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Sugar Based Rocket Propulsion System- Making, Analysis & Limitations

D. Abhijeet Singh
Department of Aerospace Engineering
MLR Institute of Technology, Dundigal Village
Quthbullapur Mandal, Hyderabad
Telangana - India

ABSTRACT

A solid rocket or a solid-fuel rocket is a rocket with a motor that uses solid propellants (fuel/oxidizer). The earliest rockets were solid-fuel rockets powered by gunpowder; they were used by the Chinese, Indians, Mongols and Arabs, in warfare as early as the 13th century.

The evolution of the rocket has made it an indispensable tool in the exploration of space. For centuries, rockets have provided ceremonial and warfare uses starting with the ancient Chinese, the first to create rockets. The rocket apparently made its debut on the pages of history as a fire arrow used by the Chin Tartars in 1232 AD for fighting off a Mongol assault on Kai-feng-fu.

Keywords:- LEO, SP, KN, KNSB, KNDX, APCP

INTRODUCTION

The lineage to the immensely larger rockets now used as space launch vehicles is unmistakable. But for centuries rockets were in the main rather small, and their use was confined principally to weaponry, the projection of lifelines in sea rescue, signaling, and fireworks displays. Not until the 20th century did a clear understanding of the principles of rockets emerge, and only then did the technology of large rockets begin to evolve. Thus, as far as spaceflight and space science are concerned, the story of rockets up to the beginning of the 20th century was largely prologue.

Since solid-fuel rockets can remain in storage for long periods, and then reliably launch on short notice, they have been frequently used in military applications such as missiles. The lower performance of solid propellants (as compared to liquids) does not favor their use as primary propulsion in modern medium-to-large launch vehicles customarily used to orbit commercial satellites and launch major space probes. Solids are, however, frequently used as strap-on boosters to increase payload capacity or as spin-stabilized add-on upper stages when higher-than-normal velocities are required. Solid rockets are used as light launch vehicles for low Earth orbit (LEO) payloads under 2 tons or escape payloads up to 1100 pounds.

The primary objective of this project is to understand the rocket dynamics through model rocketry. The project includes construction of model rockets, testing for thrust and launch. This enables us in understanding the clear picture behind design, construction and launch of a rocket. The secondary objective of the project is to modify the propellant and motor design for optimization of rocket performance.

In this project documentation we have initially put the definition and objective of the project as well as the design of the project which is followed by the implementation and testing phases. Finally the results and procedures are documented in this report and the results generated by this study would of value to others interested in field of amateur rocketry.

II. WHAT ARE SUGAR PROPELLANTS?

Sugar propellants (SP) or rocket candy is a type of rocket propellant for model rockets made with sugar as a fuel, and containing an oxidizer. The propellant can be divided into three groups of components: the fuel, the oxidizer, and the additive(s). The fuel is a sugar; sucrose is the most commonly used. The most common oxidizer is potassium nitrate (KNO3). Additives can be many different substances, and either act as catalysts or enhance the aesthetics of the liftoff or flight. A traditional sugar propellant formulation is typically prepared in a 65:35 oxidizer to fuel ratio.

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). Sugar propellants truly are the quintessential amateur propellant. They are inexpensive to make from locally available ingredients, don't require extensive machinery or tools and have remarkably good performance. Compare the performance of sugar at an Isp of 120to 130, to many commercial APCP motors running Isp's of 150 to 180 seconds. Look at the better density of sugar vs. APCP, and the high volumetric loading possible with the new erythritol based propellants and the performance gap narrows.

III. BASIC CONCEPTS

A simple solid rocket motor consists of a casing, nozzle, grain (propellant charge), and igniter. The grain behaves like a solid mass, burning in a predictable fashion and producing exhaust gases. The nozzle dimensions are calculated to maintain a design chamber pressure, while producing thrust from the exhaust gases.

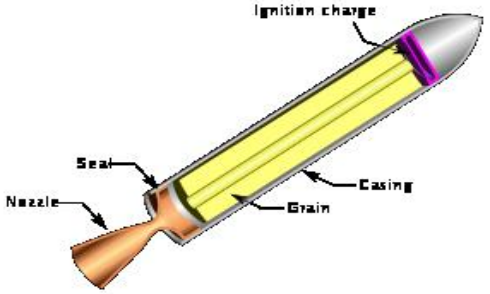


Fig 1- basic structure of a rocket

Once ignited, a simple solid rocket motor cannot be shut off, because it contains all the ingredients necessary for combustion within the chamber in which they are burned. More advanced solid rocket motors can not only be throttled but also be extinguished and then re-ignited by controlling the nozzle geometry or through the use of vent ports. Also, pulsed rocket motors that burn in segments and that can be ignited upon command are available.

Modern designs may also include a steerable nozzle for guidance, avionics, recovery hardware (parachutes), self-destruct mechanisms, APUs, controllable tactical motors, controllable divert and attitude control motors, and thermal management materials.

IV. HOW A SOLID PROPELLANT FUNCTIONS

A solid propellant is a monopropellant fuel, a single mixture of several chemicals i.e. the oxidizing agent and the reducing agent or fuel. This fuel is in its solid state and has a preformed or molded shape. The propellant grain, this interior shape of the core is an important factor in determining a rocket's performance. The variables determining grain-relative performance are core surface area and specific impulse.

Surface area is the amount of propellant exposed to interior combustion flames, existing in a direct relationship with thrust. An increase in surface area will increase thrust but will reduce burn-time since the propellant is being consumed at an accelerated rate. The optimal thrust is typically a constant one, which can be achieved by maintaining a constant surface area throughout the burn.

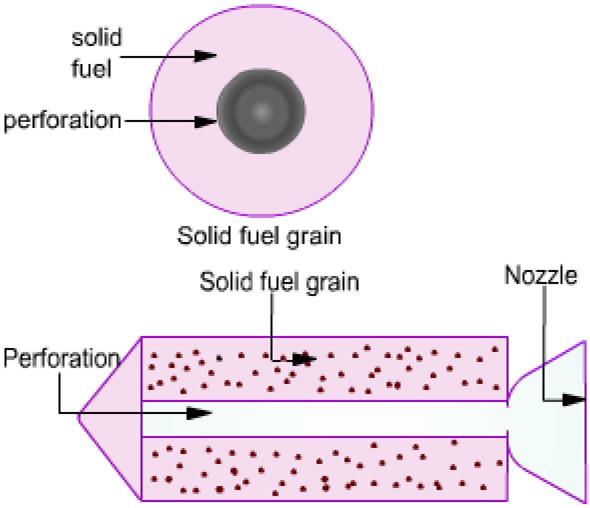


Fig 2- simple rocket engine

Examples of constant surface area grain designs include: end burning, internal-core and outer-core burning, and internal star core burning.

V. SAFETY RECORD OF EXPERIMENTERS TO DATE

The vast majority of motor builders across the world 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”.

VI. PROPELLANT CHEMISTRY

A typical sugar propellant formulation is typically prepared in a 65:35 oxidizer to fuel ratio. However, this formulation is slightly fuel rich. This ratio allows for the formulation to be more fluid in its melted state. Additives could take up between zero and ten percent of the total fuel. There are many different possible formulations that will allow for flight in model rocketry.

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 ^{o}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.

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

$$\mathbf{48\ KNO3 + 5\ C12H22O11 \rightarrow 24\ K2CO3 + 24\ N2 + 55\ H2O + 36\ CO2}$$

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

sucrose	Solid	C12H22O11
potassium nitrate	Solid	KNO3
carbon dioxide	Gas	CO2
carbon monoxide	Gas	CO
steam	Gas	H2O
Hydrogen	Gas	H2
nitrogen	Gas	N2
potassium carbonate	Liquid	K2CO3
potassium hydroxide	Liquid	KOH

Table 1- composition of exhaust

VII. PREPARATION OF PROPELLANT GRAINS

Both oxidizer and fuel can be purchased from local grocery store 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.

There are a number of different methods for preparing a sugar-based rocket propellant. Other than dry compressed, all of these methods involve heating the propellant. These various methods include: dry compressed, dry heated, and dissolved and heated.

In dry compression, the sugar and potassium nitrate are ground as finely as possible, and then mixed in a ball mill or tumbler to ensure uniform mixing of the components. This mixture is then compressed into the motor tube, similar to a method for loading black powder. However, this method is rarely used for serious experiments, and careful considerations should be made before deciding to employ this method.

Another, more common method of preparing a sugar-based rocket propellant is dry heating. First, the potassium nitrate is ground or milled to a fine powder, and then thoroughly mixed with powdered sugar. This method does not actually melt the potassium nitrate, as the melting temperature of KNO3 is 613 degrees Fahrenheit, but it melts the sugar and coats the grains of KNO3 with the melted sugar.

VIII. PERFORMANCE

Sugar based rocket propellants have an average Isp(specific impulse) of between 115 and 130 seconds. Compare that to the average Isp of an APCP (Ammonium perchlorate composite propellant), which is 150 to 180 seconds. Sorbitol and KNO3 based propellants with a typical 65:35 ratio are capable of a max thrust of up to 110 N, an Isp of between 110 and 125 seconds, and may have an average thrust of about 40 N.[3] However, sorbitol and KNO3 rockets with additives have been recorded as having average thrusts of up to 100N, total impulses of up to 735 Ns, and specific impulses of up to 128 seconds.

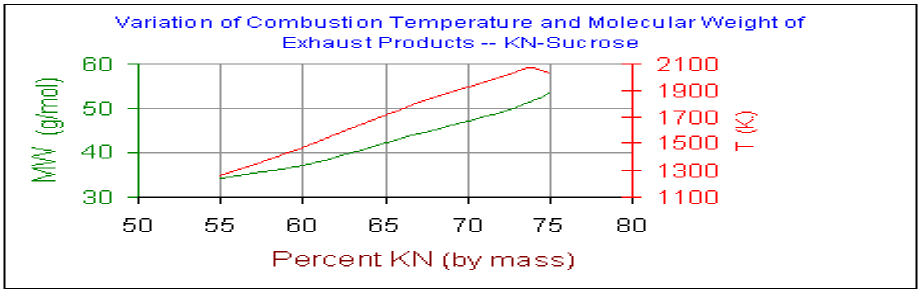


Figure 3- This chart shows the variation of combustion temperature and molecular weight of exhaust products with O/F ratio.

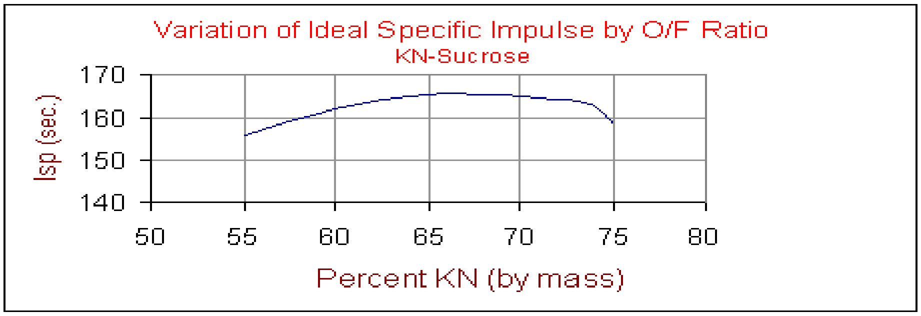


Figure4- This chart shows the variation of theoretical specific impulse with O/F (oxidizer/fuel) ratio.

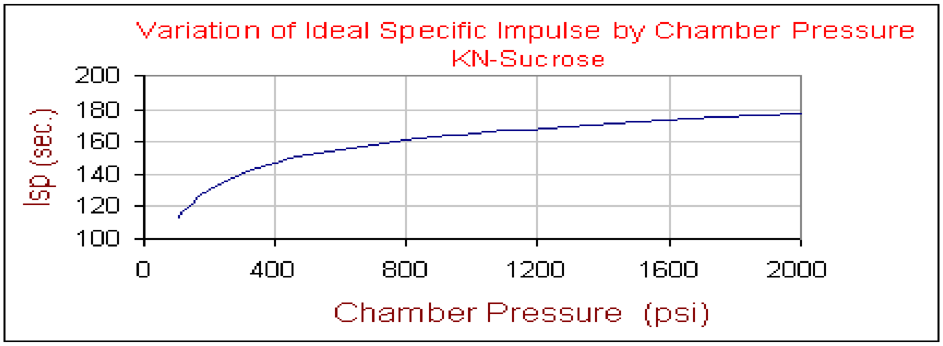


Figure5- This chart shows the variation of theoretical specific impulse with chamber pressure.

IX. APPLICATIONS

Rocket candy is also occasionally known as "caramel candy", a term that was popularized by Bertrand R. Brinley, in his pioneering book on amateur rocketry, Rocket Manual for Amateurs, published in 1960. This propellant was used in some of the amateur rockets described by Homer Hickam is his best-selling memoir Rocket Boys.

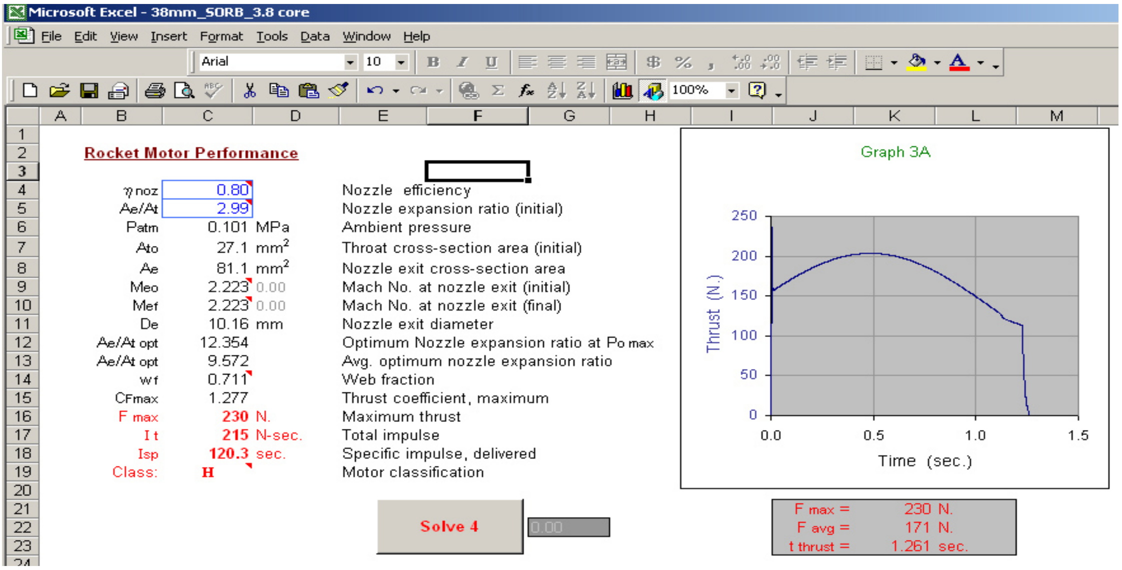
Rocket candy was also employed in a small amateur rocket described by Lt. Col. Charles M. Parkin in a lengthy Electronics Illustrated article that continued over several issues, beginning in July 1958. Parkin described how to prepare the propellant mixture by using an electric frying pan as a heat source for the melting operation. This article was reprinted in Parkin's book, The Rocket Handbook for Amateurs, which was published in 1959. Parkin's article contributed to the increasing popularity of the rocket candy propellant among amateur rocket groups beginning in the late 1950s and early 1960s.

Today there is a program called the Sugar Shot to Space Program. The "underlying goal of the Sugar Shot to Space program is to loft a rocket powered by a 'sugar propellant' into space." The goal is for a rocket with a sugar-based motor to make it into space, or 100 km (62.137 mi) high. The Double Sugar Shot rocket has reached 33 km, or one third of the goal altitude. The Mini Sugar Shot rocket, a prototype of the Extreme Sugar Shot rocket, reached an altitude of 12 km before a catastrophic motor malfunction occurred. The Extreme Sugar Shot rocket, the rocket expected to meet the goal of entering space, has not yet been completed and is a work in progress.

X. TESTING AND VALIDATION

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.



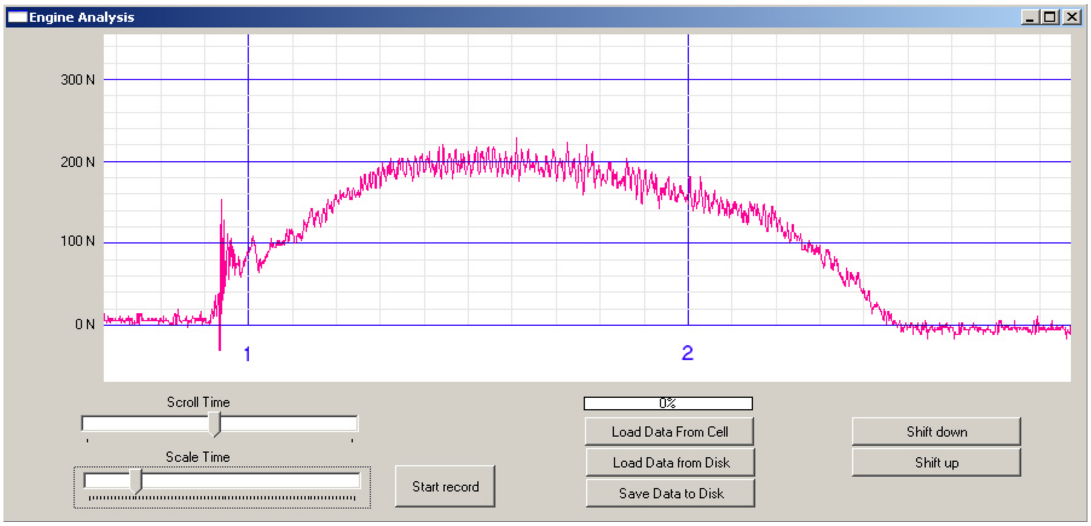
Rocket Motor Performance

η noz	0.80		Nozzle efficiency
Ae/At	2.99		Nozzle expansion ratio (initial)
Patm	0.101	MPa	Ambient pressure
Ato	27.1	mm^2	Throat cross-section area (initial)
Ae	81.1	mm^2	Nozzle exit cross-section area
Meo	2.223	0.00	Mach No. at nozzle exit (initial)
Mef	2.223	0.00	Mach No. at nozzle exit (final)
De	10.16	mm	Nozzle exit diameter
Ae/At opt	12.354		Optimum Nozzle expansion ratio at Po max
Ae/At opt	9.572		Avg. optimum nozzle expansion ratio
wf	0.711		Web fraction
CFmax	1.277		Thrust coefficient, maximum
F max	230	N.	Maximum thrust
I t	215	N-sec.	Total impulse
Isp	120.3	sec.	Specific impulse, delivered
Class:	H		Motor classification

F max = 230 N.
F avg = 171 N.
t thrust = 1.261 sec.

Screen 1 : 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.



Screen 2 : 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 above figure

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.

XI. DEMONSTRATION FLIGHT OF A SP POWERED ROCKET

The rocket motor detailed in this document is 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.

The rocket achieved a considerably good height in its flight and we are hopeful of increasing its range to more .The photos of the rocket prior to launch is updated in the document, after the successful attempt

Here is the finished Rocket I made-

Fig 6- Final pictures of completed Rocket.

XII. 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 archives at:

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

XII. RESULTS, DISCUSSION, AND CONCLUSIONS

We think the information contained in this document 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.

Problems that must be addressed in the future include finding a way to manufacture the engines such that they reach maximum chamber pressure (and thus exhaust) more quickly. Also, making PVC deformation a minimum is a priority, though this may be achieved as a side effect of making the overall burn time shorter. This is because the amount of deformation depends on the temperature of the casing, which only increases after the engine has been heated for quite some time. If the entire burn time is less than the time it takes for the engine to deform, then there will be minimal deformation. Deformation occurs as combination of pressure being exerted on the casing as a byproduct of the internal combustion reaction and the soft qualities that PVC exhibits as it is heated.

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