

## Introduction

This web page describes the KN-Dextrose rocket propellant, referred to by the acronym KNDX. This propellant is formulated as a heat-fused mixture of **potassium nitrate (KN)**, and **dextrose**. This propellant was developed as an alternative to the traditional "sugar-based" propellant, KN-Sucrose (acronym KNSU), and the more contemporary KN-Sorbitol (acronym KNSB). Although the sucrose-based propellant is, in many ways, an excellent amateur propellant, providing good performance with highly reproducible and reliable results, there are a number of drawbacks when using sucrose as the fuel/binder. Among the drawbacks are:

- Casting at an elevated temperature has certain inherent hazards that become more significant with higher melt temperatures (such as reduced margin between melt temperature and ignition temperature, reduced input energy required for ignition, and more rapid burn rate resulting from the greater thermal energy of the heated mass).
- Degradation (caramelization) of the sucrose during casting, which severely limits the pot life of the molten propellant.
- Hygroscopic nature of the cast propellant. Although not a serious drawback, it makes the propellant messy to handle in a humid environment.
- Brittle and high Elastic Modulus properties of the cast propellant, which makes it unsuitable for case-bonded grain design.

With this in mind, some years ago I began to search for an alternative to using sucrose as the rocket fuel. Since sucrose is a carbohydrate (which interestingly, are the primary sources of energy of foods), I decided to investigate other forms of similar compounds, starting with other kinds of sugars. Sucrose, often referred to as table sugar, is the most common sugar. Other naturally occurring sugars are:

- Fructose (fruit sugar)
- Lactose (milk sugar)
- Galactose
- Mannose
- Maltose (malt sugar)
- Dextrose (also known as D-glucose)

Of these, the latter is commonly available commercially. It is sold in the hydrated form as *corn sugar*, and is typically used in the making of home-brewed beer (*so I'm told!*), and as such, it is available at retail shops that sell such supplies, where it sells for about \$3 CAD (= \$2 USD) per kg., bulk. It is also available at some pharmacies, sold as an alternative sweetener, however it is more costly (a 500 gram jar costs \$4 CAD). This hydrated form of dextrose is known as *dextrose monohydrate*, which is 91 percent dextrose by weight, with the remainder present as molecular bound water. Dextrose monohydrate can be converted to *anhydrous dextrose* by dehydration at an elevated temperature, above 50 degrees C, as all the bound water is driven off

Dextrose monohydrate, as obtained in the white granular form, is essentially identical in

appearance to sucrose. It is easily ground to a fine powder by use of a *Fluid Energy Mill* (coffee grinder).

It is interesting to note that dextrose, in the form of blood sugar, is the main energy source for most living organisms.

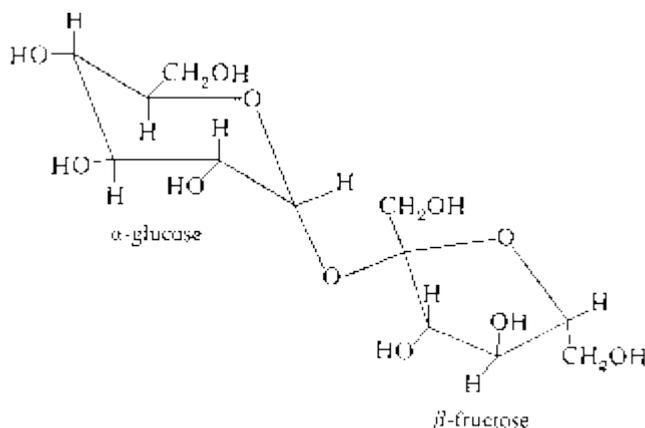


Figure 1 -- The dextrose (glucose) molecule together with the fructose molecule form the sucrose molecule

The dextrose molecule is much smaller than the sucrose molecule, in fact, its molecular weight is nearly one half that of sucrose. The chemical formula for sucrose is  $C_{12}H_{22}O_{11}$ , and for dextrose, it is  $C_6H_{12}O_6$ .

Smaller organic molecules often have a lower melting point (a sought after trait), and also have less tendency to decompose upon heating (also a sought after trait), which is a result of the molecule having less tendency to break up as it "thrashes around" due to thermal agitation.

As can be seen in Figure 1, the sucrose molecule actually consists as a bound pair of simpler sugars, the dextrose (or alpha glucose) molecule, and the beta fructose molecule. In fact, testing of the dextrose-based propellant confirmed that the melting point is significantly lower than sucrose-based, and indeed, very little caramelization (decomposition) occurs as a result of normal heating. As far as hygroscopicity is concerned, there appeared to be some improvement over sucrose-based. Although testing has not yet been conducted on the mechanical properties (such as Elastic Modulus) of the dextrose-based propellant, initial indications suggest that these properties are similar to sucrose-based propellant. Details of the results of this testing, as well as theoretical performance of the dextrose-based propellant, are being presented in this web page.

## Properties of some Sugar compounds

The following is a brief comparison of some physical and thermodynamic properties of **Sucrose**, **Dextrose Monohydrate**, and **Anhydrous Dextrose** sugars:

**Table 1 -- Sugar properties**

|                           | <b>Sucrose</b>       | <b>Dextrose Monohydrate</b> | <b>Dextrose (anhydrous)</b> |
|---------------------------|----------------------|-----------------------------|-----------------------------|
| Chemical Formula          | $C_{12}H_{22}O_{11}$ | $C_6H_{12}O_6 \cdot H_2O$   | $C_6H_{12}O_6$              |
| Molecular Weight (g/mole) | 342.3                | 198.18                      | 180.16                      |
| Melting Point (C.)        | 185 (d)              | 86 (in its water of         | 146 (d)                     |

|                                  |                                   |                                   |                  |
|----------------------------------|-----------------------------------|-----------------------------------|------------------|
|                                  |                                   | hydration)                        |                  |
| Density (g/cm <sup>3</sup> )     | 1.581                             | 1.542                             | 1.562            |
| Enthalpy of Formation (kJ/mol)   | -2221.2                           |                                   | -1274.5          |
| Enthalpy of Formation (cal/gram) | -1549.9                           |                                   | -1689.7          |
| Appearance                       | white granular or cohesive powder | white granular or cohesive powder | dry white powder |

d = decomposition initiates upon melting

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### Effects of Heating Dextrose

To investigate the potential usefulness of dextrose-based propellant, I conducted a series of experiments, on dextrose alone, as well as on dextrose-based propellant. The first of the series of experiments that were performed was to determine the effects of *elevated temperature* on dextrose monohydrate (alone). This was done by slowly heating a 250 gram batch of dextrose monohydrate in a stainless steel bowl, over an electric element. The effects of heating were noted (qualitatively, such as appearance, colour change, smell, texture, etc) as well as quantitative changes such as mass and temperature, as a function of time. Some results of this experimentation are summarized in Figure 2.

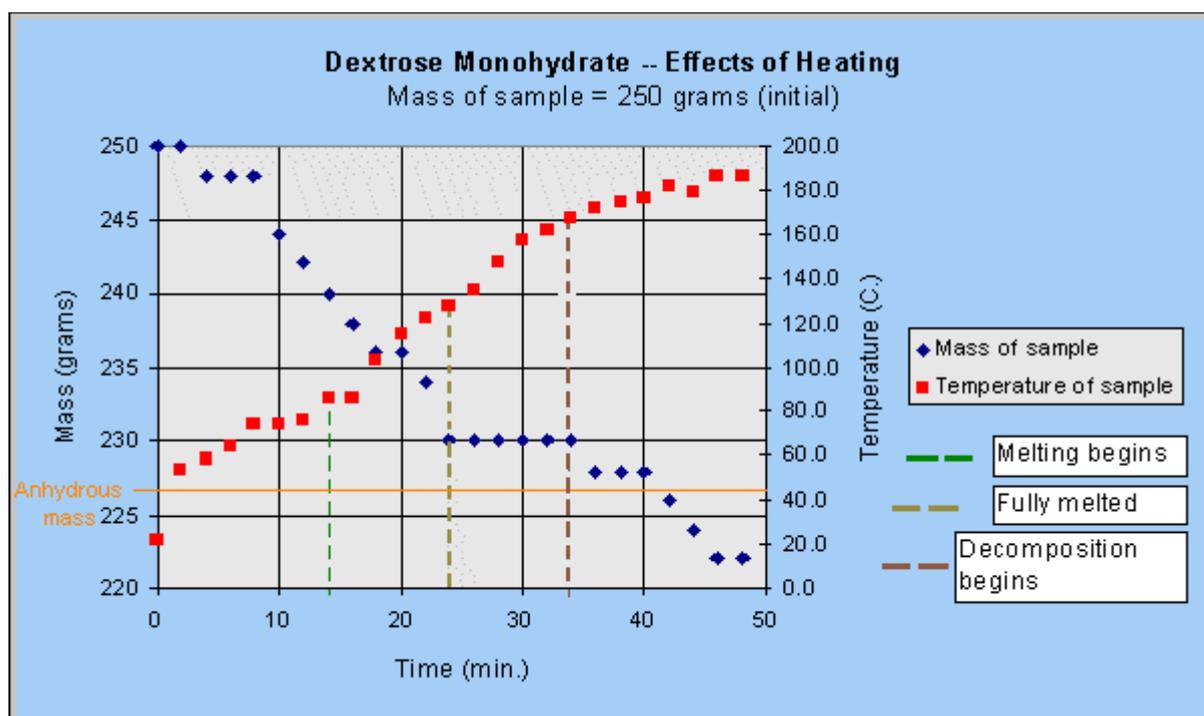


Figure 2 -- - Effects of elevated temperature on Dextrose Monohydrate

Note that the anhydrous mass of the sample was calculated to be  $180.16/198.18 * 250 = 227$  grams.

From the graph, the following observations may be made:

1. "Melting" of the sample began after 14 minutes of heating, at a temperature of 87 C. deg. It is important to note that this is not *melting* in the strict sense, rather, the dextrose actually begins to dissolve in it's water of hydration that is liberated.
2. Sample is fully "melted" after about 24 minutes, at a temperature of 125 C. deg. At this point, there is still some water present in the melted sample, the mass of which stays essentially constant until the temperature of the sample reaches the point where decomposition begins (around 167 C. deg.)
3. After all the water of hydration is driven off, and only anhydrous dextrose remains, decomposition occurs more rapidly and mass reduction rapidly occurs, as the dextrose breaks down, which is observed as active bubbling and colour change, beginning with a hint of yellow, progressing eventually to dark amber.
4. The temperature rise of the sample is approximately linear until the point where decomposition begins, then rises at a slower rate. It appears that at this point, thermal energy goes mainly into breaking up the dextrose molecule, rather than raising the thermal energy of the sample.
5. Most of the water of hydration is evaporated during the early phase when the sample is

not yet fully melted. This is made apparent by the rapid rate of mass decrease which continues until the sample is largely melted, then a "plateau" is reached, where the mass remains constant for an appreciable period of time. Apparently, once fully melted, the reduced surface area of the liquid sample (compared to powder form) results in a much slower rate of evaporation.

[Click for details of experiment and results...](#)

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## Propellant Formulation

The formulation of the basic KNDX propellant is the same as KNSU, that is, **65% KN** (oxidizer) and **35% Dextrose** (fuel/binder), by mass. This ratio was chosen based upon my experience with KNSU, representing a practical upper limit for "solids" loading, while maintaining good performance and burn rate characteristics. A *higher* O/F ratio, and thus higher "solids" loading, may give slightly enhanced performance, but leads to a thicker consistency of the melted mixture (slurry). This makes casting more difficult. The effect of using a *lower* O/F ratio is reduced performance and a slower burning rate. However, the slurry has a **thinner consistency**, which makes casting easier. It is therefore suggested that those who are casting this propellant for the first time try the **60/40 O/F ratio**.

**Potassium nitrate (KN)**, also known as saltpetre, is a commonly used chemical (used, for example, for pickling meats, and in toothpaste for "sensitive teeth") and as such is quite readily available. Other uses for potassium nitrate are for hydroponics, and in gardening for raising the nitrate level of soils. I've purchased potassium nitrate in 2 kg. lots at a veterinary chemical supply store. It is also available at many pharmacies, sold typically in 100 gram or 8 oz. tins. Potassium nitrate is also sold as 14-0-45 [fertilizer](#) at farm supply stores, typically 98-99% pure (some manufacturers label it as 13-0-46 or similar). This is by far the most economical form (cost = \$30CAD for 20kg bag), and the performance is no different that purer grade. Other commercial sources for potassium nitrate are listed in my [Links](#) webpage.

Recent [experimentation](#) has shown that *stump-remover* is a viable source of potassium nitrate, at least the particular brand tested (Wilson's). Stump-remover is readily available at garden shops, home renovation outlets, and some hardware stores. Before use, however, the product must be washed in methanol to remove the caustic coating.

It is **important to note** that 9% of the mass of **dextrose monohydrate** is bound water. As such, the ratio of potassium nitrate to dextrose monohydrate must be adjusted to achieve a given oxidizer/fuel (O/F) ratio. In other words, the required amount of dextrose monohydrate required in the mixture must be multiplied by 1.1, which is the ratio of Molecular Weights (198.18/180.16). For example, if 100 grams of KNDX propellant of 65/35 O/F ratio is required, the quantity of dextrose monohydrate required is  $0.35 * 100 * 1.1 = 38.5$  grams. Alternatively, the dextrose monohydrate can be dessicated to form **anhydrous dextrose**. The dessicating process drives out most of the water, allowing the unaltered fraction of 35% dextrose to be used. Dessicating is done by spreading the dextrose monohydrate onto a cooking sheet, to a maximum depth of 1 cm, then placing this into a preheated oven set at

80°C (175 °F.) for 2 hours. Once cooled, the resulting caked lumps may be broken up using an electric coffee grinder.

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## 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 3. The grinder hopper should be half filled, then run the grinder for about 30-40 seconds. To facilitate milling, the grinder should be slowly "gyrated" about its base. Milling will reduce the particle size to an average of 50-100 microns. As obtained, granulated potassium nitrate particles are typically 150-250 microns. Potassium nitrate often comes in the form of "prills" (tiny spheres) which must be milled.

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 alot more fluid and easier to cast if the potassium nitrate is milled for a shorter time, such as 10 seconds. The potassium nitrate will consequently have a larger particle size. The drawback is slightly reduced performance due to less efficient combustion.

Separate dedicated grinders should be used for the potassium nitrate & for the dextrose. The reason is that the seal that separates the grinding compartment from the motor compartment is not perfect. Over time, some fine powder finds its way into the motor compartment, and slowly accumulates. If the accumulated powder is solely dextrose, or solely potassium nitrate, the risk of the accumulation igniting is minimal. However, if the same grinder were used for both dextrose and oxidizer, the risk of combustion is much greater, creating an obvious hazard.

Following the grinding process, the two constituents are carefully weighed out using an accurate scale or balance beam. Enough of the powdered mixture of potassium nitrate and dextrose has to be prepared to take into account the **inevitable waste** resulting from the casting procedure, typically 30-50 grams. For example, for the *B-200* motor, which has a grain capacity of 225 grams, I would prepare 182 grams potassium nitrate, and 98 grams of anhydrous dextrose, for a total of 280 grams powdered mix. For the larger *Kappa* motor, I would prepare 293 grams potassium nitrate, and 157 grams of anhydrous dextrose for a total batch size of 450 grams for *each* of the 4 propellant segments. The final segment mass was typically 375 grams, giving a total of 1500 grams propellant for the four segments that make up the *Kappa* grain.

It should be noted that potassium nitrate, particular the finely divided form, is slightly hygroscopic and therefore a small percentage of the mass is due to moisture. If this percentage were sufficiently high, this could affect the final O/F ratio. However, actual [measurements](#) that were performed indicated moisture content of *as obtained* potassium nitrate was less than 1% and thus may be neglected with little error in the final product. If in

doubt, the potassium nitrate may be readily desiccated by placing the product onto a cooking sheet, to a maximum depth of 1 cm, then into a preheated oven set at 120°C (250 °F.) for 2 hours



Figure 3 -- This \$15 coffee grinder does a superb job of pulverizing the potassium nitrate to a fine texture.

After individually weighing out the two constituents, there is a **choice between two processes** which may be followed next:

1. The two constituents may be "dry" blended together to form an intimate, random dispersion of oxidizer and fuel particles.
2. The "dry" blending step is omitted, and casting the propellant is performed next by first melting the dextrose, then introducing the potassium nitrate into the melt. Mixing is performed in the "melted" slurry state.

I've always utilized the first method of "dry" mixing. This produces an optimum performing propellant with highly reproducible results and consistent burn rate. The second method is utilized by many experimenters, being chosen due to its inherently greater safety factor. It's true that extra care must be exercised if the first method is followed, as the blended mixture is readily combustible. No measurements have been made with regard to performance loss if the second method is followed, but *ad hoc* testing suggests the overall effect is quite small, probably no more than 5%.

For the first method, the two constituents are blended together in a single container. I built an **electric rotating mixer** for this purpose (Figure 4). The powdered mixture is loaded into a tupperware container, then secured to the rotating drum with rubber bands, and, then allowed to mix for several hours. As a guideline, I allowed **one hour per hundred grams of powdered mixture**.

Once the mixing operation has been completed, the dry mixture is transferred immediately to a closed container for safe storage. Since the propellant, at this stage, is readily combustible,

sensible precautions would be observed to keep it away from any possible ignition sources.

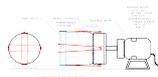


Figure 4 --Propellant "dry" mixer

## Casting Dextrose-based Propellant

The process of casting Dextrose-based propellant is essentially the same as the process used for the Sucrose-based propellant, with the exception of the casting temperature. Either a temperature controlled **oil-bath** (or paraffin-bath) or a **thermostatically controlled heating vessel** is used. Although I originally used the oil-bath method, I now use a thermostatically controlled "deep fryer". It is essential, from a long-term safety consideration, that only these methods be employed for heating propellant, the critical intent being that no exposed heating surface being of higher temperature than the melting point of the propellant. For this reason, heating the mixture in a container over an electric or gas stove element is **absolutely unacceptable** and must never be attempted (actually, common sense tells us this!). Although this propellant is highly tolerant of overheating, we want to keep this feature solely as a **valuable safety margin**. Suitable protective gear must be worn during the casting operation (see *Effects of Overheating during Casting*).



Figure 5 -- Casting setup for KNDX, employing 'tilt-table' for the heating vessel.  
(click for larger image)

For Dextrose monohydrate-based, the oil-bath (or thermostat) temperature should be in the range of **125-130°C.**, and for anhydrous Dextrose-based, it should be in the range of **150-155 °C**. A [candy thermometer](#) is ideal for monitoring the temperature of the oil-bath or propellant slurry. An electronic thermocouple temperature meter is even better.

The casting procedure involves first preheating the oil (or deep fryer) to the required

temperature, and maintaining this temperature +/- 5 degrees. Then, starting with a small amount, the powdered mix is added, and stirred often to assist melting. Once this has melted, more powdered mix is added. Stirring often helps facilitate melting. The initial colour of the melted slurry is nearly colourless, but begins to turn off-white colour as slight caramelization commences. Eventually, the colour will become that of ivory, 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, as caramelization is a function of time as well as temperature. Once all the powdered mixture has been incorporated into the melt, it is further heated and stirred, to eliminate any lumps that may be present. An additional five to ten minutes of heating will bring the slurry up to the casting temperature. Note that the slurry will **not become fluid enough to pour**. The consistency will remain quite thick, and must be simultaneously **poured and scooped with a spoon or spatula** onto the funnel, and allowed to flow into the mould. Immediately after loading, the coring tool would be 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 1/2 hour with the oil bath method, 10-15 minutes if heated directly in the deep fryer. Note -- if the colour of the slurry becomes a "peanut butter" or amber colour, this is most likely due to impurities in the potassium nitrate. The pH of the potassium nitrate must be neutral (6.5 - 7); impurities tend to make the potassium nitrate strongly alkaline, which leads to this discolourization.



A silicone spatula is ideal for mixing and scooping

As with KNSU propellant, the KNDX propellant should be removed from the casting mould and the bore rod extracted as soon as the material has fully solidified (typically 45 - 60 minutes). It is not necessary for the cast propellant to "cure" for an extended period of time, as is required with KNSB.

Casting dextrose-based propellant has an additional advantage over casting sucrose-based propellant -- the heated slurry does not 'freeze' nearly as rapidly, resulting in easier casting and a better final product. The cast propellant solidifies quite soon after cooling begins, in a similar manner to KNSU.

For the neophyte who has never cast any sugar-based propellants, it is suggested that the grain casting process be first practiced using [INERT](#) propellant. The INERT propellant is prepared in exactly the same manner as KNDX (or KNSU or KNSB), with the important exception that

**table salt** (sodium chloride) is substituted for the potassium nitrate. This "propellant" melts and casts in a similar manner to the genuine thing, however, INERT propellant is completely **non-combustible** and inexpensive.

**Casting Dextrose monohydrate-based propellant**

The heating experiments that were conducted on samples of dextrose monohydrate clearly showed that water of hydration which was released upon heating required appreciable time to fully evaporate. The implication is that propellant prepared with dextrose monohydrate will have *some* moisture remaining in the cast propellant unless it is heated long enough to ensure that all the moisture has been driven off. Otherwise, exactly how much water remains once the propellant has been cast cannot be known for certain. The presence of moisture in the propellant affects certain characteristics. It has been demonstrated by experiments, and by theoretical analysis, that moisture affects the following:

- Physical properties--propellant that was cast immediately after the sample reached the fully melted stage was, when cooled, pliable and could readily be deformed in shape. Oddly though, if the propellant is subjected to a blow, it would crack or even fracture, in a brittle manner. This was discovered when a newly cast grain was accidentally dropped onto the floor--several cracks resulted.
- burn rate--significantly affected; the greater the degree of moisture, the slower the burn rate.
- Performance--the theoretical specific impulse is slightly reduced by the presence of water e.g. by less than 1%, for 1% water present.

On the plus side, casting the propellant requires less heating than anhydrous dextrose-based propellant. The mixture melts quickly and forms a slurry that is fairly fluid (with fluidity depending on solids loading, i.e. percentage of potassium nitrate), which may be readily poured and/or scooped.

The following temperatures were measured during the casting process, utilizing a thermocouple, and are compared to sucrose-based:

**Table 2 -- Measured casting temperatures, 65/35 O/F propellant**

|                            | <b>Dextrose monohydrate-based</b> | <b>Sucrose-based</b> |
|----------------------------|-----------------------------------|----------------------|
| Initial melting            | 98 C.                             | 174 C.               |
| Fully melted               | 123 C.                            | 184-187 C.           |
| 1st sign of caramelization | 157 C.                            | 176 C.               |

In order to eliminate all residual water from the dextrose monohydrate, it is necessary to heat the melted propellant for a sufficiently long period of time. But how long a heating period? Fortunately, there does seem to be an indicator of the dessicated condition. In Figure 2, it is seen that when all the moisture has been eliminated (mass=anhydrous mass), decomposition commences. At this point, it was observed during the investigation that the colour of the sample showed a tinge of yellow, which soon became more pronounced as the sample was

heated further. Therefore, if the propellant is **heated until this colour change commences**, it is assured that nearly all the moisture has been driven off.

### **Casting Anhydrous Dextrose-based propellant**

Certainly the most obvious way to ensure that the cast propellant has minimal residual moisture is to eliminate all the water beforehand. This is done by preparing the propellant mixture using *anhydrous dextrose*, rather than dextrose monohydrate. Another advantage is that no adjustment to the O/F ratio is required in weighing out the constituents, as is required with the monohydrate.

When casting the propellant, somewhat greater heating is required before melting will commence. In fact, melting initiates at the known melting point of dextrose (not surprisingly). The following temperatures have been measured during the casting process:

**Table 3 -- Measured casting temperatures, 65/35 O/F propellant**

|                            | <b>Anhydrous Dextrose-based</b> |
|----------------------------|---------------------------------|
| Initial melting            | 145 C.                          |
| Fully melted               | 147 C.                          |
| 1st sign of caramelization | 157 C.                          |

When casting propellant prepared with anhydrous dextrose, it is not necessary to continue heating until caramelization commences; it may be poured into the mould as soon as the mixture is fully melted and blended.

### **Notes on casting dextrose propellant**

- The fully melted slurry is fairly thick, and further heating will result in only marginally reduced viscosity.
- The slurry should be poured & scooped simultaneously into the mould. A spoon with an insulated handle, or better yet a silicone spatula, works well to direct the slurry into the mould.
- Once all the mixture has been loaded into the mould, 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 is **pre-cooled in a freezer** for several hours. An alternative plunger design is a hollow metal tube, closed & sealed at one end (see Figure 5). Prior to casting, a couple of ice cubes are dropped into the plunger to chill it.  
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.

- The coring tool should be preheated in an oven set at 100°C. 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 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 should be in the colour range between *ivory* (#FFFFFF0) and *beige* (#F5F5DC), as illustrated in Figure 6 below:



Figure 6 -- Cast *Lambda* KNDX propellant grain segments

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### **Water Content and Hygroscopicity**

After casting, once the grain has cooled, the propellant surfaces are usually found to be *sticky* due to moisture deposition. This is a result of **residual moisture** in the propellant, which is forced out (by elevated vapour pressure) and collects at the grain surfaces. Even if the potassium nitrate and dextrose have both been dessicated prior to casting, it is clear that not 100% moisture is driven out. A tiny fraction of a percent remains, which shows up after casting. It has been observed, however, that the material will **dry out** after a certain period of time, typically 24 hours, if placed where the humidity is relatively low (< 60%). This drying process can be accelerated by placing the grain within a **dessicator**. A simple dessicator can be made from a *cake dome* with a layer of *calcium chloride* pellets or flakes spread over the bottom pan. Calcium chloride is readily available as an *ice & snow melter*.

It would appear that there is a relative humidity (R.H.) *threshold* that determines whether or not the propellant will be hygroscopic. As with the KNSU propellant, the KNDX propellant is hygroscopic (absorbs moisture from the air). However, the hygroscopic nature of the dextrose

propellant is far less severe than sucrose-based. As an ad-hoc experiment, I'd exposed a grain cast from KNDX monohydrate to the open air, and after about two months, it was still bone dry. The R.H. over this duration ranged from 55-60%. At high R.H. levels (around 90%), however, this propellant is indeed very hygroscopic. Interestingly, experimentation has suggested that the resistance to moisture absorption is better *if cast as dextrose monohydrate based* rather than anhydrous-dextrose based. Perhaps this is a consequence of the lower casting temperature.

### [Results of hygroscopicity experiment...](#)

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## **Theoretical Performance**

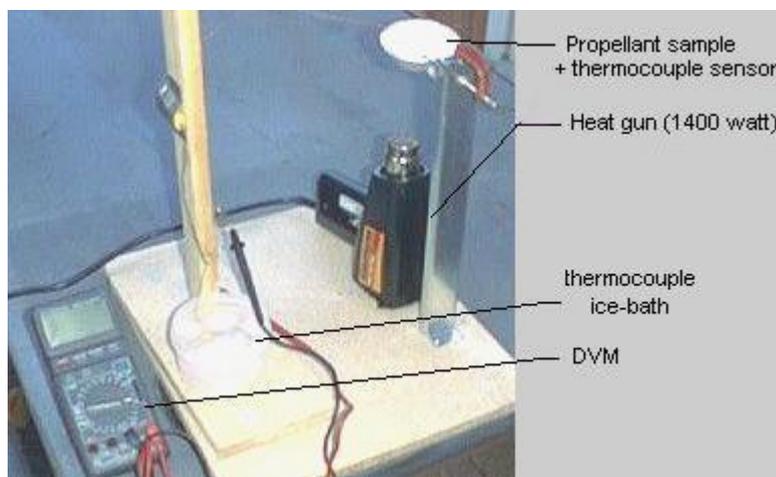
The theoretical performance of the KNDX propellant is essentially the same as that of the KNSU and KNSB propellants. For example, the specific impulse (65/35 O/F) is less than 1% lower than KNSU, the combustion temperature is nearly identical, and the products of combustion are very similar, including the mass fraction of particles in the exhaust. The ideal density of the cast propellant is also nearly identical (1.879 compared to 1.888 g./cu.cm.). Details are given in the [KN-Dextrose Chemistry & Performance Characteristics](#) web page.

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## **Effects of Overheating 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.

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 deg.F max. rating). A type-K thermocouple (chromel-alumel) was inserted into the mixture to monitor temperature. The setup for this experiment is illustrated in Figure 7.



Charred remains of overheated propellant which failed to ignite

**Figure 7 - Setup for propellant "overheating" experiment (left); Remains after conclusion of experiment (right)**

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 in Figure 7).

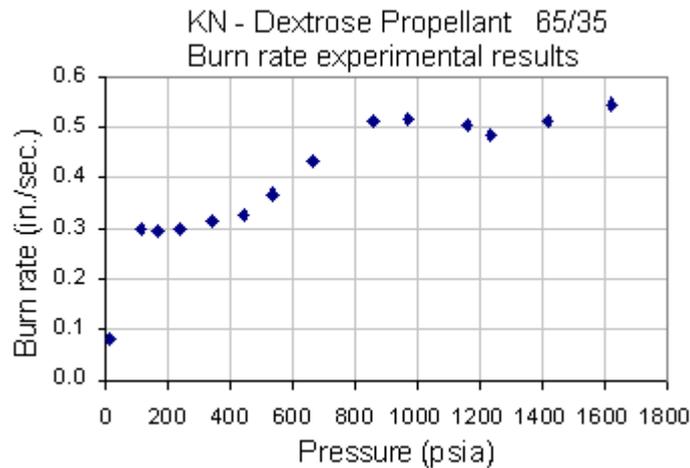
It would seem that, once decomposition of the dextrose initiates, that the added thermal energy of heating goes solely into *decomposing the dextrose*, rather than raising the thermal energy (temperature) of the propellant, a rather nice characteristic. As such, it would seem improbable that accidental ignition during casting would occur due to overheating, **provided that the proper heating method is employed** as described above in the *Casting* section, given the obvious indicators of overheating, such as severe caramelizing, and the fact that auto-ignition occurs at a temperature greater than 300° C.

*Needless to say, 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.*

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## **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, a rather extensive experimental investigation was conducted to determine the effect of pressure upon the burn rate by utilizing a *Strand Burner* apparatus. [Details](#) of this investigation are presented on another web page, but results are summarized in Figure 8. Interestingly, KNDX was found to exhibit a *plateau* burn rate behaviour, as can be seen in Figure 8, where the burn rate curve flattens off in the regime between about 800 and 1200 psi. The effect of temperature upon burn rate has also been explored, although less extensively. Details are found on the same web page.



**Figure 8 - Experimental results of the effect of pressure on burn rate**

More recently, experimentation was conducted on two **burn rate modifiers**. The modifiers were *red iron oxide* and *air-float charcoal*. It was found that the burn rate was increased by about 20% with the addition of 1% iron oxide, over the full pressure regime explored. The effect of doping the propellant with 1% charcoal was an increase in burn rate throughout the lower pressure regime. Perhaps the most significant effect of these modifiers was to dampen the plateau effect. The details on this experimentation are given in the [Burn Rate Experimentation](#) web page.

[Burn rate as a function of Oxidizer/ Fuel \(O/F\) ratio](#)  
[Motor Design Charts for KNDX propellant](#)

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## Combustion Testing and Results

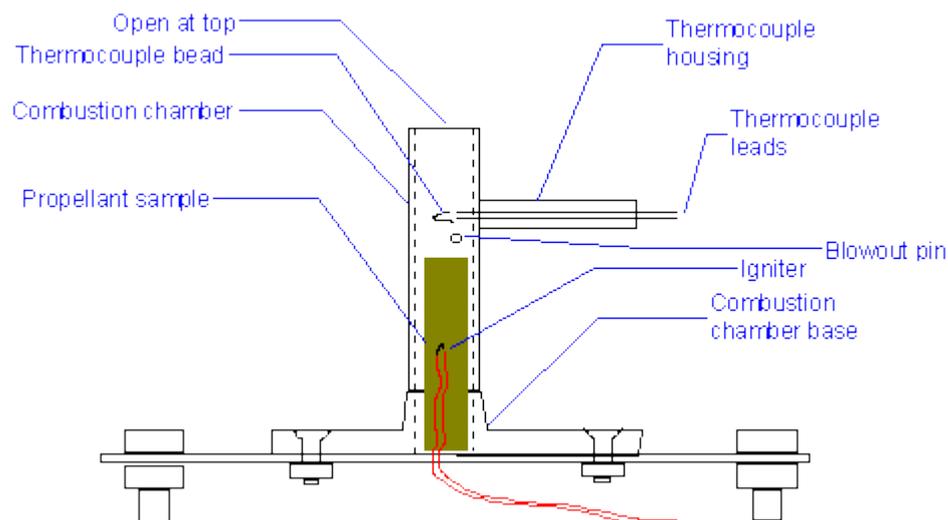
Theoretically, the dextrose-based propellant has performance characteristics (specific impulse, combustion temperature, characteristic velocity, etc.) that are nearly the same as the sucrose-based propellant. Rather than conducting motor static tests to bear this out, a simple indication of the propellant's performance is the *combustion temperature*. If testing indicated similar combustion temperatures for both propellants, it follows that the performance would likely be similar. This does not, of course, guarantee that the performance would be the same, however, if the results indicate dramatically different combustion temperatures, then surely the performance of the two would be different.

The *characteristic exhaust velocity* ( $c^*$  or *cee-star*), which is a convenient means of expressing the thermochemical merit of a propellant, is given by:

$$c^* = \sqrt{\frac{R T_0}{k \left( \frac{2}{k+1} \right)^{\frac{k+1}{k-1}}}}$$

The convenience of characteristic velocity as a measurement of performance is that, unlike specific impulse, it is independent of nozzle design (specific impulse,  $I_{sp}$ , is related to characteristic velocity by the relation  $I_{sp} = C_F c^*$ , where  $C_F$  is the thrust coefficient of the nozzle). As can be seen, it is only a function of the combustion temperature ( $T_0$ ) and the properties of the combustion products ( $k$ ,  $R$ ) (the actual properties should not differ significantly between the two propellants).

In order to measure the combustion temperature, which was done at atmospheric pressure for convenience, a fairly simple apparatus was built, consisting of a combustion chamber (open to the atmosphere) and a temperature sensor. This [Combustion Chamber](#) device is illustrated in Figure 9, below:



**Figure 9 - Combustion Chamber apparatus**

The propellant samples were cylindrical in shape, typically measuring 1 cm x 5 cm, and were 'hot glued' to the base of the chamber. All dextrose-based samples were cast using anhydrous dextrose. The samples were remotely electrically ignited, and a DVM was used to record the output from a thermocouple circuit to obtain combustion temperature readings.

Results of this testing are summarized in Figure 10, below:

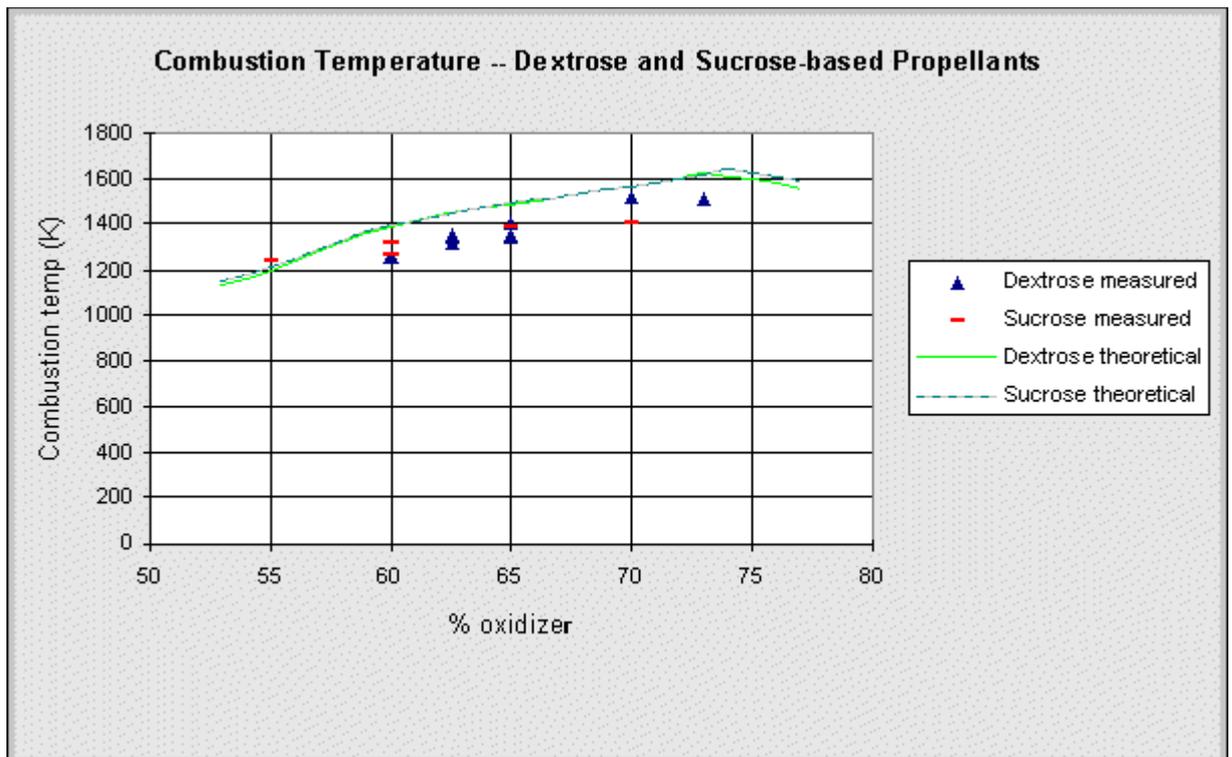


Figure 10 - Combustion testing results

The above results suggest that the combustion temperature of dextrose-based propellant is, in fact, close to that of sucrose-based propellant. This would suggest that the performance characteristics would, therefore, be similar, as predicted by the theoretical analysis of combustion.

In all cases, the actual combustion temperature was about 100-150 degrees (K) below the theoretical (adiabatic) temperature at P=1 atm. This might be explained by heat loss to the combustion vessel walls, which were fairly heavy and remained relatively cool throughout the short burn. Interestingly, the measured combustion temperature for 55/45 sucrose-based propellant is greater than predicted by theory. However, only a single test of this ratio was performed. This may very well be a result of experimental error (scatter).

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## Assessment

In the time period that has passed since I first investigated KNDX propellant (mid 1998) and subsequently posted this web page (early 1999), the KNDX propellant has been utilized extensively by AER experimenters worldwide, including myself. I have developed and successfully fired a number of motors which utilize this propellant, namely, the [Kappa](#) motor ("K" class) and [Juno](#) motor ("J" class). The latest motor to be developed is the [Lambda](#) motor ("L" class), which was recently given its maiden firing (alas, unsuccessfully, owing to inhibitor failure). This latter motor contained 4 propellant segments of 66 mm diameter, totalling 2.9 kg (6.4 lbs). The [A-100M](#) motor (a new version of the A-100 motor) has been

designed specifically for KNDX propellant and has been fired several times. The [B-200](#) motor (designated B-200DX) has also been fired a number of times with KNDX propellant.

The delivered performance of the KNDX propellant is essentially identical to that of the KNSU and better than that of the KNSB propellant. Operating in the Kappa motor, the propellant was found to deliver a respectable specific impulse of [137 seconds](#).

The burn rate of this propellant (at elevated pressure) was found to be somewhat lower than sucrose-based propellant. This allows for the design of a rocket motor with a greater burn time. One drawback of KNDX propellant is the "plateau" burn rate behaviour, which tends to complicate the design process to some degree. However, recent experimentation has shown that the "plateau" behaviour can be suppressed by doping the formulation with charcoal pigment. Iron oxide provides a similar effect, and results in a greater burn rate.

The KNDX propellant has a considerable advantage over the sucrose-based propellant with regard to ease of casting. The temperature of the melted mixture is significantly lower, which results in an improved safety margin with regard to overheating. Lower casting temperature also leads to the noteworthy advantage of less rapid "freeze-up" of the melted mixture, which results in a better cast product with fewer voids or air bubbles. Decomposition (caramelization) of the propellant due to heating is minimal, and pot life of the melted slurry is superior to that of KNSU (although less than that of KNSB).

The mechanical properties of cast dextrose-based propellant are very similar to both the sucrose-based and sorbitol-based propellants, that is, rigid and brittle, whether prepared using monohydrate or anhydrous form of dextrose. However, the strength of dextrose-based propellant (and of the sucrose & sorbitol-based) is appreciable, and does not appear to pose any practical limitations on grain size or geometry.

The hygroscopic nature of this propellant appears to be less problematic than that of the sucrose-based or sorbitol-based propellants, particularly if cast in the monohydrate form. As well, the ambient relative humidity (R.H.) seems to play a significant role. It would appear that there is a R.H. threshold that determines whether or not the propellant is hygroscopic. It has been determined by experience that if the R.H. is maintained less than approximately 60%, the propellant will remain completely dry to the touch.