University of Colorado

Department of Aerospace Engineering Sciences
Senior Projects – ASEN 4018

SAS Solid Propellant Additive Manufacturing (SPAM)
Conceptual Design Document

9/28/15

1.0 Information

1.1 Project Customer

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2.0 Project Description (10 pts)

The primary directive is to modify an existing additive manufacturing system such that it will print solid rocket propellant in more complex designs than possible with traditional casting methods. Such a machine would enable highly adaptable and unique solid rocket motors (SRMs). These would include intricate cross sectional areas--a parameter that directly affects burn rate and thrust over time.[4] Certain objectives must be met in order to qualify as a successful project. These include:

Identifying and integrating the necessary modifications to the baseline machine.

Successfully producing a simple shape using a manual analogue of the 3D printing method.

Successfully producing a simple shape using the modified printer.

Characterizing the propellant curing process and testing its physical properties in all stages of the process, and

Producing multiple different cross sectional geometries to within a ± 3mm tolerance.

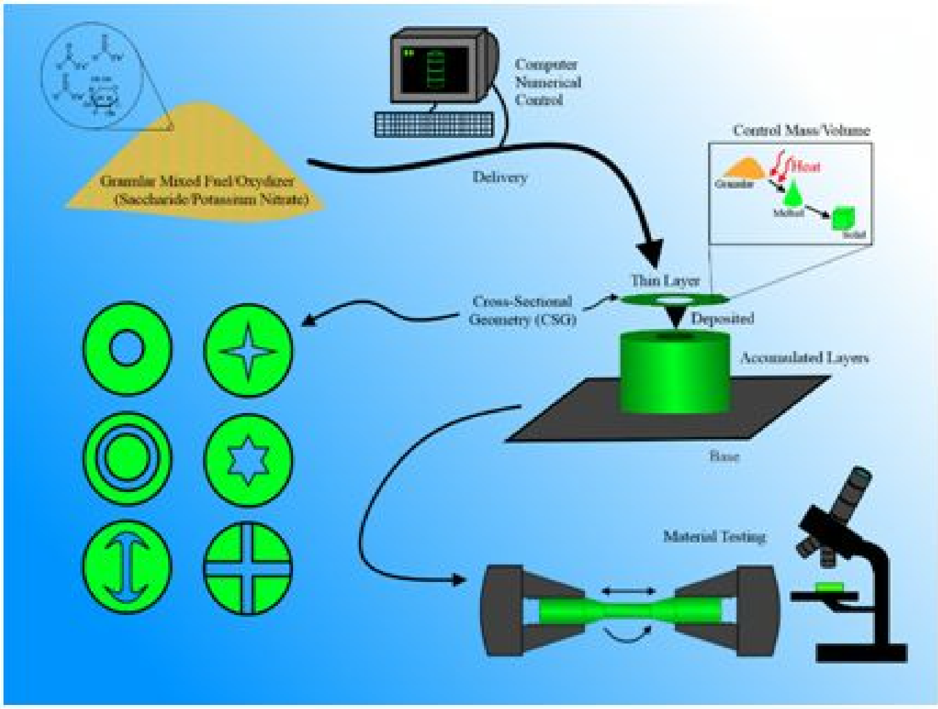

Figure 1: CONOPS, high level interface for the project

The concept of operations (CONOPS) diagram in Figure 1 demonstrates the general flow of the project architecture and operation. First, the fuel and oxidizer will be mixed as a homogeneous powder. The fuel will then be delivered to the additive manufacturing machine, heated to curing temperature, and layered in small volumes on top of the previous layer. 3D modelling software will likely be modified in order to print a desired 3D geometric shape. To verify the method is a viable one to produce propellant, test samples will be printed and materially tested to determine tensile strength, hardness, density, and other parameters. Results will be compared to tests of traditionally cast sugar rockets of the same dimensions.

The functional block diagram (FBD) in Figure 2 provides an integrated systems overview of project functionality. The diagram illustrates how each process element will be acquired, modified, or constructed, and how these components interact with each other. Arrows indicate whether data, heat, or propellant is transferred between elements according to a color code.

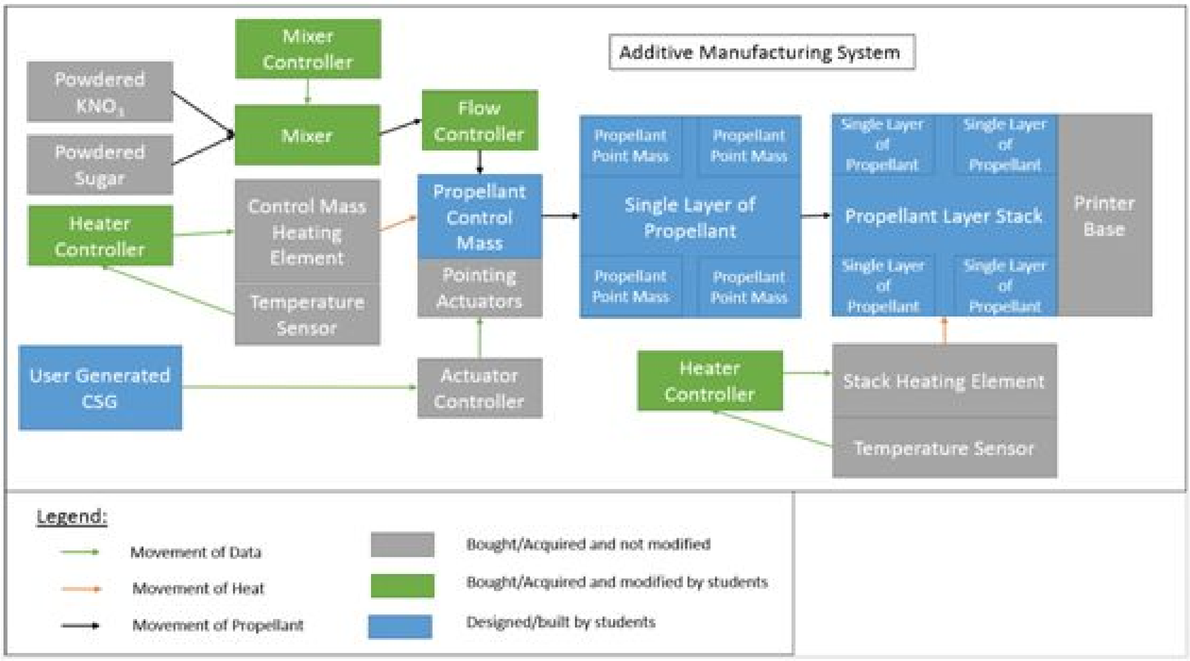

Figure 2: FBD with legend for how each component will interact with each other.

In general, the project requires a mixing and holding system that can homogeneously combine the propellant in powder or melted form. A delivery system moving propellant from reservoir to printing area must account for at least temperature and pressure to ensure safe operation. Software modifications must account for the printing volume as well as the print rate so the propellant can settle and cure as needed. Finally, a rigorous gauntlet of testing is needed to quantitatively measure tensile strength, density, hardness, resistance to crumbling, etc, of the printed motors vs traditional casting. Basic functional requirements are defined in greater detail in the following section.

3.0 Design Requirements (20 pts)

Project requirements drive the trade studies and design choices. These requirements ultimately take root from:
Requirement 0: The project shall produce a 3D printer capable of manufacturing solid rocket motors.
The requirements then become more defined as physical limitations are imposed on the design, such as maximum budget or required print volume. Five design requirements are derived and outlined in detail below. To summarize, the goal is to produce an automated 3D printer capable of additively manufacturing a monopropellant solid rocket motor for comparison with a casted solid rocket motor. From this basic premise, the rest flow down and allow a trade study:

1. The project shall produce a 3D printer capable of automated additive manufacturing.
   1.1. The printer shall have a functional 3D positioning system.

        1.1.1. The printer shall be capable of manufacturing user defined propellant cross sectional geometries (CSGs) given a CAD file input.
2. The rocket propellant shall be a solid monopropellant consisting of oxidizer and fuel.
    2.1. The fuel and oxidizer shall be mixed into an homogeneous mixture prior to heating.
3. The printer shall assemble the rocket propellant via the addition of small control masses of heated propellant.
    3.1. Each control mass shall bond to the previous and following control mass.
4. The printer shall have a mechanism to deliver the mixed fuel and oxidizer to the propellant manufacturing area
    4.1. The flow rate of the propellant shall be steady.
5. The printed propellant properties shall be compared to traditionally casted propellant properties.
        5.1.1. The additively manufactured propellant and cast propellant shall each be characterized by density, void fraction, tensile strength, crush strength, and energy release.
            5.1.1.1. The density shall be measured by massing a propellant sample of 8 cm^3.
            5.1.1.2. The void fraction shall be measured by visual inspection of a 10x magnified 1 cm^2 cross section.
            5.1.1.3. Tensile strength shall be measured using an Instron machine.
            5.1.1.4. Crush strength shall be measure by a column load test.
            5.1.1.5. Energy release shall be measured by a bomb calorimeter.

Requirement 1.1 and its child ensure that the 3D printer design is not the goal of this project. The methodology behind 3D printing is mostly established. Therefore, the hardware and software of the positioning system should function without team input, leaving more time to dedicate to the specific problem of printing propellant. Similarly, Requirement 2 and its children ensure that the project differentiates itself from hybrid propellant additive manufacturing projects. Additionally, requirements 4 and 4.1 dictate that the propellant arrives safely and at a rate usable by the printer to the print area. This will translate directly to uniform and accurate print layers. Finally, the fifth group of requirements will reveal the advantages of additively manufacturing solid rocket motors if any.

4.0 Key Design Options Considered (20 pts)

Six methods of additive manufacturing were considered.

FDM Roller Pump Delivery:

The roller (or peristaltic) pump delivery method considered uses the same technology in dialysis pumps to move the molten fuel from a reservoir to a nozzle without having to mix or heat it. Roller pumps are used with high viscosity fluids and are unique in that they never contact the fluid they are pumping.

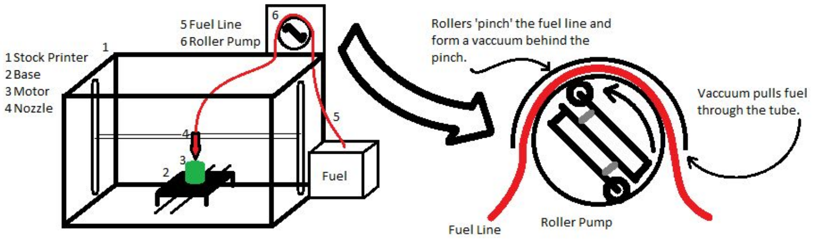

Figure 3: Roller Pump Schematic

<u>Pros:</u>

The pump is a widely used technology designed with high viscosity fluids in mind.

The pump is relatively simple and can be set up to avoid pressure spikes.

Cons:

A tubing system will be needed that can handle high viscosity, high pressure, and high temperature. Hooking these tubes up may prove to be very complex.

FDM Plunger Extrusion:

Heavily modified printers exist on the market that are able to print out Play-Doh. These systems use small, pre-filled syringes of material (ie. rocket candy) and a plunger mechanism to extrude the needed material. Systems can be bought or modified to hold several syringes of different materials. Videos posted by individuals selling these modified printers suggest that they are fast, accurate, but expensive. In addition, Play-Doh doesn't hold its shape very well.

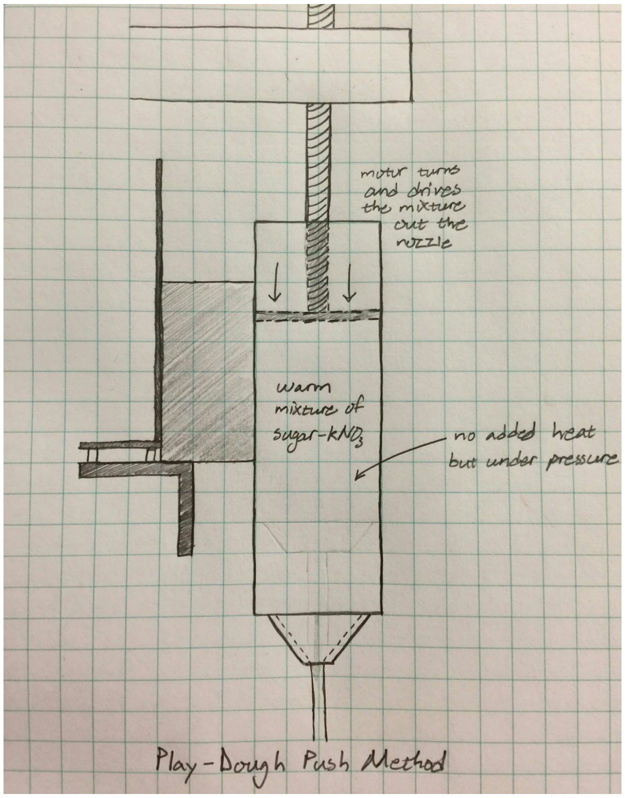

Figure 4: FDM Plunger Extrusion Schematic

Pros:

Proven to work with very high viscosity fluids with no modifications.[3]

As accurate as the printer or software being used.[3]

Cons:

Expensive off the shelf and comes with closed source software that makes modifying the system difficult.

The material the printer is designed to extrude (Play-Doh) does not hold its shape well. Further testing is needed to find if rocket candy can hold its shape after extrusion.

The provided syringes are very small (c. 25cc) and may need to be replaced by hand during the printing process.

Purchase a Selective Laser Sintering (SLS) Machine:

Selective Laser Sintering is a proven additive manufacturing technique that involves a large bed of material in a powdered form (ie. metal powder, sucrose) and a laser that partially melts (sinters) the material into a solid shape, thin layers at a time. Each time a layer is complete a roller pushes another thin layer of material from a reservoir over the printing area and the process continues. Two viable options exist for using SLS to produce solid rocket motors. The first is to buy a complete machine and modify it, the second is to buy requisite components and build one.

Pros:

It has been shown that SLS can manufacture with sucrose, the main component of rocket candy.

The material to be printed will be stored in a raw, powdered form. This makes storage and transportation much easier, as well as safer as the fuel is much less volatile when in powdered form.

The printing area will be isolated from the outside, where engineers will be observing. In the rare event of auto-ignition, the ensuing fire will be isolated to an enclosed space.

Cons:

Large amounts of raw material will be needed for even a small motor. While much of it can be reused, in the event of a fire there will be a lot more fuel to burn.

The process requires shooting a laser at a bed of volatile material. This sounds dangerous for obvious reasons and the laser will need to be accurately monitored during the printing process.

The laser will need to be calibrated very carefully to avoid the fuel from getting too hot and igniting, or too cold and not sintering properly.

SLS machines are extremely expensive. Even used ones push the project budget too far.

Build a SLS Machine:

Individuals have managed to convert laser cutters into impromptu SLS machines with minimal modifications, and post their results on the Internet. The technology and process are the same, but purchasing an old laser cutter, or the components needed to create one from scratch, is far less expensive than the purchase of a new or used SLS machine.

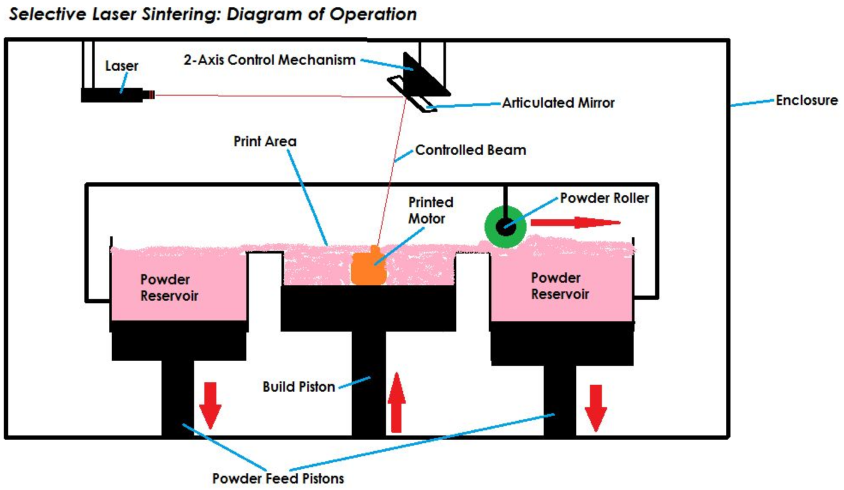

Figure 5: Selective Laser Sintering Schemati

Pros:

Same benefits as the purchased SLS machine above, and...

Much cheaper than buying an SLS machine, including costs of parts needed for modifications.

Depending on the route the team chooses to go the software and hardware may be open source and heavily customizable.

A precedent exists for modifying a laser cutter to perform as an SLS machine specifically using sugar as its working material.

Cons:

Same cons as the purchased SLS machine, and...

Modifying an already complex machine (a laser cutter) to complete a task it was never designed to do (print rocket motors) will require many modifications and a lot of technical knowledge.

Dry Delivery:

When the raw ingredients for rocket candy (sucrose and potassium nitrate) are kept separate they are almost completely inert. With this in mind a printer may be modified to keep the two ingredients in different reservoirs and only mix them in, or very near, the extruding nozzle.

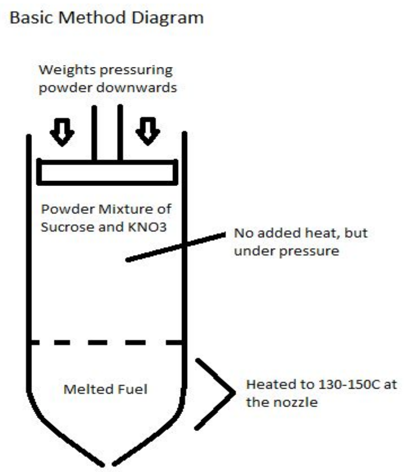

Figure 6. Dry Delivery Method Schematic

<u>Pros:</u>

When kept apart, each ingredient of the fuel is inert. The risk of a fire is very low.

The printer will be as accurate as the printer the delivery system is put on.

<u>Cons:</u>

Flow control will be a challenge and comparable to stopping sand from flowing through a funnel.

For maximum effectiveness the ingredients need to be mixed together very well, it may not be feasible to mix them well enough in the nozzle, alone.

Stereolithography (SLA):

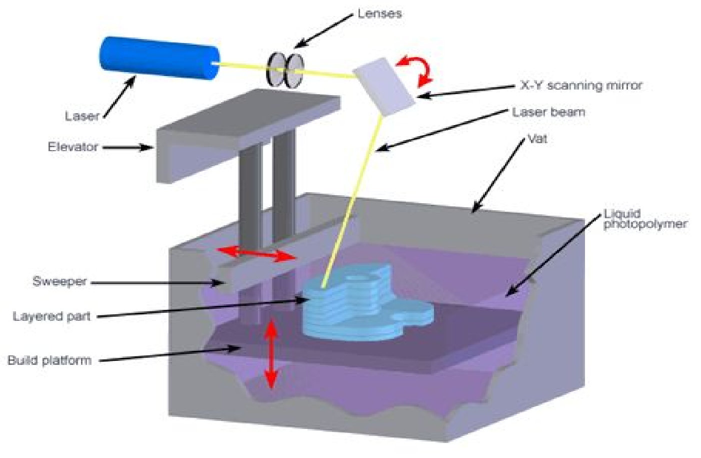

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Figure 7[1] . SLA manufacturing process

SLA uses a vat of photopolymer resin, a chemical that reacts with UV light to form a solid. A UV light source to produce solid shapes small layers at a time. SLA has been used extensively as a quick and accurate way to create prototypes out of various plastics.

Pros:

SLA is a very quick process with each layer of material being exposed to UV light. This is in contrast to other methods of additive manufacturing that require a nozzle to trace over the entire shape.

The alternative would require little or no modification if the photopolymer still cures after being mixed with oxidizer.

Cons:

SLA machines are expensive and so is the fluid/fuel. This will push the current budget to its limits.

Finding a photopolymer that can be used as a rocket fuel may not be feasible. In addition, the project lacks the time to research the viability of the photopolymer mixture.

5.0 Trade Study Process and Results (30 pts)

A trade study was conducted to analyze and differentiate between the design alternatives listed in Section 4.0. The study considered seven parameters: Printing Accuracy, Cost, Number of Modifications Needed, Complexity of Fuel Delivery Method, Feasibility of Concept, Design Safety, and Software Available.

Accuracy:

The printing accuracy of each solution was difficult to estimate numerically. Further, the order of accuracy is difficult to determine because none of the methods have been used with the fuels considered. In light of this, the methods were ranked by the reported accuracy of each overarching method (FDM, SLS, SLA). The solution with the highest accuracy was scored a five while the other methods were assigned decreasing scores with decreasing print accuracy.

Cost:

This metric was included to factor in the estimated cost of each solution, including the machine and print material. The design alternatives evaluated were rated by how much the method would cost to pursue. A score of zero indicates prohibitive cost (even while factoring in possible discounts, sponsorships, and grants) to 5 being well within the budget. The scale used to score the methods is shown in Figure 8.

Number of Modifications:

All of the design alternatives will require some degree of modification to the commercial product. This parameter was defined as the total number of individual changes, which gives an indication of the overall modification complexity. Projected modifications were discussed, counted, and summed while accounting for worst-case scenarios. Design solutions requiring no modification scored a five while increasing numbers of modifications were marked with lower scores. See Figure 8 for the scoring scale.

Complexity of Fuel Delivery Method:

This metric was used to gauge the complexity of the fuel “delivery” system. This parameter accounts for how, when, and where the propellant undergoes state changes, as well as the mechanisms required to physically move the propellant during the manufacturing process. If a solution involves highly complex systems just to bring the propellant to the print bed, it earns a low score. If a solution has a simple transport process, it earns a high mark. Scores range between five and one.

Feasibility:

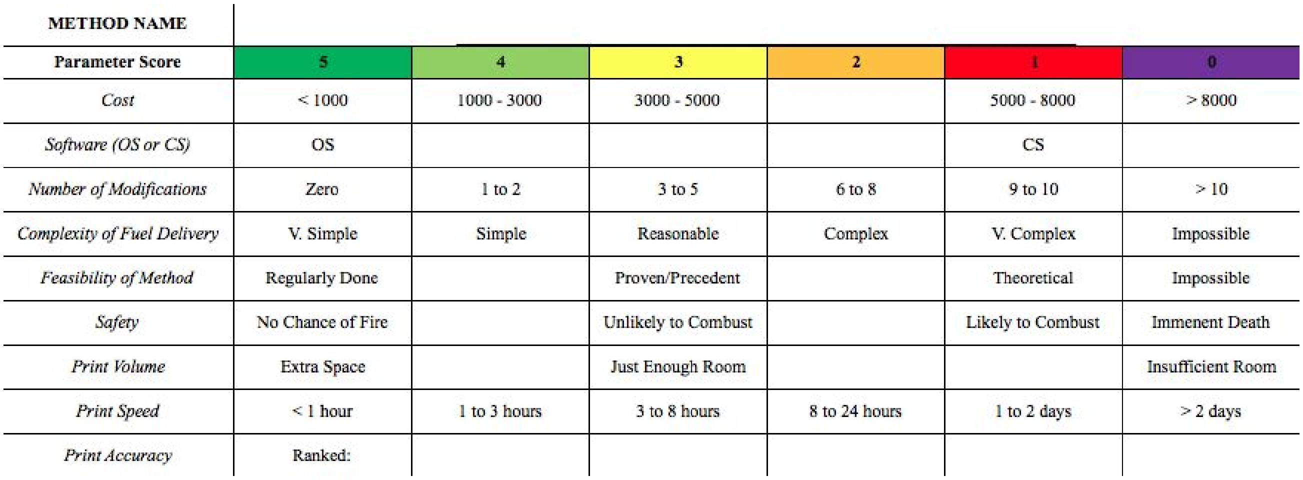
If the proposed solution is demonstrated with sugar as the working material then the method is considered 'feasible' and earns a five. Low scores are awarded if the method is theoretical. A score of three is given to methods that have a precedent with a simulant material.

Safety:

An operating assumption for this project is that an unavoidable safety hazard will occur, despite any and all safety precautions. This category considers how bad the failure will be, how much damage will be done, and how difficult it would be to isolate and minimize the damage. Catastrophic failure that is impossible to negate and will result in the destruction of the machine earns the method a one. Minimal damage that is easily avoidable earns the method a five. Scores range in between.

Software:

Any method chosen will involve modifications. Part of the modifications will involve control software (ie. controlling flow rate, heating elements, laser intensity). Open source software is simpler to modify and therefore earns the method a five. Closed source (and difficult, or illegal, to modify) earns a zero. The overall printer design trade study rubric is shown below in Figure 8.



METHOD NAME						
Parameter Score	5	4	3	2	1	0
Cost	< 1000	1000 - 3000	3000 - 5000		5000 - 8000	> 8000
Software (OS or CS)	OS				CS	
Number of Modifications	Zero	1 to 2	3 to 5	6 to 8	9 to 10	> 10
Complexity of Fuel Delivery	V. Simple	Simple	Reasonable	Complex	V. Complex	Impossible
Feasibility of Method	Regularly Done		Proven/Precedent		Theoretical	Impossible
Safety	No Chance of Fire		Unlikely to Combust		Likely to Combust	Immenent Death
Print Volume	Extra Space		Just Enough Room			Insufficient Room
Print Speed	< 1 hour	1 to 3 hours	3 to 8 hours	8 to 24 hours	1 to 2 days	> 2 days
Print Accuracy	Ranked:					

Figure 8. The trade study scoring matrix. *This figure shows how the different values were assigned for all trade study parameters. A parameter with a "5" was considered good and a parameter with a "0" was considered bad.*

Two parameters included in Figure 8 were eliminated from the final trade study; "Print Volume" and "Print Speed." Print volume was determined as insignificant because the desired print volume can be achieved by all printing methods, and all methods therefore received the same ranking for "print volume." Print Speed was eliminated because the speed at which the rocket propellant can be manufactured is not a key design requirement or goal, and therefore took away from the weight of other, more important parameters. All of the methods were capable in printing under eight hours so they scored similarly.

After assigning each parameter a value of zero through five, the weighting of each parameter in the overall trade study was assigned. The weights were provided as a percent to indicate how much each parameter affects print mechanism selection. The weights assigned to each parameter in the trade study can be found in the "Weight" row in Table 9.

Design Parameter	**Wt.**	**Rationale**
Accuracy	5%	Print accuracy of the manufacturing method was not determined to be as important as other factors. However, there is a wide range of accuracies among methods.
Cost	15%	Printing method must remain within project budget, but expense is not necessarily a major factor in design choice given the number and diversity of options.

Number of Mods.	15%	Each modification to an existing 3D printer would necessarily increase the difficulty of implementing that specific additive manufacturing method.
Feasibility	25%	The goal is to modify an existing machine to print a novel material. A close match makes this a huge design driver.
Software	5%	All printing methods would require similar software. The only differentiating factor for software was whether the source code was open source or closed source. However, many "hacks" and open source
Safety	20%	Safety is important when manufacturing volatile materials. A weighted safety refers to the ability of the additive manufacturing machine to avoid accidental ignition of the propellant as well as the physical safety of the students building and operating the additive manufacturing machine. At the same time, the propellant is generally safe to handle before curing, as confirmed by empirical tests, and advice from Dr. Nakka. (See Appendix A & B)

	Accuracy	Cost	#Mods	Complex.	Feasibility	Safety	Software	TOTAL
Weight	0.05	0.2	0.2	0.2	0.25	0.05	0.05	1
Roller	3	4	3	1	3	3	5	2.9
Play-Doh	2	3	4	3	2	3	0	2.75
Buy SLS	4	0	5	5	5	3	0	3.6
Build SLS	4	4	1	5	5	3	5	3.85
Dry Delivery	3	4	3	2	1	4	5	2.65
SLA	5	0	5	5	1	3	0	2.65

Table 9. Trade Study Results

6.0 Selection of Baseline Design (20 pts)

The many design choices described in section 4.0 have vastly different mechanisms of operation. These options created the first pivotal trade study that evaluated each of the printing methods. An initial trade study was evaluated by computing the design which ranked highest based on the most heavily weighted factors. These key factors were determined to be the cost, complexity of the fuel delivery system, feasibility for using propellant through the given method, and the estimated number of modifications. The top scoring design possibilities were the two SLS methods (purchase and building). Further research into the various options proved that purchasing an SLS printer would completely over extend the budget. As a result, we selected building an SLS printer as the best alternative.

A second trade study was not necessary for the selection of the fuel and oxidizer because each of the methods were closely paired with one fuel. For example, the FDM methods required the use of sorbitol because of its high caramelization temperature. Also the stereolithography method required the use of a photopolymer. The chosen method will use sucrose as the fuel because of the tests already conducted with this fuel. The oxidizer was chosen from customer requirements: potassium nitrate.

The SLS printing method was the clear and logical choice as the conceptual design. As seen in the trade studies from section 4.0, a constructed SLS printer is safer to work with, easy to modify, proven effective with sucrose, and has a relatively simple fuel delivery method. The safety aspect comes from using the propellant in powdered form instead of a preheated and pressurized mixture. This prevents local pooling of heat and any buildup of pressure all together which otherwise might cause ignition. Sucrose has also already been proven as a viable printing material for SLS which greatly decreases the risk in whether or not the method is possible with sugar based propellant. Although the printer will be assembled by hand, all documentation from RepRap is publically available and the open source nature of the system allows for modifications to be built directly into the printer. Finally, the fuel delivery system for this method is just as simple a mechanic as would exist for the other methods. In conjunction with one another these characteristics combined to provide the clear choice for the conceptual design in this project.

7.0 References:

[1] "Overviews," Rapid Prototyping Accessed 27 September 2015. Available: http://www.custompartnet.com/wu/stereolithography

[2] "Overviews," *Rapid Prototyping* Accessed 27 September 2015. Available: http://www.custompartnet.com/wu/selective-laser-sintering.

[3] "Hyrel 3D," Accessed 27 September 2015. Available: http://www.hyrel3d.com.

[4] Sutton, George; Biblarz, Oscar (2001). *Rocket Propulsion Elements*. Willey. ISBN 9781601190604.

8.0 Appendix

Appendix A: Email Correspondence with Richard Nakka

On Fri, Sep 25, 2015 at 11:50 AM, Richard Nakka

<richard.rocketry@gmail.com <mailto:richard.rocketry@gmail.com>> wrote:

Hi Jonathan,
Thanks for the message, I am pleased to hear about your additive manufacturing project. Certainly an interesting and challenging one.

I have not done much in terms of quantifying the melting behaviour or properties. The melting temperatures have been measured. Other than that, I can provide some qualitiative info that may be of use.

Here are typical casting temperatures:
KNFR (fructose base) 100-110C
KNSB (sorbitol base) 120-140
KNDX (dextrose base) 130-150C
KNSU (sucrose base) 180- 200C
Note that KNSU decomposes at that temperature (a function of time) and may not be a good choice for your application.

What actually happens when a mixture if heated is that the sugar
component melts (at its melting point temperature). A certain fraction
of the KN then dissolves into the sugar, the fraction being a function
of temperature. This is why the melted slurry becomes less viscous
with temperature, to a certain limit.

The most viscous is KNSU, the least viscous is KNFR and KNSB.

Viscosity can be reduced, if needed, using certain techniques.

Residual moisture plays a significant role in the melted product and
to some extent in the final product. For example, even a small amount
of moisture (<1/2 %) will greatly reduce viscosity initially, until
water is driven off. It may be best to fully dessicate the sugar and
KN to have a common baseline.

Porosity may be an issue. I don't have much knowledge of additive
manufacturing but understand that porosity may be present. Porosity
affects propellant by increasing burn rate, and should be kept below
5%.

The above are some thoughts that came to mind while writing this
reply. If you have any further question, I will be happy to try to
answer such. Good luck with the project.

cheers
Richard Nakka

*Richard Nakka *<richard.rocketry@gmail.com> Mon, Sep 28, 2015 at 12:22 PM
To: Jonathan.Sobol@colorado.edu
On 9/25/15, Jonathan Sobol <Jonathan.Sobol@colorado.edu

> We plan on performing some material testing as early as tomorrow
> (Saturday)...We will wait to use University facilities to cook it into a
> slurry, but first we want to grind/mill/mix some and get a feel for the
> powder qualities. If the powder is amenable, SLS may prove to be a simple,
> elegant, albeit highly expensive option.

For starters, I recommend careful reading my webpages on the different
sugar propellants (KNSU, KNSB & KNDX). Each have their own merits and
quirks.

>
> The team and I do have some questions, if you are willing. Any guidance
> would be great and truly appreciated.
>
> What are the pressure effects on the propellant? For example, if I were to
> propose running the "slurry" through a pump at a low flow rate, does that

> scream out "Oh God No!!"? What if I used a blood pump? ie, no contact
> between fluid and machinery?

I expect pressure should have no adverse effect on sugar propellant.

>
> You suggest desiccating the sugar and KNO3 to reduce water content...I'm
> curious how water affects the cooking process. Did you prefer to
> add/minimize water, and what is more safe to handle at high temperatures?

Water makes heating and casting easier (lower viscosity) and lowers the melting temperature. But there's a downside. Heated in an open vessel, the water evaporates and the properties revert toward the dry properties. For typical propellant casting, it's therefore unsure how much residual water there is once cast. Residual water affects the post-cast properties (stiffness), burn rate, and Isp. Starting with dessicated constituents, you have a common baseline and more consistent final results.

>
> How volatile/explosive is a sample of desiccated powder mixture? If I
> suggested pulsing a laser at a small sample of powder propellant, is that a
> terrible, horrible, really bad idea?

Its not explosive (unless contained) but can burn quite fast. The powder does not ignite readily with a flame, as it tends to melt first (depends also on the type...KNSB is harder to ignite than KNSU). But does ignite readily, for example, with a glowing wood splint.

>
> How likely is an autoignition event at casting temperatures/sub-casting
> (2-10 degrees below)?

Based on my testing, not possible. The temperature range between casting and autoignition is over 200C.

>
> If the propellant were to ignite inside of a closed container (not sealed),
> and with proper ducting, would we be able to flood the container with CO2,
> argon, or some other gas to nullify the combustion process? It seems like
> it would just keep burning no matter what, since there is "built-in"
> oxidizer and fuel...at the same time, if the printer is destroyed we are
> finished.

Flushing with CO2 would not help extinguish. Flushing with water would.

>
> Finally, how long can the "slurry" be held at casting temperature? You

> mention that sucrose is not a good choice as it decomposes with time...this
> might be a minor or a major constraint, depending on how long we're
> talking. Would the propellant lose viability after 10 minutes? 30 minutes?
> Sooner?

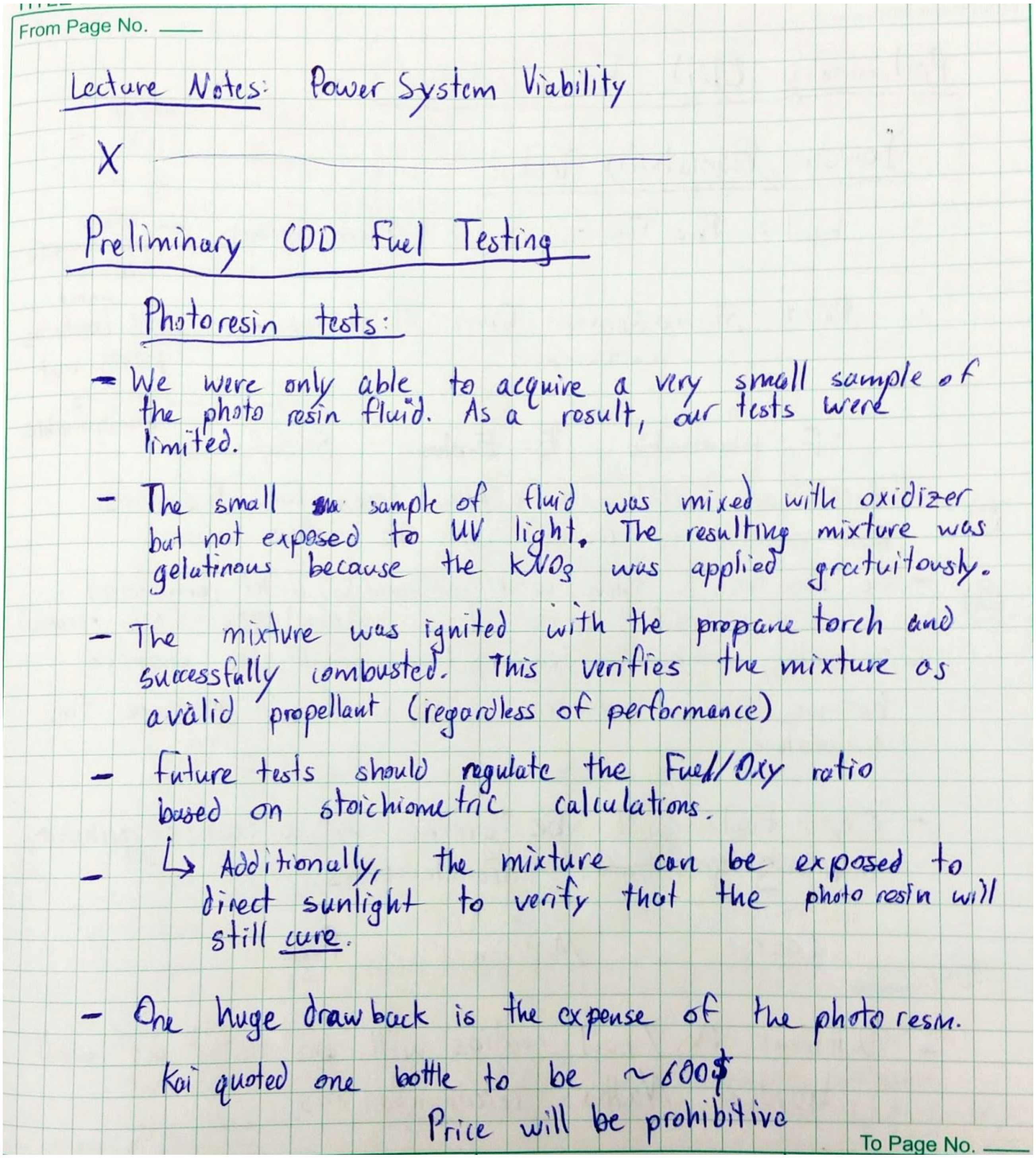
I have never quantified this, but would guesstimate about 30 minutes for KNSU, depending on casting temperature. KNSB has no known time limit, as it does not decompose at casting temperature. KNDX is somewhere in between, it decomposes slowly at casting temperature.

>
> I realize I've written you a wall of text and you have a life and a job. I
> really appreciate any and all help you can give, even if its just a
> list of links. Please take your time in replying and again thank you for your
> help!

Glad to help. If you have further questions or need clarification, feel free to write.

Richard

Appendix B: Preliminary Propellant Test Results



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Lecture Notes: Power System Viability

X

Preliminary CDD Fuel Testing

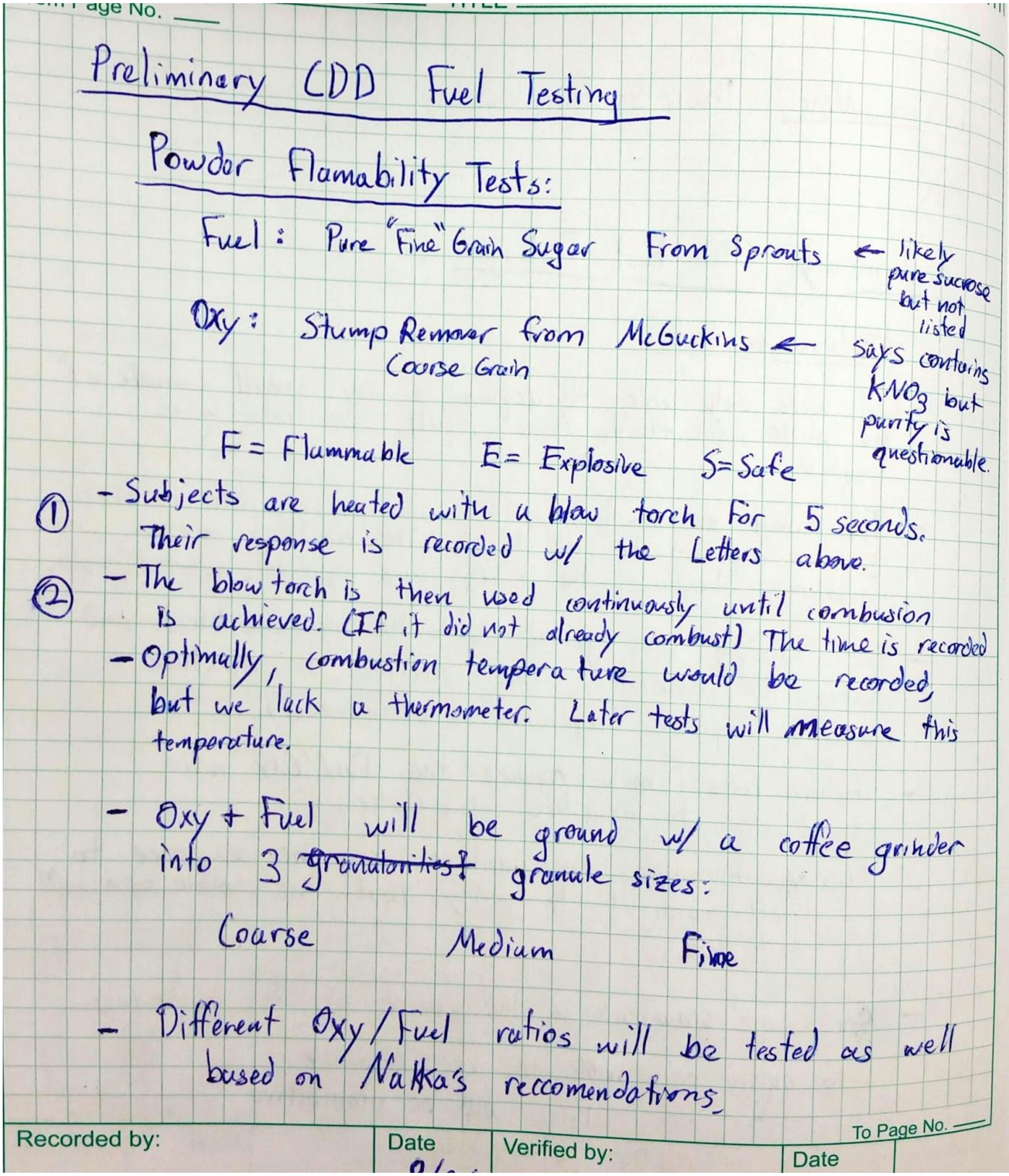
Photoresin tests:

- We were only able to acquire a very small sample of the photo resin fluid. As a result, our tests were limited.
- The small sample of fluid was mixed with oxidizer but not exposed to UV light. The resulting mixture was gelatinous because the KNO_3 was applied gratuitously.
- The mixture was ignited with the propane torch and successfully combusted. This verifies the mixture as a valid propellant (regardless of performance)
- Future tests should regulate the Fuel/Oxy ratio based on stoichiometric calculations.
- ↳ Additionally, the mixture can be exposed to direct sunlight to verify that the photo resin will still cure.
- One huge drawback is the expense of the photo resin.

Kai quoted one bottle to be ~600$

Price will be prohibitive

To Page No. ____



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Preliminary CDD Fuel Testing

Powder Flamability Tests:

Fuel: Pure "Fine" Grain Sugar From Sprouts ← likely pure sucrose but not listed

Oxy: Stump Remover from McGuckins ← says contains KNO_3 but purity is questionable.
Course Grain

F = Flammable E = Explosive S = Safe

① - Subjects are heated with a blow torch for 5 seconds. Their response is recorded w/ the Letters above.

② - The blow torch is then used continuously until combusion is achieved. (If it did not already combust) The time is recorded

- Optimally, combustion temperature would be recorded, but we lack a thermometer. Later tests will measure this temperature.

- Oxy + Fuel will be ground w/ a coffee grinder into 3 ~~granularities?~~ granule sizes:

Coarse Medium Fine

- Different Oxy/Fuel ratios will be tested as well based on Nakka's reccomendations.

Recorded by:	Date	Verified by:	Date

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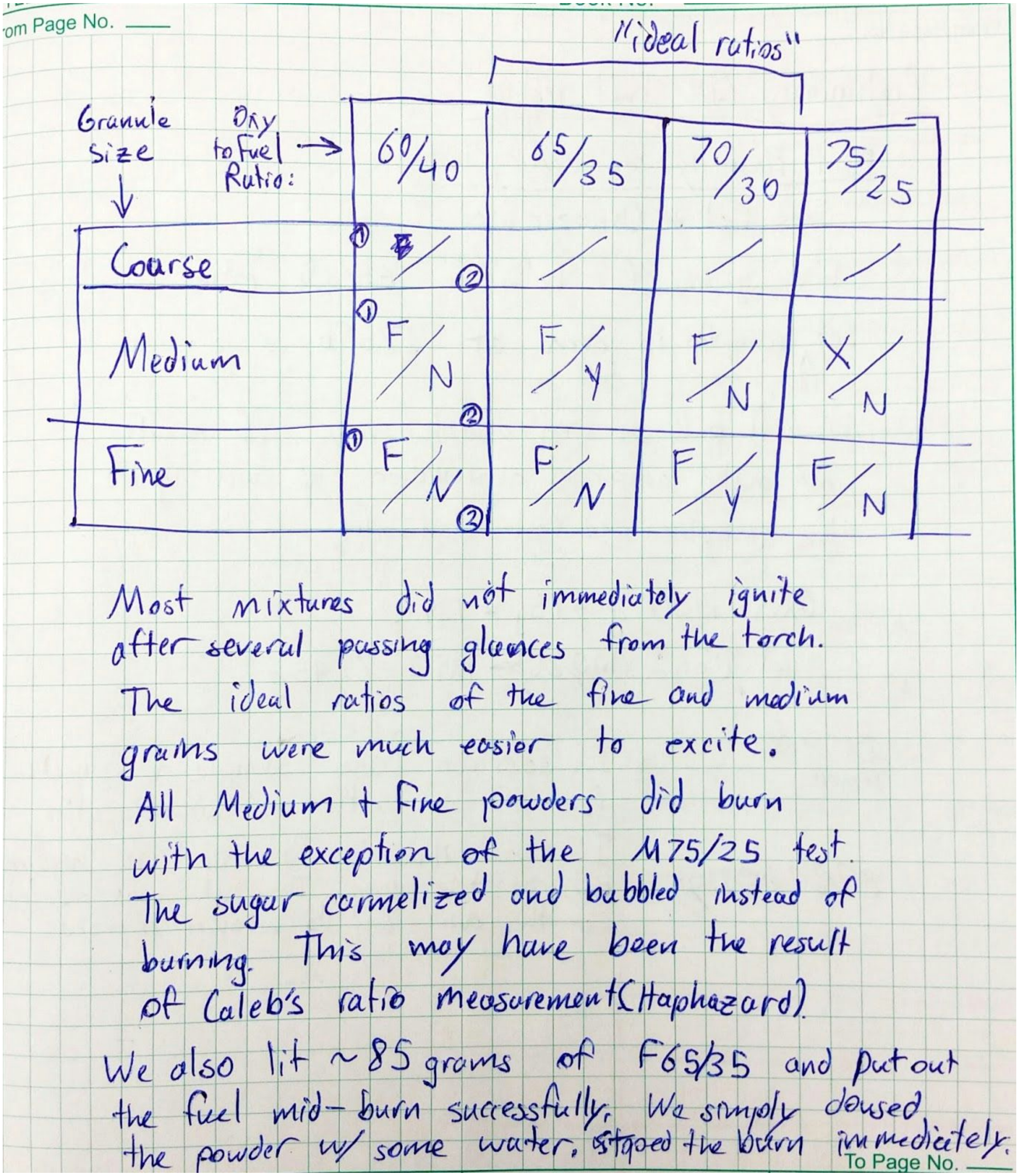


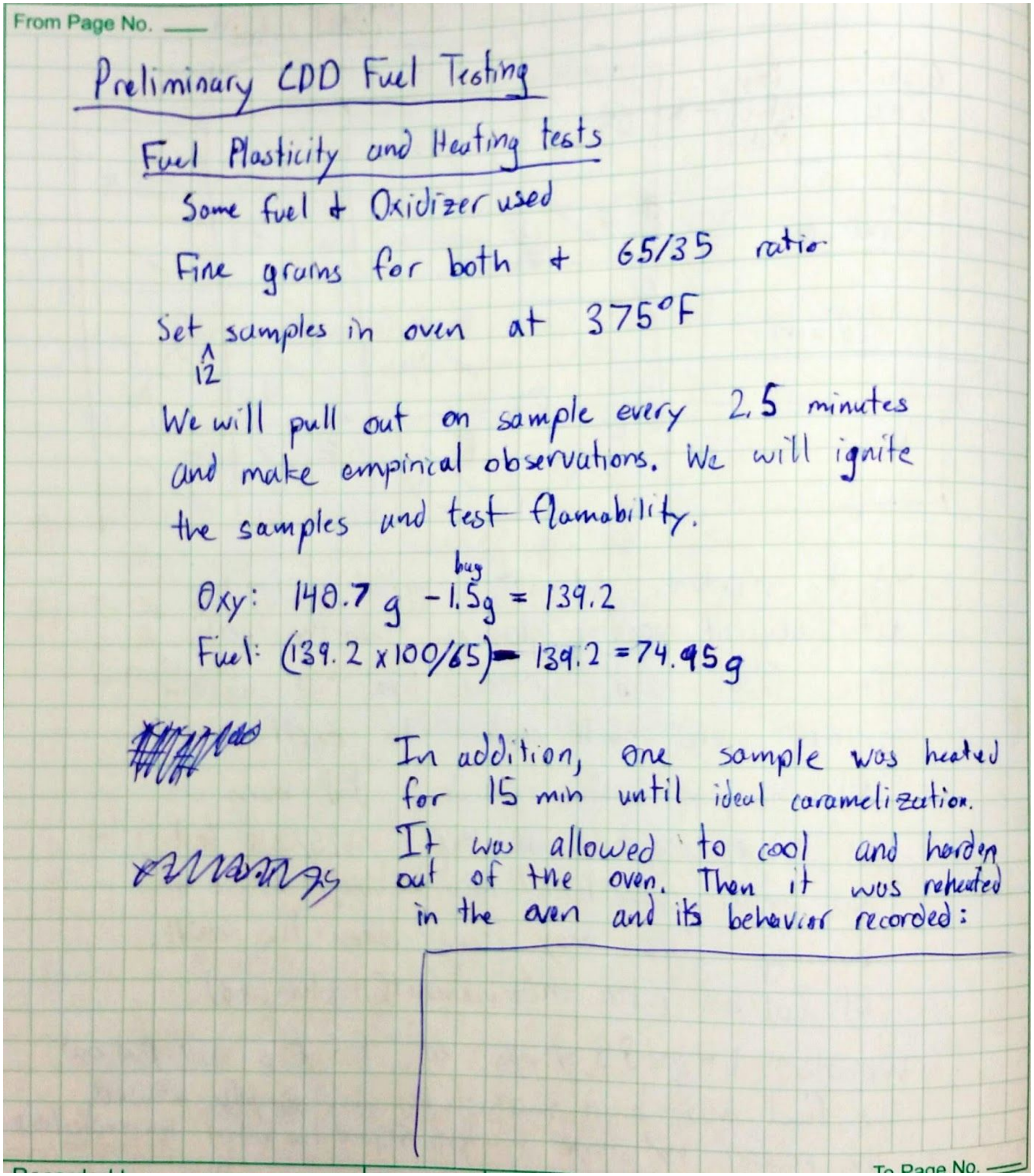
"ideal ratios" (65/35, 70/30)

Granule size ↓	Dry to Fuel Ratio: → 60/40	65/35	70/30	75/25
Course	① / ②	/	/	/
Medium	① F/N ②	F/Y	F/N	X/N
Fine	① F/N ②	F/N	F/Y	F/N

Most mixtures did not immediately ignite after several passing glances from the torch. The ideal ratios of the fine and medium grains were much easier to excite.

All Medium + Fine powders did burn with the exception of the M75/25 test. The sugar carmelized and bubbled instead of burning. This may have been the result of Caleb's ratio measurement (Haphazard).

We also lit ~85 grams of F65/35 and put out the fuel mid-burn successfully. We simply doused the powder w/ some water, stoped the burn immediately.



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Preliminary CDD Fuel Testing

Fuel Plasticity and Heating tests

Some fuel + Oxidizer used

Fine grains for both + 65/35 ratio

Set 12 samples in oven at 375°F

We will pull out on sample every 2.5 minutes and make empirical observations. We will ignite the samples and test flamability.

Oxy: $140.7\,g - \overset{bag}{1.5}\,g = 139.2$

Fuel: $(139.2 \times 100/65) - 139.2 = 74.95\,g$

In addition, one sample was heated for 15 min until ideal caramelization. It was allowed to cool and harden out of the oven. Then it was reheated in the oven and its behavior recorded:

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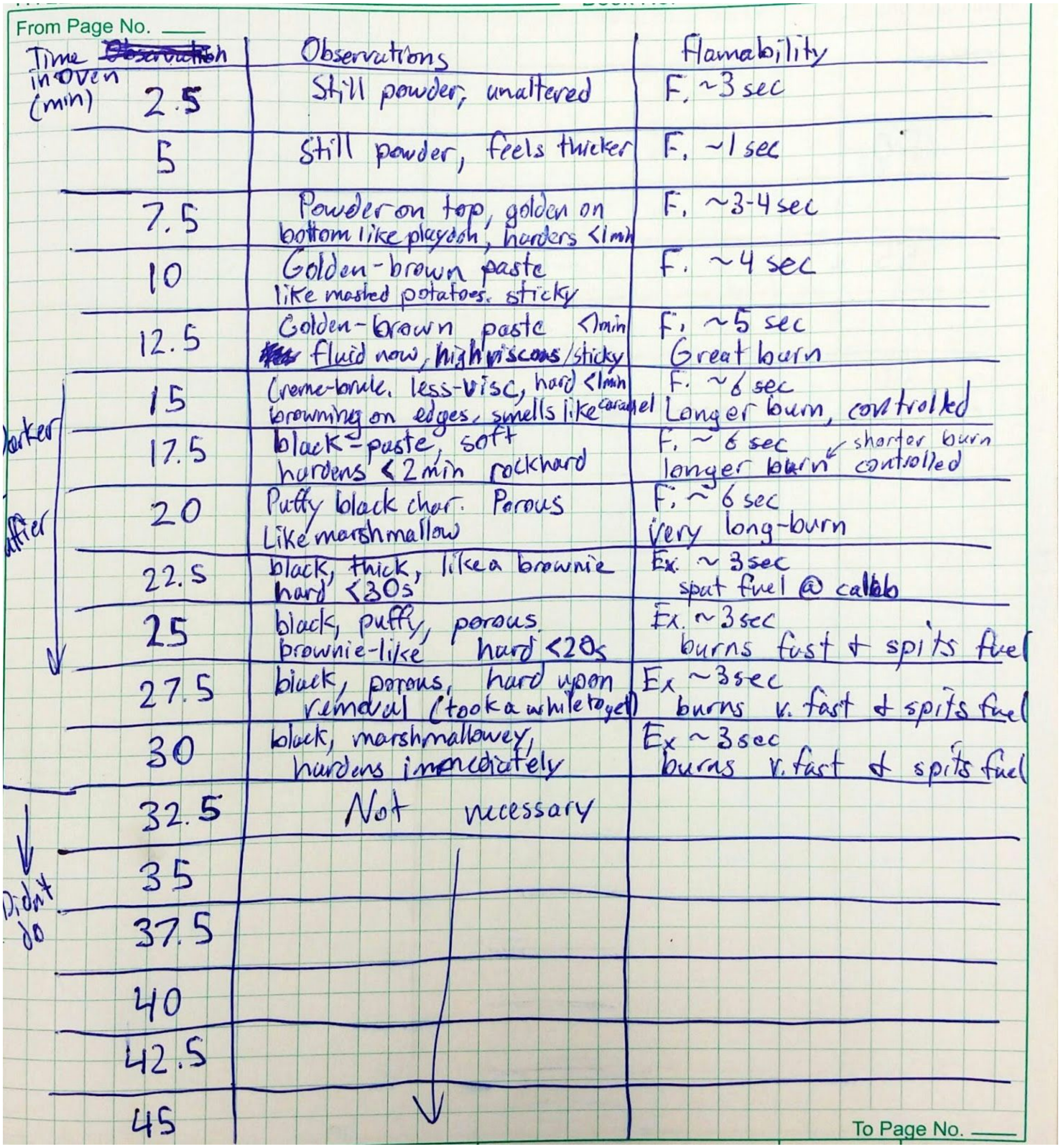

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Time ~~Observation~~ in oven (min)	Observations	Flamability
2.5	Still powder, unaltered	F. ~3 sec
5	Still powder, feels thicker	F. ~1 sec
7.5	Powder on top, golden on bottom like playdoh, harders <1min	F. ~3-4 sec
10	Golden-brown paste like mashed potatoes. sticky	F. ~4 sec
12.5	Golden-brown paste <1min fluid now, high viscous/sticky	F. ~5 sec Great burn
15	Creme-brule. less-visc, hard <1min browning on edges, smells like caramel	F. ~6 sec Longer burn, controlled
17.5	black-paste, soft hardens <2min rockhard	F. ~6 sec longer burn ↙ shorter burn controlled
20	Puffy black char. Porous Like marshmallow	F. ~6 sec very long-burn
22.5	black, thick, like a brownie hard <30s	Ex. ~3sec spat fuel @ callab
25	black, puffy, porous. brownie-like hard <20s	Ex. ~3sec burns fast + spits fue
27.5	black, porous, hard upon removal (took a while to get)	Ex ~3sec burns v. fast + spits fuel
30	black, marshmallowey, hardens immediately	Ex ~3sec burns v. fast + spits fuel
32.5	Not necessary	
35	↓	
37.5		
40		
42.5		
45	↓	

arker
ffier
↓

Didn't do

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