

**PROPOSAL FOR THE INCLUSION OF KNO₃/SUGAR PROPELLANTS IN
THE TRA EXPERIMENTAL ROCKETRY PROGRAM**



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TRA Board of Directors

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EXECUTIVE SUMMARY

Sugar propellants (SPs) have been used by rocket amateurs and experimenters since the 1940's. These motors consist of an oxidizer, usually potassium nitrate, combined with a sugar or "sugar alcohol". Most commonly used fuels are sorbitol, dextrose, and sucrose. At least four methods have been used to prepare sugar propellants: dry ramming, melting/casting, moist pressing, and recrystallization. Melt/casting is by far the most common method.

Substantial research has been performed on sugar propellants in recent years, such that they are now well-characterized and predictable. Propellant behavior matches theoretical design closely, so that safe and effective motors can be developed with a minimum of trial-and-error. Software tailored to SPs is readily available and enables experimenters to design new motors safely. Use of sorbitol and dextrose as fuels permits melt/casting at much lower temperatures than older methods, improving both safety and reproducibility.

Advances in technique also provide for greater safety in the production of SPs than in the past. An informal survey of SP users indicates that the propellant can be made safely, provided that proper precautions are taken and safety rules are observed. Respondents reported making more than 1900 motors with only five accidental fires, all of which could have been prevented by implementing and following appropriate safety procedures. No significant injury or property damage was reported. SPs have an additional safety advantage in that they are made from non-toxic components. Tripoli officials have confirmed that the inclusion of SPs in the Tripoli Research program will not violate any federal/state regulations and will not adversely affect the current insurance policy.

A sample project is presented, illustrating a method by which sugar propellant can be produced, formed into grains, and used in loading a commercial reloadable rocket motor. The propellant was melt/cast potassium nitrate-sorbitol (KNSB), and the motor casing used was of the Aerotech/Dr. Rocket design, model 38/360. The motor was loaded with three Bates grains and test-fired on a digital test stand. The measured thrust curve conforms closely to the predicted curve, supporting the validity of propellant characterization, propriety of design criterion, and quality of motor construction. Additional samples of the motor described will be demonstrated for review by the Tripoli Board of Directors.

An alternative method (recrystallization) of propellant preparation is presented to illustrate the sort of results that can be attained by experimentation with SPs. Recrystallized potassium nitrate-sucrose (KNSU) was produced, formed into grains, and a motor loaded in a manner similar to the sample project. A dozen static tests were conducted with nominal performance.

Storage concerns of SP due to the hygroscopic nature of the propellant have been resolved with the use of freezer bags that keep the grains dry. Motors that have absorbed moisture become very difficult to ignite and their burn rate is reduced substantially. However, improperly stored propellant becomes sticky and the appearance changes noticeably, alerting the experimenter to discard them. SP to be discarded can be destroyed simply by soaking in water, much the same as blackpowder motors.

Based upon the evidence of reasonable safety, predictability, and consistent performance, the authors propose that sugar propellants be accepted within the Tripoli Research Program, thus permitting their use at Tripoli Experimental launches.

INTRODUCTION AND ACKNOWLEDGMENT

KNO₃ based Sugar Propellants (SP) have been utilized in experimental rocketry for many years. These propellants were some of the earliest available and have been well characterized through the contributions of many individuals. We propose that motors made from these propellants can be safe and reliable and would make an excellent educational tool for experimenters interested in learning more about rocket motor development.

While the specific impulse (I_{sp}) of this propellant is not as high as many ammonium perchlorate (AP) based propellants, the SP propellants are simple to prepare and require very little equipment. We have prepared the following proposal in the hopes of illustrating for TRA the importance of including these motors in the TRA Research program. In addition, this proposal may provide an introduction to new developers and provide a simple technique for getting started in experimental rocketry.

This proposal would not be possible had it not been for the excellent work provided by Richard Nakka, who graciously allowed the use of his material for this project. All of the propellant chemistry information in this proposal has been “borrowed” directly from his website, while most of the “original” work is based on concepts provided by him. The rocketry community is indebted to him for the thorough documentation of SP’s he has provided with his work, and his web page (<http://www.nakka-rocketry.net/>) should be considered a “must read” starting point for anyone beginning their own developments with these propellants.

WHAT ARE SUGAR PROPELLANTS?

Sugar propellants (SP) are moderate-performance propellants in which the binder-fuel is one of the common sugars (sucrose, dextrose, maltose, etc.) or one of the so-called “sugar alcohols” such as sorbitol. Technically, SPs are composite propellants, since they have separate fuel and oxidizer components. However, the binder-fuel is not a polymer and is already partially oxidized. These two properties provide two useful characteristics to the propellants. First, the binder decomposes more readily than does a polymer, and so a lower-energy oxidizer such as potassium nitrate can be (and is) employed with good results. Second, a lower proportion of oxidizer can be used with good results. Sulfur, charcoal, and other auxiliary fuels are not typically included in sugar propellants, though there are some reports of their use.

Sugar propellants are intermediate in performance. Typical delivered specific impulse (I_{sp}) is around 130 seconds, which is not strongly dependent on the fuel. For comparison, I_{sp} of blackpowder is usually reported as 80-90 seconds, while most ammonium perchlorate composite propellants (APCP) provide I_{sp} of 190-210 seconds. Burn rates of sugar propellants approximate those of APCP.

Sugar propellants ordinarily are prepared by melting of the ingredients in some fashion. This simplifies “loading” of the propellant into the casting tube. Early trials of sugar propellant used potassium nitrate with ordinary table sugar (sucrose). This mixture has a rather high melting point, which made processing somewhat more complex and reduced reproducibility to some extent. More recent experiments with lower-melting sugars and sugar alcohols make propellant processing much simpler and, presumably, much safer. Such fuels also appear to improve reproducibility.

The sugar propellants discussed in this proposal all have the designation KN for potassium nitrate oxidizer. They include KNSB (sorbitol fuel), KNDX (dextrose fuel), and KNSU (sucrose fuel).

BRIEF HISTORY OF SUGAR PROPELLANTS IN EXPERIMENTAL ROCKETRY

The following is a general timeline illustrating the development of SP's over the years.

1944 First experiments with KN/sucrose by William Colburn of the Rocket Missile Research Society (later Rocket Motor Research Group) followed by first launch of a sugar rocket in 1947. The first propellant, designated TF-1 was dry-mixed KN/sucrose moistened with water and pressed into the motor tube. (from Bill Colburn via Richard Nakka's website)

1950 Melting of KN/sucrose by Dirk Thyse allows casting of propellant grains, thus different configurations are available and larger motors can be produced. (Colburn via Nakka)

1957 First use of hydraulic press to make grains by Bill Colburn allows creation of Bates-type grains without the need to melt propellant components.

1960 Publication of "Rocket Manual for Amateurs" by B. R. Brinley includes a brief description of KN/sucrose propellant. This book has inspired many amateurs (notably Richard Nakka) to try sugar propellants, as well as serving as a manual for many high-school rocketry clubs, which often favored sugar propellant (John Wickman, personal correspondence.)

1975 BVRO (Flemish Rocketry Organization) begins first scientific investigation of this KN/sucrose propellant and its performance characteristics. Culminates in the 1980 publication of "The Potassium Nitrate - Sugar Propellant" by Antoon Vyverman. This group recognized problems of case-bonding in large sugar motors. Contains first mention of KN/sorbitol and KN/mannitol, first used by this group in 1977. (Vyverman 1980, Vyverman, personal correspondence)

1983 David Sleeter of Teleflite Corporation, releases the book "Building Your own Rocket Motors, " and a booklet entitled: "The Incredible Five-Cent Sugar Rocket" using KN/sucrose and sulfur. These publications were advertised in magazines such as *Popular Science*, and so presumably found wide audience.

1993 NERO performs substantial tests of KN/sorbitol, which allows melting and casting at lower temperature than sucrose, perceived to be safer. (Vyverman, personal correspondence)

1996 First use of KN/dextrose by Richard Nakka. KN/DX offers a melting point only a little higher than KN/sorbitol, with a more predictable burn rate. Also, aRocket discussion group opens, facilitating discussion of amateur/experimental rocketry in general. Sugar propellants are a common topic on this list.

1997 Richard Nakka opens his website on experimental rocketry, devoted primarily to the use of sugar propellants. His creative and careful technical work provides a scientific foundation for experimenters working with sugar propellants. It includes substantial treatments of rocketry theory in general, so as to be commendable to users of other propellants as well. Also, Al Bradley uses hydraulic press to compress sugar propellant moistened with 60/40 water/ethanol, resulting in grains which air-dry to a very hard consistency.

1998 Publication of *Rocket Boys* by Homer Hickam and subsequent movie *October Sky* (1999) stirs new interest in rocketry, creating a distinct class of "Born-Again Rocketeers." KN/sucrose was one of the propellants used by the "Rocket Boys," ostensibly co-invented by them independent of knowledge of previous experimenters. (Hickam 1998)

2000 Invention of the "Candymatic," by Paul Kelly allows automated, remote melting of propellants. It is a bread machine modified to heat and stir propellant to the melting point, allowing the operator to remain at a distance. (2001 Jay Ward places a photo of the Candymatic on the Web.)

2001 Publication of the recrystallization process by Jimmy Yawn resolves some limitations of KN/sucrose.

2002 Substantial dialogue regarding sugar propellants on the Arocket discussion list prompts formation of the SugPro list, specifically for the discussion of sugar-based propellants. List owners are Dave McCue and David Muesing. SugPro currently has 100 members (September 2002).

2002 "Yuv" reports melting of KN/sorbitol in a boiling-water bath. The propellant mix is enclosed in a plastic bag and immersed in hot water. This may be the safest method yet of melting sugar propellants.

2002 Two different companies produce and market kits for making sugar-propelled rocket engines. Woody Stanford of Stanford Systems and Jon Drayna of October Science each produce such kits. Sugar propellant knocks at the door of consumer rocketry.

SAFETY RECORD OF EXPERIMENTERS TO DATE

To assess the safety experience of those already experimenting with SP's, a poll was conducted on *Rec.Models.Rockets*, *Arocket* and *Sugpro*. Each participant was asked to list their years of experience, number of motors made, range of motor classes and any incidents occurring while preparing propellant.

The respondents constructed a total of 1,929 motors from 1947 to present, ranging from "A" to "M" class. There were a total of five incidents (fires) experienced in making the propellant. Two of these fires were the result of the builders testing small amounts of propellants in close proximity to the mixing bowl, resulting in ignition of the propellant in the bowl. One fire was due to the builder using a propane torch for heating an oil bath, igniting the oil then the propellant in the mixing bowl. Another fire was not observed igniting but is assumed to have started when oil from an oil bath dripped onto an electric heating element then ignited the propellant in the mixing bowl. The final fire occurred when the builder stored propellant in pre-mixed powder form and it was inadvertently ignited. In all of the incidents, the fire was limited to the mixing bowl as the experimenters were preparing propellant outdoors.

The vast majority of motor builders reported no incidents at all and followed stringent safety procedures in creating their motors. While all of the above incidents could have been avoided with better safety procedures, it is important to remember that accidents can happen and motor builders should always assume the propellant in the mixing bowl could ignite. A properly setup work area and protective clothing are essential in the event that it does. The greatest danger in preparing these propellants (and many others) is safety complacency. With many batches of propellant prepared, and not even a "close call", it is easy to allow oneself to take shortcuts or eliminate the inconvenience of safety equipment. It is essential however to remain vigilant as many of the reported incidents were from experienced builders that "knew better".

PROPELLANT SAFETY CONSIDERATIONS

The primary safety consideration for this propellant is ignition of the propellant while heating. However, a series of experiments performed by Richard Nakka help to demonstrate that overheating of the propellant is not a likely source of ignition. The following sections demonstrate the results of his tests with sorbitol and dextrose.

Effects of Overheating Sorbitol During Casting

Since the casting process of this propellant involves operation at an elevated temperature, it is important to know how much of a "safety margin" one has with regard to possible hazards associated with inadvertent overheating, although sucrose has been tested in a similar manner.

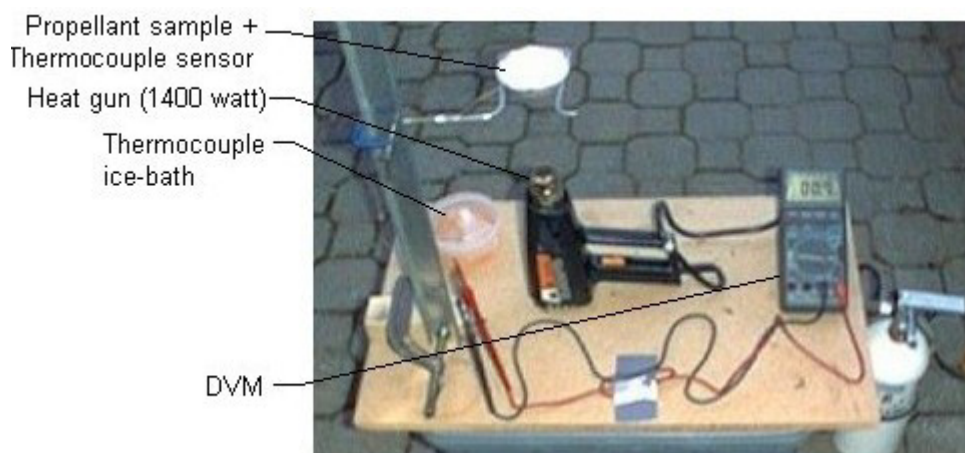


Figure 1: Setup for initial overheating experiment

To determine the effects of overheating during the casting process, an experiment was performed in which a sample of KNSB (potassium nitrate-sorbitol) propellant, of 65/35 O/F ratio was overheated. This involved placing a small sample (16 grams) of the KNSB powdered mixture into an aluminum pan, and heating the sample with a forced-air heat gun (1400 watt; 1100 deg.F max. rating). A type-K thermocouple (chromel-alumel) was inserted into the mixture to monitor temperature.

Soon after the sample became fully melted, the material around the edges of the pan began to turn a slight yellowish colour. The temperature of the sample, at this point, was 175 °C. The colour eventually became a greyish-amber, after 11 minutes of heating with the temperature around 225 °C. Bubbles began to be noticed, and shortly after, puffs of smoke, accompanied by a strong burning caramel odour. The temperature was recorded at 250 °C. These indicators of strong decomposition continued, until after 19 minutes, at a temperature of just over 300 °C. it was decided to terminate further heating.

This was done to allow for an examination of the sample, to see in detail the degree of decomposition that had occurred to this point. Some charring had been visible, and upon closer examination, it was seen that the entire bottom layer of the sample was severely charred. As such, it would seem improbable



that accidental ignition during casting would occur due to overheating, given the obvious indicators of overheating, in particular, the colour change from white to greyish-amber, bubbling combined with smoke, and the strong burning odour. As well, auto-ignition occurs at a temperature greater than 300 °C., whereby the normal casting temperature is below 135 °C.

minum pan containing heated sample of KNSB

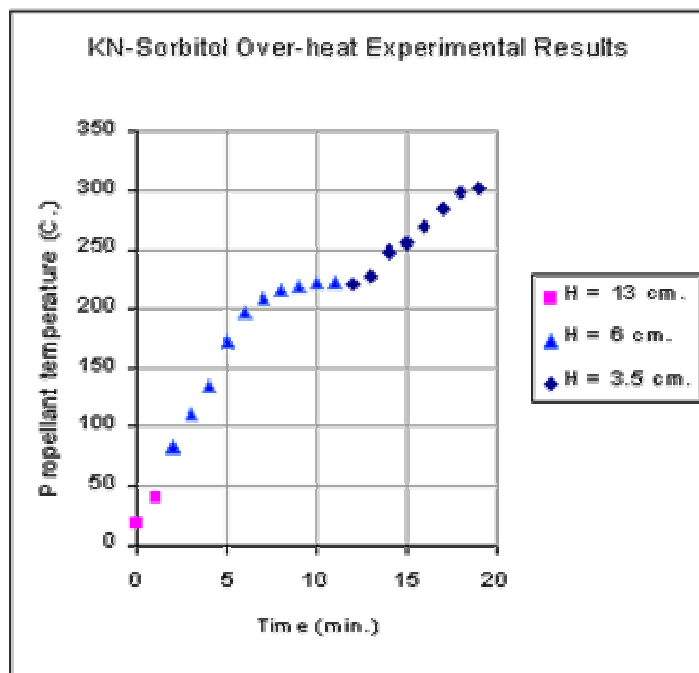


Figure 3: Temperature-time curve for heating of KNSB propellant.

Legend indicates distance from pan to heater.

Effects of Overheating Dextrose During Casting

To determine the effects of overheating during the casting process, an experiment was performed in which a sample of KNDX (anhydrous) propellant, of 65/35 O/F ratio, was overheated. This involved placing a small sample (approx. 10 grams) of the KNDX powdered mixture into an aluminum pan, and heating the sample with a forced-air heat gun (1400 watt; 1100 °F max. rating). A type-K thermocouple (chromel-alumel) was inserted into the mixture to monitor temperature. The setup for this experiment is illustrated below.

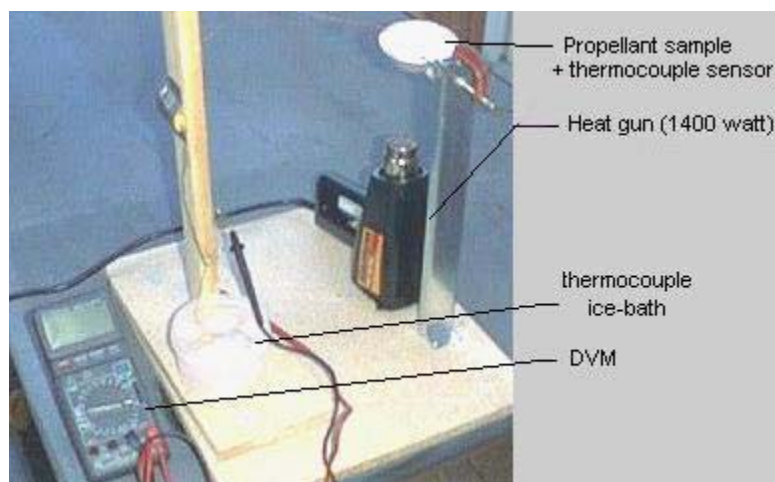


Figure 4: Setup for KNDX propellant "overheating" experiment

Melting of the mixture was rapid, owing to the high output of the heat gun, and brown coloured regions soon appeared in the melted mixture, as rapid decomposition of the dextrose began. The sample soon fully caramelized, with the temperature

recorded at 167 °C. (333 °F.). Interestingly, the temperature of the propellant reached a "plateau" at this point, and would not rise until after several minutes of further heating, after which the propellant was highly decomposed with much charring. Only then did the temperature start to climb, eventually reaching a recorded maximum of 300 °C. (572 °F.). Heating was stopped at this point, with the propellant failing to ignite (the charred appearance of the remaining propellant after this experiment is shown at the left).



Charred remains of overheated propellant which failed to ignite

It would seem that, once decomposition of the dextrose initiates, that the added thermal energy of heating goes solely into *decomposing the dextrose*, rather than raising the thermal energy (temperature)

of the propellant, a rather nice characteristic. As such, it would seem improbable that accidental ignition during casting would occur due to overheating, provided that the proper heating method is employed, given the obvious indicators of overheating,

such as severe caramelizing, and the fact that auto-ignition occurs at a temperature greater than 300° C.

Appropriate safety precautions must always be taken when casting the propellant. Inadvertent ignition due to other unforeseen causes (e.g. electrical short, static electricity, etc.) must be considered as a possibility. Appropriate apparel must be worn when casting the propellant, such as face & hand protection, as well as body & arm protection. Face shield or welders facemask, leather gloves, long-sleeve leather



jacket are the absolute minimum. The fact that the KNDX propellant is highly tolerant of overheating must not lead to lax standards of safety, rather, this characteristic should only be considered to be a valuable margin of safety.

Leather welding gloves are helpful in preventing burns

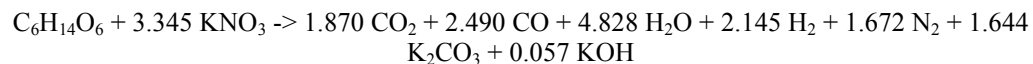
PROPELLANT CHEMISTRY

The original SP's utilized sucrose (ordinary table sugar) as the fuel to combine with the potassium nitrate oxidizer. While this provides an excellent propellant, it is not recommended for beginners due to its tendency to "caramelize" while melting. This can lead to inconsistent characteristics between batches of propellant. Even with more experienced developers, this propellant is no longer as popular as it once was, since new alternatives provide similar I_{sp} but are easier to work with.

The fuel used for the sample motors in this proposal was sorbitol. This fuel provides excellent working time while melted and provides a slightly longer burn time than sucrose motors. It also melts at a relatively low 250 °F. A more readily available and cheaper fuel alternative is dextrose. This is also easy to work with and provides good burn characteristics as well. This section will discuss the chemical properties of both KNDX and KNSB. The data in this section has been provided by Richard Nakka, and experimenters are encouraged to visit his web site for a more in-depth look at the chemistry behind these propellants.

KN-Sorbitol Propellant Chemistry and Performance Characteristics

For the KNSB propellant, with an oxidizer-fuel (O/F) ratio of 65/35, the theoretical combustion equation is as follows:



at a pressure of 68 atmospheres, and where the following compounds are symbolized as:

sorbitol	solid	$\text{C}_6\text{H}_{14}\text{O}_6$
potassium nitrate	solid	KNO_3
carbon dioxide	gas	CO_2
carbon monoxide	gas	CO
steam	gas	H_2O
hydrogen	gas	H_2
nitrogen	gas	N_2
potassium carbonate	liquid	K_2CO_3
potassium hydroxide	gas	KOH
The mole numbers for each of the products shown above were determined from PROPEP (Propellant Evaluation Program).		

Figure 5: Characteristics of the KN-Sorbitol Propellant (65/35 ratio)

	Parameter		Units	Note
	Process method	Cast		
I _{sp}	Specific Impulse, ideal	<u>164</u>	sec.	[1]
C*	Characteristic exhaust velocity, theoretical	<u>3076</u> (938)	ft/s (m/s)	
To	Combustion temperature, theoretical @1000	1327 (<u>1600</u>)	deg Celsius (K)	[2]
To	Combustion temperature, measured@1000	1 TBD	deg Celsius	
	Density, ideal	1.841	g/cm ³	
	Density, as cast	1.82	g/cm ³	[3]
X	Mass fraction of condensed-phase products	<u>0.436</u>	-	
k	Ratio of specific heats	<u>1.042</u>	-	[4]
M	Effective molecular wt. of exhaust products	<u>39.9</u>	g/mole	[5]
	Burn rate behaviour	inverted-mesa		
r ₀	Burn rate @ 1 atm.	<u>0.102</u> (2.6)	in/s (mm/s)	
r	Burn rate @ 1000 psia	<u>0.443</u> (11.3)	in/s (mm/s)	
T _{cr}	Auto-ignition temperature	<u>≥ 300</u>	deg. Celsius	

[1] At 1000 psi pressure; exit pressure one atmosphere

[2] PROPEP combustion results

[3] Measured (liquid displacement method), typical

[4] Effective (2-phase), at chamber conditions

[5] System mass /number of gas moles

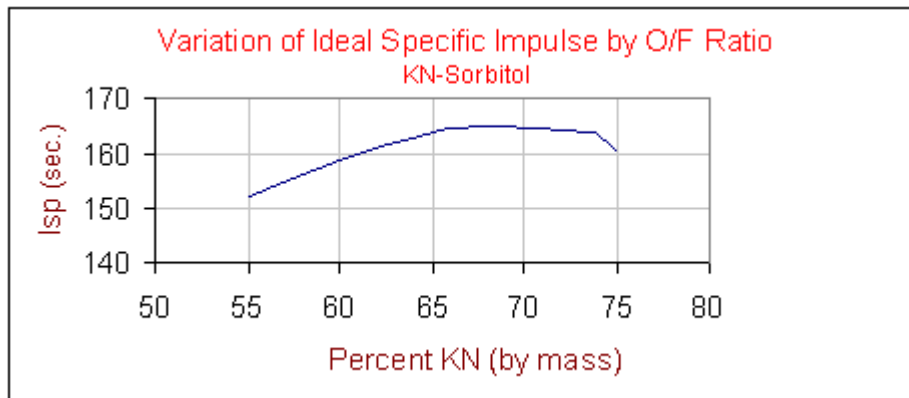


Figure 6: Variation of theoretical specific impulse of KNSB with O/F (oxidizer/fuel) ratio.

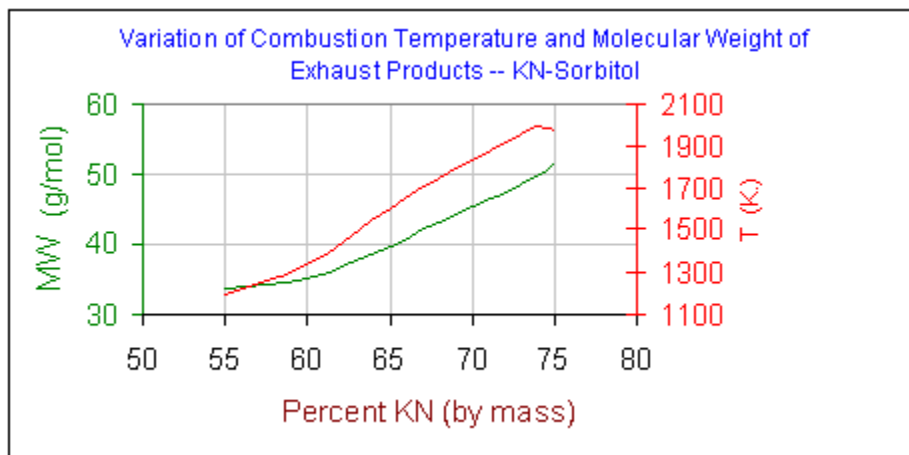


Figure 7: Variation of combustion temperature of KNSB and molecular weight of exhaust products with O/F ratio.

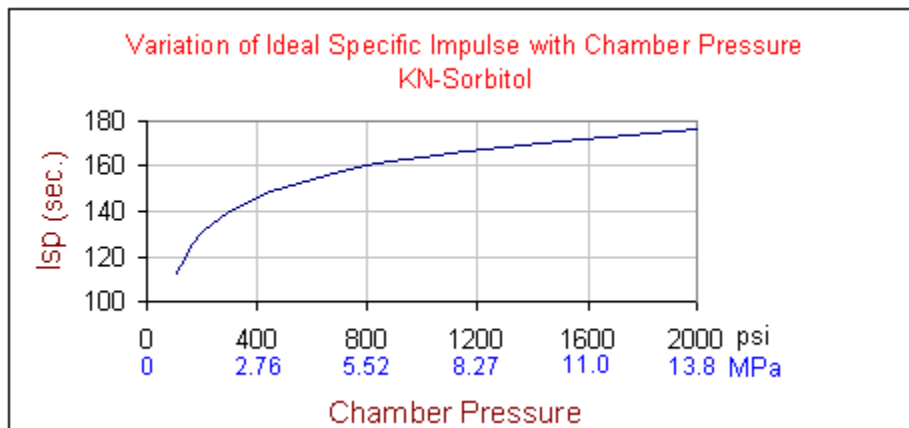
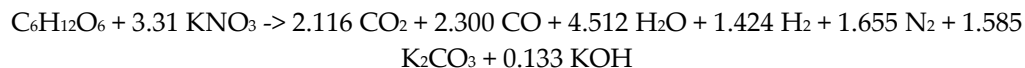


Figure 8: Variation of theoretical specific impulse of KNSB with chamber pressure

KN-Dextrose Propellant Chemistry and Performance Characteristics

For the KN-dextrose propellant, with an oxidizer-fuel (O/F) ratio of 65/35, the theoretical combustion equation is as follows:



at a pressure of 68 atmospheres, and where the following compounds are symbolized as:

dextrose (anhydrous)	solid	$\text{C}_6\text{H}_{12}\text{O}_6$
potassium nitrate	solid	KNO_3
carbon dioxide	gas	CO_2
carbon monoxide	gas	CO
steam	gas	H_2O
hydrogen	gas	H_2
nitrogen	gas	N_2
potassium carbonate	liquid	K_2CO_3
potassium hydroxide	gas	KOH
The mole numbers for each of the products shown above were determined from PROPEP (Propellant Evaluation Program).		

Figure 9: Characteristics of the KN-Dextrose Propellant (65/35 ratio)

	Parameter		Units	Note
	Process method	Cast		
Isp	Specific Impulse, ideal	<u>164</u>	s	[1]
Isp	Specific Impulse, measured	137	s	[6]
C*	Characteristic exhaust velocity, theoretical	<u>2993</u> (912)	ft/s (m/s)	
C*	Characteristic exhaust velocity, measured	2922 (891)	ft/s (m/s)	[7]
To	Combustion temperature, theoretical @1000 p	1437 (<u>1710</u>)	deg Celsius (K)	[2]
To	Combustion temperature, measured@1000 ps	TBD	deg Celsius	
	Density, ideal	1.879	g/cm ³	
	Density, as cast	1.859	g/cm ³	[3]
X	Mass fraction of condensed-phase products	<u>0.425</u>	-	
k	Ratio of specific heats	<u>1.043</u>	-	[4]
M	Effective molecular wt. of exhaust products	<u>42.39</u>	g/mol	[5]
	Burn rate behaviour	plateau		
r _o	Burn rate @ 1 atm.	<u>0.084</u>	in/s	
r	Burn rate @ 1000 psia	<u>0.509</u>	in/s	
T _{cr}	Auto-ignition temperature	> <u>300</u>	deg. Celsius	

[1] At 1000 psi pressure; exit pressure one atmosphere

[2] PROPEP combustion results

[3] Measured (liquid displacement method), typical

[4] Effective (2-phase flow), at chamber conditions. For static conditions, k=1.131

[5] System mass /number of gas moles

[6] Static Test KDX-002

[7] Closed Vessel test, CV-2, Dec.8, 2000

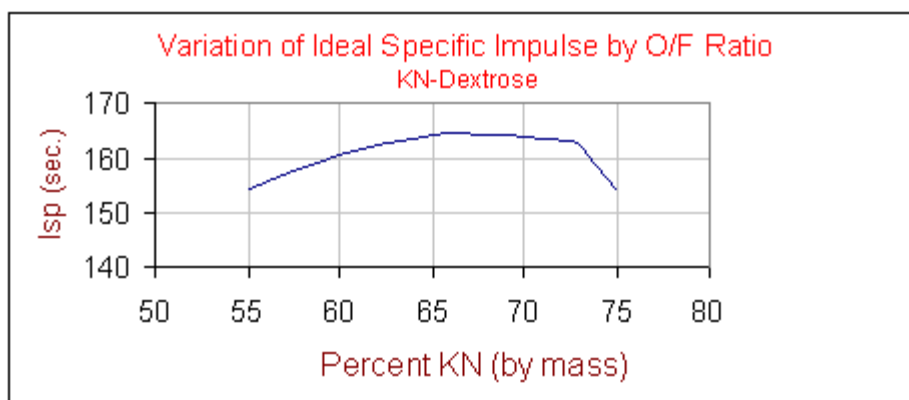


Figure 10: Variation of theoretical specific impulse of KNDX with O/F (oxidizer/fuel) ratio.

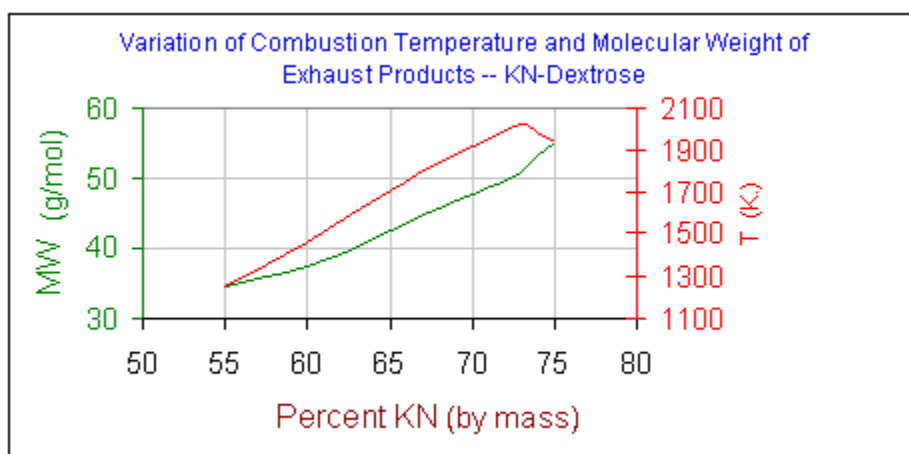


Figure 11: Variation of combustion temperature of KNDX and molecular weight of exhaust products with O/F ratio.

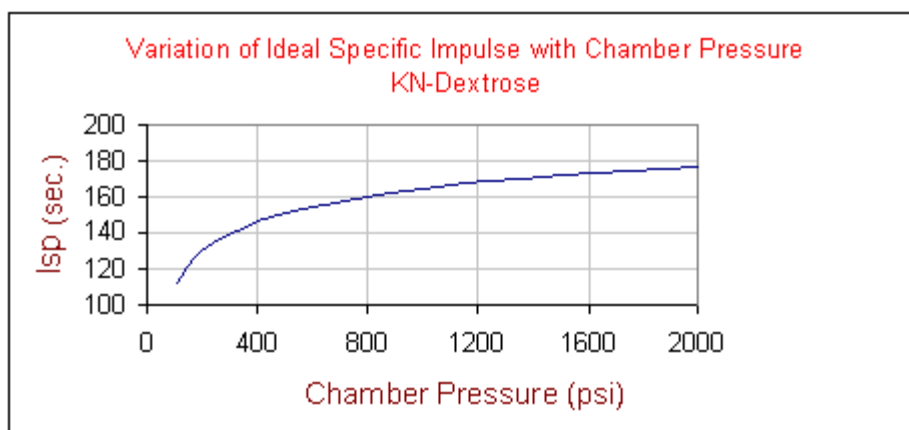


Figure 12: Variation of theoretical specific impulse of KNDX with chamber pressure

Design Charts- Optimizing K_n

This section provides design charts which may be used to determine the steady-state chamber pressure of a solid rocket motor. Figures 13 and 14 are design charts for KNSB and KNDX propellants, respectively. To use the design charts, the desired chamber pressure is selected, and the area ratio (K_n) corresponding to that chamber pressure is found. The motor is then designed to operate at that value of K_n .

For the chart data to be considered valid, it is necessary that the propellant be prepared by the "standard" method:

- The propellant is heat-cast.
- The oxidizer is finely ground such that the maximum particle size is 75-100 micron (e.g. ground by an electric coffee grinder).
- The constituents are very well blended prior to casting (e.g. 3 hours per 100 g. in a rotating mixer).
- The propellant uses the standard 65/35 O/F ratio.

The term *steady-state* infers the operating condition whereby chamber pressure is solely a function of grain burning-surface area. In other words, the generation of combustion gases, and outflow of gases through the nozzle, are in a state of equilibrium (balance). This excludes the initial pressure build-up as well as the pressure tail-off at burnout. Thus, these areas of the thrust curve are not well predicted by the design charts. Nonetheless, general motor performance is very closely predicted by the charts, as will be seen.

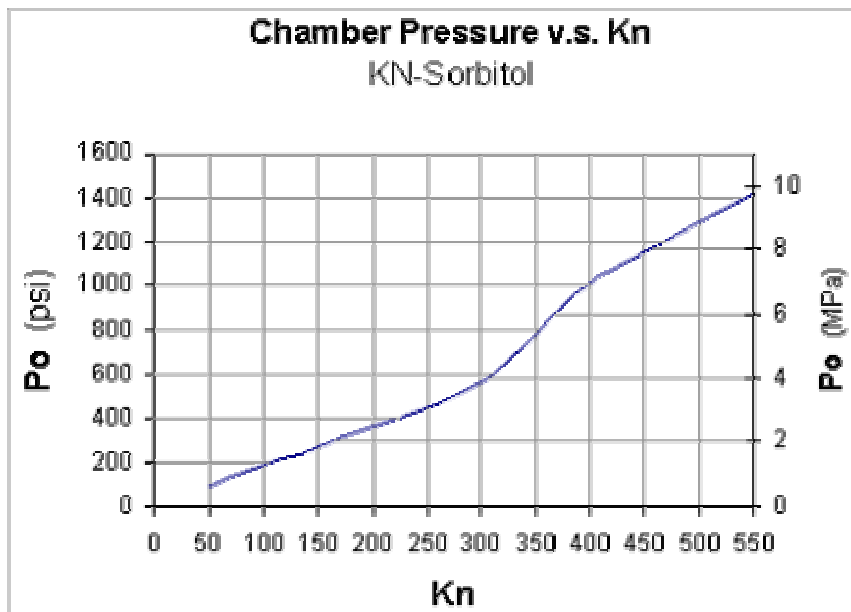


Figure 13: Design chart for KNSB propellant.

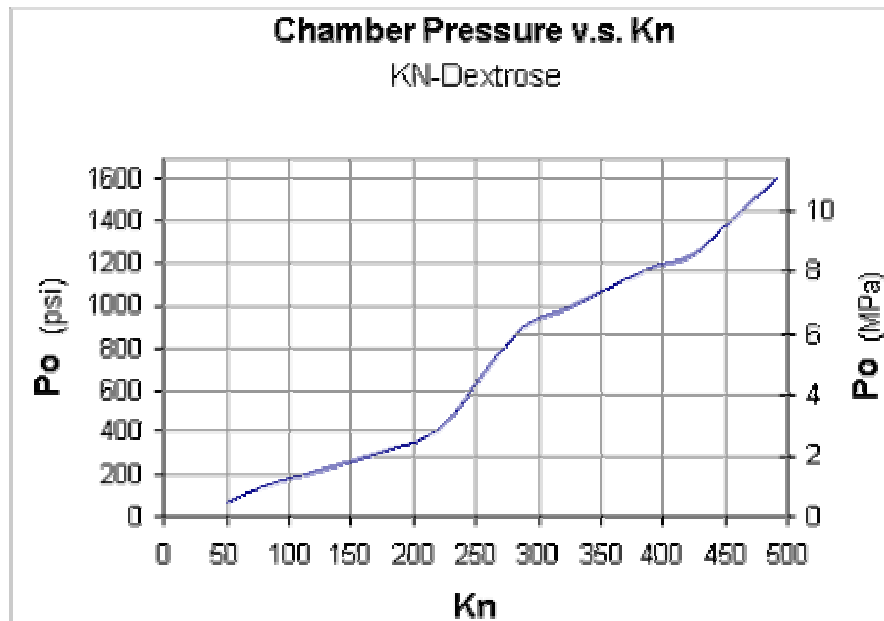


Figure 14: Design chart for KNDX propellant.

MOTOR HARDWARE REQUIREMENTS

Much of the development work with these propellants in the past has utilized custom motor hardware to contain the propellant. A range of materials including aluminum, steel, phenolic and even PVC have been used successfully. Since we would like to keep the focus of this proposal on the propellant, we will utilize readily available commercial hardware for testing and demonstrations. This approach also serves as an “easy entry” for new developers since it eliminates the need for expensive machine tools and facilities.

Parts List and Sources

The place to start is the motor hardware. One *Aerotech* (or *Dr. Rocket*) 38mm reusable rocket motor with a 360 N-s casing is required and can be purchased through most hobby shops and online rocketry vendors. These are the “reusable” parts of the motor we are making. The purchased hardware should include:

- Casing- 360 N-s size
- Plugged forward closure
- Aft closure

Note that the “plugged forward closure” is not typically sold as part of a complete motor and is usually purchased separately.

The rest of the parts are used one time only. Many can be made at home, or purchased more cheaply in other places, but for the sake of simplicity they can all be purchased in small quantities from RCS at <http://www.rocketmotorparts.com/>. RCS part numbers are included.

(1) 1 Casting tube- 1.308" O.D. X 1.274" I.D. X 22.75" long (part no. 03170)

Three 1.8" lengths of this will be needed for casting grains

(1) Paper motor liner- 1.380" O.D. X 1.313" I.D. X 5.625" long (part no. 02060)

(2) Forward and aft insulator washers- 1.375" Dia. X 0.062" (part no. 05404)

(1) Forward O-ring- 1-3/8" O.D. X 1-1/8" I.D. X .139" thick (part no. 00216)

(1) Aft O-ring- 1-3/8" O.D. X 1" I.D. X .210" thick (part no. 00318)

(1) Nozzle- 1.000" O.D. X .180" Throat X .438" Exit (part no. 01500)

This will be drilled to the proper throat diameter during construction

While it is entirely feasible to add proper delay o-rings, liners and commercial (or homemade) delay grain with a standard forward closure, we have left these out at this time to keep a simple focus on propellant. We will rely on electronic altimeter deployment for the rocket flown at the demonstration launch.

PREPARATION OF PROPELLANT GRAINS

Both oxidizer and fuel can be purchased online from companies such as *Firefox* (<http://www.firefox-fx.com/>) etc. at a range of prices. For successful propellant, it is important that the components be in a fine powder form. Many experimenters have had great luck with grinding granular forms of these materials to powder with coffee-grinders. Beginners may wish to purchase materials in the fine powder form initially. This insures good useable results immediately. The part numbers for *Firefox* are listed below:

Potassium Nitrate - Stock #C170 - OX

Sorbitol - Stock #C187C6

While there are many different grain designs that can be utilized in motor design, the Bates grain is probably the most common and the simplest. The demonstration motors will utilize this grain configuration. They were designed using software (SRM.XLS) provided by Richard Nakka that can be found at <http://www.nakka-rocketry.net/>. The grain dimensions used in Aerotech commercial reloads provide satisfactory proportions for these motors as well, so these dimensions will be used for the demonstration. They have the added advantage of allowing the full range of Aerotech casing sizes to be utilized. With a little work, a more uniform burn could be achieved by varying the length and core size of these dimensions but we will leave that for further experimentation.

For the demonstration, we will be utilizing the KNSB propellant, and will outline its preparation here.

1. Potassium nitrate (170 g) was weighed and placed in a suitably sized



“Rubbermaid” type storage bowl. Accuracy is paramount. A triple beam balance or electronic scale good to 0.1 g is strongly recommended, but a fairly accurate balance can be constructed from household materials (see Nakka’s web site for an example).

Figure 15: Mixing bowl with lid

2. Sorbitol (91.5 g) was weighed and added to the potassium nitrate.

The lid was placed on the bowl and

the bowl shaken vigorously for five minutes (a timer was used). It is essential that the propellant is mixed thoroughly. See Nakka’s site for a home made propellant mixer that can provide very consistent results. Consistent results have been obtained with the hand mixed method, but batch sizes are limited to what the arms can endure for five minutes. My limit seems to be about 5 propellant grains worth at one time!

3. To “cook” the grains, a temperature-controlled deep fryer seems to be the tool of choice. While many have successfully created propellant by mixing directly in such a fryer, an oil (Crisco vegetable shortening) bath and a secondary container for propellant offers better temperature control. The photo below shows such a setup, including the metal strainer that came with the fryer. The strainer helps keep the



metal mixing bowl off the bottom of the pan.

While most deep fryers have a dial with temperatures printed on it, they are usually not very accurate. A traditional “candy” thermometer or a digital thermometer with probe is more accurate and reproducible.

The fryer was heated to about 250 °F and Crisco was melted in it to a depth of

about two inches. The thermometer was placed in the oil, and the dial of the fryer was adjusted to maintain about 250-260 °F.

4. A stainless steel bowl was placed in the oil bath (a handle on the bowl is pretty handy) and allowed to come up to temperature. Half of the mixed propellant was placed in the bowl. A wooden spoon was used to stir the powdered propellant gently, every 20 seconds or so. The powder slowly began to melt. Once the initial batch was melted, the remaining powder was added to the bowl. Mixing was continued until this had melted as well. Before pouring, the mixture was examined to insure that it was a smooth white/ivory colored paste, with no lumps.



Figure 17: Left: Starting to melt the propellant mix. Right: Propellant ready for casting

5. A piece of waxed paper was placed on a wooden cutting board. Three precut casting tubes were stood on end on the waxed paper, with a few inches between them so that there was room to place the propellant in each tube.



6. A Popsicle stick worked well for placing the hot propellant in the

Figure 18: Adding propellant to casting tube

casting tubes. A “dollop” was scooped out and immediately placed at the bottom of the tube, and this operation was repeated. Care was taken not to trap air in the propellant during processing. To avoid trapped air, propellant was continually placed in the middle, so that it tended to melt out towards the edges and eliminate air pockets. Each casting tube was filled flush to the top, and the Popsicle stick was used to flatten the top even with the tube. The propellant stayed very hot in the tube so working time does not appear to be a problem with this propellant. Care was taken not to lift the tube from the wax paper while filling. When this occurred, the tube was simply pushed back onto the surface. Propellant that leaked out was trimmed off later.

7. Each of the three tubes was filled using the same technique. Once filled, they were allowed to cool overnight.

8. The cores were then drilled at low speed with a drill press and 3/8” bit. A 1/2 inch core might be better for beginners since it is less prone to erosive burning. While drilling the cores, the bit tended to fill with propellant. This may lead to rougher cores that might create an initial thrust spike due to the added burning surface area. To avoid the problem, the bit was cleaned frequently during drilling. Shavings and scraps were allowed to dissolve in water overnight, then flushed down the drain.



Figure 18: Cooled KNSB grains



Figure 19: Grains after drilling

ALTERNATIVE GRAIN PREPARATION TECHNIQUES

Recrystallization is a process of making SP by dissolving fuel, oxidizer, and a texturizer in hot water, then drying it with moderate heat. This method avoids many of the problems associated with the traditional melting process, and produces a propellant with some unique and useful characteristics. Components most commonly used are potassium nitrate and sucrose, with light corn syrup as the texturizing agent. We are including this brief description of this process as developed and performed by Jimmy Yawn to illustrate that there are many new developments yet possible with further

experimentation with SPs. A more detailed explanation of this method can be found at the web site: <http://www.jamesyawn.com/rcandy/index.htm>

Advantages of Recrystallization:

- Operator is not exposed to hot propellant during the cooking process.
- No need to grind or mill the components
- Putty-like texture allows it to be formed by hand or gently pressed into a mold.
- Stores well when properly sealed.
- Can be re-heated and formed into grains days, months, or years after preparation.
- Is somewhat less brittle than melt/cast propellants.
- Burn rate can be adjusted somewhat by the extent of “cooking”.
- Produces very little waste, compared to the casting method.

In addition, this propellant retains the advantages of traditional KNSU in that it is nontoxic and low in sensitivity. Its ignitability and burn rate can be increased with opacifiers and catalysts.

Disadvantages of Recrystallized KNSU:

- It is dried in an oven, normally found in a kitchen, which may not be a good location for making propellant.
- The operator is exposed to hot propellant for a brief period, during which great caution is advisable.
- Like melt/cast KNSU, it is still hygroscopic, rather brittle, and has lower I_{sp} than many other propellants.

The Recrystallization Process:



The components were weighed, placed in a pan with a measured amount of water, and dissolved over heat. The proportions were 60% KNO_3 , 30% sucrose, and 10% corn syrup. Since corn syrup is largely water with assorted sugars, the final oxidizer/fuel balance is close to the standard 65/35 ratio.



This solution was poured into flat glass baking-pans, forming a thin layer. The pans were then placed in a 300 °F oven until most of the water was evaporated. Oven temperature was reduced to 250 °F to finalize the drying process.

The resulting flakes were scraped together; they could have been pressed into a cake for hand-kneading, but instead were placed in a food-processor (shown) for mechanical mixing. At this point the flakes consolidate into a cohesive mass with a texture resembling modeling clay.



The propellant could have been molded immediately, but was stored for later forming. It became very hard when cooled. Molded grains can be used as soon as they are cool - no curing period is required as for composite propellant. Poorly formed grains and scraps can be re-heated and re-molded.



A burn inhibitor was wrapped around the grains to insure a uniform burn from the core to the outer wall. The inhibitor was glued to the propellant with epoxy to prevent delamination. The finished grains were loaded into a motor in the same fashion as described for KNSB propellant.

ASSEMBLY OF THE MOTOR



Figure 20: Motor components
before assembly

The grains that were created in the *Preparation of Propellant Grains* section match the dimensions of *Aerotech* commercial 38mm APCP grains. This allows the same motor assembly method to be followed that is familiar to many already.

The motor that we will be assembling and using for our demonstration flight is calculated to be an H180. It will have a total impulse of 216 N-sec.

Before beginning assembly, the nozzle must be drilled to the proper diameter. The diameter should be 15/64 inches for the three-grain sorbitol motor demonstrated here. This corresponds to an initial K_n of about 310, which in turn corresponds to a chamber pressure of roughly 600 psi (from Figure 13).

Aside from the use of KNSB propellant, the assembly procedure is the same as that given with commercial *Aerotech* reloads. The motor liner should first be lightly coated with petroleum jelly (or even better, *Radio Shack Lubricant with Teflon* part no. 64-2326). The threads of the closure are also lubricated and the O-rings are lightly lubricated per *Aerotech* instructions. Grains are then inserted into the liner tube, and the liner tube inserted into the casing. A delay insulator is inserted into the forward end of the casing, followed by the forward O-ring. The plugged forward closure is then screwed onto the casing. The aft delay insulator is inserted into the aft end of the casing, followed by the aft O-ring. The nozzle is then inserted inside the aft O-ring, and the aft closure screwed into place. The motor is now ready for launch.

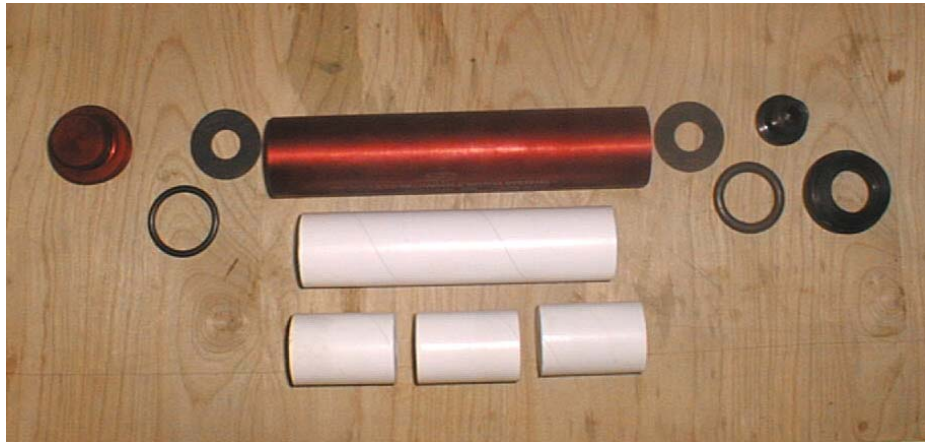


Figure 21: Components laid out in relation to their position of assembly

IGNITION CONSIDERATIONS

If the grains are stored as outlined in the “Storage Considerations” section, ignition ordinarily is very straightforward. Standard high power rocket motor igniters appear to bring the motor to operating pressure very rapidly. The igniter below is made with a pyrogen dip from *Firefox* surrounding nichrome wire wrapped leads. In many early experiments, bare nichrome wire was found to ignite the motor reliably, but the motor did not come up to pressure quickly enough for a reliable rocket launch. The pyrogen assures proper ignition.



Figure 22: Pyrogen-dipped igniter for KNSB

TESTING RESULTS

The demonstration motors were designed with Richard Nakka's SRM.XLS Excel spreadsheet. A screen shot of the anticipated thrust curve is shown in the image below.

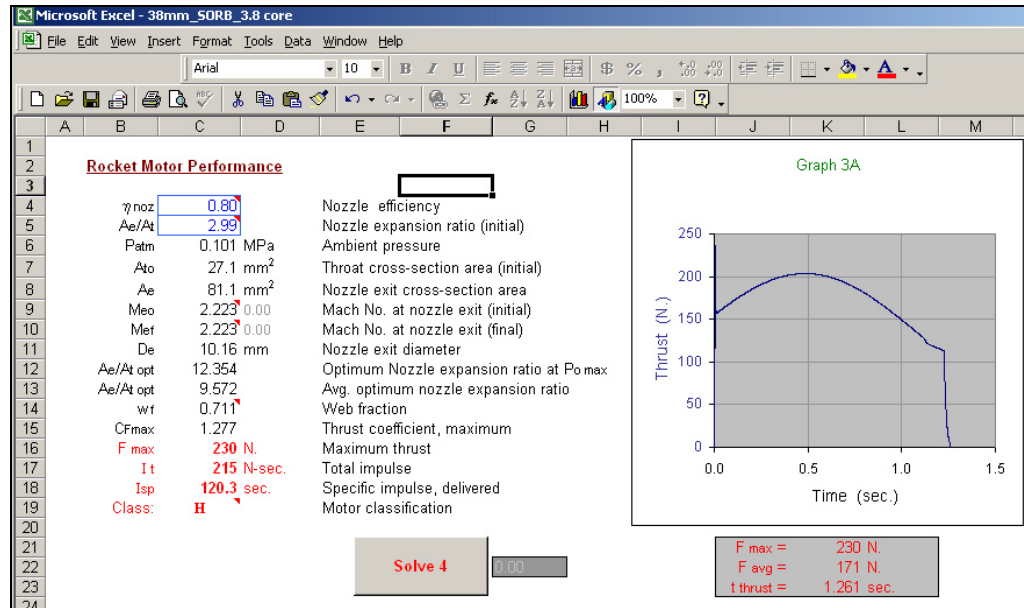


Figure 23: Excel spreadsheet for simulating motor performance. Note Graph 3A on the right, which depicts the expected performance of the test motor.

The 3 grain motor was then assembled and launched on a digital test stand to verify the performance. The following graph is a screen shot of the software written to interface with a home-made digital test stand.

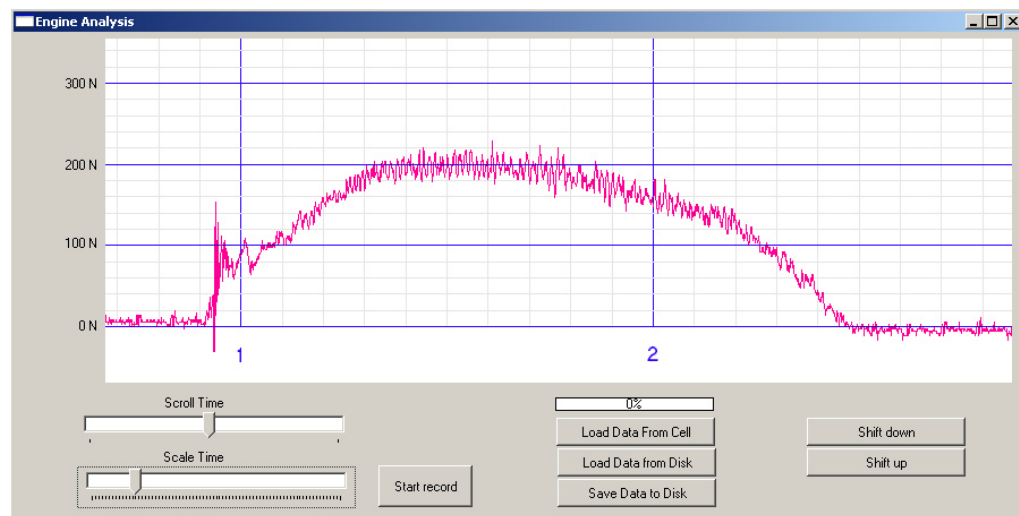


Figure 24: Actual thrust curve from 3-grain KNSB motor described in proposal. Note that the maximum thrust and burn time compare favorably to the prediction from Figure 23.

The actual result seems to follow the predicted performance very well, differing only as expected in the initial pressure and fall off pressure ends of the graph. The spreadsheet is a very handy piece of software for designing these motors.



Figure 25: Motor components after test

After the test, the motor components looked very similar to those of a typical *Aerotech* reload, as shown in Figure 25. The liner was charred on the inside, but the outside remained in good shape. The o-rings showed no visible signs of wear and might be usable again, though this is not recommended. The insulator washers were burned on the inside edge extensively, but held up well where in contact with the o-ring. The nozzle was eroded approximately $1/32$ of an inch in diameter. No damage to the reusable hardware was observed.

STORAGE AND HANDLING CONSIDERATIONS

Most SPs are hygroscopic. If the propellant absorbs moisture, the surface may appear “gummy” or very sticky, rather than having the clean waxy appearance of fresh propellant. Moisture can inhibit ignition and reduce reliability. Therefore, it is recommended that SB propellant that appears to have absorbed moisture be disposed of, by allowing the propellant to stand overnight in water, then flushing down a sanitary sewer.

Since this propellant is hygroscopic, grains must be sealed from the environment if stored. Two zipper-type freezer bags, one inside the other, appear to protect the propellant adequately. Sample grains in these bags that have been stored for six months (including a humid New York summer) with no noticeable signs of water



absorption. These “test grains” have been transported to launches over the summer and left in the back of a hot car to insure they can be treated the same as commercial propellants. In all cases they have held up well, and no change in performance has been noted.

Figure 25: Storing KNSB propellant grains

It may be preferable to drill the core for the grain just prior to use as an extra precaution. This minimizes exposure of the propellant surface to moisture. If the grain is left exposed to the environment during a humid period, it can absorb enough water to turn into a solution overnight! While this is handy from a safety standpoint (any missed scrap becomes harmless pretty quickly) it underscores just how important it is to protect these grains from moisture. Richard Nakka has stored grains in a freezer as an added precaution.

AVAILABLE SOFTWARE TOOLS TO ASSIST IN DEVELOPING SPS

There are a number of programs available that take a lot of the “guesswork” out of developing motors with SP’s. Following is a list of programs that have proven helpful in our development work:

- ***SRM.XLS (Solid Rocket Motor design – EXCEL Spreadsheet)*** This is probably the most important and useful software for SP development. It is a spreadsheet that Richard Nakka created for evaluating Bates grain configurations. The chemical properties of dextrose and sorbitol based propellants are included, making motor development more predictable. The spreadsheet computes K_n over the duration of the burn, generates a pressure-time curve and a thrust-time curve, and calculates performance parameters such as total impulse and delivered specific impulse. It can be found at:

<http://www.nakka-rocketry.net/>

- ***CASING.XLS*** - This is an EXCEL spreadsheet written by Richard Nakka that is used to determine the Design Pressure and Burst Pressure of a solid rocket motor casing. Also determines the elastic deformation of the casing under pressure (important for case-bonding consideration). Strength and mechanical properties are supplied for many casing materials such as steels, aluminum alloys, PVC, etc. This is a must have for anyone making their own hardware. . It can be found at the same site as SRM.XLS.
- ***Grains2.xls (or Grains2000.xls if you can find it)*** This spreadsheet allows simulation of a wide range of grain types. It works for many propellants and requires the user to enter basic propellant characteristics. The *Grains2000* version integrates a ProPep interface but seems to still be in beta at this point. This is an excellent tool for experimenting with alternative grain configurations. It can be found in the Arocket archives at:

<http://arocket.mid-south.net/software/spreadsheets/>

TRIPOLI INSURANCE AND LEGAL CONSIDERATIONS

Bruce Kelly of TRA was contacted and asked if he was aware if the inclusion of SP's would affect the current TRA insurance policy or come under any additional legal scrutiny. He has looked into this and informed us that there will be no problem with either of these issues.

DEMONSTRATION FLIGHT OF A SP POWERED ROCKET

The "H" Class motor detailed in this proposal will be built and installed in a rocket for a demonstration flight. This motor will serve as a "simple to make" motor and will not incorporate a delay element, instead relying on altimeter deployment of the parachute.

The flight will be documented with video and photography from the ground. A data collecting altimeter and accelerometer will record flight information as well. The flight data and images will be added to this proposal upon completion of the demonstration.

CONCLUSION

We think the information contained in this proposal shows that SPs are safe, reliable propellants that can provide an effective tool in drawing new experimenters into the hobby. Their ease of preparation combined with minimal cost and long track record of safety make them an excellent place for beginners to get a taste of the excitement that rocket motor development has to offer. With TRA members free to utilize these propellants at EX launches, we believe there will be many further exciting developments in this area.