Richard Nakka's *Experimental Rocketry* Web Site

Potassium Nitrate/Sucrose Propellant (KNSU)

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Introduction

This web page describes the "classic" sugar-based rocket propellant comprised of a fused mixture of Potassium Nitrate serving as the oxidizer, and Sucrose (table sugar) serving as the fuel and binder. This propellant is usually refered to by the acronym **KNSU**. I first became familiar with the Potassium Nitrate/Sugar propellant way back in the early 1970's from Captain B.R.Brinley's book *Rocket Manual for Amateurs*. In his book, Brinley briefly describes this propellant, focusing mainly on its drawbacks. To his credit, however, he did state that "it might be worth your while to undertake a development project on this particular propellant...". And so this is exactly what I proceeded to do, and spent many years experimenting with this propellant.

I conducted numerous static motor tests in order to determine the optimum oxidizer/fuel (O/F) ratio, measured burning rate at various temperatures, pressures and O/F ratios, tried various grain configurations, performed combustion product analysis (using the now-antiquated *Orsat* apparatus, as well as apparatus of my own design), measured the propellant "impetus" by use of "closed vessel" combustion. I performed further investigation on this propellant during my final year at university in 1984, in particular, the theoretical performance, and wrote my graduation thesis *Solid Propellant Rocket Motor Design and Testing* based on both my theoretical and experimental work.

And of course, I launched many rockets powered by this propellant, over 57 flights in total, between the years 1972 and 1984. So I got to know this classic propellant quite well indeed! Modern sugar propellants using low melting-point sugars such as dextrose and sorbitol have made KNSU largely obsolete. Nevertheless, it is worthwhile to discuss this notable propellant that served the author and many other experimenters very well. Advent of the potassium nitrate/sucrose propellant led to a much safer era of amateur rocketry compared to the earlier use of hazardous propellant materials that were tried by enthusiastic, but ill-informed, rocketeers at the dawn of the space age.

The makeup of KNSU, and its behaviour in a rocket motor is, in essence, the *same as professional rocket propellants*. Of course, it has certain shortcomings such as much lower performance. However the way the propellant is prepared (cast), the form of its grain (cylindrical), its burning behaviour in a rocket motor (recedes normal to exposed surface and follows St.Robert's burning law), its internal ballistics behaviour (follows steady, one-dimensional compressible fluid flow behaviour of an ideal gas) and its well-known thermochemical properties allow for *rational rocket motor design* that can deliver predictable results. In other words, KNSU (and the other sugar propellants) provide for a bonafide introduction to rocket engineering.

Figure 1 -- KNSU propellant grain for the B-200 motor

Formulation

The standard ratio of constituents for KNSU is 65% Potassium Nitrate and 35% Sucrose, by mass. This ratio has proven to give the best overall performance combined with acceptable casting qualities. Theoretically, the highest specific impulse is delivered at a 66/34 ratio, although the standard 65/35 ratio tends to be used by most experimentalists. There are three reasons for this:

1. The propellant characterization data has been obtained mainly for the 65/35 ratio
2. The performance difference is slight (about 1%).
3. The combustion temperature rises sharply with increased O/F ratio. At the 65/35 ratio, steel nozzles suffer little or no erosion, as there is an adequate margin between the theoretical flame temperature (1450C) and the melting point of steel (approx. 1500C). At higher O/F ratios, this margin is reduced such that a small error in weighing during preparation could result in a heat damaged nozzle.

Viscosity of the melted slurry is strongly dependant upon the O/F ratio. The standard O/F ratio of 65/35 is not pourable, and must be scooped into the casting mould. If a 60/40 O/F ratio is used, the viscosity has been found to be sufficiently less that pouring (with some scooping) can be done. For making small diameter grains (e.g less than 2cm diameter), the 60/40 ratio is best used, with some loss of performance to be expected.

The Sucrose that I used was the very fine powdered form, commonly referred to as icing (or confectioners) sugar, rather than the common granular (table) sugar. Granular sugar is also useable, it simply needs to be ground to a fine powder first.

Potassium nitrate, also known as saltpetre, is a commonly used chemical (used, for example, for pickling meats, and in toothpaste for "sensitive teeth"). I’ve purchased potassium nitrate in 2 kg. lots at a veterinary chemical supply store. Potassium nitrate is also sold as 14-0-45 fertilizer at farm supply stores, typically 98-99% pure. This is by far the most economical form, and the performance is *generally* no different that purer grades. Sadly, nowadays the sale of potassium nitrate has had restrictions placed on it, making is harder for prospective rocket engineers to carry on their calling.

Preparation and Mixing

The first step in preparation of the propellant is to grind, or mill, the potassium nitrate to a fine texture. This may easily be done with the use of an electric coffee grinder, such as that shown in Figure 2. Adding two tablespoons (30ml) to the hopper, the grinder is then run about 20-25 seconds. To facilitate milling, the grinder is slowly "gyrated" about its base. Milling as such will reduce the particle size to an average of 50-100 microns.

It should be noted that the viscosity of the melted propellant slurry is highly dependant upon the particle size of the potassium nitrate. When prepared as described above, the slurry will not be fluid enough to cast, and as such it is necessary to scoop the propellant into the casting mould. The slurry will be more fluid and easier to cast if the potassium nitrate is milled for a shorter time, such as 10 seconds. Or if the potassium nitrate is obtained as a fine granular form (similar to table salt), it can be used "as is". The drawback is slightly reduced performance due to less efficient combustion, combined with a slightly longer burn time compared to propellant made with fine-grind oxidizer.

Figure 2 -- This low-cost coffee grinder does a superb job of pulverizing potassium nitrate to a fine texture.

Following the milling process, the two constituents are carefully weighed out using an accurate scale. Enough of the powdered mixture of potassium nitrate and sucrose has to be prepared to take into account the inevitable waste resulting from the casting procedure, typically 20-25% additional for small batches, less for larger batches.

After individually weighing out the two constituents, the two are blended together in a single container. Complete mixing of the two is necessary for optimum and consistent performance. I built an electric tumbler for this purpose (Figure 2). The powdered mixture is loaded into a tupperware container, then secured to the rotating drum with rubber bands, then tumbled for one-half hour or longer, depending on the quantity being tumbled. My tumbler rotates at 30 RPM. I have since built a new tumbler that rotates at approximately 100 RPM.
Videoclip of tumbler in action

Once the mixing operation has been completed, the powdered mixture is transferred immediately to a closed container for safe storage. At this stage, the mixture is readily combustible amd sensible precautions are observed to keep it away from any possible ignition sources.

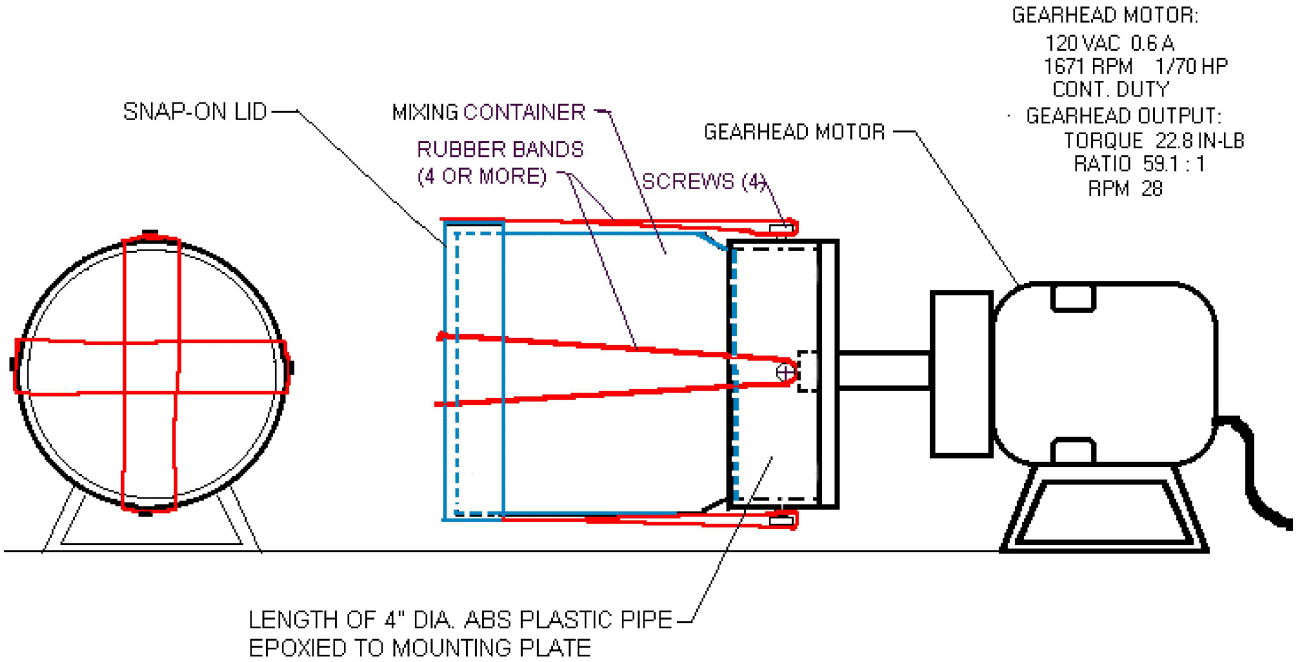


Figure 3 --Propellant powder tumbler

Casting

The casting process involves heating of the powdered mixture until it becomes molten, then casting into a mould to produce the propellant grain of the desired shape. The required temperature that the mixture must attain is just above the melting point of sucrose (186C or 367F). The potassium nitrate, which has a much higher melting

point, remains as solid particles that partly dissolve in the sucrose. The result is a *slurry* of solid oxidizer particles suspended in liquid sucrose medium. Sucrose tends to decompose (caramelize) at this temperature. Caramelization has been found to be a function of both temperature and time. Since caramelization is detrimental to the performance of KNSU, keeping the temperature as low as possible is important. As well, heating time should be minimized, although this has been found to be far less critical than temperature.

Heating the mixture is done using a **thermostatically controlled** electric "deep fryer", with the thermostat set to 380F/193C. (Figure 4). A thermostatically controlled skillet may also used for heating KNSU.

It is essential, from a long-term safety consideration, that **only a thermostatically controlled heating vessel with no exposed elements be used for heating propellant**, the critical intent being that no exposed heating surface is of significantly higher temperature than the melting point of the propellant.

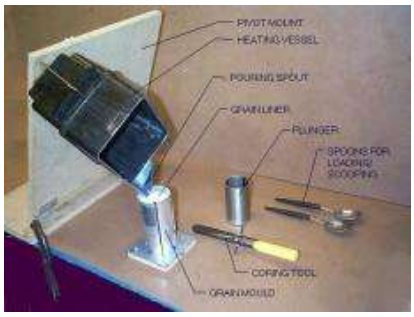


Figure 4 -- Casting setup for KNSU employing 'tilt-table' for the 'deep fryer" heating vessel.
(click for larger image)

To monitor the temperature of the heated slurry, a dial-type candy thermometer, a digital thermometer equipped with a probe sensor, or an infrared thermometer may be used. The casting procedure involves adding about half the powdered mix to the heating vessel, and stirring often to assist melting. Once this has melted, the remaining powdered mix is added, and heating is continued. Stirring often is important to prevent overheating, which leads to a greater degree of caramelization, and consequently reduced performance of the propellant. Caramelization is characterized by a darkening of the melt. The initial colour of the melted slurry is nearly colourless, but begins to turn tan colour as caramelization commences. Eventually, the colour will become that of peanut butter, as the whole mixture becomes fully molten, and is ready to be cast. A colour darker than this implies that the mixture has been heated too long or at too high a temperature.

Figure 5 -- A silicone spatula is ideal for mixing and scooping

The consistency of standard KNSU slurry will remain quite viscous and must be simultaneously **poured and scooped with a spatula** into the mould. Immediately after loading, the coring tool is inserted into the mould, making certain it is *fully inserted all the way down*. This completes the casting operation. The mixture is then allowed to cool and harden. The entire casting operation, from start of melting, to final pouring, usually took me about fifteen minutes for a B-200 grain.

I found that it was very important to remove the KNSU grain from the mould after an exact amount of time had elapsed. If allowed to cool too long, it would be difficult to remove the grain. If removed too soon, the grain may still be flexible and could become deformed. I found that 45 minutes was the required cooling period. Following coring tool removal, the grain is trimmed as needed, and (importantly) accurately weigh and measured. I would also typically record colour and amount and type of defects (such as any bubbles or voids), then place it inside a plastic bag with a dessicant packet. Better yet, vacuum seal the grain. At this point, the grain would be put inside a protective container and stored in a deep freeze until ready to be loaded into the motor. Two finished grains for the B-200 motor are shown in Figure 6.

Notes on casting KNSU

- The fully melted slurry is quite viscous, and further heating will result in only marginally reduced viscocity.
- The slurry should be poured & scooped simultaneously into the mould. A silicone spatula works well to direct the slurry into the mould.
- Once the mould has been loaded, I pick up the mould then firmly tap the bottom against a hard surface repeatedly. This is **an important step**, as it serves to force any trapped air to rise to the surface. Optionally, a **plunger** is used to press & compact the mixture and to squeeze out any trapped air. The plunger can be a steel or aluminum rod, of approximately 90% of the diameter of the mould. To prevent the propellant from sticking to the plunger, the plunger may be **pre-cooled in a freezer** for several hours. Compacting the propellant in this manner is very effective in eliminating air bubbles, and the resulting grains typically have a density of 95-97% theoretical.
- To allow for ease of removal of the coring tool, it is lightly coated with **silicon grease** (plumbers lubricant works very well). The most effective means to remove the coring tool after the propellant has solidified is to clamp the end of the coring tool in a work vise. The grain (mould) is then given a forceful rotational *twist*. The coring tool will then snap free and can be subsequently withdrawn with minimal effort.

The cast propellant is typically within the colour range of the two grains shown in Figure 6 below:

Figure 6 -- Two completed propellant grains: Top is 60/40 O/F ratio; Below is 75/25 O/F ratio. Note colour difference.

Alternative Casting Methods

There are alternative methods of casting KNSU propellant that other rocketry experimenters have developed. Two methods that I am aware of deserve particular attention. Both involve the inclusion of **water** and/or **corn syrup** to the basic propellant ingredients. One method involves dissolving the potassium nitrate and sucrose in water, then boiling until all the water has been eliminated. The suggested ratio of water to potassium nitrate/sucrose is 2 to 3. Interestingly, the thermostat of the heating vessel may be set to a lower temperature than with the slurry method, typically 130 to 150°C. (260 to 300° F.).

Although I have not used this technique to cast an actual propellant grain, I have conducted preliminary experimentation of both the standard 65/35 ratio, as well as the 60/40 ratio. For both, I have have produced small samples of propellant, including strands for burn rate measurement. It was found that the water boils away quite rapidly. An off-white slurry results, which must be heated further to drive out all residual water. This condition is indicated by a slight odour of caramelization. Further heating is done until the colour of the slurry is a light tan. The viscosity of the 65/35 rato is definitely thicker than that of the melted slurry method, and the propellant needs to be *packed* into the mould rather than poured or scooped. However, it was found that the viscosity of the 60/40 ratio is sufficiently lower such that it may be cast in a manner similar to regular KNSU. Curiously, when the propellant cools and hardens, it is completely dry, unlike propellant prepared by the slurry method, which tends to develop a sticky film immediately after casting due to humidity. Indeed, the hygroscopic nature of the propellant seems to be reduced...a sample strand that had been left in the open air for 6 months, at humidity levels ranging from 50 to 70%, remained bone dry.

There are interesting advantages to using water as a medium for the propellant constituents during the heating process. There is no need to premix or to grind up the constituents, as both fully dissolve in the water. Combustion appears to be more efficient -- samples burned left a reduced amount of residue. Importantly, the water solution would clearly add additional safety to the process, at least during the initial phase where the water content is great. The casting temperature may also be lower. As well, the fact that both potassium nitrate and sucrose are soluble in water should produce a more homogenious propellant, which differs from the "composite" mixture of the heated slurry technique. Burn rate measurements at ambient pressure indicate a burn rate slightly greater than the "composite" version (0.45 cm/s versus 0.40 cm/s, typical). The difference in burn rate at elevated pressure, if any, is not known.

Rocketeer Dan Pollino has developed a similar technique, with certain differences. Dan's formulation consists of 60% KN, 36% sucrose, and 4% corn syrup. To this, water is added to the tune of 10% of the constituents mass. The inclusion of the corn syrup apparently improves the fluidity of the melted mixture, which improves castability. I have not tried Dan's method but I know it is popular with some rocketry experimenters.

James Yawn (www.jamesyawn.net) has also developed a method of producing sucrose-based propellant using a *recrystallization* technique. With James's method, instead of casting in the style of KNSU, a putty-like consistency is produced, which can be *packed* into the mould. James's method is quite popular, however, I have never tried this technique.

TIP: Easy way to remove coring rod after casting NEW

Effects of Overheating

As the casting process of KNSU 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. To determine the effects of overheating during the casting process, an experiment was performed in which a sample of KNSU propellant was *overheated*. This involved placing a small sample (approx. 10 grams) of the propellant mixture into an aluminum pan, and heating the sample with a heat gun (1400 watt; 1100 deg.F max. rating). A type-K thermocouple was inserted into the propellant mixture to monitor temperature. The setup for this experiment is illustrated in Figure 7.

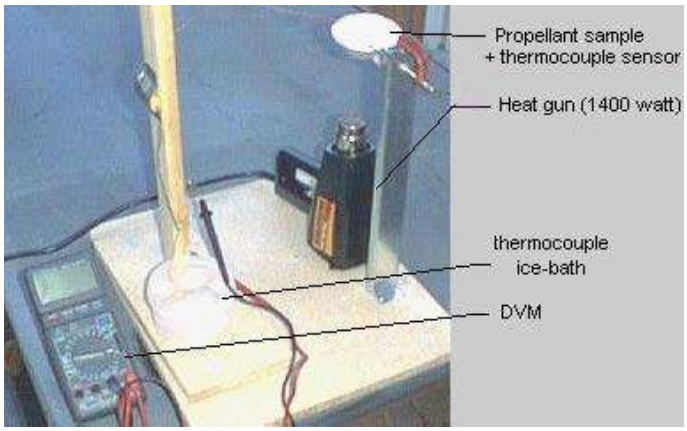


Figure 7 -- Setup for propellant "overheating" experiment

Melting of the mixture was rapid, owing to the high output of the heat gun, and brown coloured regions soon appeared within the melted mixture, as decomposition of the sucrose began. The sample soon fully caramelized, with the temperature recorded at 200 C. (395 F.). Interestingly, the temperature of the propellant reached a "plateau" at this point, and would not rise even after several minutes of further heating, At this point, the propellant was a highly decomposed, with the appearance being that of a charred mixture of brown and black fused together, with some smoke emanating. Since the temperature of the mixture was not increasing beyond this plateau, it was decided to "force" ignition of the mixture by placing the tip of the heat gun about 2-3 cm. away from the sample, directed down from above. This caused a black carbon "skin" to form on the propellant closest to the heat source. After about 10 seconds, ignition occurred, and propellant sample burned nearly instantly, due to its greatly elevated temperature.
It would seem that, once decomposition of the sucrose initiates, that the added thermal energy of heating goes solely into *decomposing the sucrose*, rather than raising the temperature of the propellant, a rather comforting trait. As such, it would seem improbable that accidental ignition during casting would occur due to overheating,

given the obvious indicators of overheating, such as severe caramelizing, black streaks, burnt sugar odour and eventually smoke emanation. Of course, inadvertent ignition due to other unforseen causes (e.g. electrical short, static electricity, etc.) must be considered as a possibility and appropriate safety protocol must be followed during the entire heating and casting operation.

Safety

Needless to say, safety is the number one priority when engaging in rocketry. Propellant preparation and handling is one of those aspects of rocketry that requires the upmost attention in order to conduct safe practise. Mixed oxidizer and fuel, in the powdered form, ignites readily. Proper handling and storage is necessary to keep ignition sources away. The most potentially hazardous part of propellant preparation is **heating and melting** the dry mix. When hot and molten, KNSU burns very rapidly, much faster than solid room temperature propellant. As well, the molten propellant ignites much more readily than cold propellant. Safety of heating and melting the propellant is therefore paramount. Wearing proper protective gear and using the proper heating vessel are the two cornerstones of doing one's upmost to keeping safe.

1. Leather (not rubberized fabric) gloves, leather jacket and safety eyewear are the minimum items to wear whenever heating KNSB. A leather apron is a good supplemental safety item, as is a faceshield. I wear a faceshield to prevent injury from any hot propellant that may *spatter* at some point during the casting or pouring operation (which happened once, not serious, but most unpleasant).

2. It is essential that only a **thermostatically temperature-controlled** heating vessel be used for heating and melting KNSU, such as an electric skillet or electric deep fryer. The reasoning being twofold. One, to provide an even temperature in the correct range to do the job in a safe manner. And two, the complete absence of any heating surface that is hot enough to ignite the propellant. Obviously, an open-flame heating system is forbidden, as is an exposed electric element forbidden. Figure 8 shows two hot-plate units that are forbidden.

Figure 8 -- Unsuitable and hazardous hot-plate units

This videoclip dramatically illustrates why a hot-plate type heating system is hazardous.

A suitable electric skillet is illustrated in Figure 9. Note the temperature control knob.

Figure 9 -- A thermostatically temperature-controlled skillet

The heating vessel (skillet or deep fryer) should be made of aluminum, not stainless steel. Aluminum conducts heat evenly. Stainless steel is a poor conductor of heat and undesirable hot spots may develop.

Finally, I always keep a large bucket of water (with a good handle) nearby as well as a fire extinguisher. Not that I have ever needed either, but these do contribute to peace of mind, as a minimum. Sort of like insurance.

In all the years of my rocketry propellant making, I never had an accident that resulted in injury. Mishaps, and the unexpected, certainly occurred, but because I always took sensible precautionary measures, and considered

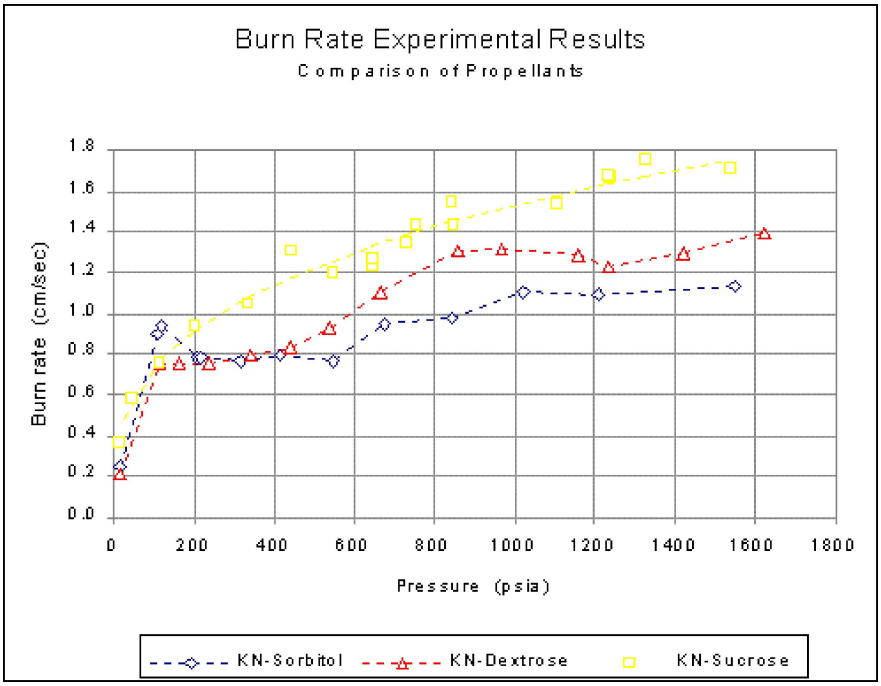
safety as the number one priority, no harm resulted.

Propellant Chemistry and Performance Characteristics

Details of the KNSU propellant chemistry, combustion equation, and performance characteristics are detailed here.

Propellant Burn Rate

The burn rate of a propellant is a key parameter used in rocket motor design. This is explained in detail on another web page (Details). Briefly, burn rate will vary dependant upon **pressure** and **temperature**. The effect of pressure is far more pronounced. As such, an experimental investigation was conducted to determine the effect of pressure upon the burn rate by utilizing a *Strand Burner* apparatus. Results are summarized in Figure 8 for KNSU as well as KNSB and KNDX for comparison. Unlike KNSB and KNDX propellants, KNSU follows "de St.Robert" burning law behaviour with a single *pressure exponent, n* and *coefficient, a*.



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Drawbacks of the KNSU propellant

There are a number of drawbacks to the KNSU propellant, the most significant of which are:

- *Casting at an elevated temperature*. Since hot propellant ignites and burns more readily than cold propellant, this requires that suitable precautions be taken during the casting process to prevent ignition, and measures must be taken to mitigate, should ignition happen (e.g. wearing of fire-proof gear).
- The propellant rapidly begins to harden as it cools, requiring that the pouring operation be conducted quickly. The melted mixture is also quite sticky (as one might expect!). Lubrication of the coring tool is necessary to prevent sticking.
- The sucrose in the mixture, once heated to melting temperature, begins to caramelize (decompose), which reduces the performance of the propellant. Therefore, the heating process must be conducted over the minimum possible time duration.
- *High elastic modulus* and *brittle* nature of the propellant grain. Although KNSU has reasonable strength and toughness, it is brittle in nature, meaning that if overstressed, will crack or break, rather than plastically deform to absorb energy. Care must be taken during handling to avoid cracking a grain. Before

loading a grain into the motor, it should be inspected for cracks. I have found that a visual inspection is sufficient to detect cracks, owing to the translucent nature of the propellant which tends to make a crack readily visible. My experience has shown, however, that if a grain is overstressed, it will almost always break rather than crack, owing to the high elastic modulus.

- *Hygroscopic* nature of the propellant grain. Once cast, the KNSU propellant is hygroscopic, meaning that it readily absorbs moisture from the air. Of course, the more humid the air, the more significant the problem. The outer surface will become "sticky" and if left exposed to moist air for more than a few hours, the material will soften and and become gummy. Ignition of a damp grain becomes significantly more difficult. Some performance loss will result due to slower flame-spread over the grain during motor startup.

- *Corrosive nature of exhaust products*. One of the products of combustion is potassium carbonate, which is hygroscopic, absorbing moisture from the air to form an aqueous solution of hydroxide ions which can be rather corrosive. As well, the trace amount of KOH that forms exacerbates this. Although this is not a serious problem, it is a nuisance. Metals, especially aluminum, become etched or corroded if not cleaned immediately with warm water. It is best to shield any equipment or other components to prevent exposure, or to paint any surfaces that cannot be shielded. As well, the skin may can be irritated by the residue, if exposure is prolonged. Disposable vinyl gloves should be worn when handling anything exposed to KNSU exhaust residue.

Assessment

The KNSU propellant may not be a particularly "sophisticated" one, nor is it a high-performance propellant. It does have certain drawbacks especially in comparison to modern sugar propellants such as KN-Dextrose Propellant (KNDX) and the KN-Sorbitol Propellant (KNSB). Although very similar, KNDX and KNSB propellants have notable advantages over the "classic" KNSU, such as a much lower casting temperature and minimal caramelization. In fact, I never use KNSU anymore for my rocket motors. Nevertheless, KNSU is a propellant that can be used with good success under certain circumstances, such as when alternative sugars are not locally available.

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