Sugar Motors

I've been struggling for some time to come up with a basic, easy to understand way to present sugar motor design/building for the beginning amateur rocketeer. This is my attempt, call it Scott's Sugar Motor's 101 if you will. I will deal with the two forms of sugar I usually use, regular sucrose and erythritol.

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 120 to 130, to many commercial APCP motors running Isp's of 150 to 180 seconds. Look too 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. Once considered a childish and finicky propellant, sugar propellants are now scorned only by those that have not used them, or seen the amazing performance they are capable of!

First, you should read my page on Sugar Propellant Casting Tips and Safety. Then read this document, then revisit the safety page again!

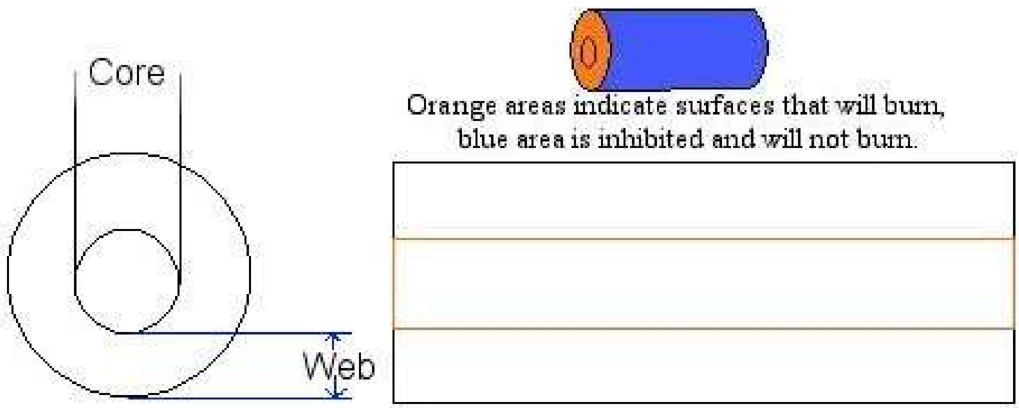
The first thing I do, is take a look at the rocket I intend to fly. What are the requirements of the flight? A heavy rocket will require a lot of thrust off the pad to get the rocket into stable flight, so a fast burning propellant, or a very long motor may be in order. A lighter rocket can get by with a slower burning, lower thrust motor. A very basic rule applies here, the motor should produce at least 5 to 6 times the rockets liftoff weight in initial thrust to get the rocket into stable flight by the time it clears the launch rod.

A couple of things before we get started. Isp, or specific impulse; in simple terms is the measure of a propellants efficiency. A propellant that has an Isp of 120 (often referred to as 120 *seconds*) will deliver 120 pound seconds of impulse per pound of propellant. 120 pounds seconds is 120 pounds of force for 1 second, or 60 pounds of force for 2 seconds, or 20 pounds of force for 6 seconds, and so on. So it's fairly easy to estimate a motors total impulse if you have a good idea of the Isp of the propellant you plan to use. Most sugar propellants, depending on how you prepare them and the pressure you burn them at, will deliver an Isp between 115 and 130. In most cases running a motor at lower pressure creates the biggest drop in performance of a propellant, it also slows the burn rate.

Now let's design a sugar motor for a hypothetical rocket. Let's do a mid-size rocket, say 3.5" diameter, perhaps 6' long and it weighs 7 pounds without a motor or propellant. Let's also plan on keeping the motor a reasonable size, remember, start small and work into bigger projects as you gain skill and experience. With a smaller motor, it is probably best to use a faster burning propellant, so we'll use sucrose rather than slower burning erythritol as our fuel. KNO3, or potassium nitrate will be our oxidizer. KNO3 is commonly abbreviated as KN, sucrose as SU, thus the propellant is called KNSU.

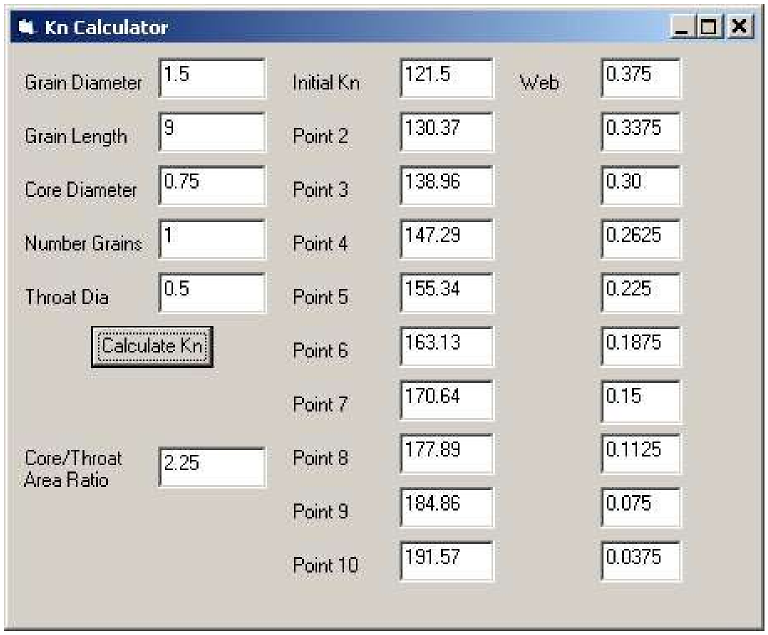
Now comes the fun part, it's time to start playing with some numbers. I wrote two software programs that I use every time I start playing with motor ideas. They are Kn calculator and Density 2. You can download both from my software page. First you need to understand what Kn is, it's not the same as the KNO3 abbreviation KN! Kn refers to

the ratio of the propellant burning surface area to the nozzle throat area. The propellant grains we are going to make are called Bates grains, a Bates grain is cylindrical, with a hole (core) running through the center of the cylinder.

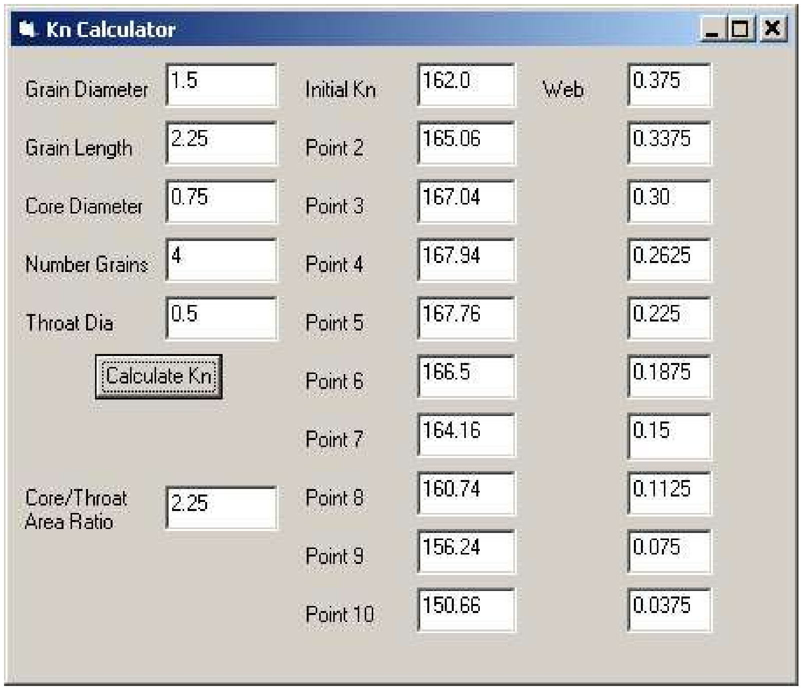


Here is a typical Bates Grain

The outside surface of a Bates Grain is inhibited so it won't burn, leaving the two end surfaces and the core free to burn. To be true Bates Grains, you will use multiple segments, or grains in a motor. The number of grain segments varies with the motor design, from 2 grains on up. I've used as many as 10 grains in a motor. The whole idea behind using Bates Grains is to keep the burning surface area of the propellant fairly constant. Consider this, if you put one long grain in a motor, what would happen? The propellant would burn from the inside (core) out towards the inhibited outside, and from the ends in (making the grain shorter). But of course the burning from the core would reach the outside before the ends met in the middle. So the burning surface area would increase dramatically as the propellant burned. You can do the math to calculate the burning surface area, but it's a lot easier to use my Kn calculator.



Here's a screen capture of Kn calculator using a single grain in an example motor. Notice how the Kn starts at 121.5 and keeps climbing. What this would do in a motor is start out with low chamber pressure and low thrust, then keep building pressure and thrust until the motor finally burns out. With a single grain like this, it's likely the motor wouldn't develop enough thrust at ignition to get a rocket into stable flight. It's also possible the motor would build up too much pressure at the end of the burn and cato (rupture casing or blow out a nozzle or bulkhead).



Here's another capture showing the same amount of propellant only cutting it into four grains. Notice now the Kn starts out mid range, peaks about in the middle of the burn and then drops off towards the end of the burn. This would be a good Kn profile to use in our motor, good thrust at ignition, then thrust tails off slightly at the end of the burn.

You can tailor a Kn profile by varying segment lengths, core diameter, grain diameter and the nozzle throat diameter. You need to play with the Kn calculator a while to get the feel of what happens when you change any given parameter. In general, more shorter grain segments will give you a higher Kn at the start of the burn, and lower Kn at the end of the burn. It's usually best to try for a reasonably neutral Kn profile. It's really important to understand how the Kn affects a motor burn. I've seen quite a few people make a motor with one long grain thinking that will keep the chamber pressure low in a motor, when exactly the opposite occurs.

{Note on using Kn Calculator: Your grain segments don't all need to be the same length. As long as each grain is at least twice as long as the web thickness, you can just add up all the grain lengths, then divide by the number of segments. Think about it, two 3" long grains would give you the same burning surface area as one 2" grain and one 4" grain.}

Notice in the lower left corner of the Kn calculator there is a box Core/Throat Area Ratio. That number tells you how large the surface area of the core is in relation to the area of the nozzle throat. Keep in mind as the propellant burns it has to flow through the core to get out the nozzle. A very small core could lead to grains cracking, or at the least erosive burning. (Erosive burning is where the fast moving gases burn off propellant faster near the nozzle.) As a general rule, I like to keep the core area at 2 times the throat area. Although I do at times run it as low as 1.5.

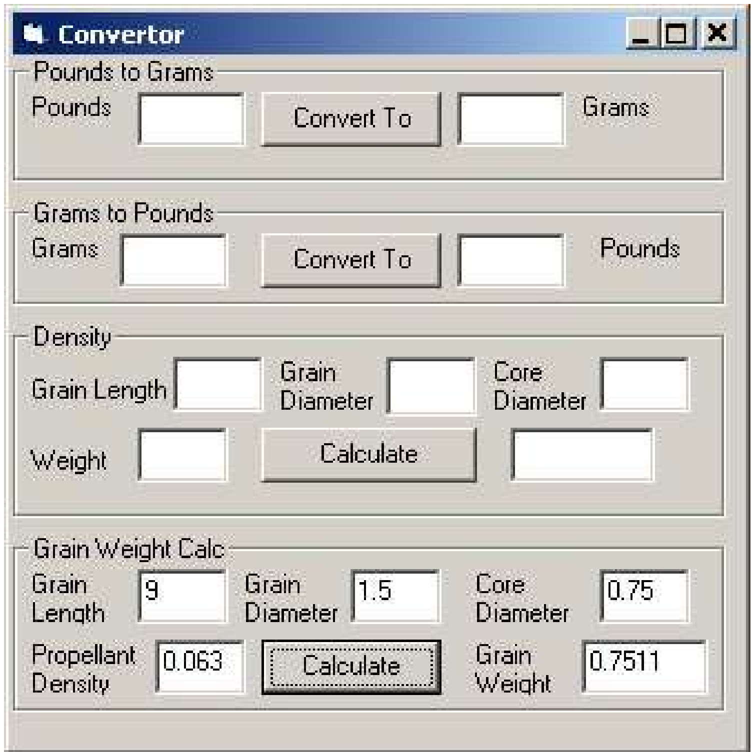
One other thing to look at is the far right column in Kn calculator. It shows the web thickness, of which the first number is going to give us an idea of the burn time of our motor... But a caveat here. Burns rates can really vary from one person to the next. Differences in humidity, chemical sources, preparation and casting techniques from one person to the next can have a large effect on burn rates and performance. I'm going to give you some starting numbers that work for me, but you'll have to do some experimenting to find your own values. I always start out conservative on new designs, then, after testing I ramp up the Kn and/or propellant load to its maximum potential.

We're going to use the second screen capture (the four segment motor) for our motor in our hypothetical rocket. To come up with those numbers, basically I used trial and error. I put numbers in Density 2 to get an approximate grain size and total propellant weight, then played with those numbers in Kn Calculator until the Kn and total propellant weight were where I wanted them. After designing a few motors, it becomes a bit intuitive as well. KNSU will burn in a predictable manner in a Kn range from under 100 to over 200. But Kn's above 200 can be tricky, any mistakes at high Kn's can result in a motor cato. A Kn below 100 will result in a severe loss of performance. I'd recommend for a typical motor with a calculated burst pressure of 2,000 psi and above, to use a Kn in the 140 to 170 range.

One of the problems of KNSU is that it is very hygroscopic (absorbs water from the air). Depending on the humidity on a given day, and the duration of exposure to humidity, the burn rate will vary a fair amount. A Kn of 170 will typically result in a chamber pressure of between 500 and 750 psi., and a Kn of 230 will be between 700 and 1,200 psi.

I had two bad experiences with soggy KNSU propellant. At one early launch attempt I had about 6 spectators (the most ever at the time) to watch my magnificent creation soar to the heavens. Well, I lit the motor, it chuffed a couple of times, then went into a stable, but really slow burn. The rocket eased up the launch rod a couple of feet, then slowly sank back down on the rod, where it continued to burn for another 10 seconds or so. In the process it melted the lower portion of the plastic body tube. Needless to say that experience was very humbling. One other occasion, I launched a similar rocket with damp propellant. While this rocket made it off the pad, the propellant burned so slowly the rocket flew a nice low arc, imagine throwing a football... No big crowds this time, but reinforced my resolve to keep the propellant dry. Moral of the stories; KNSU burn rate is highly dependent on its moisture level, and I don't have a really good way to help you determine the moisture content. Just do your best to keep the propellant dry in the first place. More on that later...

We'll use an expected Isp of 120, and a burn rate of .5"/ second. Now it's time to go to the second program I mentioned before, Density 2.



This a capture from Density 2, using the data from the grains we will use. I'm using a propellant density of .063 pounds per cubic inch, that's real ballpark of the density you can expect from KNSU propellant. Notice I added the length of all the grain segments together. You could calculate one grain, then multiply by four but it's easier just to add them up first.

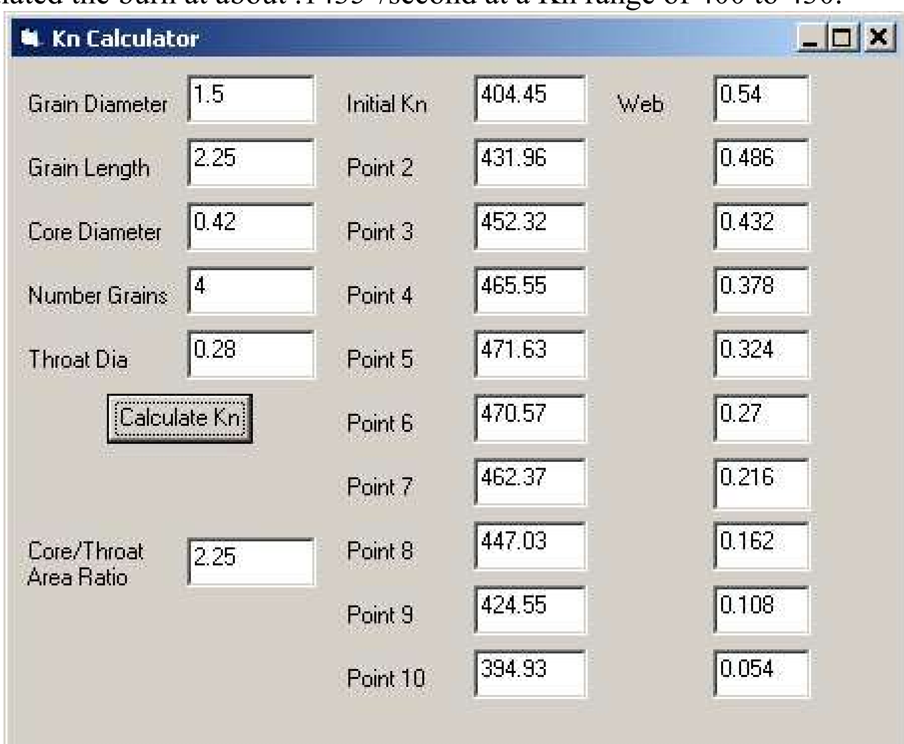
As you can see, our estimated grain weight is .7511 pounds. Now it's very easy to calculate the total impulse of our motor. Using our expected Isp of 120, simply multiply Isp * propellant weight. 120 * .7511= 90.132 pounds seconds total impulse. 90 pounds seconds of total impulse puts our motor into the "I" class designation. See my page with a table on motor class designations. These motor class designations were devised for sport rocketry, and are just an easy way to indicate the general total impulse of a motor. Each progressive letter class designation has twice the impulse as the prior.

To estimate the burn time of the motor, divide the web thickness by the burn rate. . 375" / .5"/sec. = .75 seconds burn time. In reality, the motor usually burns longer than this, there is some time for all surfaces to ignite, then there is some tail off time as well. But this calculated time is generally close to correct for the meaningful duration of the propellant burn.

One more thing we should calculate is the average impulse. That will tell us the approximate thrust the motor will give us at any given point during the burn if you have a fairly neutral Kn. To calculate average thrust, divide total impulse by burn time. In our case, 90.132 / .75 = 120.176 pounds of thrust. So with a neutral Kn, we should have about 120 pounds of thrust at any given moment during the motor burn. We can use this number to see if we have enough thrust with this motor to get our rocket into stable flight off the launch rod. Remember we want at least 6 times the weight of our rocket in thrust to get it stable, and our rocket was 7 pounds. Now we can add about 2 more pounds to the rocket weight for the motor and propellant for a lift off weight of 9 pounds. So our thrust to weight ratio is calculated by dividing the average thrust by the rocket weight. Or, 120 / 9 = 13.3. So we have about 13.3 pounds of thrust for each pound of rocket weight, that's well above the 6 we needed. So our motor should be able to provide plenty of thrust off the pad.

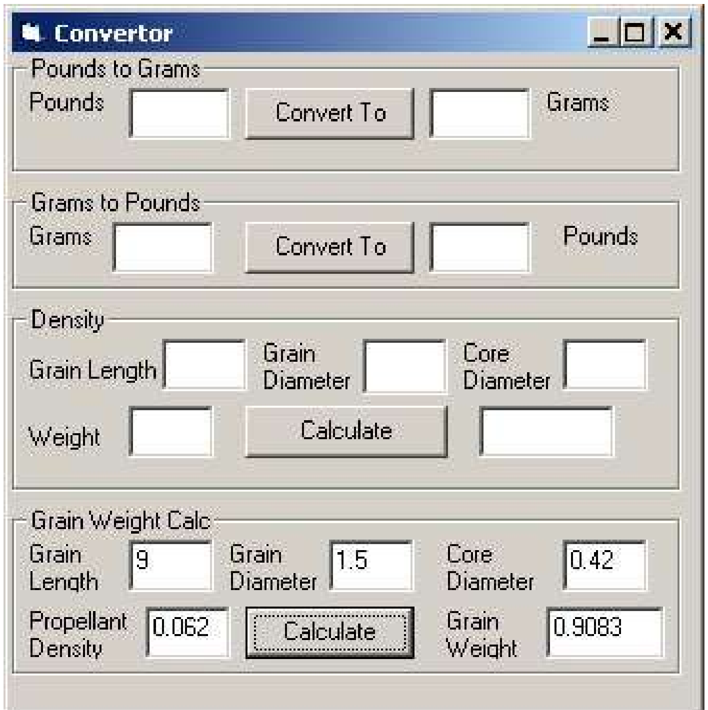
Erythritol Based Propellant:

Let's take a look at using the above scenario, only using erythritol instead of sucrose in our propellant. We will use the same percentage, 65% oxidizer and 35% fuel, this propellant is refereed to as KNER (KNO3 and Erythritol). The main difference when using ER as the fuel in sugar propellant is that it burns much slower, so the Kn must be increased dramatically. I've found the best Kn range is from about 400 to 450. Kn's much below 400 and the motor will hardly sustain steady combustion, and the Isp drops frighteningly low. Kn's above 500 increase the burn rate with only a slight increase in Isp. I've calculated the burn at about .1435"/second at a Kn range of 400 to 430.



Here is a screen capture from Kn Calculator showing the same motor now using KNER propellant.

The big thing to notice here is that our nozzle throat has been made muh smaller to increase the Kn. As a result of the smaller throat diameter, the core can also be smaller. To find out if that helps us, let's run Density 2 again with these numbers.



Two things of note on this capture, it shows a grain weight of .9083 pounds, using a slightly lower propellant density of .062 pounds per cubic inch.

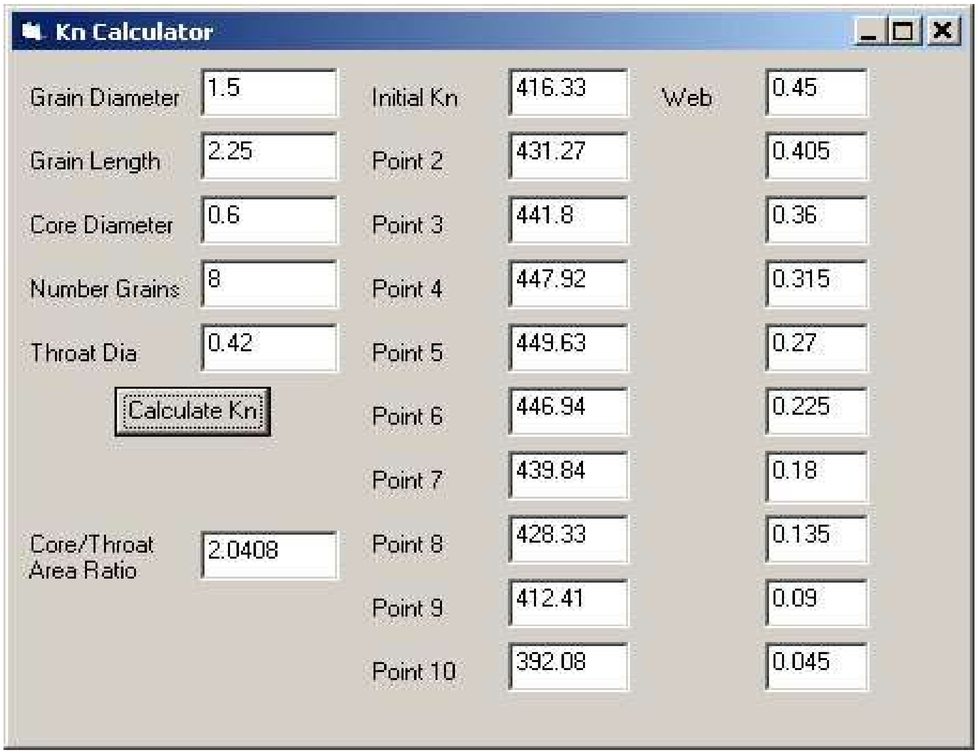
Our original sucrose propellant in the same motor held .7511 pounds of propellant, because of the smaller core, the same motor now holds .9083 pounds of propellant. That's an increase in propellant mass of over 17%! That's the reason KNER propellant has better volumetric loading, more propellant in the same motor casing.

Now let's see how these numbers work in our test motor. Looking at Kn Calculator again, we see the web thickness is .54" on these grains; burn time is .54" / .1435"/sec = 3.763 seconds. Our expected total impulse of the motor is; .9083 pounds propellant * 120 Isp = 108.996 pound seconds. Average Impulse would be: 108.996 / 3.763 seconds = 28.965 pounds of average thrust.

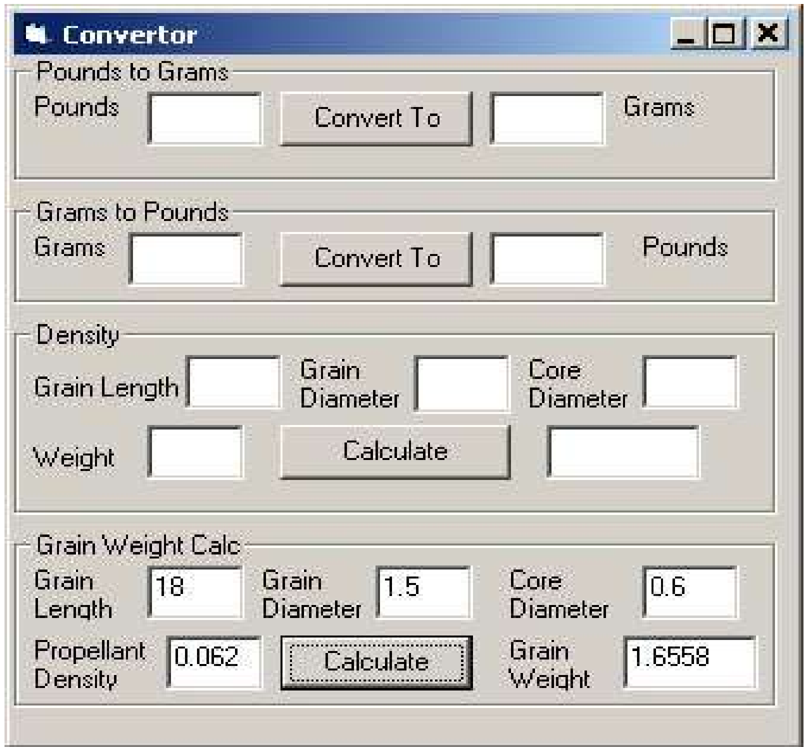
Now we run into a problem, remember we needed at least 6 times the rocket weight in thrust to get it stable off the launch rod. In this case our average thrust of 28.965 pounds / 9 pounds rocket weight = 3.218, or 3.218 pounds of thrust per pound of rocket weight. Back on the first page of this document, I mentioned a heavy rocket would require a fast burning propellant or a longer motor using a slower burning propellant. Now you see what I meant.

KNER propellant for this reason is better suited to larger motors. You need a long motor to get enough propellant burning to give adequate thrust. Of course, we could use the motor we just designed in a smaller rocket, or redesign the motor to make it longer.

Below is an example of a longer motor.



Here is a new scenario where I doubled the number of grains in our motor.



The corresponding increase in propellant weight.

Now let's calculate the performance changes. Total Impulse will be: 1.6558 pounds propellant * 120 Isp = 198.696 pound seconds total impulse. Burn time will be: .45" web / .1435"/sec. = 3.136 seconds. Average Thrust is: 198.696 total impulse / 3.136 sec. = 63.358 pounds average thrust. Since our motor is heavier, the rocket lift off weight will increase to about 11 pounds. To see if we have enough average thrust: 63.358 average thrust / 11 pounds rocket weight = 5.76 pounds of thrust per pound of rocket weight. Now we're in the 5 to 6 ratio we need, although we're still borderline. One other thing we could do is to use a longer launch rod, giving the rocket a chance to get moving faster while it's still guided by the rod. You should also avoid launching rockets with marginal thrust to weight ratios on windy days.

Of course, by increasing the propellant we also increase how high the rocket will fly. We have gone from an "I" class rocket to a "J" class rocket. Just to give you an idea, our KNSU powered rocket would fly to about 1,475'. Our KNER powered rocket with the larger propellant load would fly to about 3,183'.

The real advantage of KNER propellant is in larger motors, but it doesn't end there.

The propellant is virtually non-hygroscopic, in that it won't absorb water from the air. I've left test strands of propellant out in summer humidities for days with no adverse effects. I even taken to storing grains in a simple locked cabinet, with no provisions for keeping them dry at all.

Another advantage is that the propellant seems to deliver a good Isp at fairly low chamber pressures. This makes motor construction less problematic, reducing the likelihood of a cato. In the Kn ranges of 400 to 470 the propellant is well behaved, delivering nice, predictable thrust curves. Unlike sorbitol and xylitol which have odd burn rate behaviors at normal operating pressures.

The low melting point (250 F.), it's fast to set up, (being fully cured when cool, again, unlike sorbitol and xylitol that may take days to fully set up) and its very pourable (low viscosity) nature make casting grains a breeze are all added benefits to KNER propellant.