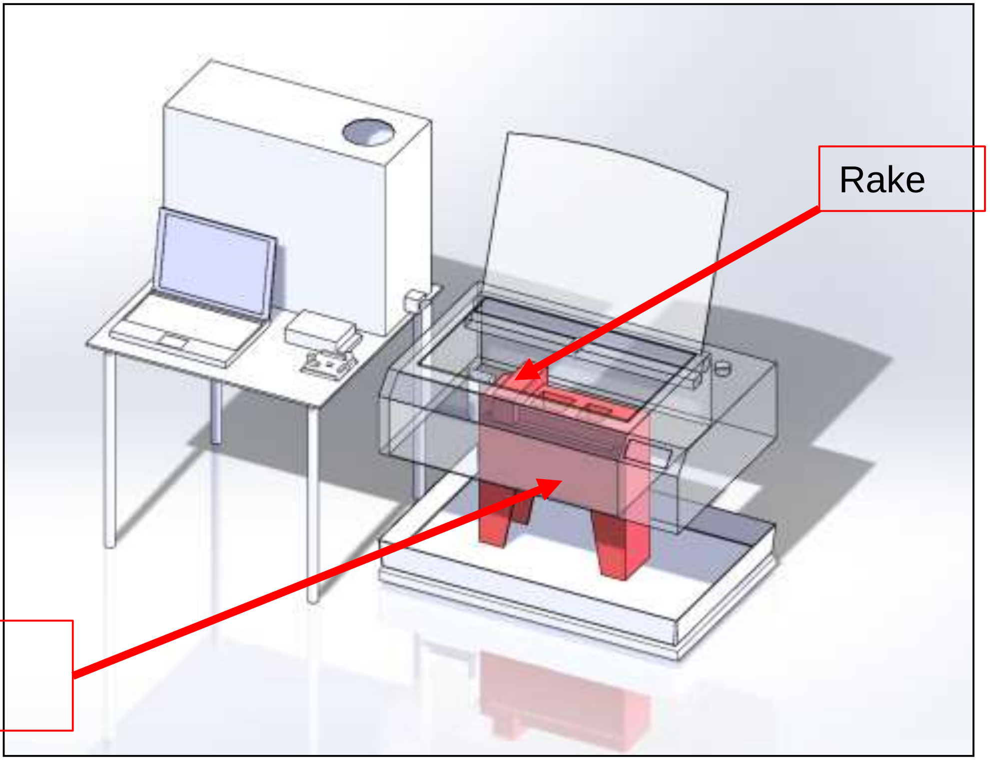
Baseline Design:

Implement SoH sensors with emergency relief reservoir of water

CPE #3: Powder Bed

CPE #3: Powder Bed

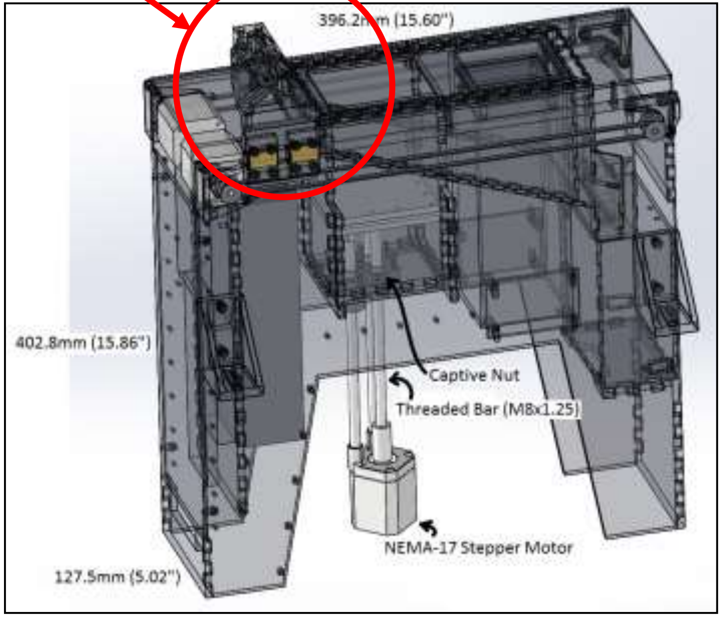
- Holds printed product and powdered propellant
- Consistently spreads the powder across the bed
- Contain surplus powder



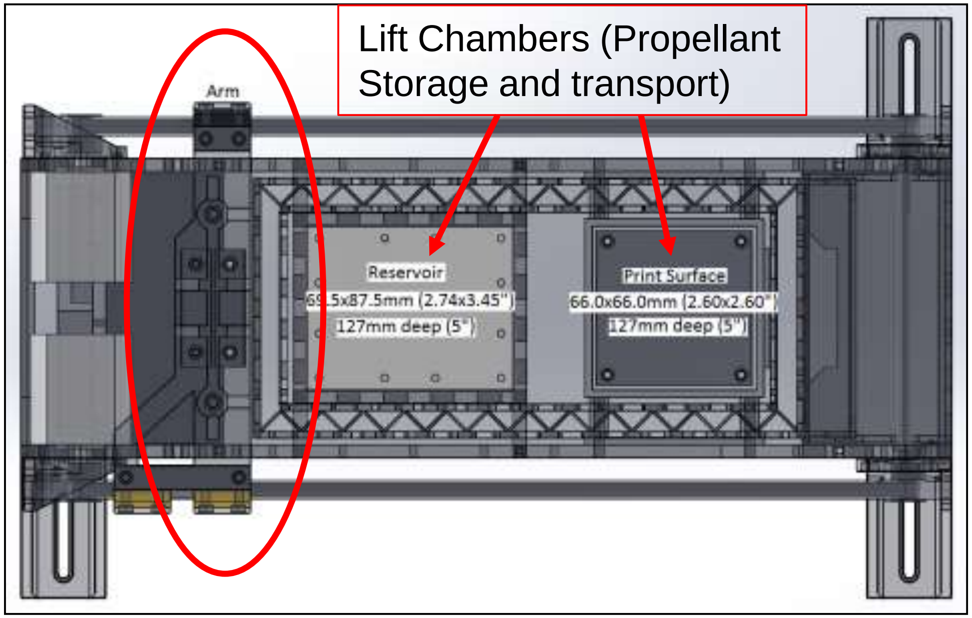
Baseline Design: Powder Bed System

CPE #3: Powder Bed Components

Motorized Rake



Powder Bed Mechanical Design[21]



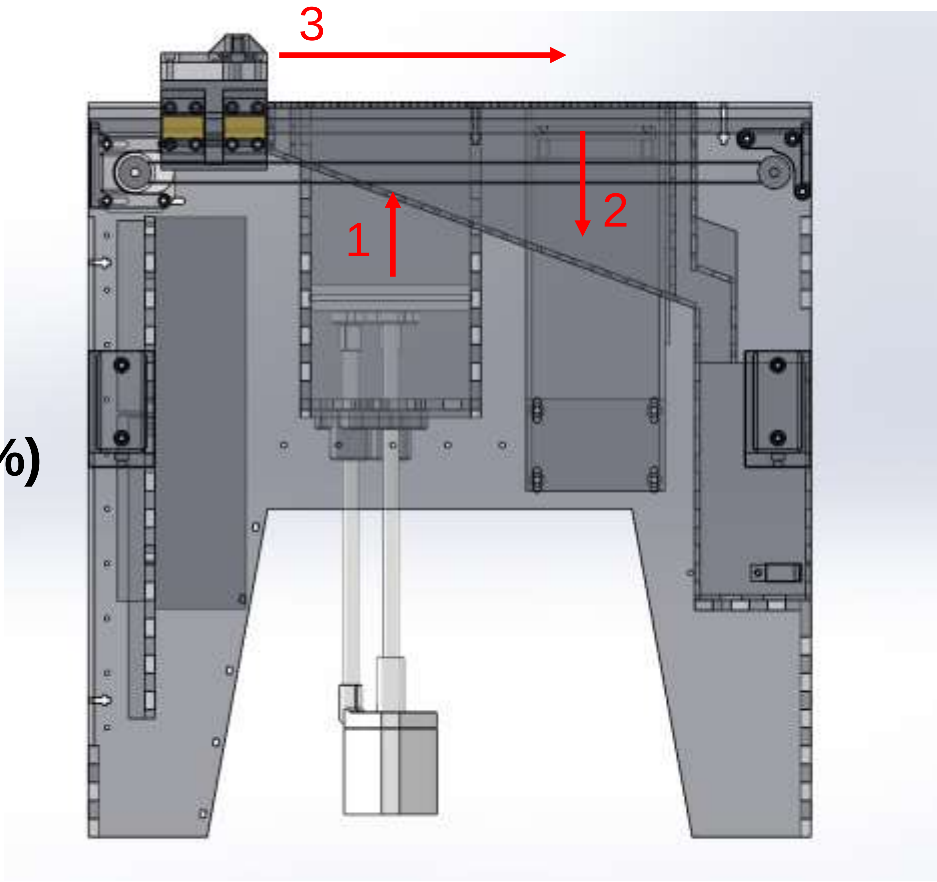
Lift Chambers (Propellant Storage and transport)

Powder Bed Aerial View[21]

Lift Feasibility: Resolution

$$\Delta Z = \frac{\theta_{rot} P}{360°}$$

θ_{rot} = Motor rotation (1.8°±5%)
P = Thread pitch (1.25mm)
ΔZ = Vertical travel (0.004mm±5%)



1. Powder Reservoir
2. Print Surface
3. Arm/Rake

Powder Bed Requirements Fulfillment

Functional Requirement:

FR 3: The printer shall have a mechanism to deliver the mixed fuel and oxidizer to the manufacturing area.

Design Requirement:

DR 3.1: The printed layer of propellant shall be no more than 1.0 mm.

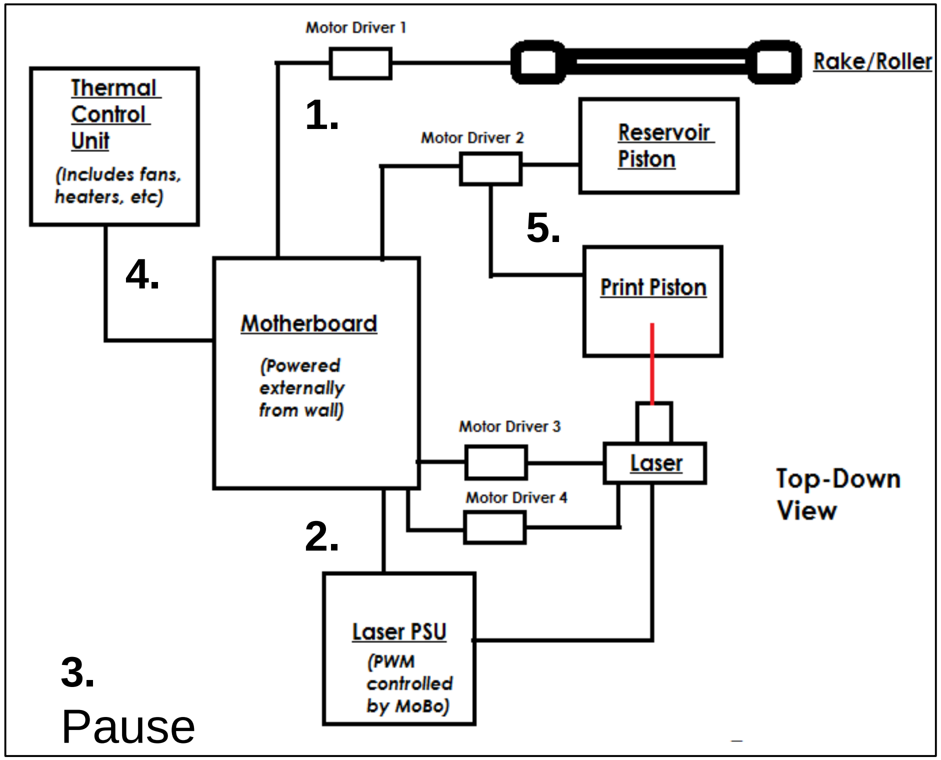
DR 3.2: Each layer shall have a tolerance of ±30%.

Baseline Design:

Manufacture using a pre-existing open source design – R2 Module

CPE #4: Software and Electronics Integration

CPE #4: Software Integration



Software Integration Diagram

SLS Printer Software Control

1. **Rake motor activated to spread powder**
2. **Laser cutter activated for a single cut**
3. **Wait 2 minutes to allow layer to cure**
4. **Thermal control sensors checked**
5. **Activate reservoir piston motors**
    a. **Powder reservoir moves up**
    b. **Print bed moves down**
6. **Repeat loop until propellant is completely manufactured**

CPE #4: RAMBo Board

- Used for integration with Computer Numerical Control (CNC) machines
- Programmable using Arduino software
- Laser pulse rate 0.125 mHz
- Arduino-mega clockrate is 16 mHz

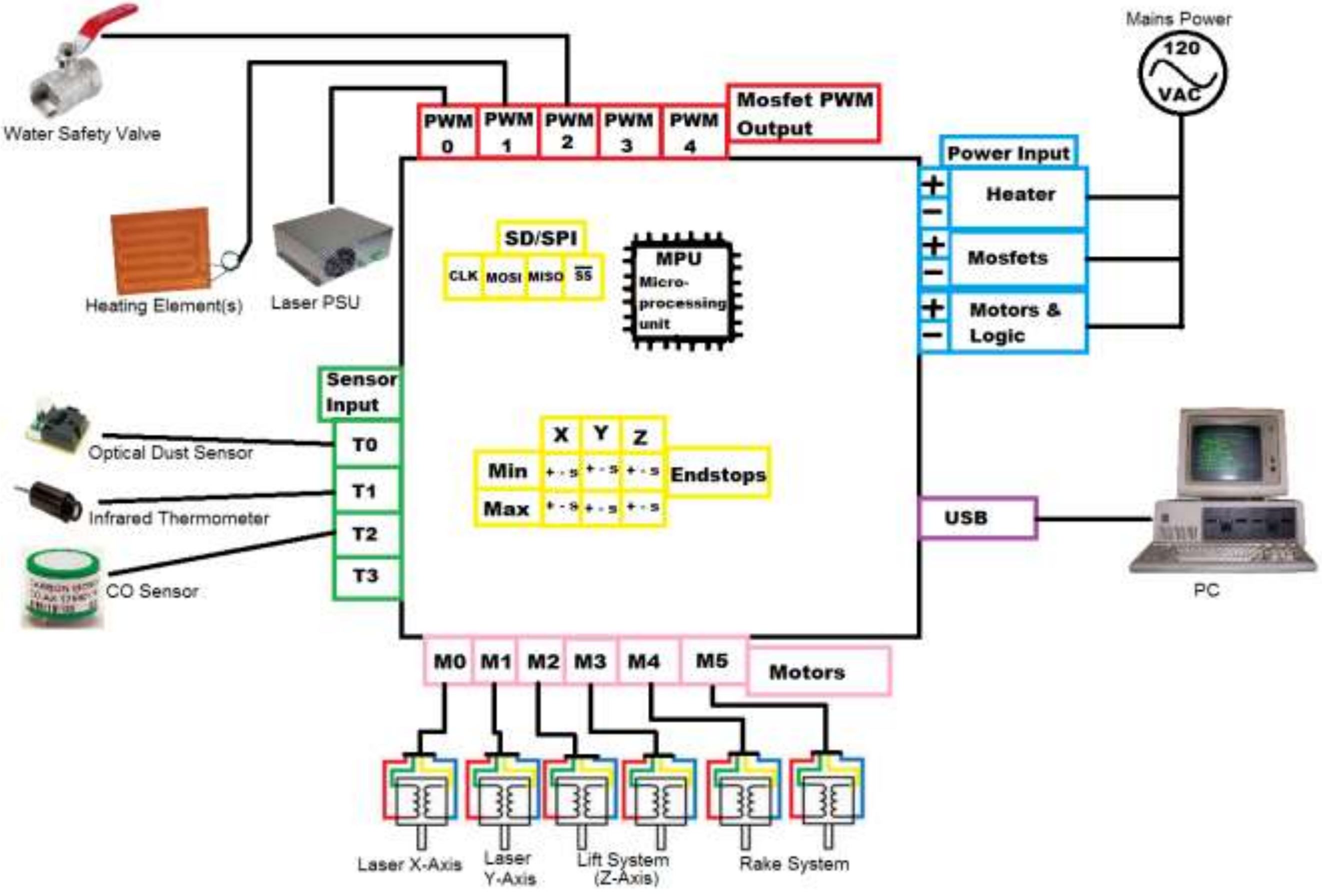


Diagram of RAMBo Board Layout

CPE #5: Material Testing

CPE #5: Propellant Structural Testing

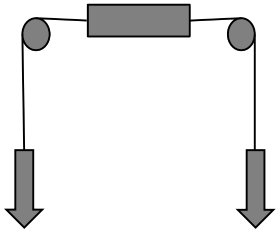
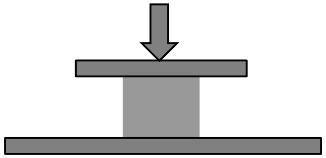
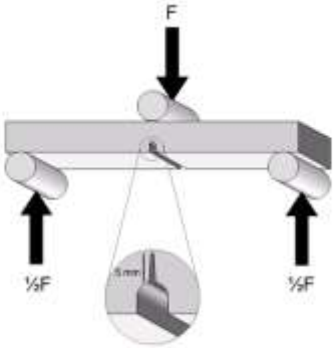
- Common Tests in Industry
  - Tension, Torsion, Compression, Shear, Fracture Toughness, Stiffness, Creep, and Temperature Cycling
  - Intended to assure safety and performance

- SPAM Testing
  - Stress/Strain curves, Poisson's Ratio, Fracture Toughness, Critical Crack Length, Young's Modulus

stress: $\sigma = F/A$ strain: $\varepsilon = \Delta L/L$

CPE #5: Propellant Material Testing

Instron machine[8]

Alternate Test Apparatus Configurations		
Tension	Compression	Fracture Toughness
		

Fracture Toughness Diagram[9]

Material Testing Requirements Fulfillment

Functional Requirement:

FR 4: The printed propellant properties shall be compared to traditionally cast propellant properties.

Design Requirements:

DR 4.1: The additively manufactured propellant and cast propellant shall each be characterized by density, tensile strength, crush strength, and energy release.

Baseline Design:

Material testing through accessible or analogous machinery

Status Summary

Critical Project Element Feasibility Review

CPE	Critical Proofs of Feasibility		
	Metric	Result	Safety Factor or Error Margin
SLS Method (Thermal Model)	- Maximum Operating Temperature Below 400°C	- Maximum Operating Temperature 200°C	2
Safety Design	- Energy release from propellant ignition can be contained (1.7MJ)	- Water safety system can contain any energy release (4.1MJ)	2.4
Powder Bed	- Lift and Rake assembly can transport a mass of 2.5Kg to print area	- Powder Bed motors use 0.43 Nm - 0.0273 Nm of torque is required	15.75
Software and Electronics Integration	- Software can be modified and/or is available as Open Source - Motherboard has sufficient functionality	- Software is Open Source (RepRap) - 6 motor pin outs available, designed for SLS manufacturing	N/A
Material Testing	- Motors can be safely tested for structural performance	- 72.1MPa axial loading before predicted auto-ignition, axial loading will be applied up to 24.0MPa if needed	3

Budget Analysis

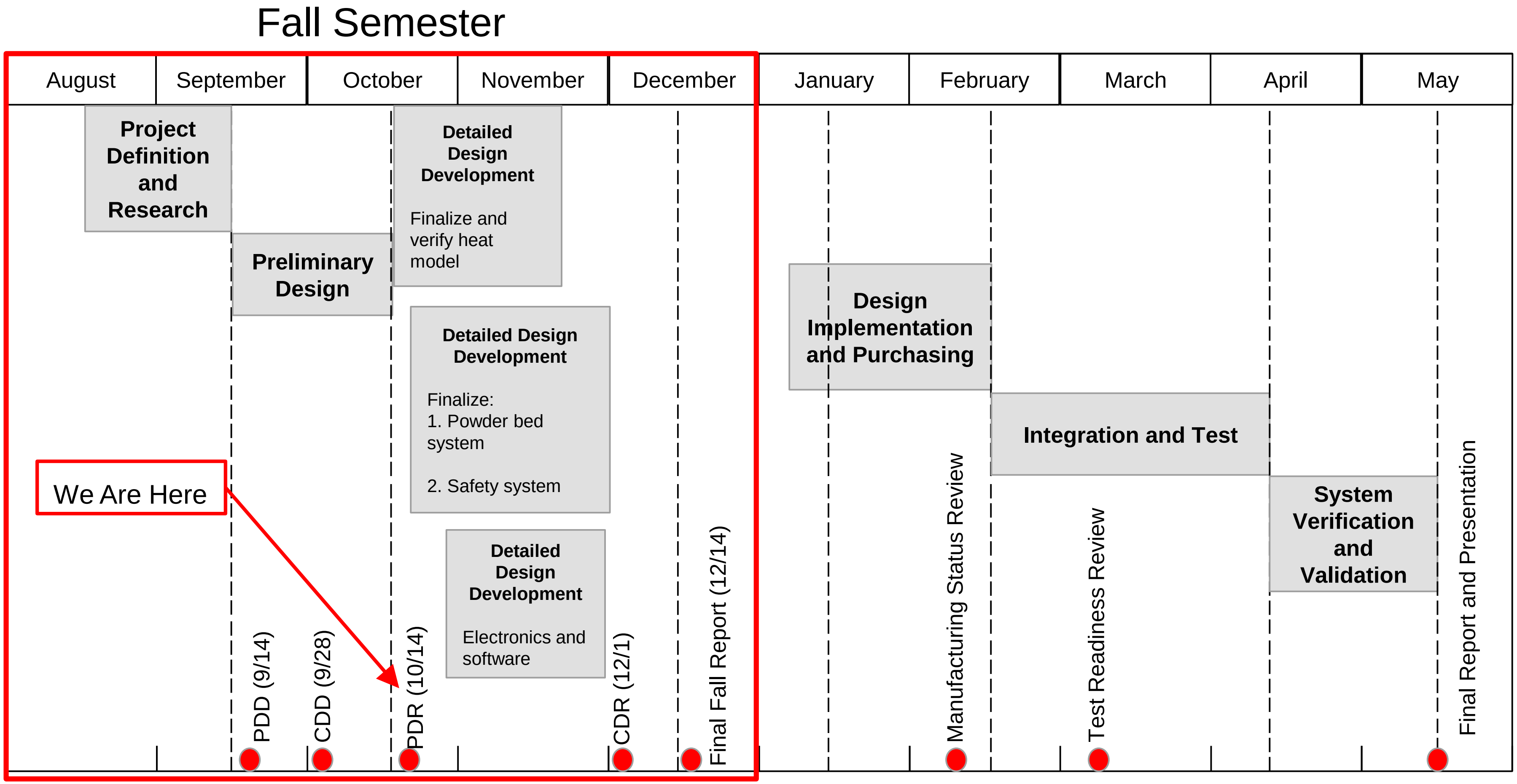
- Budget is driven by cost of laser cutter
- Because laser power is not imperative to system functionality, lower power lasers can be used (40W instead of 60-80W) and money can be saved
- Budget Margin **35%**

System	**Cost**
Laser Cutter (CNC 40 Watt CO2) *Free Shipping	$2,200.00
Powder Bed	$220.00
Propellant Raw Materials (Sugar and KNO3)	$400.00
Safety Equipment	$200.00
Integration Hardware and Electronics	$230.00
Grand Total	**$3,250.00**

Steps in Moving Forward

- Compile safety documentation before testing and manufacturing
- Testing to verify mathematical models
    - Laser tested on melting sucrose
    - PWM control tested for a laser diode
- Compile list of individual powder bed components and corresponding manufacturing material
- Software and Electronics Integration
    - Timing of mechanical components/trade-offs
    - Automated powder bed control
    - Water safety system software design and circuit integration

Schedule Timeline (Overall Project)



Fall Semester

August | September | October | November | December | January | February | March | April | May

Project Definition and Research

Preliminary Design

Detailed Design Development

Finalize and verify heat model

Detailed Design Development

Finalize:
1. Powder bed system
2. Safety system

Detailed Design Development

Electronics and software

Design Implementation and Purchasing

Integration and Test

System Verification and Validation

We Are Here

PDD (9/14)

CDD (9/28)

PDR (10/14)

CDR (12/1)

Final Fall Report (12/14)

Manufacturing Status Review

Test Readiness Review

Final Report and Presentation

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Backup Slides

Agenda

- Project Overview
  - Project Motivation
  - CONOPs
  - FBD
  - Baseline Design
- Evidence of Baseline Feasibility
  - Thermal Model
  - Safety Analysis
  - Powder Bed Design
  - Software and Component Integration
  - Structural Testing
- Status Summary

Backup Slides

Sugar-based rocket fuel

FDM

SLA

Trade Study

CPE #1

CPE #2

CPE #3

Testing

Risk Matrix

Manufacturing Sugar Based Solid Rocket Fuel

Traditional Method: Casting

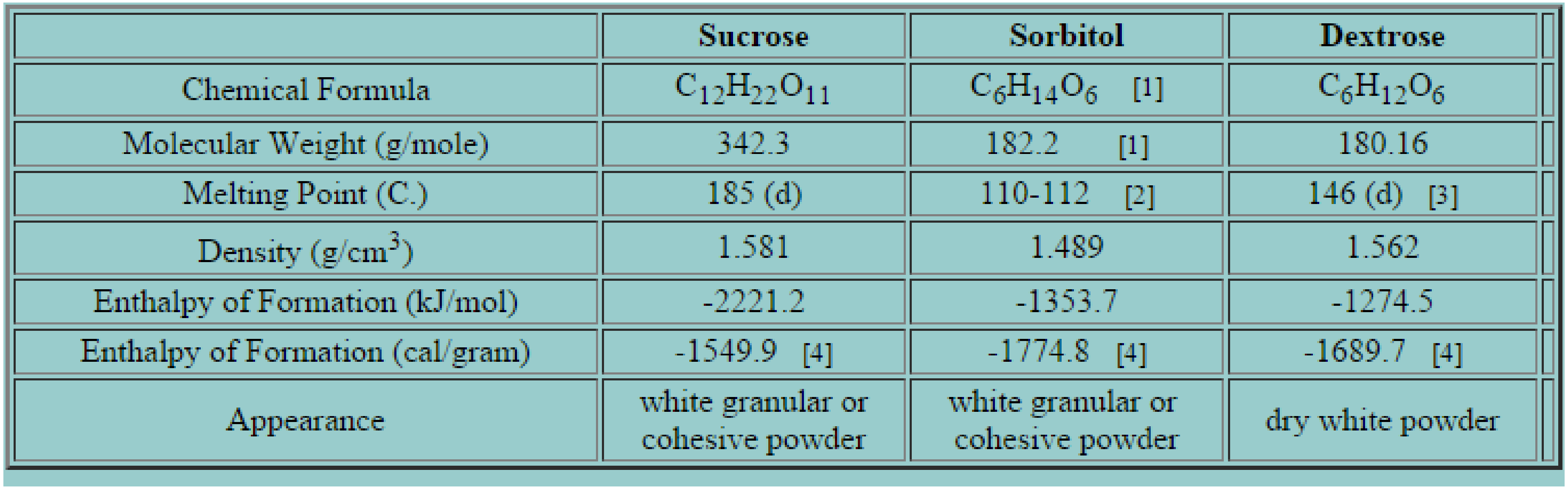
1. Mix KNO_3 and Sucrose powder into homogeneous mixture
2. Heat mixture on stove top for ~20-30 min
3. Pour molten mixture into a cast
4. Let propellant set for several hours

Casted Propellant Curing in Mold[10]

Casted Propellant Showing Grain Shape[11]

Link

Sugar Properties Table



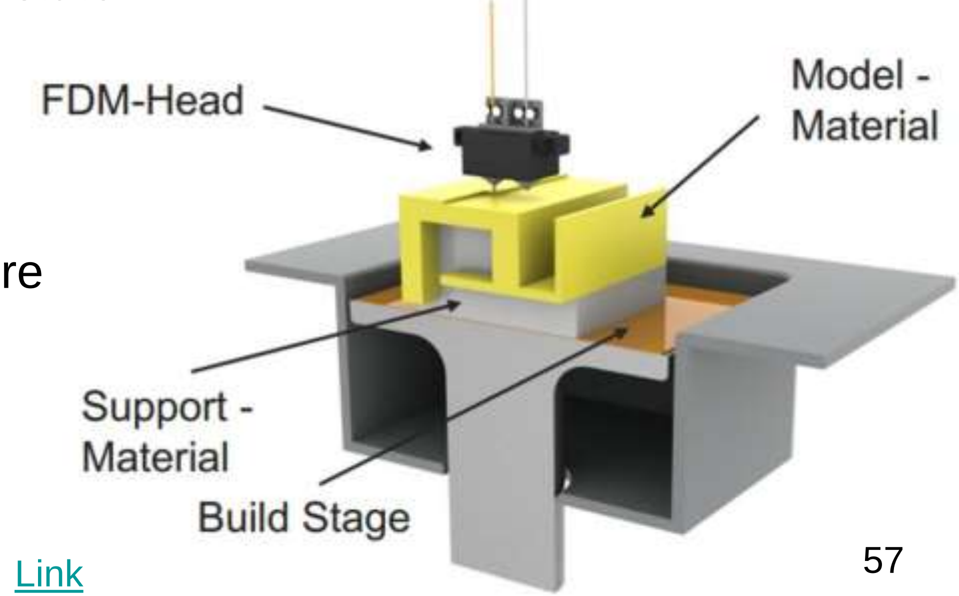
	Sucrose	**Sorbitol**	**Dextrose**
Chemical Formula	$C_{12}H_{22}O_{11}$	$C_6H_{14}O_6$ [1]	$C_6H_{12}O_6$
Molecular Weight (g/mole)	342.3	182.2 [1]	180.16
Melting Point (C.)	185 (d)	110-112 [2]	146 (d) [3]
Density (g/cm^3)	1.581	1.489	1.562
Enthalpy of Formation (kJ/mol)	-2221.2	-1353.7	-1274.5
Enthalpy of Formation (cal/gram)	-1549.9 [4]	-1774.8 [4]	-1689.7 [4]
Appearance	white granular or cohesive powder	white granular or cohesive powder	dry white powder

Link

FDM - Fused Deposition Modeling

The material is melted and extruded onto the print surface by the nozzle. The nozzle, print surface, or both may move.

Not feasible
- propellant cannot be held in molten state without decomposing [2]
- maximum ~30min of pliability
- additional safety concerns holding propellant at high temps for extended periods under pressure



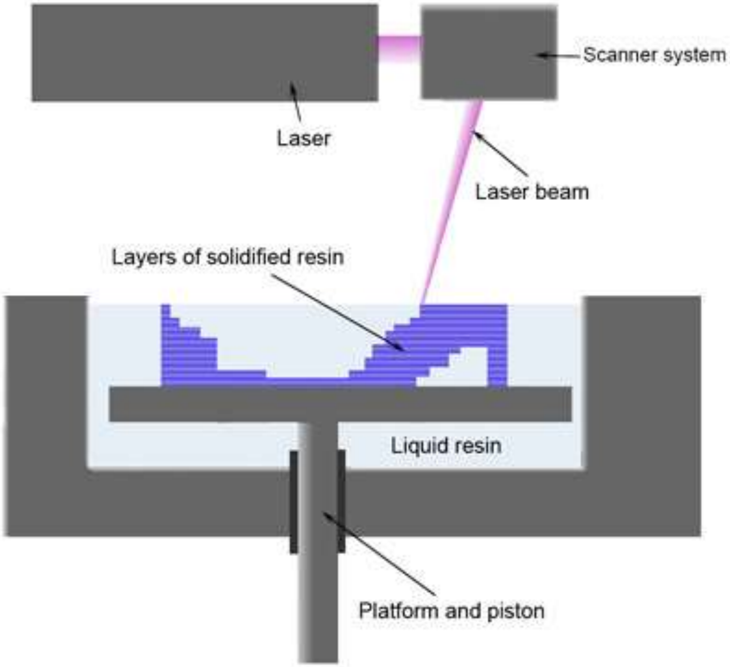
Link

SLA - Stereolithography

Focus a beam of ultraviolet light on a vat of photopolymer.
The beam cures each layer of the resin onto a moveable platform.

Not feasible

- photoresin is prohibitively expensive
- photopolymer is the only possible fuel
- No time to test/too much research



Link

Baseline Design Trade Study

<u>Design Decision</u>: Modify Laser Cutter Machine

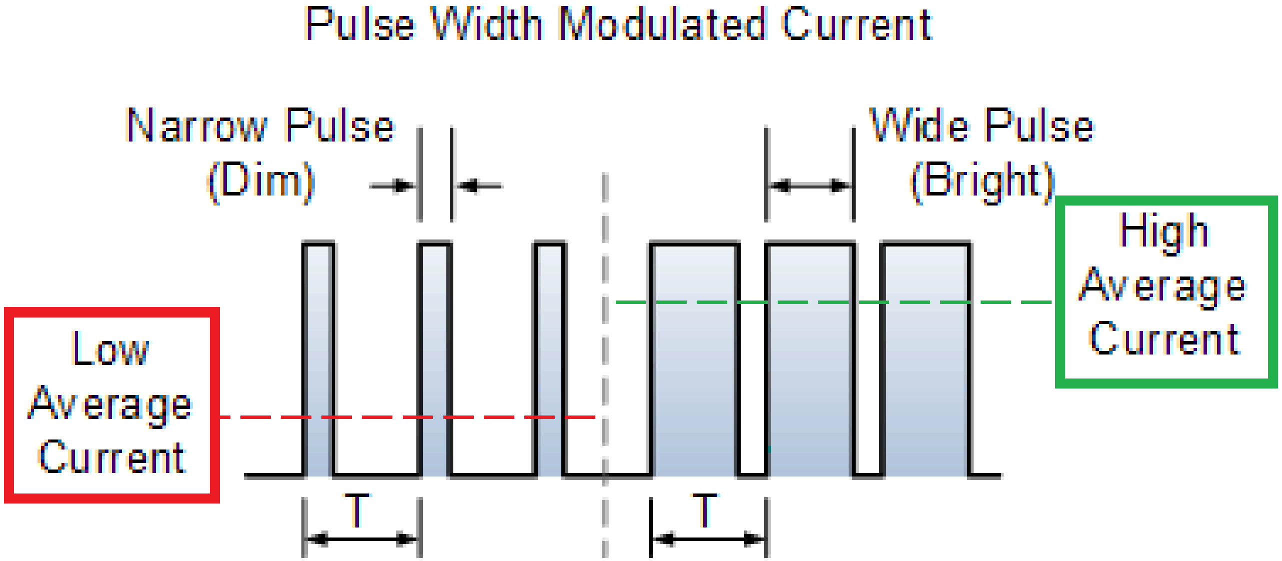
- Laser must be integrated and calibrated by the team
- Print chamber must be designed and fabricated
- Higher cost
- Team must design and build system around safety requirements

		Lulzbot	***Laser Cutter***
Metric	**Weight**	**Score**	**Score**
Laser	**25%**	**3**	**5**
Print Chamber	**10%**	**0**	**3**
Safety	**25%**	**2**	**4**
Est. Cost	**15%**	**2**	**3**
Est. Time	**10%**	**0**	**2**
Precedent	**15%**	**2**	**4**
Weighted Total:	**100%**	**1.85**	**3.8**

Link

CPE #1: Thermal Model - Software

Laser power output can be tuned with Pulse Width Modulation (PWM)



Link

CPE #1: Heat Transfer Model

- Boundary conditions:
  - $\partial_x u(0,t) = \frac{\phi_{beam}}{K_0}$
  - $u(L,t) = T_b$
- Initial condition:
  - $u(x,0) = T_b$
- Solution to heat equation:

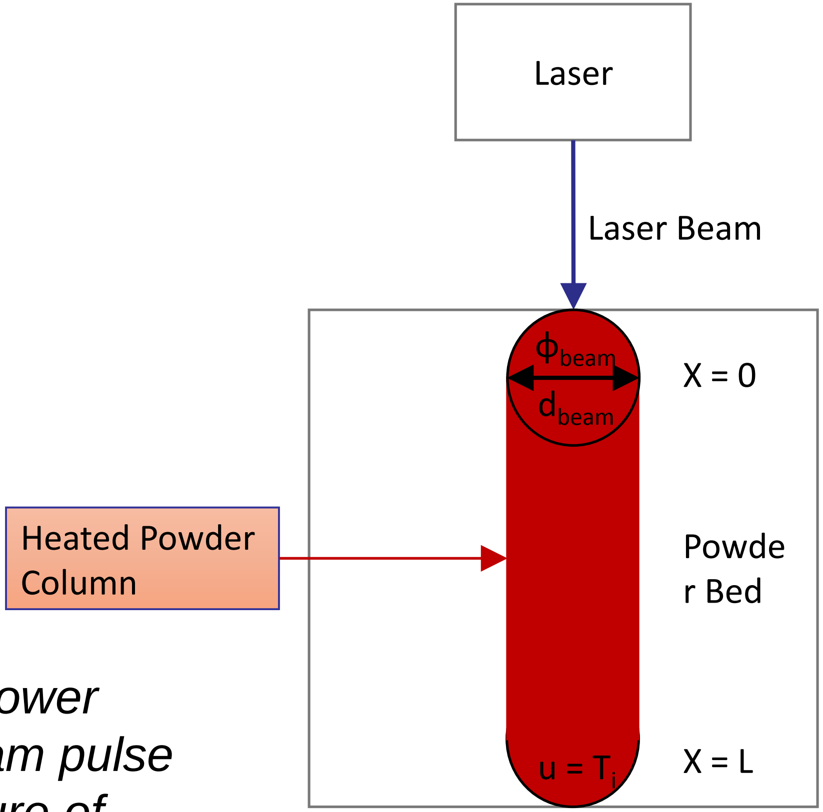
$$u(x) = \frac{\phi_{beam}}{K_0}(L - x) + T_b$$

$$\phi_{beam} = \frac{P_{beam}\Delta t}{\pi \frac{d^2}{4}}$$

Where:

- K_0 = thermal resistivity
- *L = length of "rod"*
- ϕ_{beam} *= heat flux of beam*
- *d = beam diameter*

- *P_{beam} = beam power*
- *Δt = time of beam pulse*
- *u(x)= temperature of rod in C^0*

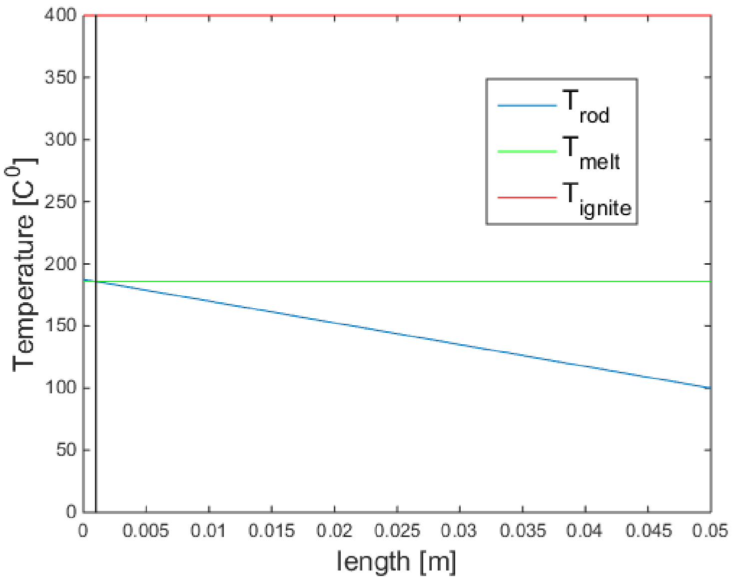


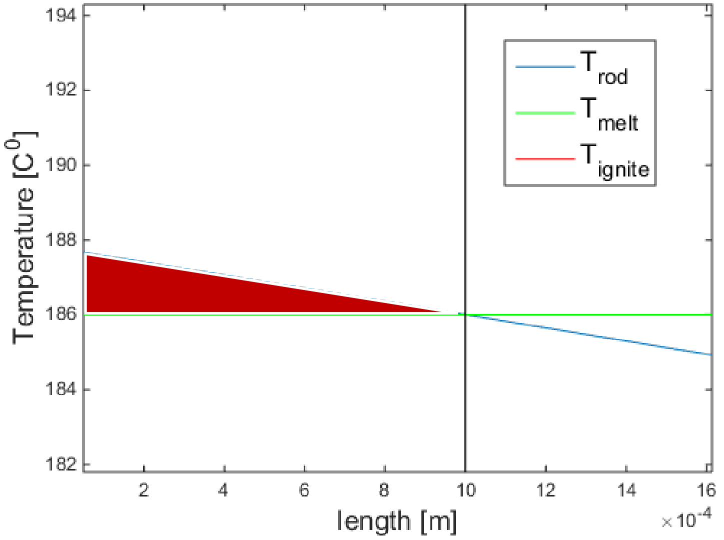
Link

CPE #1: Results for the 100 C^0 Powder Bed

P_{beam} = 6.92 mW
φ_{beam} = 0.88 kJ/m^2

- Red region = melted powder

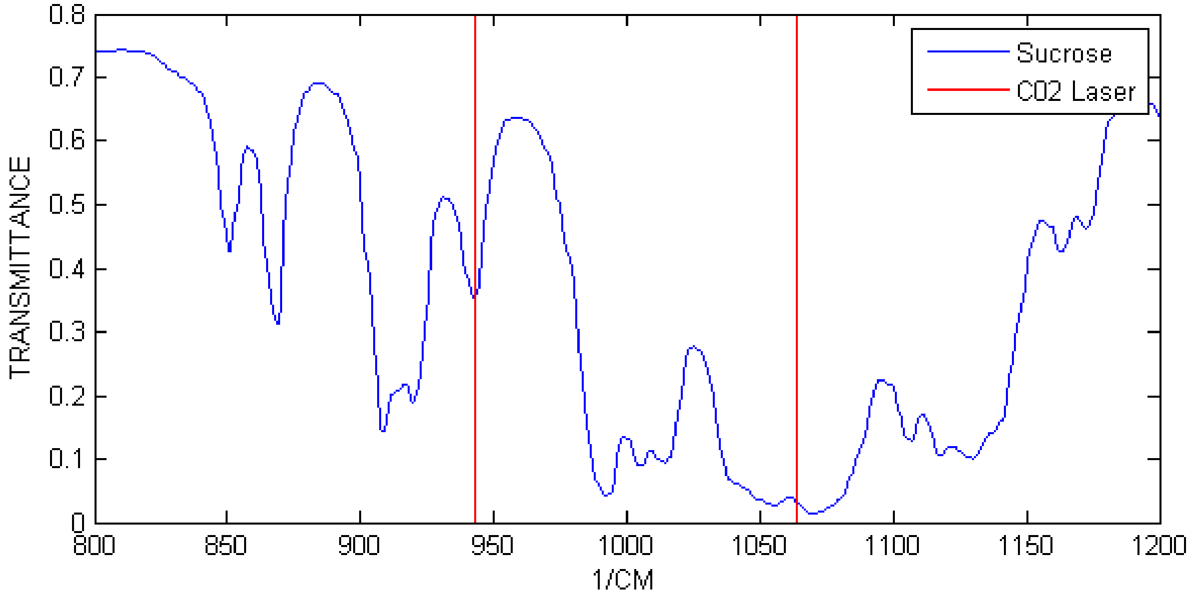




Link

CPE #1: Laser Wavelength Selection

- Most Common: CO_2 Lasers
- Two Main Wavelengths: 94,000 and 106,000 Angstroms
- Sucrose absorbs ~95%



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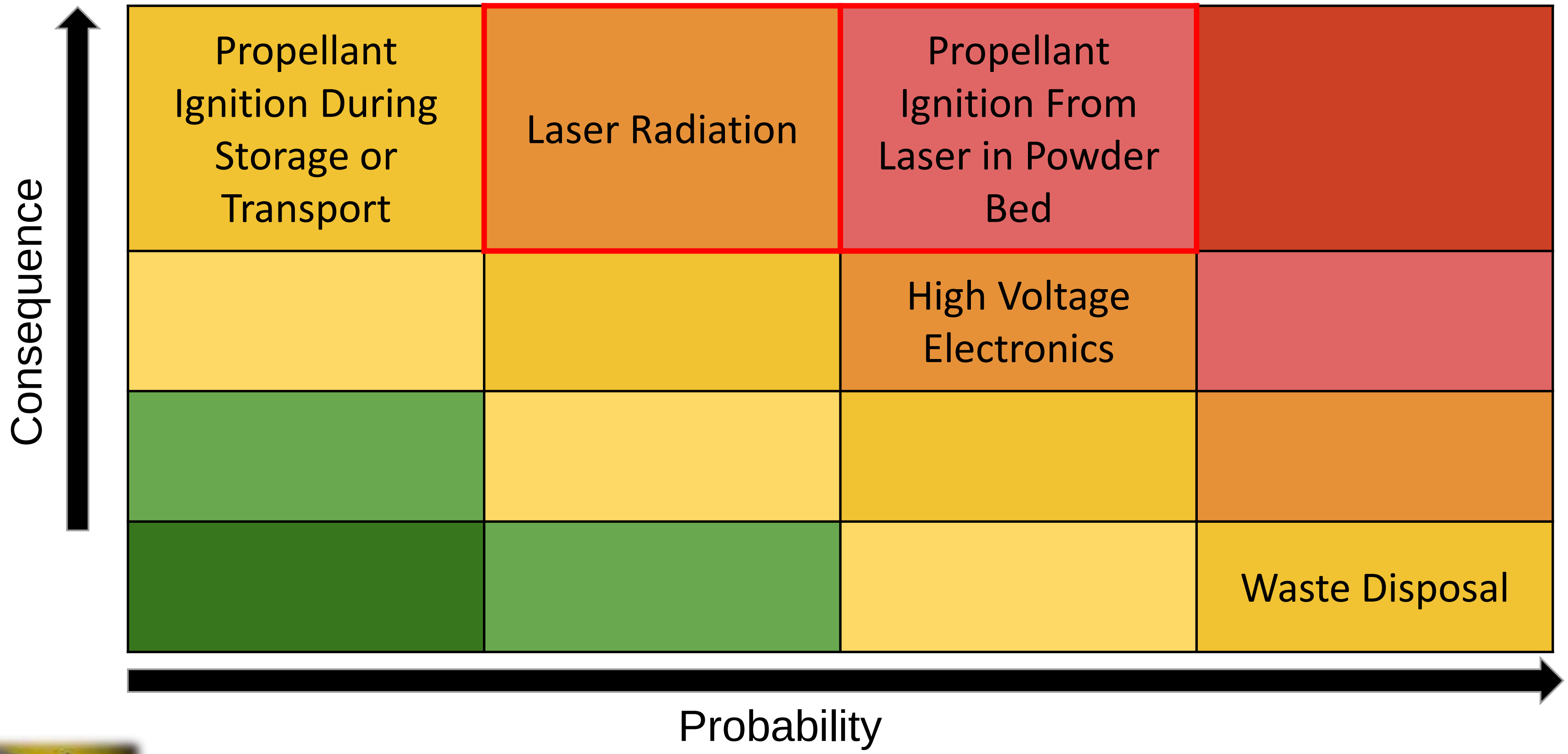
CPE #2: Safety Design - Risks



Propellant Ignition During Storage or Transport	Laser Radiation	Propellant Ignition From Laser in Powder Bed	
		High Voltage Electronics	
			Waste Disposal

Link

Energetic Material Safety

Detonation =/= Deflagration

- Deflagration ~ low velocity burn rate
- Detonation ~ supersonic shock front propagation

Example of Detonation: TNT burns at **5.8 km/s**[17]

Example of Deflagration: Sugar propellant burns at **386 mm/s**[2]

Therefore, we make a couple more assumptions:

- The propellant will only deflagrate and not detonate during the manufacturing process (powder held at standard conditions: 1 atm, 25 °C)
- Deflagration occurs uniformly

Link

Chemistry Calculations

Key:
Solid
Gas
Liquid

$C_{12}H_{22}O_{11} + 6.29\ KNO_3 \rightarrow 3.80\ CO_2 + 5.21\ CO + 7.79\ H_2O +$
$3.07\ H_2 + 3.14\ N_2 + 3.00\ K_2CO_3 + 0.27\ KOH$

Heat:

- Calculate Energy Release of Reaction using Specific Enthalpy
  - Per Gram: 1.231 kJ
  - Total Powder Bed: 1.737 MJ
- Products Assumed to be at STP
  - Upper Bound on Energy

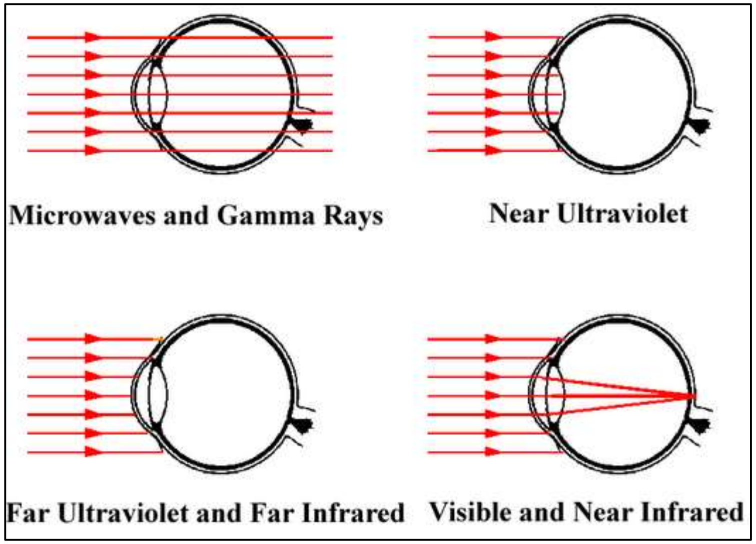
Gas Volume:

- Calculate Volume of Gaseous Products
  - Per Gram: 321.7 cm^3
  - Total Powder Bed: 0.454 m^3

Link

CPE #2: Laser Safety

- CO_2 Lasers operate on the infrared wavelength spectrum (they are not visible to the naked eye)
  - Retinal burns and/or blindness can occur
- All team members will complete training:
  - OSHA General Industry (29 CFR 1910) and Construction Industry (29 CFR 1926) training requirements for Laser Safety
- Laser-Safe Facilities:
  - Prof. Starkey’s Lab (will need to confirm)
  - JILA (Joint Institute for Lab Astrophysics) operates lasers



Link

Facilities

Propellant Storage:

- Fuel and oxidizer materials will be stored separately in locker
- When fuel-oxidizer material has been mixed it will be disposed of at any RCRA waste approved facility
  - Option: Hazardous Waste Disposal in Boulder County

System Storage:

SLS system must be stored in a facility that is approved for the systems 40Watt CO_2 laser

On Campus Laser Facility Options:

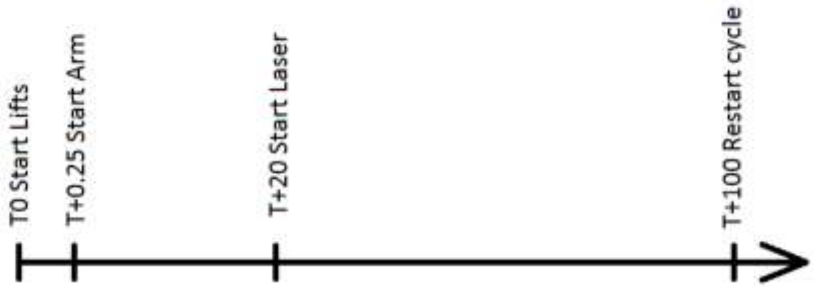
- Dr. Ryan Starkey’s Lab
- Joint Institute for Lab Astrophysics (JILA) facility

Link

Cycle Time Profile

3 Major 'Phases'

- Activate Lifts
- Activate Arm
- Run Lasers



NEMA-17 RPM: 20-200

- Torque loss with high RPM

$$T_{lift} = \frac{\Delta Z}{P\omega_{lift}}$$

P = Thread pitch (1.25mm)
ω_{lift} = Rotation speed (1/3 rps)
ΔZ = Vertical distance (0.1mm)
T_{lift} = Time to lift (0.24 sec)

$$T_{arm} = \frac{\omega_{arm}\Delta X}{\pi r}$$

r = Radius of wheel (5mm)
ΔX = Travel distance (230mm)
ω_{arm} = Rotation speed (4/3 rps)
T_{arm} = Time to sweep (19.53 sec)

Link

CPE #3: Powder Bed Feasibility

The Motosh Equation[10,11]

$$T_{in} = F_p[\frac{P}{2\pi} + \frac{\mu_t r_t}{\cos(\beta)} + \mu_n r_n]$$

F_P = Load on nut (~2.5kg, 24.525N)

P = Thread pitch

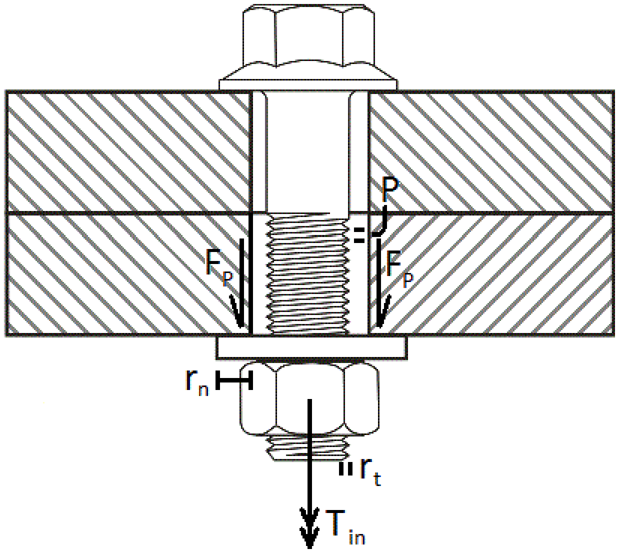
$\mu_{t/n}$ = Coef. of friction of thread surface

$r_{t/n}$ = Radius of thread surface contact

β = Half angle of thread (30°)

T_{in} = Torque to spin nut (0.0273Nm)

Max torque of chosen motor: 0.43Nm



Parameters for the Motosh Equation[12]

Link

Testing Safety

Thermoelastic stress analysis

$\Delta T = - T_0\ \alpha/(\rho\ c_p)\ \Delta\sigma_{kk}$

Assume: ← Temperature increase due to plane stress

- $\rho = 1000$ kg/m^3
- $c_p = 3.89$ kJ/kg
- $T_0 = 293$ K
- $\alpha = 70\ e^{-6}$ m/m/K

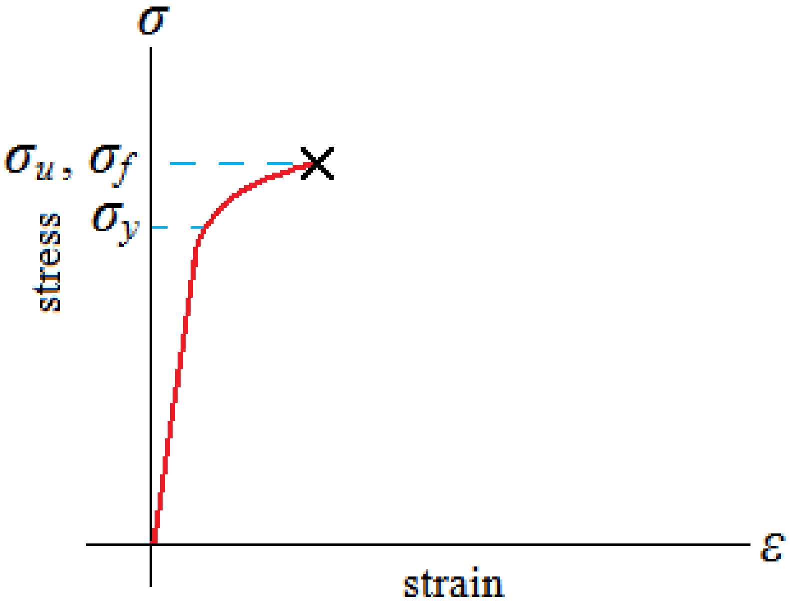
$\Delta\sigma_{kk} = \sigma_{kk} = 72.1$ MPa to cause auto-ignition

Approx. 2x ultimate strength of concrete.

Link

Tensile Testing

- Dogbone of both cast and printed propellant
- Brittle material cannot interface with the Instron
  - Dip ends in epoxy resin to avoid crush
- Test to failure
- Stress versus Strain curve reveals:
  - material classification
  - yield strength: σ_y
  - ultimate strength: σ_u
  - Poisson's Ratio: $\nu = -\varepsilon_t/\varepsilon$
    - expect ~1/3 for brittle material
  - Young's Modulus: $E=\sigma/\varepsilon$

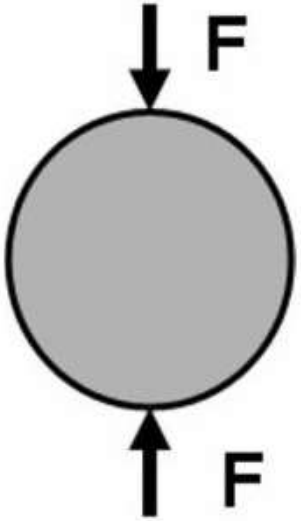


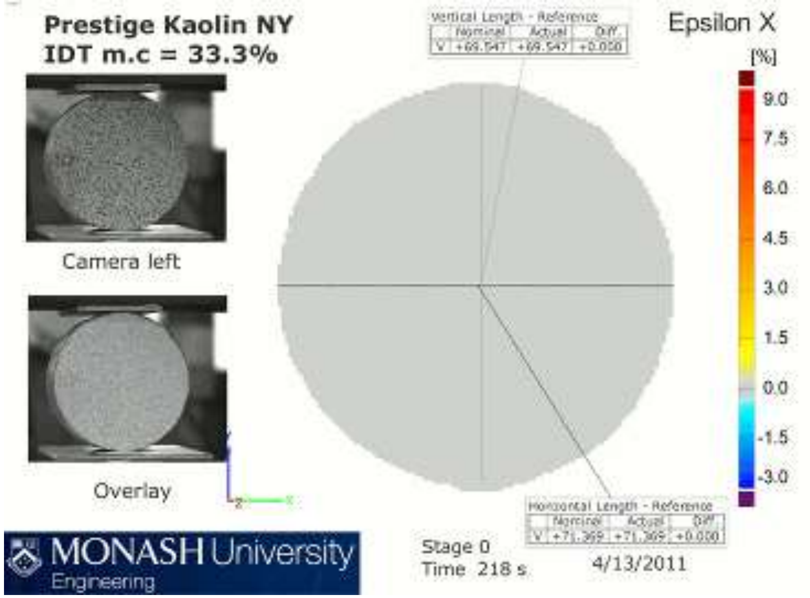
Stress-Strain Diagram [8]

Link

Indirect Tensile Testing

- Propellant is loaded diametrically
- The loading causes a tensile deformation perpendicular to the loading direction



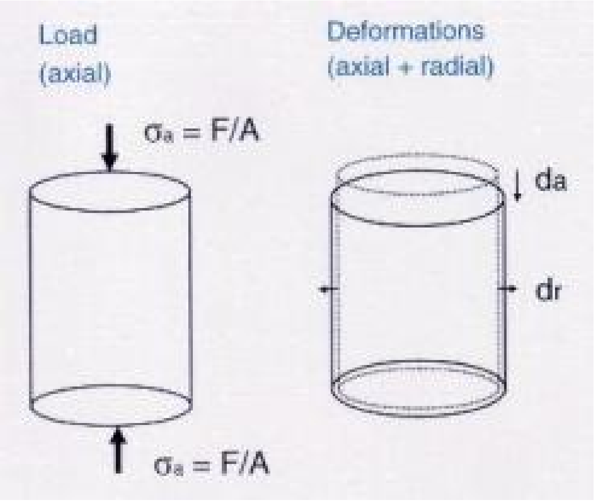


Load Induced Cracking from Indirect Tensile Test [22]

Link

Uniaxial Compression Test

- Specimen is loaded axially until failure using the loading platens
- Deformation measurement equipment is attached around the specimen
- Radial and axial strain vs axial stress data is recorded
- Volumetric strain and crack volume strain vs axial stress data is also recorded
- Safety note
    - Estimated stress of 72.1 MPa before reaching auto-ignition temperature



Compression Test [24]

Link

Fracture Toughness

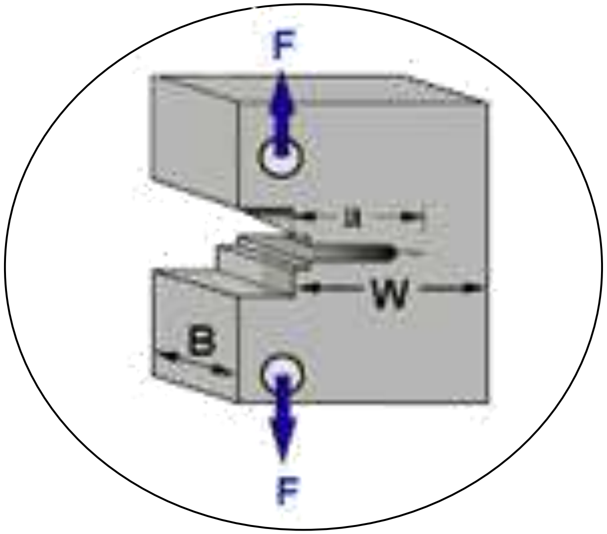
Which propellent is more resistant to crack propagation? Which has the shorter critical crack length?

$K_{Ic}=\sigma(\pi a \beta)^{½}$

- Expect ~25 $MN/m^{1/2}$

$B \geq 2.5(K_{Ic}/\sigma_y)^2$

- for best results



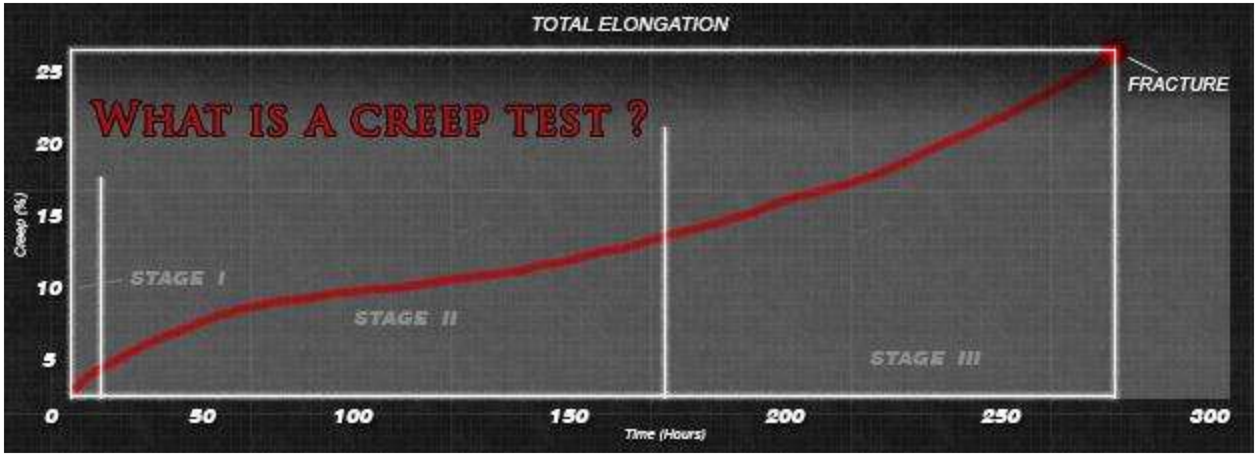
Fracture Toughness Sample [13]

- Pre-crack the sample and tensile test to failure

Link

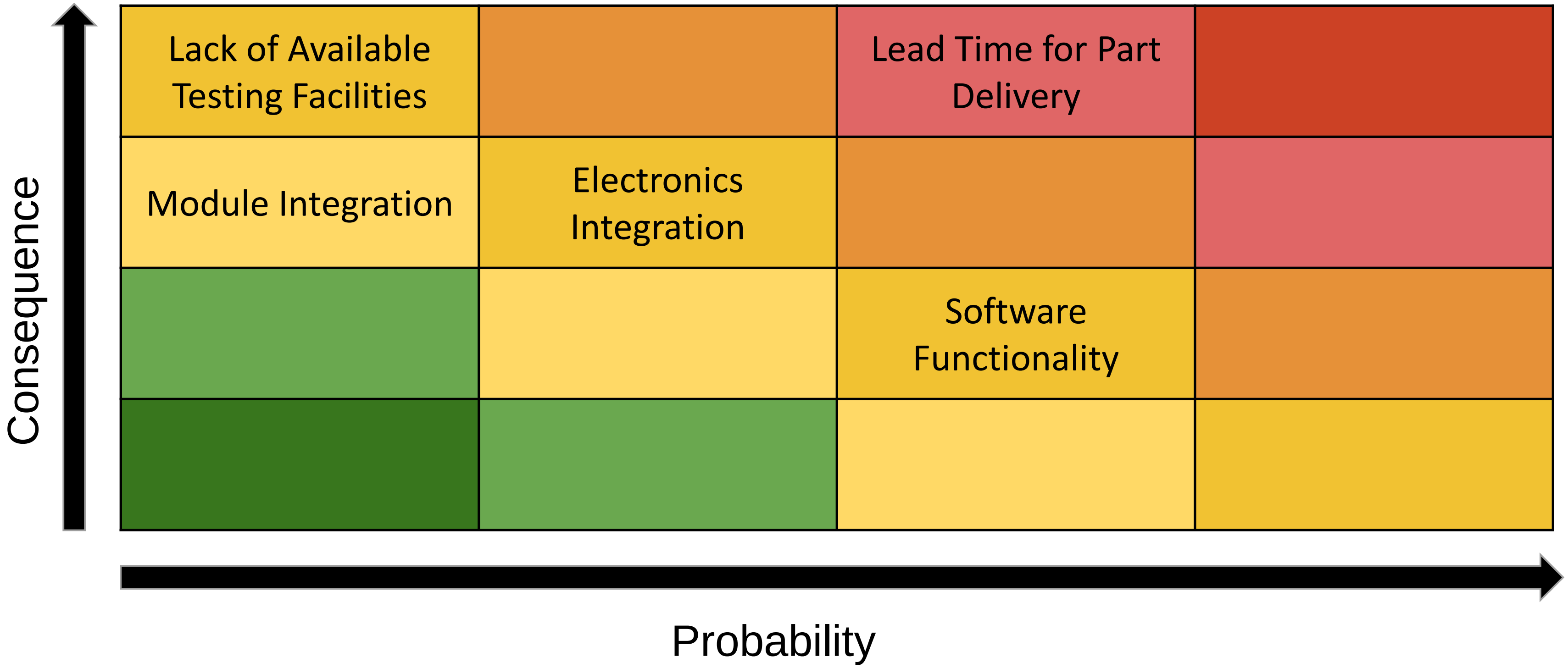
Creep Testing

- High temperature progressive deformation at constant stress
- Strain is recorded
  - Stage 1: non steady rate of creep
  - Stage 2: steady state creep
  - Stage 3: creep rate accelerates as cross sectional area decreases due to necking of the specimen



What is a Creep Test? [23]
Link

Project Risk Matrix



Lack of Available Testing Facilities		Lead Time for Part Delivery	
Module Integration	Electronics Integration		
		Software Functionality	

Link