

Investigation of Dextrose Monohydrate with regard to
consideration as a possible Solid Rocket Propellant
Fuel and Binder

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Abstract:

This report covers several tests that were performed to investigate the possible usefulness of Dextrose Monohydrate, commonly referred to as "corn sugar", as a solid rocket propellant fuel and binder. For these tests, two basic assumptions are taken regarding the form that propellant made with this fuel would take:

- potassium nitrate (KNO_3) is to be used as the oxidizer
- propellant grains are to be heat cast, with the procedure being essentially identical to that of KNO_3 -sucrose propellant.

Tests were performed on dextrose, either alone, or in combination with KNO_3 as a homogeneous mixture. For comparison purposes, many of these tests were also performed using sucrose. These tests include:

- Effects of elevated temperature on dextrose, both monohydrate and anhydrous forms, and on sucrose.
- Burnrate measurements, under ambient conditions, with various oxidizer/fuel (O/F) ratios.
- Combustion experiments to determine temperature of combustion, which is a useful parameter to compare performance of the dextrose and sucrose-based propellants.
- Investigation of the castability of the dextrose-based propellant, including temperature measurements of the propellant during heating.
- Determining the effects of overheating the propellant, with regard to safety concerns during casting.

Results of these tests suggest that dextrose-based rocket propellant is feasible and has some significant advantages over the sucrose-based propellant.

These advantages include a lower casting temperature which results in grain casting being a safer procedure as well as experiencing less rapid "freeze-up" of the molten slurry, and essentially no decomposition (caramelization) of the dextrose occurs at normal casting temperatures.

Testing also suggests that the performance of the dextrose-based propellant is similar to sucrose-based, as predicted by theoretical analysis.

A possible disadvantage of the dextrose-based propellant is that the burnrate was found to be approximately one-half that of sucrose-based, at ambient conditions. This result, however, may not be the case under pressurized condition. Further testing in this regard is necessary before further assessment can be made.

Objective :

To determine the effects of moderate heating on Dextrose Monohydrate.

Method:

A sample of 200 grams of consumer grade Dextrose (corn sugar) was carefully weighed using 2 kg digital scale (2g resolution). The form was very fine granular, similar to "fruit sugar". The sample was weighed in a sheet aluminum pie pan, which also served as the containment vessel during heating. The sample was placed in a pre-heated oven at 300°F and observed. Tare weight of pan was 12 grams.

Results

The oven thermometer reading was initially 275°F when the sample first place in it. No sign of melting after 30 minutes, so thermostat increased by 25°F. After about 40 minutes, sample was about 10% melted. Thermometer reading was 325, so thermostat adjusted back down to original setting.

After 1 hour, the sample appeared to be largely melted; many bubbles were present. Thermometer reading was 300°F, and colour was transparent.

After 80 minutes, sample was about 90% melted. Thermometer reading was 300°F, and colour was very light amber.

After 90 minutes, sample had active bubbling. Thermometer reading was 300°F, and colour was very light amber.

After 120 minutes, sample was fully melted, with much active bubbling. Thermometer reading was 290°F, and colour was medium amber. A candy thermometer was inserted into the sample, and temperature was just above 285°F

After 150 minutes, with much active bubbling; thermometer reading was 285°F, and colour was medium amber._

After 180 minutes, with active bubbling; thermometer reading was 285°F, and colour was somewhat darker amber, similar to motor oil._

After 3 hours, sample was removed from oven and allowed to cool. No odour was apparent.

Sample was allowed to cool for 30 minutes, then was weighed.

194 g	pan + Dextrose
182	Dextrose only

(Note scale has a resolution of 2 grams, thus range may be 181 to 183 g.)

Sample has a caramelized taste. After some hours, surface was slightly damp, making it sticky to the touch.

Sample was particularly brittle, and broke with sharp edges.

Objective :

To determine the effects of lightly heating Dextrose Monohydrate.

Method:

A sample of 200 grams of consumer grade Dextrose (corn sugar) was carefully weighed using 2 kg digital scale (2g resolution). The form was very fine granular, similar to "fruit sugar". The sample was transferred to a pyrex glass heating container, and slowly heated over an electric element set a low heat. A thermocouple (type K) monitored the temperature of the sample. As well, a high quality meat thermometer (0-100°C) was occasionally used to measure the temperature.

Results:

Shortly after heated commenced, the sample began to "cake", slightly at first, increasing with time.

<u>Sample</u>	<u>Thermocouple readings</u>	<u>Thermometer *</u>
light caking	1.7 mV	
	1.8	
	2.3	
medium caking	2.8	
much caking	3.7 - 4.0 mV	46°C
	5.2	51°C
heavy caking	5.1	
1 st sign of melt	4.3	
	4.6	
largely melt	4.5 - 4.7	
clear melt	5.3 - 5.5	
	4.7	83°C
	4.7	81°C

The temperature of the melted sample was taken; sample was a slurry (some lumps): 4.6 mV

The colour at this time was off white; no odour apparent.

After about 25 minutes, the sample was mostly melted, with only a few small lumps present: 4.9 - 5.0 mV

After 30 minutes, sample removed from heat source: 5.7 - 5.8 mV
Thermometer reading was greater than 100C. The appearance was that of a very clear liquid, like water, with many tiny bubbles forming a froth on the surface, apparently caused by the stirring. The viscosity was surprisingly low, like that of 18% cream or vegetable oil.

The melted sample was very "sticky".

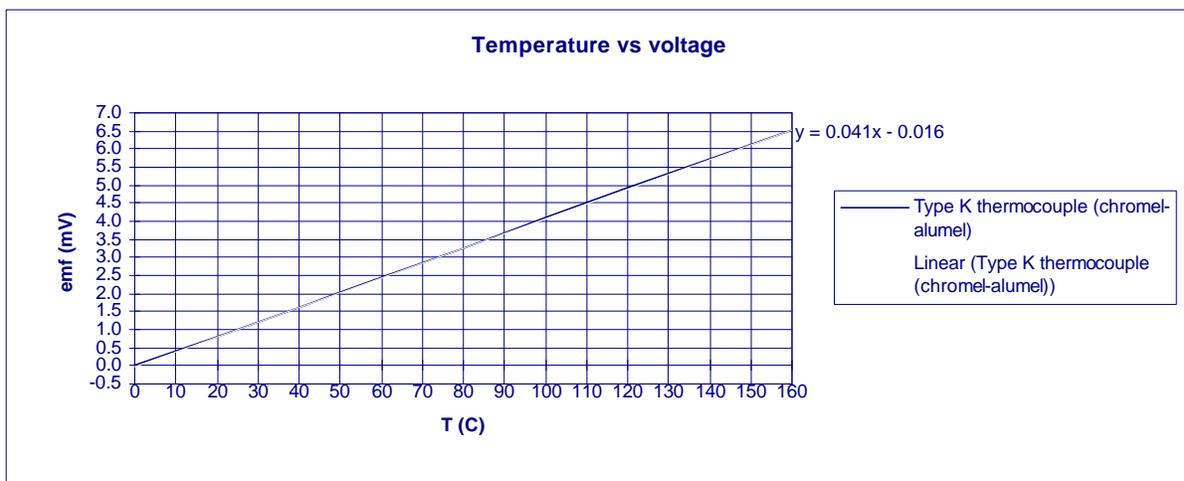
The sample was allowed to cool at room temperature. After 3.5 hours, when the sample was fully cooled, a knife was used to probe

the sample. It was quite pliable, or plastic, and stringy when cut and drawn.

After 24 hours, the surface of the sample was completely dry to the touch. Much of the surface was translucent crystalline in appearance, although in middle of surface, the sample was transparent. Once the surface was broken (with a knife) in the transparent area, spots of liquid (water?) appeared. Beneath the surface, the sample was gummy and formed strings when pulled with a knife. Felt dry to the touch, however. The translucent regions of the sample were completely dry and hard, however.

Weights after 24 hours: sample + pot = 948 g.
 pot = 758 g.
 Therefore, sample weight = 948-758=190 g.

Conversion of emf to Temperature				
	mV	mV	C	C
light caking	1.7		42	0
	1.8		44	
	2.3		56	
medium caking	2.8		69	
	3.7	4.0	91	98
heavy caking	5.2		127	
	5.1		125	
1st sign of melting	4.3		105	
	4.6		113	
largely melted	4.5	4.7	110	115
	5.3	5.5	130	135
clear melt	4.7		115	
	4.7		115	



Ref. OMEGA Temperature Hdbk.Vol.29

* Accuracy of the "candy thermometer" readings are in doubt, due to slow response rate.

Objective :

To determine the effects of *reheating* the Dextrose sample that was lightly heated in Test DX200798-1.

Method:

The sample, now in the form of a white coloured circular block, was slowly reheated, in a pyrex pot, using an electric heating element. The temperature of the sample was measured using the same thermocouple (type K).

Results:

Melted slurry: emf 3.6 - 3.7 mV

Sample tended to bubble when inadvertently overheated (e.g .tipping pot to dip probe in sample).

The sample turned to a completely transparent liquid once fully melted, with the viscosity similar, or same, as during original heating (like vegetable oil).

Melted liquid: emf 5.3 mV

Sample was allowed to cool. Appearance returned to that of appearance before reheat test.

Objective :

To determine the effects of *reheating* the Dextrose sample that was moderately heated in Test DX180798-1.

Method:

The sample, now in the form of an amber coloured, transparent circular block, was slowly reheated, in a pyrex pot, using an electric heating element. The temperature of the sample was measured using the same thermocouple (type K).

Results:

Melted, initially: emf 3.7 mV

The sample, when fully melted had a viscosity similar, or same, as during original heating (like liquid honey).

Melted liquid: emf 3.0 - 4.0 mV

A small amount of sample was intentionally formed around the thermocouple probe, and allowed to harden. The approximate emf when the sample had hardened (no longer pliable) was about 1.9 mV.

Sample was allowed to cool. Appearance returned to that of appearance before reheat test.

Objective :

To determine the effects of prolonged heating on a sample of Dextrose Monohydrate.

Method

A sample of 200 grams of consumer grade Dextrose (corn sugar) was carefully weighed using 2 kg digital scale(2g resolution). The sample was transferred to a pyrex glass heating container, and slowly heated over an electric element set a low heat. A thermocouple (type K) monitored the temperature of the sample.

Wt. of pot = 974 g.

Wt. of pot + sample = 1174 g.

Results:

As with the previous tests, the sample began to cake then eventually melted into a slurry. Heating continued and sample began active bubbling (emf 6.0, 6.1 mV).

Bubbling became more rapid: emf 6.3, 6.4 mV

Sample became very clear, thin liquid: emf 6.6, 6.7, 6.8 mV

Continued rapid bubbling, clear liquid: emf 7.2,7.3, 7.4 mV

Continued rapid bubbling, light amber liquid: emf 7.4 mV

Continued rapid bubbling, sample began to reduce; medium amber liquid: emf 7.6 mV

Continued rapid bubbling, sample continued to reduce; colour and viscosity that of motor oil; somewhat sweet odour: emf 7.8 mV

Continued rapid bubbling; distinctive odour, faintly like cloves? sample then removed from heat: final emf 7.9 mV

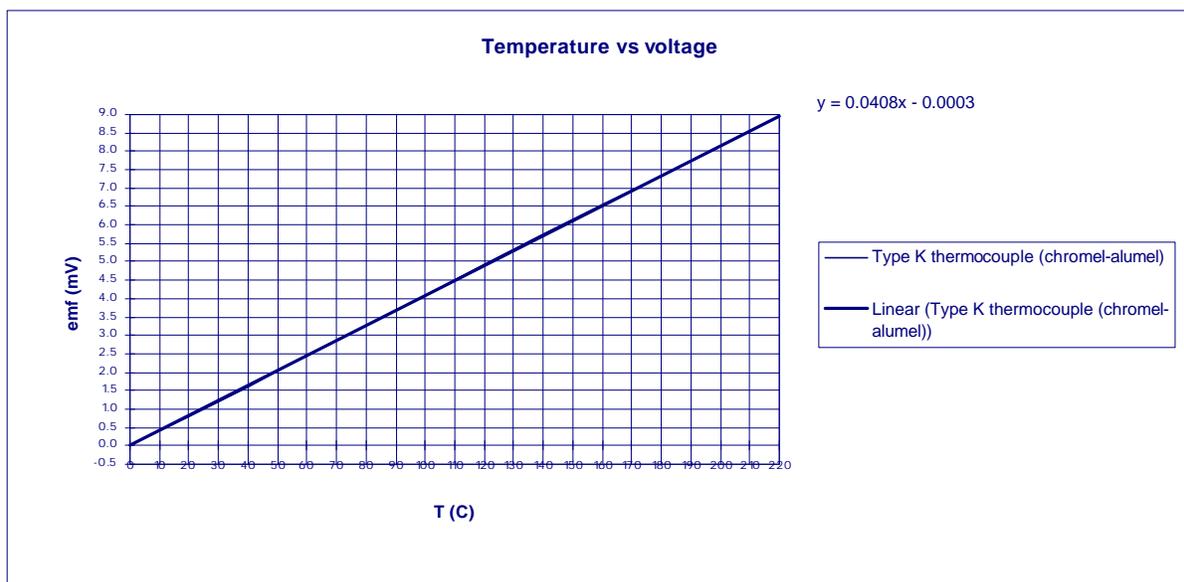
Total heating time was about 25 minutes.

Sample was cooled by setting pot in a bath of cool water, then weighed when fully cooled to room temperature.

Wt. pot + sample = 1154 g.

Therefore, final sample wt.= 1174 - 1154 = 180 g.

		Conversion of emf to Temperature	
		mV	C
rapid bubbling		6.0	147
		6.1	150
		6.3	154
thin, clear liquid		6.4	157
		6.6	162
		6.7	164
		6.8	167
colour light amber		7.2	176
		7.3	179
		7.4	181
	colour medium amber	7.6	186
	resembles motor oil	7.8	191
		7.9	194



Ref. OMEGA Temperature Hdbk.Vol.29

Objective :

According to Merck Index, Dextrose Monohydrate changes to the anhydrous form (D-glucose) above 50°C. The object of this test is to investigate the effects of heating a sample of consumer grade Dextrose (corn sugar) above this temperature, and in particular, to determine if there is a weight loss associated with such, indicating a change to the anhydrous form.

Method

A 200 gram sample of consumer grade Dextrose was carefully weighed using 2 kg digital scale (2g resolution). This was then spread out onto a heavy gauge, baking-paper lined aluminum baking pan (approx. 30x45 cm), typical depth 1 cm. This was then placed in a pre-heated oven set at minimum (140°F). An oven thermometer indicated an initial temperature of about 150°F (66°C); during the heating period, which was 100 minutes the temperature gradually rose. Near the end of the heating period, the temperature had risen to close to 200°F (93°C).

Results:

At the end of the heating period, a slight amount of melting was apparent near the edge of the sample in one region. Most of the sample, however, looking similar to its original condition, although had a much "drier" appearance, with a crust formed over the top of the sample. When the sample was transferred from the pan to a weighing container, it was in the form of large "caked" pieces and dry powder. Appeared to have a significantly lower density than original form. The colour was pure white, and the appearance was powdery or granular (varied).

Final weight: container + sample = 196 g.
 Container = 14 g.

Therefore, sample final weight = 182 g.

Discussion:

The final weight, which was 18 grams less than the weight before heating, strongly suggests that it changed to the anhydrous form of Dextrose (D-glucose)*. This value matches the predicted weight loss given by the following:

M.W. Dextrose Monohydrate	$C_6H_{12}O_6 \cdot H_2O$	198 kg/kmol
M.W. D-glucose	$C_6H_{12}O_6$	180 kg/kmol

Mass of water: $(198-180)/198 * 200 = \underline{18.2 g}$.

* Keeping in mind the 2 g. resolution limitation of the weighing apparatus.

Objective :

To obtain a rudimentary indication of Dextrose as a propellant fuel and binder by testing a sample of KNO_3 -Dextrose propellant prepared with previously heated Dextrose.

Method:

The Dextrose left over from test DX210798-3 (prolonged heating) was reheated to allow for removal of a portion of the sample to be used for this test. The colour, which did not change during the reheating, was a medium amber, similar in appearance to heavy motor oil. The consistency was very similar to honey when melted, including the tendency to form "strings" when the stirring utensil was lifted from the melted sample.

After cooling, the portion was then partially ground using a mortar and pestle. The colour and consistency of the ground material was similar in appearance to sawdust, being a orange-tinged amber in colour, not unlike "sponge candy".

The taste was basically sweet, with a sharp bitter undertaste.

A sample size of 44 g. was carefully weighed, and mixed with 82 g KNO_3 , which was lightly ground using a mortar and pestle. This gives an O/F ratio of 65/35. The mixture was then stirred and shaken for about 5 minutes. Then the mixture was further ground using a mortar and pestle for about 5 minutes.

A fraction of the mixture was then slowly heated in a deep fryer set at minimum heat. The temperature was taken of the sample, using a thermocouple (type K) probe.

Results:

Initial melting: emf 4.0 mV

Heating continued: emf 4.3 mV

Fully fluid: emf 5.0 mV

The molten mixture was then removed, and formed into a number of "standard" strands for burnrate testing. The appearance was identical to the usual KNO_3 -sucrose propellant, being light brown in colour with identical texture.

Cooled strands soon began to become slightly sticky on outer surfaces (hygroscopic).

A burnrate test was conducted on two strands:

Lg1 = 2.4 cm

Lg2 = 2.7 cm

tb1 = 8.66 s.
r1 = 0.277 cm/s

Tb2 = 13.41 s.
r2 = 0.201 cm/s

In both cases, recorded burnrates are maximum values, as false ignition occurred, as a drop of molten product ignited strand below the flame front.

Burned similar to usual 65/35 sucrose based propellant, except that burnrate was clearly slower, and many white "balls" of product were produced and scattered during burning, not unlike the effect of burning a KNO_3 -rich propellant. Quite a lot of carbon was present after burning.

Discussion:

Casting the propellant was very similar to casting sucrose-based propellant, however, the casting temperature was markedly lower.

The burning characteristics of this sample were inferior, as the burnrate was markedly less (0.36 cm/s for sucrose based 65/35) and unclean burning. However, this may well be the result of minimal blending of the constituents and also the oxidizer particle size, which was only slightly ground.

The intent of this test was mainly to *qualitatively* determine whether the feasibility of Dextrose based propellant was real, rather than produce a fine specimen.

Conclusion:

It is concluded that there is definite merit in Dextrose based propellant (eg lower cast temperature- compares to 360-380F for sucrose based; possibility of greater pot life), if acceptable burning characteristics and performance can be met. Further testing is therefore both justified and necessary.

		Conversion of emf to Temperature		
		mV	C	F
Initial melting		4.0	98	208
continued melting		4.3	105	222
Fully fluid		5.0	123	253

Objective :

To observe the effects of heating *anhydrous Dextrose* (sample from test DX220798-1) and in particular, to determine melting point.

Method:

A sample of about 50 g (not weighed) anhydrous Dextrose was placed in a pyrex pot and slowly heated over an electric element. Temperature of the sample was monitored using a thermocouple (type K) probe.

Results:

Sample seemed to take longer to melt than the hydrated form of Dextrose, and required slightly higher heat setting.

Initial melting: emf 5.9 - 6.0 mV

Continued melting: emf 5.7 - 5.8 mV
emf 5.7 - 6.0 mV

The appearance of the largely melted sample was a translucent white (tiny bubbles?); no active bubbling.

First hint of caramelization: emf 6.4

Active bubbling commenced: emf 7.0 mV

Heating was ceased at this point. Pot was place in a water bath to cool.

Sample was nearly transparent, with a very light amber colour. Appeared to be hard and brittle. Surface was somewhat sticky (hygroscopic).

Discussion:

The initial melting occurred at 145°C, which corresponds to the m.p. of D-glucose. This compared to an initial melting point of 105°C that was measured for the Dextrose Monohydrate. It may be concluded that the anhydrous form of Dextrose Monohydrate is, in fact, D-glucose. This is confirmed by the results of test DX220798-1 which indicated a mass loss during dehydration which corresponded to the change from Dextrose Monohydrate to D-glucose.

M.W. Dextrose Monohydrate $C_6H_{12}O_6 \cdot H_2O$ m.p. = 86°C
 M.W. D-glucose $C_6H_{12}O_6$ m.p. = 146°C (d)

(Ref. CRC Hdbk. Of Chemistry & Physics, 54th ed.)

	Conversion of emf to Temperature	
	mV	C
Initial melting	5.9	145
	6.0	147
continued melting	5.7	140
	5.8	142
1st sign of carameliz.	6.4	157
Active bubbling	7.0	172

Objective :

To determine the effects of heating, on a sample of sucrose, as a comparison to Dextrose.

Method:

A sample of sucrose (powdered form, icing sugar) of approximately 100 grams (not weighed) was slowly heated, over an electric element, in a pyrex pot. A thermocouple probe (type K) was used to measure the sample temperature.

Results:

A greater degree of heating was required to initiate melting compared to the Dextrose samples.

Initial melting: emf 7.5 mV

Significant caramelization began immediately as sample melted, including distinctive smell. The initial colour of the slurry was light brown. This quickly darkened upon further heating.

Well melted slurry: emf 7.7 to 7.8 mV

Fully melted and fluid: emf 7.9 - 8.0 mV

The appearance of the fully melted sample was a murky brown mixture, with many tiny bubbles (due to stirring?). Strong smell of caramel.

Heating was stopped at this point, and sample was cooled by placing pot in a water bath. The surface soon became sticky due to moisture absorption (hygroscopic). Total heating time was 15-20 minutes.

The taste was like caramel, and the appearance was brown colour and translucent bordering on transparent. Sample was hard and seemed brittle.

		Conversion of emf to Temperature	
		mV	C
Initial melting		7.5	184
	well melted	7.7	189
fully melted		7.8	191
		7.9	194
		8.0	196

Objective :

To determine the burnrate of anhydrous Dextrose based propellant, 65/35 O/F, prepared with minimal heating.

Method

A sample of mixture was prepared
Anhydrous Dextrose 44 g
Potassium Nitrate 82 g (ground)

Mixed for 3.5 hr.

A small sample of this was cast (approx. 20 g) into strands.
The colour of strands was "dirty white". Quite hygroscopic.

Results:

Sample 1 Lg = 26.0 mm
 tb = 13.00 s.
 giving r = 0.200 cm/s.

Burned very nicely, only small balls of spatter. Orange flame (daylight).

Sample 2 Lg = 25.0 mm
 tb = 12.72 s.
 giving r = 0.197 cm/s.

Objective :

To determine the burnrate of Dextrose Monohydrate based propellant, 65/35 O/F (true), prepared with minimal heating, moderate heating, and strong heating.

Method

A sample of 126 g. (true) mixture was prepared:

Dextrose Monohydrate $1.1 \cdot 0.35 \cdot 126 = 48.5$ g (ground)

Potassium Nitrate $0.65 \cdot 126 = 82$ g (ground)

Actual mass of mixture = 132 g.

Mixed for TBA hrs.

Three sample strands were cast:

- 1) immediately after mixture fully melted
- 2) After moderate heating, approx. 10 min.
- 3) After mixture began to caramelize, about 15 min.

Appearance of strands:

- 1) Very white, matte surface, not too hygroscopic, flexible
- 2) Dirty white, shiny surface, hygroscopic, brittle
- 3) Caramelized (similar to sucrose based with minimal heating), shiny surface, hygroscopic.

Results:

Sample 1 Tamb = 28°C
 Lg = 35.5 mm
 tb = 23.94 s.
 giving r = 0.148 cm/s.

 Lg1 = 21.0 mm
 Lg2 = 21.0 mm
 tb1 = 14.61 s.
 tb2 = 29.43-14.61=14.82 s.
 giving r1 = 0.144 cm/s.
 r2 = 0.142 cm/s.

Burned seemingly slower, otherwise similar, however, the burning surface did not burn evenly -edges burned at a slower rate, sort of hollowing effect. Due to moisture on surfaces?

Sample 2 Tamb = 19°C
 Lg1 = 50.0-25.5=24.5mm
 Lg2 = 25.5 mm
 Lg3 = 50.0 mm
 tb1 = 14.95 s.
 tb2 = 30.00-14.95=15.05 s.

giving

$$tb3 = 30.00 \text{ s.}$$

$$r1 = \underline{0.164} \text{ cm/s.}$$

$$r2 = \underline{0.169} \text{ cm/s.}$$

$$r3 = \underline{0.167} \text{ cm/s.}$$

Dextrose Test

DX250798-2

(cont.) Date 25/26 July 1998

Sample 3

Tamb = 19°C

Lg1 = 60.0-27.0=33.0 mm

Lg2 = 27.0 mm

Lg3 = 60.0 mm

tb1 = 18.92 s.

tb2 = 34.50-18.92=15.58 s.

tb3 = 34.50 s.

giving

r1 = $\frac{0.174}{}$ cm/s.

r2 = $\frac{0.173}{}$ cm/s.

r3 = $\frac{0.174}{}$ cm/s.

Burned very nicely, clean burning surface, no balls formed, no sparks.

Objective :

To determine the burnrate of Dextrose (anhydrous) based propellant, 60/40 O/F (true).

Method

The 110 g. remaining mixture of the 65/35 ratio (DX250798-1) was modified by the addition of anhydrous Dextrose to change the ratio to 60/40.

Anhydrous Dextrose $m_{ado} = 0.35 \cdot 110 = 38.5$ g.
Calculate mass of anhydrous Dextrose to be added (m_{ad}'):

where $m_{ad}' = (ff \cdot m_{po} - m_{ado}) / (1 - ff)$
 ff = mass fraction of fuel in propellant
 m_{po} = original propellant mass
 m_{ado} = original fuel mass

Therefore $m_{ad}' = (0.40 \cdot 110 - 38.5) / (1 - 0.40) = 9.2$ g.
Giving $m_p = 110 + 9.2 = 119.2$ g.

Sample was mixed for 1 hr., then cast. Melted mixture was more fluid than 65/35 mixture. Strands were poured for burnrate testing (quite hygroscopic).

Results:

Strand 1 $T_{amb} = 19^\circ\text{C}$
 $L_{g1} = 55.0 - 26.0 = 29.0$ mm
 $L_{g2} = 26.0$ mm
 $L_{g3} = 55.0$ mm
 $t_{b1} = 14.80$ s.
 $t_{b2} = 27.72 - 14.80 = 12.92$ s.
 $t_{b3} = 22.72$ s.
giving $r_1 = \underline{0.196}$ cm/s.
 $r_2 = \underline{0.201}$ cm/s.
 $r_3 = \underline{0.198}$ cm/s.

Strand 2 $L_g = 28.5$ mm
 $t_b = 13.59$ s.
giving $r = \underline{0.210}$ cm/s.

Both strands burned very nicely, orange lower flame, pink upper flame (nighttime), appeared to be similar to a sucrose based flame. Essentially no spatter.

Objective :

To repeat burnrate tests for four previously produced strands:

- 1) DX220798-2 Caramelized Dextrose
- 2) DX250798-1 Anhydrous Dextrose 65/35, ground KNO₃
- 3) DX240798-2 Anhydrous Dextrose 65/35, granular KNO₃
- 4) DX240798-2 Anhydrous Dextrose 60/40, ground KNO₃

Method

Burnrate tests were conducted for the four samples

Results

Sample 1)

Lg1 = 41.7 mm
Lg2 = 32.6 mm
tb1 = 21.91 s.
tb2 = 15.2 s. (estimated; false ignition)
giving r1 = 0.190 cm/s.
r2 = 0.21 cm/s. (estimated)

The strand burned with much white spatter. White balls formed on the burning surface, and sparks were emanating. False ignition was caused by a ball that rolled down and ignited strand base.

Balls of spatter were very hygroscopic, even deliquescent.

Sample 2)

Tamb = 23°C
Lg = 29.7 mm
tb = 14.72 s.
giving r = 0.202 cm/s.

Sample 3)

Tamb = 23°C
Lg = 38.0 mm
tb = nil s.
giving nil

False ignition occurred due to spatter.

Sample 4)

Tamb = 23°C
Lg = 31.3 mm
tb = 15.50 s.
giving r = 0.202 cm/s.

Strand burned very nicely, linear, even flame front, and clean.

Objective :

To determine the burning characteristics of 55/45 O/F ratio Dextrose based propellant.

Method

The remaining mixture for test DX250798-3 (60/40 true) was altered by the addition of anhydrous Dextrose to obtain 55/45 O/F ratio.

Anhydrous Dextrose mado = 0.35*110=38.5 g.
Calculate mass of anhydrous Dextrose to be added (mad'):

where $mad' = (ff*mpo-mado)/(1-ff)$

ff=mass fraction of fuel in propellant = 0.45
mpo=original propellant mass = 92 g.
mado=original fuel mass = 0.40*92=36.8 g.

Therefore $mad' = (0.45*92-36.8)/(1-.45)= 8.4$ g.
Giving $mp = 92+8.4=100.4$ g.

The sample strands were cast in the usual manner, cast well with much fluidity. The appearance of the cooled strand was shiny, and quite pure white. Hygroscopic.

Results:

Burnrate testing was conducted on one strand.

Tamb = 25°C
Lg1 = 41.0-21.0.0=20.0 mm
Lg2 = 21.0 mm
Lg3 = 41.0 mm
tb1 = 14.12 s.
tb2 = 29.44-14.12=15.32 s.
tb3 = 29.44 s.
giving r1 = 0.142 cm/s.
r2 = 0.137 cm/s.
r3 = 0.139 cm/s.

Strand burned quite slowly, with very many carbon flakes produced.

Objective:

To determine the burning characteristics of 70/30 O/F ratio Dextrose (anhydrous) based propellant.

Method:

A sample of 70/30 mixture was prepared using finely ground anhydrous Dextrose and finely ground potassium nitrate*. The sample size was approximately 90 g. It was mixed for 1 hour.

Greater heating was required to melt the mixture, and the resulting consistency was thicker than usual.

Very slight caramelization occurred. The cast strands had a somewhat grainy appearance, and the colour was white with a hint of yellow.

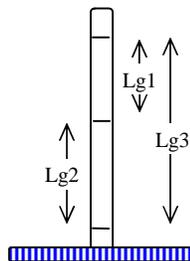
Results:

Burnrate testing was conducted on one strand.

$$\begin{aligned}
 T_{amb} &= 23^{\circ}\text{C} \\
 L_{g1} &= 49.0 - 23.5 = 25.5 \text{ mm} \\
 L_{g2} &= 23.5 \text{ mm} \\
 L_{g3} &= 49.0 \text{ mm} \\
 t_{b1} &= 18.33 \text{ s.} \\
 t_{b2} &= 34.56 - 18.33 = 16.23 \text{ s.} \\
 t_{b3} &= 34.56 \text{ s.} \\
 \text{giving } r_1 &= \frac{0.139}{\text{cm/s.}} \\
 r_2 &= \frac{0.145}{\text{cm/s.}} \\
 r_3 &= \frac{0.142}{\text{cm/s.}}
 \end{aligned}$$

There was a great deal of spatter and drops of white solid that formed around the base of the strand holder. This material had a very slippery feel when wet, and is presumed to be potassium carbonate. The burning surface receded at a rather uneven rate.

Typical strand setup



* An electric coffee grinder was used to finely grind the constituents. This has been standard procedure since test DX250798-1

Objective:

To determine the burning characteristics of 65/35 O/F ratio Dextrose Monohydrate based propellant (a repeat of test DX250798-2). In particular, to determine the effects of residual moisture on burnrate, and compare to earlier results of this test.

Method:

The sample from test DX250798-2 was heated slowly. A thermocouple monitored the melt temperature.

<u>Sample</u>	<u>Approx. Time</u>	<u>emf (mV)</u>	<u>Strand appearance</u>
1)	4 min.	5.0	pure white, hygroscopic
2)	8 min	6.9	dirty white with slight yellowing
3)	12 min	7.5	light caramel colour

Results:

Burnrate testing was conducted on one strand.

Sample 1)	Tamb = 23°C
	Lg1 = 58.0-30.8=27.2 mm
	Lg2 = 30.8 mm
	Lg3 = 58.0 mm
	tb1 = 17.74 s.
	tb2 = 36.87-17.74=19.13 s.
	tb3 = 36.87 s.
giving	r1 = <u>0.153</u> cm/s.
	r2 = <u>0.161</u> cm/s.
	r3 = <u>0.157</u> cm/s.
Sample 2)	Tamb = 23°C
	Lg1 = 52.5-25.4=27.1 mm
	Lg2 = 25.4 mm
	Lg3 = 52.5 mm
	tb1 = 14.49+1.0=15.49 s.(est.)
	tb2 = 29.57+1.0-15.49=15.08 s.
	tb3 = 29.57+1.0=30.57 s.(est)
giving	r1 = <u>0.175</u> cm/s. (est)
	r2 = <u>0.168</u> cm/s.
	r3 = <u>0.172</u> cm/s. (est)

An error occurred while operating stopwatch and approximately one second was lost at start of burn. Therefore, one second was added onto times shown.

Dextrose Test DX270798-2 (cont.)

Sample 3) $T_{amb} = 23^{\circ}C$
 $Lg1 = 54.3 - 28.0 = 26.3 \text{ mm}$
 $Lg2 = 28.0 \text{ mm}$
 $Lg3 = 54.3 \text{ mm}$
 $tb1 = 14.95 \text{ s.}$
 $tb2 = 30.78 - 14.95 = 15.83 \text{ s.}$
 $tb3 = 30.78 \text{ s.}$

giving $r1 = \frac{0.176}{\text{cm/s.}}$
 $r2 = \frac{0.177}{\text{cm/s.}}$
 $r3 = \frac{0.176}{\text{cm/s.}}$

All three samples burned very nicely and evenly.

		Conversion of emf to Temperature	
		mV	C
Initial melting		5.6	137
continued melting		6.9	169
Caramelized		7.5	184

Objective:

To determine the burning characteristics of 70/30 O/F Dextrose (anhydrous) based propellant. The sample for test DX270798-1 was used to cast two strands.

Method:

A strand prepared earlier (27 July), as well as two new strands were tested in the same manner as for test DX270798-1.

Results:

Strand 1

giving Tamb = 24°C
Lg1 = 44.8 mm
Lg2 = 26.8 mm
tb1 = 32.88 s.
tb2 = 17.62 s.
r1 = 0.136 cm/s.
r2 = 0.152 cm/s.

The burning surface was quite uneven, making exact timing difficult.

Strand 2

giving Tamb = 24°C
Lg = 44.0 mm
tb = 31.22
r = 0.141 cm/s.

Strand 3

giving Tamb = 24°C
Lg = 39.0 mm
tb = 26.56 s.
r = 0.147 cm/s.

The burning surface was quite uneven, making exact timing difficult. As well, the slow burn rate added to the inaccuracy in obtaining burn times.

Objective:

To determine the burning characteristics of 62.5/37.5 O/F Dextrose (anhydrous) based propellant.

Method:

A sample of 128 grams mixture was prepared, using the balance-beam scale for precision weighing of the constituents. Mixed for 1.5 hrs.

Three strands were cast. Very hygroscopic.

Results:

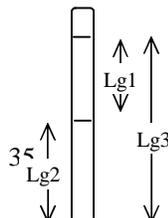
Strand 1) Tamb = 16°C
 Lg1 = 22.6 mm
 Lg2 = 27.9 mm
 Lg3 = 50.5 mm
 tb1 = 12.12 s.
 tb2 = 14.79 s.
 tb3 = 26.91 s.
 giving r1 = $\frac{0.187}{\text{cm/s}}$
 r2 = $\frac{0.189}{\text{cm/s}}$
 r3 = $\frac{0.188}{\text{cm/s}}$

Burned v.nicely, even burning surface.

Strand 2) Tamb = 16°C
 Lg1 = 27.1 mm
 Lg2 = 29.7 mm
 Lg3 = 56.8 mm
 tb1 = 14.33 s.
 tb2 = 15.58 s.
 tb3 = 29.91 s.
 giving r1 = $\frac{0.189}{\text{cm/s}}$
 r2 = $\frac{0.191}{\text{cm/s}}$
 r3 = $\frac{0.190}{\text{cm/s}}$

Strand 3) Tamb = 16°C
 Lg1 = 21.4 mm
 Lg2 = 24.9 mm
 Lg3 = 46.3 mm
 tb1 = 11.30 s.
 tb2 = 13.20 s.
 tb3 = 24.50 s.
 giving r1 = $\frac{0.189}{\text{cm/s}}$
 r2 = $\frac{0.189}{\text{cm/s}}$
 r3 = $\frac{0.189}{\text{cm/s}}$

Typical strand setup



Objective:

To determine the burning characteristics of 65/35 O/F Dextrose (anhydrous) based propellant.

Method:

A sample of 80 grams mixture was prepared, using the balance-beam scale for precision weighing of the constituents. Mixed for 1.0 hr. Three strands were cast. The colour was typical, off-white, and v.slightly caramelization (?).

Results:

Strand 1) Tamb = 27°C
 Lg1 = 26.7 mm
 Lg2 = 35.5 mm
 Lg3 = 62.28 mm
 tb1 = 14.24 s.
 tb2 = 18.63 s.
 tb3 = 32.87 s.
 giving r1 = $\frac{0.188}{\text{cm/s}}$.
 r2 = $\frac{0.191}{\text{cm/s}}$.
 r3 = $\frac{0.189}{\text{cm/s}}$.

Some small balls formed on burning surface.

Strand 2) Tamb = 27°C
 Lg1 = 29.3 mm
 Lg2 = 28.05 mm
 Lg3 = 57.32 mm
 tb1 = 15.65 s.
 tb2 = 15.19 s.
 tb3 = 30.84 s.
 giving r1 = $\frac{0.187}{\text{cm/s}}$.
 r2 = $\frac{0.185}{\text{cm/s}}$.
 r3 = $\frac{0.186}{\text{cm/s}}$.

Strand 2 sat in sun for about 6 minutes.

Strand 3) Tamb = 27°C
 Lg1 = 22.68 mm
 Lg2 = 28.46 mm
 Lg3 = 51.14 mm
 tb1 = 12.39 s.
 tb2 = 16.14 s.
 tb3 = 28.53 s.
 giving r1 = $\frac{0.183}{\text{cm/s}}$.
 r2 = $\frac{0.176}{\text{cm/s}}$.
 r3 = $\frac{0.179}{\text{cm/s}}$.

No apparent reason why burnrate of Strand 3 was less.

Objective:

To determine the burning characteristics of 60/40 O/F Dextrose (anhydrous) based propellant.

Method:

A sample of 66 grams mixture was prepared, using the balance-beam scale for precision weighing of the constituents. 39.872 g. KNO₃; 26.525 g. dextrose
Mixed for 1.5 hr.
Three strands were cast. The colour was very white.

Results:

Strand 1)	Tamb = 27°C
	Lg1 = 26.63 mm
	Lg2 = 27.04 mm
	Lg3 = 53.67 mm
	tb1 = 14.18 s.
	tb2 = 14.26 s.
	tb3 = 28.44 s.
giving	r1 = <u>0.188</u> cm/s.
	r2 = <u>0.189</u> cm/s.
	r3 = <u>0.188</u> cm/s.

Some very small balls formed on burning surface.

Strand 2)	Tamb = 27°C
	Lg1 = 25.22 mm
	Lg2 = 29.97 mm
	Lg3 = 55.19 mm
	tb1 = 13.21 s.
	tb2 = 15.89 s.
	tb3 = 29.10 s.
giving	r1 = <u>0.191</u> cm/s.
	r2 = <u>0.189</u> cm/s.
	r3 = <u>0.190</u> cm/s.

Strand 3)	Tamb = 27°C
	Lg = 43.24 mm
	tb = 23.50 s.
	r = <u>0.184</u> cm/s.

Objective:

To determine the burning characteristics of 65/35 O/F Sucrose based propellant, as well as the casting temperature of the molten mix.

Method:

A sample of 61 grams mixture was prepared, using the balance-beam scale for precision weighing of the constituents. 39.872 g. KNO₃; 21.541 g. sucrose (icing sugar).

Two strands were form-cast. Casting of strands was difficult, as mixture tended to freeze rapidly. The colour was medium caramel. The strands seemed less hygroscopic than dextrose based strands.

Initial melting: 7.1 mV (174°C)
Fully melted: 7.5-7.6 mV (184-187°C)

Results:

Strand 1) Tamb = 22°C
Lg1 = 30.8 mm
Lg2 = 29.8 mm
Lg3 = 60.6 mm
tb1 = 8.08 s.
tb2 = 8.23 s.
tb3 = 16.31 s.
giving r1 = 0.381 cm/s.
r2 = 0.362 cm/s.
r3 = 0.372 cm/s.

Some false ignition may have occurred due to spattering (?).

Strand 2) Tamb = 20°C
Tgrain = 19°C achieved ambient temp in room
Lg1 = 31.5 mm
Lg2 = 39.2 mm
Lg3 = 70.7 mm
tb1 = 8.86 s.
tb2 = 10.92 s.
tb3 = 19.78 s.
giving r1 = 0.356 cm/s.
r2 = 0.359 cm/s.
r3 = 0.357 cm/s.

Objective:

To determine the burning characteristics of 60/40 O/F Sucrose based propellant, as well as the casting temperature of the molten mix.

Method:

A sample of 66 grams mixture was prepared, using the balance-beam scale for precision weighing of the constituents. 39.872 g. KNO₃; 26.525 g. sucrose (icing sugar). Mixed for 3.5 hours.

Two strands were form-cast. Casting of strands was difficult, as mixture tended to freeze rapidly. The colour was medium caramel. The strands seemed as hygroscopic than dextrose based strands. Mechanically, the strands seemed weaker than dextrose based.

Initial melting: 6.0 mV (147°C)

Fully melted: 7.1 mV (174°C)

Results:

Strand 1) Tamb = 24°C
 Lg = 41.6 mm
 tb = 11.75 s.
 giving r = 0.354 cm/s.

Strand burned very nicely, with an orange violet flame (evening).

Strand 2) Tamb = 24°C
 Lg1 = 28.0 mm
 Lg2 = 31.0 mm
 Lg3 = 59.0 mm
 tb1 = 7.80 s.
 tb2 = 8.77 s.
 tb3 = 16.57 s.
 giving r1 = 0.359 cm/s.
 r2 = 0.354 cm/s.
 r3 = 0.356 cm/s.

Objective:

To determine the burning characteristics of 65/35 O/F Dextrose based caramelized propellant; essentially a repeat of test DX260798-1 #1.

Method:

A single strand was cast from sample of DX220798-2. A burnrate test was conducted.

Results:

	Tamb = 24°C
	Lg = 50.43 mm
	tb = 25.93 s.
giving	r = <u>0.195</u> cm/s.

Objective:

To determine the burning characteristics of 70/30 O/F Sucrose based propellant, as well as the casting temperature of the molten mix.

Method:

A sample of 35 grams mixture was prepared, using the balance-beam scale for precision weighing of the constituents. 24.92 g. KNO₃; 10.503 g. sucrose (icing sugar). Two strands were form-cast. Casting of strands was very difficult, due to thick consistency, and as mixture tended to freeze rapidly. Neither strand could be pour cast and instead had to be formed into a strand like working putty. The shape was approximately rectangular, 10x4 mm. The colour was very light tan. The strands seemed less hygroscopic than 65/35 strands.

Results:

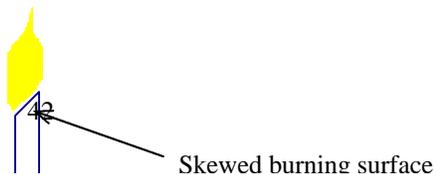
Strand 1)	Tamb = 25.5°C
	Lg1 = 27.4 mm
	Lg2 = n/a mm
	Lg3 = 55.2 mm
	tb1 = 5.92 s. (est.)
	tb2 = n/a s.
	tb3 = 10.47 s.
giving	r1 = <u>0.463</u> cm/s.
	r2 = <u>n/a</u> cm/s.
	r3 = <u>0.527</u> cm/s.

False ignition occurred after passing first gauge mark, as a ball rolled down strand and ignited lower region. Strand burned very rapidly. Balls formed on surface with much spatter. Second strand was accidentally ignited by this spatter. Strands burned very unevenly as burning progressed (ie burn surface not normal to strand axis, but skewed sharply).

Strand 2) (consumed accidentally by spatter)

Discussion:

The reason for rapid burnrate may be due to *forming* the strands rather than pour casting. As the slurry was rapidly freezing at this point, there may have been a large number of microcracks formed while trying to press the partially solidified melt into strands. This hypothesis is backed by the fact that burning progressed very unevenly, which was not normally seen during previous tests.



Objective:

To determine the burning characteristics of 55/45 O/F Sucrose based propellant.

Method:

A sample of 36 grams mixture was prepared, using the balance-beam scale for precision weighing of the constituents: 19.936 g. KNO₃; 16.290 g. sucrose (icing sugar).

Two strands were prepared. Casting of strands was difficult, as mixture tended to freeze rapidly. However, first strand could be pour cast nicely, but second had to be formed into a strand. The shape was somewhat flattened oval, 3.5x10 mm. The strands were hygroscopic and a very light tan in colour

Results:

Strand 1)	Tamb = 25.5°C
	Lg1 = 32.5 mm
	Lg2 = 34.5 mm
	Lg3 = 67.0 mm
	tb1 = 11.93 s. (est.)
	tb2 = 12.73 s.
	tb3 = 24.66 s.
giving	r1 = <u>0.272</u> cm/s.
	r2 = <u>0.271</u> cm/s.
	r3 = <u>0.272</u> cm/s.

Burned very nicely, evenly, with an orange coloured flame, lots of smoke (with a brownish tinge) and carbon flakes forming at burning surface.

Stand 2)	Tamb = 25.5°C
	Lg = 36.7 mm
	tb = 13.94 s.
giving	r = <u>0.263</u> cm/s.

Objective:

To determine the burning characteristics of 70/30 O/F Sucrose based propellant, as well as the temperature of the cast melt.

Method:

A sample of 85 grams mixture was prepared, using the balance-beam scale for precision weighing of the constituents: 59.808 g. KNO₃; 25.455 g. sucrose (icing sugar). Mixed for 2.0 hours. Three strands were prepared utilizing a newly fabricated extruding tool with a 0.25 inch extrusion hole. Extruder was preheated in an oven to 325°F to allow for more time for mixture to remain in molten state. Extruding required a fair amount of plunger force. The first strand was thicker than typical, about 8 mm diameter. Second strand was typical, about 6 mm diameter. The third strand was about 6 mm triangular cross-section and quite short. Slurry was solidifying at this point and strand had to be formed after extruding. The strands seemed to be less hygroscopic than usual. Strands were cast on 6th August. Burnrate testing was conducted on 7th August.

Initial melting: 6.1 mV (150°C)
Fully melted: 7.2 mV (176°C)

Results:

Strand 1) Tamb = 21°C (very humid)
 Tgrn = 67°F (19.4°C)
 Lg1 = 44.7 mm
 Lg2 = 39.4 mm
 Lg3 = 84.1 mm
 tb1 = 13.18 s. (est.)
 tb2 = 12.13 s.
 tb3 = 25.31 s.
 giving r1 = 0.339 cm/s.
 r2 = 0.325 cm/s.
 r3 = 0.332 cm/s.

Balls were forming and sparks were emanating from surface. Very nice and even burning.

Stand 2) Tamb = 22°C (very humid)
 Tgrn = 68°F (20°C)
 Lg = 43.5 mm
 tb = 13.00 s.
 giving r = 0.335 cm/s.

Stand 3) Tamb = 22°C (very humid)
 Tgrn = 68°F (20°C)

giving $L_g = 27.0$ mm
 $t_b = 7.37$ s. (est.)
 $r = \underline{0.366}$ cm/s.

False ignition occurred and burn time was therefore estimated.

Objective:

To determine the burning characteristics of 75/25 O/F Sucrose based propellant, as well as the temperature of the cast melt.

Method:

A sample of 50 grams mixture was prepared, using the balance-beam scale for precision weighing of the constituents: 37.380 g. KNO₃; 12.46 g. sucrose (icing sugar). Mixed for 2.0 hours. Two strands were prepared utilizing the extruding tool. Extruder was preheated in an oven to 325°F. Extruding required a fair amount of plunger force. The first strand has a particularly rough surface (grainy looking). Strands were cast on 6th August. Burnrate testing was conducted on 7th August.

Initial melting: 6.1 mV (150°C)
Fully melted: 7.6 mV (187°C)

Results:

Strand 1) Tamb = 22°C (very humid)
 Tgrn = 68°F (20°C)
 Lg1 = 29.2 mm
 Lg2 = 31.7 mm
 Lg3 = 60.9 mm
 tb1 = 19.33 s.
 tb2 = 19.12 s.
 tb3 = 38.45 s.
 giving r1 = 0.151 cm/s.
 r2 = 0.166 cm/s.
 r3 = 0.158 cm/s.

Large balls formed on the burning surface which had a greenish-yellow colour while molten, then became pure white, hard substance when cooled -- very hygroscopic, even deliquescent, forming puddles in the very humid air after an hour or so.

Stand 2) Tamb = 22°C (very humid)
 Tgrn = 68°F (20°C)
 Lg = 32.1 mm
 tb = 18.81 s.
 giving r = 0.171 cm/s.

Objective:

To determine the mass change and temperature change due to heating of Dextrose Monohydrate.

Method:

A sample of 250 grams of Dextrose Monohydrate was weighed using the balance beam scale. Exact weight was 249.20 grams. The digital scale (2 gram resolution) was used for all subsequent weighing for convenience. A different supply of Dextrose was used for this test, a 500 g. container (Bio-Health) that was left over from Aug. 1996 tests.

The sample was transferred to a stainless steel bowl for heating over an electric element. Initial weight of the bowl + sample was 430 (on the verge of 432) grams.

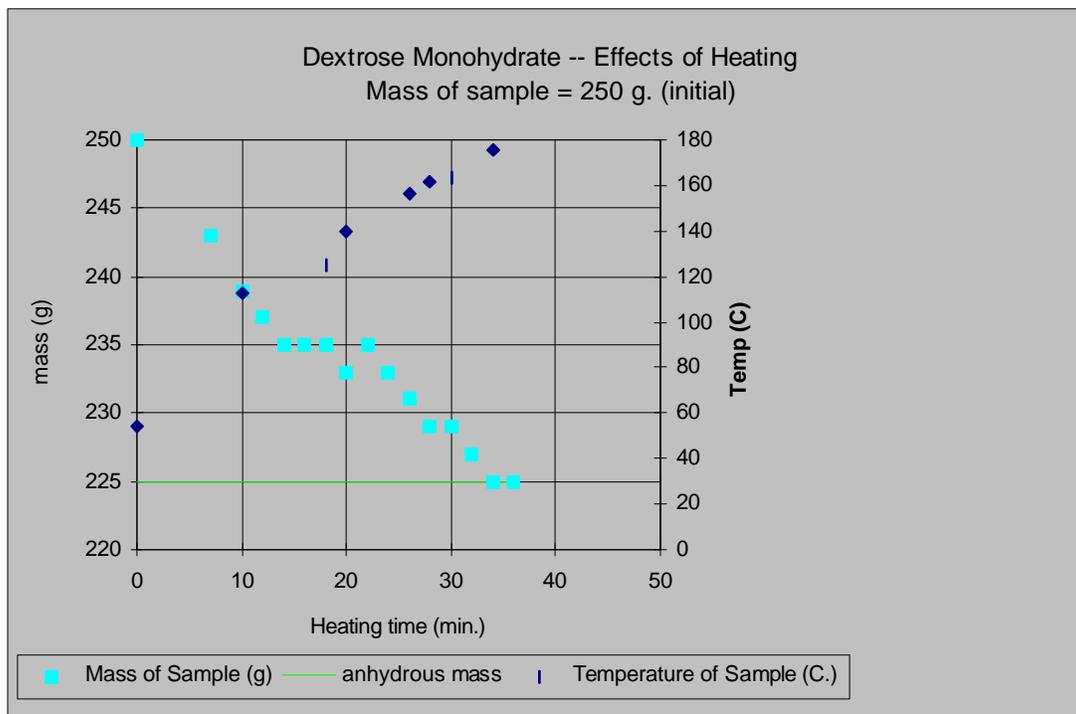
The sample was heated with moderate heating, fairly well stirred. A K type thermocouple was used to sample the temperature of the sample occasionally.

Once the sample was fully melted, stirring occurred less frequently. The mixture was initially maintained just below the "active bubbling" stage, although at later stages of heating, active bubbling could not be avoided.

Results:

Time (min.)	TC emf (m.v.)	Wt(g)*	Colour	Comment
n/a	2.2 - 2.3	n/a	n/a	Powder form
n/a	2.6	n/a	n/a	Caked powder
n/a	2.7 - 2.8	n/a	n/a	Well caked powder
n/a	3.3	n/a	n/a	Partially melted
n/a	4.6	n/a	n/a	Fully melted
n/a	-	424	n/a	Well caked
n/a	-	420	n/a	Largely melted
0.00	-	418	n/a	Melted, but lumpy
2.0		416		
4.0		416		
6.0	5.1	416		Light active bubbling
8.0	5.7	414		Light active bubbling
10.0		416		
12.0		414		
14.0	6.4	412		Slight yellow
16.0	6.6	410		Light yellow
18.0	6.7	410		
20.0		408		Medium yellow
22.0	7.2	406		Golden yellow
24.0		406		Light amber

* weight of sample + bowl

Results : (cont.)Discussion:

In the above chart, the mass of the sample only (less tare) is shown. Also, 12 minutes are added to the times, to account for start of heating as $t=0$. (estimated).

It is apparent that significant heating is required to drive off all the moisture in the hydrated dextrose. As the moisture is removed, the temperature of the melt increases, at roughly a linear rate and continuously. Since $t=0$ is the fully melted state, if heating was stopped at this point (as may be the case with propellant preparation), most of the water remains in the end product. To remove all the water (anhydrous state), it is necessary to continue heating until pure D-glucose (dextrose anhydrous) is remaining.

Objective:

To determine the mass change and temperature change due to heating of Dextrose Monohydrate (a repeat of test DX090898-1). For this test, time was started immediately upon heating the (powder) sample.

Method:

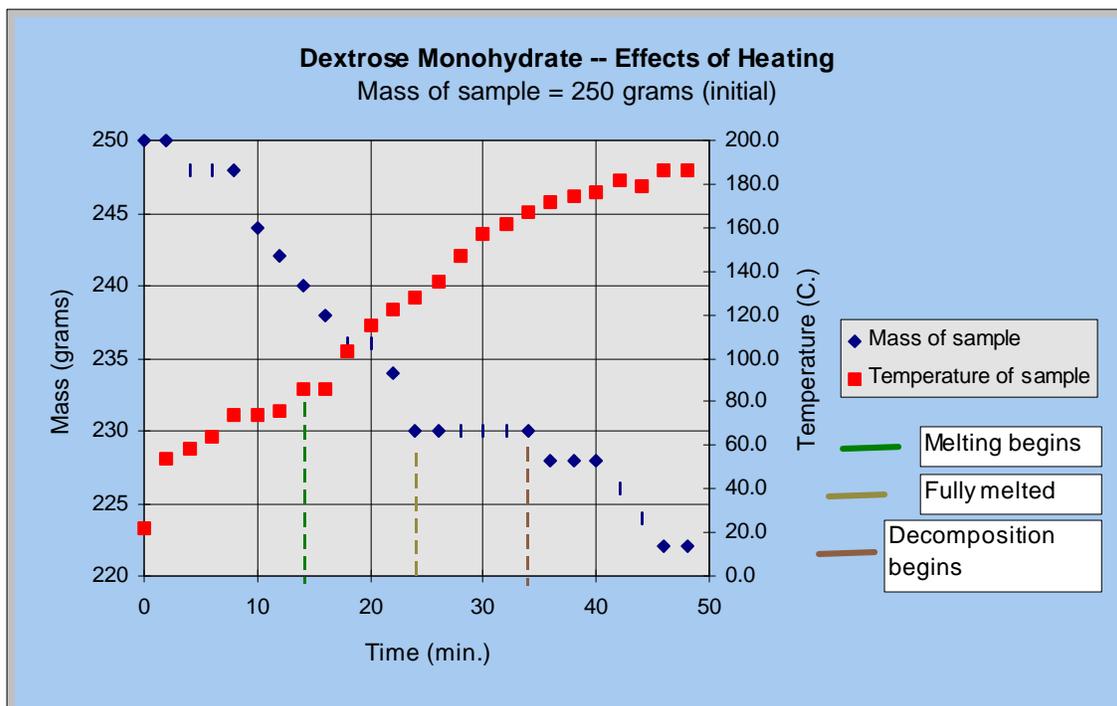
A sample of 250 grams of Dextrose Monohydrate was weighed using the digital scale (2 gram resolution). A thermocouple (type K) was used to monitor the sample temperature every two minutes. As well, the sample was briefly removed from the heating element and weighed (using the same scale). Tare weight of the bowl was 182 grams. Heating was moderately low (2 setting) and stirring was done regularly.

Results:

Time	Gross Mass	Sample Mass	k-thermo emf	Temp	Texture	Colour
min.	grams	grams	mV	C.		
0	432	250	0.9	22.1	powder	pure white
2	432	250	2.2	53.9	slight caking	pure white
4	430	248	2.4	58.8	some caking	pure white
6	430	248	2.6	63.7	some caking	pure white
8	430	248	3	73.5	some caking	pure white
10	426	244	3	73.5	heavy caking	pure white
12	424	242	3.1	76.0	heavy caking	pure white
14	422	240	3.5	85.8	some melting	pure white
16	420	238	3.5	85.8	lumpy	pure white
18	418	236	4.2	102.9	no powder left	pure white
20	418	236	4.7	115.2	lumpy slurry	pure white
22	416	234	5	122.6	largely melted	greyish white
24	412	230	5.2	127.5	largely melted	greyish white
26	412	230	5.5	134.8	fully melted	greyish white
28	412	230	6	147.1	fully melted	milky grey
30	412	230	6.4	156.9	thin liquid	milky grey
32	412	230	6.6	161.8	thin liquid	slight yellowish
34	412	230	6.8	166.7	thin liquid	yellowish
36	410	228	7	171.6	thin liquid	yellow
38	410	228	7.1	174.0	slightly reduced	yellow
40	410	228	7.2	176.5	slightly reduced	golden yellow
42	408	226	7.4	181.4	reduced	amber, clear
44	406	224	7.3	178.9	well reduced	medium amber
46	404	222	7.6	186.3	thin syrupy	medium amber
48	404	222	7.6	186.3	thin syrupy	medium amber

Anhydrous mass = $180.2/198.2 * 250 = 227 \text{ g}$.

Results (cont.).



Discussion:

The results are very similar to the previous test. A heating time of about 42 minutes is required to eliminate all the water from the sample. At this point, some decomposition has occurred, although to quite a minor degree.

It is interesting how the mass of the sample reaches a plateau once it is fully melted and remains until decomposition begins, as shown on the above chart. A similar plateau is seen on the graph of the previous test.

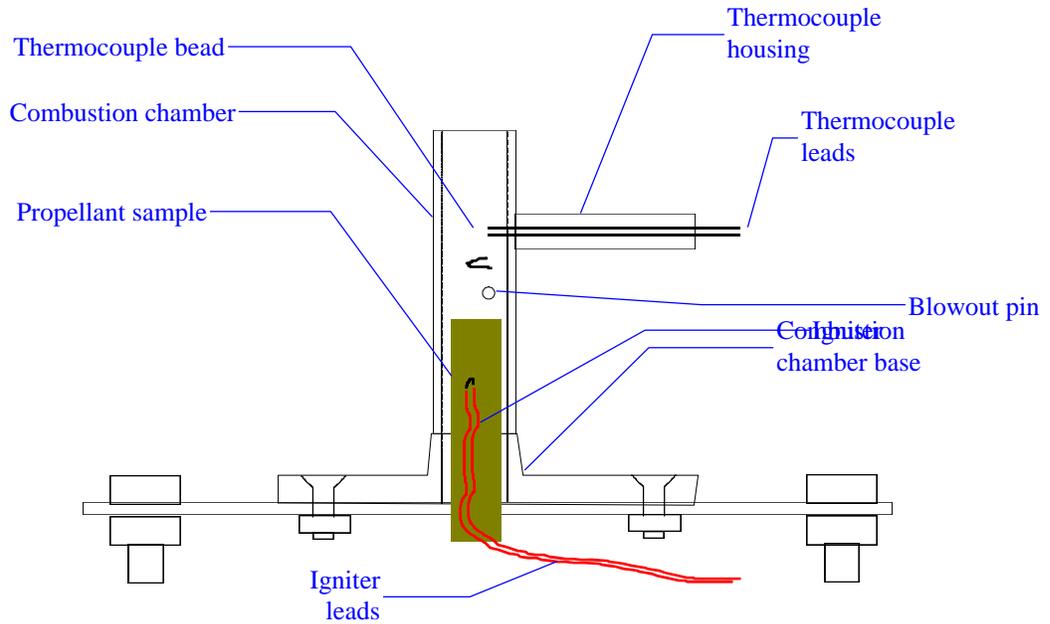
It is also seen the temperature rises nearly linearly until decomposition begins, then the rise tapers off.

Objective:

To conduct a trial testing of the combustion chamber apparatus. This apparatus is utilized to measure the combustion temperature (AFT) of various propellant samples. This is useful data, as the characteristic exhaust velocity (a measure of the performance of a propellant) is related to combustion temperature.

Method:

The apparatus consists of a pipe in which the sample is housed, closed at the bottom end (where the sample is placed) but open at the top end. A thermocouple is situated about 2/3 way up the pipe, used to measure the temperature of the combustion gases. The sample used is 65/35 sucrose based propellant cast earlier (stored in freezer) for test DX010898-3. The sample is electrically ignited using a nichrome wire igniter.



Combustion chamber: 1/2 black iron pipe thread 1/2NPT bottom end

Thermocouple: Type C, Tungsten-5% Rhenium vs Tungsten-26% Rhenium

Thermocouple housing: 1/8 black iron pipe, threaded 1/8NPT one end with two ceramic insulating tubes epoxied within

Results:

The sample immediately ignited, and burned for about 2 seconds. The DVM feature for recording max. emf did not record maximum, as the TC was connected incorrectly, resulting in negative readings (hence a minimum). However, I watched the digital readout and noticed -18 mV (approx) as the minimum. The apparatus worked perfectly.

Note that for this test, a single TC was used, ie a second TC (in an ice bath) was not used.

Discussion:

A reading of 18 mV converts to 990°C (1263 K). This value is lower than theoretical AFT by about 200°. This may be due to the short burn time (sample was too small), heat loss to vessel walls, or lack of a reference temperature (ice bath), which would also contribute to error.

Objective:

To conduct a trial testing of the combustion chamber experiment. Basically, a repeat of test DX140898-1, but for this test, the TC was connected properly, and a larger sample size was used. The sample propellant was 62.5/37.5 Dextrose based, cast for test DX310798-2 (stored in freezer).

Method:

Identical to previous test.

Results:

Sample ignited immediately upon depressing ignition switch. Burned for about 6 seconds. Max. emf was recorded at 17.4 mV.

Discussion:

This value of max. emf converts to a temperature of to 954°C (1227 K), which neglects lack of reference temperature.

The test apparatus again worked perfectly.

Objective:

To measure the combustion temperature of various propellant samples, both sucrose and dextrose based, and of varying O/F ratios.

Method:

Six propellant "slugs" were prepared: 5 were cast from existing prepared mixtures, and one had been previously cast (70/30 KNO₃-dextrose). The slugs varied in size, but were generally round to squarish in cross-section, approximately 1cm x 5cm length. The six slugs were as follows:

Slug #1)	60/40	sucrose-KNO ₃
Slug #2)	60/40	dextrose (anh.)-KNO ₃
Slug #3)	65/35	sucrose-KNO ₃
Slug #4)	62.5/37.5	dextrose (anh.)-KNO ₃
Slug #5)	70/30	dextrose (anh.)-KNO ₃
Slug #6)	70/30	sucrose-KNO ₃

All slugs were superficially damp on exposed surfaces.

Slugs were hot glued to chamber bottom, and igniter attached to side of slug, near the top. A second thermocouple was put in series with the primary, and placed in an ice-bath, for reference.

Results:

Slug #1 (60/40 sucrose-KNO₃)

Slug ignited immediately, and burned for about 2 seconds. The maximum DVM reading was recorded as 19.1 mV.

Slug #2 (60/40 dextrose-KNO₃)

Slug ignited immediately, and burned for about 5-6 seconds. The maximum DVM reading was recorded as 18.0 mV.

Slug #3 (65/35 sucrose-KNO₃)

Slug ignited immediately, and burned for about 5-6 seconds. The maximum DVM reading was recorded as 20.2 mV.

Slug #4 (62.5/37.5 dextrose-KNO₃)

Slug ignited immediately, and burned for 7.5 seconds (timed). The maximum DVM reading was recorded as 19.6 mV.

The flame emanating from the top of the combustion chamber was about 4" high, reddish-orange colour (nighttime).

Slug #5 (70/30 dextrose-KNO₃)

Slug ignited immediately, and burned for about n/a seconds. The maximum DVM reading was recorded as 22.6 mV.

Slug #6 (70/30 sucrose-KNO₃)

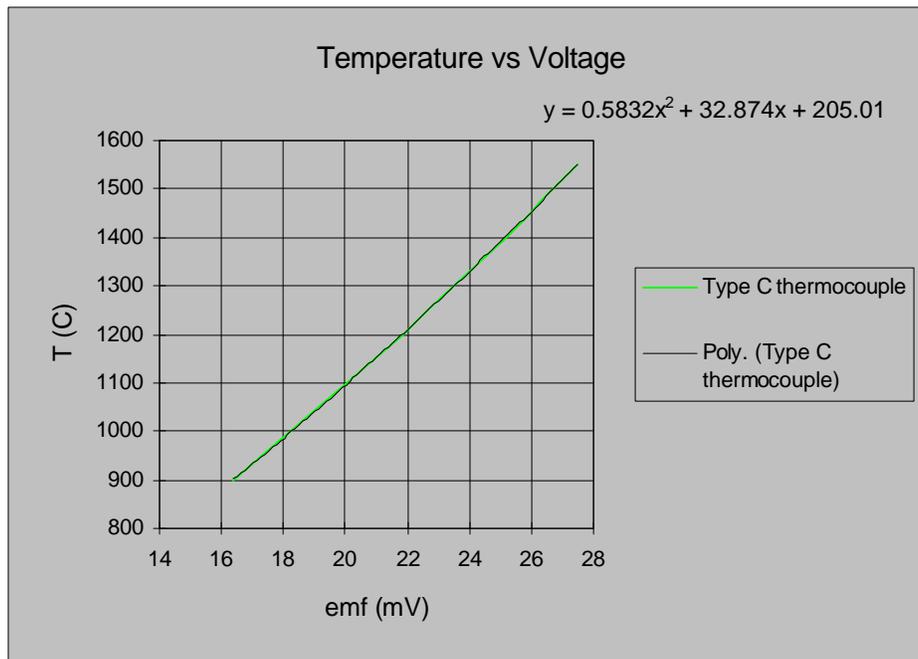
Slug ignited immediately, then shortly after shot out of top of combustion chamber. Maximum DVM reading was recorded as 19.8 mV however, was still rising when anomaly occurred.

Discussion:

The following table summarizes the results:

	Measured °C	Measured °K	Theoretical °K
Slug #1 (60/40 sucrose-KNO3)	1046	1319	1390
Slug #2 (60/40 dextrose-KNO3)	986	1259	1384
Slug #3 (65/35 sucrose-KNO3)	1107	1380	1486
Slug #4 (62.5/37.5 dextrose-KNO3)	1073	1346	1440
Slug #5 (70/30 dextrose-KNO3)	1246	1519	1564
Slug #6 (70/30 sucrose-KNO3)	invalid		

The measured values are in reasonable agreement with the theoretical values, in particular, the trend. Heat loss undoubtedly occurs via radiation losses to the combustion chamber walls. This would be reduced by using a highly reflective surface (low emissivity) on the inside walls.



Objective:

To measure the combustion temperature of various propellant samples using the combustion chamber apparatus.

Method:

The pipe comprising the combustion chamber was ground on the inside surfaces using an emery wheel in order to make it more reflective and thus lower the emissivity, in order to reduce radiation heat losses to the walls. As well, a pin was installed just below the TC bead, to protect it in case of slug blow out. Otherwise, the procedure was identical to test DX140898-2.

Five samples of propellant were tested:

Slug #1)	70/30	KNO3-sucrose
Slug #2)	70/30	KNO3-sucrose
Slug #3)	60/40	KNO3-dextrose
Slug #4)	60/40	KNO3-sucrose
Slug #5)	62.5/37.5	KNO3-dextrose

These samples were cast earlier, when producing strands for burnrate testing. These had been stored in a plastic vacuum-sealed bag and appeared to be in fine condition, without abnormal moisture absorption. Typical slug size was approximately 1 cm diameter by 4 to 5 cm length. However, the slug for the 5th sample was somewhat smaller.

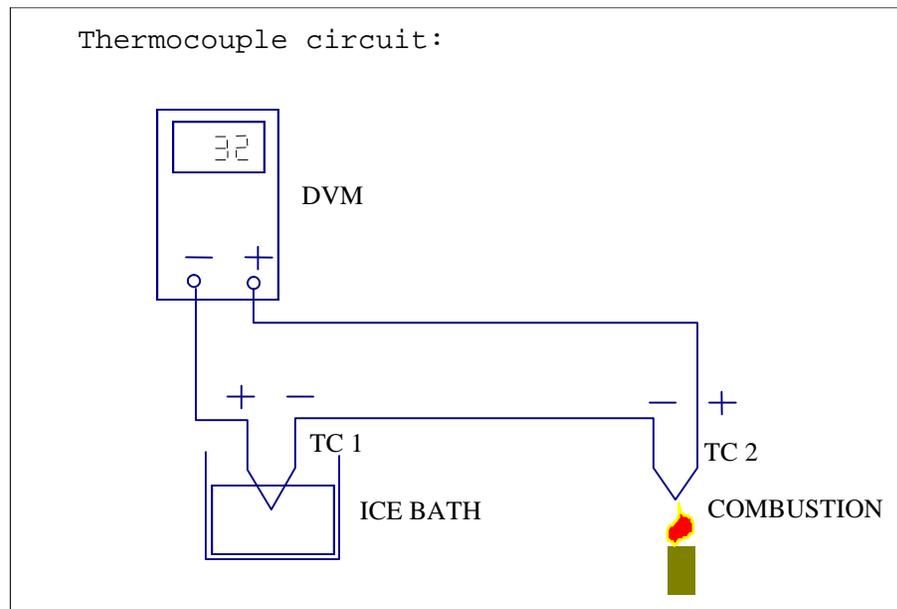
Results:

Slug #1:	Ignited immediately. Burn time was approximately 1.5-2 seconds. Maximum emf= <u>20.6 mV</u> .
Slug #2:	Ignited immediately. Burn time was approximately 1.5-2 seconds. Maximum emf= <u>20.6 mV</u> .
Slug #3:	Failed to ignite on first attempt. Igniter was replaced and ignition occurred immediately. Burn time was approximately 4 seconds. Maximum emf= <u>18.0 mV</u> . Ice in bath (thermocouple) was nearly depleted.
Slug #4:	Ignited immediately. Burn time was approximately 2 seconds. Maximum emf= <u>18.2 mV</u> . Ice in bath (thermocouple) was nearly depleted.
Slug #5:	Ignited immediately. Burn time was approximately 6 seconds. Maximum emf= <u>19.1 mV</u> . Ice in bath was replenished.

Discussion:

The following table summarizes the results:

	Measured °C	Measured °K	Theoretical °K
Slug #1 (70/30 sucrose-KNO3)	1130	1403	1564
Slug #2 (70/30 sucrose-KNO3)	1130	1403	1564
Slug #3 (60/40 dextrose-KNO3)	986	1259	1384
Slug #4 (60/40 sucrose-KNO3)	996	1269	1390
Slug #5 (62.5/37.5 dextrose-KNO3)	1046	1319	1440



Objective:

To measure the combustion temperature of various propellant samples using the combustion chamber apparatus.

Method:

The procedure was identical to test DX230898-1.

Two samples of propellant dry mix were prepared (65/35 KNO₃-sucrose and 73/27 KNO₃-dextrose) and two existing mixes were used to cast slugs for this test . The 65/35 KNO₃-sucrose was mixed 3 hours and the 73/27 KNO₃-dextrose was mixed 2.25 hours. The slug samples were as follows:

Slug #1)	55/45	KNO ₃ -sucrose	DX020898-2
Slug #2)	65/35	KNO ₃ -sucrose	
Slug #3)	65/35	KNO ₃ -dextrose	DX010898-1
Slug #4)	73/27	KNO ₃ -dextrose	

Typical slug size was approximately 1-1.4 cm diameter by 5-6 cm length.

Results:

- Test #1: 65/35 KNO₃-sucrose slug. Igniter was placed near bottom of slug. Did not ignite first attempt; igniter changed. Ignited immediately. Burn time was approximately 1 second. A loud whoosh sound was heard. Maximum emf= 19.6 mV.
- Test #2: 65/35 KNO₃-dextrose slug. Ignited immediately. Burn time was approximately 5 seconds. After the test, it was noticed that the blowout pin was (inadvertently) not installed. Maximum emf= 20.5 mV.
- Test #3: 65/35 KNO₃-sucrose slug. Igniter placed near top to increase burn time. Ignited immediately. Burn time was approximately 1-1.5 seconds. Maximum emf= 17.4 mV.
- Test #4: 73/27 KNO₃-dextrose slug. Igniter failed on first attempt and was replaced. Ignited immediately. Burn time was approximately 8 seconds. After reaching the maximum emf of 22.4 mv, the reading was noticed to be constant for about two seconds, then the readings became abnormal (TC had failed). Maximum valid emf= 22.4 mV.

Test #5: 55/45 KNO₃-sucrose slug. Ignited immediately. Burn time was approximately 4 seconds. Maximum emf= 17.6 mV.

Test #6: 65/35 KNO₃-dextrose slug. Ignited immediately. Burn time was approximately 5-6 seconds. Maximum emf= 19.7 mV.

Discussion:

The results for Tests 1 and 3 (65/35 KNO3-sucrose) are of questionable validity, owing to the short burn times that occurred. Since the DVM has a data sample integration period of about 0.5 seconds, the burn times of between one second and 1.5 seconds would not result in true maximum values of emf being displayed and recorded by the DVM. Rather the average over the integration period would be obtained.

Clearly the pressure in the chamber built up beyond atmospheric, accounting for the rapid burn rate. The whoosh sound that was heard attests to this assumption.

The following table summarizes the results:

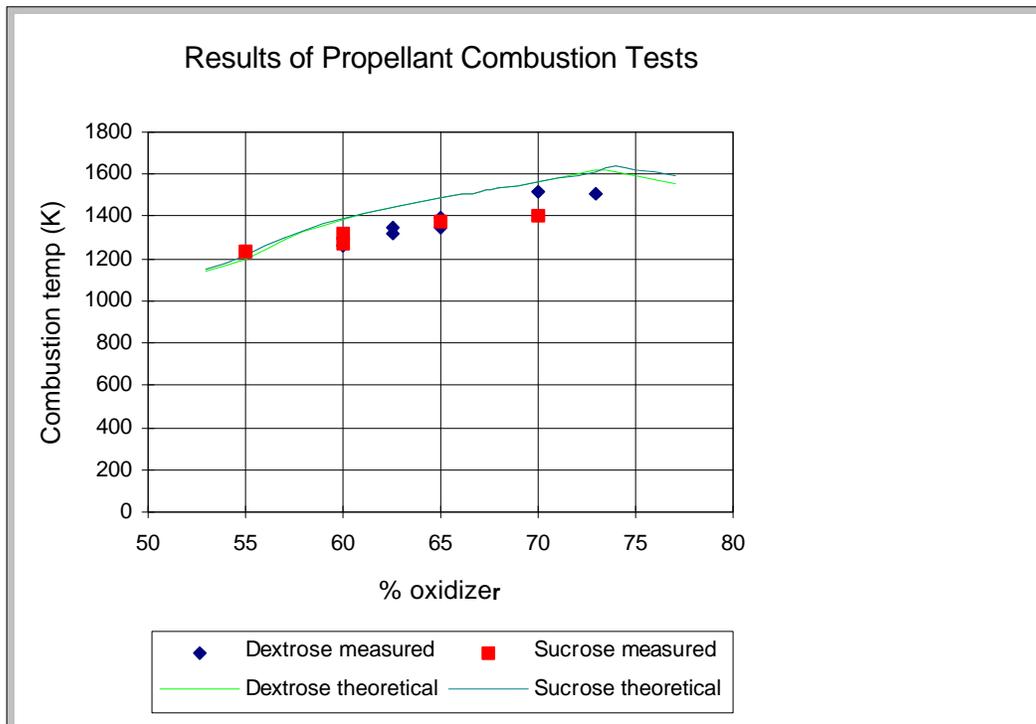
	Measured °C	Measured °K	Theoretical °K	
Test #1 (65/35 sucrose-KNO3)	1073	1346	1486	*
Test #2 (65/35 dextrose-KNO3)	1124	1397	1485	
Test #3 (65/35 sucrose-KNO3)	954	1227	1486	*
Test #4 (73/27 dextrose-KNO3)	1234	1507	1620	
Test #5 (55/45 sucrose-KNO3)	964	1237	1211	**
Test #6 (65/35 dextrose-KNO3)	1079	1352	1485	

* Valid?

** measured > theoretical

Theoretical based on CET runs.

Summary of Results -- Combustion Temperature Tests to Date



Dextrose Test DX301098-1

Date 30 October 1998

Objective:

To cast a sample propellant grain using dextrose monohydrate-based propellant, to determine how well the molten mixture casts as a grain with a central bore. Also, to investigate the properties of this grain with regard to physical properties.

Method:

A batch of 65/35 true O/F ratio KNO₃-dextrose monohydrate was prepared, for a total of 140 grams mixture. The batch was mixed for a total of about 3 hours. The mould was a 6" length of pipe (same as that used for B-200 casing) lined with a sheet of oil-soaked "24 lb." paper, with a B-200 nozzle mounted at one end. The nozzle convergent section was coated with bearing grease. The bore rod was a 5/8" steel rod, tapered at the insertion end, and coated with corn oil. Before the casting operating commenced, the mould and bore rod were placed in an oven set at minimum (140 °F.), and were removed just prior to the pouring procedure.

Results:

Upon heating, the mixture melted readily, and after about 10 minutes, it was ready for pouring. The consistency was quite fluid and poured fairly easily, but nevertheless required scooping with a spoon to get all the molten mixture into the mould (an open funnel made from a piece of sheet aluminum aided the process). The preheated bore rod was then inserted, and went in easily. A steel

washer was used to keep the bore rod centred inside the mould during cooling.

The casting was left to cool for 35 minutes and examined. Although it had largely cooled, it was still too pliable to attempt removal. After a further 10 minutes, the grain was removed, and came out of the mould (with paper attached to the grain) very easily. The paper peeled away cleanly, and the bore rod slipped out with almost no effort. There were no observable air bubbles, although the surface did have irregular features.

After the grain was completely cooled, its physical properties were examined. The colour was off-white, and was somewhat translucent. The grain was pliable such that the shape could be deformed by hand. If forced to deform quickly, however, the grain material would start to tear (in a "ragged" manner).

The grain was not at all hygroscopic, although this may be due to the low relative humidity in the room (compared to earlier "summertime" testing).

The grain was accidentally dropped on the floor, which resulted in several cracks in the grain, unexpectedly. Since the grain exhibited a "plastic" nature, brittle fractures were a surprise. A portion of the grain was then broken away, and was dealt a blow with a hammer. The piece shattered into several smaller pieces. After 24 hours, the grain was re-examined. The surface was still totally dry. The grain appeared to be slightly less plastic. A sample of the cast propellant was then ignited. It ignited quite easily, and burned well, very evenly, with an orange flame. The burnrate was not measured, but appeared to be consistent with earlier burnrate testing.

Density measurement test:

Using a laboratory grade graduated cylinder, 100 ml of mineral spirits was measured out, and poured into a 150 ml flask (5% rated accuracy). The reading indicated 104 ml. The grain was then placed in the flask and the volume was indicated at 140 ml. This give the volume of the grain as 140-104=36 ml.

The grain was then weighed using the beam balance scale. The mass was recorded to be 66.9 grams.

This gives the density of the cast propellant as

$$\rho = 66.9/36 = 1.858 \text{ g./cm}^3$$

Discussion:

Casting of this propellant was similar to casting the sucrose-based propellant, with some significant exceptions:

- Much quicker melting of the mixture.
- No indication of decomposition (caramelization) although some bubbling was observed at times, likely due to the water of hydration that was being released, and boiling in contact with the surface of the heating vessel.
- The molten slurry was noticeably "less hot", which made working with it (stirring, etc.) more pleasant.
- The slurry was much less viscous, and could be poured into the mould more effectively.
- Once cooled, the grain could be extracted from the mould and bore rod easily, unlike sucrose-based cast grains, which were often a pain to extract.

Although the mechanical properties of the cast grain are of a "plastic" nature, which would be advantageous, the material also exhibits an oddly brittle nature, negating the apparent "plastic" advantage. Whether the material retains this odd mechanical behaviour over time is something which need further investigation. The lack hygroscopicity is somewhat puzzling, as this propellant exhibited significant hygroscopicity during earlier strand testing. This could be explained, however, by the lower relative humidity typical at this time of the year.

The measured density is slightly lower than ideal (1.879 g./cm³), which would be expected owing to slight residual moisture.

Objective:

To determine the effects of overheating dextrose-based propellant, and in particular, to ascertain the risk of accidental ignition.

Method:

A sample size of about 10 grams of powdered anhydrous dextrose-based propellant (65/35 O/F ratio, prepared 98/08/16) was placed in a small aluminum pan. The pan was supported by a rig such that a forced-air heat gun (1400 Watt.; 1100 °F max. rating) was placed beneath, aimed upward. The tip of the gun was initially about 6 inches from the bottom of the pan. A type K chromel-alumel thermocouple was placed in the mixture to monitor temperature. The sample was then heated and the temperature monitored, as well as the observed physical changes to the sample.

Result:

After melting, the sample quickly started to develop brown regions. A metal rod was then used to stir the sample, to try to even out the heating and avoid "hot spots".

<i>Brown coloured areas first appear</i>	5.8 mV
<i>Well caramelized</i>	6.8 mV

After about 4 minutes of heating, the temperature reached a plateau at 6.8-7.2 mV.

Continued heating did not raise the temperature of the sample, but the colour continued to darken and black carbonized regions began to appear. Some bubbling was noticed, and a strong caramel odour. After several more minutes of heating without a temperature increase, the heat gun tip was moved closer to the pan (about 2 inches away).

The temperature reluctantly rose above 7.2 mV, then began to rise more rapidly, and eventually reached 12.3 mV. By this point in time, the sample was highly decomposed, the appearance being of a charred mixture of brown and black fused together, with some smoke apparent.

Heating was then stopped, with sample failing to attain ignition.

Conversion of emf to Temperature		
	mV	T (C)
Brown areas first appear	5.8	142
Well caramelized	6.8	167
Plateau reached	6.8	167
Temperature rise begins	7.2	176
Max. recorded	12.3	301

Discussion:

It is interesting that a temperature "plateau" was reached at about 167 °C. This corresponds to the temperature of decomposition that was observed in the test DX120898-1 (effects of heating dextrose monohydrate).

It would seem that added thermal energy goes into decomposing the dextrose, rather than increasing the thermal energy of the propellant. This would seem to be of value as a safeguard against severe overheating.

It was difficult to maintain uniform heating of the propellant. Some areas were clearly decomposing at a faster rate. As such, the temperature recorded by the thermocouple is a "local" temperature. As such, the maximum temperature recorded (301°C.) may not correspond to the maximum temperature experienced by the sample. The actual maximum could conceivably be higher.

A piece of the charred sample was later tested to see how it would ignite and burn. It ignited in a typical manner, and burned quite well, almost the same as pristine propellant.

A great deal of decomposition of the propellant results from overheating, commencing as soon as the propellant reaches a temperature that may be considered to be the onset of "overheating", around 167°C. The decomposition is readily apparent by abrupt colour change, odour, some bubbling and, if heated sufficiently, smoke. Black carbonated areas appear as heating is continued. Even when highly decomposed and the temperature begins to escalate, ignition was not achieved.

With such indicators of overheating, combined with the reluctance of the temperature to increase significantly, and the apparent resistance to ignition even when the temperature has risen well beyond the normal heating range, it would therefore seem improbable that accidental ignition of this propellant could occur through unintentional overheating during the casting operation.

(it should be noted that safety precautions must nevertheless always be taken when casting the propellant, as ignition through other means is always a possibility e.g. electrical short, static electricity, etc.)

Objective:

To determine the effects of overheating sucrose-based propellant, and in particular, to ascertain the risk of accidental ignition. Similar to test DX011198-1.

Method:

A sample size of about 10 grams of powdered sucrose-based propellant (65/35 O/F ratio, prepared for test DX280898-1) was placed in a small aluminum pan. The pan was supported by a rig such that a forced-air heat gun (1400 Watt.; 1100 °F max. rating) was placed beneath, aimed upward. The tip of the gun was initially about 4 inches from the bottom of the pan. A type K chromel-alumel thermocouple was placed in the mixture to monitor temperature. The sample was then heated and the temperature monitored, as well as the observed physical changes to the sample.

Result:

After melting, the sample quickly started to develop brown regions. A metal rod was then used to stir the sample, to try to even out the heating and avoid "hot spots".

<i>Brown coloured areas first appear</i>	8.5 mV
<i>Well caramelized</i>	9.0 mV

After about 5 minutes of heating, the temperature reached a plateau at 8.5-9.0 mV.

Continued heating did not raise the temperature of the sample, but the colour continued to darken and black carbonized regions began to appear. Much bubbling was noticed, and a strong caramel odour. The sample became highly decomposed (more so than dextrose-based sample), the appearance being of a charred mixture of brown and black fused together, with some smoke apparent.

It was decided that the heat gun would then be placed such that the hot stream of air would contact the sample on the top surface, in order to initiate ignition. The gun tip was placed about 1 inch away from the sample. 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, literally in a bright flash.

Conversion of emf to		
	mV	T (C)
Brown areas first appear	8.5	208
Well caramelized	9.0	221

Discussion:

As with the dextrose-based propellant, a temperature "plateau" was reached, although at a different temperature, about 208-221 °C. It would seem that added thermal energy goes into decomposing the sucrose, rather than increasing the thermal energy of the propellant.

This would seem to be of value as a safeguard against severe overheating.

It was difficult to maintain uniform heating of the propellant. Some areas were clearly decomposing at a faster rate. As such, the temperature recorded by the thermocouple is a "local" temperature.

A great deal of decomposition of the propellant results from overheating, commencing as soon as the propellant reaches a temperature that may be considered to be the onset of "overheating", just above 200°C. The decomposition is readily apparent by abrupt colour change, odour, some bubbling and, if heated sufficiently, smoke. Black carbonated areas appear as heating is continued. Even when highly decomposed and the temperature begins to escalate, ignition was not achieved. The ignition was "forced" to observe the consequence of such.

With such indicators of overheating, combined with the reluctance of the temperature to increase significantly, and the apparent resistance to ignition even when the temperature has risen well beyond the normal heating range, it would therefore seem improbable that accidental ignition of this propellant could occur through unintentional overheating during the casting operation.

(it should be noted that safety precautions must nevertheless always be taken when casting the propellant, as ignition through other means is always a possibility e.g. electrical short, static electricity, etc.)

Objective:

To cast a sample propellant grain using dextrose monohydrate-based propellant, to determine how well the molten mixture casts as a grain with a central bore. Also, to investigate the properties of this grain with regard to physical properties.

This is basically a repeat of test DX301098-1, except a larger batch of propellant is being cast, enough to produce a full size B-200 grain (except with a 5/8" bore rather than 9/16" bore).

Method:

A batch of 65/35 true O/F ratio KNO₃-dextrose monohydrate was prepared, for a total of about 280 grams mixture. The batch was mixed for a total of about 4 hours. The mould and procedure was identical to test DX301098-1.

Results:

Upon heating, the mixture melted readily. Although the mixture was fully melted after about 15 minutes, heating was continued for another five minutes to attempt to increase the fluidity (did not change much). The slurry poured fairly easily, but nevertheless required scooping with a spoon to get all the molten mixture into the mould. The preheated bore rod was then inserted, and went in easily. A steel washer was used to keep the bore rod centred inside the mould during cooling.

The casting was left to cool for about 1 hour. The grain came out of the mould (with paper attached to the grain) very easily. The paper peeled away cleanly, and the bore rod slipped out with almost no effort. There were no observable air bubbles, although the surface did have irregular features.

After the grain was completely cooled, its physical properties were examined. The colour was ivory, and was nearly opaque. The material was completely rigid, very similar to sucrose-based propellant. The grain was not at all hygroscopic. When a small sample was ignited, it burned in a manner seemingly typical of the anhydrous form of this propellant (although burnrate not measured).

Discussion:

The comments that were made in regard to the casting process in the discussion of test DX301098-1 are also applicable to this test. The final cast product, however, differed in mechanical properties, as noted above. This is undoubtedly due to the longer heating time, which would have driven off all moisture of hydration. This additional heating would therefore seem to be beneficial, as the final product form seems to be very good (see photo below).

